LA-14426

Preliminary Volcanic Hazards Evaluation for Los Alamos National Laboratory Facilities and Operations

Current State of Knowledge and Proposed Path Forward

Los Alamos
NATIONAL LABORATORY
EST. 1943

Edited by Hector Hinojosa, Group IRM-CAS.

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Issued: September 2010

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List of Abbreviations

CdR	Cerros del Rio
DOE	U.S. Department of Energy
GIS	geographic information system
GPS	global position system
INEL	Idaho National Engineering Laboratory
JMVF	Jemez Mountains Volcanic Field
Ka	kilo annum; thousand years
km	kilometer
kybp	thousand years before present
LANL	Los Alamos National Laboratory
LANS	Los Alamos National Security, LLC
m	meter
Ma	mega annum; million years
mybp	million years before present
NNSA	National Nuclear Security Administration
NPH	natural phenomena hazards
PC	performance category
PVHA	probabilistic volcanic hazard assessment
SSCs	structures, systems, and components
SSHAC	Senior Seismic Hazard Analysis Committee
TA	Technical Area
USGS	U.S. Geological Survey

Acknowledgments

This work was supported by the Los Alamos National Laboratory (LANL) Natural Phenomena Hazards program funded by the U.S. Department of Energy. The concepts developed in this report build on earlier planning work at LANL by Frank Perry, Jamie Gardner, Julie Canepa, Jim Aldrich, Greg Valentine, Lee Steck, and Leigh House. The geologic summary, preliminary volcanic hazards evaluation, and recommendations benefited from discussions and reviews by David Broxton, Jamie Gardner, Frank Perry, Peter Roberts, Doug Volkman, and Giday WoldeGabriel. An extensive review by Kevin Coppersmith provided thoughtful guidance on developing a probabilistic volcanic hazards assessment at LANL. We thank Doug Volkman and Larry Goen for their support of this work.

Executive Summary

The integration of available information on the volcanic history of the region surrounding Los Alamos National Laboratory (LANL or the Laboratory) indicates that the Laboratory is at risk from volcanic hazards. Supporting evidence includes

- Quaternary (<2.6 million years before present) eruptions of rhyolite in the Valles Caldera and rift-related basalt beneath LANL and along White Rock Canyon,
- Volcanic tephra (ash and pumice) layers from these eruptions up to 2 m thick on the Pajarito Plateau,
- Distinct intrusions of magma for the post-Bandelier Tuff eruptions in the Valles Caldera, indicating ascent of fresh magma at frequent intervals,
- Geochemical and petrologic evidence from the youngest eruptions (ca. 50 thousand years ago), indicating influx of new basaltic magma into the magma system that may trigger a future eruption,
- Geophysical evidence, indicating that magma currently resides in the crust beneath the Valles Caldera, and
- Ongoing rift-related basaltic volcanism along the Rio Grande rift, as indicated by ongoing magma intrusions in the Socorro Magma Body.

Potential volcanic hazards to LANL facilities and operations may include explosions, ballistic projectiles, tephra (ash, pumice, and scoria) falls, lava flows, pyroclastic flows and debris avalanches, lahars and flooding, earthquakes, ground deformation, landslides, atmospheric effects, and acid rains and gases.

Estimated average recurrence rates for both Valles Caldera silicic volcanism and rift-related basaltic volcanism are about 1×10^{-5} per year. These rates lie within the range for dormant basaltic fields in the western United States and are similar to recurrence rates at Idaho National Laboratory and Hanford. In order to translate these regional recurrence rates to probabilities of impact to Laboratory facilities and operations, spatial and event models are required. Although the estimated recurrence rates for both silicic and basaltic volcanism are similar, silicic volcanism poses the greater hazard to LANL because silicic volcanism has occurred much more recently and because impacts of silicic eruptions are generally more widespread due to greater ash volume and dispersal.

Volcanism in the vicinity of the Laboratory is unlikely within the lifetime of the facility (ca. 50–100 years) but cannot be ruled out. The recurrence rate of 1×10^{-5} (for an eruption occurring somewhere in the region) is an order of magnitude less than the performance goal of 1×10^{-4} for the most hazardous facilities at the Laboratory. Nevertheless, a recurrence of silicic volcanism in the Valles Caldera or basaltic volcanism along the Rio Grande rift floor could severely impact the Laboratory for an extended period of time (months to years) until volcanic activity stopped.

This evaluation provides a preliminary estimate of recurrence rates for volcanic activity. If further assessment of the hazard is deemed beneficial to reduce risk uncertainty, the next step would be to convene a formal probabilistic volcanic hazards assessment to confirm recurrence rates and to quantify specific volcanic hazards for use in the assessment of existing facilities or the design of new facilities at LANL.

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Abstract

The integration of available information on the volcanic history of the region surrounding Los Alamos National Laboratory indicates that the Laboratory is at risk from volcanic hazards. Volcanism in the vicinity of the Laboratory is unlikely within the lifetime of the facility (ca. 50–100 years) but cannot be ruled out. This evaluation provides a preliminary estimate of recurrence rates for volcanic activity. If further assessment of the hazard is deemed beneficial to reduce risk uncertainty, the next step would be to convene a formal probabilistic volcanic hazards assessment.

1 Background

1.1 Regulatory Framework

Los Alamos National Security, LLC (LANS) operates the Los Alamos National Laboratory (the Laboratory or LANL) for the U.S. Department of Energy (DOE) and the National Nuclear Security Administration (NNSA). The operating contract between LANS and the NNSA requires that LANS follow DOE Orders and Standards in operating the Laboratory. DOE Order 420.1 (b), *Facility Safety* (DOE 2007), is one of the Orders that LANS is obligated to follow and is part of the operating contract between LANS and NNSA.

DOE Order 420.1B and DOE Guide 420.1-2, *Guide for the Mitigation of Natural Phenomena Hazards for DOE Nuclear Facilities and Nonnuclear Facilities* (DOE 2000), state that DOE facility structures, systems, and components (SSCs) must be able to withstand natural phenomena hazards (NPH) and ensure (1) confinement of hazardous materials, (2) protection of facility occupants as well as the general public, (3) continued safe operation of essential facilities, and (4) protection of government property. The list of primary NPH to be addressed includes volcanic events (DOE 2000). As of the issuance of DOE Order 420.1B, the design and construction of new facilities and major modifications to existing facilities and SSCs must address potential damage to and failure of SSCs resulting from NPH events. SSCs in existing DOE facilities should be evaluated when there is significant degradation in the safety basis for the facility.

DOE Standard 1022-94, *Natural Phenomena Hazards Site Characterization Criteria*, states that in regions where recent volcanic activity has occurred (within the Quaternary Period—2.6

million years before present, mybp until present), the likelihood of renewed volcanic activity and the associated potential hazards shall be addressed (DOE 2002a). This geologic time period encompasses periods of major activity within the Jemez Mountains Volcanic Field (JMVF) and adjacent Rio Grande rift. Potential volcanic hazards may include explosions, lava flows, ballistic projectiles, tephra (ash, pumice, and scoria) falls, pyroclastic flows and debris avalanches, lahars and flooding, seismic activity, ground deformation, landslides, and acid rains and gases (DOE 2002a).

DOE Standard 1023-95, *Natural Phenomena Hazards Assessment Criteria*, describes requirements for assessing hazards associated with seismicity, wind, and flood, but it does not provide criteria for conducting NPH assessments associated with volcanic activity (DOE 2002b). This document states that, "the minimum criteria necessary for these and other NPH assessments of DOE facilities should be derived from relevant consensus national codes and standards, or appropriate local codes wherever available."

In *Design-Load Basis for LANL Structures, Systems, and Components*, Cuesta (2004) identifies the requirement of a probabilistic volcanic hazards assessment (PVHA) for the design and construction of Performance Category (PC)-3 and PC-4 structures at LANL based upon a defined driver in DOE-STD-1022-94 (DOE 2002a). LANL does not currently have existing or planned PC-4 facilities. Performance goals for SSCs are expressed as the mean annual probability of exceedance of acceptable behavior limits of structures and equipment as a result of the effects of natural phenomena. For PC-3 facilities, the probability threshold for unacceptable performance is 1×10^{-4} per year. Each PC is assigned a target performance goal in terms of the probability of unacceptable damage resulting from specific natural phenomena. The unacceptable level of damage is related to the safety function of the SSC during and after the occurrence of NPH. Consideration of NPH, including volcanic and seismic activity, must be given for the safety of LANL PC-3 and PC-4 facilities, since such facilities are being placed within a seismically active rift and adjacent to active volcanic centers, according to DOE regulatory drivers and LANL SSC design-load guidance (Cuesta 2004; DOE 2007).

1.2 Previous Volcanic Hazards Studies at LANL

Limited evaluation of volcanic hazards to LANL has been undertaken. The potential impact on LANL by volcanic activity in the JMVF has been noted by two national volcanic hazards studies. Heiken et al. (1995) emphasized the primary impact of ash and pumice fallout on the electrical grid and DOE facilities, including LANL, in their report, "*Volcanic Hazards and Energy Infrastructure.*" The U.S. Geological Survey (USGS) recently rated the Valles Caldera a "moderate threat" (along with Mauna Kea, HI; Coso Volcanic Field, CA; Mount Bachelor, OR; and others) and recommended enhanced monitoring of the JMVF (Ewart et al. 2005) (see Section 3.4).

As part of a description of the design-load basis for LANL facilities Cuesta (2004) provides a brief overview of volcanic activity in the Jemez Mountains and associated hazards to LANL. No quantitative assessment of volcanic hazards was performed. The document concludes that, since eruptions have occurred near LANL within the Quaternary Period, PC-3 and PC-4 facilities at LANL require PVHA to inform design load calculations for new buildings (Cuesta 2004).

1.3 Volcanic Hazards Studies at Other DOE Nuclear Facilities

Studies of NPH that have included volcanic hazards at DOE nuclear facilities are also limited. An assessment of volcanic hazards at Idaho National Engineering Laboratory (INEL) cited no regulatory drivers (Hackett and Smith 1994). The study used geologic mapping, interpretation, and age dating to define hazard zones (lava flows, tephra fall, volcanic gases, and ground deformation) based on past volcanic activity on the Snake River Plain and analogues worldwide. Recurrence rates for basaltic eruptions ranged from 1×10^{-5} to 6.2×10^{-5} per year.

Volcanic hazards at the Hanford Site, Washington, were considered as part of a NPH study in response to DOE Order 5480.28, *Natural Phenomena Hazards Mitigation,* as well as DOE-STD-1020-94, DOE-STD-1022-94, and DOE-STD-1023-95 for implementing NPH loads (Conrads 1998). The study referred to a USGS PVHA of the nearby Cascades Range in order to quantify the annual probability of exceeding tephra fall thicknesses of 1, 10, and 100 cm (1×10^{-3}, 2×10^{-4}, and 1×10^{-7} per yr, respectively) at the Hanford Site. Based on these probabilities, ashfall design loads were developed for various facility performance categories, ranging from 14.6 to 146.5 kg/m^2.

