UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Geology of the Arco-Big Southern Butte area, eastern Snake River Plain, and potential volcanic hazards to the radioactive waste management complex, and other waste storage and reactor facilities at the Idaho National Engineering Laboratory, Idaho

by

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With a section on Statistical treatment of the age of lava flows

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ABSTRACT

The Arco-Big Southern Butte area of the eastern Snake River Plain, Idaho, includes a volcanic rift zone and more than 70 Holocene and late Quaternary basalt volcanoes. The Arco volcanic rift zone extends southeast for 50 km from Arco to about 10 km southeast of Big Southern Butte. The rift zone is the locus of extensional faults, graben, fissure basaltic volcanic vents, several rhyolite domes at Big Southern Butte, and a ferrolatite volcano at Cedar Butte. Limited radiometric age data and geological field criteria suggest that all volcanism in the area is younger than 700,000 years; at least 67 separate basaltic eruptions are estimated to have occurred within the last 200,000 years. The average volcanic recurrence interval for the Arco-Big Southern Butte area is approximately one eruption per 3,000 years.

Radioactive waste storage and reactor facilities at the Idaho National Engineering Laboratory may be subject to potential volcanic hazards. The geologic history and inferred past volcanic events in the Arco-Big Southern Butte area provide a basis for assessing the volcanic hazard. It is recommended that a radiometric age-dating study be performed on rocks in cored drill holes to provide a more precise estimate of the eruption recurrence interval for the region surrounding and including the Radioactive Waste Management Complex. It is also recommended that several geophysical monitoring systems (dry tilt and seismic) be installed to provide adequate warning of future volcanic eruptions.

INTRODUCTION

Purpose of study

Recognition of youthful volcanic features at the Idaho National Engineering Laboratory (INEL) led the Office of Waste Management, Idaho Operations Office, U.S. Department of Energy, to request that the U.S. Geological Survey investigate the distribution in space and time of past volcanism for the purpose of evaluating whether a credible volcanic hazard exists at the INEL site.

This report summarizes the geological data from the southwestern part of INEL and adjoining lands that has been used to document the spatial and temporal distribution of volcanism defined thus far.

The INEL and the area covered by this report are located on the northwest margin of the eastern Snake River Plain, Idaho, an area of Pleistocene and Holocene basaltic and rhyolitic volcanism (fig. 1). Evaluation of the volcanic history of the area and of associated potential volcanic hazards is based primarily on geologic field mapping, a limited number of radiometric age dates of lava flows, and a statistical assessment of volcanic recurrence intervals.

A geologic map of the Arco-Big Southern Butte area will be referred to frequently throughout this report (Kuntz, 1978), as it contains much of the geologic and radiometric age data on which this study is based.

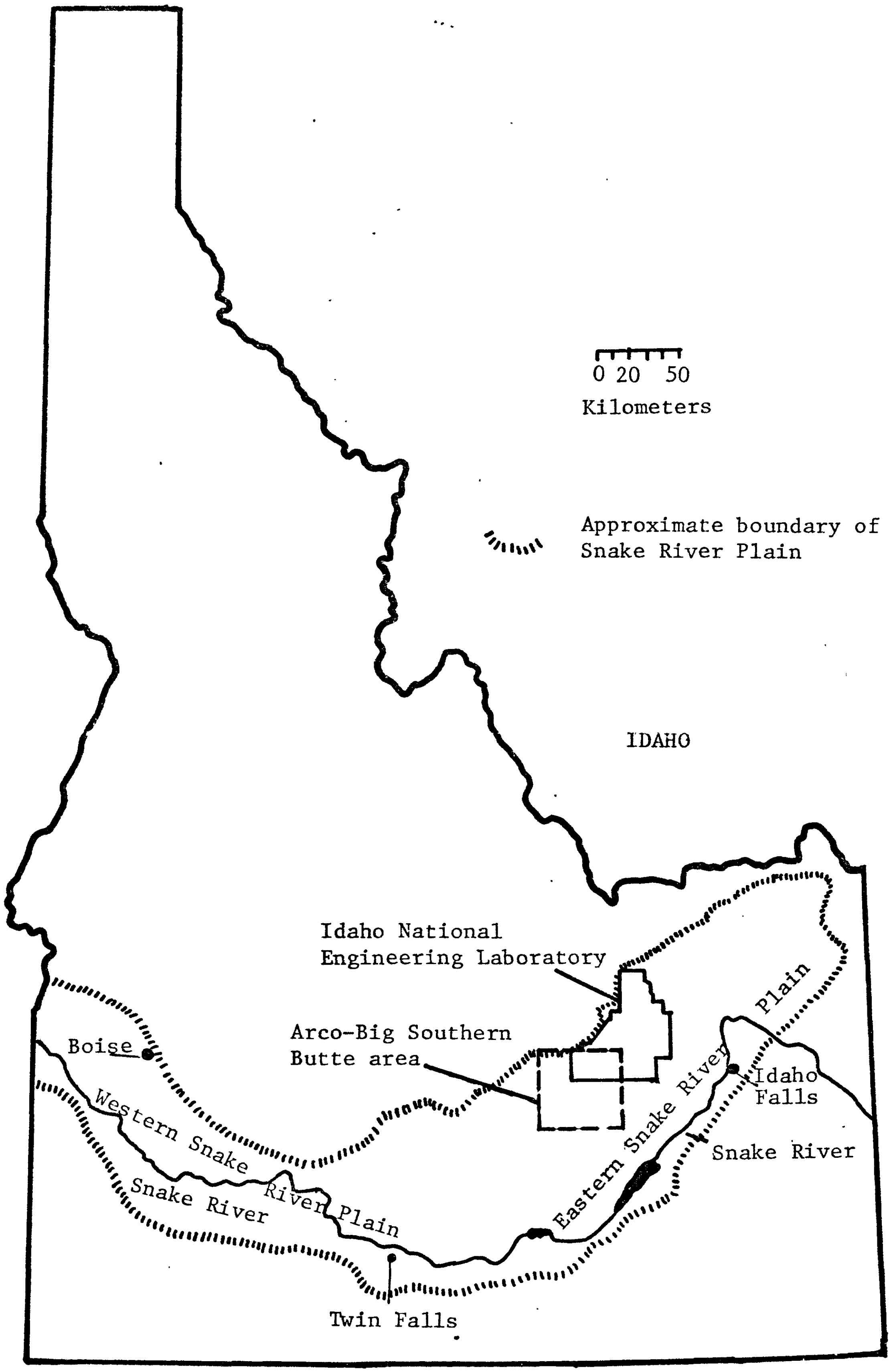


Figure 1.--Map of Idaho showing location of the Snake River Plain, Snake River, Idaho National Engineering Laboratory, and Arco-Big Southern Butte area.

Scope of study

Radioactive waste storage and reactor facilities at INEL are subject to a variety of natural hazards such as earthquakes, floods, and volcanoes. This report deals chiefly with volcanic hazards, but seismic activity accompanying volcanism and faulting on the eastern Snake River Plain and the impoundment and diversion of drainage by lava flows are discussed where appropriate. This report describes the kind of volcanic processes and products that may constitute a potential volcanic hazard, but it does not treat engineering, chemical-reaction, and contamination-dispersal problems that might occur from the possible interaction between volcanic products and stored wastes or reactor facilities at INEL.

Because geologic studies on the eastern Snake River Plain are still in progress, this report is preliminary. Nonetheless, the writer feels that early release of this assessment of volcanic hazards may be useful for planning purposes; results of continuing studies may alter the fine details of the judgments presented here but not their essential form.

GEOLOGY OF THE ARCO-BIG SOUTHERN BUTTE AREA

Introduction

This section briefly describes a range of volcanic phenomena and products typical of "plains" or rift-controlled basaltic volcanism, in order to evaluate the spatial and temporal distribution of volcanism in the Arco-Big Southern Butte area and the nature of possible volcanic hazards to facilities at INEL. The section also provides some generalizations about the character and distribution of basaltic volcanic rocks on the eastern Snake River Plain (hereafter abbreviated ESRP), and inferences are made about the processes which accompanied past volcanism and may occur during future volcanism.

Rhyolitic volcanism has occurred in the Arco-Big Southern Butte area and elsewhere on the ESRP, but its temporal and spatial distribution are more limited than for basaltic volcanism. Thus, discussion of rhyolitic volcanism and its role in volcanic hazards is cursory in this report.

Similarities exist between basaltic volcanic landforms and products erupted in historic time (particularly Hawaii) and those recognized on the ESRP. This relationship suggests that we can make reasonably good inferences about the kinds of volcanic processes that have operated on the ESRP in the past. Thus, the discussion which follows, with some examples based on Hawaiian eruptions, is believed applicable to past and future eruptions on the ESRP.

In order to evaluate the potential volcanic hazard to facilities at INEL, the geologic history of the Arco-Big Southern Butte region, a 1,700-km^2 area roughly centered on the Radioactive Waste Management

Complex, has been reconstructed. It is assumed that future volcanic events in the area will be of the same general type, magnitude, and duration as those inferred to have occurred in the past. Based on the geologic history of this area, several models of various kinds of volcanic eruptions can be prepared to show the possible range of volcanic processes and possible volcanic hazards that may accompany future eruptions.

Eruptive processes and products in basaltic volcanism

Basaltic volcanism occurs as fissure eruptions within volcanic rift zones in many parts of the world, including Hawaii (Macdonald and Abbott, 1970), Iceland (Macdonald, 1972), and the ESRP (Kuntz, 1977a, 1977c). Volcanic rift zones are belts of structures and volcanic landforms in which eruptions of a region are localized. A volcanic rift zone is marked by a rectilinear array of open fissures, faults, graben, eruptive fissures, spatter cones and spatter ramparts, cinder cones, lava cones, pit craters, and shield volcanoes whose vents are elongated over eruptive fissures (Wentworth and Macdonald, 1953; Kuntz, 1977a, 1977c).

Typical eruptions in Hawaii and probably in the ESRP consist of distinct though gradational stages summarized below. The hours preceding an Hawaiian eruption are characterized by harmonic tremor, ground cracking, and occasional and local steam-fume activity. The first few hours of the eruption typically consist of a long line of lava fountains extending for hundreds of meters and occasionally for a few kilometers along a single fissure or a series of en echelon fissures in a volcanic rift zone. The basaltic lava in the early eruptive stages is extremely fluid and heavily charged with dissolved gases. Release of the gas due to a decrease in confining pressure and magma pressure leads to eruption of lava to heights of as much as 500 m. Such fountaining is generally accompanied by voluminous outwelling of fluid lava along nearly the entire fissure. The early stages of an eruption lead to the development of spatter ramparts, low walls of agglutinated spatter, along both sides of erupting fissures. Fine tephra erupted above a vent may fall out as much as several hundred meters downwind, depending on height of lava fountains and the speed of prevailing winds.

After several hours or days, the length of an erupting fissure typically diminishes and lava fountains become localized along short segments of fissures. The fountains may reach their greatest height during this phase. Spatter ramparts are succeeded by spatter cones or, more rarely, cinder cones, which are built up around the lava fountain. Generally one or more lava flows drain away through gaps in the cone walls during the cone-building stage.

After several hours, days, or weeks, a decrease in magma pressure and amount of dissolved gas in the magma leads to a corresponding decrease in size of lava fountains and thus to a change in the types of volcanic processes and landforms. During long-lived Hawaiian activity, lava fountaining diminishes and is followed by quiet but voluminous outpouring of lava over or through the existing spatter or cinder cone. A continued period of overflow of lava tends to produce a lava cone, composed largely of sheets of pahoehoe lava that mantle the older cone structure. Lava-cone summits are typically indented by an elongated crater. The elongation of the crater is generally parallel to the underlying fissure or rift, which serves as a channelway for access of magma to the vent. Large craters are formed by collapse of the crater walls, accompanied by repeated crater filling and draining. Lava cones are generally several kilometers wide and may reach heights of several hundred meters. Their sides slope at angles generally less than 5 degrees.

Prolonged eruption of fluid basaltic lava extending over periods of months and possibly years at a single vent leads to the formation of large lava cones called shield volcanoes. They are formed by the continued build-up of thin, far-spreading pahoehoe and, to a lesser extent, aa lava flows. The flows produce a broad, rounded, flat shield-shaped landform as high as about 2,000 m and as wide as 30 km. Very little explosive activity is involved in the shield-building stage. This stage is typically represented by formation of lava lakes, filling and draining of lava in the crater, collapse of crater walls, and effusion of predominantly pahoehoe lava flows. (See Macdonald, 1972; Macdonald and Abbott, 1970; Wentworth and Macdonald, 1953.)

