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United States Nuclear Regulatory Commission
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NUREG-1890

Evaluating Igneous Activity at Yucca Mountain

Technical Basis for Decisionmaking

Advisory Committee on Nuclear Waste and Materials

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ABSTRACT

Eighty thousand years ago a small-volume basaltic volcano, the Lathrop Wells volcano, erupted about 20 kilometers south of the Department of Energy's proposed high-level nuclear waste repository at Yucca Mountain, Nevada. Lathrop Wells is one of a series of infrequent basaltic volcanoes that have occurred near the proposed repository site during the past 10 million years. This report presents the Advisory Committee on Nuclear Waste and Materials (ACNW&M) summary and analysis of the range of current technical views on the nature, likelihood, and potential consequences of future igneous activity at the proposed repository. This report responds to the request of the U.S. Nuclear Regulatory Commission in Staff Requirements Memorandum M06011B, February 9, 2006. The technical views have been abstracted from published literature and public agency reports and presentations. The alternative views reflect uncertainties of the igneous processes that have occurred in the region and those that are likely to occur in the future, as well as the interaction of these processes with the proposed repository. Analysis of the views and observations is based on professional judgment and quantitative considerations within the scope of the resources available to ACNW&M.

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EXECUTIVE SUMMARY[1]

Eighty thousand years ago a small-volume basaltic volcano (Lathrop Wells) erupted about 15 miles south of the Department of Energy's (DOE) proposed high-level radioactive waste (HLW) repository in Yucca Mountain, Nevada. Lathrop Wells is one of a series of infrequent basaltic volcanoes that have occurred near the proposed repository site during the past 10 million years. This NUREG report presents the Advisory Committee on Nuclear Waste and Materials (ACNW&M) summary and analysis of the range of current technical views on the nature, likelihood and potential consequences of future igneous activity at the proposed repository. This report responds to the request of the U.S. Nuclear Regulatory Commission (NRC) in SRM M06011B, February 9, 2006. The technical views have been abstracted from published literature and public agency reports and presentations. The alternative views reflect uncertainties of the igneous processes that have occurred in the region and those that are likely to occur in the future, as well as the interaction of these processes with the proposed repository. Analysis of the views and observations is based on professional judgment and quantitative considerations within the scope of the resources available to the ACNW&M.

Two possible scenarios that involve different processes and consequences can be associated with the potential intersection of the repository with igneous activity. The extrusive (volcanic) scenario involves intersection of a volcanic-cone-forming conduit through the repository to the surface, possibly causing destruction of the waste packages intersected by the conduit and dispersal of contaminated volcanic ash over the Yucca Mountain vicinity. Very small particles of radioactively-contaminated ash from the volcanic eruption would be inhaled by the reasonably maximally exposed individual (RMEI). Current performance assessment calculations indicate that the largest dose from igneous activity is from a volcanic intersection during the first thousand years after closure of the repository. These calculations suggest that the maximum probability-weighted dose is only a fraction of the current dose standard and decreases with time. The principal factors in determining risk from the extrusive scenario are the probability of the event, including consideration of the probable location of future events and their recurrence rate, the number and contents of waste packages disrupted and entrained in the erupted ash, the eruption volume and the dispersal of the contaminated ash, the size distributions of the waste particles and ash, surface remobilization of contaminated ash by water and wind, and inhalation of the ash by humans.

The other scenario involves intrusion of an igneous dike into the repository, leading to possible damage or destruction of waste packages and premature release of the waste to infiltrating waters that pass through the repository to the vicinity of the RMEI where radioactive materials in the waste could be ingested directly or indirectly from vegetation and animals that have taken up the radioactively contaminated ground water. The maximum effect of the igneous intrusion scenario is not expected to occur for tens of thousands of years due to slow movement of the water from the repository to the vicinity of the RMEI. Present performance assessment calculations indicate the maximum probability-weighted dose from the intrusive scenario also is likely to be only a fraction of the current standard. The major factors in determining risk from the intrusive scenario, in addition to the probability of the event, are the number of waste packages affected by the intruding molten rock (magma) (determined by the viscosity of the magma and

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[1] References to sources of information presented are excluded in the Executive Summary. Detailed references to all specific sources of information and views on future igneous activity at Yucca Mountain are provided in the body of this report.

the magnitude and duration of the pressure upon entry), the extent of dissolution of radionuclides by infiltrating ground water, the rate at which ground water transports radionuclides to the vicinity of the RMEI, and the amount of radionuclides ingested by the RMEI.

The risk from these scenarios depends on the likelihood of the occurrence of an igneous event during the compliance period of the repository and the effect of or consequences from the event. Consequences depend on the nature of the anticipated igneous activity which is informed by investigations of past geologic and tectonic activity in the Yucca Mountain region, interpreted within the constraints of knowledge of geologic and physical processes. The nature, likelihood, and consequences of future igneous activity intersecting the proposed repository make up the risk triplet.

More than a quarter of a century of study of the volcanic history of the Yucca Mountain region has provided an almost unprecedented amount of information on igneous activity that is useful for predicting future volcanic activity. As a result, the divergence of views among investigators regarding the nature of future igneous events is relatively small. General agreement exists that future igneous activity is likely to be a small-volume, single-episode basaltic volcano similar to the 80,000-year-old Lathrop Wells volcano. Although uncertainties remain, this agreement extends to related parameters of the event such as power and duration, volume and type of erupted products, size of the volcanic conduit supplying lava to the surface, spatial relationship of the eruption to the topographic surface, geochemical characteristics of the magma, and igneous dike characteristics from which the volcano originates.

Recent detailed studies of nearby basaltic volcanoes in the Yucca Mountain region have provided an improved understanding of nominal eruptive behavior, including the style of lava effusion, that place controls on the nature of the possible igneous event scenarios. For example, the conditions necessary for explosive phreatic eruptions (maar volcanism, involving heating and expansion of groundwater) do not exist at Yucca Mountain. There is also no evidence that maar volcanoes formed near Yucca Mountain during the last 10 million years and they are not expected in the future.

One of the more challenging aspects of the igneous activity investigation is to estimate the likelihood of the occurrence of future igneous events. There are no recognized contemporary indicators of igneous events that could occur thousands of years in the future, sources of magma have not been found in the nearby Earth’s crust, there is no evidence that the repository footprint has been intersected by igneous activity in the last 13 million years, and the number of volcanic events in the region from which to extrapolate into the future is limited compared to other basaltic volcanic regions in the southwestern United States. As a result, there is a range of views on conceptual models used to predict probability of igneous events and uncertainties exist in parameters used in evaluating the models. Nonetheless, there is general agreement based primarily on the location and recurrence rate of volcanism over the past 5 million years that the range of probability of an igneous event intersecting the proposed repository is from 10^{-9}/yr to 10^{-7}/yr. The assumption of igneous event probabilities larger than 10^{-7}/yr is inconsistent with the number of volcanic events that have occurred during the past 5 million years. Moreover, care is necessary in comparing probability estimates because of changes in igneous event definitions during the past few decades that have progressively included the probability of intersecting dikes and sills of igneous material in addition to extrusive (volcanic) activity.

The consequences of an igneous event are less well understood than other components of the risk triplet. The study of consequences from the igneous intrusion scenario has been more limited than other aspects of the igneous activity program and there are no generally appropriate analogs. Thus the models and parameterization for intrusion consequence analysis are less mature than other segments of the program and considerable uncertainty exists in both consequence models and parameters. The principal difference in views of the intrusive scenario is associated with magma/drift/waste interaction and the distance that intruding magma will flow into the drifts as a result of uncertainties in the viscosity of the magma and the magnitude and duration of the pressure upon entry into the drifts. Models that do not incorporate evidence that the magma may have relatively high viscosities, consider quenching of magma on the drifts and waste packages, evaluate the role of progressive solidification of invading magma, and consider potential barriers to magma flow from drift-roof collapse may overestimate both the number and extent of damage to waste packages. Additional uncertainties exist in the extrusive scenario consequence analysis, e.g., the range of size of spent fuel particles and ash and the effects of large floods on the transport of contaminated ash of significance to the inhalation dose.

Consideration of the full range of current views on the nature, probability, and consequences of igneous activity which are summarized in Tables 5 and 10 lead to the following general observations:

1. *The nature of the occurrence and consequences of an igneous event in the Yucca Mountain vicinity lead to differing professional judgments and alternative views on the potential effect of igneous activity on the proposed high-level waste repository. As a result, evaluation of risk from an igneous event requires quantitative consideration of credible alternative views taking into account geological evidence and their physical bases. These analyses will be useful in evaluating risk and determining whether further investigations are warranted to reduce uncertainties.*
2. *There is general agreement on many aspects of the nature of potential igneous events and the range of probability of these events in the future, despite the broad range of conceptual models and parameters that have been used to investigate the potential effects of an igneous event intersecting the proposed high-level waste repository. The consequences of an igneous event on the repository are more controversial and less well understood, but these models and their characterization are evolving. The significance to risk of differences in these views is not well documented.*
3. *Limitations in fundamental information and knowledge of processes result in inherent uncertainties in evaluating igneous activity models. For example, the very low rate of basaltic volcanic activity over the past 5 million years in the Yucca Mountain region in comparison with other areas of the region leads to lower igneous activity probability estimates, but increases the uncertainty in the probability of such rare events.*
4. *Both the extrusive (volcanic) and intrusive scenario could occur in the vicinity of the proposed repository in Yucca Mountain. The extrusive scenario is likely to cause a larger risk and the effect is greatest within the first thousand years. In time the shorter half-life, more radioactive nuclides in the waste will largely have decayed. The maximum effect of the intrusion scenario on the RMEI will not occur for several tens of thousands of years. Preliminary performance assessment indicates that the risk from both scenarios would be only a fraction of the current dose standard.*
5. *Future igneous activity in the Yucca Mountain region will likely be similar to the characteristics of the small-volume, single-episode basaltic Lathrop Wells volcano and will likely occur within basins as has most of the igneous activity over the past several million years in the region. Certain styles of volcanism are not expected. For example, the conditions necessary for explosive phreatic eruptions (maar volcanism, involving heating and expansion of groundwater) do not exist at Yucca Mountain. There is also no*

evidence that maar volcanoes formed near Yucca Mountain during the last 10 million years and they are not expected in the future.

6. *General, but not total, agreement is that the igneous activity at Yucca Mountain is waning, with the probability that future igneous activity based on nearby volcanism over the past several million years is in the range of* 10^{-9} *to* 10^{-7}*/yr. The ongoing elicitation of volcanic experts in the DOE's Probabilistic Volcanic Hazard Assessment – Update, which incorporates the latest geophysical and drilling data from the Yucca Mountain region, will be the most up-to-date, credible estimate of the range of igneous activity intersection with the proposed repository.*

7. *Significant disagreements exist regarding the nature of the flow of magma into drifts of the repository during an intrusive igneous event and the number of waste packages that would be damaged or destroyed by invading magma. The "dogleg" scenario in which the invading magma breaks out to the surface through a secondary vent after traversing along the drifts and interacting with the waste packages is considered to be of extremely low probability based on both available evidence and expert opinion. Magma physics indicates that flow of intruding magma into drifts would be limited and a secondary (satellite) vent branching from a drift (including the "dogleg" scenario) is unlikely to form at any time in the style of volcanism expected at Yucca Mountain.*

8. *The current technical bases of several aspects of igneous activity appear to be insufficiently developed or supported by available information and analyses. These include the range of waste particle sizes in the ash and the ash that will contribute to inhalation dose, the effects of large floods on the volume and distribution of contaminated ash in the vicinity of the RMEI, the amount of waste incorporated into ash versus lava during the early eruptive phase of the extrusive scenario, and the importance of setbacks of the repository from faults and fractured zones that are likely locations for dikes leading to either eruptive or intrusion scenario events. Also, there is a need to consider newly available information regarding volcanic conduit widths at repository depth.*

GLOSSARY

aa flow	native Hawaiian word, pronounced “ah ah”; lava flows typified by a rough, jagged, spinose, clinkery surface (Neuendorf et al., 2005)
actinides	heavy elements with atomic number of 80 or greater; the series is named for the element actinium, element 89, and includes all heavier elements; actinide radionuclides are found in spent nuclear fuel.
adiabatic expansion	increase in the volume of a substance during which no gain or loss of heat is allowed to occur (Lewis, 1993)
aeromagnetic	perturbation of the main geomagnetic field that is caused by
agglomerate	a chaotic assemblage of coarse, angular, pyroclastic (volcanic ejecta) materials; a volcanic breccia
Alkali	silicate minerals that contain alkali metals but little calcium (Neuendorf et al., 2005)
alluvium	a general term for unconsolidated materials deposited during comparatively recent geologic time by a flowing body of water as a fan at the base of a slope
alpha particle	nucleus of the element helium, made up of two protons and two neutrons; alpha particles generally do not penetrate very far any material, do not penetrate the outermost dead layer of the skin, but can damage cells in the body if inhaled or ingested; the penetration range of typical alpha particles in tissue is 50-80 microns
AMAD	activity median aerodynamic diameter; the diameter of a sphere, of density 1 gm/cm^3, that has the same terminal settling velocity in air as that of an aerosol particle whose activity is the median for the entire aerosol (Shleien et al., 1998)
amphibole	a group of dark, rock-forming ferromagnesian silicate minerals (examples include hornblende, anthophyllite, cummingtonite, tremolite, and actinolite)
anomalies	variations in the magnetization of the nearby Earth’s crust
aphyric texture	said of the texture of a fine-grained or aphanitic igneous rock which lacks phenocrysts
ash	volcanic ejecta under 2 mm in diameter

asthenosphere	the layer or shell of the Earth below the lithosphere, which is weak and in which isostatic adjustments take place, magma may be generated in this shell, and seismic waves are strongly attenuated; it is part of the upper mantle (Neuendorf et al., 2005)
basalt	general term for dark-colored mafic igneous rocks, commonly extrusive but locally intrusive composed chiefly of calcic plagioclase and clinopyroxene
base surge	a ring-shaped cloud of gas and suspended solid debris that moves radially outward at high velocity as a density flow from the base of a vertical explosion column accompanying a volcanic eruption
bocca	an aperture on any part of a volcano from which magma or gas escapes
caldera	a large, generally roughly circular, basin-shaped volcanic depression formed by collapse after a voluminous volcanic eruption
cation	an atom or molecule that has lost an electron and thus acquired a positive electric charge (Lewis, 1993)
clast	an individual constituent, grain, or fragment of a sediment or rock, produced by the mechanical weathering of a larger rock mass
clinopyroxene	a group name for pyroxenes crystallizing in the monoclinic system and sometimes containing considerable calcium with or without aluminum and the alkalies (examples include diopside and hedenbergite)
committed dose equivalent	dose to a specific organ or tissue that is received from an intake of radioactive material by an individual over a specified time after the intake; for radiation protection purposes, the specified time is to the age of 70, which is normally taken to be 50 years for a radiation worker and 70 years for a member of the public
compliance period	period of time that the repository must result in a dose to human(s) that does not exceed a specified standard dose
corrosion	the electrochemical degradation of metals or alloys due to reaction with their environment, which is accelerated by the presence of acids or bases (Lewis, 1993)
coseismic	simultaneous earthquake activity or simultaneous with earthquake activity
crust	the outermost layer (or shell) of the Earth that is roughly 30 km thick in the vicinity of Yucca Mountain

density	mass per unit volume (Lewis, 1993)
dike	a tabular (sheet-like) igneous intrusion that cuts across the bedding of the country rock (Neuendorf et al., 2005)
dilatent	a change in volume due to change in internal openings
drift	a nearly horizontal passageway in (the repository) (Merriam-Webster,1988)
elicitation	a formal, highly structured, and well-documented process for obtaining the judgments of multiple experts (Kotra et al., 1996)
en echelon	said of geologic features that are in an overlapping or staggered arrangement (Neuendorf et al., 2005)
eolian	borne, deposited, produced, or eroded by the wind (Merriam-Webster,1988)
equilibrium constant	a number that relates the concentrations of starting materials and products of a reversible chemical reaction to one another (Lewis, 1993)
equivalent	committed effective dose equivalent for internal exposure; the **equivalent dose** is the product of the absorbed dose, quality factor, and all other necessary modifying factors at the location of interest; the **committed dose equivalent** is the dose received from an intake of radioactive material during the 50-year period following the intake (Shleien et al., 1998)
equivalent dose	is a measure of the **radiation** dose to tissue where an attempt has been made to allow for the different relative biological effect of different types of **ionizing radiation**
exsolve	to separate or unmix from a solid solution into two distinct phases (Neuendorf et al., 2005)
extrusive scenario	hypothetical future event in which a volcanic conduit (which develops along a dike) intersects an underground repository, interacts with waste packages, incorporates some nuclear waste material in volcanic ash, and carries it to the surface
felsic	an adjective applied to a light-colored rock such as granite or rhyolite
Fickian diffusion	the spontaneous mixing of one substance with another when in contact or separated by a permeable membrane; the rate of diffusion is proportional to the concentration of the substances; the theoretical principles are stated in Fick's laws (Lewis, 1993)

fission product	a fragment (usually 2 or 3) produced in fission (splitting) of a nucleus; most fission products decay by beta-gamma, positron, or electron capture decay; many fission products have relatively short half-lives (less than 100 years)
fluvial	pertaining to rivers
geodetic data	data pertaining to the position on the Earth's surface or the Earth's size, shape, and surface deformation
graben	an elongate, relatively depressed crustal unit or block that is bounded by (normal) faults on its long sides
half-life	the time needed for a radioactive material to decay to one-half of original amount
high-level radioactive	(1) the highly radioactive material resulting from the reprocessing
Holocene	an epoch of the Quaternary period, from the end of the Pleistocene to the present time (Holocene began 11,800 yrs ago - International Commission on Stratigraphy: http://www.stratigraphy.org/chus.pdf)
horst	an elongate, relatively uplifted crustal unit or block that is bounded by faults on its long sides
hydrovolcanic	term encompassing all volcanic activity that results from the interaction between lava, magmatic heat, or gases and meteoric or connate water at or near the Earth's surface (Neuendorf et al., 2005)
igneous activity	processes involving magma (molten rock)
ignimbrite	deposits of rhyolite ash derived from flowing ash clouds erupted from a volcano that flow along the Earth's surface
intrusive scenario	hypothetical future event in which a basaltic dike intersects an underground repository and interacts with high-level waste packages
isothermal	at constant temperature (Lewis, 1993)
kernel	a weighting function used in non-parametric estimation techniques; kernels are used in kernel density estimation to estimate the density function of random variables, or in kernel regression to estimate the conditional expectation of a random variable
liquidus	the line (or curve) of points in a temperature-composition diagram representing the maximum solubility (saturation) of a solid component or phase in the liquid phase

lithosphere	the outer, relatively rigid layer of the Earth, including the crust, which responds to stress by folding or faulting
lithospheric plate	a torsionally-rigid, plate-like segment of the outer layer of the Earth
lithostatic	vertical stress derived from the weight of the overlying rocks
lognormal distribution	a normal distribution that is the distribution of the logarithm of a random variable (see **normal distribution**) (Merriam-Webster 1988)
maar	a low relief, coneless volcanic crater formed by a single explosive eruption; it is surrounded by a crater ring and is commonly filled by water (examples in northern Death Valley, Ubehebe Crater and associated smaller maars)
mafic	said of igneous rock composed chiefly of one or more ferromagnesian, dark-colored minerals (e.g., basalt)
magma	naturally occurring molten or partially molten rock material generated within the Earth and capable of intrusion and extrusion (Neuendorf et al., 2005)
magnetic	pertaining to magnetic fields
mantle rock	rock existing in zone in the Earth above the core and below the crust
micron	micrometer (one millionth of a meter)
Miocene	an epoch of the upper Tertiary period, after the Oligocene and before the Pliocene (Miocene began 23.03 Myr ago and ended 5.33 Myr ago according to the International Commission on Stratigraphy: http://www.stratigraphy.org/chus.pdf)
nanostrain	10^{-10} mm
neutron activation	nuclear reaction between a neutron and a stable element to form a radioactive form of the target element; metals that have been exposed to high neutron flux, like the metal components of a nuclear reactor, contain neutron activation products
normal distribution	a probability density function that approximates the distribution of many random variables (Merriam-Webster, 1988)
normal fault	a fault in which the hanging wall appears to have moved downward relative to the footwall; the angle of the fault is usually 45-90º
order of magnitude	a range of values that begins at any value and extends to ten times that value (Lewis, 1993)

orogeny	the process of forming mountains
oxidation	originally, a reaction in which oxygen combines chemically with another substance; usage has broadened to include any reaction in which electrons are transferred; the substance that loses electrons is oxidized; the substance that gains electrons is reduced (Lewis, 1993)
paleosurface	surface of the Earth formed in previous time
petrology	origin, composition, occurrence, structure, and history of rocks
phenocryst	term used for relatively large, conspicuous crystals in rocks that contain crystals of different sizes
phreatic	said of a volcanic eruption or explosion of steam, mud, or other material that is not incandescent; it is caused by the heating and consequent rapid expansion of groundwater due to an underlying igneous heat source
plagioclase	a group of triclinic feldspar minerals of the general formula $(Na, Ca)\ Al(Si,Al)Si_2O_8$)
plate tectonic paradigm	theory of the movement of crustal plates on the Earth through geologic time
Pleistocene	an epoch of the Quaternary period, after the Pliocene of the Tertiary period and before the Holocene (Pleistocene began 1.81 Myr ago and ended 11,800 years ago according to the International Commission on Stratigraphy: http://www.stratigraphy.org/chus.pdf)
Pliocene	an epoch of the Tertiary period, after the Miocene and before the Pleistocene (Pliocene began 5.33 Myr ago and ended 1.81 Myr ago according to the International Commission on Stratigraphy: http://www.stratigraphy.org/chus.pdf)
pyroclastic	clastic rock formed from materials (ejecta) derived from a volcanic eruption
radiation dose	a generic term that includes absorbed dose (the amount of ionizing radiation absorbed in matter), effective dose, equivalent dose, committed effective/equivalent dose (see **total effective dose equivalent**) (Shleien et al., 1998)
radioactive decay	the decay of an atomic nucleus by emission of a particulate and electromagnetic radiation; radioactive decay is described by an exponential function
radioactive material	any material exhibiting radioactivity (see **radionuclide**)

radioactivity	a property of some matter whose atoms undergo spontaneous transformation in its nuclear resulting in the emission of particulate and electromagnetic radiation
radionuclide	an isotope of an element (either natural or artificial) that exhibits the property of radioactivity (Lewis, 1993)
remobilization	the action by wind or flowing water to move deposited ash or other fine particulate material downwind or downstream from the original point of deposition
Reynolds number	the function used in fluid flow calculation to determine whether flow is streamline or turbulent; proportional to flow velocity and density; inversely proportional to viscosity (Lewis, 1993)
rheology	study of the deformation or flow of matter and the relationship between stress and strain, and the responses of rock to deformation (Neuendorf et al., 2005)
rhyolite	volcanic form of granite, felsic volcanic rocks
RMEI	the reasonably maximally exposed individual is a hypothetical person who (a) lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination; (b) has a diet and living style representative of the people who now reside in Amargosa Valley, Nevada; (c) uses well water with average concentrations of radionuclides based on an annual water demand of 3000 acre-feet; (d) drinks 2 liters of water per day from wells drilled into the ground water at the location as specified in item a; and (e) is an adult (10 CFR 63.312)
scoria	large size pyroclasts irregular in form and generally very vesicular
sedimentary	pertaining to or containing sediment (Neuendorf et al., 2005)
seismicity	the phenomenon of movements in the Earth’s crust (Neuendorf et al., 2005)
spent fuel cladding	the outer jacket of nuclear fuel elements which contains and supports the fuel material, protects the fuel, and prevents the release of fission products into the reactor coolant
spent nuclear fuel	nuclear fuel that is removed from a nuclear reactor after a period of time, either because fission is no longer maximally efficient or because some desired product is to be extracted; spent fuel contains fission products, actinides formed by neutron capture and decay, and neutron activation products, as well as some unreacted fissile material

stratovolcano	a volcano that is constructed of alternating layers of lava and pyroclastics
Strombolian	a type of volcanic eruption characterized by jetting of clots or fountains of fluid basaltic lava from a central crater (Neuendorf et al., 2005)
subduction	the process of a lithospheric plate descending beneath another plate (Neuendorf et al., 2005)
tabular	sheet-like intrusion
tachylite	a volcanic glass formed from basaltic magma that is commonly found as chilled margins of dikes, sills, or flows
tectonic event	a geologic event involving the deformation or fracturing of the Earth
tephra	a collective term used for all pyroclastic material ejected during an explosive volcanic eruption
tomographic methods	determining the physical property (e.g., velocity) distribution from a multiplicity of observations using combinations of source and receiver locations
total effective dose	the sum of the dose equivalent for external exposure and the
TPA (also TSPA)	total performance assessment of the proposed repository; performance assessment is a process which (1) identifies the features, events, processes and sequences of events that might affect the Yucca Mountain disposal system and their probabilities of occurring during 10,000 years after disposal, (2) examines the effects of these on the performance of the disposal system over the compliance period, and (3) estimates the dose incurred as a result of releases (10 CFR 63.2); TPA is the acronym for the NRC performance assessment code, and TSPA is the DOE performance assessment code system
transtension	a system of stresses that tends to cause oblique extension (i.e., combined extension and strike slip)
viscosity	the internal resistance to flow exhibited by a fluid (Lewis, 1993)
volatile	an element or compound that has a vapor pressure equal to or greater than 0.1 mm Hg that is not a gas at ambient temperatures (Lewis, 1993)

waste (HLW)	of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; (2) irradiated reactor fuel (10 CFR 63.2)
xenolith	an inclusion in an igneous rock to which it is not genetically related; as used here it refers to pieces of country rock from the walls of a volcanic conduit that are carried to the surface during an eruption, and often have outer rinds of quenched magma

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ABBREVIATIONS

AMAD	activity mean aerodynamic diameter (for particles)
BSC	Bechtel SAIC Company LLC
CFR	*Code of Federal Regulations*
CNWRA	Center for Nuclear Waste Regulatory Analyses (San Antonio, TX)
CRWMS M&O	Civilian Radioactive Waste Management System Management and Operating Contractor
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FEP	Features, Events, and Processes
FGR	Federal Guidance Report
HLW	high-level radioactive waste (also see glossary)
ICPR	Igneous Consequences Peer Review (Panel) (Detournay et al., 2003)
NMSS	(NRC's) Office of Nuclear Material Safety and Safeguards
NRC	U.S. Nuclear Regulatory Commission
NTS	Nevada Nuclear Test Site
NWTRB	U.S. Nuclear Waste Technical Review Board
OCRWM	(DOE's) Office of Civilian Radioactive Waste Management
PVHA	Probabilistic Volcanic Hazard Assessment
PVHA-96	Probabilistic Volcanic Hazard Assessment published in 1996
PVHA-U	Probabilistic Volcanic Hazard Assessment – Update (final report to be published in mid-2008)
RMEI	reasonably maximally exposed individual
SNF	spent nuclear fuel
TPA	NRC's Total-System Performance Assessment
TSPA	DOE's Total System Performance Assessment
USGS	U.S. Geological Survey
YMP	(DOE's) Yucca Mountain Project
YMR	Yucca Mountain region

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Evaluating Igneous Activity at Yucca Mountain:
Technical Basis for Decisionmaking

A Report

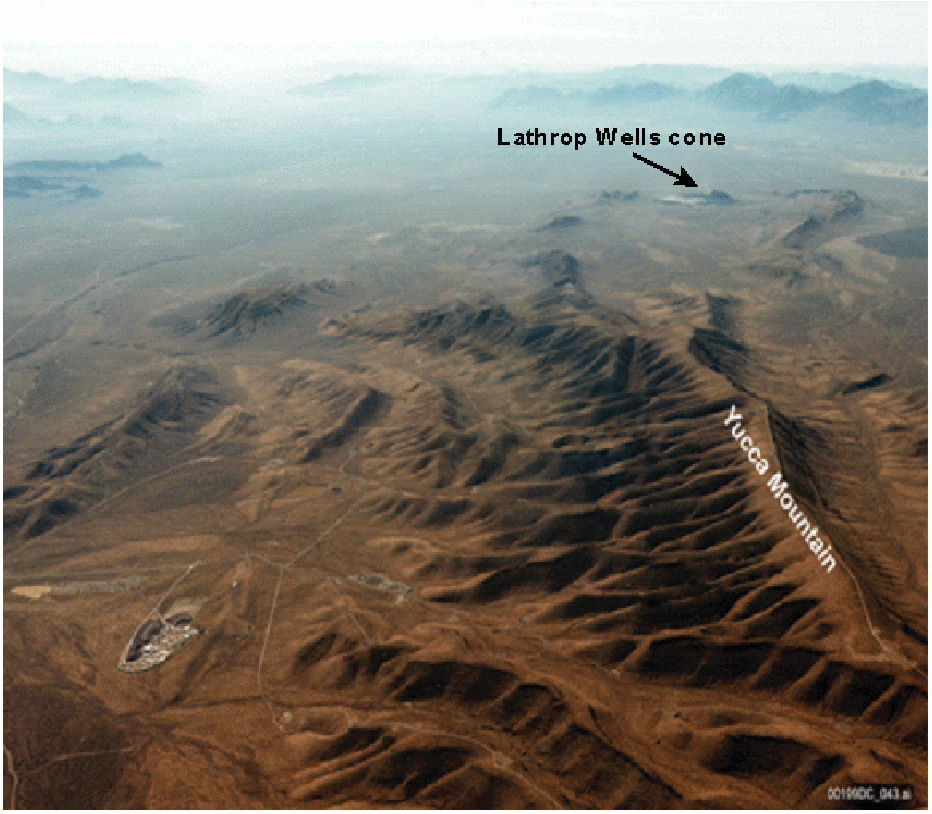
Prepared by the

Advisory Committee on Nuclear Waste and Materials

U.S. Nuclear Regulatory Commission

Given for one instant an intelligence which could comprehend all the forces by which nature is animated and the respective situation of the beings who composed it — an intelligence sufficiently vast to submit these data to analysis — it would embrace in the same formula the movements of the greatest bodies of the universe and of the lightest atom; for it, nothing would be uncertain and the future, as the past, would be present to its eyes.

— P-S. Laplace, 1776



Looking south along the crest of Yucca Mountain, Nevada, toward Amargosa Valley and the extinct Lathrop Wells volcano.

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1. Introduction

1.1. Igneous Activity and the Proposed Yucca Mountain Repository

Eighty thousand years ago a small-volume *basaltic*[2] volcano, the Lathrop Wells volcano erupted about 15 miles south of the Department of Energy's (DOE) proposed high-level waste (HLW) repository in Yucca Mountain, Nevada (see Figures 1 and 2). This was the first volcanism in the immediate vicinity of Yucca Mountain for a million years, but one of a series of infrequent basaltic volcanoes that have occurred in the vicinity of the proposed repository site during the past 10 million years. This NUREG report presents the Advisory Committee on Nuclear Waste and Material's (ACNW&M) summary and analysis of the range of views of the ACNW&M, the U.S. Nuclear Regulatory Staff (NRC) staff, and other stakeholders on the nature, likelihood and potential consequences of future igneous activity at the proposed Yucca Mountain repository. This NUREG includes additional information that was not available when the report was first published in June, 2007 (ACNW&M, 2007b). An article that summarizes highlights from this NUREG report was recently published in *Eos* (Hinze et al., 2008).

Considering the documented ongoing volcanism, the proposed Yucca Mountain repository could be compromised by igneous activity during its compliance period. Accordingly, potential risk resulting from hypothetical *igneous activity* interacting with the proposed repository has been investigated as part of the assessment of the Yucca Mountain site. A risk-informed performance assessment uses the risk triplet for this evaluation (Kaplan and Garrick, 1981; Garrick and Kaplan, 1995). Components of the risk triplet for igneous activity are: What is the nature of a potential igneous event? What is the probability of an igneous event intersecting the proposed repository? And if the repository is intersected, what are the consequences of the igneous activity to the repository, the stored high-level radioactive waste (HLW), and the impact of the potential release of the waste to the environment and on dose to the reasonably maximally exposed individual (*RMEI*) assumed to be residing in the near vicinity to Yucca Mountain? Uncertainty in these studies results in a spectrum of professional views regarding the potential impact of igneous activity. A review and analysis of the technical bases for the range of views to these questions is the subject of this report.

1.2. Objective and Rationale of Report

This report responds to the following direction from the NRC in the Staff Requirements Memorandum (SRM) M060111B, dated February 9, 2006:

> The [ACNW&M] Committee should provide the Commission with an analysis of the current state of knowledge regarding igneous activity which the Commission can use as a technical basis for its decisionmaking.

This report presents an overview of the current, publicly available perspectives regarding igneous activity. It is not intended to be an exhaustive study, but a presentation of the major components of current views and their principal supporting evidence.

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[2] Words defined in the glossary are italicized the first time they are used in the report.

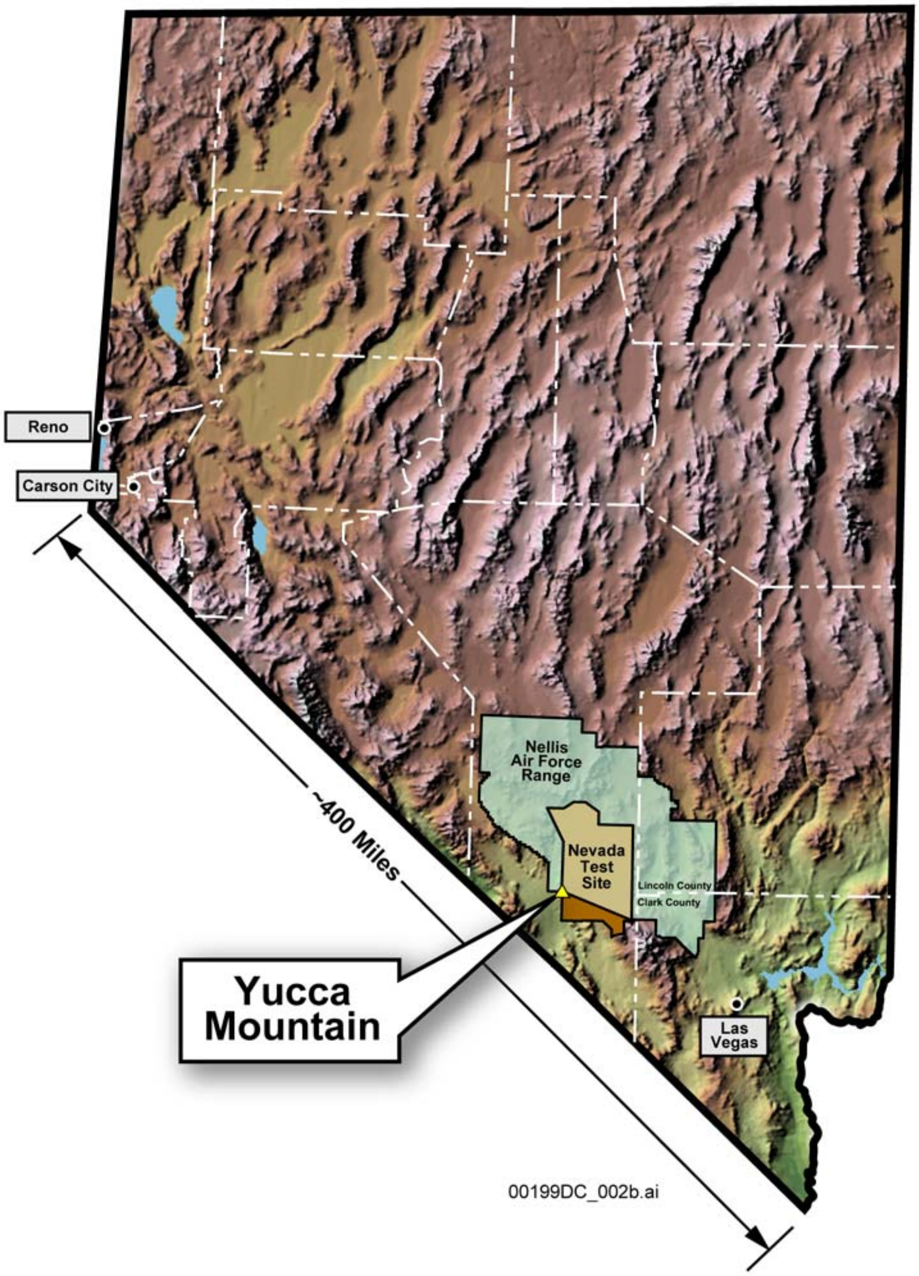

Figure 1 Map showing the location of Yucca Mountain in southern Nevada. Also shown are the boundaries of the Nevada Test Site and Nellis Air Force Range, and the major cities of Las Vegas, Reno, and Carson City (Source: U.S. Department of Energy).

Figure 2 **View looking south from the crest of Yucca Mountain toward the Lathrop Wells volcanic cone and the Amargosa Desert (Permission to use this copyrighted material granted by Abe van Luik at http://www.thoughtsandplaces.org).**

Accordingly, this report contains no conclusions or recommendations regarding the risk from igneous activity intersecting the proposed high-level waste repository at Yucca Mountain. Such decisions will be made by the NRC during a review of the license application for construction of a repository at Yucca Mountain. The NRC anticipates that the DOE will file for a license sometime in 2008.

The NRC has not established definitive views on igneous activity at Yucca Mountain, and maintains a position of neutrality and independence during the pre-license period. Nonetheless, the NRC and its contractors have conducted extensive studies of the nature, likelihood, and consequences of igneous activity at Yucca Mountain in preparing for the review of the anticipated license application. The perspectives reached by the NRC from these studies as reported in the published literature and public documents and presentations are described in this report, but it is understood that these are not definitive positions of the NRC. Additional information about the programmatic and technical activities of the NRC and its reviews of the Yucca Mountain Project may be found in Appendix B (also see NRC, 2007).

Igneous activity describes processes associated with the origin, nature, transport, emplacement, and solidification of molten rock, or magma. Magma comes from rock melted in the Earth that may rise to the surface because of the net effects of *tectonic* stresses, density variations, and gas pressure. Rising magma may solidify at depth to form intrusions or may breach the surface to form volcanoes or other volcanic deposits (i.e., lava sheets or ash flows (*ignimbrites*)). Volcanic and intrusive activity is restricted to regions that are actively undergoing sub-*crustal* dynamic or tectonic processes, and the location of the proposed DOE HLW repository at Yucca Mountain occurs within such a region Risks to health may arise if humans are exposed to radioactive materials released from the repository during volcanic activity by resuspension of deposited or remobilized material or by premature release to ground water of radionuclides from waste packages damaged by magma entering into the proposed repository. As a result, the DOE has conducted extensive studies over the past few decades to evaluate the potential risk from igneous activity at the Yucca Mountain site and surrounding region. Other interested parties including the NRC also are studying the potential risk from igneous activity.

Evaluation of hazards and risk from igneous activity over periods of thousands of years or more is a major challenge to the scientific community. Long-term quantitative predictions, as required in the case of the HLW repository, have been made only in recent decades using primarily probabilistic techniques based on past igneous events of the region. However, procedures for implementing predictions and the nature of the data used in making predictions are not standardized and there are limitations in data and experimental evidence. This leads to varying professional judgments with attendant uncertainties and variations in hazard estimates, particularly in the case of infrequent, low-volume basaltic volcanism, as in the Yucca Mountain region.

There is a base of knowledge regarding the fundamental magmatic processes leading to volcanic activity and near-surface intrusions in the Yucca Mountain region, but many uncertainties remain. In addition, it is difficult to determine the existence of low-volume magma source zones at their sub-crustal depths as well as the controls on the movement of magma through the Earth's crust which could be useful in long-term predictions of the occurrence of volcanic events.

Estimation of risk from igneous activity is further complicated by differences in views regarding the nature and behavior of magma and its potential impact on entering underground openings that contain waste packages. Appropriate geologic analogs of consequences from the intersection of magma and underground openings do not exist. As a result, both evaluating the probability of igneous activity at the proposed repository and the impact of this activity on the repository throughout the compliance period have been the subject of extensive investigations and considerable variation in professional views.

During the past few decades significant progress has been made in determining the technical bases for predicting risk from an igneous event at the HLW repository. Accordingly, the purpose of this report is to present the range of views and their current technical bases, including the nature and probability of igneous activity intersecting the repository during the mandatory time of compliance, the potential consequences of this interaction, and hypothetical radiation doses.

The EPA and NRC regulations pertaining to the proposed Yucca Mountain HLW repository specify that assessment of the performance of the repository provide reasonable assurance that the EPA dose standard will be met throughout the time of compliance. Performance assessment is used for the quantitative evaluation of the repository. It is a probabilistic method that incorporates the uncertainty in the scenarios, models, and parameters and involves repeated calculation of the performance of the repository ("realizations") using samples of the input parameter distributions. Cumulative distributions of the results are compared to the standards established by the EPA for the repository.

1.3. Scope of Report

This report reviews the technical bases for estimating the risk from igneous activity that could occur at the proposed Yucca Mountain high-level waste repository during its prescribed time of compliance. Accordingly, the scope of this report is limited to the post-closure period of the repository. The post-closure period is defined as the 10,000 years following closure, the period of time that has been considered in the majority of current igneous activity investigations of Yucca Mountain. The Environmental Protection Agency's (EPA) current draft revised standards for the Yucca Mountain repository prescribe that consideration of features, events, and processes (FEPs), which includes igneous events, shall be based on the 10,000 years following repository closure as had been detailed in the current regulation at 40 CFR Part 197. This is incorporated into the proposed changes to 10 CFR Part 63 (70 FR) based on the EPA's assertion that data and models used to prepare performance assessment for the first 10,000 years provides adequate support for projections through the period of geologic stability and limits uncertainties associated with speculation of performance over very long time periods (i.e., hundreds of thousands to a million years).

This report provides a review of the current public perspectives taken by the DOE, NRC, and other interested parties on issues dealing with the nature, probability, and impact of igneous activity on the proposed Yucca Mountain repository. Where appropriate, observations are provided on perspectives unsupported by measurement or extrapolated from existing data or on perspectives that differ from EPA standards or NRC regulations. Every attempt is made to identify uncertainties in perspectives and issues. The State of Nevada has not established specific views on the impact of future igneous activity at Yucca Mountain, however, contractors supported by the State of Nevada have published several professional journal articles related to the probability of an igneous event intersecting the proposed repository. These articles are reviewed in this report.

1.4. Content and Organization of Report

Chapter 2 is a brief review of the geologic history of the Yucca Mountain region and serves as the basis for subsequent chapters on the nature of future igneous activity and the likelihood of its occurrence. Figures in this chapter show the geographic location of various geologic features treated in subsequent chapters.

Chapter 3 presents an overview of the principal processes involved in igneous activity. Chapters 4, 5, and 6 review the state of knowledge available in documents and published materials regarding the nature, likelihood, consequences, and risk from potential igneous activity in the context of the risk triplet questions. Chapter 7 summarizes our conclusions.

The essential components involved in answering each question are shown in the logic diagrams (Figure 3, Figure 4, Figure 5, and Figure 6). They include and expand on consequence effects of a figure originally published in Crowe et al. (2006). The oval shapes in the figure are uncertain elements of the logic flow that are treated probabilistically, while the rectangular shapes are decision parameters that have been determined either subjectively or by general agreement of the engineering and scientific community based on the inputs feeding into them in the logic diagrams. The bold ovals are conditional parameters that are convolved (multiplied) to determine the probability-weighted dose as a function of time which is compared to the standards of the repository and the irregular hexagon is the performance assessment probability.

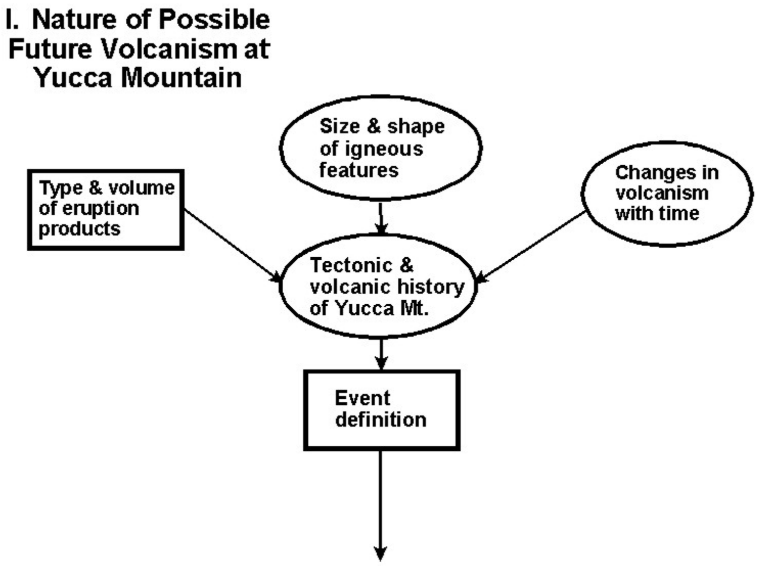

Figure 3 Logic chart of components involved in defining the nature of possible future igneous events at Yucca Mountain.

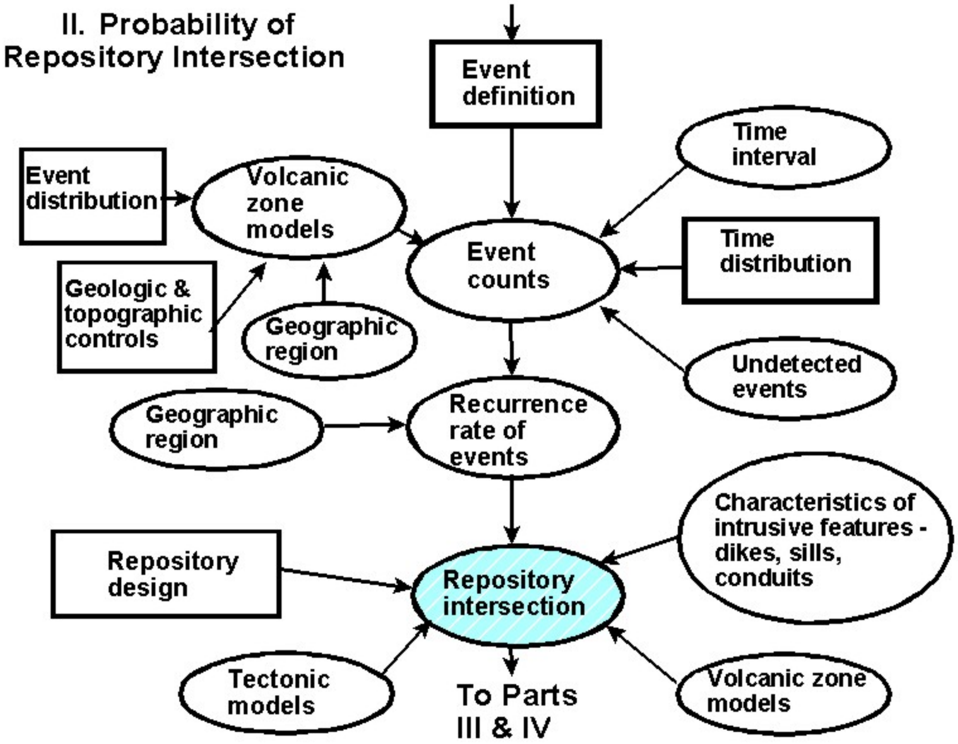

Figure 4 Logic chart of components involved in defining the probability of future igneous activity intersecting the proposed Yucca Mountain HLW repository.

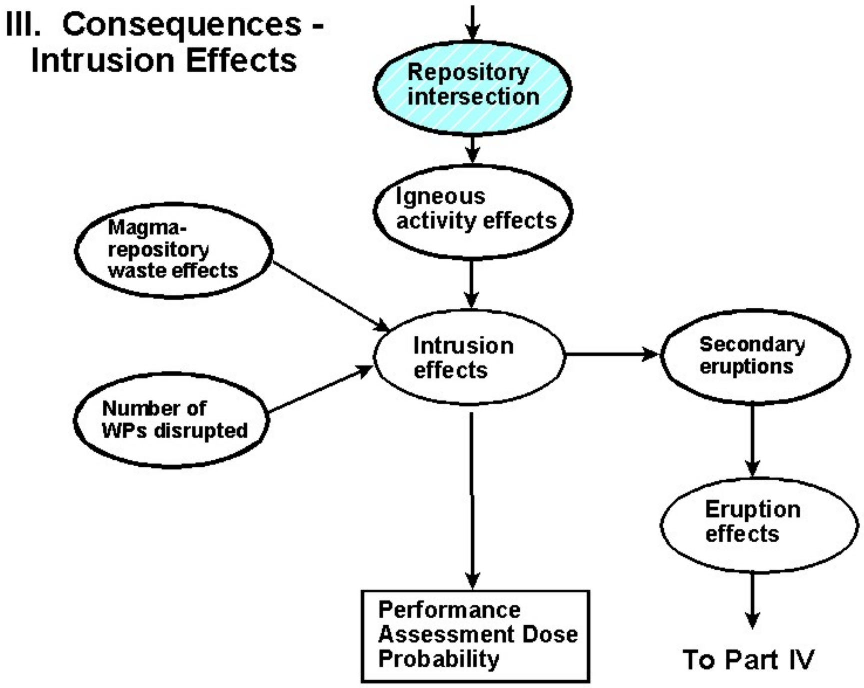

Figure 5 Logic chart of components involved in defining the consequences of a dike intersecting the Yucca Mountain HLW repository (intrusive scenario).

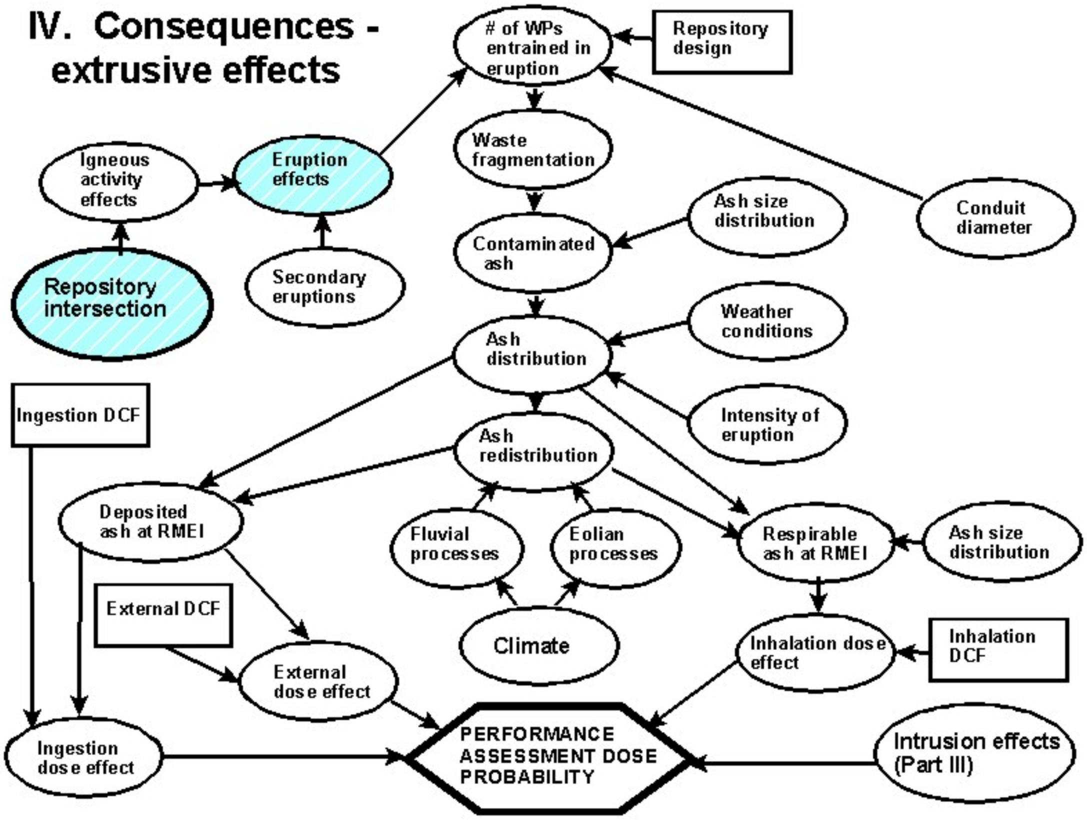

Figure 6 Logic chart of components involved in defining the consequences of a volcanic conduit intersecting the Yucca Mountain HLW repository (extrusive scenario).

The NRC has reported risk insights for various aspects of igneous activity and scenarios and the NRC has assigned relative rankings of medium to high significance to waste isolation (NRC, 2004). A number of these rankings are illustrated in Figure 7. For example, the probability of an igneous event is considered to have high significance with respect to waste isolation. Wind speed and direction are considered to have medium significance to waste isolation.

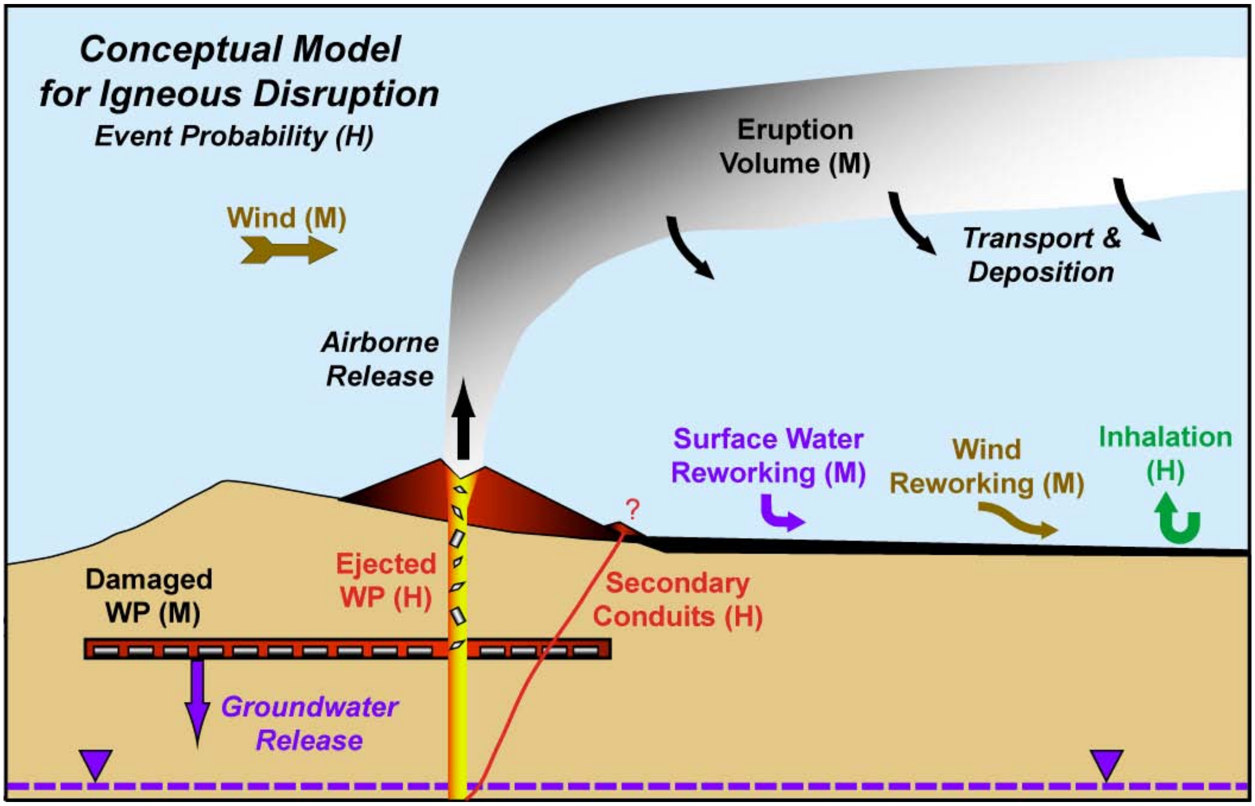

Figure 7 NRC view of risk-significant aspects of igneous activity (After Hill, 2007).

The NRC's (2004) risk insights were generally framed around the risk triplet. Risk insights were stated in terms of a scenario, essentially as a statement of the feature, event, or process that might exist or occur in the post-closure repository system. The risk insights baseline provided context for understanding the likelihood that the feature, event, or process will exist or occur during the compliance period. The baseline also included a discussion of the consequence of the feature, event, or process, in terms of its beneficial or adverse effect on the waste isolation capabilities of the repository system. Effects on waste isolation subsequently affect the estimated dose to an individual, in other words, risk. Although individual risk insights are supported by quantitative analyses, classifying the risk insights by relative significance to waste isolation was more qualitative. Staff judgment was used when combining information from different analyses. The NRC evaluated significance relative to the waste isolation capabilities of the repository system. Three criteria were considered (NRC, 2004) in evaluating the significance of the risk insights:

- Effect on the integrity of waste packages;
- Effect on the release of radionuclides from the waste form and waste package; and
- Effect on the transport of radionuclides through the geosphere and biosphere.

High significance is associated with features, events, and processes that could (1) affect a large number of waste packages; (2) significantly affect the release of radionuclides; or (3) significantly affect the transport of radionuclides through the geosphere or biosphere. Medium significance is associated with a lesser effect on waste packages, radionuclide releases, or radionuclide transport, and low significance is associated with no or negligible effect (NRC, 2004).

The summary and conclusions reached in this ACNW&M report are presented in Chapter 7. A listing of the status of NRC key technical issue responses and the agencies, organizations, and individuals receiving an initial draft of this report for their review and comment, plus the agenda and minutes of the Working Group held on February 13 and 14, 2007, are provided as appendices. Other appendices include the NRC's programmatic and technical activities in review of igneous activity associated with the Yucca Mountain project (NRC, 2007), and EPRI's new report on conceptual models for future volcanism at Yucca Mountain and their expected consequences.

1.5. Report Preparation Process

This report has been prepared by members and staff of the ACNW&M with the assistance of a consultant who is an expert on igneous activity and magma physics. An initial draft of the report was sent to the NRC, the DOE, the State of Nevada, and other stakeholders, and to a group of external experts in related disciplines for their review and comment (see the list in Appendix D). Subsequently, the stakeholders were invited to a working group meeting convened by the ACNW&M to discuss igneous activity at Yucca Mountain and to provide them with an opportunity to recommend appropriate revisions to the report. Specifically, stakeholders were requested to address the following questions:

- Does the ACNW&M report address the risk-significant topics related to igneous activity at Yucca Mountain?
- Does the report capture the range of views of the interested parties with respect to the technical bases for decisionmaking on these topics including definitions of volcanic events, geologic periods of interest in predicting probability, igneous activity probability, magma/drift interaction leading to both extrusive, intrusive scenarios, potential consequences for the risk from a high-level waste repository, etc.? If not, the positions detailed in the report will be clarified from published position papers in the final ACNW&M report.

Additionally, at the working group meeting a group of distinguished experts on the various aspects of igneous activity and high-temperature processes provided an overview of the challenges facing technical decisionmaking on igneous activity at Yucca Mountain and a description of the status of knowledge of relevant volcanic features, events, and processes. The experts also participated in a panel discussion on the completeness and quality of the content of the ACNW&M report where they commented on the following questions:

- Has an effective and accurate understanding of the various views on volcanism been identified and documented in the report?
- Have the risk significant topics regarding igneous activity been identified?
- Are the technical bases for positions taken for determining risk from igneous activity at Yucca Mountain scientifically correct?

- Are there risk-significant topics regarding igneous activity that have not been adequately addressed considering the current state of the science? If so, how can they be addressed?

The public also was invited to present their comments on the draft. All of the comments and results of the discussion of the working group were reviewed and considered by the ACNW&M as part of finalizing the report.

1.6. Constraints on the Report

There are several constraints on the report and its conclusions that limit the technical bases for decisionmaking regarding igneous activity. These include the following:

- Critical decisions about the design of the repository and waste packages that may affect the probability and consequences of igneous activity are not final. For example, there is as yet no decision on the maximum temperature of the repository. This decision will affect the distribution of waste packages and the areal size of the repository, both important parameters in establishing the probability and consequences of igneous activity. Pending decisions about backfill of the drifts, the alloy to be used in construction of the waste packages, and the use of an inner canister also are important to the effects of igneous activity. (Note: Although changes in the areal footprint of the repository could affect probability calculations, the tendency for dikes to follow pre-existing faults or to be influenced by topographic effects could compensate for this by diverting dikes away from emplacement drifts.)
- Ongoing DOE and NRC studies that relate to the probability and effects of igneous activity have not been included in this report. The DOE, for example, is currently in the process of updating the 1996 Probabilistic Volcanic Hazard Analysis (PVHA – 96) with a new expert elicitation using data from new geosciences investigations (PVHA-U). The NRC is conducting studies of eolian (wind) redistribution of contaminated ash to the vicinity of the RMEI, the interaction of magma and the repository and waste packages, and the significance to risk from secondary satellite volcanic vents that may occur adjacent to the main vent of a volcano.
- Many process models are incorporated into the performance assessment of igneous activity at Yucca Mountain, but few of these models have been validated with realistic data or simulations. Accordingly, there are limitations in the confidence that can be placed in the results of the analyses. For example, the volcanic models used to determine the hazard from basaltic volcanism are largely determined from past volcanic events of the region, but prediction of basaltic volcanism over several time slices within the past 10 million years (10 Ma) in the Yucca Mountain region (Crowe, 2005) using previous volcanism and the geologic structure of the region as a predictive tool were not notably successful in specifying the location of actual new clusters of volcanoes or volcanic fields that occurred within the region over the period of the time slice. Figure 8 shows the results of Crowe's prediction of volcanism between 4 and 2 Ma based on the record of basaltic volcanism in the Yucca Mountain region between 6 and 4 Ma. The actual volcanism observed from this time period is shown in Figure 9. As noted by Crowe (2005) in this figure the actual volcanism (results) are mostly unexpected based on the basaltic volcanism of the previous 2 Ma.

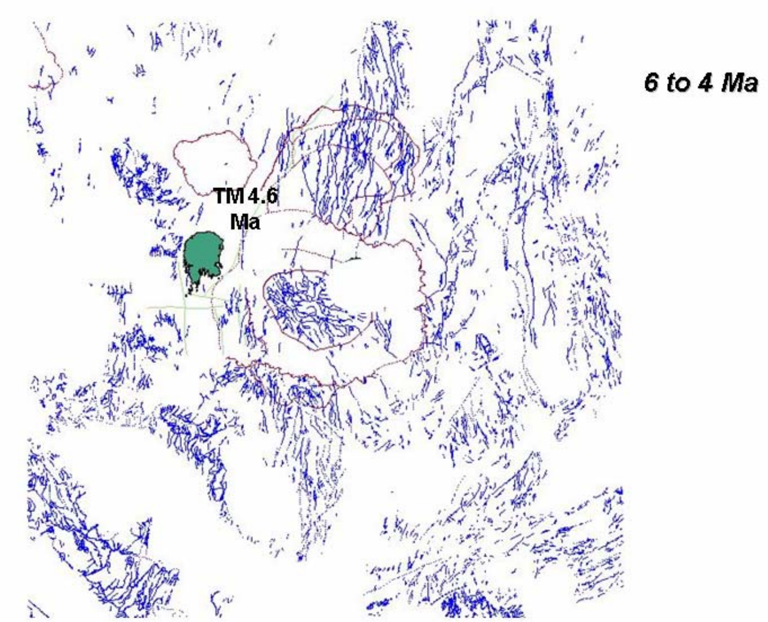

Figure 8 Basaltic volcanism during the period 6 to 4 Ma in the Yucca Mountain region used by Crowe (2005) to predict volcanism in the following 2 Myr. Extent of volcanism shown in green (After Crowe, 2005).

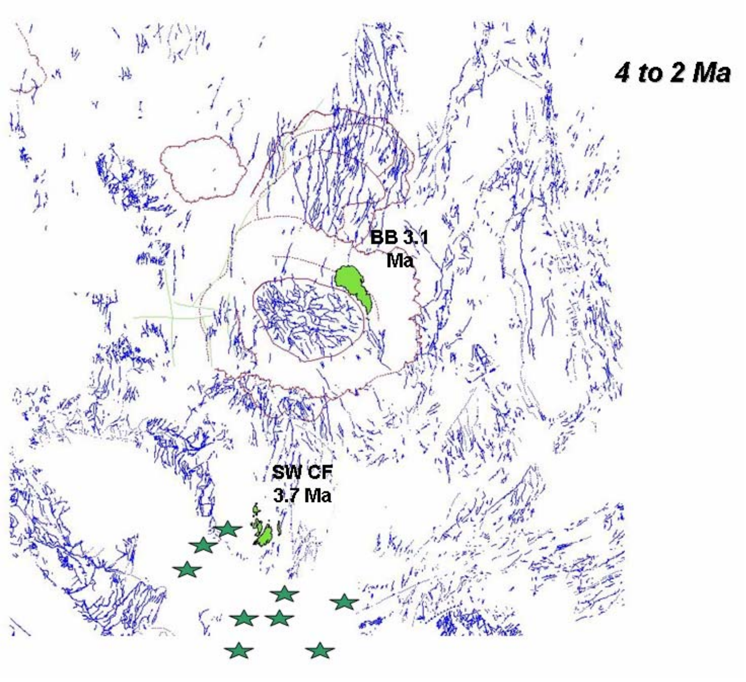

Figure 9 Actual basaltic volcanism during the period 4 to 2 Ma in the Yucca Mountain region. Exposed basalts of this age range are shown in green and green stars are magnetic anomalies that are interpreted to have a source of basaltic volcanism during this time interval. Note the significant spatial displacement of much the volcanism during this period from the basaltic rocks of the previous 2 Myr (Figure 8) (After Crowe, 2005).

- Studies related to igneous activity at Yucca Mountain published in professional journals generally are subjected to intense peer review. As a result, data and conclusions of journal articles are credible. However, subsequent studies may show different results and interpretations of the data. Thus, conclusions presented in journal articles, such as those referenced in this report, must be carefully evaluated in the light of subsequent publications. A case in point is geodetic data that describe the ambient strain of the Yucca Mountain region which has considerable importance to understanding and predicting potential seismicity and volcanic activity in the region. Geodetic observations prior to mid-1999 that were obtained from point global positioning satellite (GPS) observations replicated at intervals showed a strain of an order of magnitude greater than indicated by geologic observations which reflect mean long-term strain rates (Wernicke et al., 1998). This led Wernicke et al. (1998) to conclude that hazard analysis may be underestimated by an order of magnitude. However, follow-on investigations suggest that these results may be in error (Savage et al., 1999) or represent a geologically recent spike of increased crustal strain (Connor et al., 1998; Wernicke et al., 2004). Subsequent GPS studies in the Yucca Mountain region are based on continuous observations which enhance the data quality. They suggest that the earlier strain rates may be too high by a factor of roughly two (Wernicke et al., 2004).

- The scope of this report is limited to the post-closure period of the repository after the underground repository has been sealed off from the surface. Preclosure igneous activity is not considered. Although the unlikely probability exists that igneous activity could occur during the preclosure period with its resulting impact upon waste stored on the surface for aging purposes and emplaced in drifts of the repository as well as on workers and surface structures, systems, and components at the repository, there is no evidence from precursor indicators that imminent igneous activity is likely over the short span of the preclosure period (~100 years). DOE (1999) in its preclosure event prevention strategy is designing preclosure structures, systems, and components to withstand bounding igneous events, but the NRC (2005a) has pointed out the lack of consideration of tephra and ash falls which could impact the roof loads and effects on ventilation and filter systems. The NRC (2005a) also has written that the DOE should provide the technical basis to exclude hazards from lava flows to the potential repository surface operations area. It is unclear to ACNW&M why the NRC has preclosure concerns about lava flows. Lavas extruded in Crater Flat could not reach the ridge-top location of Yucca Mountain. The genesis of lava on the mountain itself at the repository site has an extremely low probability (10^{-9}/yr to 10^{-7}/yr) that falls below the cutoff value (1 chance in 10,000) for consideration as a Category 2 event during preclosure (10 CFR 63.2). Finally, the genesis of lavas on the eastern side of Yucca Mountain where preclosure facilities would be located should have an even lower likelihood of occurrence than on the mountain itself because there is no evidence of post-Miocene volcanism in Jackass Flats.

1.7. Previous Reviews of Igneous Activity Technical Bases

Understanding and predicting the role of igneous activity throughout the lifetime of the proposed Yucca Mountain repository has been one of the more challenging topics of the characterization of the repository site. Accordingly, progress on the technical bases for making decisions on igneous activity has been under review for nearly two decades. The Nuclear Waste Technical Review Board (NWTRB) has monitored progress in the DOE program at regular intervals and the NRC's program in igneous activity has held the interest of the ACNW&M since the inception of the Committee. The igneous activity program of the NRC and the differing opinions regarding the results of the program among the State of Nevada, the DOE, and the NRC has encouraged reviews by standing advisory (review) committees and ad hoc panels of specialized experts.

The ACNW&M has sent eight letters to the Chairman of the Commission with its observations and recommendations on the NRC's igneous activity since 1989. (Committee letters since 1989 are available on the NRC's Web site at http://www.nrc.gov/reading-rm/doc-collections/acnw/letters/.) These letters have dealt with the importance of a multidisciplinary approach to igneous activity studies, magma/drift/waste package interaction in the intrusion scenario, the significance of accurate isotopic dating of basalts of the Yucca Mountain region to the estimation of the probability of future igneous events, the importance of minimizing uncertainties in the results of the studies, and the need for a risk-informed approach to igneous activity studies. In addition, the Center for Nuclear Regulatory Waste Analyses (CNWRA), the laboratory supporting the NRC's repository analysis program, has conducted external previews of their igneous activity studies (Hill, 1995; McKague, 1998; Sparks and Woods, 1998). These reviews have made specific recommendations regarding topics that have received special attention.

The DOE's igneous activity study program, supported by personnel from Los Alamos National Laboratory and the U.S. Geological Survey, has been complemented with external peer review panels. In 1996 the DOE completed a 2-year expert elicitation, the Probabilistic Volcanic Hazards Assessment, which established the probability distribution of the annual frequency of intersection of the proposed repository by volcanic activity on the basis of the evaluation of ten experts following the guidelines for expert elicitations set forth in NUREG-1563 (Kotra et al., 1996). This elicitation is being updated (Probabilistic Volcanic Hazards Assessment – Update) taking into the account the considerable amount of new geosciences information about igneous activity at the proposed repository. Support for this new elicitation came from the DOE's external Igneous Consequences Peer Review (ICPR) Panel (Detournay et al., 2003) which was constituted to review the potential consequences and effect upon risk due to an igneous intrusion intersecting the proposed repository. A major emphasis of this panel, which released its final report in 2003, was to review the interaction between the intruding magma and the repository drifts and to recommend studies by the DOE that would reduce uncertainties in the overall igneous activity program. The results of these reviews have brought knowledgeable, fresh insight into the program.

The NWTRB reviews the DOE studies on igneous activity on a regular basis. The NWTRB has reported the results of these reviews and suggestions for further studies in regular reports to Congress and letters to the DOE Office of Civilian Radioactive Waste Management since 2000 (NWTRB; 2001, 2002, 2003, 2004).

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2. Brief Geologic History of the Yucca Mountain Region

The geologic history of the Yucca Mountain region, including both its structural development (tectonics) and history of volcanic activity, form the foundation for understanding the past and for predicting future igneous activity in the region. The geological structure of the region has a direct impact on the magma source zones and the specific location of volcanic activity. As a result, the nature of tectonism is critical to predicting the probability and nature of volcanism. As stated by McKague et al. (2006) in referring to the implications of tectonic models on the probability of occurrence of a volcanic eruption or igneous intrusion at Yucca Mountain:

> For volcanism to occur, the physical and chemical conditions for magma formation must exist at some depth, and a path must be established between this magma source and the Earth's surface. Both these sets of conditions together with the style and frequency of igneous activity are determined by tectonic setting. More locally, the in situ stress state and presence or absence of faulting and fracturing are factors controlling magma ascent through the crust.

This section provides an overview of the tectonic and igneous activity history of the region. The literature on this topic is too extensive to cover comprehensively in this report, but useful recent reviews of the subject that contain critical references have been prepared by Crow et al. (1995; 2006), Parsons (1995), O'Leary (1996, 2007a), Grauch et al. (1999), and McKague et al. (2006), Lipman (2007), and Stuckless and O'Leary (2007). A simplified history of the Yucca Mountain region is illustrated in Figure 10.

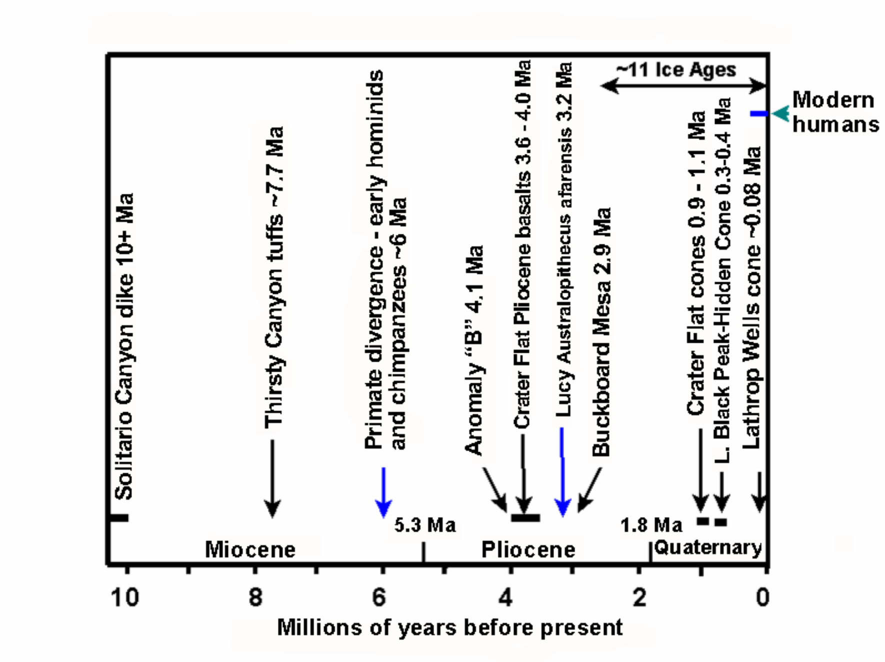

Figure 10 **Timeline of events in the Yucca Mountain region related to igneous activity, geological periods of time, and events in human evolution.**

The State of Nevada and the Yucca Mountain region are located in the Central Basin and Range geological province (the Western Great Basin) which is noted for topography consisting of generally north-south trending, alternating elongate valleys (basins) and mountain ranges that extend into adjacent states and continue south into northwestern Mexico (Figure

11). The geological history of this region is long and complex with periods of tectonic activity, as illustrated in the general geologic map of the region (Figure 12). The area was last subject to mountain building during the Laramide *orogeny* that occurred as a series of tectonic pulses separated by quiescent periods, from about 70 to 40 Ma[3]. The Rocky Mountains, with generally easterly-directed thrust faults and folds that extend from Alaska to northern Mexico, originated during this orogenic event. The mountain building episode was caused by collision of a *lithospheric plate* off the west coast with the North American plate. The western plate was *subducted* beneath the North American plate at a low angle resulting in the broad zone of mountain building observed in the western United States. The *sedimentary* and *igneous rocks* that form the base of the volcanic rocks in the Yucca Mountain region were complexly faulted and folded during the Laramide and earlier orogenies (Dickinson, 2006).

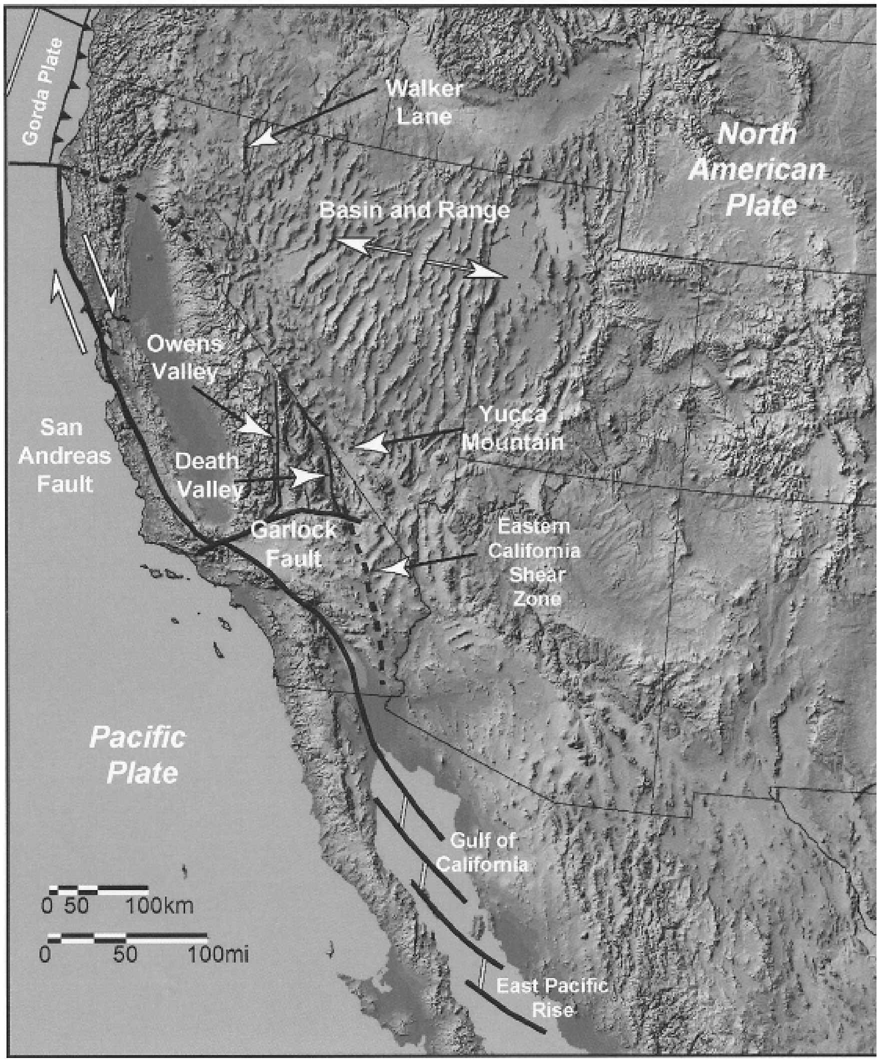

Figure 11 **Elevation map of the southwestern United States showing the position of Yucca Mountain and major geologic, structural, and topographic features (After McKague et al., 2006).**

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[3] Ma is the abbreviation for age in millions of years; Myr is the abbreviation for a duration of time in millions of years.

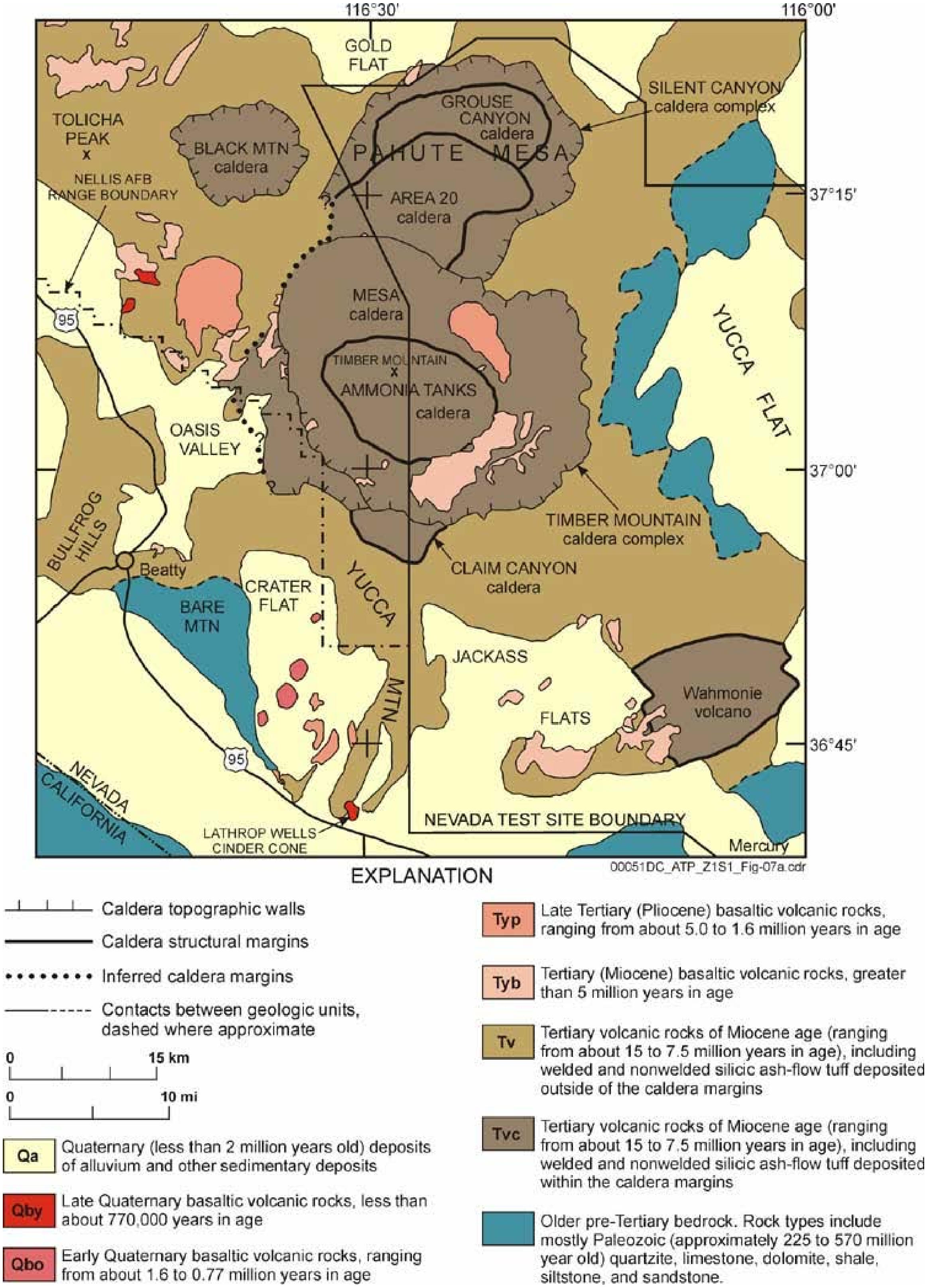

Figure 12 Geological Map of the Yucca Mountain Region (From DOE, 2002).

The Basin and Range province is an active extensional region within the North American western Cordillera. It is named for the topographic manifestation of the most recent mode of extension which consists largely of block faulting with *normal faults* typically dipping at a steep angle to the west. The current tectonic activity within the region is indicated by its high heat flow, seismic activity, recent basaltic volcanism, thin crust, and observed strain rates. Unlike most rifts that have undergone normal faulting and *lithospheric* extension, the Basin and Range province is very broad, reaching a width of more than 900 km. Extension commenced about 25 Ma ago resulting in a variable amount of stretching across the region with an average total extension of approximately 100%. Relatively small magnitude extension in the Yucca Mountain region of the Central Basin and Range from approximately 13 to 10 Ma produced the steep (~ 60^o) normal faulting that results in the characteristic Basin and Range topography with ranges such as Yucca Mountain and basins such as the adjacent Crater Flat basin and Jackass Flats (Figure 13). The Crater Flat basin is described as a half-*graben* which is "…the southern extremity of a much deeper, broader crustal depression that hosts the caldera of the southwestern Nevada volcanic field." (O'Leary, 2007a). It is shown by the geophysical interpretation in to extend from Bare Mountain to east of Yucca Mountain into Jackass Flats. Also see the map by Faulds et al. (1994) that describes the geology of eastern Crater Flat basin. The source of the extension causing the half-graben is uncertain, but it is thought to originate from the Pacific Plate moving northwest relative to the North American Plate. This same force created the San Andreas fault. Other forces may be involved, including those related to the movement of the North American Plate over the spreading center associated with a plate to the west. There is evidence that an early stage of extension may have occurred at the end of the Laramide orogeny as a result of gravitational collapse of an overthickened crust, followed by extension related to spreading of the continental crust associated with disintegration or steepening of the plunge of the subducting oceanic plate.

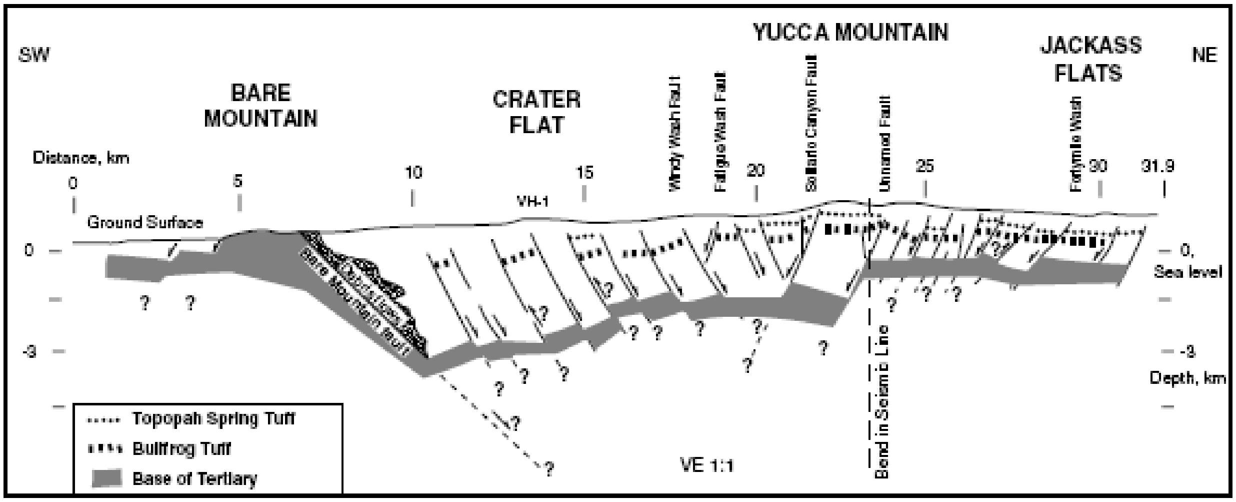

Figure 13 **Interpretation of seismic reflection profile across Crater Flat and Yucca Mountain (After BSC, 2004b).**

In addition to the late-stage normal faults, several other types of faulting have occurred in the region. Low-angle normal faults that occur in isolated locations represent an earlier stage of extension, but their origin is controversial. The Yucca Mountain region is a complex structural belt resulting from its location in the transition between the Walker Lane, which lies on the eastern margin of a distributed shear zone, the Eastern California Shear Zone (Figure 11), that extends north-northwest from the southeastern corner of Nevada, across Nevada, and into California, and the Basin and Range province to the north and east. The Walker Lane structural feature, dating back a few tens of millions of years, is characterized by north-northwest striking right-lateral displacement and north-northeasterly directed left-lateral displacement faults and consists of an assemblage of independent structural units. Its origin lies in distributed shear forces arising from movements in the continental crust to the west. Both normal faults of the Basin and Range province and the shear faults of the Walker Lane are prominent in the Yucca Mountain region.

Several tectonic models have been proposed to explain the origin of the structures of the Yucca Mountain region and to assist in extrapolating those features into the subsurface. It is their subsurface extent and orientation that have a significant role in relating them to volcanic and seismic activity. The models can be classified into three groups based on the principal mode of deformation that is incorporated into their explanation: extension, shear, and volcanic. This is not surprising because of the overlap in the region of shear deformation associated with the Walker Lane, the extensional forces prominent in the Basin and Range province, and the massive, intense volcanism 11 to 15 Ma ago. McKague et al. (2006) recognize eleven viable models and present a description of and the bases for each of these models employing the most recent geologic, geodetic, and geophysical data. They conclude that no single tectonic model explains the structural deformation of the region. However, they point out that the active faults, high strain rates, and deep faults identified with the shear models are of concern when considering the potential for igneous activity in the Yucca Mountain region over the lifetime of the repository. O'Leary (2007a) identifies the pure shear (planar fault) model as the preferred tectonic model for the region.

Igneous activity appears to coincide with the Basin and Range province extension, but the relationship is variable across the province. Magmatism is particularly well correlated with the early stage of extension involving low-angle faulting, but not necessarily with late stage normal faulting. The widespread igneous activity over the Basin and Range province is well summarized by Parsons (1995).

