

Tension cracks, eruptive fissures, dikes, and faults related to late Pleistocene–Holocene basaltic volcanism and implications for the distribution of hydraulic conductivity in the eastern Snake River Plain, Idaho

Mel A. Kuntz*

U.S. Geological Survey, MS 913, Box 25046, Federal Center, Denver, Colorado 80225, USA

Steven R. Anderson

U.S. Geological Survey, Department of Geosciences, Idaho State University, P.O. Box 8072, Pocatello, Idaho 83209, USA

Duane E. Champion

Marvin A. Lanphere

U.S. Geological Survey, MS 910, 345 Middlefield Road, Menlo Park, California 94025, USA

Daniel J. Grunwald

U.S. Geological Survey, MS 913, Box 25046, Federal Center, Denver, Colorado 80225, USA

ABSTRACT

Tension crack–eruptive fissure systems are a key characteristic of most late Pleistocene–Holocene basaltic lava fields in the eastern Snake River Plain, Idaho. Models based on elastic displacements that accompany dike intrusion and the dimensions of tension cracks and eruptive fissures give new perspectives on the size and shapes of dike systems in the eastern Snake River Plain. Elastic-displacement models predict faults related to dike intrusion, but these are absent at the late Pleistocene–Holocene lava fields. Numerous faults in the Box Canyon area of the Arco–Big Southern Butte volcanic rift zone can be misinterpreted as being related to dike-emplacement processes. Our data strongly suggest that these faults are tectonic in origin and related to the Lost River range-front fault.

Data about size and shapes of dike systems, in conjunction with detailed mapping and regional paleomagnetic studies, are used to interpret the style of volcanism in a part of the Idaho National Engineering and Environmental Laboratory and for the entire eastern Snake River Plain. The mapping–paleomagnetic studies suggest that sections of dike systems as long as ~40 km can be active simultaneously or within periods of time as short as a few hundred years.

The characteristics and locations of dikes, eruptive fissure systems, and tension cracks have implications for the movement of groundwater and migration of radioactive and chemical wastes in the Snake River Plain aquifer at the Idaho National Engineering and Environmental Laboratory. Buried zones of northwest-trending dikes, eruptive fissures, and tension cracks, referred to as vent corridors, are perpendicular to the regional direction of groundwater flow and probably control some of the lowest and highest estimates of hydraulic conductivity in the aquifer.

*E-mail: mkuntz@usgs.gov

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INTRODUCTION

Like eruptions in Hawaii and Iceland, a characteristic aspect of the basaltic volcanism on the eastern Snake River Plain is that eruptive fissures, which represent the breaching of the Earth's surface by ascending dikes, dominate its early stages. Other structures associated with dike emplacement and fissure-dominated eruptions in the eastern Snake River Plain are tension cracks (Kuntz et al., 1992; Hackett and Smith, 1996; Smith et al., 1996) and faults (Hackett and Smith, 1992; Smith et al., 1996). Eruptive fissures and dike-induced tension cracks are clearly displayed at several late Pleistocene–Holocene lava flows in the eastern Snake River Plain, but our field investigations show that faults are absent at these localities. We have studied these late Pleistocene–Holocene lava fields in detail because they are remarkably preserved. The eruptive fissures and tension cracks at these lava fields are described in detail because they represent typical examples of the processes and products of basaltic volcanism of the eastern Snake River Plain and because the dimensions of the tension cracks and eruptive fissures can be used to interpret the geometry of dike systems at shallow crustal levels.

Faults are present in the Arco–Big Southern Butte and Spencer–High Point volcanic rift zones (Fig. 1) near the margins of the eastern Snake River Plain. At both localities, the faults are part of collinear extensions of major, range-front faults for basin-and-range mountains at the margins of the eastern Snake River Plain. Elastic-deformation models suggest that faults related to dike emplacement are aligned in the zone of tension cracks, but the absence of faults in the late Pleistocene–Holocene lava fields and the geometric association of faults with extensions of range-front faults suggest that faults at the two localities on the margins of the eastern Snake River Plain are of tectonic rather than volcanic origin. We discuss reasons for the near absence of faults and the dike-emplacement mechanisms that favor formation of tension cracks in place of faults.

Through detailed field mapping, paleomagnetic studies, and petrographic correlations, we have discovered that eruptions in one area of the eastern Snake River Plain are not typical of the style of most eastern Snake River Plain basaltic eruptions. The atypical eruption style is the result of an exceptionally long dike system, which produced several small shield volcanoes along a linear belt ~40 km long.

The style of volcanism and characteristics and locations of tension-crack and eruptive fissure systems also have implications for the movement of groundwater and migration of radioactive and chemical wastes in the Snake River Plain aquifer at the Idaho National Engineering and Environmental Laboratory (INEEL) (Fig. 1). These northwest-trending systems, referred to as vent corridors where they are inferred in the subsurface, are perpendicular to the regional direction of groundwater flow and probably control some of the lowest and highest estimates of hydraulic conductivity in the aquifer. Near-vent volcanic de-

posits, dikes, fissures, and cracks probably provide localized preferential pathways and barriers to groundwater flow.

GENERAL FEATURES OF TENSION CRACKS AND FAULTS ASSOCIATED WITH ERUPTIVE FISSURES

Previous studies

Recognition and physical description of the widespread and prominent tension cracks in the eastern Snake River Plain resulted from early analyses of aerial photographs and satellite imagery. Prinz (1970) first mentioned tension cracks in his discussion of the Idaho rift system, now termed the Great Rift volcanic rift zone (Kuntz et al., 1988, 1992). Prinz used the term Great Rift set for the eruptive fissures, tension cracks, and vents for lava flows of the composite Craters of the Moon lava field (Fig. 1). His term "Open Crack rift set" corresponds to two pairs of tension cracks that extend southeast from the southeast margin of the Craters of the Moon lava field (Figs. 1 and 4). Prinz's "Kings Bowl rift set" refers to an eruptive fissure and a flanking pair of tension cracks that are part of the Kings Bowl lava field, and his "Wapi rift set" refers to the inferred feeder dikes and elongated vent area for the Wapi lava field (Figs. 1 and 2). Greeley et al. (1977) and King (1977) discussed and showed in several oblique aerial photographs the eruptive fissure system and the flanking pair of tension cracks for the Kings Bowl lava field. A pair of tension cracks is exposed beyond the northwest margin of the Hell's Half Acre lava field (Figs. 1 and 3; Kuntz et al., 1992). Tension cracks have not been recognized at the Cerro Grande (Fig. 1) and Shoshone lava fields (Kuntz et al., 1992), but cracks at those localities may have been covered by their own lava flows or formed in rocks beyond the margins of the lava fields where they are not easily preserved or recognized.

Field aspects of tension cracks and faults

Our inspection of tension cracks in the eastern Snake River Plain shows that they exhibit evidence of purely extensional movement. The walls of the cracks have jagged surfaces that consist of blocks of lava that broke along preexisting fractures, mainly columnar joints. Projections of the fracture and/or joint surfaces on one side of the crack match perfectly with indentations on the other side of the cracks. Prinz (1970) described the tension cracks in his rift sets as having widths of 6–8 ft, and he stated that there is no evidence of vertical or rotational movements. We have found that crack widths are typically ~1 m but are as wide as 2 m; these widths reflect true amounts of dilation. Where crack widths are locally wider than 2 m, blocks of lava have fallen into the cracks, but this is not common.

Faults associated with tension cracks and eruptive fissures have not been recognized at the late Pleistocene–Holocene lava fields. At these localities, surfaces of lava on opposite sides of cracks are at the same elevation, except at localities where un-

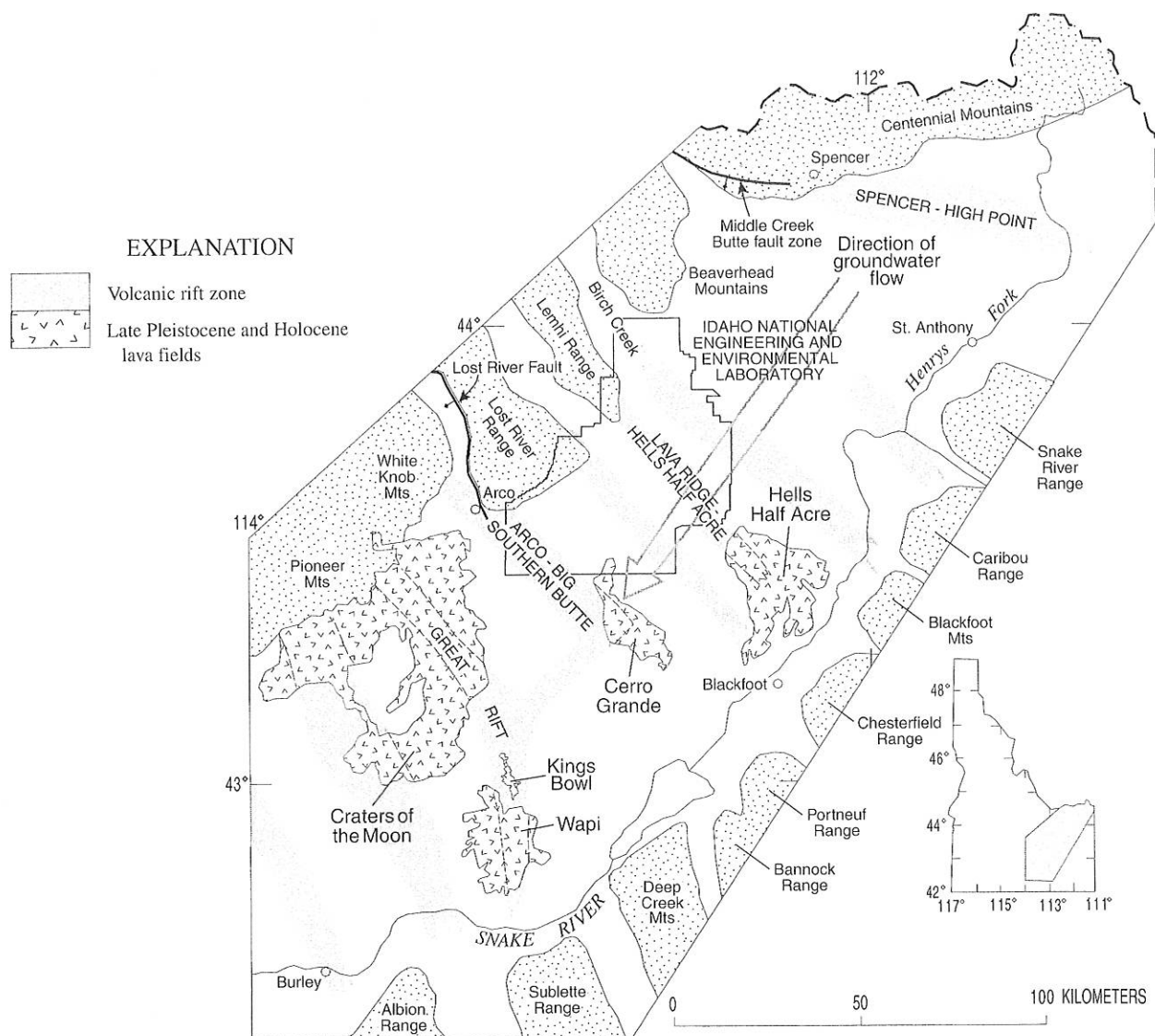


Figure 1. General map of part of eastern Idaho showing volcanic rift zones, late Pleistocene and Holocene basaltic lava fields, and other geologic and geographic features referred to in text. Only volcanic rift zones referred to in text are identified by name in this figure (modified from Kuntz et al., 1992).

supported blocks of lava have slumped into the crack. Faults having offsets of 0.5 m or more would be obvious from analysis of topography on 1:24 000 scale topographic maps having contour intervals of 10 ft, and faults have not been observed on aerial photographs. We suggest that dike-induced faults associated with the late Pleistocene–Holocene lava fields in the eastern Snake River Plain, if present, are extremely rare.

Laboratory methods of analysis of tension cracks and eruptive fissures

Tension cracks and eruptive fissures were identified on 1:30 000 and 1:40 000 scale black and white air photos and mapped on 1:24 000 scale map bases with the aid of a Kern

PG-2 stereoplotter. Dimensions of these structures were measured from the 1:24 000 scale maps; those data are summarized in Table 1. The cracks and fissures were digitized and Figures 2, 3, and 4 herein were prepared using illustration software from the digitized data.

PRESERVATION AND RECOGNITION OF TENSION CRACKS

Several factors are key in identification and preservation of tension cracks. (1) The cracks must have formed in basalt flows that are relatively young and covered by little if any loess. (2) The cracks must have formed in basalt flows rather than in

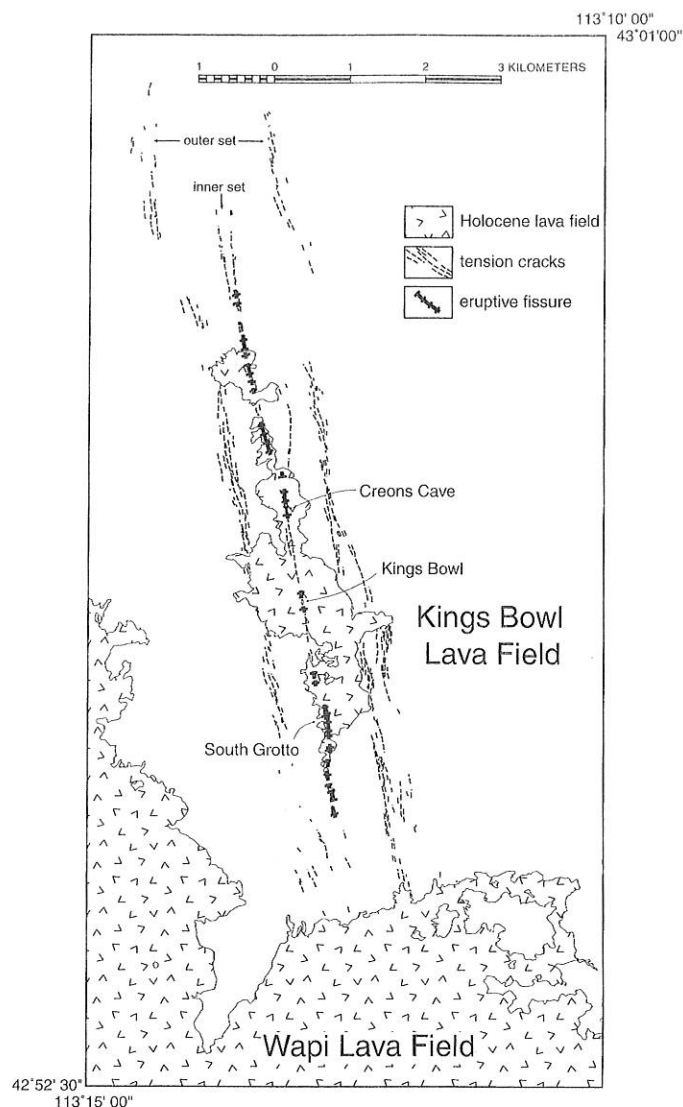


Figure 2. Map of tension cracks and eruptive fissures for Kings Bowl lava field, south-central Idaho. Figure prepared from Covington (1977) and from analysis of 1:40 000 scale black-and-white aerial photographs taken in 1973.

rocks that are friable or easily eroded. (3) At least some parts of the cracks were not resurfaced by younger lava flows.

