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Accumulation and subsidence of late Pleistocene basaltic lava flows of the eastern Snake River Plain, Idaho

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ABSTRACT

Studies of cores from drill holes with detailed petrographic descriptions, paleomagnetic characterization and correlation, and conventional K-Ar and $^{40}Ar/^{39}Ar$ dating allow examination of the process of accumulation of basaltic lava flows in a part of the eastern Snake River Plain, Idaho. Core holes at various locations in the Idaho National Engineering and Environmental Laboratory (INEEL) demonstrate variable accumulation rates that can be fitted by linear regression lines with high correlation coefficients. Hiatuses of several hundred thousand years are represented in many of the core holes, but accumulation of flows resumed in most of the areas sampled by these core holes at rates nearly identical to previous rates. The studies show that an area of the eastern Snake River Plain north of its topographic axis, including the area of the INEEL, has undergone a hiatus in eruptive activity for the past ~200 k.y. The data also allow enhanced interpretations of the volcanic hazard to the INEEL with regard to lava flow inundation, prediction of lava flow thickness, and assessment of eruption recurrence-time intervals.

GEOLOGIC SETTING

The eastern Snake River Plain rises 1000 m in elevation from Twin Falls, Idaho, to the Yellowstone Plateau. The relatively flat surface has a northeast-southwest–trending central axis that connects those two areas. The plain is bounded on the northwest and southeast by Tertiary block-faulted mountains of the Basin and Range Province, underlain mainly by folded and thrust-faulted Precambrian, Paleozoic, and Mesozoic sedimentary rocks and Mesozoic and younger plutonic rocks. The plain terminates to the northeast in the Pliocene and Quaternary Yellowstone Plateau volcanic field. The Snake River flows along the southern boundary of the eastern Snake River Plain (Fig. 1) along a course defined in part by the extrusion of the lava flows; there is no evidence that the river ever crossed the lava surface (Walker, 1964).

At the surface, the eastern Snake River Plain comprises basaltic lava flows, shield volcanoes, minor associated pyroclastic deposits, and more widespread sedimentary accumulations of variable thicknesses. The surface is locally covered by a thin discontinuous mantle of loess. Most of the surface flows have normal magnetic polarity associated with the Brunhes Normal Polarity Chron, and are thus younger than 780 ka. Pleistocene and Holocene lava fields cover large parts of the eastern Snake River Plain, suggesting that renewed lava shield formation must be considered a possibility anywhere along the length of the eastern Snake River Plain. Several andesitic to rhyolitic flows and domes crop out along the axial area of the eastern

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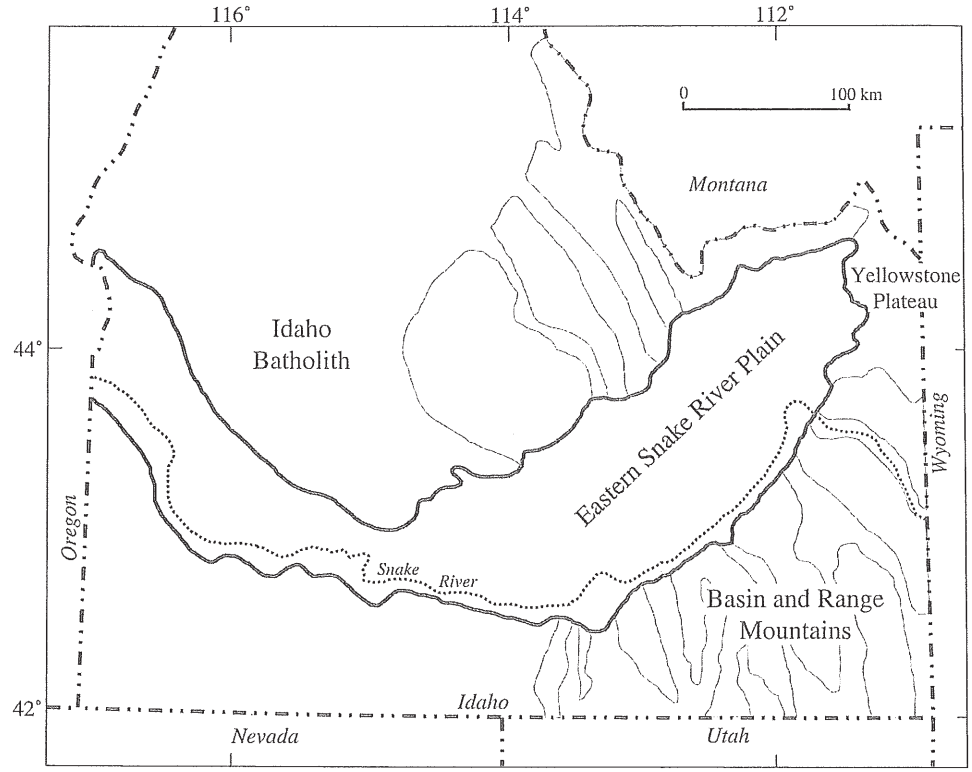

Figure 1. Generalized map of southern Idaho showing geologic and geographic features referred to in text, including eastern Snake River Plain.

Snake River Plain and have ages ranging from 1.4 to 0.3 Ma (Kuntz et al., 1994). Lava flows of evolved composition have been considered to be a very minor constituent of the eastern Snake River Plain, but recent work suggests that a larger amount of higher silica lava flows may be found at depth (Hughes et al., 1997). Outcrops of rhyolite pumice-fall deposits and welded tuff only occur at the margins of the plain; similar rocks occur at great depth (>730 m) in the deepest wells of the Idaho National Engineering and Environmental Laboratory (INEEL), but play no part in the surface or near-surface stratigraphy of the plain.

The distinctive low relief and low-slope morphology of basalt lava flows of the eastern Snake River Plain prompted Greeley (1982) to give the name "basaltic plains volcanism" to the eruptions of the eastern Snake River Plain to distinguish them from the more voluminous flood-basalt eruptions of plateau volcanism and from Hawaiian volcanism, which produces greater surface relief. Basaltic plains volcanism is dominated by low shield volcanoes of modest overall volume (5 ± 3 km^3) formed from fluid, gas-rich lavas. Eruptions may begin from a system of fissures and typically consolidate in long-lived eruptions to one or several vents along the original fissure system. The eruptions produce hundreds of lava flow units that extend tens of kilometers from the vent during a time no longer than a few decades. This type of eruption doesn't flood a surface 100 m thick with single flow units or pile up an equant mass of lava. Rather, flow directions follow subtle creases in the topography, moving great distances by endogenous flow when the effusion rate is appropriately maintained. The net effect is to produce nearly planar surfaces puddled by successive effusions, and widespread overlapping of lava fields.