1.4 Recommended Approach

The objective of a volcanic hazards assessment for LANL is to evaluate the probability of adverse effects to lands, facilities, and operations within the LANL boundary by a volcanic event within a specified period of time (e.g., Marzocchi et al. 2006) as required by DOE O 420.1b (DOE 2007) and DOE G 420.1-2 (DOE 2000). In more detail,

Hazard = event recurrence rate *x* event definition

and

Risk = hazard (probability of event) *x* consequences

(e.g., UNESCO 1972; Marzocchi et al. 2006). Volcanic hazards analyses focus on defining these three important quantities: ***recurrence rate*** (number of events in a given time period), ***event definition*** (spatial extent of various events), and ***consequences*** (effects of events on facilities and operations). Given that a volcanic eruption can produce many different products and processes (e.g., explosion, tephra fall, lava flows, lahars, pyroclastic flows), the total hazard represents the summation of the probability of applicable events. The event definition is derived from assessments of the area affected by various volcanic processes vs the total area of the region surrounding LANL. A true risk assessment assesses the costs of the consequences in terms of personal and property damage, lost productivity, mitigation measures, etc. This report presents a preliminary overview of volcanic hazards to LANL and recommendations for a formal hazards assessment. The discussions are presented in terms of information required regarding recurrence rate, event definition, and consequences.

DOE standards documents do not provide guidance about the specific methodology for conducting volcanic hazards assessments at nuclear facilities (e.g., DOE-STD-1023-95). However, design-load basis calculations for PC-3 and PC-4 facilities at LANL require input in the form of probability of exceedance of NPH events, e.g., volcanic ashfall thickness (Cuesta 2004). Precedent for the use of a probabilistic volcanic hazards approach has been established in the NPH assessment for the Hanford Site (Conrads 1998), and Cuesta (2004) concludes that a

PVHA is required for LANL design-load basis. It is therefore recommended that LANL adopt the PVHA approach described for evaluating NPH by the Senior Seismic Hazard Analysis Committee (SSHAC). As described by Hanks et al. (2009) in their overview of recent SSHAC application experiences, it is the emphasis on quantifying uncertainties that makes this methodology appropriate for quantifying all NPH. The following brief summary of SSHAC Levels for hazard assessment, and their requirements and applicability, is based on descriptions in SSHAC (1997) and Hanks et al. (2009).

> ***SSHAC Level 1*** studies involve an evaluation (by a person or small team) of existing literature, datasets, and models associated with hazards of interest. The person or team quantifies hazards and uncertainties, and the resulting report is peer reviewed.
>
> ***SSHAC Level 2*** studies include Level 1 activities and expand to include communications with the scientific community regarding applicable databases and alternative models and viewpoints. Topical meetings are convened to resolve questions about key topics, but workshops are not employed. Peer review includes review of the process followed to develop technical basis as well as the calculated hazard results.
>
> ***SSHAC Level 3*** studies include Level 1 and Level 2 activities and expand to bring model proponents and resource experts together with the analysis team in a series of workshops to discuss the strengths and weaknesses of various datasets, models, and methods pertinent to the hazards at the site. Peer review is typically participatory during the development of hazards calculations and their technical basis, sensitivities, and associated uncertainties.
>
> ***SSHAC Level 4*** studies include the highest level of rigor and required resources and expense. Model proponents and resource experts interact with multiple separate hazard evaluators, rather than a single analyst or team. Separate hazard calculations and associated uncertainties are combined by an integrator to develop a community distribution. Peer review of both the process and outcome is conducted during the course of the (often multi-year) process.

Required resources and associated costs increase with increasing SSHAC Level of study. The choice of a particular level of analysis depends on the level of assurance that the sponsor requires that the hazard analysis, as a representation of the informed technical community and associated uncertainties, will meet regulatory and/or public approval and the desire for long-term stability of the assessment results.

One of the first recommended activities resulting from this preliminary study is to establish the appropriate SSHAC Level to define a formal PVHA. Given the expected level of Agency and public scrutiny of the results of a volcanic hazards assessment for LANL, discussions of data gaps and further analyses in this report are formulated in terms of **SSHAC Levels 2 and 3**.

2 Volcanic and Tectonic History of the Jemez Region

LANL is situated on the flanks of the potentially active JMVF and within an active continental rift, the Rio Grande rift (Figure 1). The JMVF covers about 2700 km^2 beneath and to the west of LANL and represents about 2000 km^3 of volcanic output spanning the last 13 million years (Ma) (Goff and Gardner 2004). The nearby Rio Grande rift is a major tectonic feature along which the North American continent is slowly, but inexorably, being torn apart in a dominantly east-west direction, forming a north-south-trending series of asymmetrical basins (e.g., Kelley 1979; Sanford et al. 1991; Baldridge et al. 1995; Kelson and Olig 1995). LANL lies within the Española Basin of the Rio Grande rift. The Rio Grande rift has been regionally active for at least 30 Ma and continues to be tectonically and magmatically active (e.g., Baldridge et al. 1984; Wolff and Gardner 1995; Machette et al. 1998; Steck et al. 1998). The volcanic edifice of the Jemez Mountains and the low-lying basalt fields of the rift floor form the two primary potential source areas for volcanism that may impact LANL during its operational lifetime.

Rift-related volcanic activity has occurred locally over the last 25 Ma, producing mafic basalt flows along the western rift boundary and on the rift floor (WoldeGabriel et al. 2001, 2006). Early Jemez volcanism (Keres Group, Miocene—about 13 to 6 mybp) included mafic to felsic lavas and was centered on the rift-bounding Cañada de Cochiti fault zone in the southern part of the JMVF (Figure 2a). Rapid rift basin development apparently accompanied Keres Group volcanism in the JMVF, as indicated by the interbedding of volcanic rocks with immature, basin-fill conglomerates and debris flow deposits (Gardner and Goff 1984; Self et al. 1988; Heiken et al. 1990; Wolff et al. 2000). Between 10 and 7 mybp, voluminous eruptions of intermediate composition (andesite) lavas occurred along the Cañada de Cochiti fault zone and are estimated to comprise approximately half the volume of the volcanic field. Small-volume basalts were also produced from numerous vents on the rift floor during this time.

Around 6 mybp, eruptions of andesite and rhyolite ceased and new eruptions of dominantly mixed magma began, but overall volcanic activity was sharply reduced in concert with a decline in tectonic activity in the vicinity of the JMVF. From 7 to 4 mybp, a lull in volcanism occurred, and the Cañada de Cochiti fault zone became inactive. In contrast to the earlier pattern of eruption along active faults, pockets of mantle- and lower-crust derived magmas coalesced during this period to form the hybrid dacites of the Tschicoma Formation (Polvadera Group). These dacite domes and lavas form the Sierra de los Valles, the highland immediately west of LANL (Figure 2). The Puye Formation, a broad volcaniclastic alluvial fan shed eastward off this highland, was deposited between 7 and 4 mybp.

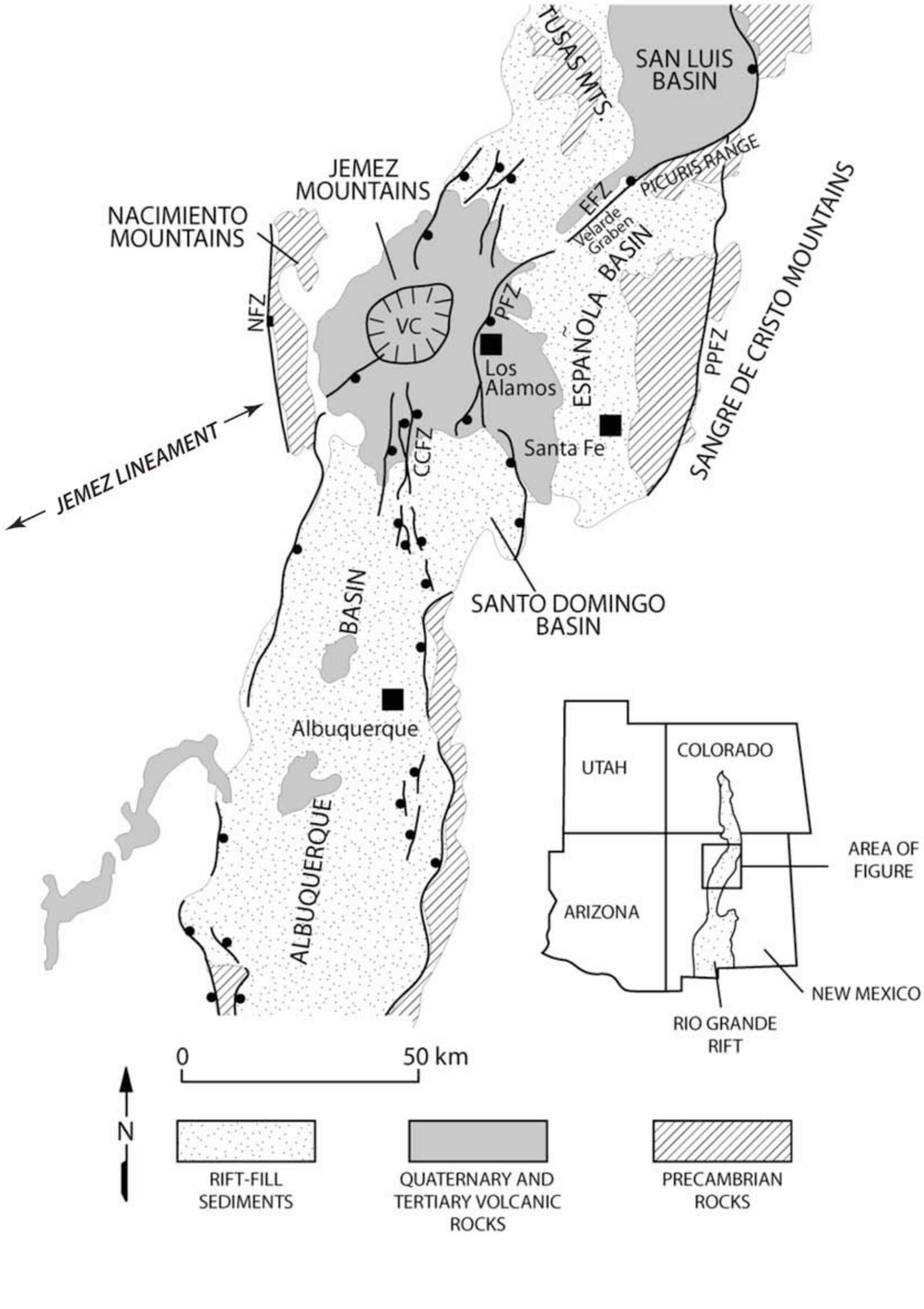

Figure 1. Tectonic locator map for the Jemez Mountains Volcanic Field and Los Alamos. Generalized fault zones: CCFZ = Cañada del Cochiti, PFZ = Pajarito, EFZ = Embudo, PPFZ = Picuris-Pecos, NFZ = Nacimiento. VC is Valles Caldera. Modified from Gardner and Goff (1984).

The focus of tectonic activity shifted from the Cañada de Cochiti to the Pajarito fault system between 5 and 4 mybp (Figures 1 and 2). This shift was accompanied by renewed basaltic activity at 4 mybp, peripheral to and east of the JMVF (in the rift). Rift basalts erupted to form the Cerros del Rio (CdR), Santa Ana Mesa, and El Alto basalt fields (Figure 2b).

The most recent eruptive period (Tewa Group—about 3 to 0 mybp) produced the sequence of caldera eruptions, voluminous tuffs, and rhyolite domes for which the Jemez Mountains are most well known (Figure 2c). The upper and lower Bandelier Tuffs produced during the caldera eruptions form the upper layers in the landscape of the Pajarito Plateau. This period also includes the youngest basaltic eruptions in the CdR field, emplaced both east of the Rio Grande and extending up to 11 km west of the river, under the Pajarito Plateau and LANL.

