Volcanic Hazards of the Idaho National Engineering and Environmental Laboratory, Southeast Idaho

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ABSTRACT

Potential volcanic hazards are assessed, and hazard-zone maps are developed for the Idaho National Engineering and Environmental Laboratory (INEEL) and adjacent areas. The basis of the hazards' assessment and zonation is the past volcanic history of the INEEL region, assuming that late-Quaternary volcanism is representative of future volcanism. The most significant hazards to INEEL facilities are related to basaltic volcanism, chiefly lava flows, which move slowly and threaten property by inundation or burning. Other hazards are volcanic gases and tephra, and the ground disturbance associated with the intrusion of dikes beneath the volcanic zones. Several volcanic zones in the INEEL area contain most of the volcanic vents and fissures of the region and are the most probable sites of future INEEL volcanism.

Volcanic-recurrence estimates are given for each of the volcanic zones based on the geochronology of the lava flows and the lithologic investigations of cogenetic volcanic deposits and magma-induced deformation. Probabilities of basaltic volcanism within the INEEL volcanic zones range from 6×10^{-5} per year (16-17 Ka interval between eruptions) for the axial volcanic zone near the southern INEEL boundary and the Arco volcanic-rift zone near its western boundary to 1×10^{-5} per year (average 100-Ka interval between eruptions) for the Howe-East Butte volcanic rift zone, a geologically old and poorly defined feature of the central INEEL.

Maps identify hazard zones for basaltic lava flows, tephra and gas, and extensional deformation associated with dike intrusion. The maps are useful in land-use planning, site selection, and safety analysis. The potential effects of ground deformation, tephra, and gases are largely restricted to near-vent areas within the volcanic zones, but lava flows may travel far from their sources. The statistics of INEEL lava flow lengths and areas are used to define two lava-flow hazard zones, which are more extensive than zones for tephra, gases, and ground deformation. The zone of high lava-flow hazard is within 10 km of volcanic vents younger than 400 Ka.

A site-specific volcanic-hazard assessment for the Central Facilities Area, south-central INEEL indicates that the probability of lava inundation is 1×10^{-6} per year, if no mitigation is possible, and 4×10^{-7} per year if mitigation is attempted.

Key words: basaltic volcanism, volcanic hazards, volcanic-hazard zone maps, eastern Snake River Plain, Idaho National Engineering and Environmental Laboratory

INTRODUCTION

In this paper we discuss the characteristics, frequency, and magnitude of volcanic phenomena in the area of the Idaho National Engineering and Environmental Laboratory (INEEL). We use INEEL geologic data, together with information from analog regions such as Iceland and Hawaii, to construct hazard-zone maps for lava flows, tephra and gas, and ground deformation associated with the intrusion of basaltic dikes. Interpretation of the local

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geology, particularly the record of late-Quaternary volcanism, is the basis for estimating the frequency and magnitude of future INEEL volcanic events, on the premise that "the past is the key to the future." Kuntz and others (1992) and Kuntz (1992) give essential information about eastern Snake River Plain (SRP) regional geology, and recent summaries of INEEL geology include Hackett and Smith (1992) and Kuntz and others (1994). Previous volcanic-hazard assessments of the INEEL area include Kuntz (1978), Kuntz and Dalrymple (1979), and the Volcanism Working Group (1990). These assessments have been outdated by subsequent information, are insufficiently quantitative, or address only specific INEEL localities. In this paper, we give a quantitative assessment of the entire INEEL area.

Volcanic hazards have been evaluated for the INEEL because critical facilities and long-term waste-storage sites have more stringent performance requirements than residential dwellings, and because the regulations governing such facilities demand that all potentially hazardous phenomena be examined in the interests of safety. We have designed the scope and format of this assessment to accommodate future INEEL geologic information. In particular, new geochronologic data might lead to a revision of the recurrence estimates. Recurrence estimates for the INEEL volcanic zones in turn are the basis of probabilistic volcanic-hazard and volcanic-risk assessments for existing or planned INEEL facilities.

Although at times the two terms are used interchangeably, there is a difference between "hazard" and "risk" (Fournier D'Albe, 1986; Reiter, 1990). "Volcanic hazards" describe the potential for dangerous phenomena associated with volcanism. Direct hazards result from eruptions of magma onto the land surface (e.g., lava flows) or into the atmosphere (e.g., volcanic ash or gases). Indirect hazards are attributed to the events that accompany such eruptions, the secondary effects of eruptions, or the underground movement of magma that does not erupt (e.g., dike-induced tensile fissuring and faulting). "Probabilistic volcanic-hazards assessment," the focus of this paper, addresses the probabilities of specific volcanic phenomena occurring within defined source areas. In addition, we develop a site-specific probabilistic volcanic hazards assessment for the Central Facilities Area (CFA) of the south-central INEEL. Here we estimate the annual probability of inundation by lava flows at that site.

"Volcanic risk" describes the extent of losses to people, property, or environment due to occurrences of particular volcanic phenomena. A "probabilistic volcanic-risk assessment" is therefore a quantitative statement concerning the impact or consequences of particular volcanic phenomena. Although we have not addressed the consequences of lava inundation, our assessment is a necessary first step in developing probabilistic volcanic-risk assessments of INEEL facilities.

Our general approach to volcanic-hazards assessment follows Blong (1984) and Latter (1989), with additional information on lava-flow hazards from Fink (1990) and Kilburn and Luongo (1994). Observations of active volcanoes in the analog regions of Hawaii (Decker and others, 1987) and Iceland (Sigurdsson, 1980; Gudmundsson, 1987) also help with understanding the potential effects of future volcanism at the INEEL. We model our quantitative volcanic-hazards assessment after Mullineaux and others (1987) and Wright and others (1992) for the Hawaiian Islands, and our conceptual framework is also influenced by a qualitative study of Iceland (Imsland, 1989).

VOLCANIC GEOLOGY OF THE INEEL AREA

The INEEL is located near the northern margin of the eastern SRP (Figure 1), a region that underwent explosive silicic volcanism during its early development, between about 7 and 4.3 Ma (Pierce and Morgan, 1992). Younger volcanism of the past 4 Ma has largely involved the effusion of basaltic lava flows (Figure 2).

The general characteristics of volcanism in the INEEL area are summarized in Table 1. Early volcanism of the region may be related to the Yellowstone mantle plume, a proposed source of heat and magma that has passed beneath southern Idaho during the past 15 Ma, leaving the 600-km-long SRP in its wake (Pierce and Morgan, 1992; Smith and Braile, 1993). As the North American continent drifted southwestward, the mantle plume left a trail of large silicic eruptive centers that become progressively younger to the northeast and culminate in the Quaternary Yellowstone Plateau volcanic field. The main products of the early explosive eruptions were voluminous and widespread silicic ash-flow tuffs. Beneath the INEEL area, voluminous silicic ash-flow tuffs and lava flows were emplaced about 6.5 to 4.3 Ma (Morgan and others, 1984; Pierce and Morgan, 1992). The present Yellowstone plume is considered to underlie northwestern Wyoming, where it is marked by geophysically anomalous crust and upper mantle (Smith and Christiansen, 1980), by regional uplift of the Yellowstone Plateau, by voluminous silicic volcanism of the Yellowstone Plateau volcanic field during the past 2.1 Ma (Hildreth and others, 1991), and by the present-day high heat flow and geothermal features of the Yellowstone caldera.

The observed, regional space-time pattern of early silicic volcanism on the eastern SRP and the apparent

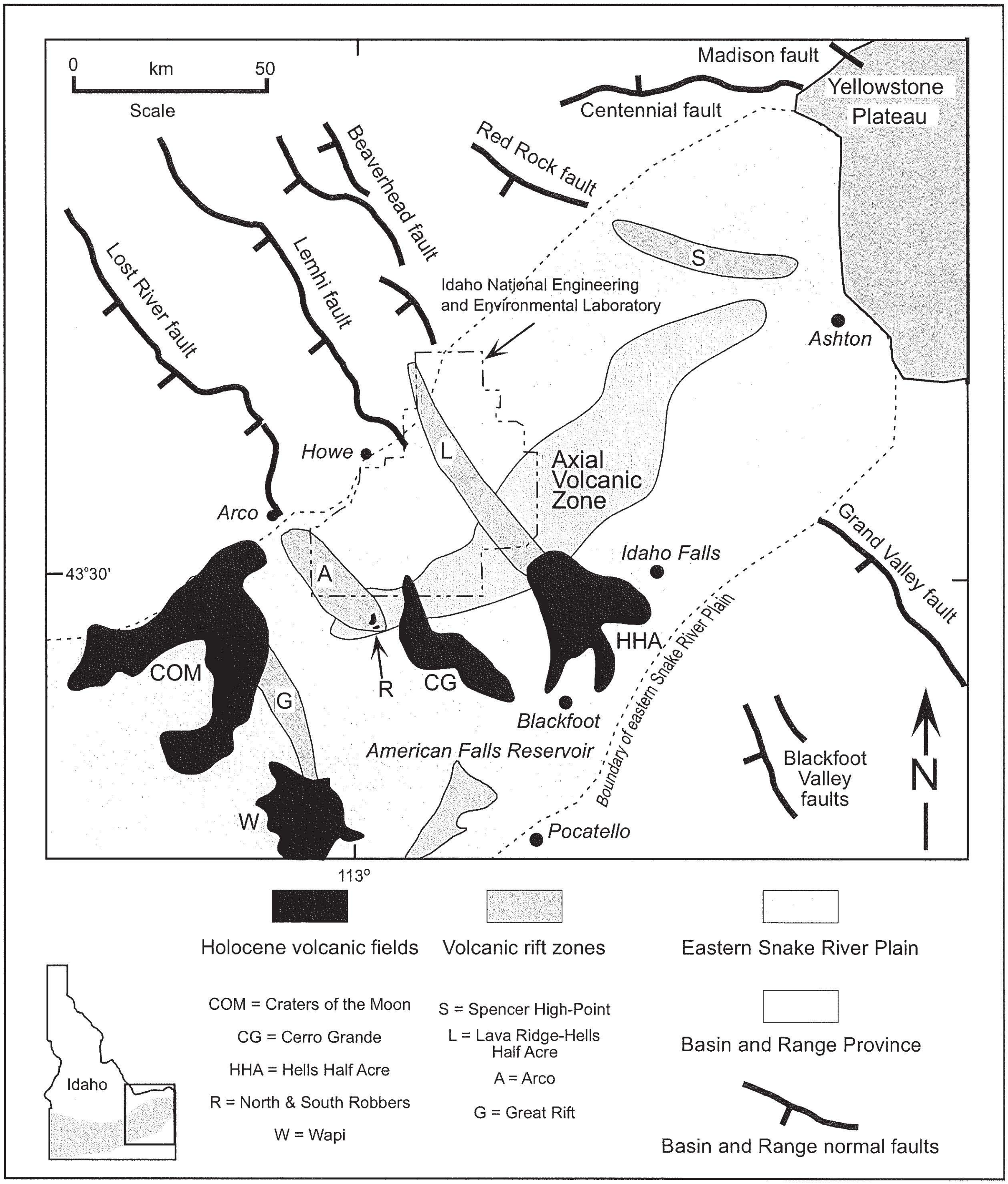

Figure 1. Index map of the eastern SRP, showing INEEL, population centers, and major volcanic and tectonic elements of the region.