Voluminous felsic volcanism occurred in the Yucca Mountain region ~7 to 15 Ma ago. This is the final portion of the extensive "ignimbrite flare up" of felsic, relatively high silica volcanism which advanced across the Basin and Range province from the north to the Yucca Mountain region. The source of the felsic volcanic rocks is largely from the melting of crustal rocks as a result of heat from the mantle and intrusions into the lower crust. The felsic rocks are the result of collapse of calderas over felsic magma chambers causing immense flows of the hot ash (ignimbrites) and ash falls which make up Yucca Mountain. These rocks which have been subsequently faulted by late stage normal faulting and shear faulting of the Walker Lane make up the repository rocks. They consist of both welded and unwelded tuffs. The welded tuffs are ash flows deposited in a sufficiently hot state that the ash particles welded together.

During the period from about 9 to 11 Ma the felsic volcanism in the Yucca Mountain region transitioned to mafic (basaltic) magmatism. Basaltic volcanism was widespread over the southwestern United States during the subsequent period of time and much more voluminous in many other areas in contrast to the Yucca Mountain region. At least four known pulses of basaltic volcanism occurred (DOE, 2003) in the Yucca Mountain vicinity. These include the

~80 ka Lathrop Wells cone and flows (Heizler et al., 1999), ~1 Ma events (Pleistocene or Quaternary[4]) in Crater Flat (Figure 15), and multiple events dated ~3–5 Ma (Pliocene) and ~8–13 Ma (Miocene). No basaltic volcanism is known to have occurred between 5 and 7 Ma.

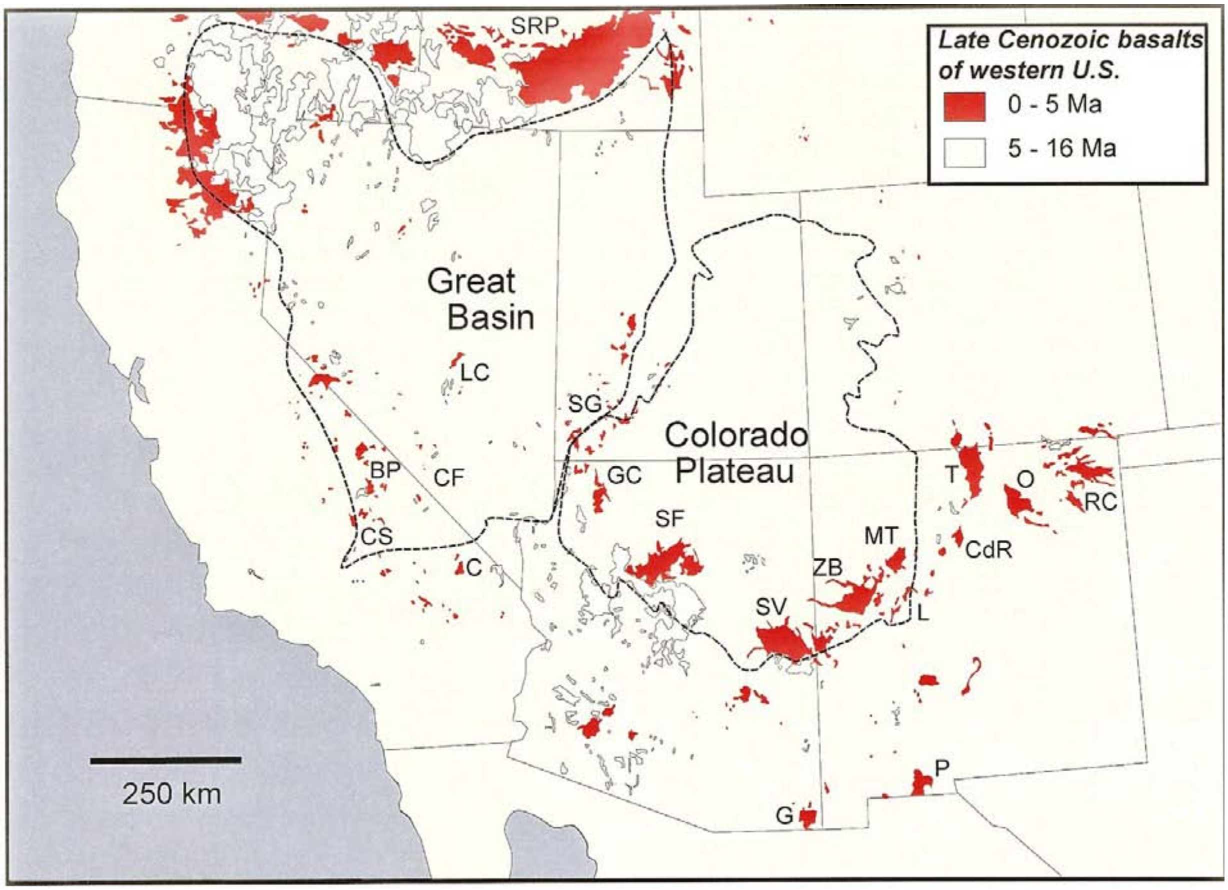

Figure 14 **Late Cenozoic (16 Ma to present) basaltic rocks of the southwestern United States. Note the small amount of basalts in the vicinity of Yucca Mountain (CF-Crater Flat) (After Perry, 2002).**

Other young basalts in the Yucca Mountain region (YMR) include Little Black Peak (~0.3 Ma) and Hidden Cone (~0.4 Ma), located about 35 km NW of Yucca Mountain. Large exposures of Miocene basalts occur in Jackass Flats, at Dome Mountain in the Timber Mountain caldera complex, and in proximity to the Black Mountain caldera. Miocene-age basalts also occur in western Crater Flat, and as a dike complex in Solitario Canyon on the northwestern flank of Yucca Mountain. All of these occur within the Southwestern Nevada

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[4] The Pleistocene Epoch and the Quaternary Period are used synonymously in this document and much of the literature on igneous activity of the Yucca Mountain region for the time period between 11.8 ka and 1.8 Ma. Note that by international agreement the Quaternary formally extends from the present time to 2.5 Ma (Intl. Commission on Stratigraphy, 2006).

Volcanic Field (Christiansen et al., 1977; Grauch et al., 1999) which is the site of intense episodic, voluminous magmatism and variable intense extension over the period from 9 to 17 Ma and subsequent waning basaltic volcanism (Figure 16). It covers an irregular area with a radius of roughly 50 km generally centered on the Timber Mountain Caldera Complex immediately north of the proposed repository.

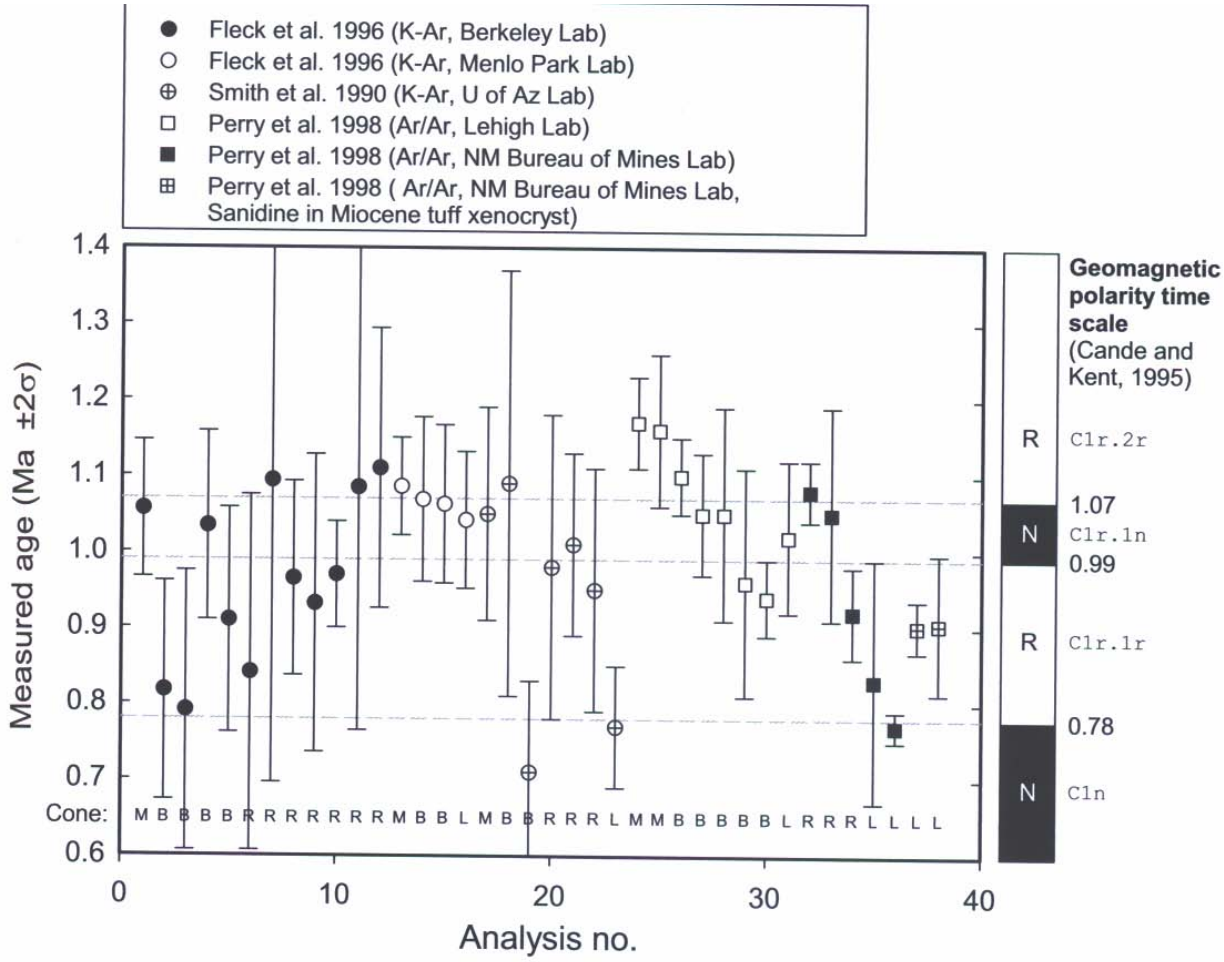

Figure 15 Summary of K-Ar and $^{40}Ar/^{39}Ar$ radiometric ages for the Quaternary basalts of Crater Flat. Error bars represent ±2σ. Symbols at bottom of chart are abbreviations for each cone (M=Makani Cone; B=Black Cone; R=Red Cone; and L=Little Cones) (After Valentine et al., 2006, Figure 2) (σ = standard deviation) (Permission to use this copyrighted material is granted by the Geological Society of America).

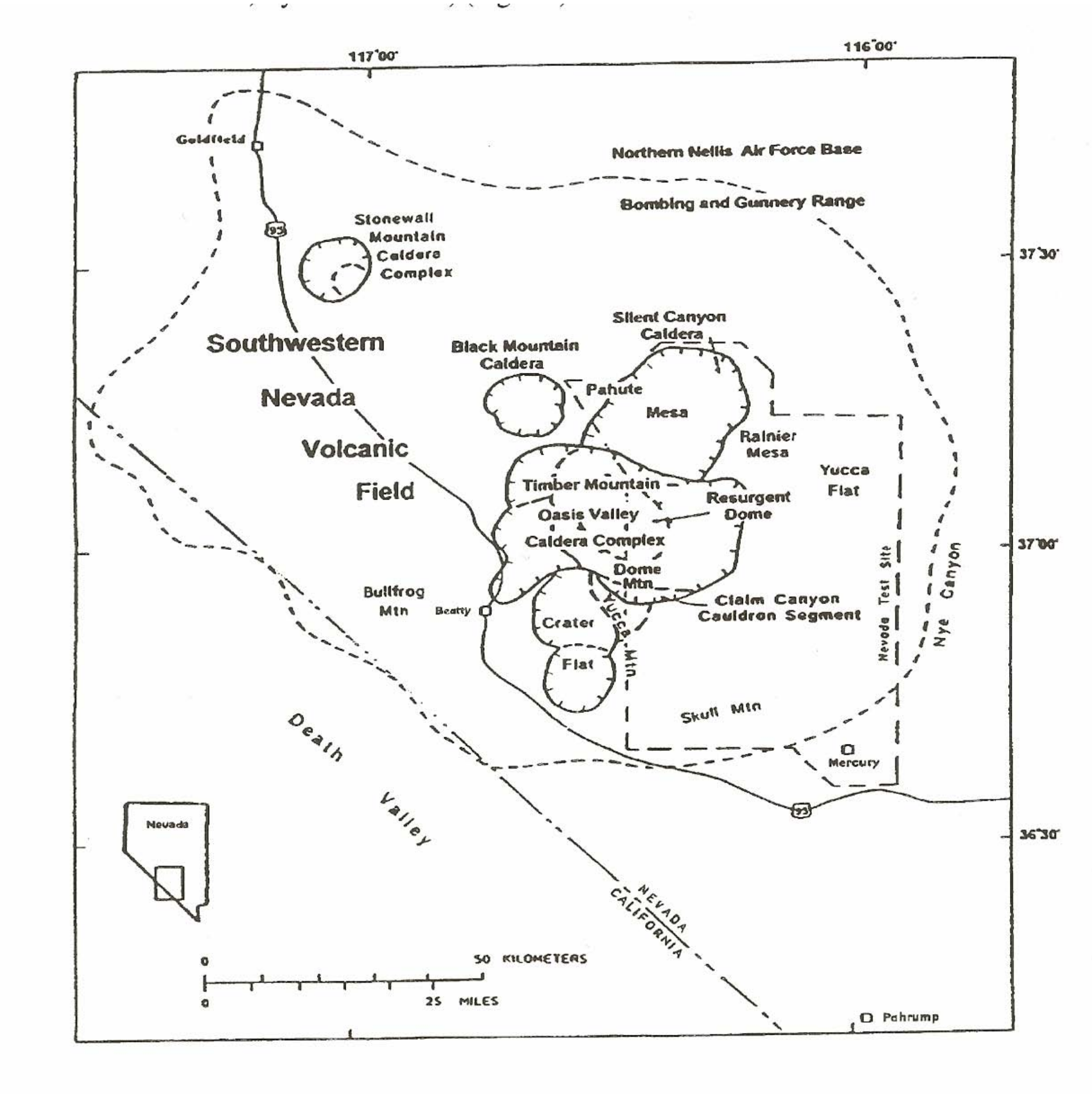

Figure 16 Southwestern Nevada volcanic field. The limit of the Southwestern Nevada Volcanic Field indicated by the dashed line (from Byers et al., 1989). Several volcanic calderas have been identified as the sources of the intense felsic volcanic activity in the field. The Crater Flat caldera is no longer generally recognized (After Crowe et al., 1995) (Permission to use this copyrighted material is granted by the American Geophysical Union).

The frequency and volumes of basaltic volcanism have declined significantly since Miocene time (DOE, 2003). For example, Jackass Flats has widespread Miocene basalts but no known post-Miocene volcanism. *Magnetic* surveys indicate that additional basalts may be buried beneath alluvium in Crater Flat and the Amargosa Desert (Stamatakos et al., 1997; Connor et al., 2000; O'Leary et al., 2002; Hill and Stamatakos, 2002; Perry et al., 2005). Basaltic rocks have an intense magnetization in contrast to the alluvial sediments of the basins and thus are readily mapped by *anomalies* in the normal Earth's magnetic field. The *magnetic* variations (anomalies) resulting from buried basalts may be either positive or negative depending on the polarity of the Earth’s magnetic field at the time the basalts solidified. Additional details regarding the temporal and spatial occurrence of basalts dating back to 10 Ma are presented in Chapter 5.

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3. Overview of Igneous Activity Processes

3.1. Introduction

The logic charts of Figure 3, Figure 4, Figure 5, and Figure 6 show the components involved in evaluating the nature and likelihood of future igneous activity at Yucca Mountain and the potential consequences of this activity. The consequences are based on both the *intrusive* and *extrusive* (volcanic) scenarios and their interaction with the repository and the waste packages. The processes involved in these scenarios are integral to the technical bases for decisions about igneous activity at the proposed Yucca Mountain HLW repository. Accordingly, this chapter briefly explains processes related to the origin and nature of igneous activity (Figure 3), magma/repository interaction (Figure 4, Figure 5, and Figure 6), dispersal of contaminated ash and its remobilization (Figure 6), and the doses to the RMEI from the contaminated ash (Figure 6).

3.2. Origin and Nature of Igneous Activity

3.2.1. Magma Generation

The origin and nature of igneous activity is important to understanding the processes that may impact the risk from the proposed Yucca Mountain repository. Knowledge of the scientific basis of igneous activity has progressed steadily during the past century, but growth has been particularly dramatic in the past 40 years with the development of the *plate tectonic* paradigm and rapid advances in the geochemistry of igneous rocks and modeling of magmatic processes (e.g., Fisher et al., 1997; Decker and Decker, 1997; Schmincke, 2004).

Magma is primarily generated at depths of several tens of kilometers in the lower *crust* and upper *mantle* along crustal boundaries where plates making up the outer *lithosphere* of the Earth are colliding (convergent boundaries) or being pulled apart (divergent boundaries) by sub-lithospheric movements within the mantle. Plates at convergent boundaries may be drawn into the Earth (subducted) to depths great enough to cause partial melting of the upper surface of the plate. At divergent boundaries, along mid-ocean ridges and continental rifts, lateral extension or rifting of the lithosphere moves deep, hot rock upward. This rock then undergoes partial melting in response to the decrease in pressure. Partial melting leading to magma production in Earth's mantle also occurs in response to isolated 'thunder-head-like' motion. Rising plumes of hotter rocks occur independent of plate margins and produce localized igneous activity and voluminous volcanism on the continents (e.g., Yellowstone) and in the oceans (e.g., Hawaiian Islands). The deep-seated processes giving rise to the magmas responsible for the igneous activity in the Yucca Mountain region are not well understood. This magmatism probably reflects residual heat effects and chemical variations in the upper mantle associated with the extensional tectonics that has been the hallmark of the area for the past 25 Myr.

Partial melting of mantle rock produces buoyant basaltic magma, which ascends as magma-filled cracks (dikes) and as magmatic plumes (diapirs). Most basaltic magma does not reach the Earth's surface, but becomes encumbered at depth due to solidification or loss of buoyancy. In continental terrains, stalled basaltic magma contains sufficient heat to melt the already hot adjacent lower continental crust, generating fresh magma that moves upward toward the surface as in the case of the volcanism that pervaded the Yucca Mountain region 10 to 12 Ma ago. This rising magma reflects the composition of the local continental crust, which is much closer to *granite* (i.e., *rhyolitic*) in composition, and is distinctly non-basaltic, as are the volcanic rocks making up Yucca Mountain. Volcanism in continental terrains, like the western United States (including Yucca Mountain), is thus commonly bimodal, with rhyolitic magmas from melting of the lower crust and basaltic magmas from the venting of small, deep-seated mantle reservoirs of partial melts. Small-volume basaltic volcanism, as has occurred over the past several million years in the Yucca Mountain region, is commonly inferred to be derived from small pockets of magma that are formed and triggered into movement toward the surface by motion in the mantle reflected by crustal tectonic movements. This magma undergoes some fractionation and contamination while traveling upward through the crust. For additional discussion about background theory on magma chambers see Marsh (2000, 2006).

3.2.2. Magma Composition

The physical nature and behavior of magma intimately reflects its chemical composition. All Earth magmas are *polymeric* solutions of silica (SiO_2) diluted by varying amounts of cations (mainly, Al, Fe, Mg, Ti, Ca, Na, K, P). The silica content of magma, the basis of all rock classification schemes, varies from ~50 to 75 percent by mass reflecting the chemistry of the source rock from which the magma was generated. There is a complete compositional gradation from basalts with ~50 percent silica to rhyolites (essentially molten granite) with 70-75% silica. The temperature range of crystallization, the *viscosity* (or *rheology*), and most other transport properties are strongly dependent on magma silica content. Basalts crystallize at much higher temperatures and are much less viscous than rhyolites. This reflects the less polymerized nature of the melt forming the magma. The viscosity of a melt increases and the melt becomes more difficult to deform as it becomes more silica-rich and thus more polymerized. At the same temperature and free of crystals, basalt is a factor of ~10^4 times less viscous than rhyolite.

A critical parameter in determining the consequences of igneous activity at Yucca Mountain is rheology. The single most important influence on the rheology of any given magma is the buildup of crystals as magma crystallizes. Most magmas crystallize over a span of about 200^o C in temperature. Crystals build up from none at the *liquidus* to 100% by volume at the *solidus*. Liquidus temperatures vary from the order of 1200^o C in basaltic rocks to as low as 700^o C in granitic rocks depending on their composition, depth, and volatile content. Higher concentration of crystals strongly increases magma viscosity and as the maximum packing of crystals approaches ~50 percent, the magma becomes a rigid, *dilatant* solid that expands upon shear and resists all motion. At maximum packing, as in a cup full of ice cubes, all solids (crystals) are touching and cannot undergo shear unless the assemblage expands as neighboring crystals move outward and past one another. With magma held within solid rock, there is no room for expansion. Consequently, no magma is ever erupted containing more than ~50 percent crystals of a given size.

Volatiles dissolved in magma are of central importance in determining the nature of volcanism and the risk from igneous activity at the proposed repository. Apart from the availability of volatiles, magma composition, temperature, and confining pressure are the major factors in controlling the concentration of volatiles in magma. The principal magmatic volatiles are H_2O, CO_2, and SO_2, with water the most common primary constituent. The solubility of water in magma is a function of water vapor pressure. The solubility is directly proportional to pressure and also to magma silica content. A silica-rich magma, like rhyolite, can contain far more water than basalt at the same pressure and temperature. Because the solubility of water in magma is zero under surface conditions of one atmosphere total pressure, as magma approaches the Earth's surface it inevitably becomes saturated with water and generates bubbles, much as when a diver gets the bends from bubbles forming in the blood as the diver rises toward the surface. Volatiles also have a major effect on the viscosity of magma. Water in solution, for example, de-polymerizes the melt structure, greatly reducing viscosity. Adding 5% (mass) water to a rhyolite at 1000°C and sufficiently high pressure (several MPa) will reduce the viscosity by a factor of 10^7. The effect is much smaller with basalt, but still important. Water also significantly reduces the temperatures of crystallization.

3.2.3. Volcanoes and Their Products

Magmas rise from source regions of molten rocks by buoyancy due to lower density of the melt and gas bubbles of vapor and when the overpressure exceeds the tensile strength of the overlying rocks. The melts rise largely as near-vertical disk-like slabs or dikes, which are typically several meters wide in the Yucca Mountain region. In the absence of pre-existing weaknesses in the overlying rocks, the dikes propagate in the direction perpendicular to the least compressive stress (Valentine and Krogh, 2006; Keating et al., 2007; Perry et al., 2006, Connor et al., 2000). Otherwise dikes tend to follow paths of least resistance, which typically are existing fracture zones. The magma may freeze within the crust and stop rising, but if the magma reaches the surface a volcanic eruption occurs with the ejection of molten lava, gases, and fragmental materials through a vent into the atmosphere (Figure 17). The nature of the eruption controls the characteristics of the volcanic deposits and the relative proportion of eruptive products. For example, at the 80 ka-old Lathrop Wells volcano the eruption began with cone building. Next, the fan-like lava flows that to violent *Strombolian* activity with episodes of sustained eruption columns that deposited tephra over the adjacent region (depending on the wind direction) and produced the major portion of the scoria cone. The latter was accompanied by additional lava flows as indicated in D. The estimated volumes of the products of the Lathrop Wells volcano (Krier et al., 2006) are (1) fallout, 0.039 km^3, (2) scoria cone, 0.018 km^3, and (3) lava flows, 0.029 km^3 (total volume ~0.086 km^3).

The NRC approach currently assumes that all waste packages entrained in a *conduit* would be extruded as volcanic ash fallout. In his presentation to ACNW&M, Sparks (2007) noted that the 1973 Eldfell eruption (Iceland) included the simultaneous extrusion of degassed lava and explosive activity. Sparks considers this eruption to be a close analog to the eruption at Lathrop Wells, 80 kyr ago. Based on observations at several analog eruptions he suggests that the magma starts at a temperature ~1000^o C, but erupts at 1030^o-1055^o C due to the heat production attending the latent heat of crystallization. Insights provided by Sparks (2007) suggest that the extrusion scenario for Yucca Mountain should consider that a substantial fraction of waste entrained within a volcanic conduit would become locked up in lava flows or a *scoria* cone. Because these features resist erosion over hundreds of thousands of years, any contained waste would contribute little or no dose to the RMEI.

Volcanic cones accumulate around erupting magma fountains. The pile of material forming the volcano, in volume, textural detail, and composition, reflects the nature and sequence of arrival of the ascending magma. Two convenient measures of the material type and of volcanic activity itself are the explosivity and mobility of erupted materials. The most explosive and devastating eruptions, by far, involve large volumes (10s to 1000s of km^3) of silica-rich and volatile–rich magma (ash flows) that erupt as dense clouds of ash and gas that flow along the surface move under the force of gravity to lower elevations.

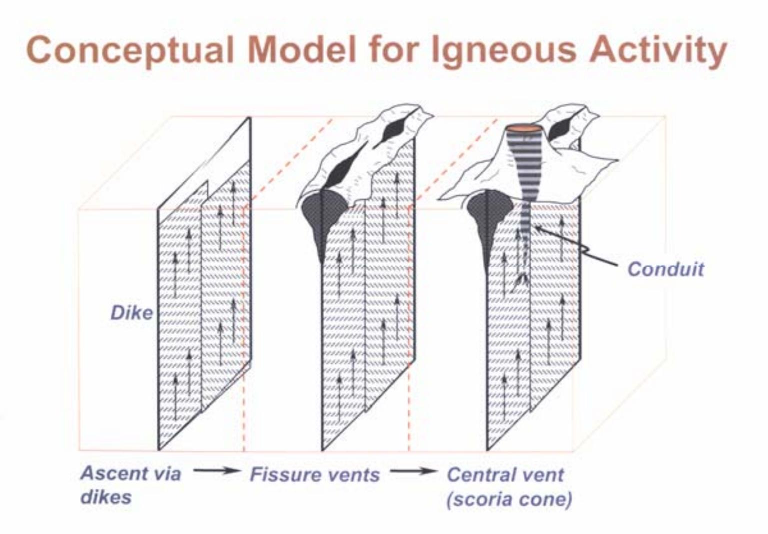


Figure 17 Conceptual model of igneous activity. Magma rises via dikes (left) leading to effusion of magma fountains along the length of dikes that reach the surface (center) and finally to focusing magma eruption in a conduit resulting in a volcanic cone (right). Arrows indicate vertical component of flow (After Valentine, 2006).

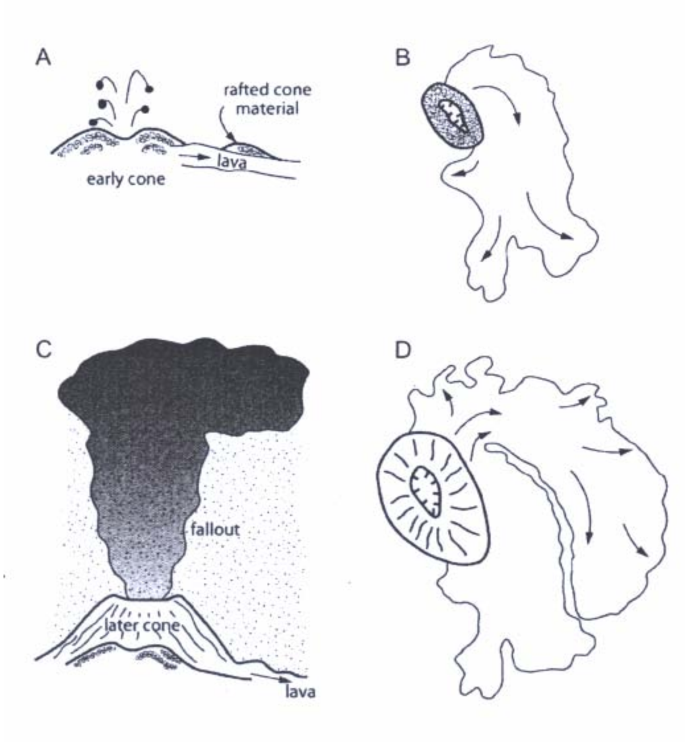


Figure 18 Inferred eruption events at the Lathrop Wells volcano. Presented are respectively simplified (a) cross-section and (b) plan view of the early stage of eruption; also illustrated are the later stage of eruption with cone building dominated by fallout (c) and effusion of the eastern lava field (d) (After Valentine et al., 2005) (Permission to use this copyrighted material is granted by the Geological Society of America).

Silicic ash flow eruptions have not occurred in the Yucca Mountain region for roughly 8 million years (Thirsty Canyon tuffs; ~7.7 Ma). Instead, the region has experienced eruptions of small volume silica-poor, basaltic magma. Basaltic magmatic systems characteristically low in volatiles, like Hawaii, emit mainly high temperature (i.e., low crystallinity), low viscosity, low explosivity lavas of high mobility that can flow considerable distances (10s of km). Flow distance depends greatly on erupted volume and terrain slope. On the other hand, basaltic magmas of high volatile contents (>~1% by mass) become saturated in volatiles in approaching the surface and generate a bubble phase that can expand rapidly, fragmenting the magma into material ranging from fine ash (mm) to coarse tephra (cm) or cinders. The overall process is somewhat akin to the uncapping of a vigorously shaken bottle of soda. The early phase of the eruption is marked by high explosivity with the transport of ash into the atmosphere. Distribution of the ash to the surrounding region depends on the intensity of the explosivity and the local meteorological conditions. This phase of the eruptive sequence is called the Strombolian phase in reference to the Stromboli volcano in the Mediterranean Sea, which has delivered gas-charged eruptions of this type. The extrusion of sluggish, high viscosity, low mobility lava flows generally follows but can accompany the Strombolian phase (Sparks, 2007). The outpourings are generally short-lived (~1 yr) and occur in a single (i.e., monogenetic) episode. Small volume (<~5 km^3) cinder (scoria) cone systems of this nature are typical of those in the Yucca Mountain region. None of the cinder cones in the Yucca Mountain region are interpreted as polygenetic. Because cinder cone events often commence with eruption from a fissure ~1 km long or greater (Figure 17), there is the potential that a dike associated with a cinder cone event adjacent to Yucca Mountain could reach far enough into Yucca Mountain to intersect the repository.

3.3. Magma/Repository Interaction

3.3.1. Nature of Magma Ascent

Low viscosity magmas flow like thick syrup, travel rapidly in small meter-wide cracks and spread rapidly as lava flows. The transfer of basaltic magma in the upper crust, especially during establishment of a new volcanic vent, is mainly by magma-filled elastic crack propagation, as evidenced by the common occurrences of dikes of basalt in eroded volcanic terrains. The rate of propagation is limited by the ability of the magma to flow into the opening crack. If magma viscosity becomes too large, dike propagation and ascent stall and magma may pool or solidify in place.

3.3.2. Key Features of Magmatic Dikes

The features of magmatic dikes that are critical to a Yucca Mountain igneous event are rapid rate of propagation, the azimuthal orientation, and the large aspect ratio (length/width). Typical aspect ratios can be of the order of 100 to 1000. The dike is envisioned as a thin disk expanding upward in all directions from the point of initiation and driven by an internal overpressure or buoyancy. A dike one meter thick can lengthen to one kilometer or more as it approaches Earth's surface. The volume of available magma limits the size of any dike as well as the number of dikes that can be generated in a single event. Once the dike intersects the surface, the internal driving pressure is dissipated through venting of the magma, compromising further expansion. Propagation is normally in the plane of the least principal stress, which in the Earth is generally vertical, and the strike or azimuthal orientation of the dike is strongly influenced by the principal horizontal stresses, whose magnitude and orientation reflect the structural makeup of the crust and the prevailing tectonic conditions. These are generally referred to as 'regional stress patterns.' Local topographic conditions, which alter the local stress field, can literally steer the dike to a limited degree as it reaches the surface (e.g., Gaffney and Damjanac, 2006). BSC (2004a) reports that the topography of Yucca Mountain would have little effect on dike propagation. Gaffney and Damjanac (2006) show a more detailed analysis of flow focusing given a dike ascending beneath variable topography.

3.3.3. Basic Nature of Eruptive Event

The nature of the eruptive event as the dike intersects the surface depends critically on the type of magma, its viscosity and, especially, the volatile content of the magma. With the amount of volatiles expected for typical basaltic magmas in the Yucca Mountain region, the magma will be undersaturated with volatiles until it comes within about 5 km of the surface. At the point of saturation a separate vapor phase will form as an assemblage of bubbles to further accelerate ascent. The increasing strength of this vapor phase event will eventually fragment the magma and form an explosive eruptive column into the atmosphere of hot gas laden with quenched particles of magma. The sizes of these particles will vary from fine ash to popcorn-like tephra. The strength and duration of an event depends on the volume of magma involved, the volatile inventory, the number of eruptive vents, and the geometry of the eruptive system. Lava can push out from the central vent through the base of the cone and flow outward under gravity. In these eruptions, explosive activity commonly switches back and forth between Strombolian activity and eruption of lavas (Valentine et al., 2006, 2007; Valentine and Keating, 2007).

3.3.4. Magma Interaction with Repository and Waste Packages

In the unlikely event that volcanic activity would intersect a repository (Figure 19), there are several scenarios for potential interaction. The consequences for future radiological exposures vary significantly among these. These scenarios are the intrusion scenario (including the so-called “dogleg” scenario) and the extrusion (i.e., volcanic) scenario.

The first scenario, the intrusion scenario, involves hypothetical intersection of the repository drifts by a volcanic dike (Figure 5 and Figure 20). An ascending dike could theoretically be deflected around a repository by topographic and/or thermal-mechanical stress (Hardy and Bauer, 1991). Nonetheless, the NRC, DOE, and EPRI have considered the possible consequences by assuming that a dike could intersect and propagate through the repository and interact with the waste packages in the tunnels (drifts). As a dike approaches the level of the drifts, the crack tip would advance ahead of the magma front. This advancing vapor-filled cavity would be the first part of the propagating dike to reach the drift. The DOE models the pressure in this cavity to be negligible because of the very high gas permeability of the fractured nature of the local tuffaceous rock (Detournay et al., 2003).

Detournay et al. (2003, p. 49) also commented on the possible effects of a repository on dike propagation, as follows:

> The stress barrier that develops around a hot repository during the intermediate period spanning the first 2000 years (since closing of the repository) could cause the dike to be deflected so as to avoid crossing of the repository, promote the creation of a sill, or halt propagation of the tip approaching the repository if the dike is centered a few kilometers north or south. Such protection is time-limited, however; it is therefore conservative to assume that the dike would propagate vertically under all circumstances and would intersect the repository. The major impact of the thermal perturbation would be to reduce significantly the size of the tip cavity ahead of the magma front and perhaps to increase the magma pressure gradient behind the magma front.

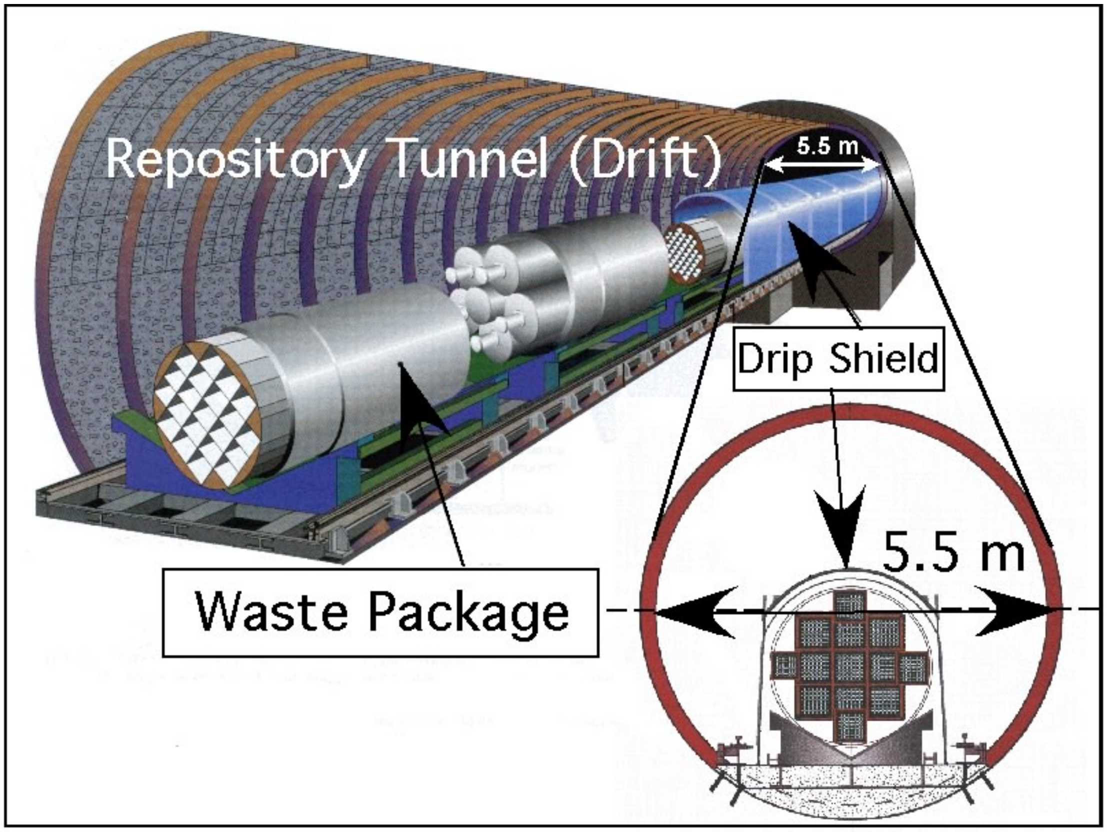
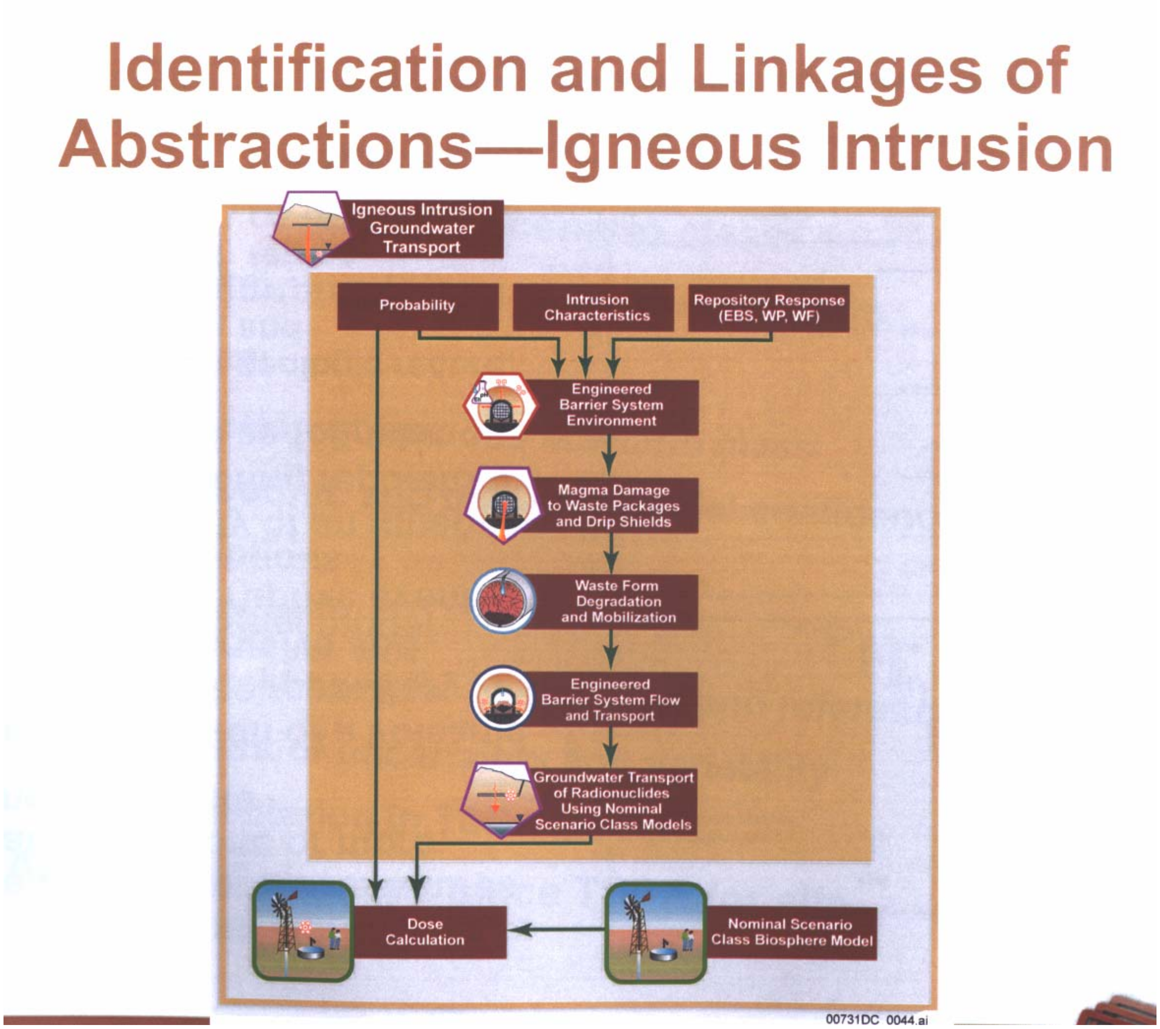


Figure 19 **Schematic depiction of the anticipated repository tunnel (drift) containing waste packages within Yucca Mountain.**

The stress barrier described by Detournay et al. (2003) would apply during the time when potential risk is greatest. After the first 1000 years, the hypothetical doses from the volcanic extrusion scenario would diminish significantly (Figure 39) because substantial amounts of shorter-lived radionuclides would have decayed away.

As the basaltic magma moves upward it may degas steadily or catastrophically. Steady release of gas would diminish the volatile content such that the magma front would not likely produce violent explosive behavior when it encounters the repository. It would instead flow effusively into the drifts. In the hypothetical case where gas explosively *exsolves*, magma could flow into drifts as a two-phase gas-magma flow, generating tephra instead of a magma flow. The flow of magma into drifts may slow the progress of the magma front to the surface, but it should have little effect on the tip of the dike cavity, which would already have begun accelerating given the diminishing overburden pressure as it approaches the surface. The dike tip would probably reach the surface in seconds after passing the repository horizon (BSC, 2003a). Flow of magma into a drift would lower the pressure in the dike directly above the drift, but this would last only as long as it takes for the drift to become filled with magma or to become obstructed by a plug of tacky, incandescent tephra. The presence of backfill either intentionally placed or as a result of drift-roof collapse, could be beneficial from the standpoint of intrusive volcanism because it would minimize contact of magma with waste packages. Backfill would not significantly alter the extrusive scenario because if a volcanic conduit intersects a waste drift it would likely entrain both waste packages and the backfill itself.



Identification and Linkages of Abstractions—Igneous Intrusion

Igneous Intrusion Groundwater Transport

Probability

Intrusion Characteristics

Repository Response (EBS, WP, WF)

Engineered Barrier System Environment

Magma Damage to Waste Packages and Drip Shields

Waste Form Degradation and Mobilization

Engineered Barrier System Flow and Transport

Groundwater Transport of Radionuclides Using Nominal Scenario Class Models

Dose Calculation

Nominal Scenario Class Biosphere Model

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Figure 20 **Identification and linkages of abstractions in the igneous intrusion scenario of DOE's TSPA (After Valentine, 2006).**

If a dike reaches the level of the repository, magma would be available to flow into drifts at a rate that would strongly depend on the magma viscosity and the rate of magma solidification as it contacts the relatively cold drip shields, waste packages, and drift walls. The flow rate would also be influenced by frictional losses at the dike/drift interface and partial obstruction of the tunnel by waste packages and drip shields. The DOE (2003) estimates that magma could fill a drift in about 5 minutes, given a dike ascent rate of 1 m/s and very low viscosities between 10 Pa·s and 100 Pa·s. Magma rising at 10 m/s could fill a drift in less than 1 minute. The filling time depends critically on the magma viscosity and pressure head driving the flow, on which there have been differing views (discussion in Chapter 6). For example, EPRI (2004) suggested viscosities several orders of magnitude greater than values given by the DOE and NRC in modeling of lava flowing into drifts. Other recent work also suggests that magma viscosities could be orders of magnitude greater than previously assumed, which would reduce the rate of magma entry to drifts (Marsh and Coleman, 2006; 2008). The potentially critical effects of quenching and solidification on waste packages and drift walls have not been fully evaluated by the DOE and NRC.

A variation of the intrusion scenario for magma-repository interaction has been proposed whereby magma might fill a drift and create enough pressure to generate (at a distance from the entry point) a secondary dike to the surface as illustrated in Figure 21 (Woods et al., 2002). This so-called “dogleg” scenario may affect a large number of waste packages. The key factor here is whether the magma has the ability to fill the drift quickly and re-pressurize it to the extent of nucleating a new dike elsewhere along the drift, in spite of the initial flow continuing to the surface. This proposed process arose from the observation that magma sometimes also erupts from separate, secondary vents in the neighborhood of the original central vent. This “dogleg” model was analyzed by BSC (2003a) which considered the propagation of pressure and stress through the dike system and the effect of magma cooling. Detournay et al. (2003) considered the propagation of either a magmatic or *pyroclastic* “dogleg” scenario to be improbable, but recommended further analyses to assess the impacts of this process on repository performance. The viability of the “dogleg” scenario is treated more fully in Chapter 6.

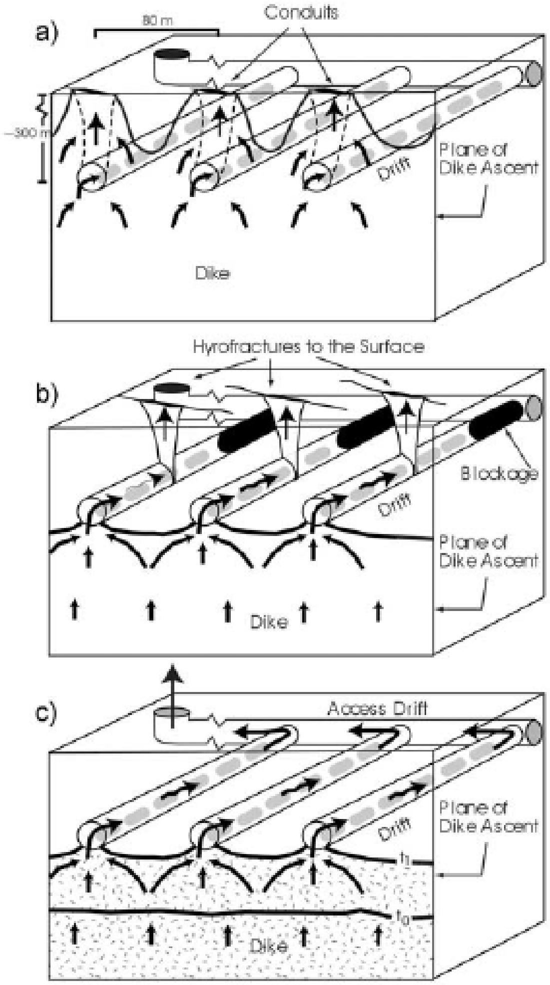

Figure 21 **Dogleg scenario. Schematic of the steady flow geometry that may enable a steady basaltic eruption to develop (dogleg scenario): (a) with flow along the original dike; (b) with magma being diverted along the drift before surfacing along a new fissure; and (c) with magma being diverted along the drift and into the main access drift from where it vents to the surface (After Woods et al., 2002) (Permission to use this copyrighted material is granted by the American Geophysical Union).**

The extrusive igneous scenario involves the intersection of a tephra-cone-forming volcanic conduit with the repository drift (Figures 6, 22, and 24). A volcanic vent is the surface expression of a conduit. The transition from flow in dikes to conduit flow occurs early in an eruptive sequence, and vents form under various conditions. In low-viscosity basalts, the transition may occur when narrow parts of the dike freeze followed by mechanical and thermal erosion of wider sections as the flow is repartitioned (e.g., Bruce and Huppert, 1990). A key difference between a volcanic conduit and a dike is that the conduit is much smaller in diameter (tens of meters) than a dike is long (kilometer scale). Given a repository drift spacing of >50 m, a conduit could directly intersect only one drift along with a relatively small number of waste packages within the cross-section of the conduit. Due to the perceived complexity of the processes involved, both the NRC (Mohanty et al., 2004) and DOE (2003) assume that the small number of waste packages (approximately 1-10) entrained within a conduit would be completely destroyed and the contents carried to the surface and ejected as contaminated tephra of varying particle sizes. The degree to which ceramic or glass waste forms could be reduced to fine particulate materials in a volcanic conduit is uncertain, particularly during the first 1000 years when the waste packages and waste forms should still be relatively intact. The manner and degree to which the fragments would be incorporated in volcanic tephra also is uncertain, but would involve magma quenching.

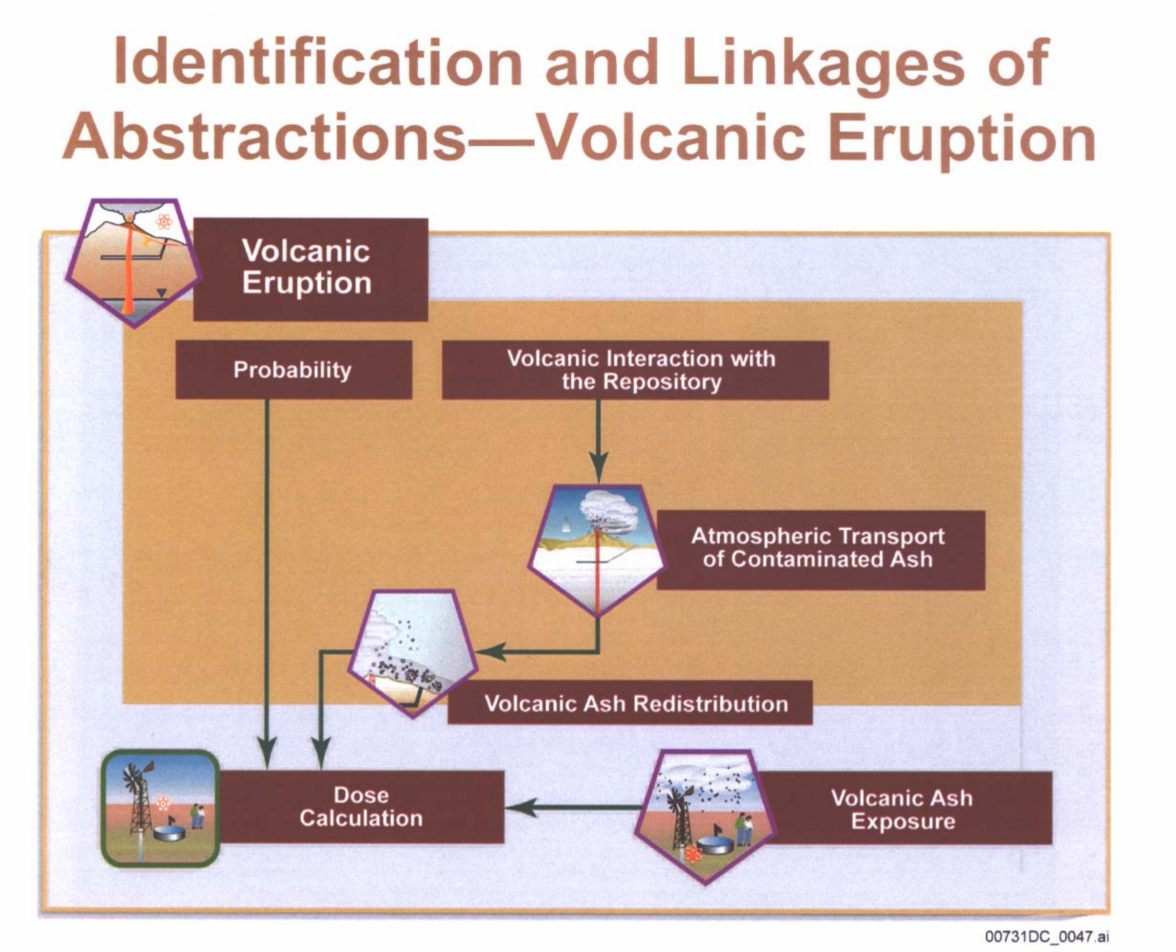

Figure 22 **Identification and linkages of abstractions in the eruption scenario of DOE's TSPA (After Valentine, 2006).**

3.4. Dispersal of Contaminated Ash

Ash emitted during an extrusive event that erupts through the proposed repository may contain fragmented radioactive waste. The contaminated ash will contribute to the dose to the RMEI primarily through inhalation (Figure 22). If the ash is not contaminated by radioactive materials, and is present in sufficient concentration, it can cause respiratory problems, but these will be minor and transient in healthy individuals (Calabrese and Kenyon, 1991). Accordingly, studies of the impact of ash on health effects associated with the Yucca Mountain repository have been directed at radioactively contaminated ash (DOE, 2002a).

3.4.1. How is Ash Dispersed?

Contaminated ash would in essence be dispersed in the same way as uncontaminated ash from a violent Strombolian eruption. The ash plume consists of a vertical high-speed jet, of which the volume and vertical extent depend on the power and duration of the eruption. The mixture of gases and particles rises *adiabatically* to an altitude where its buoyancy is neutral; i.e., where the plume temperature is the same as the ambient temperature (DOE, 2000). At that altitude, further dispersion of the ash depends on meteorological conditions. Wind has a first-order effect, and meteorological conditions that impact the crosswind movement of gases and particles have a second-order effect (Wark et al., 1998).

Dispersion of ash particles by meteorological conditions can be modeled and predicted in several different ways. The Suzuki model (Suzuki, 1983), which is generally accepted as representing the dispersion of ash from a violent Strombolian eruption, correlates well with reported data on ash fallout (Suzuki, 1983; Hill et al., 1998). The basic premises of this model are as follows:

- Movement of dispersing particles in the air is random.
- Small particles diffuse both vertically and horizontally in response to local concentration gradients.
- The scale of horizontal turbulence is much greater that the scale of vertical turbulence.

The Suzuki models involve turbulent diffusion by combining several theoretical diffusion formulations with empirical observation instead of using the *Fickian diffusion* equation that most Gaussian models employ (e.g., Wark et al., 1998).

3.4.2. How does Ash become Contaminated?

The dispersed ash from the postulated extrusive event would be contaminated by the incorporation of spent nuclear fuel particles over a wide range of sizes as well as by weakly volatile radioactive compounds. Incorporation depends on the relative densities of ash particles and spent fuel particles. The major constituent of spent fuel is uranium dioxide, which is about four times as dense as volcanic ash, so that incorporation of this material would result in relatively dense ash (Jarzemba, 1997; Jarzemba and La Plante, 1996). Less dense radionuclides, although likely to adhere to or condense on ash particles, would not increase the ash particle density significantly.

Suzuki postulates ash particles from a violent Strombolian eruption with a mean actual diameter of about 1000 *microns* and standard deviations of 1000, 4000, and 20,000 microns. He also postulates ash particle densities between 0.1 and 2.4 gm/cm^3, but includes in his model particle densities up to 10 gm/cm^3. Assumptions about ash particle diameter and density are important to modeling both the direct air dispersion as well as the remobilization of ash particles by wind. As expected, particles of larger mass as a result of size or density will fall out of the eruption plume closer to the vent. Suzuki (1983) models the footprint of the plume of smaller (1000 to 4000 microns) ash particles as extending as far as 60 km downwind. The range postulated by Suzuki encompasses the Jarzemba and La Plante (1996) assumption that the density of contaminated ash could vary up to 5 gm/cm^3.

Figure 23, provided here as an example, shows a sample of Suzuki model output produced by modeling an eruption at Irazu volcano, Costa Rica.

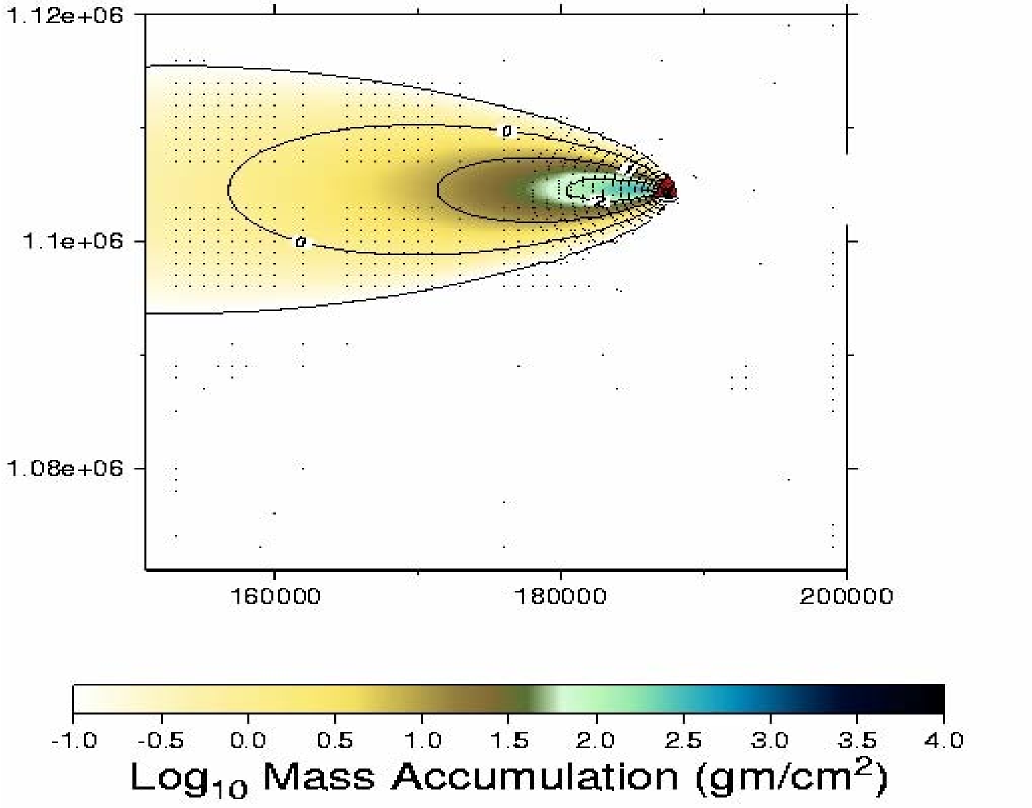

Figure 23 **A contour plot illustrating the expected tephra dispersion for a violent Strombolian eruption. The plot coordinates indicate location of the deposited material with respect to the eruption site. Wind is blowing from right to left. The vertical axis is in a northerly direction; the horizontal axis, easterly. The numbers refer to universal transverse Mercator UTM grid locations; units are meters (Source: http://www.cas.usf.edu/~cconnor/parallel/tephra/tephra.html#input).**

3.5. Remobilization and Resuspension of Contaminated Ash

Remobilization refers to the movement of ash from the initial tephra deposit to the vicinity of the RMEI, and is accomplished by either wind or water. Resuspension occurs when deposited ash becomes airborne and can be inhaled by the RMEI.

After deposition, the loose ash in a tephra sheet would be exposed to surface processes Particles with activity mean aerodynamic diameter (AMAD)[5] larger than about 100 microns, as well as particles with density greater than about 5 gm/cm^3, would generally fall to the ground before reaching terminal velocity (Wark et al., 1998). Settling of these particles would most likely be within tens of meters of the eruption vent. Smaller and less dense particles could then be remobilized. Precipitation, wind, and ephemeral surface water flow would begin to erode, rework, transport, sort, and redistribute the finer-grained ash. Intense, ephemeral floods associated with major storms have the potential to extensively erode tephra deposits, but the large flood discharges also can transport radioactive materials long distances, to the vicinity of the RMEI or beyond. Fine-grained materials can be moved to the vicinity of the RMEI where they can be resuspended by surface winds and inhaled by the RMEI. Current models assume potential health effects from both the inhaled ash and ash incorporated into soils and foods grown from those soils. Particles containing radioactive material of AMAD 10 microns or less contribute more than larger sized particles to calculated doses because of the patterns of deposition in the human respiratory tract (Figure 24)

In NRC's TPA code, version 4.1J, wind was treated as unidirectional, always blowing toward the RMEI. A more realistic treatment of wind is now being incorporated in version 5 of the NRC's TPA code. Most of the volcanic ash would not be contaminated, and only particles with AMADs less than about 50 microns would be lofted by the wind. Radioactively contaminated particles of AMAD 20 microns or less contribute more than larger sized particles to calculated doses because of the patterns of deposition in the respiratory tract of humans. Larger particles would contribute only minimally to a RMEI dose, if at all.

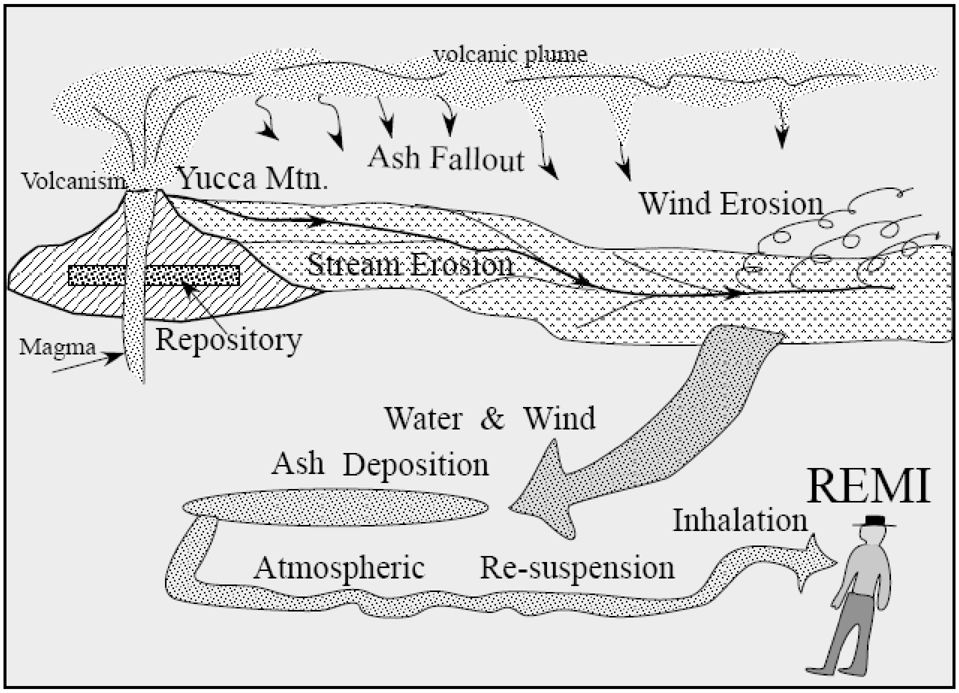

Figure 24 Schematic diagram of processes involved in ash remobilization.

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[5] Movement of particles is often modeled by giving particles the radial dimension they would have if they were spherical particles of density 1 g/cm^3. This is the activity mean aerodynamic diameter, or AMAD.

Anspaugh et al. (2002) have developed both a short-term and a long-term model for resuspension and the dispersion of resuspended material. Anspaugh et al. (2002) point out that there is at least an order of magnitude uncertainty in any long-term model of resuspension. Anspaugh (2004) points out that very little deposited material will be available for resuspension 15 or more years after the particles are deposited (Figure 25). This suggests that several decades after an eruption, little resuspended ash would be available for inhalation by the RMEI.

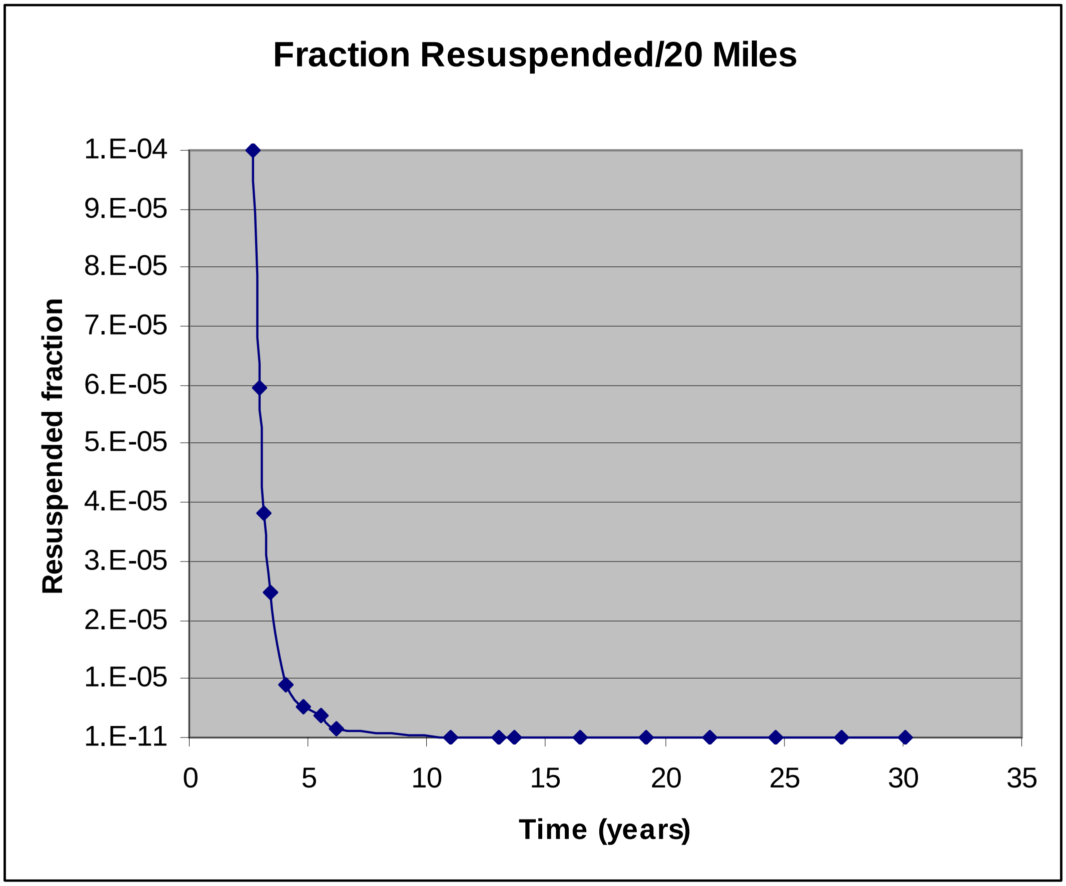

Figure 25 **Resuspended fraction of deposited material from the Anspaugh et al. (2002) equation for long-term resuspension, redrawn using a linear presentation.**

4. Nature of Potential Igneous Events in the Yucca Mountain Region

4.1. Introduction

The initial question in the risk triplet (Figure 3) – What can happen? is the subject of Chapter 4. What can happen in this case is an igneous activity event that intersects the proposed Yucca Mountain repository. Events may be initiated directly beneath the proposed repository or may reach the tunnels of the repository by dikes associated with the event extending into the footprint of the repository.

The volcanic history of Yucca Mountain, and the changes in volcanism that have occurred with time in the Yucca Mountain region, suggest that a future igneous activity event would involve a particular type and volume of volcanic eruption and produce volcanic conduits of a particular size and shape. This assumption is supported by the geologic and tectonic history and the comprehensive site characterization of the Yucca Mountain region that have provided information on basaltic volcanism during the past 10 Myr. Additionally, geologic investigations of other volcanic regions of similar age of the Basin and Range province and volcanological studies of modern volcanoes and their processes contribute useful information about the range of anticipated igneous events. There is general agreement among investigators on many, but not all, of the characteristics of possible future igneous activity. These views and their current status are identified in this chapter.

4.2. Volcanic Analogs

To evaluate the likelihood and consequences of an igneous event intersecting the proposed repository it is necessary to estimate the type, size, and shape of future igneous events, and their location and orientation, The importance of these attributes is illustrated in comparing a volcanic conduit of limited diameter to a dike whose length is measured in kilometers. Note that a volcanic conduit at repository depth would likely be much smaller than the size of the vent at the surface. A dike is more likely to intersect the repository than is a conduit. Volcanic vents typically form along dikes at sites where eruptive activity becomes locally concentrated, resulting in erosion and expansion of a local segment of dike to form a conduit or vent. Accordingly, if the repository were to be intersected by a volcanic conduit, it would also be intersected by at least one dike. The orientation and length of dikes is important because of the possibility of a dike extending into the repository from outside Yucca Mountain and the control these dike characteristics have over the number of drifts of the repository that would be intersected by the dike.

Examination of volcanic analogs, in particular those originating during the past several million years (Table 1), provides a practical method for estimating the characteristics of volcanic features. The time period used to evaluate future volcanism should be reasonably representative of present-day conditions in the Yucca Mountain region. The DOE has emphasized the Pliocene-Pleistocene (Plio-Pleistocene) time period[6] for extrapolation of events, consistent with the approach by members of the 1996 PVHA expert panel (Geomatrix Consultants, 1996). However, several members of that panel considered the Pleistocene

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[6] The Plio-Pleistocene time period includes both the Pliocene (5.3 - 1.8 Ma) and the Pleistocene (1.8 Ma - 11.8 ka) Epochs.

(previous 1.8 Ma) Epoch to be the most representative and the preferred time period from which to extrapolate. For young (Pleistocene) volcanoes, the presence of tephra cones conceals the actual dimensions of the underlying conduit, but provides useful information on the nature and volume of the events. Pliocene vents, such as those cropping out in the Crater Flat basin, can be evaluated in some detail because they have been deeply eroded, exposing interior cores filled with *agglomerate* (pyroclastic debris). The dimensions of the agglomerate mass provide an estimate of former conduit size.

The volcanic cones and lava flows of Pleistocene age near Yucca Mountain (Figure 26) provide direct analogs of the igneous activity events that could occur in the region. The Pleistocene volcanic cones of the Crater Flat basin, along with the Lathrop Wells cone, all occur in basin areas although two of the eight Pleistocene volcanoes in the Yucca Mountain region occur on topographic highs. The dimensions of the Crater Flat basin volcanoes indicate that the volume of volcanic material ranges from 0.002 km^3 (Makani volcano) to 0.06 km^3 (Red and Black Cones), while Pliocene volcanoes in Crater Flat basin and elsewhere within the Yucca Mountain region have significantly greater volumes (Table 1). The products of these events also provide information on the eruptive power of future volcanic events anticipated in the Yucca Mountain region. The presence of tephra (ash) suggests that in addition to Strombolian activity, violent Strombolian activity occurred, with plumes of volcanic material injected into the atmosphere, during portions of the volcanic events. As shown in Figure 27, Strombolian eruptions, and violent Strombolian events which are in the upper range of Strombolian eruptions, are in the lower portion of the volcanic explosivity index which is used to classify the intensity of global volcanic eruptions. As noted in this figure Strombolian eruptions are the most common volcanoes globally and are associated with small volume eruptions of lava and tephra (ash). A photo illustrating a Strombolian eruption (Cerro Negro Volcano, Nicaragua) is shown in Figure 28.

The maximum lava effusion rate for the Pleistocene Crater Flat basin volcanoes is about 1 to 4 m^3/s while the effusion rate of the Pliocene volcanoes is an order of magnitude larger (Table 1). Valentine and Perry (2006) have concluded that the total length of the fissures associated with the Pleistocene volcanoes, which is the length of the intersection of the originating dike with the surface, is less than 2 km, while Pliocene volcanoes are associated with fissures (dikes) roughly twice this length. Valentine et al. (2005) have investigated the makeup of the Lathrop Wells cone and find that the bulk of the cone is composed of fine grained eruptive materials consistent with sustained columns of well-fragmented eruptive materials and laterally extensive fallout deposits as much as 20 km from the vent.

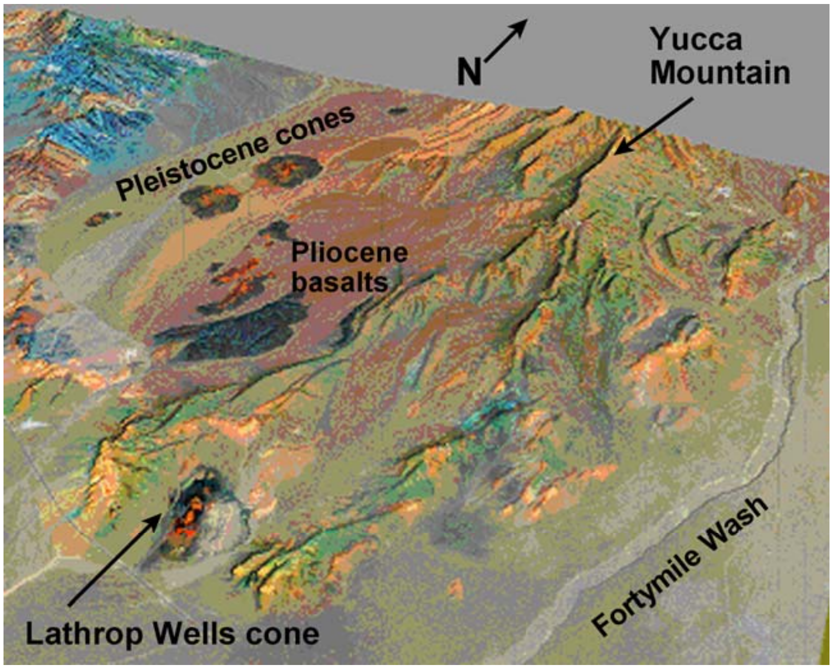
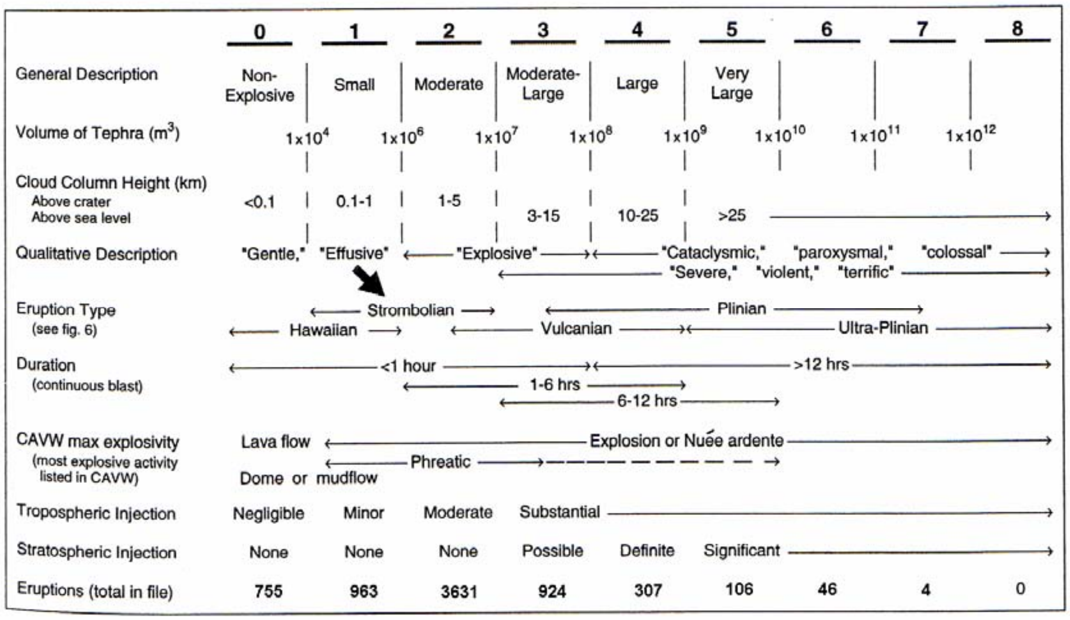


Figure 26 Pleistocene and Pliocene volcanoes in Crater Flat. The 80,000-yr-old Lathrop wells cone is the youngest volcano in this area. Diagram courtesy of Dennis W. O'Leary, U.S. Geological Survey.



	0	1	2	3	4	5	6	7	8
General Description	Non-Explosive	Small	Moderate	Moderate-Large	Large	Very Large			
Volume of Tephra (m^3)		1×10^4	1×10^6	1×10^7	1×10^8	1×10^9	1×10^{10}	1×10^{11}	1×10^{12}
Cloud Column Height (km) Above crater Above sea level	<0.1	0.1-1	1-5	3-15	10-25	>25 →			
Qualitative Description	"Gentle,"	"Effusive"	← "Explosive"	→	← "Cataclysmic," ← "Severe,"	"paroxysmal," "violent,"	"terrific" →	"colossal" →	
Eruption Type (see fig. 6)	← Hawaiian →	← Strombolian →	←	Vulcanian →	← Plinian		Ultra-Plinian →		
Duration (continuous blast)	←	<1 hour	← 1-6 hrs	→ ← 6-12 hrs	→ ←	>12 hrs →			
CAVW max explosivity (most explosive activity listed in CAVW)	Lava flow Dome or mudflow	← Explosion or Nuée ardente → ← Phreatic → - - - - →							
Tropospheric Injection	Negligible	Minor	Moderate	Substantial →					
Stratospheric Injection	None	None	None	Possible	Definite	Significant →			
Eruptions (total in file)	755	963	3631	924	307	106	46	4	0

Figure 27 Volcanic explosivity index, showing the position (bold arrow) of Strombolian eruptions like those that have occurred within the last 2 Ma in Crater Flat adjacent to Yucca Mountain. Violent Strombolian refers to eruptions in the "moderate" range of the general description. Note that the maximum cloud column (plume) height for Strombolian volcanoes is up to 5 km and the maximum volume of tephra (including ash) is roughly 0.1 km^3 (from Siebert and Simkin, 2002) (Permission to use this copyrighted material is granted by the Smithsonian Institution).

The change in rate and volume of the volcanoes and of fissure length is indicative of waning volcanism, such as evidenced in the Reveille Range, which is approximately 100 km north of Yucca Mountain (Yogodzinski et al., 1996). Valentine et al. (2006, 2007) have concluded that the Pleistocene Crater Flat volcanoes are each derived from a single conduit (monogenetic) formed in a single eruptive episode lasting only a few years. Field studies indicate that there were shallow breakouts or secondary vents from the main conduits that fed lava flows (these vents are typically referred to as *boccas*). Valentine and Perry (2006) have inferred that some dikes rise vertically with limited lateral propagation and have a curved, convex upward leading edge in a shape similar to a tongue depressor. The occurrence of volcanoes on local topographic highs (Little Black Peak and Hidden Cone), without vents that intersect the surface at lower elevations, provide evidence for the lack of extensive lateral propagation. Most basaltic dikes of Miocene age, as mapped by Valentine and Krogh (2006) in the Paiute Ridge volcanic center located east of Yucca Flat (Nevada Test Site), occupy normal faults. Similarly, Valentine and Perry (2006), based on geophysical data and field evidence, suggest that Plio-Pleistocene volcanoes erupted along existing faults.

Table 1 Ages, volumes, and eruptive characteristics of Pliocene-Pleistocene volcanoes in the Southwestern Nevada Volcanic Field (Valentine and Perry, 2006) (Permission to use this copyrighted material is granted by the American Geophysical Union).

Volcano	Age, Ma	Rock type	Volume, km^3	Fissure length, km	Lava flow length, km	Maximum lava effusion rate, m^3/s	Brief description
Thirsty Mountain	4.63± 0.02	Basaltic trachy-andesite	2.28	5	6	80	Broad shield volcano with stacked lava flows
Pliocene Crater flat	3.73± 0.02	Basalt	0.56	3.6	4	40	Low shield volcano with multiple lavas
Buckboard Mesa	2.87± 0.06	Basaltic trachy-andesite	0.84	2.5	7.3	100	Large lava field
Black Cone	0.986± 0.047	Trachy-basalt	0.06	0.6 (1.8)[a]	1	0.9	Pyroclastic cone remnant and two lava fields
Red Cone	0.977± 0.027	Trachy-basalt	0.06	0.5 (1.6)[a]	1.4	3	Pyroclastic cone remnant and two lava fields
SW Little Cone	1.042± 0.045	Trachy-basalt	0.03	0.3 (0.8)[a]	0.7	0.4	Pyroclastic cone remnant, open to the south, with single lava field
NE Little Cone	1.042± 0.045	Trachy-basalt	Included with SW Little Cone	0.2 (1.8)[a]	1.8	4	Pyroclastic cone remnant, open to the south, with single lava field
Makani volcano	1.076± 0.026	Trachy-basalt	0.002	0.4	0.4	0.1-0.2	Small lava mesa with pyroclastic deposits

Volcano	**Age, Ma**	**Rock type**	**Volume, km^3**	**Fissure length, km**	**Lava flow length, km**	**Maximum lava effusion rate, m^3/s**	**Brief description**
Little Black Peak	0.323± 0.027	Basalt to trachy-basalt	0.014	0.4 (1)[a]	1.3	2	Pyroclastic cone with lavas that extend from its base
Hidden Cone	0.373± 0.042	Basalt to trachy-basalt	0.03	0.3 (0.8)[a]	1.6	4	Pyroclastic cone on side of butte with two lava fields
Lathrop Wells	0.076± 0.005	Trachy-basalt	0.09	0.8 (1.8)[a]	1.6	4	Single pyroclastic cone with two lava fields

[a] value represents diameter of main cone, which is the source for all preserved eruptive material, representing the expected value. Value in parentheses is the total length that could be buried by all eruptive deposits, representing the maximum possible value.

Figure 28 **The 1968 Strombolian eruption of Cerro Negro Volcano, Nicaragua. In the foreground is a small crater that is emitting fire fountains of magma that are feeding a lava flow during the central crater's Strombolian eruption. Diameter of the base of the volcano is about 1.5 km (After Melson (2002) from a photo by Robert Citron).**

4.3. NRC and DOE Perspectives

4.3.1. NRC/DOE KTI Agreement on the Likely Range of Tephra Volumes

A Key Technical Issue (KTI) agreement related to the likely range of tephra volumes from volcanoes in the Yucca Mountain region was reached by the DOE (2003) and NRC. This agreement is reflected in a letter from the NRC (Kokajko, 2005) to the DOE. However, in this letter the NRC expressed concern that the range of tephra volumes used by the DOE in performance assessment did not correspond to the volumes interpreted for volcanoes that have occurred in the Crater Flat basin during the time interval used in the DOE's probability calculations. For example the eroded remnants of scoria cones of Pliocene volcanoes in Crater Flat basin, which are included in the DOE probability results, indicate larger tephra volumes than those accounted for in the current DOE parameter range (BSC, 2003b). However, the magnitude of differences between the DOE and NRC estimates of tephra volumes for past Yucca Mountain region volcanic events (NRC, 1999) does not appear to affect performance calculations significantly (NRC, 2004).

4.3.2. DOE Approach to Event Definition

The DOE (2003) evaluated characteristics of volcanic features in their Technical Basis Document (#13) on volcanic events. In the PVHA expert elicitation (Geomatrix Consultants, 1996), the expert panel defined a volcanic event as a point in space representing a volcano, and an associated dike having length, orientation, and location relative to the point. Associated eruptive products may include ash, tephra, and lava flows. The Paiute Ridge intrusive/extrusive center, dated at 8.6 Ma and located on the northeastern margin of the Nevada Test Site (DOE, 2003; Valentine and Krogh, 2006), is a possible analog. A study of this center can elucidate the relationship between intrusive and extrusive components of a volcanic event. Paiute Ridge is a small-volume Miocene volcanic center comparable in volume and composition to Pleistocene volcanoes near Yucca Mountain. Like the Pleistocene cones, Paiute Ridge igneous activity is believed to have occurred during a brief magmatic pulse represented by a single volcanic event. The vents and associated dike system formed in a NNW-trending extensional graben, and exposures of the system include remnants of surface lava flows, volcanic conduits, and dikes and sills intruded into tuff country rock at depths of ~250 m from the *paleosurface*. Dike lengths at Paiute Ridge range from less than 1 km to 5 km and widths from 1.2 to 9 m. At Paiute Ridge parts of some dikes terminated within ~100 m of the surface without erupting, while other parts of the same dike did erupt, as evidenced by associated lava flows and volcanic conduits. This contrasts with the current assumption by both the DOE and NRC that any dike which intersects the repository will vent out to the surface. However, an event may consist of multiple dikes; only one of those dikes will feed eruptions, while the others might stall just below the surface. This is consistent with field analog studies (Valentine and Krogh, 2006; Keating et al., 2007) and is also reported in ANL-MGR-GS000002 Rev 03 (under review at the DOE).

Volcanic events occurring outside of the repository footprint must have sufficient length to intersect and breach the repository. Longer event lengths will result in higher intersection probabilities. The mean dike length associated with a volcanic event in the Yucca Mountain region is 4 km, and 95 percent of dikes are shorter than 10 km (DOE, 2003), consistent with observed volcanic features in the Yucca Mountain region. The maximum aligned-vent spacing in the Yucca Mountain region is 5.4 km between Black and Makani (Northern) Cones, and volcanic-vent alignment lengths are typically in the range of 2 to 5 km (e.g., Hidden Cone-Little Black Peak, Amargosa aeromagnetic Anomaly A, and Red Cone-Black Cone) (DOE, 2003).

The longest proposed vent alignment is the Pleistocene Crater Flat feature with a length of about 11 km, if one assumes it represents only one volcanic event. If in fact that alignment represents a single event, the effect would be to reduce the Plio-Pleistocene recurrence rate significantly.

Dikes such as those at Paiute Ridge range in length from less than 1 to 5 km. Dike and vent alignments of the 3.7 Ma basalts in the Crater Flat basin are no more than 4 km long. More recent studies have indicated much smaller dike (fissure) lengths as specified in Table 1 and discussed in Section 4.2 of this chapter.

The DOE (2003) cites Delaney and Gartner (1997) in noting that 97 percent of the 174 dike lengths measured in the San Rafael volcanic field are less than 5 km. The median of the length distribution at San Rafael is approximately 1 km, and the longest dikes are 8 to 9 km. The DOE (2003) estimated a measure comparable to dike half-length, the distance from the end of the dike nearest the repository to the point of origin (the midpoint) of the volcanic event, using information elicited in the PVHA (Geomatrix Consultants, 1996). The mean of this distribution is 2 km, the 5th-percentile is 0.2 km, and the 95th-percentile is 5.6 km, agreeing well with observed volcanic-event features near Yucca Mountain.

It was noted in Section 4.2 that some dikes have limited lateral propagation. Crowe et al. (1983) measured basaltic dikes intruded into tuff at eroded volcanic centers of the Yucca Mountain region, and observed dike widths ranging from 0.3 m to 4 m. Most dikes were between 1 and 2 m wide. The typical dike-width dimension assigned by the PVHA experts was 1 m (Geomatrix Consultants, 1996). The DOE (2003) reports that most basaltic volcanoes near Yucca Mountain are small in volume and fed by one main dike. Sets of dikes (dike swarm) may be present with spacing between individual dikes of up to a few hundred meters. There may also be small dikes that radiate outward from the conduit of the main cone, analogous to the crudely radiating dikes that are enclosed in near-vent scoria at the eroded Pliocene basalt centers of Crater Flat basin. The Paiute Ridge volcanic complex may have as many as 10 dikes, in addition to sill-like bodies.

Data from a variety of basaltic fields indicate that the spacing between multiple dikes (dike swarm) can vary from about 100 m to approximately 1 km (DOE, 2003). For the Paiute Ridge complex, measurements suggest that the mean dike spacing for dikes greater than 1 km long is approximately 1 km (maximum 1,440 m; minimum 250 m) (Perry et al., 1998). For the 3.7-Ma-old Crater Flat basalts, dike spacing is approximately 400 m (Perry et al., 1998). Dike spacing in the Yucca Mountain region ranges from about 100 m to 690 m (DOE, 2003).

The expected frequency of basaltic intersection is 1.7×10^{-8}/yr (Geomatrix Consultants, 1996). If this rare event should occur, the DOE has estimated that an average of 77 percent of the basaltic, repository-intersecting intrusive events would result in at least one volcano within the repository footprint. This is based on observed vent spacing in the Yucca Mountain region and an assumption that the volcanoes could occur randomly along the length of the dike or localize near a repository drift.