The subsurface record of the eastern Snake River Plain is generally similar to the lava and sediment accumulations at the surface environment (Walker, 1964; Anderson et al., 1996; Anderson and Liszewski, 1997). In many core holes in the southern half of the INEEL, fine-grained sediments separate flows of significantly different ages. Anderson and Liszewski (1997) suggested an average sediment content of 15% for wells drilled in or near the INEEL. Sands and gravels recovered in southern INEEL core holes suggest that these are fluvial deposits associated with buried courses of the Big Lost River. The course of that stream has been displaced frequently as the plain has subsided to positions peripheral to new lava fields. Thick accumulations of sediments are typical of wells drilled or cored in the sinks area of the Big Lost or Little Lost Rivers or in the Mud Lake area. Sediment contents range from 26% to 46% for the deepest of the wells from those areas (Lanphere et al., 1994). By contrast, the proportion of sediment in core holes and drill holes along the southern boundary of the INEEL near the topographic axis of the eastern Snake River Plain is generally low, typically <5%. For example, Core Hole #1, located on the axis of the plain between East and Middle Buttes, has <1% sediments over a depth range of 600 m.

Kuntz et al. (1992) suggested that as many as nine volcanic rift zones cross the eastern Snake River Plain following Basin and Range trends. Four of these, the Arco–Big Southern Butte, Howe–East Butte, Lava Ridge–Hell's Half Acre, and Circular Butte–Kettle Butte volcanic rift zones cross the INEEL. The

Lava Ridge–Hell's Half Acre volcanic rift zone can be documented through the Test Area North (TAN) area of the INEEL (Fig. 2); core holes show that the subsurface section is composed of sediment-poor, flow-on-flow sequences to depths >300 m. Topographic freeboard arising from frequent eruptions prevents accumulation of sediments, thus sediment-poor sequences indicate near-vent locations for nearly all flows. In comparison, core holes to the northeast and south of the TAN area contain more than 100 m of sediment over the same depth range, indicating that their locations are on the flanks of volcanic edifices located in the vent zone.

PURPOSE OF THE PRESENT STUDY

We studied the stratigraphy of basaltic lava flows and sediments in 20 core holes at the INEEL by conventional logging, petrographic, paleomagnetic, $^{40}Ar/^{39}Ar$, and conventional K/Ar dating methods. These studies have yielded detailed information about the rates at which the lava flows and sediments have accumulated. The data indicate that the flows and sediments accumulate predictably with linear accumulation rates. The data for some core holes show that episodes of nearly constant accumulation rates were separated by hiatuses of several hundred thousand years. However, the hiatuses were followed by the resumed accumulation of lava flows and sediments, typically, but not universally, at a linear rate nearly identical to the prior rate. Accumulation rates also varied considerably in magnitude at various locations in the study area.

In this chapter we document the techniques used in this study, describe the accumulation rates found, and discuss the influences of these rates and their geographic distribution on the character of basaltic volcanism and on the potential volcanic hazards of the eastern Snake River Plain.

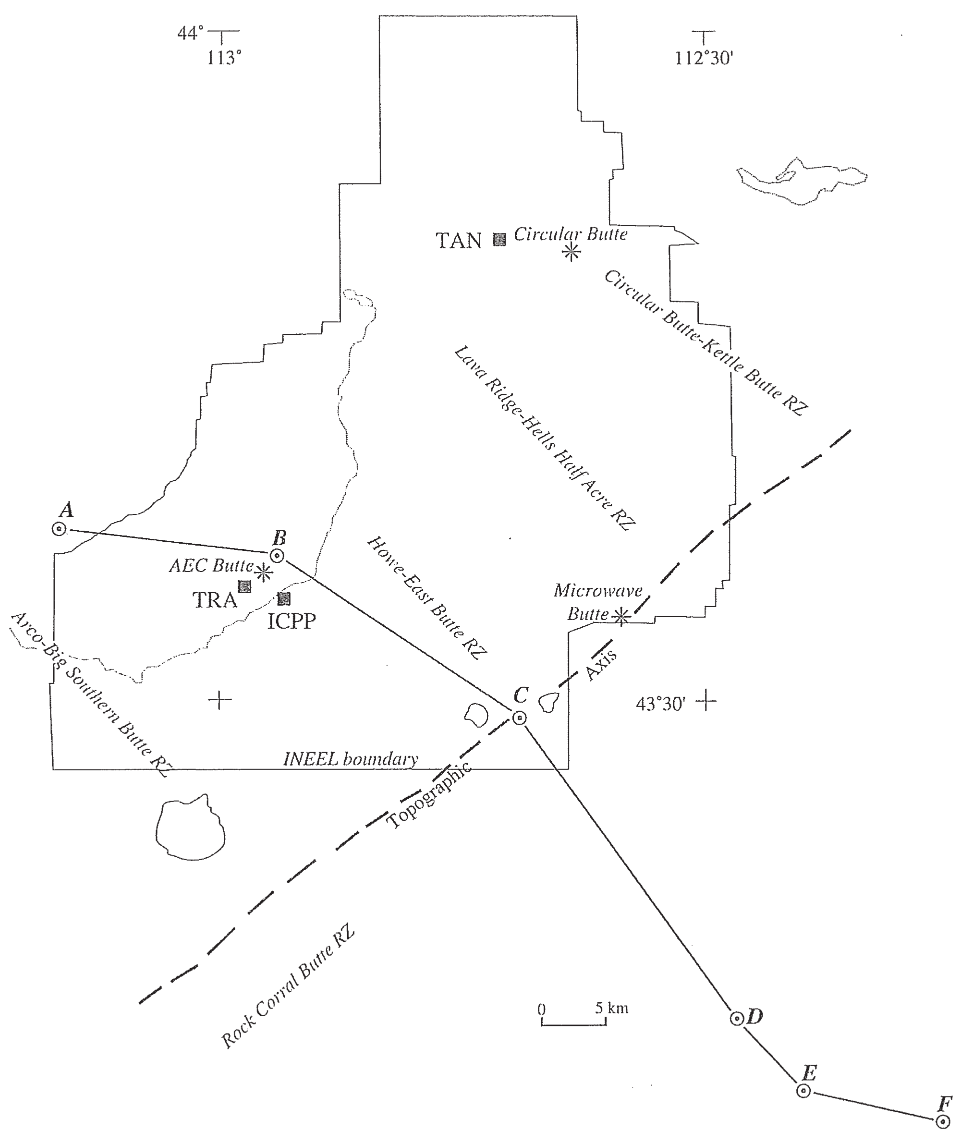

Figure 2. Map of part of eastern Snake River Plain at and near Idaho National Engineering and Environmental Laboratory (INEEL) showing geologic and geographic features referred to in text. Line A-F shows location of cross section in Figure 17. TAN, Test Area North; ICPP, Idaho Chemical Processing Plant; TRA, Test Reactor Area, RZ, rift zone.