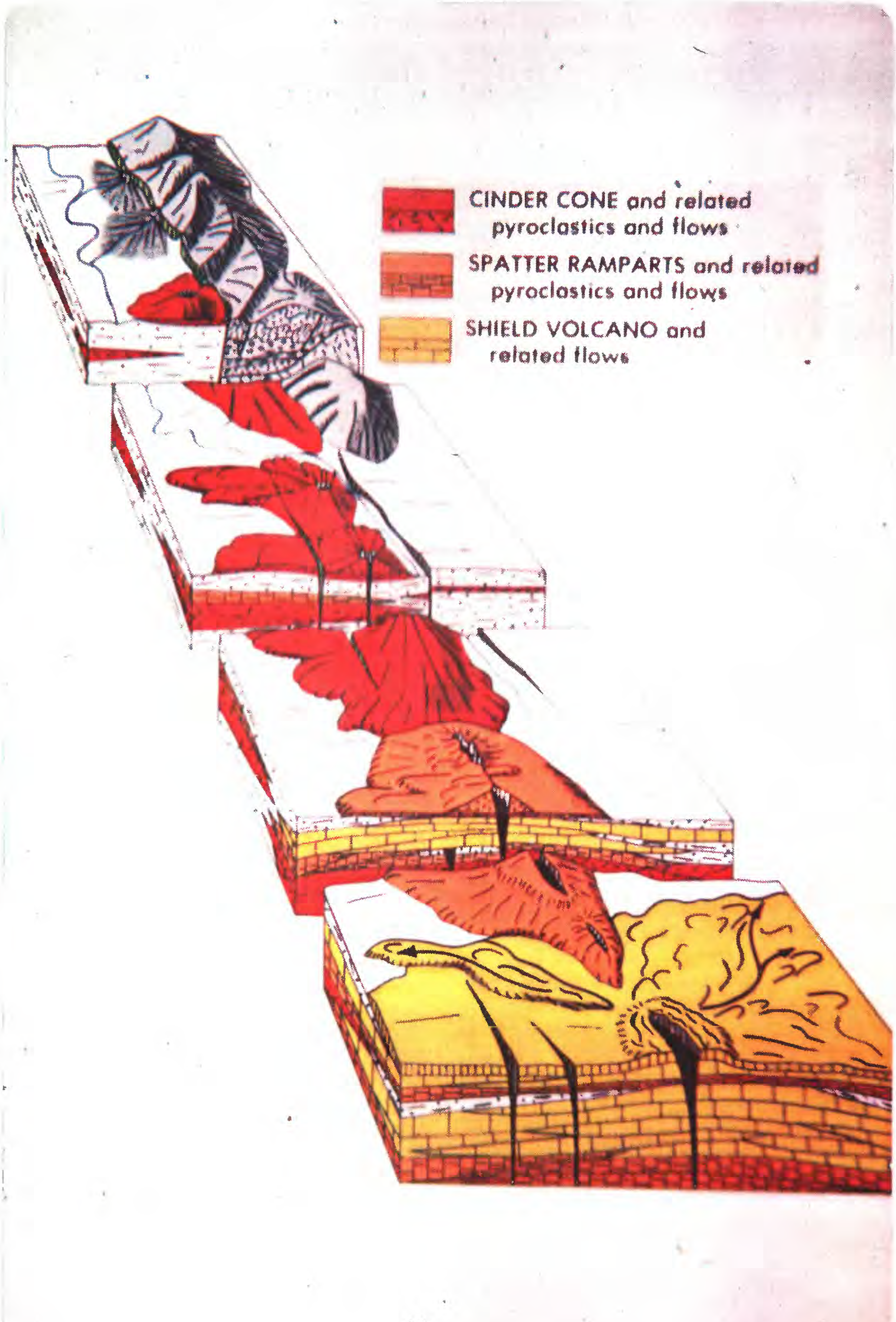
The phases described above represent a generalized gradational sequence during a prolonged basaltic eruption, and individual eruptions may include only some of the phases described. Distinctive volcanic landforms representative of each phase of such an eruptive cycle are found throughout the ESRP, indicating that the generalized eruptive cycle has occurred in the ESRP.

Basaltic volcanism of the eastern Snake River Plain and the Arco-Big Southern Butte area

Volcanic rift zones

That some volcanism on the ESRP is localized on volcanic rift zones has been known for some time (Stearns, 1928; Stearns and others, 1938, Prinz, 1970). However, Kuntz (1977b, 1977c) suggested that nearly all Quaternary volcanoes of the ESRP represent rift- or fissure-controlled eruptions and that their distribution is not random as has been stated by some workers. Figure 2 is a diagrammatic representation of the distribution of structural and volcanic features in a typical volcanic rift zone in the ESRP. Kuntz (1977c) noted that most of the volcanic rift zones in the ESRP appear to be extensions onto the plain of basin-range range-front faults and older structures, such as thrust faults, which occur in the mountains outside the plain. An example of a volcanic rift zone as an extension of a basin-range structure is the Arco rift zone--an extension onto the ESRP of the range-front fault along the western side of the Lost River range (Kuntz, 1977a). Additional examples of volcanic rift zones in the ESRP are (1) the Lava Ridge-Hells Half Acre and Circular Butte-Kettle Butte rift zones--extensions of boundary faults on the eastern side of the Lemhi Range and western side of the Beaverhead Range, respectively, (2) the Howe-East Butte rift zone--an extension of a boundary fault on the eastern side of the Lost River Range, and (3) the Great Rift zone--an extension of a belt of normal faults and thrust faults in the Pioneer Mountains (fig. 3). These relations suggest that basin-range and older structures are present in the upper crust beneath the ESRP and that their continued

Figure 2.--Diagrammatic representation of features in a typical volcanic rift zone in the eastern Snake River Plain.



tectonic development is expressed in the form of volcanic rift zones in the overlying volcanic pile.

The Arco rift zone extends for about 50 km southeastward from the northern margin of the ESRP at Arco to the long axis of the plain southeast of Cedar Butte (fig. 3). The Arco rift zone is the locus of extensional faults, graben, numerous fissure-controlled basalt volcanoes, the rhyolite domes of Big Southern Butte, and the ferrolatite volcano at Cedar Butte (Kuntz, 1977a, 1978). The Arco rift zone terminates southeast of Big Southern Butte and Cedar Butte, where it is intersected by structures of the northeast-trending Rock Corral Butte rift zone (fig. 3). The unique spatial relationships between these rift zones suggest that they are the surface expression of both basin-range structures and other crustal zones of weakness (fig. 3). The northeast trend of the Rock Corral Butte rift zone, nearly perpendicular to other volcanic rift zones, suggests that this rift zone may be related to a crustal zone of weakness of pre-Tertiary (Precambrian?) origin.

The area between the Arco rift zone and the Great Rift is the site of numerous dispersed fissure-controlled volcanoes (Kuntz, 1978). This suggests that although the structural deformation and density of volcanoes are concentrated in the two rift zones they are not limited to them exclusively. Crustal extension and volcanism between the two rift zones have continued concurrently with deformation and volcanism in the two rift zones. The Great Rift zone has indistinct boundaries and its most recent activity has been centered along a narrow belt in its central part, particularly in Craters of the Moon National Monument (fig. 3, LaPoint, 1977).

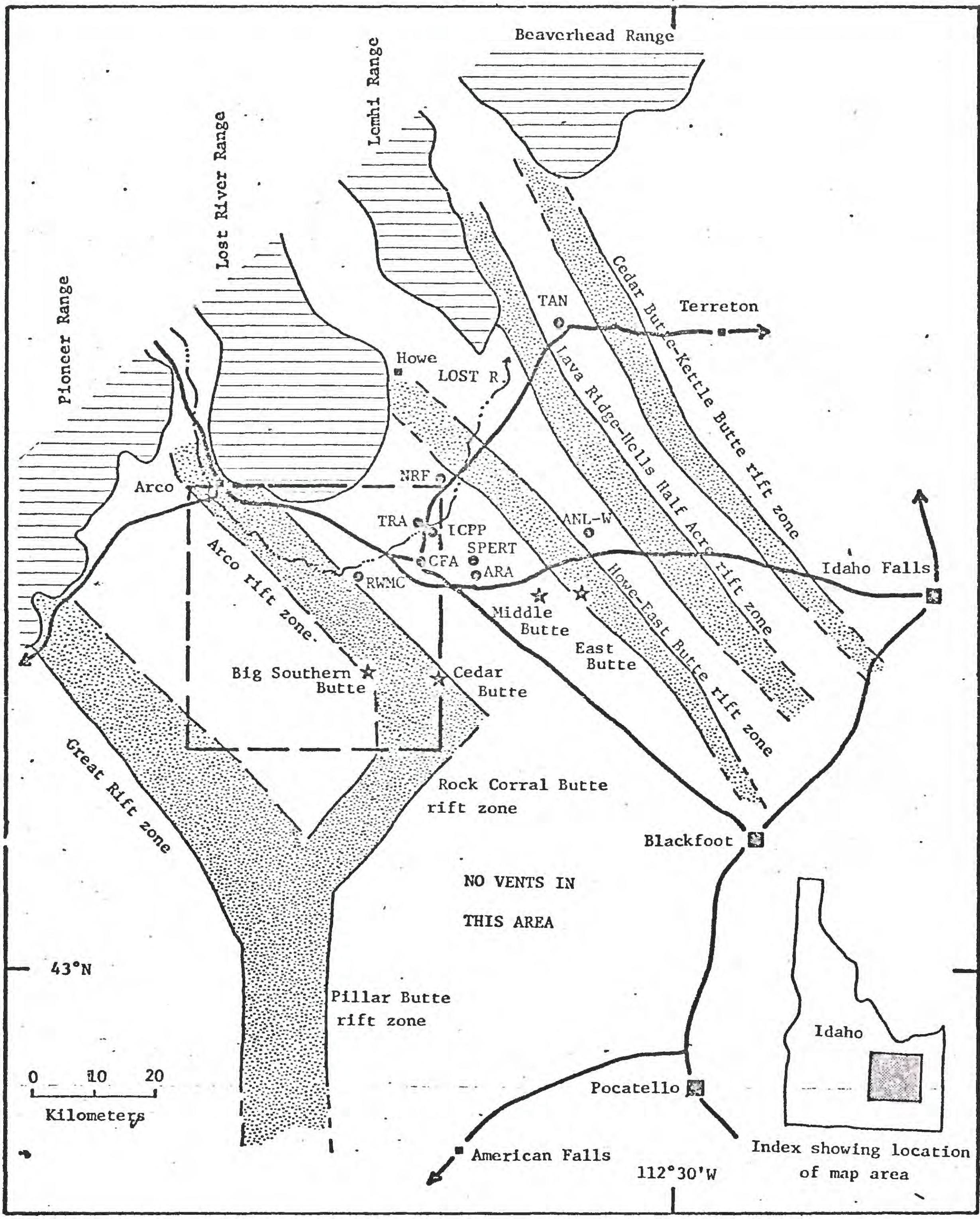


Figure 3.--Volcanic rift zones (stippled pattern) of the north-central part of the eastern Snake River Plain; contacts dashed where boundaries are uncertain. Solid lines are major highways; dashed line is the outline of the Arco-Big Southern Butte area shown in the geologic map (Kuntz, 1978).
INEL facilities:
RWMC, Radioactive Waste Management Complex; CFA, Central Facilities Area; ARA, Advanced Reactor Area; SPERT, Special Power Excursion Reactor Test; TRA, Test Reactor Area; ICPP, Idaho Chemical Processing Plant, NRF, Naval Reactors Facility; TAN, Test Area North; ANL-W, Argonne National Laboratories-West.

Volcanic rift zones are well defined northeast of the Arco rift zone, but less clearly so to the southwest. This is probably due to the fact that basin-range faults are more prominent to the northeast; basin-range structure is particularly striking northeast of the Lost River Range. The Pioneer Mountains are not as obviously traversed or bounded by major basin-range faults; thus, volcanic rift zones are spread widely across the ESRP opposite the Pioneer Mountains.

The continuation of basin-range faults across the margins of the ESRP and the lack of geological and geophysical evidence for faults parallel to the boundary of the ESRP suggest that the ESRP is not a graben structurally decoupled from the surrounding mountains but rather a downwarp (Kirkham, 1931) developed within the Basin and Range province.