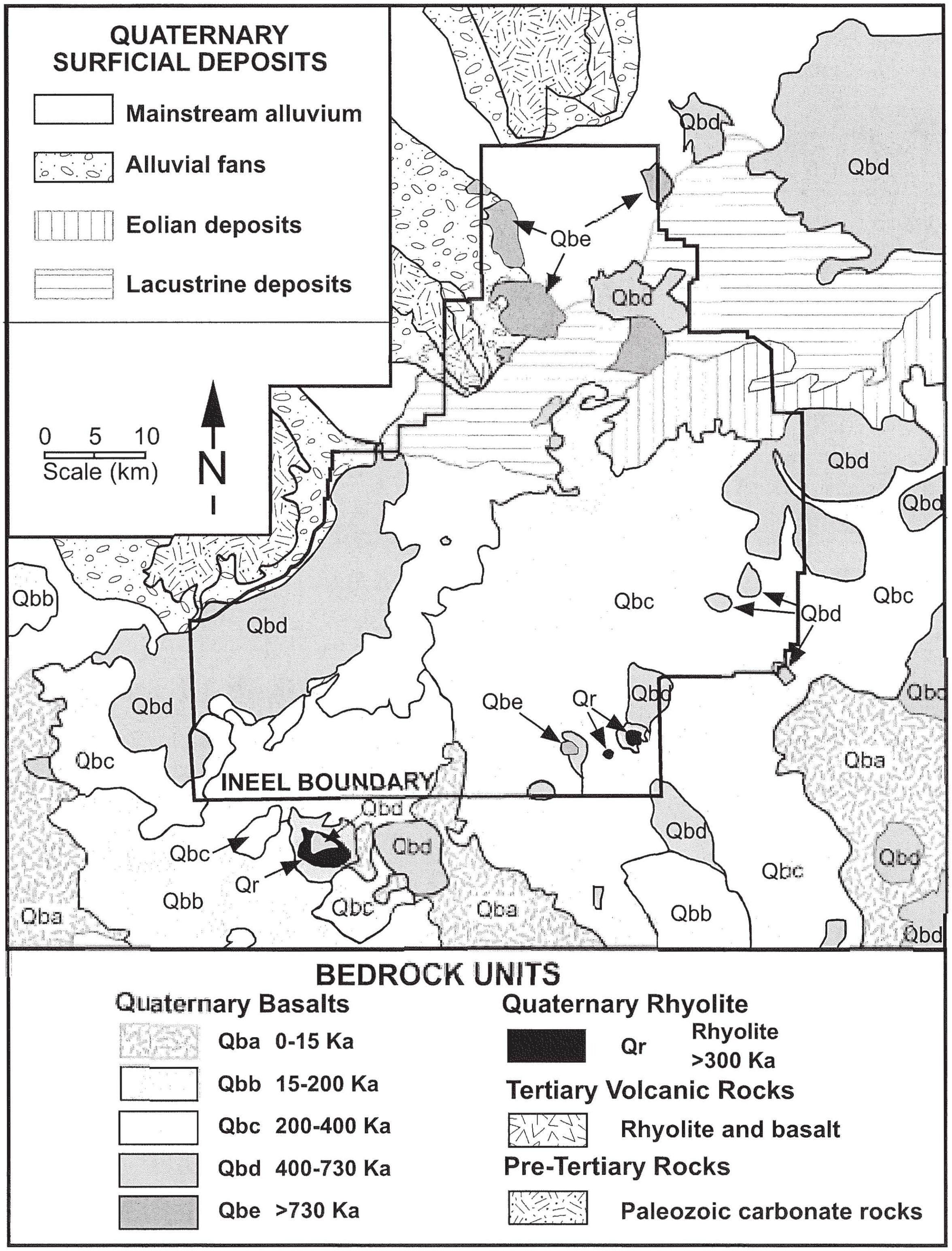

Figure 2. Generalized geologic map of the INEEL area (adapted from Kuntz and others, 1994; Scott, 1982). Quaternary basaltic lava-flow groups Qba through Qbe are based on whole-rock K-Ar (Kuntz and others, 1994) and radiocarbon dates (Kuntz and others, 1986).

Table 1. Characteristics of volcanism in the INEEL area. See Figure 1 for map distribution of volcanic zones and related features.

	Caldera Formation	**Rift-Zone Volcanism**	**Axial-Zone Volcanism**	**Areas Between Volcanic Zones**
Magma Types	Rhyolite (viscous and gas-rich)	Basalt (fluid and gas-poor)	Basalt and subordinate rhyolite	Basalt (and minor rhyolite?)
Volcanic Style and Products	Highly explosive; voluminous pumice and fine ash blankets entire regions	Mild and effusive; erupts mainly lava flows from fissures, low shield volcanoes, and small tephra cones	As per rift zones, but also local rhyolite domes and intrusions (Big Southern, Middle, East buttes) with local explosive phenomena	As per volcanic rift zones and axial volcanic zone
Stratigraphy	Calderas filled with as much as several km of welded, silicic ash-flow tuffs, lava flows, and volcaniclastic sediment [Heise Volcanic Group]	Piles of 1- to 30-m-thick basalt lava flows and minor inter-bedded sediment; total lava thickness as much as 1 km in INEEL area [Snake River Group]	Basaltic lava flows and dispersed small tephra cones; isolated rhyolite domes and intrusions [Snake River Group]	Fine clastic sediment of fluvial, lacustrine, and eolian origin; fewer lava flows than near volcanic rift zones [Snake River Group]
Tectonics and Physical Configuration	Collapse: broad, oval depressions, 10-100 km wide and 1-2 km deep, ringed by inward-dipping fractures	Extensional: NW-trending belts of open fissures, monoclines, small normal faults, and basaltic vents	Extensional, but magma-induced fissures or faults are rare; a diffuse, NE-trending, volcanic highland along the ESRP axis	Subsidence(?): broad, low topographic basins between extensional and constructional volcanic highlands; seldom disturbed by magma intrusion
Geologic Age in INEEL Area	6.5-4.3 Ma, now covered by younger basaltic lava. [2.1-0.6 million years on Yellowstone Plateau]	Surficial INEEL basalts: 1.2-0.05 Ma; most are 0.7-0.1 Ma. Inception of major basaltic volcanism occurred about 4 Ma.	Basalt: >1 Ma (Middle Butte) to 5.4 Ka (Hell's Half Acre). Rhyolite: >1 Ma (near East Butte) to 300 Ka (Big Southern Butte)	As per volcanic rift zones
Quaternary Eruption Frequency	None in INEEL area; Quaternary calderas closest to INEEL occur on Yellowstone Plateau	Low; one eruption per 17 Ka to 100 Ka (see Table 3)	Low: one basaltic eruption per 16 Ka (see Table 3); one rhyolitic intrusion or dome every 200 Ka or longer	Very low; by definition less frequent than within rift zones; one eruption per 100 Ka or longer

northeastward migration of the early silicic volcanic centers have three implications for INEEL volcanic-hazards assessment. First, the available evidence from the Quaternary Yellowstone Plateau volcanic field suggests that major silicic eruptions were separated by about 500 Ka (annual probability less than 2 x 10^{-6}). Second, explosive silicic volcanism associated with plume passage in the INEEL area took place 6.5 to 4.3 Ma. Recurrence intervals during that period were approximately 700 Ka, and about six recurrence intervals have therefore elapsed since the most recent caldera-forming eruptions of the INEEL area. Third, during the past 4.3 Ma, the major centers of explosive silicic volcanism have migrated to the Yellowstone region, several hundred kilometers northeast of the INEEL. Together, these three factors imply that the INEEL is unlikely to be significantly affected by future, explosive silicic volcanism (Volcanism Working Group, 1990).

During approximately the past 4.3 Ma, the eastern SRP has been repeatedly inundated by basaltic lava flows, which today largely cover the earlier silicic deposits. Much of the 2,315-square-km tract of the INEEL is underlain by basaltic lava flows, either exposed on the present land surface or lying beneath Quaternary sediment of alluvial, eolian, and lacustrine origin (Scott, 1982; Kuntz and others, 1994). Deep boreholes on the INEEL have intersected up to 1 km of late-Tertiary and Quaternary basalt lava flows and interbedded sedimentary deposits overlying Neogene silicic tuffs (Hackett and Smith, 1992). Unlike the early silicic volcanism, no systematic eastward migration of basaltic volcanism is apparent on the SRP, and Holocene lava flows occur across the province. No eruptions have occurred on the eastern SRP during recorded history, but basaltic lava flows of the Hell's Half Acre lava field erupted near the southern INEEL boundary as recently as 5.4 Ka, and eruptions occurred as recently as 2.1 Ka along the Great Rift, 30 km southwest of the INEEL (Kuntz and others, 1986).

Isolated volcanic domes of Quaternary rhyolite also occur on the eastern SRP. The domes were emplaced between about 1.4 and 0.3 Ma along the northeast-trending, central topographic axis of the eastern SRP (Kuntz and others, 1994). They are composed of fractured, lithoidal rhyolite and are surrounded by talus, alluvial-fan deposits, and younger basaltic lava flows.