ANALYTICAL TECHNIQUES

Each core hole was logged to establish tops and bottoms of individual lava flows, positions of sedimentary interbeds and unrecovered intervals, and generally to sample the cores for thin-section petrographic examination. Detailed petrographic descriptions were made of lava flows and flow units. Multiple paleomagnetic samples (typically seven for each flow or flow unit) were taken to establish mean remanent inclination values, and then compared one to another, assuming that lava flows of the same age share identical inclinations while lava flows of different ages typically have different mean inclinations or even different polarities. The inclination values were based on the assumption that each sampled core slug was vertical; this assumption can be tested using borehole deviation logs. The analytical techniques associated with the sampling, measurement, and demagnetization of basalt lava flow paleomagnetic specimens followed well-established protocols (Irving, 1964).

The K-Ar dating followed the established procedures of Dalrymple and Lanphere (1969). The application of those procedures to young basalts of very low potassium concentrations and the high success rate of our experiments merit some explanation. Careful thin-section evaluations were used to determine whether samples were suitable for dating (Mankinen and Dalrymple, 1972). The K_2O measurements were made in duplicate on each of two splits of powder by flame photometry (Ingamells, 1970). Argon mass analyses were done on a computerized multiple-collector mass spectrometer (described by Stacey et al., 1981). Weighted-mean ages for duplicate samples (some triplicate) were calculated by the method of Taylor (1982). These methods produced ages that stack well, generally in ascending age order with decreasing depth. In addition, ages from different core holes on flows correlated by petrography or remanent magnetization are the same, within analytical uncertainty.

Some basalt samples were also analyzed by the $^{40}Ar/^{39}Ar$ technique, which employs the radioactive decay of ^{40}K to ^{40}Ar as a chronometer in a different way (Dalrymple and Lanphere, 1971, 1974; Lanphere and Dalrymple, 1971). In the $^{40}Ar/^{39}Ar$ method, the sample is irradiated with fast neutrons, along with a monitor mineral of known age, to induce the reaction $^{39}K(n, p)^{39}Ar$. The age of the sample is calculated from the measured $^{40}Ar/^{39}Ar$ ratio after determining the fraction of ^{39}K converted to ^{39}Ar by analyzing the monitor mineral. The important difference between the two methods is that while quantitative measurements of the contents of radiogenic ^{40}Ar and ^{40}K are required by the conventional method, for the $^{40}Ar/^{39}Ar$ method only the ratios of Ar isotopes are measured. There is currently a widespread mistaken belief that $^{40}Ar/^{39}Ar$ dating has rendered conventional K-Ar dating obsolete. A direct comparison of the two dating techniques (Lanphere, 2000) finds consistency between ages determined by the two techniques. Whereas the mean K-Ar and $^{40}Ar/^{39}Ar$ ages are statistically identical, the precision of individual $^{40}Ar/^{39}Ar$ ages is generally better than the precision of K-Ar ages.

Accumulation rates were calculated from graphs of age of lava flows plotted against depth. A linear regression was fitted to the depth versus age data points, yielding the accumulation rate and regression coefficient, R.

CORE DESCRIPTIONS

Because most of the following cores have been described previously (Lanphere et al., 1993, 1994; Champion et al., 1988, 1981; Champion and Lanphere, 1997; Kuntz et al., 1980; Doherty, 1979), this section includes only information specific to the discussion of accumulation rates; i.e., the number of eruptive events, their K-Ar and $^{40}Ar/^{39}Ar$ ages, and thicknesses. In some cases, age information has improved since the original reports, either through the acquisition of new ages or by averaging multiple ages from what we have later learned to be the same flow in adjacent core holes. A diagram (Fig. 3) shows the locations of core holes examined for this study, and Tables 1–4 contain the detailed data pertinent to our study of lava flow and sediment accumulation through time. In addition, data on lava flow thicknesses and recurrence intervals are given in Tables 1–4 for use in a later discussion concerning volcanic hazards.

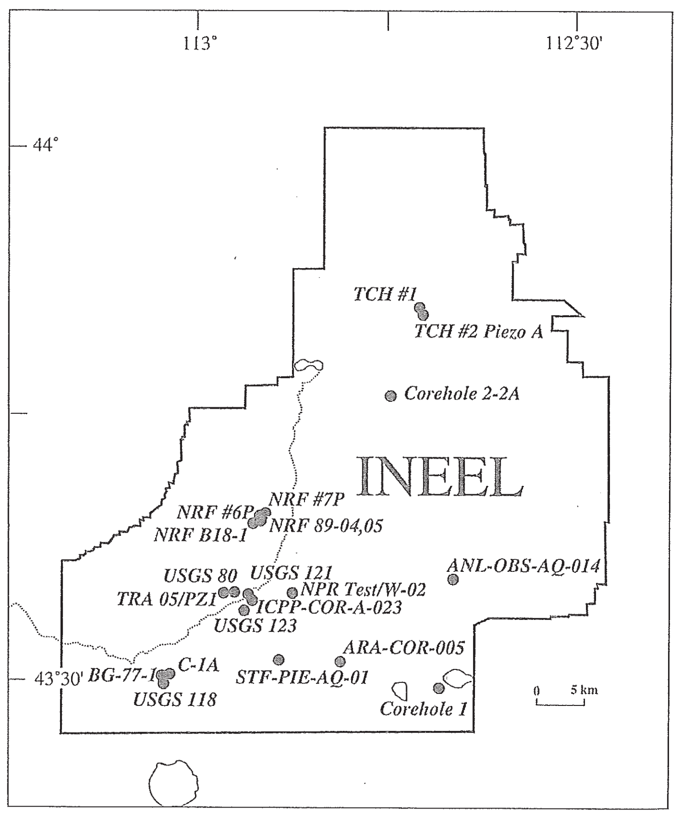

Figure 3. Map of Idaho National Engineering and Environmental Laboratory (INEEL) showing locations of core holes examined for this study (see text for designations).