Structures in the Arco rift zone (ARZ)

Faults

Faults are abundant and well developed along the Big Lost River about 8 km southeast of Arco. Extensional faults that have as much as 10 m of vertical displacement here have produced a graben that controls the course of the Big Lost River (Kuntz, 1978).

The straight courses and sharp bends in the Big Lost River at this locality demonstrate strong structural control by faults with trends of N. 45° W. and N. 45° E. Few of the faults in this area are visible at the surface; most older faults and graben are probably buried by younger lava flows. Most of the faults show clear scarps (fig. 4), but some faults display reverse drag of surface basalt in the downthrown block

Figure 4.--Fault in lavas in the Arco Rift zone, 4.5 km east of Sixmile Butte. (See pl. 1.) Vertical displacement approximately 3.5 m. Big Southern Butte in background.

and only partial offset of the lava flow along the fault (fig. 5). Fault traces range from rectilinear to curving. The amount of offset on individual faults is greatest near the central part of the trace and decreases to zero at either end. The lengths of traceable individual faults range from several tens of meters to as much as 4 km. Most fault scarps are relatively fresh. The few slickenslides observed suggest a purely dip-slip component of last movement. The amounts of displacement on all faults are similar to those of faults associated with the Hebgen and Dixie Valley earthquakes (Witkind, 1964; Richter, 1958); thus all of the offset on faults in the Arco rift zone (ARZ) could have formed in a single episode of deformation.

Displacements on faults generally decrease to the southeast and, about 15 km southeast of Arco, the faults pass into open fissures that have purely horizontal displacement. This relationship illustrates a fundamental difference in present tectonism between areas outside and within the ESRP; broad-scale extension is manifested in vertical and horizontal strain and resulting basin-range topography in mountains north and south of the ESRP but apparently only in horizontal extension near the axis of the ESRP. Two explanations may be given for this relationship: (1) the amount of vertical offset produced by extension is greater in the mountain ranges north and south of the ESRP and decreases toward the axis of the plain, or (2) fault scarps on the plain are covered by synchronous and younger laval flows.

The ESRP is aseismic based on historic earthquake records and short-term microearthquake studies (Smith and Sbar, 1974; Pennington and others, 1974). Yet it seems clear that the faulting in the Arco rift

Figure 5.--Fault in lavas in the Arco Rift zone, near tracks of Union Pacific Railroad, 10 km southeast of Arco. (See Kuntz, 1978.) Vertical displacement approximately 10 m. Note draping or reverse drag of lavas in the downthrown block (right) along the fault scarp. View to southeast; Big Southern Butte in background.

zone (ARZ) must have been accompanied by earthquakes. Correlations between fault length and earthquake magnitude (Bonilla and Buchanan, 1970; Seed and others, 1969) suggest that faults in the ARZ (as much as 4 km in length) may have been accompanied by earthquakes with magnitudes on the order of 2.5 to 5.5. if the observed displacements took place in a single event.

Lineaments

Lineaments of various trends are conspicuous on airphotos of the Arco-Big Southern Butte area. Those with northeast trends reflect eolian features and prairie-fire scars based on examination in the field and, thus, they are not plotted on the geologic map (Kuntz, 1978).

Lineaments with a northwest trend were examined in the field to determine whether they reflect underlying structural deformation. Several of the lineaments are extensions of fissures and faults. Some are elongated depressions in surficial sediments and occur parallel to nearby fissures and faults. Other lineaments are zones of more luxuriant growth of grass or sagebrush but lack a surface depression or other obvious relation to bedrock deformation. However, all lineaments of the latter type parallel known faults and fissures, suggesting that they too are the surface expressions in soils of underlying faults and fissures.

Volcanoes

Volcanoes representative of all types of basaltic volcanism that have been described in the preceding discussion, from fissure eruptions through spatter ramparts and cinder cones to lava cones and shield volcanoes, are present in the Arco-Big Southern Butte area. The following discussion of the volcanism of the Arco-Big Southern Butte area is based on models of the processes and products of various types of basaltic volcanism. This emphasis is used to relate the volcanic landforms and products observable in the Arco-Big Southern Butte area to the volcanic processes responsible for their formation and to aid in the interpretation of volcanic hazards.

Fissure eruptions

Fissure eruptions have occurred in the past along the Arco rift zone and the Great Rift throughout the Arco-Big Southern Butte area. These eruptions are characterized by the eruption of both large and small volumes of lava from fissure vents, by attendant lava-fountain activity, and by development of spatter ramparts and cinder cones. Tephra emitted from the fissure may be carried vertically to heights of as much as 100 m and carried horizontally for as much as several kilometers downwind. These eruptions are relatively explosive at the vent areas throughout their eruptive history.

Fissure eruptions in the Arco rift zone have occurred southeast of Big Southern Butte at the North Robbers and South Robbers vent areas (Kuntz, 1978). The eruptions at these two localities produced relatively small lava flows (tables 1 and 2). Spatter ramparts and

Table 1.--Areas and volumes of lava flows from fissure vents, shield volcanoes, and lava flows in Hawaii, Iceland, and the eastern Snake River Plain, Idaho

Lava flow	Location	Area(km^2)	Volume(km^3)	Reference
Fissure vents				
1950 flows, SW rift, Mauna Loa.	Hawaii	92	0.47	Wentworth and Macdonald, 1953.
1823 flows, SW rift, Kilauea.	Hawaii	10.0	.10	Do.
Craters of the Moon (flows from many vents).	ESRP	~300	~30.0	LaPoint, 1977.
North Robbers flow---	ESRP	5.4	.04	Kuntz, 1978.
South Robbers flow---	ESRP	3.1	.02	Kuntz, 1978.
King's Bowl----------	ESRP	4.5	.08	LaPoint, 1977.
Shield volcanoes and lava cones				
Mauna Loa-----------	Hawaii	13x10^3	42.5x10^3	Bargar and Jackson, 1974.
Mauna Kea-----------	Hawaii	6x10^3	24.8x10^3	Do.
Kilauea-------------	Hawaii	---	19.4x10^3	Do.
Mauna Iki-----------	Hawaii	13	.6	Wentworth and Macdonald, 1953.
Skjaldbreidur--------	Iceland	15	17	Macdonald, 1972.
Hells Half Acre------	ESRP	425	8.6	LaPoint, 1975.
Wapi----------------	ESRP	300	12.2	Do.
Cerro Grande---------	ESRP	180	3.6	Do.
Little Grassy-------- Ridge.	ESRP	340	8	Do.
Kettle Butte[1]	ESRP	310	10.9	Do.
Quaking Aspen Butte.[1]	ESRP	120	6.1	Kuntz, 1978.
Fingers Butte--------	ESRP	45	1.1	Do.
Serviceberry--------- Butte.[1]	ESRP	120	2.7	Do.
Crater Butte*	ESRP	240	3.6	Do.

1 Because distal flows are covered by younger flows from nearby vents, length is minimum value.

Table 2.--Length of lava flows from shield volcanoes in the Arco Big-Southern Butte area

Vent	Maximum length of lava flows from vent (km)
Crater Butte	26
Quaking Aspen Butte	25
Cerro Grande	20
Fingers Butte	13
Serviceberry Butte[1]	12
Rock Corral Butte	10

1 Because distal flows are covered by younger flows from nearby vents, length is minimum value.

small cinder cones are present at several localities along the fissures in each of these vent areas. Coyote Butte is a spatter rampart aligned along a fissure northwest of Big Southern Butte (Kuntz, 1978).

Fissure eruptions in Craters of the Moon National Monument (LaPoint, 1977) have produced lava flows that extend as much as 30 km from their source vents. Comparison of the lengths of lava flows from fissure vents at Craters of the Moon National Monument and at other localities in the ESRP suggests that 30 km represents maximum values and that lengths of 5-10 km are average values.

Tephra blankets extend downwind as much as 1 km from source fissure vents at various localities in the ESRP. The ESRP is in a belt of prevailing southwesterly winds (Energy Research and Development Administration, 1977); thus tephra deposits typically accumulate to the northeast of source vents.

Lava cones

Lava cones are small shield volcanoes consisting largely of lava flows containing very little pyroclastic material. Excellent examples of lava cones are found throughout the Arco-Big Southern Butte area. Lava cones along the margins of the Arco rift zone are Lavatoo Butte, Teakettle Butte, Lost River Butte, and Wildhorse Butte (Kuntz, 1978). These lava cones range in width from about 1 to 5 km and in height from about 50 to 100 m. Their summits are indented by elongated craters; the elongation trends parallel to source fissures.

Shield volcanoes

Lava flows that erupted throughout a long period of time have produced shield volcanoes at widely scattered localities in the Arco-Big Southern Butte area. Examples of shield volcanoes in the Arco-Big Southern Butte area are Quaking Aspen Butte, Serviceberry Butte, Crater Butte, Sixmile Butte, and Cerro Grande Butte (Kuntz, 1978). Such eruptions probably began as fissure eruptions and reached the shield-eruption stage after months or years of eruptive activity. The early-stage eruptive processes are similar to those described above for the fissure-eruption model. Later-stage eruptive processes involve piston-like filling and draining of magma in the vent, collapse of vent walls, and repeated discharges of large volumes of low-viscosity ($\sim$1 poise), high-temperature (1,200 to 1,000^{o}C) lava.

Depending upon such factors as viscosity, temperature and composition of lava, volume and duration of eruption, and pre-flow topography, lava flows in the Arco-Big Southern Butte area have travelled considerable distances from their shield source vents (table 2). The data in tables 1 and 2 emphasize that long-duration, relatively high volume eruptions of the shield-volcano type have the potential of erupting lavas that can move great distances from their source vents.

The distribution of volcanoes of various types sheds some light on the fissure and fault "plumbing" system of the Arco-Big Southern Butte area and particularly of the Arco rift zone. Kuntz (1977c) has noted that vents which represent early-stage or short-duration, low-volume eruptions (spatter ramparts and cinder cones) are generally more common along volcanic rift zones near the plain margins, whereas shield volcanoes are more common near the axis of the plain. However, the Arco rift zone presents an exception to this general rule: shield volcanoes occur throughout the Arco rift zone. These relationships suggest that fissures and faults provide surface access to large volumes of basalt magma regardless of position within the Arco rift zone.

Hydromagmatic eruptions

A small but significant number of basaltic eruptions in the ESRP have been of the hydromagmatic variety. These were moderately violent, but local, eruptions that occurred when basaltic magma encountered ground water at relatively shallow levels, including water contained in alluvial-fan deposits. In hydromagmatic explosions, rapidly expanding steam blows much of the magma apart, forming a spray of tiny fragments that harden into particles of glassy ash, largely of pebble, sand, and dust size. The cone formed of the unconsolidated ash is called an ash cone. The Menan Buttes (LaPoint, 1977; Hamilton and Myers, 1962) represent the largest volcanic deposits on the ESRP produced by this mechanism. Volcanic deposits from vents at this locality were distributed for a minimum distance of 1.5 km but probably for not more than 5 km from their source vents. At China Cup, located about 15 km south of Big Southern Butte (Kuntz, 1978), volcanic deposits were distributed less than 1 km from their source vent.

Rhyolite eruptions

Two types of rhyolitic eruptions have affected the ESRP in late Tertiary and early Quaternary time. The first type is caldera eruptions, such as those that have occurred within the last 1.9 m.y. in the Yellowstone-Island Park rhyolite plateau (Christiansen and Blank, 1972). This area has been the site of three cycles of rhyolitic volcanism, each of which culminated in the eruption of large ash-flows and was followed by caldera collapse; the three cycles have been dated at 1.9 m.y., 1.2 m.y., and 0.6 m.y., respectively (Christiansen and

Blank, 1972). No evidence exists that ash-flows erupted from calderas in the Arco-Big Southern Butte area, but such rocks may exist beneath the basalt cover of the region. The inferred caldera history of the ESRP has been summarized by Armstrong, Leeman, and Malde (1975).

The second type of rhyolite eruption is that which produces rhyolite domes, as at Big Southern Butte (Kuntz, 1978) and East Butte (LaPoint, 1977). Schoen (1974) and Spear (1977) have described Big Southern Butte and East Butte as volcanic domes formed by the non-explosive extrusion of plugs of rhyolite magma. Both Schoen and Spear speculated that the volcanic domes represent extrusions of hot, remobilized rhyolite that is believed to underlie the basalt.