LANL overlies the active western boundary of the Rio Grande rift, which is locally defined by the Pajarito fault system (Gardner and House 1999; Gardner et al. 2003). Tectonic activity along this fault zone has continued through the Quaternary and into the Holocene (Gardner and House 1987; Lewis et al. 2009). Maximum vertical throw of the Tshirege Member of the Bandelier Tuff (dated at 1.256 Ma; Phillips et al. 2007) is about 200 m along the Pajarito fault system. Numerous localities show faulting of Quaternary units younger than the Bandelier Tuff along this fault system (Gardner and House 1987; Goff and Shevenell 1987).

The current state of interaction between magma movement beneath Valles Caldera and seismicity on the Pajarito fault system has not been quantified. The Pajarito fault system is a region of active prehistoric, historic, and modern seismicity (Gardner and House 1987, 1999; McCalpin 1998, 1999; Reneau et al. 2002; Lewis et al. 2009). At least three earthquakes of magnitude 7 have occurred on the Pajarito fault system within the last 11 Ka (Lewis et al. 2009) and three microearthquakes (magnitude ≤2) were identified by the Los Alamos Seismic Network and felt by numerous local residents in the 1990s (Gardner and House 1999). Steck and others (1998) observed that the Valles Caldera itself is largely aseismic (quiet), although numerous very small (magnitude ≤0.5) earthquakes have been detected on the southern caldera flanks near Peralta Ridge. This lack of significant seismicity is probably due to high temperatures in the subcaldera crust caused by episodic volcanism and intrusion over the last 13 Ma. This stands in contrast to moderate levels of seismicity observed in areas surrounding the caldera.

The presence of magma (melt) in the crust beneath the Valles Caldera has been identified. Geophysical studies of the JMVF in the 1990s identified an oblong low-velocity zone and horizontal sills at depths of between 5 and 13 km beneath the geothermally active western portion of Valles Caldera, containing at least 10% melt and possibly as much as 100% melt (Steck et al. 1998; Aprea et al. 2002). Recent modeling studies of the western U.S. identify the presence of strong mantle upwelling beneath the Rio Grande rift, whose flow is partly responsibly for magmatic activity along the Jemez lineament and for continued active rifting in the region (Moucha et al. 2008).

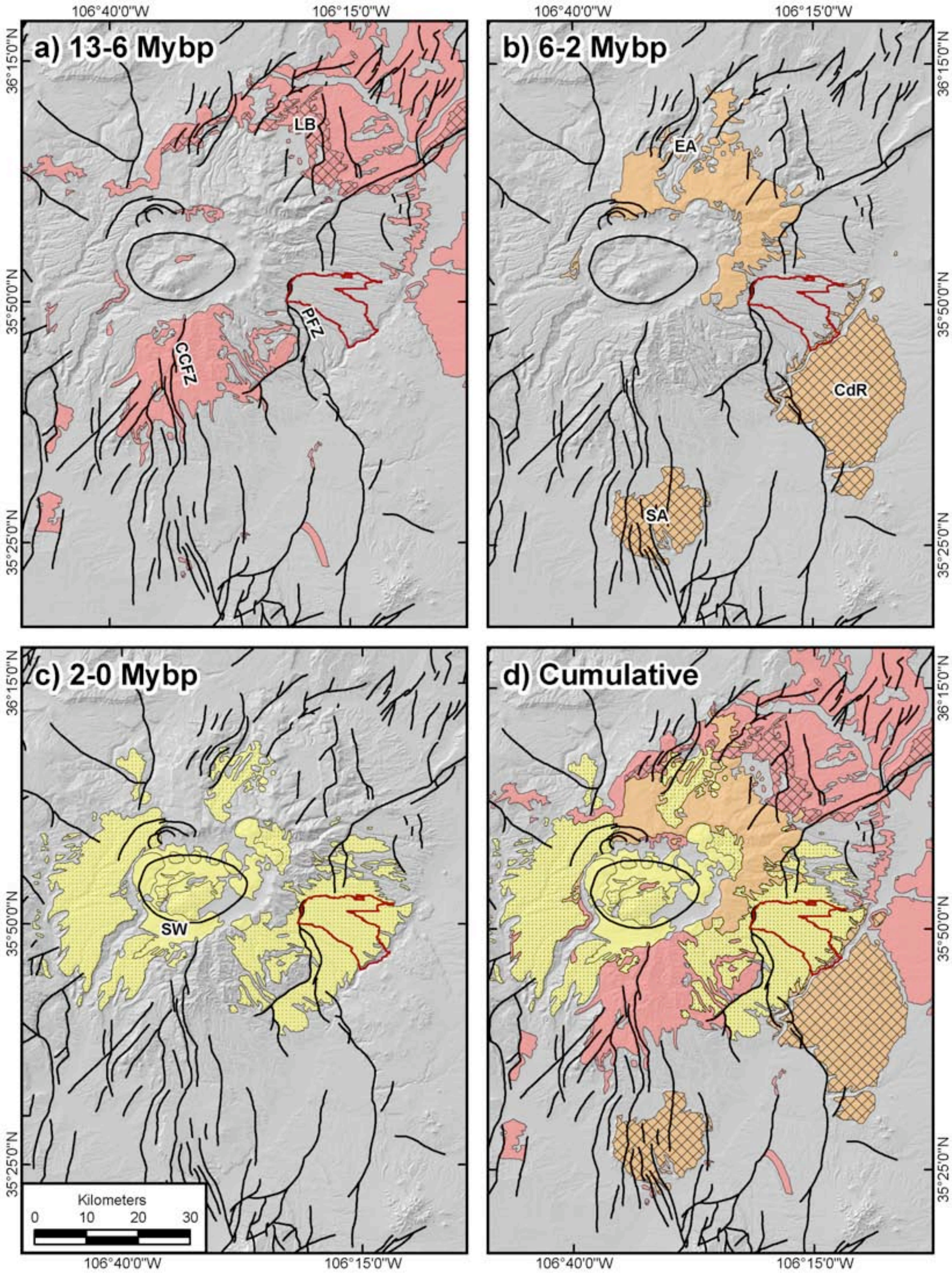

Figure 2. History of volcanism in the JMVF with time slices roughly corresponding to Keres, Polvadera, and Tewa Groups. Mybp = million years before present. Cross-hatch pattern denotes mafic (basaltic) units, and stippled pattern denotes Bandelier Tuff. Faults are shown as black lines: CCFZ is Cañada del Cochiti Fault Zone; PFZ is Pajarito Fault Zone. LB is Lobato Basalt; EA is El Alto Basalt; CdR is Cerros del Rio Basalt; SA is Santa Ana Mesa Basalt; SW is Southwest Moat Rhyolites. LANL boundary shown in red. Digital geologic data from Green and Jones (1997).

As required by DOE-STD-1022 (DOE 2002a), in regions where volcanic activity in the Quaternary Period has occurred, the likelihood of renewed activity and associated hazards must be assessed. The eruptive history of the JMVF includes several distinct phases of tectonic and volcanic activity, including two major caldera-forming eruptions and numerous episodes of post-caldera volcanism within the Quaternary Period (2.6 mybp until present). Based on a review of pertinent published geological analyses, the post-caldera volcanism (≤1.2 mybp) is deemed to be the most applicable for evaluating volcanic hazards to LANL. This period includes the following eruptive activity: 1) post-caldera rhyolite domes, lava flows, ashflows, and tephra falls venting explosively from within the footprint of the Valles and Toledo Calderas (1.2 to 0 mybp), as well as associated debris flows and flooding, and 2) explosive and effusive basaltic eruptions in the CdR volcanic field beneath and to the east of the Pajarito Plateau and LANL lands (4 to 1 mybp).

The eruptive history of mafic to silicic volcanism in the JMVF and mafic volcanism on the rift floor is summarized below.

2.1 Keres Group (13 to 6 mybp)

Early basaltic and rhyolitic volcanism of the Keres Group accompanied active extension of the Rio Grande rift, especially along the Cañada de Cochiti fault zone (Gardner et al. 1986) and extending along northeast-oriented faults in the northern part of the Jemez Mountains (Figure 2a). Lavas and tephras from these early eruptions consisted of mantle-derived tholeiitic basalts, high-silica rhyolites resulting from crustal melting, and voluminous andesite (intermediate) lavas resulting from differentiation of the basalts with minor mixing with the crustal components (Figure 3a). The voluminous andesites of the Paliza Canyon Formation may total 1000 km^3 and dwarf the deposits of the tholeiites and rhyolites (Gardner et al. 1986).

2.2 Polvadera Group (14 to 2 mybp)

Early Polvadera Group eruptions produced the Lobato Basalts from numerous vents and fissures in the northern part of the JMVF (Figures 2b, 3) (Aldrich and Dethier 1990). Voluminous (500 km^3) intermediate dacite and andesite lavas of the Tschicoma formation erupted to form domes and flows in the northern part of the JMVF, mainly between 7.5 and 3 mybp (Gardner et al. 1986; Broxton et al. 2007), although Tschicoma lavas as young as 1.9 mybp are preserved only as sedimentary clasts within the Puye alluvial fan (Turbeville et al. 1989). The Tschicoma lavas form the Sierra de los Valles on the skyline immediately west of LANL and preserve the most noticeable remnants of the pre-caldera highland from the Los Alamos vantage. Notably, these dacite and minor andesite lavas extend east of the mountains beneath the Pajarito Plateau, having been observed in recent drill holes on the LANL campus (Samuels et al. 2007). At about 2 mybp El Rechuelos Rhyolite was emplaced onto the northern flank of the Tschicoma highlands. Eruptive styles for the intermediate to silicic eruptions were explosive, as indicated by pumice falls, ignimbrites, and block-and-ash flows identified in the Puye Formation alluvial fan on the eastern flank of the JMVF (Turbeville et al. 1989). Several explosive eruptions in the Tschicoma center produced widespread fall blankets on the Pajarito Plateau (Turbeville et al. 1989).