TABLE 1. AGE, RECURRENCE INTERVAL, DEPTH AND THICKNESS DATA FOR LAVA FLOWS SAMPLED BY DRILL CORES NEAR FACILITIES IN THE SOUTH-CENTRAL PART OF THE INEEL*

Flow number	Age (ka)	Recurrence interval (1 k.y.)	Flow top depth (m/*ft*)	Thickness (m/*ft*)
USGS 80		*419+*		
1	419 ± 33	(−5)	13/*44′*	9/*29′*
2	[414 ± 8]	161	23/*76′*	18/*60′*
3	(575)	62	44/*144′*	5/*18′*
4	[637 ± 35]	—	54/*177′*	8/*27′* +
USGS 123		*229+*		
1	[229 ± 28]	73	10/*34′*	23/*74′*
2	(302)	4	34/*113′*	1/*4′*
3	(306)	44	36/*118′*	11/*36′*
4	[350 ± 40]	26	50/*163′*	13/*43′*
5	(376)	30	64/*209′*	12/*39′*
6	(406)	55	76/*248′*	9/*31′*
7	[461 ± 35]	30	87/*284′*	29/*98′*
8	[491 ± 80]	52	116/*382′*	12/*38′*
9	(543)	56	129/*424′*	22/*73′*
10	(599)	18	151/*497′*	4/*12′*
11	[617 ± 22]	20	155/*509′*	17/*55′*
12	[637 ± 35]	112	172/*564′*	37/*123′*
13	(749)	26	211/*691′*	10/*33′*
14	(775)	—	221/*724′*	5/*17′*
NPR Test/W-02		*229+*		
1	[229 ± 28]	82	2/*7′*	29/*96′*
2	(311)	39	34/*112′*	6/*21′*
3	350 ± 40	71	41/*136′*	33/*107′*
4	(421)	40	81/*267′*	9/*30′*
5	[461 ± 35]	30	92/*303′*	29/*96′*
6	491 ± 80	59	129/*424′*	10/*32′*
7	[550 ± 10]	67	139/*456′*	11/*35′*
8	[617 ± 22]	20	150/*492′*	20/*65′*
9	[637 ± 35]	—	182/*596′*	30/*98′*†
10	B/M-780 ± 5		216–234/*710–768′*	
ICPP-COR-A-023		*229+*		
1	[229 ± 28]	62	12/*41′*	16/*51′*
2	(291)	29	28/*92′*	3/*9′*
3	(320)	30	38/*126′*	5/*18′*
4	[350 ± 40]	22	52/*170′*	4/*12′*
5	(372)	89	57/*188′*	5/*18′*
6	[461 ± 35]	57	63/*206′*	46/*152′*
7	(518)	(−27)	110/*360′*	3/*10′*
8	[491 ± 80]	125	113/*371′*	6/*19′*
9	[616 ± 61]	(−6)	119/*390′*	24/*78′*
10	(610)	55	143/*468′*	19/*61′*
11	(665)	(−28)	162/*533′*	2/*7′*
12	[637 ± 35]	144	165/*540′*	40/*131′*
13	(781)	(−22)	205/*671′*	6/*21′*
14	[759 ± 12]	—	211/*692′*	14/*47′*
USGS 121		*77+*		
1	77 ± 39	—	10/*34′*	6/*19′*
2	—	—	16/*53′*	12/*39′*
3	—	—	28/*92′*	7/*22′*
4	—	—	35/*114′*	5/*16′*
5	376 ± 81	30	41/*134′*	16/*54′*

(*continued on next page*)

USGS 80

The stratigraphy, petrography, age, and paleomagnetic inclination stratigraphy of flows in core hole USGS 80 were originally reported by Lanphere et al. (1993), who found four lava flows of normal polarity to a depth of 62 m (Fig. 4; Table 1). Pairs of K-Ar ages on three of the flows define an ~220 k.y. span, from 637 to 419 ka. Anderson et al. (1997) fit the age versus depth data with a regression line of high correlation (R = 0.998), yielding an accumulation rate of ~18 m/100 k.y. Additional age measurements have altered the accumulation-rate calculation. Flow #2 is paleomagnetically and petrograph-

TABLE 1. AGE, RECURRENCE INTERVAL, DEPTH AND THICKNESS DATA FOR LAVA FLOWS SAMPLED BY DRILL CORES NEAR FACILITIES IN THE SOUTH-CENTRAL PART OF THE INEEL* (*continued*)

Flow number	Age (ka)	Recurrence interval (1 k.y.)	Flow top depth (m/*ft*)	Thickness (m/*ft*)
USGS 121 (continued)		*77+*		
6	(406)	55	57/*188'*	17/*56'*
7	[461 ± 35]	82	76/*248'*	23/*76'*
8	543 ± 48	(−52)	99/*324'*	21/*68'*
9	[491 ± 80]	125	126/*412'*	2/*6'*
10	616 ± 61	(−12)	129/*422'*	14/*46'*
11	(604)	41	143/*468'*	16/*54'*
12	(645)	(−8)	160/*525'*	5/*15'*
13	[637 ± 35]	51	165/*540'*	14/*46'*
14	(688)	12	179/*586'*	5/*16'*
15	(700)	29	184/*603'*	12/*41'*
16	(729)	30	196/*644'*	18/*60'*
17	759 ± 12	—	215/*704'*	9/*30'*
TRA 05/PZ1		*365+*		
1	(365)	49	21/*69'*	5/*18'*
2	[414 ± 8]	120	27/*89'*	19/*61'*
3	(534)	59	47/*155'*	5/*15'*
4	(593)	44	56/*185'*	6/*21'*
5	[637 ± 35]	149	67/*220'*	16/*54'*
6	786 ± 23	—	84/*276'*	6/*21+*
ANL-OBS-AQ-014				
1			0/*1'*	15/*50'*
2			16/*51'*	3/*12'*
3	358 ± 46		19/*63'*	35/*115'*
4			55/*181'*	24/*80'*
5			80/*261'*	33/*110'*
6			113/*372'*	9/*29'*
7			122/*400'*	12/*40'*
8	565 ± 94		134/*440'*	37/*122'*
ARA-COR-005				
1	[229 ± 28]		3/*10'*	26/*85'*
2			30/*98'*	26/*86'*
3			56/*185'*	2/*6'*
4			59/*193'*	57/*187'*
5			116/*380'*	19/*61'*
6			135/*443'*	5/*15'*
7			140/*458'*	43/*142'*
8			183/*602'*	20/*64'*
9			202/*666'*	14/*46'*
10	[550 ± 10]		217/*712'*	16/*53'*
STF-PIE-AQ-01				
1			6/*20'*	16/*52'*
2	[229 ± 28]		26/*84'*	16/*54'*
3			43/*141'*	13/*43'*
4			56/*184'*	6/*21'*
5			63/*208'*	26/*86'*
6			90/*295'*	69/*228'*
7	[550 ± 10]		166/*543'*	30/*100'*

Note: Ages in square brackets from another core, or from averaging ages in multiple cores; ages in parentheses derived from accumulation rate line fits; negative recurrence intervals in parentheses due to errors in age determinations or in line fits to same data.
*INEEL—Idaho National Engineering and Environmental Laboratory.
†Thickness of flow 9, core hole NPR-Test derived from basal depth estimate in adjacent core W-02.

ically correlated with flow #2 in adjacent well TRA-05, and the pooled age estimate from the original K-Ar and new $^{40}Ar/^{39}Ar$ ages is 414 ± 8 ka, substantially younger than the original estimate of 461 ± 24 ka. Flow #4, which is correlated with flows from AEC Butte, also has a different age than originally presented; averaging two pairs of K-Ar ages from wells USGS 80 and USGS 123 and one pair of ages from a nearby surface outcrop yields a slightly younger age of 637 ± 35 ka instead of 643 ± 64 ka. These revised ages decrease the accumulation rate for this core hole to 16 m/100 k.y. and lower the regression slightly (Fig. 4), but do not significantly alter conclusions regarding accumulation rates.