Cedar Butte (Kuntz, 1978) is a relatively steep sided lava cone consisting of ferrolatite lava flows. Ferrolatite is a unique lava composition for basalts of the Snake River Plain. Leeman (1974) described nearly identical lavas from Craters of the Moon National Monument as "evolved" lavas, and he suggested that they may have originated by moderately high pressure fractionation of olivine tholeiite magma and/or by contamination of basaltic lava by granitic or granulitic crustal rocks. A pyroclastic cone consisting of rhyolite and obsidian blocks in a fine-grained rhyolite matrix exists in the center of the vent area at Cedar Butte. The presence of rhyolitic rocks in the pyroclastic cone provides a strong argument for a contamination origin for the ferrolatite lavas. Big Southern Butte and Cedar Butte occur at the intersection of the Arco rift zone and the Rock Corral Butte rift zone. This structural relationship, the remobilized rhyolite of the domes at Big Southern Butte, and evidence suggesting the involvement of rhyolitic rocks in ferrolatite lavas and the pyroclastic cone at Cedar Butte all clearly indicate that the southeastern end of the Arco rift zone (ARZ) is an area of fundamental, structural deformation that affects both near-surface and deep crustal rocks.

Age of Volcanism

The ages of volcanoes in the Arco-Big Southern Butte area have been determined by four techniques: (1) degree of weathering, erosion, and soil cover on lava flows; (2) stratigraphic relationships between flows; (3) determination of magnetic polarity of rocks; and (4) radiometric age-dating methods. The first three methods yield relative ages; the fourth method yields absolute ages.

These methods have been used to construct a preliminary time framework for the eruptive products in the Arco-Big Southern Butte area. Magnetic polarity studies indicate that all surface flows in the Arco-Big Southern Butte area are of normal polarity; they belong to the Brunhes normal-polarity epoch and therefore are younger than about 700,000 years. The radiometric age data presently available indicate that Cedar Butte ($\geq$ 400,000 yrs) is the oldest volcanic vent in the area and that four lava flows are younger than 12,000 yrs (Kuntz, 1978). However, because many of the lava flows in the Arco-Big Southern Butte area have not been dated by radiometric methods, the age classification of lava flows in the geologic map (Kuntz, 1978), Plate 1 is quantitative. The approximate ages assigned to lava flows between 12,000 years and 400,000 years are based entirely on the three relative dating methods listed above. A quantitative age classification must await further radiometric studies.

General conclusions about volcanism in the Arco-Big Southern Butte area are that the Arco rift zone and adjacent areas comprise an active volcano-tectonic region for the last 400,000 years and that this region has been the locus of much of the recent volcanism in the ESRP. As such, this region is likely to be the site of volcanism and tectonism in the future.

Volume-time relationships

Simple calculations give some perspective on the volcanic history of the ESRP and the Arco-Big Southern Butte area. The calculations may also be used to give a rough idea of recurrence intervals for eruption of shield volcanoes for the ESRP.

Recurrence intervals for shield-volcano eruptions on the ESRP may be estimated using the basic data in table 3. Assuming that 75 percent of the basalt volume on the ESRP is represented by shield volcanoes and assuming that the average volume of old shield volcanoes is the same as that of exposed shield volcanoes (about 7 km^3), it can be estimated that roughly 2,500 shield volcanoes exist on the ESRP. Then, assuming that an average age for the beginning of dominantly basalt volcanism for the ESRP is about 3.5 m.y., a rough estimate for the recurrence interval for shield volcanoes on the ESRP is about 1,500 years. From the data in table 3, it can be calculated that the average volume of volcanic material erupted per year in the ESRP is approximately 7×10^{-3} km^3, or 7,000 km^3/m.y. Holocene (<12,000 years) lava flows in the ESRP have been dated by radiocarbon methods (table 4), and thus it is possible to calculate the average amount of basalt erupted during this period:

Table 3.--Data and calculations involving time-volume relationships of basaltic volcanism in the eastern Snake River Plain, Idaho

1. Area of eastern Snake River Plain (Twin Falls to Island Park)
   Width--82 km
   Length--288 km
   Area--23,600 km^2
   Volume--23,600 km^3 (assuming average fill of basalt of 1 km--see Zohdy and Stanley, 1973).

2. Average volume of a shield volcano on ESRP: 7 km^3 (see table 1). Assuming that 75 percent of the basalt fill of the ESRP is represented by shield volcanoes, then $(0.75 \times 23{,}600)/7 \approx 2{,}500$ shield volcanoes for the ESRP.

3. Average age of beginning of basalt volcanism in ESRP: 3.5 m.y. (Calculated from the data of Armstrong and others, 1975, as follows: ESRP from Twin Falls to Island Park was divided into eight segments. A smooth curve was drawn at the base of basalt in the cross-section (Armstrong and others, 1975, fig. 2), assuming an initiation of basalt volcanism of the Glenns Ferry Formation at Twin Falls at 4 m.y. (H. E. Malde, oral commun., 1978), and on age of 0 year at Island Park. The age of the onset of basalt volcanism in each of the eight segments was estimated from the curve, and an average value was determined.)

   Then, $$\frac{3.5 \text{ m.y.}}{2{,}500 \text{ shield volcanoes}} \approx \frac{1{,}500 \text{ yr}}{\text{shield volcano}}$$

   This then is an average value for recurrence interval of shield volcanoes in the ESRP.

4. Area of Arco-Big Southern Butte region: 1,700 km^2 or 7 percent of the ESRP. Assuming that shield volcanism is randomly distributed throughout the ESRP, then the probability of a shield eruption occurring within the Arco-Big Southern Butte area is 1 in 14, or once in approximately every 21,000 yrs. This order-of-magnitude estimate of recurrence interval is believed to be too conservative for all types of volcanism in the Arco-Big Southern Butte area, but it may be a fair estimate of the recurrence interval of shield volcanoes for the area. (See section on statistical analysis of volcanic recurrence intervals.)

5. Average volume of basaltic lava erupted per year on the

   $$\text{ESRP} = \frac{23{,}600 \text{ km}^3}{3.5 \text{ m.y}} \approx \frac{7\times10^{-3} \text{ km}^3}{\text{year}}$$

   or approximately 6,500 km^3 per million years.

Table 4.--Age and volume of Holocene lava flows, eastern Snake River Plain, Idaho

Lava flow	Volume(km^3)	Age(^{14}C yrs)	Source	Area
Craters of the Moon.	~ 30	12,000 to 2,000	Kuntz, 1978---	Great Rift.
Wapi--------	12	2,360	Duane Champion, USGS, (oral commun., 1978).	Great Rift.
King's Bowl	.1	$2,130\pm130$	Prof. J. King, SUNY-Buffalo (oral commun., 1977).	Great Rift.
Cerro Grande	4	$10,780\pm300$	Kuntz, 1978---	Arco rift zone.
North Robbers	.04	$11,940\pm300$	Kuntz, 1978---	Arco rift zone.
South Robbers	.02		Kuntz, 1978---	Arco rift zone.
Hells Half Acre	9	$4,100\pm200$	Meyer Rubin, USGS (unpub. data, 19__).	South-Central ESRP.

~ 56

$$\frac{\sim 56\ km^3}{12{,}000\ yrs} \approx 4.6\times10^{-3}\ km^3/yr$$

about 5×10^{-3} km^3/yr, a value in reasonable agreement with the average volume of basalt erupted per year for the entire ESRP.

The mean occurrence rate for all types of volcanism in the Arco-Big Southern Butte area is one eruption per 3,000 years (see next section); thus, although the Arco-Big Southern Butte area is only 7 percent of the area of the ESRP, the data in Table 5 suggest that a significant proportion of the volcanism for the ESRP has occurred in the Arco-Big Southern Butte area. This relationship is further emphasized by the fact that much of the Holocene volcanism of the ESRP has been erupted within the Arco rift zone or in the Great Rift (table 4).

Table 5.--Data relating to volcanism of the eastern Snake River Plain and the Arco-Big Southern Butte area, Idaho

Area of ESRP----------------------------------	23,600 km^2
Area of Arco-Big Southern Butte area----------- (See Kuntz, 1978).	1,680 km^2 (7% of ESRP).
Area of eruption basin. (See figure 8)--------	826 km^2 (49% of Arco-Big Southern Butte area).
Number of discrete volcanic vents in Arco-Big Southern Butte area.	74
Number of discrete volcanic vents in eruption basin.	47 (63%)
Number of discrete volcanic vents in eruption basin represented by shield volcanoes.	12 (25%)
Mean occurrence time for shield volcanoes on ESRP (table 3).	1 in every 1,500 years.
Mean occurrence time for all types of volcanism in Arco-Big Southern Butte area. (See section on statistical treatment of age of lava flows.)	1 in every 3,000 years.

Statistical Treatment of Age of Lava Flows

by John O. Kork

Statistical Model

In the absence of a deterministic model to explain the occurrence of volcanic eruptions in a given study area, the eruptions may be regarded as a sequence of random events in time. Even though a specific eruption is fully determined by physical processes and is not really random, statistical parameters describing the long-term average eruption rate of volcanism in a specific area can be estimated from the data. Predictions based on such estimates can provide meaningful information about possible future eruptions.

The simplest model for a sequence of volcanic eruptions is the Poisson Process model. The two main assumptions required for the validity of this model are that the average number of eruptions per unit time remains constant throughout the process and that occurrences of eruptions in separate time intervals are statistically independent (Hahn and Shapiro, 1967). Although these assumptions may ultimately prove to be too restrictive for describing the volcanism in the Arco-Big Southern Butte area, the data at hand are so sparse that an attempt to use a more sophisticated model is not justified.

The basic parameter for the Poisson Process is the mean occurrence rate, , measured in number of eruptions per unit time, and this parameter is assumed to be constant throughout the life of the process. The time between any two successive eruptions (the "gaps" in the process) follow an exponential distribution with mean recurrence time, 1/ . We will estimate the mean occurrence rate from the data and use this value in the exponential distribution to predict the time until the next eruption in the Arco-Big Southern Butte area.

Data Analysis and Prediction

Geological field criteria, such as stratigraphic relationships between flows and degree of weathering, erosion, and soil cover on lava flows, can be used to obtain relative ages of vents and flows. Using the above criteria, Kuntz estimated the age class of each volcano in the Arco-Big Southern Butte area and concluded that 67 separate eruptions had occurred in the past 200,000 years. The estimated mean occurrence rate is then

$$= \frac{67}{200,000} = 0.355 \times 10^{-3} \text{eruption/year},$$

or roughly one eruption per 3,000 years. Because evidence of older volcanoes could be obscured by younger flows and because Kuntz took care to insure that each vent he counted represents a separate occurrence of volcanism in the area, the value of 0.335×10^{-3} eruption per year is more likely to be an underestimate of the true mean occurrence rate than an overestimate.

We wish to estimate the probability that the time, T, until the next eruption in the Arco-Big Southern Butte area is less than t_o years for various values of t_o. This is the same as estimating the proportion of exponentially distributed "gaps" shorter than t_o years. A $(1 - \hat{\nu})$ 100 percent lower confidence limit for this probability is given by

$$L = 1 - \exp\left[\frac{\hat{\nu} - t}{1 + k \quad (1/n)}\right]$$

where $\hat{\nu}$ is the estimate of the parameter ν, n is the sample size, and k is that value of a standard normal variable that will be exceeded with probability α (Benjamin and Cornell, 1970).