The Hell's Half Acre volcanic field illustrates the first factor. Cracks northwest of the field (Fig. 3) formed in flows that are covered by 0.5–1 m of loess. Many of the cracks are wholly or partly covered by loess, but their size and extent can still be deciphered on aerial photos by recognizing openings in the cracks where loess has drained into them. Subtle linear belts of darker colors in the loess that overlies the cracks can also be used to recognize the Hell's Half Acre cracks. If the loess were thicker, it is possible that these cracks could not be recognized in the field or on air photos.

The second factor is illustrated by some cracks in the Craters of the Moon lava field. Eruptive fissures, tension cracks, and near-vent cinder and ash deposits are concentrated in a narrow belt in the northern part of the Craters of the Moon lava field. Tension cracks associated with the Trench Mortar Flat eruptive fissures formed along the eastern flank of Big Cinder Butte, where they are partly buried by cinders (Kuntz et al., 1989).

The third factor is illustrated by the cracks at the Kings Bowl, Hell's Half Acre, and the Open Crack rift set (Figs. 2, 3, and 4). At these three localities, some parts of the tension cracks are covered by younger flows, but the uncovered parts yield enough field data to make reasonable inferences about the nature of the original, complete set of tension cracks.

EXAMPLES OF ERUPTIVE FISSURES AND TENSION CRACKS IN THE EASTERN SNAKE RIVER PLAIN

We here discuss the character of eruptive fissures and tension cracks for three late Pleistocene–Holocene basaltic lava fields in the eastern Snake River Plain. We begin with the Kings Bowl lava field because the eruptive fissures and tension cracks there are easily identified and studied in the field and easily mapped on air photos. We then discuss eruptive fissures and tension cracks in the Hell's Half Acre lava field and the Open Crack rift set, where spatial relationships between the cracks and fissures are less obvious and where parts of the eruptive fissure–tension-crack systems are covered by young lava flows.

Kings Bowl lava field

The Kings Bowl lava field is the locus of source vents for the small, 2220 yr old Kings Bowl lava field that covers an area of 3.3 km² and has an estimated volume of 0.005 km³ (Kuntz et al., 1986, 1992; Fig. 2). Eruptive fissures and tension cracks extend over a distance of 11.3 km (Table 1). The eruptive fissure system, 6.1 km long, consists of 18 en echelon eruptive fissure segments that range from 220 m to 900 m long. The south end of the eruptive fissure system consists of five short (<100 m) eruptive segments that are surrounded by patches of lava that are each <200 m in longest dimension. During the initial phases of the Kings Bowl eruptions, some of the short segments may have been part of longer segments of eruptive fissures or they may represent en echelon fingers that merge at depth with a single dike having a length of ~6 km. Delaney and Gartner (1997) suggested that dikes in the San Rafael Swell, Utah, illustrate the latter case. In addition, areas between present-day eruptive fissure segments may have been covered by some of the youngest flows of the Kings Bowl lava field (Covington, 1977).

The eruptive fissure system is halfway between two sets of outer, parallel, tension cracks (Fig. 2). These cracks formed in

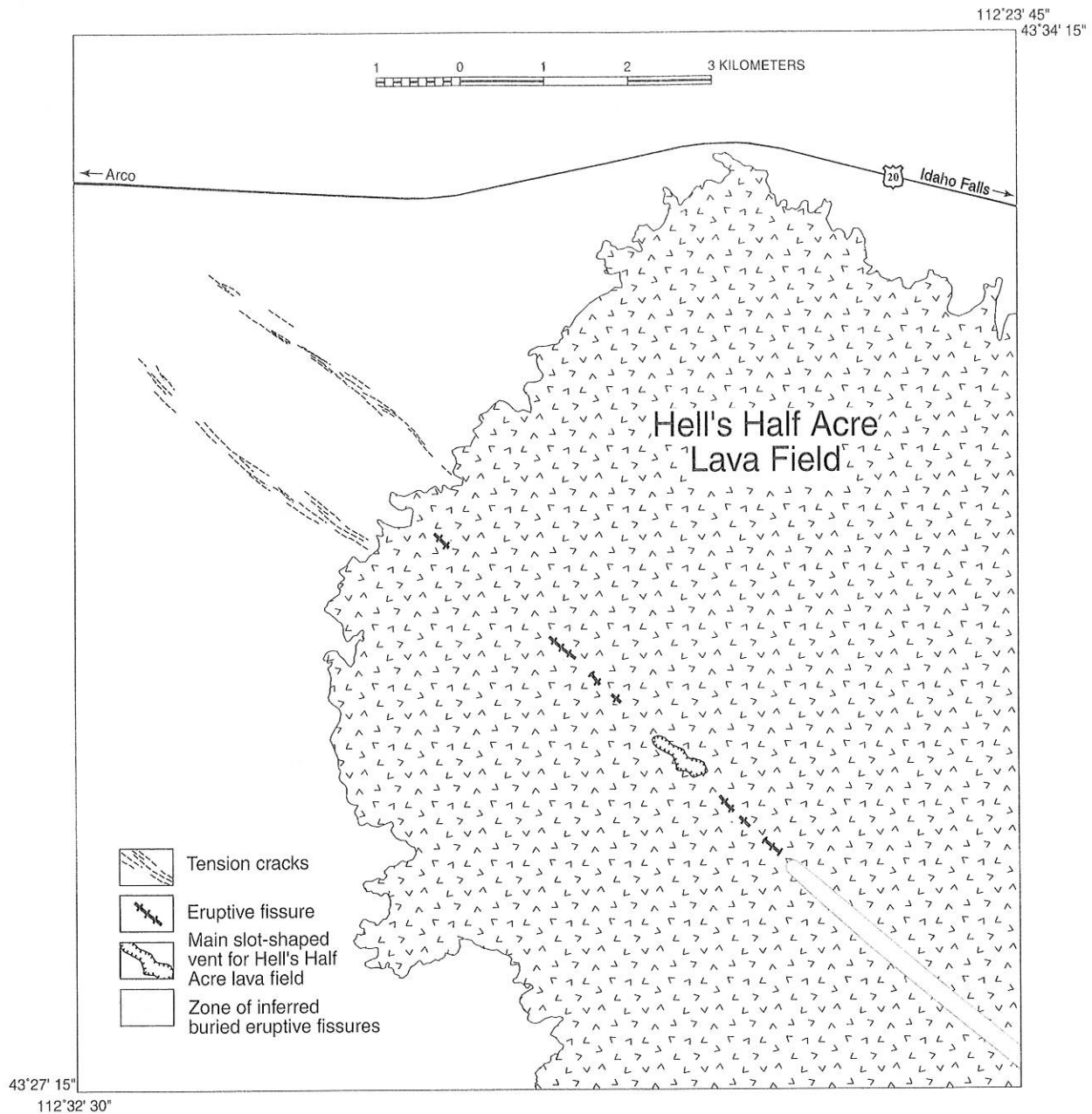


Figure 3. Map of tension cracks, eruptive fissures, and slot-shaped vent area for Hell's Half Acre volcanic field, east-central Idaho. Data from Kuntz et al. (1994) and from interpretation of 1:30 000 scale true-color aerial photographs taken in 1973.

relatively young lava flows that have not been covered by loess; thus they are easily identified in the field and on aerial photographs. The eastern set of cracks is nearly continuous along the length of the eruptive fissures except near Kings Bowl, where it is locally covered by Kings Bowl flows. The eastern set of cracks ranges in width from ~100 to 500 m and trends N10°W. There appears to be a 1-km-long gap in the eastern set of cracks ~2.5 km north-northeast of Creon's Cave. The western set of tension cracks is nearly continuous for a distance of ~9 km

north of South Grotto. South of that locality, the crack set is diffuse. The width of the western set of cracks ranges from 100 to 200 m north of South Grotto and is as wide as 800 m south of that locality. The western set of cracks trends N11°W. Along the trace of the eruptive fissures, the distance between the pair of tension cracks is ~1250 m. A second pair of inner tension cracks extends for a distance of ~1.5 km north of the northernmost eruptive fissures (Fig. 2). The distance between the inner pair of cracks ranges from ~50 m on the south to ~200 m on

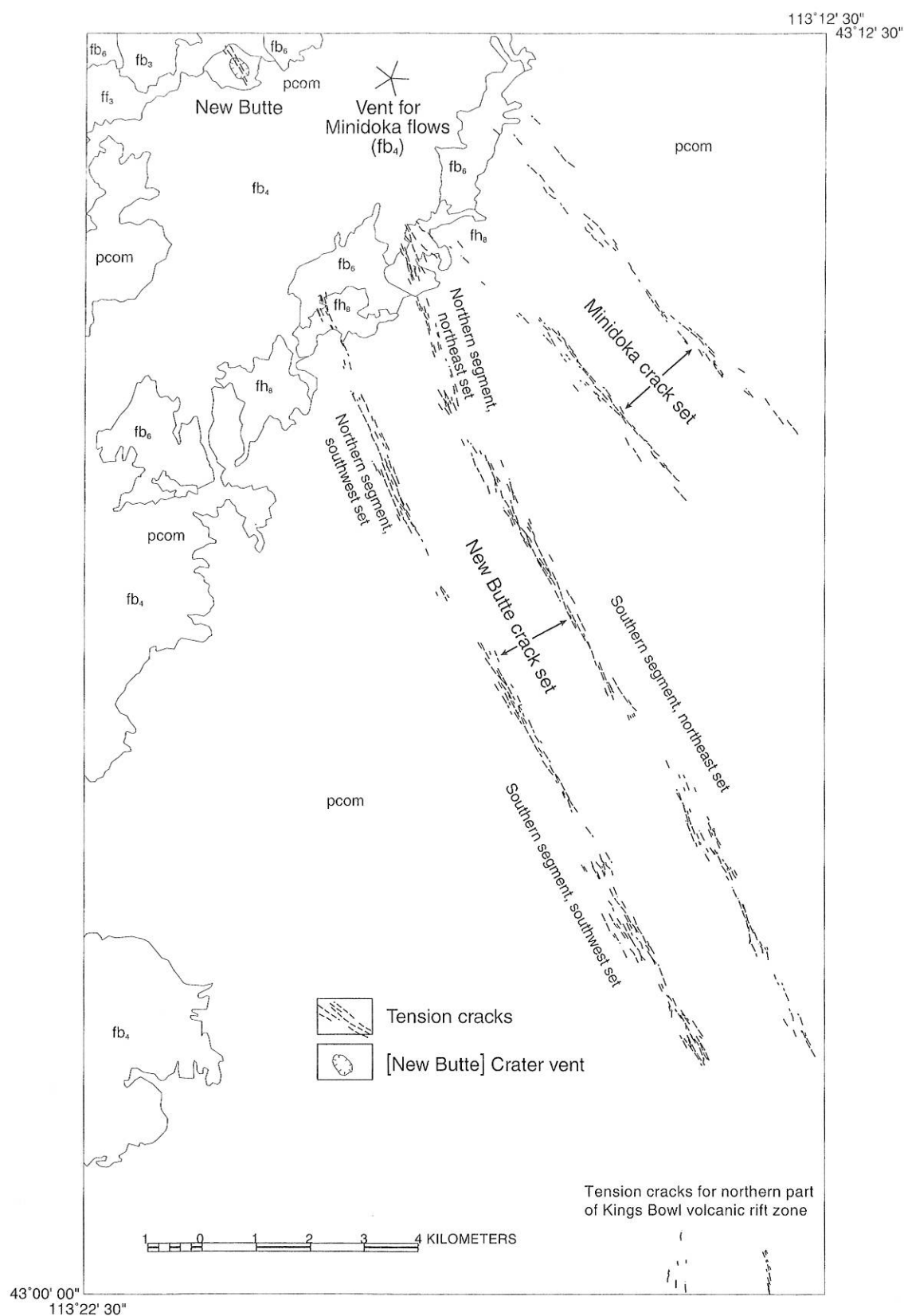


Figure 4. Tension cracks of Open Crack rift set and stratigraphic relationships among flows of Craters of the Moon lava field, south-central Idaho (from Kuntz et al., 1988). Flow designations as follows: fb₃, Devils Cauldron; fb₄, Minidoka; fb₆, Rangefire; ff₃, Bottleneck Lake; fh₈, Brown; pcom, pre-Craters of Moon. See Kuntz et al. (1988) for details of stratigraphy and age designations for flows of Craters of the Moon lava field.

TABLE 1. DATA FOR TENSION-CRACK AND ERUPTIVE FISSURE SYSTEMS IN THE EASTERN SNAKE RIVER PLAIN, IDAHO

Crack systems	Measured length of cracks (km)	Average distance between crack pairs (m)	Length of eruptive fissures (km)	Inferred length of dikes (km)
Kings Bowl	11.3	1,250	6.1	15*
Hell's Half Acre	4.3	1450	5.5	24#
Open Crack rift set				
Minidoka set	8	2000	n/a	20*
New Butte set				
Northern segment	5	1800	n/a	16*
Southern segment	13	1810	n/a	13*
North and South segments	16	1800	n/a	40#

*Minimum estimate

#/Maximum estimate

n/a—not applicable

the north. A northward projection of the northernmost eruptive fissures bisects the inner pair of tension cracks.

Hell's Half Acre lava field

A set of parallel tension cracks extends ~4 km northwest of the 5200 yr old Hell's Half Acre lava field (Kuntz et al., 1986, 1992; Fig. 3). These tension cracks formed in loess-covered lava flows and thus are not as obvious in the field as are the tension cracks in the Kings Bowl area. Many of the Hell's Half Acre tension cracks are exposed only along short segments where loess has drained or been washed into the tension cracks. However, the extent and character of the crack system is clearly evident on 1:30 000 scale, true color aerial photographs taken in 1973. The tension cracks are denoted on the photos by short segments of open tension cracks, aligned pits in loess, and dark-toned lineaments that are parallel to or extensions of the exposed tension cracks.

Individual tension cracks average ~500 m long; the longest crack is ~1 km long and some cracks are as short as 100 m. Each of the crack sets consist of en echelon cracks; at any one locality, the crack set may consist of one to as many as five tension cracks. The width of the crack sets ranges between 60 m and 240 m. The average distance between the two crack sets is ~1450 m. The southwesterly set of tension cracks trends N56°W and the northeasterly set of tension cracks trends N52°W.