Basaltic eruptions begin from dikes that focus into roughly conical (base upward) conduit eruptions. The best data on conduit diameters and depths to which conduits extend come from observations of basaltic volcanic necks that have been exposed by erosion. However, few volcanic necks have been mapped in detail, at least those with the basaltic compositions of interest in the Yucca Mountain region. Without such mapping, estimates of potential conduit diameters are based on measurements at analog volcanoes (DOE, 2003). The transition from magma flow in a subplanar dike to flow in a conduit has been inferred at many field locations (e.g., Delaney and Pollard, 1981; Hallett, 1992). A planar dike is the preferred form for movement of magma through brittle and elastic host rock, whereas a conical conduit is the preferred form for magma flow and delivery to the surface (Delaney and Pollard, 1981). Once a zone of widening and flow focusing has initiated, the evolving conduit may continue to widen via erosive and hydromagmatic processes. Solidifying magma may choke portions of a conduit so that only a fraction of the vent may be active at any given time during an eruption. Basaltic conduits vary greatly in diameter, depth and geometry. Valentine and Groves (1996) used the well-established sedimentary stratigraphy beneath tephra deposits at the Lucero Volcanic field (New Mexico) to evaluate variations in conduit size beneath a basalt center. They calculated that the conduit ranged in diameter from 3.5 to 10 m. Conduit-size calculations based on the proportion of rock fragments 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.

The diameter of the Grants Ridge conduit in New Mexico (Keating and Valentine, 1998; WoldeGabriel et al., 1999) suggests that an upper bound for basaltic conduit diameter in the Yucca Mountain region is 150 m. This is a conservative upper bound for Yucca Mountain because the Grants Ridge volcanic neck formed during an eruption of <1 cubic kilometer of alkali basalt (compared, for example, to the much smaller Lathrop Wells volcano with its approximate total volume of 0.09 km^3) (DOE, 2003). The volume of the Grants Ridge eruption is reported in ANL-MGR-GS000002 Rev 03, now under review at the DOE (ACNW, 2007). Doubik and Hill (1999) used a process that may overestimate the volume fraction of tuff xenoliths to estimate a 50-m conduit diameter for the Lathrop Wells scoria cone. Thick Miocene volcanic units beneath the Lathrop Wells volcano are lithologically similar, making it difficult to assign relative proportions of those units represented by rock fragments of the walls of the feeder. Given the limitations on specific data to test the assumptions made by Doubik and Hill (1999), their estimate of a 50-m conduit diameter for the Lathrop Wells Cone was used as a most likely value for conduit diameter at depth for potential eruptions at Yucca Mountain (DOE, 2003). New work to be reported in DOE's ANL-MGR-GS-000002, Rev. 03 (under review at the DOE) supersedes the DOE range of conduit diameters at repository depth with a lower mean value based on recent analog studies (ACNW, 2007).

Based on data from the Yucca Mountain region and selected analogs, the conduit diameter for a future basalt volcano was constrained at its lower bound by 1- to 2-m wide dikes, and at its upper bound by the 150-m Grants Ridge plug (DOE, 2003). The ongoing PVHA-U has been tasked with reevaluating the volcanic event definition used in the 1996 expert elicitation. The panelists have been asked to assess the following aspects of future volcanic events that could hypothetically affect Yucca Mountain during the next 1 million years:

- Magnitude of event
- Intrusive event geometry
    - Dike system length, azimuth, and location relative to point event and dike width (similar to the 1996 assessment)
    - Description of dike swarm (e.g., number and spacing of parallel dikes along length of dike system)
    - Influence of repository opening on dike intersection.
- Extrusive event geometry
    - Number and location of eruptive centers (conduits) associated with a volcanic event

  - Conduit diameter at repository level
  - Influence of repository opening on eruptive conduit location.

The final report of the PVHA-U is not expected to be published until 2008, therefore this report cannot incorporate the revised assessments. Based on ACNW&M observations of PVHA-U proceedings, some significant changes are being considered to the 1996 study (Geomatrix Consultants, 1996). Most panelists appear to emphasize the nature of Pleistocene activity (instead of earlier activity), consider dikes that are shorter in length, discuss the possibility of sills, and consider increased flexibility in possible dike orientations. Event (eruption) cycles are being discussed, and fewer hidden events are now being considered based on the results of drilling of aeromagnetic anomalies that have been interpreted as possibly derived from hidden basaltic igneous events.

The latest estimate of the conduit diameter at the Lathrop Wells volcano is provided by Valentine et al. (2007). Using data on xenolith abundance, and assuming a cylindrical conduit through the 335 m thick Miocene tuff sequence beneath the volcano, they estimated an average conduit diameter of only ~8-9 m. They further reasoned that if the lavas and fallout deposits at Lathrop Wells have a similar xenolith content (which is unlikely based on observations) the added volume of xenoliths would imply a maximum average conduit diameter of about 21 m. Because Lathrop Wells is an excellent analog of a hypothetical eruption through a repository, the estimates of conduit diameter by Valentine et al. (2007) represent the most current and plausible estimate for Yucca Mountain. A conduit diameter of 21 m would significantly limit the number of waste packages that could become entrained in a volcanic eruption.

4.3.3. NRC Approach to Event Definition

The NRC/CNWRA, in Connor et al. (2000), noted that the most prominent vent alignment in the Yucca Mountain region is the arcuate northeast trending Pleistocene Crater Flat alignment consisting of five cinder cones. Three magnetic anomalies are mapped along the alignment that reveal the presence of older, buried basaltic lavas. They propose that geological and geophysical mapping indicate that the Crater Flat alignment is up to 16 km long and may have been reactivated through time. However, recent high-resolution aeromagnetic surveying provides no support for connecting the outcropping and sub-cropping vents. The aeromagnetic data show no indication of anomalies related to magnetic intrusive dikes connecting the vents.

The alignment of magnetic Anomalies G, F, and H (Figure 29) provides further evidence of NE-trending alignments. At aeromagnetic Anomaly G (Figure 29), drill hole USW VA-2 confirmed that 3.8 Ma basalt lies at a depth of 119 m. Based on alignment and similar magnetic signatures of Anomalies H and F, these anomalies are also interpreted to be related to Pliocene basalts. Other vent alignments in the region include the 0.3 Ma Sleeping Buttes alignment, consisting of two cinder cones aligned on a NE-trend ~40 km northwest of Yucca Mountain, and the Pliocene Crater Flat vents, which form a north-trending alignment of 6–8 vents that erupted 3.8 Ma ago. In all, five vent alignments with a total of 18 vents have formed or reactivated during Plio-Pleistocene time. Six remaining Plio-Pleistocene vents are not included in recognized alignments. Four of these are known only from magnetic mapping and one from drilling (Anomaly B, basalt of Pliocene age). There may be multiple vents associated with some of these anomalies. It is possible that future volcanic activity may produce similar alignments.

Connor et al. (2000) estimated the probability of future volcanic intersection at Yucca Mountain assuming that half of any future volcanic events would not create alignments and would only disrupt the repository if they fell within the site boundary, and that the remaining half would form alignments that could intrude areas 5.5 to 8 km beyond the midpoint of a dike. Connor et al. (2000) point out that the three youngest alignments in the Yucca Mountain region trend along azimuths 20–30°, parallel to the maximum principal horizontal compressional stress in the region (Morris et al., 1996). Connor et al. (2000) also pointed out that existing faults may locally control the locations of vents regardless of whether vent alignments develop. For example, a normal fault crossed by a strike-slip fault will tend to dilate more at the fault intersection, creating additional space for the intrusion of ascending magma. They reported evidence of such localization of cinder cones along faults in the Yucca Mountain region. The Pliocene aged basalt of Anomaly B (Figure 29) occurs at the intersection of the north-trending Gravity and Rock Valley faults in the Amargosa Desert. The Carrara fault basalt is located at the intersection of north-trending normal and NW-trending strike-slip faults. The Lathrop Wells volcano is located along the trend of the Stage Coach fault, south of Yucca Mountain at the intersection with several north-trending faults (Connor et al., 2000).

The igneous activity parameters used in the most recently published version of total performance assessment by the CNWRA are shown in Table 2 (Mohanty et al., 2004). This table shows that the geographic orientation of a dike intersecting the repository is assumed to be N7.5^{o}E with a range from N0^{o}E to N15^{o}E. The mean width of the dike is assumed to be 5.5 m with a range from 1.0 to 10.0 m and the mean length of the dike is 6.5 km with a range of 2 to 11 km. Multiple conduits are assumed to form along a dike during a single igneous event, but the base case is only one conduit. The range of diameters of the conduit is uniform from 25 to 78 m with a mean of 51 m. The volume of ash associated with an eruption event is estimated using better preserved volcanoes which serve as analogs to the basaltic volcanism of the Yucca Mountain region. The NRC (1999) observes that the range of ash-to-cone volume ratios at historical analog volcanoes range from approximately 1:1 to 6:1. Based on these ratios and estimation of the power and duration ranges of potential igneous events, the ash-volume ranges from 6×10^5 to 3×10^8 m^3 with an average volume of 3×10^7 m^3. In contrast, the DOE has determined an average volume of 1×10^8 m^3 with a range of 2×10^6 to 4.4×10^8 m^3.

4.3.4. EPRI Approach to Event Definition

EPRI considers the Lathrop Wells basalt center as the best example of a natural analog of a future eruption in the Yucca Mountain region (Morrissey, 2006). The original character of erupted material refers to the physical state of magma in the conduit or fissure prior to erupting. The physical state of magma reflects the composition, water content, crystal content, and temperature of magma. These four properties are used as part of EPRI's criteria for defining a natural analog for future volcanism. Other important criteria for a natural analog are volcano type and tectonic setting.

In contrast to the Lathrop Wells volcanic center, the Pliocene basalt centers in the Crater Flat basin are deeply eroded and poorly exposed, although they, too, provide valuable predictive data for other parts of the igneous scenario analysis (Morrissey, 2006). Lathrop Wells, however, is representative of the largest monogenetic basaltic eruption that might be anticipated in the future around Yucca Mountain. EPRI used features of the Lathrop Wells basalt center to define the following criteria for selecting appropriate natural analogs to future eruptions in the Yucca Mountain region (Morrissey, 2006):

1. Magma composition is alkali basalt with 1.9-4.6 wt.% H_2O and < 4 vol. % phenocrysts of olivine, amphibole and/or clinopyroxene.
2. Monogenetic scoria cone.

3. Total eruption volume < 0.1 km^3.

4. Extensional tectonic setting.

In addition to magma composition, phenocryst phases and water contents are included in EPRI's criteria. These two parameters constrain the eruption temperature that is a governing factor of eruption style. Lathrop Wells basalts, along with all basalts < 1.1 Ma in the Yucca Mountain region, are characterized by a crystal assemblage exclusively of olivine and some contain clinopyroxene and/or amphibole. Plagioclase phenocrysts are rare in these basalts. Plagioclase does occur in these basalts as microcrysts or groundmass crystals indicating that these grew at shallow depths during rapid decompression. The absence of plagioclase as a phenocryst phase with olivine indicates a lower liquidus temperature or eruption temperature (975-1010°C) than if plagioclase were present (Sisson and Grove, 1993; Nicholis and Rutherford, 2004). An eruption temperature of 975-1010°C yields a viscosity for basalt of 100-1000 Pa·s, whereas an eruption temperature of 1100-1200°C yields a viscosity of 1-10 Pa·s (Lore et al., 2000). The different viscosities tend to favor different eruption styles. EPRI believes phenocryst assemblage to be a vital criterion for selecting an appropriate analog to a Strombolian eruption in the Yucca Mountain region. Therefore EPRI's analog criteria include aphyric texture (< 4 vol.% phenocrysts) and phenocrysts of olivine and amphibole (or clinopyroxene).

EPRI found that proposed analogs such as Paricutin, Grants Ridge, Tolbachik, and Longuimay are not appropriate because they do not meet at least two criteria. Use of such analogs should be restricted to understanding processes associated with an igneous event but not to quantify a characteristic property. Analogs such as Basalt Ridge, Paiute Ridge, Boulder Dam dikes, and Red Cones in California fit the criteria. Field observations of eruptive characteristics at these analogs to the Crater Flat basin may reduce the uncertainty associated the intrusive and extrusive scenario. Volcanic fields that have been proposed as analogs to the Crater Flat volcanic field include Coso, Cima, Death Valley, Lunar Crater, Reveille Range, Nye Canyon, and El Jorollo. Based on only composition and tectonic environment, Reveille Range, Death Valley and Clayton Valley may be good analogs. EPRI considers the others to be questionable as they include cinder cones with a wide range of composition and eruption type.

In addition to the above considerations, as part of their comments on the ACNW&M's draft report, EPRI provided a revised description of their conceptual model for natural analogs of future volcanism. This material is an addendum to EPRI's internal report on igneous events. Because this addendum may not be readily available in the public record, it is provided (with minor editing) as Appendix C to this report, along with its own figures, table, and reference list. Appendix C is tltled "EPRI's conceptual model for defining natural analogs for future Yucca Mountain volcanism and expected consequences."

4.3.5. Comments on Hydromagmatic (Maar) Volcanism

The principal condition necessary for explosive phreatic eruptions (maar volcanism, involving heating and expansion of groundwater) is a shallow groundwater table in a largely unconsolidated, highly permeable medium (i.e., alluvial basin). This condition does not exist at the Yucca Mountain site which is an elevated block of consolidated volcanic rocks with a deep water table. The depth of the water table is not expected to change by more than 20 to 30 m over the next million years as a result of climate change in southern Nevada. There is also no evidence that maars formed in alluvial basins near Yucca Mountain during the last 10 million years.

McBirney (2005), in a presentation to the PVHA-U expert panel, concluded that the probabilities of phreato-magmatic eruption are largely a function of the ground-water level and the permeability of the sediments invaded by magma. These conditions have existed in the Crater Flat basin and could recur there in the future, but they do not exist on Yucca Mountain. The principal hazards of such an eruption in the basin are damage to surface structures from ballistic ejecta and *base-surge* flows. These hazards are limited to a radius of about five kilometers from the vent.

4.4. Summary

A concise summary of the views regarding the nature of future Yucca Mountain region igneous activity is constrained by the lack of published materials that discuss current investigations. The DOE (2006) anticipates that changes to the input parameters to performance assessment, based on analog geologic data, will involve:

- Dike length, width, orientation, and number of dikes,
- Conduit size, and number and locations of conduits, and
- Fraction of eruptive material in tephra, cone, and lavas.

There are several areas of agreement between the DOE and NRC regarding the nature of igneous events impacting the proposed repository. These are based on geologic analogs and the geological and tectonic history of the Yucca Mountain region. They include the following:

- Igneous events will be of similar nature to the Pleistocene volcanoes of the Yucca Mountain region and particularly the most recent volcano, Lathrop Wells. Accordingly, igneous events will occur as small-volume basaltic volcanoes that have effusion rates, power, and duration similar to the Lathrop Wells volcano. The occurrence of high power and volume and long duration volcanic events involving felsic ash flows typical of those of Miocene age in the Yucca Mountain region are not supported by evidence.
- A portion of the duration of any volcanism will involve violent Strombolian activity with plumes of ash distributed over the Yucca Mountain region. Analogous with the Lathrop Wells eruption, fallout from a sustained eruption plume is likely to result in ash falls extending to a few 10s of kilometers.
- Multiple dikes including en echelon dikes are possible associated with an igneous event. The dike orientation will be parallel to the maximum horizontal compressive stress in the region, roughly spanning an azimuth from N to N30^{o}E. New work to be reported in DOE's ANL-MGR-GS-000002, Rev. 03 (under review at DOE) ties dike strike more closely to pre-existing faults, as supported by analog field data (ACNW, 2007).
- The diameter of the volcanic conduit assumed by both the NRC and DOE has a mean value of about 50 m. NRC anticipates a range in diameter of 25 to 75 m, while the DOE cites diameters from 15 to 150m. New work to be reported in DOE's ANL-MGR-GS-000002, Rev. 03 supersedes the DOE range of conduit diameters at repository depth with a significantly lower mean value based on recent analog studies (ACNW, 2007).
- Any dike intersecting the repository will continue to the surface above the repository.

Table 2 **Igneous activity input parameters to Total-System Performance Assessment (CNWRA, 2004).**

Parameter	Mean Value	Distribution
Volcano model (1 = geometric, 2 = distribution)	1	—
Time of next volcanic event in region of interest	5.05×10^{3} years	Finite exponential; 100.0, 10,000.0, 1.0×10^{-7}
X location in region of interest	5.48×10^{5} m	—
Y location in region of interest	4.08×10^{6} m	—
Random number to determine if extrusive or intrusive volcanic event	5.00×10^{-1}	Uniform; 0.0, 1.0
Fraction of time volcanic event is extrusive	9.99×10^{-1}	—
Angle of volcanic dike measured from north—clockwise	7.50°	Uniform; 0.0, 15.0
Length of volcanic dike	6.50×10^{3} m	Uniform; 2,000.0, 11,000.0
Width of volcanic dike	5.50 m	Uniform; 1.0, 10.0
Diameter of volcanic conduit	5.13×10^{1} m	Uniform; 24.6, 77.9
Density of air at standard pressure	1.29×10^{-3} g/cm3	—
Viscosity of air at standard pressure	1.80×10^{-4} g/cm-s	—
Constant relating fall time to eddy diffusivity	4.00×10^{2} $cm^{2}/sec^{5/2}$	—
Maximum particle diameter for particle transport	1.00×10^{1} cm	—
Minimum fuel particulate size	1.00×10^{-4} cm	—
Mode fuel particulate size	1.00×10^{-3} cm	—
Maximum fuel particulate size	1.00×10^{-2} cm	—

Parameter	**Mean Value**	**Distribution**
Minimum ash density for variation with size	0.8 g/cm^3	—
Maximum ash density for variation with size	1.60 g/cm^3	—
Minimum ash log diameter for density variation	- 2.00	—
Maximum ash log diameter for density variation	- 1.00	—
Particle shape parameter	5.00×10^{-1}	—
Incorporation ratio	3.00×10^{-1}	—
Wind direction	- 90°	—
Wind speed	1.20×10^{3} cm/sec	Exponential; 8.3×10^{-4}
Volcanic event duration	4.85×10^{5} sec	Log-uniform; 1.80×10^{5}, 1.30×10^{6}
Volcanic event power	4.31×10^{10} W	Log-uniform; 3.59×10^{9}, 5.30×10^{11}
Volcanic column constant beta	1.00×10^{1}	—
Ash particle size distribution standard deviation	1.00	—
Relative rate of blanket removal	0.0007	—
Fraction of precipitation lost to evapotranspiration	6.80×10^{-1}	—
Fraction of irrigation lost to evapotranspiration	5.00×10^{-1}	—
Fraction of year soil is saturated from precipitation	5.40×10^{-3}	—
Fraction of year soil is saturated from irrigation	2.00×10^{-1}	—
Ash bulk density	1.40 g/cm^3	—

Parameter	Mean Value	Distribution
Ash volumetric moisture fraction at saturation	4.00×10^{-1}	—
Depth of the rooting zone	1.50×10^{-1} m	—
Subarea of volcanic event (Model 2)	2.00	—
Number of waste packages contained by ejecta (Model 2)	50.677	Beta 1.0, 150, 1.0, 2.0
Number of magma induced mechanical failures remaining in drift (Model 2)	37.40	Log uniform; 1.0, 1402.0

Areas of disagreement between the DOE and NRC include:

- The DOE assumes a single eruption volcanic event associated with each dike approaching the surface. Each event might have one to three conduits, but each conduit might have shallow breakout vents that feed lavas from the lower flanks of growing cones. In contrast NRC supports the possibility of multiple vents including the potential for flank eruptions from a volcanic cone leading to satellite (secondary) eruptions of lesser intensity.
- The length of potential intruding dikes remains an issue of disagreement. The DOE currently uses a probability distribution function of dike length from PVHA-96, ranging from 1 to 10 km with a mean of 4 km. NRC considers a mean dike length of roughly 6 km with a range from 2 to 11 km based on dike lengths interpreted from both Pliocene and Pleistocene igneous activity.
- In the event of formation of multiple dikes, the DOE has considered the dikes to have a width ranging from 0.5 to 5 m with a mean value of 1.5 m. Recent analog work by DOE indicates that this range and mean may increase at repository depth (however, this is not a sensitive parameter in the DOE TSPA igneous consequences calculations (ACNW, 2007)). The NRC assumes a wider range of dike widths from 1 to 10 m with a mean of roughly 5 m.

EPRI used features of the Lathrop Wells basalt center to define the criteria for selecting appropriate natural analogs to future eruptions in the Yucca Mountain region. EPRI developed the following criteria (Morrissey, 2006):

1. Magma composition is alkali basalt with 1.9-4.6 wt.% H_2O and < 4 vol. % phenocrysts of olivine, amphibole and/or clinopyroxene.
2. Monogenetic scoria cone.
3. Total eruption volume < 0.1 km^3
4. Extensional tectonic setting.

Additional summary observations include the following:

Two possible scenarios that involve intersection of the repository by igneous activity include different processes and risk consequences. The extrusive (volcanic) scenario involves intersection of a volcanic-cone-forming conduit through the repository to the surface causing waste in the conduit to contaminate the ash and be dispersed over the Yucca Mountain vicinity. The greatest risk from such an event will occur during the first thousand years due to the presence of significant quantities of short half-life radionuclides. The intrusive scenario involves intrusion of an igneous dike into the repository leading to damage or destruction of the waste packages and premature release of the waste to infiltrating waters passing through the repository, but does not involve a volcanic conduit directly to the surface.

There is general agreement regarding the nature of any future igneous event (i.e., power and approximate duration of event, volume and types of erupted products, general magma type and its volatile content, and the characteristics of the crustal pathways (dikes) for the magma). There is also agreement that dikes (which can locally evolve into volcanoes) tend to follow pre-existing fault zones where faults exist in proximity to an ascending dike. Thus, current DOE plans to avoid existing faults in constructing the repository (setback strategy) will minimize the likelihood of an extrusive event intersecting the repository.

The majority of past volcanic activity in the Yucca Mountain region occurred within a basin, e.g., Crater Flat basin, the northern Amargosa Desert, and Jackass Flats, not on ridges like Yucca Mountain. Although one ancient (>10 million year old) basaltic dike exists on the western flank of Yucca Mountain, no volcanic activity is known to have intersected the repository footprint since the surface rocks were deposited 13 million years ago.

Igneous event definitions have evolved during site characterization and analysis. Prior to the mid-1990s, the definition of the event was largely restricted to volcanic eruptions. Subsequently, the importance of dike intersection with the repository has been emphasized as well as volcanic events. Even more recently, studies of similar small-volume basaltic igneous events dating back to 10 million years ago in the nearby Nevada Test Site suggest that igneous sills, which are near-horizontal tabular igneous intrusions, should be considered in event definition. This evolution in event definition may be important in evaluating published igneous event probabilities because of the change in definition from point events to long (dikes) and perhaps broad igneous features (sills).

Finally, the conditions needed to support a phreatic (maar) eruption do not exist at Yucca Mountain today and are not expected to exist in response to climate change.

5. Probability of Potential Igneous Activity

5.1. Introduction

The second question of the risk triplet, What is the probability of an igneous event intersecting the proposed repository?, is the subject of Chapter 5. Considering the limitations in knowledge of the past basaltic volcanism in the Yucca Mountain region and the imperfections in the understanding of volcanic processes, it is impossible to specify the time and location of future igneous activity precisely. The probability of an event is further complicated by the range of characteristics of the dikes from the igneous event that may intersect the repository (i.e., length, orientation, as well as location). However, it is possible to predict, in a stochastic framework, the recurrence rate of such an event within an area encompassing Yucca Mountain. The predicted recurrence rate can be translated into the probability of repository intersection given the footprint of the proposed repository and assumptions regarding the volcanic zone and tectonic models and the nature of the igneous activity. A useful review of the methods of prediciting igneous activity at Yucca Mountain and a history of probability estimates is given by Crowe et al. (2006).

The Environmental Protection Agency (EPA) set the generic standard for geologic high-level waste repositories (EPA, 1993) and confirmed, in the standard for the proposed Yucca Mountain repository (EPA, 2001), that an event, such as a volcanic eruption, does not require evaluation if the probability of occurrence is less than 0.01% in ten thousand years, i.e., less than one chance in one hundred million (10^{-8}) per year. This is roughly equivalent to the probability estimated for mass global extinction of life caused by the impact of an extra-terrestrial body on the Earth (Crowe et al., 2006). Estimates for the annual recurrence frequency of repository intersection by an igneous event range from one part in a million to one part in a billion (10^{-9} to10^{-6}), thus necessitating consideration of the risk from such an event.

In evaluating the probability of an igneous event intersecting the proposed repository it is important to understand the impact on the standards and the regulations for licensing the repository of the change in the time of compliance from 10,000 years to a million years. The EPA's current draft revised standards (EPA, 2005) and the NRC's draft revised regulations (NRC, 2005b) prescribe that consideration of features, events, and processes (FEPs), which includes igneous events, shall use the results obtained for the 10,000 years following repository closure. This is based on the assertion that the data and models of the first 10,000 years provide sufficient support to analyze performance during time periods up to a million years without invoking undue uncertainty associated with long term projections. As a result, the probability estimates based on a 10,000 year repository lifetime that were made prior to the lengthening of the repository time of compliance remain valid and are discussed herein.

The logic diagram showing the major components that enter into the evaluation of the probability of an igneous event intersecting the repository is shown in Figure 4. These include results presented in the previous chapter regarding event definition and the number of events that have occurred in the germane region over a specified duration of geologic time. This evaluation also requires estimates of the number of undetected events and change in number of events with time. Assumptions regarding volcanic zone models and to a lesser extent tectonic models also enter into the evaluation as indicated in the logic chart (Figure 4).

It is useful to understand that the issue of probability of volcanism at Yucca Mountain poses an interesting paradox. Crowe et al. (2006) describe this contradiction. The small number of past eruptions is the best evidence that the probability of future volcanism near

Yucca Mountain will be small. Had there been more volcanic events to study there would be more data on spatial and temporal patterns to project future volcanism with less uncertainty. But in that hypothetical case the risk from future volcanism would be substantially higher than is the case for Yucca Mountain.

As discussed below, the volume of basaltic volcanic material near the site has dramatically declined over time. Accordingly, the Crater Flat basin volcanic field represents a zone of very small activity compared to other volcanic fields in the region (e.g., Lunar Crater-Reveille Range, NV; Cima, CA; and Springerville, AZ).

5.2. Spatial and Temporal Distribution of Igneous Events

5.2.1. Introduction

The spatial distribution of basaltic igneous events in the Yucca Mountain region and their absolute age is fundamental to formulating volcanic zone and temporal models of igneous activity used in predicting the probability of future activity at the proposed repository site. Geologic mapping has identified numerous surface features, both volcanic cones or their remnants and dikes. Isotopic dating of volcanic material has been used to determine their age to a high degree of accuracy. Detritus eroded from the topographic highlands (ranges) has been deposited in the adjoining basins and may have buried older igneous event features. Fortunately, the basaltic rocks have a significantly stronger magnetization than the alluvium in the basins. Thus, hidden basaltic features in the basins can be isolated by geophysical mapping of magnetic anomalies. However, alternative sources of the magnetic anomalies are possible. Thus, drilling on the magnetic anomalies or a representative of a group of anomalies to test for the presence of basalt is required to complete the analysis. Basalt samples obtained from the drill core are dated to determine the age of the feature. The resolution of the magnetic method is limited, so that deeply buried, small, and thin basaltic features may not be mapped. Thus, undetected basaltic features may be present in the region. Accordingly, the geographic location of surface and buried basaltic volcanic rocks and their absolute age, and the possible presence of undetected features, are all considered in estimating the probability of intersection of the proposed repository by an igneous event.

5.2.2. Surface Exposures

Figure 29 shows the locations of surface exposures of basalts in the vicinity of Yucca Mountain. At least four known pulses of basaltic volcanism have occurred (DOE, 2003) in the Yucca Mountain vicinity. These include the ~80 ka Lathrop Wells cone and flows (Heizler et al., 1999) (Figure 30 A), ~1 Ma events in Crater Flat basin (Red Cone, Black Cone, Northern (Makani) Cone, and Little Cones) (Figure 30 B), and multiple events dated ~3–6 Ma (Pliocene-Upper Miocene) and ~8–13 Ma (Miocene). Other young basalts in the Yucca Mountain region include Little Black Peak (~0.3 Ma) (Figure 30 C) and Hidden Cone (~0.4 Ma), 35 km northwest of Yucca Mountain.

The Lathrop Wells cone has undergone extensive research because of its relative youth and its proximity to Yucca Mountain. It is the only known igneous activity that occurred in the immediate vicinity of Yucca Mountain since the formation of the ~1-Ma-old-cones in Crater Flat. Two large basalt flows associated with the Lathrop Wells cone extend east and south of the cone and were emplaced during a range of pyroclastic activity (see Valentine et al., 2007 and ANL-MGR-GS-000002 Rev 03 which is now under review at DOE) (ACNW, 2007).

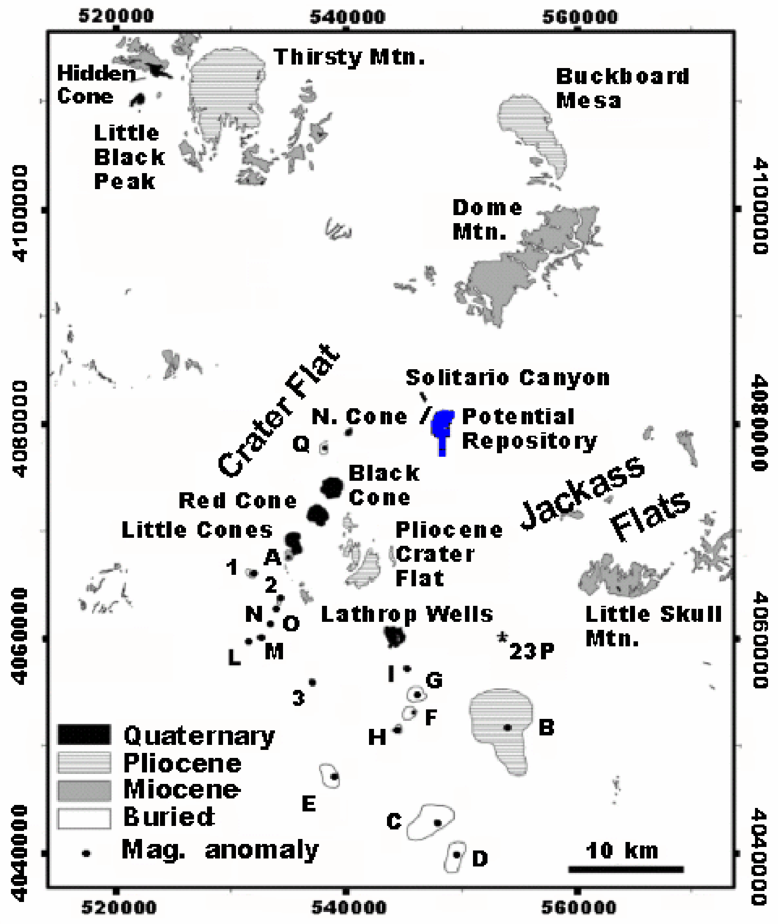


Figure 29 Locations of basaltic volcanoes in the Yucca Mountain region. Letters and numbers are magnetic anomalies of high to moderate confidence that represent possible buried basalts. Drilling at “A”, “B”, “D”, “G”, 23P, and JF-3 (not shown-just north of 23P) has detected basalts. Map coordinates in UTM Zone 11 Meters, North American Datum 1927 (After Connor et al., 2002).

Pliocene-age basalt flows and several remnants of volcanic conduits occur in eastern Crater Flat (Figure 31). Other Pliocene basalts occur east of Little Black Peak near Thirsty Mountain, and at Buckboard Mesa on the margin of the Timber Mountain caldera complex. Large exposures of Miocene basalts occur in Jackass Flats, at Dome Mountain in the Timber Mountain caldera complex, and in proximity to the Black Mountain caldera. Miocene-age basalts also occur in western Crater Flat, and as a dike complex in Solitario Canyon on the northwestern flank of Yucca Mountain.

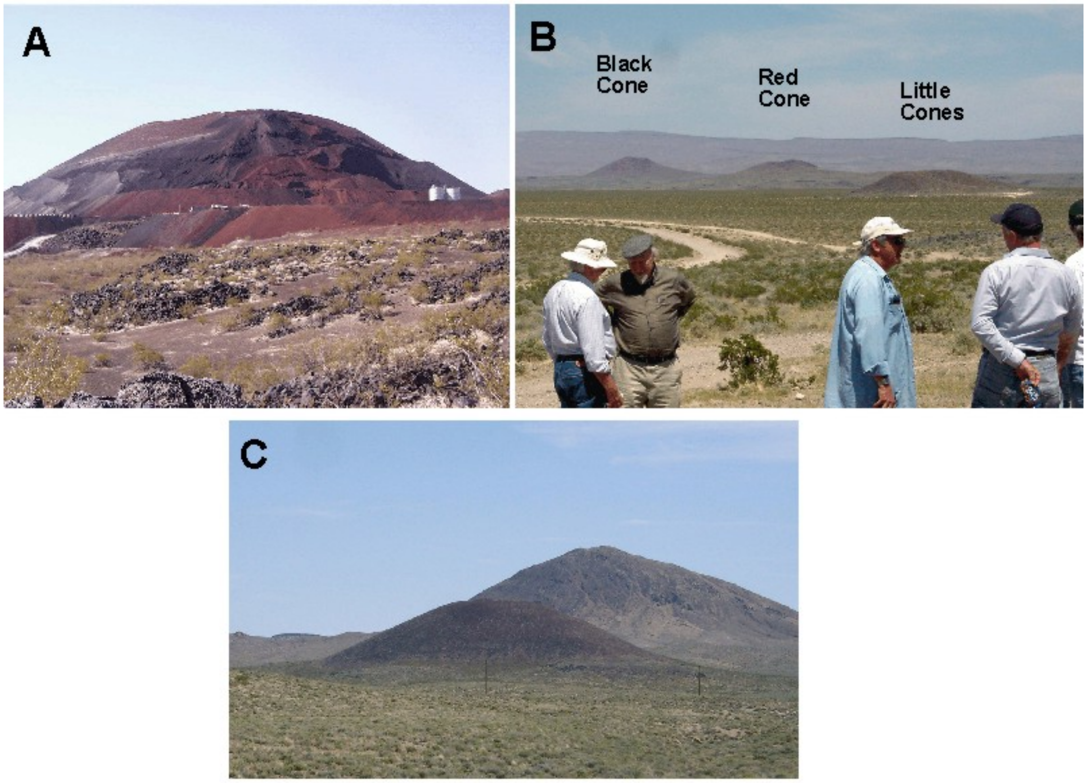


Figure 30 Photos of Yucca Mountain area. (A) Lathrop Wells cone (Age is 80 ka (Heizler et al., 1999) and height is ~130 m). (B) View of the ~1 Ma old cinder cones in Crater Flat, as seen looking northeast from Steve's Pass at the southern margin of Crater Flat. Yucca Mountain is on the far horizon at right side of image. (C) Little Black Peak, ~0.3 Ma (in foreground).

Figure 31 Photo of Yucca Mountain area at Crater Flat. Person at left is standing on a dike of Pliocene age in southeastern Crater Flat. The distant cone at center is the Pleistocene-aged Black Cone. Between Black Cone and the figures at right are the eroded remnants of two Pliocene vents (conduits).

5.2.3. Known Occurrences of Buried Basalts

Samples obtained from drilling in the alluvial basins show that buried basalts exist at several locations around Yucca Mountain, and magnetic surveys also indicate that additional basalts may be buried beneath the alluvium in Crater Flat and the Amargosa Desert (Connor et al., 2000; O'Leary et al., 2002; Hill and Stamatakos, 2002; Perry et al., 2005). Anomaly ‘‘B’’ in Figure 29 was confirmed by drilling to be a Pliocene basalt (~3.8 Ma) buried under 73 m of alluvium (Perry et al., 1998; O'Leary et al., 2002; DOE, 2003; Ziegler, 2003). A basalt in borehole NC-EWDP-23P located S-SE of Yucca Mountain has a Miocene age (9.48 ± 0.05 Ma) (Ziegler, 2003). This basalt lies buried beneath 400 m of alluvium. Another buried basalt was penetrated by drill hole VH-2, with a Miocene K/Ar age of 11.3 ± 0.4 Ma (Carr and Parrish, 1985). Basalt was also found in drill hole J-11 in northeastern Jackass Flats and at Anomaly “D” in Figure 29.

In support of the updated PVHA-U expert elicitation, a 30 × 30 km, high-resolution aeromagnetic survey was conducted in 2004 of Yucca Mountain, Crater Flat, Jackass Flats, and northern Amargosa Desert by the DOE to optimize detection of buried basalts. The helicopter-borne survey was made along east-west flight lines at 60 m spacing. Over flat terrain the magnetometer was maintained at an altitude of ~45 m and roughly twice that over mountainous terrain to ensure the safety of the aircraft. In a presentation to ACNW&M in July, 2006, Frank Perry (LANL) described the new survey as providing high resolution and broad coverage that allows better interpretation of buried basalt vs. alluvium and tuff, faults beneath shallow alluvium, and relationships between faulting and volcanic features (Perry et al., 2006). Based on the new magnetic map and modeling of magnetic anomalies, anomaly targets were chosen for further study with drilling using the following criteria:

- Location with respect to impact on probability estimates (distance from repository, impact on event lengths),
- Sampling of each major cluster or alignment of anomalies,
- Consideration of a range of potential ages based on differences in burial depth and magnetic polarity, and a
- Balance of “high confidence” vs. “low confidence” anomalies (basalt vs. tuff).

Seven new drill holes were completed at locations of magnetic anomalies in Crater Flat basin, Jackass Flats, and the northern Amargosa Desert. Their locations are shown on the high-resolution magnetic anomaly map (Figure 32) together with selected existing drill holes and selected geologic features and the repository area. Table 3 summarizes the results of the drilling. Four of the seven drill holes penetrated basalt. Only in one case, Anomaly "Q," was unexpected basalt encountered (faulted tuff was the predicted source). Preliminary age determinations have been obtained revealing that three of the anomalies are due to buried Miocene basalt, one is due to Pliocene basalt, two are caused by Miocene tuffs, and one anomaly (JF-6) is probably due to faulted tuff (but is possibly due to Miocene basalt).

Table 3 Summary Information for Completed PVHA-U Drill Holes (footnotes are interpretations presented by Perry et al., 2006).

Magnetic Anomaly	Drillhole	Location	Magnetic Source	Predicted Source	Depth and Thickness of Basalt (m)	Age (Ma)
A[a]	USW VA-1	Crater Flat	Basalt (basanite)	Basalt	148 / 62	~10.1 Ma (Miocene)
Q[b]	USW VA-4a	Crater Flat	Basalt	Tuff	141 / >22	~11.1 Ma (Miocene)
JF-5[c]	UE-25 VA-10	Jackass Flats	Basalt	Basalt	77 / >17	~9.4 Ma (Miocene)
JF-6[d]	UE-25 VA-11	Jackass Flats	Likely tuff	Unknown	n/a	n/a
I[e]	USW VA-5	Amargosa Desert	Tuff	Tuff	n/a	n/a
O[f]	USW VA-3	Amargosa Desert	Tuff	Tuff	n/a	n/a
G[g]	USW VA-2	Amargosa Desert	Basalt	Basalt	119 / 31	~3.8 Ma (Pliocene)

[a] Basanite represents a *mafic* magma composition not previously seen in the Yucca Mountain region; the drilled body may be an intrusive sill.

[b] Anomalies “R” and “4” are considered an expression of the same basalt; possible stratigraphic correlation with basalts of VH-2 and southern Crater Flat.

[c] Basalt correlates with basalts in drill holes J-11 and Nye 23P.

[d] Likely due to faulted tuffs. Any basalt that may exist below borehole depth of 196 m is likely to be Miocene.

[e] Drillhole terminated in tuff at 200 m.

[f] Similarity of magnetic signatures suggests that anomalies “L,” “M,” and “N” also represent faulted tuffs, not a volcanic alignment.

[g] Alignment and similar magnetic signatures of anomalies “H” and “F” suggest that these likewise represent Pliocene basalts.

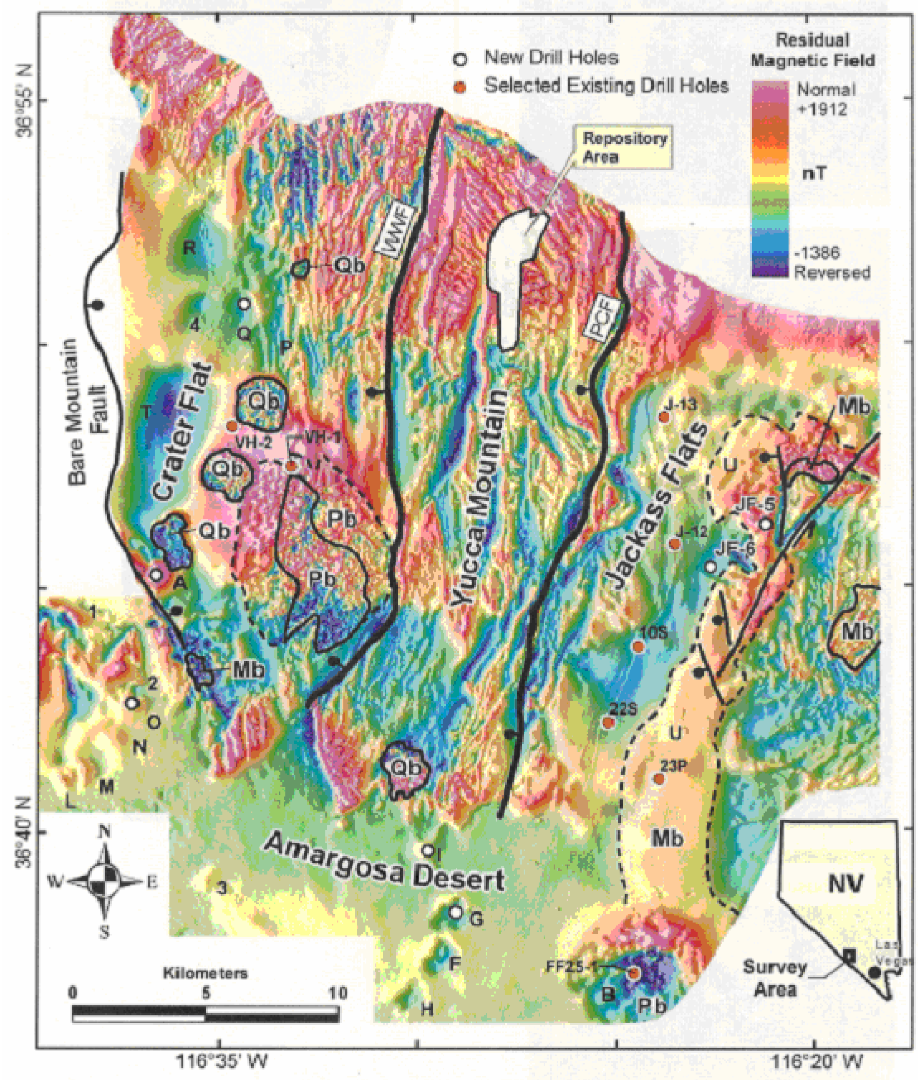


Figure 32 **High-resolution aeromagnetic anomaly map and locations of holes (solid white circles) drilled to determine if the magnetic anomalies are derived from basalts. Solid red circles indicate selected pre-existing drill holes that provide key constraints on the location of buried basalt near Yucca Mountain. Qb=Quaternary basalt, Pb=Pliocene basalt, Mb=Miocene basalt (After Perry et al., 2005; Perry et al., 2006) (Permission to use this copyrighted material is granted by the American Geophysical Union).**

Hill and Stamatakos (2002) presented a relative ranking of low-medium-high confidence in the interpretation of buried basalts associated with magnetic anomalies prior to the high-resolution magnetic survey. Their table of confidence rankings shown herein as Table 4 provides previous rankings by the USGS (O'Leary et al., 2002) and by the expert panelists of PVHA-96 (Geomatrix Consultants, 1996).

Table 4 Previous Confidence Rankings for Anomalies Now Reinterpreted with Data from PVHA-U Drilling and Dating (After Hill and Stamatakos, 2002).

Magnetic Anomaly	**O'Leary et al. (2002)**	**Geomatrix Consultants (1996)**	**Hill and Stamatakos (2002)**	**Source of Anomaly**	**Age (Ma)**
A	1[a]	0.20[b]	Hc	Basalt (basanite)	~10.1 Ma (Miocene)
Q	4	n/r[d]	M	Basalt	~11.1 Ma (Miocene)
R	4	n/r	L	Basalt - interpreted similar to Q by Perry et al. (2006)	Miocene
4	4	n/r	L	Basalt - interpreted similar to Q by Perry et al. (2006)	Miocene
JF-5	n/r	n/r	n/r	Basalt	~9.4 Ma (Miocene)
JF-6	n/r	n/r	n/r	Likely tuff (Perry et al. (2006)	n/a
I	2	n/r	M	Tuff	n/a
O	3	n/r	M	Tuff	n/a
L	3	n/r	M	Tuff - interpreted similar to O by Perry et al. (2006)	n/a
M	3	n/r	M	Tuff - interpreted similar to O by Perry et al. (2006)	n/a
N	3	n/r	M	Tuff - interpreted similar to O by Perry et al. (2006)	n/a
G	1	0.36	H	Basalt	~3.8 Ma (Pliocene)
F	1	0.37	H	Basalt -interpreted similar to G by Perry et al. (2006)	Pliocene
H	1	n/r	H	Basalt -interpreted similar to G by Perry et al. (2006)	Pliocene

The results of drilling on anomalies following completion of the 2004 aeromagnetic survey reduce some of the uncertainty about buried basalts in the region and can be used to update previous probability models. Consider, for example, dataset CFB_plio-quat-Mag (Connor et al., 2002), which represents 29 Plio-Pleistocene events (dated basalts + 10 anomalies that were assumed to be post-Miocene basalts) in the Crater Flat basin. The number of basaltic events in this dataset is now reduced to 22 events by eliminating seven anomalies (A, I, L, M, N, O, and Q). This lowers the apparent Plio-Pleistocene volcanism recurrence rate from 5.5×10^{-6}/yr (Coleman et al., 2004) to 4.2×10^{-6}/yr., which is also consistent with the Pleistocene recurrence rate of 4.4×10^{-6}/yr that is based solely on the eight known Quaternary basalts that exist in the Yucca Mountain region (Coleman et al., 2004). These results show that the new data will influence some statistical-mathematical models by lowering the probability of future repository intersection by volcanism. It is significant that no post-Miocene basalt was found in Jackass Flats at drill holes JF-5 and JF-6. If buried Pliocene basalts had been found there, that would suggest that the Plio-Pleistocene volcanic zone of the Crater Flat basin extends through Yucca Mountain significantly increasing the modeled probability of future repository intersection.

The occurrences of buried basalt features help to interpret the pattern of surface basalts. For example, the Lathrop Wells cone, which previously appeared to be an isolated volcanic event in an area of no prior activity, is now seen as occurring midway along a band of Pliocene basalts that extend from the Crater Flat basin southeastward to the buried basalts of Pliocene age found at Anomalies G and B.

The CNWRA has recently reevaluated the geophysical information used to detect and characterize buried basalts in the Yucca Mountain region (Stamatakos et al., 2007). Their analyses update the initial evaluation of aeromagnetic data provided in the 2002 CNWRA report "Evaluation of Geophysical Information Used to Detect and Characterize Buried Volcanic Features in the Yucca Mountain Region" (Hill and Stamatakos, 2002). The 2002 report had concluded that there may be twice as many basaltic volcanoes in the Yucca Mountain region than considered in the original 1996 DOE hazard assessment. These additional buried volcanoes could potentially lead to a tenfold increase in probability estimates for igneous activity at Yucca Mountain. Stamatakos et al. (2007) concluded that the new DOE analyses have reduced the overall uncertainty in the number of past events. Specifically, many of the anomalies that were previously ranked as having a high or medium likelihood of being the result of buried basalt are now confirmed buried basaltic features while several anomalies ranked as having a low likelihood of being buried basalt are now confirmed as being the result of faulted tuff. Moreover, the aeromagnetic data and drilling program have identified previously unknown Miocene basalt buried in Fortymile Wash (Stamatakos et al., 2007).

The new DOE information and analyses also support the hypothesis that past volcanism in the region was temporally clustered (Stamatakos et al., 2007). The most active of these temporal clusters occurred between 3.6 and 4.7 Myr ago when at least 12 to 17 volcanoes formed. This leads to an episodic recurrence rate of 11 to 16 volcanoes per million years, which is substantially greater than the longer term average rate of about 5 volcanoes per million years and an order of magnitude greater than the 1 to 3 volcanoes per million years in the original 1996 DOE assessment. Additional temporal clusters are recognized for the period between 9 and 11.2 million years ago and one between 80,000 and 1 million years ago. Based on these data, it appears temporal clustering is an important feature at Yucca Mountain that should be accounted for in volcanic probability models (Stamatakos et al., 2007).

New data and modeling of the drill core at anomaly "A" reveal what appears to be a very thick intrusion or sill rather than a buried volcanic lava flow or cone (Stamatakos et al., 2007).

This is the first documented evidence of a possible basaltic sill in the Crater Flat structural basin. The presence of a sill raises the possibility that, in addition to existing igneous activity scenarios in which a dike intersects repository drifts or a volcanic conduit forms thorough the repository, a basaltic sill could form within or beneath the potential Yucca Mountain repository. However, the potential “sill” was found to be 10 Myr old (Miocene age), and may have formed in response to the higher magma volumes produced at that time, analogous to Miocene age sills to the east at Paiute Ridge on the Nevada Test Site. There is no evidence of Quaternary-age basaltic sills near Yucca Mountain.

The new DOE data improve resolution of buried basaltic volcanic features and thereby reduce but do not eliminate uncertainties in spatial and temporal recurrence rates. Magnetic data alone cannot differentiate basalt from faulted tuff in areas with extensive tuff outcrops. Magnetic properties of tuffs and basalts are comparable, and without additional information, magnetic anomalies arising from fault to tuff or basalt appear quite similar. This ambiguity was apparent in interpretations of anomaly Q, which the U.S. Geological Survey ranked as unlikely to be buried basalt. The drill hole at anomaly Q encountered basalt at 140–163 m. Thus, areas with faulted tuff at or near the surface could contain additional, undetected basalt. This “present but undetected” designation adds uncertainty to volcano counts used in probability studies (Stamatakos et al., 2007).

5.2.4. Undetected Igneous Activity

Some analyses of the probability of igneous activity at Yucca Mountain (e.g., Geomatrix Consultants, 1996) provide for estimates of the number of basaltic events in the Yucca Mountain region that remain undetected. One objective of the 2004 high-resolution magnetic survey was to minimize the number of these events that need consideration in the analysis. The basalt of well 23P provides an example of the ability of the high-resolution survey to detect deeply buried basalts. This Miocene-aged basalt lies buried beneath 400 m of alluvium but nonetheless is associated with a magnetic anomaly, a normally magnetized, linear anomaly identified as “U” in Figure 32. On the other hand, there are some practical constraints on the resolution of the survey. For example, the Solitario Canyon dike, also of Miocene age, was not detected by the high-resolution survey, probably because it is a narrow and discontinuous tabular feature (<1 m wide), and the Tiva Canyon tuffs which were invaded by the dike can have locally enhanced magnetization that can mask the magnetic signature of the dike. Failure to detect these and other Miocene basalts that may be masked by the magnetic signature of tuffs, are deeply buried by alluvium, or occur as narrow dikes have no significant adverse effect on probability models that are based on the rates of Pleistocene or Plio-Pleistocene volcanic activity. The NRC considers Miocene volcanism in some of its probability analyses, but the DOE places a low weighting on Miocene basaltic volcanism in its evaluations.

The DOE (2003) has reported partial burial of Pleistocene volcanic features. Nonetheless, Coleman et al. (2004) argue that erosion and deposition during the arid to semi-arid climates of the Quaternary Epoch should be sufficiently limited to preserve the surface evidence of Pleistocene volcanic activity. Accordingly it is unlikely that Pleistocene events are undercounted. This conclusion is supported by the results of the recent drilling associated with PVHA-U, which has not found buried Pleistocene basalts. Most of the newly drilled basalts are Miocene in age. Anomaly G, and by association Anomalies F and H, are now interpreted as Pliocene basalts, which is consistent with the previous discovery of extensive buried basalts of similar age (~3.8 Ma) at Anomaly B (Figure 29 and Figure 32). The depth of these buried basalts is a function of their age, the elevation of the paleosurface on which they were deposited, proximity to paleodrainage systems, and local sedimentation rates since the time of volcanic activity. The buried Pliocene basalts occur at depths between 73 m (Anomaly B) and 119 m (Anomaly G). The buried Miocene basalts range in depth from 77 m (JF-5) to 400 m (Nye 23P).

The rocks that comprise Yucca Mountain record an integrated tectonic-volcanic history since the ~13 Ma tuffs were deposited by large-scale pyroclastic flows and volcanic ash falls. More than 20 years of intensive site characterization studies have included detailed geologic surface mapping, geophysical surveys, and construction and mapping of ~6 km of drifts in or near the repository. Hundreds of surface drill holes of varying depths have been drilled in the Yucca Mountain site vicinity. Coleman et al. (2004) conclude that it is unlikely that multiple dikes could exist in the repository footprint and escape detection in the site characterization. Drilling is an ineffective way to discover near-vertical dikes, but the deepest drill holes in the repository footprint were deep enough to locate basaltic sills if they were present. None were found. Aeromagnetic methods also can have difficulty locating basalts if dikes are small, because of interference with high amplitude, short-wavelength anomalies produced by faulted tuffs (Hill and Stamatakos, 2002). The best technique for finding basaltic dikes in the repository footprint was the detailed mapping of drift walls and the mapping of surface geology. In particular, the detailed mapping of fault expressions at the surface greatly enhanced the likelihood of locating dikes if they were present.

No dikes have been found in the potential repository footprint at Yucca Mountain − this is a key observation. The northern part of the *horst* block that forms Yucca Mountain appears to represent a zone of relative volcanic quiescence during the last 10 Myr. Since that time volcanism has instead mainly focused within the alluvial basins to the east, west, and south, with no evidence of post-Miocene activity east of Yucca Mountain in Jackass Flats. If in the future the repository footprint were to be expanded westward, then one known dike would exist within that footprint, the Solitario Canyon dike, which intruded segments of the Solitario Canyon fault 10-12 Myr ago during Miocene time. Although changes in the areal footprint of the repository could affect probability calculations, the tendency for dikes to follow pre-existing faults or to be influenced by topographic effects could compensate for this by tending to divert dikes away from emplacement drifts.

5.2.5. Change in Basaltic Volcanism with Time

Rates of extension and volumes of basaltic volcanism have significantly declined in the four recognized episodes during the last 11 Myr (since late Miocene time) (Figure 33). There is compelling evidence that volcanism has waned in concert with this reduction in crustal strain. Fridrich et al. (1999) suggested that the ascent of basalt through the crust is structurally controlled in the Crater Flat basin because volcanic vents form a northwest-trending belt that coincides with the strongest *transtensional* (lateral and extensional) deformation in the basin. The approximate temporal correlation of volcanism and rates of extension suggest that they represent a single phenomenon—a tectonic system that may once have been among the most active zones in the Great Basin, comparable to tectonism in Death Valley today. Fridrich et al. (1999) interpret that the Crater Flat basin remains tectonically active, but is now in an advanced stage of decline. Although the overall pattern is declining, extensional faulting has been cyclical and has varied generally in parallel with episodic volcanism.

The cumulative extension map of Fridrich et al. (1999) integrates the extension over the last 12 Myr in Crater Flat. It was previously known that the volumes of volcanic events significantly declined after Miocene time. Figure 34, developed by Frank Perry (2006), shows that volumes of Pliocene to Pleistocene volcanism have also declined, suggesting that magmatic systems near Yucca Mountain are dying. Further evidence lies in the declining maximum lava effusion rate and fissure length of Plio-Pleistocene basaltic activity in the Yucca Mountain region (Figure 35).

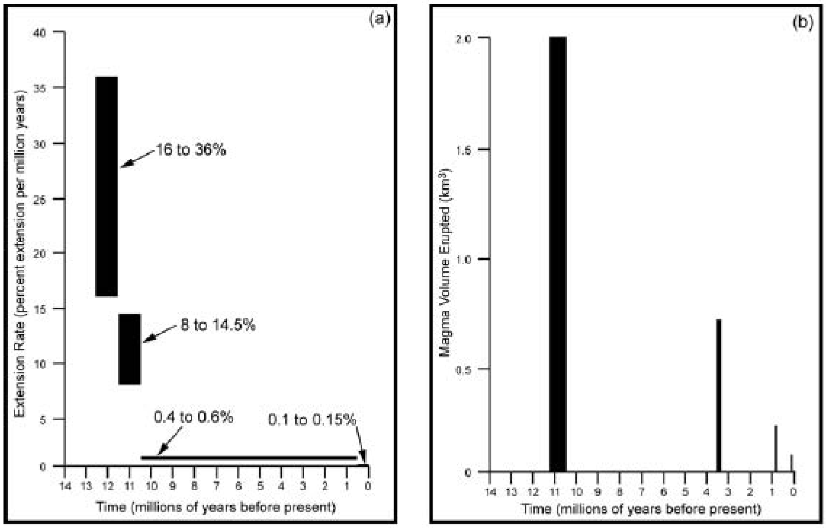


Figure 33 **Estimated extension rates in Crater Flat basin as a function of time and magma volume erupted as a function of time (From DOE, 2003).**

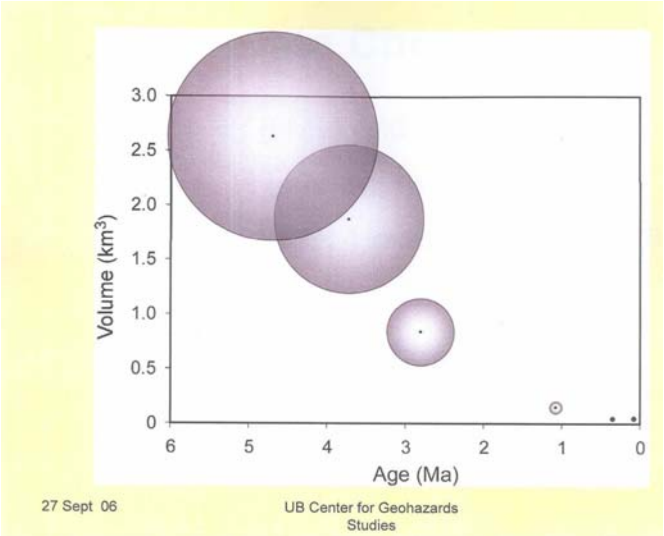


Figure 34 **Age vs. volume of Plio-Pleistocene volcanic episodes in the Yucca Mountain region. Figure includes buried Pliocene basalts in the northern Amargosa Desert. The diameter of the circles is proportional to volume. The dot at far lower right represents Lathrop Wells. The dot to its left represents Sleeping Butte. The small circle at 1.1 Ma represents the five Pleistocene cones of Crater Flat (After Perry, 2006).**

Perry and Valentine (2007) discussed regional factors that may help explain long-term trends for volcanism in the Yucca Mountain region. Following the end of major caldera-forming silicic volcanism in the Southwestern Nevada Volcanic Field (SNVF), at least 10 episodes of alkalic basaltic volcanism occurred over the last ~11 Ma. A program of geophysics, drilling, radiometric dating, and geochemistry conducted since 2004 by Los Alamos National Laboratory and the U.S. Geological Survey, combined with previous and ongoing petrogenetic and physical volcanology studies, sheds more light on the early and middle evolution of the volcanic field, much of which has been buried in alluvial basins. Volumes of erupted basalt in this volcanic field greatly declined over time from as much as 50 km^3 in the Miocene to about 0.5 km^3 in the Pleistocene. The volume decrease was accompanied by a dramatic decrease in extension rate, suggesting a close link between magmatism and tectonism. Neodymium and strontium isotopic analyses indicate that enriched lithospheric mantle has been the source of basalt throughout the history of the field. Decreasing eruption volumes were accompanied by a doubling of Ce/Yb ratios, indicating that the volume decrease reflects a decrease in degree of partial melting of the lithospheric source. Eruption style has also changed with time, reflecting an increase in magma volatile content consistent with decreased amounts of partial melting of a volatile-bearing source. These observations are consistent with a model in which the lithospheric mantle source was hottest during the period of major silicic volcanism (Miocene) and the presence of an active plate subduction system. After the breakdown of subduction, continued thermal input into the lithosphere ended and the lithosphere started to cool. Melt accumulation in non-convecting, static lithosphere is probably related to mantle heterogeneities enriched in hydrous minerals that are partially melted. During regional extension, these zones are relatively weak and preferentially deform, forming melt bands of increased porosity that concentrate melt and lead to dike generation. Decreasing regional extension results in less melt accumulation and decreasing eruption volumes. Without a new source of heat and limited lithospheric extension, it is likely that the next million years of volcanic activity in the field will likely be characterized by eruptions similar to those that have occurred in the past million years: infrequent eruptions of small-volume (<0.1 km^3), volatile-rich alkali basalt magmas within the most tectonically active southern and western margins of the volcanic field (Perry and Valentine, 2007).

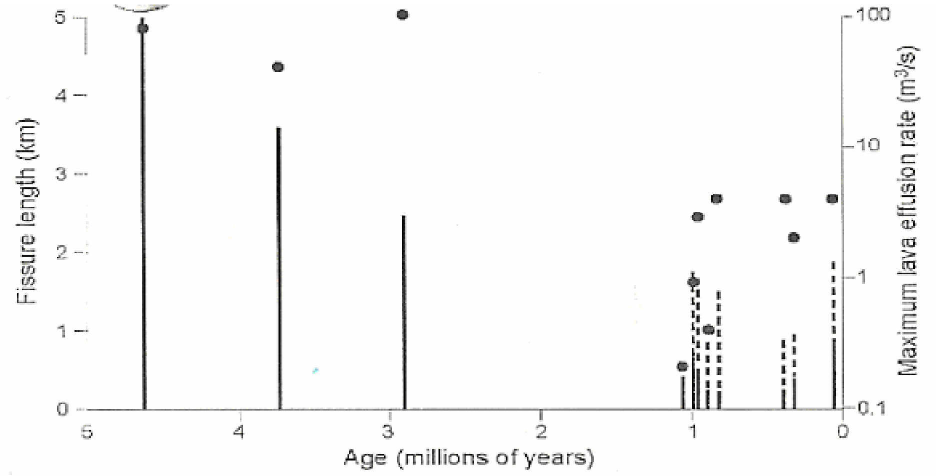


Figure 35 **Plot of fissure length (lines) and lava effusion rate (dots) for Plio-Pleistocene volcanoes of the Southwestern Nevada Volcanic Field. Note that age determinations do not allow discrimination of relative ages amongst the five Pleistocene volcanoes in Crater Flat, therefore they are plotted in random order around 1 Ma. The eruptive products of SW and NE Little Cones are largely buried by alluvium and mapped by aeromagnetic anomalies (Valentine et al., 2006); their volumes are lumped together in this plot (After Valentine and Perry, 2006) (Permission to use this copyrighted material is granted by the American Geophysical Union).**

Valentine and Perry (2007) summarize physical volcanological, geochemical, and time–volume characteristics of the Plio-Pleistocene part of the Southwestern Nevada Volcanic Field (SNVF) as an example of an extremely low volume-flux end member of basaltic fields. The SNVF has produced 17 volcanoes of dominantly trachybasaltic composition over the past 5 Myr with a total volume of slightly less than 6 km^3. Eruptive fissure lengths, volumes, and inferred lava effusion rates decreased between Pliocene- and Pleistocene-age volcanoes. Major element data suggest that most of the magmas underwent similar degrees of fractionation during ascent, and trace element compositions indicate a decrease in the degree of partial melting of the lithospheric mantle source since about 3 Ma ago. Isotopic data support an interpretation where magmas ascended quickly from their source regions with little if any interaction with crustal rocks. Relationships between age and cumulative erupted volume indicate that the repose interval between eruptive episodes is determined by the volumes of prior episodes and, since approximately 3 Ma, an average eruption rate of ~0.5 km^3/Myr, i.e., the field is time-predictable. These features support a model where magmatism is a passive result of regional tectonic strain. Partial melt resides in pockets of lithospheric mantle that are relatively enriched in hydrous minerals. Slow deformation focuses melt, occasionally resulting in sufficiently high melt pressure to drive dikes upward and feed eruptive episodes. Larger source volumes result in larger eruptive volumes and wider dikes that relieve relatively more strain in the crust than smaller volume events, and therefore are followed by longer repose intervals required for recovery of crustal stresses. Valentine and Perry (2007) suggest that time-predictability may be a fundamental property of tectonically controlled basaltic fields, where melt accumulation and ascent are controlled by tectonic strain rate. This behavior contrasts with magmatically controlled fields where magma flux is great enough to overwhelm local tectonic strain, eruptions are primarily caused by magmatic processes that build pressure in reservoirs, and the systems are more likely to be volume-predictable (Valentine and Perry, 2007).

Valentine and Perry (2007) conclude that if basaltic volcanism in the SNVF continues to exhibit tectonically controlled, time-predictable behavior with a ~0.5 km^3/Myr eruptive volume flux, their linear regression model (time to next episode is dependent on previous episode's volume) suggests that the next episode of volcanic activity somewhere in the volcanic field will occur ~270 kyr after the Lathrop Wells episode (with a 90% prediction interval of ±290 kyr reflecting the small data set), or about 190 kyr in the future (Valentine and Perry, 2007). The interval to the next episode predicted by the time−volume relationship is consistent with SNVF recurrence intervals that have been estimated using probabilistic approaches. One caveat they offer is that it is possible that the ~77 ka eruption of Lathrop Wells volcano might be the start of an episode rather than comprising an entire episode. The lapsed time since the Lathrop Wells event suggests that it is likely to have been the sole event in its episode, but this cannot be proven. This highlights the value of probabilistic approaches that incorporate uncertainties into temporal recurrence models, rather than relying only on deterministic, empirical time-predictable behavior. Time-predictability in a tectonically controlled field does not constrain the size or location of potential future episodes, requiring the incorporation of additional information. The fact that most of the basaltic episodes (except the ~2.9 Ma Buckboard Mesa event) have occurred near existing clusters suggests that the magmatic footprints of future events will probably also occur near or within those clusters. General similarities in volcano size and eruptive styles during the past ~1.1 Myr suggest that the future events during the next 100s of kyr will have similar characteristics (Valentine and Perry, 2007).

The 80-ka Lathrop Wells volcano (Heizler et al., 1999) represents the youngest event in the vicinity of the Crater Flat basin. Fridrich et al. (1999) report that it lies between the southern ends of the Windy Wash and Stagecoach Road faults, the most active site of late Pleistocene faulting in the Crater Flat basin. They also report a close spatial and temporal relationship between sites of extension and volcanism throughout this basin. The occurrence of the three episodes of post–Miocene volcanism in the southwestern part of Crater Flat basin suggests that volcanism is less likely to occur at Yucca Mountain, which lies outside the transtensional zone in an area where no post-Miocene volcanism has occurred. Fridrich et al. (1999) reported that other geologic and geophysical studies provide corroborative evidence that areas of maximum extension in the southwestern Crater Flat basin correspond closely to volcanic source zones.

Alternatively, Smith et al. (2002) and Ho et al. (2006) suggest that the volcanism in the Yucca Mountain region is related to a common mantle zone of melt that extends from Death Valley through Crater Flat to the Lunar Crater volcanic field roughly 140 km north of Yucca Mountain (Figure 36). They hypothesize that the episodic volcanism of the Crater Flat-Lunar Crater trend shown in Figure 37 is related to varying strain accumulation in the lithosphere and "volcanism is not dead and another eruption peak is possible" (Smith et al.,2002, p. 9). The implication of their model is that the recurrence rate of volcanism in the Yucca Mountain region could increase dramatically in the future, perhaps by as much as an order of magnitude, to the rates observed in Lunar Crater volcanic field. However, as argued by Perry et al. (2005), there are major differences between volcanic activity in Lunar Crater and the Yucca Mountain region that indicate it is unlikely there is a connection between the volcanism in these regions. In addition to the significant differences in the recurrence rate and volume of volcanic activity, there are major variations in the trace element chemistry of the Pleistocene volcanic rocks of the two areas (Farmer et al., 1989) that indicate quite different source zones for magma in the mantle rocks. Accordingly, the Yucca Mountain region source may be unlikely to produce frequent or large volumes of basalt.

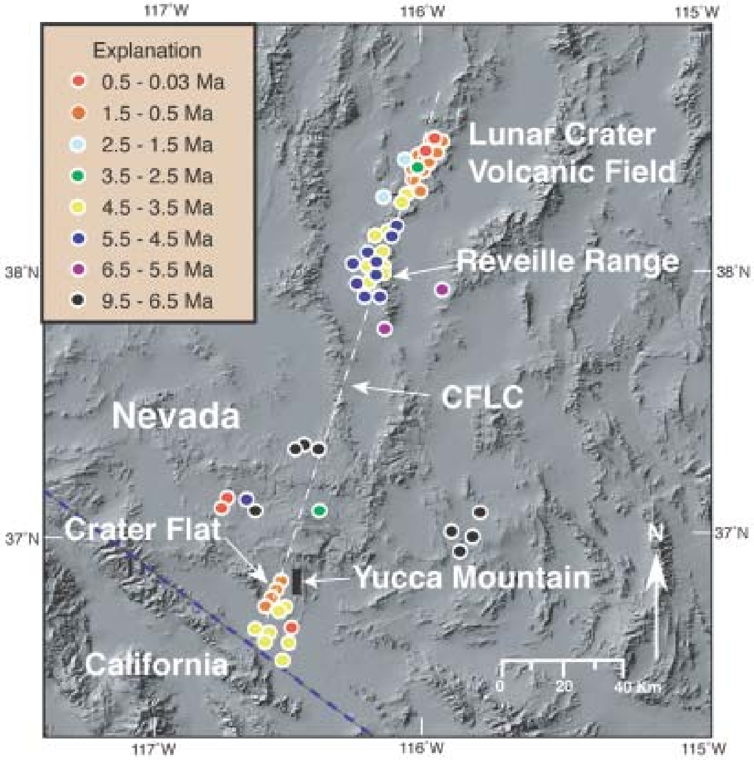


Figure 36 **Age and distribution of Pliocene-Pleistocene basaltic volcanoes in Crater Flat-Lunar Crater zone (CFLC) (After Smith and Keenan, 2005) (Permission to use this copyrighted material is granted by the American Geophysical Union).**

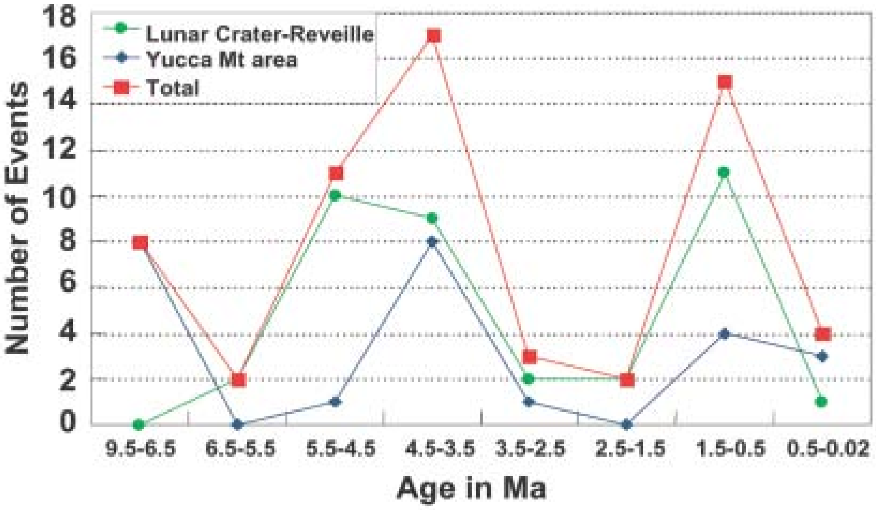


Figure 37 **The number of volcanic events as a function of time in the Lunar Crater-Reveille Range and Yucca Mountain areas. Note that the scale for the time axis does not have equal intervals (After Smith et al., 2002) (Permission to use this copyrighted material is granted by the Geological Society of America.**

Although Figure 37 appears to support periodicity of volcanism, this view is distorted by the nonlinearity of the time scale. Furthermore, regional extension rates (Figure 33), magma volumes (Figure 34), and fissure lengths and lava effusion rates (Figure 35) show evidence of clustering (and declining) activity over time but do not provide evidence of periodicity.

5.3. Time Period Used in Extrapolation of Igneous Activity

The time period used to evaluate future igneous activity should be reasonably representative of present-day geologic and tectonic conditions. For example, there is no evidence that the extensive felsic pyroclastic eruptions that formed the surface rocks at Yucca Mountain ~13 Myr ago will recur. The dramatic decline in both tectonism and basaltic volcanism over the last 11 Myr indicates that crustal conditions during post-Miocene time (<5.3 Ma) are more representative of present-day conditions than of those that prevailed during the Miocene Epoch. The last tuff-forming eruptions occurred in the region ~7.7 Ma ago, depositing the Thirsty Canyon Tuff. There is also greater uncertainty about the actual numbers of Miocene events because of concealment by younger volcanics and the longer time available for physical erosion and burial by alluvium. In developing estimates of volcanism recurrence rates, more reliable counts can therefore be made of Pliocene, and especially of Pleistocene, events for extrapolation purposes (Coleman et al., 2004).

5.4. Controls on Occurrence of Igneous Activity

In developing a sound basis for estimating the probability of igneous events, it is necessary to identify the most likely areas of the Yucca Mountain region for the occurrence of igneous activity. An active magma chamber and crustal conditions favorable for the magma to rise to the surface are both needed for basaltic igneous activity to occur.

Efforts have been made to isolate active magma chambers in the upper mantle of the Yucca Mountain region using tomographic methods to identify seismic velocity variations associated with the partial melts of the magma chambers (e.g., Evans and Smith, 1992 and 1995; Connor and Sanders, 1994). Unfortunately, these studies have not led to definitive results. Evans and Smith (1995) find a weak low seismic velocity feature beneath Crater Flat that may represent crustal heating beneath the basin. Biasi (2005) reported to the PVHA-U panel that he has mapped variations in seismic velocity in the upper mantle in the Yucca Mountain region that he relates to surface features. He interprets the velocity variations within the mantle as a dehydrated root extending to depths of 300 km beneath the Timber Mountain/Silent Canyon caldera complex north of Yucca Mountain that is related to the caldera volcanism. Post-Miocene basaltic events occur on the margin of the dehydrated root. Beneath parts of Crater Flat basin, Biasi's data indicate slow velocity mantle that is separate from the fast velocity root beneath the calderas. The position of the proposed repository is in the diffuse boundary between these two areas. Biasi suggests that the waning volcanism in this area is more indicative of the effect of the dehydrated root than cooling of the system. His investigations indicate that the Plio-Pleistocene volcanism has dehydrated the mantle underlying Crater Flat, thus somewhat cooling it and increasing its melting temperature, suggesting that the area may be less prone to volcanism in the future. Other remote sensing techniques of isolating the magma chambers are insufficiently sensitive to the minor effects of the magma reservoirs associated with the basaltic volcanism.

O'Leary (2001) described possible tectonic controls on basaltic volcanism near Yucca Mountain. He noted that the Plio-Pleistocene basalts near Yucca Mountain are transitional alkaline-olivine basalts or trachybasalts, which are typical of other basalts of that age in the western Great Basin. Such basalts are generally thought to originate as partial melts of lithospheric mantle, uncontaminated by crustal components. Each volcano probably represents a batch of magma collected from a resident equilibrium melt, with upward pathways being provided by local tectonic conditions. Given the low rate of post-Miocene extension, O'Leary (2001) proposed that present-day melt generation near Yucca Mountain would not be influenced by decompression, and further stated that the small extrusive volumes are not likely to be influenced by buoyancy.

Most of the volcanic centers originating over the past 5 Myr are located in Crater Flat basin or in the Amargosa Desert. Some of the cones show a NNE-oriented alignment. This alignment of small-volume eruptions, the relatively high volatile content of the erupted materials, and lack of crustal contamination or evidence of fractionation suggest that the magmas ascend directly from an upper mantle source along fractures influenced by right-lateral transtension (O'Leary, 2001). A tectonic model that treats Crater Flat basin and the Amargosa trough as a graben/rift feature modified by right-lateral shear, and accounts for extension effects and fracturing in the upper mantle melt zone, provides a mechanism for basalt rise through the crust as well as a structural association with observed tectonic features. Consistent with the apparent waning volcanism, activity should decrease over time as local magma reservoirs are depleted and the magma solidification temperature is pushed to greater mantle depths with a cooling lithosphere (O'Leary, 2001).

O'Leary (2007b) described the Crater Flat basin as a half-graben controlled by subsidence along the Bare Mountain fault (Figure 13). The basin can be interpreted as a southward propagated rift within the older, shallower Amargosa trough. This trough is a seam between major crustal blocks: the Spring Mountains block and the Funeral Mountains-Bare Mountain blocks. The trough is probably pre-middle Miocene in age. Crater Flat basin originated about 12 Ma, during and following deposition of the Paintbrush and Timber Mountain Groups (tuffs). Basin subsidence, along with right-lateral transtension, produced the present structure and configuration of Yucca Mountain. O'Leary (2007b) proposed a rift propagation model for Crater Flat basin, based on stress history and on analysis of enhanced satellite image data and recently acquired high-resolution aeromagnetic data. Rift propagation of Crater Flat basin as a wedge-like opening under influence of dextral transtension explains problematic structures in the transition zone between Crater Flat basin and the Amargosa Desert, and also provides a context for the Miocene to Pleistocene basaltic volcanism in this area (O'Leary, 2007b).

The DOE (2003) summarizes stress conditions near Yucca Mountain. Along with faulting, magma intrusion is an important component of worldwide crustal extension (Parsons and Thompson, 1991). Yucca Mountain lies in the southern Great Basin in the Basin and Range province, which is undergoing active ESE–WNW extension (Zoback and Zoback, 1989). The crustal stress in the Yucca Mountain region has been investigated using hydraulic-fracturing stress measurements, borehole breakouts, drilling-induced fractures, earthquake focal mechanisms and fault-slip orientations (Stock and Healy, 1988). Dikes tend to strike orthogonal to the direction of the least compressive horizontal stress (parallel to the direction of the greatest compressive horizontal stress; Pollard (1987)). The orientation of the greatest compressive horizontal stress in the Yucca Mountain region is approximately N30°E ±15 degrees. Uncertainty in this orientation results from both inaccuracies in measurement and real variations in stress with depth and location which vary by up to 40° in Yucca Mountain drillholes (Stock et al., 1985).

The Crater Flat structural domain is a basin bounded on the west by the Bare Mountain fault (Figure 11) and on the east by structures beneath Jackass Flats. Seismic reflection surveys show that the Crater Flat basin is deepest on the western side (Brocher et al., 1998). It includes the Crater Flat topographic basin on the west and Yucca Mountain near the center of the structural domain. Because the potential repository lies within the Crater Flat structural basin, the structural and geophysical features of the domain, and the degree to which they influence the location of volcanism within the domain, have been key factors in conceptual models for assessing hazards to the repository (DOE, 2003).

Connor et al. (2000) hypothesized that magmas ascending a steeply dipping fault may be diverted laterally by as much as 5 km depending on the depth of dike capture by the fault and the dip of the fault plane. Dikes also have a tendency to break out of the fault system and propagate vertically at shallow depth because of rapid changes in the magnitude and orientation of the stress field. Therefore cinder cones are often located beside faults in the hanging wall of the fault. The arcuate map pattern of the Pleistocene Crater Flat alignment may partly owe its origin to this mechanism. The dip of the Bare Mountain fault shallows progressively northward (Ferrill et al., 1996) and cinder cones along the alignment are displaced progressively eastward. Basin and Range normal faults commonly grow by formation, propagation, and amalgamation of smaller normal faults (Ferrill et al., 1999). This progressive fault growth commonly involves development of *en echelon* fault systems. Ferrill et al. (1999) identified the Solitario Canyon fault and related west-dipping faults on the western edge of Yucca Mountain as one such set of left-stepping en echelon faults produced by progressive deformation. The Pliocene vents immediately south and west of these fault segments reflect this trend, forming a left-stepping array of vent alignments. En echelon fault geometries may therefore provide preferential pathways to the surface for magmas ascending along fault segments. Linear, north-trending magnetic anomalies intersect Northern (Makani) Cone, located in the Crater Flat basin. These anomalies result from vertical offsets across faults that are arguably part of the same array of left-stepping normal faults. At the western edge of the proposed repository, a Miocene-aged dike intruded a segment of the Solitario Canyon fault. Such relationships indicate that the en echelon array of faults has hosted dikes at least three times in Miocene through Pleistocene time.

Spatially, most of the Plio-Pleistocene basalts near Yucca Mountain erupted in basins rather than on topographically high ranges. Basalts in basins include the Pleistocene aged cones of Crater Flat, the Lathrop Wells cone, Pliocene Crater Flat, and buried basalts of Pliocene age located by drilling (Anomalies B and G, and by inference, Anomalies F and H). There is a clear preference for Plio-Pleistocene basalts to erupt in basins, the shortest path to the surface for dikes. Panelists of the ongoing PVHA-U have discussed this phenomenon and have requested that DOE develop a dataset of lithostatic (overburden) pressure variations to compare with areas where past volcanism has occurred. At Yucca Mountain itself intrusions may have been inhibited over the last 10-12 Myr by higher rock pressure compared to the Crater Flat basin area to the west. Lithostatic pressure data provide information on likely magma flow paths in the upper crust. In waning volcanic systems like the Crater Flat region, the driving energy of the magma systems is small enough that lithostatic pressure variations may be sufficient to help guide magma flow paths. Eruptions from such systems would hypothetically be favored to occur in basins where the pressure from the overlying rocks is lower rather than in adjacent topographically high areas like Yucca Mountain. This concept was investigated by Parsons et al. (2006) using three-dimensional finite-element modeling to determine the sensitivity of basalt intrusions and faulting to the magnitude and orientation of the least principal stress in extensional terranes such as the Yucca Mountain region. They found that in the absence of fault slip, lithostatic pressure variations favored intrusions into Crater Flat. However, when faults were allowed to slip, intrusions were not favored in either the Crater Flat basin or the central Yucca Mountain block, but rather near fault terminations. They find the latter situation is consistent with the Lathrop Wells volcano.

There are exceptions, but most of the basaltic eruptions near Yucca Mountain occurred in the basins. More energetic magma systems of greater volume (e.g., Reveille Range-Lunar Crater) could be less sensitive to lateral lithostatic pressure variations and, therefore, show a lesser tendency to concentrate eruptions in topographic lows.

Gaffney and Damjanac (2006) investigated topographic effects on dike propagation and conduit formation. They modeled magma flow in a dike rising in a fault whose strike extends from a highland to an adjacent lowland. Their results indicate that a dike rising from great depth near the transition from a lowland to a highland, and striking across that transition, will preferentially erupt toward the lowland and will avoid intrusion into the highland. The concentration of flow away from the ridge will focus advective heat flow in that region, maintaining low viscosities, which will in turn favor conduit localization in the lowland portion of the strike length of the dike (e.g., Wylie et al., 1999). Separation of the geometric effect of the topography from its effect on lateral confining stresses on the crack indicates that both contribute to the diversion effect but that the effect of stress is less important. The authors concluded that their analysis explains the tendency for eruptions to occur in lowlands, but does not preclude eruptions on highlands. Gaffney and Damjanac (2006) further concluded that the scenario they modeled mimics topography around the proposed repository at Yucca Mountain, so that their results may indicate some reduction in volcanic hazard to the repository site. Along with insights about locations of enhanced crustal extension, the topographic analysis by Gaffney and Damjanac (2006) helps to explain why Plio-Pleistocene volcanism near Yucca Mountain focused in lowlands rather than on topographic highs. The number of events in the basins is approximately an order of magnitude greater than in highlands.

Gaffney et al. (2007) further investigated the effects of pre-existing geologic structures on the propagation of dikes. They examined the capture of vertically rising dikes by faults, using a combination of an analytic solution, numerical simulations, and field observations. One of the numerical solutions and the field observations also provide insights about the intrusion of sills into the hanging wall of faults that are reactivated when lubricated by magma. The approximate analytic solution indicates that dike capture by a fault will be limited primarily to steeply-dipping faults. Capture will become easier, meaning that it will be possible for faults with shallower dips, as the intersection of the dike with the fault occurs at smaller depths. Capture will also be easier as it is harder for a crack to grow in the hanging wall. Gaffney et al. (2007) interpreted this in terms of a higher tensile strength, shorter preexisting cracks, or higher fracture toughness. Numerical analysis using a discrete element code confirms this conclusion but also shows that the analytic solutions overestimate the difficulty of intruding a pre-existing fault, the maximum deviation occurring for faults dipping at 45°. This finding that dike capture by faults should be restricted to high-angle faults and shallow depths is supported by field observations of exhumed Miocene basaltic volcanics in central Nevada. Gaffney et al. (2007) attributed differences in style seen in other regions to the rock properties and the regional stress field. The numerical solutions also indicate that synintrusive fault slip is likely to lead to formation of sills in the hanging wall at depths of a few hundred meters or less: a finding that is also consistent with the field observations in Nevada. Gaffney et al. (2007) report that their results should be applicable to basaltic volcanic fields in tectonically neutral to extensional environments (on a local or regional scale) where dike injection is mostly vertical and where normal faults are abundant. This combination is most likely to occur in low magma flux systems such as the Southwestern Nevada Volcanic Field (Valentine and Perry, 2006). In higher flux basaltic fields, normal faults are less abundant because tectonic strain is taken up by magma injection instead of faulting.

5.5. Calculation Methods

Many methods have been used to predict future volcanism. Most are directed toward the near real-time eruption of existing volcanoes. These predictions are increasingly successful with increasing knowledge of the cause and mechanisms of volcanic activity. However, consideration of volcanic activity at Yucca Mountain involves the likelihood, location, and nature of new igneous activity that could intersect the repository over time frames of tens and hundreds of thousands of years. In this section the methods of prediction are described including the use of physical precursors, analysis of hypothetical linkages between volcanic fields, and various mathematical and statistical methods that can be used to analyze past spatial and temporal patterns of volcanism. The latter is the generally used method for studying Yucca Mountain region igneous activity and thus is the primary focus.

5.5.1. Physical Precursors

Many volcanoes repeatedly erupt in one place over geologic time (polycyclic volcanoes). Examples include Kilauea, Mount Suribachi, Mount Etna, Vesuvius, and the Cascade volcanoes (Mounts Rainier, St. Helens, Hood, and many others). The main eruption of Mount St. Helens in 1980 was anticipated by real-time phenomena, such as an increase in seismic activity, changes in gaseous emissions from the summit crater, and changes in the volcano’s topography. Nine main pulses of activity have occurred at Mount St. Helens in the last 40,000 years, with multiple eruptions in each pulse (Tilling et al., 1990). In contrast, there is no evidence that the basaltic eruptions during the last 5 million years near Yucca Mountain were polycyclic (Valentine et al., 2006). They formed discrete cinder cones and associated lava flows. The most recent volcanic activity near Yucca Mountain formed the Lathrop Wells cone and basalt flows that have undergone extensive study (Zreda et al., 1993; Fleck et al., 1996; Heizler et al., 1999; Nicholis and Rutherford, 2004; Valentine et al., 2005, 2007).