The value of $\hat{\nu}$ for the Arco-Big Southern Butte area is 0.355×10^{-3} occurrence per year and is based on n = 67 observations. For t_o = 10,000 years, the 95 percent lower confidence limit for the proportion is given by

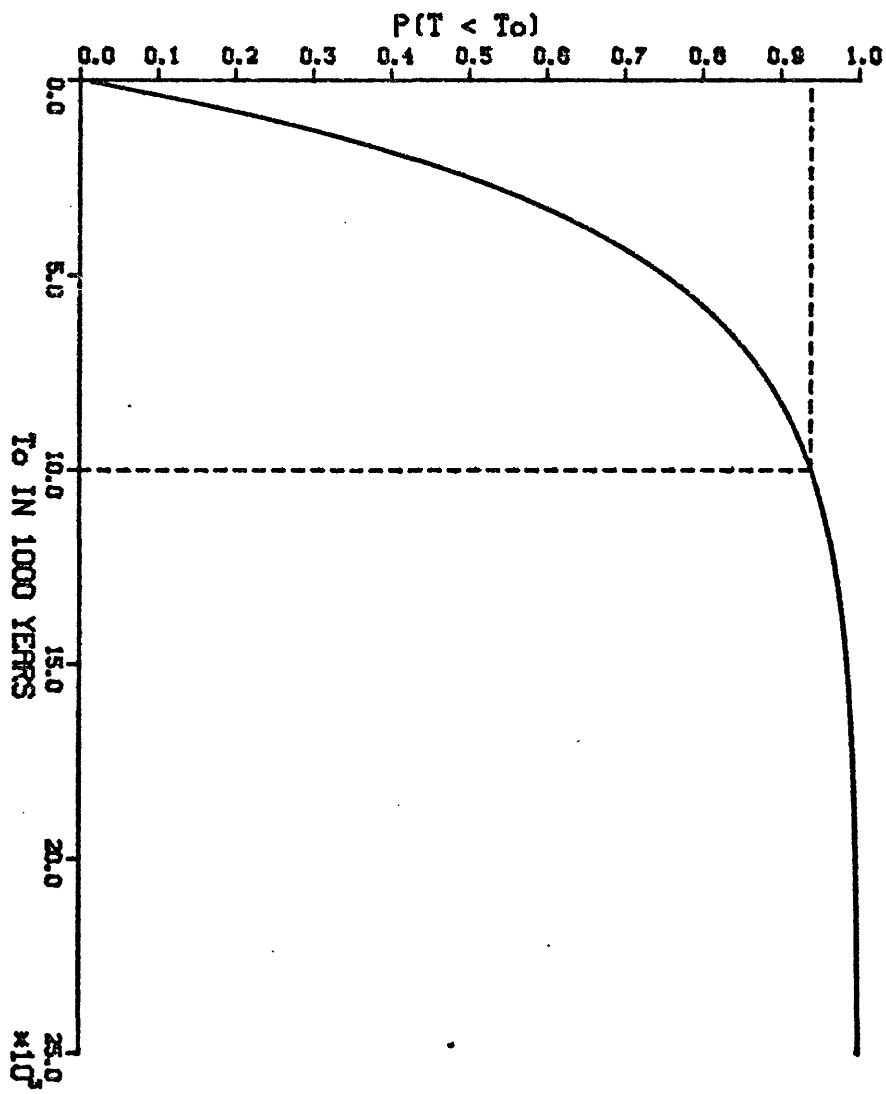
$$L = 1 - \exp\left[\frac{-(.355) \times 10^{-3})\ (10^{4})}{1 = 1.645\ (1/67)}\right] = 1 - e^{-2.79} = 0.9386$$

Thus we can say with 95 percent confidence that the proportion of gaps less than 10,000 years is greater than 0.9386. In other words we are 95 percent confident that the following statement is true: "The probability that a volcanic eruption will occur in the Arco-Big Southern Butte area within the next 10,000 years exceeds 0.9386."

Figure 6 shows a graph of the lower limit, L, as a function of t_o for the Arco-Big Southern Butte area. The value just calculated for t_o = 10,000 years can be found graphically by locating 10,000 years on the horizontal axis and following the dashed line to the curve and then to the vertical axis. The lower limit, L, can be read from the vertical axis.

The probability estimates in this section are based on the rough age classification of vents using geological field criteria, and they provide no more accuracy than that inherent in the original data. The information in the original data is, however, represented in a form in which it can readily be used for decisions and planning.

Figure 6.--Lower 95 percent confidence limit for P(T<T).



POTENTIAL VOLCANIC HAZARDS

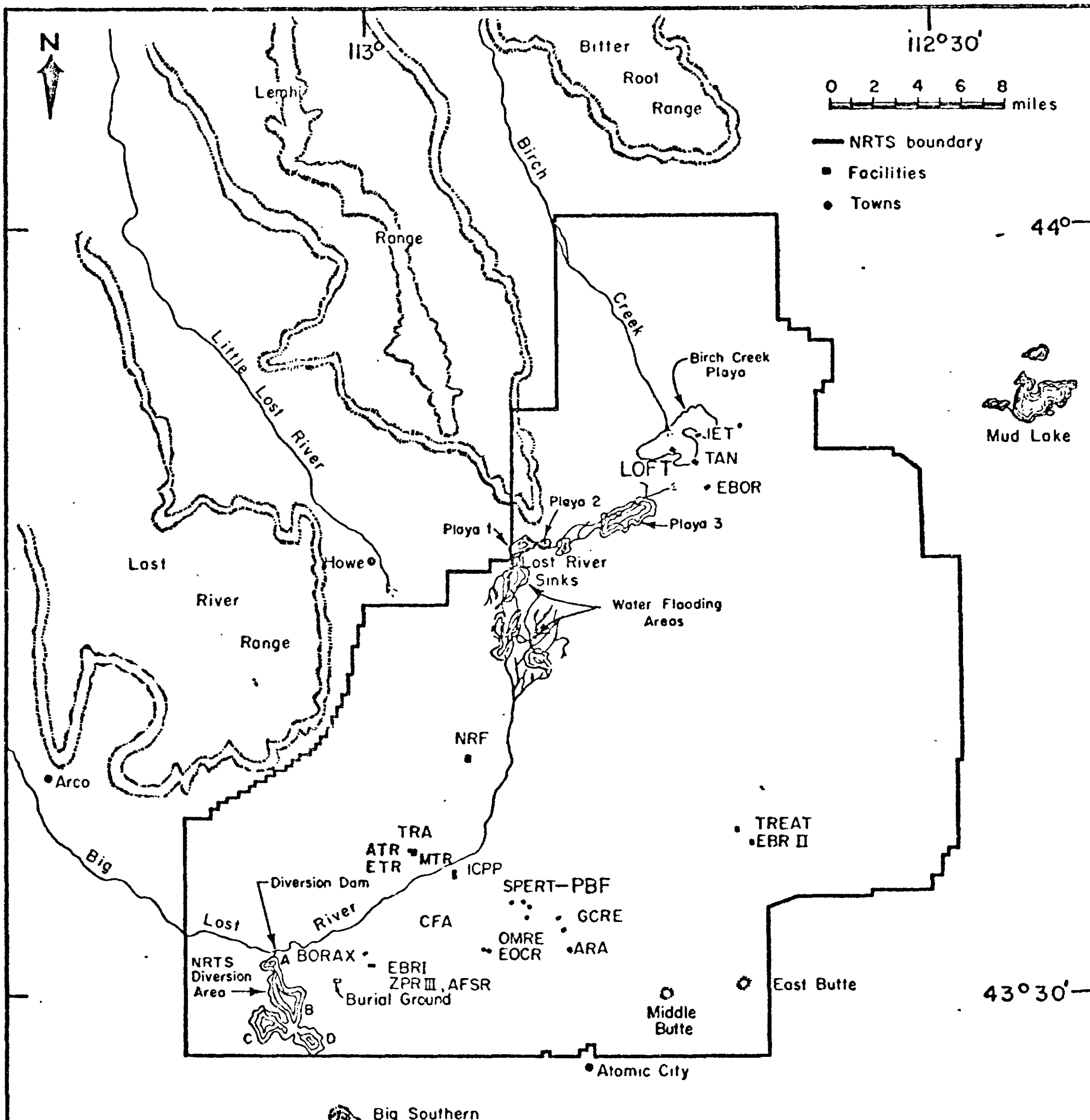
Introduction

Radioactive wastes are stored chiefly at six sites at the Idaho National Engineering Laboratory: Radioactive Waste Management Complex (RWMC), Idaho Chemical Processing Plant (ICPP), Test Reactor Area (TRA), Test Area North (TAN), Argonne National Laboratories-West (ANLW), and the Naval Reactor Facility (NRF). The potential volcanic hazards will be treated separately for each facility, except for the ANL, which is considered in a separate report.

Because some of the stored radioactive wastes at INEL have particularly long half-lives (for example, some radioisotopes of plutonium, uranium, iodine, radium, nickel, and others), and because of the potential biological harm and radiotoxicity of other wastes (for example, radioisotopes of plutonium, americium, cesium, strontium, and iodine), dispersal of these wastes into the environment by interaction with volcanic processes and products might cause severe environmental and health problems. The assessment presented here may be used to evaluate the risk from future volcanic activity for long-term and short-term storage of radioactive wastes.

Radioactive Waste Management Complex (RWMC) area

The RWMC occupies 144 acres in the southwest corner at INEL (fig. 7; Kuntz, 1978). In addition to wastes generated at INEL, the RWMC also receives wastes from the U.S. Department of Energy's (DOE) Rocky Flats Plant near Denver, Colorado, and other DOE facilities. The



EXPLANATION

TABULATION OF FACILITIES AT THE NATIONAL REACTOR TESTING STATION

Name	Abbreviation	Name	Abbreviation
Advanced Test Reactor	ATR	Idaho Chemical Processing Plant	ICPP
*Argonne Fast Source Reactor	AFSR	*Initial Engineering Test Facility	IET
Auxiliary Reactor Area	ARA	Loss of Fluid Test Facility	LOFT
*Boiling Water Reactor	BORAX	Materials Testing Reactor	MTR
Central Facilities Area	CFA	Naval Reactors Facility	NRF
Engineering Test Reactor	ETR	*Organic Moderated Reactor Experiment	OMRE
*Experimental Beryllium Oxide Reactor	EBOR	Special Power Excursion Reactor Test	SPERT
*Experimental Organic Cooled Reactor	EOCR	Test Area North	TAN
*Experimental Breeder Reactor No. 1	EBR-I	Test Reactor Area	TRA
Experimental Breeder Reactor No. 2	EBR-II	Transient Reactor Test Facility	TREAT
		Zero Power Reactor No. 3	ZPR-III
*Gas Cooled Reactor Experiment	GCRE	Power Burst Facility	PBF

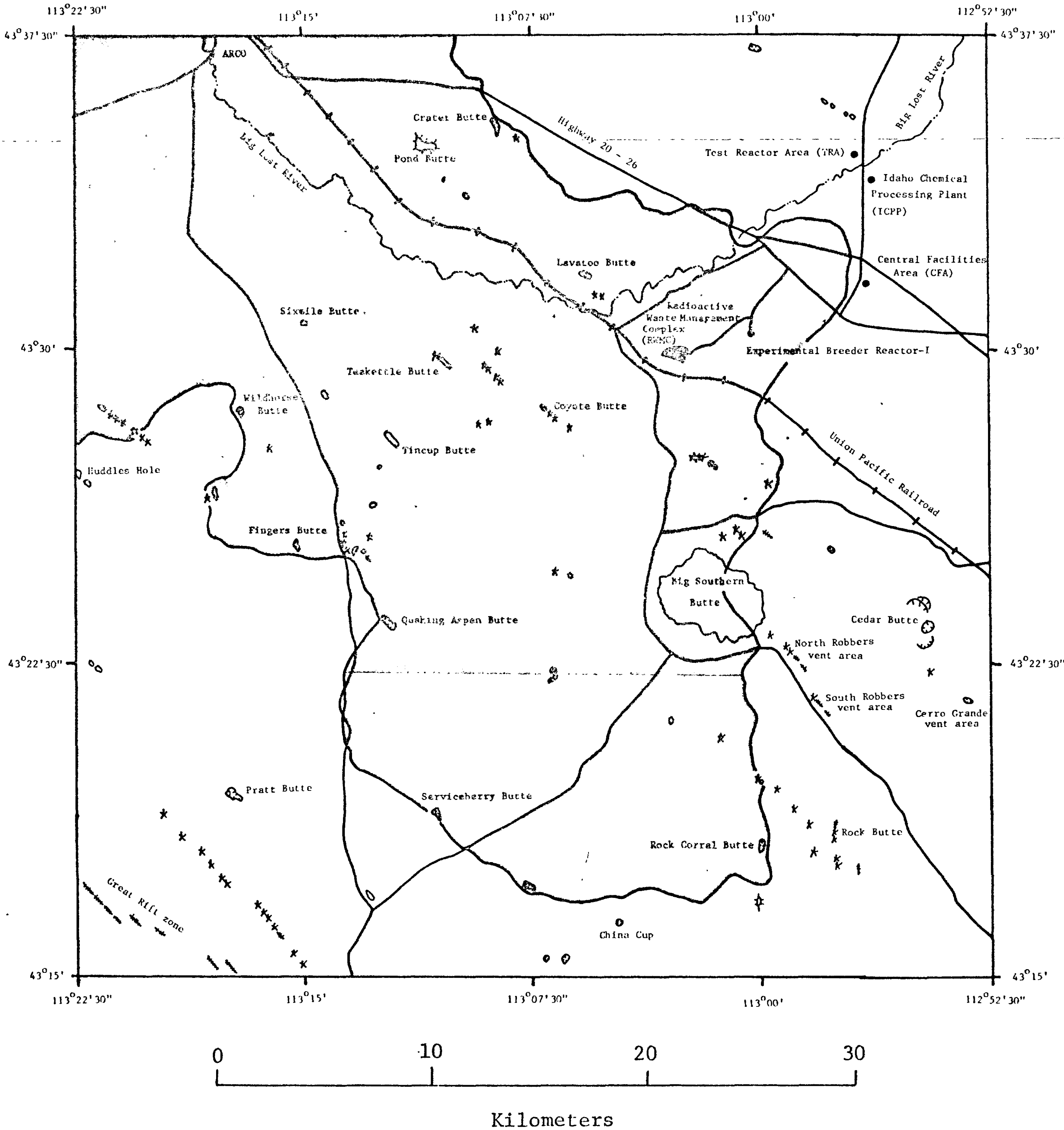
Figure 7.--Map showing major facilities at the Idaho National Engineering Laboratory (formerly called the National Reactor Testing Station--NRTS). Diagram from Robertson, Schoen, and Barraclough, 1974, p. 4.