The main eruptive center for the Hell's Half Acre lava field is a slot-shaped vent, 800 m long and 100–200 m wide (Fig. 3). There is strong evidence of repeated episodes of piston-like draining and filling of the crater and overflow of the crater walls by thin, shelly, pahoehoe flows. Small spatter cones and eruptive fissures extend northwest and southeast of the main crater. Recent analysis of aerial photographs has identified a partly buried, 300-m-long, eruptive fissure segment just 400 m from the northwest margin of the lava field. Owing to a regional northwest to southeast slope direction, much lava from the main Hell's Half Acre vent area flowed to the southeast and probably covered parts of the southeastern end of the eruptive fissure

system. A lava-tube system that originates along the eruptive fissure system ~1000 m southeast of the main vent area has rootless vents that contributed lava that resurfaced at the southeast end of the eruptive fissure system (Kuntz et al., 1994). The exposed part of the entire eruptive fissure system for the Hell's Half Acre lava field is 5.5 km long. Assuming that the eruptive fissure–tension-crack system is symmetrical, i.e., that the main vent area for the Hell's Half Acre lava field is in the center of the system, then that system may be ~19 km long.

Open Crack rift set

The Open Crack rift set consists of two pairs of tension cracks that extend southeast from the southeast margin of the Craters of the Moon lava field (Fig. 4; Kuntz et al., 1988). We use the term Minidoka set for the northeast pair of cracks and the term New Butte set for the southwest pair of cracks. Compared to the Kings Bowl and Hell's Half Acre tension-crack sets discussed here, the Minidoka and New Butte crack pairs are unique because neither pair can unequivocally be related to an eruptive fissure system.

The Minidoka pair of cracks is the shorter and less well developed of the two pairs. In the Minidoka pair, the northeast set of cracks is 8 km long and trends N45°W. The southwest set of cracks is 6.5 km long and trends N41°W. The distance between the pair of cracks is 1920 m near the margin of the Craters of the Moon lava field and 2100 m near the southeast end. The central and southeast ends of each pair of cracks are easily identified in the field and on aerial photographs. The northwest ends of each pair of cracks are more diffuse, i.e., the cracks are fewer and less easily identified in the field and on aerial photographs because they formed in flows that have a significant cover of loess. Cracks of the Minidoka set cut Range-fire flows (fb₆ in Fig. 4) of the Craters of the Moon lava field, are believed to be about 4500 yr old. However, the cracks are covered by Minidoka flows (fb₄ in Fig. 4) of the Craters of the Moon lava field, also believed to be about 4500 yr old, but stratigraphically younger than Range-fire flows (Kuntz et al., 1986, 1988). These relations indicate that the Minidoka cracks

formed during eruptive period B of the Craters of the Moon Lava field and are about 4500 yr old.

When cracks are projected northwest along strike, the vent area for the Minidoka flows bisects the Minidoka crack pair. This vent area is obscure, but its location is denoted as a topographically high, lava-filled depression from which lava-tube systems radiate in all directions. The distance from the Minidoka vent area to the southeast end of the tension-crack system is 10.2 km. Assuming the symmetry shown in Figure 2, the Minidoka eruptive fissure—tension-crack system has a presumed length of ~20 km.

The New Butte tension-crack set consists of two pair of tension cracks (Fig. 4). Each set of tension cracks consists of two segments; each segment has a slightly different trend. The northern segment of the southwest set of cracks extends 5 km from the southeast of the margin of the Craters of the Moon lava field and has a trend of N22°W. The average distance between the northern segments of the New Butte crack system is 1800 m. The southern segment of the southwest set of cracks has a length of 10 km and trends N27°W. The northern segment of the northeast pair of cracks is 4 km long and trends N16°W. The southern segment of the northeast set of cracks is 13 km long and trends N27°W. The average distance between the southern segments of the New Butte crack system is 1800 m. When projected northwest along strike, the New Butte set of cracks is on either side of the vent area for New Butte; thus New Butte is believed to be the site where the dike that formed the New Butte crack system breached the surface. Assuming the symmetry shown in Figure 2 and that the dike that breached the surface at New Butte is associated only with the northern segments of the New Butte set of cracks, the New Butte eruptive fissure—tension-crack system may have a length of ~16 km. If New Butte represents the center of an eruptive fissure—tension-crack system that includes both the northern and southern segments of the New Butte crack set, then the eruptive fissure—crack system may be as long as 40 km.

The differing trends of the two segments suggest that the New Butte crack system may consist of two sets representing two dike systems. In this case, the New Butte crack system may consist of the northwest set that has New Butte as the vent area, and the southeast set of cracks may represent a 13-km-long dike that failed to breach the surface.

FAULTS IN VOLCANIC RIFT ZONES OF THE EASTERN SNAKE RIVER PLAIN

Spencer–High Point volcanic rift zone

The Spencer–High Point volcanic rift zone extends ~70 km in a west-northwest–east-southeast direction on the southern flank of the Centennial Range in the northeastern part of the eastern Snake River Plain (Figs. 1 and 5; Kuntz et al., 1992). This zone has the highest concentration of vents of any volcanic rift zone in the eastern Snake River Plain. The vents at that

locality are mainly of the eruptive fissure and lava-cone types, forming small-volume lava fields that are long and narrow because they moved down a relatively steep slope (1°–2°) to the south. The eruptive fissures and elongated vents in the zone have a remarkable degree of parallelism; they are aligned in a trend of N63° ± 2°W.

The western end of the volcanic rift zone consists of two small 4.1 Ma rhyolite domes (Indian Creek Buttes) and ~10 vents for small basaltic lava fields. There are also numerous, west-northwest–east-southeast–trending, down-to-the-south, normal faults that are part of the Middle Creek Butte fault zone (Fig. 5). The main part of the volcanic rift zone begins where the Middle Creek Butte fault zone enters the basalt-flow terrain of the eastern Snake River Plain near Spencer. The graben ~5 km south of Spencer and the graben ~3 km east of Experimental Crater are linear extensions of the Middle Creek Butte fault zone into the basalt-flow terrain. These grabens are very narrow (<100 m wide) when compared to the width of pairs of tension cracks and faults that are assumed to form in the zone of tension cracks (~1500–2500 m) in the late Pleistocene–Holocene lava fields in the eastern Snake River Plain (cf. Figs. 2, 3, 4, and 5). These relations suggest that these grabens cannot unequivocally be ascribed to emplacement of basaltic dikes, but rather they are likely the expression in overlying basalt flows of faults in bedrock beneath the flows.

A graben ~3 km north and a graben ~7 km west of Morgan's Crater (Fig. 5) may be related to dike emplacement. The northern graben is ~700 m wide and 1.4 km long. The northern boundary of this graben is very linear and has steep walls as high as 10 m. The southern wall is less steep and is as high as 5 m. Rubin and Pollard (1988) and Rubin (1990) showed that maximum displacement on faults related to single dike-injection events in Iceland, Hawaii, and Afar are typically <1 m. This relationship implies that numerous dikes were repeatedly injected beneath this graben to achieve the amount of fault offset observed. The graben is filled at both ends by younger lava flows, thus its length is a minimum value. It is collinear with Swan Butte, a major basaltic tephra cone 1.5 km to the east-southeast, and with an eruptive fissure just 300 m to the west. The eruptive fissure has several pit craters, suggesting that magma withdrawal may have led to formation of the pit craters and possibly the graben.

The graben west of Morgan's Crater is 2.5 km long and ranges from 200 m to 250 m wide. Its steep, linear southern wall is as high as 12 m; the northern wall is less steep and as high as 7 m. As for the graben cited previously, the amount of offset on the graben-bounding faults is an order of magnitude larger than the offset related to dike emplacement in Iceland, Hawaii, and Afar (Rubin and Pollard, 1988; Rubin, 1990). This graben is not collinear with any basaltic vents; it trends N76°W, which is significantly different than the N62°W trend of a 14-km-long eruptive fissure system located just 1 km north of the graben (Fig. 5). The divergence in trends of the dike-controlled vents and the large amount of total offset on the graben-

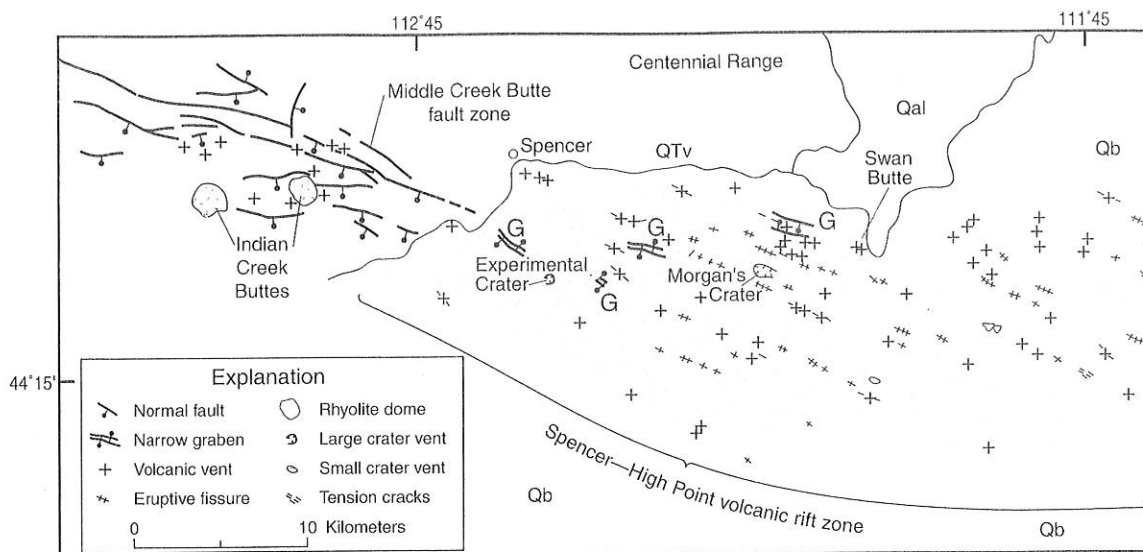


Figure 5. Generalized geologic map of Spencer-High Point volcanic rift zone, eastern Idaho. Abbreviations: QTv, Quaternary and Tertiary rhyolitic flows and ignimbrites of southern flank of Centennial Range; Qb, Quaternary basalt flows; Qal, Quaternary alluvium; G, grabens referred to in text. Modified from Kuntz et al. (1992).

bounding faults suggest that the graben west of Morgan's Crater may not be related to dike emplacement, but rather to tectonic faulting in bedrock beneath the flows.

Arco-Big Southern Butte volcanic rift zone

The Arco-Big Southern Butte volcanic rift zone extends 45 km southeast from the northwest margin of the eastern Snake River Plain at Arco (Fig. 6) to the long axis of the eastern Snake River Plain near Cedar Butte (Kuntz et al., 1994). This volcanic rift zone is the location of extensional faults, grabens, and fissure-controlled basaltic vents along the margins of the zone (see Kuntz et al., 1992, 1994).

Faults in this area, which are abundant and well developed along the Big Lost River ~8 km southeast of Arco, were discussed and/or mapped by Kuntz (1977, 1978a, 1978b), Kuntz et al. (1994), Smith et al. (1989, 1996), and Hackett and Smith (1992). Extensional faults having purely dip-slip movement mark the boundaries of a large graben in the Box Canyon area (Fig. 6). The faults have offsets of 1–8 m and form a broad graben that is ~10 km long and ranges from 2.7 to 3.5 km wide. The faults range in length from several tens of meters to as much as 4 km and form an echelon pattern. Fault traces form curving, irregular, locally indistinct boundaries for the sides of the broad graben. At the end of some faults, the surface basalt is unbroken but shows substantial drag across linear extensions of surface ruptures, forming monoclines. Displacement on faults in the Box Canyon area generally decreases to the southeast, and ~15 km southeast of Arco, the faults pass into open cracks that have purely horizontal displacement.

There are no volcanic vents within the Box Canyon graben, but Coyote Butte, a small (<0.1 km³) fissure-dominated lava

field, and several other small lava cones are ~5–10 km south-east of the graben. Shield volcanoes such as Crater Butte and Sixmile Butte and fissure-dominated vents such as Teakettle Butte, Lavatoo Butte, and two unnamed vents ~7 km southeast of Butte City are all found on the flanks of the graben. The lack of volcanic vents within the graben and the presence of many volcanic vents on the margins of the graben suggests that regional strain is accommodated by tectonic faulting and graben formation at the northwest end and by dike emplacement and formation of large lava fields along the margins and in the central and southeastern parts of the Arco-Big Southern Butte volcanic rift zone.

The northwest part of the Arco-Big Southern Butte volcanic rift zone contains faults that may qualify as dike-induced faults; we now discuss that locality. Along the southwestern side of the main graben is a smaller graben, known informally as Paula's graben, named after Paula LaPoint Jagmin, the first to study the area (Fig. 6). This graben is ~1.5 km long and 0.4 km wide. A down-to-the-east, curving, fault-monocline scarp trends north-south at its southern end and N31°W at its northern end, and forms the west wall of the graben. The eastern wall of the graben mirrors the west wall in trend, has offsets of 4–8 m, and may be considered as a paired antithetic fault to the main fault on the west side of the graben. Immediately south of Paula's graben is a north-south-trending monocline, 1.2 km long, which has ~0.5 m displacement, but is down to the west. There are also two north-south-trending cracks at this locality that are covered by sediment but observed on air photos.