As reported by Fridrich et al (1999) there is an observed relationship in the Yucca Mountain region between strain rate and volcanism. Wernicke et al. (1998) suggested that the region is experiencing an epoch of anomalously rapid crustal strain accumulation, and that hazard analyses based only on the local record of magmatic and tectonic events would underestimate the probability of future events by an order of magnitude. The claim of anomalous strain was countered by Savage (1998) who reported a N65°W strain rate of 8 ± 20 nanostrain/yr. He found that Wernicke et al. (1998) did not include monument instability in their error budget and did not give proper weight to the strain effects of the nearby 1992 Little Skull Mountain earthquake. Later work by Savage et al. (2001) continued to find that the principal extension rate averaged over their 50-km geodetic array is substantially less than reported by Wernicke et al. (1998) and is consistent with the low extension rate inferred from the geologic record. Likewise, Connor et al. (1998) noted that the lack of a known volcano younger than the Lathrop Wells event diminished the argument that volcanic recurrence rates have been underestimated by an order of magnitude. Therefore, present-day strain rates do not support an order of magnitude increase in hazard from tectonic or magmatic events. Furthermore, as discussed above, seismic tomographic methods have not provided definitive information on the presence of magma chambers within the mantle because of their great depth and limited size.

5.5.2. Proposed Linkages to Other Volcanic Zones

Smith et al. (2002) and Ho et al. (2006) propose that the volcanoes near Yucca Mountain are part of a larger zone of basaltic volcanism associated with a common area of hot mantle that extends from Death Valley northward to the Reveille Range-Lunar Crater (RLC) volcanic area (Figure 36). Within this zone, volcanism is of similar age with three peaks of volcanism: one between 9.5 and 6.5 Ma, the second from 4.5 to 3.5 Ma, and the most recent between 1.5 and 0.5 Ma (Figure 37). Smith et al. (2002) report that volcanism in this zone is relatively quiet at present, with only three eruptions in the last 80,000 years. Episodic volcanism in the Crater Flat-Lunar Crater zone may be related to episodes of rapid strain accumulation in the lithosphere. They concluded that a zone of hot, buoyant mantle exists beneath this zone and provides a common driving force for magmatism. Smith et al. (2002) propose that the magma that erupted in these volcanic zones had a common source.

Volcanism recurrence rates in the RLC are approximately four times higher than in Crater Flat near Yucca Mountain. Smith and Keenan (2005) suggested that the higher recurrence rates in the RLC may occur in the future in the Yucca Mountain area. They concluded that the higher recurrence rates, along with data from future geophysical surveys, could result in a probability of volcanic disruption of a repository that is one to two orders of magnitude greater than the EPA guideline for consideration of disruptive events. Smith and Keenan (2005) suggested that the probability of repository disruption could be as high as 10^{-7}/yr to 10^{-6}/yr. A key implication of their model is that recurrence rates in the Yucca Mountain region could increase to rates typical of the Lunar Crater volcanic field in the future. Perry et al. (2005) commented that the hypothesis is inconsistent with the Quaternary volcanic history of the two volcanic fields, which for the past million years have differed significantly in recurrence rate and eruption volume. Compared to the eight Quaternary cones in the Yucca Mountain region (with a total eruption volume of <0.5 km^3), there are ~80 Quaternary cones in the Lunar Crater field, with a total eruption volume that is one to two orders of magnitude greater than in the Yucca Mountain region during the Quaternary. These major differences, plus major differences in neodymium and strontium isotopic composition (Farmer et al., 1989), are consistent with models of hotter *asthenospheric* mantle and colder lithospheric mantle sources for the Lunar Crater volcanic field and Yucca Mountain region, respectively. The contrasting eruptive histories and mantle sources with different magma production potentials, suggest the two volcanic fields should not be linked for purposes of assessing volcanic hazards at Yucca Mountain (Perry et al., 2005). Smith and Keenan (2005) have suggested that the isotopic differences between the volcanic fields could be explained by contamination of rising magma by lithosphere of different composition or age.

Tynan et al. (2004) proposed that “mega-rings” surround the Timber Mountain caldera complex, defining a zone ~80-100 km in diameter centered on Timber Mountain. The mega-rings encompass known smaller rhyolitic nested Miocene calderas (~11-15 Ma, < 10 km circular to elliptical small "rings") and later stage basaltic features (< 11 Ma, small flows, cones, dikes) in the Southwest Nevada Volcanic Field. Miocene rhyolitic calderas cluster within the central area and on the outer margin of the interpreted larger mega-ring complex. Tynan et al. (2004) commented that the mega-ring interpretation is consistent with observations of regional physiography, tomographic images, seismicity patterns, and structural relationships. Mega-rings consist of arcuate faulted blocks with deformation patterns showing a genetic relationship to the Timber Mountain volcanic system; they appear to be spatially associated and temporally correlated with Miocene volcanism and two geophysically identified crustal/upper mantle features (Tynan et al., 2007).

Carlson (2005) gave a presentation to the PVHA-U expert panel titled “Spatial Distribution: Why is Volcanism Where it is Around Yucca Mountain?” For Miocene and post-Miocene basalts, he described the appearance of a nearly circular volcanic field centered around the Timber Mountain caldera complex with a more-or-less random distribution and some suggestion of spatial clustering. In Miocene time volcanism was active in Jackass Flats but not in post-Miocene time. Carlson (2005) described several plausible patterns for post-Miocene volcanism, depending on whether the basalts of Buckboard Mesa are included. In one case he described a shrinking circular volcanic field centered on the Timber Mountain caldera complex. In a second case (excluding Buckboard Mesa) the pattern suggests contraction of the original volcanic field to a linear vent alignment that reflects strong control by the local structure and stress field. He suggested it may be possible to decide between the two cases by investigating the causes of magnetic anomalies in the region through the drilling and dating of buried basalts.

5.5.3. Expert Elicitation

Although acquisition and analysis of physical data are the primary methods of determining the probability of an igneous event intersecting the proposed repository, the complexity of the igneous process and limitations in knowledge of the process and related parameters has led to a variety of professional opinions resulting in contrasting hazard evaluations. In an effort to evaluate the probability in the face of these contrasting views and the lack of a clear path to resolving them, the DOE implemented an expert elicitation of the volcanic hazard, the Probabilistic Volcanic Hazard Analysis (PVHA). Expert elicitation is a formal, highly structured, and well-documented process whereby the judgment of a range of experts in the discipline is determined and combined to provide a composite evaluation and the range of uncertainty associated with that evaluation. The experts do not create knowledge, rather they synthesize disparate and often conflicting sources of information to produce an integrated picture (Hora, 1993). The use of expert elicitation is accepted in the licensing arena providing that a series of protocols are faithfully followed in organizing, conducting, documenting, and evaluating the process (Kotra et al., 1996).

The goal of the DOE’s expert elicitation was “To represent the center, the body, and the range of the technical interpretations (regarding volcanic hazards) that the larger informed technical community would have if they were to conduct the study.” (Coppersmith, 2007). The results of this evaluation of the views of ten experts are described by Geomatrix Consultants

(1996) and are referred to as PVHA-96. The Geomatrix Consultants report describes the organization, process, and the results of the elicitation. Kevin Coppersmith, the Technical Facilitator Integrator for the PVHA-96 as well as the current PVHA-Update, has described specific aspects of the process. His description of the expert elicitation process with minor editing is provided below.

With regard to spatial distributions of future events, there was a range of assessments across the expert panel and for any given expert (i.e., the experts were free to exercise multiple conceptual models). Spatial PVHA models define the spatial variation in the relative intensity of future events and, when combined with a temporal model define the rate of future events for any location within the region of interest. One spatial model used by some experts called for a homogeneous spatial distribution ("random") within expert-defined zones. Uncertainties associated with this model were quantified, including alternative zone configurations and uncertainty in the zone boundary locations. Additional spatial models used by some experts result in a future spatial distribution defined by proximity to past events (e.g., spatial smoothing models) or proximity to groups of past events (e.g., field shape models).

In PVHA-96, there were no assumptions made regarding either the temporal or spatial distribution of volcanic events in time. The assessment of future distributions varied with the individual expert and, in some cases, individual experts used more than one model. Across all experts, three temporal models were used: a homogenous Poisson model (commonly thought of as "random"), non-homogenous Poisson models (allowing for a time-dependent rate that can be either increasing or decreasing), and a time-volume model that considers the change in cumulative magma volume and volume-per-event over time in estimating the current and future rate. For all three approaches the rate was estimated based on the number of expert-identified volcanic events over a time period identified by the expert as relevant (e.g., over Quaternary time).

Several temporal models were considered by the experts, including models with time-dependent rates and models that focus on the change in magma volume over time. An interpretation of "waning" volcanism over the past several million years has been made primarily on the basis of observed decreases in cumulative volume and volume-per-event, but not necessarily on the basis of observed decreases in rate. For example, it is well documented that the rate of events in the Yucca Mountain region was low during the 3.7 to 1 Ma timeframe, but this was followed by a period of higher rate about 1 Ma ago (Figure 37). The time-volume models used by some experts were developed explicitly to capture these changes and generally led to estimates of decreases in the volumes over time.

The PVHA process concentrated on quantifying uncertainties and arriving at a full probability distribution. Subsequent to the study, the focus has been on the mean value of probability as a summary measure for the results. The mean value exceeds the limit for screening out events, and the mean level of seven of the ten experts was at or above the screening level (i.e., 10^{-8}/yr). However, the entire probability distribution of the annual probability of dike intersection is passed to the DOE's TSPA, obviating confusion about the PVHA results. For convenience and discussion, the mean or median (or some percentile) of the distribution may be cited, but the risk analysis incorporates the entire distribution. As a probabilistic analysis designed to capture uncertainties, the PVHA process discouraged invoking conservatisms or optimisms to deal with uncertainty. Rather, experts were encouraged to identify and to quantify their uncertainties in conceptual models and parameters.

With respect to volcanic source zones, the experts considered that any part of the Southern Basin and Range would have a finite likelihood of hosting a basaltic igneous event, albeit at a low recurrence rates. This is due to the extensional tectonic environment and the observations throughout the region of basaltic igneous events as a response to crustal extension. Generally, the experts used the rates of events over larger regions (e.g., the Southern Basin and Range region) to estimate the rates for these zones. The experts also used comparisons with other zones in the Yucca Mountain region and assessments of the relative rates of volcanism. However, in other evaluations where the Yucca Mountain block was within a zone with no known past events, they used the approaches described above to estimate a rate for that zone. However, in some cases, the Yucca Mountain block was within a zone that included past events (such as the Crater Flat basin or events to the north at Thirsty Mountain and Buckboard Mesa). The relative distribution of recurrence rate was defined by the spatial model and temporal model for that zone.

With regard to rates of volcanic activity, there is an important distinction between “event frequencies” and “intersection frequencies.” The first is an expression of recurrence rate and is given as a rate density (i.e., number of events per year per square kilometer) and varies with location according to a spatial model. Intersection frequencies are the rates of events that intersect with the repository. The latter is developed considering both event frequencies and dike geometries (azimuth and length), considering both those events (points) that are located within the repository footprint and those events whose dike would extend into the repository footprint. Volcanic event frequency is illustrated in Figure 38, where the variation in rate is aggregated across the PVHA assessments displayed as mean frequency per year per square kilometer. The location of the repository is shown as the black rectangle on the figure.

The PVHA-type elicitation process involves a number of attributes (e.g., multiple experts, dissemination of databases, interactions of experts, vetting of proponent views, feedback) that are all designed to improve the precision of the assessments. This is much more complex and requires greater engagement and learning on the part of the experts than merely eliciting experts on a particular technical topic.

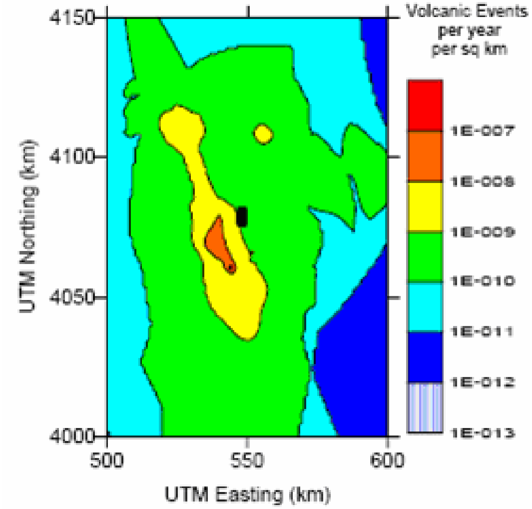


Figure 38 **Spatial distribution of expected volcanic event frequency defined by the Probabilistic Volcanic Hazard Analysis Expert Panel. The map represents the mean results averaged over 10 experts and over each expert’s logic tree. The black area in the center of the map is the location of the proposed repository (From Figure 6-11 of BSC, 2004b).**

5.5.4. Mathematical and Statistical Techniques

Various methods can be used to analyze spatial and temporal patterns of past volcanism to gain insights about where future events might occur (e.g., Connor and Hill, 1994). Most volcanic fields are only partially characterized. The Crater Flat volcanic field is relatively well-studied both in terms of surface exposures and buried basalts that have been identified with geophysical studies and subsequently drilled and dated. Extensive field geology and petrographic work also have been performed on basalts near Yucca Mountain.

5.5.4.1. Data-Based Approach

Estimates of the probability of an igneous event intersecting the proposed repository have employed a general methodology used for predicting events in existing volcanic fields. The critical variables in this methodology are the spatial and temporal models developed from the intensive studies of the volcanoes in the Yucca Mountain region. However, interpretation of the results of these studies has led to differing input parameters to the methodology, resulting in a range of probabilities covering roughly two to three orders of magnitude.

The general method used in determining the probability of a future intersecting event is the product of two quantities: (1) the estimated recurrence rate, N(R,T)/T, the recurrence rate, which is the number of igneous events within a specified volcanic zone adjacent to or including the site of the repository over a specified time period [N(R,T)] divided by the specified time period (T), and (2) the conditional probability of disruption within the footprint of the repository (a_r), given the occurrence of an igneous event, a_r/A which is the area of the footprint of the repository divided by the area of the volcanic zone (A) used in establishing the number of igneous events. The conditional probability of disruption relates the recurrence rate to the footprint of the repository and the area over which the recurrence rate is calculated. Thus, the probability of a future igneous event intersecting the repository per year.

$$P = [N(R,t)/T] \times [a_r/A],$$

where the time duration (T) is given in years.

A variation on this methodology has been considered by Ho et al. (2006) that incorporates procedures prescribed by the US Federal Aviation Administration for licensing commercial space launches and reentry to limit risks to public health and safety.

The recurrence interval is based on the spatial and temporal distribution of events which in turn is determined from the volcanic, geologic, and tectonic history of the Yucca Mountain region. It requires consideration of numerous components as illustrated in the logic chart (Figure 4) including definition of the following:

- an igneous event,
- the volcanic zone model which specifies the area and geographic location of the region of similar volcanic features adjacent to or including the proposed repository,
- the temporal model which specifies the number of igneous events in the volcanic model zone mapped from surface exposures and geophysical exploration and the number of events that are assumed to occur without being detected,
- the interval of time extending into the past which is representative of future igneous events at the proposed repository, and

- the location and area of the repository.

There is considerable uncertainty in most of these components except for the location and area of the repository and the number of igneous events mapped by surface exposures, geophysical studies, and drilling and dating. As a result the evaluation of probability is treated statistically by including the potential range of uncertainty assigned to each component of the probability equation. The result is a range of probabilities of intersection of the proposed repository which is incorporated in the performance assessment analysis. The uncertainty in P can be constrained by incorporating distribution functions specified by assumed controls on the occurrence of events in the equation for P (e.g., Connor et al., 2000). This is sometimes referred to as a Bayesian approach.

The recurrence rate term dominates the estimate of the probability of intersection and is the main source of uncertainty. Most estimates of the recurrence rate (events per year) range from 10^{-6} to 10^{-5} and conditional distribution probability values vary from 10^{-3} to 10^{-2}. Thus, in the simplest case the probability of intersection ranges from 10^{-9} to 10^{-7} per year.

5.5.4.2. Locally Homogeneous Spatial and Temporal Models

Temporal models that describe the frequency of occurrence of an event include both homogeneous and non-homogeneous models. Homogeneous models are based on a uniform rate of volcanism over the specified duration of time over the area of the volcanic zone model. In contrast nonhomogeneous models assume a non-uniform rate of igneous activity. Spatial models employ identified spatial source zones which reflect the presence and nature of igneous events and assumed geologic controls (e.g., faults and topography) on future igneous events in the zone. These source zones may consider nonhomogeneous, nonparametric models based on the location of existing events and their limits may be smoothed using various functions to describe the change in recurrence rate over the source zone.

Homogeneous Poisson models are commonly used to represent hazards from rare events. A key assumption is that one can identify a region where the rate of occurrence of volcanic events can be considered uniform in space and time over the period of interest. The Poisson model provides a reasonable representation for the combined effects of multiple independent processes, even when the individual processes may be non-Poissonian (Geomatrix Consultants, 1996). Areas of interest are divided into non-overlapping zones within which the frequency of intersection of volcanic events is estimated. One zone might be a large region with diffuse (background rate) volcanic activity, while another zone might display more concentrated volcanic activity. The rate of occurrence is estimated from data from a zone. The maximum likelihood estimate is given by the number of observed events in a time interval, divided by that interval.

5.5.4.3. Nonhomogeneous Spatial Models

5.5.4.3.1. Parametric Spatial Density Function

Parametric methods are mathematical procedures for hypothesis testing that assume that the distributions of the variables being assessed belong to known families of probability distributions. For example, analysis of variance assumes that the underlying distributions are normally distributed and that the variances of the distributions being compared are similar. While parametric techniques are robust (statistically powerful), some distributions violate the underlying assumptions so much that non-parametric methods are more likely to detect differences or similarities.

Sheridan (1990) developed a model for volcanic fields that represents the spatial density of events using a bivariate Gaussian distribution. The resulting mathematical representation has an elliptical shape defined by five parameters: coordinates of the field center, lengths of the major and minor axes, and the orientation (azimuth) of the major axis. Members of the PVHA (Geomatrix Consultants, 1996) used this method and others, estimating the parameters of Gaussian volcanic fields using data from the Yucca Mountain area.

5.5.4.3.2. Nonparametric Spatial Density Function

Non-parametric methods differ from parametric methods because the model structure is determined entirely from data. No assumptions are made about the frequency (or other) distributions of the variables being assessed. A histogram is an example of a simple nonparametric estimate of a probability distribution. The Chi-square test is one of the most frequently used non-parametric statistical tests.

Stochastic kernels are commonly used in parameter density estimation. Connor and Hill (1995) presented three nonhomogeneous spatial models for evaluating volcanic hazards. These three models included kernel density estimation, spatial-temporal nearest neighbor density estimation, and nearest neighbor kernel density estimation. Connor and Hill (1995) and Connor et al. (2000) presented a geologic and statistical basis for probabilistic hazard assessment at Yucca Mountain. Connor et et al. (2000) and Connor et al. (2002) developed software and accompanying data sets that use kernel density estimators to calculate probability surfaces using the location and timing of past, discrete volcanic events. They used both *Gaussian* and *Epanechnikov* kernels. The software by Connor et al. (2002) added several features, including the ability to represent the length and orientation of dikes and vent alignments. Also, isostatic gravity anomaly data could be incorporated into the analysis using a weighting factor determined by the user.

Coleman et al. (2004) used the software and data sets of Connor et al. (2002) to evaluate numbers of volcanic events in the region that should have been expected if recurrence rates were as large as claimed by some researchers. For example, some have claimed that the probability of volcanic intersection at Yucca Mountain could be as high as 10^{-6}/yr. The model and data sets of Connor et al. (2002) suggest that 40 to 192 eruptions should have been expected in the region in the last million years if the probability is as high as 10^{-6}/yr. However, only 8 events are known in all of the Pleistocene (1.8 Ma).

5.5.4.4. Nonhomogeneous Temporal Models

Several investigators have used nonhomogeneous models. Ho (1991, 1992) suggested that the rate of volcanic activity in the Yucca Mountain Region was not stationary in time and that the rate of activity could be modeled as a nonhomogeneous Poisson process using a *Weibull* function. Crowe (1995) applied a model in which the event rate of igneous activity intersecting the proposed repository was estimated by dividing the instantaneous rate of magma production by the time-varying volume per volcanic event. One PVHA expert used this method in his analysis (Geomatrix Consultants, 1996).

5.6. Treatment of Probability in Performance Assessments

The NRC, the DOE, and EPRI have performed detailed performance assessments of the proposed repository at Yucca Mountain using varying ranges and point values of the probability of an igneous event intersecting the proposed repository.

5.6.1. DOE Analysis

The DOE used the probability range developed by expert elicitation in the 1990's (Geomatrix Consultants, 1996). That probability range was recalculated (BSC, 2003a, p. 113) using PVHA outputs to account for the proposed license application (LA) repository footprint (the outline of the waste emplacement area) and extended to include the probability of an eruption within the proposed LA repository footprint, conditional on dike intersection (5th percentile = 7.4×10^{-10}/yr; mean = 1.7×10^{-8}/yr; 95th percentile = 5.5×10^{-8}/yr; median = $9 \text{ x}10^{-9}$/yr). It is expected that if the repository layout is changed or expanded, that would be considered in the documentation for a license application. An update of the PVHA is now being conducted that includes new information gathered since 1996, including the results of a magnetic anomaly exploratory drilling program.

The DOE had agreed to resolve the probability issue with NRC by

> providing in the Site Recommendation and License Application, in addition to DOE's licensing case, the results of a single point sensitivity analysis for extrusive and intrusive igneous processes at an annual probability of 10^{-7}. By agreeing to provide these analyses, [the NRC] staff consider the probability subissue closed-pending, because the 10^{-7} analyses provide a reasonably conservative approach for evaluating risks from igneous activity (Hill and Connor, 2000, p. 74).

5.6.2. EPRI Analysis

EPRI (2005) has adopted the PVHA (Geomatrix Consultants, 1996) mean probability value (i.e., 1.7×10^{-8} /yr) and an approximate intersection probability range of 10^{-9} to 10^{-7} per year.

5.6.3. NRC Analysis

The NRC performance assessments do not use a range of values for volcanism probability, but instead use the single-point value of 10^{-7}/yr as the probability that a volcanic conduit (extrusive scenario) could intersect a repository drift (Mohanty et al., 2004). The ACNW&M has commented (ACNW&M, 2005) that instead of using a single value of probability in performance assessments, the NRC should consider a range of estimates on the order 10^{-8}/yr to 10^{-7}/yr based on studies published by NRC (Connor et al., 2000) and previous ACNW&M views. If the staff decides to use a single-point value approach, the staff should document how this decision would support a risk-informed review of the consequences of an igneous event in a potential license application. The NRC (Reyes, 2006) responded that:

> the significance of alternative conceptual probability models can be evaluated as single values in performance calculations. By using a representative probability value as a baseline in calculations, staff can evaluate the risk significance of any available probability value by simple comparison to the baseline value. Staff continues to evaluate new data and conceptual models for igneous event probabilities developed by DOE and other scientists, as well as DOE's ongoing expert elicitation on Probabilistic Volcanic Hazard Assessment and associated field and laboratory investigations. The potential risk significance of this new information can be determined and communicated by using a combination of review methods.

The NRC's use of a constant intersection probability value of 10^{-7}/yr appears to be overly conservative – it does not represent a mean estimate but instead lies near the upper limit of most calculated probability ranges. This deterministic and bounding approach by the staff is inconsistent with the risk-informed approach used elsewhere in their Total-System Performance Assessment (TPA) for Yucca Mountain and does not provide a basis for directly reviewing the probabilistic analysis expected from DOE.

For the extrusive scenario, dose consequences are largest for events that occur soon after repository closure, while the relatively short-lived radionuclides are present in significant quantities (see Figure 39, derived from Figures 3-44 and 3-45 of Mohanty et al., 2004). Igneous events after the first 1000 years would involve reduced dose.

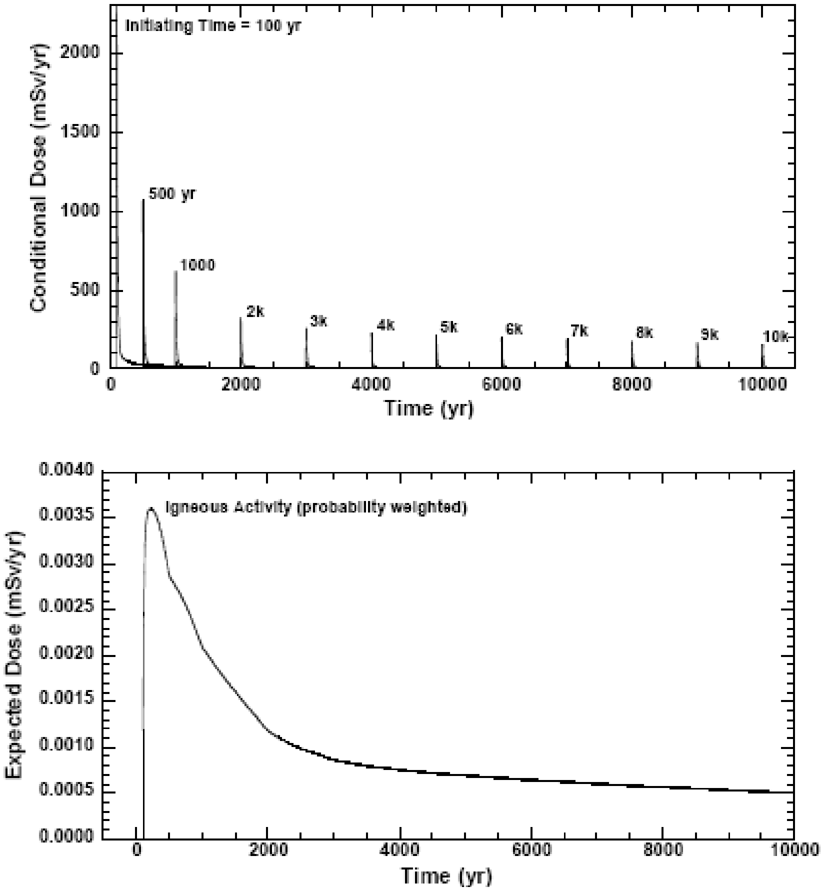


Figure 39 **Conditional dose and expected dose from extrusive igneous activity. Top frame - mean dose arising from extrusive igneous activity shown with various times for the volcanic event in 350 realizations. Lower frame - contribution of extrusive igneous activity to the total dose, weighted by an annual probability for the volcanic event of 10^{-7}/yr (After Mohanty et al., 2004, p. 3-84).**

5.7. Perspectives on Igneous Activity Probability

Table 5 presents a summary of published views on the probability of an igneous event intersecting the proposed high-level waste repository at Yucca Mountain.

Table 5 Summary of Published Perspectives on Probability of Igneous Activity.

Source	**Probability range for volcanic disruption**	**Notes**
Crowe et al. (1982)	10^{-10}/yr to 10^{-8}/yr	Based on two estimation methods: one based on rate of magma production in the Nevada Test Site area and a second using the number of volcanic vents over a specified time period.
Smith et al. (1990)	Assigned the site of the Yucca Mountain repository to risk-category 3	Based on a proposed qualitative index of volcanic risk for areas in the Yucca Mountain region. In this index, risk level 5 is highest and 1 is lowest.
Ho et al. (1991)	Probability not specified – see notes	Estimated the recurrence rate of volcanic eruption (not the probability of intersecting a repository). Values obtained: 5×10^{-6}/yr 5.9×10^{-6}/yr 5×10^{-6}/yr.
Crowe et al. (1993)	2.6×10^{-8}/yr	Median value of probability distribution.
Connor and Hill (1995)	$1\text{-}5 \times 10^{-8}$/yr	Range of 3 alternative models for probability of an eruption (volcanic conduit intersecting the repository).
Crowe et al. (1995)	1.8×10^{-8}/yr	Median value of 22 alternative probability models.
Geomatrix Consultants (1996)	1.5×10^{-8}/yr 5.4×10^{-10}/yr to 4.9×10^{-8} /yr	Expected frequency of intersection. 90% confidence interval
Ho and Smith (1997)	1.4×10^{-7}/yr to 3.0×10^{-6} /yr	Consideration of Bayesian methods.
Ho and Smith (1998)	(1) 1.5×10^{-8}/yr (2) 1.09×10^{-8}/yr to 2.83×10^{-8}/yr (3) 3.14×10^{-7}/yr	Authors presented 3 alternative models.

Source	**Probability range for volcanic disruption**	**Notes**
Wernicke et al. (1998)	Probability not specified – see notes	Yucca Mountain area experiencing epoch of anomalously rapid strain accumulation. Hazard analyses based on local geologic record may underestimate volcanism probability by an order of magnitude. Lathrop Wells may represent onset of a cluster of volcanism that could continue over the next few tens of thousands of years.
Savage (1998)	Reply to Wernicke et al. (1998)	Savage (1998) countered the claim of anomalous strain reported by Wernicke et al. (1998), and reported a N65°W strain rate of 8 ±20 nanostrain yr^{-1}. He concluded that Wernicke et al. (1998) had not included monument instability in their error budget and did not give proper weight to the effects of the 1992 Little Skull Mountain earthquake. Later work by Savage et al. (2001) continued to find that the principal extension rate is substantially less than reported by Wernicke et al. (1998), consistent with the low extension rate inferred from the geologic record.
BSC (2003a)	1.7×10^{-8}/yr 5th percentile = 7.4×10^{-10}/yr 95th percentile = 5.5×10^{-8}/yr	Revision of probability based on change in area of proposed repository footprint for License Application.
CRWMS M&O (1998)	2.5×10^{-8}/yr	Sensitivity analysis that conservatively assumes all magnetic anomalies in Amargosa Desert have Pleistocene age (less than 1.8 Ma).
Connor et al. (2000)	10^{-8}/yr to 10^{-7}/yr	Use of diffusion-based model with gravity weighting, and use of data sets that assume most magnetic anomalies represent post-Miocene basalts.

Source	**Probability range for volcanic disruption**	**Notes**
Hill and Connor (2000)	10^{-7}/yr	NRC staff considered the probability issue closed-pending based on DOE agreement to evaluate risk using this value.
Hill and Stamatakos (2002)	Up to an order of magnitude increase in the probability of volcanic disruption. Compared to Connor et al. (2000), this infers a probability up to 10^{-6}/yr	At least ten additional basaltic volcanoes may be represented by magnetic anomalies in the YMR. The first-order effect on probability models could range from negligible, to an order of magnitude increase in volcanic recurrence rates.
Smith et al. (2002)	No estimate provided, but this report cited Smith et al. (1990) and Ho and Smith (1997; 1998)	Petrologic arguments suggest that recurrence rates of volcanism used by DOE and NRC may be under-estimated. Higher rates typical of the Lunar Crater–Reveille Range volcanic zone may be applicable to Yucca Mountain. If models of hot mantle are correct, another eruption peak is possible.
ACNW&M (2002)	The range of estimated probabilities, ~10^{-9} to ~10^{-7} per year, of an intrusion into the repository used by DOE in its performance assessment is reasonable. New information from a recently completed aeromagnetic survey (2000) needs to be evaluated more fully to determine possible changes in the appropriate probability range.	ACNW&M letter dated August 1, 2002.
Detournay et et al. (2003)	No estimate provided	Analog evidence from recent (< 5 Ma) igneous events that were close to Yucca Mountain (Crater Flat and Lathrop Wells) should be given more weight than earlier or more distant events.
ACNW&M (2004)	10^{-8}/yr to 10^{-7}/yr	Letter to NRC Chairman dated November 3, 2004.

Source	**Probability range for volcanic disruption**	**Notes**
Coleman et al. (2004)	Expected value 5×10^{-8}/yr with a 95% upper bound of 1×10^{-7}/yr	Claims of high intrusion frequency (i.e., 10^{-6}/yr) fail tests of volcanic recurrence in the Yucca Mountain region; analyses conservatively assume 5-15 magnetic anomalies are post-Miocene buried basalts; model results also suggest Lathrop Wells event was not the start of a new volcanism cluster.
Mohanty et al. (2004; 2005)	1×10^{-7}/yr	Use of single value only – no probability range was used.
ACNW&M (2005)	10^{-8}/yr to 10^{-7}/yr	ACNW&M recommended that the NRC staff reevaluate the use of a single probability value for volcanic intersection and consider a range of estimates on the order 10^{-8}/yr to 10^{-7}/yr based on published NRC studies and previous ACNW&M views.
NRC (2005a)	1×10^{-7}/yr	Use of single value only – no probability range was used.
EPRI (2005)	1.6×10^{-8} /yr	EPRI (2005) adopts the PVHA 1996 probability value (the expected frequency of intersection).
Smith and Keenan (2005)	Up to 10^{-7}/yr to 10^{-6}/yr	Range that may result by adding data from future geophysical surveys and higher recurrence rates.
Reyes (2006)	No probability specified in letter – however, the baseline used in a recent NRC performance assessment (Mohanty et al., 2004) was a single value of 1×10^{-7}/yr	Response to ACNW&M (2005) letter: "As an alternative (to using a probability range), the significance of alternative conceptual probability models can be evaluated as single values in performance calculations. By using a representative probability value as a baseline in calculations, staff can evaluate the risk significance of any available probability value by simple comparison to the baseline value."

Source	**Probability range for volcanic disruption**	**Notes**
Ho et al. (2006)	No probability specified.	The authors present a strategy to evaluate “hazards areas” based on a debris-fall model developed for the space transportation industry.
Coleman and Marsh (2007)	Estimated repository dike penetration frequency of 4.2E-8/yr	Result incorporates latest data from drilling and dating of basalts; NRC PVHA model was applied using an updated Plio-Quaternary dataset reduced to 22 basaltic events (CFB_plio-quat-Mag from Connor et al., 2002); the 95% upper confidence bound was not given in the GSA abstract but is reported here as 6.0×10^{-8} /yr (based on confidence limits for expectation of a Poisson variable, given that n = 22; Pearson and Hartley, 1970).
Valentine and Perry (2007)	Did not estimate a repository intersection frequency, but based on a regression model suggested the next episode of volcanic activity somewhere in the volcanic field will occur ~270 kyr after the Lathrop Wells event (with a 90% prediction interval of ±290 kyr in consideration of the small data set).	Based on the assumption that basaltic volcanism in the SNVF will continue to exhibit tectonically controlled, time-predictable behavior with a ~0.5 $km^{3/}$Myr eruptive volume flux, the authors applied a linear regression model (time to next episode is dependent on previous episode's volume).
PVHA-Update (ongoing expert elicitation)	-----	Work by expert panel is in progress. Final report not expected until mid-2008.

5.7.1. NRC Analysis

The NRC has not adopted a preferred time period for extrapolating the future occurrence of volcanic events. However, Connor et al. (2000) state the following:

> The proposed high-level radioactive waste repository at Yucca Mountain, Nevada, is located within an active volcanic field. Probabilistic volcanic hazard models for future eruptions through the proposed repository depend heavily on our understanding of the spatial controls on volcano distribution at a variety of scales. On regional scales, Pliocene-Quaternary volcano clusters are located east of the Bare Mountain fault.

> Extension has resulted in large-scale crustal density contrast across the fault, and vents are restricted to low-density areas of the hanging wall. Finite element modeling indicates that this crustal density contrast can result in transient pressure changes of up to 7 MPa at 40 km depth, providing a mechanism to generate partial melts in areas where mantle rocks are already close to their solidus. On subregional scales, vent alignments, including one alignment newly recognized by ground magnetic mapping, parallel the trends of high–dilation tendency faults in the Yucca Mountain region (YMR). Forty percent of vents in the Yucca Mountain region are part of vent alignments that vary in length from 2 to 16 km. Locally, new geological and geophysical data show that individual vents and short vent alignments occur along and adjacent to faults, particularly at fault intersections, and leftstepping *en echelon* fault segments adjacent to Yucca Mountain. Conditions which formed these structures persist in the YMR today, indicating that volcanism will likely continue in the region and that the proposed repository site is within an area where future volcanism may occur. On the basis of these data the probability of volcanic disruptions of the proposed repository is estimated between 10^{-8}/yr and 10^{-7}/yr.

Hill and Connor (2000, p. 74) state the following:

> Prior to the August 2000 Technical Exchange with the DOE, staff had identified 12 specific technical concerns regarding the probability subissue....To address these concerns, the DOE agreed to resolve the probability subissue by providing in the Site Recommendation and License Application, in addition to DOE's licensing case, the results of a single point sensitivity analysis for extrusive and intrusive igneous processes at an annual probability of 10^{-7}. By agreeing to provide these analyses, staff consider the probability subissue closed-pending, because the 10^{-7} analyses provide a reasonably conservative approach for evaluating risks from igneous activity.

Hill and Stamatakos (2002, p. xi) state the following:

> The U.S. Geological Survey recently completed a large-scale aeromagnetic survey of the Yucca Mountain region. Interpretations of this survey and associated Center for Nuclear Waste Regulatory Analyses ground magnetic surveys indicates there may be twice as many basaltic volcanoes in the Yucca Mountain region than previously recognized. Additional volcanoes also may be present but undetected within approximately 20 km [12 mi] of the proposed repository site due to relatively low resolution of the aeromagnetic survey. Without direct information on the age and composition of these buried volcanoes, associated effects on probability models and risk calculations are highly uncertain. The potential risk significance of this uncertainty ranges from negligible to an order of magnitude increase in the probability of volcanic disruption of the proposed repository site. This uncertainty can be reduced through drilling of anomalies likely to be caused by buried basalt, and to a lesser extent by additional ground magnetic surveys. At present, the range of uncertainty in these interpretations and associated new information clearly exceeds uncertainties and information considered by the U.S. Department of Energy (DOE) during probability model development in 1995. An update to the DOE probability elicitation appears necessary for acceptable use in licensing.

5.7.2. DOE Analysis

The DOE has primarily adopted the Plio-Pleistocene time period for extrapolation of events, consistent with the approach by the majority of members of the 1996 PVHA expert panel. Several members of that panel considered the Pleistocene to be the preferred time period for extrapolation. BSC (2003a, p. 113) states the following:

> The result of the PVHA [Geomatrix Consultants, 1996] has been recalculated using PVHA outputs to account for the proposed LA repository footprint (the outline of the waste emplacement area) and extended to include the probability of an eruption within the proposed LA repository footprint, conditional on a dike intersection. A conceptual framework for the probability calculations, based on PVHA outputs and subsequent studies, accounts for deep (mantle) and shallow (structural control) processes that influence volcanic event distribution and recurrence rate in the YMR [Yucca Mountain region]. The framework presented here emphasizes the close correlation between the distribution of volcanic events and areas of crustal extension and faulting in the YMR, and within this context, the appropriateness of volcanic source zone boundaries defined in the PVHA. It also emphasizes the appropriate selection of parameter distributions that affect probability models and provides support for comparison of alternative scenarios and parameter selection, within the framework of the volcanic history of the YMR. Alternative models presented by Connor et al. (2000) that result in higher eruption probabilities (10^{-7} versus 1.3×10^{-8} per year) than those presented here are found to employ input parameters that either represent extreme values (e.g., event length) or assume a specific geologic control (i.e., crustal density) on spatial distribution while not considering more defensible and observable controls (i.e., crustal extension and structure). Spatial density models weighted by crustal density result in higher event frequencies at the proposed repository site, while the same models weighted by an alternative geologic control such as cumulative crustal extension across the Crater Flat structural domain would likely lead to decreased event frequencies at the site. Connor et al. (2000) state that the highest value (10^{-7} per year) in their range of calculated probability values (10^{-8}–10^{-7} per year) cannot be considered more or less likely than any other value they have calculated using alternative probability models. The analysis in this report suggests that the choice of input parameters used by Connor et al. (2000) compared to those used in the PVHA logically places their highest probability value at the extreme upper tail of a probability distribution.

The DOE (2003, p. 2-9) states the following:

> In summary, the areas of greatest likelihood for future volcanic activity in the region are those where previous volcanism has occurred, and where extensional deformation has been and continues to be greatest, (i.e., the southwestern part of the Crater Flat structural domain) (Figure 2-5) (Geomatrix Consultants, 1996, pp. RC-5, BC-12, AM-5, MS-2, GT-2, and expert zone maps). Analysis by the U.S. Nuclear Regulatory Commission (NRC) also indicates that the highest likelihood of future volcanic activity is in southwestern Crater Flat (Reamer, 1999 [Sections 4.1.5.4 and 4.1.6.3.3; Figure 28]). The southern and southwestern part of the Crater Flat basin is the most extended (Ferrill et al., 1996; Stamatakos et al., 1997; Fridrich et al., 1999) and is the locus of post-Miocene volcanism (Fridrich et al. 1999; Reamer, 1999). Therefore, the volcanic source zones defined in the PVHA (Geomatrix Consultants, 1996 [Figure 2-5]) are consistent with the tectonic history and structural features of the Crater Flat structural domain.

5.7.3. Probabilistic Volcanic Hazard Analysis (PVHA)

The Probabilistic Volcanic Hazard Analysis (Geomatrix Consultants, 1996, p. 4-14) states the following:

> The results of the PVHA analysis are that the aggregate expected annual frequency of intersection of the repository footprint by a volcanic event is 1.7×10^{-8}, with a 90-percent confidence interval of 7.4×10^{-10}/yr to 5.5×10^{-8} after adjustment for the change in size of the repository footprint. The median value without adjustment for the footprint size is 9×10^{-9}/yr. The major contributions to the uncertainty in the frequency of intersection are the statistical uncertainty in estimating the rate of

> volcanic events from small data sets and the uncertainty in modeling the spatial distribution of future events. Although there are significant differences between the interpretations of the 10 experts, most of the uncertainty in the computed frequency of intersection is due to the average uncertainty that an individual expert expressed in developing the appropriate PVHA model.

5.7.4. DOE Igneous Consequence Peer Review (ICPR) Panel

The ICPR panel did not evaluate the probability of future volcanism at Yucca Mountain. However, they did provide conclusions and recommendations that relate to evaluating probability.

Detournay et al. (2003, p. 19-20) state the following:

> There are ten known unburied eruptive vents in the Yucca Mountain region younger than 5 Ma, and seven buried volcanoes were identified in aeromagnetic surveys up to 1995. This gives a sum of 17 volcanic events over the past 5 Ma, assuming, for illustrative purposes, each anomaly represents an independent volcanic event. If the magnetic anomalies recently identified (Blakely et al., 2000; O'Leary et al., 2002) represent buried basalt flows or tephra deposits that are less than 5-Myr old, then the total number of post-Miocene vents is ~30, roughly double previous estimates. If all of the most recently identified aeromagnetic anomalies are relatively young (e.g., ~ 0.5 Ma to 1 Ma) with eruptive volumes ~ 0.05 km^3, then eruption probabilities would increase significantly. Alternatively, if the buried volcanics are at the opposite end of the age spectrum (e.g., 2 Ma to 4 Ma), the probability picture changes — although not dramatically, provided volumes associated with individual anomalies are ~ 0.05 km^3 or less. Finally, if all buried volcanics (magnetic anomalies) are pre-Pliocene, eruption probabilities change little. A preliminary conclusion is that until better information regarding the number, volume and the age distribution of buried basaltic lavas and tephra is available, it will be difficult to know how to adjust estimates of volcanism rate and recurrence interval most relevant to disruptive igneous activity at the proposed Yucca Mountain region. One of the recommendations of this Panel is that further attempts be made to define the ages and volumes of the buried magnetic anomalies.

Detournay et al. (2003, p. 20) also state the following:

> High-precision geochronological information would enable better estimates of volcanic recurrence rates at Crater Flat relevant to igneous consequences at the proposed YMR at relatively modest cost. This issue could be clarified, or at least significantly better constrained, by an intensive high-resolution geochronological program.

Detournay et al. (2003, p. 76) state the following:

> As far as the range of quantitative characteristics of the igneous event considered is concerned, we have reviewed all the literature available and conclude that the approach adopted so far — namely, that the analog evidence from recent (< 5 Ma) igneous events that have occurred close to [Yucca Mountain] (Crater Flats, Lathrop Wells) be given more weight than earlier events or those further afield — is entirely reasonable. We recommend that further high-resolution geochronological work be performed to better constrain the ages of exposed Pliocene and Quaternary basalts in Crater Flat as well as possible basaltic volcanic rocks identified by aeromagnetic studies.

Detournay et al. (2003, p. 77) state the following:

> The probability that a violent erupting mixture could follow dogleg conduits, thus potentially entraining a larger number of waste packages, is, in our opinion, small and is more than offset by the level of conservatism built into the existing estimates ... The Panel has not been able to quantify the probability of a dogleg conduit in any rigorous fashion, nor its effect on waste packages. The opinion expressed ... above was arrived at by combining our separate independent views of where the upper limits would lie.

5.7.5. EPRI Analysis

EPRI (2005, p. vii) state the following:

> There is evidence of volcanic centers near the proposed site at Yucca Mountain, Nevada for a geologic repository for the disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW). This evidence indicates that potential future igneous activity (i.e., an “igneous event scenario”) may be a factor in the assessment of post-closure risk for the proposed repository. In 1996, a panel of independent technical experts for the Yucca Mountain Project’s Management and Operations (M&O) contractor … conducted a study, the Probabilistic Volcanic Hazards Analysis (PVHA) study, that estimated a mean annual probability of an igneous event occurring at/near the Yucca Mountain site at 1.6 x 10-8/year [Geomatrix Consultants, 1996]. This probability, though extremely low, fell just above the 1.0 x 10-8/year regulatory threshold that had been established for the dismissal of extremely low probability events.

EPRI (2005, p. viii to ix) state the following:

> The objectives of this report, which is a companion to EPRI (2004a), are to analyze the intrusive-release case and determine the potential impact on repository performance and safety, expressed as probability weighted mean annual dose rate, for the latter scenario. EPRI’s analyses contained in this report adopt the igneous event probability of 1.6 x 10^{-8}/year previously derived by the Probabilistic Volcanic Hazards Analysis (PVHA) panel [Geomatrix Consultants, 1996]. The analyses also reflect recent data on basaltic eruptive centers in the Yucca Mountain region that support the conclusion that relatively low-temperature (~1010°C), high viscosity basaltic magmas, as opposed to the ~ 1200°C magmas postulated by the DOE, are the most representative characteristics of future igneous events. Lower temperature implies lower and less prolonged thermal-perturbation of the host rock and contacted waste packages, and magma of much higher viscosity. The high viscosity supports the contention that such magma will only partially penetrate into emplacement drifts intersected by the magmatic dike, thereby only impacting a limited number of waste packages.

5.7.6. State of Nevada Contractors

Smith et al. (1990) introduced a risk rectangle concept that suggests that future volcanism will occur either to the northeast or southwest of existing volcanoes in the Yucca Mountain region. This view relies heavily on the concept of volcanic chains and the northeast alignment of volcanoes.

Smith et al. (1990) state the following:

> The proposed area of most recent volcanism (AMRV) includes all known post-6 Ma volcanic complexes in the Yucca Mountain area and encompasses the four volcanic centers in Crater Flat, the Lathrop Wells cone, several centers in southeast Crater flat, two centers at Sleeping Butte, and a center at Buckboard Mesa within the moat of the Timber Mountain Caldera. The delineation of high-risk zones for volcanism

within the AMRV is an important goal in any risk assessment study. The dimensions and orientation of high-risk zones were based on structural and volcanic chain length data obtained by detailed studies of Plio-Pleistocene volcanic centers in the Yucca Mountain area. Analog studies of Pliocene volcanic centers in the Fortification Hill field (Lake Mead area, Arizona and Nevada) and the Reveille Range (south-central Nevada) were also used to establish the nature of structural control of volcanic vents and to determine the lengths of volcanic chains. Two high-risk rectangles were constructed at each cluster of Quaternary centers. The smaller-dimension rectangle is 12 km long and 1 km wide and is equivalent to the dimensions of the Crater Flat chain. The larger-dimension rectangle is 25 km long and 3 km wide and is equivalent to the dimensions of volcanic chains in the Fortification Hill field and the Reveille Range. Based on geologic studies and the high-risk rectangles, five risk levels were defined with risk level 5 representing the highest relative risk and 1 the lowest. Based on this risk scale, the site of the proposed high-level nuclear waste repository is assigned to risk-category 3.

Bradshaw and Smith (1994) state the following:

Alkali basalts erupted during the Quaternary at Crater Flat, Nevada, record a complex history of polycyclic and polygenetic volcanism. Magmas from the two main centers (Black Cone and Red Cone) are petrographically and geochemically similar, although field evidence suggests a number of separate emptive events. High incompatible element concentrations, low Nb/La and high Zr/Y indicate that the magmas were derived by small degrees of partial melting from the lithospheric mantle. At Red Cone, a significant range of Sr, La, Ce, Ba and Th concentrations is observed with time (e.g.. Sr range 1308-1848 ppm): the youngest samples having the more elevated values. However, there is only limited variation in the compatible trace elements (e.g., Sc and Ni). The array of compositions at Red Cone could not have been produced by changes in the degree of partial melting, or by fractional crystallization. Rather, a model of magma mixing is proposed between relatively enriched and depleted end-members. The cluster of Black Cone data falls consistently at the least-enriched end of the Red Cone sample arrays, suggesting that the Black Cone magma represents one of the mixing end-members. The modeling indicates that the magmatic plumbing systems of the two centers were linked, at least during the early stages of volcanism. Moreover, volcanic activity may have occurred at a number of sites along the length of the magmatic feeder zone during a single eruptive phase. This could have significant implications for volcanic hazard assessment' in the region around Yucca Mountain, and the proposed nuclear waste repository.

Ho et al. (1991, p. 56) state the following:

At this preliminary stage of our work, all we can conclude is that the probabilistic results of Crowe et al. (1982) are based on idealized model assumptions, a premature data base, and inadequate estimates of the required parameters. For the reasons discussed, we think that Crowe et al. underestimate the risk of volcanism at the proposed Yucca Mountain repository site.

Ho and Smith (1998, p. 508) state the following:

The instantaneous temporal recurrence rate (at present time) estimated from a PLP [power-law process] is about 5.9×10^{-6}/year. Thus, the combined temporal-spatial recurrence rate calculated for the 3-D NHPP [non-homogeneous Poisson process] is between 1.36×10^{-9} and $3.54 \times 10^{-9}/(\text{year} \times \text{km}^2)$. The recurrence rate obtained based on a 3-D HPP [homogeneous Poisson process] (= 1.88×10^{-9}) is in this interval. For this study, the estimated overall probability of at least one disruption of a repository at the Yucca Mountain site by basaltic volcanism for the next 10,000 years (= hazard) is: 1.5×10^{-4} for a 3-D HPP; 1.09×10^{-4} to 2.83×10^{-4} for a 3-D NHPP if λ_s

> [recurrence rate] is estimated as 2.3×10^{-4} to 6.0×10^{-4}; and 3.14×10^{-3} for a Bayesian approach. We also note that the hazard based on an HPP and an NHPP are very comparable as long as the area of the sample region A (was estimated as 1953 km^2 for the 3-D HPP) is bounded between 1035 km^2 and 2701 km^2.

Smith et al. (2002, p. 9) state the following:

> A knowledge of recurrence rates is crucial to the calculation of probability of magmatic disruption. We contend that there is more uncertainty in recurrence rate estimates than assumed by the DOE, the expert panel, and the NRC. Our petrologic data suggest that volcanic fields in the Crater Flat–Lunar Crater zone are linked to a common area of hot mantle. Also, we show that volcanism is episodic with a good possibility of a new peak of activity occurring in the future. These observations imply that volcanism is not dead in the Yucca Mountain area and that a future pulse of activity could have recurrence rates equivalent to those recorded in the Lunar Crater–Reveille area of the Crater Flat–Lunar Crater zone. Specifically, the DOE and the NRC have used recurrence rates of from 3.7 to 12 events per m.y. to calculate probability of volcanic disruption (Connor and Hill, 1995; Crowe et al., 1998; Connor et al., 2000). Based on our arguments, recurrence rates of 11 to >15 events per m.y. are possible. Because higher recurrence rates raise the likelihood of magmatic disruption of the repository, we recommend that future probability studies factor these higher rates into probability models.

Smith and Keenan (2005, p. 317-321) state the following:

> Perry et al. [2004] speculated that the 20 additional volcanic centers discovered by the aeromagnetic surveys would raise the probability of site disruption by about 40%. This number is a minimum figure because the surveys do not cover the entire area.

Volcanic recurrence rates for the RLC (Reveille–Lunar Crater) are as high as 12 events per million years, four times the rate calculated for the Yucca Mountain area. These figures are minimum estimates because only 70% of the volcanic centers in the RLC are dated.

A linkage between Yucca Mountain and RLC implies that higher recurrence rates may occur in the Yucca Mountain area. Adding data from future surveys of uncovered areas and higher recurrence rates may result in a probability of disruption 1–2 orders of magnitude greater than the EPA standard. A longer health standard, as ordered by the U.S. Court of Appeals, makes a disruptive event during the period of compliance even more likely." In this article by Smith and Keenan (2005), they imply that using higher recurrence rates and adding data from future aeromagnetic surveys may result in a probability of disruption of up to 10^{-6}/yr.

5.7.7. Nuclear Energy Institute (NEI)

The Nuclear Energy Institute issued a policy statement (NEI, 2006) titled "Common Objections to the Yucca Mountain Project, and What the Science Really Says." This policy statement gave frequently cited objections to the Yucca Mountain project and the NEI response based on scientific analysis. For volcanoes (igneous activity), the cited concern is that "A volcano could erupt through the repository."

The NEI position is as follows:

- A volcanic eruption that affects the repository is a highly improbable event.
- There has not been a single volcanic eruption through Yucca Mountain in 10 million years.

- Millions of years of history show that the region surrounding Yucca Mountain is becoming less volcanically active with time.
- Nevertheless, NRC is requiring that DOE analyze the consequences of such an event and include this analysis in the repository performance assessment.
- The volcano itself is likely to cause more harm than any radiation it might release.

5.7.8. Other Estimates of Probability

Crowe et al. (1982, p. 185) state the following:

> The calculated probabilities of volcanic disruption of a high-level radioactive waste repository buried within the Yucca Mountain site of the NTS area are exceedingly small (range calculated for a one year time period of 10^{-8} to 10^{-10}). These values provide a numerical expression of the low past rates of volcanism in the region. However, there are several precautions that must accompany the calculations: First, they assume that volcanism is a random process although geologic studies on a global scale have shown that volcanism is commonly nonrandom in both space and time. We have attempted to compensate for this shortcoming by restricting the calculation parameters to a defined volcanic province and by developing a method for determining the area ratio (a/A) based on the distribution of volcanic centers. Second, calculated rates of volcanic activity (λ) are averaged over a time scale of millions of years. They are therefore relatively insensitive to short-term variations in rates of volcanism. Such short-term variations may be less than or on the order of the required containment period of waste elements. Third, the calculated rates of volcanism are based on the past record of volcanism and not on a complete understanding of the future controlling processes of magma generation. They were calculated from a limited number of data points and are projected into the future assuming future rates will be the same as in the past. Some degree of confidence can be placed in this projection however due to the relatively uniform rate of volcanic activity in the NTS region for the last 6 to 8 m.y.

Coleman et al. (2004, p. 3) also state the following:

> Analysis indicates that a dike intersection rate of 10^{-6}/yr (one expected per million years) is unrealistically high. If this rate prevailed in the last million yrs, an expected 40 to 96 volcanoes would have erupted in the YMR (or 80–192 without gravity weighting). This far exceeds the 8 events known to have occurred in all of the Pleistocene (1.8 Myr), yielding a recurrence rate of only 4.4 per million years. Dividing these numbers by 10 reduces the time scale to 100,000 years. This time scale is especially interesting because we can test whether the youngest-known volcanic event in the region, Lathrop Wells, began a new pulse of volcanism, as suggested by Wernicke et al. (1998). For a dike penetration rate of 10^{-6}/yr, the PVHA results indicate 4–10 (8–19 without gravity weighting) volcanic events would have been expected in the YMR in the last 100,000 yrs. Only one is known. We conclude that claims of high intrusion frequency fail tests of volcanic recurrence in the YMR at time scales of 10^6 and 10^5 yrs.
>
> We consider that spatial and temporal patterns of Pleistocene volcanism provide the best available representation of trends in recent geologic time... If future volcanism follows this pattern, the expected frequency of dike intersection is 5.4×10^{-8}/yr using the PVHA_YM code with zero gravity weighting, file ‘‘Quaternary_8events,’’ and a recurrence rate of 4.4×10^{-6}/yr (8 events in 1.8 Myr). Considering the statistical uncertainty of the frequency based on eight events, a 95% upper confidence bound for the intersection frequency is 9.8×10^{-8}/yr [Pearson and Hartley, 1970]. The recurrence rate would be even smaller if some of the Pleistocene events in Crater Flat represent fewer events.

> We agree with Connor et al. [2000] that rates of basaltic volcanism at Yucca Mtn. (i.e., ~2–12 events/Myr) have not been comparable to recurrence rates in more active zones, such as the Cima volcanic field, CA (i.e., ~30 events/Myr). Our analysis raises doubts about claims that a potential repository could be penetrated by a basaltic dike with a frequency as high as 10^{-6}/yr (on average, one per million years). Such claims fail simple tests at four time scales. Furthermore, spatial-temporal models that predict future penetration frequencies >2 × 10^{-7}/yr are overly pessimistic, based on nondetection of dikes in the potential repository footprint.

Organization for Economic Cooperation and Development (OECD, 2002, p. 15), in its joint report by the NEA and the IAEA, states the following:

> 3.3 Disruptive events and human intrusion Disruptive events — Volcanism at Yucca Mountain is a very low probability event. With regard to volcanism, more explosive rhyolitic eruptions can occur at the same time as basaltic eruptions (so-called "bimodal volcanism"). That was not discussed in the TSPA-SR. It is recommended that the probability of bimodal basaltic-rhyolitic volcanism be estimated and, if relevant, the consequences be analyzed. The IRT considers that the TSPA-SR adequately addresses seismological influences and finds the analysis in line with other international studies.

Although this peer review made this recommendation, available evidence points to the fact that the silicic volcanism that spawned multiple calderas and formed the surface rocks at Yucca Mountain had already ended by late Miocene time.

5.7.9. ACNW&M Observations of PVHA-U

The panelists participating in PVHA-U are incorporating new information available since 1996 in their estimates, including interpretations based on lithostatic pressure variations and geochemical analyses. Based on the ACNW&M's observations of PVHA-U proceedings, most panelists appear to be placing greater emphasis on Pleistocene events rather than on older events. Eruption cycles are being discussed, and fewer hidden events are now being considered based on the results of drilling of anomalies.

5.8 Summary (Igneous Event Probability)

The rocks that comprise Yucca Mountain record an integrated tectonic-volcanic history since the ~13 Ma old surface rocks were deposited. No basaltic dikes have been found in the potential repository footprint at Yucca Mountain despite more than 25 years of intensive site characterization studies. It appears that the northern part of the fault-bounded block that forms Yucca Mountain has been a zone of relative volcanic quiescence during the last 10 Myr. Since that time volcanism has instead mainly focused within the alluvial basins to the east, west, and south, with no evidence of post-Miocene activity (younger than ~5 Ma) east of Yucca Mountain in Jackass Flats.

The volume of basaltic volcanism near Yucca Mountain has dramatically declined during the last 10 Myr such that the Crater Flat basin volcanic field represents a zone of low activity compared to other volcanic fields in the region (e.g., Lunar Crater-Reveille Range, NV, Cima, CA, and Springerville, AZ). This decline suggests that magmatic systems near Yucca Mountain are waning. Further evidence of this lies in the declining maximum lava effusion rate and fissure length of Plio-Pleistocene basaltic activity in the Yucca Mountain region. There are no precursory indicators that volcanic activity is likely in the immediate future in the region.

Results of recent drilling on magnetic anomalies following completion of the 2004 aeromagnetic survey have not yet been incorporated into published estimates of the probability of igneous activity intersection of the proposed repository. However, the information from the drilling will reduce some of the uncertainty about the number and age of buried basalts and will influence the statistical-mathematical models used in determining evaluating probability.

Both DOE and EPRI currently rely on probability estimates from the 1996 PVHA expert elicitation (i.e., ~2 × 10^{-8}/yr). This PVHA is now being updated with new information but published results will not be available until 2008. In response to NRC concerns, the DOE has agreed to provide (along with their licensing case) the results of a single point sensitivity analysis for extrusive and intrusive igneous processes at a repository intersection probability of 10^{-7}/yr. The NRC considers that the 10^{-7}/yr analyses will provide a reasonably conservative approach for evaluating risks from igneous activity. However, using a single point value fails to capture the impact of the uncertainty in probability estimates inherent to a performance assessment and could significantly limit the usefulness of the results and the risk-informed insights that can be gleaned from such an analysis.

The State of Nevada contractors suggest that the probability of future volcanism may be at least an order of magnitude higher based on temporal clustering of volcanic activity, hypothetical linkages between volcanism in the Crater Flat basin and the Lunar Crater-Reveille Range area, and incorporation of new data that they recommend be acquired in regions beyond the latest aeromagnetic survey. However, claims of frequent recurrence of volcanism much higher than the PVHA results are inconsistent with the small number of events known to have occurred during the past 5 million years. If the probability of repository intersection were 10^{-6}/year, many (~40 to 192) eruptions should have occurred in the Yucca Mountain region in the last million years, and approximately four to 19 eruptions should have occurred in the last 100,000 years (Coleman et al., 2004). However, only 8 events are known to have occurred over the past 1.8 million years and only one occurred in the last 100,000 years. No volcanism has occurred near Yucca Mountain since the eruption of the Lathrop Wells volcano 80,000 years ago and no post-Miocene (< 5.3 Ma) volcanism is known to have occurred at the Yucca Mountain site or in Jackass Flats.

A probability range for repository disruption of 10^{-9}/yr to 10^{-7}/yr is consistent with most previous studies (Figure 40), the observed rate of Pleistocene volcanic activity (8 events in the Yucca Mountain region in 1.8 Myr), and the latest drilling results which reduce the number of suspected buried basalts of post-Miocene age. It is significant that no post-Miocene basalt was found in drilling magnetic anomalies in Jackass Flats. If buried Pliocene basalts had been found there, that would suggest that the Plio-Pleistocene volcanic zone of Crater Flat basin extends through Yucca Mountain significantly affecting the spatial models of volcanism and increasing the modeled probability of future repository intersection.

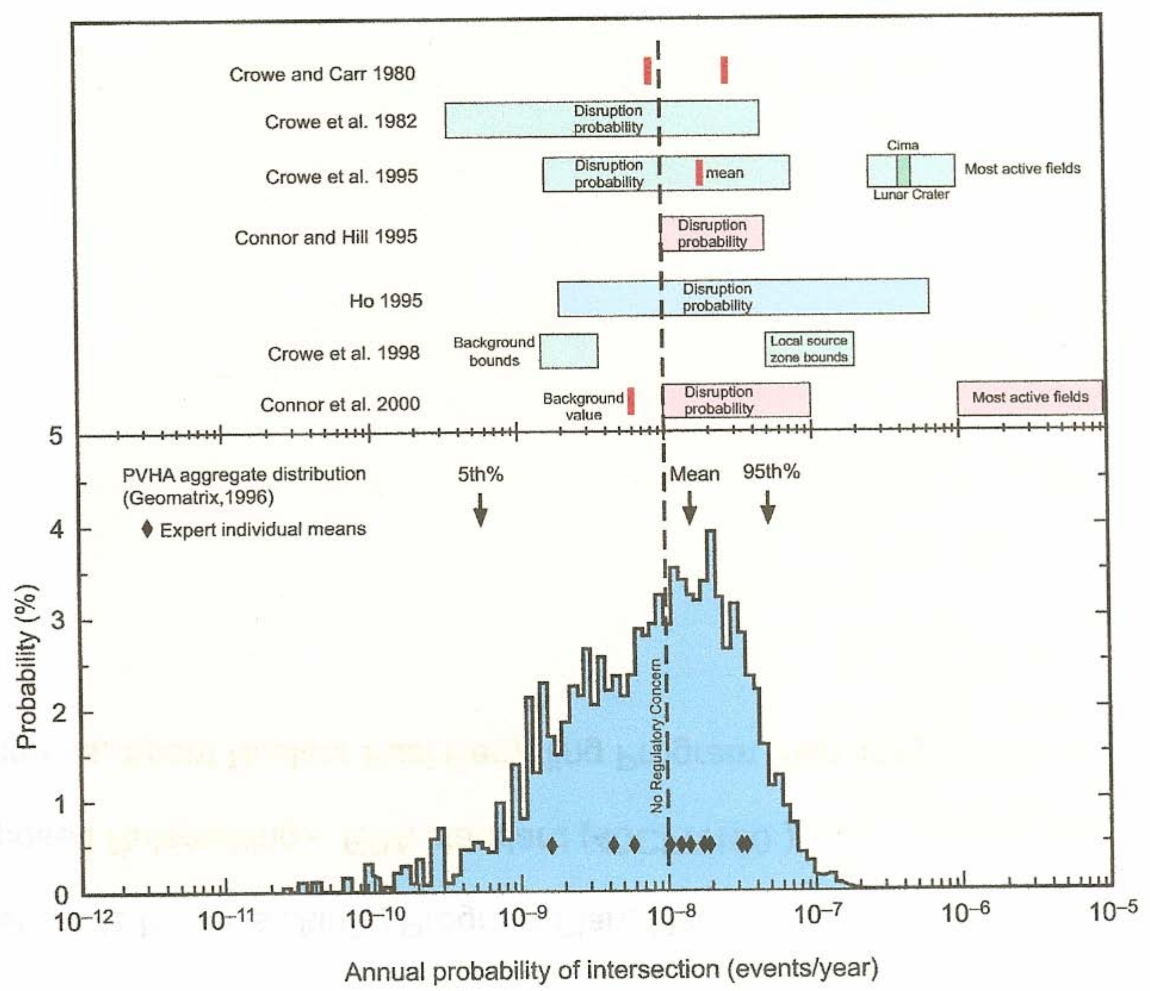


Figure 40 Comparison of selected estimates of the probability of future volcanic intersection of a repository at Yucca Mountain (from Perry et al., 2000).

6. Consequences of Igneous Activity Intersecting the Repository

6.1. Introduction

This chapter will discuss the final question of the risk triplet: If the repository is intersected, what are the consequences of the igneous activity to the repository and to the stored HLW, and what is the impact of its potential release to the environment upon humans? The consequences for future radiological exposures vary significantly among the hypothetical scenarios for volcanic interaction with the repository (described in previous sections). They include an intrusive event, an extrusive (volcanic) event, and secondary breakouts of magma from a repository at some distance from the point of initial intersection (the "dogleg" scenario). The logic flow charts, Figure 5 and Figure 6, show the components that enter into consideration of these scenarios. The dogleg scenario is a variation of the intrusion scenario which results in a secondary volcanic eruption. As mentioned already, the potentially critical effects of quenching and solidification on waste packages and drift walls have yet to be fully evaluated by the DOE and NRC. However, they do have the potential to limit the distance that magma can penetrate into drifts, making the "dogleg" scenario much less likely to occur than the other scenarios.

6.2. Effects from an Intrusive Event (Magma/Drift/Waste Interaction)

Many quantitative studies have been published on the basaltic magma involved in igneous activity at Yucca Mountain. Discussed here are only those studies most pertinent to the present analysis of magma invading a repository drift.

6.2.1. Critical Magmatic Aspects

To evaluate the impact of a basaltic dike intersecting the proposed repository, the magma type, approximate composition, volatile content, and viscosity must be known or estimated.

6.2.1.1. Magma Composition

The composition of the magma likely to erupt at Yucca Mountain is best estimated from nearby eruptive examples that have occurred in this region over the past 10 Myr. Each interested party has used this approach in specifying the most likely future magma type, and has assumed that the most likely magma will be alkali basalt. For example, decisions made with regard to the magma type and composition state the following:

> The base case chemical composition of basalt…was derived…through analysis of 45 samples taken from the Lathrop Wells Cone. The Lathrop Wells Cone is the youngest volcanic center in the Yucca Mountain region, and, therefore is considered an adequate analog for the composition of a possible igneous intrusion into Yucca Mountain. (BSC, 2004, p.4-6)

and

> Magmas in the Yucca Mountain region are typically alkali basalts. (EPRI, 2003, p. 2-9)

On the subject of magma volatile content, all parties have used petrologic indicators in the nearest erupted lavas (e.g., Lathrop Wells) to estimate indirectly the pre-eruptive volatile content of the magma. The presence of the mineral phase amphibole in lavas at Crater Flat indicates a magma temperature at or below 1050°C that, coupled with an overall low phenocryst content, suggests the magma was near its liquidus temperature. Magma water content had to have been in the range of about 1-4 wt.% for basaltic magma to have such a low liquidus temperature. Hence, the following assessments are made:

> No magmatic water has a zero probability of occurrence. This statement reflects our knowledge that very low volatile contents are rare. With 1 to 3 percent magmatic water, the probability should be uniform, reflecting that this is the most likely range of water contents. The probability should decrease linearly between 3 and 4 wt.%, so that it is zero at 4 wt.%, representing the expectation that at about 4 wt.%, basaltic magmas will crystallize before reaching the surface to erupt." (DOE, 2000, p. 54)
>
> H_2O concentrations in the range 2.5 wt to 4 wt.% with bulk mass H_2O/CO_2 ratios around 6-20 are representative." (Detournay et al., 2003, p.16)
>
> These basalts may have water contents of 0-4 wt.% and a wide range of thermo-mechanical properties that reflect the water content and bubble (void) fraction." (EPRI, 2003, p. 2-9).

The context of the last quote from EPRI is that the magma involved may be understood as a range of processes to contain the stated amounts of water. That is, the original magma may contain 4 wt.% water, but upon degassing it may as a lava, for example, contain far less water.

It is also important to note that, besides water, basaltic magmas typically contain significant amounts of CO_2 and SO_2 and lesser amounts of fluorine and chlorine. There are no reliable straightforward methods to estimate the pre-eruption concentrations of these volatile species, although enough is understood about CO_2 in basalt to know that the ratio of H_2O to CO_2 is commonly in the range of about 6 to 20. Nicholis and Rutherford (2004) have investigated the range of estimates of water content through experimental phase equilibria studies using a sample of Lathrop Wells lava.

In summary, the type of magma likely to erupt in the future at Yucca Mountain, and its chemical composition and volatile content are agreed upon. Of these three features, the exact basalt type and chemical composition are not of great importance, but the volatile content is important to know well for several reasons, including characterizing the style of the eruption and gauging the rheology of the lava that may enter the repository drifts.

6.2.1.2. Magma Viscosity

In the present context, there is no other magma property more important to know than viscosity. To clarify, this is the usual viscosity characterizing viscous shear flows and is sometimes denoted as the shear viscosity, or Newtonian viscosity, as opposed to the bulk viscosity, which is associated with volumetric expansion of fluids as in the work associated with adiabatic expansion.

There is no single value of viscosity that can be used to characterize the probable entire magmatic process at Yucca Mountain. There are at least four distinct phases of the magma, each of which will have a characteristic viscosity even though the viscosity will vary continuously from one phase to another. Because the solubility of water in magma increases strongly with pressure or depth, at depths greater than about 6 km the anticipated magma will be undersaturated in water and will be a single fluid phase with a viscosity of about 5 Pa·s

(50 poise, see below). Bubbles will form as the magma ascends and becomes saturated in water, and this magma will be described by a second viscosity. The magma itself at this stage is still a basalt containing a dispersed collection of bubbles. With continued ascent, the bubble or gas phase becomes volumetrically the dominant or continuous phase with dispersed fragments of quenched magma, which is characterized by a third viscosity (see

Figure 41 A). If the magma ascends under conditions conducive to allow extensive and continuous degassing, and it extrudes as lava, this lava will be characterized by a fourth viscosity (see Figure 41B). In addition, within each of these phases, temperature and crystallinity, particle content, or bubble content will have a significant effect on viscosity.

The approach of all parties has been to estimate viscosity from the bulk chemical composition of the given basaltic magma at its liquidus temperature and the estimated amount of water. The most important factors governing magma viscosity are chemical composition (especially silica content), temperature, water content, and crystal content. Water and crystallinity have strong effects on viscosity. Water lowers viscosity, and crystals increase viscosity. Bubbles can raise or lower viscosity depending mainly on their size. The effects of other volatile species are mixed and, at the concentrations expected, are not likely to be major factors in affecting viscosity. The effect of crystals has generally been ignored in the Yucca Mountain studies primarily because the associated lavas (e.g., Lathrop Wells) contain only ‘sparse’ amounts of phenocrysts, which are relatively large (~ 1 mm) conspicuous crystals that grew at depth long before eruption. In contrast to phenocrysts, groundmass crystals are very small and grow in response to the sudden cooling or quenching attending various aspects of eruption.

The paucity of phenocrysts found in the lavas of the nearby basaltic magmas suggests the pre-eruptive state of these magmas was at a temperature near the liquidus (~1000°C) and the magma contained 2-4 wt.% water. Given these conditions, it is straightforward to estimate viscosity using a number of reliable models. The viscosity of this pre-eruptive magma is generally in the neighborhood of 5 Pa·s (50 poise), although there is significant disagreement. This issue should be evaluated further.

Detournay et al. (2003 [Appendix A2.6.1]) give a detailed discussion of magma rheology at various stages in the eruption sequence, especially during the critical eruptive stages when the magma is saturated with vapor and contains bubbles. In terms of rheology, the central issue is the behavior of the bubbles and their size. Small bubbles act as rigid spheres and increase viscosity, sometimes to the point of introducing non-Newtonian behavior. Large bubbles are deformable and, in effect, act to lubricate the magma, thus reducing viscosity. The quantitative difference between small and large bubbles is measured by the *capillary number* (Ca), which is a relative measure of the energy (i.e., work) of viscous shear relative to the interfacial surface energy (σ) between vapor and magma. That is, viscous work is measured by the product of the local shear or strain rate (G), a characteristic length scale, which is given by bubble radius (r_b), and magma viscosity (μ). The capillary number is then given by $Ca = G\ r_b\ \mu/\sigma$. The effect of bubble concentration as a function of Ca on the relative viscosity of the magma is given in Figure 42. Relative viscosity (μ_r) is the ratio of the viscosity of the mixture of melt and bubbles (often called the psuedofluid) relative to the viscosity of the melt itself (i.e., melt free of bubbles).

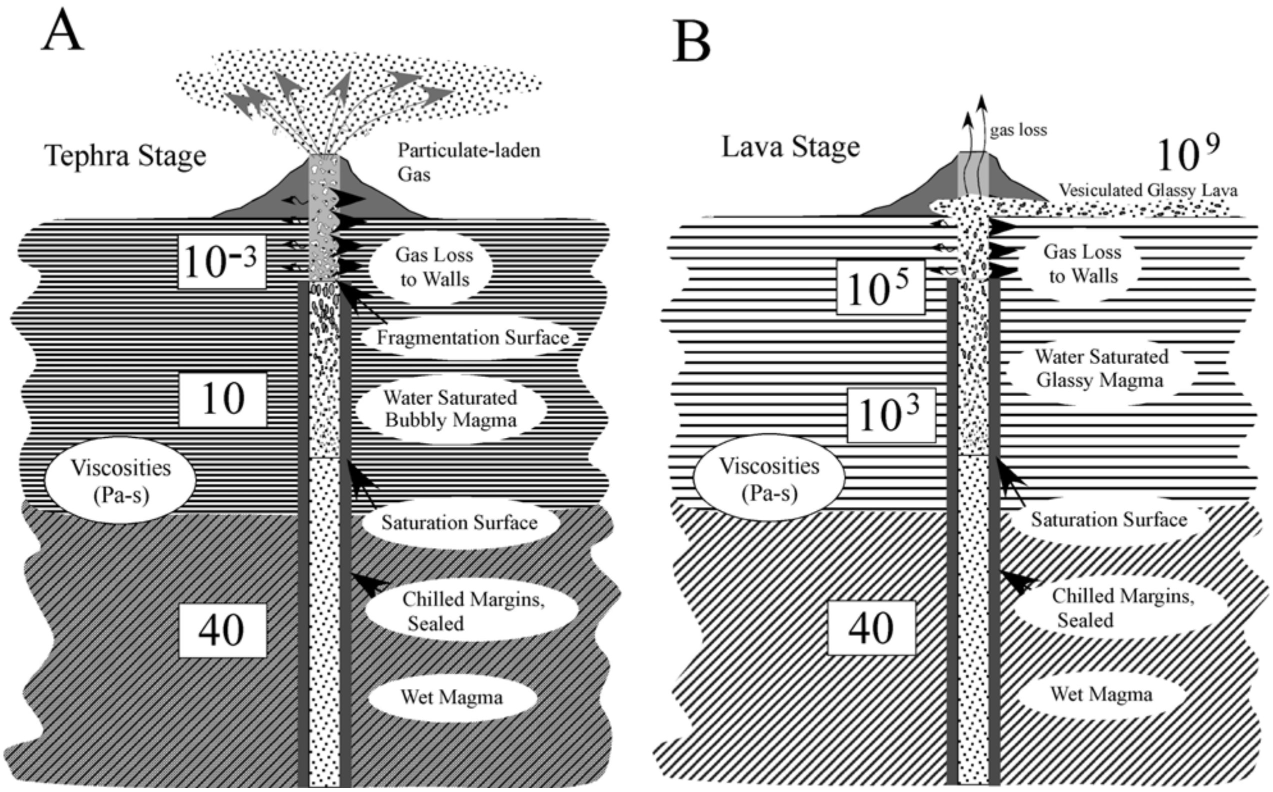


Figure 41 **Schematic depiction of cinder cone volcanism and the underlying magmatic eruptive column.**

Magma, rich in dissolved volatiles, saturates and vesiculates with approach to Earth's surface and reduction in confining pressure. In essence, the magma gets the 'Bends.' Increased bubble formation eventually leads to fragmentation of the magma and the explosive production of tephra and ash. Also shown are the governing magma viscosities (left column) as estimated for each stage of the eruptive process. Notice the large contrast in viscosity between the gas rich tephra and the late stage lava flows. Observations suggest that the sequence of eruptive styles is variable and that explosive and effusive activity can be interspersed with other and probably coeval from a single eruptive center (Valentine et al., 2006, 2007; Valentine and Keating, 2007; and ANL-MGR-GS-000002 Rev 03 now under review at DOE).
(A) Cinder Cone formation and eruption, schematically depicting explosive tephra and ash production leading to formation of the volcanic cone and an ash plume.
(B) Stage of Cinder Cone eruption where the ascending magma has progressively degassed with approach to the surface and the eruption is dominated by the extrusion of highly viscous, sluggishly moving lava flows emanating from the basal area of the cone.

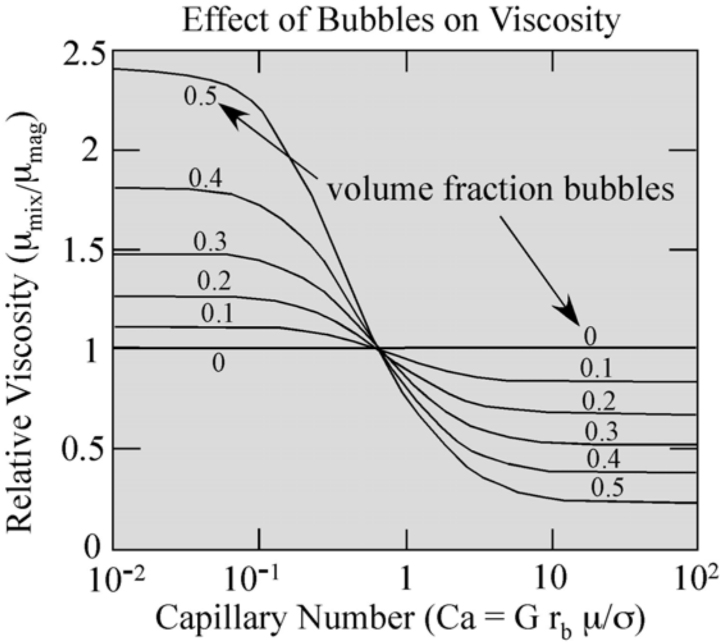


Figure 42 **Relative viscosity as a function of capillary number (After Detournay et al., 2003).**

The important result is that the overall effect of capillary number on viscosity is relatively small. For small Ca (i.e., Ca <1) the bubbles are 'hard' spheres and viscosity is increased at most by a factor of about 2.5 for a volume fraction of 0.5. At the other extreme for large Ca (i.e., Ca >>1), where the bubbles are easily deformable by the shear flow, viscosity is reduced by a factor of about four. This occurs because the high viscosity fluid (i.e., melt) still forms a continuum, which essentially controls the rheology. The overall effect, however, also depends on the bubble size distribution, which controls packing and, ultimately, the bubble concentration at the point of melt continuum breakdown and, eventually, the process of melt fragmentation.

In light of these results, in the regime where the magma contains bubbles but is still a continuum of melt (i.e., the bubble concentration is below about 50 vol.%) containing isolated bubbles, the dominant viscosity is determined by the composition of the magma. The effects of the bubbles themselves are not large. There is another effect, however, that has caused some confusion in defining the dominant viscosity.

Magma viscosity is not only highly sensitive to chemical composition, including the amount of dissolved water, but also to the concentration of solids or crystals in suspension. Crystal content increases systematically with cooling from the liquidus (0 vol.% crystals) to the solidus (100 vol.%). As the concentration of crystals reaches maximum packing at ~ 50 vol.%, the crystals interlock, and viscosity increases essentially without limit to that of an assemblage of solids. This effect is shown in Figure 43 where viscosity is measured against crystal fraction (Φ). There are many formulations available to calculate this effect and several are used here to show the range of estimates (Marsh, 1981). The most critical factor in each calculation is the point of maximum packing or critical crystallinity (Φ_c), which is well known for magmatic crystals to be Φ_c~0.55 (i.e., 55 vol.%). When the magma contains water, bubbles will eventually appear as crystallization proceeds, and these will also affect the viscosity as noted in Figure 42.

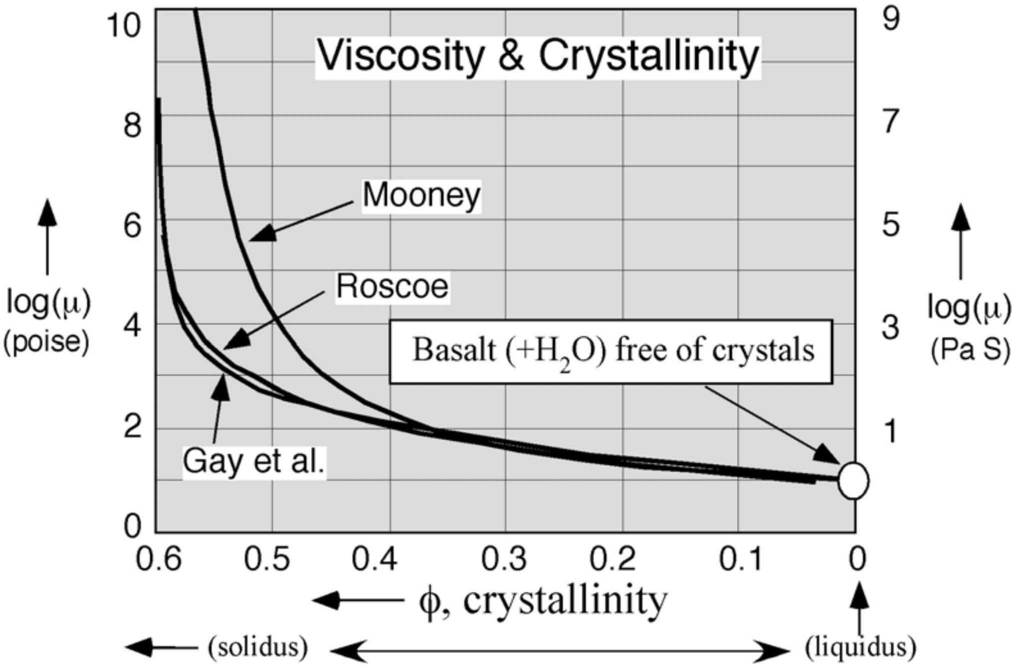


Figure 43 Viscosity (μ) as a function of crystallinity (Φ) (After Mooney, 1951; Roscoe, 1952; Gay et al., 1969; Marsh, 1981).

It is important to realize that this effect occurs relative to the liquidus and solidus, which are each highly sensitive to the water content of the magma. As water is added to magma, the liquidus and solidus are systematically (to a point) reduced in temperature. And, because overall viscosity is a strong function of temperature (which includes the effect of crystal buildup), it is essential when estimating magma viscosity to do so relative to the liquidus, at whatever temperature it may be. Viscosity cannot be estimated from temperature alone.

Groundmass volume fractions in pyroclastic materials at Lathrop Wells that have been quantified to date range from 20-30% (volume). Values of viscosity in ANL-MGR-GS-000002 Rev03 (under review by the DOE) are reported clearly as values at the liquidus for appropriate temperatures and water contents and are consistent with the plot in Figure 43 in the range of log(viscosity,poise) = ~2.7-1.9 for water contents of 0-4 wt.%.

Lore et al. (2000), in studying the effect of cooling on fracturing of basalt lava from the Snake River Plain, presented a figure showing the viscosity of anhydrous basalt covering an unusually wide temperature range from 1500°C to 100°C. These results are shown in Figure 44 along with other information that has been used by EPRI (2005) to estimate the viscosity of possible Yucca Mountain magma.

The approximate liquidus and solidus for a basalt of this type is indicated along with a curve, labeled basalt + crystals, showing the variation of viscosity for a magma of this composition undergoing crystallization as it solidifies. This variation is in accordance with the results presented above. Beginning at the liquidus, where the viscosity is about 100 poise (10 Pa·s), the viscosity increases strongly midway through the crystallization interval as the crystal content approaches 50 vol.%. This is in contrast to the curves of Lore et al. (2000) that continue smoothly through the crystallization interval and only rise strongly below the glass transition temperature at about 700 °C, which is some 300°C below the solidus, where the magma is completely solid and its viscosity is effectively infinite. The reasoning behind the curve of Lore et al. is the assumption that the basalt does not crystallize but becomes a glass (solid curve) containing 20 vol.% crystals (dashed curve). Because they are interested in rapidly cooled lava, this is an appropriate approximation at sub-solidus temperatures. However, their curves are not accurate near the liquidus nor within the melting range in general. Because this is an anhydrous (i.e., water-free) basalt lava, these results do not directly pertain to the possible Yucca Mountain magma at depth where it is expected to contain 2-4 wt.% water.

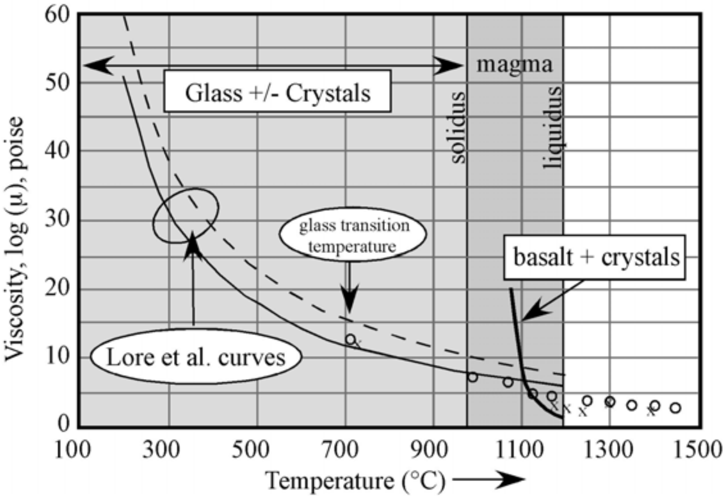


Figure 44 **Magma phase diagram showing change in viscosity (μ) as a function of temperature.**

6.2.1.3. Perspectives on Magma Viscosity

6.2.1.3.1. DOE Perspective

The DOE (DOE, 2004, p.6-29) summarized the flow regimes for basaltic magma:

- Homogeneous with small, low Reynolds number bubbles moving with the melt
- Bubbly flow with bubbles rising faster than the melt
- Slug flow with bubble sizes approaching the width of the dike (Vergniolle and Jaupart, 1986).

The DOE goes on to explain these regimes and the final choices for modeling as follows. The operative flow regime will be a function of many variables including, but not limited to moisture content, other gases present, pressure, melt viscosity, and surface tension. Figure 45 shows the phase equilibria diagram for Lathrop Wells basalt, inverted from the normal presentation, together with the eruption column anticipated for these phases. As the magma first encounters a drift, it may do so under slug flow. As time progresses and the magma front continues up the dike, the flow entering the drift may become bubbly. The viscosity of the bubbly flow is very complicated and in certain cases will be non-Newtonian. This could include either shear thinning or shear thickening depending on the variables listed above (Detournay et al., 2003; Appendix 2, p. 1, Figure 2B). Therefore, it is not possible to determine the effect of this uncertainty.