RWMC consists of three disposal areas: (1) The Subsurface Disposal Area is an 88-acre plot of land used for the near-surface burial (1 to 7 meters deep) of nontransuranic solid wastes; (2) The Transuranic Disposal Area is an asphalt pad within the Subsurface Disposal Area used for the permanent disposal of uranic and transuranic wastes having less than 10 nCi of activity per gram of waste; (3) The Transuranic Storage Area is a 66-acre plot of land consisting of an asphalt pad used for the temporary storage of transuranic wastes containing more than 10 nCi of activity per gram of waste (Energy Research and Development Administration, 1977).

The RWMC lies in a topographic depression--the floodplain of the Big Lost River. At the point where the Big Lost River makes a nearly right angle change of course (Kuntz, 1978), approximately 3 km northwest of the RWMC, the riverbed is approximately 15 m higher than the average elevation at the RWMC.

The shaded area in figure 8 shows all the area topographically above the RWMC. Lava flows originating within this area would flow toward the east-central part of this topographic basin near the RWMC. This topographic basin may also be defined as an "eruption basin"; eruptions occurring within the basin all have the potential of reaching the RWMC. Lava flows exposed at the surface at RWMC were erupted from two separate source vents shown on figure 8. The older flows (estimated age, 150,000±50,000 yrs) are from a series of aligned fissure-controlled vents in the Arco rift zone, located about 5 km north of Big Southern Butte and 5 km south of RWMC. These flows moved chiefly north and east from their source vents and now cover about 90 percent of the area

Figure 8.--Planimetric map showing topographic-volcanic eruption basin (shaded) of Arco-Big Southern Butte area. Heavy lines are major roads.



underlying the RWMC. The younger flows (>40,000 ^{14}C yrs, estimated age of 60,000 yrs) emanated from the vent at Quaking Aspen Butte, about 17 km southwest of the RWMC, and cover the northern 10 percent of the area underlying the RWMC. The distal ends of flows from the vent at Quaking Aspen Butte now form a topographic ridge that separates the present channel of the Big Lost River from the RWMC facilities. The configuration of the flow-ridge suggests that the flow filled an old channel of the Big Lost River.

The location of these two source vents and the extent of their flows suggest that the RWMC may be subject to inundation from future lava flows from both distant and nearby source vents in the shaded area in figure 8.

Eruptions and lava flows that might occur outside the limits of the eruption basin pose less of a volcanic hazard to RWMC.

The subsurface geology of the RWMC site has been studied by the U.S. Geological Survey (Barraclough and others, 1976) and will not be described in detail here. Their study shows, however, that monitoring wells in and near the RWMC, penetrating to depths of 200 m below the surface, encounter at least six basalt flows and a few sedimentary interbeds of eolian and fluvial origin. Individual basalt flows examined by the writer in cores from the RWMC range from about 6 m to as much as 30 m thick. Flows as thick as 30 m imply ponding of lava flows in a depression, probably a channel of the ancient Big Lost River.

Based on the geologic setting and the past eruptive history of the Arco-Big Southern Butte area, the chief volcanic hazards to RWMC are from future eruptions of basaltic volcanoes within the RWMC or within the eruption basin described above and shown in figure 8. Future rhyolitic eruptions in and near the ESRP pose a less serious volcanic hazard to RWMC, because they have occurred much less frequently than basaltic eruptions and, thus, are unlikely events for the future.

The chief volcanic hazard associated with fissure eruptions, should they occur within the RWMC, would be the rupture of waste containers and the explosive dispersal of buried and surface stored wastes from areas within and near the eruptive fissure. Dispersal of radioactive wastes in tephra and steam clouds could cause severe contamination of the atmosphere, soil, surface water, and, possibly, ground water. High temperatures would be created in the soil cover over the buried wastes within a few tens of meters of the eruptive fissure, possibly volatilizing their contents and/or jeopardizing the integrity of waste containers. Steam explosions caused by heated ground water in sedimentary interbeds below the buried trenches, pits, and storage pads might also accompany fissure eruptions. Wastes contained in flowing lava or in tephra blown out of the fissure may be carried for distances of as much as several tens of kilometers away from the burial site (table 2).

Volcanic hazards from a fissure eruption at a distant vent could involve inundation of the RWMC by lava flows and/or tephra deposits. The danger from lava flows would depend on such factors as volume and velocity of lava and locations of source vent and lava flows relative to topographic features in and near the RWMC. The danger from tephra deposits would depend on such factors as position of source vent with respect to wind direction, distance of source vent from RWMC, and height of eruption and tephra cloud. Based on unpublished studies by the writer of tephra thicknesses in Craters of the Moon National Monument, more than 1 m of tephra may accumulate in areas downwind but within 1 km of a source vent, and less than 1 m of tephra may accumulate at distances greater than 1 km from a source vent.

Ground water in the Snake River Plain aquifer exists in porous basalt and thin sediment interbeds at depths greater than 180 m beneath the RWMC (Barraclough and others, 1976), probably too deep for significant danger from a hydromagmatic eruption. However, should an eruption occur in areas covered by several meters or tens of meters of alluvial gravels along the Big Lost River north of the RWMC, particularly when they are water-saturated, at least the initial stages of the eruption could be hydromagmatic. If a hydromagmatic eruption occurred so as to dislodge and distribute wastes stored at RWMC, specific hazards would be the contamination of the atmosphere, soil, surface water, and ground water by dispersal of radioactive materials in the ash blanket. A hydromagmatic eruption from a vent within several miles of the RWMC could produce an ash blanket several meters thick that might be hot enough to damage containers stored at the surface.

A shield eruption within the RWMC would pose a serious threat to buried wastes and wastes stored on pads on the surface. The early-stage eruptive processes would be similar to those described above for fissure eruptions. The later-stage eruptive processes could involve piston-like filling and draining of magma in the vent, collapse of vent walls, and discharge of large volumes of fluid, low-viscosity ($\sim$ 1 poise), high-temperature (1,200 to 1,000^{o}C) lava. The repeated draining and filling of shield vents by magma could raise and lower entrained radioactive wastes to the level of the Snake River Plain aquifer; the aquifer, however, could be shielded from the conduit by congealed magma. A shield eruption within the RWMC could inundate the area by as much as several hundred meters of basaltic lava, thus subjecting containers and their wastes to temperatures as high as 1,000$\pm$100^{o}C. The chief hazard from this type of eruption would be the rupture or melting of waste containers, possible volatilization of radioactive materials, and engulfment of the radioactive materials and their dispersal in lava flows.

A shield eruption outside the RWMC also could produce flows that would inundate the area. Lava flows could well become ponded and attain thicknesses of several tens of meters. It is conjectural whether or not the clay cover, as thin as 3 m, would protect buried wastes from the thermal effects of an overriding flow. It is, however, reasonable to assume that such a lava flow would cover the buried wastes and not exhume them, but the flow would surely have a thermal effect on the clay cover and possibly on the wastes beneath it. The actual mechanisms of the interaction between lava and wastes stored on surface pads involve engineering and chemical considerations beyond the expertise of this writer and thus are not discussed further here.

Caldera eruptions have occurred within the last 1.9 m.y. in the

Island Park-Yellowstone region. Geological and geophysical information (Eaton and others, 1975) currently available suggests that eruptions of this type may occur in the future in the Island Park-Yellowstone region, but the chance of their occurrence in the ESRP or nearby regions within the next million years seems extremely remote. If such an eruption should occur in the Yellowstone area in the future, it seems unlikely that ash deposits and ash-flow deposits would traverse the approximately 250-km distance to reach the RWMC.

A second type of potential rhyolite eruption would be one that produces rhyolite domes like those that form Big Southern Butte and East Butte. These domes erupted relatively quietly, and they were not accompanied by major amounts of ejecta, tephra, and pyroclastic flows. However, eruption of some rhyolite domes is explosive, associated with pyroclastic flows and air-fall tephra. Collapse of rhyolite domes may produce block- and ash-flows capable of moving several kilometers down moderately steep slopes. A rhyolite-dome eruption would constitute a volcanic hazard if it took place within the RWMC or within about 10 km of this facility. Additional hazards associated with the eruption of a rhyolite dome would be the local heating of ground water and change of ground-water elevations and flow patterns.

Potential volcanic hazards to other waste-storage and reactor facilities At INEL

The volcanic hazards to other radioactive waste-storage and reactor facilities at INEL are the same as those described above for the RWMC. The probability and magnitude of the hazards are less, however, because these areas are farther from volcanic rift zones where future volcanic activity is most likely to occur.

Central Facilities Area (CFA), Idaho Chemical Processing Plant (ICPP), and Test Reactor Area (TRA)

Reactor, waste-storage, and administrative facilities at the CFA, ICPP, and TRA (fig. 7; Kuntz, 1978) may experience volcanic hazards from two possible sources: (1) from eruptions occurring on a volcanic rift zone that passes through AEC Butte (Kuntz, 1978), and (2) from inundation by lava flows that might reach this area from source vents in the Arco Rift Zone and from source vents in the area between Big Southern Butte and East Butte (Kuntz, 1978; LaPoint, 1977).

Vents at AEC Butte and a volcano located 4 km northwest of AEC Butte (Kuntz, 1978) lie on a volcanic rift zone. The two vents produced small shield volcanoes. It seems reasonable to conclude that future eruptions on this rift zone would be of this type. Volcanic eruptions on the Howe-East Butte rift zone (fig. 3) pose a less serious threat to facilities at CFA, ICPP, and TRA, because they lie farther to the northeast and are lower in elevation than the waste and reactor facilities. A considerable thickness of alluvial fill along the floodplain of the Big Lost River exists in the CFA, ICPP, and TRA; the possibility of a hydromagmatic eruption thus exists in this area.

Lava flows from the vent at Crater Butte have travelled about 26 km to cover areas near TRA and CFA. Lava flows from the fissure-controlled vents north of Big Southern Butte have flowed northeast for distances of at least 15 km and covered the CFA area and possibly the ICPP area. These relations show that large-volume shield eruptions originating within the eruption basin for RWMC and in areas to the north and east all have the capability of producing flows that could reach the CFA, ICPP, and TRA.

Auxiliary Reactor Area (ARA) and Special Power Excursion Reactor Test (SPERT) Area

The ARA-SPERT facilities (fig. 7) lie between the Arco and Howe-East Butte volcanic rift zones (fig. 3; Kuntz, 1978). The land surface in this area slopes northwestward away from the topographic axial ridge of the ESRP. Because of the topography, the source-vent area that constitutes the chief volcanic hazard for the ARA-SPERT facilities lies along the axial ridge near Middle Butte (LaPoint, 1977). Volcanoes in this area apparently have not been active more recently than about 100,000 years ago. The potential volcanic hazard to the ARA-SPERT facilities thus is significantly less than that for the RWMC area. East Butte and Middle Butte (?) are rhyolite domes; their proximity to the ARA-SPERT area (8-12 km) suggests that reactor facilities at these two localities face an additional potential volcanic hazard from the eruption of future rhyolite domes. The ages of these domes (table 6) suggest that the eruption of rhyolite domes along the axis of the ESRP has occurred sporadically in time.