The northeastern margin of the Box Canyon graben consists of two smaller grabens, which together form the Railroad graben (Fig. 6). The northwesternmost graben is 1.1 km long and 0.4 km wide. A curving fault scarp that trends roughly

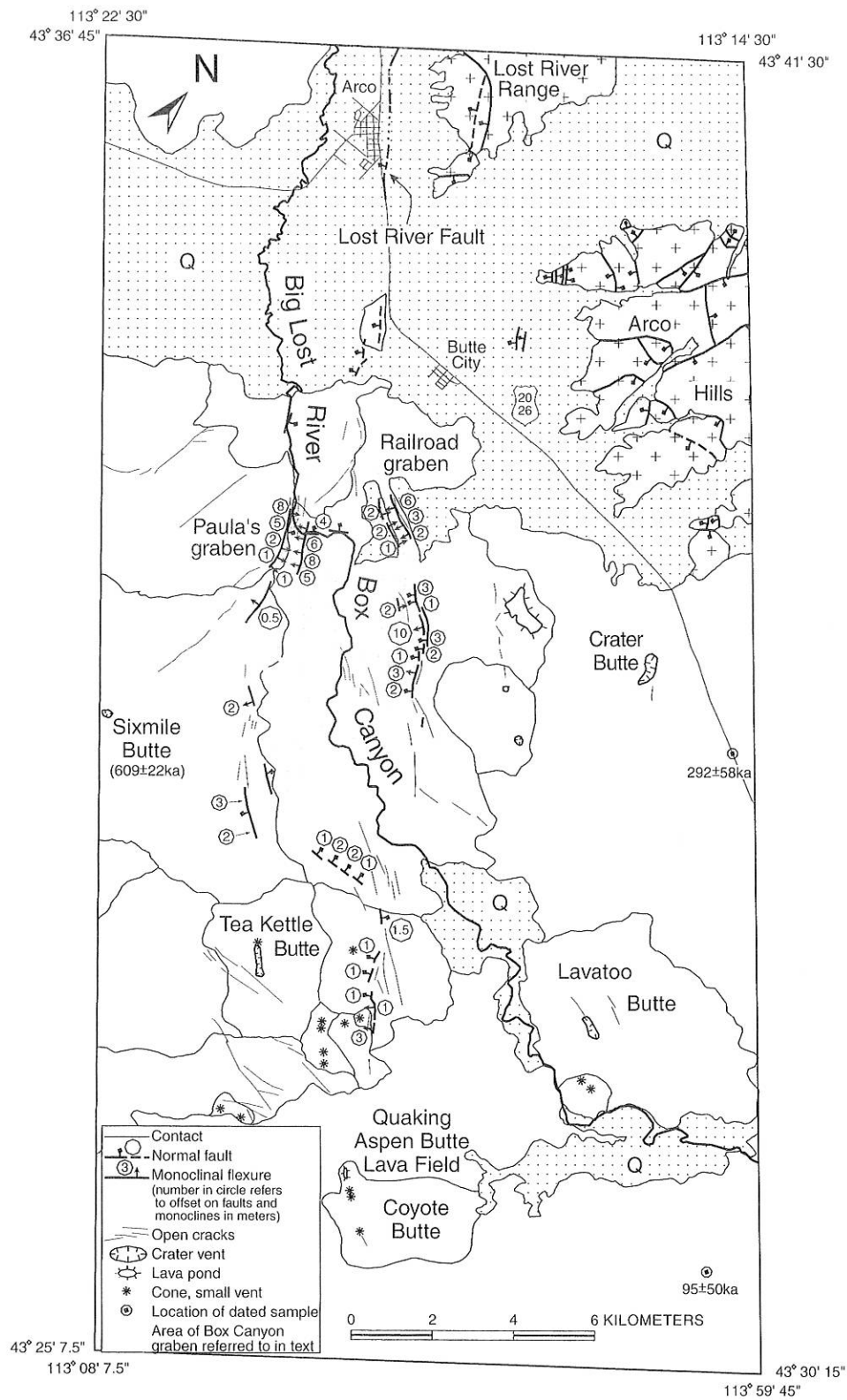


Figure 6. Generalized geologic map of northwestern part of Arco-Big Southern Butte volcanic rift zone, south-central Idaho. Surficial deposits are shown by dot pattern and labeled Q. Paleozoic and Tertiary rocks of Lost River Range and Arco Hills are shown by plus pattern. Basaltic lava flows have no pattern. See Kuntz et al. (1994) for more detailed geologic map of this area.

N70°W forms the northeast wall of the graben. Offsets along this scarp range from 2 to 6 m and the fault surface is vertical. The southwestern wall of the graben mirrors the northeastern wall in trend, has displacement of 1–2 m, and may be considered as a paired, antithetic fault to the main fault on the northeast side of the graben. The second graben, southeast of the previously described graben, is bounded on the northeast by a set of curving faults, 2.3 km in total length, which have displacements of 1–10 m. The southwest wall of this graben is short (0.8 km) and has displacement of 2 m. The general trend of the second graben is N42°W.

MODELS RELATING DIKES AND ASSOCIATED TENSION CRACKS AND FAULTS

Having described the field characteristics of eruptive fissures, tension cracks, and faults at various localities in the eastern Snake River Plain, we now examine models that describe the processes responsible for their formation and then focus on the description and interpretation of the field geometry between these structures. In view of the fact that tension cracks and eruptive fissures are such prominent structures and because faults are so rare in the late Pleistocene–Holocene lava fields we studied, the application of models offers explanations for these field relationships and possible explanations for the lack of dike-induced faults.

Elastic-displacement models for the genetic relationship between dikes, tension cracks and faults

Pollard et al. (1983) studied elastic displacements induced by dike emplacement and described the structures related to and formed by those displacements. Their models were derived to account for structures related to blade-like dikes (dikes that are tens of kilometers long and only a few kilometers high; see Fiske and Jackson, 1972) that were intruded into volcanic rift zones from a summit magma reservoir at Kilauea volcano, Hawaii. The dikes were approximated in the models by planar cracks in an elastic medium subjected to distributions of internal magma-driving pressure and remote stresses represented by gravitational loading.

The elastic-displacement model can be best summarized by the following (Pollard et al., 1983, p. 573–574):

Crack dilation perturbs this stress field especially over the top of the dike. Contours of the maximum principal stress outline a region of tensile stress that spreads outward and upward from the dike top (see Fig. 7B of this paper). Two maxima, one on each side of the dike plane, occur at the surface and are separated by a distance roughly equal to twice the depth to the dike top (see Fig. 7A). The tension decreases beyond the maxima, becoming a compressive stress at a distance somewhat greater than the depth to the crack center. Trajectories of potential tension cracks are vertical at the surface and dip steeply at depth (see Fig. 8). A surprising result of this analysis is the “bimodal” distribution of tensile stress at the free surface (see Fig.

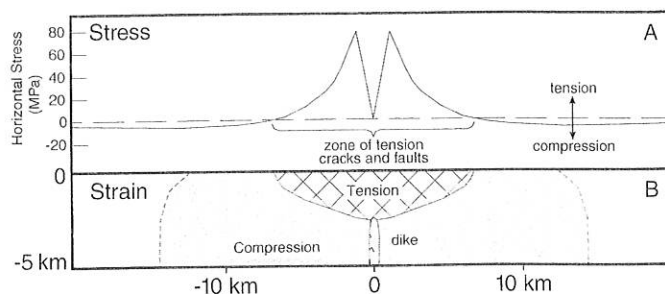


Figure 7. Diagrams illustrating relationship of horizontal stress (A) and zones of tensile and compressive strain (B) related to emplacement of dike into shallow crust, based on elastic displacement models of Pollard et al. (1983) and Rubin (1992). A: Example of theoretical horizontal stress based on January rifting event at Krafla volcano, Iceland (Pollard et al., 1983, Fig. 14), illustrating bimodal maxima of horizontal stress that predicts set of parallel tension cracks centered over dike. B: Zones of compressive and tensile stress in subsurface resulting from dike emplaced to depth of 2.5 km (Rubin, 1992, Fig. 6).

7A). The great tension at the crack tip induced by dilation is not transferred directly upward to the surface. Indeed the point immediately over the crack at the surface is stress free. This is a general result for nearly vertical pressurized cracks. It provides an explanation for the clustering of open cracks and normal faults into two parallel strips separated by relatively unbroken ground over the top of a dike (see Figs. 2, 3, 4 and 7A of this paper). It also enables predictions of the location and depth of a dike to be made from a map of surface structures.

Pollard et al. (1983) also showed that the elastic displacements accompanying emplacement of a single dike elevate the flanks of the area directly over the dike and may produce concomitant normal faulting (shown schematically in Fig. 8) in the zone of tension cracks. Rubin and Pollard (1988) and Rubin (1992) used elastic-displacement models to study faults and graben subsidence produced by the lateral propagation of basalt dikes that do not breach the surface over distances of tens of kilometers in volcanic rift zones in Hawaii, Iceland, and Afar. Their models indicate that lateral dike intrusion decreases compression beyond the ends of a laterally propagating dike, thus favoring faults at that locality. They also show that dike opening tends to compress and lock faults on either side of the dike, thus slip must occur on faults that intersect the dike near its top above the zone of dike-induced compression (zone of tension in Fig. 7B), or on faults that slip ahead of the dike as it propagates laterally (Rubin and Pollard, 1988). Pollard et al. (1983) documented vertical fault displacements of as much as 15 cm in the zone of tension cracks during fissuring events at Kilauea, and Rubin and Pollard (1988) and Rubin (1992) noted that slip of as much as 1 m occurred on graben-bounding faults during dike events in Iceland and Afar.

Because of the lack of erosion, observable dikes are nearly absent in the eastern Snake River Plain and thus structures such as offsets, steps, and ridges in the dikes cannot be used to determine the directions of dike propagation (Delaney and Gart-

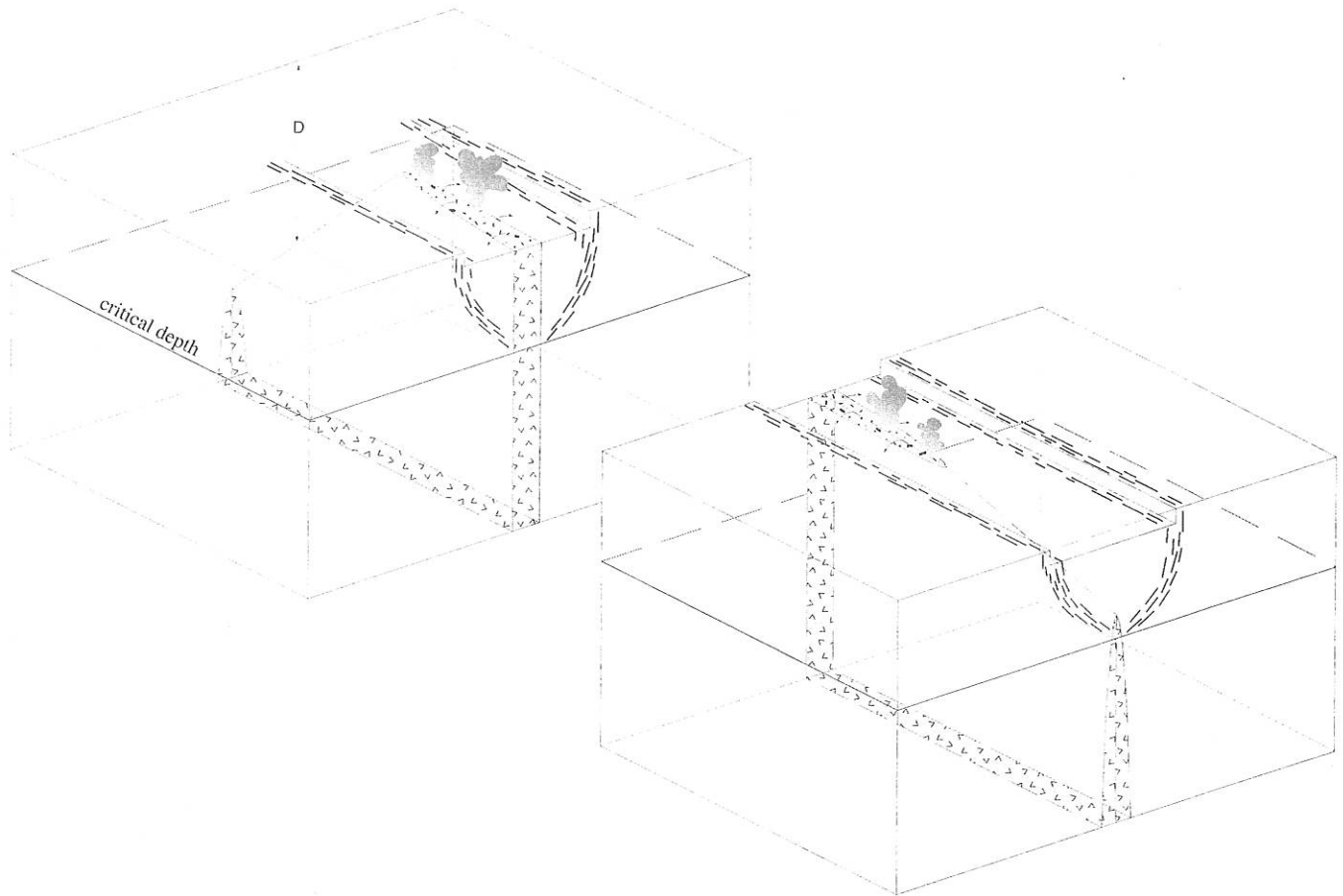


Figure 8. Geometric model showing relationships between tension cracks and faults formed by intrusion of vertical dike. D is critical depth (~ 750 – 1000 m in eastern Snake River Plain) at which tensional stresses caused by rising, vertical dike exceed strength of overlying rocks and create tension cracks and incipient faults. See text for discussion. Prepared from data of Pollard et al. (1983), Rubin (1992), and from field relationships shown in Figure 2.

ner, 1997; Delaney and Pollard, 1981). Several lines of evidence (admittedly weak) suggest that dikes in the eastern Snake River Plain ascended mostly vertically from great depth rather than having intruded almost exclusively by lateral motion from a high crustal level magma reservoir. First, caldera-like structures related to withdrawal of magma from shallow reservoirs are absent on the eastern Snake River Plain. Second, the vast majority of eastern Snake River Plain basalts are olivine basalts that contain olivine and plagioclase crystals that are typically <1 mm long; there is little evidence for the accumulation or growth of crystals in crustal reservoirs (Kuntz et al., 1992; Kuntz, 1992). Third, most eastern Snake River Plain basalts are highly uniform in textural, mineralogical, and chemical characteristics, and they show little if any evidence of differentiation or contamination. These features suggest that most eastern Snake River Plain basalt magmas represent near-primitive magmas tapped directly from a partially melted lithospheric mantle (Kuntz et al., 1992, and references therein) and that most magmas did not reside in magma reservoirs within the crust. We believe that the eastern Snake River Plain basaltic dikes were

emplaced in a manner similar to that of the mafic dikes of the San Rafael Swell, Utah, described by Delaney and Gartner (1997, p. 1185):

The horizontal propagation of the San Rafael dikes differed substantially from the lateral propagation of dikes along volcanic rift zones (Rubin and Pollard, 1987). Whereas rift-zone dikes propagate from high-level magma reservoirs, the San Rafael dikes ascended from great depth.

Geometrical and field relationships between eruptive fissures, tension cracks, and faults

The Kings Bowl lava field contains the best exposed and most complete set of eruptive fissures and tension cracks in the eastern Snake River Plain. The spatial association of the eruptive fissures and parallel set of tension cracks provide a classic example of the stress-displacement models of Pollard et al. (1983); i.e., the eruptive fissure bisects a set of parallel tension cracks and there is a nearly constant distance between the ten-

sion cracks (Fig. 2). These relationships suggest an ideal symmetry (Fig. 8) for an eruptive fissure-tension-crack system that may be applied to other of these systems in order to determine the dimensions of dikes in the eastern Snake River Plain. Based on the Kings Bowl model, we assume that other dike eruptive fissure-tension-crack systems in the eastern Snake River Plain had the same or similar geometry, i.e., that the ascending dike formed the tension cracks, and continued upward emplacement of the dike formed eruptive fissures or a central vent along the highest part (typically the midpoint) of the dike.

