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QUATERNARY VOLCANISM, TECTONICS, AND SEDIMENTATION IN THE IDAHO NATIONAL ENGINEERING LABORATORY AREA

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INTRODUCTION

In this article, we discuss the regional context and describe localities for a two-day field excursion in the vicinity of the Idaho National Engineering Laboratory (INEL) (Fig. 1). We address several geologic themes: (1) Late Cenozoic, bimodal volcanism of the Eastern Snake River Plain (ESRP), (2) the regional tectonics and structural geology of the Basin and Range province to the northwest of the ESRP, (3) fluvial, lacustrine, and aeolian sedimentation in the INEL area, and (4) the influence of Quaternary volcanism and tectonics on sedimentation near the INEL. Recent overviews of the Quaternary history, geomorphology, volcanic geology and tectonics of the Eastern Snake River Plain include Baker and others (1987), Kuntz and others (in press), Kuntz (in press), Pierce and Morgan (1990 and in press), and Malde (1991).

HISTORICAL AND TECHNOLOGICAL SIGNIFICANCE OF THE INEL

Established in 1949 as the National Reactor Testing Station, the INEL today includes a number of facilities within an 890-square-mile area of sagebrush desert, on the Eastern Snake River Plain of Idaho. The climate is semi-arid, with an average annual precipitation of about 8.5 inches (216 mm). The site was originally chosen for nuclear-safety research because of its isolation and unsuitability of the land for agriculture. In 1951 the INEL hosted one of the most significant accomplishments of the century — the first use of nuclear fission to produce electricity, in Experimental Breeder Reactor 1, now a National Historic Landmark. Fifty-two reactors, most of them first-of-a-kind facilities, have been built here. Several are still operable, and others were phased out upon completion of their research missions.

The INEL is also a National Environmental Research Park, preserving habitat and fostering biologic, archaeologic, and geologic research within its relatively undisturbed environment. Today, the INEL is administered by the U.S. Department of Energy, together with about seven major contractors. It is an important center for nuclear-safety research, defense programs, nuclear-waste technology, and advanced energy concepts.

Geotechnical data, including regional geology and geophysics, are widely used by INEL scientists and engineers in the design, construction, and safety analysis of INEL facilities. Thus, much of the information we present in this article has been obtained within the context of our attempts to assess the potential impacts of future volcanic, seismic, and climatic events on INEL facilities.

REGIONAL GEOLOGIC SETTING OF THE IDAHO NATIONAL ENGINEERING LABORATORY

The INEL is located near the northwestern margin of the ESRP, and lies in an area influenced by two distinct geologic provinces (Fig. 1). The ESRP is a northeast-trending zone of late Tertiary and Quaternary volcanism that transects the northwest-trending, normal-faulted mountain ranges of the surrounding Basin and Range province. The topographically subdued ESRP, the dominant geomorphic feature of southern Idaho, is a relatively aseismic region in the midst of the high-relief, seismically active Basin and Range province.

Volcanic and sedimentary rocks of the Snake River Plain form a 60- to 100-kilometer-wide belt, extending about 600 km from the Idaho-Oregon border to the Yellowstone Plateau. The inception of voluminous silicic volcanism on the Snake River Plain becomes younger toward the northeast (Fig. 2), supporting the interpretation of the Eastern Snake River Plain as the track of a mantle plume, formed during the past 16 Ma due to southwestward relative movement of the North America plate at a rate of about 3.5 cm/yr (Armstrong and others, 1975; Rodgers and others, 1990; Pierce and Morgan, 1990 and in press). The plume now underlies the Yellowstone Plateau (Iyer and others, 1981), and is the source of heat for the spectacular geothermal features and more than 6,000 km^3 of Quaternary silicic-volcanic rocks comprising the Yellowstone Plateau volcanic field (Hildreth and others, 1991). No basalt has yet erupted within the Yellowstone caldera, but in the wake of the plume, extensive late Tertiary and Quaternary mafic volcanism and sedimentation have occurred on the ESRP.

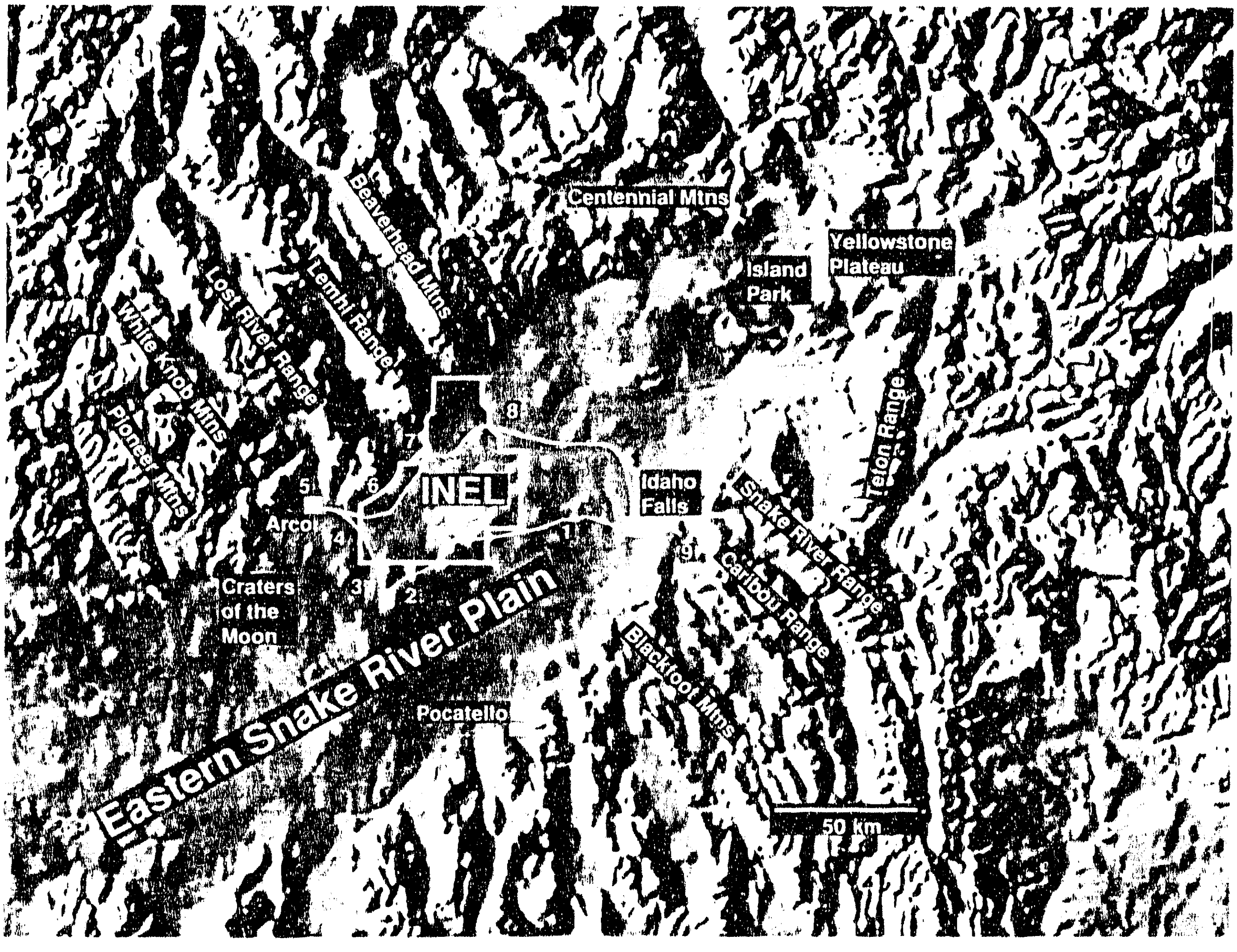

Figure 1. Index map, showing the location of the Idaho National Engineering Laboratory on the Eastern Snake River Plain volcanic province, the surrounding Basin and Range tectonic province, the field-trip route, locations of stops 1-9, and selected points of geographic and geologic reference; BSB = Big Southern Butte, CB = Cedar Butte, MB = Middle Butte, EB = East Butte, JB = Juniper Buttes. The digital-topographic base is from Richard Pike, U.S. Geological Survey.

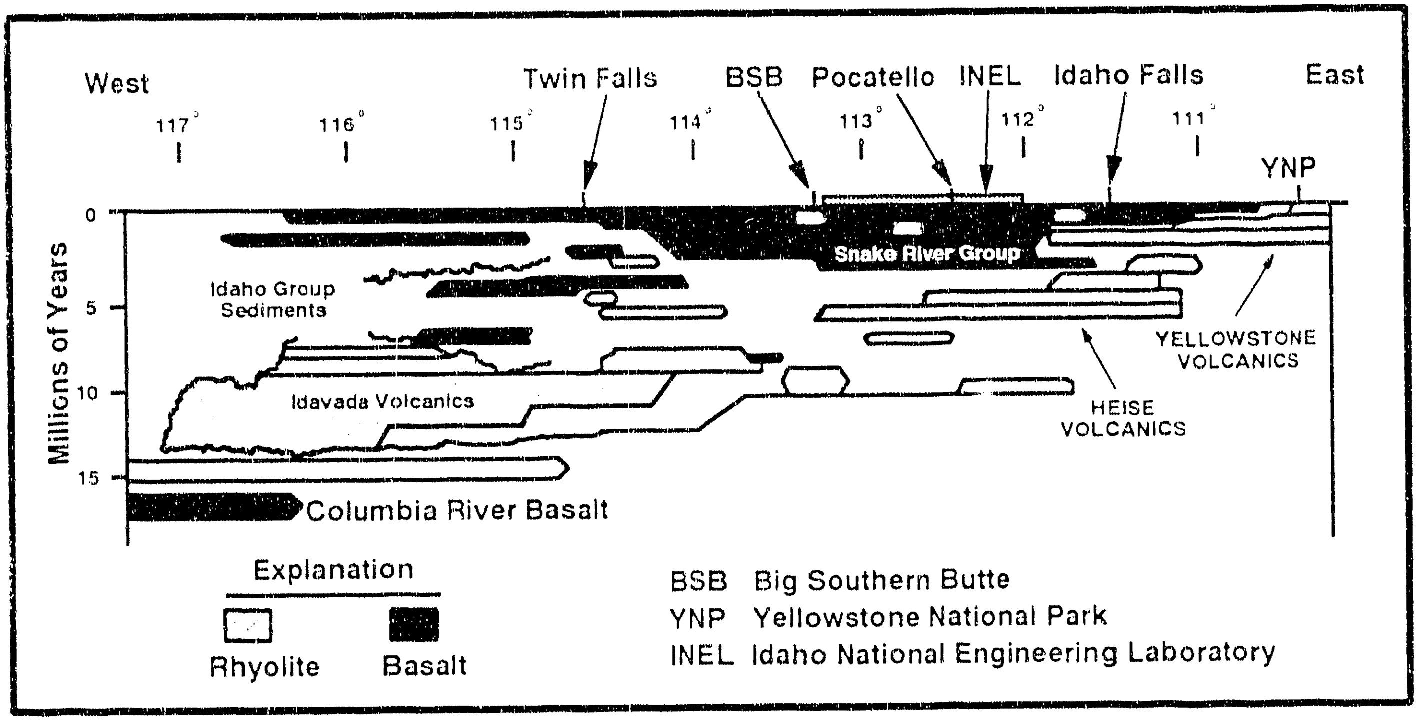

Figure 2. Age-distance plot of late Cenozoic, bimodal volcanism in the Snake River Plain-Yellowstone province (adapted from Armstrong and others, 1975; Hackett and Morgan, 1988; Rodgers and others, 1990). Two features are emphasized: the onset of voluminous rhyolitic volcanism becomes progressively younger toward the northeast, and the Tertiary eruptive complexes have been subsequently covered by Quaternary basalts and sediments of the Snake River Group.