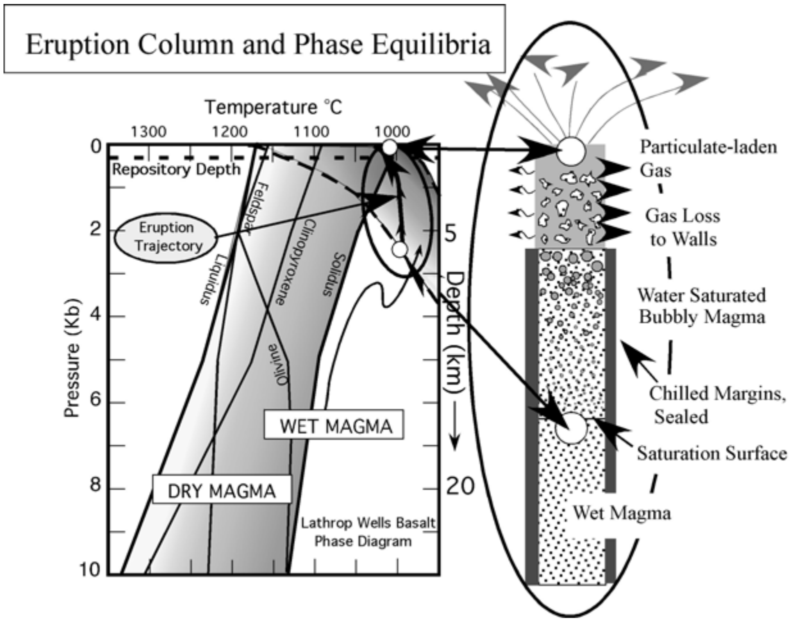


Figure 45 Phases in a volcanic eruption column showing the three regimes (wet magma, water saturated bubbly magma, and particulate-laden gas) and associated phase equilibria diagram for Lathrop Wells basalt under conditions of water free (denoted as Dry Magma) and containing about 4 wt.% water (denoted as Wet Magma). The approximate depth of the repository is also marked. Notice the large effect of water in lowering the crystallization range of the magma to the extent that as the Wet magma approaches the surface it is at a temperature where it would be completely solid if it were on the surface.

6.2.1.3.2. EPRI Perspective

Using the experimental phase equilibria on basalts near Yucca Mountain, EPRI (2005, p.3-1) estimated magma viscosity as follows. Based on phase-equilibria stability diagrams (Nicholis and Rutherford, 2004), the magma ascended from depths >7km (>175 MPa) with temperatures <975°C for the Little Cone samples and 1000-1010°C for the Lathrop Wells samples. The corresponding viscosities for this range of temperatures at repository depths are 10^5-10^7 Pa·s (10^6-10^8 poise) (Lore et al., 2000); Delaney and Pollard, 1982) and a magma rheology characteristic of an *aa* flow (Soule et al., 2004).

The problem with this approach in estimating viscosity is that these temperatures cannot be used directly with the above curves of Lore et al. because the liquidi of the hydrous Yucca Mountain magma and the dry Snake River Plain basalt are greatly different. With each magma at the respective liquidus temperature, the Yucca Mountain magma will actually have a viscosity lower than that of the Snake River Plain basalt because the Yucca Mountain magma contains water. That is, the Yucca Mountain magma at about 1000°C and containing water will have a viscosity about ten times smaller than the Snake River Plain magma at 1200°C and containing no water.

In terms of estimating the viscosity of the degassed Yucca Mountain magma, which may form a glassy basalt through rapid cooling during ascent, the viscosity from the Lore et al.

(2000) curves at a temperature of ~1000°C would be about 10^{10} poise (10^9 Pa·s). Strictly speaking, under these conditions this value may be correct.

6.2.1.3.3. Additional Comments on Magma Viscosity

The various possible rheological regimes experienced by hydrous basaltic magma as it decompresses on approach to the surface are appreciated by all parties. But the application of this information is inconsistent. The central point of confusion concerns the rheology of basalt as it degasses with ascent under isothermal conditions. That is, the most sophisticated calculations show that basalt degassing under adiabatic conditions will ascend essentially isothermally due to crystallization (Mastin and Ghiorso, 2001). For hydrous basalt beginning its ascent at a temperature of about 1000°C, as has been suggested from experimental phase equilibria, an isothermal ascent will produce either rapid crystallization or quenching to a glass (vitrification) containing some crystals. In either case the viscosity increases enormously. Rapid crystallization or vitrification occurs because the hydrous basalt begins its final ascent at a temperature (~1000°C) that is at or below its low-pressure (i.e., near surface) solidus temperature. This is illustrated in Figure 46 (Marsh and Coleman, 2006; 2008). As the concentration of solids (i.e., crystals) approaches that of maximum packing, which for basaltic magma is at ~50-55vol.%, viscosity increases to ~10^{18} Pa·s with complete crystallization (Marsh, 1981; Pinkerton and Stevenson, 1992). If the basalt, instead, quenches to a glass, with a modest (~10-20 vol.%) amount of crystals, the viscosity will become ~10^{10} to 10^{12} Pa·s, depending on the exact temperature. The attainment of this condition is reflected in the lack of mobility of lavas from Lathrop Wells.

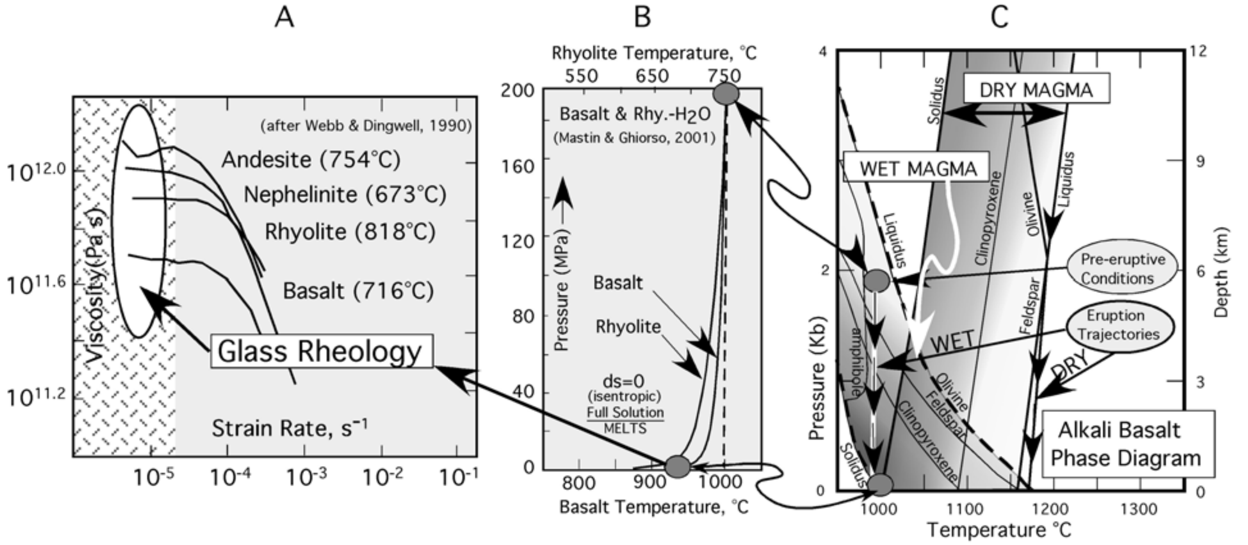


Figure 46 Details of the near surface eruption thermal trajectory and the possible rheology if the magma quenches to a glass. Phase diagram (C on the RHS) for Lathrop Wells basalt under dry and wet conditions. Note the contrasting ascent trajectories of Dry versus Wet magma. The detailed temperature history for an adiabatic ascent (B above) for both basalt (lower temperature scale) and rhyolite (upper scale) as calculated by Mastin and Ghiorso (2001) where the effect of loss of gravitational potential energy has been included. The magma reaches the surface undergoing strong cooling. If the ascent is rapid enough the magma will quench to a glass the rheology of which is given by diagram A (LHS) as a function of strain rate. The probable range of viscosity is also indicated (After Webb and Dingwell, 1990; Marsh and Coleman, 2006; 2008).

On the other hand, water-poor or anhydrous basaltic magma ascends along its high temperature liquidus and erupts at near liquidus temperatures. The viscosity is very low, about 10 Pa·s, and the magma is highly mobile. The bottom line is that hydrous magmas are explosive as the gas exsolves and escapes, but the ensuing lavas are relatively immobile. Dry magmas are not explosive, but the lavas are highly mobile. This is emphasized more explicitly in Figure 47 where the near surface ascent (last ~ 5 km) is shown in detail along with the associated variations in viscosity due to crystallinity alone without glass formation.

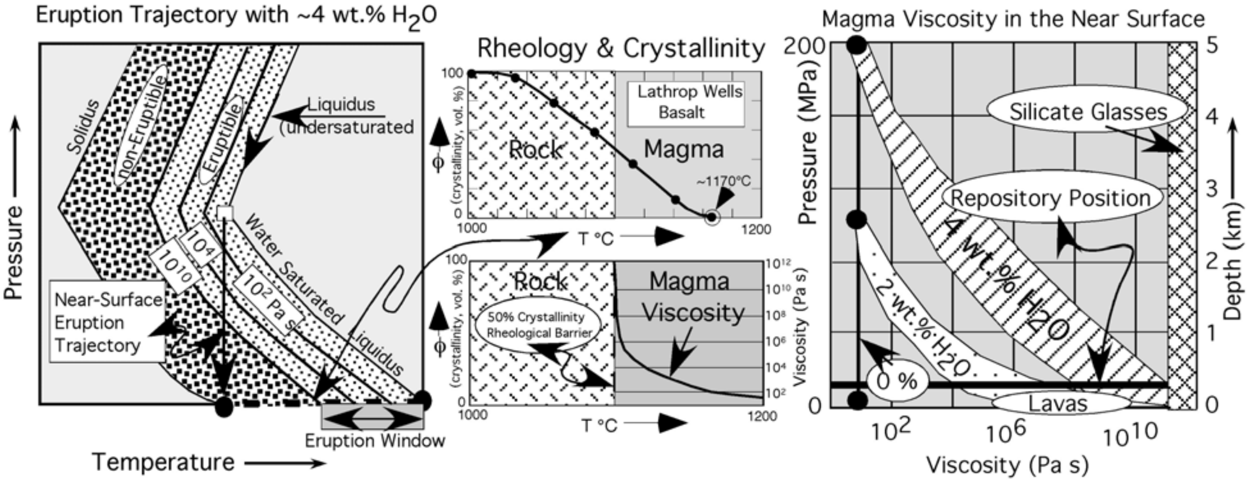


Figure 47 **The increase in viscosity in response to increasing crystallinity during the final stages of ascent for a water-saturated magma containing 4 wt.% water (left). The eruption window is noted within which the crystallinity is less than ~50 vol.%. The effect of latent heat due to crystallization, keeping the magma isothermal, has been taken into account. The general increase in crystallinity with decreasing temperature for Lathrop Wells basalt is shown in the center (upper) panel and the concomitant increase in viscosity is shown by the lower center panel. The increase in viscosity during the final stages of ascent for basaltic magma containing 4, 2, and 0 wt.% water is also shown (right) along with the position of the repository and the range of viscosity for silicate glasses. The largest increase in viscosity occurs for magma containing the most water, because at its liquidus it is the coolest prior to eruption. For magma free of water (i.e., dry magma) there is no (or minor) crystallization immediately prior to eruption and no significant increase in viscosity (After Hinze et al., 2008).**

There is confusion in all of the modeling over the viscosity of the basalt in the near surface regime. Either the magma is assumed to have its high-pressure, water-rich viscosity all the way to the surface (DOE, 2004, p. 6-30) or the magma is assumed to be unusually hot (~1200°C) and highly mobile. EPRI (2005) does assume a high viscosity magma, but for incorrect reasons. In particular, the DOE states (BSC, 2004, p. 6-30-31):

> Many of the calculations used in this model are for magma less dense than 1300 kg/m^3, which consists of more than 50 percent by volume gas. The viscosity of such a mixture is uncertain, so a viscosity of range of 10 Pa·s to 40 Pa·s, equivalent to the pure silicate liquid is used. The range of viscosities used in this analysis is derived from Detournay et al. (2003, Figure 2-1e). Most of the results in this report are for a viscosity of 10 Pa·s, representing a fluid magma that would quickly fill the drifts and, therefore, a more conservative condition from the perspective of dike/drift interaction.

The Detournay et al. (2003, Figure 2-1e) results referred to here are shown in Figure 48 where the assumed conditions of the calculation are that the magma is at 1150°C, which is near the dry liquidus temperature, as opposed to about 1000°C for the potential Yucca Mountain wet magma.

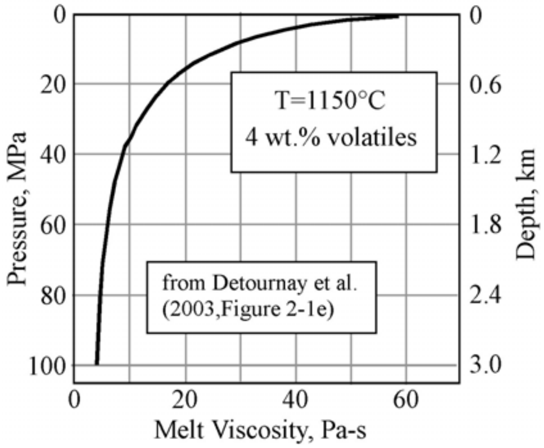


Figure 48 Magma viscosity calculated at 1150^{o} C during near-surface ascent and degassing (After Detournay et al., 2003).

Assuming this high temperature of 1150°C avoids having to consider the effects of crystallization and vitrification. This result is used by Detournay et al. (2003) as an illustrative assumption and should not be construed to represent the true rheology of the ascending basaltic magma. This can be seen by comparing this assumed temperature to the phase relations shown by Figure 46. A more meaningful calculation is to put the magma at a starting temperature at 1000°C and, as it ascends, follow it through the course of crystallization and/or vitrification, which is done schematically in Figure 47 and can also be done using Figure 44 from Lore et al. (2000). In this case, the magma viscosity reaches the much higher values mentioned earlier of 10^{10} to 10^{12} Pa·s.

It is important to appreciate the individual processes involved in forming crystals and glass in magma due to heat loss as opposed to crystallization induced by rapid depressurization associated with ascent and extrusion. As mentioned already, crystallinity is absolutely critical to magma mobility, as no lava has ever been erupted carrying more than 55 vol.% phenocrysts (Marsh, 1981). In cooling from liquidus to solidus all magmas either crystallize to a network of solids, quench to a glass, or go to a combination of each. For crystallization, the increase in viscosity in cooling from the liquidus to the point of beyond 55% solids is by a factor of more than 10^{14}; perhaps the largest change in any earth material physical property. The actual end product depends on the rate of cooling relative to the rates of crystal nucleation and growth. The rate at which any local region of magma can be cooled is limited by the thermal diffusivity ($K \sim 10^{-02}$ cm^2/s) and the spatial position (L) of the locale relative to the proximal cooling surface; from scaling the heat equation, cooling time is $t \sim L^2/K$. When L is small quenching to a glass is possible, but deeper in the magma interior crystallization will always occur, especially in basaltic magmas. Temperature-induced crystallization operates, in essence, as a surface force: It must propagate in from a surface.

Pressure-induced crystallization is a much different process. Pressure-induced crystallization due to de-volatilization operates much as a body force. Like gravity, it can operate throughout the magma essentially instantaneously. (It can propagate at the rate of an acoustic wave.) The rate-limiting step is the rate of local diffusion of water into bubbles. This diffusion time ($t \sim d^2/D$, where D is H_2O diffusivity $\sim 10^{-6}$ cm^2/s) is given by the same equation, but here the length scale (d) is a local length scale and can be made arbitrarily small due to increased bubble nucleation density. Quenching to a glass can happen throughout the body and is dependent on the rate of ascent, the amount of water present, and, perhaps most important, the form of the phase diagram. The degree of quenching or crystallization depends strongly on the amount of water present. For a dry magma, as seen in the above figure, there is no crystallization pressure effect in ascending along the (almost isothermal) liquidus. For a magma rich in water, rapid depressurization with attendant gas loss will quench the magma to a combination of crystals and glass. Motion is still possible, albeit as a highly viscous mass.

There is a field example of what happens to basaltic magma when it tries to flow through a narrow tube in rock that is relatively cold (251-256ºC) compared to magma. In Iceland, on September 8, 1977, magma reached the depth range of boreholes in the Námafjall geothermal field. Three tons of very fine volcanic ash erupted through an 1,138 m deep drillhole, forming a tephra sheet with a volume of 26 m^3 (Larsen et al., 1979). The drillhole was part of the infrastructure for a hydrothermal field. The eruption lasted ~20 minutes. The drillhole was cased to 625 m, had an uncased diameter of 0.16 m, and the main producing zones were reported at depths of 638 m and 1038 m (Larsen et al., 1979). Tephra composition indicated temperatures at the time of chilling of 1153-1158°C. Compared to lava at Yucca Mountain, this Icelandic magma was dry and relatively mobile, but lava never flowed out of this drillhole, which indicates limited vertical rise of magma due to quenching on drillhole walls and increasing flow resistance and viscosity during ascent.

The short eruption time can be used to estimate a lower limit for the magma viscosity. It is assumed that, after the initial pyroclastic phase, degassed magma entered the drillhole via the deeper producing zone and began traveling up the uncased section. Using Poiseuille's Law for pressure-driven flow, and given an overburden pressure of $>2 \times 10^7$ N/m^2, viscosities for this mobile magma must nonetheless have exceeded 100 Pa·s, otherwise the velocity of the liquid magma front would have been great enough to reach and seal the cased part of the borehole in 20 minutes. This did not happen because steam production continued from this borehole after the magmatic event. For comparison, previous workers (Woods et al., 2002 and 2006) assumed low viscosities of 10-100 Pa·s for relatively immobile, wet magmas at Yucca Mountain.

Dartevelle and Valentine (2007) analyzed the Námafjall borehole eruption. They noted that the eruption provides a unique test case for multiphase processes because its vertical extent of ~1 km is similar to that of natural volcanic conduits and its geometry is well known. They modeled the eruption by solving time-dependent governing equations for conservation of mass, momentum, and energy of the gas and particle phases. Their analysis allowed for drag and heat transfer between the phases. The model results indicate the development of transient waves of high particle concentration that propagatee up the borehole, resulting in ejection of particles in pulses like those observed at Námafjall. Dartevelle and Valentine's (2007) results indicate that transient multiphase behavior is probably common in volcanic conduit flows. They suggest that a key topic of future research is quantifying the time-dependent behaviors and their impacts on eruption column dynamics.

In sum, researchers must be consistent in how they estimate the viscosity of Yucca Mountain basalt as it ascends and degasses near the surface. There has been a tendency to assume rheological properties pertaining to both wet, cool magmas and dry, hot magmas, leading incorrectly to the postulate of a highly explosive system with highly mobile lavas. The potential Yucca Mountain magma is likely a wet, cool magma. Wet basaltic magma is explosive, but relatively immobile as lava. Dry (e.g., Icelandic) magma is not explosive, but highly mobile as lava.

6.2.2. DOE, EPRI, and NRC Perspectives on the Magma/Waste Package Interaction

6.2.2.1. DOE Perspective

The DOE (e.g., BSC, 2004) and EPRI (2004, 2005) have considered many aspects of the dynamics of dike propagation, magma flow into drifts, magma-waste package interactions, and subsequent waste package-water interaction. For magma flow into a drift the DOE uses various coupled models, analytical and numerical, of fluid flow from the dike to the drift. The magma is given a viscosity of 10-40 Pa·s, and the drift is filled in about 15 minutes. Effects of solidification on magma rheology are mentioned, but not explicitly used in flow modeling. This analysis suggests that waste packages may be softened, deformed, and corroded by the magma, but not be easily moved, and glassy waste forms are unlikely to be significantly altered by the magma. Yet because of the many uncertain facets of the process encountered in this investigation, the DOE concluded (BSC, 2004, p. 6-111) that “On balance, it would be proper to adopt the conservative position that all waste packages and associated drip shields that come in contact with basalt magma immediately fail.”

6.2.2.2. EPRI Perspective

EPRI (2004) analyzed an extrusive release scenario for Yucca Mountain and concluded that the waste package, if intact and still strong, can provide a significant barrier to inhibit the volcanic release of radionuclides. EPRI analyzed several failure mechanisms, including a direct hit on a waste package from below, and found reasonable expectation that no waste packages would fail. EPRI (2004) therefore concluded that the expected consequence of an igneous extrusive event would be no release of radionuclides to the atmosphere. EPRI did note that waste packages located directly within a magmatic conduit could conceivably contribute radionuclides during the Strombolian stage of an eruption.

Use of more reasonable (to them) assumptions in EPRI’s (2005) work lead them to de-emphasize the importance of igneous scenarios in estimating probability-weighted peak doses. They suggest that the DOE and the NRC have used so many compounding conservatisms in their evaluations that igneous scenarios have taken on greater apparent risk importance than is justified. They conclude that present DOE and NRC assessments of repository performance are conservative, and state that reliance on more realistic scenarios and input data would demonstrate an even greater margin of compliance. Based on the results of two summary reports, EPRI (2004; 2005) reached the overall conclusion that there is reasonable expectation that an intrusive or extrusive igneous event at Yucca Mountain would not be expected to result in dose levels exceeding those levels anticipated for a base-case scenario with no igneous event, and that no further work need be pursued to address the igneous scenarios.

A key aspect of the EPRI (2005) analysis concerns the realization that magmatic eruptive temperatures are apt to be significantly lower than they (and DOE) have previously assumed. This stems from experimental phase equilibrium studies on basalt from the nearby Crater Flat basin by Nicholis and Rutherford (2004). Their work suggests that, although the magma was at or near its liquidus temperature, because of the magma water content this temperature was much lower than previously assumed (i.e., ~1000°C vs 1150-1200°C). EPRI (2005) then used the viscosity-temperature relations of Lore et al. (2000) to find a much larger magma viscosity of 10^5 to 10^7 Pa·s. The difficulty with this approach is that the relation shown by Lore et al. (2000) is based on experiments for water-free melts and glasses and cannot be used for hydrous magmas. Even though the new temperature is much lower, the fact that it is at the liquidus of a water-rich magma means that the intial viscosity at depth will be as low (or possibly lower) than that initially assumed by EPRI and DOE. The correlation and regression given by Lore et al. (2000) is useful as an overall indication of rheology from melt to glass in lava, but as discussed above it does not capture the detailed changes due to crystallinity, water content, and bulk composition within the liquidus-solidus range for magma in general.

6.2.2.3. NRC Perspective

As mentioned already, Woods et al. (2002) also analyzed the hypothetical case in which magma diverts along multiple emplacement drifts and into the main access drift, from which it vents to the surface. Intersected drifts could thus quickly fill with magma, and a large number of waste packages in the repository could be affected. Woods et al. suggested that prolonged magma flow through the repository, enveloping and bathing the waste packages for days to months results in failure of waste packages and provides a mechanism to transport waste to the surface. They did not consider the effects of solidification on rheology or of quenching on waste packages.

Woods et al. (2002) also suggested the possibility of generation of a shock wave, which propagates through the drifts as the dike cuts the drift. The ideal experimental situation by which to produce a shock wave is to puncture a diaphragm separating a fluid under high pressure from a space at much lower pressure. Disruption of the diaphragm produces a pressure wave with a discontinuity in pressure at its leading edge.

Shock waves have indeed been recorded in volcanic eruptions at well-established volcanoes associated with island arcs such as at Nguaruhoe in New Zealand (Nairn, 1976) and Mount St. Helens (Reed, 1980). Shock waves have not been observed during venting of a dike in establishing a fissure-style eruption. The basic structure of island arc stratocone volcanoes, however, makes them ripe locations for shock wave production. Stratocone volcanoes almost always emit magma from a central summit vent. Korovin volcano on the island of Atka in the Aleutian Islands, for example, has such a cylindrical vent about 300 m wide and 1 km deep that has been periodically observed to be empty and later brimming with magma (Marsh, 1990). Should the summit area become plugged with congealed magma, which is commonplace, rising magma along with the inevitable exsolution of volatiles will overpressure the volcano until it suddenly ruptures. Moreover, many highly explosive island arc volcanoes erupt high crystallinity magma that is near the point of critical crystallinity (~55 vol. %; Marsh, 1981) where the magma becomes a shear resistant dilatant solid, forming an effective plug at the summit. Merapi volcano in Indonesia is a clear example of this condition (e.g., del Marmol, 1989). Thus, large volcanoes repeatedly issuing magma from a central summit vent are, in essence, almost ideal shock wave generators. A dike entering a drift at Yucca Mountain would be distinctly different from this occurrence.

A propagating dike is a magma-filled elastic crack. The leading edge of the dike is knife-like and the width of the dike increases slowly away from the tip. Although this is sometimes difficult to calculate in highly fractured country rock with complex elastic properties, examples are available from field occurrences. For example, in the north wall of the east end of Wright Valley in the McMurdo Dry Valleys, Antarctica, the leading edge of the dike associated with the emplacement of the 300 m thick Basement sill is fully exposed (Marsh, 2004). Over a distance of about 5 km the dike thickness increases progressively from 1 cm at the leading tip to 300 m. A dike intersecting a subsurface cavity or drift will gradually open to its full thickness. Rapid quenching of (most probably) low crystallinity magma along all margins will further impede the rate of opening so that the pressure release will not be catastrophic, as with a punctured diaphragm, but will ramp-up over a finite time and not allow development of a discontinuity in the pressure field.

The scenario analyzed by Woods et al. (2002) creates a shock wave because of the way the problem and simulation is set up. The imposed initial conditions (both geometric and dynamic) essentially presuppose the solution. But it is the magma physics before the assumed initial conditions that actually determines the outcome. The proper portrayal of this part of the problem (e.g., the gradual opening of a leaky fracture into a cavity) precludes formation of a shock wave. BSC (2004) and EPRI (2004) also analyzed the possibility of generation of a shock wave and found magma-drift interactions to be far less severe than those hypothesized by Woods et al. (2002).

6.2.2.4. Summary of Views

A recent numerical analysis by Dartevelle and Valentine (2005) builds on the Woods et al. (2002) approach but includes full time dependence, 2-D geometry, and a multiphase flow of steam and pyroclastic particles. Although this work has attractive features in time dependence, spatial deposition of particles, and spatial dependence of flow speed and pressure, it also suffers in its fixed (i.e., non-time dependent) 2-D geometry. A shock wave forms at the outset in response to the fixed geometry and the initial conditions of the pressure contrast between the dike flow and the drift.

Detournay et al. (2003) present an extensive discussion of igneous consequences at Yucca Mountain, including the potential interactions between a basaltic dike and a repository. In their opinion, the probability that a violent erupting mixture could follow dogleg conduits is small and more than offset by the degree of conservatism built into the existing estimates. They recommended that a number of new analyses be made, including development of a coupled 3D model for unsteady dike-drift flow for the scenario of a drift being intersected by a vertical dike, and that experimental studies be made on the chemical and mechanical effects of basaltic magma on waste packages in drift and conduit flows.

Overall, it appears that significant conservatisms exist in the DOE and NRC analyses of igneous scenarios. These conservatisms exist, in a large part, because of major uncertainties in the understanding of the interaction of magma with the repository, and much of the uncertainty centers on the problem of the thermo-viscous state of magma as it undergoes solidification. For example, Woods et al. (2002) assume that magma moving through a repository drift remains isothermal with “water-like” flow characteristics. This is based on the assumption that magma flow rates will be rapid (10 to 100 m/s, or 22 to 220 mph) and the thermal inertia of the flow will be large as in flow in a lava tube. But repository drifts are small (~5.5 m diameter) and cool (100-300°C) and lava, being always within its crystallization interval (Figure 47), quenches and stagnates on all it touches. By not considering realistic scenarios for the thermal interaction of magma with tunnel openings, waste packages, and tunnel walls, there is a real possibility that important processes could be missed. This would not only have implications for understanding other processes (e.g., entrainment and eruption of waste) but also in correctly estimating the overall seriousness of the magma disruption process itself. A prime example in previous work is the serious omission of the exceedingly common phenomenon of magma solidification and quenching. An explanation for this view is given below after first describing the physical situation.

6.2.3. Number of Waste Packages Potentially Affected by Dike Intrusion

The extent to which a repository could be affected by a hypothetical dike intrusion depends on how far magma could penetrate drifts before it solidified. As discussed in the preceding section, this would be determined by the composition, rheology, and driving pressure of the magma if it should encounter tunnels. Both the DOE and EPRI have performed quantitative analyses of the number of waste packages that could be affected by hypothetical dike intrusion.

6.2.3.1. DOE Analysis

The DOE (2004) states that the rate of magma flow into drifts will be limited by the rate of magma supply, except probably when the supply is very large (velocity on the order to 10 m/s) and the magma viscosity is on the order of 40 Pa·s. The time needed to fill 500 m of drift would be on the order of 15 minutes given a magma velocity of 1 m/s. The time needed depends on the supply rate, and the results can be linearly scaled to other drift lengths.

The presence of the drift will have an impact on the rise of the magma inside the dike. In fact, the magma front may stop rising, and a steady state flow into the drift (total magma flow inside the dike diverted into the drift) may be reached before it is completely filled. However, the magma will rise several tens of meters above the drift before if fully invades it. Pressures in the drift will be minimal (a few kilopascals) while the magma is invading it.

Uncertainty exists in the magmatic effects on waste package integrity. Flow of magma into drifts is likely to result in plastic deformation of waste packages, but it is unlikely to result in movement of waste packages over large distances. Exposure of packages to the high temperatures and corrosive gases of the magmatic environment are expected to enhance corrosion.

The DOE assumes that commercial spent fuel will eventually be reduced to relatively small particles due to oxidation. Glassy waste forms are not expected to be significantly altered by interaction with magma. On balance, it would be proper to adopt the conservative position that all waste packages and associated drip shields that come in contact with basalt magma immediately fail (BSC, 2004, p. 6-111).

DOE (2004) documents calculations of the number of waste packages that could be damaged in a potential future igneous event. The igneous intrusion scenario shows a range of consequences, extending from virtually no waste packages damaged to nearly all waste packages in the repository. The 50th percentile value indicates approximately 1,600 waste packages could be impacted, out of over 11,000 waste packages in the repository. DOE made the following assumptions in these analyses:

1. For any drift intersected by a dike, all of the waste packages located in that drift will fail. In other words, they will provide no further protection for the waste.
2. For any drift not intersected by a dike, none of the waste packages located in that drift will fail.

The rationale for these assumptions is:

1. Since the emplacement drifts will not be backfilled, there are no credible mechanisms to block or mitigate the resulting effects from the dike intrusion upon the waste packages.

2. The presence of backfill in ventilation drifts, access drifts, and turnouts will serve as credible mechanisms, provided sufficient engineering is implemented, to protect waste packages in emplacement drifts which are not exposed directly to magma (i.e., drifts which are not intersected by a dike).

6.2.3.2. EPRI Analysis

The results of EPRI's (2005) analysis of hypothetical magma intrusion are summarized in Table 6 Within the "red" zone they estimate that 0-6 waste packages could become engulfed by magma intrusion in a waste emplacement drift. They further estimate that in the "blue" zone 14-24 waste packages could be significantly affected by heat and corrosive gases.

Table 6 Summary of the impacts on waste packages and specifically containment and controlled-release functions of barriers, for each of the three zones for the expected intrusive-release variant case (After EPRI, 2005) (Permission to use this copyrighted material is granted by the Electric Power Research Institute).

Zone	Description of Zone	Extent of Zone	Total No. of Waste Packages (both directions)	Condi-tion of Clad-ding	Condition of Alloy-22 Waste Package Outer Barrier and Drip Shield	Impact on Transport Properties
Red	Waste packages engulfed by magma intrusion	0-20 m from magmatic dike	0-6	Failed	Additional considerations: • WPs are unlikely to fail by over-pressurization because of restraint by the external magmatic load. • Creep failure is considered unlikely as the magma will prevent sufficient strain of the WP. • Potential for DS displacement by magma intrusion.	Fractured basalt - Flow diversion - sorption - fractured matrix
Blue	Waste packages experiencing significant thermal impacts	37-66 m from end of Red zone (front of magma intrusion	14-24	Failed	All of the WPs in the 'Blue Zone' are conservatively assumed to fail by creep. Additional considerations: • 1-2 WPs in the region immediately in front of an intruding magma plug, in addition a single WP that might be only partially engulfed by magma plug, are likely to fail by over-	Open air

Zone	Description of Zone	Extent of Zone	Total No. of Waste Packages (both directions)	Condi-tion of Clad-ding	Condition of Alloy-22 Waste Package Outer Barrier and Drip Shield	Impact on Transport Properties
					pressurization. • The hottest WPs may become sensitized and subject to enhanced general corrosion and greater localized corrosion susceptibility. • Corrosion due to volatile gases will range from 0.1-1 mm for the 10 hottest WPs. • Drip shield displacement unlikely.	
Green	Waste packages contacted by magmatic gases	The remainder of the inter-sected emplacement drift beyond the limit of the “Blue” zone	All of the remaining WPs in the emplacement drift outside the “Red” and “Blue” zones	Intact	No WP failures are expected in the ‘Green Zone’. Additional considerations: • No WP failures due to overpressurization because of the relatively low temperatures. • No creep failures are predicted in the ‘Green Zone’. • WP temperatures are too low to cause thermal aging of the Alloy 22. • Extent of corrosion due to exposure of approximately 12 WPs to volatile magmatic gases is expected to be <0.1 mm. • DS displacement unlikely.	Open air

6.2.3.3. NRC Considerations

In TPA 4.1 (Mohanty et al., 2004) the NRC estimated a mean value of 37 magma-induced mechanical failures from an intrusive event, based on a log uniform distribution from 1 to 1402 waste package failures. Igneous activity causes the largest increase in dose conditionally from both groundwater and airborne pathways, but the risk is still small when the probability of the volcanic event is factored into the calculations. The probability-weighted dose from igneous activity is approximately 3.6 µSv/yr (0.36 mrem/yr), which is greater than the base case groundwater dose of 0.00021 mSv/yr (0.021 mrem/yr), but still small compared to the regulatory criterion of 0.15 mSv/yr (15 mrem/yr) (Mohanty et al., 2004).

6.2.3.4. ACNW&M Comments on Magma Viscosity and Potential Dike Intrusion

The question of the number of waste packages involved in an eruptive event involves, in part, the length of drift exposed to magma. This is dependent on the number of drifts intersected by the magmatic event and the extent to which magma flows into each drift. Magma viscosity and the pressure gradient driving the magma into the drift are key factors in evaluating the distance of magma penetration. The eruptive event can be separated into two periods or styles. In the earliest stages, the initial magma is characterized by a low viscosity, gas-rich, particle-laden pyroclastic fluid. As the eruption proceeds, over days to weeks, the eruption will transition to the extrusion of high viscosity lava, which reflects the arrival of degassed magma into the near surface. This evolutionary sequence from pyroclasitcs to lava may not necessarily be a strict succession, but the eruption may, right from the beginning, change back and forth from pyroclastic to lava and vice versa (e.g., Sparks, 2007). Some examples of this behavior are Paricutin, Mexico (1943-1952) and Eldfell, Iceland (1973), although neither of these is particularly similar in magma composition or water content to what is expected at Yucca Mountain. Recent work by Valentine et al. (2007; see their Figure 3) also suggests a similar behavior at Lathrop Wells.

6.2.3.4.1. Magma/drift Interaction Scenarios

If the initial eruptive material breaching the repository is pyroclastic debris, given a delivery rate of ~1 m^3/s or more, a local small subsurface cinder cone, in effect, would quickly form near the entry point, plugging the drift through avalanching and welding. On the other hand, if the eruptive is low viscosity (e.g.~10^2 Pa·s) lava, as has often been assumed for this process, the flow rate is rapid (10-100 m/s) and a significant distance of drift may become involved. If the flow rate is 10s of meters per second, the drifts would be filled with lava to 100s of meters in a very short time (minutes). The flow of lava through a drift can be estimated by assuming flow through a pipe whose radius shrinks in time due to magma solidification around the margins of the drift. A prime difficulty in performing such calculations is in the proper choice of the viscosity of the lava. Given the magma composition, temperature, volatile content, and crystallinity, the estimation of viscosity is straightforward (e.g., Marsh, 1981). Each of these characteristics can be estimated for magma similar to alkali basalt erupted nearby at Lathrop Wells, but there is a major problem in using this approach. As explained already in association with

Figure 41, Figure 45, Figure 46, and Figure 47, because of the anticipated high volatile content, this magma will undergo volatile saturation at depth (~5 km, Figure 49) long before it reaches the surface and will begin devolatilizing and solidifying and/or vitrifying rapidly in approaching the surface. This huge loss of volatiles causes a commensurate large increase in magma viscosity. Moreover, when the degassed magma reaches the surface it will already be near its 1-atm solidus temperature and will be, in essence, a glassy paste-like material of enormous viscosity. This is strongly reflected in the limited extent of the lava flows at Lathrop Wells, which can be analyzed to yield an estimate of the effective viscosity controlling the extrusion of the lava.

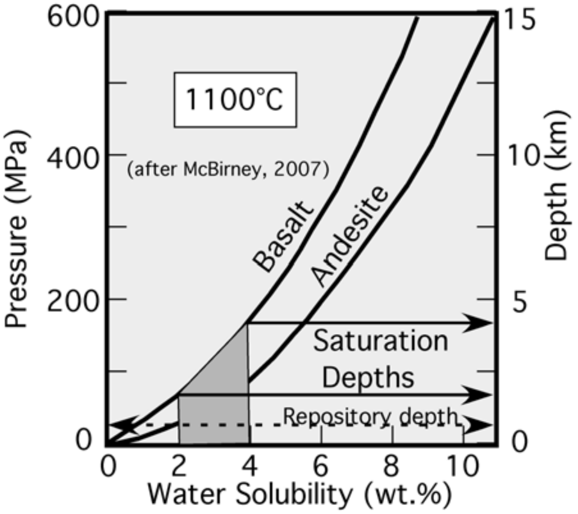


Figure 49 **The solubility of volatiles in magmas is a function of temperature, pressure, and the compositions of the liquids and gases. This diagram shows the solubility of water, which is the major volatile species in most magmas, in basaltic and andesitic magmas as a function of total pressure at 1100° C. The dominant control on water solubility is pressure; the effect of temperature is relatively minor. The pressure of another gas, such as carbon dioxide, would decrease the solubility of water. At Earth surface conditions (pressure = 1 bar), the solubility of water is virtually zero (vertical axis of diagram is marked in kilobars) (After McBirney, 2007). For a basaltic magma containing 2-4 wt.% water, saturation will occur at depths of, respectively, about 2-5 km, and by the time it reaches the surface it will have lost all water. Notice that at the depth of the repository (300 m), the magma could still contain ~0.7 wt.% water.**

6.2.3.4.2. Estimating Viscosity using Lava Flows

The radial extent of the flow field at Lathrop Wells is about 1 km, and the volume of the lava field is about 0.03 km^3 (e.g., Heizler et al., 1999; Valentine et al., 2007). Although the duration of the flow is not known with any certainty, because of the nature of the flow the viscosity controlling the flow can be estimated. The flow can be approximated as a gravity current of viscous fluid spreading on a nearly flat surface (e.g., Huppert, 1982). This method has also been used to examine lava dome and lava growth associated with the 1979 eruptive event on Soufriere on St. Vincent Island (Huppert et al., 1982).

Approximating the radial spreading of lava as an isothermal viscous gravity flow is but one of several mechanisms suggested that govern lava spreading and lava dome growth (e.g., Fink and Griffiths, 1998; Griffiths, 2000; Lescinsky and Merle, 2005). The strength of the enveloping crust, the internal yield stress, and the role of damming at the toe of the flow may each also dominate the flow at certain stages of growth or stages of cooling. Although the rates of radial growth predicted by the various models are similar, lava dome height over time tends to favor growth controlled by the yield strength of the surficial crust. In terms of revealing an effective viscosity of the lava itself, however, the various models are mutually exclusive. That is, each model yields a set of physical properties not found in the other models, and additional, more detailed, physical features added to a model often yield a better fit to observation. The viscous model, for example, can be made to fit better if the effect of damming at the toe is larger or if the lava viscosity is significantly larger than that independently estimated from lava composition and temperature. In the latter respect due to the sudden loss of volatiles with approach to the surface, the Lathrop Wells alkali basalt underwent rapid quenching and may well have attained a viscosity much larger than otherwise anticipated. And this viscosity is remarkably consistent with that found from modeling the Lathrop Wells lavas as gravity flows. On these grounds and the fact that only through this model can an estimate of viscosity be found, preference is given to modeling the spread of lava as a viscous gravity flow.

The radial extent (R) of the viscous flow of a fixed volume of released magma is given by (Huppert et al., 1982), where the radial extent of the flow is a function of gravity, initial flow volume, lava kinematic viscosity (= μ/ρ where μ is shear viscosity and ρ is density), and time. The flow can be modeled with this approach as the spreading of (1) a fixed volume of fluid deposited on a surface all at once and allowed to spread, as (2) the spreading of a fluid supplied at certain flux (e.g., m^3/sec), or as (3) a specific volume of fluid released by a flux rate applied over a specific period of time. Results from this equation for the first two cases, which perhaps bracket the volcanic situation, are shown by Figure 50 for a variety of viscosities, total lava volume, lava flow thickness, and effusive flux as a function of the duration of the event. The results are not highly dependent on the means of emplacement of the lava.

From these results and with a maximum flow extent of ~1 km, the effective kinematic viscosity of the lava is unusually large, being in the vicinity of about 10^8 to 10^9 Pa·s. The exact duration of this ~80,000 year old flow is not known, but flow events of this nature generally last about a month to a year. The *aa* character of these flows suggests a flux rate of about 12 m^3/s (Wood, 1980), which when used in concert with the observed volume suggests a duration of about 30 days. If on the other hand, the total volume of lava at Lathrop Wells is assumed to have been emplaced in the span of a single year, then the effective flux would have been about 1 m^3/s.

A significantly larger viscosity (2 x 10^{11} Pa·s) was similarly deduced by Huppert et al. (1982) for Soufriere volcano, which, apparently not believing the result, they ascribed to the influence of a high viscosity skin or quench rind enclosing the lava. Although this effect may be important, the fact that the Soufriere lava contains almost 50 vol.% crystals is also a major factor in greatly increasing the viscosity (Marsh, 1981), making the derived result clearly realistic. At Lathrop Wells, although the crystallinity was not large, there is evidence in the steep flow fronts, the rafted well-formed vent blocks supported by the flow, and the degassing sequence of extrusion (more below) that the viscosity was large.

A last somewhat independent result (Figure 51) shows the relationship between the length of a single lava flow moving on an inclined surface (1 degree incline) as through a channel or other accommodating terrain. Results are shown for various flow viscosities and flow thicknesses. For flows of thicknesses of 5-10 m and extending 500 m over the period of about a month the governing viscosity is in the range of 10^7 to 10^8 Pa·s. Flow thicknesses in some instances may be as much as 15 m at Lathrop Wells (Valentine et. al., 2007), which would further increase the estimated viscosity. Using a similar approach based on the Jefferys equation, which also describes flow down an inclined surface, Manley (1992) found similar results for blocky basaltic andesite and andesite flows. He noted that these values are some 1.8 to 3.6 orders of magnitude above that predicted for the lava itself based simply on chemical composition (Manley, 1992).

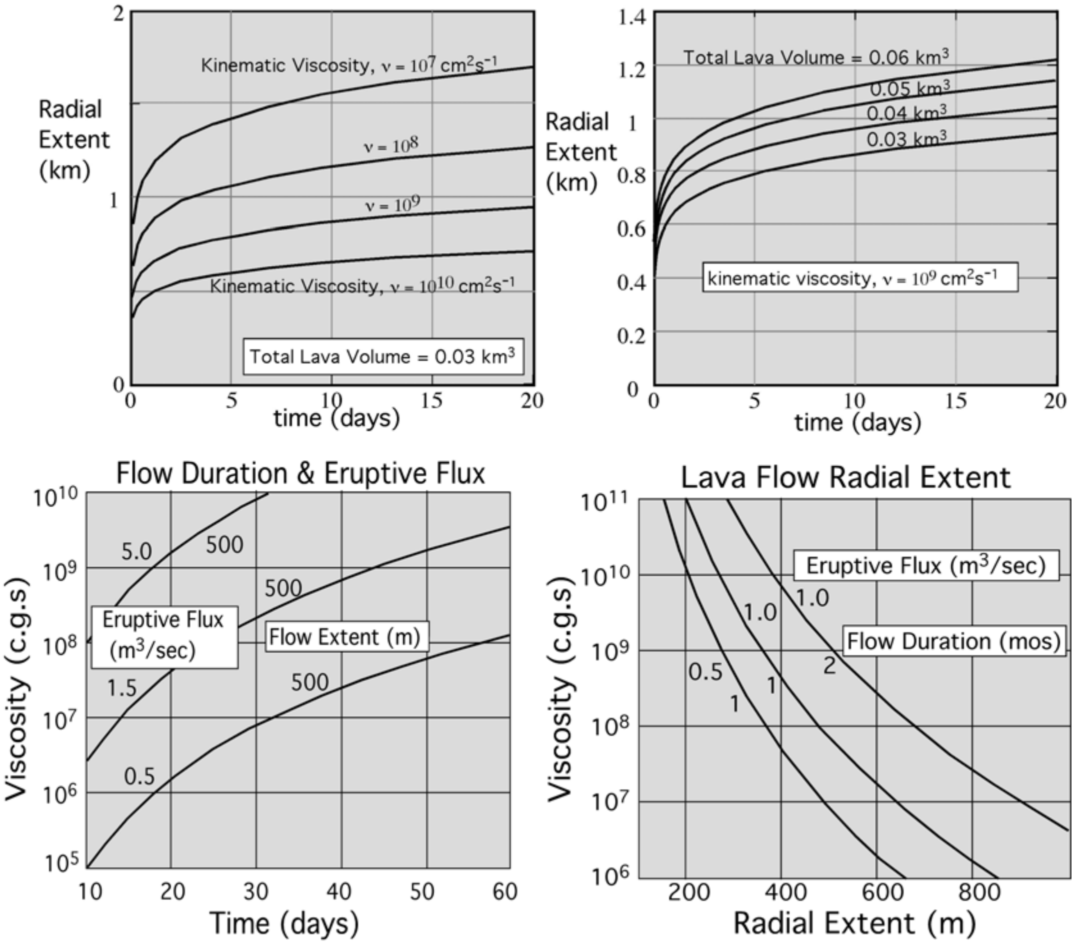


Figure 50 **Radial extent of the Lathrop Wells, Nevada, lava field as a function of the duration of the flow event. The observed extent of the lava field is about 1 km, but this most likely is the culmination of a series of lavas The upper two panels describe the flow of a fixed volume of magma over time as a function of viscosity (upper left) and total lava volume (upper right). The lower panels describe the flow of lava at a given rate of effusion or flux. The lower left panel shows the relationship between lava viscosity and flow time to establish a flow 500 m long for flux rates of 5, 1.5, and 0.5 m^3/s. The lower right panel shows the relationship between lava viscosity and radial extent as a function of eruptive flux and flow duration (in months).**

There is also direct evidence in the lavas from Lathrop Wells of the petrologic conditions favoring such large estimated values of effective viscosity. This evidence is in the form of the modal concentration of crystals, mainly plagioclase, and glass in the lavas and in the spatial variations in these quantities with distance outward from the central vent. Photomicrographs of three representative samples (from a larger suite collected by ACNW&M staff) are shown as Figure 52 (after ACNW&M, 2007b). The modal amount of crystals (i.e., degree of crystallinity) and the coarseness of the crystals increase with distance from the vent from about 40 vol.% to about 70 vol.% at ~1km from the vent. The presence of glass (quenched magma) is readily apparent (brown interstitial material) and this decreases in abundance with distance from the vent and increased cooling. Since viscosity effectively becomes infinite when crystallinity exceeds about 60 vol.%, the lava fragments into large blocks and moves more as a debris flow than a viscous fluid. This fragmentation increases the volume of the lava and when this occurs in a confined space, as in the subsurface or a repository drift, the lava dilates upon shear to plug the vent, stifling further flow. Dilatantcy of this nature is a common property of all granular material (e.g., Marsh, 1981).

The overall sense of these results, together with the asymptotic character of some of these curves, suggests that the viscosity range noted above may well be reasonable for degassed magma and can be used in calculations of lava travel distance and for gaining insight on the flow of magma through the repository drifts.

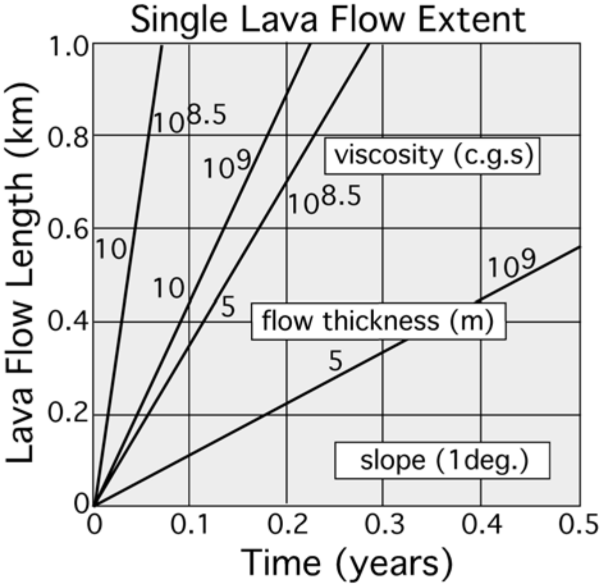


Figure 51 **The extent of flow of a single lava flow on an inclined surface as a function of time, flow thickness and lava effective viscosity (After Marsh and Coleman, 2008).**

6.2.3.4.3. Magma Flow into Drifts

In modeling the flow of magma into a Yucca Mountain repository, insight into the nature of the magma likely to be involved has been gathered from the nearby alkali basalt cinder cones. The almost universal tendency has been to use a volatile-rich basaltic magma as the characteristic magma involved in all interactions with the repository. This is the deep pre-eruptive magma containing 2-4 wt.% water and with a viscosity of 5-50 Pa·s, making it both explosive and highly mobile. Typical calculated flow velocities are 10-100 m/s (e.g., Woods et al. (2002) estimated steady magma flow speeds of 10 m/s through a tunnel by assuming 2 wt.% water, isothermal flow without quenching, and a low viscosity of 10 Pa·s). This hypothetical lava would flow a distance of 1 km in 10-100 seconds. A similar flow, assuming availability of enough magma and a continuous downhill path, would reach the outskirts of Las Vegas (150 km) in as short a time as 40 minutes. There is nothing in the character of the erupted lavas in the region of Yucca Mountain that would suggest any behavior of this nature. On the contrary, the flows from the cinder cones scattered throughout the region are exceedingly limited in spatial extent (~1 km in radius). This limited extent is also not merely due to the limited volume of these eruptions, although this is certainly partly the reason. If the Lathrop Wells governing viscosity is reduced to 10 Pa·s (e.g., as in Woods et al., 2002), keeping the volume at 0.03 km^3, the flow would have traveled 5 km in about 2 days.

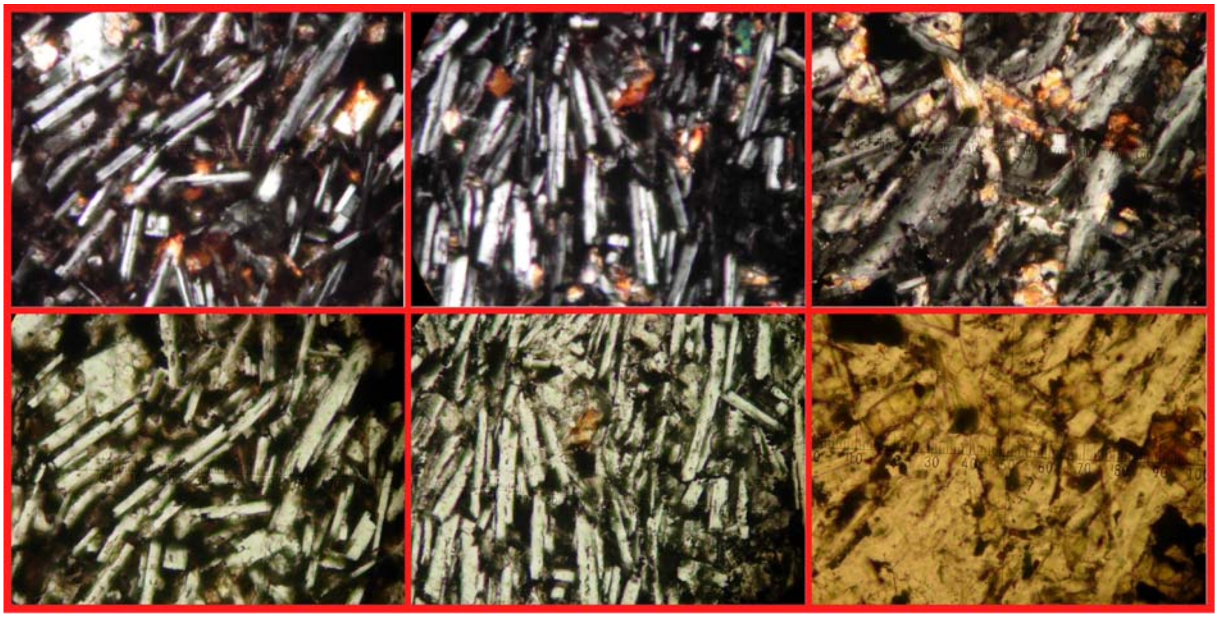


Figure 52 **Photomicrographs of thin sections of samples of lava from Lathrop Wells. The field of view in each view is ~1 mm, and the upper row is under crossed Nicols and polarized light and the bottom row are the same sections in uncrossed Nicols. The white laths are plagioclase and the brown interstitial material is glass. The left pair of thin sections is nearest the vent and the others to the right are at successively greater distances from the vent, approximately evenly spaced out to a distance of approximately 1 km. The degree of crystallinity increases from left to right from about 40 vol.% to over 70 vol.% and the crystals coarsen in size, which reflects the overall cooling of the flow with distance from the vent. As the effective viscosity becomes very large, the flow moves more as a debris flow than as a viscous fluid.**

Altogether this suggests that, should alkali basalt of the general nature of that erupted at nearby Lathrop Wells intersect and enter repository drifts at Yucca Mountain, the extent of flow would be exceedingly limited. Even based simply on the nature of the flows at Crater Flat, the lava would be blocky and sluggish and advancement would be difficult in a cylindrical drift, especially one filled with waste packages. It certainly would not be a simple case of a viscous, non-solidifying fluid flowing along a pipe. And, contrary to the analysis of Woods et al. (2002), there is no chance that the lava would undergo any form of wholesale thermal convection (Marsh, 1989; Brandeis and Marsh, 1989 and 1990; Hort et al., 1999).

Prior to the arrival of lava, however, the leading region of the ascending dike would be laden with gas and tephra. That is, should an ascending dike of water-saturated basaltic magma encounter the repository, the already rapidly quenching magma will undergo even stronger exsolution-induced quenching. Instead of fluid magma entering the drift and flowing along to eventually fill it, as in filling a bathtub, a small cinder cone would begin developing at the point of intersection. Cinders would avalanche into the drift, rapidly piling up and plugging the drift; the fragmental material will not flow far, especially given the presence of waste packages and other components of the engineered barrier. The insulating effect of the close rock wall will minimize air-fall and radiant heat loss, allowing the pile of cinders and tephra to tack or partially anneal together to form a mass of considerable strength. Magma will continue to quench on this mass of cinders and tephra. This process would form a plug in the drift, sealing the point of intersection, which would either force the magma to continue upward to erupt on the surface or simply seal off the dike locally, redirecting the flow to other portions of the dike that have already reached the surface. This sequence of events would also be expected for a scenario involving the intersection of multiple dikes with the repository.

The initial 'hole' (at the point of tunnel intersection) in the wall of the ascending dike causes a local depressurization producing a perturbation in the pressure field driving the dike upward. This pressure perturbation will travel outward into the dike, informing, in effect, the broader flow of the presence of this vent. But because the vent into the repository is small relative to the surface area of the dike (for a typical dike length of 1 km, this ratio is ~10^{-5}), this perturbation is relatively small and will not travel far in the thin (~1-10 m wide) dike before (<~1 s) the rapidly ascending dike (~km/s) reaches the nearby surface, short-circuiting the flow from the repository drift to the surface.

The formation of a plug at the point of magma entry into the repository will also allow pressures on the dike side of the plug to return to the initial pressure. The initial magma pressure within a basaltic dike at Yucca Mountain would likely be in the range of 4.5 MPa to 8.0 MPa (i.e., ~1 MPa larger than the horizontal far-field stress at repository depth) (BSC, 2004). The initial magma pressure can be approximated by the lithostatic pressure at repository depth (i.e., <7 MPa at 300 m, given a mean tuff density of <2400 kg m^{-3}). The magnitude and temporal evolution of this governing pressure is of considerable uncertainty and is also central to understanding the dynamics and rate of magma penetration into the drifts. This will be returned to again below. But, for the present discussion, the above range is sufficient for consideration of the mentioned effects. This can be compared to the expected strength of the tephra plug.

Schultz (1995) has measured the strength of the Cohassett basalt flow of the Columbia River Basalt Group. Intact basalt at 20°C and at < 9 MPa confining pressure has a compressive strength of 266 ± 98 MPa, a cohesive strength of 66 MPa, and a tensile strength of ~14 ± 3 MPa. Basalt has shear strength in the range of 20-60 MPa. A welded tephra plug need only achieve ~3% of the compressive strength or 1/3 to 1/8 of the shear strength of intact basalt to withstand the full pressure that could be exerted by magma in an adjacent dike. A compressive strength of 7 MPa, for example, is more typical of clay soils than of rocks. Increasing temperature into the melting range, however, significantly reduces the strength of basalt. The strength of partially-molten basaltic magma under tension has been estimated from a summary of experimental and observational results by Marsh (2002). At ~50% crystals strength increases from about 0.03 MPa to about 30 MPa at ~ 100% crystals and about 1000°C. For compressive strength, these estimates increase by a factor of 10-20 (e.g., Jaeger and Cook, 1979). Although these estimates hold only for massive, intact material, fragmental tephra will tend to tack together and form a continuum under these high temperature conditions.

The tephra plug also could not readily be pushed along the drift by either later higher density tephra or magma. Tephra will tend to tack to the tunnel walls and waste packages/drip shields and also be obstructed by waste packages aligned in series. More important, perhaps, is that tephra, being fragmental material at maximum packing will, like any particulate medium at near maximum packing, dilate upon shear and form a stiff plug (e.g., Marsh, 1981). The net effect is that, after a brief local perturbation, magma is most likely to continue flowing to the surface in the original dike. The area of the drift affected by the invading magma may be minimal, and the number of waste packages affected may therefore be very limited.

After the initial tephra phase, little magma would flow through the interstices of any welded tephra plug because of the high viscosity of the degassing magma, which would move as a high temperature glass.

In light of these effects it is, nevertheless, essential to appreciate a full range of possible effects that will influence the distance that magma will penetrate a typical drift. Perhaps the most extreme case is where all the dynamics of flow, cooling, and solidification are ignored and assume that magma flows from the intersecting dike into the drift at ~ 1 m^3/sec, which is the rate estimated by assuming the full volume of Lathrop Wells lava (~0.03 km^3) erupted in one year from a single vent. Magma entering an 800 m long drift of 5.5 m diameter at 1 m^3/sec would fill the drift in about 5.5 hrs. It is clear from this example that the rate of flow into the drift is important to estimate. Another, more realistic, example is to assume that magma moves through the drift just as a lava flow moves on the surface as described above in estimating the viscosity of lava moving down a slightly inclined surface. For a flow of thickness 5 m with a viscosity of about 10^8 Pa·s, the flow will travel about 100 m in a month. Here again all the effects of solidification, the presence of obstacles (waste packages), and drag due to the drift walls have been ignored.

Next we consider viscous magma flowing in a cylindrical drift with an effective initial diameter of 3.5 m that reduces in time due to the effects of solidification. The rate of solidification is modeled to agree with all results from measured rates from Hawaiian lava lakes (e.g., Wright and Okamura, 1977) and lava flows (e.g., Hon et al., 1994). The flux of magma flow is calculated as a function of time, magma viscosity, and the magnitude of the driving pressure; the penetration distance is found by normalizing the time-integrated flux to the drift volume per meter. The flux (Q) is controlled by several variables that are best appreciated by considering the following simplified equation.

$$Q \sim (\Delta P/L)\, a(t)^4/\mu$$

Here, ΔP/L is the horizontal pressure gradient driving the flow, a(t) is the effective drift diameter which varies with time due to solidification, and μ is the effective viscosity of the magma. Methods of estimating magma viscosity have already been considered during the later stages of ascent and flow on the surface as lava. The possible effect on the overall drag of the gravity slump at the leading free surface of the magma flow as it enters the empty drift is ignored. This can be in some instances an important effect (Lejeune et al., 2002), but for the large viscosities anticipated here the front will be steep and will only further impede flow. There is also the possibility that, if the dike is under a large pressure gradient when it encounters the drift, the sudden pressure reduction in the dike flow with the transition to the atmospheric pressure of the drift may cause pinching or collapse of the dike locally and/or also fracturing and collapse of the wall/drift rock at the dike (Woods et al., 2002).

Of these critical parameters, the driving pressure is perhaps the most difficult to estimate; ΔP is the pressure difference acting, in effect, over a distance L along the flow. At one extreme ΔP is the pressure difference ($\Delta P = \rho g h$) created by gravity acting on a standing (i.e., hydrostatic) column of magma (of density ρ) extending from the drift at a depth of h (=300 m) to the surface, which for a magma density of 2500 kg/m^3 amounts to about 7.35 MPa (=ΔP). If, once established, this standing column is suddenly allowed to flow into the drift, the governing driving pressure is that acting over the distance L (i.e., $\Delta P/L$). If L is allowed to become exceedingly small, the local pressure gradient becomes enormous and the flow, over a short distance is exceedingly rapid. (Recall in the earlier discussion that if L is allowed to approach zero a shock wave can be generated.) As the flow develops, the length L increases and the pressure gradient systematically lessens.

At another limit is the pressure gradient driving a lava flow down an inclined slope; here $\Delta P \sim \rho g\ h \sin(\theta)$, where now h is the thickness of a lava flow (~10 m). This pressure difference, for ρ = 2500 kg/m^3, and a slope of 5°, amounts to about 2.5 x 10^{-2} MPa. This is 300 times smaller than the previous estimate based on a standing column of magma extending from the repository to the surface. That is, the two estimates of driving pressure gradients are equivalent when the length scale L in the first estimate is 300 m. Results for the penetration distance of magma into a drift are given in Figure 53 where the effects of solidification on the effective diameter of the drift are taken into account (the full formulation is given by Marsh and Coleman, 2008).

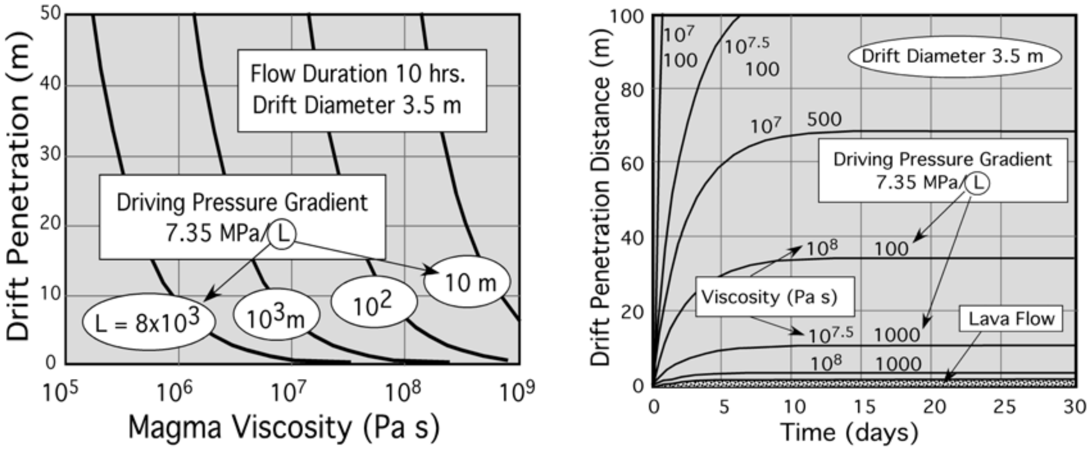


Figure 53 **The penetration distance of magma into a repository drift as a function of magma viscosity (left panel) and as a function of time (right panel). Each panel covers a range of pressure gradients, denoted by the effective length scale L, covering those possible for various styles of magma flow discussed in the text. The left panel (LHS) is for a flow period of 10 hours, and the right panel covers a range of specific viscosities. The initial effective drift diameter is 3.5 m in all cases. For magma flowing as a lava flow, the penetration distance is indicated on the lower part of the right panel (After Marsh and Coleman, 2008).**

The strong effect of the pressure gradient is clear in these results. As L decreases and the pressure gradient increases, penetration distance for any viscosity increases strongly. For a magma viscosity of 10^8 Pa·s and L = 100, the penetration distance is about 35 m. If L is increased to 1000, penetration decreases to less than 5 m, and if L further increases to about 3000, as for a lava flow, the penetration distance is only a few meters or less. If viscosity is decreased to 10^7 Pa·s and L = 500, the magma penetrates about 70 m into the drift. In the actual process the driving pressure will decrease in response to the evolution of the flow. Others have also noted the difficulty in estimating this governing pressure gradient. Detournay et al., (2003) discuss this is some detail and mention the possibility that, because of the porous and permeable nature of the wall rock, the leading edge of the ascending magma-filled dike (after the dike has been established) may be at or near atmospheric pressure at the level of the drift. This would make the dynamics of inflow more akin to a lava flow. And they go on to estimate this driving pressure by relating it to the head (h) of magma above the drift that results from the interaction of the ongoing dike flow and magma loss into a series of drifts.

The best estimate of the drift penetration distance comes from a full consideration of a specific eruption scenario and not simply from an isolated calculation detailing a specific physical part of the entire process. For example, any eruption is most likely to commence as a gas-rich tephra and agglutinate-laden Strombolian phase. This will deposit, and possibly plug as discussed already, a great deal of material in the drift at the intersection with the dike. As this Strombolian phase wanes and dense magma approaches the surface and reaches the level of the repository, the magma may well lack sufficient driving pressure to reach the surface all at once (as observed at Paricutin), and it may flow into the repository drift as a lava flow. The overlying dike to the surface, will be filled with porous tephra and agglutinate, the dike walls would suffer permanent (i.e., unrecoverable) deformation, and the overpressure may approach atmospheric pressure at the repository depth of 300 m. That is, the overlying dike may be structurally more like an open mineshaft than a fluid-filled column under hydrostatic pressure. The presence of pre-existing deposits of tephra will greatly subdue the effective pressure gradient driving the magma laterally and will also act as a granular plug to stifle progress of the magma. In addition, with approach to this depth the magma, still saturated with water (it will contain ~ 0.5-0.7 wt.% water), will be degassing through rapid vesiculation and crystal growth and/or glass formation. Degassing may be by rapid gas escape through tiny cracks throughout the basalt. If vesiculation occurs, it would cause a significant increase in magma volume that will go to further plugging of the drift, greatly decreasing the penetration distance. If the drift is sealed by plan or accident, there is also the possible effect of the inflow being resisted by progressive compression of the air by the advancing flow. Lejeune et al. (2002) show that this could be a major effect in retarding the inflow, regardless of fluid viscosity. Throughout this process, the driving pressure will change in concert with the motion of the magma itself. To properly estimate the penetration distance of magma flowing into the drift, each of these effects and factors must be simultaneously taken into account. With due care and insight into the physics of magmatic processes with consideration of the full eruptive scenario this can be done, but it has not been so far attempted by any group.

In summary, these calculations suggest the high-velocity entry of magma into repository drifts is unlikely. Any flow of magma into drifts would be sluggish and of limited extent, perhaps reaching only a few tens of meters depending on the driving pressure. Alternatively, it is likely that a tephra plug could form at the point of dike intersection with a drift, potentially sealing off the drift from magma entry.

6.2.3.4.4. Quenching Effects on Waste Packages

Magma on and near the Earth’s surface is always experiencing crystallization. There is no natural way to arrest crystallization. All sudden local changes in temperature due to cooling of any kind will cause enhanced crystal nucleation and/or glass formation, if cooling is rapid enough. This is the process of quenching, and magma in this state quenches on all that it touches from water to trees to other cooler solid objects (Figure 54). Geologists at Hawaii, wanting a sample of an active lava flow, will throw a hammer on a long wire into the lava and immediately retrieve the hammer containing a grapefruit size mass of lava quenched on the cool hammer. Hawaiian magmas contain relatively little dissolved water (<~0.5 wt.%) and the lavas erupt at much higher temperatures than is anticipated for the magmas common to the Yucca Mountain region. As discussed earlier, the magmas anticipated for the Yucca Mountain area are likely to be much more water rich than Hawaiian magmas and will erupt at much lower temperatures, making them much more responsive to quenching.

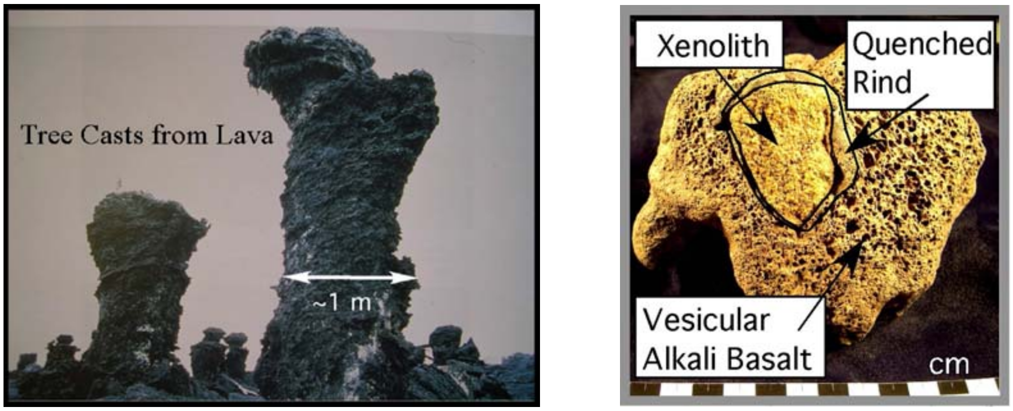


Figure 54 **Photos of quenched magma. Examples of magma quenching on trees in Hawaii (left) and on a piece of wall rock from the upper mantle (right). Lava quenches against the trees that burn away to leave a cylindrical column of glassy basalt. Foreign pieces of rock (xenoliths) are common in many basalts and are commonly encased in a layer of quenched magma (left panel is from Takahashi and Griggs, 1987).**

Quenching will occur on all surfaces with which the magma comes in contact, even on the waste packages at the their highest anticipated temperatures (~200°C). The rate of quenching is rapid and is given by an equation of the form: $t = (C(\kappa)^{0.5})^{-2} d^2$, where t is time (secs), C is a constant, κ is thermal diffusivity, and d is the thickness of the quenched rind. The form of this equation holds for a wide spectrum of situations involving solidification (e.g., Carslaw and Jaeger, 1959). The group $C(\kappa)^{0.5} = 1.87 \times 10^{-4} T - 6.58 \times 10^{-2}$, where T is a particular isotherm in °C and the overall units are cm-sec$^{0.5}$ (after Wright and Okamura, 1977; Mangan and Marsh, 1992; Hon et al., 1994; and Marsh and Coleman, 2008). Example calculations from this formulation are given by Figure 55. A quenched rind of a thickness of 10 cm will form on a waste package and on the drift walls in about one minute. With time the rind will continue to thicken, although the rate of growth, as in any diffusively-controlled process, will systematically diminish. It is emphasized that the magma need not completely solidify to form a stagnant quenched rind, but only have its temperature reduced to near the solidus, which will render it stagnant as a crystal-bearing glass. Moreover, the proper thermal conditions leading to quenching are significantly enhanced by the anticipated nature of the magma, which is thought to be initially water rich and erupt at or near the solidus temperature.

Once formed, there is also the question of the possible later reheating or ‘burning back’ of the quenched rind. Because of the anticipated nature of the magma, in terms of temperature and duration and style of eruption, this is highly unlikely. The high viscosity of the magma ensures that any flow will be sluggish and cooling will be by conduction with or without latent heat depending on the extent of crystallization and glass formation. There is no possibility of the magma undergoing thermal convection (Marsh, 1989; Hort et al., 1999). When magma touches a cooler surface the temperature at the interface or contact becomes approximately the average of the two initial temperatures. That is, the interface temperature $T = 0.5 (T_1+T_2)$, where T_1 and T_2 are the initial temperatures of the magma and object contacted. This is a well known result (e.g., Jaeger, 1968; Turcotte and Schubert, 1982; Marsh, 1989). Strictly speaking, this result only holds if there is no latent heat of crystallization involved, and if latent heat is included the constant changes to 0.65. For magma at 1050°C and a waste package at 200°C, the interface temperature will be about 650°C, which is far below the magma solidus temperature, promoting massive quenching. In the cooling of two juxtaposed planar sheets of material, this temperature does not change until the cooling front has reached the center of the hotter body and then this contact temperature slowly decreases with time. This condition of planar sheets is not met for magma against a cylindrical waste package in a repository drift, but it is approximately met for a rind that is thin relative to the radius of curvature of the waste package. An estimate of the actual magma temperature necessary to reverse cooling can be determined by finding the conditions when cooling is arrested, which can be determined by employing the well known Schwarz solution (Carslaw and Jaeger, 1959). The most general result shows that for no quenching, the sum given above (i.e., T_1+T_2) must be twice the melting temperature of the wall material. If the quenched rind is taken as the wall material at a temperature of 650°C, which at the very least has a 'melting' temperature of 1050°C, then the magma temperature must be about 2100 - 650 = 1450°C, which is well beyond the eruption temperature of any known terrestrial basaltic magmas.

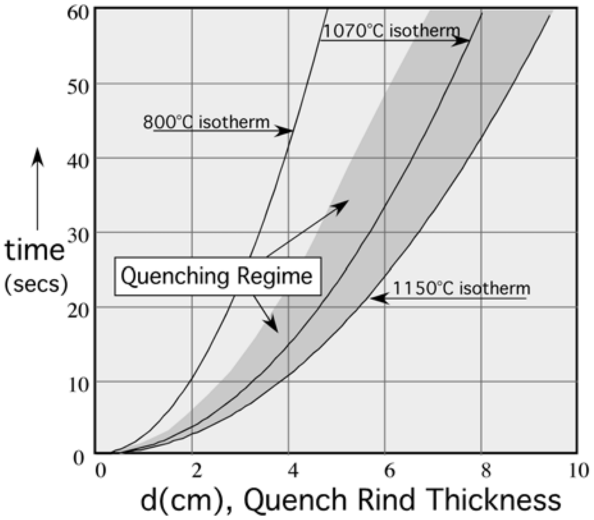


Figure 55 The time to grow a quenched rind on a cool surface as a function of time for a basaltic magma or lava. A quenched rind about 10 cm thick will form on a waste package in about 1 minute (After Marsh and Coleman, 2008).

Quenching on the walls of the drift will also occur and there is the question of the effect of earlier radiant heating by ash and tephra on quenching. The drift wall could, in effect, be possibly heated enough to become insulating. Although the problem needs to consider the full development of the eruptive scenario, surficial heating of the drift wall will produce a thin skin of high temperature (less than the magma temperature) that will dissipate quickly. In essence, upon contact with magma this skin thickness will, in a thermal sense, become part of the magma thermal anomaly, which will be quickly dissipated by the reservoir of underlying cooler wall rock. If magma were to enter a drift, the cool wall rock reservoir would produce a classic thermal entry effect, which is very much unlike the flow of magma in lava tubes. The much hotter wall rock of lava tubes on long-term active volcanoes like Etna and Kilauea cannot be used as analogs for flow in repository drifts.

Although the effect of quenching has been considered in various earlier investigations, primarily by the DOE, the context under which it has been studied has generally been under the unrealistic assumptions that the inflowing magma will be of unusually low viscosity and will be much hotter than anticipated herein for hydrous basalt. Because of these assumed conditions, magma has been generally inferred to flow at 10 – 100 m/s (i.e., 22-220 mph).

6.2.3.4.5. Secondary Venting and Magma Flow in Drifts

It is useful to consider the potential paths that magma may take if it encounters the repository. Magma flow along a drift, filling and over-pressurizing or re-pressurizing the drift to the degree that a new fissure is forced to the surface forming a secondary vent has been described earlier (see Section 3.3.4) in connection with the so-called ‘dogleg’ scenario. But there is also the possibility that a secondary vent might develop as a natural consequence of the volcanic process itself (e.g., Fiske and Jackson, 1972; Ryan et al., 1981). That is, once the magma in the ascending dike breaches the surface the eruptive flow has the natural tendency to concentrate into a single vent, which gives rise to the common occurrence of cinder cones and the associated lava flows. But it is also not uncommon to find systems that form a secondary, commonly less powerful, vent along the initial fissure at some distance from the main central vent. This apparently occurs in response to, in effect, ‘capping’ of the initial vent by the volumetric weight of erupted materials. Sustained pressure in the ascending magma reopens the initial fissure and the eruption moves to a new location, although simultaneous eruption from both vents is also possible. Secondary vents could also form in response to further lateral propagation at depth of the magma-filled dike as it moves into areas of new topography that are conducive to venting. An example of this latter process has been modeled by Gaffney and Damjanac (2006). They show that for the topography characteristic of Yucca Mountain the flow to an initial vent at higher elevations might, in effect, be siphoned off by a vent at lower elevations at some distance from the repository. If the dike associated with the new vent transects the repository, a secondary conduit might form. Secondary vents are generally significantly weaker and shorter lived than primary vents. The possibility that magma would flow from the primary vent to the new vent, using repository drifts as an interconnecting conduit, is unlikely in the face of the constraints imposed by the highly viscous nature of the expected magma. This process, nevertheless, has been considered by the DOE (2004; Dike-Drift Interactions) and by NRC (2005a; e.g., p. 47) in response to the DOE and the wider implications of the possible ’dogleg’ scenario of Woods et al. (2002). The NRC has also discussed this possibility at length in letter IA.2.18 (10 January 2005) addressing an Igneous Activity Key Technical Issue (hereafter Kokajko, 2005b).

The concept of a secondary vent is sometimes synonymous with a satellite or Bocca vent, stemming from the formation in 1968 in the central crater of Mt. Etna of a second eruptive pit or Bocca Nuova (i.e., New Mouth) accompanying the original Chasm pit (La Voragine), which was established in the 1950’s. Interest in the formation of a secondary eruptive vent at Yucca Mountain centers on the greatly increased exposure of waste packages to magma were it to flow a considerable distance along a drift (perhaps several hundred meters) and then vent to the surface at a secondary vent. The steady flow of magma, even at a slow rate along the drift, could possibly expose waste packages to unusually prolonged high temperatures. The dynamics of this process was treated in some detail by Detournay et al. (2003) and subsequently more extensively by DOE in their Dike/Drift Interactions report of 2004. Although each group found that a flow of this type was highly unlikely, the NRC (e.g., NRC, 2005a, p. 43-57) discusses this issue in a way that suggests this process may indeed be possible and perhaps even likely. This is evidenced in the following NRC discussion of the DOE results.

From NRC (2005a), page 43:

> In addition, some physical conditions could potentially result in horizontal flow of magma along a drift, with a conduit forming some lateral distance away from the point of initial intrusion intersection (Woods, et al., 2002). Although conditions for this horizontal flow pathway now appear less likely to occur (BSC, 2004), **if this process occurred**, it could affect a significantly larger number of waste packages than a

> simple vertical conduit. Damage to waste packages intersected by a subvolcanic conduit likely occurs from the high thermal and mechanical stresses created by a basaltic magma during an eruption (e.g., BSC, 2003d). Although detailed process models for these effects have not been developed, available information indicates the current waste package design would not provide the physical integrity necessary for waste isolation after direct entrainment in an erupting volcanic conduit (BSC, 2003d; NRC, 1999). [**boldface added]**

And from page 54:

> An alternative conceptual model for magma ascent at a location away from the point of initial drift intersection is proposed by Woods, et al. (2002). This model is based on consideration that topographic variations above a drift could potentially result in stress conditions more favorable for magma ascent at a location away from the point of initial drift intersection. The significance of this alternative model is horizontal flow paths along a drift could be significantly longer than 150 m [492 ft], which is the maximum diameter of subvolcanic conduits, and thus entrain more waste packages than modeled by a simple vertical conduit. DOE provides extensive evaluation of this alternative conceptual model in BSC (2004). This evaluation uses the same hydrofracture model used to evaluate the initial ascent of magma. This model concludes that if a fracture were to occur at the distal end of a potentially intersected drift, magma could ascend through this fracture once the drift was filled. However, magma also would continue to simultaneously rise along the original plane of intersection. The rate of magma ascent along the distal fracture would be no more than half the ascent rate as modeled along the original plane of ascent because magma in the distal fracture is supported only by magma in the potentially intersected drift. In contrast, magma in the original vertical fracture is supported by magma from depth, which gives a larger effective fluid pressure to dilate the fracture. Thus, magma modeled along the distal fracture will likely cool more rapidly, and ascend much more slowly, than along the original plane of ascent. These effects will cause the magma along the original ascent fracture to reach the surface well before magma along the distal fracture can ascend far from the drift. The DOE model concludes magma ascent to the surface along a distal fracture appears highly unlikely, relative to continued ascent along the original vertical fracture. Based on the mechanical analysis presented in BSC (2004), **conditions for this alternative conceptual model currently appear less likely to occur than conditions for the model of continued ascent along the original plane of ascent**. [**boldface added**]

Moreover, the key feature in the NRC perspective is that, although the ‘dogleg’ scenario as analyzed by the DOE and the ICPR may be highly unlikely during the initial eruptive phase (i.e., “initial minutes” KTI IA.2.18, p. 5), at any later time in the eruptive cycle, perhaps days to months later, a secondary eruptive center or vent may yet appear. They base this perspective on the occasional occurrence of this style of activity at other, perhaps comparable, volcanic centers, like Tolbachik and Paricutin and even nearby Lathrop Wells. In the latter case, more detailed recent work has not found evidence of secondary vents (Valentine et al., 2007). The physics behind this NRC perspective is that whereas in the initial phase of the eruption the driving pressures in the shallow dike system drop significantly once the ascending dike reaches the surface, later flow will fill breached drifts with magma to the point of producing sustained overpressures large enough to “dilate secondary fractures in the drift walls” (KTI IA.2.18, p.5). The sustaining of these over-pressurized drift conditions throughout the entire volcanic event, the NRC feels, provides the necessary conditions for secondary breakouts to appear at any time “throughout the duration of the volcanic eruption” (KTI IA.2.18, p.5). The NRC bases these findings on a series of research efforts by Woods et al. (2002; 2004; 2006), Bokhove et al. (2004) and Lejeune et al. (2002).

The primary aspects of these works deal with two broad subjects: 1) the ascent of an isothermal, isoviscous fluid (e.g., 30 Pa·s; Bokhove et al., 2004) in elastic wall-rock or as in the filling of a drift; and 2) the ascent of bubble-rich, isothermal and isoviscous fluid in terms of acceleration of the fluid due to bubble expansion and coalescence. Although there are aspects of these works that are valuable to understanding magma ascent and eruption in a broad perspective, several fundamental features of this work may make it of limited usefulness to understanding the possible behavior of magma at Yucca Mountain. First the fluids used are isothermal, isoviscous, and of low viscosity. As discussed already, volatile-rich basaltic magma, which these cited studies are intended to simulate, will be undergoing severe pressure quenching (i.e., rapid solidification) as it ascends and de-volatilizes with approach to the surface in the vicinity of the drifts and its viscosity will be increasing exponentially. The magma will either fragment, if the gasses cannot escape, quench to a glass, if the gas escapes and ascent is rapid enough, or quench to a glass containing myriads of tiny acicular crystals (i.e., plagioclase microlites (Figure 52)). Second, elastic-walled dike work is premised on the assumption that the dike is connected to a deeper, large magma chamber feeding magma to the dike and also supplying overpressure to propagate the dike and, in some respects, act as a shock absorber in the system. The existence of a deep-seated, large volume magma chamber is highly unlikely in the small volume, cinder cone volcanisms characteristic of the Yucca Mountain region. Third, the longevity of magma residing in a drift as a molten material is very short. Taking an extreme conservative example, if Hawaiian lava were to quickly fill a drift it would solidify in about 25 days. Hawaiian lava is much hotter, of much lower viscosity, and further from solidification than the hydrous, low temperature basalt anticipated at Yucca Mountain. Because of the extreme rate of pressure quenching, this basalt will already be near solidification and its longevity in a drift as mobile magma will be hours to days (Figure 47 and Figure 53). Thus the time is severely limited over which a magma-filled drift can be sustained in a pressurized state to allow inception of a secondary fracture into which magma can flow to establish a secondary vent on the surface. More of the quantitative reasoning behind this conclusion can be gained from an appreciation of complementary work on this process by Detournay et al. (2003) and the DOE. And although the NRC relegates the relevance of some of these results mainly to the very early or initial phase of the magmatic event, they do, in fact, have a bearing on the full cycle of the event. In this context there are three critical processes to consider: (1) the flow of magma into and along the breached drift to fill and pressurize the drift, (2) the initiation of a new fracture in the drift roof or wall, and (3) the flow of magma to the surface in this new fissure. Each of these issues is considered in turn.

6.2.3.4.5.1. Flow of Magma to Pressurize the Drift

The rate of flow of magma into a breached drift will depend, as discussed above, on the pressure gradient driving the magma, the viscosity of the magma, and the rate at which magma is supplied from the parent dike. The first two of these parameters have been discussed at length above and here it is important to contrast them with the DOE model assumptions and results. First, almost without exception the DOE assumes a magma viscosity of 10 to 40 Pa·s (BSC, 2004a, Table 6-2), which follows from similar values assumed by Detournay et al. (2003). The DOE summarizes their findings (BSC, 2004a, p. 6-111):

> The rate of magma flow into drifts will be limited by the rate of magma supply, except probably when the supply is very large (*v* [deep velocity] on the order to [sic] 10 m/s) and the magma viscosity is high (on the order of 40 Pa·s). The time needed to fill 500 m of drift will be on the order of 15 minutes for a magma velocity of 1 m/s. It obviously depends on the supply rate, and the results can be linearly scaled to other drift lengths.

A central part of the calculation leading to this summary is that the flux supplied by the main dike is equated to the flux into the drift, with due care for the geometric transition as outlined by Detournay et al. (2003). And since in this calculation the viscosity of the magma is uniform (10-40 Pa·s) for all the magma, regardless of the rate of degassing and the effect of rapid quenching by depressurization, the supply rate essentially controls the entire process. For supply rates based on magma flow in the dike of 1-10 m/s, within 10 seconds of breaching the flux into the drift reaches, respectively, 50-1000 m^3/s, filling the drift to 10-50 m in this time (BSC, 2004a, Figures 6-50 and 6-51). At the same time the magma in the central dike rises to, respectively, 2 m to 300 m above the drift. The effect of the presence or absence of waste packages and whether the viscosity is 10 or 40 Pa·s has relatively little effect on the results. But this influence will change markedly if the viscosity of the dike magma increases strongly with loss of pressure and approach to the drift and surface. Repeating this calculation in this case, where the viscosity is changing strongly, will make the region with the largest viscosity, which is the drift, the rate-controlling region for flow. This was also emphasized by Detournay et al. (2003, p. 56):

> The sustained propagation of a secondary dike requires considerations beyond the simple condition that the magma pressure in the drift has to exceed the normal stress across the fracture. The supply of magma into the drifts and up to the primary dike above the repository is best characterized as flux-limited.