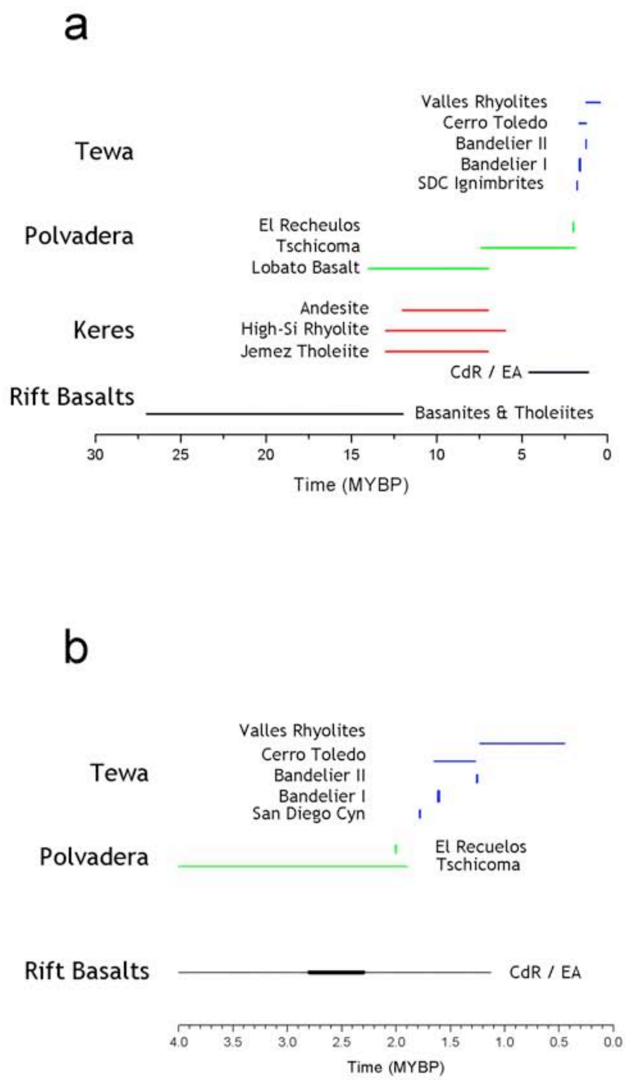

Figure 3. Time series of volcanism in the JMVF and nearby rift-related basalts. Solid bars and vertical line symbols show periods of active volcanism and brief events, respectively, for rift volcanism (black), Keres (red), Polvadera (green), and Tewa (blue) Groups. A) 30 to 0 mybp; B) 4 to 0 mybp. SDC is San Diego Canyon; CdR/EA is Cerros del Rio/El Alto basalts. The Quaternary Period begins at 2.6 mybp.

2.3 Tewa Group (3.65 mybp to present)

The style of eruption in the JMVF changed radically after 2 mybp as a series of cataclysmic caldera-forming eruptions altered the landscape. The development of a large silicic magma chamber under the JMVF toward the end of the Polvadera time produced a series of large-volume rhyolitic eruptions that resulted in partial collapse of the volcanic highlands, high Plinian eruption columns, and the deposition of tephra fallout and ignimbrite layers across the landscape. The earliest of these eruptions produced the San Diego Canyon ignimbrites around 1.8 mybp, flowing southwest from a vent somewhere beneath the later Valles Caldera (Turbeville and Self 1988; Spell et al. 1990).

[Note: The geologic nomenclature for the Tewa Group has recently been revised, including name changes for the San Diego Canyon ignimbrites and Cerro Rubio Quartz Latite and details of the Valles Rhyolite and Bandelier Tuff (Gardner et al. 2010). However, because this revised nomenclature was published shortly before the finalization of this hazards evaluation, the older nomenclature will be retained in this report. Subsequent LANL volcanic hazards studies should migrate to the new nomenclature.]

The first of two major caldera-forming eruptions occurred at 1.61 mybp (Figure 3b), forming the Toledo caldera and producing the lower, or Otowi Member, of the Bandelier Tuff, visible near the base of canyons in the Pajarito Plateau (Spell et al. 1996). The second major eruption occurred at 1.256 mybp (Phillips et al. 2007), forming the Valles Caldera and depositing the upper, or Tshirege Member, of the Bandelier Tuff. This tuff forms the upper bedrock layer on the Pajarito Plateau, beneath LANL. Each of these Bandelier eruptions released about 300 km^3 of magma (Broxton and Vaniman 2005) and resulted in massive evacuation of the magma chamber and resultant collapse of the overlying crust to produce a deep caldera. Eruptions of both the upper and lower Bandelier Tuff originated from large-zoned magma chambers and may have been initiated by injection of new (less fractionated) magma from a similar source region (Hervig and Dunbar 1992).

In the interval between these two cataclysmic eruptions (1.61 to 1.256 mybp), many smaller eruptions produced rhyolite flows and ignimbrites. These deposits are collectively known as the Cerro Toledo Rhyolite, and the tuffs and volcaniclastic sediments are grouped into the Cerro Toledo Interval deposits (Spell et al. 1996; Jacobs and Kelley 2007). Source areas for these eruptions were located on the east side of the JMVF and include Rabbit Mountain and Paseo del Norte (southeastern part of the JMVF) and the Los Posos and other domes within the Toledo Embayment (northeastern part of the Toledo Caldera).

Immediately following the eruption of the upper (Tshirege) Bandelier Tuff and collapse of the Valles Caldera, a series of small-volume, high-silica rhyolite domes and flows were erupted, collectively known as the Valles Rhyolite (Figure 3b). The earliest of these rhyolites (Deer Canyon and Redondo Creek Members) accompanied the resurgence of magma into the evacuated Valles magma chamber, forcing up the roof of the magma chamber and the caldera-filling Bandelier Tuff to form the resurgent dome of Redondo Peak, now 3000 feet above the floor of Valle Grande (Gardner et al. 1986; Phillips et al. 2007). Additional eruptions over the subsequent 700 Ka (1.2 to 0.5 mybp) produced eight prominent dome complexes on the caldera floor. These eruptions are thought to have emanated through the ring-like set of fractures along which the Valles Caldera collapsed (Goff and Gardner 2004). The oldest of these domes, Cerro del Medio (1.229 mybp) is composed of five main lava flows for a total of about 5 km^3 (Gardner et al. 2007). Gardner and others (2007) estimate that this dome complex may have been active for 50 to 100 Ka. Magma feeding the post-caldera rhyolites was chemically distinct from the earlier Bandelier magmas, and separate small magma batches apparently fed the Deer Canyon and Redondo Creek rhyolites (Phillips et al. 2007). Geochemical and geochronological data from the post-caldera domes indicate that the Valles Rhyolite originated from four separate magma batches, separated by significant time intervals (Wolff and Gardner 1995). A 460 Ka quiescent period lasted from the eruption of the final ring-fracture dome (South Mountain, 0.521 Ma) to the beginning of the most recent silicic eruptive phase in the JMVF (Spell and Harrison 1993; Reneau et al. 1996).

The most recent silicic eruptions occurred in the southwest moat of the Valles Caldera and produced El Cajete pumice fall, the Battleship Rock ignimbrite, and the Banco Bonito lava flow (Figure 2c). The first two eruptions occurred between 50 and 60 Ka (Reneau et al. 1996), followed shortly afterward by the Banco Bonito at 35–45 Ka (Goff and Gardner 2004). The lower-silica magma that produced these eruptions is chemically distinct from the earlier (1.2 to 0.5 mybp) Valles Rhyolites (Gardner et al. 1986; Self et al. 1991) and may represent a new phase of eruptive activity in the JMVF (Wolff and Gardner 1995).

2.4 Rift Basalts

Basaltic eruptions on the rift floor have occurred since the onset of rifting about 30 mybp (Baldridge et al. 1995). Early eruptions of mafic lavas in the Española Basin occurred at 27–12 mybp as small-volume monogenetic centers, for example at the north end of the Basin, under the Pajarito Plateau, and at the southern end of the CdR field (Wolff et al. 2000). Three loci of basaltic eruptions dominated the latest Polvadera and Tewa times: Santa Ana Mesa on the southern end of the JMVF, the CdR field along White Rock Canyon, and the El Alto field in the northeastern JMVF (Figure 2b). This discussion focuses on the CdR as most applicable to hazard evaluations for LANL, due to its proximity.

CdR eruptions occurred between 4.6 and 1.1 mybp (Gardner et al. 1986; Thompson et al. 2008), with the period of greatest activity between 2.8 and 2.3 mybp (Figure 3b; WoldeGabriel et al. 1996). The youngest CdR lava flow is found intercalated between the upper and lower Bandelier Tuffs, constraining the youngest age for CdR activity to the Pleistocene age of the Tschirege member, or upper Bandelier Tuff (Wolff et al. 2000). CdR basalts erupted from the western floor of the Española Basin, totaling about 180 km^3 (Thompson et al. 2008). The exposed part of CdR field is roughly 40 km north-south and 20 km east-west, located mainly east of the Rio Grande, but it extends an additional 11 km beneath Pajarito Plateau and LANL lands where it is covered by the Bandelier Tuff (Figure 4). Westward migration of basin-bounding faults was followed by volcanic centers, which utilized regional faults as conduits for three major eruptive pulses at 2.8–2.6, 2.5–2.2, and 1.5–1.1 mybp (Thompson et al. 2008).

The westward extent of observed basalts under the Plateau lies beneath LANL Technical Areas (TAs) 21, 53, 46, 15, 37, and 39, within 1 km of TA-55 and within 3 km of TA-3 (Broxton and Vaniman 2005). The CdR tholeiites, basaltic trachyandesites, and trachyandesites erupted effusively to form low shield volcanoes in the Caja del Rio plateau and explosively in numerous maar volcanoes observed in White Rock Canyon and in drill holes beneath the Pajarito Plateau. Altogether these flows were erupted from at least 80 major and minor vents (WoldeGabriel et al. 1996; Broxton and Vaniman 2005). Beneath the Pajarito Plateau, CdR basalts typically range in thickness from 61 to 183 m and reach a maximum thickness of 300 m within a north-south-oriented paleovalley beneath the southeastern part of LANL lands (Broxton and Vaniman 2005). Cinder cone and maar vents for late CdR tholeiites are observed (in surface exposure and in drill holes) at TA-33, near the junction of Pajarito Road and State Road 4, and at Well R-34. Lava flows from these vents flowed east, in part underlying White Rock.