Neogene Silicic Volcanism

Neogene silicic tuffs and lava flows of the Heise volcanic field are considered to be the oldest plume-related volcanic rocks of the ESRP, and are the ancestral equivalents of the Quaternary Yellowstone volcanics (Morgan and others, 1984; Morgan, 1988; Pierce and Morgan, 1990 and in press). Three widespread and voluminous rhyolitic ignimbrites are key lithostratigraphic units of the Heise volcanics, occurring in outcrops around the margins of the ESRP and in deep drillcores of the ESRP (Fig. 3). The major ignimbrites are the 6.5-Ma tuff of Blacktail, the 6.0-Ma Walcott Tuff (formerly the tuff of Blue Creek), and the 4.3-Ma tuff of Kilgore (Morgan, 1988). Vent regions of the Heise tuffs and lavas are largely covered by Quaternary/late Tertiary basalts and sediments of the Snake River Group (Fig. 2), but lithologic, paleomagnetic and structural evidence strongly suggests that they were erupted from calderas buried beneath basalts and sediments of the ESRP (Fig. 4) (Morgan, 1988). Such evidence includes the petrology and volcanic facies of the tuffs themselves; the possible occurrence of ring fractures and related faults in isolated places on both ESRP margins; contemporaneous silicic lava flows which may have issued from ring-fracture zones, and the great thicknesses of rhyolite found in the two deep INEL drillholes beneath the Quaternary basalt-sediment pile [ca. 2500 m of rhyolite in INEL 1 (Doherty, 1979), and 380 m in WO-2 (Hackett and others, unpublished data)]. These thicknesses are substantially greater than those of equivalent outflow-facies ignimbrites exposed outside the ESRP. To the northeast, the Island Park region (Fig. 1) is a transitional area between the basaltic-lava plains of the ESRP and the Yellowstone Plateau, where no basalt has yet erupted within the Yellowstone caldera. Partial filling of the Quaternary Henrys Fork caldera at Island Park by basaltic lava flows (Christiansen, 1982) is an example of the beginning of the burial process. Concurrent with basaltic volcanism, subsidence of the ESRP is predicted by thermal modelling of the response of the continental lithosphere to passage of the mantle plume (Blackwell, 1989).

Quaternary Basalt, Sediment and Rhyolite

Basalts and sediments of the ESRP are part of the Snake River Group, composed largely of tholeiitic-basalt lava flows emplaced during the past 4 million years (Fig. 2). Most eruptions were effusive, and typical landforms of Quaternary mafic volcanism on the ESRP are small shield volcanoes with summit pit craters, fissure-fed lava flows associated with zones of tensional fracturing, and relatively uncommon tephra cones of magmatic or phreatomagmatic origin (Greeley, 1982).

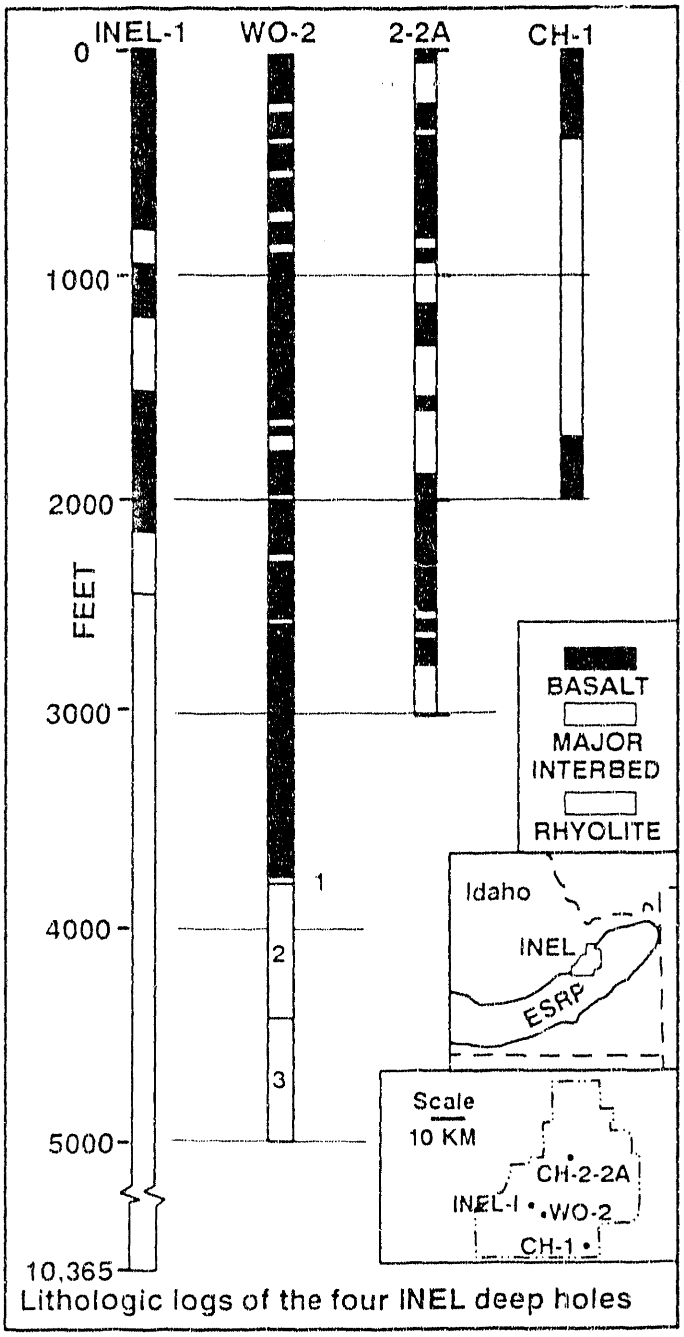

Figure 3. Simplified lithologic logs from deep drillholes in the INEL area. Only INEL-1 and WO-2 intersect Tertiary rhyolite, beneath basalts and sediments of the Snake River Group. Lithologic data are from Doherty and others (1979) for INEL-1; Doherty (1979a) for hole CH-1; and Doherty (1979b) for corehole 2-2A.

Based on field mapping, and limited geochronometry and paleomagnetic data, Kuntz and others (1990) (Fig. 5) identify five Quaternary basalt lava-flow groups in the INEL area, ranging in age from 5,200 years to greater than 730,000 years. The estimated ages of most lava flows in the INEL area are based on qualitative geomorphic and stratigraphic criteria: the youngest lava fields show little or no eolian sand and loess cover, and are largely unweathered. Older flows are covered by progressively thicker sediment and are more deeply weathered. These factors, together with stratigraphic age relationships among adjacent lava fields, form the subjective basis for assigning lava fields to their respective age units.

Basaltic vents on the ESRP typically form linear arrays of fissure flows, small shields and pyroclastic cones, pit craters and open fissures, which collectively define northwest-trending volcanic rift zones (Fig. 6). Volcanic rift zones have similar trends as normal faults in the adjacent Basin and Range province to the north, but are not strictly colinear with those faults. The most well-known and recently active of ESRP volcanic rift zones is the Great Rift (Kuntz and others, 1988), where eight eruptive episodes occurred at Craters of the Moon, and several smaller, monogenetic lava fields were formed during the past 15,000 years. In the INEL area, most basaltic rift-zone volcanism seems to have occurred during Pleistocene time, generally between about 0.1 and 0.7 Ma. Most subaerially exposed lavas have normal magnetic polarity, and are therefore younger than about 730,000 years. Several well-dated Holocene lava fields (Kuntz and others, 1986) erupted from northwest-trending fissures to the south of the INEL, on the northeast-trending axial volcanic zone.

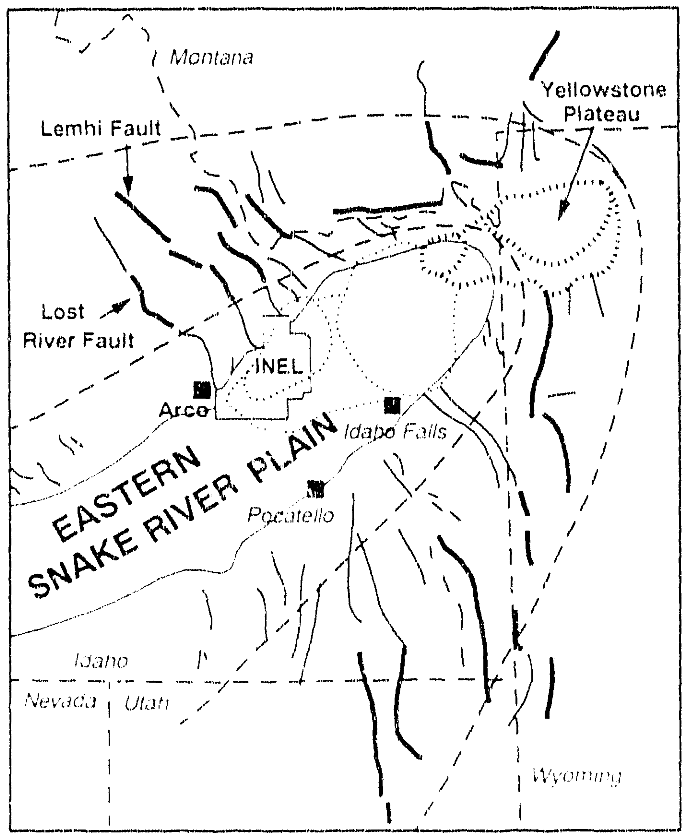

Figure 4. Map showing the generalized locations of Neogene silicic calderas (dotted ellipses) that are inferred to be buried beneath the ESRP (Morgan and others, 1984; Morgan, 1988), the exposed Quaternary calderas of the Yellowstone Plateau volcanic field (Christiansen, 1984), the parabolic region of historical seismicity centered on the Yellowstone plateau (enclosed by dashed curves; Anders and others, 1989), and major normal faults around the ESRP (bold lines indicate fault segments with Holocene displacement).