In their brief analysis of the possible effects of increased viscosity due to cooling and crystallization in the primary 'dogleg' scenario, the DOE indeed came to a similar conclusion (BSC, 2004a, p. 6-144):

> The effect of only 10 to 20 percent of crystals on the rheology of the partially crystallized magma is dramatic. This increase in percent crystals results in an increase in viscosity of 1.5 to 2 orders of magnitude, a roughly indicated by the highlighted region in Figure 6-75.

And on the same page:

> In light of the very rapid increase of apparent viscosity as temperatures drop, the temperature at which the apparent viscosity reaches 1000 Pa·s has been chosen as *T*s [solidification temperature] in Table 6-11.

That is, they consider that with an increase of viscosity to 1000 Pa·s, the magma can be taken as being solidified and thus no longer mobile. And from the earlier detailed discussion of magma viscosity during ascent (Figure 43, Figure 44, Figure 46, and Figure 47), the viscosity will certainly exceed 1000 Pa·s. Sparks (2007) also concludes that the viscosity at the drift depth will be beyond this limit. The rate of filling the drift is thus greatly reduced, and the movement of magma along the drift is similarly reduced (Figure 53).

6.2.3.4.5.2. Initiation of a New Fracture in the Drift Roof or Wall

If the magma in the drift is of high viscosity and in essentially a solid state, as suggested here, the drift cannot be properly pressurized to produce the conditions necessary for initiation of a new fracture and to transmit magma to the surface. In the DOE analysis of the conditions necessary for this process they investigated the rate of opening of new fractures relative to the arrival of the primary dike to the surface and thus short-circuiting magma from breached drifts to the surface. They explore the effects of several prime physical properties, including wall rock elasticity, initial crack width, and magma viscosity. They find (BSC, 2004a, Figure 6-61, and p. 6-129):

> Because a dimensional and scaling analysis was not carried out, simulations of Cases 116 through 120 were conducted to investigate the effect of an increase in magma viscosity from 10 Pa·s to 100 Pa·s. As expected, an increase in magma viscosity results in a proportional increase in time scale. For example, in Case 103 (viscosity 10 Pa·s) it takes 13 s to reach a 10-mm thickness increase; whereas, in Case 117 (viscosity 100 Pa·s) the thickness increase is reached after 130 s.
>
> Even if the argument of magma freezing is not used, among all of the 20 analyzed cases, only in Cases 103 and 112 to 115 does a magma front inside the joint move faster than 0.5 m/s. That result implies that the magma front inside the original dike (which could also be 80 m or more above the repository level) will reach the ground surface much sooner than the magma injected into joints inside the drift.

Raising the viscosity still higher to the range of > 10^4 Pa s, as suggested earlier and by Sparks (2007), will proportionally reduce the potential crack propagation rate to rates of less than $5x10^{-3}$ m/s, making this process not competitive with the main dike flow.

6.2.3.4.5.3. Flow of Magma to the Surface in the New Fissure

If magma is going to reach the surface in a fracture newly generated from a drift roof or wall, it must be able to avoid solidification as it enters and traverses to the surface. This is exceedingly difficult in small cracks because the cooling time is vanishing small and the new dike immediately fills with quenched magma, stalling any further advance. Both the DOE (BSC, 2004a) and Detournay et al. (2003, p. 56) evaluate this effect and come to the same conclusion:

> An important consideration relevant to magmatic dog-legs is that it is very difficult to start a dike in cold rock. In order for a dike to escape an early thermal death, it must widen elastically (due to propagation of the tip) faster than it freezes shut. Flow of hot liquid through a cold channel can be divided into a thermal entrance region, where most of the heat still resides in the liquid, and a downstream region, where most of this heat has been lost to the surroundings. The thermal entrance length [*this is the distance over which a fluid adjusts to a sudden change in wall temperature*] is proportional to the product of the flow velocity and the cooling time, where the latter is proportional to the channel thickness squared. For a dike driven by a constant-pressure source, both the flow velocity and dike thickness are proportional to length. Thus, the thermal entrance length is proportional to the dike length cubed, and sufficiently short dikes are always longer than the thermal entrance length and near the temperature of the host rock (Rubin, 1995). In Appendix 3.4, we estimate that basaltic dikes in cold rock would not widen elastically faster than they freeze shut until the dike length was tens of meters and the thickness several centimeters. As a concrete example, a typical dike thickness:length aspect ratio is ~ 1:1000, and a typical propagation velocity for a km-scale dike is 1 m/s. A reasonable estimate is that a 1-m long dike is ~ 1-mm wide, propagates at ~ 1 mm/s, and widens at ~10^{-3} mm/s. The chilled margin in the same dike would reach 1 mm (the dike thickness) in ~ 1 s. Such a dike could not grow. This is not an argument that dikes cannot form — clearly, they do. However, those that survive thermally must satisfy conditions …. that cannot easily be met by dikes initiating from a drift.

The DOE (BSC, 2004a, p. 6-145) finds that “Clearly, such cracks will not be able to grow to any appreciable width before they are halted by solidification.”

And further on this same page in their overall synthesis:

> Comparing this growth history for a constant viscosity magma with the results of the chill-zone growth rate, it is seen that the dike will never be able to propagate more than a few meters from the drift because the magma will chill rapidly, blocking off the

> flow of fluid to drive the crack growth. Note, however, that the effect of advection on the heat balance has been neglected in deriving this result.

Neglecting the thermal effect of advection, which is forced convection of magma within the growing dike, is clearly warranted by the large viscosity of the magma.

In summary, although the analysis of DOE (BSC, 2004a) and Detournay et al. (2003) was primarily concerned with the formation of a secondary vent branching from a drift early in the eruptive episode, the basic physics and thermal considerations are, for the most part, applicable at all times during the volcanism. Drifts will be difficult to fill to a sustained overpressure state; new elastic cracks will be difficult to initiate in drift walls; and magma were it available, would quench and stall in new-forming cracks. The basic magma physics underlying this work is well founded. It is therefore unlikely that a secondary vent branching from a drift will form at any time in the style of volcanism expected at Yucca Mountain. The principal means of magma transfer in the near-surface region is expected to be through the main system of dikes.

6.2.3.4.6. Overview

There are two broad areas where almost all specific approaches to the evaluation of igneous consequences can be improved. The first is in appreciating the full implications of the phase equilibria of ascending hydrous basaltic magma. The strong effect of water on greatly lowering the temperature of the magma as it approaches Earth's surface, beginning at depths of about 5 km, colors all further analysis regarding eruption scenarios, magma viscosity, and quenching. Aspects of magma flow, cooling, and general behavior from studies of Hawaiian and Etna lavas cannot be assumed to hold also for Yucca Mountain magmas. In prior studies, almost universally, the magnitude of magma viscosity has been underestimated by a factor of 10^4 to 10^5, depending on the specific process being considered, and the strong quenching character of the magma has been similarly underestimated. Second, it is important to place individual studies in as realistic a context as possible within likely eruption scenarios. For proper realistic quantitative analysis, most specific aspects of magma ascent, drift intersection, drift penetration, degassing, tephra formation, lava effusion, and other more detailed processes each depend on the full sequence of processes attending magma delivery, extrusion, and solidification. The initial conditions assumed in each simulation are critically important to the outcome. Yet in most quantitative studies the initial conditions have been assumed in isolation to the remainder of the eruptive scenario. In this context, the eruptive scenarios based on field geology proposed by Valentine and associates for the Crater Flat basin and Lathrop Wells cones are highly valuable. But there have been no similar detailed petrologic studies of the lavas themselves. All consequence scenarios rely heavily on the inferences of the experimental study by Nicholis and Rutherford (2004) that the Crater Flat magma may have contained 2-4 wt.% water. This is based on the occurrence of amphibole in Crater Flat lavas. However, inspection of a suite of thin sections of lavas from Lathrop Wells found no amphibole, and the study often referenced by Vaniman et al. (1982) is primarily concerned with geochemistry. Sophisticated, detailed petrologic studies involving geothermometry, crystal size distribution analysis in concert with heat transfer, need to be carried out on these lava fields. Studies as described above would lead to further reduction of uncertainty in igneous consequences.

6.3. Effects from an Extrusive (Volcanic) Event

The extrusive scenario involves the intersection of a tephra-cone-forming volcanic vent (i.e., conduit) with the repository drift (see Figure 6). The transition from flow in dikes to vent flow occurs early in an eruptive sequence, and vents form under various conditions. In low-viscosity basalts, the transition may occur when narrow parts of the dike freeze followed by mechanical and thermal erosion of wider sections as the flow is repartitioned (e.g., Bruce and Huppert, 1990). A key difference between a volcanic conduit and a dike is that the diameter of a vent is much smaller (generally <75 m) than the length of a dike (1-5 km or more). Given a repository drift spacing of >50 m, a vent could directly intersect only one drift and a relatively small number of waste packages in the cross-sectional area of the vent. New work to be reported in DOE's ANL-MGR-GS-000002, rev. 03 (under review at DOE) supersedes the DOE range of conduit diameters at repository depth with a lower mean value based on recent analog studies (ACNW&M, 2007).

Due to the perceived complexity of the processes involved, both NRC (Mohanty et al., 2004) and DOE (2003) assume that the small number of waste packages (approximately 1-10) entrained within a conduit would be completely destroyed and the contents carried to the surface and ejected as tephra of varying sizes. DOE has commented (ACNW&M, 2007) that it is important to keep in mind the range of dynamics in a conduit and the period of time (months to years) during which magma in various forms could interact with waste packages. The degree to which ceramic or glass waste forms could be reduced to fine particulate materials in a volcanic conduit is uncertain, particularly during the first 1000 years when the waste packages and waste forms should still be relatively intact (see additional discussion in Section 6.3.3, Comments on Potential Fate of High-Level Waste in a Volcanic Conduit or Vent). The manner and degree to which the fragments would be incorporated in volcanic tephra is uncertain, but would involve the well-known phenomenon of magma quenching.

6.3.1. DOE and NRC Approaches

The DOE has estimated that the median number of waste packages that would be disrupted in a volcanic eruption scenario (i.e., intercepted by a conduit) is fewer than 10 (DOE, 2004; Number of Waste Packages Hit by Igneous Intrusion). The NRC has determined that the number of waste packages affected by an extrusive volcanic event would have high significance to waste isolation because the consequences are directly proportional to how many waste packages would be intersected by an erupting volcanic conduit. Apparently due to the complexity of the processes involved, neither the NRC (Mohanty et al., 2004) nor DOE (2003) rely on evaluations of magma-drift-waste package interactions in any detail. They instead assume that a small number of waste packages are completely destroyed and the contents are carried to the surface via a volcanic conduit in a cone-forming event. Nevertheless, it is as yet unclear how or whether the Alloy-22 waste packages or the ceramic or glass waste forms themselves would be reduced to particles of respirable size, as is currently assumed by the DOE and NRC.

The number of affected packages is estimated based on observed conduit size at analog volcanoes. Alternative models of how a volcano may interact with repository drifts and develop a conduit could increase the number of entrained waste packages and thus increase the concentration of radionuclides in erupted ash. The following material is from NRC (2004):

> Normally, in the absence of subsurface drifts, volcanoes form roughly cylindrical conduits along the vertical plane of magma ascent. Based on analogy with deposits at active or deeply eroded volcanoes, the NRC staff determined that conduit diameters from 5 to 50 m represent the most likely range of diameters for a potential future eruption at the potential repository site (NRC, 1999; Doubik and Hill, 1999). In contrast, DOE considers potential conduit diameters up to 150 m, albeit with very low likelihoods of occurrence (e.g., CRWMS M&O, 2000b; DOE, 2003). Actively erupting volcanic conduits have high temperatures and large physical stresses that most likely would completely disrupt any waste package directly intersected by the conduit

> (NRC, 1999; CRWMS M&O, 2000b). Thus, both NRC and DOE have concluded that any waste package entrained in an erupting volcanic conduit would reasonably fail to provide containment and release its contents into the rapidly flowing magma.
>
> Open drifts at depths of 300 m could potentially cause magma ascent and flow processes to behave differently than in undisturbed geologic settings, because rising magma is a fluid with an overpressure sufficient to fracture and dilate surrounding wall rock. Intersection with a subsurface drift at essentially atmospheric pressure provides a horizontal pathway out of the original plane of vertical magma ascent, allowing flow localization and nonequilibrium expansion of volatiles (NRC, 1999; Woods et al., 2002). Using the alternative conceptual model [dogleg scenario] from Woods et al. (2002), magma could potentially flow down an intersected drift and break out at some point away from the point of original intersection. For randomly located points of intersection and breakout and a single drift containing 155 waste packages, an estimated average of 51 waste packages would be located along the alternative flow path. In contrast, a normal, vertical conduit would intersect an estimated average of 4.5 waste packages using the TPA Version 4.1j code. There is a directly proportional relationship between the number of waste packages entrained and conditional dose (i.e., dose not weighted by the probability of scenario occurrence). This sensitivity appears reasonable, as the mass of high-level waste potentially entrained is relatively small compared to the mass of magma. It is assumed that high-level waste is uniformly distributed in the mass of a modeled eruption; thus, high-level waste behaves as a trace phase in the magma and does not appreciably affect the transport characteristics of a modeled eruption plume (NRC, 1999; CRWMS M&O, 2000b; DOE, 2003).
>
> In addition to alternative conceptual models for the magma-flow pathway, the number of volcanic conduits created during an igneous event also is uncertain. Using vent location information in Hill and Stamatakos (2002) and assuming medium-to-high confidence magnetic anomalies represent buried volcanoes, it is estimated that there are 17 paired and 13 nonpaired volcanoes in the Yucca Mountain region; most volcano pairs occur in alignments of three to five volcanoes. Volcano pairs have an average spacing of 2.0 ± 1.3 km. Assuming that there is a uniform probability of one, two, or three volcanoes intersecting the repository during a potential extrusive event, and that the overall eruption character remains unaffected by the number of volcanic conduits, dose increases by approximately a factor of two from this process.

The expert panel of the ongoing PVHA-U has been asked to provide expert opinions about volcanic conduit size in the Yucca Mountain region. However, the final report of the PVHA-U proceedings is not expected to be available until sometime in 2008.

The NRC approach to evaluating an extrusive event is documented in Mohanty et al. (2004), which is NRC's "System-Level Performance Assessment of the Proposed Repository at Yucca Mountain Using the "System-level Performance Assessment of the Proposed Repository at Yucca Mountain Using the TPA Version 4.1 Code." This NRC document outlines how the repository is described for the NRC calculations in TPA 4.1:

> A final design for a repository at Yucca Mountain has not yet been identified by DOE, but would be contained in a license application (now expected in 2008). The waste emplaced at Yucca Mountain is assumed to total 70,040 MTU in an area of 5,400,000 m^2 {approximately 5,000 m long and 1,000 m wide}. Assuming an average of 7.89 MTU per waste package and an equivalence between the spent nuclear fuel and other types of wastes, such as DOE spent nuclear fuel and glass high-level waste, approximately 8,877 waste packages will be needed for waste disposal. The initial inventory activity is ~6.65×10^{20} Bq [1.8×10^{10} Ci]. Waste packages with a 5.3-m length and a 1.6-m diameter are emplaced in drifts 5.5 m in diameter, spaced 81.0 m apart. The average age of the spent nuclear fuel is 26 years.

The NRC currently assumes that volcanic conduits will have an average diameter of ~50 m (Mohanty et al., 2004). If the center of a conduit were to coincide with the axis of a drift, then ~5 waste packages would be entrained within the cross-section of the conduit and potentially transported to the surface (the worst case situation). The NRC/CNWRA staff has also performed calculations assuming that up to 100 waste packages could be impacted by an extrusive event (Mohanty et al., 2005). In considering eruptions from satellite vents in the TPA 4.1 analyses (Mohanty et al., 2004), the staff assumed that a mean value of 51 waste packages could be entrained by an extrusive event and contained in volcanic ejecta.

Radiologic risks associated with volcanic eruptions are calculated in the TPA Version 4.1 code by modeling airborne releases of radionuclides for simulated eruptions. The volcanism modules assume that a small number of waste packages become entrained in a developing volcanic conduit (vent). These waste packages are assumed to be destroyed within the conduit and their waste contents move upward with volcanic tephra to the land surface. At the surface the mixture of tephra and spent nuclear fuel is ejected into the atmosphere, from which it settles to form tephra deposits.

Igneous activity contributes to waste package failures for both extrusive and intrusive events. As modeled, extrusive events result in the direct release and deposition of radionuclides on the ground surface, whereas intrusive events contribute to releases to groundwater. In the NRC performance assessment, an igneous event occurs between 100- and 10,000-years postclosure, with a recurrence rate of 1×10^{-7} per year. After the hypothetical volcanic event penetrates the repository and exhumes spent nuclear fuel, the areal density of deposited ash and radionuclides is computed at the compliance point. A new revision of the NRC TPA code is now being prepared that will incorporate fluvial and eolian remobilization of tephra.

6.3.2. EPRI Approach

EPRI has summarized their views regarding the potential consequences of future volcanism at Yucca Mountain, if it should occur, are clearly stated in the executive summary of their report on the intrusive release scenario (EPRI, 2005). In brief, EPRI has reached an overall conclusion that there is reasonable expectation that neither an intrusive nor extrusive igneous event in the Yucca Mountain region would result in doses exceeding those anticipated for the case of no igneous event. The summary from EPRI (2005) is quoted below:

There is evidence of volcanic centers near the proposed site at Yucca Mountain, Nevada for a geologic repository for the disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW). This evidence indicates that potential future igneous activity (i.e., an “igneous event scenario”) may be a factor in the assessment of post-closure risk for the proposed repository. In 1996, a panel of independent technical experts for the Yucca Mountain Project’s Management and Operations (M&O) contractor conducted a study, the Probabilistic Volcanic Hazards Analysis (PVHA) study that estimated a mean annual probability of an igneous event occurring at/near the Yucca Mountain site at 1.6×10^{-8}/year (Geomatrix Consultants, 1996). This probability, though extremely low, fell just above the 1.0×10^{-8}/year regulatory threshold that had been established for the dismissal of extremely low probability events.

Based on the findings of the 1996 PVHA Panel, a number of speculative analyses of the possible consequences of a future igneous event at Yucca Mountain have been conducted by the Yucca Mountain Project (CRWMS M&O, 2000c; 2001), and the NRC, in conjunction with NRC’s contractor, the Center for Nuclear Waste Regulatory Analysis (CNWRA) (e.g., Woods et al., 2002). In brief, the igneous event itself is characterized as a rising dike of basaltic magma that intersects one or more emplacement drifts containing nuclear waste packages, shown schematically in Figure ES-1 (Figure 56). Based on an in-depth, independent scientific review conducted by an Igneous Consequences Peer Review (ICPR) panel of experts (Detournay et al., 2003), the dike is postulated to most likely progress directly to the surface, intercepting a minimal number of waste packages in the conduit of the eruptive vent. Limited lateral magma flow through unbackfilled emplacement drifts is a credible possibility according to Detournay et al. (2003). Such lateral flow would lead to contact, and possible envelopment, of a limited number of "satellite" waste packages by magma away from the main locus of the dike-drift intersection.

Thus, two principal variant cases for a given igneous event can be specified:

- The extrusive-release case in which magma rising vertically in the conduit contacts waste packages in its path causing them to fail and possibly release radionuclides that would subsequently be erupted with the magma at the surface with subsequent radionuclide transport controlled by atmospheric and surficial processes, and
- The intrusive-release case in which waste packages, either directly contacted by the lateral flow of magma into the impacted drifts or indirectly affected by the elevated temperature and potential release of volatiles species from the intruding magma, would fail and release radionuclides via groundwater pathways at an earlier time than for waste packages unperturbed by these localized effects from an igneous event.

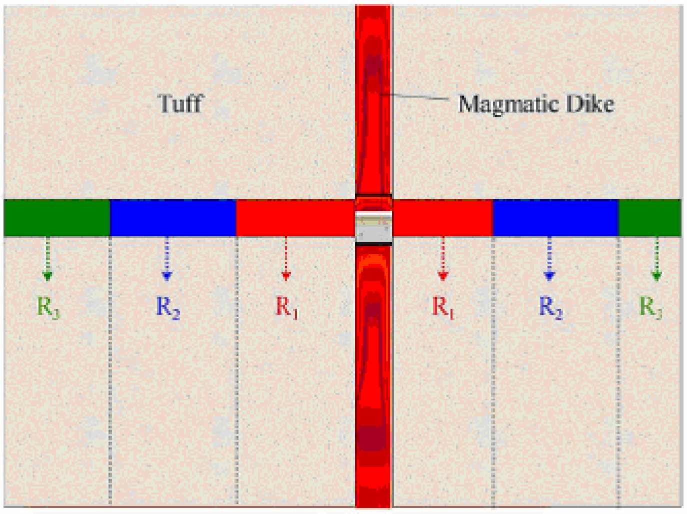


Figure 56 Schematic of zones of intruding magma effects in a repository drift on the engineered barrier system (EBS). Magma is assumed to completely fill the spaces in the "Red Zone," with significant thermal/chemical effects on Alloy 22 in adjacent "Blue Zones." No effects on the EBS are assumed for the "Green Zones" (After Figure ES-1 of EPRI, 2005) (Permission to use this copyrighted material is granted by the Electric Power Research Institute).

EPRI, as part of its efforts to provide an independent technical/scientific assessment of issues that are anticipated to be important to the licensing of the proposed Yucca Mountain repository, has previously evaluated the extrusive-release case (EPRI, 2003; 2004a). This analysis critiqued and cast considerable doubt on several of the more speculative consequences put forward by Woods et al. (2002) while indicating that the expected dose consequence for the extrusive-release variant case is at or near zero because of multiple factors including waste package durability, finite extent, duration and magnitude of likely future igneous events, and limitations imposed by realistic consideration of magma-waste package and magma-waste form interactions (EPRI, 2004a).

The objectives of this report, which is a companion to EPRI (2004a), are to analyze the intrusive-release case and determine the potential impact on repository performance and safety, expressed as probability weighted mean annual dose rate, for the latter scenario.

6.3.2.1. EPRI Analyses

EPRI's analyses contained in this report adopt the igneous event probability of 1.6×10^{-8}/year previously derived by the Probabilistic Volcanic Hazards Analysis (PVHA) panel (Geomatrix Consultants, 1996). The analyses also reflect recent data on basaltic eruptive centers in the Yucca Mountain region that support the conclusion that relatively low-temperature (~1010°C), high viscosity basaltic magmas, as opposed to the ~1200°C magmas postulated by the DOE, are the most representative characteristics of future igneous events. Lower temperature implies lower and less prolonged thermal-perturbation of the host rock and contacted waste packages, and magma of much higher viscosity. The high viscosity supports the contention that such magma will only partially penetrate into emplacement drifts intersected by the magmatic dike, thereby only impacting a limited number of waste packages.

Partial intrusion of magma into emplacement drifts with controlled cooling and solidification of the magma implicitly leads to development of three "zones" within the emplacement drift (Figure 56):

- The 'Red Zone,' the area immediately adjacent to the rising magmatic dike and where drip shields and waste packages are assumed to be fully engulfed by magma. The 'Red Zone' is characterized by displaced/ disrupted drip shields, thermally sensitized Alloy-22, and spent fuel cladding that fails at the time of the igneous event,
- The 'Blue Zone,' the area just beyond the 'Red Zone' where drip shields and waste packages are not contacted directly by magma but experience significantly elevated, high temperatures. The 'Blue Zone' is characterized by intact drip shields, but failure of the Alloy-22 waste package outer barrier and spent fuel cladding within a relatively short time after the igneous intrusion event,
- The 'Green Zone,' the area beyond the 'Blue Zone' where waste packages experience modest (<350°C) and transitory high temperatures, with possible deposition of reactive magmatic volatiles onto the waste package surface. The 'Green Zone' is characterized by intact drip shields, Alloy-22 waste package outer barrier and spent fuel cladding that are unperturbed from their nominal corrosion behavior.

The range of the spatial extent and the number of waste packages in each zone are also derived in this EPRI report. These analyses show that the number of waste packages in the 'Red Zone' is extremely limited while those in the 'Blue Zone,' albeit more extensive, are still less than a majority of the waste packages in the impacted drifts.

Modification of the existing near-field source-term and radionuclide transport sub-model in EPRI's Yucca Mountain total system performance assessment (TSPA) model, IMARC (EPRI, 2005), is made to specifically model radionuclide releases for each of the three zones. The release rate behavior for waste packages in the 'Green Zone' exactly conforms to the nominal case following failure of the Alloy-22 waste package outer barrier. The potential for favorable water diversion by solidification of massive basalt around waste packages in the ‘Red Zone’ is shown through sensitivity analyses, but this potential contribution is also conservatively ignored in the presented analyses. Near-field sub-model calculations show that there is a delay in the release of radionuclides from the ‘Red Zone’ attributable to sorption properties of the encompassing basalt, but that the long-term release rates for key dose-contributing radionuclides (^{99}Tc, ^{129}I, ^{237}Np, ^{229}Th) from the ‘Red Zone’ and ‘Blue Zone’ eventually converge. The long-term release rates, on a per waste package basis, from both the ‘Red’ and ‘Blue’ zones are found to be higher (by a factor of ~40) than that for the nominal case (and ‘Green Zone’) because the time-dependent distribution of cladding failure would not be a factor in these cases.

A set of IMARC analyses was conducted to investigate the total system performance implications of the observations and analyses in each component of the system. First, IMARC was used to explore conditional dose analyses (“conditional” in the sense that the probability of occurrence of a magma intrusive event is set to one), to evaluate the dose consequences of the magma intrusion. There is reasonable expectation that the magma will only affect some of the waste packages in a drift intersected by a rising dike, with the remaining waste packages in the impacted drifts functioning in the same way as in drifts not intersected by the dike. In this situation, the peak conditional dose from the affected part of the repository is smaller than that produced from the unaffected part of the repository due to the small percentage of the total repository waste packages that are impacted. If the probability of a magma intrusion is also factored in, the contribution to overall probability-weighted peak dose becomes minuscule. Even when a series of conservative, “bounding” assumptions are made (e.g., full penetration of the magma into the drifts, and 100% of the drifts affected), the probability-weighted estimated bounding dose rates from such a bounding event only rise to be on par with the peak dose rates from the nominal case. It is therefore concluded there is reasonable expectation that magma intrusion is inconsequential with respect to peak dose.

Combining this conclusion with that of the earlier EPRI analysis of the extrusive igneous scenario (EPRI, 2004a) results in the overall EPRI conclusion that there is reasonable expectation that an igneous event in the Yucca Mountain region, either intrusive or extrusive, will not result in dose levels exceeding the levels anticipated for the nominal release (i.e., no igneous event) case. Given the above, robust conclusions regarding the relative lack of importance of the igneous scenarios to probability-weighted peak dose estimates, and the regulatory requirement that the DOE demonstrate that the probability-weighted peak doses for the repository will comply with applicable regulations, EPRI has concluded that no further activities need be pursued to address the igneous scenarios.

6.3.2.2. EPRI Comments on Tephra Dispersal Models

EPRI (2004) conducted additional analyses using three alternative computer codes for volcanic plume modeling (i.e., BENT, PUFF, ATHAM). Several assumptions in TEPHRA (or ASHPLUME) were identified as conservative. EPRI (2004) also reported that ASHPLUME, like other models based on comparable physics, tends to overestimate accumulation of tephra at the compliance point, since it tends to underestimate the dispersion of the plume. The DOE and NRC implementation of ASHPLUME accentuates this conservatism in potential deposition at the compliance point because of the fine grain size and rather large column height used as input parameters.

6.3.3. ACNW&M Comments on Potential Fate of High-Level Waste in a Volcanic Conduit

Available information provides practical insights about the plausible fate of high-level radioactive waste (HLW) if it should become entrained within a volcanic vent (conduit) and transported to the surface. The following points need to be considered in a realistic assessment of volcanic processes (also see discussion in Weiner and Coleman, 2008).

Most of the waste planned for disposal at Yucca Mountain consists of spent nuclear fuel rods from PWR and BWR reactors. The physical form of the waste is ceramic pellets of UO_2, about a centimeter in diameter, with a melting point of >2800°C. This is much higher than the magma temperatures of 1000-1200°C. Spent fuel would not dissolve in magma; therefore the size range of transported fragments would largely be determined by pre-existing particle sizes in fuel rods. This range would differ from that of volcanic ejecta.

A volcanic conduit is not born full size. Its diameter increases as the eruption proceeds. This means that only one nuclear waste package could be initially entrained in the conduit, with others becoming entrained within the final radius of the conduit at depth. Therefore additional waste packages would be exposed to varying stages of the eruption sequence. It is also possible that a conduit intersecting a repository could form in the separation distance between drifts, and although an intrusive event could occur, no waste packages would be directly intersected by the conduit. Volcanic conduits would be significantly smaller 300 m below the surface at repository depth than at ground surface (Figure 57). This would minimize the number of waste packages that could be intersected by a conduit. Lithostatic pressure keeps the opening smaller at depth, whereas at the surface the vent periphery in the zone of fragmentation grows in diameter through active erosion by expelled tephra. The DOE reports they have now better constrained the conduit size at depth and agrees that the diameters are smaller than previously assumed (ACNW&M, 2007).

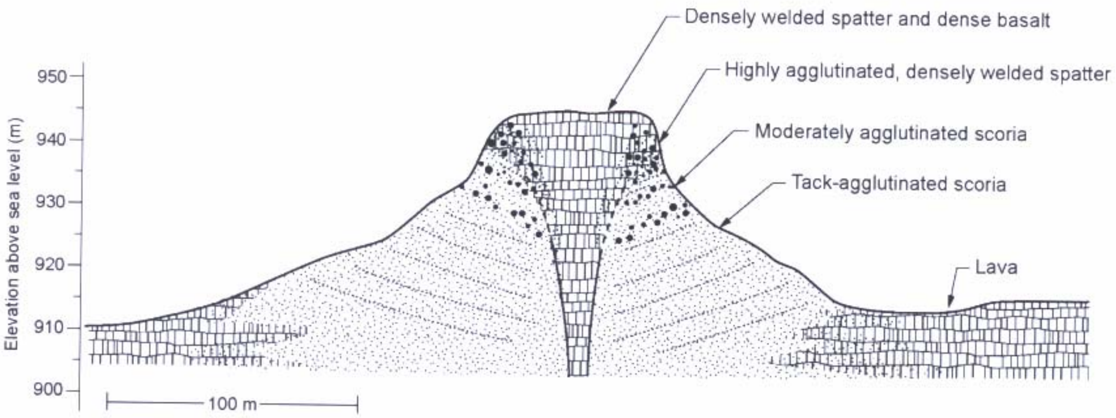


Figure 57 **Schematic cross-section through Shirtcollar Butte, Crater Flat, Nevada, a Pliocene (3.7 Ma) basalt volcano. The degree of fusing and welding of scoria increases up-section and grades into dense basalt on the top of the butte (After DOE, 2006).**

Present information shows that dikes are more likely to be injected into pre-existing faults. Conduits form along dikes, therefore if the DOE continues to use a “setback” strategy from major faults (places waste tunnels at a minimum distance from faults), this would reduce the likelihood of a hypothetical extrusive event impacting the repository.

The expected time of travel in a conduit from repository depth to the surface would be approximately one minute or less. This allows little time for erosion of ceramic pellets, but does permit rapid quenching of magma onto the relatively cold waste packages and their contents. The formation of a quench rind on waste pellets would protect them during their rapid transit to the surface within a flowing column of frothy magma. This protective quenching effect in volcanic conduits has not been considered in the DOE and NRC performance assessments (Mohanty et al., 2004; Codell, 2004; DOE, 2003).

Since the time of TPA version 3.2 (Mohanty and McCartin, 1998; Mohanty, 1999), the NRC has used relatively consistent assumptions about the size range of spent fuel particles that would hypothetically be incorporated in volcanic ash. Fuel particle sizes using a triangular distribution from 1-100 microns (Figure 58) are sampled in the TPA. For comparison, a grain of table salt is about 100 microns across, and a grain of talcum powder is about 10 microns across. The low end of the NRC size range is at 1 micron, which happens to be the wavelength of light in the near infrared band (just above the wavelength of visible light). A CNWRA study for NRC (Jarzemba and LaPlante, 1996, their Figure 4), suggested a log triangular distribution from 0.01 to 1.0 cm (100 to 10,000 microns), based on the observed fracturing and crazing of irradiated fuel pellets, as shown in Figure 59.

A variable range of spent fuel particle diameters is to be expected. However, in documenting the assumed distribution for the size range of spent fuel particle size, TPA 4.0, (Mohanty et al., 2002) cite an NRC handbook that evaluated the consequences of major accidents in nuclear fuel cycle facilities (NUREG-1320; Ayer et al., 1988). Review of this report shows that it does not support the use of a greatly reduced size range for particle sizes. It instead suggests that a larger size range should be used for ejected fuel particles. Ayer et al. (1988, pp. 4.87-4.103) present results of crush-impact experiments on glass, aggregates, and ceramics, including spent UO_2 fuel pellets.

Figure 60a is taken from this report, and shows results of crush-impacts on fuel pellets that had previously been irradiated. About 2% of the fuel (by weight) was reduced to particles smaller than 1000 microns. Reardon et al. (1992) reported results of crushing tests at energies of 10 to 1000 J/g using irradiated fuel (22 and 33 GWd/MTU KWO). At 10 J/g, <30% of the mass of irradiated fuel was reduced to particle sizes <100 microns, and <10% of the mass was reduced to <10 microns. At 1000 J/g, ~60% of the mass was reduced to less than 100 microns and <30% was reduced to under 10 microns. These size fractions do not consider the effects of fuel cladding or magma quenching on ejected waste particles in volcanism scenarios, which would significantly increase particle diameters (Weiner and Coleman, 2008).

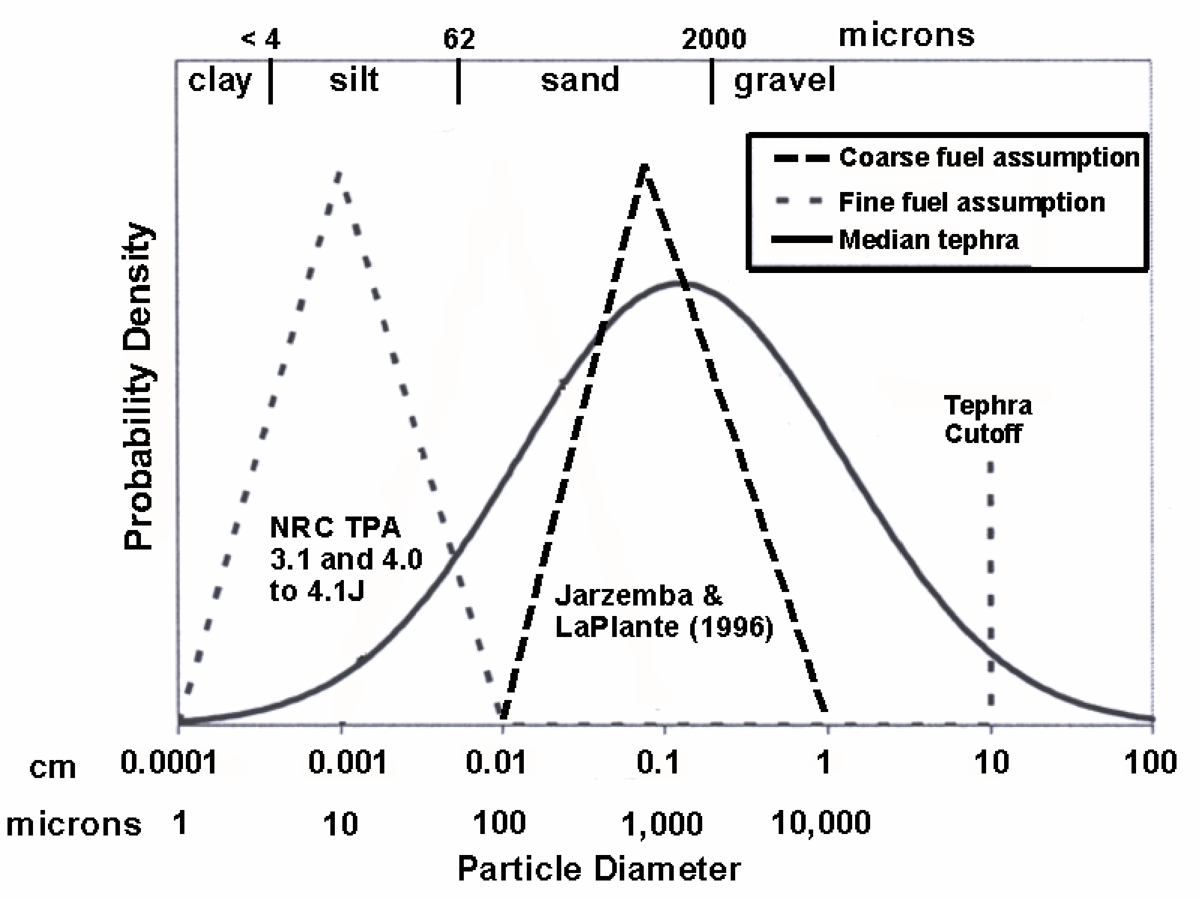


Figure 58 Median tephra diameter distribution plotted with spent fuel particle size distributions used in TPA versions 3.1 to 4.1. For comparison the size distribution suggested by Jarzemba and LaPlante (1996) is also shown. The Wentworth scale of particle sizes appears at top of figure for comparison. The intermediate size distribution used by Codell (2004) is not shown, but is a triangular distribution that ranges from 10 to 1000 microns. The distribution for median tephra particle diameter is a sampled parameter in the TPA code. The distribution of tephra particle sizes was postulated by Hill et al. (1998) based on data from the 1995 Cerro Negro eruption (Codell, 2004). The tephra “cutoff” identifies the maximum particle size that can be transported through convective dispersal (Mohanty et al., 2002, p. A-165). Particles larger than 10 cm would fall in close proximity to the volcanic vent.

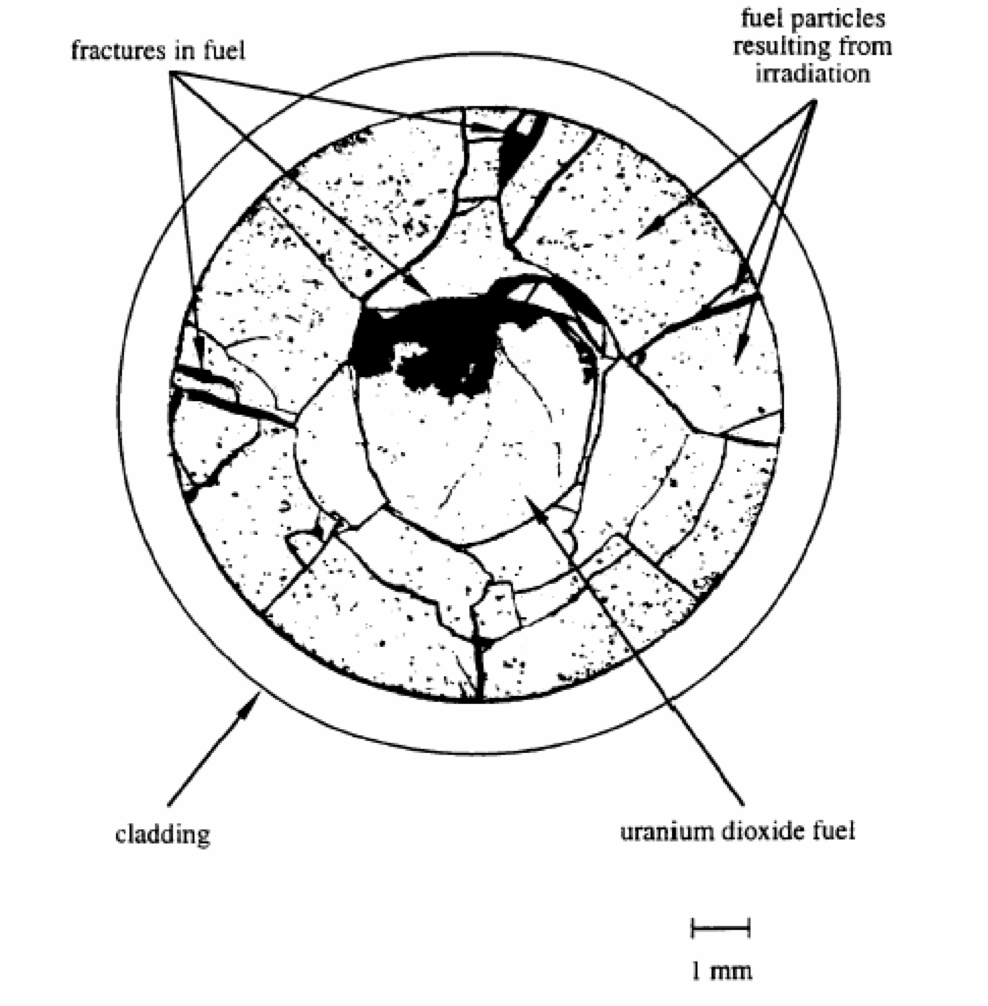


Figure 59 **Cross-section of a fuel pellet after irradiation in a reactor core (After Jarzemba and LaPlante, 1996, Figure 3).**

Calculated doses are highly sensitive to assumptions about fuel particle size because of the strong dependence on respirability, which decreases sharply as particle diameters increase beyond 10 microns. The TPA code, version 4.1j, using several particle size distributions as input, was used by the ACNW&M staff to assess the sensitivity of dose estimates to fuel particle sizes assumed in the volcanism scenarios. Using a size range of 100-10,000 microns (also see test data set in Manteufel et al., 1997) results in approximately a 200-fold reduction in calculated dose as compared to the range of 1 to 100 microns, which indicates significantly reduced consequences from extrusive volcanism. Using an intermediate fuel size range of 10-1000 microns reduces calculated dose by a factor of two (Codell, 2004).

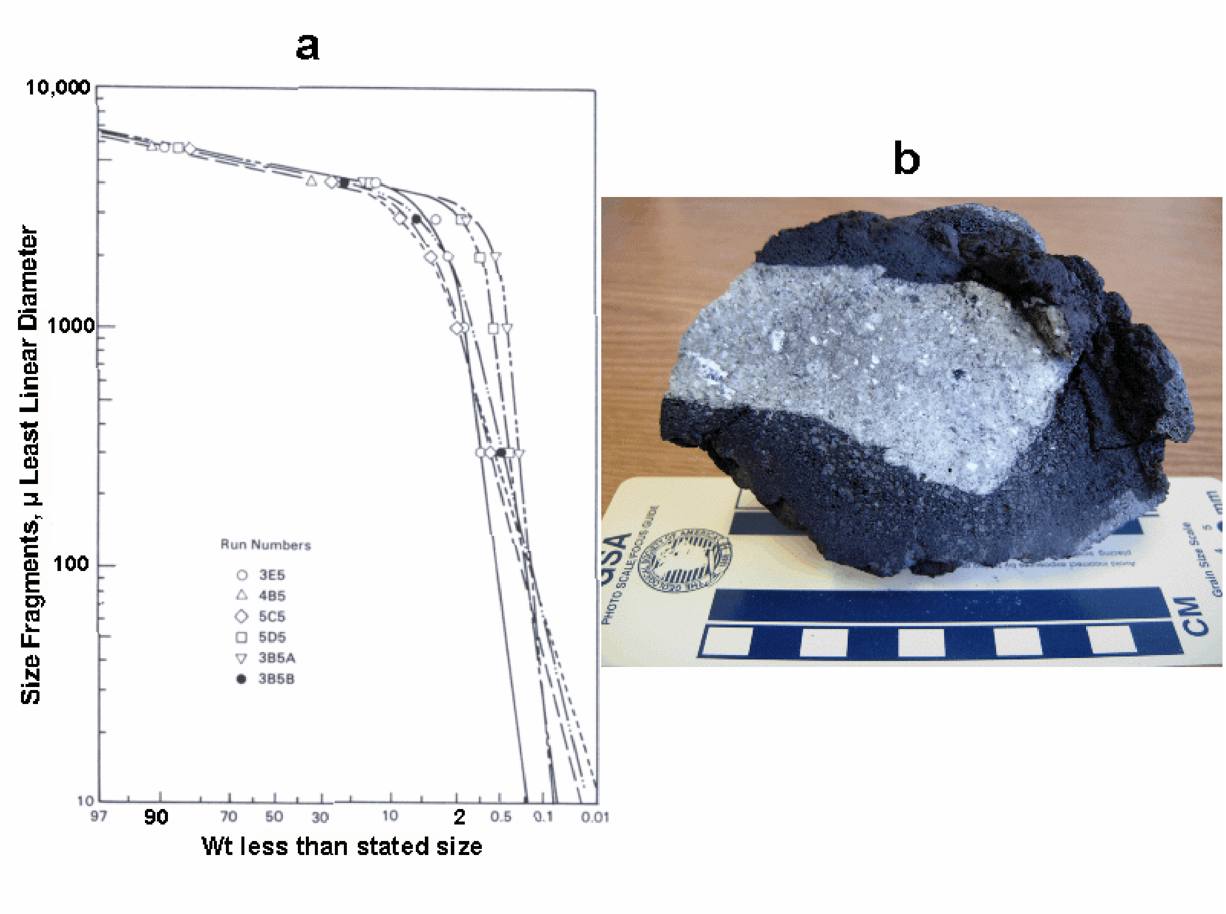


Figure 60 Crush-impact experimental results and photo of xenolith with basalt rind.

(a) Crush-impact experimental results - size distribution of fragments from fuel pellets irradiated to 6000 MWd/MTU (After Ayer et al., 1988, Figure 4.12). (b) Tuff xenolith with basalt rind, collected from the scoria cone at Lathrop Wells. Scale is in cm.

The relative volume of ash deposits vs. volume of scoria cone and lava flows can be used to estimate practical limits on the fraction of ejected waste in the form of fallout that could be available for fluvial and eolian transport. The 80,000-year-old Lathrop Wells Cone is larger in volume than the older Pleistocene-aged Red Cone and Black Cone in Crater Flat (see Valentine et al., 2006). BSC (2003c) estimate the total volume of eruptive products at Lathrop Wells at ~0.09 km^3 (cone, 0.02 km^3; lavas, 0.03 km^3; fallout, 0.04 km^3). Valentine et al. (2007) estimated a larger fallout volume of 0.07 km^3. The fallout comprised approximately half of the eruptive products. The DOE agrees that fallout (inferred violent Strombolian eruptive style) accounts for a fraction of total products of an individual volcano. At Lathrop Wells the fallout volume is about 1.4 times the cone plus lava volumes. Current modeling by the DOE is accounting for the relative fractions in terms of quantities of material available for violent Strombolian dispersal during a potential future eruption (ACNW, 2007). Waste incorporated in lava flows or scoria cones would be protected from erosion and transport for many hundreds of thousands of years, as demonstrated by the million-year-old cones and flows in Crater Flat near Yucca Mountain.

Over this time scale the lava flows experienced very little erosion. The scoria cones have experienced erosion during the pluvial climates of the Quaternary, when the climate of Yucca Mountain was significantly wetter than today for most of the time. Valentine et al. (2006) document that these cones are highly eroded, and only remnants of the inward dipping beds of the inner cones are preserved at Red and Black cones. However, entrainment of waste in scoria cones would immobilize the waste far beyond the time of peak risk from extrusive volcanism.

EPRI (2003b) also noted that waste could be entrained within lava, as well as in tephra. The solidified lava presents a mechanically durable matrix for entrained and dissolved radionuclides. Both erosion and aqueous dissolution are mechanisms that may lead to subsequent release, but Quaternary age and older lava flows are well preserved in the arid environment surrounding Yucca Mountain.

At Lathrop Wells, lithic fragments of conduit wall rock (tuff) are commonly found embedded within the scoria that make up the cinder cone (Heizler et al., 1999). The nonwelded to partly welded tuff fragments were eroded from the walls of the volcanic conduit, vary in size from a fraction of a cm to 6 cm or larger, and have quenched rinds of basalt.

Figure 60b shows a xenolith 9 cm long that was collected by ACNW&M staff at Lathrop Wells. These expelled wall rock fragments are so abundant that they have been used to estimate the eroded volume of the Lathrop Wells conduit (Valentine et al., 2007). The size of the lithic fragments suggests that spent nuclear fuel pellets and fragments could be expelled in similar fashion during the cone-building phase of an eruption, intact and with protective quench rinds. The result is that entrained HLW would be likely to remain in relatively large fragments that would be deposited in or near a tephra cone, rather than as far-strewn, fine-grained ash. A xenolith 30 cm in diameter has been found at the Lathrop Wells cone (Heizler et al., 1999). The existence of this and many other xenoliths is further evidence that UO_2 pellets could be expected to survive relatively intact over the short conduit travel distance from repository depth to the surface (only ~300 m). This is especially true for the period of greatest hazard from a volcanic event (i.e., the first 1000 years; Figure 39) when waste packages and waste forms should still be relatively intact.

Based on the available information about properties of UO_2 fuel and volcanic processes, including consideration of magma quenching and observations of xenoliths, there is no evidence that most of the spent fuel contained in HLW packages intersected by a volcanic conduit woule be reduced to fine-grained material and subsequently erupted and transported as volcanic ash. A significant fraction of waste would likely be entombed in a scoria cone and lava flows. Use of a more realistic size range for spent fuel particle sizes leads to substantially lower doses, based on analysis using TPA 4.1j. NRC has now updated this code and its accompanying user's guide. The revised code version is TPA 5.1 (NRC, 2007a).

6.4. Remobilization of Contaminated Volcanic Ash

6.4.1. Introduction

Future basaltic volcanism intersecting the proposed repository at Yucca Mountain could lead to eruption of contaminated ash to the surrounding countryside during a violent Strombolian eruption phase. The contaminated ash would be derived from destruction of the waste packages within the volcanic conduit and entrainment of the fragmented waste into the erupting magma. It is unclear how much of the entrained radioactive waste could be ejected from the subsurface and to what degree the waste would be fractionated, thus there are differences in views about the resulting consequences of such an event. The discussion here pertains only to the fate of contaminated ash hypothetically ejected during a volcanic event and deposited in the drainage basin of Fortymile Wash where it would be subject to erosion and transport by both water (fluvial) and wind (eolian) processes into the immediate vicinity of the RMEI. Contaminated ash deposited elsewhere in the vicinity of Yucca Mountain would not reach the RMEI.

Fluvial processes are limited in the Yucca Mountain region because the climate is arid to semi-arid with high rates of evapo-transpiration and low annual precipitation that averages about 165 mm/yr. Stream flow results from infrequent regional storms, mostly during the winter, and from localized but intense thunderstorms that occur primarily during summer months. There are no perennial streams in the Yucca Mountain area, and even the larger streams in the region are ephemeral. Throughout the Death Valley Basin, perennial flow only occurs downstream from springs and around the margins of low-lying playas (dry lake beds) where the water table intersects the land surface.

6.4.2. Characteristics of the Fortymile Wash Drainage System

Fortymile Wash is a fluvial system about 150 km long, that drains an area of 815 square km on the east and north of Yucca Mountain. It is an important fluvial system because it drains into the area near the RMEI where contaminated ash could be deposited from a volcanic vent intersecting the proposed repository. Surface water at Yucca Mountain drains mainly eastward toward Fortymile Wash, a tributary of the Amargosa River. The main tributaries to Fortymile Wash are Yucca Wash, located north of the proposed repository, Drill Hole Wash, which drains most of the potential repository area, and Busted Butte (Dune) Wash located south of the proposed repository.

Fortymile Wash crosses Highway 95 immediately east of Lathrop Wells (Amargosa Desert) and continues southward, ultimately intersecting the Amargosa River. The Amargosa River drains an area of about 8,000 square km by the time it reaches Tecopa, California. The mostly-dry river bed extends another 100 km before ending in Death Valley. Fortymile Wash has four distinct segments (Figure 61) with different morphologies: (1) a broad northern area comprised of ephemeral streams (washes) that feed a central channel that is incised in bedrock; (2) a central reach that deeply incises an alluvial fan of Plio-Pleistocene age; (3) a segment near the intersection with Highway 95 that is referred to as the “active” fan (northernmost part of the depositional basin); and (4) the remainder of the depositional basin that consists of anastomosing channels that terminate at the juncture with the Amargosa River.

The erosion, transport, and deposition of the sediments in Fortymile Wash are directly related to the flow characteristics of the ephemeral stream and particularly to its flood characteristics. Numerous continuous streamflow and peak-flow gauges have been operated and monitored in the Yucca Mountain area. However, as of September 30, 1995, all but three continuous and most of the peak-flow gauges were discontinued (DOE, 1997, p. 3-14). As of September 30, 1997, the only continuous streamflow gauges operating near Yucca Mountain were on Fortymile Wash near well UE-25 J-13 (“narrows” gauge) and near Amargosa Desert (Bonner et al., 1998).

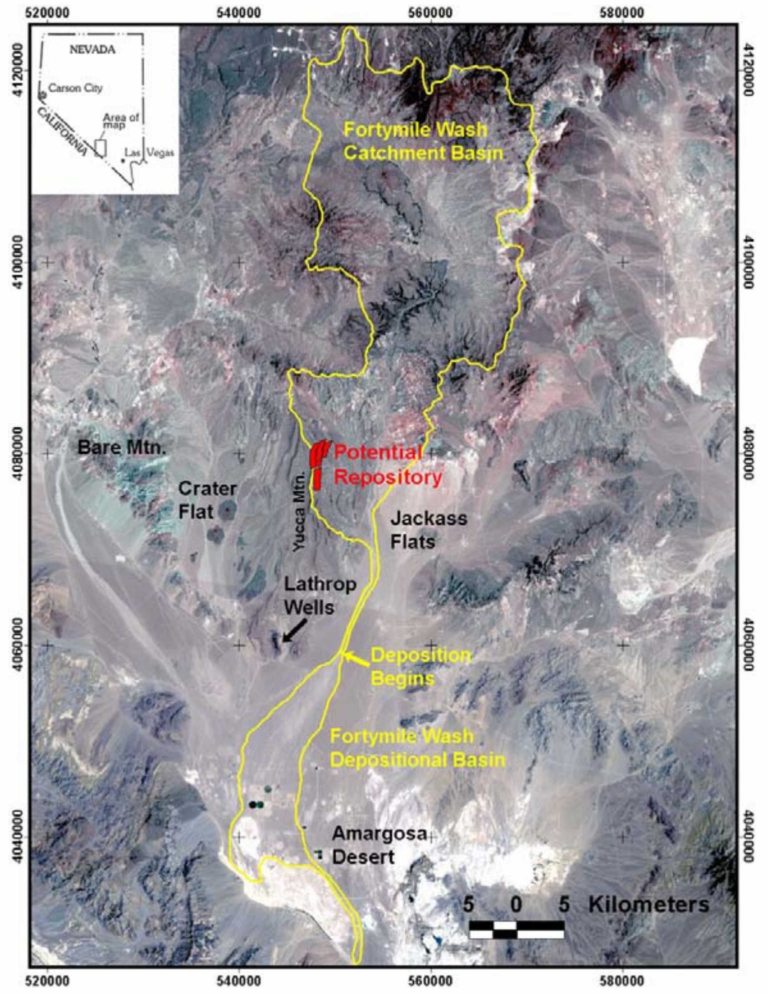


Figure 61 **LANDSAT Thematic Mapper image showing the Fortymile Wash drainage system. The Pleistocene depositional basin has an Area of 136 km^2. Map Projection: Universal Transverse Mercator, Zone 11 North, in meters (After Hooper, 2005, Figure 3-1).**

The period of record for flooding in Fortymile Wash is less than 40 years. Waddell et al. (1984) reported that the U.S. Geological Survey has collected monthly crest-stage data in the Yucca Mountain region since the early 1960s, using flood data from 12 crest-stage sites to estimate flood characteristics in the region. Data from 1969 to 1993 from six gauging stations are shown in Table 7.

The largest recorded flows occurred after a storm in February 1969, when the upper Amargosa River near Beatty, Nevada, carried a maximum flow of 450 m^3/s. Squires and Young (1984) estimated that in Fortymile Wash this flood had an estimated discharge of 93 m^3/s and that the peak discharge may have reached 560 m^3/s (Glancy and Beck,1998). The 100-yr peak discharge for Fortymile Wash has been estimated at 340 m^3/s (Squires and Young, 1984).

Table 7 Peak discharges at stream gauges along Fortymile Wash (After Table 1-2 of Hooper, 2005, which was based on data from CRWMS M&O, 2000a, and Tanko and Glancy, 2001).

Date	Fortymile Wash at Narrows	Yucca Wash Near Mouth (tributary)	Drillhole Wash at Mouth (tributary)	Fortymile Wash Near Well J-13	Dune Wash Near Busted Butte (tributary)	Fortymile Wash Near Amargosa Valley
Jan. 25, 1969	–	–	–	–	–	42.5
Feb. 24-26, 1969	–	–	–	570	–	93.5
Mar. 3, 1983	43.0	2.83	–	16.1	–	11.3
Jul. 21-23, 1984	20.7	26.6	22.4	52.7	–	40.5
Aug. 14-16, 1984	1.42	–	–	–	–	–
Aug. 18-20, 1984	19.3	0.88	1.22	24.4	0.40	10.5
Jul. 19-20, 1985	0.33	0.0003	0.48	0.17	2.66	0.09
Feb. 23, 1987	–	–	–	–	–	0.02
May 7, 1987	–	<0.003	–	–	–	–
Nov. 6, 1987	–	–	–	–	–	0.02
Sep. 23, 1990	–	–	–	–	–	0.02
Aug. 12-13, 1991	–	–	–	–	–	–
Sep. 7, 1991	–	–	–	–	0.12	–
Feb. 12-15, 1992	0.68	0.42	–	–	0.04	–
Mar. 30-31, 1992	–	<0.03	–	–	0.03	–
Jan. 17-19, 1993	1.50	2.26	–	–	–	–
Feb. 9, 1993	–	–	–	–	–	–
Feb. 23, 1993	–	–	–	–	–	–
Jan. 25-27, 1995	0.20	5.24	–	–	0.08	–
Mar. 11-13, 1995	85.0	–	0.003	85.0	0.08	34.0
Feb. 23-24, 1998 †	5.7	6.2	0.7	5.7	nd ‡	9.6

Sources: CRWMS M&O, 2000; Tanko and Glancy, 2001

*Dash symbol means either no streamflow was recorded or stream gaging site was not operating during period of streamflow.

†Cumulative streamflow volumes for the 1995 and 1998 storm runoffs were estimated differently because most of the streamflow gaging stations were discontinued prior to the 1998 flood.

‡Site disturbed by road crews prior to measurements (nd = not determined).

The first documented case of a regional water-flow event during site characterization studies, in which Fortymile Wash and the Amargosa River flowed simultaneously throughout their reaches, took place on March 11, 1995 (Beck and Glancy, 1995). USGS and Nevada Test Site rain gauges showed that cumulative precipitation ranged from 5 to 15 cm during March 9 to 11, with the largest amounts falling at higher altitude sites. High-altitude snowmelt also probably contributed to the 10- to 12-hour runoff event in Fortymile Wash. The peak flow near the location where the existing Yucca Mountain access road crosses Fortymile Wash was reported at ~100 m^3/s (Glancy and Beck, 1998, p. 7). This flow is much less than that calculated as a 100-year *flood* event for Fortymile Wash (i.e., 340 m^3/s).

Squires and Young (1984) calculated discharge, area, width, mean velocity, and maximum depth of flood flows for 100-year and 500-year exceedence recurrence frequencies and maximum flood peak for various profiles across Fortymile Wash and its three major tributaries in the Yucca Mountain area. Estimated peak discharges are shown in Table 8.

Table 8 Estimated peak discharges (m^3/s) along stream channels of Fortymile Wash at Yucca Mountain.

Wash	Drainage Area (sq km)	100-year	500-year	Regional Maximum
Fortymile	810	340	1,600	15,000
Dune Wash (Busted Butte)	17	40	180	1,200
Drill Hole	40	65	280	2,400
Yucca	43	68	310	2,600

Fortymile Wash apparently has not overflowed its banks near Yucca Mountain for thousands of years. In the vicinity of wells J-12 and J-13, the channel is deeply incised in alluvial fan deposits, and paleoindian artifacts are commonly seen on the surface adjacent to both channel banks. They have not been carried away or buried by overbank flows.

6.4.3. Approaches to Fluvial Sediment Transport and Erosion Evaluation

6.4.3.1. NRC Approach to Fluvial Volcanic Ash Redistribution

Basaltic materials are common in the alluvial deposits along Fortymile Wash. Much of this material probably originated from the extensive basalts in Jackass Flats, but some cobbles and boulders have been rounded by abrasion during long-distance transport and may have originated from the basalt units in the northern part of the drainage basin (i.e., Buckboard Mesa and the basalts of Dome Mountain).

The NRC has developed a sediment budget approach to model the long-term fluvial redistribution of basaltic tephra in Fortymile Wash (Hooper, 2005). In the event that extrusive volcanism intersects the repository and transports waste in the volcanic tephra plume, deposition of radionuclides may occur at the RMEI location from the remobilization of tephra by water after initial deposition. A sediment budget was estimated to demonstrate the quantitative relationship between components such as sediment yield, discharge to the depositional fan, balance of remaining tephra, dilution by mixing of contaminated sediment with ambient sediment, and associated changes in sediment storage over time. Using parameters specific to Fortymile Wash and a hypothetical eruption at Yucca Mountain, Hooper (2005) concluded that substantial tephra deposits can persist for more than 1,000 years in arid terrains, even with a period of accelerated erosion after the eruption. Hooper (2005) estimated that ~98 percent of the tephra deposit remains in the Fortymile Wash catchment basin after 100 years and 50 percent remains after 1,800 years. These results suggest that the amount of remobilized tephra may be large—even when mixed with ambient sediment—and could significantly affect airborne radioactive particle concentrations for the RMEI. However, see the discussion in Section 6.3.3 regarding the potential fate of spent fuel in a volcanic conduit. The physical and chemical properties of spent fuel suggest that this material could retain much of its integrity even if transported through a conduit to the surface.

The amount and distribution of hypothetical tephra deposits were calculated using the TEPHRA code (visit http://www.cas.usf.edu/~cconnor/parallel/tephra/tephra.html; Connor et al., 2001). For each realization in performance assessment, the calculated tephra deposit is partitioned into (i) initial deposits (if any) at the receptor location, (ii) potential deposits in the Fortymile Wash drainage system that are subject to fluvial redistribution, and (iii) potential deposits in areas subject to wind erosion and transport (Benke et al., 2006). Areas of Fortymile Wash that lack tephra deposits are assumed to contribute uncontaminated sediment with the pre-eruption ambient sediment yield. A dilution factor is calculated as the ratio of contaminated sediment volume to the total (uncontaminated + contaminated) sediment volume assuming uniform mixing of sediments. The duration that Fortymile Wash yields contaminated sediment was estimated as the time for significant flow events to fully deplete the ash in the Fortymile Wash drainage system (Benke et al., 2006).

The NRC approach to fluvial ash redistribution assumes that all contaminated ash that is fluvially remobilized is deposited in the “active” fan, outlined in red in Figure 3-2 of Hooper (2005) (Figure 62), but leaves the fan only by wind erosion. Wind then blows contaminated ash from the depositional fan toward the RMEI. However, wind is not permitted to remove contaminated ash from the drainage basin where ash was originally deposited. The entire tephra blanket in the drainage basin is assumed to ultimately be removed.

These assumptions appear to be conservative, leading to overestimates of hypothetical dose, because all contaminated ash removed by flooding is assumed to be deposited and accumulated near the RMEI in a 24 km^2 area. The assumption that wind alone is permitted to move contaminated ash from the fan to the RMEI is inconsistent with the erosion model, in which the tephra blanket is eroded only by water - wind is not allowed to remove contaminated ash from the drainage basin. In reality, large floods would dominate the process of fluvial erosion and transport and would carry contaminated ash beyond the active fan to the Amargosa River and beyond. For example, in the short period of historical record, at least two large floods have reached Death Valley. The finer-grained materials that are potentially significant to the inhalation dose and could eventually be remobilized by wind would be the most likely components to stay in suspension during floods and to be deposited at and far beyond the active fan, the location of the RMEI. Moreover, major rain events can occur in parts of the system and not necessarily throughout the entire Fortymile Wash.

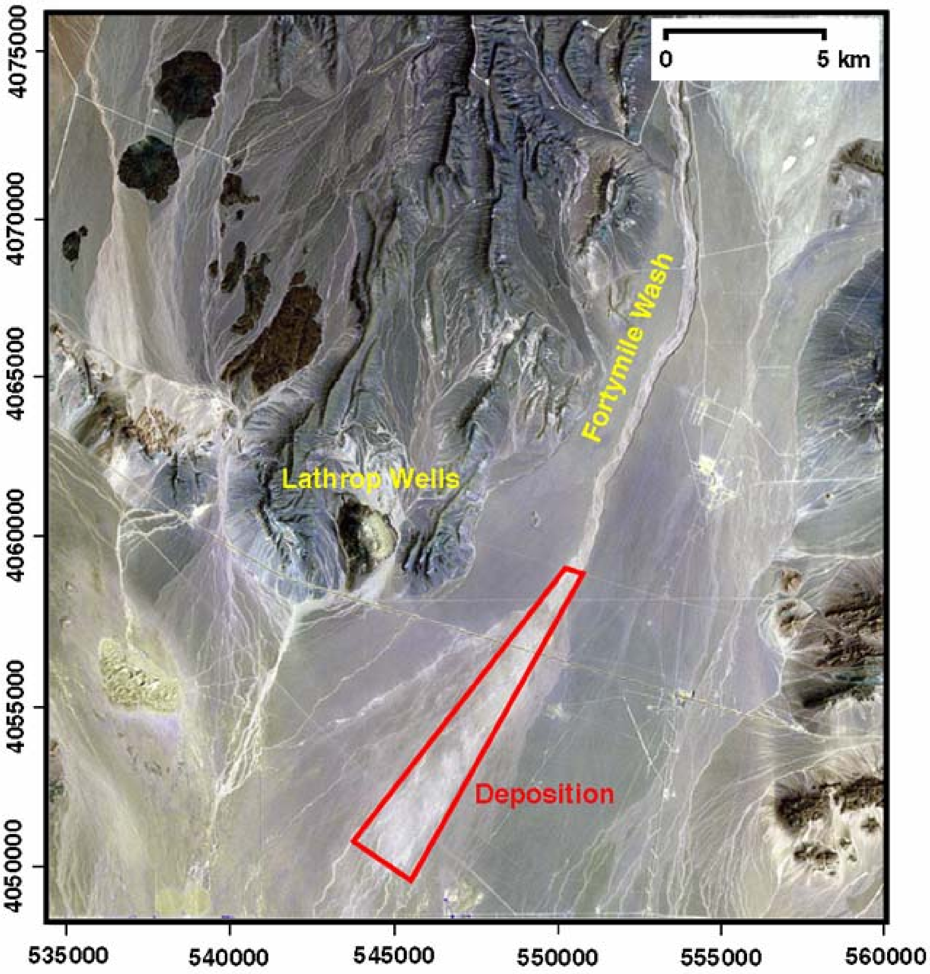


Figure 62 **Landsat Thematic Mapper image showing the hypothesized active part of the Fortymile Wash depositional (or alluvial) basin in red. Area of the active fan is 24 ± 2 km^2. Map projection: Universal Transverse Mercator Zone 11 North, in meters (After Hooper, 2005, Fig. 3-2).**

Figure 63 shows the estimated sediment yield following a hypothetical eruption at Yucca Mountain. This is much more protracted than the sediment yield seen at Paricutín volcano, where the sediment yield returned to ambient conditions after ~30 years (Segerstrom, 1950). Hooper (2005) suggests that the humid climate of Paricutin makes that volcano a poor analog for Yucca Mountain. Nonetheless, it is unclear why sediment yields after hypothetical volcanism at Yucca Mountain would remain elevated more than 800 times longer than at Paricutín volcano. Very large floods have been documented in Fortymile Wash. Large floods in this ephemeral dryland system (Coleman, 2007) have the potential to erode and move large quantities of sediment with high suspended sediment concentrations and high bedload transport efficiency (Rathburn, 2007).

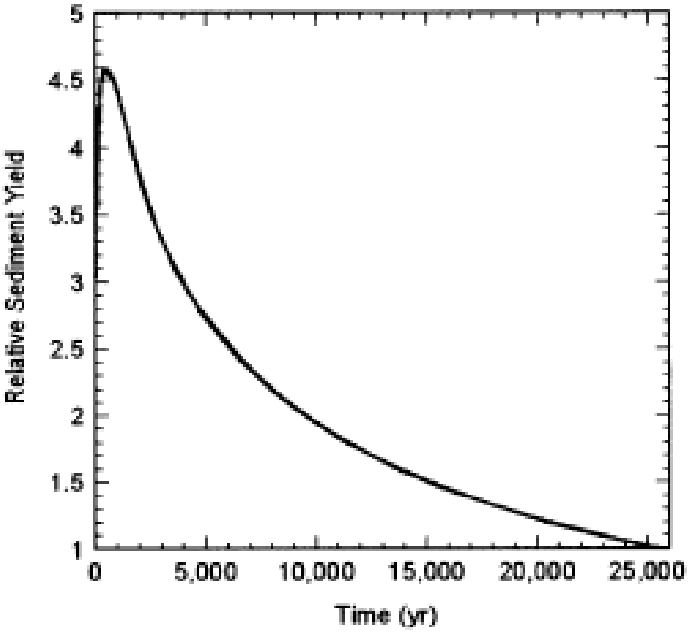


Figure 63 **Plot of calculated accelerated erosion following potential tephra fall in the Fortymile Wash drainage system. After an eruption, there would be an increase in sediment yield due to accelerated erosion, followed by a gradual decrease in sediment yield from these elevated values until conditions return to preeruption conditions (represented by a relative yield of 1.0 in the figure) (After Hooper, 2005, Figure 4-4).**

Sara Rathburn (Colorado State University) provided comments (ACNW, 2007) regarding the report by Hooper (2005). She compared the relative importance of fluvial versus eolian transport of sediment in Fortymile Wash. In her view, fluvial transport will be much more important than wind in transporting the greatest volume of sediment. She considers that sediment production in the Fortymile Wash basin will always be relatively high, given the lack of vegetation and the constancy of weathering of substrate material. Every time Fortymile Wash receives flow there is a flood that will transport sediment downstream until transmission losses overwhelm transport capacity. The sediment transport will be episodic and punctuated by the large flows, some of which have been shown historically to deliver water and sediment to the Amargosa River. Dr. Rathburn also noted that Hooper (2005) has no discussion of uncertainty, or of an attempt to quantify the uncertainty related to sediment transport in Fortymile Wash. If limited or no field data are used, and if the physical characteristics of the sediment (ash) are unknown (e.g. clumps of ash crystals vs. individual crystals), then using empirical equations in the sediment budget involves major assumptions that will have a large bearing on the results and how they are to be used. It is imperative that an effort be made to bracket the estimates of sediment production, delivery to channels, and transport. Otherwise, the discussion by Hooper (2005) reads with an unjustified amount of confidence in its sediment budget numbers.

Overall, the NRC approach appears to be a simplistic view of ephemeral stream dynamics. Fortymile Wash is not always dominated by erosion and the active fan is not always dominated by deposition. Small flow events would not even reach the fan and instead would produce deposits in the Wash that are flushed out by the largest flow events. Precipitation in this basin is not homogeneous in space or time because most of the Fortymile Wash drainage basin occurs to the north at higher elevations. It is possible to have isolated rain events to the north that cause major flooding in the wash (and erosion of the depositional fan) but no local sheet wash erosion of the tephra blanket. Also, in arid regions such as Yucca Mountain, most of the erosion and long-distance sediment transport takes place during the largest discharge events, which are infrequent. The sediments most likely to be suspended and transported long distances are the smallest particles [7]. The sediments of the Fortymile Wash fan are relatively coarse, consisting mainly of sand and gravel pavements that dropped out of suspension quickly following Stokes' Law, while the finer materials have been winnowed out and carried downstream. The smallest particles of concern in health physics will not settle out of overland flows until the water infiltrates, evaporates, or ponds. Long-distance transport of contaminated ash would result in extensive dilution of this material by uncontaminated sediments along the Fortymile Wash-Amargosa River drainage system. As discussed in Section 6.3.3, less contaminated ash would be available for transport if a more realistic treatment of spent fuel particle sizes (i.e., a coarser particle distribution) were to be applied.

6.4.3.2. EPRI Analysis of Fluvial Transport from Extrusive Volcanic Activity

EPRI (2004) commented on various conservatisms used in the NRC and DOE analyses. EPRI's model of ash transport modeling showed that particles smaller than 130 microns in diameter would not be deposited at the compliance point (the RMEI). Both DOE and NRC use a conservative assumption that all deposited material is in the respirable size range, although neither the NRC nor DOE discuss realistic mechanisms that would break down ash in this way.

6.4.3.3. DOE Volcanic Ash Fluvial Redistribution Model

The DOE (2003) has developed a model for fluvial redistribution of volcanic ash that initiates with tephra being transported by hillside erosion. Sediment then moves into drainages and is transported via drainages that coalesce into larger and larger channels. Water and sediment from different channels begin a mixing process that ultimately leads to a homogeneous sediment containing materials from all drainages in the basin (Folk,1980). This mixing of sediments occurs everywhere that sediment is transported by water, including intermittent streams. Mixing occurs at higher rates and involves larger clasts in larger drainages than smaller ones and on steeper hillslopes than on low-gradient land surfaces. Sediment mixing also occurs from wind transport across the landscape. Drainage channels that develop across newly deposited tephra sheets exhibit the same processes as observed in streams, and, produce well-mixed sediment loads.

In the Yucca Mountain area, sediments in drainage channels are commonly clasts of welded tuff and wind-blown quartz sand, which are more durable than basaltic tephra. Mixing of sediments occurs very rapidly, and welded tuff clasts and quartz sand/silt deposits are more abundant in the larger channels, so that the ash component from the Lathrop Wells volcano has been progressively diluted during transport relative to the total sediment volume. Eolian processes also mix sand and silt with the fluvially transported materials. The ratio of basaltic ash to non-ash continues to decrease with the passage of time.

The DOE (2003) has performed studies of ash redistribution near the Lathrop Wells volcano to evaluate the fraction of basaltic ash components as a function of transport distance.

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[7] The Wentworth scale classifies silt particles in the range from 4 - 62 microns. Clay particles are smaller than 4 microns. In a motionless water column, all of the sand drops out in 40 seconds and silts drop out of suspension in 2 hours (re: Stokes Law). After 2 hours only clays would remain in suspension.

These data indicate that the concentration of basaltic ash in sediments decreases to about 50 percent within 1 km of the head of the tephra sheet drainage on the eastern side of Lathrop Wells, whereas the channel on the west side has less than 40 percent basaltic ash after 1 km of transport. The indicated dilution factor is 50 to 60 percent per kilometer.

Fortymile Wash is a major 815-km^2 drainage basin that includes the entire eastern slope of Yucca Mountain and the Fortymile Wash alluvial fan. Understanding the redistribution processes along Fortymile Wash is important to volcanic-eruption consequence scenarios. The fan spreads out into the Amargosa Valley from the mouth of Fortymile Wash. In the upper or northern half of the fan, the channels are well defined and widely spaced, with sizable interstream area between all pairs of channels. These interstream divide tracts are more prominent on the upper fan. On the lower fan they are neither as topographically prominent nor as wide because the distributary channels become progressively closer on the lower fan. Previous worldwide above ground nuclear tests introduced radioactive ^{137}Cs into the atmosphere. ^{137}Cs forms a time-stratigraphic marker in alluvial or eolian deposits and can be used to assess the extent of local erosion and deposition. The depth to which ^{137}Cs infiltrates into the soil can be used as a general proxy for the depth to which sorbing radionuclides may infiltrate after deposition with volcanic ash (DOE, 2003). To evaluate erosion rates on the upper Fortymile Wash fan, soil samples were taken for analysis of ^{137}Cs concentrations (BSC, 2003b). The analyses show that the upper-fan inter stream divide areas have been eroding over the last 50+ years and have lost 1 to 2 cm of the upper soil horizon, most likely as a result of wind erosion, rather than from removal by fluvial processes (BSC, 2003b). There is also evidence of some eolian deposition on these same surfaces.

The majority of the fan surface is interstream divide area, from which 1 to 2 cm of material, on average, has been removed during the last 50 years. When large floods occur, the flood waters can carry large quantities of sediment rapidly southward across the fan to the Amargosa River and may overflow channel banks forming small patches of overbank deposits. As flood levels subside, the suspended and bedload materials in the channel flow are deposited within the channels and are stored in the channel until the next flood occurs (BSC, 2003b). In contrast to the inter stream divide areas, the amount of sediment deposited in channels varies greatly from location to location. In TSPA, the DOE models distributary channel areas as having a layer of contaminated ash of uncertain thickness that appears immediately following the eruption. This layer will be of variable thickness, ranging from zero to several tens of centimeters (represented by a uniform distribution from 0 to 15 cm) (DOE, 2003). Although sediment thickness may exceed 15 cm, it is likely that contributions to dose from radionuclides at greater depths will be negligible. Observations of ^{137}Cs content also indicate that radionuclides are unlikely to migrate more than 9 cm into sediment below the ash layer due to the widespread presence of carbonate layers in soil (DOE, 2003). Within any portion of the fan contaminated ash will be removed and deposited continuously, and average values for layer thickness are used as input in TSPA. Dilution of contaminated tephra would occur during transport in distributary channels. However, field data are insufficient to quantify this reduction in concentrations for the Fortymile Wash drainage and fan (DOE, 2003). DOE’s TSPA conservatively assumes that the concentration of radionuclides in the contaminated sediment in the channel areas is the same as that derived from ASHPLUME for the mid-line of a plume about 18 km from the vent. The extent to which this assumption overestimates concentrations is not well known but may be large, especially for eruptive events in which the wind is blowing from the west or southwest and the ash deposition occurs upstream from the location of the RMEI. The DOE considers the use of a single concentration to represent a spatially variable parameter to be reasonable because exposures would be integrated over a region that is large compared to the scale of local variability (BSC, 2003b).

The DOE reports that their approach to redistribution is being completely replaced with a process-based landscape model of redistribution and sediment mixing. This comment was made by the DOE in their review of the draft version of this report (see ACNW, 2007).

The DOE reports, based on observations from the Lathrop Wells Cone, that volcanic ash would not remain indefinitely in the channel area. The time needed to remove most tephra from the basin is unknown but is substantially less than the age of the Lathrop Wells Cone (DOE, 2003). Given the limited amount of residual ash observed near Lathrop Wells, the time required to remove most ash from the basin may be very short, perhaps on the scale of centuries. The DOE's TSPA approach applies a uniform removal rate to channel deposits such that the initial layer is entirely removed within an uncertain period of time that is sampled uniformly between 100 and 1,000 years. Some residual contamination will likely persist indefinitely after the tephra deposits are eroded (DOE, 2003). The latest results from Valentine et al. (2007) indicate that a significant portion of the proximal and medial tephra deposits from Lathrop Wells are buried by fluvial deposits, rather than eroded away.

DOE's current approach in modeling atmospheric dispersal and deposition of tephra from a potential volcanic eruption at Yucca Mountain is documented in the model report BSC (2005). The report documents the conceptual and mathematical model (ASHPLUME) for atmospheric dispersal and subsequent deposition of ash on the land surface from a potential volcanic eruption. The report also documents the conceptual model for ash (tephra) redistribution. The ASHPLUME conceptual model accounts for incorporation and entrainment of waste fuel particles associated with a hypothetical volcanic eruption through the repository and downwind transport of contaminated tephra. The ASHPLUME mathematical model describes the conceptual model in mathematical terms to allow for prediction of contaminated ash deposition on the ground. BSC (2005) also describes the conceptual model for tephra redistribution within Fortymile Wash and on its alluvial fan. Sensitivity analyses and model validation activities for the ash dispersal and redistribution models are presented. The DOE considered models for atmospheric dispersal of contaminated tephra during and after violent Strombolian eruptions of the type that could occur in the Yucca Mountain region and for redistribution of contaminated tephra after the volcanic eruption. If such an eruption were to intersect the repository, the possibility exists for wastes to become entrained in the eruptive mixture and be transported via the same mechanisms as the ash plume. Although other eruption types that include nonviolent as well as violent phases exist, the violent Strombolian eruption has the greatest potential to erupt ash and waste particles high into the atmosphere, thus increasing the potential distance of dispersal. The DOE's ASHPLUME conceptual model includes only the eruptive ash plume, convective/dispersive transport of contaminated ash particles downwind, and deposition on the ground surface. The ASHPLUME mathematical model can be used to evaluate ash and waste concentration at any point or multiple points on the surface relative to the volcanic vent. The DOE's ash redistribution conceptual model describes the erosion and subsequent deposition of contaminated ash. Recently acquired wind data collected at Desert Rock (near Mercury, Nevada) were used to calculate wind speed and direction up to a height of 13 km. This data set replaces the Nevada Test Site data that were used for the TSPA-SR. Parameterization for the atmospheric dispersal model used in all ASHPLUME versions was documented in Igneous Consequence Modeling for the TSPA-SR (BSC, 2001). Tephra deposit thicknesses were simulated using ASHPLUME 1.4LV and compared with actual tephra deposit thicknesses from the 1995 eruptive event at the Cerro Negro volcano in Nicaragua. The DOE's ash redistribution conceptual model is new and was not used in the TSPA-SR.

BSC (2005, Appendix I) also developed an alternative numerical model for ash and fuel redistribution that calculates near-surface and at-depth fuel (waste) concentrations through time in soil columns near the RMEI location. This alternative model was designed to provide a more complete representation of the redistribution mechanisms involved, and to eliminate the mass balance conservatism of the simplified ash redistribution conceptual model. This alternative model is still under development by the DOE (BSC, 2005, Appendix I). It uses a spatially-distributed Geographic Information System (GIS) framework to calculate the ash and fuel transported to the RMEI location from the upper Fortymile Wash watershed by hillslope and fluvial processes. This redistributed ash and fuel is combined with any primary ash and fuel that was hypothetically deposited directly on the RMEI location. By explicitly modeling the primary ash fall and redistribution processes, the model directly computes how much volcanic ash and fuel would be transported to the RMEI location under any wind conditions.

The DOE's alternative redistribution model (BSC, 2005, Appendix I) further considers the fate of ash and fuel delivered to the RMEI location, distinguishing between channels and recent (< 10 kyr) depositional surfaces (i.e., "channels"), and older (> 10 kyr) interchannel divide surfaces on the RMEI location. In the model, ash and fuel delivered from the upper Fortymile Wash watershed are deposited only in channels. This treatment assumes that areas of the RMEI location that have not been subject to fluvial erosion or deposition over the last 10 kyr will not be subject to fluvial activity within the next 10 kyr. The model also distinguishes between channels and divides for the purposes of modeling fuel redistribution in the soil profile. Vertical redistribution within the soil profile is modeled as a diffusion process. The lower boundary of the soil layer represents the presence of impermeable soil horizons. The alternative redistribution model evaluates over time the surface and depth-averaged fuel concentration on channels and divides at the RMEI location after an eruption (BSC, 2005, Appendix I).

The alternative model does not incorporate eolian erosion or deposition or the long-term geologic dynamics of fan interchannel divide and channel interactions (BSC, 2005, Appendix I). Several key assumptions are made under the alternate model. First, it is assumed the climate through much of the regulatory period will be similar to today's climate and will have relatively little impact on the Fortymile Wash alluvial fan even with a projected increase in annual precipitation. The rationale for this is that the expected effects of increased precipitation would include more vegetation and this will result in less ash being derived from the hillslopes. Total precipitation during a pluvial climate would be greater, but increased storm intensities or peak channel discharges would not be expected. The precipitation increase would come primarily from more frequent rainfall events (BSC, 2005, Appendix I).

The second assumption is that the model assumes distributary channels in the RMEI location do not migrate (BSC, 2005, Appendix I). Therefore, the areal fraction of channels and interchannel divides would not change with time. The rationale for this is that fans are dynamic landforms that can evolve topographically over both long and short time scales. A distinction can be made, however, between the evolution of alluvial fans over millions of years and the evolution of "entrenched" alluvial fans over shorter time scales. In tectonically-active areas and over millions of years, alluvial fans aggrade by sedimentation in channels and by channel migration. Over these long time scales, alluvial fans are best considered to be subject to redeposition across the entire fan area. The Quaternary period has caused cycles of channel aggradation and incision on alluvial fans in the western US. As a result, fluvial activity on many fans is restricted to a small fraction of the piedmont area near the modern channels. Older terraces are commonly preserved from previous episodes of aggradation and incision, but are no longer subject to fluvial activity even during extreme events based on evidence of pavement development. Surface characteristics observed in the field, including well-developed desert pavement and varnish, provide evidence for the stability of channels and the lack of significant, soil-disruptive floods on interchannel divides. Well-developed desert pavements and varnish have been observed on divides near the RMEI location, indicating that most of these interchannel divides are Pleistocene in age and have not been flooded for at least 10,000 years. As a result, they may be considered stable for treatment in performance assessment (BSC, 2005, Appendix I).

The third assumption is that in the model eolian transport to the RMEI location can be neglected compared with fluvial transport processes (BSC, 2005, Appendix I). The rationale for this is that fluvial transport is considered the dominant redistribution process for ash and source material from the upper Fortymile Wash because (1) the prevailing wind is away from the RMEI location and towards the drainage basin (so eolian transport is most likely to redistribute ash into the drainage basin, away from the RMEI location), and (2) fluvial transport processes in a tributary drainage system focus transported material onto the RMEI location, while eolian processes disperse ash by repeated episodes of entrainment, turbulent dispersion in the atmosphere, and redeposition (BSC, 2005, Appendix I).

6.4.3.4. NWTRB Comments on Potential Consequences of Igneous Activity

The Nuclear Waste Technical Review Board (NWTRB) has commented (NWTRB, 2002) that performance assessment calculations appear to show that “igneous activity is the largest contributor by far to radioactive dose during the first 10,000 years,” an observation that was repeated in a report the following year (NWTRB, 2003). However, the NWTRB observed in its 2002 report that the igneous activity model proposed by NRC may be a “conservative end-member” model. This particular report of the NWTRB predates many of the observations and analyses discussed in previous sections of the present report.

At the September, 2002, meeting of the NWTRB, Dr. William Melson, a consultant on igneous activity issues to the NWTRB, commented that studies of the mama-waste package interaction should focus on identifying conditions that would lead to disruption of the waste package and release of radioactive material from the package, in particular the effects of temperatures up to 1200° C and the effects of corrosive gases on the package welds. Dr. Melson also commented on the “dogleg” scenario, in which magma moves down the drift and then out through a secondary vent. This scenario would involve the largest number of waste packages with magma entering the drift. Dr. Melson noted that this was a worst-case scenario, and its probability of occurrence was small (Melson, 2003).

In 2003, the NWTRB made three recommendations regarding igneous activity:

- that the DOE conduct modeling studies of compressible fluids
- that the DOE study the waste package-magma interaction, including both chemical and mechanical interactions and
- that the DOE study aeromagnetic anomalies near the Yucca Mountain site.

These recommendations were repeated in the NWTRB’s 2004 report to Congress (NWTRB, 2004).

6.4.4. Effects of Transport of Contaminated Ash on Dose to the RMEI

6.4.4.1. How Transport Can Result in a Dose

6.4.4.1.1. Potential Dose from an Extrusive Scenario

According to some stakeholders, a number of waste packages would be completely destroyed in the extrusive scenario, and at least some of the spent fuel contents would be reduced to small particles that are dispersed over the surrounding region by the eruption plume. The extrusive scenario accounts for this phenomenon by analyzing the fate of the fraction of the ejected radioactively contaminated ash particles that will be deposited on the ground. This deposited particulate matter can be remobilized and thereby moved into the vicinity of the RMEI by surface water (fluvial remobilization) or wind (eolian remobilization). Moreover, any remobilized material can be resuspended by wind or mechanical action. Thus transport of radioactive particulate matter could result in a radiation dose to the RMEI. Although radionuclides can persist in the environment and can cause exposure hundreds to thousands of years after the event, erosion and mixing with uncontaminated soil will decrease the concentration of radionuclides and thus the exposure of the RMEI. The emphasis in this section is on eolian remobilization and resuspension. Fluvial remobilization is discussed in the preceding section.