USGS 123

The stratigraphy, petrography, age, and paleomagnetic inclination stratigraphy of core hole USGS 123 were reported by Lanphere et al. (1993), who found 14 lava flows of normal polarity to a depth of 226 m (Fig. 5; Table 1). Pairs of K-Ar ages on five of the flows defined an ~550 k.y. span, from 775 to 229 ka. Petrographic and paleomagnetic correlations of numerous lava flows in USGS 123 to flows in core hole NPR Test (Fig. 1) allow ages in NPR Test to be pooled with ages from USGS 123, yielding six points of accumulation-rate measure. The accumulation rate is 39 m/100 k.y.; the linear regression coefficient is 0.994.

NPR Test/W-02

The stratigraphy, age, and paleomagnetic inclination stratigraphy of core hole NPR Test (where NPR refers to New Production Reactor) were reported by Champion et al. (1988), who found eight lava flows of normal polarity, and one of reversed polarity (Big Lost Reversed Polarity Subchron of the Brunhes Normal Polarity Chron) to a depth of 186 m (Fig. 6; Table 1). A detailed description of the petrography of the core hole was provided by Morgan (1990), who divided the uppermost flow into three flow units, raising the overall flow count to 11. Four pairs of K-Ar ages, one set of four K-Ar ages, and one single K-Ar age for six flows, provide age control and define an ~500 k.y. span, from 637 to 229 ka. In addition, core hole W-02, located only 100 m from NPR Test, includes the Matuyama Reversed Polarity Chron–Brunhes Normal Polarity Chron boundary (hereafter referred to as the Brunhes-Matuyama boundary) between the top of reversed polarity flows at 234 m and the base of normal polarity flows at 216 m. Petrographic and paleomagnetic correlation of numerous lava flows in these core holes with flows in core hole USGS 123 allows age data in that well to be pooled with ages in NPR Test and W-02 to yield seven points of accumulation-rate measure. The accumulation rate is 43 m/100 k.y.; the high regression coefficient is 0.984.

ICPP-COR-A-023

The stratigraphy, hand-specimen petrography, and paleomagnetic inclination stratigraphy of flows in core hole ICPP-023 (where ICPP stands for Idaho Chemical Processing Plant) is reported on by Jobe and Champion (2002), who describe 14 lava flows of normal polarity to a depth of 225 m (Fig. 7; Table 1). Although no K-Ar ages have been measured on this core, correlations of flows in ICPP-023 with flows in adjacent core holes (USGS 121 and USGS 123) together with paleomagnetic and petrographic data allow ages to be assigned to seven flows. The ages define an ~530 k.y. span, from 759 to 229 ka. The accumulation rate is 36 m/100 k.y., and the linear regression coefficient is 0.964. The lower coefficient of regression suggests errors in the dates, or possibly in correlations of flows from other wells.

TABLE 2. AGE, RECURRENCE INTERVAL, DEPTH AND THICKNESS DATA FOR LAVA FLOWS SAMPLED BY DRILL CORES NEAR THE NAVAL REACTOR FACILITY (NRF) AT THE IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY

Flow number	Age (ka)	Recurrence interval (1 k.y.)	Flow top depth (m/*ft*)	Thickness (m/*ft*)
NRF 89-04		*303+*		
1	[303 ± 30]	92	6/*21′*	26/*85′*
2	[395 ± 25]	126	36/*119′*	22/*71′*
3	521 ± 31	25	60/*196′*	7/*22′*
4	[546 ± 47]	—	67/*221′*	8/*27′* +
NRF 89-05		*303+*		
1	303 ± 30	92	6/*21′*	26/*86′*
2	[395 ± 25]	97	36/*118′*	23/*76′*
3	492 ± 56	29	60/*196′*	3/*12′*
4	521 ± 31	—	63/*208′*	10/*34′* +
NRF B18-1		*303+*		
1	[303 ± 30]	92	11/*35′*	16/*53′*
2	[395 ± 25]	97	27/*88′*	31/*102′*
3	[492 ± 56]	29	58/*190′*	10/*34′*
4	[521 ± 31]	—	68/*224′*	8/*27′* +
NRF #6P		*303+*		
1	[303 ± 30]	92	3/*11′*	24/*78′*
2	395 ± 25	126	27/*89′*	23/*76′*
3	[521 ± 31]	25	50/*165′*	14/*45′*
4	546 ± 47	181	64/*210′*	44/*143′*
5	727 ± 31	157	108/*354′*	29/*64′*
6	[884 ± 53]	—	127/*418′*	25/*83′* +
NRF #7P		*303+*		
1	[303 ± 30]	92	7/*25′*	20/*67′*
2	[395 ± 25]	126	32/*105′*	14/*46′*
3	[521 ± 31]	25	46/*152′*	6/*20′*
4	[546 ± 47]	181	52/*172′*	56/*184′*
5	[727 ± 31]	*(53)*	109/*358′*	13/*44′*
6	<780	*(104)*	123/*404′*	6/*21′*
7	884 ± 53	—	130/*428′*	22/*73′* +

Note: Ages in square brackets from another core, or from averaging ages in multiple cores; depths in parentheses from limiting age data in core hole NRF #7P.

USGS 121

The lithology and paleomagnetic inclination stratigraphy of core hole USGS 121 are reported by Jobe and Champion (2002), who describe 17 lava flows of normal polarity to a depth of 227 m (Fig. 8; Table 1). A single K-Ar age and four $^{40}Ar/^{39}Ar$ ages, as well as three K-Ar ages correlated from adjacent wells, establish a set of eight age and depth measures. The data define lava flow accumulation for the entire span of the Brunhes Normal Polarity Chron, ~780 k.y. The age versus depth graph displays a distinct "dog leg" in the upper 35 m of the well (not shown in Fig. 8), reflecting an interval of slower accumulation. An accumulation rate of 43 m/100 k.y., and a regression coefficient of 0.953, is derived for the majority of the core hole. This somewhat lower regression coefficient may reflect errors in the ages, or possibly in the correlations of flows from other wells.