Five groups of Quaternary basaltic lava flows have been mapped in the INEEL area (Figure 2), based on geologic field relations, geochronology (whole-rock potassium-argon, radiocarbon, and paleomagnetism), degree of weathering, and thickness of sediment cover (Kuntz and others, 1994). Quaternary volcanic rocks, chiefly basaltic lava flows, are exposed over approximately 58 percent of the INEEL and the adjacent land area, and they occur in the subsurface across most of the eastern SRP. Figure 3 shows the relative areas of subaerially exposed Quaternary volcanic rocks in the INEEL region. Several aspects of Figures 2 and 3 are relevant to INEEL volcanic-hazards assessment. More than two-thirds of the subaerially exposed basaltic lava and all of the silicic lava of the INEEL land surface and adjacent areas are older than 200 Ka (Figure 3: map units Qbc, Qbd, Qbe and Qr). No Holocene vents occur on the INEEL, but Holocene basaltic lava flows (Qba) cover 12 percent of the eastern SRP in the INEEL area and have erupted from vents along the axis of the eastern SRP as recently as 5.4 Ka. A minuscule percentage of the INEEL area is occupied by silicic volcanic domes (map unit Qr), and these isolated features occur along the axis of the eastern SRP near the southern INEEL boundary. Relative to basaltic volcanism, future silicic volcanism and its related hazards are, therefore, expected to be infrequent and to affect small areas of the axial volcanic zone.

Volcanic vents are not randomly distributed on the eastern SRP but occur within several volcanic zones (Figure 1). The axial volcanic zone is a northeast-trending, constructional-volcanic highland. Volcanic vents are also abundant in the southern parts of several northwest-trending volcanic rift zones where they merge with the axial volcanic zone. Volcanic rift zones are the surface expressions of underlying dike swarms. During ascent, dikes orient themselves perpendicular to the direction of least horizontal compressive stress, and magma pressure forces overlying rocks apart, forming northwest-trending belts of extensional deformation above the dikes. The resulting structural features include tensile fissures up to a meter wide and several hundred meters long, and normal-fault scarps and monoclines up to 10 m high and several km long (Smith and others, 1989; Hackett and Smith, 1992; Kuntz and others, 1992). The volcanic rift zones are also marked by linear arrays of fissure-fed basaltic lava flows,

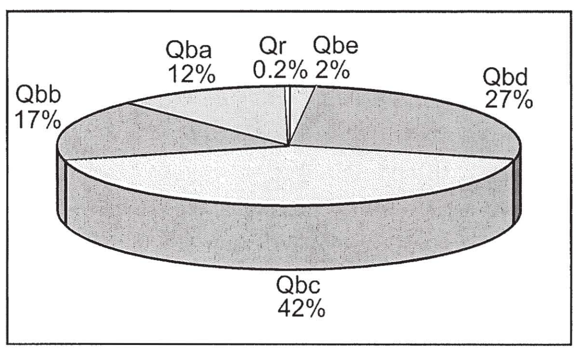

Figure 3. Relative areas of exposed Quaternary volcanic materials in the INEEL region. See Figure 2 for description of map units.

small-shield volcanoes, pyroclastic cones, and collapse craters. The volcanic and structural features of eastern SRP volcanic rift zones are generally similar to those of the Hawaiian and Icelandic rift zones. The eastern SRP volcanic rift zones are more diffuse than those of Hawaii, and their northwest trend conforms with the regional, northeast-southwest extension of the eastern SRP and the adjacent Basin and Range Province, rather than the radial pattern resulting from intrusive and gravitational forces during the growth of huge Hawaiian shield volcanoes. The axial volcanic zone of the eastern SRP has fewer dike-induced fissures and faults than the volcanic rift zones to the north, perhaps because it has a greater number of vents and has been resurfaced more frequently by lava flows. Between the INEEL volcanic rift zones are broad, low-lying basins such as the Big Lost River Sinks of the northern and central INEEL. Borehole data suggest that these basins may have received more late-Quaternary sediment and fewer lava flows than the volcanic zones (Anderson and Lewis, 1989).

The main style of Quaternary eastern SRP basaltic volcanism is Hawaiian, and eruptions typically involved mild effusions of fluid, gas-poor, pahoehoe lava flows from fissures and small shield volcanoes. Many eastern SRP basalt flows are tube fed (Greeley, 1982), as shown by the widespread collapse depressions developed along lava tubes of the region. Strombolian volcanism is marked by small pyroclastic cones on eruptive fissures, many of which occur along the axial volcanic zone. Examples include the summit-forming tephra cone of Cedar Butte and the group of small basaltic tephra cones near Atomic City to the south of the INEEL. Tuff cones and tuff rings, resulting from phreatomagmatic steam explosions during the interaction of basaltic magma with shallow ground water, do not occur in the INEEL area but are found elsewhere on the eastern SRP (Womer and others, 1982; Hackett and Morgan, 1988), probably because the INEEL water table is too deep.

INEEL VOLCANIC HAZARDS

The INEEL area has experienced predominately basaltic volcanism during the past 4.3 Ma, and phenomena associated with basaltic volcanism are, therefore, most important to INEEL hazard assessment. Table 2 outlines the principal hazards associated with eastern SRP basaltic volcanism. Effusion of pahoehoe lava flows (Self and others, 1998) is the most common late-Quaternary phenomenon and, therefore, the most significant hazard on the eastern SRP. Observations of active lava flows in Hawaii (Tilling and Peterson, 1994) indicate that basaltic lava flows on gentle terrain similar to that of the INEEL advance relatively slowly and mainly threaten property by inundation or burning.

Gas release is universally associated with fissuring and eruption, but poisonous or asphyxiating gases are generally serious hazards only within a few hundred meters of active vents. Several kilometers downwind, reactive gases may cause respiratory irritation, affect crops, and cause corrosion. Upon cooling, heavier-than-air gases (carbon dioxide, sulfur, sulfur dioxide, hydrogen fluoride, and hydrogen chloride) may collect in closed topographic depressions. Persistent winds and the broad expanse of most topographic basins on the INEEL mean that volcanic gas is unlikely to be a significant hazard, with the possible exception of the confined basin of the Big Lost River sinks and the Birch Creek sinks in the north-central INEEL (Smith, 1994).

Explosive pyroclastic volcanism and significant tephra fall are rare during mild, Hawaiian-type basaltic eruptions such as those of the eastern SRP. Tephra fallout would involve the deposition of coarse pyroclastic material within a few hundred meters of volcanic vents. Areas of tephra hazard are therefore similar in size and geometry to the areas affected by volcanic gases.

Indirect hazards associated with basaltic volcanism are ground deformation and seismicity associated with dike intrusion beneath volcanic rift zones. Surface fissuring and tumescence occur during dike intrusion with or without the eruption of magma. Tensile fissures on the eastern SRP have widths ranging from 0.1 m to about 1 m, and normal-fault scarps rarely exceed 5 m.

Small- to moderate-magnitude earthquakes also occur during dike intrusion. Most dike-induced seismic events have magnitudes less than 3, and maximum magnitudes are estimated to be less than 5.5 on the eastern SRP (Jackson, 1994; Smith and others, 1996; Hackett and others, 1996).

Future silicic lava domes may erupt along the axial volcanic zone, but the hazardous effects would probably be restricted to a several kilometer radius. Historical observations of active silicic lava domes have shown that such domes commonly produce small-volume pyroclastic flows and tephra-fall deposits as a result of internal explosions and slope failure (Fink, 1990). However, no evidence of such deposits from silicic domes near the INEEL has yet been identified through geologic mapping and borehole investigations. The shallow intrusion of silicic magma during the growth of lava domes may also lead to the uplift of large tracts of land. Middle Butte in the axial volcanic zone is a block of old (Qbe) lava flows that was presumably uplifted by a silicic lava dome that failed to breach the surface (Kuntz and Dalrymple, 1979), and the emplacement of Big Southern Butte raised

Table 2. Hazards associated with basaltic volcanism on the eastern Snake River Plain. Entries are listed from highest to lowest relative hazard.

Phenomenon	**Relative Frequency**	**Size or Area of Influence**	**Comments**
Lava flow	Common	0.1 km^2 to 400 km^2 in area; up to 25 km in length based on sizes of ESRP lava flows of the past 400 Ka	Significant hazard; typical basaltic phenomenon; lava from fissures or shield volcanoes may inundate large areas downslope of vents
Ground deformation: fissuring, faulting, and uplift	Common; associated with virtually all shallow magma intrusion and eruption	Fissuring could affect areas to 2 x 10 km; minor tilting and broad uplift in areas to 5 x 20 km	Significant hazard; due to shallow dike intrusion; "dry" intrusion may occur without lava flows; affects smaller areas than for lava inundation
Volcanic earthquakes	Common; associated with magma intrusion before and during eruption	Maximum M = 5.5 and most events M < 4; ground vibration may affect facilities within 25 km	Low to moderate hazard; swarms of shallow earthquakes (< 4 km focal depth) occur as dikes propagate underground
Gas release (toxic and corrosive vapors)	Common; associated with fissuring and lava eruption	Restricted to near-vent areas; may affect several square-km area downwind	Low hazard; local plume of corrosive vapor, downwind from eruptive vent or fissure; cooled vapor may collect in local topographic depressions
Tephra fall (volcanic ash and bombs)	Common	Restricted to near-vent areas; may affect several square-km area downwind	Low hazard; basaltic eruptions are inherently nonexplosive and may form small tephra cones but little fine ash to be carried downwind
Base surge (ground-hugging blast of steam and tephra)	Rare	Effects limited to radius of several km from vent; < 10 km^2 area	Low hazard; steam explosions due to interaction between ascending magma and shallow ground water; water table too deep under most of INEEL (> 200 m)
Tephra flow (ground-hugging flow of hot, pyroclastic material)	Extremely rare	Near vent; may affect area < 1 km^2	Very low hazard; as per tephra fall but affecting even smaller areas

a 900-m-thick block of basaltic lava flows on its northern flank (Spear and King, 1982; Fishel, 1993).