In eolian transport, deposited ash is resuspended by wind, and the resuspended ash is carried predominantly downwind. The plume shape of the resuspended ash depends on particle size and density and on meteorological conditions. A review of atmospheric dispersion, including the dispersion of the initial plume from the eruption, is presented in Section 3.4. The present section expands on that initial discussion and on the relationship between the dispersed ash plume and radiation dose to the RMEI.

Radioactively contaminated ash to which the RMEI is exposed can potentially deliver the following types of radiation doses: an external dose from groundshine (direct radiation from radioactive material on the ground), an external dose from cloudshine (direct radiation from radioactive material in the air), an ingestion dose, and an inhalation dose. A groundshine dose would be significant only at the time of the eruption and is not considered for this analysis because direct hazards during an eruption would involve more serious risks. Cloudshine doses are rarely significant under any circumstances (Neuhauser et al., 2000) and are therefore not considered in this analysis.

An ingestion dose to the RMEI would depend on uptake of radionuclides by food crops and the ingestion of these crops. Anspaugh et al. (2002) reviewed measurements of vegetation uptake of deposited radionuclides at the Nevada Test Site following atmospheric nuclear tests. Table 9 shows the computed fractions of fallout particles that were intercepted by vegetation.

Table 9 Summary of computed mass interception fractions of fallout from nuclear tests at the Nevada Test Site (After Anspaugh et al., 2002).

Parameter	Computed values of mass interception fractions m^2 of contaminated surface/kg vegetation dry weight			
	Native desert vegetation		Pasture-type vegetation	
	Total fallout	≤44 μm	Total fallout	≤44 μm
Arithmetic mean	0.18	0.81	0.20	1.9
Standard deviation	0.25	1.3	0.29	4.29
Geometric mean	0.062	0.37	0.081	0.82
Standard deviation	6.3	3.7	4.8	3.2

Smaller particles are more likely to be taken up by vegetation than larger particles, and dissolved material is the most likely to be absorbed. Lee et al. (2005) have observed that rainfall would have to increase about ten fold to provide enough water for locally grown crops or enough water for families to grow a significant fraction of their own food. Most water used for irrigation in the Amargosa Valley is groundwater rather than surface water (Fenelon and Moreno, 2002), and groundwater would not be affected by surface remobilization of contaminated ash. Virtually no agricultural products intended for human consumption are produced in the area occupied by the RMEI and any ingestion dose would probably be limited to meat and milk for this scenario. Some immediate fallout could be absorbed by pasture-type vegetation, since alfalfa is grown in the Amargosa Valley, but there is not enough locally grown alfalfa to maintain either beef or dairy cattle[8]. Therefore, any ingestion dose would be a minor, probably negligible contributor to a radiation dose to the RMEI.

An inhalation dose would be the only significant dose to the RMEI. The inhalation dose is the dose delivered by an inhaled radionuclide to the organ of the body in which it is lodged. This Committed Effective Dose Equivalent (CEDE) is summed over 50 years and assigned to the year the intake occurs (Schleien et al., 1998). The dose delivered by an inhaled and absorbed radionuclide also depends on metabolism and particle size; the most penetrating particles are about 0.3 microns (AMAD). The energy absorbed by various organs and the type of radiation are reflected in the dose conversion factors (DCFs) for each radionuclide (Eckerman and Ryman, 1993; Eckerman et al., 1999; Leggett and Eckerman, 2003). These DCFs are specific to the pathway by which the RMEI is exposed (ingestion, inhalation), and to the organ absorbing the radionuclide, and take into account both radioactive decay and physiological elimination from the body.

6.4.4.1.2. Potential Dose from an Intrusive Scenario

An intrusive scenario could result in a dose to the RMEI only through ingestion of groundwater or crops that absorbed radionuclides from the groundwater. The only radionuclides significant to dose in the intrusive scenario are those that would travel in the groundwater: ^{129}I, ^{99}Tc, and ^{237}Np. The contribution to the RMEI dose of ^{129}I is the subject of a recent study by Moeller et al. (2005), which provides an insight into the role of stable (non-radioactive) iodine in calculating doses from ^{129}I (also see Killough and Rohwer, 2005). Moeller and Ryan (2005) noted:

> The science of internal dosimetry has undergone significant progress and dramatic change during the years [since 1960]…. It is essential, therefore, that the analysts and regulators acknowledge that these changes have occurred, that the dose estimates will differ depending on the basis on which they are made, and that caution must be exercised to ensure that these factors are taken into consideration in interpreting the outcomes …. Differences in dose coefficients can result in changes in dose estimates by an order of magnitude depending on the source from which [the dose coefficients] were obtained.

For example, the dose conversion factor for ^{129}I is strongly influenced by the intake of stable iodine in food and water in the diet (Moeller and Ryan, 2004). Another example is from a recent paper on dose conversion factors for tritium and ^{14}C (Richardson and Dunford, 2001). This paper notes:

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[8] As was observed in the 2004 ACNW&M tour of the Amargosa Valley, the one commercial farm, a dairy farm, imports most of its alfalfa.

> It is shown how the dose coefficients for intakes of tritium and ^{14}C compounds are affected by different interpretations of the methods recommended by the ICRP for two of the three classes of vapors and gases. Some aspects of the ICRP models, such as the percent oxidized, would benefit from reconsideration so as to produce tritium and ^{14}C biokinetics that are less dependent on the radionuclide.

6.4.4.2. NRC Analysis

Jarzemba et al. (1997) modified the Suzuki ash transport model and incorporated it into the TPA code to calculate the distribution of the released radionuclides during a hypothetical eruption through the repository. The composition of the radionuclide layer on the ground takes into account the thickness of the ash deposit, leaching and erosion rates, and radionuclide decay. In the TPA analysis the wind direction during an eruption was assumed to always be in the general direction of the RMEI. A more realistic treatment of wind is now being incorporated in TPA. This is especially important given that the two parameters most influential to eolian dispersion are the mass of soil in the air above a fresh volcanic ash blanket (mass loading) and the wind speed (Table 4-5 of Mohanty et al., 2004).

The calculated risk from volcanism appears to be small within the 10,000-year simulation period (Mohanty et al., 2004). Results from a range of alternative conceptual models for waste form dissolution, waste package lifetime, and radionuclide transport resulted in calculated doses to the RMEI that were well within the EPA standard.

The most recent NRC simulations of extrusive volcanism at Yucca Mountain are documented in Mohanty et al. (2005, p. iii), where the NRC summarized the following overall results:

> Analyses to assist staff in understanding the significance of features, events, and processes associated with extrusive volcanism include estimates of the impact of (i) wind-field variability assumptions, (ii) ash deposition and remobilization, (iii) ash mass loading, (iv) assumptions regarding spent nuclear fuel incorporation and initial plume velocity, and (v) drift degradation on magma-waste package interactions. Results of these analyses for 10,000 years indicate (i) current assumptions for ash mass loading and wind-field speed and direction are reasonable; the assumptions have the potential to affect the dose estimate by approximately one order of magnitude, (ii) alternative mass loading reduces dose estimates by approximately a factor of two, (iii) current and alternative models for spent nuclear fuel incorporation and initial plume velocity cause only small differences in dose estimates, and (iv) no effects on the peak eruptive risk are estimated from coupling drift degradation with the number of entrained waste packages. Ash remobilization and wind variations are implemented in an alternative model.

Mohanty et al. (2005) present the following conclusions related to the volcanic extrusion scenario and ash deposition/remobilization:

- Redistribution of contaminated ash appears unlikely to increase significantly the estimated peak dose arising from a volcanic eruption over the case in which the ash is directly deposited at the RMEI location. Although not a likely bounding approach, fixing the wind direction to the south appears reasonable to account for the effect of remobilization of the contaminated ash.
- Overall, results suggest variability in the wind field does not significantly alter the estimated peak dose at the RMEI location. Fixing the wind direction to the south appears a reasonably conservative approach to account for the effect of a variable wind field.

- Analysis estimates composite daily mass loading varies by approximately a factor of two for a wide range of duration for the peak values (i.e., 5 to 50 percent of the time). Using the medium value for the composite mass loading for fresh ash conditions (i.e., 1.12 mg/m^3 (7.0 × 10^{-8} lbm/ft^3)) and soil conditions (i.e., 0.1 mg/m^3 (6.2 × 10^{-9} lbm/ft^3)) in the TPA code resulted in approximately a factor of two reduction in the overall dose estimate. The results from this analysis were considered in developing mass loading parameters in the latest version of the TPA code.

The groundwater dose from an intrusive event is similar to the dose in the base case with faulting events (see Mohanty et al., 2004, Figure 3-14). The increase in groundwater dose from igneous activity is smaller than that for faulting events because only 53 waste packages fail by intrusive igneous activity as compared to 208 waste packages by the faulting event in the mean value, single-realization case.

Dose conversion factors (rem per curie) are computed in the TPA Version 4.1 code by using GENTPA, a modification of the GENII computer code (Napier et al., 1988). Subsequent versions of the TPA code use the dose conversion factors tabulated in Federal Guidance Report 13 (Eckerman et al., 1999).

6.4.4.3. DOE Analysis

The 50-year record of deposition and remobilization of ^{137}Cs on the Nevada Test Site suggests that eolian removal of material has been the major process causing erosion (DOE, 2003). In the interstream divides, erosion removes sediment at a relatively rapid rate of 1 to 2 cm per 50 years. The DOE's TSPA model calculates doses using the initial ash-layer thicknesses and radionuclide concentrations from ASHPLUME, modified by a time dependent soil removal factor, estimated to range from 0.02 to 0.04 cm/yr (DOE, 2003). Given these erosion rates, ash layers will be removed within a few centuries, depending on initial thickness. Based on field observations, it is likely some fine-grained ash and radionuclides will persist in the soil below the surface ash layer, and some additional radionuclides may be brought into the interstream divide areas by infrequent flooding events that cover the entire fan. Residual contamination after erosion removal of the tephra deposits is estimated to be on the order of 0.01 of the initial ASHPLUME radionuclide concentration (BSC, 2003b).

Like the NRC, the DOE uses the generally accepted convention that airborne resuspended material is dispersed in the same way as any airborne material. The DOE has recently validated both its dispersion and inhalation models by using measurements of total suspended particulates raised both by resuspension and by mechanical disturbance of the soil surface, as in farming (BSC, 2006). The DOE's literature review suggest that ash from basaltic volcanoes has a somewhat smaller concentration of very fine particles than ash from other volcanoes (like Mt. St. Helens), but that these are the particles that are carried farthest from the eruption site to the vicinity of the RMEI. In addition, BSC (2006) cites extensive literature reports of measurements of particle sizes that can contribute to inhalation dose, concentrating on particles of 10 microns diameter or less (particles designated as PM_{10} by EPA). The DOE biosphere model assumes that particles of 1 micron AMAD play the greatest role in inhalation dose (BSC 2006, p. 6-23) and, like Jarzemba and LaPlante (1996) assumes a triangular distribution.

DOE has validated its ASHPLUME modeling by examining the distribution of ash from the Lathrop Wells volcanic cone as well as from Cerro Negro volcano (DOE, 2004). Hill et al. (1998) have also verified the use of the Suzuki (1983) formulation in modeling ash distribution from Cerro Negro. Apparently, the DOE does not use the Anspaugh model for eolian redistribution, but depends on its own validation.

6.4.5. Remobilization Summary

The consequences to the RMEI associated with an extrusive igneous event depend on estimation of the following parameters:

- particle size and density of spent fuel and radionuclides released in the event
- particle size and density of ash into which radioactive material is incorporated
- power of the eruption and total mass of material from an igneous event
- areal extent and thickness of ash layer in Fortymile Wash drainage basin
- wind direction
- meteorologic parameters used in the Suzuki and atmospheric dispersion models
- areal extent of vegetation exposed to deposited material
- elapsed time between the igneous event and exposure of the RMEI
- DCF reference document used to calculate dose
- RMEI breathing rate.

The consequences associated with an intrusive igneous event depend on:

- agricultural crops and livestock exposed to potentially contaminated groundwater
- elapsed time between the igneous event and exposure of the RMEI.

Both the NRC and DOE favor using Federal Guidance Report (FGR) 13 (Eckerman et al, 1999) because the uptake models of FGR 13 are a considerable refinement over earlier clearance models.

The potential dose to the RMEI is the compliance criterion, and is also the culmination of all the assumptions that have gone into the analysis of an igneous event. Both the NRC and the DOE consider the inhalation dose (including inhalation of resuspended material) much more significant than an external dose. Neither agency has considered the possibility of an ingestion dose.

The NRC employed several alternative models, varied the degree to which SNF was incorporated in ash, varied the wind direction and other dispersion parameters, considered a range of remobilizations, and notes that the differences result in variations of the inhalation dose to the RMEI by factors between two and ten. This appears to be a useful approach to generating performance assessment inputs (inputs to the TPA) and results in a risk-informed analysis. The NRC considers that the maximum contribution to inhalation dose is from particles of approximately one micron AMAD (Compton, 2004) or less.

The DOE (2004) uses the same assumptions as the NRC about the range of size and density of spent nuclear fuel particles that can be incorporated into ash particles, and also cites Jarzemba and La Plante (1996). The DOE defines the particle density as a function of the fraction of magma incorporated into the ash particle. The resulting range of contaminated ash particle densities is similar to that postulated by the NRC. The DOE does make the point that the frequency of wind blowing toward the RMEI location is considerably smaller than for wind blowing away from the RMEI, so that the probability of an inhalation dose from resuspended material is relatively small. The DOE further postulates that the high winds in the vicinity of the RMEI make persistence of a thick remobilizable layer of undiluted contaminated ash unlikely.

The DOE considers two scenarios for RMEI exposure: (1) exposure to contaminated ash due primarily to eolian dispersion, and (2) exposure due to fluvially remobilized resuspended ash. The DOE postulated the first as less likely because of the relatively infrequent high winds in the direction of the RMEI.

6.5. Summary

The consequences for future radiological exposures vary significantly among the hypothetical scenarios for volcanic interaction with the repository. These scenarios are an extrusive (volcanic) event and an intrusive event. The latter includes hypothesized secondary breakouts of magma from a repository at some distance from the point of initial intersection (so-called “dogleg” scenario).

Extrusive event – The number of waste packages that could be damaged or destroyed by extrusive volcanism depends on the diameter of a volcanic conduit at the depth that it intersects a repository drift. The DOE has estimated that the median number of waste packages that would be disrupted in an eruption scenario is fewer than 10. The NRC currently assumes that volcanic conduits would have an average diameter of ~50 m. If the center of a conduit were to coincide with the axis of a drift, then ~5 waste packages could be entrained within the cross-section of the conduit and their contents potentially transported to the surface. The ongoing PVHA-U expert elicitation is evaluating the potential size range of volcanic conduits based on analog studies. Final results of that elicitation will not be available until 2008, but are expected to provide the best available estimate of conduit diameter at repository depth.

Magma/drift/waste interactions in the extrusive scenario are incompletely understood. Due to the perceived complexity of the processes involved, neither the NRC nor DOE evaluate magma/drift/waste package interactions in any detail. In the DOE and NRC performance assessment codes the assumption is made that all spent fuel entrained in a volcanic conduit in the extrusive scenario would be reduced to a very fine powder, incorporated in tephra, erupted into the atmosphere, and distributed across the countryside by prevailing winds. This appears to be a conservative assumption because the ceramic pellets that comprise spent nuclear fuel have great strength and a melting point of 2600^{o} C, much higher than magma temperatures of about 1100^{o} C. Also, the ejected fuel pellets and fragments may be encased in a protective layer of quenched magma, consistent with natural volcanic analogs of wall rock materials that have been caught up in the magma and brought to the surface in volcanic conduits (i.e., xenoliths). The result is larger fragments that are unlikely to be inhaled. It is unclear how or whether the Alloy-22 waste packages or the ceramic or glass waste forms themselves would be reduced to particles of respirable size, as currently assumed by the DOE and NRC. EPRI has concluded, based on multiple lines of evidence, that it is unlikely that waste packages would be breached by magma during an active eruption period. EPRI found that the expected consequence of an igneous extrusive event would be zero releases of radioactive matter from the repository to the atmosphere.

Slightly more than half of the eruptive products of basaltic volcanoes in the Yucca Mountain region consists of ash that was dispersed from the eruption plumes. The remainder occurs as volcanic cone fragments and lavas, which are resistant to erosion. Radioactive waste incorporated in the cone and lava flows would contribute little to the RMEI dose because of this resistance to erosion.

Intrusive event – the DOE has estimated the number of waste packages that could be damaged in a potential future igneous event. The igneous intrusion scenario shows a range of consequences, extending from virtually no waste packages damaged to nearly all waste packages in the repository. The 50th percentile value indicates approximately 1600 waste packages could be impacted, out of over 11,000 waste packages in the repository. In TPA 4.1 the NRC estimated a mean value of 37 magma-induced mechanical failures from an intrusive event, based on a log uniform distribution from 1 to 1402 waste package failures. Igneous activity causes the largest increase in dose conditionally from both groundwater and airborne pathways, but the risk is still small when the probability of the volcanic event is factored into the calculations. EPRI concluded that magma viscosity would be larger than previously assumed. They estimate that only 0-6 waste packages could become engulfed by magma intrusion in a waste emplacement drift. They further estimate that 14-24 waste packages could be significantly affected by heat and corrosive gases (but not engulfed by magma).

Viscosity is the most important magma property to understand because it controls the flow behavior and the distance that magma could penetrate a repository in the unlikely event of volcanic intersection. ACNW&M observes that previous researchers have not been consistent in their approach to estimating the viscosity of the Yucca Mountain basalt as it ascends and degasses with approach to the surface. There has been a tendency to assume rheological properties pertaining to both wet, cool magmas and dry, hot magmas, leading incorrectly to the postulate of a highly explosive system with highly mobile lavas. Therefore, previous claims of severe consequences of igneous intersection appear to be poorly founded. The potential Yucca Mountain magma is likely a wet, cool explosive magma with relatively immobile lavas. The Pleistocene lava flows in the Crater Flat basin and at Lathrop Wells demonstrate that the lavas had high viscosities and were relatively immobile. Characteristics of these lava flows indicate viscosities orders of magnitude larger than had been assumed in analyses of igneous interaction with a repository. These high viscosities, along with magma solidification effects, would significantly reduce the distance that magma could penetrate into tunnels and thereby reduce the number of impacted waste packages.

The so-called “dogleg” scenario (Woods et al., 2002) refers to a hypothetical scenario proposed by the NRC in which magma might rapidly fill a drift and create enough pressure to generate (at a distance from the entry point) a secondary dike to the surface. This “dogleg” model was analyzed by the Igneous Consequences Peer Review (ICPR) Panel (Detournay et al., 2003), by EPRI, and by the DOE. In TPA 4.1 analyses the NRC assumed that a mean value of 51 waste packages could be entrained by an extrusive event and contained in volcanic ejecta. The ICPR considered the propagation of either a magmatic or pyroclastic “dogleg” scenario to be quite improbable, found that the initial and boundary conditions in the model are unrealistic, but recommended further analyses to assess the impacts of a partially coupled pyroclastic flow scenario on repository performance. EPRI concluded that their independent modeling results show that pressure conditions in a repository intersected by magma would be significantly less forceful than postulated by the NRC. The DOE concluded that the “dogleg” model overestimates the violence of magma-repository interaction. Use of realistic boundary conditions (including compressible walls and backfill, permeable country rock and backfill, phase separation in the magma-volatile mixture, partial blockage of the drift by waste packages and other engineering features, and the axial spacing of the waste packages) would greatly reduce the amplitude of any shock wave that might form. Use of realistic initial conditions such as a dike tip would preclude shock waves for all but the most rapid magma ascent rates.

Overall, the “dogleg” intrusion/extrusion scenario is not credible. Increased magma viscosity, quenching of magma on waste packages and drift walls, and reduction of magma pressure at a distance from the drift entry point, would inhibit magma from moving from the main conduit, through the repository, and to the surface at a secondary vent at any time during the eruptive cycle.

The presence of backfill, either intentionally placed or as a result of drift-roof collapse, could be beneficial from the standpoint of intrusive volcanism because it would minimize contact of magma with waste packages. Backfill would not significantly alter the extrusive scenario because in the unlikely event that a volcanic conduit were to intersect a waste drift it would likely entrain both waste packages and the backfill itself.

Remobilization – Assuming a hypothetical volcanic eruption through a repository, the DOE has performed studies of ash redistribution near the Lathrop Wells cone to evaluate the fraction of basaltic ash components as a function of distance from the tephra sheet. These data indicate that the concentration of basaltic ash in sediments would decrease to about 50 percent within 1 km of the head of the tephra sheet drainage on the eastern side of Lathrop Wells, whereas the channel on the west side has less than 40 percent basaltic ash after 1 km of transport. The DOE’s TSPA model calculates doses using the initial ash-layer thicknesses and radionuclide concentrations from ASHPLUME, modified by a time dependent soil removal factor, estimated to range from 0.02 to 0.04 cm/yr. Given these erosion rates, ash layers would be removed within a few centuries, depending on initial thickness.

The NRC has developed a sediment budget approach to model the long-term fluvial redistribution of basaltic tephra in Fortymile Wash. Using parameters specific to Fortymile Wash and a hypothetical eruption at Yucca Mountain, they concluded that substantial tephra deposits can persist for more than 1,000 years in arid terrains, even with a period of accelerated erosion after the eruption. It is estimated that ~98 percent of the tephra deposit remains in the Fortymile Wash catchment basin after 100 years and 50 percent remains after 1,800 years. The NRC suggests that the amount of remobilized tephra may be large—even when mixed with ambient sediment—and could significantly affect airborne radioactive particle concentrations for the RMEI. The NRC assumes that all contaminated ash that is fluvially remobilized would be deposited in an “active” fan located west of the RMEI, but once it gets there, no ash is permitted to leave this fan area except by wind erosion.

The ACNW&M has observed that large floods would dominate the process of fluvial erosion and transport and would carry contaminated ash beyond the active fan and all the way to the Amargosa River and beyond. In the short period of historical record, at least two (and probably three) large floods in the Fortymile Wash/Amargosa River system have reached Death Valley. The sediments most likely to be suspended and transported long distances are the smallest particles – the same particles of concern for respiration or ingestion. Long-distance transport of contaminated ash would result in extensive dilution of this material by uncontaminated sediments along the Fortymile Wash-Amargosa River drainage system.

EPRI has commented on various conservatisms used in the NRC and the DOE analyses. EPRI’s model of ash transport modeling showed that particles smaller than 130 microns in diameter would not be deposited at the compliance point. Both the DOE and NRC use a conservative assumption that all deposited material is in the respirable size range, although neither NRC nor the DOE discuss realistic mechanisms that would break down tephra in this way.

Eolian (wind) transport could result in an inhalation dose to the RMEI in the extrusive scenario. Eolian transport can move radioactively contaminated ash from fluvial deposits as well as from material deposited on the surface of the ground as a result of the eruption itself. The mechanism of eolian transport is the same in both cases: ash is remobilized by wind, and the remobilized ash is carried and dispersed predominantly downwind. The shape of the remobilized plume depends on particle mass and density and on meteorological conditions.

Both the DOE and the NRC have estimated triangular particle size distribution of ash particles, with the mean and mode at 1 micron aerodynamic diameter. Both agencies have estimated the dimensions and density of spent fuel particles that could be incorporated into and dispersed with the ash. The code ASHPLUME has been used to model this dispersion. The NRC has designed a new module, REMOB, for estimating resuspension and remobilization, but ACNW&M has not seen the equations or results for that model. If there is an igneous event, the peak dose to the RMEI would occur earlier in the postclosure period than in the absence of an igneous event, and the dose to the RMEI would probably be larger. The difference between doses calculated using these scenarios gradually decreases with time, and is approximately an order of magnitude at 10,000 years.

Like the NRC, the DOE uses ASHPLUME to model the initial eolian dispersion of contaminated ash, as well as the generally accepted convention that airborne resuspended material is dispersed in the same way as any airborne material. The DOE appears to have accepted the Anspaugh formulation of both long-term and short-term resuspension. The DOE makes the point that the frequency of wind blowing toward the RMEI location is considerably smaller than wind blowing away from the RMEI, so that the probability of an inhalation dose from resuspended material is relatively small. The DOE further postulates that the high winds in the vicinity of the RMEI make persistence of a thick remobilizable layer of undiluted contaminated tephra unlikely. The NRC does not appear to have accepted the Anspaugh formulation, but has postulated a larger fraction of resuspended material considering the longer times during which resuspension of contaminated ash can take place. The NRC also assumes that all resuspended material, resuspended at any time after the eruption, is ash (i.e., none of it is overburden). The DOE has validated its ASHPLUME modeling by examining the distribution of ash from the Lathrop Wells cone as well as from the Cerro Negro volcano. Both the NRC and the DOE favor using Federal Guidance Report (FGR 13) (Eckerman et al, 1999) rather than FGR 11 and 12 as a source of dose conversion factors. Since the uptake models of FGR 13 are a considerable refinement when compared to earlier clearance models, FGR 13 dose conversion factors are widely accepted and agreed to.

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7. SUMMARY/CONCLUSIONS

7.1. Introduction

As the studies on the impact of igneous activity on the proposed high-level waste repository at Yucca Mountain mature, it is appropriate to review and analyze the current state of knowledge regarding igneous activity that provides the technical bases for decisionmaking.

Due to inherent uncertainties in the igneous processes that have occurred and may occur in the future in the Yucca Mountain region, and limitations in knowledge of controlling parameters, there is a range of professional views regarding the features, events, and processes associated with igneous activity and their impact on risk. These views involve the nature of anticipated igneous activity during the compliance period of the repository, the likelihood that igneous activity will occur, and the consequences of igneous activity due to potential release of waste to the environment. This report summarizes these views and analyzes them based on professional judgment and quantitative considerations within the scope of resources available to the ACNW&M.

Taking into account the different role and responsibilities of the stakeholders in license preparation and review, the views of the DOE, NRC, and others have been abstracted from the published literature and public agency reports and presentations. In addition, a draft of this report was distributed for review to the aforementioned stakeholders and to an international group of experts in igneous activity and high-temperature processes. The response to the ACNW&M's request was generally excellent. Also, written reviews and oral presentations at an ACNW&M Working Group meeting held in early 2007 have been used to revise this report by taking into account the latest and best available information.

Several alternative models describe potential future extrusive (volcanic) and intrusive igneous scenarios at Yucca Mountain. Although many of these models are relatively mature, others, particularly those involved in consequence modeling, are undergoing continuing improvement. As a result, this report, which serves as a benchmark for evaluating the technical bases for igneous activity decisionmaking, is a snapshot based on current understanding of the views on igneous activity. Ongoing studies by the DOE, NRC, and others may modify the results presented in this report.

Based on current views regarding potential igneous activity at Yucca Mountain, performance assessment calculations by stakeholders (including the NRC, DOE, and EPRI), indicate that dose consequences are largest for events that occur soon after repository closure, while the relatively short-lived radionuclides are present in significant quantities. The probability-weighted dose associated with risk from extrusive volcanism, according to present assessments, is smaller than the 10,000-year dose standard of 15 millirem/yr and decreases gradually after 1,000 years in proportion to the rate of decay of radionuclides in the waste. The risk from an intrusive event, based on current calculations, reaches a maximum after several tens of thousands of years, but the maximum probability-weighted dose is only a fraction of the current 10,000-year standard.

In determining risk, both the probability and consequence of the igneous event are considered. Factors important to the extrusive event scenario are probability of the event, including both spatial and temporal considerations, the number of waste packages entrained (volcanic conduit diameter), the eruption volume and dispersal of the contaminated ash, the size distribution range of the spent fuel particles and ash, surface remobilization of contaminated ash by water and wind, and inhalation of contaminated ash by humans. In the intrusive scenario, the major factors in determining risk, in addition to probability of the event, are the number of waste packages affected by the intruding magma, the distance magma can flow into the drifts (which is determined by the viscosity of the intruding magma and the magnitude and duration of the driving pressure upon entry into the drifts), the degree of dissolution of waste released from damaged waste packages into the ground water, the transport of the waste contaminated ground water to the RMEI, and the ingestion of released radionuclides by the RMEI.

The views of the NRC, DOE, and others pertaining to igneous activity at Yucca Mountain are summarized in the final sections of Chapters 4, 5, and 6. In addition, the accompanying table (Table 10) presents a brief, simplified summary of the current views on significant igneous activity topics abstracted from the published literature and public presentations. A fuller explanation of these views is in the text and the original documents referenced in this report. The germane sections of this report that pertain to these items and that reference original literature are cited in each cell for reference by the reader. This table shows that there is general agreement on many of the topics, particularly those dealing with the nature and probability of igneous events. However, there is considerable difference in the views pertaining to the consequences of igneous activity, especially those involving the intrusive scenario.

In the following sections of this chapter, the views on the nature of anticipated igneous activity affecting the proposed repository, the likelihood of igneous activity, and its consequences are summarized and commented on. Additionally, conclusions are given in sections that summarize uncertainties in igneous activity and the role of alternative models in evaluating risk due to igneous activity.

7.2. Nature of Anticipated Igneous Activity

1. Two possible scenarios that involve intersection of the repository by igneous activity include different processes and risk consequences. The extrusive (volcanic) scenario involves intersection of a volcanic-cone-forming conduit through the repository to the surface causing waste in the conduit to contaminate the ash and be dispersed over the Yucca Mountain vicinity. The greatest risk from such an event will occur during the first thousand years due to the presence of significant quantities of short-lived radionuclides. The intrusive scenario involves intrusion of an igneous dike into the repository leading to damage or destruction of the waste packages and premature release of the waste to infiltrating waters passing through the repository, but does not involve a volcanic conduit directly to the surface.
2. One volcano has erupted near Yucca Mountain during the time of modern humans. The Lathrop Wells volcano, which erupted 80,000 years ago, is generally agreed to represent the type of igneous activity possible in the region during the compliance period of the repository. This is a small-volume, single-episode basaltic volcanic event, lasting perhaps a year, with the largest volume of material in the form of ash and other ejecta and lesser amounts in lava flows and the volcanic (scoria) cone. Other volcanoes that occurred during the past few million years in the Yucca Mountain region are of a similar nature.
3. There is general agreement regarding the nature of any future igneous event (i.e., power and approximate duration of event, volume and types of erupted products, general magma type and its volatile content, and the characteristics of the crustal pathways (dikes) for the magma). There is also agreement that dikes (which can locally evolve into volcanoes) tend to follow pre-existing fault zones where faults exist in proximity to

an ascending dike. Thus, current DOE plans to avoid existing faults in constructing the repository (setback strategy) will minimize the likelihood of an extrusive event intersecting the repository.

4. The current 50-75 m width assumed for volcanic conduits beneath volcanoes appears to be a reasonable upper bound based on regional analogs. This width is important because it constrains the number of waste packages that could become entrained and ejected in a volcanic eruption (i.e., ≤5 waste packages). Recent studies indicate that conduit widths at repository depth are likely to be significantly smaller, perhaps a few tens of meters, and could therefore intercept fewer waste packages.

5. The majority of past volcanic activity occurred within a basin, e.g., Crater Flat basin, the northern Amargosa Desert, and Jackass Flats, not on ridges like Yucca Mountain. Although one ancient (>10 million year old) basaltic dike exists on the western flank of Yucca Mountain, no volcanic activity is known to have intersected the repository footprint since the surface rocks were deposited 13 million years ago.

6. Igneous event definitions have evolved during site characterization and analysis. Prior to the mid-1990s, the definition of event was largely restricted to volcanic eruptions. Subsequently, the importance of dike intersection with the repository has been emphasized as well as volcanic events. Even more recently, studies of similar small-volume basaltic igneous events dating back to 10 million years ago in the nearby Nevada Test Site suggest that igneous sills, which are near-horizontal tabular igneous intrusions, should be considered in event definition. This evolution in event definition may be important in evaluating published igneous event probabilities because of the change in definition from point events to long (dikes), and perhaps broad igneous features (sills).

7. Recent detailed studies of nearby basaltic volcanoes in the Yucca Mountain region have provided an improved understanding of nominal eruptive behavior, including the style of lava effusion, that place controls on the nature of the possible igneous event scenarios. For example, the conditions necessary for explosive phreatic eruptions (maar volcanism, involving heating and expansion of groundwater) do not exist at Yucca Mountain. There is also no evidence that maar volcanoes formed near Yucca Mountain during the last 10 million years and they are not expected in the future.

In conclusion, there is general agreement that igneous activity may occur either in an extrusive or intrusive scenario. The nature of igneous activity that could occur over the compliance period of the repository will probably be similar in composition, structure, and style to the 80,000-year-old Lathrop Wells volcano, the most recent volcanism in the area.

7.3. Probability of an Igneous Event Intersecting the Repository

1. Published estimates of the probability of an igneous event intersecting the proposed repository range from 10^{-10}/yr to 3×10^{-6}/yr (see Table 5 for the full range of probability estimates). The 1996 DOE expert elicitation (Probabilistic Volcanic Hazard Analysis (PVHA)) estimated a range after adjustment for the size of the repository footprint (90-percent confidence interval) of 7.4×10^{-10}/yr to 5.5×10^{-8}/yr with a mean value of 1.7×10^{-8}/yr, which exceeds the 10^{-8}/yr limit for screening out events. The mean value of seven of the ten experts was at or above the screening level. The highest estimated probabilities, as reported by the State of Nevada contractors, were obtained by

assuming a new cluster of volcanism is about to occur, although there is no evidence of impending igneous activity.

2. Claims of frequent recurrence of volcanism much higher than the PVHA results are inconsistent with the events known to occur during the past 1.8 million years. If the probability of repository intersection were 10^{-6}/year, many (~40 to 192) eruptions should have occurred in the Yucca Mountain region in the last million years. Approximately four to 19 eruptions should have occurred in the last 100,000 years. However, only 8 events are known to have occurred over the past 1.8 million years and only one occurred in the last 100,000 years. No volcanism has occurred near Yucca Mountain since the eruption of the Lathrop Wells volcano 80,000 years ago and no post-Miocene (< 5.3 Ma) volcanism is known to have occurred at the Yucca Mountain site or in Jackass Flats.
3. Trends in rates of crustal extension and volume of basaltic volcanism within the Yucca Mountain region suggest that the deep source of the igneous activity is waning, although the frequency of eruption has not notably decreased over the past 5 million years. Waning of igneous activity is consistent with the observed significant reduction in crustal extension rates over the last 10 million years. These changes suggest that the volcanism recurrence rate of the last few million years is most important to use in projections of future volcanic activity. Although there is some indication of a crude periodicity in the occurrence of igneous activity in the Yucca Mountain region, the existence of a periodic relationship remains a matter of differing opinions.
4. Magnetic anomalies that were interpreted to be caused by buried basalts near Yucca Mountain were recently investigated by exploratory drilling. This investigation reduced uncertainty because it showed that most of the anomalies are either not due to basalts or are caused by 8- to 13-million-year-old basalts that would have limited influence on recurrence models based on rates of activity during the last 5 million years. These new results have not yet been considered in published estimates of the probability of future igneous intersection of the repository. Probability estimates that assumed the existence of numerous buried (“hidden”) basalts less than 5 million years old will now need to be reconsidered.
5. Based on review of available information, the probability of intersection of the repository during the compliance period is believed to be in the range of 10^{-9}/yr to 10^{-7}/yr. An updated estimate is now being developed by the expert panelists of the ongoing DOE PVHA-U, which will incorporate the latest geophysical and drilling data and a wide range of views on alternative models for estimating probability. Results will include appraisal of the probability over one million years as well as 10,000 years. The final report of the PVHA update is not expected until 2008, but will provide the most up to date, credible estimate of the probability of igneous activity intersection with the proposed repository.
6. The NRC has asked that the DOE provide (along with their licensing case) the results of a single point sensitivity analysis for extrusive and intrusive igneous processes at a repository intersection probability of 10^{-7}/yr. The NRC considers that the 10^{-7}/yr analyses will provide a reasonably conservative approach for evaluating risks from igneous activity. However, the use of a single point value fails to capture the impact of the uncertainty in probability estimates and could significantly limit the usefulness of the results and the risk insights that can be gleaned from such an analysis.

In conclusion, the anticipated nature of future igneous events in the Yucca Mountain region and the record of volcanism, particularly during the past 5 million years, suggest a variety of alternative models for evaluating the probability of future igneous activity. Considering the technical bases of these views, the range of probability of an

igneous event intersecting the proposed repository is believed to be between 10^{-9} and 10^{-7}/yr. The results of the ongoing PVHA-U will incorporate the latest geophysical and drilling data and will provide the most up-to-date, credible estimate of the probability of an igneous event intersecting the proposed Yucca Mountain repository.

7.4. Consequences of an Igneous Event

1. Consequence modeling for the intrusion scenario is evolving. This is particularly true of modeling the movement of magma into the drifts and of the interaction of magma with the waste packages and with radioactive material from breached packages in the intrusive scenario. The movement of magma into drifts depends on the viscosity of the magma and the magnitude and duration of the magma driving pressure on entry into the drifts. Previous studies and current views of the NRC and DOE appear to have underestimated the magnitude of the viscosity by as much as 10^5. The magma driving pressure is uncertain by a factor of about 10^2. Nevertheless, within these bounds consideration of magma physics shows that the flow of magma into the drifts would be sluggish, significantly slower than estimated by the DOE and NRC. The beneficial effects of quenching and progressive solidification of invading magma on the movement of magma in repository drifts and on the waste packages may also have been underestimated and damage to and releases from waste packages consequently overestimated. Likewise, the possible formation of tephra plugs in intersected drifts would limit the inflow of magma to drifts. This phenomenon has not been considered by either the DOE or NRC. Ongoing studies are clarifying these issues, but full technical resolution and agreement among the DOE, NRC, and other interested parties is unlikely before the presently planned license application date (mid-2008).
2. The so-called “dogleg” intrusion scenario of Woods et al. (2002) is not credible. In this scenario, highly fluid, low-viscosity magma is assumed to enter and flow rapidly throughout the repository drifts, possibly breaking out to the surface at a significant distance from the drift entry point. But this is not the expected behavior of magma in the drift. Increased magma viscosity, quenching of magma on waste packages and drift walls, and reduction of magma pressure at a distance from the drift entry point, would inhibit magma from moving from the main conduit, through the repository, and to the surface at a secondary vent at any time during the eruptive cycle.
3. Slightly more than half of the eruptive products of basaltic volcanoes in the Yucca Mountain region consists of ash that is dispersed from the eruption plume. The remainder occurs as volcanic cone fragments and lavas, which are resistant to erosion. Radioactive waste incorporated in the cone and lava flows would contribute little to dose to the RMEI because of this resistance to erosion.
4. Based on the estimated size of volcanic conduits, approximately one to ten waste packages could be entrained within a conduit during extrusive volcanism. Magma/drift/waste interactions in the extrusive scenario are incompletely understood. Accordingly, both the DOE and NRC assume that entrained packages would be destroyed and the contents incorporated into volcanic ash that would be distributed across the surrounding countryside by prevailing winds.
5. In the DOE and NRC performance assessment codes, the assumption is made that all spent fuel entrained in a volcanic conduit in the extrusive scenario would be reduced to a very fine powder, incorporated in tephra, and erupted into the atmosphere. However, the ceramic pellets that comprise spent nuclear fuel have great strength and a melting point of 2600^{o} C, much higher than magma temperatures of about 1100^{o} C. Also, the ejected

fuel pellets and fragments may be encased in a protective layer of quenched magma, consistent with natural volcanic analogs of wall rock materials that have been caught up in the magma and brought to the surface in volcanic conduits (i.e., xenoliths). The result is larger fragments that are unlikely to be inhaled.

6. The presence of backfill, either intentionally placed or as a result of drift-roof collapse, could be beneficial from the standpoint of intrusive volcanism because it would minimize contact of magma with waste packages. Backfill would not significantly alter the extrusive scenario because in the unlikely event that a volcanic conduit were to intersect a waste drift it would likely entrain both waste packages and the backfill itself.
7. Modeling the redistribution of deposited ash by water needs to account for the preferential removal of the smaller-sized fraction of the ash and other volcanic ejecta from both the catchment and depositional areas of drainage systems. Remobilization models need to consider the effects of large floods in Fortymile Wash (adjacent to Yucca Mountain) that have historically transported sediments as far as the Amargosa River and beyond. Long-distance transport of contaminated ash would result in extensive dilution of this material by uncontaminated sediments along the Fortymile Wash-Amargosa River drainage system that would result in a significantly lower calculated dose to the RMEI than if these effects are ignored.

In conclusion, a clear understanding of the processes involved in interaction between magma and drifts, waste packages, and waste is evolving and providing new insights, especially with regard to magma/drift/waste package interaction. As a result, there is limited consensus regarding the consequences of igneous activity in either the extrusive or intrusive scenario. The proposed alternative models differ significantly from each other. The application of magma physics will reduce differences and conservatisms particularly in the intrusive scenario.

7.5. Uncertainties in Igneous Activity

1. Limitations and differing interpretations of field and laboratory data cause significant model and parameter uncertainty in the analysis of the potential risk from igneous activity at the proposed Yucca Mountain repository.
2. As a result of more than a quarter of a century of investigations of igneous activity in the Yucca Mountain region, uncertainties in the general nature of anticipated volcanism in this region are relatively small. The 80,000-year-old Lathrop Wells cone and lava flows provide useful analogs of possible future volcanism in the vicinity of Yucca Mountain. Uncertainties remain regarding the volcanic conduit size at repository depth, range of water content of the intruding magma, dike characteristics, etc. These parameters are important to probabilistic performance assessment. Uncertainties in defining conceptual models appear to exceed parameter uncertainty in the evaluation of probability of intersection with the proposed repository.
3. Estimates of the probability of an igneous event intersecting the proposed repository include significant uncertainties because of difficulties in predicting the temporal recurrence rate as a result of limited volcanic activity over the past 5 million years and in identifying the spatial distribution of events due to the few igneous events that have occurred in the region over the last few million years. Additional uncertainties are caused by the failure to identify magma sources within subcrustal rocks that are the source of the magma, and the location of the proposed repository in the spatially-sensitive region near the boundary of the geologic/topographic Crater Flat basin

structure, which has been the center of volcanic activity in the Yucca Mountain region over the past 5 million years.

4. Consequence models are evolving and being improved. Recent detailed geologic investigations of basaltic volcanoes in the Yucca Mountain region are adding significant new insights into processes and parameters. Improved models incorporating magma solidification effects on magma flow, quenching around waste packages, and the formation of tephra plugs in drifts are providing new information for consideration in the intrusive scenario. Significant uncertainties in evaluating igneous consequences due to model and parameter uncertainty can be reduced by proper consideration of magma physics.

In conclusion, variability and uncertainty exist in evaluating conceptual models in estimating the probability of an igneous event intersecting the repository, and in estimating the consequences of such an event, particularly in the intrusive scenario.

7.6. Alternative Models and Risk from the Proposed Repository

1. Determining the validity of the differing professional opinions regarding igneous activity at Yucca Mountain and its consequences with certitude is not possible, but it is possible and useful to determine the bases and impact of credible alternative models and parameters through consideration of magma physics and geological evidence.
2. Quantitative evaluation of the impact of specific alternative models can determine their significance to risk and the importance of further studies of the models and understanding and constraining their uncertainties.
3. Available analyses of differing models of igneous activity processes and scenarios have generally not captured the importance of each model to risk. This is particularly true of consequence models.

In conclusion, assessment of the performance of the proposed repository as a result of igneous activity requires evaluation of a range of credible views on both the extrusive and intrusive scenarios and the range of parameter uncertainty. These analyses will be useful in determining the risk from the repository as well as those aspects of igneous activity that are important to risk and thus worthy of further investigation to reduce uncertainties. Presentation of the full range of results of each analysis will be useful in evaluating the model and the parameters to which the analysis is most sensitive.

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Table 10 **Summary of views on significant igneous activity topics (organized by the risk triplet). This table is a simplification and generalization of views that are reviewed in the report. The reader is encouraged to read the text on each topic in the section of the report specified with each view. Cells in the table that are marked by dashes indicate that published or publicly-presented views on the topics are unavailable.**

TOPIC	NRC	DOE	EPRI	OTHER
WHAT IS THE NATURE OF POTENTIAL IGNEOUS EVENTS IN THE YUCCA MOUNTAIN REGION?				
Igneous scenarios	Extrusive (volcanic) and intrusive igneous scenarios **(Sec. 6.2.2.3; 6.3.2)**	Extrusive (volcanic) and intrusive igneous scenarios **(Sec. 6.2.2.1; 6.3.1)**	Extrusive (volcanic) and intrusive igneous scenarios **(Sec. 6.2.2.2; 6.3.3; Appendix C)**	------
Volcanic event	Small-volume, single-episode basaltic volcano similar to Lathrop Wells volcano (< 0.1 km^3). Multiple vents possible; possible flank eruptions via dogleg through the drifts of repository **(Sec. 3.3.4; 4.3.3; 4.4)**	Small-volume, single-episode basaltic volcano similar to Lathrop Wells volcano (< 0.1 km ^{3}). Multiple vents possible on single principal dike **(Sec. 4.3.2; 4.4)**	Small-volume, single-episode volcano similar to Lathrop Wells volcano (< 0.1 km^3). Multiple vents possible; vent(s) are all located along one dike **(Sec. 4.3.4; Appendix C)**	-------
Volcanic conduit diameter	25 to 78 m (average of ~51 m) **(Sec. 4.3.3)**	Lathrop Wells average 8-9 m, with maximum average diameter of 21 m **(Sec. 4.3.2)**	Conduit diameters >10 m; not expected below 100-150 m. **(Sec. 4.3.4)**	------

TOPIC	NRC	DOE	EPRI	OTHER
Dike length	6 km (2-11 km) **(Sec. 4.3.3; 4.4)**	2 km (0.4-8 km); **(Sec. 4.4)**	2.0 km (0.5-5 km) **(Sec. 4.3.4)**	-------
Dike width	5 m (1-10 m) **(Sec. 4.3.3)**	8 m (1-12 m) **(Sec. 4.3.2)**	1.5 m (0.3-4 m) **(Sec. 4.3.4)**	------
Number of dikes	---------	Multiple dikes, spacing from 100 to 1000 m **(Sec. 4.3.2)**	3 dikes (1-10 dikes), spacing from 100 to 690 m **(Sec. 4.3.4)**	------
Controls on occurrence of igneous activity	Nature and orientation of crustal stress, gravity anomalies (lithostatic pressure), faults **(Sec. 5.4)**	Nature and orientation of crustal stress, faults, topographic effects **(Sec. 5.4)**	Local stress field, surface topography, existing fractures, heterogeneous rock strength, thermally induced stresses **(Sec. 5.4)**	Lithostatic pressure (Parsons et al. (2006)) **(Sec. 5.4)**
WHAT IS THE PROBABILITY OF POTENTIAL IGNEOUS ACTIVITY INTERSECTING THE REPOSITORY?				
Time period used in extrapolating igneous activity	-------	Emphasis on last 5 million years and the last 2 million years in particular **(Sec. 5.7.2)**	Adopted PVHA probability which suggests emphasis on last 5 million years **(Sec. 5.7.5)**	Last 5 million years with emphasis on last 2 million years (Coleman et al.(2004)); Emphasis on last 5 million years (Detournay et al. (2003)) **(Sec. 5.78; 5.74)**

TOPIC	NRC	DOE	EPRI	OTHER
Probability of IA in regulatory period **(Table 5-3)**	10^{-7}/yr for TPA purposes and license application review; 10^{-8} to 10^{-7}/yr with possibility of increase by an order of magnitude **(Sec. 5.6.3; 5.7.2)**	10^{-9}-10^{-7}/yr; mean of 1.7 x 10^{-8}/yr (Geomatrix Consultants, 1996; now being updated) **(Sec. 4.3.2; 5.6.1; 5.7.1)**	Adopted PVHA-1996 results; 10^{-9}-10^{-7}/yr, mean of 1.7 x 10^{-8}/yr **(Sec. 5.6.2; 5.7; 5.7.5)**	Up to ~3 x 10^{-6}/yr (Ho and Smith (1997)) **(Sec. 5.7.6)**
Temporal trend in igneous activity (waxing/waning)	------	Waning **(Sec. 5.2.5)**	Waning **(Sec. 5.2.5)**	Possible waxing based on conceptual model [Smith and Keenan (2005)] **(Sec. 5.2.5; 5.7.6)** Possible waning from seismic studies of mantle (Biasi, 2005) **(Sec. 5.4)**
WHAT ARE CONSEQUENCES OF IGNEOUS ACTIVITY INTERSECTING THE REPOSITORY?				
Magma viscosity upon entering repository	Remains liquid for significant time; no rapid solidification **(Sec. 6.2.2.4)**	Homogeneous flow; small bubbles; no rapid solidification; 10-40 Pa·s **(Sec. 6.2.1.3.1; 6.2.2.1)**	10^{5}-10^{7} Pa·s for lava at its eruption T of 975-1010°C; magma crystallizes rapidly and terminates flow **(Sec. 6.2.1.3.2)**	10^{7} to 10^{8} Pa·s (Marsh and Coleman (2008)) **(Sec. 6.2.1.2)** Up to 10^{4} to 10^{5} Pa·s (Sparks (2007)) **(Sec. 6.2.1.3.3)**

TOPIC	NRC	DOE	EPRI	OTHER
Magma eruption temperature	------	1150°C [Detournay et al. (2003)] **(Sec. 6.2.1.3.3)**	975-1010°C **(Sec. 6.2.1.3.2);**	~1000°C (Marsh and Coleman (2008)) **(Sec. 6.2.1.1)** 1030-1055°C (Sparks (2007)) **(Sec. 3.2.3)** 975-1010°C (Nicholis and Rutherford (2004))
Magma drift inflow rate	10 to 100 m/s (22 to 220 mph) **(Sec. 6.2.2.4, 6.2.3.4)**	10 m/s (22 mph) **(Sec. 6.2.3.1)**	0.04 to 10 m/s **(Appendix C, where EPRI cites Nicholis and Rutherford, 2004)**	
Number of waste packages affected: extrusive event	<10 packages completely destroyed & all waste reduced to fine powder **(Sec. 6.2.2.3)**	<10 packages completely destroyed & all waste reduced to fine powder **(Sec. 6.2.2.1)**	No mechanical failure, but possible failure by ovepressurization near conduit **(Sec. 6.2.2.2; 6.3.3)**	------
Number of waste packages affected: intrusive event	37 packages (1-1402 packages- lognormal distribution) **(Sec. 6.2.2.3, 6.2.3.3)**	1600 packages (0-11000 packages) **(Sec. 6.2.2.1; 6.2.3.1)**	0-6 packages engulfed by magma; 14-24 packages failed by high-temperature creep **(Sec. 6.2.2.2; 6.2.3.2)**	--------
Dogleg scenario with secondary eruption	Possible with 50 packages destroyed and contents entrained into ejects **(Sec. 6.2.2.3; 6.3.1)**	Dogleg model improbable **(Sec. 6.2.2.4)**	Dogleg model highly unlikely **(Sec. 6.3.3)**	Dogleg model improbable (Marsh and Coleman (2008)) **(Sec. 6.2.1.3.3; 6.2.2.3)**
Ash redistribution by wind	Effects of redistribution of ash by wind transport currently	Effects of redistribution of ash by wind transport	-------	-------

TOPIC	NRC	DOE	EPRI	OTHER
	being incorporated into performance assessment analysis **(Sec. 6.4.4.1)**	incorporated into dose calculations **(Sec. 6.4.4.2)**		
Ash redistribution by water	All contaminated ash eroded and transported with dilution to vicinity of compliance point, neglects transport in largest floods beyond this point **(Sec. 6.4.3.1)**	Water erosion and transport of ash with dilution to vicinity of compliance point and beyond **(Sec. 6.4.3.3)**	Particles < 130 microns would not be deposited at the compliance point **(Sec. 6.4.3.2)**	-------
Inhaled particle size at RMEI	All deposited, remobilized, and resuspended particles < 10 microns contribute to inhalation dose **(Sec. 6.4.3.1; 6.4.4.1)**	All deposited, remobilized, and resuspended particles < 10 microns contribute to inhalation dose **(Sec. 6.4.3.3; 6.4.4.2)**	Deposited material > 130 microns; not respirable **(Sec. 6.4.3.2)**	------
Conversion factors for inhalation dose	FGR and 13 **(Sec. 6.4.5)**	FGR 13 **(Sec. 6.4.5)**	ICRP 72 (equivalent to FGR 13) **(Sec. 6.4.5)**	--------

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APPENDIX A. STATUS OF NRC IGNEOUS ACTIVITY KEY TECHNICAL ISSUE RESPONSES (2006)

The current status of differences between the DOE and the NRC is given by the status of the Igneous Activity Key Technical Issues (KTI) as identified by the NRC. The following table which is based on a 2006 compilation gives a brief description of each KTI the DOE response date and the status of the agreement between the DOE and NRC. The significance of each KTI to overall performance of the repository is also given. Of the 20 KTIs, fourteen have been satisfactorily agreed to by both agencies, while six await further information from the DOE and evaluation by the NRC. Four of the KTIs are ranked as having high importance to risk and three of these remain open (IA. 1.02.2.07, 2.17, and 2.18).

NRC KTI Responses

KTI	Response Date	Description	Status	Risk
IA.1.01	4/30/2001	In addition to DOE's licensing case, include for Site Recommendation and License Application, for information purposes, the results of a single point sensitivity analysis for extrusive and intrusive igneous processes at 10E-7.	Complete	Medium
IA.1.02	11/5/2004	Examine new aeromagnetic data for potential buried igneous features (see U.S. Geological Survey, Open-File Report 00-188, Online Version 1.0), and evaluate the effect on the probability estimate.	NAI	High
IA.2.01	4/30/2001	Re-examine the ASHPLUME Code to confirm that particle density is appropriately changed when waste particles are incorporated into the ash.	Complete	Low
IA.2.02	4/14/2003	Document results of sensitivity studies for particle size, consistent with (1) above. (Eruptive AC-4) DOE agreed and will document the waste particle size sensitivity study in a calculation document.	Complete	Low
IA.2.03	3/31/2005	Document how the tephra volumes from analog volcanoes represent the likely range of tephra volumes from Yucca Mountain region (YMR) volcanoes.	Complete	Medium
IA.2.04	4/30/2001	Document that the ASHPLUME model, as used in the DOE performance assessment, has been compared with an analog igneous system.	Complete	Low
IA.2.05	6/6/2001	Document how current approach to calculating the number of waste packages intersected by conduits addresses potential effects of conduit elongation along a drift.	Complete	Medium

KTI	Response Date	Description	Status	Risk
IA.2.06	6/6/2001	Develop a linkage between soil removal rate used in TSPA and surface remobilization processes characteristics of the Yucca Mountain region (which includes additions and deletions to the system).	Complete	Medium
IA.2.07	6/6/2001	Document the basis for airborne particle concentrations used in TSPA in Rev. 1 to the Input Values for External and Inhalation Radiation Exposure AMR.	Complete	High
IA.2.08	4/30/2001	Provide additional justification on the reasonableness of the assumption that the inhalation of particles in the 10-100 micron range is treated as additional soil ingestion, or change the BDCFs to reflect ICRP-30.	Complete	Low
IA.2.09	3/31/2005	Use the appropriate wind speeds for the various heights of eruption columns being modeled. (Eruptive AC-5) DOE agreed and will evaluate the wind speed data appropriate for the height of the eruptive columns being modeled.	Complete	Medium
IA.2.10	2/13/2003	Document the ICNs to the Igneous Consequences AMR and the Dike Propagation AMR regarding the calculation of the number of waste packages hit by the intrusion.	Complete	Medium
IA.2.11	6/14/2004	Provide an analysis that shows the relationship between any static measurements used in the TSPA and expected types and durations of surface disturbing activities associated with the habits and lifestyles of the critical group.	NAI	Medium
IA.2.12	8/2/2002	Provide clarifying information on how PM10 measurements have been extrapolated to TSP concentrations. This should include consideration of the difference in behavior between PM10 and TSP particulates under both static and disturbed conditions.	Complete	Low
IA.2.13	4/25/2002	Provide the justification that sampling of range of transition period BDCFs is necessarily conservative in evaluating long-term remobilization processes.	Complete	Low
IA.2.14	6/14/2004	Provide information clarifying the method used in TSPA to calculate how deposit thickness effects the average mass load over the transition period.	Complete	Low
IA.2.15	2/4/2004	Clarify that external exposure from HLW-contaminated ash, in addition to inhalation and ingestion, was considered in the TSPA.	Complete	Low

KTI	Response Date	Description	Status	Risk
IA.2.16	8/20/2002	Document that neglecting the effects of climate change on disruptive event BDCFs is conservative. DOE will document that neglecting effects of climate change on disruptive event BDCFs is conservative in a subsequent revision to AMRs.	Complete	Low
IA.2.17	1/10/2005	DOE will evaluate conclusions that the risk effects (i.e., effective annual dose) of eolian and fluvial remobilization are bounded by conservative modeling assumptions in the TSPA-SR, Rev 00, ICN1.	NAI	High
IA.2.18	1/10/2005	DOE will evaluate how the presence of repository structures may affect magma ascent, conduit localization, and evolution of the conduit and flow system.	NAI	High
IA.2.19	11/07/2006	DOE will evaluate waste package response to stresses from thermal and mechanical effects associated with exposure to basaltic magma, considering the results of evaluations attendant to IA Agreement 2.18.	Complete	Medium
IA.2.20	11/07/2006	DOE will evaluate how ascent and flow of basaltic magma through repository structures could result in processes that might incorporate HLW, considering the results of evaluations attendant to IA Agreements 2.18 and 2.19.	NAI	Medium

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APPENDIX B. THE PROGRAMMATIC AND TECHNICAL ACTIVITIES OF THE NRC STAFF IN REVIEWING IGNEOUS ACTIVITY ASSOCIATED WITH THE YUCCA MOUNTAIN PROJECT

This appendix is largely based on NRC (2007), which provided comments on the ACNW&M's Draft White Paper on Igneous Activity at Yucca Mountain.

No single document presents the technical and programmatic activities of the staff of the U.S. Nuclear Regulatory Commission (NRC) regarding igneous activity at Yucca Mountain or the staff's history of prelicensing interaction with the U.S. Department of Energy (DOE). Instead, numerous documents and publications available through the NRC's public record system (the Agencywide Documents Access and Management System (ADAMS)) and the Licensing Support Network (http://www.lsnnet.gov/) provide that history. Two key licensing-related documents do give important summaries of the relevant technical background and criteria for a future review of a license application. These are the Integrated Issue Resolution Status Report (NRC, 2005) and the Yucca Mountain Review Plan (NRC, 2003). The NRC has posted the staff's approach to resolution of key technical issues (KTIs) on the agency's public Web site at http://www.nrc.gov/waste/hlw-disposal/reg-initiatives/resolve-key-tech-issues.html.

Since the early 1980s, the NRC staff has systematically developed focused technical investigations to enhance review capabilities in areas of potential risk significance, probe risk-significant areas of DOE information, gain risk insights for alternative conceptual models, and integrate technical information into an independent total system performance assessment.

The purpose of these investigations has been to develop an independent and neutral expertise on igneous features, events, and processes in preparation for reviewing the anticipated DOE construction license application. In response to questions and concerns with the DOE program for igneous activity, the NRC developed technical investigation programs to provide an independent assessment and review capability for igneous activity issues. Early results from these programs provided a technical basis for evaluating uncertainties in, for example, probability models (e.g., Connor and Hill, 1993; Connor and Hill, 1995; Condit and Connor, 1996); use of historically active volcanoes to help interpret characteristics of past activity in the Yucca Mountain region (e.g., Connor, 1993; Connor and Hill, 1994; Hill, et al., 1995); and modeling airborne transport from basaltic volcanoes (e.g., Jarzemba et al., 1997; Hill, et al., 1996).

The NRC staff has produced many reports and interacted with DOE. This information provides a detailed record of how the available information, including the NRC staff's independent information, was synthesized and applied to understanding and resolving technical uncertainties in the DOE information. The staff used available information to understand risk-significant uncertainties in the DOE program and provide early identification of potentially significant issues. For example, external review of the Center for Nuclear Waste Regulatory Analysis (CNWRA) program (McKague, 1998) identified the potential risk significance of magma-drift interaction processes, which supported the identification of this issue as significant in NRC staff comments on the DOE Viability Assessment (Travers, 1999) and Site Recommendation (Meserve, 2001). Initial results from first-order models for gas-bearing (Bokhove and Woods, 2000; Woods, et al., 2002) and gas-absent (Lejeune et al., 2002) flows supported numerous technical exchanges with DOE, which resulted in a DOE agreement to provide additional support for the information used in the site recommendation (Reamer, 2001). The independent NRC staff information provided a technical basis for determining the high significance of this issue in terms of repository performance (Mohanty, et al., 2004; NRC, 2004) and for resolving technical concerns with DOE information (Kokajko, 2005a; NRC, 2005). This information was developed to probe the DOE program and respond to NRC staff and other stakeholder concerns with the DOE program.

Independent external reviews of the CNWRA igneous activity program were conducted in 1994 (Hill, 1995) and 1997 (McKague, 1998; Sparks and Woods, 1998). These reviews evaluated many of the risk-significant areas associated with potential igneous events and assessed planned and ongoing NRC/CNWRA technical investigations in these areas. The NRC staff has developed an independent understanding of the tectonic and magmatic framework for basaltic volcanism in the Yucca Mountain region, which is the foundation for evaluating the likelihood of future igneous activity in this region. Part of the technical basis the NRC staff has developed in this area appears in Connor and Hill (1994); Stirewalt et al. (1995); Hill and Connor (1996); Stamatakos and Ferrill (1998); Stamatakos et al. (1998); and Waiting et al. (2001).

Staff work to understand methods to evaluate probability model utility in forecasting future igneous events, effects of potential buried volcanoes, and uncertainties in recurrence rate estimates for basaltic volcanic fields appears in such papers as Condit and Connor (1996); Connor and Sanders (1994); Connor et al. (1997, 2000); Magsino et al. (1998); Connor and Hill (1994b, 1995a); Hill et al. (1994); Conway et al. (1997; 1998); and Connor and Conway (2000). Probability models prepared by the staff have emphasized the development of review capabilities for probability issues. In the area of igneous event consequences, Bokhove and Woods (2000), Lejeune et al. (2002), Bokhove et al. (2005), Woods et al. (2006), and Menand and Philips (2005) have performed work to support staff understanding of potential magma-repository interactions. Analyses presented by Smart (2004) are relevant to understanding thermo-mechanical response of drift walls and the potential for magma-drift interactions. In addition to the above papers, NRC (2005) presents important information on waste package response to potential igneous events, which supports the models used in Mohanty et al. (2004). Information provided in NRC (1999), Jarzemba et al. (1997), and Codell (2004) supports the consideration of waste form response to potential intrusive igneous events. The KTI resolution process (e.g., Schlueter, 2003; Kokajko, 2005b) has presented additional discussion about igneous event consequences.

Hill (1996), Doubik and Hill (1999), NRC (2005), and Woods et al. (2005) provide information relevant to understanding NRC staff perspectives on subvolcanic conduit development and the hypothetical formation of secondary breakouts (i.e., the “dogleg scenario”) beyond that discussed in Woods et al. (2002). Kokajko (2005a) discusses the KTI resolution process in relation to the extrusive event. Information relevant to understanding the modeling of airborne transport of radionuclides appears in Jarzemba et al. (1997); Jarzemba (1997); Hill et al. (1998); Connor et al. (2001); and Mohanty et al. (2004). Hill and Connor (2000); Mohanty et al. (2004); and Hill (2004) present the development of associated parameters.

Codell (2004) and Spradley (2006) present NRC staff information relevant to understanding significance or limitations in alternative conceptual models. Hill and Connor (1995); Hill et al. (1995, 1996, 2001); Jarzemba (1997); and McKague (1998) discuss characteristics of volcanic deposits and associated airborne mass loads. Information developed for NRC staff perspectives on postvolcanic redistribution effects includes analyses in Hill and Connor (2000) and NRC (2004). Initial models and associated information relevant to understanding long-term redistribution processes also are discussed by Hooper (2004) and Mohanty et al. (2005), with additional information presented in Hooper and Benke (2006) and Benke et al. (2006).

The NRC staff recognizes that limited data for difficult-to-observe igneous processes can lead to alternative views on the probability and consequences of potential igneous events. The NRC staff has developed an integrated program that uses quantitative modeling and professional judgment to evaluate the risk significance of technical issues and associated uncertainties. Examples of these risk insights appear in NRC (2004, 2005) and Mohanty et al. (2004, 2005). In addition, the NRC staff has used risk information to focus, and at times resolve, key technical uncertainties using DOE information. For example, igneous activity KTI Agreement 2.02 used a DOE sensitivity analysis to conclude that existing uncertainties in particle size distributions were not significant to risk (Schlueter, 2003). The influence of risk insights on the evolution of many other uncertainties can also be determined by consideration of the information in the Risk Insights Baseline Report (NRC, 2004).

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APPENDIX C. CONCEPTUAL MODEL FOR DEFINING NATURAL ANALOGS FOR FUTURE YUCCA MOUNTAIN VOLCANISM AND EXPECTED CONSEQUENCES

Addendum to EPRI 2006 Internal Report on Igneous Events (by Meghan M. Morrissey, Colorado School of Mines, 2007)

As part of their comments on a draft of this report, EPRI provided a concise description of their conceptual model for natural analogs of future volcanism in the Yucca Mountain region (YMR). This material is an addendum to EPRI's internal report on igneous events. Because this addendum may not be readily available in the public record, we provide it here as an appendix (with minor editing) along with its own figures, table, and list of references.

Introduction

This report presents an updated version of EPRI's conceptual model for a possible future ($< 10^6$ yr) igneous event at Yucca Mountain from which natural analogs are defined. The most credible and defensible basis for assigning characteristics to a postulate future volcanic eruption at Yucca Mountain is the geological evidence from recent volcanic events in the region. Field observations and petrologic data (Crowe et al., 1988; Perry et al., 1998; Nicholis and Rutherford, 2002; OCRWM, 2003; BSC, 2004; Valentine et al., 2005) made at basalt centers found in the Yucca Mountain region (YMR) that include Thirsty Mesa, Amargosa Valley, southeast Crater Flat, Buckboard Mesa, Quaternary basalts of Crater Flat, Sleeping Butte, and Lathrop Wells, suggest that a future eruption in YMR will likely be a typical basaltic fissure eruption in which < 0.1 km^3 of magma could reach the surface. The Lathrop Wells basalt center is considered the best example of a natural analog of a future eruption in the YMR. EPRI continues to support the hypothesis that any magma that erupts in the Yucca Mountain region within the next 10^6 year will be a low volume (< 0.1 km^3) water bearing, crystallizing basaltic magma with an eruption temperature between 975-1010ºC. The expected series of eruptive events for a future igneous event in Yucca Mountain within the next 10^6 yr would be comparable to that at the Lathrop Wells basalt center. Recent data published by DOE and professional journals (i.e., Nicholis and Rutherford, 2002; BSC, 2004; Valentine et al., 2005) on Lathrop Wells basalt center have provided new insight on the interpretation of the eruption history at the center. This report is divided into two sections: summary of Lathrop Wells volcanology and inferred eruption history, and expected scenarios for a future eruption in the Yucca Mountain region.

Summary of Lathrop Wells Physical Volcanology and Eruption History

Physical Volcanology

The Lathrop Wells basalt center (0.09 km^3; Fig. 1) consists of a large scoria cone and three or four sets of fissures marked by accumulations of spatter, bombs and scoria deposits that represent eroded smaller cones (possibly 3-10 small scoria cones (Crowe et al., 1988)). Multiple eruptive events occurred along two sets of fissures that extend 0.2-2 km. The main scoria cone (Lathrop Wells cone) is 140 m high, has a base of 875 m by 525 m, and is roughly 0.018 km^3 in volume. Based on data from a recent petrologic and field study of deposits at Lathrop Wells (Valentine et al., 2005), it has been suggested that the cone may have been built from several distinguishable eruptive events occurring essentially in two phases. The first phase (Fig. 2A) produced the lower portion of the cone (0.006 km^3) comprised of lapilli and bomb sized scoria, ribbon and spindle shaped bombs meter in length (Valentine et al., 2005). This phase began with a fire fountain event that produced a thin (1 m) scoria deposit at the base on the cone containing mostly sideromelane clasts (quenched reddish-brown glass). Overlying this sideromelane rich layer are 4-5 layers of coarsening upward tachylite (crystalline clasts) rich layers (lower portion of the cone) suggesting pulsating eruptive events. The south (0.015 km^3) *aa* lava flow (Fig. 2B) is thought to have occurred contemporaneously with the initial cone building stage. The second phase was the upper cone-building stage that was accompanied by a sustained eruption column from which 0.04 km^3 of mostly tachylite tephra was produced (Fig. 2C). As noted in Valentine et al. (2005), the contact between the upper and lower cone deposits is sharp suggesting a dramatic change in emplacement and eruption mechanisms. The lower cone deposits appear to dip both inward and outward and have characteristic features of grain avalanches (Valentine et al., 2005). The upper cone deposits appear to mantle the lower deposits characteristic of emplacement from fallout and are finer grain then the lower cone deposits (Valentine et al., 2005). The upper cone-building stage also emitted the northeastern (0.015 km^3) lava flow (Fig. 2D). The last eruptive event was a small hydrovolcanic event. The hydrovolcanic event is thought to involve a shallow groundwater source, in particular, water stored in the alluvium or sand ramp deposits or pre-volcanic surficial deposits (BSC, 2004).

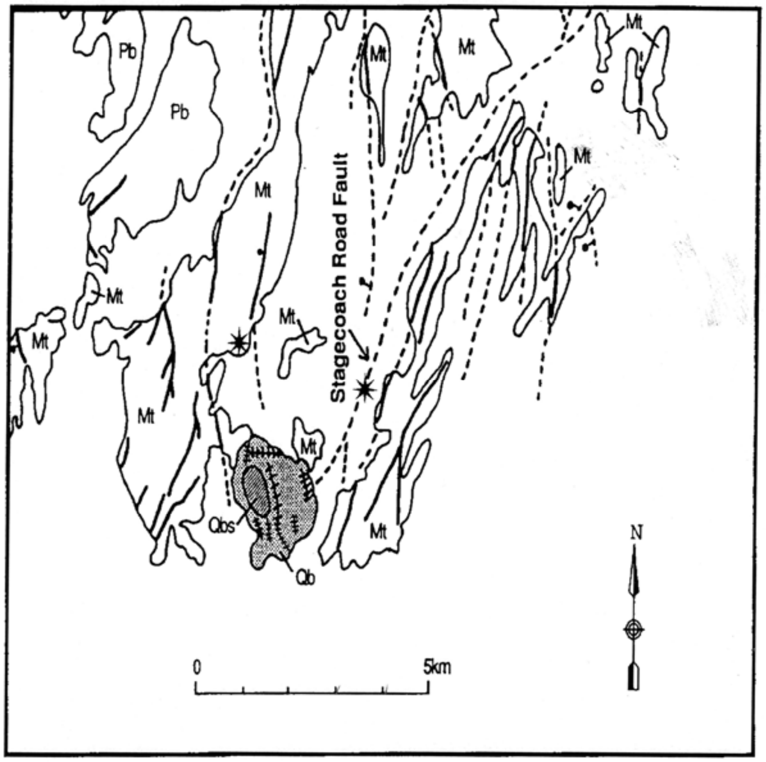


Figure 1: Geologic setting of the Lathrop Wells basalt center (Fig. 2.8 in Perry et al., 1998). Lathrop Wells main cone (denoted by Qbs within the dark grey area) is located along two sets of fissure (cross-hatched lines). Stars mark sites where distal fall deposits have been found (Perry et al., 1998). Mt and Pb identify locations where Miocene tuff and Pliocene basalt are exposed.

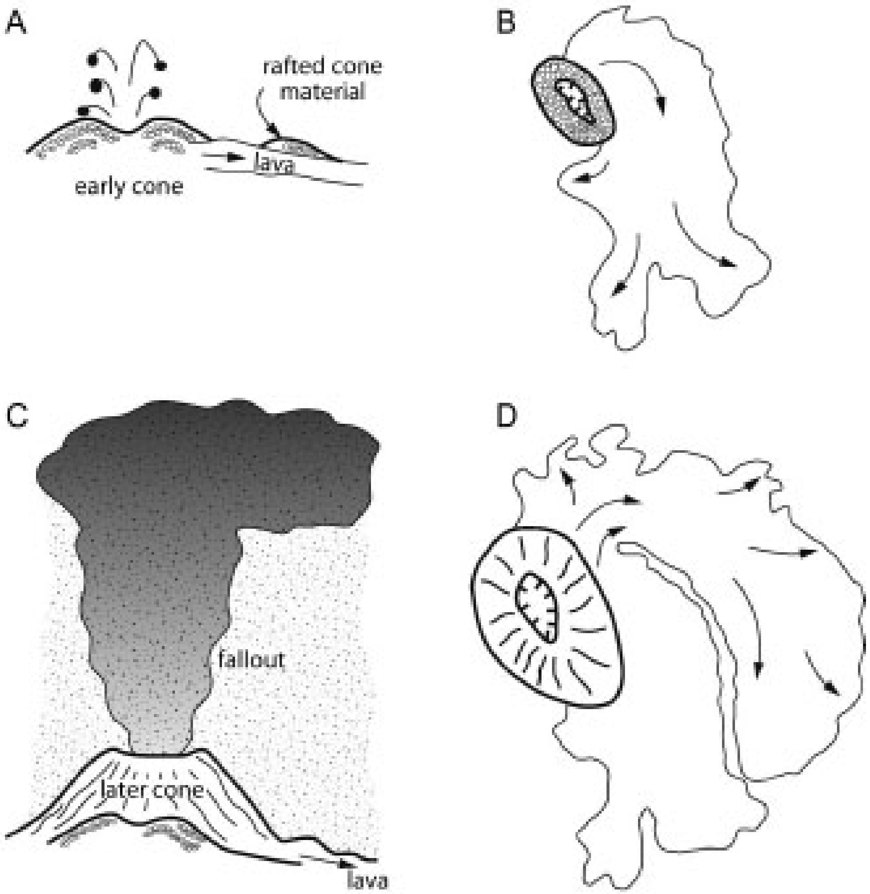


Figure 2: Schematic of (A-D) four possible eruptive events for the main cone at Lathrop Wells basalt center (Valentine et al., 2005).

Clast Analysis

Clast component analyses of scoria deposits from the two phases provide a method for assessing the magma ascent history. For instance, magma that was transported to the Earth's surface rapidly, then fragmented and quenched while airborne, produces reddish-brown basaltic glassy clasts known as sideromelane. Sideromelane droplets are thought to be products of energetic lava fountains or Hawaiian eruptions (Heiken and Wohletz, 1985; BSC, 2004). Magma that was transported to the Earth's surface slower and/or stopping along its way will crystallize producing crystalline clasts known as tachylite. Tachylites pyroclasts are microcrystalline textured fragments of basalt that have been described as "quenched crystal" textures (Heiken, 1978). A significant number of samples from scoria deposits at Lathrop Wells were collected and analyzed for clast components by DOE (BSC, 2004). Six different clast types were identified in each sample (BSC, 2004): tachylite, glassy tachylite, sideromelane and crystals (broken olivine, amphibole and/or feldspar phenocrysts) or lithics (tuff or carbonate). Results from this study (BSC, 2004) show that the earliest material erupted produced mostly sideromelane clasts whereas material erupted during the lower and upper cone building phases produced mostly tachylite clasts.

Crystal size measurements of both phenocrysts (> 1 mm) and microlites (< 0.01 mm) can be used to determine ascent rates from results from decompression petrologic experiments (Cashman, 1992; Geschwind and Rutherford, 1995). Isothermal decompression experiments can determine the pressure and temperature conditions of crystal phase equilibrium observed in tephra and lava samples. A study of this type was conducted on tephra and lava samples collected at Lathrop Wells (Nicholis and Rutherford, 2004). According to Nicholis and Rutherford (2004), most of the Lathrop Wells samples contain < 2-4 vol.% phenocrysts of olivine and amphibole. The phenocrysts assemblage along with the known water content of < 4.6 wt.% from previous experiments (Luhr and Housh, 2002) suggested a phenocryst-melt equilibrium pressure and temperature of < 175 MPa and 1010º-975 ºC, respectively (Nicholis and Rutherford, 2004). Plagioclase (An_{69}) is found rarely as microphenocrysts (>0.1 mm) in a crystalline groundmass (microlites) of plagioclase (Nicholis and Rutherford, 2004). The experiments determined that to achieve the crystal size range of the plagioclase microlites observed in the samples, an ascent rate of > 0.04 m/s is required for magma with < 4.6 wt % H_2O (Nicholis and Rutherford, 2004). Equilibrium conditions can also be determined from reactions rims of amphibole (water-bearing mineral) crystals that are very reactive with the liquid phase of magma (melt). The rims of amphiboles in Lathrop Wells' samples suggest a short-lived residence time at a depth roughly 800 m below the surface. At this depth, amphiboles react with the liquid phase of magma to produce the reactions rims visible on amphibole phenocrysts (Nicholis and Rutherford, 2004).

Lathrop Wells Eruption History

The above mentioned petrologic and field data are used by EPRI to derive an eruption history and a magma plumbing system for the Lathrop Wells basalt center. EPRI's eruption history is divided into two phases as recognized by DOE from field deposits (Valentine et al., 2005). Within each phase, a series of eruption styles are described that correspond to eruption products at Lathrop Wells basalt center described by DOE (BSC, 2004; Valentine et al., 2005). The first eruptive phase begins with a series of fissure eruptions that lasted only a few days that transitioned to focused eruptions where the main cone is located. This phase includes the lower cone building deposits and *aa* lava found to the south of the cone. The lower cone building eruption is thought to have formed from Strombolian eruptive events whereas the *aa* lava was eruptive effusively (non-explosive, less energetic than the Strombolian events).

As noted by Valentine et al. (2005), the lower cone deposits have characteristic features related to an emplacement and eruption mechanism modeled by McGetchin et al. (1974) as ballistic trajectories of hot fluid fragments of magma. The travel distance is not sufficient to solidify large fragments (bomb size) such that partially welding of ejected material occurs. The model (McGetchen et al., 1974) also considers the accumulation of scoria as rim deposits that may develop into grain avalanches. This model appears to be applicable to the lower cone deposits and is commonly used to describe scoria cone formation. The second phase includes the northern lava flow and the final cone-building event that produced a sustained ash column (Valentine et al., 2005). As noted by Valentine et al. (2005), the upper cone deposits have characteristic features unrelated to the ballistic emplacement model (McGetchin et al., 1974). They propose that the magma in the later stages was likely more viscous and fragment similarly to more silicic magmas thus producing the sustained column of finer grain tephra (Valentine et al., 2005).

EPRI's Interpretation of the Magma Plumbing System at Lathrop Wells

The magma plumbing system (Figs. 3A-3B) during the first phase is inferred from the relative amount of sideromelane and tachylite clasts found in the respective pyroclastic deposits and crystal content of lavas following a similar approach taken by Corsaro and Pompilio (2004) at Mt. Etna. Lathrop Wells basalts are thought to have originated from 7-8 km depth and transported through the crust in a system of dikes (ICRP, 2002; Nicholis and Rutherford, 2004). Magma that reached the surface first and erupted along the fissures was essentially crystal poor associated with lava fountains. Magma erupted at this time (Fig. 4) is characterized as fragments of molten magma carried by exsolved gases as an annular flow or dispersed flow (Verniolle and Manga, 2000) and was likely partially depleted in volatiles (< 1 wt.% H_2O; Holloway and Blank, 1994). This interpretation is based on the presence of sideromelane clasts (quenched glass basalt) found in deposits at the base of the lower portion of the cone (BSC, 2004). To form quenched glass, magma ascended rapidly through the dike to inhibit the formation of microlites then cooled rapidly as it erupted at the surface during the lava fountain phase. The later part of the lower cone building event erupted more crystalline magma based on the predominate appearance of tachylite in the samples from deposits from the lower portion of the cone (BSC, 2004). Magma that reached the surface during the later part of the lower cone building event may have ascended slower allowing crystals to begin nucleating and growing in magma. Tachylite pyroclasts are also thought to form from quench crystallization of fragmented basalt that becomes clogged in the vent during a Strombolian eruptive event (Heiken, 1978). Unlike magma that erupted along the length of the fissure, magma associated with lower cone building Strombolian events erupted from a point source along the fissure. Strombolian style of eruption (characterized by ballistic spatter bombs) is thought to be produced by the expansion and bursting of gas slugs (Fig. 4) at the surface or vent produces the (Verniolle and Manga, 2000). Gas slugs form in rising magma from exsolved volatiles that form bubbles and rise through magma and coalesce to form larger bubbles (slugs) when the bubble fraction reaches at least 70% (Verniolle and Manga, 2000). Slugs are thought to be separated by regions of magma containing bubbles (Verniolle and Manga, 2000).

The transition from a fissure eruption (lava fountains) to a point source or conduit eruption (Strombolian) is thought to occur when magma cools to near its solidus temperature along the dike where the thickness is < 2 m (ICRP, 2003; Delaney and Pollard, 1982). Magma erupted at the surface from the thicker or wider portion of the dike would produce Strombolian activity (Fig. 3A). The contemporaneous occurrence of Strombolian activity and *aa* lava extrusion suggest a lateral variation in crystallization and bubble content along the length of the dike at depth. These two processes are controlled in part by cooling rates. Lava likely extruded from a thinner portion of the dike adjacent to where the conduit developed (Fig. 3A). The thinner regions of the dike (< 2 m) conductive heat loss at the wall rock will induce crystallization of magma (Delaney and Pollard, 1982; Carrigan, 2002) and as magma crystallize it will become more viscous eventually reaching a critical crystal content at which it freezes (Delaney and Pollard, 1982). Exsolved volatiles (bubbles) in magma in the thinner regions of the dike may either move into less viscous magma located in the thicker, hotter, less viscous part of the dike or be released into permeable wall rock.

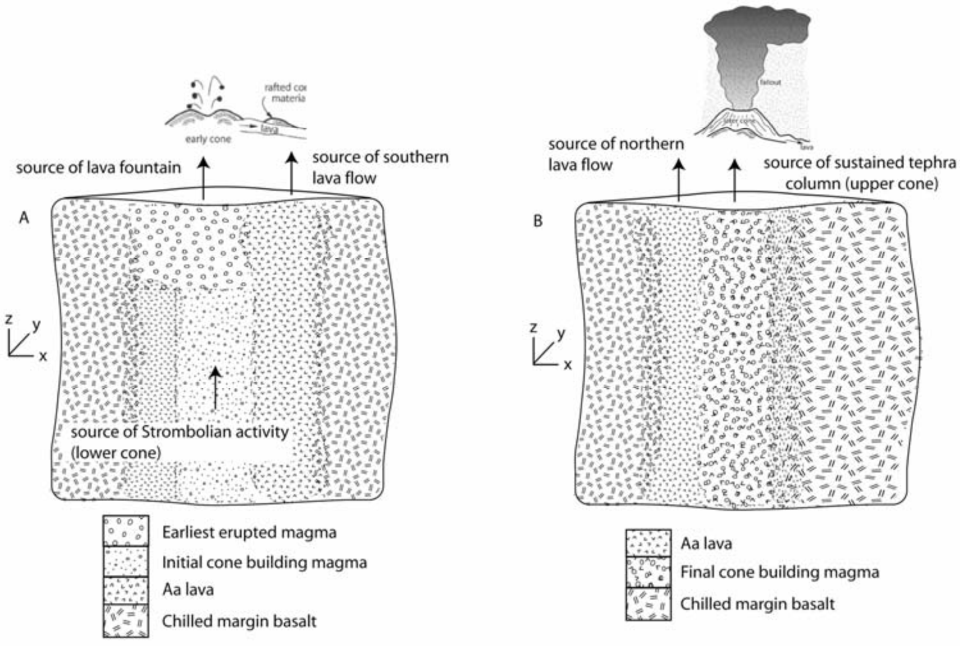


Figure 3: Schematic drawing of EPRI's conceptual model of the magma plumbing related to the Lathrop Wells basalt center (not to scale).

The second phase includes the northern lava flow and the final cone-building event that produced a sustained ash column (Valentine et al., 2005). From the observed reaction rims on amphiboles from Lathrop Wells samples (Nicholis and Rutherford, 2004), magma erupted during this time may have resided at depths of 800 m for a few days. At this depth, basaltic magma moving up from depth containing < 4.6 wt.% H_2O would exsolve at least half of its H_2O (Holloway and Bank, 1984). The slow ascent or stalling of magma in the lower portion of the conduit (Fig. 4) would allow for the formation of microlites as suggested by the tachylite textures in eruptive products associated with this phase. The presence of crystals in magma would increase the viscosity. The ascent from 800 m would exsolve volatiles that would rise at the same rate as the magma (more viscous then earlier magma) thus forming a bubbly or homogenous fluid (Fig. 4; Sparks et al., 1997). As this magma approaches the surface volatiles will continue to exsolve and the magma will begin to fragment into an ash-gas mixture when the bubble fraction reaches roughly 75% (Wilson et al., 1980). The formation and behavior of bubbles in this later more crystalline magma would be similar to that in a silicic magma (Valentine et al., 2005). This process would explain the sustained eruption column (Valentine et al., 2005). During this phase of the eruption, more crystalline degassed magma (< 1 wt.% H_2O; Holloway and Blank, 1994) is brought up to the surface at the northern end of the cone producing the later lavas.

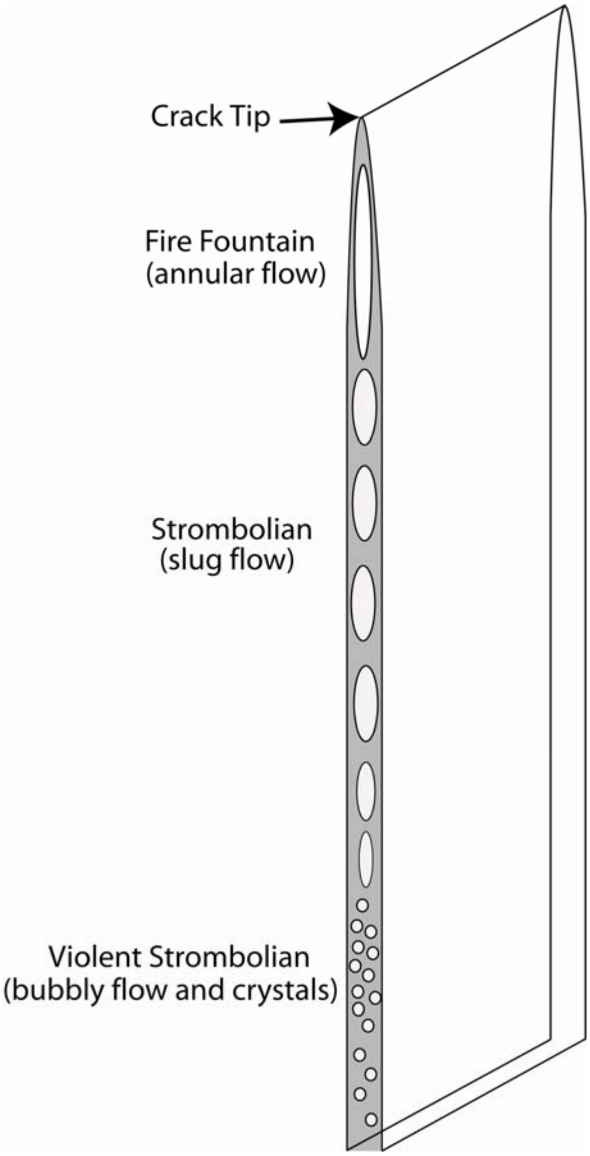


Figure 4: Conceptual model of the change in bubble content with depth in the magma column for Lathrop Wells. Not to scale.