TABLE 3. AGE, RECURRENCE INTERVAL, DEPTH AND THICKNESS DATA FOR LAVA FLOWS SAMPLED BY DRILL CORES NEAR THE RADIOACTIVE WASTE MANAGEMENT COMPLEX (RWMC) AT THE IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY

Flow number	Age (ka)	Recurrence interval (1 k.y.)	Flow top depth (m/*ft*)	Thickness (m/*ft*)
BG 77-1		*95+*		
1	95 ± 50	37	1/*4'*	12/*41'*
2	(132)	79	16/*51'*	16/*51'*
3	211 ± 16	19	32/*105'*	38/*126'*
4	230 ± 85	*(285)*	77/*252'*	10/*33'*
5	515 ± 85	35	88/*288'*	23/*76'*
6	550 ± 10	—	112/*367'*	57/*188'*
7	—	—	170/*557'*	13/*43'* +
C-1A		*95+*		
1	95 ± 50	25	2/*8'*	9/*28'*
2	(120)	91	11/*36'*	23/*75'*
3	211 ± 16	19	34/*111'*	36/*118'*
4	230 ± 85	(—)	73/*239'*	15/*50'*
5	—	(—)	89/*293'*	12/*39'*
6	515 ± 85	35	101/*333'*	20/*64'*
7	550 ± 10	133	121/*397'*	48/*158'*
8	(683)	37	173/*569'*	15/*50'*
9	(720)	19	189/*620'*	7/*25'*
10	(739)	41	197/*645'*	16/*53'*
11	B/M-780 ± 5	—	213/*700'*	—
USGS 118				
1	<180	—	4/*14'*	28/*92'*
2	211 ± 16	(—)	34/*112'*	34/*112'*
3	—	(—)	76/*250'*	4/*13'*
4	—	(—)	81/*265'*	10/*33'*
5	515 ± 85	35	91/*300'*	25/*81'*
6	550 ± 10	—	116/*381'*	57/*186'*

Note: Ages in parentheses derived from accumulation rate line fits; recurrence intervals in parentheses represent hiatuses in accumulation.

TRA 05/PZ1

In core hole TRA 05/PZ1, six lava flows of normal polarity occur to a depth of 91 m (Fig. 9; Table 1). The K-Ar ages on three lava flows, redating by $^{40}Ar/^{39}Ar$ on two of the flows, and correlation of lava flows to those in well USGS 80 define an ~400 k.y. span, from 786 to 365 ka. The three points of age control define an accumulation rate of 16 m/100 k.y., and a high regression coefficient of 0.994.

STF-PIE-AQ-01

There is no report on the stratigraphy, petrography, age, and paleomagnetism of a 218 m core hole drilled at the Safety Test Facility (STF). Paleomagnetic studies have designated nine lava flows; thicknesses and depths to tops of flows are listed (Table 1). A preliminary accumulation rate for the upper seven lava flows can be derived from age information correlated to this core hole for flows #2 and #7. Flow #2 can be paleomagnetically correlated with the top flow in core holes NPR Test/W-02 and USGS 123. The weighted mean K-Ar age of these two flows is 229 ± 28 ka. Flow #7 is part of the sequence of flow units of the Big Lost Reversed Polarity Subchron, which has an age of 550 ± 10 ka (Champion et al., 1996). The age and depth data suggest an average accumulation rate of 50 m/100 k.y. for this core hole.

ARA-COR-005

There is no report on the stratigraphy, petrography, age, and paleomagnetism of a 261 m core hole drilled at the Auxiliary Reactor Area (ARA). Paleomagnetic studies have designated 11 lava flows; thicknesses and depths to tops of flows are listed in Table 1. A preliminary accumulation rate for the upper 10 flows can be derived from age information correlated to this core hole for flows #1 and #10. Flow #1 can be correlated with the top flows in core holes NPR Test, W-02, and USGS 123 that have a weighted mean K-Ar age of 229 ± 28 ka. Flow #10 is one of the sequence of flow units of the Big Lost Reversed Polarity Subchron, which has an age of 550 ± 10 ka (Champion et al., 1996). The age versus depth data suggest an average accumulation rate of 67 m/100 k.y. for this location.

ANL-OBS-AQ-014

The age and paleomagnetic inclination stratigraphy of core hole ANL-OBS-AQ-014 were reported by Champion and Lanphere (1997), who described 27 lava flows of both normal and reversed polarity to a depth of 582 m. Four $^{40}Ar/^{39}Ar$ ages and one K-Ar age (Kuntz et al., 1994) suggest a history of alternating fast and slow accumulation at this location close to the central axis of the eastern Snake River Plain. Until more age information and petrographic details are available for this core hole, a detailed accumulation analysis is premature. A preliminary accumulation rate for the majority of the Brunhes Normal Polarity Chron lava flows can be derived from the ages of 358 ± 46 ka for flow #3 and 565 ± 94 ka for flow #8 (Table 1). The age and depth data suggest an average mid-Brunhes Normal Polarity Chron accumulation rate of 56 m/100 k.y.

NRF core holes

The stratigraphy, petrography, age and paleomagnetic inclination stratigraphy of two core holes at the Naval Reactor Facility (NRF) (Fig. 3) were reported by Lanphere et al. (1993). They found five lava flows of normal polarity in the NRF 89-04 and NRF 89-05 core holes to depths of 76 m and 74 m, respectively. Other core holes in and near the facility, NRF B18-1, NRF #6P, and NRF #7P, have now been studied by paleomagnetic inclination methods and $^{40}Ar/^{39}Ar$ ages have been obtained on five flows (Table 2). Ages have been measured on virtually all lava flows within the shared section in core holes NRF #6P and NRF #7P. The horizontal separation of the different core holes is only 1000 m, so they can be interpreted with a single accumulation rate for a single location. Core holes NRF #6P (Fig. 10A) and NRF #7P (Fig. 10B) were both cored

TABLE 4. AGE, RECURRENCE INTERVAL, DEPTH AND THICKNESS DATA FOR LAVA FLOWS SAMPLED BY DRILL CORES NEAR TEST AREA NORTH (TAN) AT THE IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY