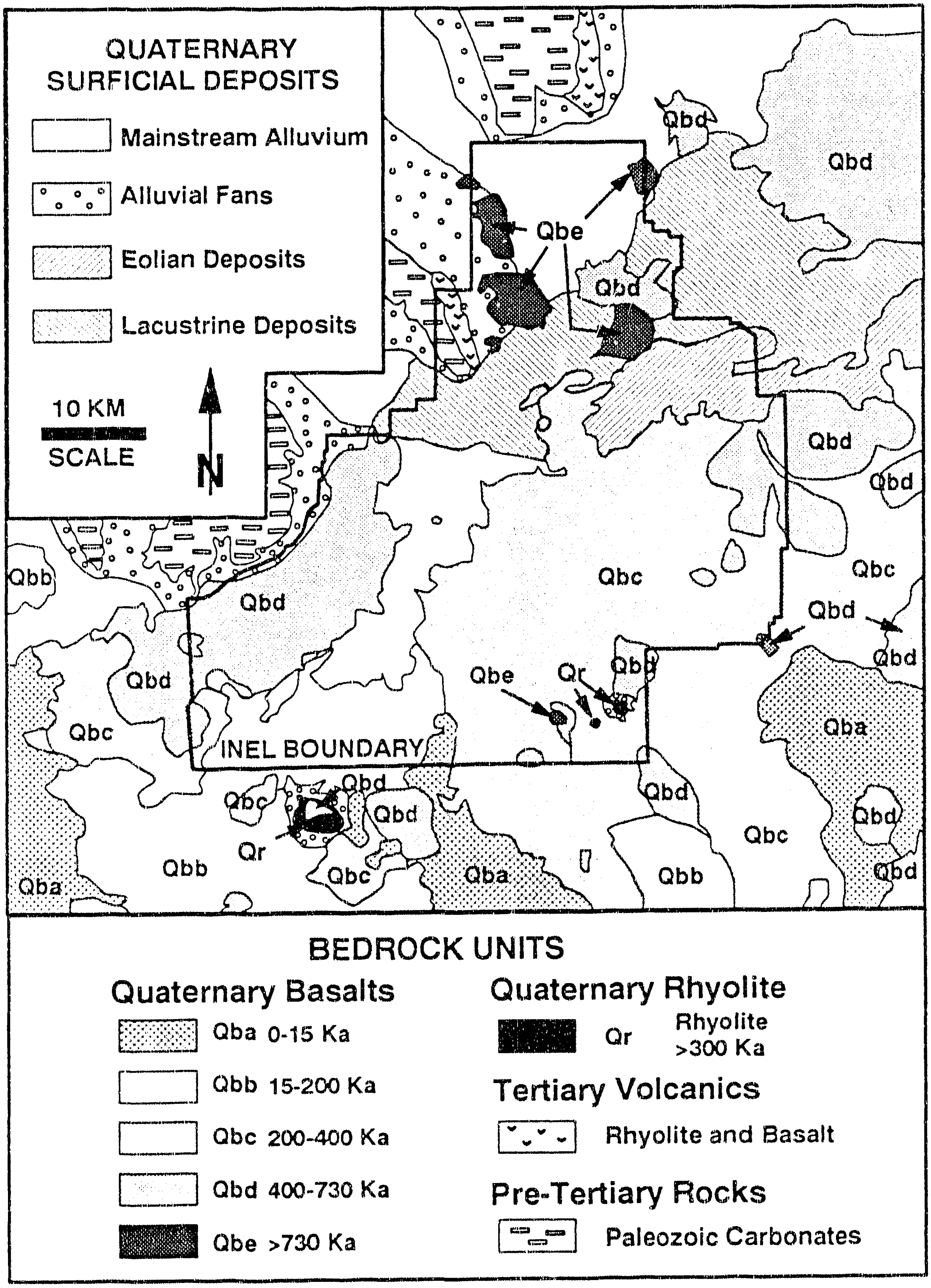

Figure 5. Generalized geologic map of the INEL area, showing the distribution of major basalt lava-flow groups and sedimentary deposits (adapted from Kuntz and others, 1990; Scott, 1982).

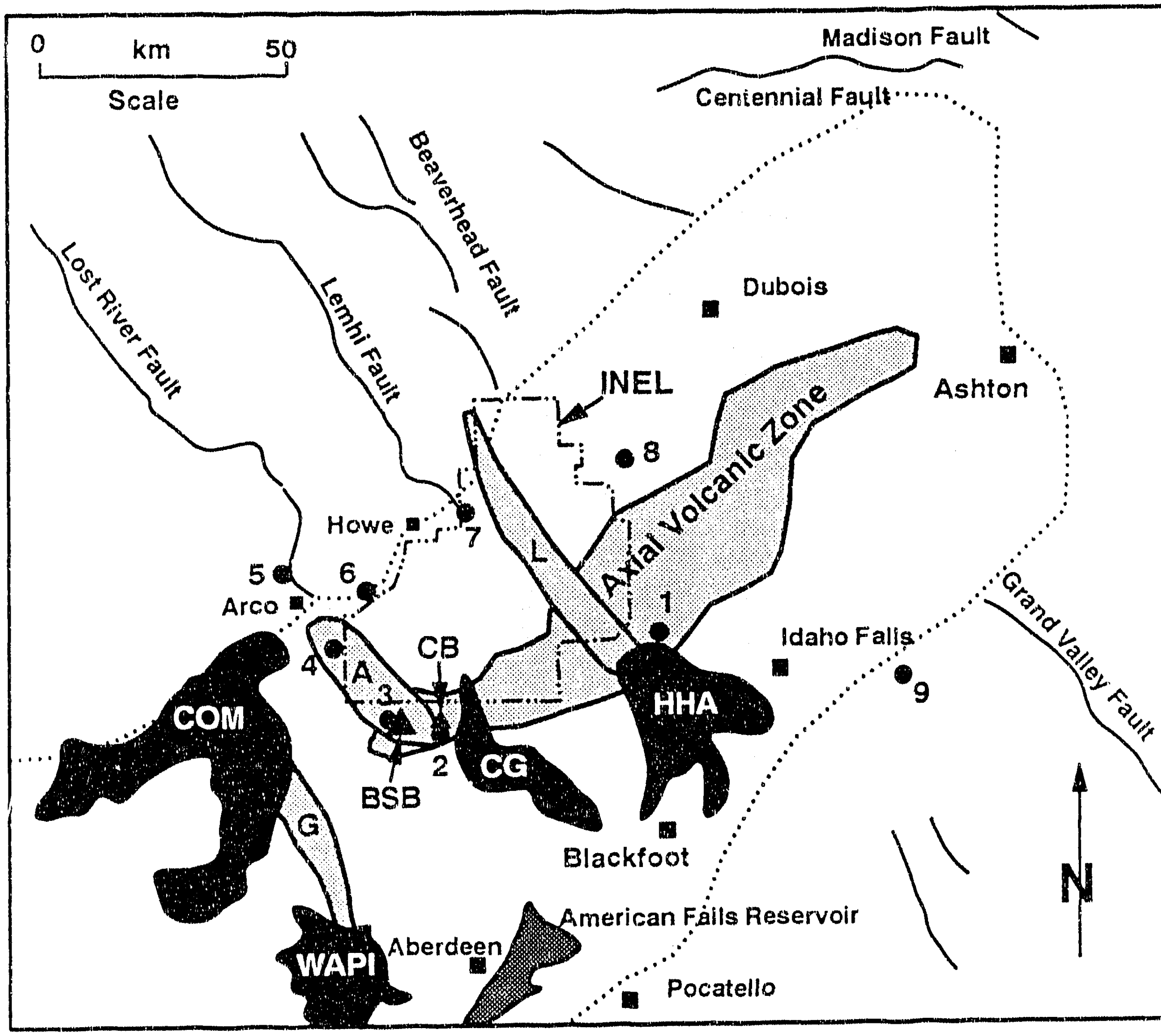

Figure 6. Map showing the major volcanic and tectonic elements of the INEL area, including northwest-trending normal faults of the Basin and Range tectonic province, northwest-trending volcanic rift zones on the ESRP, and the northeast-trending axial volcanic zone (a central, constructional region of volcanic vents). Holocene lava fields near the INEL are Hell's Half-Acre (HHA), Cerro Grande (CG), Wapi, and Craters of the Moon (COM). Locations of stops 1-9 are indicated.

Pleistocene rhyolite domes also occur along the axial volcanic zone on the ESRP (Fig. 7). Big Southern Butte is formed of two, coalesced exogenous rhyolite domes (Spear and King, 1982), with an uplifted, north-dipping block of basalts, ferrolatites and sedimentary interbeds on its north flank (Fishel,1992). The Cedar Butte eruptive center (Spear, 1979; Hayden, 1992) is a complex assemblage of landforms and lava types, mostly mafic in composition but including a small, undated rhyolitic dome. A topographic escarpment southeast of the Cedar Butte summit may be the result of uplift associated with late-stage silicic-magma intrusion beneath the complex, or the draping of mafic lava flows over a steep-sided silicic flow. Middle Butte is a stack of about twenty basalt lava flows, apparently uplifted in pistonlike fashion by a buried silicic intrusion (cryptodome) of unknown age. East Butte is an exogenous rhyolitic dome, in places containing centimeter-sized clots and blocks of mafic material.