Table 6.--Ages of rhyolite domes along the axis of the central part of the eastern Snake River Plain, Idaho

Rhyolite dome	Age	Reference
East Butte--------	0.58±0.09 m.y.	Armstrong and others, 1975.
Middle Butte------	Rhyolite not exposed; basalt flow capping butte is 1.9±1.2 m.y.	Armstrong and others, 1975.
Unnamed dome between Middle Butte and East Butte.	1.42±0.02 m.y.	G. Brent Dalrymple, USGS, unpublished data, 19__.

Naval Reactors Facility (NRF) area

The reactor and liquid waste storage facilities at NRF (fig. 7) are subject to volcanic hazards from vents that may originate in three main areas: the Howe-East Butte rift zone, the Arco rift zone, and the topographic axis of the ESRP (fig. 3). Knob Butte and State Butte form part of the Howe-East Butte rift zone, which lies about 3 km north of NRF. The degree of erosion and the thick soil cover (as much as 1 m) on lavas exposed at these two buttes indicate that they possibly are of the same age and that both are probably older than 100,000 years. The potential volcanic hazard from eruptions along this volcanic rift zone thus appears to be relatively insignificant. The chief volcanic hazards to NRF would be lava flows from fissure vents, vents producing shield volcanoes, and hydromagmatic eruptions, as described above. Lava flows from the vent at Crater Butte have extended beyond NRF, indicating that flows originating in the Arco rift zone also constitute a more serious hazard for NRF because these flows are younger.

Test Area North (TAN) area

Potential volcanic hazards exist for the liquid-waste-storage sites and reactor facilities of TAN (fig. 7). These hazards are posed by volcanic vents along the Lava Ridge-Hells Half Acre and Circular Butte-Kettle Butte volcanic rift zones (fig. 3). Studies of the paleomagnetic properties of rocks from both of these rift zones indicate that vents near TAN are significantly older than vents on these two rift zones near the axis of the ESRP. Many of the rocks from vents at Lava Ridge and the Circular Butte area are magnetically reversed, indicating ages of the Matuyama polarity epoch, older than about 700,000 years. However, young vents at Kettle Butte and Hells Half Acre (4,100±200 ^{14}C years B.P.) indicate that parts of these volcanic rift zones have been locally active very recently, suggesting that parts of the volcanic rift zones near TAN are also potential sites for future volcanism. The chief volcanic hazards to facilities at TAN would be lava flows from fissure vents and shield volcanoes, and hydromagmatic eruptions, as described above.

PRECURSORY ERUPTIVE PHENOMENA AND INDIRECT HAZARDS ASSOCIATED WITH VOLCANIC ERUPTIONS

Precursory events that typically precede basaltic eruptions include (1) vertical and horizontal ground displacement above and near the site of the future volcanic vent(s), (2) seismic activity, (3) new or increased fuming near the site of the future vents(s), and (4) changes in the composition and temperatures of hot springs or fumaroles near the volcano. (See Swanson and others, 1976; Jackson and others, 1975.)

Ground displacement prior to volcanism is believed to represent the elastic response of the crust to increased pressure related to the rise of magma from a deep source area to a shallow crustal magma reservoir. The effect of displacement, often termed inflation, consists of the vertical rise of the ground surface over the magma reservoir and the outward, radial tilt of the ground surface away from the reservoir. As magma moves from the reservoir to the surface and erupts, or if magma moves laterally in the crust, deflation may take place. Vertical and horizontal deformation accompanying both inflation and deflation can be monitored by leveling surveys, trilateration surveys by geodimeter, and tiltmeters. It is unlikely that tilting of the ground surface would produce any potential hazard to stored radioactive wastes or to reactor facilities.

Strong earthquakes with focal depths of several kilometers or more generally precede eruptions of basalt volcanoes by several weeks or months. In Hawaii, the total number of earthquakes of shallow focal depth (typically <1 km) generally increases greatly several days to several hours prior to eruptions, reaching as many as several thousand in a 24-hour period. Local earthquakes preceding eruptions are related to opening of fissures through which the magma travels to the surface, movement of blocks of the crust in and around the volcano as it inflates, and other causes. Harmonic tremor, a rhythmic vibration of the ground, accompanies the movement of magma in a volcanic conduit or rift zone at shallow levels in the crust. Harmonic tremor generally precedes eruptions by several hours. Accurate seismic locations of tremor foci may be used to predict the sites of eruption. There appears to be no relationship between the frequency of premonitory earthquakes, the amount of energy released by them, and the magnitude of the ensuing eruption (Bolt and others, 1975).

Seismic activity accompanies most volcanic eruptions. Small to moderate earthquakes of Richter magnitude 5 or less would likely accompany eruptions of basalt and rhyolite domes. The seismic activity accompanying a caldera-forming eruption can only be inferred, but presumably it would be of high magnitude.

Ground cracking generally precedes an eruption by a few days or a few hours. The cracks, produced chiefly by extensional movement, are typically several tens of centimeters wide or less. Cracking generally extends parallel to and forms a vital part of a volcanic rift zone. Many cracks become fissure vents and emit lava, some emit only gas, and others remain unfilled by lava or gas after forming. Some cracks may become the locus of faults.

Faulting in volcanic rift zones could produce elevation changes of the ground surface and possible changes in surface drainage.

Steam and sulfurous fume clouds may form or increase in volume months, days, or even hours before an eruption begins, as upward-moving magma encounters water at shallow depths.

Lava flows could disrupt surface drainage at INEL. A lava flow entering the course of the Big Lost River could divert its flow. A lava flow entering the Big Lost River north of the RWMC could effectively block the present drainage and divert its flow into the RWMC.

SUGGESTED PROCEDURES FOR DEALING WITH FUTURE VOLCANIC ERUPTIONS

Earthquakes, ground cracking, ground tilting, and possibly faulting and steam activity are likely to precede the next volcanic eruption on the ESRP. Each of these premonitory phenomena should be monitored carefully by trained geophysicists and volcanologists to help predict the likelihood and probable location of an eruption. The location of the eruption site would aid in determining the kind of eruption that might be expected, such as fissure vs phreatomagmatic eruption. Once the probable site of an eruption has been identified, possible lava-flow routes, tephra-fall areas, ash-fall-blanket areas, etc. should be identified to determine which, if any, of the facilities at INEL might be located in potentially hazardous zones. If a particular facility appears to be in danger from the eruption, reactor operations or burial procedures should be halted and appropriate measures should be instituted to protect reactor and burial facilities.

If an eruption has begun, or appears imminent, trained geophysicists and volcanologists should be brought to the eruption site to monitor geophysical and volcanic processes and to aid in predicting the type, course, and potential hazards from the eruption.

There appear to be several methods of lava-flow diversion that could be instituted. Diversion of lava flows by bombing has been tried and is again being evaluated in Hawaii (Torgerson and Bevins, 1976; Bolt and others, 1975). Earth and rock diversion barriers have been used to divert lava flows (U.S. Army Corps of Engineers, 1975; Bolt and others, 1975). Dousing lava-flow fronts with water has also been used to slow lava-flow advance (Bolt and others, 1975).

Recommendations

1. A radiometric age-dating study should be made of samples taken from cored drill holes to determine the age of lava flows that have inundated the RWMC area in the past and to obtain a more accurate determination of volcanic recurrence intervals.

2. A monitoring system should be instituted to provide a warning system for impending volcanic eruptions in and near INEL, and to permit actions by DOE officials to minimize harmful results to burial storage sites and reactor facilities. The following, listed in order of priority, might constitute the heart of the monitoring system:

   a. Dry tilt stations (Jackson and others, 1975; Swanson and others, 1976) should be established at several localities in the Arco rift zone (ARZ) and in the Great Rift and measured at approximately 5-year intervals to identify areas of contemporary deformation.

   b. A program of leveling should be instituted to determine areas of contemporary ground deformation on the ESRP. Releveling could be performed at approximately 5-year intervals. Such a program could help to identify the general location of future eruption sites, and it would provide a data baseline for the interpretation of ground movement in the period prior to and during an eruption.

c. A program of trilateration surveying by geodimeter could be instituted to determine contemporary horizontal deformation of the ground surface in and around INEL if dry tilt and releveling surveys indicate significant amounts of contemporary deformation. The data base obtained from this program could be used to identify the strain in volcanic rift zones, to identify general areas of likely eruptions, and to provide a data baseline for the interpretation of ground movement in the period just prior to and during an eruption.

d. A network of borehole tiltmeters for detecting ground deformation in areas deemed to be the most likely sites for future eruptions could be set up if dry tilt and leveling surveys indicate significant amounts of contemporary deformations.

e. The present INEL seismic network will provide adequate routine monitoring for earthquakes of volcanic origin. An array of portable seismometers could be deployed to monitor accurately the volcanic seismicity detected by the present INEL network.

3. DOE should commission a study of the engineering and chemical effects that could occur due to the interaction of hot lava and waste containers and radioactive wastes.

APPENDIX

GEOLOGY OF THE EASTERN SNAKE RIVER PLAIN

Regional physiography

The Snake River Plain is a topographic depression varying from 50 to 100 km wide that cuts an arcuate swath across southern Idaho (fig. 9). It extends from Payette on the west for about 250 km southeast to Twin Falls and then for about 300 km northeast to about Ashton. Elevations on the plain rise from 700 m on the west to 2,000 m on the east.

The plain is bounded on the north by Mesozoic to lower Tertiary granitic rocks of the Idaho batholith and by folded Paleozoic and Mesozoic rocks that were uplifted along normal faults in the Tertiary during Basin-Range tectonism (fig. 9). The Plain is bounded on the southeast by folded Paleozoic and Mesozoic rocks of the Basin and Range Mountains. Tertiary rhyolitic and basaltic volcanic rocks of the Owyhee Mountains bound the Plain on the southwest, and upper Tertiary-Quaternary rhyolitic and basaltic volcanic rocks of the Yellowstone Plateau occur at the northeast end of the Plain (fig. 9).

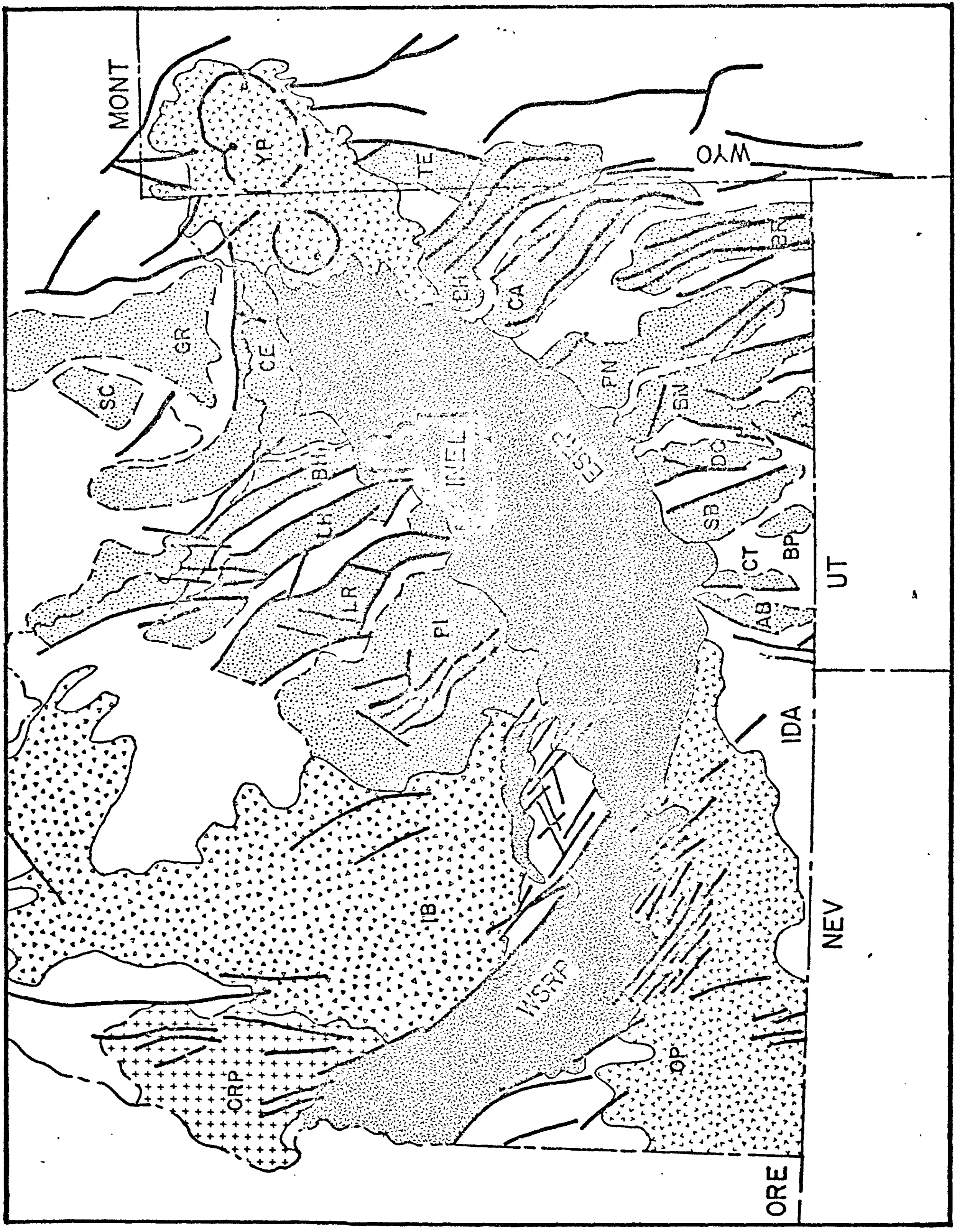
Regional Geology

The Snake River Plain, particularly the eastern part, constitutes one of the most poorly known geologic areas of the United States. Present needs for geothermal and petroleum resources and for evaluation of the environmental-geological framework for the population-agricultural corridor of Idaho have prompted studies by the U.S. Geological Survey, energy companies, and universities.