DIKE-EMPLACEMENT MECHANISMS AND THE FORM OF DIKES IN THE EASTERN SNAKE RIVER PLAIN

As the cupola of the eastern Snake River Plain dikes rose to a critical depth (depths of ~750–1000 m in Figs. 8 and 9), tension cracks formed as a result of the tensional stresses created above the dike. Pollard et al. (1983) showed that the critical depth is approximately half the average distance between the pair of tension cracks (Table 1). With continued rise, the shoulders of the dike progressively intersected the critical depth, causing the tension-crack system to migrate away from earlier formed cracks. Some dikes (e.g., Kings Bowl, Hell's Half Acre) continued upward migration and breached the surface, forming eruptive fissures (Fig. 9, A and B). Other dikes stagnated along most of their length in their upward migration after forming tension cracks, such as the dikes that formed the Minidoka and New Butte crack systems of the Open Crack rift set (Fig. 9, C–E).

The preceding discussion assumes that the dikes have a semicircular upper surface. This assumption is supported by the shapes of dike systems in the eastern Snake River Plain, which are shown at true scale in Figure 9. This figure shows longitudinal profiles of four dike systems based on the previously described field relationships between tension cracks and eruptive fissures or other single vent areas. We assume that the top of the dike slopes uniformly from the ends of the eruptive fissures or single vent areas to the critical depth below the end of the tension cracks. The nature of the ends of dikes remains equivocal in determining the form of the dikes. We do not know if the shoulders of the dike slope at similar dips for great distances beyond the position of the ends of the tension cracks or if the dike shoulders begin to dip steeply at or near that point. Perhaps future geophysical field work and modeling will reveal answers to this question.

DIKE-EMPLACEMENT MECHANISM THAT IMPEDES FORMATION OF FAULTS IN THE EASTERN SNAKE RIVER PLAIN

We believe that the absence of faults associated with tension cracks and eruptive fissures at the late Pleistocene–Holocene lava fields can be attributed to the fact that eastern Snake

River Plain dikes had a significant component of vertical ascent when compared to the mostly horizontally propagating intrusions of blade-like dikes in the Hawaiian and Icelandic examples cited herein. After formation of tension cracks and incipient faults, the continued rise of the dikes to shallower depths increased the compression adjacent to the dike walls and prevented the formation of faults or arrested the continued development of incipient faults. As can be visualized from Figure 7B, with continued vertical intrusion of the dike, the zone of compressive stress rises into the zone formerly occupied by the zone of tension (zone of incipient faulting) and inhibits continued or additional faulting.

VOLCANIC VERSUS TECTONIC ORIGIN OF FAULTS IN THE BOX CANYON AREA

Several factors suggest that the faults in the Box Canyon area were not formed as a result of dike injection. (1) The elastic-displacement models and data from the late Pleistocene–Holocene lava fields predict that faults should be extraordinarily straight and aligned with tension cracks in narrow zones, but in the Box Canyon area, faults are curvilinear and not associated with tension cracks in a narrow zone (cf. Figs. 2, 3, 4, 6, and 8). (2) The elastic displacement models predict that faults should show consistent dips facing inward toward the center of a graben, but in the Box Canyon area, faults show inconsistent senses of dip (cf. Figs. 6 and 8). (3) The scale of the faulted terrain in the Box Canyon area is not that expected from the examples from the late Pleistocene–Holocene lava fields; the distance between tension-crack pairs and supposed faults in the late Pleistocene–Holocene lava fields ranges from 1.4 to 2.2 km, but the distance between the boundaries of the major graben in the Box Canyon area is ~3 km (cf. Figs. 2, 3, 4, and 6). (4) It is significant that there are no eruptive fissures or pairs of tension cracks that would indicate that fault-forming dikes breached the surface or are at relatively shallow depth in the center of the Box Canyon area. (5) Fault offsets produced in dike-injection events in Iceland, Afar, and Hawaii are all ≤ 1 m (Rubin and Pollard, 1988; Rubin, 1992); the displacements on the various faults in the Box Canyon area (as much as 10 m) suggest that there must have been at least 10 dike-injection events to achieve the total offsets observed in the Box Canyon area. This implies that the faults were produced by dike-forming intrusive events to the exclusion of extrusive events. We believe that at least some of the hypothesized fault-forming dike intrusions (Hackett and Smith, 1992) should have produced eruptive fissures and/or pairs of open tension cracks in the Box Canyon area, but these structures are not found there.

The Arco-Big Southern Butte volcanic rift zone is a south-eastward extension onto the eastern Snake River Plain of the Lost River fault zone that forms the eastern margin of the Lost River Range (Kuntz et al., 1992; Figs. 1 and 6). We consider the Box Canyon area to be a southeasterly continuation of the Arco segment of the Lost River fault into the basalt-flow terrain

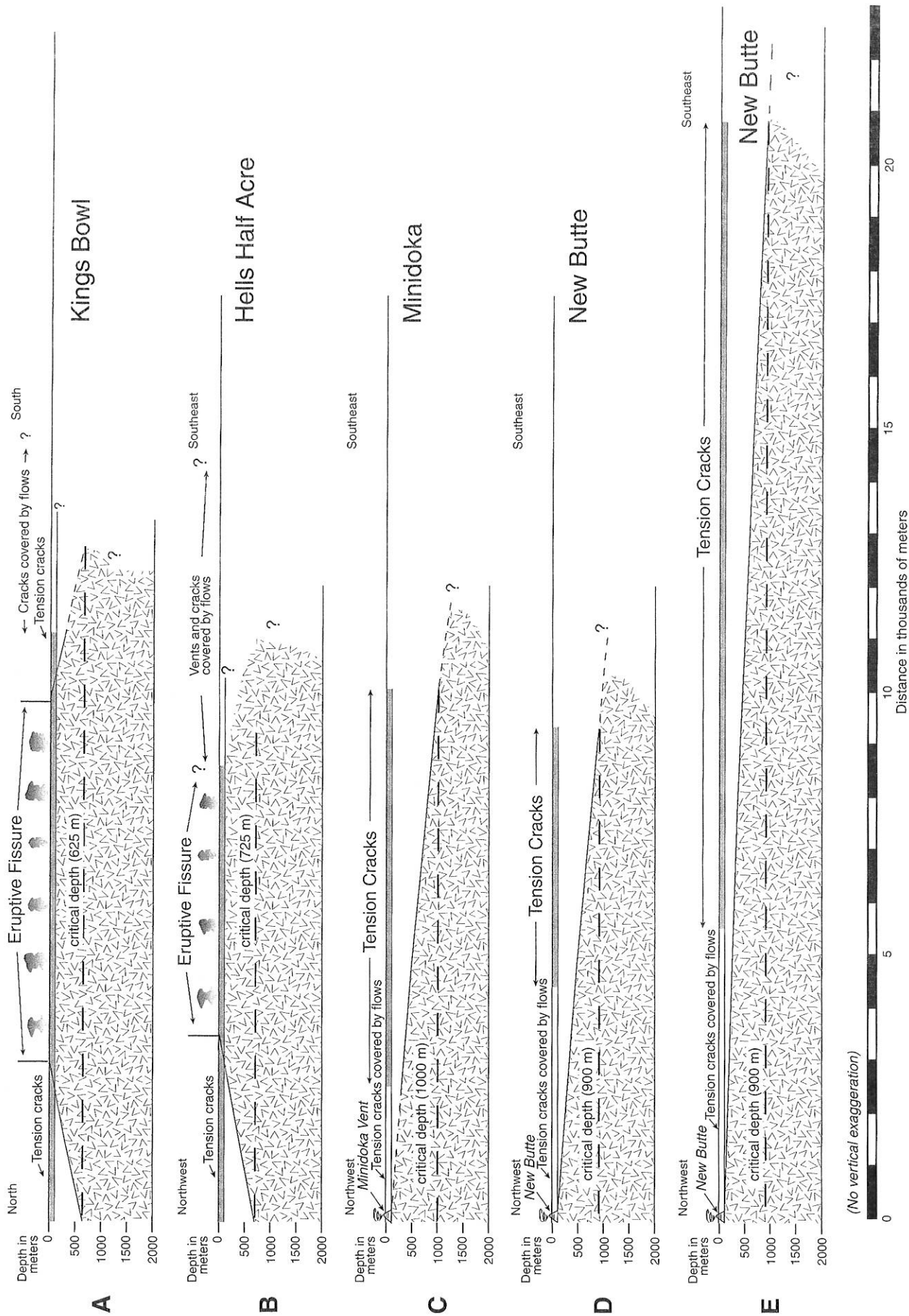


Figure 9. Longitudinal profiles along parts or most of dike systems and tension cracks at late Pleistocene and Holocene lava fields in eastern Snake River Plain. Lengths of eruptive fissures and tension cracks are based on field relationships between tension cracks, eruptive fissures, and single vents (Minidoka vent, New Butte) shown in Figures 2, 3, and 4. In all figures, dotted thick line at surface represents length of exposed tension cracks; open, thick line represents inferred tension cracks covered by basalt flows. Eruptive fissures show parts of cupola of dike that have breached surface. Critical depth is discussed in text. Shoulders of dike are assumed to slope smoothly from ends of eruptive fissures or single vent areas to critical depth beneath ends of tension cracks.

of the eastern Snake River Plain. The faults in the Box Canyon area pass southeastward into open cracks that have purely horizontal displacement. These geographical and structural relationships illustrate a fundamental difference in present tectonism between areas outside and within the eastern Snake River Plain: regional extension is manifested in nearly vertical strain that produces typical basin-and-range topography in mountains northwest and southeast of the eastern Snake River Plain, but only in horizontal extension near the axis of the eastern Snake River Plain, where extension is accommodated by dike emplacement (Parsons and Thompson, 1991). The Box Canyon area represents a transition between the areas of vertical and horizontal strain resulting from regional extension (Kuntz et al., 1992, 1994; Parsons et al., 1998).

Owing to the arguments presented here and because of the spatial relationship between the Lost River fault and the Box Canyon graben, we believe that the faults at the latter locality are mainly of tectonic origin related to the Lost River fault and have little if any genetic relationship to emplacement of dikes.

GEOMETRY OF DIKE SYSTEMS IN THE EASTERN SNAKE RIVER PLAIN

The elastic displacement model of Pollard et al. (1983), the longitudinal profiles of dikes in the eastern Snake River Plain shown in Figure 9, and the dimensions of eruptive fissures and tension cracks (Table 1) provide ways to interpret the geometry of basaltic dikes in the eastern Snake River Plain.

The length of the exposed part of the tension-crack system at Kings Bowl is ~12 km; the southern part of the crack system is covered by flows of the Wapi lava field (Figs. 2 and 9A). Because the Kings Bowl and Wapi lava flows have identical radiocarbon ages and paleomagnetic directions within analytical uncertainty (see Kuntz et al., 1986), flows from both lava fields probably erupted from a single, en echelon eruptive fissure system. Possible tension cracks and eruptive fissures associated with the Wapi lava field are covered by extensive Wapi flows, thus the length of the Kings Bowl–Wapi dike system cannot be determined. However, the Kings Bowl–Wapi dike system is at least 15 km long, when measured from the northern end of the Kings Bowl crack system to the main vent for the Wapi lava field at Pillar Butte (see Kuntz et al., 1988).

The length of the exposed part of the eruptive fissure system for the Hell's Half Acre lava field is 7 km, although part of the southeast extension of the eruptive fissure system may be covered by flows from the main vent area, as shown in Figures 3 and 9B. If it is assumed that the main slot-shaped vent is near the center of the eruptive fissures, the Hell's Half Acre eruptive fissure system may be as long as 17 km. The tension cracks extend ~4 km northwest of the northwesternmost section of eruptive fissures. Assuming a similar geometric relationship at the southeast end of the fissure-crack system, the length for the Hell's Half Acre dike system could be ~24 km.

The distance from the Minidoka vent to the southeast end

of the crack system is ~10 km (Figs. 4 and 9C), thus the Minidoka dike system may be ~20 km long. The maximum length for the Minidoka dike system would be ~40 km if it is assumed that the Minidoka vent is centered along the dike system.

The distance from the New Butte vent area to the southeast end of the northern segments of the pair of tension cracks is 10 km (Figs. 4 and 9D); thus the minimum length of the New Butte dike system may be ~20 km. If New Butte is at the center of a dike system that includes both the northwest and southeast pairs of tension cracks (Fig. 9E), the New Butte noneruptive fissure system may have a maximum length of ~40 km.

The maximum presumed lengths of the New Butte and Minidoka dike systems pose a problem for interpretation of dimensions of basalt dikes in the eastern Snake River Plain; i.e., is 40 km a reasonable length or upper length for basalt dikes in the eastern Snake River Plain and can dikes be as high as they are wide? We answer these questions by providing new field and paleomagnetic data about lava fields in the central and southern parts of the INEEL. In summary, dike systems in the eastern Snake River Plain are typically ~20 km long, but may be as long as ~40 km.

STYLE OF BASALTIC VOLCANISM IN THE TEST AREA NORTH REGION OF THE IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY

Detailed 1:50 000 scale geologic mapping, paleomagnetic, and petrographic studies have recently been completed on basaltic lava flows in the Test Area North (TAN) and central and southeastern parts of the INEEL. In the absence of detailed $^{40}\text{Ar}/^{39}\text{Ar}$ dating of all surface flows in this area, we have employed petrographic and paleomagnetic data (Table 2) as the main tools for regional correlation of flows and lava fields. These studies, in connection with the insight gained from analysis of tension cracks and dikes, give a new perspective on the character of basaltic eruptions in the TAN area and for the entire eastern Snake River Plain.

South and east of the TAN area, seven small shield volcanoes estimated to be 200–400 ka (Kuntz et al., 1994) were erupted from vents aligned northwest to southeast along the Lava Ridge–Hell's Half Acre volcanic rift zone (Figs. 1 and 10). Within this part of the volcanic rift zone, the seven lava fields can be assigned to as few as two, probably coeval, groups based on paleomagnetic data (Fig. 10; Table 2). A younger group (inclination, $I = 62^\circ$, declination, $D = 13^\circ$) consists of two vents (Qbc9 and Qbc8 in Fig. 10) that are 6 km apart. An older group ($I = 41^\circ\text{--}43^\circ$, $D = 2^\circ\text{--}6^\circ$) consists of five vents (Qbc5, Qbc6, Qbc4, Qbc2, Qbc1 in Fig. 10) in a linear trend ~40 km long. Because nearly identical inclination and declination values imply a very short span of time (~100–200 yr), it seems reasonable to assume that the five vents could have formed simultaneously. Thus, we assume that the dike system that fed the five coeval vents was ~40 km long.