Northern Basin and Range Province

The INEL is located near the northwestern margin of the ESRP (Figs. 1 and 2), where the low-lying lava plains terminate abruptly against the northern Basin and Range province, represented by the Lost River Range, Lemhi Range, and Beaverhead Mountains. Hypocenters of historical earthquakes occur in a parabolic region surrounding the ESRP and centered on the Yellowstone Plateau (Anders and others, 1989; Pierce and Morgan, 1990 and in press) (Fig. 4). The southern limb of the parabola is part of the Intermountain Seismic Belt, which continues south to the Wasatch front of Utah and marks the eastern edge of the seismically active Basin and Range tectonic province. The northern limb of the parabola is the Centennial Tectonic Belt, which extends westward from the Yellowstone Plateau and includes the epicentral area of the 1983 Borah Peak earthquake. The central, relatively aseismic area enclosed by the

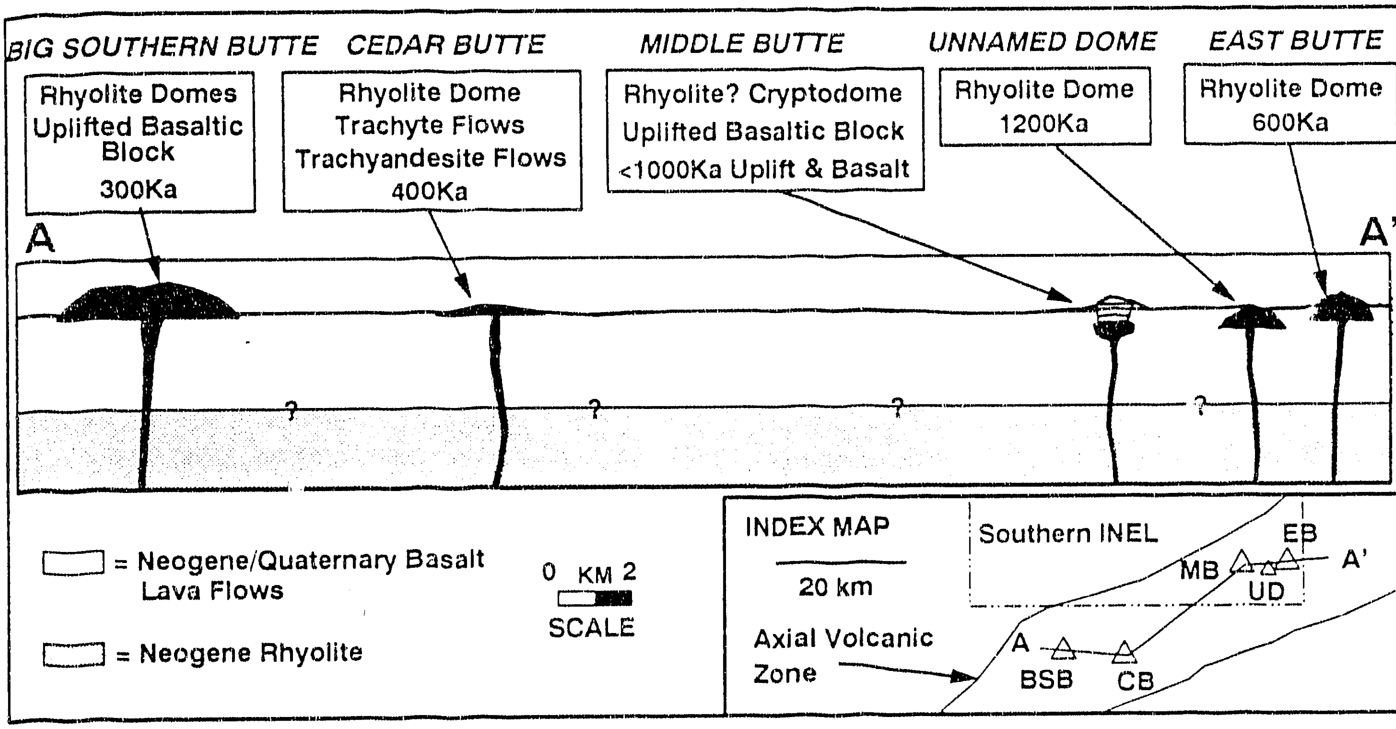

Figure 7. Schematic cross section along the axial volcanic zone of the ESRP, showing the ages, rock types and known or inferred lithostratigraphic relationships of Pleistocene silicic volcanic domes (adapted from Kuntz and Dalrymple, 1979; Spear and King, 1982; and authors' unpublished data).

seismic parabola includes not only the ESRP, but also adjacent portions of basin-and-range normal faults.

Northwest of the INEL, basin-and-range mountains are episodically uplifted along high-angle normal faults, as shown by paleoseismic investigations of fault scarps along the Lost River and Lemhi faults (Malde and others, 1971; Malde, 1987; Pierce, 1988; Hemphill-Haley and others, 1991), and coseismic deformation associated with the 1983 Borah Peak earthquake on the Lost River fault (Crone and others, 1987) Geologic mapping and fault-scarp excavations suggest that Quaternary normal faults to the north of the INEL are broken into discrete, 20- to 30-km-long segments that probably rupture independently (Crone and Haller, 1991), and that Holocene movements have not occurred on their southernmost segments adjacent to the ESRP (Pierce and Morgan, 1990 and in press) (Fig. 9). The northern Basin and Range mountains end abruptly against the low-lying ESRP (Figs. 1 and 6), suggesting that the normal faults also terminate.

Quaternary Surficial Deposits

Most lava flows in the INEL region are Pleistocene in age, have been subaerially exposed for several hundred thousand years, and are therefore blanketed with unconsolidated sedimentary deposits of eolian, alluvial and lacustrine origin (Scott, 1982) (Fig. 5). Although little is known of the detailed Quaternary lithostratigraphy of the ESRP subsurface, data from INEL drillcores generally indicate that relatively long (10^5-year) periods of sedimentation and volcanic quiescence, represented by major sedimentary interbeds, were punctuated by relatively brief ($< 10^2$- to 10^3-year) episodes of basaltic volcanism, the latter represented by rapidly emplaced lava-flow groups (Kuntz and Dalrymple, 1979; Kuntz and others, 1979, 1980; Champion and others, 1988; Anderson and Lewis, 1989; Anderson, 1991). The present distribution of surficial deposits is probably qualitatively analogous to that of subsurface deposits, involving intermittent blanketing of lava flows by loess, and the deposition of fluvial/lacustrine sediments in low-lying areas between constructional volcanic zones.

Alluvial deposits of two types are found in the INEL area: alluvial-fan deposits and mainstream alluvium. Alluvial fans are developed on the steep lower flanks of basin-and-range mountains and contain clastic material of local origin, commonly subangular/subrounded, moderately sorted gravel, dominated by Paleozoic carbonate clasts. Pierce (1988) uses carbonate-coat thicknesses and $^{230}Th/^{234}U$ disequilibrium dating to identify five age groups of alluvial-fan gravels on the southern Lost River Range, deposited about 15 ka to 160 ka. Where they have been displaced by faulting, alluvial-fan deposits are important targets in fault-scarp excavations, because they provide a sedimentological context for deciphering the absolute and relative chronology of paleoseismic events. Typically, wedges of scarp-derived colluvium are intercalated with loess or other fine-grained sediment, and the latter deposits can commonly be dated using such methods as thermoluminescence and radiocarbon.

Mainstream-alluvial deposits are associated with the channels of the Big Lost River, Little Lost River, and Birch

Creek, which longitudinally drain the northern Basin and Range province and flow southward onto the ESRP (Pierce and Scott, 1982). None of these streams reach the Snake River to the south. Instead, their ephemeral waters percolate into permeable lava flows and sediments at the Lost River Sinks of the northern INEL, a local recharge area for the Snake River Plain aquifer. Mainstream deposits are generally better sorted, rounded and bedded than those of alluvial fans, and clasts are predominantly quartzite, chert, silicified Eocene volcanic rocks, and other resistant lithologies.

Evidence for catastrophic flooding is well-known in the upper Snake River drainage where the effects of at least two Pleistocene, probably ice-dammed flood events are recognized, with likely sources on the Yellowstone Plateau (Scott, 1982). Effects of the Bonneville flood in southeast Idaho are even better known (Malde, 1968; Scott and others, 1982). Less well-known are glacial-outburst flood features of the Big Lost River (Rathburn, 1988; 1991). Near the western INEL boundary, channeled scablands, boulder bars and hyperconcentrated stream-flow deposits are products of a glacial-outburst flood. The floodwaters probably originated in the Copper Basin area, about 50 miles from the INEL, where Pinedale moraines and kame deposits are abundant. Preliminary results indicate the Big Lost River flood occurred about 19.8 ± 1.4 ka, based on cosmogenic ^3He and ^{21}Ne dating of geomorphic surfaces that were exposed during the event (Cerling and others, 1991).

Lacustrine deposits: volcanic eruptions and tectonism have periodically impounded the Snake River and its tributaries, forming lacustrine basins or areas of impeded drainage (Malde, 1982; Howard and Shervais, 1982; Scott and others, 1982; Hackett and Morgan, 1988). In the INEL region, the axial volcanic zone obstructed drainage from areas north of the ESRP. During glacial/pluvial periods, the resulting basins received more runoff than now, and contained large shallow lakes, in contrast to the present small playas of the Lost River Sinks. One such basin in the area that is now the northern INEL (Fig. 5) was occupied by Lake Terreton, whose Pleistocene deposits have been cored in the upper part of drillhole 2-2A (Fig. 3). Lake Terreton formerly covered a wide area near the present Mud Lake. Its shoreline generally follows the 4,800-foot topographic contour on the ESRP and is marked by beaches, bars and deltas. Lake Terreton sediments are the major source of material for Holocene dunes to the northeast.

Eolian deposits: Pleistocene loess deposits are widespread on the ESRP, and reach their greatest thickness along its southeastern margin. Several episodes of loess deposition are inferred from studies of loess stratigraphy and paleopedology (Pierce and others, 1982; Lewis and Fosberg, 1982; Scott, 1982). Holocene basalt flows on the ESRP have accumulated little or no loess (Kuntz and others, 1986), indicating that major loess deposition ceased about 10 to 15 ka. Late Pleistocene basalt flows and geomorphic surfaces are overlain by a single loess blanket, whereas older surfaces are generally mantled by several loess units, separated by paleosols or erosional surfaces. Pierce and others (1982) identify two widespread loess units in southeast Idaho; the upper loess (unit A) was deposited about 10-70 ka, while the lower (unit B) is less well dated but probably accumulated about 140-200 ka.

Dunes and sheets of Holocene eolian sand near Mud Lake (Fig. 5) have sources in the deflated alluvial surfaces of the Lost River Sinks, and in the abandoned shoreline and floor of former Lake Terreton to the southwest.

INTERACTION OF QUATERNARY VOLCANIC AND TECTONIC PROCESSES ON THE EASTERN SNAKE RIVER PLAIN

The ESRP is surrounded by the northern Basin and Range province, a region of actively extending lithosphere. The question of whether the ESRP is extending along with the surrounding terrain has recently been addressed by several writers. Anders and others (1989) consider that basin-and-range structures die out toward the ESRP because the integrated strength of the continental lithosphere beneath the ESRP is too great to permit extension, owing to the introduction of mantle-derived, mafic material at depth. Although the geophysical evidence of seismic refraction and regional heat flow data support the introduction of voluminous mafic-magmatic material into the middle crust and probably also the lithospheric mantle (Sparlin and others, 1982; Blackwell, 1989), the absence of strike-slip faults along the margins of the ESRP argues against decoupling of a static volcanic province from its extended surroundings. We and our colleagues have recently developed an explanation: the ESRP is extending at much the same rate as the surrounding Basin and Range province, but it does so by mafic-dike intrusion rather than by normal faulting (Smith and others, 1989; Rodgers and others, 1990; Parsons and Thompson, 1991) (Fig. 8).