Geologists and geophysicists draw a distinction between the western

Figure 9.--Map of southern Idaho and adjoining states showing physiographic and geologic features. Normal faults shown by thick lines; dashed where inferred. Boundaries of physiographic features shown by narrow lines; dashed where approximately located. Abbreviations used: ESRP-eastern Snake River Plain; WSRP-western Snake River Plain; INEL-Idaho National Engineering Laboratory; CRP--Columbia River Plateau; IB-Idaho Batholith; OP-Owyhee Plateau; YP-Yellowstone Plateau. Basin-range mountains north of the ESRP: PI-Pioneer Range; LR-Lost River Range; LH-Lemhi Range; BH-Beaverhead Range; CE-Centennial Range; SC-Snowcrest Range; GR-Grabelly Range. Basin-range mountains south of ESRP: AB-Albion Range, CT-Cotterell Range, BP-Black Pine Range, SB-Sublette Range, DC-Deep Creek Range, BN-Bannock Range, PN-Portneuf Range, BR-Bear River Range, CA-Caribou Range, BH-Big Hole Range, TE-Teton Range.

Figure 9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Snake River Plain, (WSRP) and eastern Snake River Plain, which are divided near Twin Falls at approximately the 115th meridian. Geological and geophysical features are unique to each part.

The WSRP is a Pliocene fault-bounded graben filled with rhyolite and basalt lava flows and interbedded detrital sediments. Considerable relief and extensive vertical exposures exist in the WSRP along the canyons of the Snake River and its tributaries. These features have aided in the geologic study and interpretation of the history of the region. Malde and Powers (1962) have provided a detailed account of the geology of the WSRP.

The ESRP is a broad, flat lava plain consisting, at the surface, of basalt lava flows and thin, discontinuous deposits of loess, sand dunes, and alluvial-fan materials. Drainage is dominated by the Snake River, which flows along the southeast margin of the ESRP (fig. 9). A topographic ridge extending from Big Southern Butte northeastward to Juniper Buttes near St. Anthony coincides with the long axis of the plain (LaPoint, 1977). Rivers entering the ESRP from the north are deflected by the ridge and end in closed basins. In contrast to the WSRP, erosion of rocks in the ESRP by rivers and streams is negligible; thus the topography of the region is formed by constructional geologic processes, chiefly volcanism and fluvial aggradation. River canyons are absent, and therefore little is known of the underlying rocks of the ESRP.

The mountains north and south of the ESRP are fault-block mountains of the Basin and Range province. Most of these ranges trend northwest, at right angles to the long axis of the ESRP, but the Centennial Range trends east, parallel to the northeast margin of the Plain (fig. 9). The fault-block mountains end abruptly at the plain margin, suggesting that the ranges have been truncated by boundary faults parallel to the margins of the ESRP.

Lava flows on the ESRP were erupted from fissure vents that are aligned along volcanic rift zones, which trend at right angles to the long axis of the ESRP; many appear to be extensions onto the plain of range-front faults that bound fault-block mountains on the flanks of the ESRP (fig. 9, Kuntz, 1977c).

Magnetic-polarity studies indicate that, with minor exceptions, all surface flows throughout the ESRP are of normal-polarity; they belong to the Brunhes normal-polarity epoch and therefore are younger than about 700,000 years. Radiocarbon age dating of organic soils beneath lava flows of the ESRP has shown that volcanic rocks younger than 15,000 years are widely distributed over the ESRP (table 4).

Studies of well logs that penetrate rocks of the ESRP to depths as great as 500 m suggest that basalt is greatly dominant over fluviatile and eolian sediments near the long axis of the ESRP and that sediments are relatively more abundant along its margins.

Silicic volcanic rocks, equivalent to the Miocene Idavada Volcanics of the WSRP, are exposed locally near the margins of the ESRP. Along the southern margin. these rocks range in age from about 10 m.y. for the tuff of Arbon Valley near Pocatello and for the rhyolite in the Sublett Range to less than 1 m.y. for rhyolite ash flows and lava flows in the Yellowstone-Island Park area (Armstrong and others, 1975; Christiansen and Blank, 1972). Similar silicic rocks are exposed on the northwestern margins of the ESRP at the southern end of the Beaverhead Range and along the southern flank of the Centennial Range (fig. 9); but, as yet, they are not well dated. Directional structures, distribution, and thicknesses of rhyolitic rocks suggest that their source calderas occur beneath the basalt section of the ESRP.

The Yellowstone-Island Park rhyolite plateau to the northeast has been the site of three cycles of rhyolitic volcanism, each of which was dominated by the eruptions of large ash-flow tuffs and followed by caldera collapse; the three cycles have been dated at 1.9 m.y., 1.2 m.y., and 0.6 m.y., respectively (Christiansen and Blank, 1972).

Regional geophysics

No attempt will be made here to give a detailed discussion of the geophysics of the WSRP and ESRP, but salient geophysical features of each area will be mentioned. The reader may consult the references provided here for further details.

Gravity and magnetic anomalies emphasize the contrast between the WSRP and ESRP. Elongated gravity and magnetic highs are parallel to the axis and boundary faults in the WSRP. Their configuration here suggests that the upper sialic crust is thinned, basaltic lower crust is absent, and a thick layer of dense magnetic rock, possibly of the Miocene Columbia River Basalt Group, underlies the WSRP at a depth of about 2 km (Mabey and others, 1975). Mabey (1976) suggested that the WSRP may have formed as a rift in Miocene time in response to northeast extension and that basalt and sediments, more than a kilometer thick, accumulated in the depression.

The magnetic and gravity anomalies of the ESRP are more complex than those of the WSRP, suggesting a more complex underlying geology. In general, magnetic anomalies (both highs and lows) coincide with the known northwest alignment of volcanic rift zones (Kuntz, unpub. data, 19), and they appear to be produced by volcanic rocks within 2 km of the surface (Mabey, 1978). Gravity anomalies on the ESRP differ in magnitude and width when compared to basin-range gravity anomalies in adjoining areas (Mabey, 1978). The gravity anomalies of the ESRP have approximately twice the wavelength of anomalies associated with basin-range structures adjoining the plain, and Mabey (1978) suggests that these anomalies reflect the distribution of Pliocene and perhaps lower Tertiary rocks deposited in basins about twice the width of current basins. These relations led Mabey and others (1975) to conclude that the ESRP began to form before the development of basin-range structure.

An electrical-sounding profile from Blackfoot to Arco, in the central part of the ESRP, suggests that a basalt layer approximately 600 m to 2,500 m thick overlies a sedimentary layer and/or rhyolitic ash-flow-tuff layer approximately 3,000 m thick. The geoelectrical "basement" lying below these two layers is interpreted as consisting of Paleozoic rocks, possibly similar to those exposed in the Basin and Range outside the plain (Zohdy and Stanley, 1973).

Magnetotelluric-sounding studies (Stanley and others, 1977) and reconnaissance seismic-refraction profiles (Braile, written commun., 1977) have added additional details to knowledge of the deep structure of the plain.

Regional tectonics and models for origin of the Eastern Snake River Plain

Current debate regarding the origin of the ESRP is most easily understood if traced historically. The notion that the Snake River Plain is a fault-bounded graben inundated by flood basalts was advocated by Lindgren (1898) and Russell (1902). Malde (1959) demonstrated that the WSRP is fault-bounded, but similar relationships have not been found for the ESRP. Kirkham (1931) proposed that the Snake River Plain is a downwarp, based on the fact that Cenozoic rocks dip and thicken toward the axis of the plain. This view now appears to be especially appropriate for the ESRP. Hamilton and Myers (1966) proposed that the Snake River Plain is a rift basin produced by the northwestward migration of the Idaho batholith.

Morgan (1972) suggested that Yellowstone is the present-day site of a deep-mantle plume and that the ESRP is its track for the preceding 10 m.y. Others have followed Morgan's idea and have proposed genetic models for magmatism and tectonics for the area based on the plume model (Smith and Sbar, 1974; Suppe and others, 1975). Armstrong, Leeman, and Malde (1975) established that rhyolite-basalt volcanism for the Snake River Plain is younger to the northeast; this conclusion lent support to the plume theory.

Within the last 10 years, considerable study has been made of the historical seismicity of the western United States. These studies, in connection with other geophysical and geological studies, have led to an evaluation of regional tectonics in light of the evolving theory of plate tectonics for the western United States. A zone of high seismicity, the Intermountain Seismic Belt, extends from northwestern Montana south through eastern Idaho and central Utah, and then southwestward across southwestern Utah (Smith and Sbar, 1974; Scholz and others, 1971). This zone follows the boundary between the Great Basin and the Colorado Plateau, middle Rocky Mountains, and northern Rocky Mountains; and it is postulated as a boundary between subplates of the North America plate.

Current ideas regard the dominantly east-west crustal extension and volcanism in the Great Basin as the result of upward and outward motion of the mantle in the form of a diapir (Scholz and others, 1971; Prostka and others, 1976; Thompson, 1977; Smith, 1977). These studies suggest that volcanism and spreading of the crust in the Great Basin-Snake River Plain region began about 40 m.y. ago with the inception of a mantle diapir beneath east-central Nevada. Volcanic eruptive foci then spread out radially from the diapir crest (Smith, 1977). Rhyolites were first erupted at the junction between the WSRP and ESRP 18 m.y. ago; from this area, eruptive foci progressively migrated both northeastward along the ESRP to Yellowstone and northwestward along the WSRP to north-central Oregon.

Field studies by Kuntz (1977a, 1977b, 1977c) show that volcanic rift zones of the ESRP appear to be extensions of basin-range and other structures (chiefly thrust faults) beneath the Plain, and they suggest that (1) the northeast-southwest extension characteristic of the mountains of the Basin and Range province north and south of the ESRP is also characteristic of the ESRP itself; (2) basin-range structure and possibly topography may underlie the volcanic section of the ESRP; and (3) volcanic rift zones are not superposed over possible boundary faults for the ESRP; on the contrary, they cut across possible boundary faults. These findings emphasize that the ESRP is a fundamental tectonic part of the northeastern Basin and Range and is subject to the same stresses that currently affect basin-range areas north and south of the plain.

The writer favors the idea that northeast-southwest crustal extension in the ESRP has been concentrated beneath a reactivated crustal discontinuity in basement rocks. Geological evidence for a major crustal discontinuity beneath the ESRP, possibly as old as Precambrian, is weak owing to the lack of exposures of Precambrian rocks nearby; but the ESRP is part of a northeast-trending magnetic lineament composed of magnetic highs that extends from north-central Nevada through the ESRP and Yellowstone Park area into Canada (Eaton and others, 1975). Zietz and others (1971) described similar lineaments as reflecting major structural features in basement rocks. They also stated that "the close correspondence of structural and geologic features in younger rocks with these basement magnetic and structural trends suggests that basement trends controlled or at least greatly influenced intrusion, deposition, and structural history of younger rocks." The apparent aseismicity of the ESRP, based on historical earthquake records, suggests that strain may be released by creep in the thin, hot crust in this region. It is clear that ideas concerning the origin, evolution, and future history of the ESRP will continue to undergo rapid evolution as more geological and geophysical data become available.

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