TABLE 2. PALEOMAGNETIC DATA FOR THE TAN AREA AND LAVA RIDGE-HELL'S HALF ACRE VOLCANIC RIFT ZONE

Unit Name	Site	Lat°N	Long°E	N/No	Exp.°	I°	D°	$\alpha 95^\circ$	k	R	P lat.°	P long.°
Deuce Butte-Teat Butte area												
Qbc 10	357B8	43.718	247.360	12/12	PI	62.3	13.2	2.0	975		80.5	333.5
Qbc 9	369B8	43.693	247.422	12/12	PI	64.5	12.7	3.3	166		80.7	316.5
Deuce Butte Qbc 8	4B739	43.556	247.544	11/12	30+	64.5	13.0	1.7	746	10.98659		
Teat Butte Qbc 6*	4B895	43.763	247.257	10/12	20+	42.9	11.4	1.5	1104	9.99185	69.0	37.2
Qbc 5	345B8	43.788	247.317	10/12	PI	44.3	5.9	2.1	737		71.6	50.3
Qbc 5*	4B907	43.761	247.264	11/12	30+	38.3	4.8	0.8	3318	10.99699	67.4	55.5
Qbc 5	A9619	43.783	247.244	12/12	20+	40.9	6.0	1.4	1041	11.98944	69.0	51.7
Qbc 4	465B8	43.664	247.376	11/12	PI	41.0	2.8	5.4	65		69.7	60.0
Qbc 3	B7073	43.759	247.465	12/12	30+	42.5	8.4	1.3	1135	11.99031	69.7	45.0
Qbc 3	381B8	43.651	247.456	11/12	PI	46.8	2.4	2.8	253		74.3	59.6
Qbc 2	453B8	43.617	247.428	11/12	30+	43.5	5.7	1.1	1693	10.99409	71.2	51.2
Qbc 1	477B8	43.552	247.506	11/12	30+	42.5	1.8	1.7	710	10.98592	71.0	62.6
Qbd 2	B7013	43.753	247.507	12/12	20+	64.3	30.1	1.8	595	11.98153	68.7	320.5
Qbd 1	B7085	43.724	247.462	9/12	40+	63.8	28.7	2.5	442	8.98189	69.6	322.5
Antelope Butte-Circular Butte area												
Circular Butte Qbe 9*	4B799	43.841	247.360	8/12	PI	-67.6	189.8	2.8	1065		-80.6	108.9
Antelope Butte Qbd 2	A9631	43.885	247.387	12/12	30+	65.4	328.4	2.3	361	11.96951	67.8	177.9
Antelope Butte Qbd 2	B7109	43.819	247.398	12/12	PI	64.4	334.9	3.0	236		72.2	173.9
Unnamed Qbd 3	A9643	43.878	247.344	10/12	PI	58.8	328.1	1.9	630		66.0	158.1
Lava Ridge area												
Qbe 2	B7037	43.978	247.168	11/12	PI	-53.0	157.8	1.5	1263		-69.9	313.5
Qbe 3*	4B787	43.948	247.241	12/12	40+	-47.2	158.5	2.1	434	11.97463	-66.8	302.2
Qbe 1	B7049	43.952	247.169	9/12	PI	-77.7	199.0	2.5	481		-65.3	85.3
Qbe 4	B5500	43.924	247.211	11/12	30+	-56.0	201.0	2.4	360	10.9722	-72.5	174.9
Qbe 6*	4B883	43.886	247.201	12/12	30+	-50.6	203.1	1.7	676	11.98372	-67.9	184.0
Qbe 6	B7061	43.849	247.181	10/12	30+	-50.5	203.9	1.0	2305	9.99609	-67.4	183.0
Qbe 6	B7097	43.83	247.201	11/12	30+	-52.2	202.4	1.1	1657	10.99396	-69.4	182.0
Qbe 7	B7121	43.875	247.203	12/12	PI	-71.9	161.1	2.2	568		-72.4	31.3
Richard Butte Qbe 5	B7025	43.963	247.241	12/12	30+	-65.8	194.0	2.1	426	11.97421	-79.4	129.3

Note: Unit name follows Kuntz (in prep.); *denotes data published in Kuntz et al. (1994); site is alphanumeric identifier; N/No is the number of cores used compared with the number originally taken at the site; Exp.° is the strength of the peak cleaning field, P1 denotes planes solution for site; I° and D° are the remanent inclination and declination; $\alpha 95$ is the 95% confidence limit about the mean direction; k is the estimate of the Fisherian precision parameter; R is the length of the resultant vector; P lat.° and P long.° is the location in degrees north and degrees east of the virtual geomagnetic pole (VGP) calculated from the site mean direction.

Delaney and Gartner (1997, p. 1191) suggested that because of the primitive nature of the magmas, the dikes of the San Rafael Swell must have heights "that far exceed their <10 km lengths." They also suggested that in the absence of pressure gradients in magma density and in fracture toughness for host rocks, dikes ought to assume a circular shape. These relationships suggest that the 40-km-long dike system may represent the eruptive fissure that developed from an enormous dike having a height of ≥ 40 km. This height is close to the depth of the Moho in the eastern Snake River Plain (Kuntz, 1992), which suggests that dikes of this size may be connected directly to magma sources in the upper mantle.

Paleomagnetic data for three relatively small shield volcanoes (Circular Butte, Antelope Butte, and an unnamed shield just west of Antelope Butte) indicate that the shields belong to two groups (Fig. 10; Table 2). Antelope Butte and the unnamed shield (Qbd3) have nearly identical normal-polarity inclination-declination values and thus are considered to be coeval and to have formed simultaneously on the same eruptive fissure system. This conclusion contradicts our previously held view that long-lived, shield-producing eruptions in the eastern Snake River Plain emanated from only a single, slot-shaped vent

roughly centered along an initial eruptive fissure to produce a single shield volcano (Kuntz et al., 1992).

IMPLICATIONS OF FIELD AND PALEOMAGNETIC STUDIES IN THE TAN AREA FOR STYLE OF BASALTIC VOLCANISM IN THE EASTERN SNAKE RIVER PLAIN

In an earlier publication, we described what we believe to be the typical stages of basaltic eruptions, beginning with fissure eruptions that lasted a few hours or days, and ending with relatively long lived eruptions from a single, slot-shaped vent at a shield volcano that lasted perhaps several years (Kuntz et al., 1992). These ideas were based on study of the many monogenetic late Pleistocene and Holocene lava fields in the eastern Snake River Plain. The new field and paleomagnetic data from the Lava Ridge-Hell's Half Acre volcanic rift zone presented here depict a rather startling and unexpected supplement to the simple, monogenetic model. The data indicate that significant lengths of eruptive fissure systems, 40 km or more, were in eruption at the same time or within very short periods of geologic time and formed several shield volcano types of lava fields

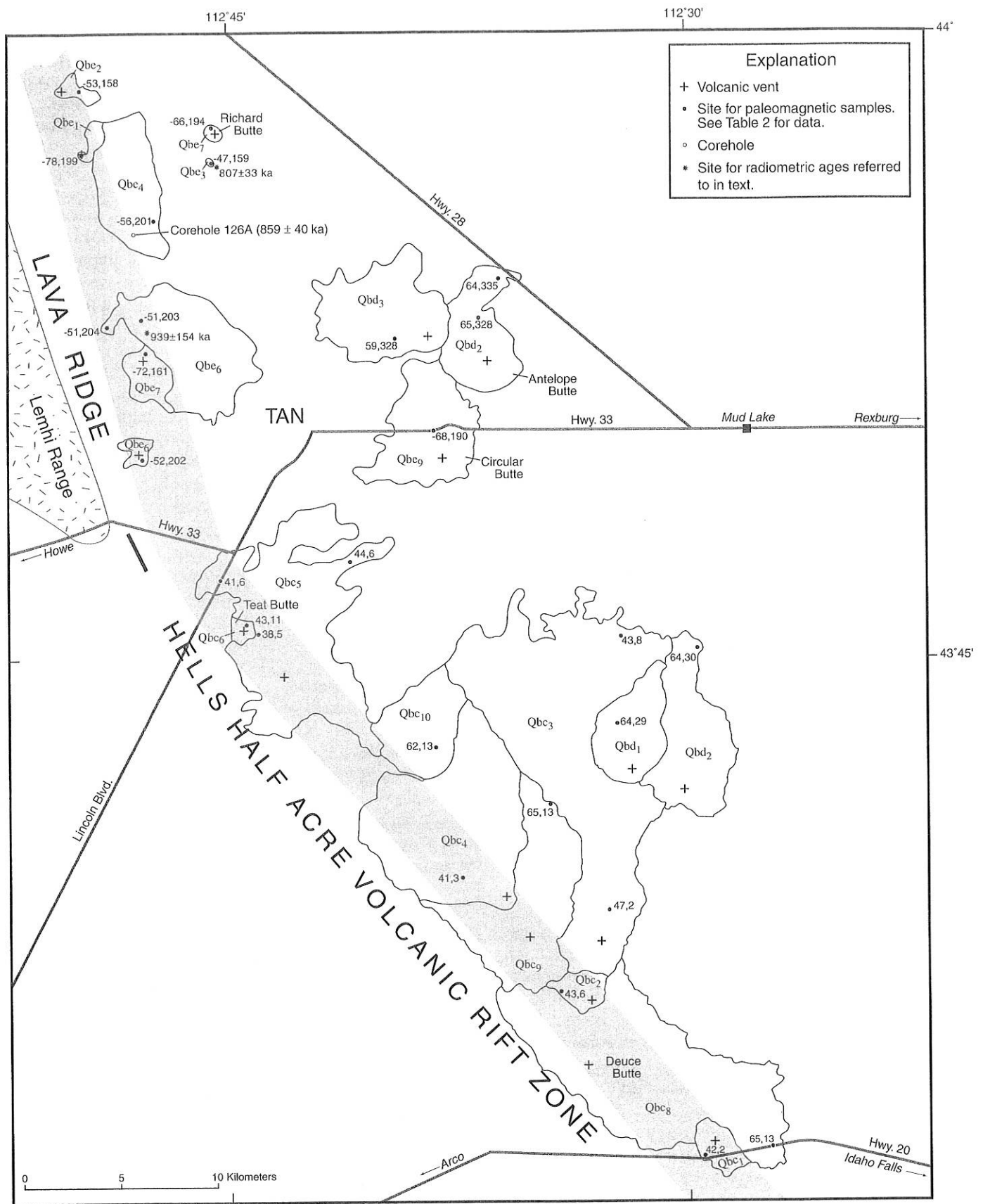


Figure 10. Generalized geologic map of Lava Ridge–Hell's Half Acre volcanic rift zone. Unit designations (e.g., Qbc8, Qbd3) and paleomagnetic inclination and declination values correspond to designations in Table 2.

at various sites along the eruptive fissure system. Other evidence tends to support such an idea. The presumed maximum lengths for inferred dike systems for the New Butte and Minidoka sets of tension cracks may be as long as 40 km (Fig. 4; Table 1). The northern and southern ends of the Great Rift volcanic rift (Fig. 1) zone erupted roughly simultaneously ~50 ka; a distance of ~60 km separates these two areas (Kuntz et al., 1988, 1992). In addition, studies of basalt-supergroups by Wetmore et al. (1997) suggest that considerable accumulations of basalt from several coeval source vents are present in the subsurface in the southern part of the INEEL.

As a result of these data, we now identify a new type of basalt eruption in the eastern Snake River Plain, which we term multiple-shield eruption style, which denotes several shield volcanoes that form simultaneously along an eruptive fissure system that may be 20–60 km long. Based on regional studies of basaltic volcanism in the eastern Snake River Plain (Kuntz et al., 1992), we believe that this style of eruption is a rare event and that the simple, short-length (10–20 km), fissure-dominated single-shield-type eruption is the typical eruption style for the eastern Snake River Plain.

Multiple-shield eruptions have important implications to be considered in evaluation of volcanic hazards for the eastern Snake River Plain. Multiple source vents and larger areas of inundation by basalt flows from a single eruption event increase volcanic hazards for certain areas of the eastern Snake River Plain. However, multiple-shield events also decrease the recurrence interval between eruptive events that were previously assumed to be widely spaced in time. The example from the Lava Ridge–Hell's Half Acre volcanic rift zone indicates that there is a strong need for applying the combined mapping-paleomagnetic-radiometric methods to clarify volcanic hazards elsewhere on the eastern Snake River Plain.

HYDROLOGIC IMPLICATIONS OF DIKES AND TENSION-CRACK AND ERUPTIVE FISSURE SYSTEMS

The characteristics and dimensions of dikes and tension-crack and eruptive fissure systems can be applied to hydrologic problems in the eastern Snake River Plain, specifically at the INEEL, where detailed hydrologic and volcanic-stratigraphic relations have been studied over the past 30 yr. The INEEL is operated by the U.S. Department of Energy, and covers ~2300 km² of the eastern Snake River Plain in eastern Idaho (Fig. 1). The INEEL is used in the development of nuclear and technological applications (Bartholomay et al., this volume). Liquid radionuclide and chemical wastes generated at the INEEL have been discharged to on-site infiltration ponds and disposal wells since 1952. Although the use of disposal wells was discontinued in 1984, past liquid-waste disposal has resulted in detectable concentrations of several waste constituents in water from the Snake River Plain aquifer underlying the INEEL (Bartholomay et al., 1997).

The migration of radioactive and chemical wastes is dependent on many factors, including those that control the hydraulic conductivity of basalt and interbedded sediment, the dominant rock units in the Snake River Plain aquifer. Primary controls of hydraulic conductivity include fracture networks and rubble zones of tube-fed pahoehoe lava flows, and grain size and sorting characteristics of sedimentary interbeds (Welhan et al., this volume, chapter 9; Mark and Thackray, this volume). In addition to these, Anderson et al. (1999) suggested controls related to dikes and tension-crack and eruptive fissure systems in the eastern Snake River Plain. These systems, which are most prevalent in volcanic rift zones (Fig. 1), are referred to as vent corridors where they are inferred in the subsurface. Deposits near volcanic vents are scoriaceous slab pahoehoe and shelly pahoehoe flows, spatter, and ash (Fig. 11) that compose zones of high permeability where they are present in the aquifer. Fissures and tension cracks are highly permeable vertical channels in layered sequences of basalt. In contrast, dikes are dense, vertical sheets of basalt that may impede the movement of groundwater. Most of these features are aligned along volcanic rift zones and vent corridors that are oriented generally north-westward, perpendicular to the regional direction of groundwater flow (Figs. 1 and 11). Many dikes, fissures, and tension cracks probably cut the entire thickness of the aquifer.

Where groundwater flows through volcanic rift zones and vent corridors at the INEEL, hydraulic conductivity probably is partly controlled by localized near-vent volcanic deposits, dikes, eruptive fissures, and tension cracks. These features are interpreted to underlie many parts of the INEEL and appear to coincide with estimates of hydraulic conductivity that vary by as much as six orders of magnitude. Many vents and most dikes, fissures, and tension cracks are concealed by surficial basalt flows and sediment, and cannot be verified by available cores and geophysical data. Because of this limitation, the relations between these features and hydraulic conductivity must be evaluated using indirect data. For example, estimates of hydraulic conductivity within vent corridors at the INEEL are similar to estimates from the islands of Hawaii, where dikes are known to control groundwater flow (Stearns, 1985; Meyer and Souza, 1995). We suggest that this simple comparison, coupled with available aquifer test data, stratigraphic interpretations, and inferred locations of individual tension-crack and eruptive fissure systems, can provide a useful first-order approximation of the geologic controls of hydraulic conductivity associated with volcanic rift zones and vent corridors at and near the INEEL.