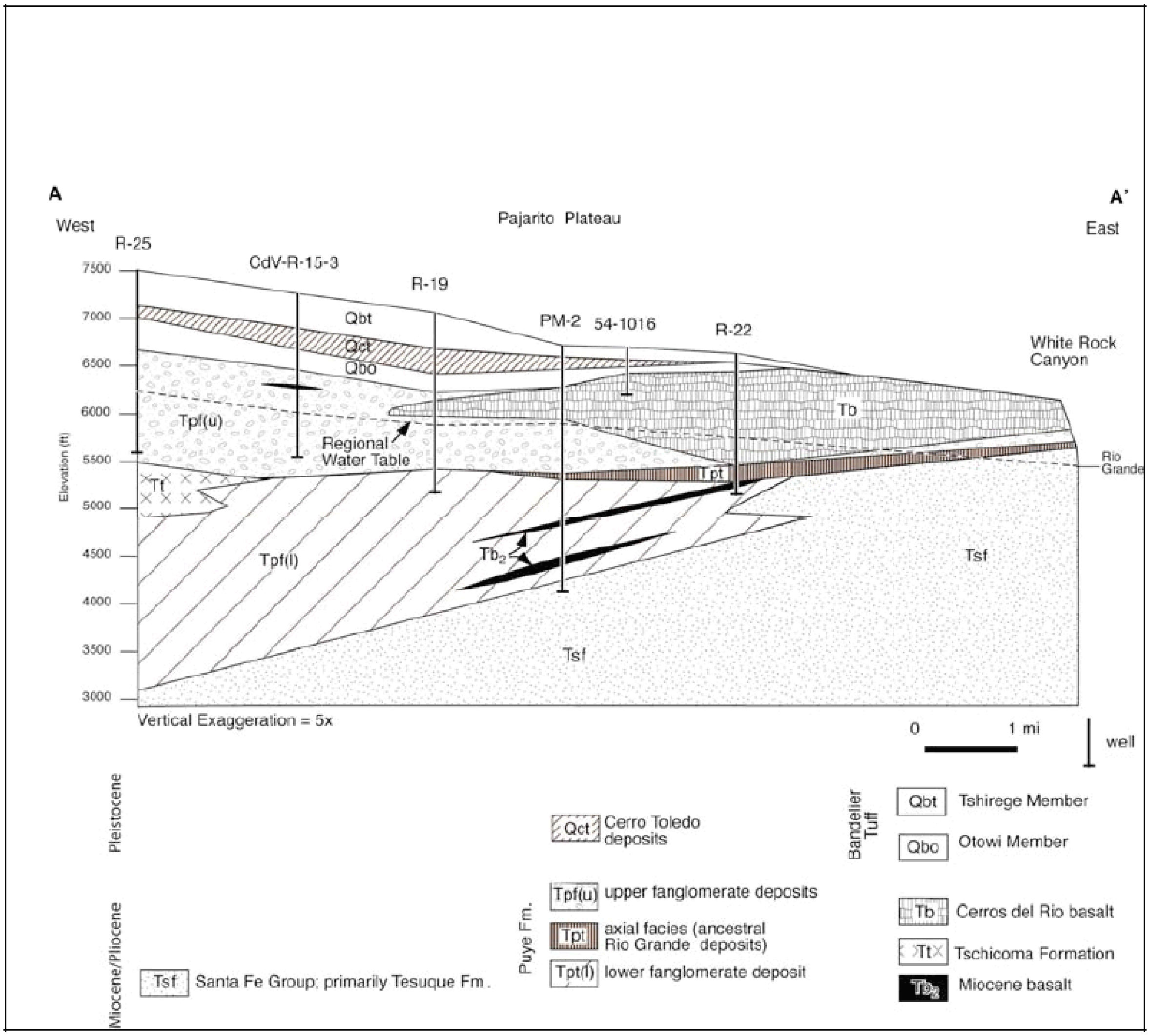

Figure 4. West-east geologic cross-section showing stratigraphic relationships for geologic units of the Pajarito Plateau. Depths and thicknesses of geologic units are constrained by canyon exposures and drill hole observations (drill holes denoted by labeled vertical lines). Note thick section of Cerros del Rio basalts (Tb) underlying much of the Plateau. Figure from Broxton et al. (2008).

Eruption rates for JMVF and rift basalts have varied throughout the last 13 Ma; Gardner and Goff (1984, Fig. 5) estimated a range of 100 to 300 km^3/Ma for most of the Keres and Polvadera Group times. Eruption rates averaged over the duration of each Group time and for specific notable formations are summarized in Table 1 and Figure 5.

Table 1. Calculation of eruption rates in the Jemez Mountains and Cerros del Rio Volcanic Fields

Group	Formation	Begin Age (Ma)	End Age (Ma)	Duration (Ma)	Volume (km^3)	Eruption Rate (km^3/Ma)	Source
Keres	(entire group)	13	6	7	1000	143	*1*
Polvadera	Tschicoma	7.4	1.9	5.5	500	91	*2, 3*
Tewa	(entire group)	1.78	0.04	1.74	690	397	age: *4*; volume: *5*
	Lower Bandelier (Otowi)	1.61		0.0001	400	4×10^6	age: *6*; includes ~20 km^3 for Guaje Pumice; duration ~100 yr
	Upper Bandelier (Tschirege)	1.256		0.0001	265	2.65×10^6	age: *7*; volume: *8*; includes 15 km^3 for Tsankawi pumice; duration ~100 yr
	Valles Rhyolite	1.23	0.45	0.78	20	26	age: *7, 9, 10*; volume: *13*
Rift Basalt	Cerros del Rio	4.6	1.14	3.46	180	52	*11, 12, 14*

Notes:

1 Gardner et al. 1986

2 Turbeville et al. 1989

3 Baldridge and Vaniman 1986

4 Spell et al. 1990

5 Turbeville and Self 1988

6 Spell et al. 1996

7 Phillips et al. 2007

8 Self et al. 1996

9 Goff and Gardner 2004

10 Self et al. 1991

11 Duncker et al. 2001

12 Wolff et al. 2000

13 Valles Rhyolite cumulative volume estimated as sum of rough estimates based on map extents.

14 Thompson et al. 2008

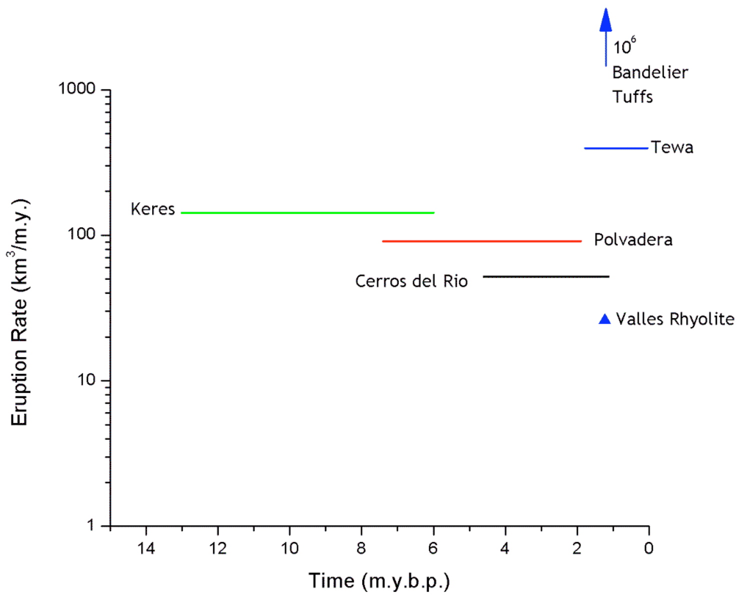

Figure 5. Estimated eruption rates for JMVF Groups and notable eruptive units. See Table 1 for calculations.

3 Overview of Volcanic Hazards to LANL

This section characterizes the timing and nature of volcanic activity relevant to assessing NPH at LANL; that is, information necessary to define the *recurrence rate* and *event definition* (Section 1). Order-of-magnitude recurrence rates for silicic and mafic volcanism are estimated and placed into the context of other areas in the tectonically and volcanically active western U.S. While it is not in the scope of this preliminary evaluation to rigorously calculate the spatial probability of future eruptions (part of the event definition), this report does include an initial characterization of the areas of high likelihood for silicic and mafic volcanism that could impact LANL.

Two main types of Quaternary volcanic activity have occurred close to LANL—explosive and effusive rhyolite eruptions in the Valles Caldera (west of LANL) and explosive and effusive basalt eruptions in the CdR field (east of and beneath the Pajarito Plateau). Each type of eruptive activity and associated hazards applicable to LANL facilities and operations is discussed in subsequent sections.

3.1 Silicic Eruption Hazards

The JMVF is located in an active tectonic setting (Figure 1) and has been volcanically active for at least 13 Ma (Figures 2 and 3). Quaternary activity includes massive caldera-forming eruptions and a series of post-caldera rhyolite dome, flow, and ignimbrite eruptions (Valles Rhyolite) centered on caldera-collapse structural features. The latest Valles Rhyolite eruption occurred approximately 35 to 45 thousand years ago (Goff and Gardner 2004). Magma feeding these post-caldera eruptions originated in distinct batches that may have been triggered by mixing of crustal melt rhyolites with fresh intrusions of mafic, mantle-derived (hotter) magma (Wolff et al. 1995; Perry et al. 1998; Goff and Gardner 2004). Geophysical studies of the JMVF have identified likely zones of molten magma at shallow to mid-crustal depths, as well as basaltic underplating at the base of the crust (e.g., Steck et al. 1998; Aprea et al. 2002).

The USGS recently rated the Valles Caldera a “moderate threat” (along with Mauna Kea, HI; Coso Volcanic Field, CA; Mount Bachelor, OR; and others) and recommended enhanced monitoring of the JMVF (Ewart et al. 2005) (see Section 3.4).

Tephra deposits up to several meters thick associated with several post-Bandelier Tuff eruptions have been documented on the Pajarito Plateau and LANL lands (Figure 6, Table 2). Primary post-Bandelier Tuff tephra deposits as thick as 2.2 m have been identified on LANL, and young tephras (either primary or reworked deposits) are common in the western half of the Laboratory campus, within the town site, and in the northern canyons of Los Alamos County. Pumice samples found on the Pajarito Plateau have been geochemically correlated to distinct post-Bandelier Tuff eruptions; however, the preserved deposits of these tephras on the Pajarito Plateau are discontinuous and highly variable, and details about the extent and volume of these deposits have not been rigorously calculated. In some instances, identified thicknesses of tephra deposits are only estimated as minima, due to erosion (Table 2).

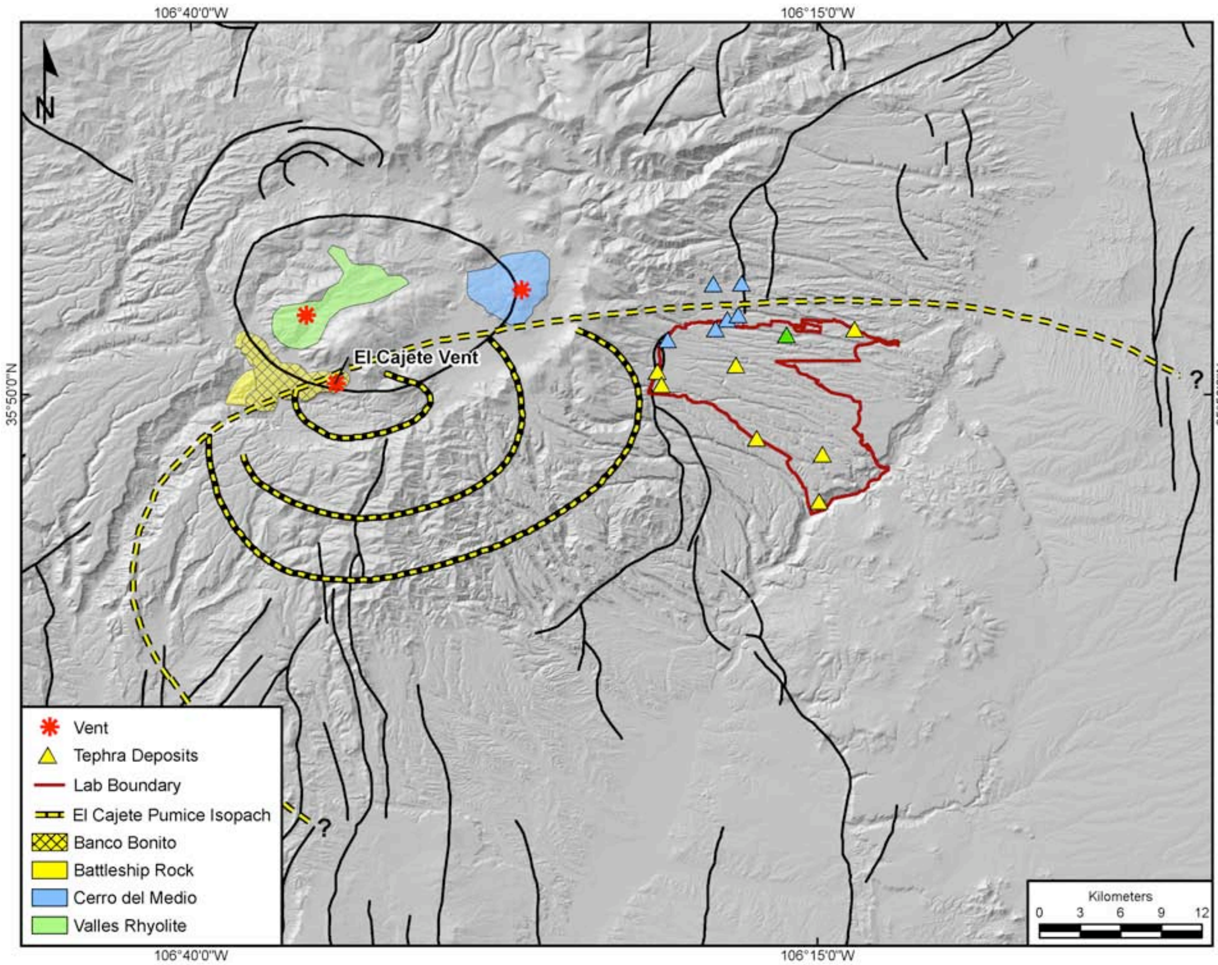

Figure 6. Summary of known silicic eruptive sources and deposits in the vicinity of LANL. Symbols on Pajarito Plateau denote locations where measurable ash and pumice have been observed; color of symbols is related to colored source areas (inferred) in Valles Caldera. Schematic thickness contours and outer extent of El Cajete Pumice, based on Self et al. (1988), provide a general sense of the shape of the tephra blanket. Note that 1 to 2 m of El Cajete pumice has been observed on the Pajarito Plateau within LANL boundaries (Table 2). El Cajete Pyroclastic Beds, Banco Bonito Flow, and Battleship Rock Ignimbrite have been recently redefined as beds within the East Fork Member of the Valles Rhyolite (Gardner et al. 2010).