None of these volcanic phenomena can be effectively controlled, and the most successful mitigation is avoidance through careful land-use planning and site selection. Once a volcanic vent has become established, the paths of lava flows can usually be predicted using terrain analysis. In some places, lava flows can be diverted with rock-rubble barriers (Barberi and others, 1993). Diversions should be constructed well upslope of threatened facilities, in opportune topographic positions, and not at the facilities themselves. Water has been used to chill and halt advancing lava flow fronts, but this requires enormous quantities of water and energy for pumping. It is generally not feasible to engineer structures to withstand ground fracturing or faulting, or the long-term effects of corrosive gases. Tephra fall is not a significant hazard in the INEEL area, and the mitigation of roof collapse by tephra loading is therefore unwarranted.

DEFINITION, FREQUENCY, AND MAGNITUDE OF VOLCANIC EVENTS

The recurrence estimates of Table 3 are based on the number of magmatic events for each INEEL volcanic zone. A magmatic event is defined as a cogenetic assemblage of intrusive and extrusive features that are the products of a single magma batch. An event occurs within the geologically brief time it takes for a batch of basaltic magma to be injected into the shallow crust and to solidify, generally months to decades. A discrete magmatic event usually produces an assemblage of cogenetic features such as multiple vents along a common eruptive fissure, several lava flows, and a belt of dike-induced extensional structures that may form with or without eruptive products. Interpreting each lava flow, vent, or fissure as the unique product of a discrete volcanic eruption is geologically incorrect and yields inappropriately short recurrence intervals, but this procedure is useful to establish bounding conditions for volcanic recurrence. Equating each lava flow, vent, or deformation feature as the product of a single magmatic event would shorten the preferred recurrence estimates of Table 3 by factors of 1.5 to 3.

To the geologic map data of Kuntz and others (1994), we have added our own field, aerial-photographic, and petrographic investigations of selected vent areas on the axial volcanic zone and the southern Arco volcanic rift zone. We conclude that the geologic field relations as mapped at 1:100,000 scale by Kuntz and others (1994) are adequate for INEEL volcanic-hazards assessment, because the products of individual eruptions are readily distinguished at that scale. We also find that lava flows from individual shield volcanoes commonly differ from lava flows of other vents in phenocryst content, groundmass mineralogy, and texture. These differences support the idea that the clusters of small shield volcanoes, pyroclastic cones, pit craters, and other vents are generally the cogenetic products of single, compositionally uniform magma batches representing a discrete magmatic event. Most eastern SRP volcanoes are small, monogenetic features, as shown by the field relations and by the overall petrographic uniformity among lava flows from the individual shield volcanoes and vent complexes. In the southern Arco volcanic rift zone, the petrographic similarities and field relations among several of the shield volcanoes suggest that in places several shield volcanoes may be the cogenetic products of a single magma batch. In several places, tensile fissures could not be related to cogenetic volcanic materials and were conservatively interpreted as the products of one noneruptive dike-intrusion event.

Cedar Butte, a large central volcano of the axial volcanic zone (Figure 4; Hayden, 1992), is an exception to the typically monogenetic volcanism of the INEEL area. At this polygenetic eruptive center, several eruption cycles have produced diverse lava compositions, ranging from basalt to rhyolite, and pyroclastic as well as effusive volcanic materials, suggesting a complex magma system that evolved either by protracted differentiation of a single batch of parental magma or by magma-reservoir replenishment.

Geologic and geophysical observations during historical rift-zone volcanism in Hawaii and Iceland show that dike intrusion, ground deformation, and lava effusion are cogenetic phenomena that develop during geologically brief eruptive periods of several weeks to a decade or so (Hackett and others, 1996). The inference that multiple lava flows and vents on the eastern SRP formed during geologically brief periods is further supported by paleomagnetic data from drill cores of INEEL lava flows (Champion and others, 1988) and by radiocarbon dates from Holocene lava flows in Craters of the Moon lava field (Kuntz and others, 1986; 1988).

RECURRENCE ESTIMATES

The recurrence estimates for INEEL volcanic zones and boreholes given in Table 3 are based chiefly on the geochronology and geologic map data of Kuntz and others (1994), and are derived by dividing the number of volcanic events into the age range of volcanism. Estimates have been rounded off to avoid implying undue precision and are expressed as frequencies of eruption and as annual probabilities of occurrence. Eruptive periods are separated by an average of about 2 Ka for some parts of the Great Rift, giving a recurrence of 5×10^{-4} per year. Future eruptions of the Great Rift would have little or no impact upon the INEEL, but these data are included because this volcanic rift zone is thoroughly studied and has been frequently active during the past 15 Ka. Its 2-Ka recurrence interval serves as a bounding value of shortest recurrence for the eastern SRP region.

Northwest-trending volcanic rift zones of the INEEL area merge with the axial volcanic zone (Figure 1). The shortest recurrence intervals (greatest annual probabilities of eruption) for INEEL volcanic zones are approximately 16 Ka (6×10^{-5} per year) for the axial volcanic zone and the Arco volcanic rift zone. The axial volcanic zone has the greatest number of volcanic vents of the INEEL volcanic zones and includes four Holocene lava fields. It is a constructional volcanic highland along the axis of the eastern SRP, apparently resulting from a greater magma supply at the center of the volcanic province. The axial volcanic zone includes relatively few dike-induced extensional structures in comparison with the volcanic rift zones. The Arco volcanic rift zone contains more vents than other volcanic rift zones of the INEEL area, and also the greatest number of dike-induced fissures and faults. Together, the Arco and axial volcanic zones account for more than two-thirds of the vents and dike-induced structures of the INEEL area.

Table 3. Estimated volcanic-recurrence intervals and corresponding annual eruption probabilities (in parentheses) for volcanic zones and boreholes of the INEEL area.

Volcanic Zone or Borehole	Data Sources	Time Interval of Volcanism	Number of Vents, Fissures, or Flow Groups	Comments	Estimated Recurrence Interval
Great Rift (25 km southwest of INEEL)	Kuntz and others, 1986, 1988	2.1-15 Ka (radiocarbon dating)	> 100 vents 8 Holocene eruptive periods (each lasting a few decades or centuries, and each including multiple flows and cones)	No impact on INEEL; most recently and frequently active of all ESRP rift zones; thus provides minimum recurrence for entire ESRP; most probable area of future ESRP volcanism	2 Ka (5×10^{-4}/year)
Axial Volcanic Zone (southern INEEL)	Kuntz and others, 1986, 1994	5-730 Ka (K-Ar dating; radiocarbon; paleomagnetic data)	73 vents and fissure sets; 4 Holocene lava fields, 3 of them shared by volcanic rift zones. 45 cogenetic vent and fissure groups	Could affect much of southern INEEL; most recently and frequently active of all volcanic zones that could impact INEEL	16 Ka (6.2×10^{-5}/year)
Arco Volcanic Rift Zone (southwestern INEEL)	Kuntz, 1978; Smith and others, 1989; Kuntz and others, 1994	10-600 Ka (radiocarbon, K-Ar and thermoluminescence dating; paleomagnetic data)	83 vents and fissure sets; 2 Holocene lava fields. 35 cogenetic vent and fissure groups	Volcanism could affect southwestern INEEL	17 Ka (5.9×10^{-5}/year)
Lava Ridge-Hell's Half Acre Volcanic Rift Zone (includes Circular Butte/Kettle Butte volcanic rift zone) (north and eastern INEEL)	Kuntz and others, 1986, 1994	5 Ka-1.2 Ma (K-Ar dating; radiocarbon; paleomagnetic data)	48 vents and fissure sets; 1 Holocene lava field: Hell's Half Acre. 30 cogenetic vent and fissure groups	Could affect northern and eastern INEEL; extremely long eruptive history; includes oldest and youngest basalts in the INEEL area	40 Ka (2.5×10^{-5}/year)
Howe-East Butte Volcanic Rift Zone (central INEEL)	Kuntz, 1978, 1992; Golder Associates, 1992	230-730 Ka (K-Ar dating; paleomagnetic data)	7 vents and fissure sets; no Holocene features. 5 cogenetic vent and fissure groups	Old, poorly exposed, and sediment-covered; identified in part by subsurface geophysical anomalies	100 Ka (1.0×10^{-5}/year)
Borehole NPR SITE E (south-central INEEL)	Champion and others, 1988	230-640 Ka (K-Ar dating; paleomagnetic data)	9 lava-flow groups (each group contains multiple lava flows, erupted over a short time)	Dates from 600-foot interval of subsurface lavas give recurrence estimate consistent with surficial geology of the area	45 Ka (2.2×10^{-5}/year)
Borehole RWMC 77-1 (southwestern INEEL)	Kuntz, 1978; Anderson and Lewis, 1989	100-565 Ka (K-Ar and TL dating; paleomagnetic data)	11 lava-flow groups (each group contains multiple lava flows, erupted over a short time)	Dates from 600-foot interval of subsurface lavas give longer recurrence interval than nearby Arco and Axial zones, reflecting flow-group (subsurface) vs. vent-counting (surface geology) methods	45 Ka (2.2×10^{-5}/year)

[1] 16 vent/fissure groups in overlap zone of Axial Volcanic Zone and Arco Volcanic Rift Zone are divided between the two zones. 17 vent/fissure groups in overlap zone of Axial Volcanic Zone and Lava Ridge-Hell's Half Acre Volcanic Rift Zone are divided between the two zones.