Estimates of hydraulic conductivity used for a first-order approximation of geologic controls were derived from single-well aquifer tests in 114 wells (Ackerman, 1991; Bartholomay et al., 1997; Anderson et al., 1999). Wells are located throughout the INEEL and include 29 closely spaced wells at the Idaho Nuclear Technology and Engineering Center (INTEC) (Fig. 12). These wells were selected because their test data were assembled and analyzed in a uniform manner and could be compared with detailed stratigraphic interpretations (Anderson et

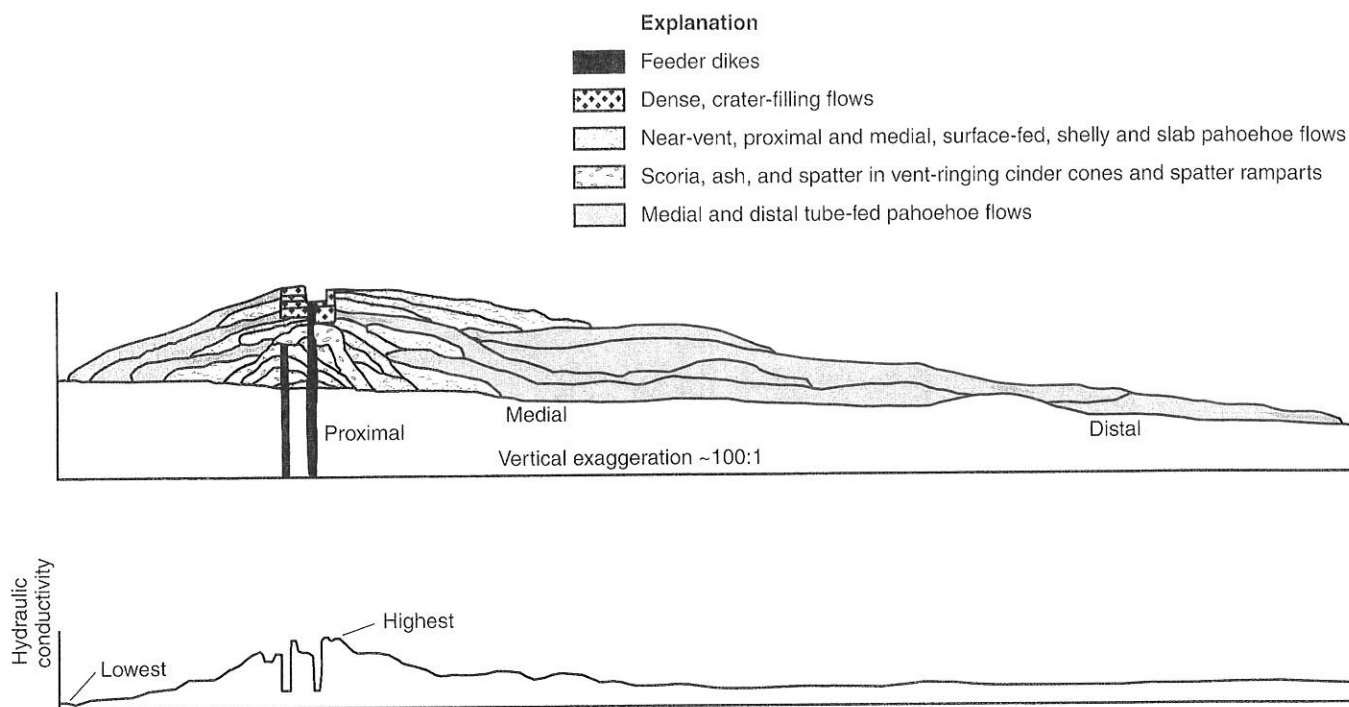


Figure 11. Basalt-flow morphology and inferred relative hydraulic conductivity through a typical shield volcano in Snake River Plain aquifer.

al., 1996). Estimates (available in Anderson et al., 1999, and summarized in Table 3) generally represent the bulk hydraulic conductivity of layered sequences of basalt. Although these estimates tend to average the down-hole variations of hydraulic conductivity observed in straddle-packer tests (Welhan et al., this volume, chapter 15), they are useful indicators of the overall permeability of any given rock sequence. This data-set samples effective open intervals that range in length from 5 to 145 m; the average length is 33 m. The intervals coincide with ~93% basalt and 7% sediment. Most wells are completed in thin pahoehoe flows, which are characterized by dense interiors separated by permeable interflow zones (Welhan et al., this volume, chapter 9).

Bulk hydraulic conductivity may vary to six orders of magnitude or more over small areas of the INEEL (Table 3). Estimates for the 114 wells range from 3.0×10^{-3} to 7.3×10^3 m/day. Two-thirds of these estimates are greater than 3.0×10^1 m/day and span two of the six observed orders of magnitude. Estimates of hydraulic conductivity for a subset of 29 wells at the INTEC range from 3.0×10^{-2} to 2.7×10^3 m/day. Two-thirds of these estimates also are greater than 3.0×10^1 m/day and span two of the five observed orders of magnitude.

Stratigraphic interpretations support the association of bulk hydraulic conductivity with different types of basalt flows and volcanic deposits. This is exemplified by a preponderance of thin (3–9 m) pahoehoe flows in 98 wells, thick (9–15 m), possibly ponded, pahoehoe flows in 6 wells, and near-vent volcanic deposits in 10 wells (Anderson et al., 1996, 1999). Estimates range from 2.4×10^{-2} to 7.3×10^3 m/day for thin flows,

from 3.0×10^{-3} to 4.9×10^0 m/day for thick flows, and from 4.9×10^1 to 1.5×10^3 m/day for near-vent volcanic deposits (Table 3). This overall range of estimates is similar to that reported by Welhan et al. (this volume, chapter 9, Fig. 3) for other estimates of field-scale hydraulic conductivity of basalt and sediment at the INEEL.

Estimates of hydraulic conductivity also are similar to estimates derived from aquifer tests and numerical simulations of groundwater flow in the islands of Hawaii (Meyer and Souza, 1995). Geohydrologic settings in Hawaii include dike complexes and dike-impounded aquifers in volcanic rift zones along the topographic crest of volcanoes. Basal aquifers, composed mainly of thin pahoehoe flows, occur along the flanks of volcanoes. Meyer and Souza (1995) suggested a plausible (measured and simulated) range of hydraulic conductivity of $\sim 3.0 \times 10^{-4}$ to 3.0×10^{-2} m/day for dike complexes, $\sim 3.0 \times 10^{-1}$ to 3.0×10^1 m/day for dike-impounded aquifers, and $\sim 3.0 \times 10^1$ to more than 3.0×10^3 m/day for basal aquifers. Although dikes in the Snake River Plain aquifer probably are more dispersed than those of volcanic rift zones in Hawaii, their hydraulic conductivity may be similar. If so, some estimates of $< 3.0 \times 10^1$ m/day at the INEEL may indicate the presence of concealed dikes.

To test this hypothesis and to evaluate the range of hydraulic conductivity with respect to other generalized rock types and structures of volcanic rift zones, Anderson et al. (1999, p. 14) delineated 45 narrow, northwest-trending zones, referred to as vent corridors. They used the locations and trends of known and inferred volcanic vents to approximate possible locations

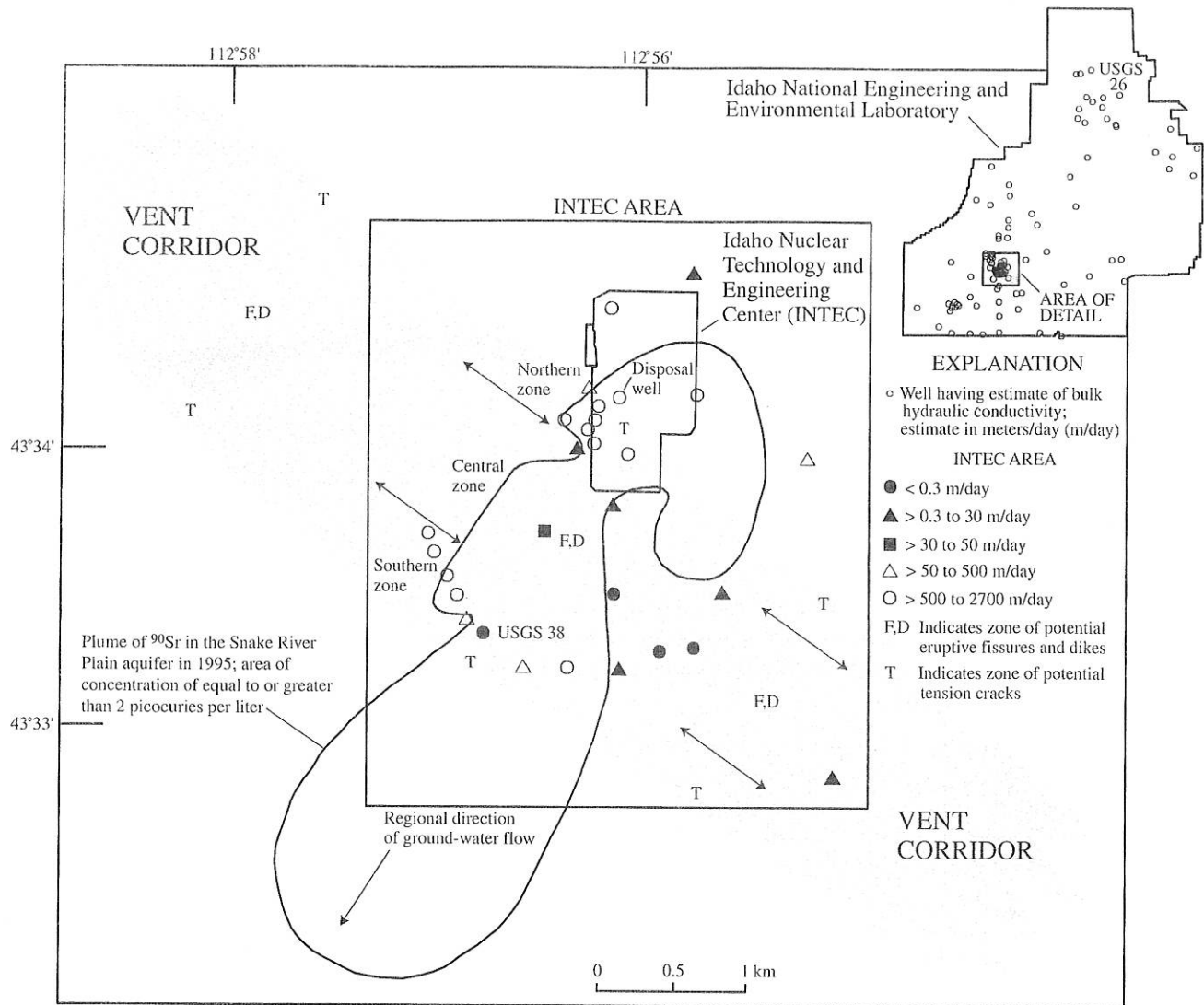


Figure 12. Locations of selected wells used to estimate bulk hydraulic conductivity in Snake River Plain (SRP) aquifer at Idaho Nuclear Technology and Engineering Center (INTEC) and Idaho National Engineering and Environmental Laboratory. Closed and open symbols at and near INTEC indicate ranges of estimates for 29 closely spaced wells open to similar stratigraphic intervals within and near a vent corridor crossed by plume of ^{90}Sr . Data are from Bartholomay et al. (1997) and Anderson et al. (1999).

of individual tension-crack and eruptive fissure systems in the subsurface. Although some zones are questionable because they rely heavily on inferred vent locations and interpretation, the dimensions of vent corridors are similar to the overall lengths and widths of exposed late Pleistocene-Holocene tension-crack and eruptive fissure systems (Table 1). Vent corridors average ~1–3 km in width and 8–24 km in length, dimensions that compare favorably with the distance between crack pairs, length of eruptive fissures, and inferred length of dikes of exposed late Pleistocene-Holocene lava fields. Although near-vent volcanic deposits and dikes likely occupy some parts of vent corridors, thin pahoehoe flows make up the largest part of their volume.

Estimates of hydraulic conductivity have a wider range

(from 3.0×10^{-3} to 7.3×10^3 m/day for 99 wells) within vent corridors relative to outside of vent corridors (4.0×10^0 to 1.7×10^3 m/day for 15 wells). Differences in ranges might be the result of sampling bias; however, differences also might indicate the presence of near-vent volcanic deposits, dikes, fissures, and tension cracks within vent corridors. Near-vent volcanic deposits are estimated to cover only 10% of any given lava field, so their overall extent is small compared to that of pahoehoe flows. Estimates from 10 wells that penetrate locations near known and inferred vents suggest that near-vent volcanic deposits are as permeable as the most permeable pahoehoe flows. The same may be true of some tension cracks, based on their inferred locations with respect to some high estimates of hydraulic conductivity.

TABLE 3. ESTIMATES OF BULK HYDRAULIC CONDUCTIVITY (K) FOR SELECTED WELLS COMPLETED IN THE SNAKE RIVER PLAIN AQUIFER AT THE IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY (INEEL) AND IDAHO NUCLEAR ENGINEERING AND TECHNOLOGY CENTER (INTEC)

Location (area)	Number of estimates	Minimum K (m/d)	Maximum K (m/d)	Median K (m/d)	Remarks
INEEL (2,300 km ²)	114	3.0×10^{-3}	7.3×10^3	1.6×10^2	K estimates mainly representative of thin (3–9 m) pahoehoe basalt flows. Sediment content averages 7%. Two-thirds of estimates are higher than 3.0×10^1 m/d; many lower estimates probably controlled by concealed dikes. Some low and high estimates probably controlled by concealed fissures and tension cracks
	98*	2.4×10^{-2}	7.3×10^3	1.3×10^2	
	6†	3.0×10^{-3}	4.9×10^0	1.6×10^{-1}	
	10§	4.9×10^1	1.5×10^3	3.4×10^2	
INTEC AREA (13 km ²)	29	3.0×10^{-2}	2.7×10^3	5.8×10^2	K estimates mainly representative of thin (3–9 m) pahoehoe basalt flows. Sediment content averages 4%. Two-thirds of estimates are higher than 3.0×10^1 m/d; many lower estimates probably controlled by concealed dikes. Some low and high estimates probably controlled by concealed fissures and tension cracks

Note: Estimates for 29 wells at the INTEC are a subset of estimates for 114 wells at the INEEL. K, in meters per day (m/d). Estimates from Anderson et al. (1999). Effective open intervals exclude basalt flow group I (Morin et al., 1993) and other dense basalt flows below the effective base of the aquifer (Mann, 1986).