Flow number	Age (Ma)	Recurrence interval (1 k.y.)	Flow top depth (m/*ft*)	Thickness (m/*ft*)
TCH #1		*1.09+*		
1	1.09 ± 0.09	0.06	13/*44'*	8/*26'*
2	(1.15)	0.10	21/*70'*	10/*34'*
3	1.25 ± 0.07	0.07	32/*104'*	37/*121'*
4	1.32 ± 0.02	0.26	69/*226'*	53/*175'*
5	1.58 ± 0.06	(0.42)	126/*412'*	9/*31'*
6	2.00 ± 0.06	0.12	137/*448'*	29/*96'*
7	2.12 ± 0.05	—	166/*544'*	17/*56'* +
TCH #2 Piezo A		*1.09+*		
1	1.09 ± 0.09	0.06	14/*47'*	9/*28'*
2	(1.15)	0.10	23/*75'*	18/*59'*
3	1.25 ± 0.07	0.07	41/*134'*	32/*105'*
4	1.32 ± 0.02	0.09	75/*247'*	61/*201'*
5	1.41 ± 0.05	(0.59)	138/*452'*	5/*17'*
6	2.00 ± 0.06	0.12	144/*473'*	34/*111'*
7	2.12 ± 0.05	0.40	179/*586'*	45/*147'*
8	2.52 ± 0.03	—	226/*742'*	107/*351'*
9			336/*1102'*	4/*12'* +
Corehole 2-2A				
1	*{Brunhes Chronozone}*		~3/*10'*	~17/*55'*
2	*{top of Matuyama*		76/*249'*	~16/*54'*
3	*Chronozone}*		~97/*319'*	~12/*41'*
4			120/*393'*	2/*7'*
5	*{Jaramillo*		124/*407'*	7/*22'*
6	*Subchronozone}*		131/*431'*	12/*38'*
7			144/*471'*	8/*28'*
8			152/*499'*	7/*22'*
9			159/*521'*	11/*37'*
10			170/*559'*	21/*69'*
11			194/*636'*	18/*58'*
12			212/*697'*	9/*28'*
13			226/*742'*	11/*35'*
14			237/*778'*	22/*71'*
15			273/*895'*	6/*21'*
16			280/*918'*	6/*19'*
17			287/*942'*	5/*16'*
	{Olduvai Subchronozone}			
18			350/*1147'*	22/*73'*
19			372/*1220'*	8/*28'*
20	2.45 ± 0.03		380/*1248'*	18/*60'*
21			399/*1308'*	4/*13'*
22			403/*1322'*	5/*15'*
23	*{approx. top of Gauss*		~477/*1564'*	~10/*33'*
24	*Chronozone}*		487/*1598'*	8/*26'*
25	*{Kaena Subchronozone}*		~541/*1775'*	~1/*3'*
26	3.26 ± 0.06		581/*1906'*	13/*43'*

Note: Ages in parentheses derived from accumulation rate line fits; recurrence intervals in parentheses represent hiatuses in accumulation; approximate depths and thicknesses in 2-2A from unrecovered cored intervals.

to 153 m, deeper than the other NRF core holes, and have six and seven identified lava flows, respectively. The two core holes bottom in a reversed polarity lava flow, and thus have the most complete record of accumulation rate. All five core holes share similar accumulation rates, between 22 m and 27 m/100 k.y.; the shallowest and most southerly core holes record the higher rates.

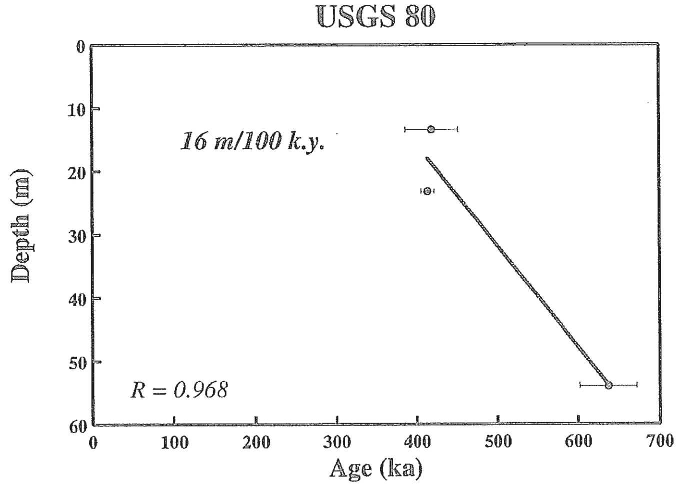

Figure 4. Graph of ages of lava flows plotted against depths to flow tops in core hole USGS 80 from Idaho National Engineering and Environmental Laboratory. One-sigma errors are plotted for age determinations, but small uncertainties in depth to tops of lava flows not shown. Accumulation rate in m/100 k.y. is calculated by straight line fit through data points; regression coefficient is also shown.

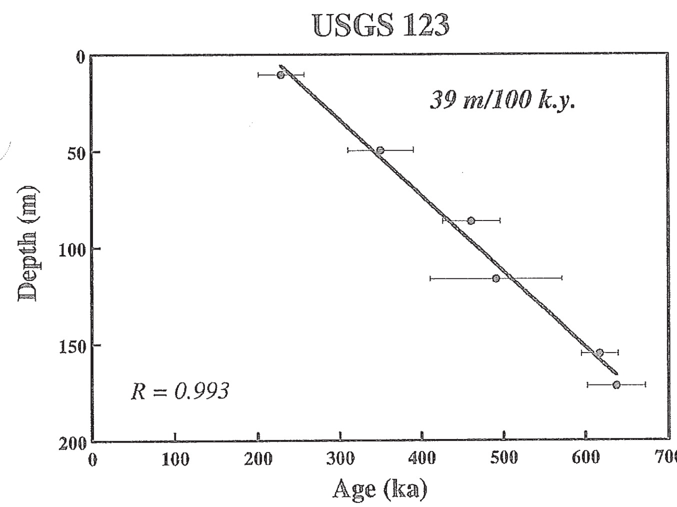

Figure 5. Graph of ages of lava flows plotted against depths to flow tops in core hole USGS 123 from Idaho National Engineering and Environmental Laboratory. Data are as in Figure 4.