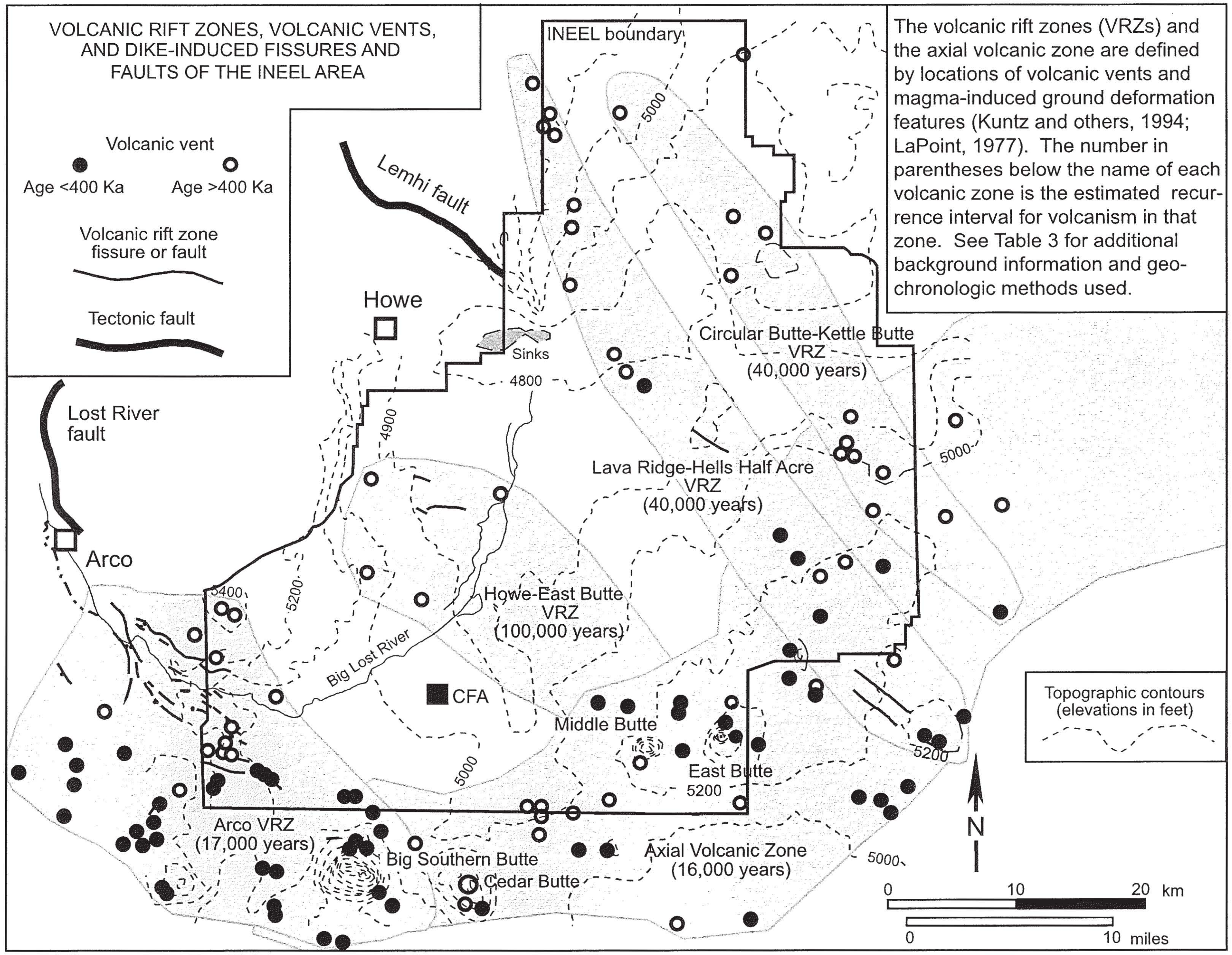

Figure 4. Map of the INEEL area, showing volcanic-vent locations and estimated recurrence intervals for the volcanic zones (gray-filled regions). Filled square shows the location of the Central Facilities Area.

We have combined the Circular Butte-Kettle Butte volcanic rift zone of Kuntz and others (1992) and the Lava Ridge-Hell's Half Acre volcanic rift zone into a single entity. They are diffuse, adjacent features with similar physiographic characteristics, periods of eruptions, and recurrence. Although the number of vents is similar to the Arco volcanic rift zone, the 40-Ka recurrence estimate for the Lava Ridge-Hell's Half Acre volcanic rift zone is longer because the lava flows of its northern part erupted about 1.2 Ma and are among the oldest known from INEEL surface outcrops.

The Howe-East Butte volcanic rift zone, included in Table 3, is identified by Kuntz and others (1992) but is poorly expressed in the INEEL surficial geology. In its northern part, this volcanic rift zone has a few vents and fissures developed in lava flows older than about 400 Ka. In contrast to other eastern SRP volcanic rift zones, its central part is not a topographic highland but a basin containing Big Lost River sediment and younger lava flows from other volcanic zones. The Howe-East Butte volcanic rift zone is marked by a large, northwest-trending, positive aeromagnetic anomaly (Zietz and others, 1978), which may represent a subsurface dike swarm. We therefore interpret the feature as an old volcanic rift zone now largely covered by younger volcanic and sedimentary deposits. Although all Howe-East Butte volcanic vents are older than 400 Ka (Kuntz and others, 1994), the time interval of 230-730 Ka given in Table 3 allows for fissuring and volcanism as young as 230 Ka. This is because the Howe-East Butte volcanic rift zone merges with the axial volcanic zone to the south, and 230 Ka is the age of young vents in this area of the axial volcanic zone. Nonetheless, the 100-Ka estimated recurrence for the Howe-East Butte volcanic rift zone is the longest of any INEEL volcanic zone.

Expansion of the time intervals of volcanism to the present (zero Ma) would be a valid consideration for the INEEL volcanic zones, because hazard assessments are necessarily concerned with the potential effects of future volcanism. This would not substantially change the recurrence estimates for the INEEL volcanic zones because most of them, except the Howe-East Butte volcanic rift zone, include lava flows younger than about 12 Ka.

The northern parts of the Arco- and the Lava Ridge-Hell's Half Acre volcanic rift zones contain fewer and older volcanic vents than their southern parts near the axial volcanic zone, and volcanic recurrence within these rift zones decreases northward. The recurrence estimates reported for the Arco- and for the Lava Ridge-Hell's Half Acre volcanic rift zones represent average values.

Borehole data are shown in Table 3 for comparison with the surface volcanic zones. Borehole recurrence estimates generally conform with those based upon surface geology, although different methods are used. For example, in the NPR Site E borehole, nine basaltic lava-flow groups are separated by sedimentary interbeds. Paleomagnetic data indicate that the lava-flow groups were emplaced within relatively brief periods of centuries to a few millennia, during the 400-Ka-dated interval of the borehole. Each lava-flow group may, therefore, be interpreted as the product of one or a few closely spaced magmatic events, perhaps representing the lava flows from several coalesced shield volcanoes. Nine eruption cycles (lava-flow groups) per 400 Ka gives the 45-Ka recurrence estimate for this borehole. A more detailed dimensional analysis of late Quaternary lava-flow groups in INEEL boreholes is used by Wetmore and others (1997) to derive an INEEL borehole-based recurrence interval of about 19 Ka (5.3×10^{-5} per year).

EVENT MAGNITUDE

To constrain event magnitude and to provide a quantitative basis for establishing INEEL lava-flow hazard zones, we used the map data of Kuntz and others (1994) to measure the lengths and areas of basaltic lava flows from the four youngest Quaternary basaltic lava-flow groups, representing volcanism of the past 750 Ka. Only flows with dimensions not obscured by younger deposits were measured, and a statistical compilation is given in Table 4.

No subaerially exposed lava flow of the INEEL area has traveled farther than about 30 km from its source. The 50th-percentile flow length is 10 km, and the length distribution is strongly skewed toward short flows. The average INEEL lava flow of the past 750 Ka covered about

Table 4. Statistical summary of late Quaternary INEEL basaltic lava-flow lengths and areas. Lava flows were measured from the geologic-map data of Kuntz and others (1994) and LaPoint (1977).

	Length (km)	Area (km^2)
Minimum	0.1	0.5
Maximum	31	400
Range	30.9	399.5
Mean	12.4	96.5
Median	10	70
Standard Deviation	7.9	94.2
Number of Flows	46	43

96 square km. Most of the flows are equant, reflecting a tendency to spread laterally on the gently sloping, low-relief terrain.

The magnitude of dike-induced ground deformation is defined as the surface area disturbed by extensional faults and fissures associated with the shallow intrusion of a basaltic dike. Hackett and others (1996) and Smith and others (1996) compile the results of numerical modeling, physical modeling, field observations of deformation during active dike intrusion in Hawaii and Iceland, and field measurements of magma-induced extensional features on the eastern SRP. They show that deformation is largely restricted to narrow belts above intruded basaltic dikes, generally less than 1 km wide and 5 km long (total area of 5 square km), and that the cumulative fault displacement or tensile fracturing associated with intrusion of one several-meter-thick basaltic dike is less than a few meters.

Although coarse pyroclastic material is produced at the onset of nearly all eastern SRP basaltic eruptions, most such material is deposited less than a few hundred meters from vents along a common eruptive fissure up to several kilometers in length. Tephra cones of the Craters of the Moon lava field to the southwest of the INEEL are among the most imposing volcanic features on the eastern SRP. Many are composed of evolved lava having a silica content greater than 50 percent, are about 100 m high, and cover an area of about 1 square km (Kuntz and others, 1988). During an unusual phreatomagmatic event on the eastern SRP, southwest winds deposited several centimeters of basaltic ash up to 1.5 km downwind from the eruptive fissure at the Holocene King's Bowl lava field (Greeley and King, 1977; Kuntz and others, 1988). More representative of the INEEL area are six small basaltic tephra cones, each less than 20 m high and 200 m in diameter, within a 15-square-km area of the axial volcanic zone near Atomic City and the southern INEEL boundary (Kuntz and others, 1992, 1994). Thus, for typical eastern SRP basaltic eruptions, significant effects of tephra fall and toxic or corrosive gases will be limited to areas within 500 m of vents.

Volcanic gas may also be liberated from both eruptive and noneruptive fissures during shallow dike intrusion and would likely be carried northeasterly by prevailing eastern SRP winds. As with ground deformation, the area affected by tephra and gas is anticipated to be a narrow, northwest-trending belt of about 5 square km, developed above and to the northeast of an ascending basaltic dike. Thus, for dike-induced deformation and for tephra and gas, the affected areas are estimated to be about one-twentieth of the area inundated by the average INEEL lava flow.

INEEL HAZARD-ZONE MAPS

Volcanic-hazard zones are founded on the assumption that future eruptions will be similar in style, magnitude and location to those of the recent geologic past, as reconstructed from the INEEL geologic record. The quantitative approach used here incorporates several primary and secondary criteria, including (1) the location and density (number per unit area) of dike-induced fissures and most recent lava flows; (2) volcanic recurrence, estimated from event counts within each of the INEEL volcanic zones and the absolute chronology of the volcanic materials (Figure 4); and (3) distance from volcanic vents or zones, relative to median lava-flow length. Additional criteria include the topographic gradients and barriers that could affect the paths of lava flows or collect volcanic gas, and the prevailing wind directions that would affect the dispersal of gas and fine tephra.