Evidence in support of these two contrasting extensional mechanisms includes geologic and geophysical data, as outlined by Hackett and others (1991): Basaltic rift zones on the ESRP are aligned northwest, parallel to the trends of normal faults in the northern Basin and Range province. Rift-zone characteristics on the ESRP are similar to those of active rifts in Iceland and Hawaii, and include both ground deformation (open fissures, small-displacement normal faults, graben) and linear volcanic features. The surface-deformation features associated with ESRP basaltic volcanism are dissimilar in style and displacement to range-bounding normal faults in the surrounding tectonic province, but are identical to those of active rift zones in other regions such as Iceland, where dike-induced extension is unequivocal. Northwest-trending, positive aeromagnetic anomalies (Zietz and others, 1978) may indicate subsurface dike swarms beneath volcanic-rift zones. Several anomalies extend beyond the margins of the ESRP, suggesting the continuation of mafic-dike swarms into the adjacent Basin and Range tectonic province. Such outboard dike intrusion may explain the general observation of decreased paleoseismicity along southern normal-fault segments adjacent to the ESRP. In

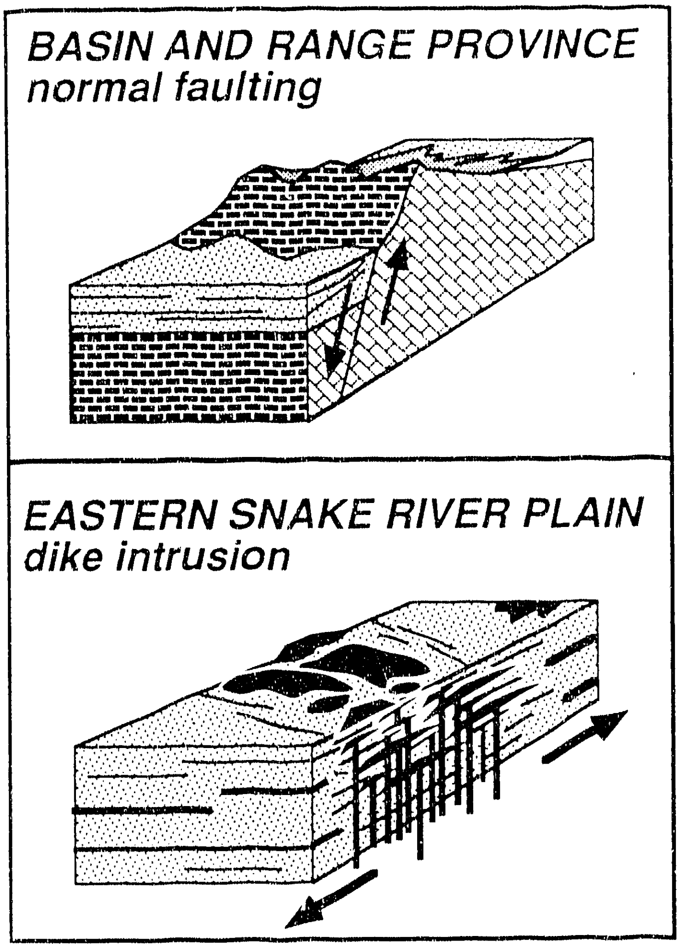

Figure 8. Schematic block diagrams showing the different modes of extension in the INEL region. On the Eastern Snake River Plain, the lithosphere apparently extends by mafic-dike intrusion. In the surrounding Basin and Range province, the lithosphere extends by normal faulting.

addition, northwest-trending, late-Quaternary volcanic rift zones are best developed on the northern half of the ESRP, adjacent to the most actively extending, northern part of the Basin and Range province.

The absence of borehole breakouts in the 3.2-km INEL-1 drillhole indicates that deviatoric stresses in the ESRP are low (Thompson and others, 1990), despite the presumed northeast-southwest extension of the ESRP. The dilation of dike walls due to the magma overpressure required for intrusion keeps ESRP deviatoric stresses low. Magma intrusion therefore effectively prevents normal faults from extending into the Snake River Plain.

By summing the inferred dike widths across Holocene eruptive centers and rift zones, we estimate total Holocene extension due to dike intrusion in the ESRP to be on the order of 10 to 20 meters. This is comparable to the estimated Holocene extension in the northern Basin and Range province, as derived from paleoseismic investigations of fault segments showing Holocene movement.

These contrasting extensional processes explain not only the strong topographic contrast between the Basin and Range tectonic province and the ESRP volcanic province, but also the relative aseismicity of the ESRP in contrast to its surroundings. Normal faults in the Basin and Range tectonic province generate large earthquakes, due to the accumulation and periodic release of elastic-strain energy. In contrast, ascending dikes would produce low-magnitude earthquake swarms, since shallow country rocks are weak under tension and little strain accumulation takes place prior to failure. Thus, although volcanic rift zones on the ESRP are potentially seismogenic sensu stricto, they are probably incapable of generating large-magnitude earthquakes, and magma overpressure in the ESRP prevents accumulation of the elastic strain that is necessary to produce large earthquakes.

INTRODUCTION TO THE FIELD GUIDE

Features to be visited on the two-day excursion include Holocene basaltic lava fields; eruptive and structural features of Quaternary basaltic-rift zones near the INEL; the southern segments of two major, basin-and-range faults near the INEL; Pleistocene rhyolitic domes along the central axis of the ESRP; Quaternary tectonic, sedimentary and volcanic features along the northern margin of the ESRP; late-Pleistocene, glacial-outburst features on the ESRP; and caldera-related, Neogene rhyolites around the margins of the ESRP.

Related guidebooks, maps and other literature of general interest include Scott, 1982; Link and Hackett, 1988; Alt and Hyndman, 1989; Bonnichsen and others, 1989; Ruebelmann, 1989; Kuntz and others, 1990; and Malde, 1991. Topographic maps of the field-trip area include the Idaho Falls 1 x 2-degree sheet, and the Arco, Craters of the Moon, Circular Butte, and Blackfoot 1:100,000 (metric) sheets.

SECURITY AND SAFETY ON THE IDAHO NATIONAL ENGINEERING LABORATORY

Our work at the INEL involves research and information affecting the defense and security of the United States. As a result, visitors to the INEL must be accompanied by an authorized escort at all times. Upon presentation of a picture identification/proof of U.S. citizenship (a valid driver's license is sufficient), security personnel may issue a visitor pass, which must be worn in plain view between the neck and waist. Personal equipment is permitted on site, but must be tagged by security. Boxes, briefcases, purses, etc. will be searched when entering and exiting controlled areas. Prohibited items include firearms and incendiary devices, alcohol and illegal drugs, portable transmitting or recording devices, and cameras. Your escort will direct you in case of an emergency situation, but two telephone numbers are important to know when visiting DOE facilities: for fire or medical emergencies dial 777; for other emergencies dial 526-1515.

LOCALITY DESCRIPTIONS

Stop 1. Hell's Half-Acre lava field

Holocene basaltic lava fields ranging in age from about 15 to 2 ka cover about 13% of the ESRP. Most are associated with either the Great Rift or the axial volcanic zone. The Hell's Half-Acre lava field was emplaced about 5.2 ± 0.15 ka, according to radiocarbon studies (Kuntz and others, 1986). The lava field is composed of about eight lobes of rapidly emplaced, basaltic pahoehoe flows, and marks the southern end of the Lava Ridge - Hell's Half-Acre volcanic rift zone (Kuntz and others, 1979). The hummocky lava-flow surfaces are typical of sheetlike basaltic lava flows worldwide, and are deflation features resulting from drainage of magma and gas from beneath the solidified lava crust. Generalized features of the Hell's Half-Acre lava field, which also apply to other lava fields on the ESRP, are shown in Fig. 9. The vent region is marked by a basaltic-shield volcano on the northwestern part of the lava field, with numerous aligned pit craters and small spatter mounds along a northwest-trending eruptive fissure. These features, together with two sets of parallel, noneruptive fissures extending northwestward beyond the lava field, indicate that the lava effusions were fed by one or more basaltic dikes.

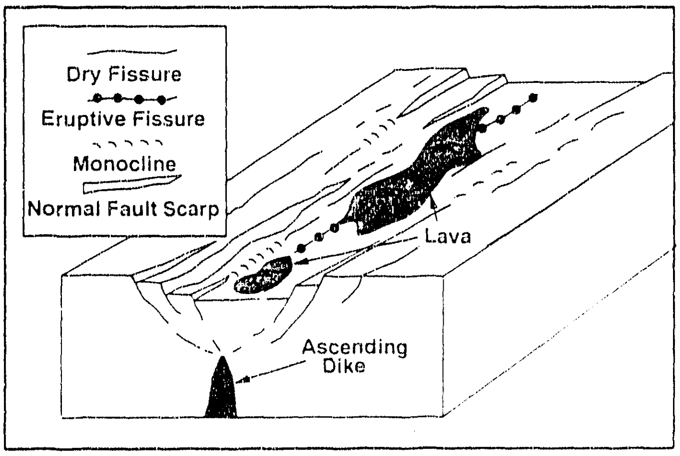

Figure 9. Schematic block diagram, showing typical eruptive and ground-deformation features of a monogenetic, dike-fed basaltic lava field such as Hell's Half-Acre.

Field studies, elastic-strain models, and the empirical results of "sand-box" experiments (Rubin and Pollard, 1988; Mastin and Pollard, 1988) have shown that ascending dikes produce overlying extensional features. Extensional structures such as graben, monoclines and open fissures commonly develop in tandem zones, symmetrically disposed around the intruded dike or its eruptive fissure. These features develop due to tensional stresses above the propagating dike tip, as country rocks are shouldered aside.

Dikes, and hence their associated ground-deformation features, are sensitive indicators of the regional-stress field. Because the ESRP is a young volcanic province, few dikes are exposed, but ground-deformation features associated with dike intrusion beneath volcanic-rift zones are nearly always northwest-trending, and thus have similar orientations as normal faults in the surrounding Basin and Range province.