EPRI's interpretation of the magma ascent history at Lathrop Wells becomes important when developing a conceptual model for possible eruptions in the Yucca Mountain region and analysis of dike-drift interaction. Previous models for dike-drift interaction assume magma entering a drift would have a viscosity of the order 1-10 Pa·s capable of filling all drifts and access drifts eventually creating secondary dikes from which magma will erupt at the surface (Woods et al., 2002). Such a model requires that all magma associated with a future eruption at Yucca Mountain remain essentially crystal-free throughout its ascent. As noted in the clast analysis of Lathrop Wells basalt samples, crystallinity of erupted material varies from quenched glass products (sideromelane) that is essentially crystal free to tachylite and crystalline lava that contain abundant microlites. Therefore, a crystal-free magma does not accurately represent Lathrop Wells magma.

Viscosity

EPRI (2006) estimated viscosities for magma in EPRI's conceptual model for the active part of the dike connected to the conduit (Fig. 4). Viscosity values (Fig. 5) for initial crystal-free basalt are available from experimental data for crystal-free, alkali basalt containing up to 5 wt. % H_2O (Murase, 1962; Cas and Wright, 1987) at four temperatures 800ºC, 100000°CC, 1200ºC, and 1400ºC (denoted in Fig. 5 by vertical columns of respective symbols) and for H_2O depleted alkali basalt at temperatures between 1100ºC to 1500ºC (Murase and McBirney, 1973; solid black line in Fig. 5). As demonstrated in Fig. 5, the exsolution of H_2O (due to decompression) from basalt increases the viscosity by 1-2 orders of magnitude depending on temperature. For example, in Fig. 3 at 1000ºC and 5 wt. % H_2O, the viscosity is approximately 40 Pa·s and at 0 wt. % H_2O the viscosity is 800 Pa·s.

EPRI (2006) estimated viscosity for basalt as a function of crystal content using the Einstein-Roscoe equation (McBirney and Murase, 1984). The Einstein-Roscoe equation estimates an apparent viscosity (η) of magma containing crystals of any size by the following expression:

$$\eta = \eta_o(1-R\varphi)^{-2.5}$$

Where η_o is the initial crystal free viscosity, φ is the crystal fraction, and R is a constant with a value 1.67 (Griffiths, 2000). The apparent viscosity for Lathrop Wells basalt just below repository depths is estimated at 110 Pa·s (arrow in Fig. 5) using an initial crystal free magma contains 2 wt.% H_2O at 1000ºC. Results from this calculation are shown in the inset of Fig. 3. For basalt containing 2 wt. % H_2O, the presence of crystals in basalt increases the viscosity by up to 5 orders of magnitude; 1.1×10^2 Pa·s to ~6.0×10^6 Pa·s for a crystal content increasing from 0 to 0.6. Lava flows tend to terminate their advancement when the crystal content reaches a critical value of 0.55-0.6, which corresponds to a viscosity on the order of 10^7 Pa·s (Marsh, 1981; Griffiths, 2000).

For the range of magma rheologies interpreted for the main magma plumbing system (Fig. 4) at Lathrop Wells, Fig. 5 is used to assign a viscosity to each magma rheology. EPRI considers ~40 Pa·s to be a reasonable viscosity for magma ascending from source depth (7-8 km) at Lathrop Wells (magma at this depth is essentially crystal free and contains up to 4.6 wt.% H_2O (Luhr and Housh, 2002; Nicholis and Rutherford, 2004). As magma ascends through the crust it will exsolve volatiles and as it does its viscosity will increase as shown in the black crosses in Fig. 5 assuming magma remains crystal free (Lathrop Wells basalts do contain a negligible amount of phenocrysts, 3-4 vol.%). Magma erupting in the first phase as lava fountains (annular flow) and Strombolian events (slugs and bubble flow alternating) will likely have a viscosity on the order of 10^2 Pa·s. Magma erupting as lava may contain some volatiles (< 1 wt.% H_2O; Holloway and Blank, 1994) and will be crystallizing therefore the viscosity will range from 10^3-10^5 Pa·s. Upon decompression, a portion of the remaining H_2O will exsolve forming bubbles that will increase the viscosity by up to an order of magnitude (Pinkerton and Sparks, 1978; Detournay et al., 2003). Decompression induces exsolution of H_2O to the lower pressure that in turn induces undercooling of the magma resulting in quenched crystallization (Sparks and Pinkerton, 1978). EPRI considers 10^3-10^6 Pa·s to be a reasonable range of viscosities for lava at its eruption temperature of 975-1010ºC. Viscosities will rapidly increase several orders of magnitude 10^7-10^8 Pa·s as the lava cools a few 10ºC below its solidus (Griffiths, 2000; Lore et al., 2000) that it is very close to when it erupts. During the second phase of expected eruptive events, a reasonable viscosity for magma before it erupts as a sustained eruption column may be at least 10^3-10^4 Pa·s accounting for microlites and bubbles in the magma.

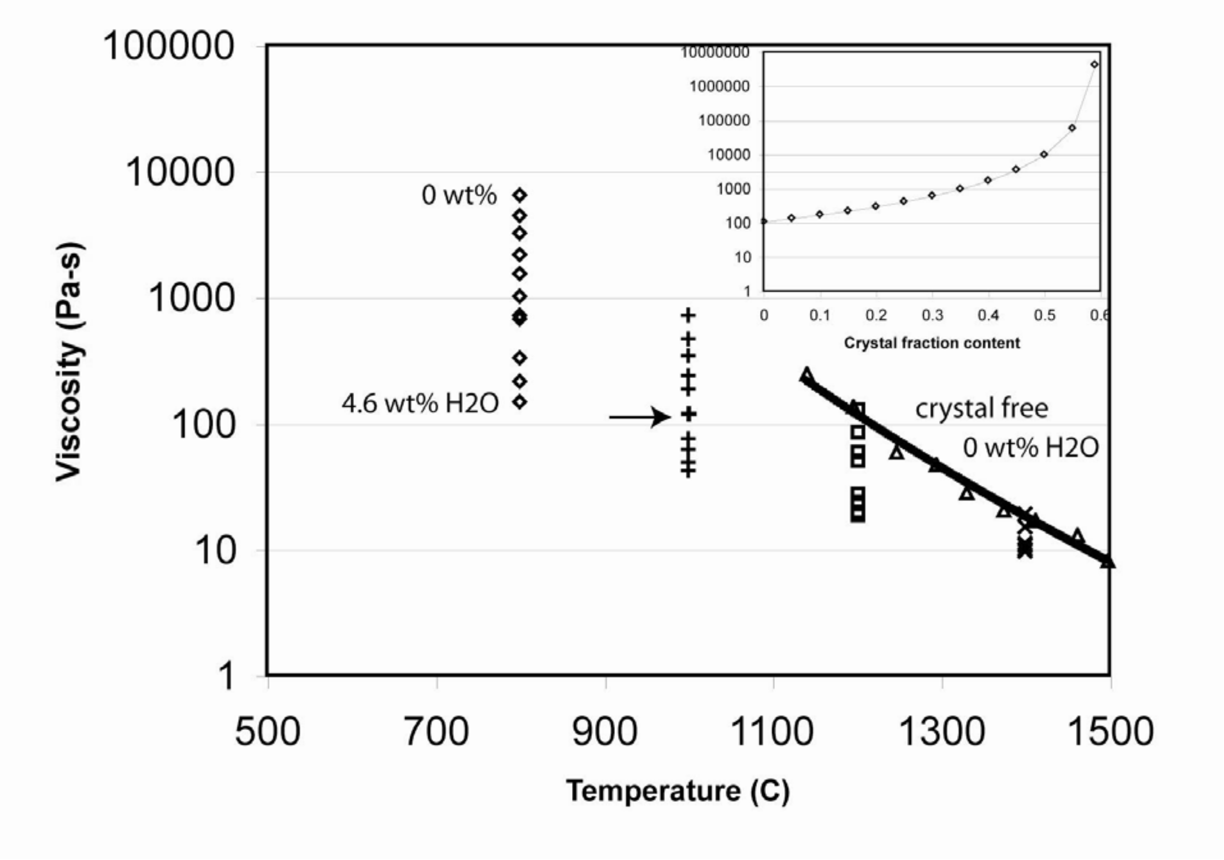


Figure 5: Viscosity as a function of temperature and H_2O content for crystal free basaltic magma (after Murase, 1962; Cas and Wright, 1987). Inset is viscosity as a function of crystal content calculated using Einstein-Roscoe equation with a crystal free starting viscosity denoted by the arrow.

Expected Igneous Consequences Scenarios

The expected extrusive igneous consequences are described in 5 stages. The expected consequences are based on the interpreted eruption history for the Lathrop Wells basalt center.

Extrusive Release Scenarios

Stage 1: Intersection of dike with drift

The first stage of the model considers the ascent of magma through the crust to depths of the proposed repository (300-400 m). The expected sequence of events during magma ascent is based on linear elastic fracture mechanic models for dike propagation (Lister, 1999; Rubin 1995). As discussed by the Igneous Consequence Review Panel (ICRP, 2003), the expected interaction of an ascending sheet dike with a repository drift would involve a < 0.2 m width and 100-200 m long crack tip propagating ahead of the magma filled dike (Fig. 6). Table 1 lists the range of values of characteristic parameters for dikes in the YMR. The ascent rate or propagation rate of a dike has been estimated from decompression experiment to be > 0.04 m/s (Nicholis and Rutherford, 2004). The maximum ascent rate observed at fissure systems in Hawaii and Iceland is 10 m/s (Lister, 1999; Rubin 1995) that provides the upper bound in Table 1.

The width of a future dike in the YMR is expected to be < 4 m at depths below 100 to 125 m from the surface (BSC, 2004). Dike width with respect to depth is constrained from recent field observations of dikes and conduits at monogenetic volcanoes in Nevada and New Mexico (BSC, 2004). Dikes are believed to reach the surface with widths < 4.0 m. As flow activity along a dike (fissure) concentrates at points along the fissure, conduits develop. Magma rising through a conduit will begin to erode the walls by several mechanisms (e.g., thermal erosion, spallation (Valentine and Groves, 1995)) to diameters as large as 125 m, however these diameters develop only in the upper 100-150 m of the surface (BSC, 2004). In EPRI's model, conduit diameters on the order of >10s m are not expected below 100-150 m.

An important part of the conceptual model is the geometry of the crack tip and dike because it provides initial conditions for modeling dike-drift interaction. According to linear elastic models for dikes expected in YMR (ICRP, 2003), the width of a crack tip is expected to be < 0.2 m and when magma reaches the drift, the dike will expand to 1.5 m, the mode width of dike found in YMR (OCRWM, 2003). The number of drifts that will be intersected by the dike will depend on the lateral extent of the dike that is expected to be 0.5-5.0 km (Crowe et al., 1983). Following the initial intersection of the dike with a drift, the ascending dike tip can be expected to reach the ground surface above a repository in a matter of minutes (ICRP, 2003; BSC, 2004).

Stage 2: Initial stage magma-drift interaction

Magma that first reaches the repository (Fig. 6) is expected to be similar to that interpreted for the first eruptive phase at Lathrop Wells. EPRI's model suggests that a dike in the Yucca Mountain region is expected to be nonuniform both laterally and vertically with respect to rheology. Magma with the lowest viscosity is expected in the center or the widest part the dike and more crystalline viscous magma is expected along the outer regions or the thinner parts of the dike. The lateral variation in magma properties will produce in general two different styles of expected activity upon entering a drift. Magma may be either a mixture of fragmented magma and gas characteristic of a lava fountain phase or crystallizing magma relatively depleted in volatiles characteristic of *aa* lava. The former type of magma would produce a spray of pyroclastics (scoria, spatter and ribbon bombs) into a drift thereby potentially bombarding and coating waste packages with magma (d1 in Fig. 7A-7B). Spray of magma onto waste packages is not expected to damage waste packages (EPRI, 2005). The latter type of magma would produce a slow moving crystallizing lava flow inside the drift (d2 in Fig. 7A-7B). The lava flow will have a viscosity of 10^3-10^6 Pa·s and will likely flow over or around waste packages forming a chilled margin upon contact with a waste package. Waste packages would be entombed in crystallizing magma (d3 in Fig. 7A-7B).

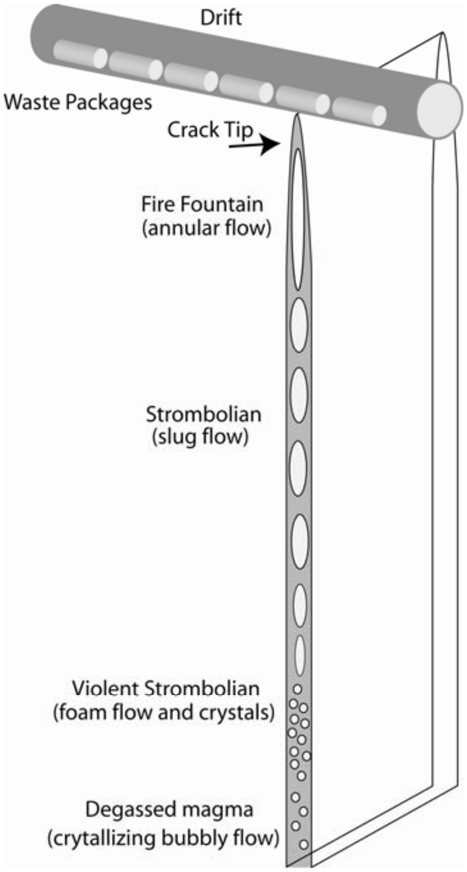


Figure 6: Conceptual model of the change in bubble content with depth in the magma column prior to intersecting a drift. Not to scale. White areas denote gas phase and grey denotes liquid magma. (adapted from Sparks, 1978; Vergniolle and Manga, 2000)

Stage 3: Initial fissure eruption

Magma that is not diverted into the drift will follow the crack tip and make its way to the surface. Magma will erupt at the surface along the fissure as a curtain of lava fountains. The initial width of the dike will be that of the crack tip (< 10 cm) and will gradually increase to 4.0 m the maximum width of fissures in the YMR (OCRWM, 2003). This phase will last hours to several days (ICRP, 2003; Delaney and Pollard, 1982), then eruption activity will localize to 1-3 locations along the fissure.

Magma in the dike will be laterally and vertically gradational with respect to volume fraction of exsolved volatiles, crystallinity and liquid magma as interpreted for Lathrop Wells basalt (Figs. 3A-3B). *Aa* lava that erupted contemporaneous with the initial cone-building phase at Lathrop Wells suggests that part of the magma in the fissure-conduit system was crystallizing and volatile depleted. Therefore, a lateral temperature gradient is expected from the margin of the dike to the center. Assuming that the width of the dike varies laterally, then it is expected that the conduit or cone building part of the eruption would develop at the widest part of the dike where cooling rates are lowest. Lava is expected to erupt along thinner parts of the dike where temperatures are lower due to high rates of heat loss by contact with the wall rock. Volcanic activity is expected to cease along the thinnest (< 1 m wide) parts of the dike within 10 days when temperatures are at or below the solidus temperature due to conductive cooling for alkali basalts similar to Lathrop Wells basalts (ICRP, 2003).

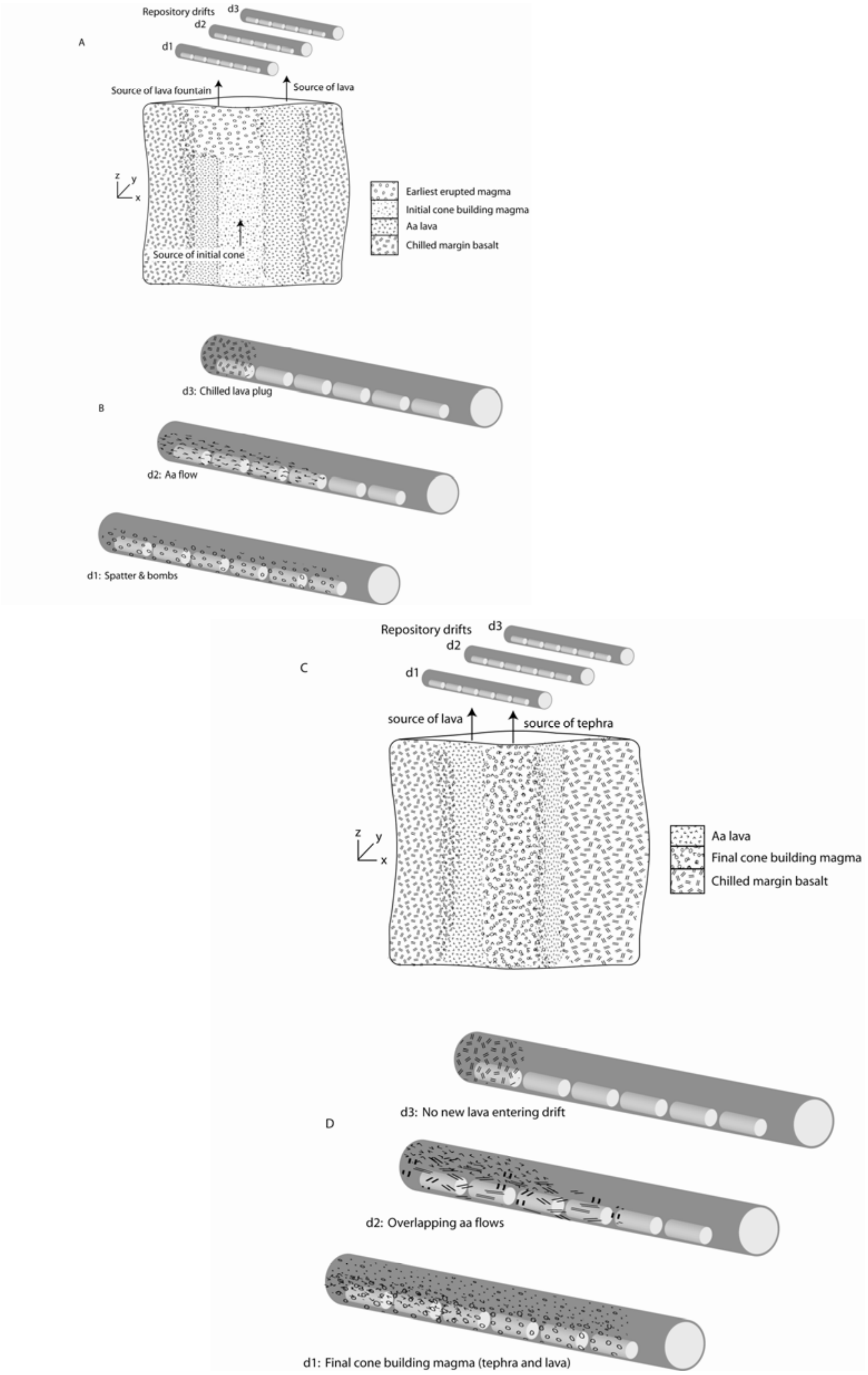
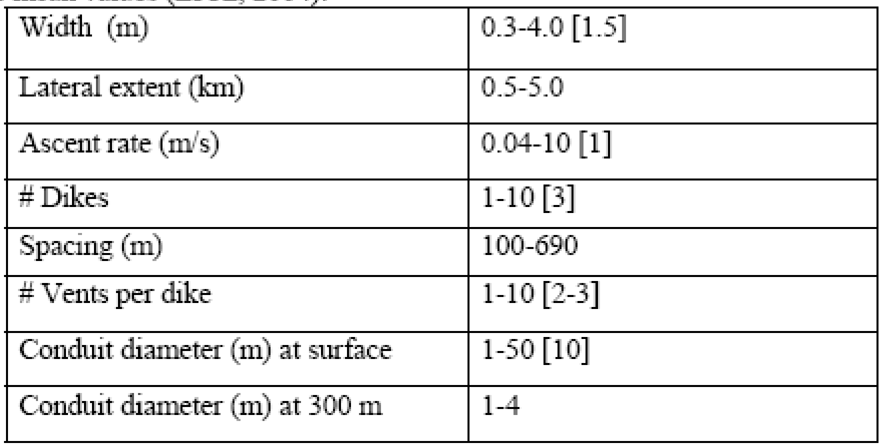


Figure 7: Conceptual model for magma-drift interaction during the (A-B) first three stages and (C-D) and last 2 stages. Not to scale. d1, d2, d3 denote three drifts located along different region of the drift. This model will be updated as new data are made available by DOE and other agencies.

TABLE 1: Summary table of dike characteristics at basaltic centers in the YMR - [ ] denotes mean values (EPRI, 2004).



Width (m)	0.3-4.0 [1.5]
Lateral extent (km)	0.5-5.0
Ascent rate (m/s)	0.04-10 [1]
# Dikes	1-10 [3]
Spacing (m)	100-690
# Vents per dike	1-10 [2-3]
Conduit diameter (m) at surface	1-50 [10]
Conduit diameter (m) at 300 m	1-4

Stage 4: Formation of conduits and central vents

Within hours to 10s of days from onset, the fissure eruption at the surface will cease and activity will be focused at 1 to 3 conduits (ICRP, 2003). At the repository, drifts that contain spatter and other pyroclastic deposits from an earlier stage and are connected to the center or the widest part the dike may be inundated by a bubble-magma mixture (Fig. 6 and d3 in Fig.7C-7D). In other drifts that contain spatter or pyroclastic material or lava and located within the narrow regions of the dike crystallizing magma may move into drifts filling space not occupied by volcanic materials (d2 in Fig.7C-7D).

At the surface, material not diverted into the drift will likely produce an ash plume capable of transporting ash > 20 km from the vent to the regulatory compliance boundary. The expected volume of scoria deposited from this phase is 0.01-0.048 km^3 (this includes the fraction of ash size material transported in the plume away from the cone, violent Strombolian event).

During this stage of the eruption, erupted magma may contain radioactive material, either as entrained UO_2 or as radionuclides dissolved into the magma, from the waste packages damaged by the initial interaction with the dike (EPRI, 2004). The mechanical processes that would result in the most damage to the waste packages include the impact of fragments of wall rock and magma from the initial intrusion of the dike into a drift. Thermal erosion of a waste package may arise if a package becomes caught in the upward flow of magma. This process may affect at least one waste package (1.8 m diameter, 5.0 m length) and possibly two, depending on the dike width (0.3 - 4 m) and the location of the dike intersection relative to it.

The amount of radioactive material that may contaminate the magma depends, in part, on the size of the conduit and how magma interacts with waste packages during this prolonged stage (EPRI, 2004). The expected conduit width at future YMR basaltic eruptions is < 4 m at the repository depth (BSC, 2005) and at depths < 100 m the conduit is expected to flare to diameters > 10-50 m (e.g., Paiute Ridge and Basalt Ridge (BSC, 2005)). Waste packages cannot be transported to the surface if the conduit widths are < 2 m. The size of an intact waste package (1.8 m diameter, 5.0 m length), assuming it could be lifted by the flow of magma, will restrict magma transport through a fissure. This constriction in the fissure and sluggish flow of magma will lead to rapid solidification of the dike in this constricted region. Thus, it may be reasonable to suggest that waste packages would only be transported to the surface in dikes with widths at the upper end of the range of YMR dikes (2-4 m).

Stage 5: Final stage magma-drift interaction

The final magma-drift interaction scenarios involve relatively degassed, crystallizing magma. Magma diverted into a drift may overlap earlier *aa* lava that entombed or covered waste packages if there is space, otherwise the drift will be sealed off from additional magma (d2 in Fig.7C-7D). If additional magma does enter, this later lava flow is not expected to completely fill the drift. Another scenario is a drift that already is closed off to the conduit by a chilled lava plug (d1 in Fig.7C-7D). No additional lava is expected to enter these drifts.

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APPENDIX D. LIST OF AGENCIES, ORGANIZATIONS, AND INDIVIDUALS RECEIVING PRELIMINARY DRAFT OF THIS REPORT FOR THEIR REVIEW AND COMMENT

A. Kalt, Churchill County, NV

R. Massey, Churchill/Lander County, NV

I. Navis, Clark County, NV

E. von Tiesenhausen, Clark County, NV

G. McCorkell, Esmeralda County, NV

R. Damele, Eureka County, NV

L. Marshall, Eureka County, NV

A. Johnson, Eureka County, NV

S. Schubert, Sen. Reid’s Office

M. Yarbro, Lander County, NV

J. Donnell, DOE/OCRWM

M. Baughman, Lincoln County, NV

L. Mathias, Mineral County, NV

J. Saldarini, BSC

M. Henderson, Cong. J. Gibbon’s Office

D. Swanson, Nye County, NV

M. Simon, White Pine County, NV

E. Sproat, DOE/OCRWM

D. Cornwall, NV Congressional Delegation

T. Story, NV Congressional Delegation

R. Herbert, NV Sen. Reid’s Office

M. Murphy, Nye County, NV

R. Lambe, NV Congressional Delegation

A. Elzeftawy, Las Vegas Paiute Tribe

J. Treichel, Nuclear Waste Task Force

W. Briggs, Ross, Dixon & Bell

R. Murray, DOE/OCRWM

G. Runkle, DOE/Washington, D.C.

C. Einberg, DOE/Washington, D.C.

S. Gomberg, DOE/Washington, D.C.

W. J. Arthur, III , DOE/OCRWM

R. Dyer, DOE/OCRWM

J. Espinoza, GAO

A. Gil, DOE/OCRWM

W. Boyle, DOE/OCRWM

M. Ulshafer, DOE/OCRWM

S.A. Wade, DOE/OCRWM

C. Hanlon, DOE/OCRWM

T. Gunter, DOE/OCRWM

A. Benson, DOE/OCRWM

N. Hunemuller, DOE/OCRWM

P. Harrington, OPM&E

M. Mason, BSC

S. Cereghino, BSC

B. Gattoni, Burns & Roe

E. Mueller, BSC

K. Kirkeby, NV Congressional Delegation

R. Loux, State of NV

S. Frishman, State of NV

S. Lynch, State of NV

P. Guinan, Legislative Counsel Bureau

R. Clark, EPA

R. Anderson, NEI

R. McCullum, NEI

S. Kraft, NEI

J. Kessler, EPRI

D. Duncan, USGS

K. Skipper, USGS

W. Booth, Engineering Svcs, LTD

C. Marden, BNFL Inc.

J. Bacoch, Big Pine Paiute Tribe of the Owens Valley

P. Thompson, Duckwater Shoshone Tribe

T. Kingham, GAO

D. Feehan, GAO

E. Hiruo, Platts Nuclear Publications

G. Hernandez, Las Vegas Paiute Tribe

K. Finfrock, NV Congressional Delegation

P. Johnson, Citizen Alert

M. Williams, DOE/OCRWM

J. Williams, DOE/Washington, DC

J. Gervers, Clark County, NV

D. Beckman, BSC/B&A

L. Rasura-Alfano, Lincoln County, NV

J. Kennedy, Timbisha Shoshone Tribe

B. Durham, Timbisha Shoshone Tribe

R. Arnold, Pahrump Paiute Tribe

J. Birchim, Yomba Shoshone Tribe

R. Holden, NCAI

C. Meyers, Moapa Paiute Indian Tribe

C. Dahlberg, Fort Independence Indian Tribe

D. Vega, Bishop Paiute Indian Tribe

Egan, Fitzpatrick, Malsch, PLLC

J. Leeds, Las Vegas Indian Center

J. C. Saulque, Benton Paiute Indian Tribe

C. Bradley, Kaibab Band of Southern Paiutes

R. Joseph, Lone Pine Paiute-Shoshone Tribe

L. Tom, Paiute Indian Tribes of Utah

E. Smith, Chemehuevi Indian Tribe

D. Buckner, Ely Shoshone Tribe

V. Guzman, Walker River Paiute

D. Eddy, Jr., Colorado River Indian Tribes

M. Boyd, Public Citizen

J. Wells, Western Shoshone National Council

D. Crawford, Inter-Tribal Council of NV

A. Robinson, Robinson-Seidler

M. Plaster, City of Las Vegas

S. Rayborn, Sen. Reid’s Office

L. Lehman, T-REG, Inc.

B.J. Garrick, NWTRB

T. Feigenbaum, BSC

M. Urie, DOE

J. Brandt, Lander County

R. Holland, Inyo County

B. Sagar, CNWRA

V. Trebules, RW/DOE

R. Warther, DOE/OCRWM

B. Neuman, Carter Ledyard & Milburn L.L.P.

Charles Connor, University of South Florida

Bruce Crowe, Battelle Memorial Institute

George Hornberger, University of Virginia

Eric Smistad, DOE (Las Vegas)

William Melson, Smithsonian Institution

Art Montana, University of City of Los Angeles

Eugene Smith, University of Nevada, Las Vegas

Steve Sparks, University of Bristol

I. Zabarte, Western Shoshone National Council

S. Devlin

G. Hudlow

D. Irwin, Hunton & Williams

P. Golan, DOE

M. Rice, Lincoln County, NV

G. Hellstrom, DOE

S. Joya, Sen. Ensign’s Office

M. Gaffney, Inyo County

L. Desell, RW/DOE

R. List, Esmeralda County

D. Curran, Harmon, Curran, Spielberg & Eisenberg, L.L.P.

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APPENDIX E. MEETING AGENDA FOR FEBRUARY 2007 ACNW&M WORKING GROUP ON THE IGNEOUS ACTIVITY WHITE PAPER

AGENDA

176th ACNW&M MEETING

FEBRUARY 13-15, 2007

TUESDAY, FEBRUARY 13, 2007, CONFERENCE ROOM T-2B3, TWO WHITE FLINT NORTH, ROCKVILLE, MARYLAND

ACNW&M WORKING GROUP ON THE IGNEOUS ACTIVITY WHITE PAPER (OPEN)

DAY 1: DISCUSSION OF THE NATURE AND PROBABILITY OF IGNEOUS ACTIVITY

1)	8:30 - 8:45 A.M.	**Opening Remarks and Introductions** (MTR/WJH/NMC) The ACNW&M Chairman will make opening remarks regarding the conduct of today's sessions. ACNW&M Member Dr. Bill Hinze will provide an overview of the first day of the Working Group Meeting, including the meeting purpose, scope, anticipated results, and introduce invited subject matter experts.
2)	8:45 - 9:15 A.M.	Dr. Steve Sparks (University of Bristol, England) will discuss the state of Volcanology science and eruption analogs for Yucca Mountain.
3)	9:15 - 9:45 A.M.	Dr. Bruce Crowe (Battelle Corporation) will discuss the volcanic history of the Yucca Mountain region and implications for the risk triplet.
4)	9:45 - 10:00 A.M.	**Questions and Round Table Discussion** (All) Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the two topics just presented.
	10:00 - 10:15 A.M.	*****BREAK*****
5)	10:15 - 10:45 A.M.	Prof. Charles Connor (University of South Florida) will provide an overview of methodologies in probabilistic volcanic hazard assessment and application at Yucca Mountain.
6)	10:45 -11:15 A.M.	Prof. Eugene Smith (University of Nevada – Las Vegas; Clark County, Nevada contractor) will discuss the importance of understanding the process of magma generation for volcanic hazard studies about the proposed Yucca Mountain repository.
7)	11:15 -11:45 A.M.	Dr. Kevin Coppersmith (DOE – YMPO; contractor, leader of PVHA & PVHA-U) will discuss the use of expert elicitation in predicting the probability of volcanic events at the proposed Yucca Mountain repository – objectives, methodology, implications of the PVHA and PVHA-U.

8) 11:45 - 12:15 P.M. **Questions and Round Table Discussion** (All)

Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the three topics just presented.

12:15 - 1:15 P.M. ***LUNCH***

9) 1:15 - 2:00 P.M. NRC staff representative will brief the Committee on the staff's regulatory role and responsibilities with respect to volcanism.

10) 2:00 - 2:15 P.M. **Questions and Round Table Discussion** (All)

Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the topic just presented.

11) 2:15 - 3:00 P.M. A representative from the US Department of Energy (DOE/YMPO) will brief the Committee about DOE's views on the ACNW&M draft White Paper in relation to the nature and prediction of igneous activity.

12) 3:00 - 3:15 P.M. **Questions and Round Table Discussion** (All)

Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the topic just presented.

3:15 - 3:30 P.M. ***BREAK***

13) 3:30 - 4:00 P.M. A representative from Clark County, Nevada will brief the Committee on the County's views on the ACNW&M draft White Paper in relation to the nature and prediction of igneous activity.

14) 4:00 - 4:15 P.M. **Questions and Round Table Discussion** (All)

Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the topic just presented.

15) 4:15 - 4:45 P.M. A representative from the Electric Power Research Institute (EPRI) will brief the Committee about their views on the ACNW&M draft White Paper in relation to the nature and prediction of igneous activity.

16) 4:45 - 5:00 P.M. **Questions and Round Table Discussion** (All)

Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the topic just presented.

17) 5:00 - 5:30 P.M. **Wrap Up**

Committee Member Hinze will lead a panel discussion, including a summary of the Working Group Meeting.

5:30 P.M. Adjourn

WEDNESDAY, FEBRUARY 14, 2007, CONFERENCE ROOM T-2B3, TWO WHITE FLINT NORTH, ROCKVILLE, MARYLAND

ACNW&M WORKING GROUP ON THE IGNEOUS ACTIVITY WHITE PAPER (OPEN)

DAY 2: DISCUSSION OF CONSEQUENCES OF IGNEOUS ACTIVITY

18)	8:30 - 8:45 A.M.	**Opening Remarks and Introductions** (MTR/WJH/NMC) The ACNW&M Chairman will make opening remarks regarding the conduct of today's sessions. ACNW&M Member Hinze will provide an overview of the second day of the Working Group Meeting, including the meeting purpose, scope, anticipated results, and introduce invited subject matter experts.
19)	8:45 - 9:30 A.M.	Prof. Bruce Marsh (Johns Hopkins University; ACNW&M consultant) will discuss the magma/repository/waste package processes in both eruptive and intrusive scenarios and implication for risk from igneous activity at the proposed Yucca Mountain repository.
20)	9:30 - 10:00 A.M.	Prof. Art Montana (University of California – Los Angeles) will discuss the thermal and mechanical magma/waste package interactions associated with the intrusion scenario at the proposed Yucca Mountain Repository.
	10:00 - 10:15 A.M.	*****BREAK*****
21)	10:15 - 10:45 A.M.	Neil Coleman (ACNW&M staff) will brief the Committee about the flooding history and geomorphology of Fortymile Wash near Yucca Mountain.
22)	10:45 -11:30 A.M.	Dr. Sara Rathburn (Colorado State University) will brief the Committee on processes of importance in fluvial and eolian transport of sediments.
23)	11:30 - 11:45 A.M.	**Questions and Round Table Discussion** (All) Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the four topics just presented.
	11:45 - 12:45 P.M.	*****LUNCH*****
24)	12:45 - 1:15 P.M.	Prof. Lynn Anspaugh (University of Utah) will discuss the resuspension of ash and implications to risk from igneous activity.
25)	1:15 - 1:30 P.M.	**Questions and Round Table Discussion** (All) Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the topic just presented.
26)	1:30 - 2:15 P.M.	A representative from the US Department of Energy (DOE/YMPO) will brief the Committee on DOE's views on the ACNW&M draft White Paper in relation to the consequences of igneous activity.
27)	2:15 - 2:30 P.M.	**Questions and Round Table Discussion** (All) Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the topic just presented.

28) 2:30 - 3:00 P.M. A representative from Clark County, Nevada, will brief the Committee on the County's views on the ACNW&M draft White Paper in relation to the consequences of igneous activity.

29) 3:00 - 3:15 P.M. **Questions and Round Table Discussion** (All)

Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the topic just presented.

3:15 - 3:30 P.M. ***BREAK***

30) 3:30 - 4:00 P.M. A representative from the Electric Power Research Institute (EPRI) will brief the Committee about their views on the ACNW&M draft White Paper in relation to Consequences of Igneous Activity.

31) 4:00 - 4:15 P.M. **Questions and Round Table Discussion** (All)

Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the topic just presented.

32) 4:15 - 4:45 P.M. NRC staff representative will brief the Committee on the staff's views of the White Paper in relation to the Consequences of Igneous Activity.

33) 4:45 - 5:00 P.M. **Questions and Round Table Discussion** (All)

Committee Member Hinze will lead a panel discussion with the invited subject matter experts on the topic just presented.

34) 5:00 - 5:45 P.M. **Wrap Up** (All)

Committee Member Hinze will lead a panel discussion including a summary of the Working Group Meeting. Some of the issues to be addressed include:

- Has an effective and accurate understanding of the various views on volcanism been identified and documented in the ACNW&M draft White Paper?
- Have the risk-significant topics regarding igneous activity been identified?
- Are the technical bases for positions taken for determining risk from igneous activity at Yucca Mountain scientifically sound?
- Are there risk-significant topics regarding igneous activity that have not been adequately addressed considering the current state of the science? If so, how can they be addressed?

5:45 P.M. Adjourn

APPENDIX F. MINUTES OF THE ACNW&M'S FEBRUARY 13 AND 14, 2007 WORKING GROUP ON IGNEOUS ACTIVITY

During February 13-14, 2007 the ACNW convened a working group meeting to solicit comments on the draft White Paper on volcanism that was published in December, 2006. At the Commission's request [SRM M060111B, February 9, 2006], the Committee has reviewed and analyzed the current state of knowledge regarding igneous activity, including the range of technical views by experts and stakeholders. A draft White Paper was developed that summarizes current knowledge of potential igneous activity at the proposed repository site,

including igneous activity scenarios and their potential impacts on the repository performance. The White Paper also provides an assessment of differing professional views, including the views of experts representing DOE, NRC, the State of Nevada, and other organizations and stakeholders.

Dr. William Hinze provided opening remarks that set the stage for the working group meeting. The Committee has invited scientifically-based criticism and recommendations for improving the draft White Paper. The bottom line is to prepare the best possible report for the Commission. Dr. Hinze noted that Day 1 of the working group would focus on the nature and probability of igneous activity at Yucca Mountain. Day 2 would focus on discussions of the consequences of igneous activity. Round table discussions would be held at various times during the meeting to gain additional insights from the invited experts. Invited experts for ACNW included Bruce Marsh (Johns Hopkins University), William Melson (Smithsonian Institution), Charles Connor (University of South Florida), and Sara Rathburn (Colorado State University).

Day 1 - Discussion of the Nature and Probability of Igneous Activity

The working group meeting began with a series of invited talks by recognized experts in volcanism, and including experts with extensive experience studying volcanism in the southwestern USA. The first of these invited talks was given by Steven Sparks (University of Bristol, England), who discussed the state of volcanology science and eruption analogs for Yucca Mountain. Professor Sparks described advances in volcanology studies and prediction, including specific discussion of the Soufrière Hills volcano, monitoring techniques, and modeling and prediction. Soufrière Hills is on the Caribbean island of Montserrat. A total of 0.7 cubic km of lava have been erupted so far at this volcano.

Professor Sparks reported an extrusion viscosity of $\sim 10^{10}$ to 10^{12} Pa·s, based on analysis of the rheology of the lava dome, which he says is 6 to 7 orders of magnitude higher than would be expected for extrusion viscosities at the Lathrop Wells volcano near Yucca Mountain. One reason for the high viscosity at Soufrière Hills is that the lava has a minimum crystal content of 65% and sometimes extrudes with a crystal content of 90%. This volcano displays episodic activity over time. During the latest eruption the volcano has been active since 1995. Professor Sparks described one of the proposed models for the Soufrière Hills volcano, which explains much of what is observed and monitored. The volcano is theorized to experience strong overpressure at depth due to resistance to outflow near the surface as a result of high viscosity. This overpressure provides an explanation for shallow earthquakes, ground deformation, and explosive activity.

Professor Sparks then discussed possible volcanic analogs for volcanism at Yucca Mountain, and provided extensive information about Eldfell eruption on Heimaey Island, Iceland, in 1973. This was a typical monogenetic (one time) basaltic eruption that was remarkably similar to what likely happened at Lathrop Wells, in many respects. The 6-month eruption began on January 22, 1973 with earthquakes and the opening of a fissure, with a classic "curtain of fire" eruption.

Interestingly, degassed lava was observed to be flowing as early as January 24th at a time when the activity was at its most intense stage, with eruption columns 8 to 9 km high. By January 31st a scoria cone had already accumulated to a height of 180 m. During the month of March lava flowed into the nearby town and measures were taken to halt this flow using high-volume sprays of seawater. This succeeded in limiting the distance that lava flowed into the town, and caused the flow to focus in another direction. The eruption was declared over in July, 1973. One of the most important observations was that explosive activity and extrusion of degassed lava can be simultaneous, involving gas segregation mechanisms.

Professor Sparks compared the petrology and geochemistry at Eldfell, Lathrop Wells, and Etna. He noted that the ACNW draft White Paper comments that the Lathrop Wells eruption occurred at temperatures around 1000°C, but he observed that this estimate does not account for the latent heat of crystallization, so magma that rises up and crystallizes will erupt at higher temperatures of 1030-1055°C. These volcanoes typically display an exponential decrease in extrusion rate. Other similarities of these volcanoes is relatively high water pressure (~4% water) and the presence of microphenocrysts (small crystals in lava) up to 40% consisting of plagioclase-olivine-oxides. An important difference was noted between Heimaey and Lathrop Wells. At the Icelandic volcano the tephra volume was small (0.02 km^3) compared to the lava volume (0.23 km^3), whereas at Lathrop Wells these volumes were roughly equal. One possible explanation is that the Icelandic study that reported these results may have underestimated the tephra volume because much fell into the sea.

Professor Sparks showed how shearing experiments were conducted at Etna in 1975, to estimate the lava viscosity. These experiments using a field rheometer yielded an upper bound for degassed trachy-basalt magma around 10^5 Pa·s. Representing a rather crystal-rich magma at Etna, this should approximate an upper bound for magmas like those that erupted at Lathrop Wells. Sparks then described viscosity estimates from a long lava flow at Lonquimay, Chile, in 1989. This was a mafic andesitic magma, which has a higher silica content and should therefore be more viscous than the Lathrop Wells magma. Viscosities were calculated using open channel flow equations. It took a year of flow time over a distance of 10 km for the viscosity to reach a level of 10^9 Pa·s.

Professor Sparks then described volcanic blast effects from the Soufrière Hills volcano. And although this kind of event is not exactly analogous to Lathrop Wells, the flow density at Soufrière Hills would be about the same as the flow density of a Strombolian jet coming out the vent at Lathrop Wells. He summarized his interpretations of phenomena that could potentially be applied to Yucca Mountain: intense explosive eruptions dominate for ~ 1 week, but with lava effusion; discharge of explosive jet at hundreds of m^3/s and up to 200 m/s speed; wet magma starts out at <1000°C, then erupts at 1030-1055°C with latent heat of crystallization; wet trachy-basalt lava extrudes with a viscosity of ~10^4-10^5 Pa·s; flow front evolves to *aa* flow (viscosity $< 10^7$ Pa·s) and blocky lava (viscosity = 10^7 to 10^{10} Pa·s); the lava viscosity evolves; buildings destroyed by *aa* flows; and high-speed gas-particle flows can be highly destructive.

Bruce Crowe (Battelle Corporation) described the volcanic history of the Yucca Mountain region and implications for the risk triplet (what can go wrong?; how likely is it?; what would the consequences be?). He presented background information about the evolution of volcanic hazard models, the setting and volcanic history of the Yucca Mountain region, and provided a discussion of risk-informed perspectives from modeling for environmental problems. Dr. Crowe was formerly a participant in the Yucca Mountain project; he is now a “distant and interested observer.” He presented a flow chart that outlined the elements of an event probability calculation (i.e., the conditional probability of repository disruption by igneous activity). There has been a multi-decade progression in probabilistic modeling, from development of a probabilistic volcanic hazard model in the early 1980's leading to probabilistic modeling for complex environmental problems in the 2000's. A current opinion is that volcanic hazard models are now relatively mature but that consequence modeling is still evolving. A remaining challenge is to quantify and reach agreement on uncertainty components.

Dr. Crowe described the regional geologic and tectonic setting for the southwest Nevada volcanic field, where Crater Flat and Yucca Mountain are located. There is a long history of studies in the Nevada Test Site region, including multiple decades of geologic mapping and geophysical studies (1950's to 1990's); drilling of a large number of boreholes for the underground testing of weapons (1950's to 1992); geologic and hydrologic studies for Yucca Mountain (late 1970's and continuing); specific boreholes for volcanic hazard studies (VH-1 and VH-2, plus seven new holes drilled in 2006 to explore aeromagnetic anomalies); and geologic and hydrologic studies for Environmental Management programs. There is an unprecedented level of knowledge of the geology and hydrology of a complex geologic and hydrologic setting that has been partly incorporated in a 3-D Earth Vision model of the Yucca Mountain site.

Dr. Crowe then gave general descriptions of various phases of volcanism in the region, starting with locations of the silicic volcanism that deposited the surface rocks at Yucca Mountain. He then described four cycles of basaltic volcanism, starting with the volcanism associated with the waning phase of the silicic pyroclastic Timber Mountain-Oasis Valley caldera complex. This basaltic episode occurred in Miocene time from ~10 to 12 Ma and produced a large volume of basalts (>3 km^3). Basalts also were produced during basin development following the eruptions of the Black Mountain Caldera (Frenchman and Yucca Flats) during 10 to 8 Ma. These post-caldera basalts had volumes of <3 to <1 km^3. Additional basalts were produced from 8.6 to 7.3 Ma showing an apparent decline in volume. Dr. Crowe then described a Pliocene volcanic cycle in the Amargosa Trough. Apparent ages range from ~4.9 to 3.0 Ma ago, with a cycle duration of about 2 Ma. The volume of basalt declined through the cycle. Finally, he discussed the Quaternary volcanic cycle of the Amargosa Trough. The eruptions occurred from about 1.1 to 0.08 Ma with volume decline through the cycle. The volume produced around 1 Ma was ~0.15 km^3, whereas the combined volume from Sleeping Butte and Lathrop Wells was 0.09 km^3. The question remains whether this Pleistocene cycle is over. Dr. Crowe noted the possibility of a 2 million-year time gap between volcanic cycles with a mean cycle duration of ~1.5 Ma. He illustrated various possibilities, one being that the next event in the Yucca Mountain region could have a recurrence interval somewhere around the range of 300,000 years. He emphasized the use of multiple permissive models as providing multiple ways to look at the probability data to try to forecast what might happen.

Dr. Crowe then described a new type of modeling approach being explored in fluid and contaminant transport models. This approach is called Bayesian Model Averaging (BMA). This methodology had previously been presented to the ACNW and is documented in the 2003 NRC report NUREG/CR-6805. This kind of approach may have applicability to volcanism models. The Bayesian perspective provides a way to integrate data to both quantify the uncertainty and to try to assemble good predictions. Dr. Crowe has shown the Yucca Mountain scenario and associated probability distributions to other decision analysts who work with environmental modeling problems. Compared to dealing with remediation and decision options for Superfund sites, those analysts found the roughly order of magnitude uncertainty in volcanic intersection at Yucca Mountain to be relatively minor by comparison.

In closing, Dr. Crowe commented that it will be difficult to be able to further reduce the uncertainty, and that limits may have been approached for the data sets available for the Yucca Mountain region. The key thing to do is to quantify the uncertainty using a variety of techniques using multiple permissive models.

Charles Connor (University of South Florida) gave an overview of methodologies in probabilistic volcanic hazard assessment and their application at Yucca Mountain. His talk was titled “Probabilistic Assessments of Volcanic Hazards at Yucca Mountain, Nevada.” He addressed the question, “What is the probability of igneous disruption of the proposed repository at Yucca Mountain?” Key factors to estimate are the spatial intensity and recurrence rate of volcanism. It is important to define the igneous event (dikes, volcanic vents and related vent structures, and sills and related intrusive structures).

Professor Connor described a model approach using maps in probability assessment scenarios, and development of a Monte Carlo event simulator that considers volcanic event types and geometries, based on analogous events. The simulator is based on a library of dike, vent, and sill geometries derived from geologic mapping at the well-exposed San Rafael volcanic field. The library includes 94 dikes, 34 vents, and 3 mapped sills. Mapping reveals basic features of dike injection associated with igneous events in basaltic volcanic fields. Dikes segment and rotate as they rise in the shallow crust. Dike trends in the shallow crust may be oblique to regional maximum horizontal compressional stress. Vents are the surface expression of conduits through which magma flows. Worldwide mapping indicates the following features of vents that are associated with basaltic volcanic fields: multiple vents are normally associated with individual events; these vents are usually distributed along one or more dikes; vents are most common at offsets in dikes; not all vents build scoria cones at the surface; and vents develop complex zones of interaction with adjacent wall rock, often involving areas >100 m in diameter. Sills occasionally form in basaltic volcanic fields. The frequency of sills in the Yucca Mountain region is not known, but sills are present at the Miocene Paiute Ridge, east of Yucca Flat on the Nevada Test Site. New drilling data indicates that magnetic anomaly A is likely a sill [age is Miocene], and other sills may be present. It is uncertain if sills accompanied Quaternary activity in the Yucca Mountain region.

Professor Connor presented several examples of event simulator output. He then described techniques used to estimate the spatial intensity of volcanism. These include homogeneous and spatially-nonhomogeneous methods (e.g., non-parametric kernel functions), Bayesian methods, and deterministic methods (such as a model that suggests there is a structural feature that dramatically lowers probability east of the Solitario Canyon fault). Non-parametric models of spatial intensity have the following advantages: (1) being based on the distribution of past volcanic events; (2) accounting for the spatial scale of volcano clustering in the Yucca Mountain region; (3) being consistent with large scale geophysical structures in the region (e.g., volcanoes in the AmargosaTrough, consistent with low velocity zones derived from sparse tomographic data; (4) avoiding discontinuities in spatial intensity that are geologically unrealistic; (5) having a physical basis – Gaussian kernel functions reflect the spatial scales of partial melting in the mantle in a manner consistent with heat and mass diffusion.

Professor Connor described how a spatial probability model must consider the uncertainty in the estimate of spatial intensity. For non-parametric models (and most other estimates of spatial intensity), a major source of uncertainty is related to the relatively few events (older volcanoes) that are used to model the probability density function (pdf) of spatial intensity. It is possible to estimate the uncertainty spatial intensity using bootstrap methods. Essentially, the pdf derived from older volcano locations is sampled to find a set of new “hypothetical”volcano locations. These new locations are used to estimate the spatial intensity at a grid point. This procedure is repeated and the range of spatial intensity reflects the uncertainty in the model due to data (aleatoric uncertainty), assuming that the statistical model is correct. The fewer events (older volcanic events) available to create the model, the greater the uncertainty.

Professor Connor then discussed the task of estimating temporal recurrence rates. He described apparent temporal clusters near Yucca Mountain (0.08 to 1 Ma; Pliocene 3.6 to

4.2 Ma; and Miocene 9.0 to 11.2 Ma). He presented a series of probability calculations. Given a temporal recurrence rate of $\lambda = 2 \times 10^{-6}$ events/yr:

Probability of dike intrusion within repository boundary is: $(0.05)(2 \times 10^{-6}) = 1 \times 10^{-7}$/yr

Probability of vent or vent structure within repository boundary is: $(0.01)(2 \times 10^{-6}) = 2 \times 10^{-8}$/yr

Probability of sill intrusion within repository boundary is: $(0.002)(2 \times 10^{-6}) = 4 \times 10^{-9}$ /yr

Uncertainty in temporal recurrence rate was estimated using the likelihood ratio to be 6×10^{-6} events/yr > λ > 2×10^{-7} events/yr (95% confidence), then:

Probability of dike intrusion within repository boundary is: 1×10^{-8} to 3×10^{-7}/yr

Probability of vent or vent structure within repository boundary is: 2×10^{-9} to 6×10^{-8} /yr

Probability of sill intrusion within repository boundary is: 4×10^{-10} to 1×10^{-8} /year

Uncertainty in spatial intensity for bandwidth = 7 km is at least a factor of five (~ 95% confidence), then:

Probability of dike intrusion within repository boundary is less than: 1×10^{-6}/yr

Probability of vent or vent structure within repository boundary is less than: 3×10^{-7}/yr

Probability of sill intrusion within repository boundary is less than 5×10^{-8} /yr ~95% confidence, accounting for uncertainty in temporal recurrence rate and spatial intensity.

Professor Connor provided additional comments about the above calculations. The expected values of the probability of igneous disruption of the repository reported above are higher than most previous estimates. For example, the original PVHA estimates for volcanic disruption of the repository had expected values for this probability of 9×10^{-9} per year (revised to 1.2×10^{-8} /yr), this is roughly the same as calculated here for the expected value of probability of disruption by vents and vent structures (2×10^{-8}/yr), but significantly less than the expected value of the probability of dike intersection (1×10^{-7} /yr). These differences in expected values arise because previous treatments of the geometry of igneous events were overly simplistic. In this analysis, igneous events are treated as geologically complex features, consistent with observations in basaltic volcanic fields. Uncertainties in temporal recurrence rate (because of few Quaternary events) and spatial intensity (because of few events) result in uncertainty in probability estimates. Cumulatively, this uncertainty is more than one order of magnitude at the 95% confidence level. No assumptions are made in this analysis about the interaction between igneous features and the repository. Rather, this analysis assumes an undisturbed setting. For example, the probability of vents and vent structures forming within the repository boundaries may be higher than indicated by this analysis. The analysis presented is not complete. For example, consideration of the geophysical setting (isostatic gravity anomalies, seismic tomographic anomalies) is not included. These factors likely increase the probability of events centered SW of the repository in easternmost Crater Flat. Based on the event simulator results, an increase in probabilities at this location tends to increase probabilities of igneous disruption of the proposed repository. The PVHA process will consider a much wider range of scenarios, such as alternative models of igneous event recurrence rates and the roles of geophysical information.

Eugene Smith (University of Nevada – Las Vegas; Clark County, Nevada contractor) discussed the importance of understanding the process of magma generation for volcanic hazard studies related to Yucca Mountain. Professor Smith commented on the influence of the mantle on magma source zones. He considers it very important to understand the process of volcanism before calculating the probability of future events. There is debate as to the depth of the boundary between the lithospheric mantle and the asthenospheric mantle under Yucca Mountain. The traditional model assumes melting in the lithosphere and implies that volcanism is waning. There is a very limited amount of material to melt in this area. If you assume the traditional model is correct and volcanism is waning, the probability of a future eruption is actually very small. Professor Smith previously proposed a model of deep melting in the asthenosphere at depths greater than about 100 kilometers. This model has broader perspective, focusing on an area extending from Death Valley all the way to Lunar Crater, including the Yucca Mountain area. The implication of this model is that a new peak of volcanism is possible, that volcanism is not dead and in the future there might have an upsurge of volcanism.

Professor Smith briefly discussed several different models of volcanism, and then compared the traditional model (assumes lithospheric mantle melting and implies waning volcanism) with a deep melting model that assumes a Lunar Crater-Death Valley belt of volcanism (and implies a new peak of volcanism is possible). He described various patterns of petrology and trace element chemistry. The deep melting model involves melting of asthenospheric mantle - lithospheric mantle does not melt. The deep melting model is supported by similar episodic patterns of volcanism and depth of melting calculations. Professor Smith showed a figure that displays an alignment of volcanoes of various ages extending from Lunar Crater to Crater Flat and then to Death Valley. He then showed a plot of the number of events versus age, comparing Crater Flat to Lunar Crater-Reveille. After about four million years, there is a synchronous pattern between Crater Flat and Lunar Crater. Prior to that, the activities were disconnected. Now one of the questions that arises is whether this pattern is common throughout the Great Basin or whether it is focused just on this belt of volcanism. There is very little correspondence between southwestern Utah and the Crater Flat/Lunar Crater Belt. But there is good correspondence with the Coso-Lone Pine volcanic field.

Professor Smith then discussed melting depth. Melting is really deep in the Crater Flat/Reveille/Lunar Crater area and becomes shallower as you go to the west or to the east. In general, most of the melting is occurring in the asthenospheric mantle and very little in the lithospheric mantle. The deep melting model must explain several things. Temperatures have to be about 200 degrees higher in the mantle in this particular area, and there must be an explanation for the very narrow belt of volcanism and the episodic pattern with basaltic volcanism occurring in the same belt for as long as 11 million years. It is important to take a step back and take a look at the history of Nevada for the past 400 to 500 million years. There have been a lot of mountain-building episodes in Nevada over the past 400 million years. The most recent of those are the Sevier Belt just to the east of the Lunar Crater/Crater Flat Belt and the Central Nevada Thrust Belt which actually goes right through the area of the Lunar Crater/Crater Flat Belt. There was ample opportunity for thickening of the lithosphere during Paleozoic and Mesozoic tectonic events and thinning of the lithosphere beneath the Sierra Nevada. Over time this has developed a keel in the mantle lithosphere. The mantle of lithosphere moves and kicks up mantle eddies. There is an edge effect where asthenospheric material is moving up along the boundary from high pressure to low pressure. And if magma moves from high pressure to low pressure, we can melt magma adiabatically (with no additional input of heat). The eddies in the very simplistic view are moving with the plate, so any time an area of hot mantle is intersected, there is the potential of producing volcanic activity. Once we reach an area of colder mantle, we get a period of quiescence and won’t get another peak of volcanic activity until another area of hot mantle is reached. Seismic tomography suggests the asthenospheric mantle is thermally very inhomogenous. There are a lot of areas that are hotter than others. The volume of material produced at any one time depends on the lengths of the melting so it is theoretically possible to get another episode of high volume material erupted within this belt if a hot spot is intersected that has a three-dimensional geometry that might be suitable.

Professor Smith presented two conclusions. It is important to know “why” in order to determine “when.” And probability studies are dependent on the petrologic model.

Kevin Coppersmith (DOE – YMPO; contractor, leader of PVHA & PVHA-U) discussed the use of expert elicitation in predicting the probability of volcanic events at the proposed Yucca Mountain repository – objectives, methodology, implications of the PVHA and PVHA-U. The objectives of his presentation were to summarize the evolution of formal expert elicitation methodologies for hazard analysis at US NRC-regulated facilities (lessons learned and solutions to identified problems); to define the essential steps in an expert elicitation; to describe the basic elements of a Probabilistic Volcanic Hazard Analysis (PVHA); to summarize the methodology used in PVHA-96; and to review the methodology being used in the PVHA-Update (PVHA-U). Issues being addressed in PVHA-U include spatial evaluation (region of interest and spatial model); source zones (alternative zonations and nature of zone boundaries); spatial smoothing (smoothing operator and distance); and other conceptual models.

Dr. Coppersmith described the historical context of formal expert elicitations, elements of the methodology, the various steps and criteria for a formal expert elicitation, and the expert selection criteria for the 1996 elicitation. He also showed various examples of temporal and spatial probability models. He then presented the following conclusions: (1) methods for conducting formal expert elicitations for probabilistic hazard analyses have evolved over the past 20+ years; (2) methodology guidance provides for essential steps that should be followed within NRC regulatory environment; (3) PVHA-96 and PVHA-U take advantage of the lessons learned; (4) each expert elicitation provides an opportunity for refinement.

Jack Davis and John Trapp (both with the Office of NMSS) gave a talk titled “NRC Staff Perspective on Igneous Activity Issues: Overview of the Licensing Process, Development of NR Review Capabilities, and Probability of Igneous Activity.” This talk presented the roles and responsibilities of the NRC, the staff’s expectations for a DOE license application, risk information, development of NRC staff review capabilities, and also gave the status of igneous activity issues. DOE’s role is to characterize the Yucca Mountain site, develop a basis for meeting performance objectives, prepare and defend the license application, and construct and operate the repository, if it is licensed. The NRC staff have developed a technical understanding and process to review a license application, have conducted prelicensing interactions on site characterization and early identification of issues, will review a license application and develop a Safety Evaluation Report and also review an Environmental Impact Statement for adoption. NRC will also oversee and inspect DOE operations if the site is licensed.

The NRC staff expectations for igneous activity in a license application were described. A transparent and traceable technical basis is needed for inclusion of site characteristics and appropriate features, events, and processes. DOE needs to provide an assessment of events with at least 1 chance in 10,000 of occurring in 10,000 years, plus evaluation of uncertainty, variability, and risk significance and consideration of alternative conceptual models. There is also an expectation of demonstrable model support. DOE is not required to “predict” igneous events. Stochastic methods are used to forecast a range of outcomes. An appropriate range of uncertainties and alternative models must be considered. DOE’s performance assessment is to consider features, events, and processes that significantly change the timing or magnitude of dose. The NRC staff will review DOE’s performance assessment, along with other relevant information, to determine if there is reasonable expectation that the site can meet the performance objectives. The NRC presenters also stated that the NRC staff has not developed a “position” on igneous activity.

Both the NRC staff and DOE hold similar views on the relative risk ranking of igneous activity. The volcanism scenario has a low probability of occurrence but has potentially large consequences, and has high risk significance within the total system analysis. The estimated risk significance of different aspects of the igneous activity scenario are given in the Risk Insights Baseline Report. Through the successful key technical issue process, the NRC staff anticipates that DOE will have sufficient information in the license application to support NRC review.

The NRC staff presenters commented that in their opinion the key concept of event definition was not clearly discussed in the draft ACNW white paper on volcanism. The NRC staff has concerns with event definition, that there many ways to define an event such as single mappable unit, vent alignment, etc. Such definitions require adjustment in number of events, size of events, recurrence rate, and other parameters. For example, is the Quaternary activity in Crater Flat one event, a vent alignment about 12 km long, or four or more individual events on the order of 1 km long?

The NRC staff considers there is high risk significance associated with the probability of igneous activity, airborne transport of radionuclides, and magma-drift interactions. A summary was provided of staff work in each of these areas and the current issue resolution status. DOE has completed drilling of 7 new boreholes to investigate aeromagnetic anomalies in support of an ongoing update of their probabilistic volcanic hazard analysis (expert elicitation). DOE is also updating several analysis model reports to address the issues of airborne transport and magma-repository interactions. The NRC staff state that they have a transparent technical approach for use in evaluating the potential significance of data and model uncertainties, and that they have the necessary tools and information to conduct a licensing review. The NRC staff states that they are ready to review DOE products as they become available.

Day 2 - Discussion of the Consequences of Igneous Activity

Several briefings that had been scheduled for Day 1 were postponed until the morning of Day 2 due to an early dismissal of NRC personnel in response to inclement winter weather. These briefings included a talk by a representative from the US Department of Energy (DOE/Yucca Mountain Project Office), who provided DOE’s views on the ACNW draft White Paper in relation to the nature and prediction of igneous activity.

Eric Smistad (DOE) gave a talk titled “Review of DOE’s Positions in the White Paper - Nature and Prediction of Igneous Activity.” He noted that the ACNW report reasonably captures much of the DOE technical work and approach. The ACNW report is a snapshot in time using available information; it cannot fully capture the technical basis for the License Application.

Mr. Smistad’s presentation gave a high-level summary of observations regarding the white paper. He noted that more detailed comments and suggestions would be provided later. Mr. Smistad noted that the ACNW report includes some speculative comments about probabilistic volcanic hazard analysis-update (PVHA-U) outcomes (e.g., suggestion of lowering of probability); the PVHA-U work is underway and no hazard calculations have been done. This work will not be complete until after submission of a license application. The report cites some “areas of disagreement” between DOE and NRC—possibility of multiple vents, dike length, and dike width

Mr. Smistad commented that the ACNW report does not include explicit discussion of DOE’s conceptual model of magma generation. This conceptual model provides important context for understanding waning volcanism, low eruption volumes, low eruption frequency, volatile-rich magmas, and the inappropriateness of proposed links between Yucca Mountain volcanism and other, more active, basalt fields originating from a more active magma source. Although Plio-Pleistocene basalts are heavily emphasized in DOE and PVHA models, Miocene episodes are still included with low weighting.

Mr. Smistad provided the following conclusions: (1) The ACNW report reasonably captures much of the DOE technical work and approach; (2) the report is a snapshot in time using available information; it cannot fully capture the technical basis for a license application; (3) this presentation is a high-level summary of observations regarding the ACNW report - more detailed comments and suggestions will be provided (examples: detectability of anomalies; and age intervals of basalt episodes - in contrast to ACNW's report, there was no volcanism between 5 and 7 Ma, and Miocene volcanism ended at approximately 7 Ma, not 8 Ma as stated.

A representative for the Electric Power Research Institute (EPRI) provided feedback to the Committee regarding the draft White Paper. Professor Meghan Morrissey (Colorado School of Mines) gave a talk titled "Preliminary comments on ACNW "Igneous Activity at Yucca Mountain: Technical Basis for Decisionmaking:" Event Probability and Nature and Characteristics." Her talk outlined key points documented in the ACNW report and provided additional comments for consideration. With respect to the probability of volcanism at Yucca Mountain, EPRI plans to review the report from the PVHA-U, to be released in 2008. Additional comments provided for ACNW consideration include: waning of basaltic volcanism in the region; dike evolution (geometry), and magma genesis in the Yucca Mountain region. With respect to the nature and characteristics of potential igneous activity, EPRI has developed three major reports. EPRI considers a "reasonably expected" volcanic scenario for the Yucca Mountain region to be based on the Lathrop Wells basalt center. EPRI considers this volcano to be the best analog for future volcanism, involving fissure eruption with fire fountains and *aa* lava, Strombolian eruptions (cone-building phase and tephra ejection), and additional *aa* lava flows.

Professor Morrissey discussed characteristics of magma ascent and magma properties. DOE previously assumed that the magma in the Yucca Mountain region would be low viscosity, slowly crystallizing, with magma temperatures of 1150-1200°C. However, Nicholis and Rutherford (2004) showed the magma temperature would actually be 975-1010°C with higher viscosity and faster crystallizing magma. Viscosities would now be expected in the range of 10^5-10^7 Pa·s (10^6-10^8 poise). With regard to styles of volcanism, EPRI provides the following comments for ACNW consideration: (1) clast component analysis of pyroclastic deposits from Lathrop Wells and reaction rims of amphibole phenocrysts provide additional information on magma ascent history at shallow depths; (2) rheology of magma in a dike will vary in 3 dimensions. Magma-drift interaction will vary along the length of a dike from a thick, tacky magma to a bubbly magma or fragmented magma; (3) if a dike should be counted as a single event, then a series of conduits (vents) located along a fissure should not be counted as separate events in PVHA-U calculations.

Professor Morrissey noted a series of volcanoes that represent "uncertain" analogs for Yucca Mountain. These include Cerro Negro, Grants Ridge, Longuimay, Paricutin, and Tolbachik. In EPRI's view, good analogs for Yucca Mountain include Basalt ridge, Boulder Dam, Paiute Ridge, and Red Cones, CA. In conclusion, EPRI has provided additional items for ACNW to consider but is in broad agreement with the technical analyses and implications made by ACNW (although ACNW has not yet completed a formal conclusions section for the white paper). EPRI will provide a set of more detailed comments as requested by the ACNW.

On Day 2, the first talk related to consequences of igneous activity was given by Bruce Marsh (Johns Hopkins University; ACNW consultant). He gave a presentation about potential magma/repository/canister processes in both eruptive and intrusive scenarios and implications for risk from igneous activity at the proposed Yucca Mountain repository. Professor Marsh described pressure-temperature phase relations for basalts, including the specific case of Lathrop Wells basalt, and how they evolve during ascent through the crust. He described the processes of convection and solidification, using paraffin as an analog medium.

Professor Marsh then described the effects of percentage of crystals on the mobility and viscosity of magma. He showed how the radial flow distance of lavas at Lathrop Wells can be used to estimate the effective viscosity of the flows during emplacement. The result obtained is an effective kinematic viscosity of 109 cm^2/s. Preliminary calculations of magma flow in repository drifts are being performed. A key conclusion reached is that eruptions of the type that occurred at Lathrop Wells involved relatively explosive “wet” magma that produced relatively viscous, immobile lavas. This would restrict the extent to which magma could penetrate repository drifts.

Art Montana (University of California – Los Angeles [retired]) discussed potential thermal and mechanical magma/canister interactions associated with the intrusion scenario at the proposed Yucca Mountain Repository. His presentation considers the potential interaction between the alloys and the containment vessels and the volcanic fluids, magmas and vapors. Professor Montana stated that we simply cannot afford to design a repository for high-level nuclear waste without assuming that an igneous event will occur and that it will impact the canisters. Serious consideration must be given to designing the drifts so that they can be backfilled which would provide for safety and predictability, rather than adhering to preconceived concepts of accessibility.

Professor Montana discussed the susceptibility of the containment vessels to corrosion and failure resulting from magmatic activity. He has worked with steels and other alloys under extreme conditions and has firsthand experience with non-ferrous alloys similar to that being considered as a protective envelope around the stainless steel containers. Considering the potential chemical interaction between magma and the canisters at elevated temperatures, the 2004 EPRI report used several sources of information to assess the extent of corrosion of the Alloy-22 shelves surrounding the stainless steel waste canister when contacted by magma, supplementing the scarcity of available data with the information on corrosion in high-temperature glasses and molten salts. Alloy-22 is largely a nickel alloy with lesser amounts of chromium and molybdenum and even lesser yet amounts of iron and cobalt. Because data for Alloy-22 are limited, EPRI used Alloy-X and Inconel 625, for which more data were available. Alloy-X is similar to Alloy-22 except that the iron to nickel ratio is higher. The chromium content of these three alloys is quite similar and that is an important feature. EPRI took the data from those three alloys at the top primarily and drew a best fit curve and concluded that the corrosion rates at magmatic temperatures range up to about 30 microns per day. This corrosion is similar for all of the chromium-containing alloys, suggesting to the investigators that it's primarily the oxidation of chromium itself to chromium oxide, providing a protective coating. Other mechanisms are possible.

Tests had been done on the corrosion of various stainless steels and high-temperature alloys in the presence of oxygen, sulfur dioxide, carbon, monoxide, methane, chlorine gas, hydrochloric acid, and others. The results also revealed that the formation of a coating of Cr (203), chromium oxide, in chromium-bearing alloys provided protection from attack by other components. However, an important point was that at temperatures above 1,000 Celsius, the chromium oxide became volatile. This might be worth looking into.

Perhaps one of the studies most relevant to Yucca Mountain is that of a Douglas and Healey in 1981, who investigated the oxidation sulfidization of unalloyed chromium and unalloyed nickel in basaltic liquid at 1150°C for as long as 96 hours. The combined effects of oxidation and sulfidization reached about 20 microns per day, with chromium again performing better than nickel. And then more recently Findlan and Peterson in 2004 conducted experiments for EPRI using Alloy-22 immersed in molten Hawaiian basalts at 1,200 degrees Celsius for periods from one hour to two weeks. Maximum penetration of a corrosion front in the longest experiments was about 300 microns, which would average about 20 to 30 microns per day, which is consistent with the previous data. A crucible removed from the magma shows the quenched basaltic liquid and either the chromium or the nickel ring inside. It looks pretty good after being at 1,200 degrees for 1 to 2 weeks, but closer examination showed that it was corroded and pitted. Then EPRI in 2004 presented the results of modeling, and concluded that an important parameter is the temperature difference between solidus and liquidus, that is, the temperature interval over which the canisters would be at contact with molten material. EPRI concluded that most of the corrosion would occur in the temperature range of 1,150 Celsius to 800 Celsius. EPRI's conclusion from these studies was that no waste package would fail during an igneous event at Yucca Mountain.

Assuming that basaltic magma penetrates the drifts at a liquidus temperature of 1,100 Celsius—it could be less, it could be more—the DOE report of November 2004 concludes—and here I'm going to quote, "Even if magma were to penetrate a waste package, the magma outside of the waste package is expected to stagnate once the drift is filled on the order of 1,000 seconds, approximately 17 minutes, so that there are not likely to be driving forces that would flow in through a waste package. Magma is likely to fill the drifts before the waste packages heat up to a point of failure." Then they conclude that "In view of these results, it is safe to conclude that in the absence of major cracking of waste packages, a significant amount of magma will not flow into or through waste packages and that the waste forms will remain in place." While that may be so, flow might continue through a dike up to the surface, resulting in a more prolonged flow of magma through at least one or more of the canisters. Professor Montana remains unconvinced that there are adequate experimental studies to support the claims that Alloy-22 shells will be inert to failure when exposed to magma and attendant vapors. Possibly there is no alloy that would provide the desired assurances.

Professor Montana then discussed the effects of corrosion on the tangential tensile strength in the containment vessels and the surrounding shield. He first assumed that magma contacted a canister or canisters and destroyed the outer 25 percent of the Alloy-22 shield, a value that's consistent with the maximum value in the EPRI model. This is the outer 5 millimeters of the 20-millimeter-thick outer shell of Alloy-22. Professor Montana showed a slide with a cross-section of a waste package, illustrating the internal tensile tangential stress (σt). The skin along the long axis is the weakest part in any cylinder. The inside surface being pulled apart by tension is where things always fail. For an uncorroded alloy shell, 20-millimeter wall thickness, the tangential stress will amount to 40 times the internal pressure. If the outer 5 millimeters is corroded, the outer 25 percent of that alloy shell, then the tangential stress is 53 times the internal pressure, an increase of about 30 percent. If we lose 75 percent of that 20-millimeter-thick shell with leaving a thickness of 5 millimeters, then the tangential stress becomes 160 times the internal pressure. For the 316 stainless steel vessel with a wall thickness of 50.8 millimeters, the tangential stress is only 15 times the internal pressure. Professor Montana described additional examples of waste package thermal response to magma.

Professor Montana presented several conclusions. The repository should either be backfilled or give serious consideration to abandoning the Yucca Mountain site. Also, he sees nothing to be gained by speculating about the probability of an igneous event at Yucca Mountain. We should accept that it will happen and enter the repository accordingly assuming the worst case scenario for temperature, corrosiveness, duration, and momentum of the magma.

Timothy McCartin (NRC staff) briefed the Committee about NRC's Regulatory Perspective on the Use of Alternative Conceptual Models. Under 10 CFR Part 63.114, there are regulatory requirements to consider alternative models consistent with available data and to account for uncertainties (e.g., number of waste packages included in an extrusive event). NRC's performance assessment (TPA) considers alternative models as parameters (examples: damage to waste packages; secondary break-outs; variation in probability) and uncertainties (examples: variation in conduit diameter and mass loading). Computational demands are minimized by linear effects. Analyses of consequences of an extrusive igneous event are primarily affected by: number of waste packages; damage to waste package; entrainment of fuel in magma; and mass loading. Mr. McCartin concluded that quantitative analysis of the significance of alternative views will assist dialogue among groups and will support review of a potential license application.

Neil Coleman (ACNW Senior Staff Scientist) briefed the Committee about the flooding history and geomorphology of Fortymile Wash near Yucca Mountain. Flooding would provide one of the key processes for eroding and transporting any contaminated volcanic ash that may be deposited by extrusive volcanism through a repository at Yucca Mountain. Mr. Coleman described how Fortymile Wash is important to volcanic extrusion scenarios, summarized key processes and the flooding history, reviewed the significance of large floods to dose scenarios, and provided comments on the potential integrity of spent UO_2 fuel in a conduit.

Mr. Coleman emphasized there is no evidence that a vent or dike has penetrated the repository footprint in the last 13 Myr. One 10-12 Myr old dike came close, on the northwest flank of Yucca Mountain, but is not known to have entered the footprint. Also, the volume of regional basaltic volcanism has greatly diminished since that time. If a volcanic vent were to intersect a waste tunnel, expelled materials could contain contamination from spent fuel. These materials would be deposited on surrounding hillslopes and flats in the adjacent drainage basins. Subsequent erosion and fluvial transport in Fortymile Wash would carry some contaminated ash toward the RMEI (reasonably maximally exposed individual). Mr. Coleman described the general characteristics of Fortymile Wash in relation to a satellite image of the region. The NRC staff assume in their fluvial redistribution model that all transported contaminants would be deposited on the distributary fan that begins just north of the intersection with highway 95 and extends southward. The Fortymile Wash channels continue south across the Amargosa Desert where they intersect the Amargosa River.

Mr. Coleman showed the inferred fallout distribution of Lathrop Wells volcanic ash, overlain on a digital elevation model, to show the kind of areal pattern associated with a past eruption in the Yucca Mountain region. In the unlikely event a future eruption were to occur through a repository at Yucca Mountain, any contaminated ash that would fall outside the Fortymile Wash drainage, such as in Crater Flat, could contribute little or no dose to the RMEI. Also, any contaminants that would become entrained in scoria cones or lava flows would not contribute to dose because these features resist erosion for hundreds of thousands of years. As Professor Sparks pointed out from the Icelandic eruption, you can have this combination of fairly quiescent lava flows along with the explosive eruption phase. It makes sense therefore to consider a fraction of any extruded waste will become entrained in lava flows. It would be a significant amount. The NRC model assumes that all extruded contaminants come out as tephra, not as lava. Mr. Coleman also showed a slide illustrating that the peak risk from igneous activity would occur in the first 1500 years. After that time the shorter lived radionuclides, such as ^{241}Am (half-life = 432 yrs), would have decayed significantly.

Mr. Coleman showed photographs of Fortymile Wash and its banks to give perspective to its size. He then showed a plot of elevations along the floor of the wash and also along the western bank of the channel. The figure shows how to the north the channel is incised 20 m, but grades into the alluvial fan further to the south. The energy slope of the channel floor is 0.011, which is quite significant. This is not a lazy eastern stream - this slope is capable of producing quite powerful floods. Mr. Coleman presented a table of flood data from the relatively short period of record. In March 1995 and February 1998, Fortymile Wash and the Amargosa River flowed simultaneously through their primary channels to Death Valley. These were the first documented cases of this conditions. The extreme 1969 flooding must also have reached the Amargosa River but this was not documented. These largest floods dominate sediment transport processes in Fortymile Wash. The smallest sediments (<62 microns in diameter) have the greatest potential to remain suspended and travel the greatest distances in big floods, especially those less than 10 microns that are the primary concern for inhalation doses.

To show that long-distance travel of floodwaters does indeed happen in the region, Mr. Coleman showed photos from the wet spring of 2005 when a large lake formed in Death Valley in response to regional precipitation and surface water flows, including flow in the Amargosa River which is one of the main channels that lead into the eastern end of Death Valley. Assessments for Yucca Mountain that neglect long-distance transport of silt and clay-sized particles by large floods will overpredict the mass of small-diameter contaminated ash that would be deposited near the RMEI.

Mr. Coleman then noted that insights about the transport of small sediments led to a reexamination of the potential integrity of UO_2 fuel in a volcanic conduit. He showed a slide that illustrated the fuel particle sizes assumed in the user's guides for NRC's version 3.0 and 4.0 codes. NRC currently uses a fuel particle size distribution of 1 to 100 microns (0.0001 to 0.01 cm), very different from a TPA 3.0 distribution of 100 to 10,000 microns. The NRC staff cite NUREG-1320 as a basis for using the smaller size distribution in 4.0. However, crushing experiments on irradiated fuel, as documented in that NUREG, produced only a small fraction of fine-grained material. Only a few percent of the material was reduced to a particle diameter <1000 microns. Available information suggests that the ceramic pellets that comprise spent fuel would retain much of their integrity in a volcanic conduit, given the short travel time and distance through a conduit and a melting point for the pellets (i.e., >2800°C) that greatly exceeds magma temperatures of ~1200°C. Magma quenching on pellets could provide a protective layer, and xenoliths provide natural analogs of large objects that survive travel through conduits. A more realistic size distribution for spent fuel would reduce calculated doses to the RMEI. This can easily be evaluated using performance assessment.

Sara Rathburn (Colorado State University) briefed the Committee about processes of importance in fluvial and eolian transport of sediments. Dr. Rathburn's talk was titled "Fluvial Processes in Dryland Rivers." Arid-region rivers are unique because they tend to be ephemeral, flood-dominated, discontinuous in time and space, and illustrate the importance of riparian vegetation and subsurface and upstream hydrology. One thing arid regions have in common is that evapo-transpiration exceeds the precipitation. Complex response describes how a channel can actually undergo two different states, erosion and deposition, as a result of the same triggering event.

Dr. Rathburn then described aspects of the fluvial system, from the drainage basin to the zone of transfer, and then to the depositional area. In arid drainage basins there are locally high rates of overland flow runoff, hillslope erosion by wash processes, or runoff infiltrates before reaching the channels. There tend to be high sediment yields in arid fluvial systems. Little subsurface flow is available for the removal of solutes. Soils tend to be thin and shallow, develop slowly, and tend to form calcretes. Mechanical weathering is dominant and clay production low. Channels tend to be wide and shallow with low sinuosity, low bank stability, are frequently braided, and may terminate in a fan in the manner of Fortymile Wash. Arid region streamflow tends to be flood-driven transient flow that produces "flashy" hydrographs (i.e., high intensity flows of short duration). As a result the flows are hard to measure. Transmission (seepage) losses through the channel bed tend to be high.

The role of floods is supreme. Floods in arid regions have the potential to move large quantities of sediment, can dramatically alter channel morphology, and disrupt in-channel vegetation. Of the 12 largest floods ever measured in the US, all occurred in semi-arid to arid regions, with 10 occurring in regions with less than 16 in (400 mm) of rainfall. Floods carry high suspended sediment concentrations with a greater size range than in other rivers. The sediment tends to move in step-wise sediment “waves.” Bedload transport efficiency is high. Erosion and deposition are discontinuous. Dr. Rathburn showed a curve developed by Langbein and Schumm which shows that the highest sediment yields are produced at a combination of effective precipitation of around 300 millimeters per year (about 12 inches per year). In areas with more precipitation, there's greater vegetation to stabilize the slopes. Where there's less precipitation there is less vegetation, but there’s not as much overland flow to carry sediments into the channels.

Dr. Rathburn also commented on eolian transport, noting that sand-sized material and smaller is transported. Eolian processes can create desert pavements. In the Lahontan basin of Nevada, soil-forming intervals were caused by eolian sediment pulses. In closing, Dr. Rathburn mentioned some of the challenges in analyzing arid region fluvial systems. It is important to understand the connectivity between these systems from the hill slopes to the channels, the tributaries down to the trunk streams. Another challenge is understanding dry land river behavior over long time scales.

Brittain Hill (NRC staff) gave a talk titled “NRC Perspective on the Risk Significance of Potential Consequences from Igneous Activity.” He noted that NRC has conducted a range of independent investigations to develop review capabilities. NRC has not developed a “position” on igneous activity. Independent information sometimes questioned DOE models in risk significant areas. DOE has often modified models or approaches in response to staff questions. Staff will consider a full range of information during review of a license application. The review will focus on the risk significant aspects of the DOE safety analysis report.

Dr. Hill discussed the potential for magma to flow into drifts. This has been rated as moderate risk with respect to waste isolation. Information from numerical and experimental models shows that if magma intersects drifts, it will depressurize, flow rapidly, and fill intersected drifts with molten magma approximately 1-5 minutes after intersection. Dr. Hill stated that the draft white paper does not cite or discuss important NRC information on magma-drift interactions, including aspects of degassed magma flow, 2-phase flow in dikes, and magma ascent. Dr. Hill then discussed possible waste package response to magma, which has been rated as high risk with respect to waste isolation. Will a package fail if exposed to magma? Available information shows combined thermal and mechanical effects from sustained (days) magmatic exposure exceed design capacity of waste packages. Alternative information does not increase dose significantly. Dr. Hill stated that the draft white paper does not cite or discuss important NRC information on waste package response to magma conditions, including materials properties and coupled igneous processes.

Dr. Hill discussed the number of waste packages that could become entrained in an eruption, which has been rated as high risk with respect to waste isolation. He stated that there is information from analog volcanoes that shows conduits widen progressively during eruptions and would intersect hot, breached waste packages. Effective conduit diameters appear to be 5-50 m [16-164 ft]. The draft ACNW white paper does not cite or discuss important NRC information on conduit development. Another topic rated as high risk is whether secondary breakouts of magma could release more waste than a single conduit? The NRC staff consider that secondary breakouts may occur because of repressurization effects during eruption, not shock effects from initial flow. Dr. Hill considers that the draft white paper does not cite or discuss important NRC information on the formation of secondary breakouts.

Airborne transport processes to the RMEI location has been rated moderate with respect to risk. Dr. Hill stated that there is available information from models and analog deposits, and good support for model performance. He considers that the white paper does not cite or discuss important NRC information on the airborne transport of radionuclides. The concentration of resuspended particles gives inhalation dose to RMEI. This topic is rated high with respect to risk by the NRC staff. Measured airborne particle concentrations are independent of particle sizes in the deposit. Dr. Hill considers that the draft white paper does not cite or discuss important NRC information on the tephra and waste particle-size distributions. The movement of tephra down Fortymile Wash after a potential eruption has been rated moderate with respect to risk. Analog information has been abstracted for a site-specific model using a sediment mass-balance approach to capture average long-term redistribution processes using site-specific information. Dr. Hill considers that the draft white paper does not cite or discuss important NRC information on the long-term redistribution of potential tephra deposits.

Dr. Hill presented the following conclusions: Sufficient information currently is available to support staff review of the potential DOE license application for igneous activity consequences. The ACNW draft white paper does not address relevant information developed by NRC in each area discussed. The ACNW draft white paper does not include consideration of risk insights and model sensitivities. ACNW's draft white paper does not address limitations in alternative conceptual models.

Dr. Mick Apted (Monitor Scientific, representing EPRI) gave a talk titled "Preliminary Comments on ACNW "Igneous Activity at Yucca Mountain: Technical Basis for Decisionmaking": Consequence Analysis." He outlined the performance assessment approach for an igneous event scenario at Yucca Mountain. It is a risk-informed approach based on a system analysis.

Dr. Apted's talk outlined key points documented in the ACNW report and provided additional comments for ACNW's consideration. One such comment was that extending the areal repository footprint may not affect the probability of dike intrusion, if the structure or topography control dike location. Another point to consider is the possible mitigation of igneous consequences by natural backfilling, as has been suggested by the CNWRA. In addition, thermo-mechanical simulations and corrosion tests with Alloy-22 and 1200°C basaltic magma suggest the waste package is robust. And will overpressurization and buckling of waste packages occur in waste packages exposed to magma? Another comment for ACNW consideration - are there credible mechanisms for waste mobilization into erupting magma from waste packages that are not entrained in a conduit?

Dr. Apted summarized the EPRI views regarding the white paper and volcanism. EPRI broadly concurs with ACNW's sequential, structured approach regarding igneous activity at Yucca Mountain, and placing 'reasonable assurance' in context with 'conservative' analyses. Risk-informed performance assessment is essential to: (1) Identify processes, assumptions, and uncertainties that are important to safety; (2) set Performance Confirmation priorities; (3) examine design options; and (4) determine sufficiency of data. Lathrop Wells is a reasonably representative analog for future volcanism. If further study is warranted regarding regulatory compliance with EPA's proposed probability-weighted, mean annual peak dose-rate criterion, greater assurance of safety is more likely to be gained by examining event 'consequences' rather than by further refinement of event 'probability' (after completion of PVHA-U report).

Mr. Eric Smistad (DOE) presented views on the ACNW draft White Paper in relation to the consequences of igneous activity. The ACNW report does not include enough quantitative discussion or detailed comparison to field data to support conclusions of conservatism in representation of magma–drift interactions and magma flow in drifts. The ACNW report also does not include results of detailed DOE analysis of topography and thermal stress perturbation (during thermal period) with respect to the impact on dike propagation.

Mr. Smistad noted that DOE will provide updates for the license application regarding various parameters based on analog work. These include dike length and width, the number of dikes in an event, the number of potential eruptive conduits in an event, conduit diameter at repository depth, and fractions of eruptive products in lava, cone, and tephra. A new process-based model is being developed for post-eruptive tephra redistribution that accounts for hill slope erosion, fluvial transport, sediment mixing, and radionuclide diffusion into soils at the site of final deposition.

Also for an update in the license application, more detailed analyses of magma–repository interactions are being prepared to examine compressible fluid and interaction with pre-existing structure and topography, potential pressure and flow transients during the igneous event, multiphase interaction between rising magma and drifts, and detailed analysis of coupled magma flow/heat transfer/solidification in repository openings. Mr. Smistad then presented a series of conclusions. The ACNW report reasonably captures much of the DOE technical work and approach. The ACNW report is a snapshot in time using available information; it cannot fully capture the technical basis for a license application. More detailed comments and suggestions will be provided later to ACNW.

A wrap-up round table discussion was held at the end of the day address any topics that may not have been adequately covered elsewhere in the meeting. Dr. Hinze also invited Working Group participants to provide additional written comments for consideration by the Committee within two weeks of the meeting, by March 1, 2007. Along with the proceedings of the working group meeting, these written comments would be used to further enhance and finalize the White Paper. The working group briefing materials, discussions, transcripts, and any follow-up written comments will assist ACNW in preparing a final version of the White Paper that will provide an analysis of the current state of knowledge of igneous activity which the Commission can use as a technical basis for decisionmaking.