Volcanic-hazard zonation maps are shown for lava flows (Figure 5), tephra fall and volcanic gases (Figure 6), and ground deformation associated with basaltic-dike intrusion (Figure 7). The hazard zone maps show areas in which the level of hazard differs from that of adjacent areas. The level of hazard may vary considerably within a zone, either gradually or abruptly. Direct volcanic hazards (lava flows, tephra, and gases) decrease gradually across zones and away from vents, but abrupt changes may occur along sharp topographic features. The degree of hazard changes gradually rather than abruptly across most zone boundaries, and zones would be most accurately rendered by contours or gradational changes in shading rather than as sharp lines. The zone boundaries are intended to show that differences in hazard exist and to facilitate description of the zones. In spite of these limitations, the hazard zone maps and associated volcanic-recurrence data are useful for land-use planning, site selection, safety analysis, and long-range mitigation planning for volcanic hazards.

LAVA-FLOW HAZARD ZONES

The length statistics of late-Quaternary basaltic lava flows (Table 4) are used to delineate hazard zones for lava inundation from vents within the INEEL volcanic zones (Figure 5). Hazard zone 1 (highest hazard) for lava flows is defined as being within 10 km of a vent or fissure younger than 400 Ka (map units Qba, Qbb, Qbc; Kuntz and others, 1994). Ten km is the median or 50th-percentile length of late Quaternary lava flows (Table 4), meaning that random sites within zone 1 are statistically expected to be inundated by about 50 percent of lava flows that may erupt from nearby sources. The general probability of inundation at the outer limit of zone 1 is, therefore, less than or equal to half the annual eruption probability for its adjacent source volcanic zone, ignoring topographic and other site-specific factors. Later, we give a detailed hazard analysis that incorporates these factors for a specific INEEL site. Hazard zone 2 is an area of lower hazard, defined as being within 20 km (the 80th-percentile lava-flow length) of a vent or fissure younger than 400 Ka. Thus, on a statistical basis, less than 20 percent of erupted lava flows are expected to reach the outer limits of hazard zone 2. Areas beyond hazard zone 2 should be inundated by fewer than 20 percent of future lava flows and have probabilities of inundation that are generally about an order of magnitude smaller than the recurrence values for nearby volcanic zones.

The lava-flow hazard zones are truncated in the northern and western INEEL, owing to the topographic effects of mountain ranges near the northwestern INEEL boundary, to the south-sloping alluvial surfaces issuing from intermontane valleys, and to the Big Lost River channel of the central INEEL. Areas outside zone 2 are sufficiently distant or upslope from the volcanic zones to be considered low-hazard areas, beyond the range of most lava flows.

TEPHRA-FALL AND VOLCANIC-GAS HAZARD ZONE

Tephra fall and gas emission are expected to accompany all volcanic eruptions, and gas emission from fissures would accompany dike intrusion even in the absence of lava eruption; our estimated recurrence for tephra and gas emission is therefore the same as for lava flows and dike-induced deformation (Table 3). Tephra deposits, however, constitute a very small part of the total volume of basalt on the eastern SRP (Kuntz and others, 1992) and as discussed earlier, the areas affected by tephra fall are much smaller than the areas inundated by affiliated lava flows. We indicate tephra and gas-hazard zones (Figure 6) within areas 0.5 km southwest and 2 km northeast of vents and fissures younger than 400 Ka within the INEEL volcanic zones. We estimate hazard zones for tephra and gases from future silicic lava-dome eruptions along the center of the axial volcanic zone to be about twice these dimensions (5-km radius). This estimate also includes pyroclastic-flow hazard due to the slope failure and explosions that are typical of silicic lava domes (Blong, 1984; Williams and McBirney, 1979). A separate zone for silicic tephra and gases is not shown within the axial volcanic zone but exists as part of the basaltic-tephra hazard zone for that area. An area of volcanic-gas hazard is indicated in the north-central INEEL, near Test Area North (TAN), within a topographic depression that could trap dense volcanic gas.

GROUND-DEFORMATION HAZARD ZONE

The widespread occurrence of fissure-erupted lava flows and the magma-induced extensional structures of eastern SRP volcanic rift zones indicate that most basaltic eruptions on the eastern SRP were fed by northwest-trending dikes. Ground deformation is expected to accompany all shallow dike-intrusion events, with or without volcanic eruption. The recurrence of ground-deformation phenomena is, therefore, considered equal to or greater than lava-flow recurrence within the INEEL volcanic zones (Table 3). As discussed earlier, the severity of vertical offset and ground fissuring will vary according to the number of dikes and their aggregate thickness, but will generally not exceed 1-2 m of vertical offset or horizontal extension within a few hundred meters of the intruding basaltic dike. The hazardous areas are therefore restricted to the volcanic zones and are substantially smaller than the hazard zones for lava inundation. We define areas within 1 km of Qb a, b, or c (post-400-Ka) vents, and all areas with magma-induced fissures and faults as constituting the zone of ground-deformation hazard (Figure 7). The Arco volcanic rift zone includes many such deformation features associated with fissure-fed lava flows and small pyroclastic cones, indicating repeated dike intrusions in the area. Some of the fissures of the northern Arco volcanic rift zone maybe of tectonic origin and related to the Lost River fault. For purposes of analyzing volcanic hazards, we take a conservative approach by assuming all of these fissures to have been induced by magma. Although generally lacking ground-deformation features, much of the axial volcanic zone is also included as part of the ground-deformation hazard zone, because it can reasonably be inferred that fissures formed but were covered by cogenetic lava flows from the many vents in the area.

Magma-induced fissures and faults of the INEEL area have not been dated, but the ages of host volcanic rocks serve to limit the maximum ages of fissures. We have conservatively assumed that magma-induced fissures without a clear cogenetic relationship to mapped volcanic materials are equivalent in age to a younger lava-flow group than the host rocks. For example, most dike-induced faults and fissures of the northern Arco volcanic rift zone are developed in lava flows older than 400 Ka, but some could have formed during the past 400 Ka and are therefore included as young vents in defining lava-flow hazard zone 1. The isolated fissures mapped near the Naval Reactors Facility (NRF) by Golder Associates (1992) occupy the northern part of the poorly defined Howe-East Butte volcanic rift zone, trend east-west, have no clear relationship to volcanic materials of the area,

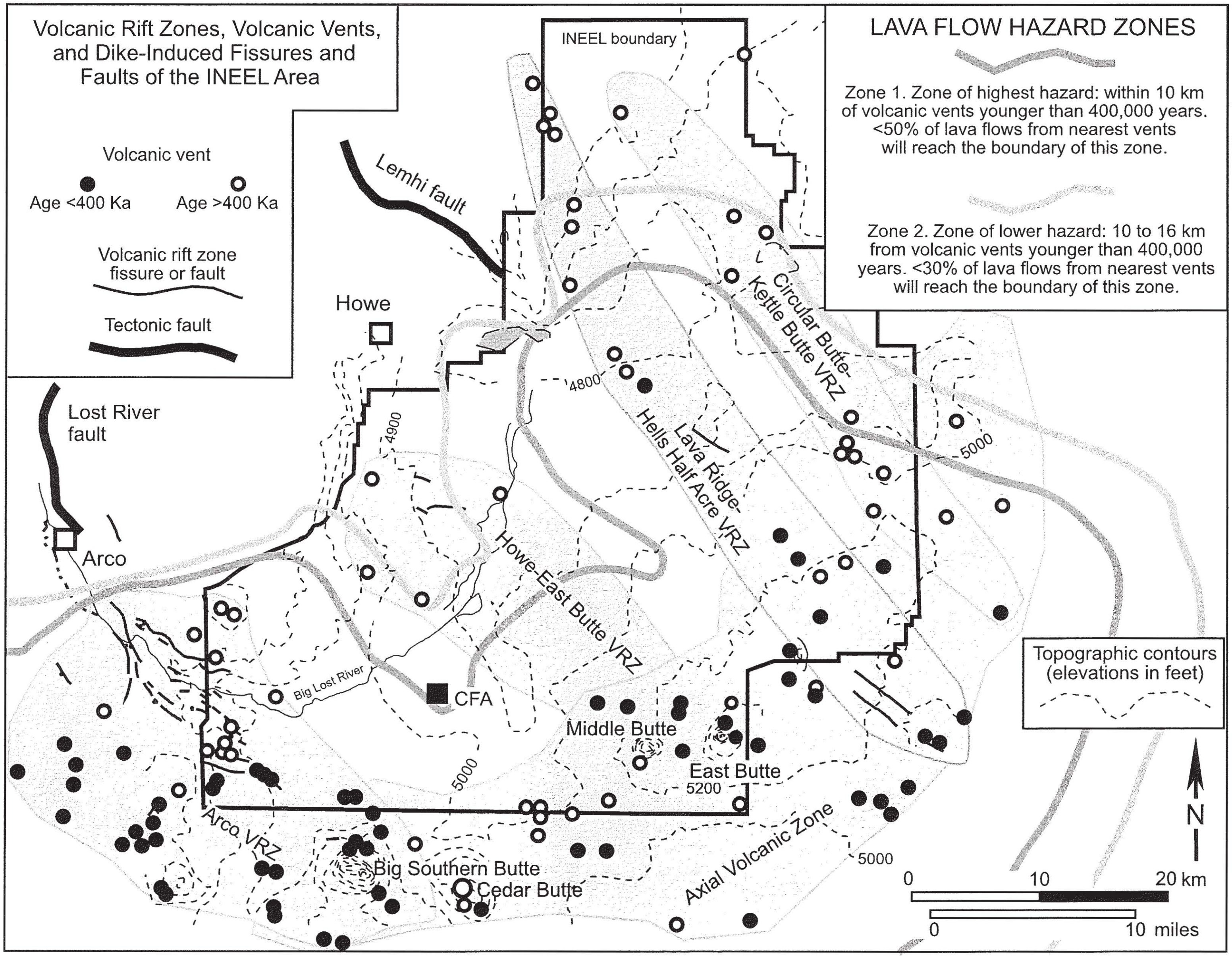

Figure 5. Lava flow hazard-zone map of the INEEL area. Filled square shows the location of the Central Facilities Area.