Stop 2. Cedar Butte eruptive center

Cedar Butte is a composite eruptive center located near the intersection of the Arco rift zone and the axial volcanic zone on the Eastern Snake River Plain (Fig. 10) (Spear, 1979; Hayden, 1992). Geologic mapping of the Cedar Butte eruptive center has identified three vent areas: a large arcuate spatter rampart, a cinder cone, and a small fissure vent to the south of the cinder cone (figure 10). Lavas and tephra exhibit a wide range of bulk compositions from about 54 to 74 weight % SiO_2 (figure 12), and include basaltic trachyandesite, trachyandesite, trachyte, and rhyolite. The arcuate spatter vent is the source of the evolved basaltic flows covering the northern portion of the eruptive center. The cinder cone is held up by erosionally resistant spatter deposits, consisting of strongly to weakly welded lapilli tuff containing red, black and white pumice lapilli in a matrix of hybrid spatter. Basaltic spatter containing mixed-magma pumice lapilli occurs on the southwestern cone rim. About one-half kilometer south of the cone, a fissure vent erupted a widespread, thin flow of basaltic trachyandesite. An older, steep-sided rhyolite lava flow at the southern margin of the volcanic complex is mostly covered by trachyte and basaltic trachyandesite flows. The volcanic stratigraphy and mixed-magma lithologies at Cedar Butte show that diverse magma types were erupted in close spatial and temporal proximity. Evidence for co-eruption and commingling of mafic-to-silicic magmas occurs at all scales of observation, from disequilibrium phenocryst assemblages, to individual clasts of hybrid pumice, mixed-tephra pyroclastic beds, and a hybrid dike.

At **Stop 2**, a hybrid dike cuts the eastern part of the cinder cone (Fig. 10), outcropping in three segments along a small gully. The dike contains an inner, silicic core (62 to 73% SiO_2), with a mantle of basaltic trachyandesite (56% SiO_2). The dike is thus an intrusive counterpart of the hybrid and mixed-tephra deposits of the cinder cone.

Stop 3. Big Southern Butte

The most conspicuous landmark on the ESRP, Big Southern Butte rises 760 m from the surrounding lava plains, at the intersection of the axial volcanic zone and the Arco-Big Southern Butte volcanic rift zone. Armstrong and others (1975) give potassium-argon dates of 0.30 ± 0.002 and 0.60 ± 0.01 Ma from rhyolite of Big Southern and East buttes, respectively. The geology of Big Southern Butte is described by Spear and King (1982) as a dome of sugary, flow-banded to massive, nearly aphyric rhyolite. The northern flank of the butte is composed of a north-dipping slab of mafic lavas,

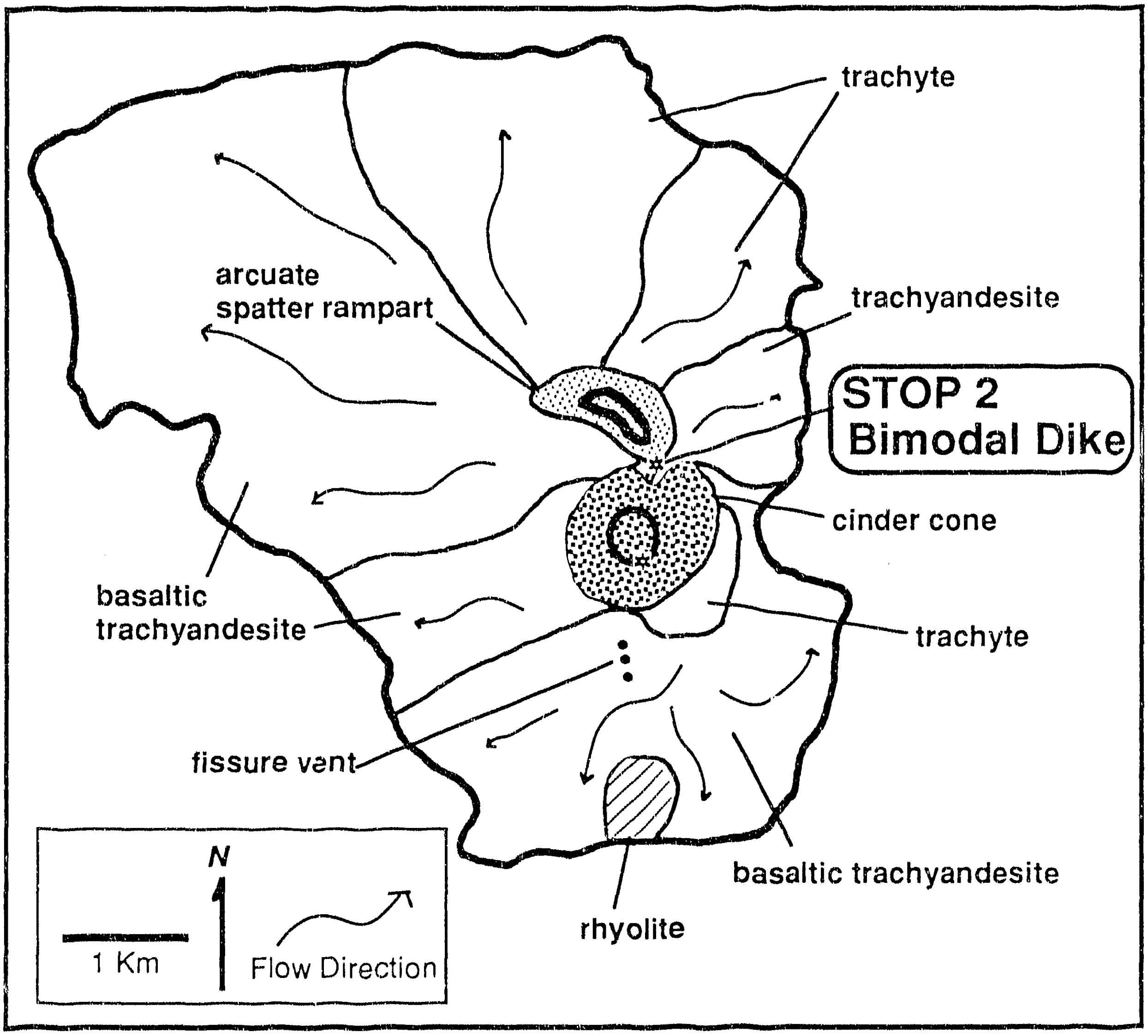

Figure 10. Generalized geologic map of the Cedar Butte eruptive center (data from Hayden, 1992), showing major map units, vent areas and position of Stop 2. All rock units are Quaternary in age, and the nomenclature of rock units is based on the geochemical data of Figure 12.

uplifted during growth of the rhyolite dome. Fishel (1992) (Fig. 11) shows that the uplifted slab of mafic lavas has a total stratigraphic thickness of about 900 m, and consists of at least thirty, 2- to 18-meter-thick lava flows, together with a few poorly exposed sedimentary interbeds. Bulk compositions of the uplifted Snake River Plain lavas range from about 45% to 67% SiO_2 (Fishel, 1992). Most rocks are tholeiitic basalts, but evolved lavas occur at the base and top of the exposed section (Fig. 11): ninety meters of welded-pyroclastic trachybasalts occur at the base of the section, and the uppermost lava flows are trachydacitic in composition. The latter are compositionally and petrographically similar to Cedar Butte eruptives (Fig. 12), suggesting that the source of the uppermost, mafic-to-intermediate lava flows on Big Southern Butte is the Cedar Butte eruptive center, about 7 km to the east.

Stop 4. Arco volcanic rift zone (multiple localities)

Volcanism and dike-induced surface deformation: A zone of northwest-elongate volcanic vents, extensional fissures, monoclines and small normal faults extends for a distance of more than 20 km between the town of Arco, Idaho and Big Southern Butte (Kuntz, 1978a,b; Smith and others, 1989; Kuntz and others, 1990). The 6-km-wide rift zone is colinear with the surface trace of the west-dipping Lost River fault, and is thus developed in the footwall of that structure. A generalized geologic map is given in Fig. 13, and Fig. 14 is an oblique-aerial photograph of a graben in the northern part of the Arco rift zone.

Surface deformation in the Arco rift zone is similar to that of active volcanic-rift zones in Iceland and Hawaii, and

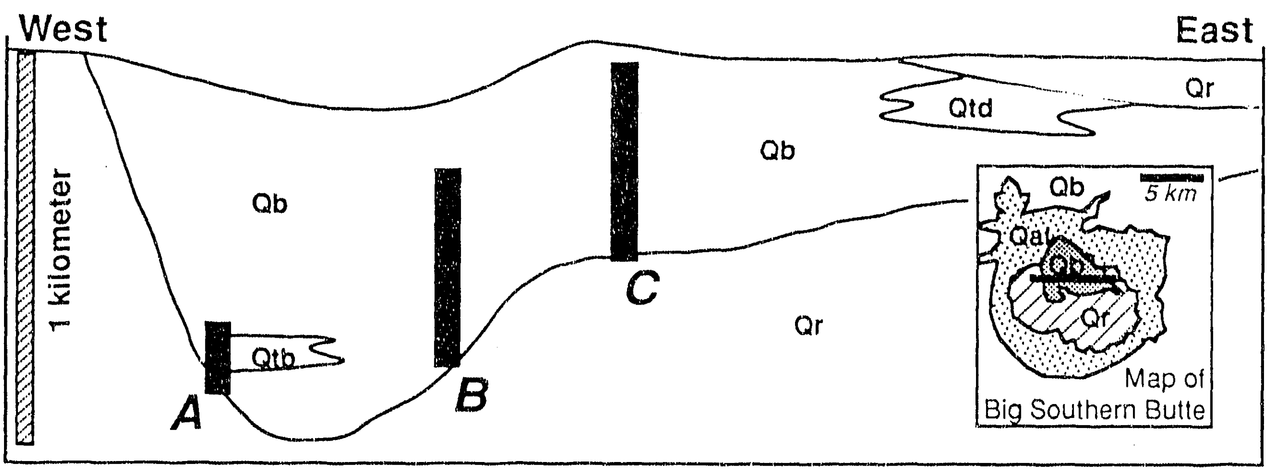

Figure 11. Schematic cross section of the uplifted slab of mafic-to-intermediate volcanic rocks exposed on the north flank of Big Southern Butte (data from Fishel, 1992). Locations of measured stratigraphic sections used in the compilation are shown as A, B, C; units dip about 45 degrees north. All deposits are of Quaternary age: Qal = alluvial-fan deposits; Qr = rhyolite of Big Southern Butte; Qb = Snake River Plain basalt lava flows; Qtb = lower trachybasalts; Qtd = upper trachydacites. See Fig. 12 for composition and nomenclature of selected rock units.