Table 2. Identified locations and thicknesses of post-Bandelier Tuff tephras* on the Pajarito Plateau

Tephra Type	Thickness	Location	Type of Study	Source
Cerro del Medio	variable; reworked	Guaje Pines Cemetery	trench	Gardner and House 1987, Reneau and McDonald 1996
Cerro del Medio	abundant; reworked in alluvium	TA-69 (Emergency Operations Center)	trench	Reneau et al. 2002
Cerro del Medio	variable; reworked	Townsite - Canyon Road near Aquatic Center	soil profile	D. Broxton, 2008, pers. comm.
Cerro del Medio	unknown	TA-61 (Landfill)	soil profile	Reneau and McDonald 1996
Cerro del Medio	Variable; extensive	North canyons of Los Alamos County, particularly Cabra Canyon	field reconnaissance	Reneau and McDonald 1996
Cerro del Medio	unknown but identifiable	NM 4 - NM 501 interchange (White Rock "Y")	field reconnaissance	Reneau and McDonald 1996
Cerro del Medio	unknown but identifiable	Los Alamos Golf Course	field reconnaissance	Reneau and McDonald 1996
Cerro del Medio	unknown but identifiable	Mesa Public Library area	field reconnaissance	Reneau and McDonald 1996
El Cajete	1 m	TA-16 (near NM 501)	trench	Reneau and McDonald 1996
El Cajete	2 m	TA-16 (WETF)	borehole	Gardner et al. 2003
El Cajete	2.2 m	TA-49	soil profile	Longmire et al. 1996
El Cajete	thin but identifiable as primary	TA-39	soil profile	Longmire et al. 1996
El Cajete	0.85 m	TA-67	trench	Kolbe et al. 1994
El Cajete	unknown but identifiable	TA-74	soil profile	S. Reneau, 2008, pers. comm.
El Cajete	≤ 40 cm	White Rock Canyon	field mapping	Dethier and Koning 2007
El Cajete	unknown but identifiable; thin; near northernmost extent of pumice bed	Pueblo Canyon near White Rock "Y"	field reconnaissance	Reneau and McDonald 1996
Valles Rhyolite	unknown	LA Canyon near airport	field mapping	
Valles Rhyolite	unknown but identifiable	Ponderosa Estates	field reconnaissance	Reneau and McDonald 1996

*Tephra sourced from explosive silicic eruptions within the Valles Caldera that are younger than 1.25 Ma.

Event Definition: Given that the Quaternary activity of the JMVF has evolved from large-volume (600 km^3) caldera-forming eruptions to smaller (1–5 km^3) rhyolite dome and flow eruptions, potential future silicic eruptions in the JMVF are likely to be similar to the most recent activity in the field, the 35 to 60 kybp southwest moat rhyolite eruptive cycle of the Valles Rhyolite (Figure 6). This phase of volcanism included explosive and effusive rhyolitic eruptions that produced 1) a large eruption crater (El Cajete); 2) extensive tephra fall >30 m thick near the vent and up to 2 m thick on the Pajarito Plateau (El Cajete Pumice); 3) energetic pyroclastic flows that produced a 120-m-thick welded ignimbrite stretching >8 km from the vent (Battleship Rock ignimbrite); and 4) a 60- to 150-m-thick rhyolite lava flow stretching 8 km from the vent (Banco Bonito) (Self et al. 1988). [Note that these eruptive units have been redefined as named flow units within the "East Fork Member of the Valles Rhyolite" by Gardner et al. 2010.] Potential future eruptions could consist of explosive, Plinian eruption columns that produce proximal and downwind tephra fallout and pyroclastic flows in topographic lows. In addition, proximal rhyolite lava flows and domes would be expected to fill topographic low areas near the vent up to a distance of several km (e.g., Banco Bonito lava flow and Cerro del Medio dome). Eruptive activity may continue for days to months for explosive eruptions (producing tephra fallout) and several years to tens of years for a single eruption cycle (e.g., tephra fall, pyroclastic flows, lava extrusion; cf. Yellowstone— Christiansen et al. 2007). The total period for a phase of eruption could last thousands of years (e.g., the southwest moat rhyolites, up to 15 Ka, or Cerro del Medio, 50–100 Ka).

Despite the relatively large magnitude of silicic eruptions, there may be little or no warning of an impending eruption. For instance, the May 1, 2008, rhyolite eruption of Chaiten Volcano, Chile, began after only 1 to 2 days of precursory seismic activity (Castro and Dingwell 2009; Carn et al. 2009). Hekla Volcano, Iceland, is notorious for providing less than an hour of warning prior to major eruptions (Soosalu and Einarsson 2002).

Recurrence Rate: The preliminary calculation of the recurrence rate for post-caldera silicic eruptions is about 1×10^{-5}, both for early Valles Rhyolites (1.256 to 0.521 mybp) or for the entire post-caldera period (1.256 to 0 mybp) (Table 3). Although the eruption record shows significant clustering of events, this simple calculation assumes a homogeneous (Poisson) process. This value is considered to be a minimum due to the possibility of unrecognized or uncharacterized eruptions in the geologic record. For reference, recurrence rates at Yellowstone Caldera have been estimated at 2×10^{-5} for a small rhyolite eruption and 5×10^{-5} for a large rhyolite eruption (Christiansen et al. 2007).

Consequences: If this phase of Valles Rhyolite volcanism were repeated in the near future and occurred within the moat of the Valles Caldera (within the caldera topographic rim), the Pajarito Plateau would likely be impacted by centimeter to meter thicknesses of tephra fallout. Heavy tephra deposits on steep, sparsely wooded slopes of the Sierra de los Valles west of LANL would likely result in the production of destructive volcanic mud-flows (lahars) in the canyons as seasonal rainfall and snowmelt mobilized the loose tephra (Janda et al. 1981; Pierson et al. 1996). Lower likelihood events (due to distance and topographic considerations) include impacts from pyroclastic flows and lava flows.

Tephra fall may deposit significant (>10 cm) thicknesses of ash on surface facilities within about 20–40 km downwind (e.g., Keating et al. 2008), i.e., over all LANL technical areas. Dry and wet loads from tephra >10 cm may result in roof or other structural collapse (Blong 1984; Heiken et al. 1995). For instance, 10 cm of dry, compacted tephra may result in a design ashfall load of about 150 kg/m^2 (Conrads 1998), and 15–20 cm of water-saturated ash may produce a load greater than 200 kg/m^2 (Spence et al. 1996). Filtration (HVAC) systems may also be damaged or rendered inoperable by high concentrations of fine (micron to mm) ash suspended in ambient air (Heiken et al. 1995; Conrads 1998). Vehicle operation can be significantly hampered due to accumulation of tephra on roadways, damage to air intake and filtration systems, and scratched windshields. In addition, civil works such as wastewater treatment, storm-water management, roads and bridges, and flood control, reservoirs, and electrical transmission facilities can be strongly impacted from even moderate ash falls (Schuster 1981; Heiken et al. 1995).

Table 3. Preliminary calculation of recurrence rates based on existing information

Silicic: Valles Rhyolite (< 1.26 mybp)		
Event	Age (Ma)	
Deer Canyon Member	1.25[a]	Recurrence for 1.256 - 0.521 mybp
Redondo Creek Member	1.22[a]	10 events / 0.735 Ma = 10 per Ma
Cerro del Medio	1.229[b]	1×10^{-5} per yr
Abrigo	1.002[c]	
Santa Rosa	0.92[c]	
San Luis	0.812[c]	
Seco	0.794[c]	
San Antonio	0.557[c]	
La Jara	0.523[c]	
South Mountain	0.521[c]	
El Cajete	0.05[d]*	Recurrence for 1.256 - 0 mybp
Battleship Rock	0.05[d]*	11 events /1.256 Ma = 9 per Ma
Banco Bonito	0.04[e]*	9×10^{-6} per yr
Mafic (< 4 Ma)		
Event	Age (mybp)	
Cerros del Rio Basalts:	4.6 – 1.14[f]	Recurrence for 4.6 - 1.14 mybp
10 volcanoes		80 events / 3.46 Ma = 23 per Ma
70 other vents		2×10^{-5} per yr

Notes:

*The eruptions of El Cajete, Battleship Rock, and Banco Bonito are considered one event based on petrologic and stratigraphic evidence (Self et al. 1991; Wolff and Gardner 1995; Gardner et al. 2010).

[a]Phillips et al. 2007
[b]Phillips et al. 2007
[c]Spell and Harrison 1993
[d]Reneau et al. 1996
[e]Goff and Gardner 2004
[f]Gardner et al. 1986; Thompson et al. 2008

3.2 Mafic Eruption Hazards

Since the inception of rifting about 30 mybp (Baldridge et al. 1995), basaltic volcanism has commonly occurred on the rift floor or margins (Figures 2 and 3). While the main activity in the CdR field occurred more than 1 mybp, magmatic activity is ongoing in the Rio Grande rift and along the Jemez Lineament, including Holocene eruptions near Carrizozo and Grants—5200 and 3000–1100 years ago, respectively (Dunbar 1999; Laughlin et al. 1994). Therefore, the potential for new basaltic magmatism in the Española Basin cannot be ruled out. Simultaneous eruption of highly differentiated, Bandelier rhyolite tuff and basaltic lavas between 1.6 and 1.2 mybp is evidence of a complex magma plumbing system and multiple batches of magma beneath the Jemez Mountains and CdR, El Alto, and Santa Ana volcanic fields. The potential for damage to LANL facilities or disruption of LANL activities due to rift-related basaltic volcanism must therefore be assessed to evaluate potential security and containment. An understanding of the regional flux rate of basaltic magma from the mantle into the crust in the region is key for defining future volcanic hazards (both mafic and silicic) to LANL.