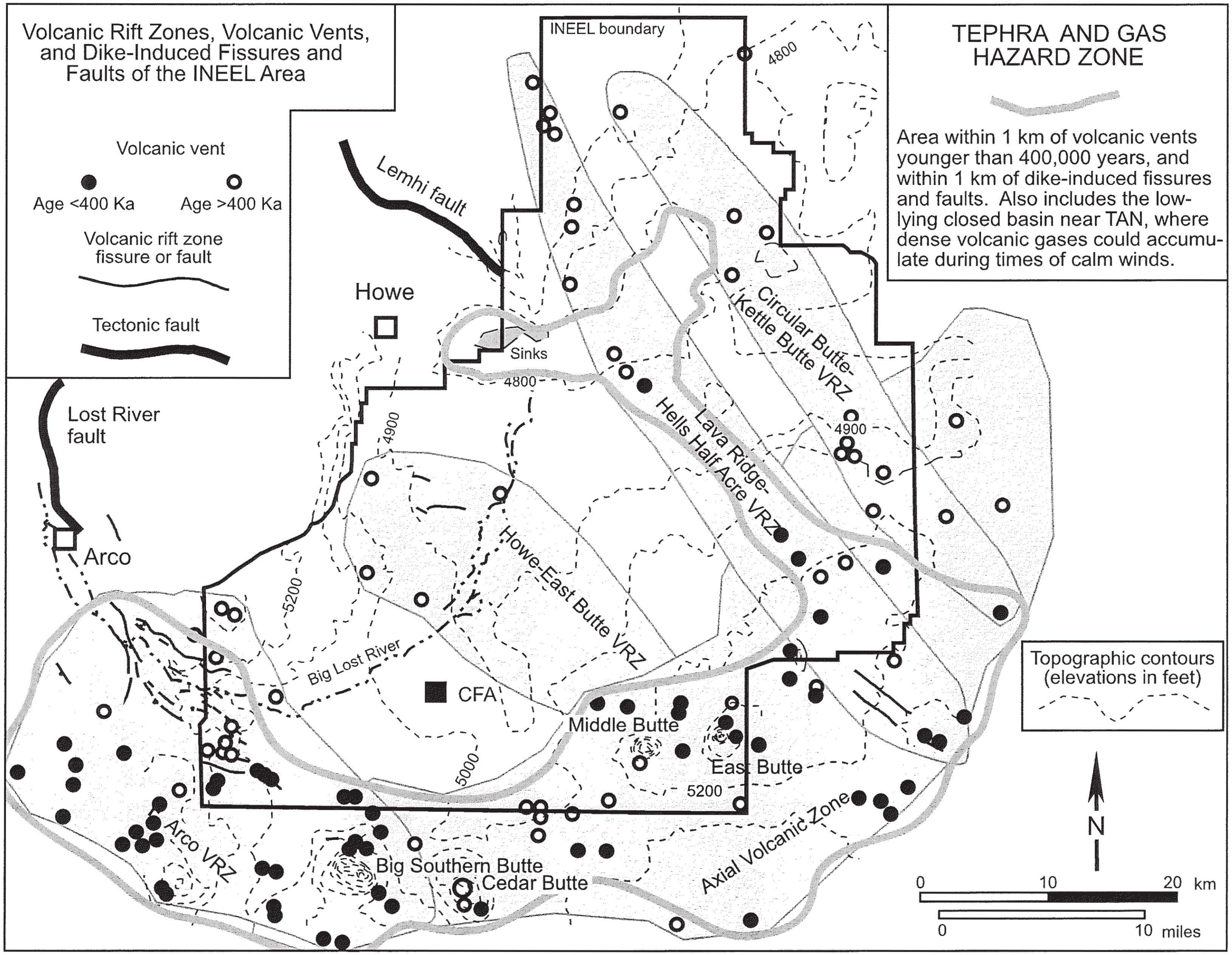

Figure 6. Tephra and gas hazard-zone map of the INEEL area. Filled square shows the location of the Central Facilities Area.

and may be related to basin subsidence rather than dike intrusion. Although these fissures are included in this hazard assessment, we do not consider them to be a likely site of future volcanism.

VOLCANIC-HAZARD ASSESSMENT OF THE CENTRAL FACILITIES AREA

The Central Facilities Area (CFA; Figure 8) is a cluster of buildings and other facilities located on the southwestern INEEL, about 15 km from vents of the volcanic zones to the west and south, and within a topographic basin about 100 m lower in elevation than the surrounding volcanic highlands. Given its distance and physiographic setting, the CFA seems unlikely to be impacted by tephra, gas or dike-induced ground deformation, but the CFA could be inundated by future lava flows from the adjacent volcanic zones. We therefore give a site-specific probabilistic hazard assessment for lava-flow inundation of the CFA.

The parameters needed to estimate the probability of lava inundation are the recurrence intervals of the volcanic source zones, the topographic setting of the CFA and the volcanic zones, the statistics of the lengths and areas of lava flows, the distance from CFA to potential sources of lava flows, the warning time prior to inundation, and the probability of successful mitigation.

We illustrate our approach with an event tree (Figure 9). The event tree is an inductive-logic modeling tool used to identify and depict the chains of events that may result in some outcome of interest, in this case an outcome important as a hazard. The event-tree modeling process begins with an initial condition which may lead to several end-states, depending on the results of subsequent events. The events can be processes, functions, conditions, mitigators, or barriers that are relevant to the outcome of interest. Event-tree branches represent decision points in modeling the combinations of events. Upward branches represent success or the achievement of a desired outcome. Downward branches represent failures of functions or barriers, or the absence of some relevant condition. Application of the event tree uses binary branching (i.e., success vs. failure, condition present vs. condition not present). Each node represents the universe of possible functional or conditional states. Therefore, the probabilities of all the possible states must sum to one. Probabilities are assigned to each event-tree branch, and the probability of each event sequence is the product of the branch probabilities.

"Eruption" is the initial condition, and the 6×10^{-5} per year recurrence value expresses the probability of volcanism at a random location within the Arco volcanic rift zone and the axial volcanic zone (Table 3), which we express as one value because of the nearly identical recurrence estimates.

The second event, "lava flows away from CFA," concerns vent location and topography relative to CFA, which lies outside the volcanic zones. On figure 8, we identify a "critical volcanic source area," which is the region that might send lava flows on a path toward the site. The critical volcanic source area is defined on its southern margin by a topographic divide. Lava flows erupting south of this divide will flow south, away from the CFA. Topographic analysis also shows that lava flows originating from any place on the axial volcanic zone northeast of East Butte will not flow toward CFA. The critical volcanic source area encompasses 660 square km, or 0.29 of the total 2,270 square-km area of the combined Arco and axial volcanic zones.

The third event, "lava stops short of CFA," addresses the probability of lava reaching CFA. If lava reaches CFA, total inundation is assumed; advanced warning and mitigation are addressed later. The CFA is located about 10 km (the 50th-percentile lava-flow length, Table 4) from the critical volcanic source area, and most of the young vents within the source area lie within 20 km (the 80th-percentile lava-flow length). We use the 70th-percentile distance of 16 km as an average distance from inferred lava-flow sources to the CFA. By statistical definition only 30 percent of lava flows from that distance will reach the CFA.

The fourth event addresses warning time for mitigation, and there is considerable uncertainty in deriving this parameter. We assume that 80 percent of lava flows would give at least 1 month advanced warning, and we consider 1 month to be adequate for effective mitigation by the removal of property or the construction of barriers. We justify this by analogy with the active basaltic rift zones of Iceland and Hawaii, where magma usually takes several weeks, commonly several months, to ascend to the surface from upper-mantle source regions. Based on seismic-velocity investigations, the inferred source of magma beneath the eastern SRP is 50-200 km deep, and ascending magma from those depths would be readily tracked by the INEEL seismic network. A second aspect of advanced warning involves lava-flow velocity, or the time to reach CFA after the onset of eruption. Observed basaltic lava flows on low-relief terrain such as the southern INEEL generally move at rates less than several kilometers per day. Tilling and Peterson (1994) summarize field observations of active lava flows from the east rift zone of Kilauea, Hawaii, and find that the average rate of advance of broad lava-flow fronts to be 5 km per day. Fink and Zimbelman (1986) also observed Hawaiian pahoehoe