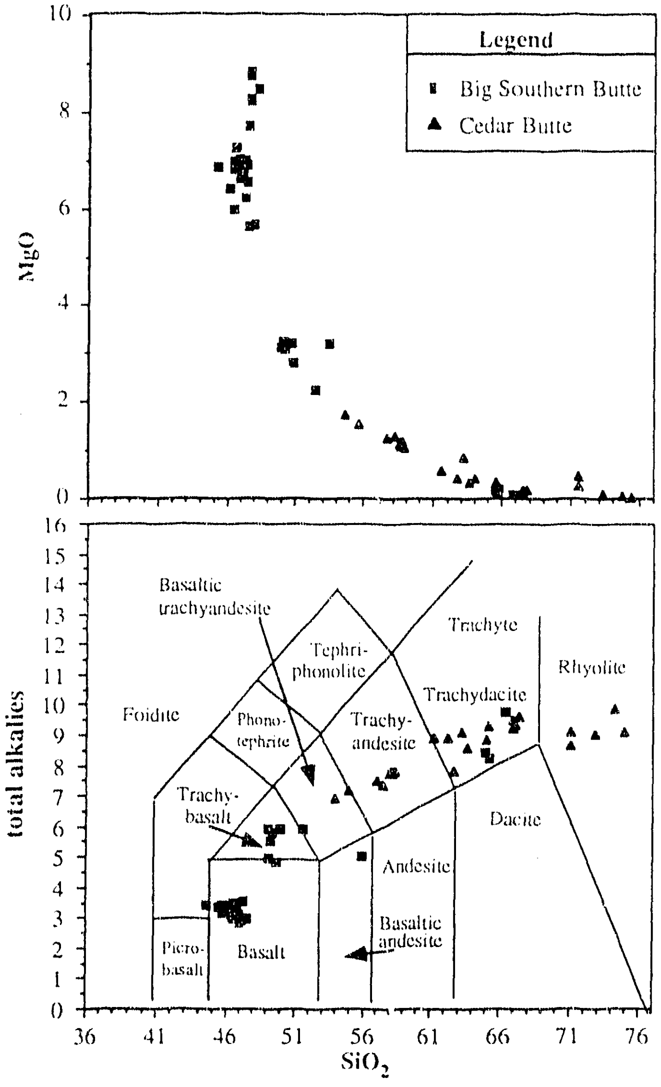

Figure 12. Bulk compositions of volcanic rocks from the Cedar Butte eruptive center and from uplifted, mafic-to-intermediate volcanic rocks on the north flank of Big Southern Butte (data from Fishel, 1992; and Hayden, 1992). Compositional fields and nomenclature are from LeBas and others, 1986.

consists of fissures, faults and monoclinal flexures that cut Quaternary basalt lava flows. Some fissures occupy the hinges of monoclines and are therefore of flexural origin, but most fissures are open vertical cracks with purely dilational displacement. Individual fissures are up to 3 km long, with dilations up to 1 meter. Although the fissures likely penetrate to basaltic-dike tips at depths of hundreds of meters to several kilometers (see Hell's Half-Acre discussion), observable depths seldom exceed 6 meters as a result of infilling by basalt rubble and loess. Fissures make up 80% of the total length of ground-deformation features in the Arco rift zone.

Fault scarps and monoclines commonly alternate with each other along linear zones. The maximum vertical displacement on faults in the Arco rift zone is about 10 meters (Fig. 13) and the maximum fault length is about 6 km. Most offsets are down-to-the-southwest, but down-to-the-northeast offsets are common. Constructional volcanic features consist of northwest-trending eruptive fissures, marked by aligned pyroclastic mounds and elongate shield volcanoes. We interpret the extensional features of the Arco rift zone as having been largely — if not entirely — caused by the intrusion of basaltic dikes, because of their close association with fissure-erupted basalts, and because the magnitude and style of displacement along faults, monoclines and open fissures are similar to those of active basaltic rift zones in Hawaii, Iceland and elsewhere. The presence of subsurface dikes beneath the Arco rift zone is also suggested by a 300-gamma, positive aeromagnetic anomaly over the area (Zietz and others, 1978). The relatively steep gradient of the water table beneath the area suggests that the subsurface basaltic dikes are aquitards.

Age and polygenetic origin of the Arco rift zone: The probable age of Arco-rift-zone volcanism and associated surface deformation ranges from about 600 ka to 100 ka. Fissures are apparently younger than about 600 ka: in the northwest part of the Arco rift zone near Box Canyon they cut basalt lavas that have been radiometrically dated at about 500 ka to 600 ka (Kuntz and others, 1990). Fissuring

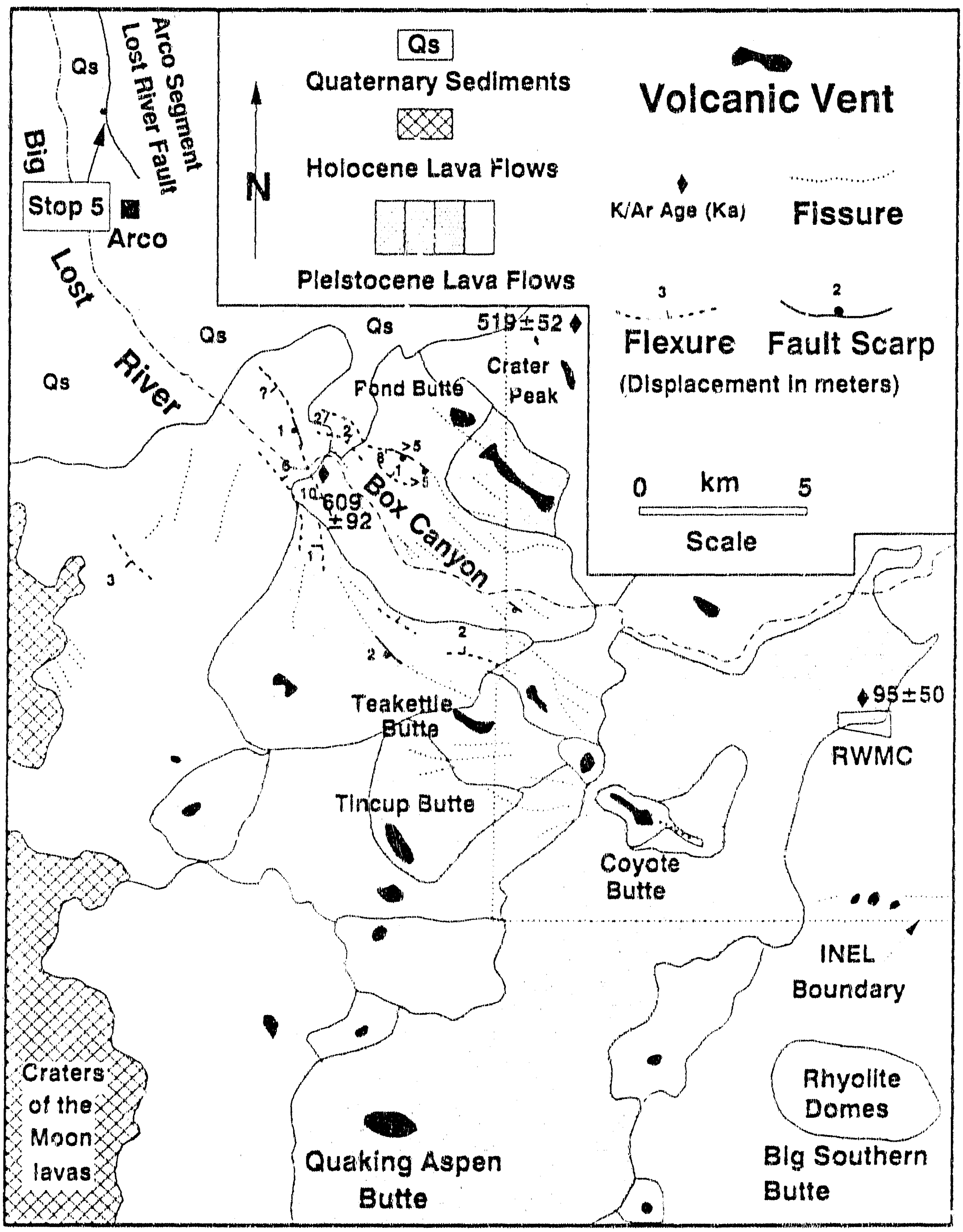

Figure 13. Generalized geologic map of the Arco rift zone (Smith and others, 1989; Kuntz and others, 1990)

and volcanism of the Arco rift zone is older than about 100 ka because a lava flow from Quaking Aspen Butte has been dated at 95 ± 50 ka, and that flow covers older lavas and fissures of the southern Arco rift zone.

In contrast to the monogenetic Hell's Half-Acre lava field, the more-complex Arco rift zone is almost certainly a polygenetic feature, as shown by the presence of multiple eruptive fissures, and several discrete groups of ground-deformation features. The fissures, monoclines and faults that we infer to have accompanied basaltic volcanism and dike intrusion are probably also polygenetic, and the large (up to 10 m) cumulative vertical displacement along one fault (Figs. 13 and 14) suggests multiple-uplift events. Geomorphic evidence supports our assertion that multiple uplifts account for the 10-meter displacement along the eastern border of the graben: the Big Lost River has incised the 15-meter-deep Box Canyon into basalt-lava flows to the east of the graben. Incision of the river apparently kept pace with multiple, meter-scale vertical displacements. Conversely, it is difficult to envision that the river could incise Box Canyon after a single, 10-meter-displacement event, and would likely have been displaced southward rather than occupying its present eastward course through Box Canyon.

Late Pinedale glacial-outburst flooding: Climatic fluctuations associated with Pleistocene glacial and interglacial episodes induced catastrophic flooding of the Big Lost River through Box Canyon (Rathburn, 1988). This large, rare event and subsequent streamflow left distinctive, mappable fluvial deposits along the length of the river. Erosional features associated with the catastrophic flooding include arcuate basalt cataracts, smoothed and scoured basalt outcrops, and a loess scarp (Rathburn, 1991). Boulder bars, and erratics of intrusive and metamorphic rocks derived from the Pioneer Mountains are the primary depositional features of the flooding. A peak discharge of 2 to 4 million cfs is estimated for the event (Rathburn, 1991) which occurred 19.8 ± 1.4 ka, based on cosmogenic ^{3}He and ^{21}Ne measured from exposed surfaces of large flood-transported boulders (Cerling and others, 1991).