*Wells open mainly to thin (3–9 m) pahoehoe basalt flows and their associated interflow fracture networks and rubble zones.

†Wells open mainly to the dense interiors of thick (9–15 m), possibly ponded, pahoehoe basalt flows.

§Wells probably open to slab-pahoehoe and shelly-pahoehoe basalt flows and scoria, ash, and spatter near volcanic vents.

Dikes probably control some of the lowest estimates of hydraulic conductivity by limiting the flow of water to wells. Estimates of hydraulic conductivity for 35 wells open mainly to thin pahoehoe flows are $<3.0 \times 10^1$ m/day. Based on the comparison with Hawaii, some of these estimates may be controlled by concealed dikes. Open intervals in these wells range in length from 5 to 86 m. Open intervals are longer than 30 m in 23 (two-thirds) of the wells, where they potentially sample from 5 to 17 interflow zones, based on the average 5 m thickness of flow lobes measured in many INEEL cores (Welhan et al., this volume, chapter 9, Table 1). The large number of potential interflow zones seems inconsistent with the low estimates of hydraulic conductivity. Although other factors, such as inadequate well development or sediment-filled interflow zones, may contribute to some low estimates, we suggest that dikes are a more likely control.

This likelihood is based on four observations. (1) Of the 35 wells having low estimates of hydraulic conductivity, 34 are located within vent corridors where there is a high potential for dikes. (2) Low estimates tend to cluster in the central parts of vent corridors where dikes are most likely to be present. (3) High estimates tend to cluster along the edges of vent corridors where dikes are least likely to be present. (4) Clusters of low and high hydraulic conductivity seem relatively insensitive to the variable lengths and depths of open intervals in wells, suggesting that the overall distribution of estimates is not biased by factors related to well construction. Because our approach does not allow the discrimination of other possibilities, dikes also may include some open fissure segments and tension cracks that filled with lava and sediment during burial.

Geologic interpretations and estimates of hydraulic con-

ductivity suggest that concealed dikes are present within a vent corridor located immediately south of the INTEC (Fig. 12). This vent corridor was delineated on the basis of eight inferred vents in the unsaturated zone, is ~ 2.3 km wide and 8 km long, and is penetrated by 25 closely spaced wells having estimates of hydraulic conductivity that vary by five orders of magnitude. These wells are open to many thin pahoehoe flows in the uppermost part of the aquifer, and are located in zones of potential dikes, eruptive fissures, and tension cracks. Nine wells are clustered in a zone of potential eruptive fissures and dikes that is ~ 1 km wide and 3 km long in the center of the vent corridor. These wells have open intervals that average 37 m in length and a median hydraulic conductivity of 2.5×10^0 m/day. Eight wells are clustered in a zone of potential tension cracks along the northern edge of the vent corridor. These wells have open intervals that average 38 m in length and a median hydraulic conductivity of 8.8×10^2 m/day. An additional eight wells are clustered in a zone of potential tension cracks along the southern edge of the vent corridor. These wells have open intervals that average 30 m in length and a median hydraulic conductivity of 5.9×10^2 m/day. Despite the similar average lengths of open intervals in wells, median values of hydraulic conductivity in the northern and southern zones of the vent corridor are two orders of magnitude larger than that of the central zone. Low estimates of hydraulic conductivity in the central zone are consistent with the presence of concealed dikes, and appear to control the distribution of a local plume of ^{90}Sr (Fig. 12), as delineated by Bartholomay et al. (1997).

The strength of this interpretation includes low estimates of hydraulic conductivity that are similar to those of dike complexes and dike-impounded aquifers in Hawaii, low estimates

that cluster in the central zone of the vent corridor where dikes are most likely to be present, and large differences in the median values of hydraulic conductivity between the central zone and adjacent zones despite the similar average lengths of open intervals in wells. The weakness of this interpretation is the present lack of direct physical evidence for dikes within the INTEC vent corridor and an incomplete understanding of how dikes might be distributed in areas of focused volcanism in the eastern Snake River Plain.

Additional complexities are apparent in eruptive fissure systems, which typically have open segments where dikes either did not reach the surface or where magma drained back down into fissures after first reaching the surface. These fissure segments and associated tension cracks are similar to the openings of large tension fractures in basalt, and are capable of being filled with lava and sediment during burial (Welhan et al., this volume, chapter 9). Some fissures and cracks probably filled with enough lava and sediment to mimic the hydraulic effects of a dike. Other fissures and cracks probably were bridged by lava flows and rubble and retain much of their original void space. Locally, these features may affect some estimates of hydraulic conductivity.

Filled fissures and tension cracks may control some low estimates of hydraulic conductivity within the INTEC vent corridor (Fig. 12). Possible locations of this effect include the central zone of the vent corridor and near well USGS 38. This well is located in a zone of potential tension cracks and has one of the lowest estimates of hydraulic conductivity at the INEEL, 4.9×10^{-2} m/day.

Open fissures and tension cracks may control some high estimates of hydraulic conductivity, such as that in the INTEC disposal well (Fig. 12). This well also is located in a zone of potential tension cracks and has one of the highest estimates of hydraulic conductivity at the INEEL, 2.7×10^3 m/day. Well USGS 26, located within another vent corridor in the northern part of the INEEL (Fig. 12), has the highest estimate of hydraulic conductivity in this data set, 7.3×10^3 m/day. This estimate seems inconsistent with a short open interval of 10 m, and could be controlled by an open fissure or tension crack.

In conclusion, simple comparisons with Hawaii, coupled with available aquifer-test data, stratigraphic interpretations, and inferred locations of individual tension-crack and eruptive fissure systems, suggest that near-vent volcanic deposits, dikes, fissures, and tension cracks may locally control the range and distribution of hydraulic conductivity in the Snake River Plain aquifer at the INEEL. Near-vent volcanic deposits may be as permeable as the most permeable pahoehoe flows. Dikes probably control many estimates of low hydraulic conductivity of $< \sim 3.0 \times 10^1$ m/day. Fissures and tension cracks may control some of the lowest and highest estimates of hydraulic conductivity. At the INEEL, these features may play an important role in the migration of radioactive and chemical wastes by providing localized preferential pathways and barriers to groundwater flow. Additional core drilling, detailed geophysical surveys, and

other detailed methods will be required to refine these preliminary interpretations.

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REFERENCES CITED

- Ackerman, D.J., 1991, Transmissivity of the Snake River Plain aquifer at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 91-4058 (DOE/ID-22097), 35 p.
- Anderson, S.R., Ackerman, D.J., Liszewski, M.J., and Freiburger, R.M., 1996, Stratigraphic data for wells at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 96-248 (DOE/ID-22127), 27 p. and 1 diskette.
- Anderson, S.R., Kuntz, M.A., and Davis, L.C., 1999, Geologic controls of hydraulic conductivity in the Snake River Plain aquifer at and near the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 99-4033 (DOE/ID-22155), 38 p.
- Bartholomay, R.C., Tucker, B.J., Ackerman, D.J., and Liszewski, M.J., 1997, Hydrologic conditions and distribution of selected radiochemical and chemical constituents in water, Snake River Plain aquifer, Idaho National Engineering Laboratory, Idaho, 1992 through 1995: U.S. Geological Survey Water-Resources Investigations Report 97-4086 (DOE/ID-22137), 57 p.
- Covington, H.R., 1977, Preliminary geologic map of the Pillar Butte, Pillar Butte Northeast, Pillar Butte Southeast, and Rattlesnake Butte quadrangles, Bingham, Blaine and Power Counties, Idaho: U.S. Geological Survey Open-File Report 77-779, scale 1:48 000.
- Delaney, P.T., and Gartner, A.E., 1997, Physical processes of shallow mafic dike emplacement near the San Rafael Swell, Utah: Geological Society of America Bulletin, v. 109, p. 1177-1192.
- Delaney, P.T., and Pollard, D.D., 1981, Deformation of host rocks and flow of magma during growth of minnette dikes and breccia-filling intrusions near Ship Rock, New Mexico: U.S. Geological Survey Professional Paper 1202, 61 p.
- Fiske, R.S., and Jackson, D.E., 1972, Orientation and growth of Hawaiian volcanic rifts; the effect of regional structure and gravitational stresses: Proceedings of the Royal Society of London, A-329, p. 299-326.
- Greeley, R., Theilig, E., and King, J.S., 1977, Guide to the geology of the King's Bowl lava field, in Greeley, R., and King, J.S., eds., Volcanism of the eastern Snake River Plain, Idaho: A comparative planetary guidebook: Washington, D.C., National Aeronautics and Space Administration, p. 171-188.
- Hackett, W.R., and Smith, R.P., 1992, Quaternary volcanism, tectonics, and sedimentation in the Idaho National Engineering Laboratory area, in Wilson, J.R., ed., Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publications 92-3, p. 1-18.
- King, J.S., 1977, Crystal Ice Cave and King's Bowl Crater, Snake River Plain, Idaho, in Greeley, R., and King, J.S., eds., Volcanism of the eastern Snake River Plain, Idaho: A comparative planetary guidebook: Washington, D.C., National Aeronautics and Space Administration, p. 153-164.
- Kuntz, M.A., 1977, Extensional faulting and volcanism along the Arco rift

- zone, eastern Snake River Plain, Idaho: Geological Society of America Abstracts with Programs, v. 9, no. 6, p. 740–741.
- Kuntz, M.A., 1978a, Geologic map of the Arco-Big Southern Butte area, Butte, Blaine, and Bingham counties, Idaho: U.S. Geological Survey Open-File Report 78-302, scale 1:62 500.
- Kuntz, M.A., 1978b, 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; with a section on statistical treatment of the age of lava flows by John O. Kork: U.S. Geological Survey Open-File Report 78-691, p. 70.
- Kuntz, M.A., 1992, A model-based perspective of basaltic volcanism, eastern Snake River Plain, Idaho, in Link, P.K., Kuntz, M.A., and Platt, L.P., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 289–304.
- Kuntz, M.A., Spiker, E.C., Rubin, M., Champion, D.E., and Lefebvre, R.H., 1986, Radiocarbon studies of latest Pleistocene and Holocene lava flows of the Snake River Plain, Idaho: Data, lessons, interpretations: *Quaternary Research*, v. 25, p. 163–176.
- Kuntz, M.A., Champion, D.E., Lefebvre, R.H., and Covington, H.R., 1988, Geologic map of the Craters of the Moon, King's Bowl, and Wapi lava fields and the Great Rift volcanic rift zone, south-central Idaho: U.S. Geological Survey Miscellaneous Investigation Series Map I-1632, scale 1:100 000.
- Kuntz, M.A., Lefebvre, R.H., Champion, D.E., and Skipp, B.A., 1989, Geologic map of the Inferno Cone quadrangle, Butte County, Idaho: U.S. Geological Survey Geological Quadrangle Map GQ-16-32, scale 1:24 000.
- Kuntz, M.A., Covington, H.R., and Schorr, L.J., 1992, An overview of basaltic volcanism of the eastern Snake River Plain, Idaho, in Link, P.K., Kuntz, M.A., and Platt, L.P., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 227–267.
- Kuntz, M.A., and twelve others, 1994, Geologic map of the Idaho National Engineering Laboratory and adjoining areas, eastern Idaho: U.S. Geological Survey Miscellaneous Investigations Series Map I-2330, scale 1:100 000.
- Mann, L.J., 1986, Hydraulic properties of rock units and chemical quality of water for INEL-1: A 10,365-foot deep test hole drilled at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water-Resources Investigations Report 86-4020 (IDO-22070), 23 p.
- Meyer, W., and Souza, W.R., 1995, Factors that control the amount of water that can be diverted to wells in a high-level aquifer, in Hermann, R., Back, W., Sidle, R.C., and Johnson, A.I., eds., Water resources and environmental hazards: Emphasis on hydrologic and cultural insight in the Pacific Rim, Proceedings of the American Water Resources Association Annual Summer Symposium: Honolulu, Hawaii, American Water Resources Association, p. 207–216.
- Morin, R.H., Barrash, W., Paillet, F.L., and Taylor, T.A., 1993, Geophysical logging studies in the Snake River Plain aquifer at the Idaho National Engineering Laboratory—wells 44, 45, and 46: U.S. Geological Survey Water-Resources Investigations Report 92-4184, 44 p.
- Pollard, D.D., Delaney, P.T., Duffield, W.A., Endo, E.T., and Okamura, A.T., 1983, Surface deformation in volcanic rift zones, *Tectonophysics*, v. 94, p. 541–584.
- Prinz, M., 1970, Idaho rift system, Snake River Plain, Idaho: Geological Society of America Bulletin, v. 81, p. 941–947.
- Rubin, A. M., 1990, A comparison of rift-zone tectonics in Iceland and Hawaii: *Bulletin of Volcanology*, v. 52, p. 302–319.
- Rubin, A.M., 1992, Dike-induced faulting and graben subsidence in volcanic rift zones: *Journal of Geophysical Research*, v. 97, p. 1839–1858.
- Rubin, A.M., and Pollard, D.D., 1988, Dike-induced faulting in rift zones of Iceland and Afar: *Geology*, v. 16, p. 413–417.
- Parsons, T., and Thompson, G.A., 1991, The role of magma overpressure in suppressing earthquakes and topography: Worldwide examples: *Science*, v. 253, p. 1399–1402.
- Parsons, T., Thompson, G.A., and Smith, R.P., 1998, More than one way to stretch: A tectonic model for extension along the plume track of the Yellowstone hotspot and adjacent Basin and Range Province: *Tectonics*, v. 17, p. 231–234.
- Smith, R.P., Hackett, W.R., and Rodgers, D. W., 1989, Geologic aspects of seismic-hazard assessment at the Idaho National Engineering Laboratory, southeastern Idaho in Proceedings, Second Department of Energy Natural Phenomena Hazards Mitigation Conference: Livermore, CA, Lawrence Livermore National Laboratory, p. 282–289.
- Smith, R.P., Jackson, S.M., and Hackett, W.R., 1996, Paleoseismology and seismic hazard evaluations in extensional volcanic terrains: *Journal of Geophysical Research*, v. 101, p. 6277–6292.
- Stearns, H.T., 1985, *Geology of the state of Hawaii*: Palo Alto, California, Pacific Books 335 p.
- Wetmore, P.H., Hughes, S.S., and Anderson, S.R., 1997, Model morphologies of subsurface Quaternary basalts as evidence for a decrease in the magnitude of basaltic magmatism at and near the Idaho National Engineering and Environmental Laboratory, Idaho in Sharma, S. and Hardcastle, J.H., eds., Proceedings of the 32nd Symposium on Engineering Geology and Geotechnical Engineering: Boise, Idaho, p. 45–48.

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