A case in point for historic rift magmatism is the well-characterized Socorro Mid-Crustal Magma Body, first noted in the 1970s by seismic studies (e.g., Sanford et al. 1977). Subsequent studies have confirmed the presence of a pair of horizontal magma bodies (sills, <150 m total thickness) located at 19-km depth and occupying 3400 km^2 near Socorro, New Mexico (Ake and Sanford 1988; Balch et al. 1997). Crustal deformation and seismicity associated with the magma body, for example the earthquake swarm that occurred in 2005, indicate that the magma body is actively inflating at a rate of a few millimeters per year (Fialko and Simons 2001; Stankova et al. 2008).

The presence of the CdR basalt field beneath LANL lands and stretching tens of kilometers to the east and south from LANL underscores the immediacy of potential hazard to LANL facilities from small-volume basaltic eruptions. Volcanic vents have been observed or inferred on LANL lands, for example cinder cones at TA-33 and TA-36 and maars (hydro-magmatic eruption craters) in Chaquehui Canyon and in the R-34 drill hole. Many tens of cinder cones and maars provided vents for the thick accumulation of basalt and tephra underlying the Caja del Rio and Pajarito Plateau, some of which are delineated on Figure 7.

Event Definition: Two main types of future basaltic eruption are possible based on observed deposits of past eruptions: 1) Strombolian eruption, which may produce a cinder cone, tephra fallout, and lava flows via fire-fountaining and low ash column, and 2) hydro-magmatic eruption, in which rising magma and ground (or surface) water combine explosively to form maar craters, surges, ash flows, and tephra fallout. New basaltic activity is most likely within the area of existing CdR basalts (Figure 7).

Recurrence Rate: The preliminary hazard from basaltic eruption can be evaluated by calculating the simple recurrence rate over an appropriate time interval, in this case the span of activity of the CdR field. For an estimated 80 eruptive events (equivalent to the estimated number of major vents in the field) in 3.46 Ma, the recurrence rate is 23 per Ma or 2×10^{-5} per year (Table 3). For perspective, this value is lower than the recurrence rates that approach 10^{-4} per year—i.e., 1 event every 10,000 years—estimated for the most active Quaternary basalt fields in the western U.S. (e.g., Cima and San Francisco fields; Connor et al. 2000; Christiansen et al. 2007) and higher than recently completed estimates for basaltic activity in the vicinity of the proposed high-level nuclear waste repository at Yucca Mountain, Nevada (between 10^{-5} and 10^{-6} per year; SNL 2008). An analysis of volcanic hazards at INEL defined annual probabilities of basaltic volcanism at 1×10^{-5} to 5.2×10^{-5} per year (Hackett and Smith 1994).

Consequences: Explosions, surges, and magma effusion may damage surface and subsurface facilities within several hundred meters of the vent. Lava flows may engulf or bury surface facilities within several km of the vent. As described for silicic fallout hazards, tephra fall may produce significant impacts on buildings, roads, stormwater management, electrical transmission, and other infrastructure (Section 3.1).

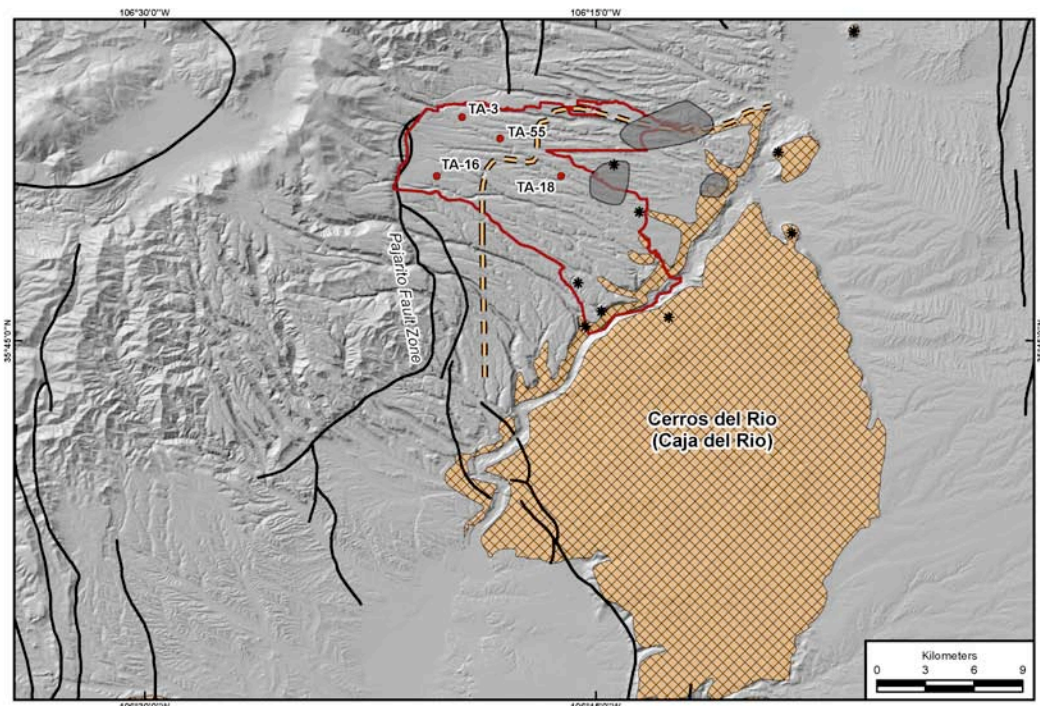

Figure 7. Summary of known basaltic eruptive features in the vicinity of LANL. Asterisks denote observed or inferred vents (not a complete set). Dark gray regions are interpreted as areas of explosive maar (hydro-magmatic) eruptions. Dashed orange line denotes the inferred extent of Cerros del Rio basalts beneath the Pajarito Plateau (buried by Bandelier Tuff) (Broxton, 2008, personal communication). LANL boundary shown in red.

3.3 Geomorphic Hazards

Event Definition: The unique topographic setting of LANL on the Pajarito Plateau includes high relief and deep, flood-prone canyons. Under the circumstances of abundant loose sediment, denuded hillslopes, and seasonal precipitation, as occurred after the Cerro Grande Fire, these conditions result in a high rate of runoff and related sediment transport and delivery down-canyon (Gallaher and Koch 2004). When this setting is combined with the potential for thick accumulations of tephra (ash and pumice) on the highlands above LANL, a significant lahar (volcanogenic mudflow) hazard results. In addition, lava flows and thick tephra deposits may temporarily dam arroyos or canyons, resulting in diversion of runoff and flooding of facilities.

Recurrence Rate: Geomorphic hazards are secondary NPH events conditional on volcanic eruption and subsequent thick tephra deposits and lava flows. The potential for impact from these secondary hazards during volcanic eruption is highly likely based on experience at historic eruptions worldwide.

Consequences: Impacts on canyon-bottom facilities and other sites within potential floodplains (TA-41, TA-2, TA-18, TA-39, etc.) could be significant. Such flows would also be able to entrain potentially contaminated sediments from legacy sites and transport the sediment loads significant distances downstream. For example, lahars produced by seasonal rains after eruptions at Mount St. Helens, Pinatubo, and Galeras traveled many kilometers down local river canyons, eroding streambeds and banks and depositing sediment in floodplains (Janda et al. 1981; Pierson et al. 1996).

3.4 Data Gaps

The complex volcanic and tectonic history of the Los Alamos region summarized in Section 2 is based on several decades of study by numerous workers. However, the available data are not sufficient for developing all information necessary for a PVHA. This section describes the kind of data that will probably be required to develop a PVHA with acceptable levels of uncertainty.

Recurrence rates discussed in this preliminary evaluation are based on calculations that assume a homogeneous (Poisson) eruption process. The data available for Quaternary silicic and mafic eruption activity in the Los Alamos region display significant clustering and will require more sophisticated analysis in order to develop a *Temporal* hazard model. *Spatial* and *Event* models for potential future eruptions in the region have not been developed in detail.

Event Definition

Tephra Deposits: Numerous post-caldera tephra deposits have been described on the Pajarito Plateau and within LANL boundaries (Figure 6 and Table 2). These preliminary data provide an important basis for defining the range of potential future tephra fall events at LANL and specific hazard zones—the event definition and spatial model. However, no comprehensive database for tephra depth and source information exists, and additional field and laboratory investigations may be necessary to define isopach maps and sources for post-caldera tephra deposits on the Plateau. The details of existing deposits, combined with spatial and temporal models, would inform the development of annual probability of exceedance of tephra thickness on buildings, for instance, as an input to design-load basis.

Compositional Trends: Characterization of the complex history of post-caldera (Valles) rhyolites is based on limited geochemical and petrographic data. A detailed petrologic time series of eruptions from distinct magma batches in the context of the tectonic framework has not been published. Such an analysis would support the characterization of trends in post-caldera activity and the magma composition, eruptive style, and related hazards of potential future eruptions. This information would directly feed spatial and event models for the PVHA.

In addition, the temporal and geochemical trends described for basalts in the CdR field imply multiple magma sources and distinct evolutionary trends for individual batches of magma. Evaluation of existing data (e.g., WoldeGabriel et al. 1996) and more detailed petrologic analysis are necessary to characterize potential future eruptive scenarios, both in terms of range of likely magma compositions and eruptive styles. Geochemical and geochronological data are sparse for the Santa Ana and El Alto fields. An understanding of the nature and timing of basaltic flux in the region is critical for understanding recurrence of both mafic and silicic volcanism in the LANL area.

Recurrence Rate

Volume: There is currently very limited data on eruptive volumes for Quaternary volcanics, either silicic (Valles Rhyolite, Southwest Moat Rhyolite) or mafic (CdR, Santa Ana, and El Alto fields). Acquisition of such data on eruptive volume (in combination with geochemical and petrologic data) would provide the basis for reconstruction of the rate of basaltic flux from the mantle, the eruptive rate history for the fields, and a more precise recurrence rate. The results of such an analysis would allow the interpretation of volume-predictable or time-predictable behavior in the system (e.g., Valentine and Perry 2007). This distinction is important for predicting future eruptions based on either repose period or volume erupted in earlier eruptive phases. The quantification of number and timing of vents for basaltic eruptions in the CdR, Santa Ana, and El Alto fields is limited, which prevents accurate calculation of the recurrence rate and repose periods in the rift basalt fields.

Dating: Sparse dating of post-caldera rhyolites has resulted in a generalized age for each rhyolite dome complex in the Valles Rhyolites. Limited study of particular domes, e.g., Cerro del Medio (Gardner et al. 2007), indicates that the domes are comprised of multiple flows or volcanic events. In concert with geologic mapping, geochemical sampling, and stratigraphic analysis, precise dating of the components flows of each rhyolite dome would provide the basis for a high-resolution chronology of Quaternary silicic eruptions. This chronology would in turn support the calculation of precise recurrence rates and repose periods. The chronology could be combined with precise volume estimates to evaluate time-predictable vs volume-predictable eruptive behavior for the JMVF as a whole (e.g., Valentine and Perry 2007); that is, how the timing or volume of future eruptions are related to the interval and magnitude of past eruption cycles.

Geophysics: The detection and analysis of present-day seismicity and ground deformation beneath the JMVF and Rio Grande rift are important for assessing ongoing migration of magma and the potential for eruption. Clearly the accurate and timely detection of eruption precursors is also critical for mitigating potential volcanic hazards to LANL. The current seismic monitoring network for the JMVF includes a single three-component (broadband) seismometer located on Peralta Ridge, south of the Valles Caldera. Several additional single-component instruments provide observations of the occurrence of earthquakes without the ability to calculate a detailed hypocenter or other related information. Based on their evaluation of the volcanic hazard level posed by the Valles Caldera, the USGS recommends that a minimum monitoring network be established, consisting of three to four broadband seismometers (Table 4). Ideally the monitoring network would consist of five to six stations: two inside the caldera and three to four located around the rim.