Stop 5. Trench site, Arco segment of the Lost River fault

Three, segmented normal faults occur to the north and west of the INEL, in the northern Basin and Range province (Fig. 1). All are of concern in seismic-safety issues at the INEL, because of their proximity to the site, and evidence for Quaternary paleoseismicity. Quaternary faulting and scarp-degradation studies in the southern Lost River Valley are discussed by Pierce (1988), from which the following summary is adapted. Along the estern side of the southern Lost River Range near the town of Arco, the scarp of the Lost River fault is about 16 to 23 meters high, and is formed in older Quaternary alluvial-fan gravels. Pierce (1985; 1988) uses geologic relations such as carbonate-coat thicknesses on alluvial-fan clasts, and U-Th disequilibrium dating to infer the history of faulting near a deep trench that was first excavated and described by Malde (1971). The total vertical displacement of units exposed in the trench is estimated at about 20 meters, and two wedges of fault-derived colluvium are exposed in the bottom of the trench. The colluvial units are overlain by loess containing volcanic ash dated at 76 ± 34 ka (N.D. Naeser, pers. comm., in Pierce, 1988), and the oldest exposed alluvial-fan deposit (160 ± 30 ka; Pierce, 1988) had been offset 4 to 7 meters by the time the ash was deposited. The youngest surface faulting along the Arco

Figure 14. North-looking, oblique-aerial photograph of the 0.3-km-wide graben in the northern part of the Arco rift zone. The Big Lost River flows from left to right, and Box Canyon is incised to the right (east) of the graben. Cumulative vertical displacement along the east side of the graben where it is intersected by the river is about 10 meters. We consider the graben, together with associated tensional fissures and monoclines, to have been produced by dike intrusion. The southern end of the Lost River Range is in the upper left, and the Arco Hills are in the upper right.

segment is estimated to have occurred about 30 ka This contrasts with more northern segments of the Lost River fault, which show evidence of Holocene, and in places historical, offset: the 1983 Borah Peak earthquake and its associated scarp occurred on the Lost River fault, about 30 miles north of Arco (Crone, 1988).

Stop 6. Nontectonic scarp along the northern margin of the Eastern Snake River Plain

The abrupt geographic transition from the northern Basin and Range tectonic province to the ESRP volcanic province, together with the comparatively low-lying terrain of the ESRP suggests that major northeast-trending, southeast-downthrown faults may be present along the northern margin of the ESRP, although no evidence for such features has yet been found (Rodgers and others, 1990). The identification of any such northeast-trending faults — especially those showing evidence for Quaternary displacement — would be important in seismic-hazard evaluation at the INEL. A subdued, northeast-trending scarp on the northern margin of the ESRP near the Arco Hills was previously mapped as a fault scarp (Scott, 1982) and was excavated in order to determine whether the feature is tectonic in origin (Breckenridge and Othberg, 1991). The now-backfilled, 3-by-40-meter trench excavation is located north of highway 33, within the INEL boundary and near the center of the north edge of section 25, T4N, R23E. Loess and alluvial-fan gravel deposits exposed in the trench walls are not offset, and the feature is therefore of nontectonic origin. The late Pleistocene loess deposit overlying alluvial-fan deposits thins across the topographic scarp, and the scarp is therefore of erosional origin, involving partial removal of the loess cover on the downhill (southeast) side. The explanation we favor is that the scarp is the result of differential erosion across a fire scar, and is similar in origin to other subdued, northeast-trending features on the ESRP. Fire scars have abrupt linear edges, and destruction of vegetation on the burnt area commonly leads to eolian stripping of loess. In places, fire scars are apparently further modified by redeposition of stripped loess within the unburned sagebrush along the edge of the fire scar, forming a subdued linear mound or scarp.

Stop 7. Howe Point, southern tip of the Lemhi Range

Features to be observed and discussed at Howe Point include Neogene rhyolitic volcanics, lake-margin sediments of pluvial Lake Terreton, and the structural geology of the southern Lemhi Range. On the west side of the southern Lemhi Range, the Lemhi fault terminates in a number of splays, displacing Paleozoic carbonate rocks and Neogene volcanic tuffs, but apparently not unconsolidated eolian deposits of late Pleistocene or Holocene age (Ron Bruhn, written commun., 1991).

Figure 15 shows the stratigraphy of Neogene rhyolitic tuffs exposed at Howe Point, an important locality for

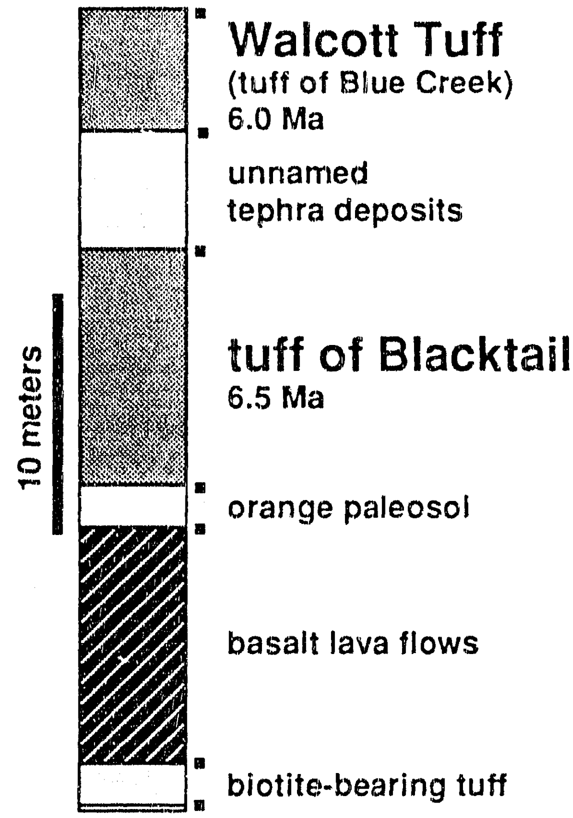

Figure 15. Simplified, composite-stratigraphic section of volcanic rocks exposed at Howe Point, Stop 7 (adapted from Hackett and Morgan, 1988).

reconstructing the nature of silicic volcanism and caldera collapse of the Heise volcanic field (Morgan, 1988). On the north side of highway 33, the 6.0-Ma tuff of Blue Creek (Walcott Tuff), one of three voluminous and regionally distributed Heise ignimbrite sheets, forms the top of the section. The tuff of Blue Creek (Walcott Tuff) at this locality is a near-vent ignimbrite, judging from its large and abundant phenocrysts and lithic-rock fragments, together with an underlying meter-thick, welded, pumice-rich, plinian-fall deposit. In addition, zones of brecciation, marked by angular tuff clasts within a white, vapor-phase-altered matrix of the same tuff, occur along faults that are interpreted as caldera ring fractures (Morgan, 1988). Below the tuff of Blue Creek (Walcott Tuff) and associated ash deposits is the 6.5-Ma tuff of Blacktail, which also has lithologic features suggesting near-source deposition.

The Lost River Sinks occur south of highway 33 within a subdued topographic basin. The basin is developed between alluvial valleys and bedrock ranges to the north, and the axial volcanic zone of the ESRP. The Sinks currently receive ephemeral water and alluvial sediment from the Big and Little Lost Rivers, but in late Pleistocene time an area approximately within the 4800-foot topographic contour was occupied by pluvial Lake Terreton, whose modern remnant is Mud Lake. As mapped by Scott (1982), the deposits of Lake Terreton cover about 600 square miles, but are concealed in places by stabilized linear dunes (see Stop 8). Near Howe Point, weakly bedded, fine lacustrine sands containing gastropod-shell fragments are exposed along curved erosional scarps, marking a former Lake Terreton shoreline.

Stop 8. Holocene/late Pleistocene longitudinal dunes, southwest of Mud Lake

Eolian sand occurs on the ESRP as stabilized dunes, and in places as active dunes (Scott, 1982; Baker and others, 1987; Malde, 1991). One area of stabilized linear dunes forms a broad band 15 km wide, stretching about 80 km northeastward from the Lost River Sinks along the margin of the ESRP. The area is marked by long, straight parallel ridges about 1 to 7 m high, 20 to 60 m wide, and tens of km long. The longitudinal dunes overlie deposits of Lake Terreton and their distribution suggests that the dunes were derived from those lacustrine deposits. Hence, the dunes are of late Pleistocene to Holocene age.

Stop 9. Rhyolitic tuffs at the Blacktail Recreation Area

About 12 miles east of Idaho Falls, several localities at the Blacktail Recreation area on Ririe Reservoir contain excellent exposures of Neogene rhyolitic tuffs. The locality is important in reconstructing the nature and regional distribution of tuffs from the Heise volcanic field. In addition, the Blacktail area contains outstanding exposures of all three genetic categories of pyroclastic deposit: fall, flow and surge. The following discussion is adapted from Hackett and Morgan (1988). Fig. 16 shows the volcanic stratigraphy.

The localities are near the inferred structural margin of the Blacktail caldera, source of the 6.5-Ma tuff of Blacktail. The basal unit is the tuff of Blacktail. North of the boat ramp, it exceeds 150 m in thickness, is crystal-rich, and contains tight flowage folds; this thick tuff represents the ponded intracaldera facies. At the boat ramp near reservoir level, the tuff thins into an undeformed outflow sheet with a basal, spherulitic vitrophyre; a massive, devitrified, densely welded interior; an upper vapor-phase zone; and a several-meter-thick cap of black vitrophyre. The tuff of Wolverine Creek is a local, obsidian-rich, nonwelded ignimbrite containing fluid-escape pipes, capped by ash-cloud (?) surge deposits. Overlying the tuff of Wolverine Creek are unnamed, planar-bedded lapilli tuffs of probable plinian-fall origin. The uppermost rhyolitic deposits are the 2.0-Ma Huckleberry Ridge Tuff, from the Yellowstone Plateau volcanic field. In places, Quaternary basalt lava flows unconformably overlie the rhyolitic tuffs.

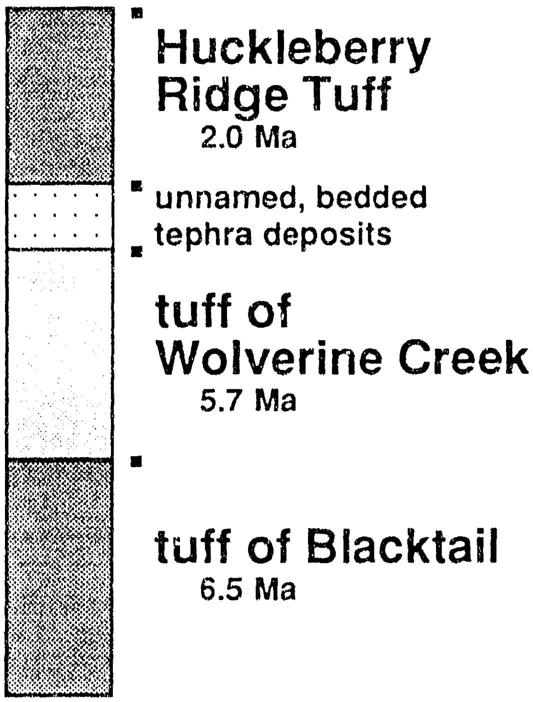

Figure 16. Generalized stratigraphy of Quaternary and Neogene rhyolitic tuffs exposed at the Blacktail Recreation area along the southern margin of the ESRP, Stop 9 (data from Morgan, 1988; Hackett and Morgan, 1988). The total section is about 300 m thick; relative thickness of the tuffs is not drawn to scale.

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