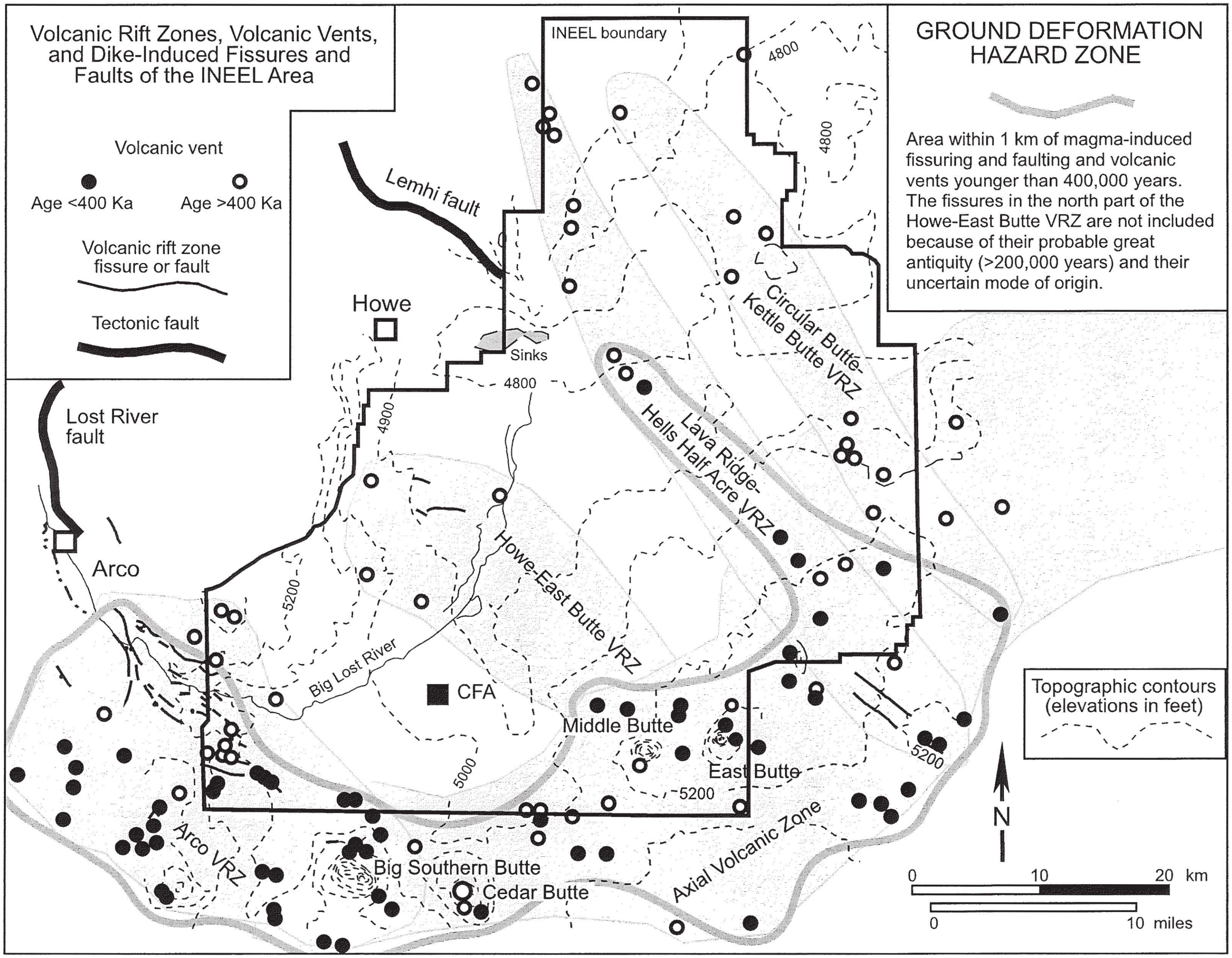

Figure 7. Ground deformation hazard-zone map of the INEEL area. Filled spuare shows the location of the Central Facilities Area.

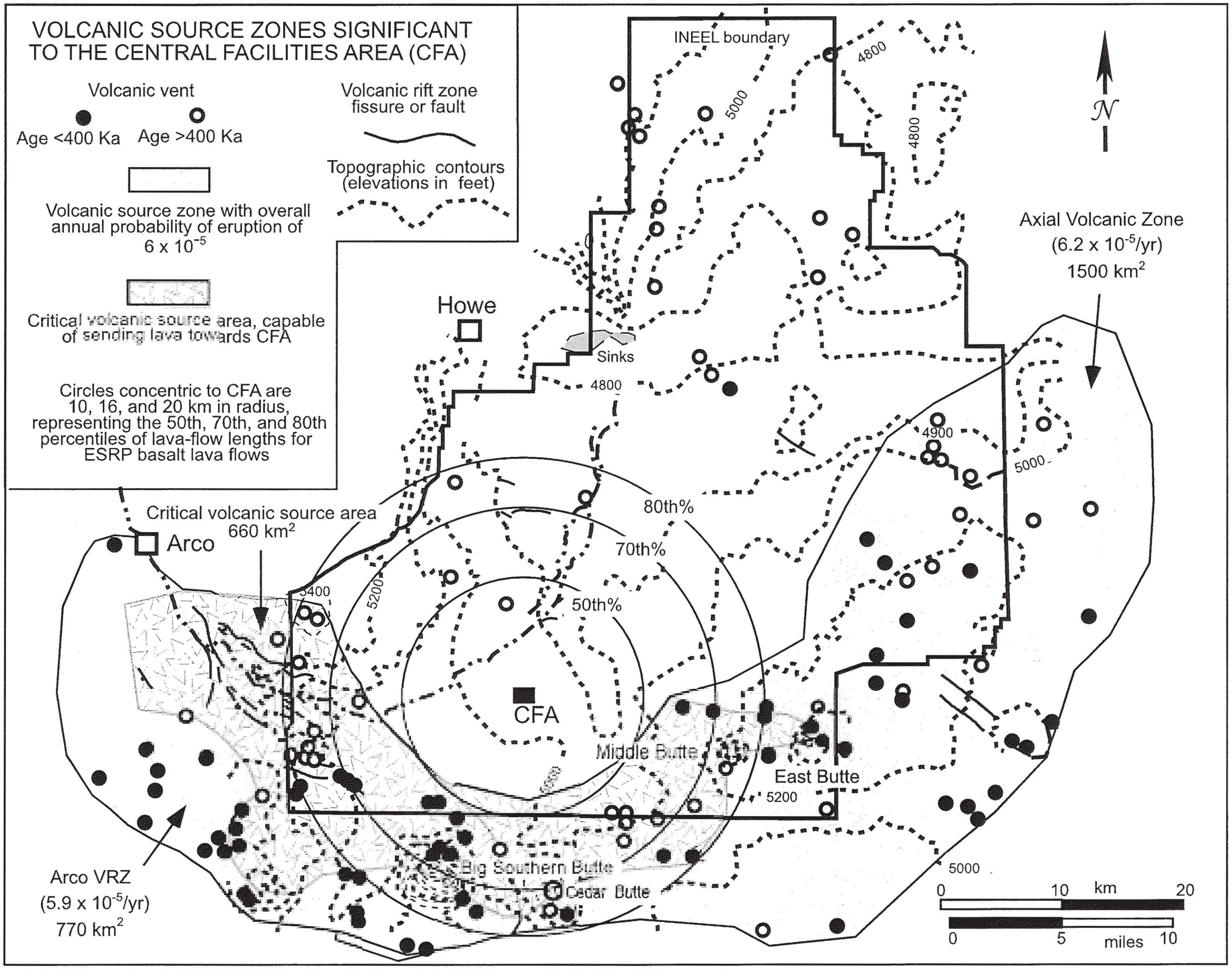

Figure 8. Volcanic source zones significant to the Central Facilities Area (CFA), INEEL.

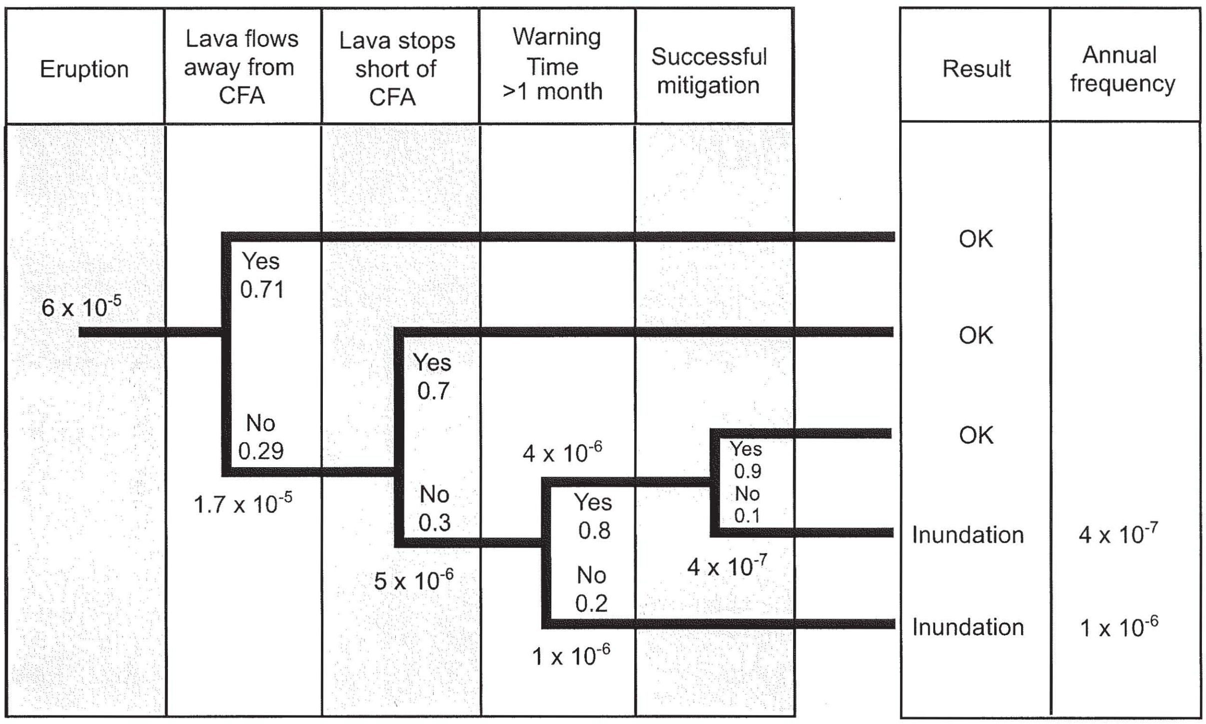

Figure 9. Volcanism event tree for lava-flow inundation of the Central Facilities Area (CFA), INEEL.

flow velocities on terrain similar to that of the INEEL to average 5 km per day. Hon and others (1994) give an average velocity of about 1 km per day for typical pahoehoe sheet flows in Hawaii. Bullard (1962) describes basaltic lava flows from several Hawaiian and Mexican volcanoes and cites near-source velocities of about 1 km per hour during the early stages of eruption, about 400 m per day after the flows had spread on gentle terrain, and as low as 1 m per day in the final stages, weeks or months after onset.

Assuming a rate of 2 km per day, it would take a lava flow about a week to travel the 16-km distance from the center of a nearby volcanic zone to the CFA. Together with several weeks of precursory seismic warning, our analysis suggests that about 1 month of advanced warning of lava inundation is probable. For event 4, our chosen probability of 0.2 assumes that only 20 percent of lava flows will fail to give 1 month of warning.

The fifth event addresses the probability of successful mitigation, given 1 month or more of warning. We assume that mitigation would be unsuccessful only 10 percent of the time. Potential actions (Barberi and others, 1993) include the removal of materials, the construction of earthen berms around CFA facilities, the building of earthen berms in the flow path to slow or divert the lava, the cooling of the lava-flow front with water sprays near critical facilities, and the use of explosives at or near the vent area to route the lava elsewhere.

Results are expressed as annual frequencies on the right of Figure 9. If no mitigation is possible, the estimated frequency of CFA property damage due to lava inundation is 1×10^{-6} per year. If mitigation is attempted, the estimated frequency is 4×10^{-7} per year.

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