Seismic tomography studies of the JMVF in the 1990s (the JTEX experiment; e.g., Roberts et al. 1991; Steck et al. 1998; Aprea et al. 2002) characterized a mid-crustal (10- to 13-km-deep) low-velocity zone beneath the Jemez that was interpreted to be a zone of partially molten rock with a minimum melt fraction of 10% and potentially up to 100% melt. Additional seismic studies should be undertaken with state-of-the-art geophysical techniques (e.g., several focused 3-D arrays) to better characterize the nature and extent of this potential magma body and its relation to potential eruption hazards.

Campaign-style global position system (GPS) studies have used annual repeat measurements in an attempt to analyze crustal movements related to regional tectonics and/or local volcanic activities (e.g., Newman et al. 2001). Permanent, continuous-recording GPS stations should be established around the JMVF to evaluate monthly, annual, and decadal variations in ground surface deformation related to regional tectonics, seasonal flux (freeze/thaw, precipitation), and local deformation due to magma migration in the crust. This approach has been used with good results at other young calderas in the U.S. (Webb et al. 1995, Vasco et al. 2007).

Table 4. USGS-recommended components of a "basic real-time monitoring system" commensurate with a "moderate threat" level for the Valles Caldera (Ewart et al. 2005)

Monitoring should provide the ability to detect and track pre-eruptive and eruptive changes in real-time, with a basic understanding of what is occurring.

Seismic	Network with three to four near-field stations and a total of at least six within 20 km of vent.
Deformation	Routinely repeated surveys. At least six continuous stations (GPS and/or tiltmeters) in vicinity of volcano. LIDAR-derived images available for active features.
Gas	Frequent airborne or campaign measurements of gas emissions (annually to monthly, as appropriate) along with support of one to two telemetered continuous sensors.
Hydrologic	Level-2 coverage (limited monitoring for change detection) along with continuous-sensing probes in features of primary interest, including water wells. LIDAR-derived DEMs for lahar-runout modeling.
Remote sensing	Level 2 coverage (limited monitoring for change detection) along with routine use of multi-channel thermal-infrared data from ASTER-class satellite. Thermal and/or SAR overflights, as indicated by other monitoring data. Where practicable, remote video camera in operation.

4 Recommended Scope of Work to Conduct PVHA

Volcanic hazards for LANL should be assessed within the framework of a coordinated NPH program such that combined hazards due to the tectonic-volcanic setting can be evaluated, for example seismic ground motion, tephra fall, and mud-flows/flooding. The existing data on volcanic eruption location, timing, and style in the JMVF provide the basis for a preliminary volcanic hazards evaluation, but further data would be required to develop a detailed volcanic hazards assessment per DOE-STD-1022-94. The recommendations in this section outline additional studies to support a PVHA that would provide hazards information in the form necessary for facility design-load basis. The recommended investigations are expected to fill the data gaps described in Section 3.4 in order to provide a reduction in uncertainty for a PVHA that is acceptable to the DOE and the public.

The first recommendation of this study is to define an appropriate SSHAC level for the PVHA. Given the expected level of Agency and public scrutiny of the results of a volcanic hazards assessment for LANL, discussions of data gaps and further analyses in this report are formulated in terms of SSHAC Level 2/3. Both levels of study involve hazards analysis by an individual or team of analysts based on data available in the literature and/or gathered as part of the PVHA process. The primary difference between these two levels of study is the use of one or more workshops (at Level 3) among hazard analysts and representatives of the informed scientific community to discuss the strengths and weaknesses of various datasets, models, and methods pertinent to the hazards at the site.

The PVHA methodology quantifies volcanic hazards and related uncertainties using three analytical models to characterize 1) the locations of future eruptive events (spatial model), 2) the characteristics of those eruptive events (event definition), and 3) the recurrence rates of those events (temporal model) (Coppersmith et al. 2009). Each model has different data needs. The *spatial model* requires information about the locations, composition, volume, and clustering of past eruptive events. The *event definition* is based on the behavior of past eruptions, including intrusive (dike) vs extrusive (lava, tephra, gas) style, magnitude of eruption, and volcanic products (tephra fall, pyroclastic flow, lava flows, etc.). This characterization is developed on the basis of data on past eruptive compositions, volume, behavior, and deposits. The *temporal model* requires input on the timing of past eruptions in various categories (e.g., silicic, basaltic) as well as temporal trends or clustering of behavior. A well-developed database of eruption ages, volume, and compositions supports the development of temporal models.

The recommendations below are divided into two sections: 1) data collection and analysis activities and 2) hazard analysis. Data collection and analysis activities are linked to support the development of appropriate models (spatial, event definition, and temporal), characterization of parameter values, and quantification of uncertainties for volcanic hazards in the LANL area. The hazard analysis is discussed in context of decisions about the appropriate SSHAC level for the study.

4.1 Data Collection and Analysis

4.1.1 Geologic Field and Laboratory Studies

Geologic mapping, sampling, and analysis campaigns are necessary to fill data gaps (Section 3.4) in both the silicic (Valles Caldera) and mafic (rift basalt) areas. These studies will result in more detailed understanding of the numbers and locations of volcanic vents, their ages and activity through time, compositional trends that indicate evolution of magma in the region, and characterization of the most likely types of future volcanic eruption behavior.

1. Assess rift basalt (CdR) eruptive centers, especially the youngest CdR vents and lava flows. Quantify number, location, and age of exposed (and subsurface) vents to provide basis for defining the basaltic recurrence rate (temporal and event models).
2. Complete mapping and analysis for geochemistry and geochronology at the Santa Ana and El Alto fields. This information will provide the basis for development of understanding of the nature and timing of Quaternary basaltic flux in the region, which drives both mafic and silicic volcanism in the LANL area (event, spatial, and temporal models).
3. Complete the geologic mapping for Valles Rhyolite (post-caldera) domes and flows to distinguish dome/flow lobes and define eruptive history, as has been done for Cerro del Medio (Gardner et al. 2007). In particular, San Antonio Mountain has at least four eruptive phases but is currently mapped as two units (J. Gardner, 2008, personal communication). These data will enhance the basis for defining the silicic recurrence rate (temporal and event models).
4. Establish detailed post-caldera eruptive chronology for rhyolite flows and domes using $^{40}Ar/^{39}Ar$ or other state-of-the-art technique, using a consistent laboratory for reproducibility and common dating framework. Existing data are limited and are difficult to interpret in a common framework due to the use of various dating methods and laboratories. These data will provide the basis for defining the silicic recurrence rate (temporal model).

4.1.2 Spatial Analysis

5. Compile all available tephra fall data on the Pajarito Plateau in a geographic information system (GIS): data on tephra composition, age, and correlation to known volcanic vents. Sources of data may include existing outcrop, trench, pit, and drillhole studies. Additional field investigations may be necessary to fill in data gaps and acquire necessary precision for the resulting maps. These data will provide the basis for defining the consequences of potential future tephra fall events at LANL; i.e., the distribution of tephra-fall depths on LANL facilities (event definition).
6. Perform GIS volume analysis for post-caldera rhyolites: individual dome flow/lobes, rhyolite flows, etc., using methods developed in previous PVHA studies (Kelley 2006). These results will provide the basis of estimates of volume from future silicic eruptions (spatial model).

7. Perform GIS volume analysis for exposed CdR basalts and reconstruction of sub-Pajarito Plateau basalts based on drillhole data. Perform similar analyses for the El Alto and Santa Ana basalt fields. These results will provide the basis of estimates of mafic magma flux in the region as well as estimates of volume from future basaltic eruptions (spatial model).

4.1.3 Petrologic Analysis

8. Develop a framework for tectonic-magmatic evolution and evaluation of recent and potential future magmatic activity. Characterize the temporal and spatial trends in composition for rift basalts and post-caldera rhyolites. Undertake geochemistry and petrologic studies to assess trends in most recent (<2 Mybp) silicic and mafic eruptions with respect to sources and eruptive mechanisms (e.g., fresh batches of mafic magma, crustal melting, magma mixing) and the relationship to seismic tomography studies indicating regions of possible partial melt in deep and shallow crust. Tasks include review of existing geochemical data and potential additional sampling, analysis, evaluation.

4.1.4 Geophysics

9. Establish a seismic network to monitor potential for shallow crustal magma movement as precursors to eruption; USGS recommends a “basic real-time monitoring network” (Ewart et al. 2005) consistent with the Valles Caldera’s threat level (see Table 4). Current monitoring includes a single three-component (broadband) station on the south edge of the caldera. The upgraded network, including five to six digital, broadband, telemetered seismometers, could be established in one to two field seasons (monitoring and event definition).
10. Perform a high-resolution, active source seismic reflection/refraction study to establish the nature of magma body(s) beneath the JMVF (e.g., Steck et al. 1998; Aprea et al. 2002). A major improvement over the previous JTEX experiment would be several focused 3-D surveys (event definition).
11. Install a network of permanent GPS receivers in JMVF to evaluate regional strain and relative motion of the Field relative to intrusion of new magma; precursors to eruption (Table 4) (monitoring and event definition).

4.1.5 Modeling

12. Perform tephra dispersal modeling using Ashplume (e.g., Keating et al. 2008) or similar code to model the dispersal and deposition of tephra resulting from both silicic and mafic eruptions near the Pajarito Plateau. Modeling would be based on characterization of previous eruptive behavior both silicic (post-caldera Valles Rhyolites, especially El Cajete, Battleship Rock, and Banco Bonito) and mafic (cinder cone and maar eruptions in the CdR volcanic field). This modeling activity would assess the range of possible tephra fall impacts on facilities at LANL by simulating a range in vent locations, column heights, erupted volume and duration, and wind conditions. Validate the model using observed tephra thicknesses on the Plateau (event definition).

13. Perform surficial process modeling: lahar (volcanic mudflow) runout modeling and sediment transport modeling to define extent of hazard associated with post-eruption geomorphic processes. Define potential hazard mitigation activities (event definition).

4.2 Hazards Assessment

4.2.1 Preliminary Activities

1. Scoping study to identify key hazard-significant issues
2. Assembling applicable data into a project database
3. Evaluating available hazard methodologies
4. Selecting appropriate hazard methodology for the LANL volcanic hazards assessment

4.2.2 SSHAC Level

One of the first decisions to be made regarding a PVHA at LANL is the appropriate SSHAC level for the analysis (Section 1.4; see also Hanks et al. 2009). While Level 2 studies are most common for hazard studies, they are typically for nonnuclear facilities. A Level 3 study may provide the necessary regulatory and public approval for a volcanic hazard assessment at the LANL site. Level 3 studies include workshops to identify and discuss hazard-significant issues and available databases, discuss and debate alternative models and interpretations, and consider hazard feedback. A Technical Integrator conducts the study that includes LANL scientists with peer review of hazards calculations and their technical basis, sensitivities, and associated uncertainties.

4.3 Proposed Schedule

- Year 1: Planning, scoping studies
  - consider and define hazard methodology
  - determine data needs
  - assemble published data

- Years 2–3:
  - Data acquisition and development of databases
  - Conduct PVHA: analysis and modeling, workshops, peer review

- Year 4:
  - Final report

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