Radioactive Waste Management Complex core holes

The stratigraphy, petrography, age, and paleomagnetic inclination stratigraphy of core hole BG-77-1 were reported by Kuntz et al. (1980) and Champion et al. (1981), who found seven lava flows, six having normal polarity and one having reversed polarity, to a depth of 183 m (Fig. 11; Table 3). The single reversed polarity flow, situated within the normal polarity lava flows, was initially miscorrelated with the Emperor Reversed Polarity Subchron of the Brunhes Normal Polarity Chron, but later identified as a new polarity event, the Big Lost

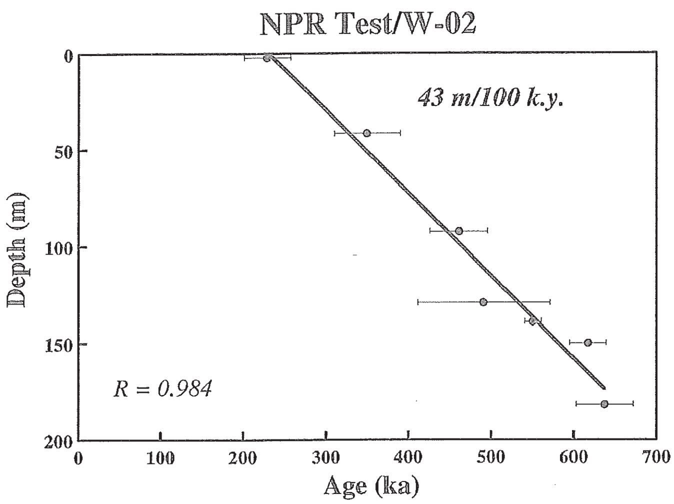

Figure 6. Graph of ages of lava flows plotted against depths to flow tops in core holes NPR Test and W-02 from Idaho National Engineering and Environmental Laboratory. Data are as in Figure 4.

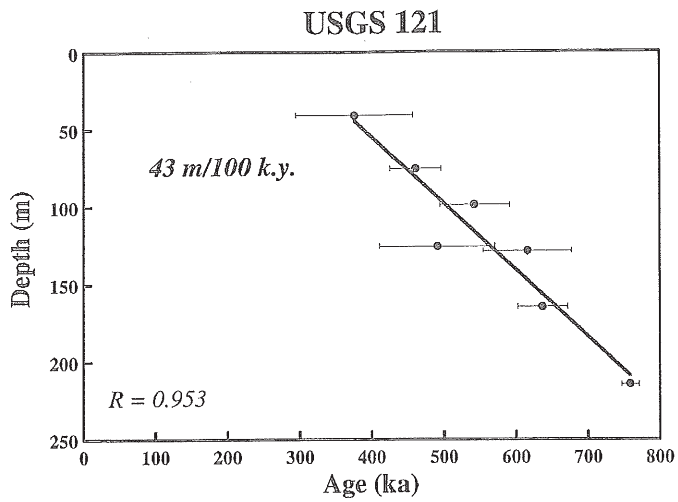

Figure 8. Graph of ages of lava flows plotted against depths to flow tops in core hole USGS 121 from Idaho National Engineering and Environmental Laboratory INEEL. Data are as in Figure 4. Data point at 77 ka is not plotted nor used in linear regression.

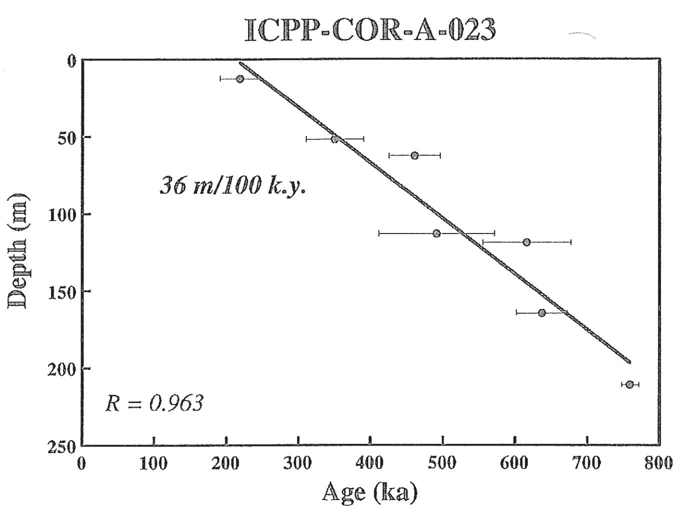

Figure 7. Graph of ages of lava flows plotted against depths to flow tops in core hole ICPP-COR-A-023 from Idaho National Engineering and Environmental Laboratory. Data are as in Figure 4.

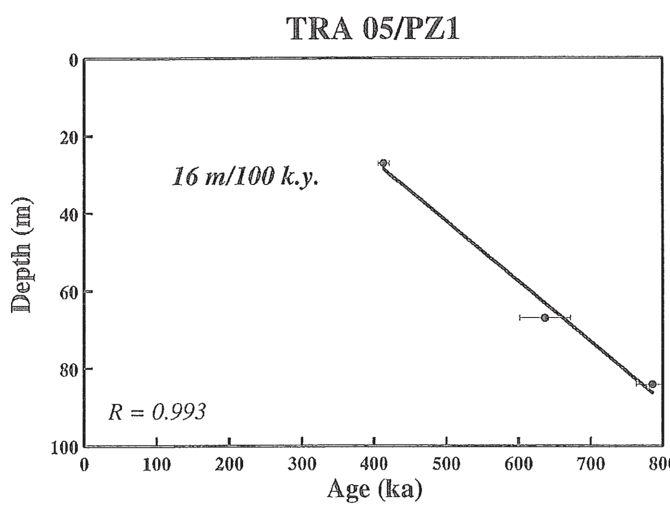

Figure 9. Graph of ages of lava flows plotted against depths to flow tops in core hole TRA 05/PZ1 from Idaho National Engineering and Environmental Laboratory. Data are as in Figure 4.

Reversed Polarity Subchron (Champion et al., 1988). The event was assigned an age of 565 ± 14 ka on the basis of K-Ar dating, but subsequent $^{40}Ar/^{39}Ar$ dating improved the age assignment to 550 ± 10 ka (Champion et al., 1996). Core hole BG-77-1 is near the Radioactive Waste Management Complex (RWMC) of the INEEL (Fig. 3). Like the Naval Reactor Facility area, dozens of wells have been drilled and cored to various depths in the vicinity of that facility. We have analyzed results from three of the deeper core holes, BG-77-1, C-1A, and USGS 118, that form a short north-south transect across the RWMC. These three core holes sample the same stratigraphic interval with minor variations. The Matuyama-Brunhes boundary in core hole C-1A occurs at a depth of about 213 m at the boundary between reversed and normal polarity flows (Fig. 12; Table 3). As many as six age versus depth pairs can be assigned to flows in these core holes, and accumulation rates can be calculated. Accumulation rates range between 20 m and 28 m/100 k.y. and have relatively low regression coefficients. The low (<0.95) coefficients of regression suggest these are apparent accumulation rates, to use a term coined by Anderson et al. (1997) to reflect hiatuses related to vent construction, periods of decreased volcanism, and differential subsidence and uplift. In particular, a hiatus was recognized at the ~90 m level in many RWMC wells by Anderson and Lewis (1989), and they assigned a duration of 285 k.y. to the hiatus based on flow ages in Champion et al. (1981). Consequently, we fit the ages to

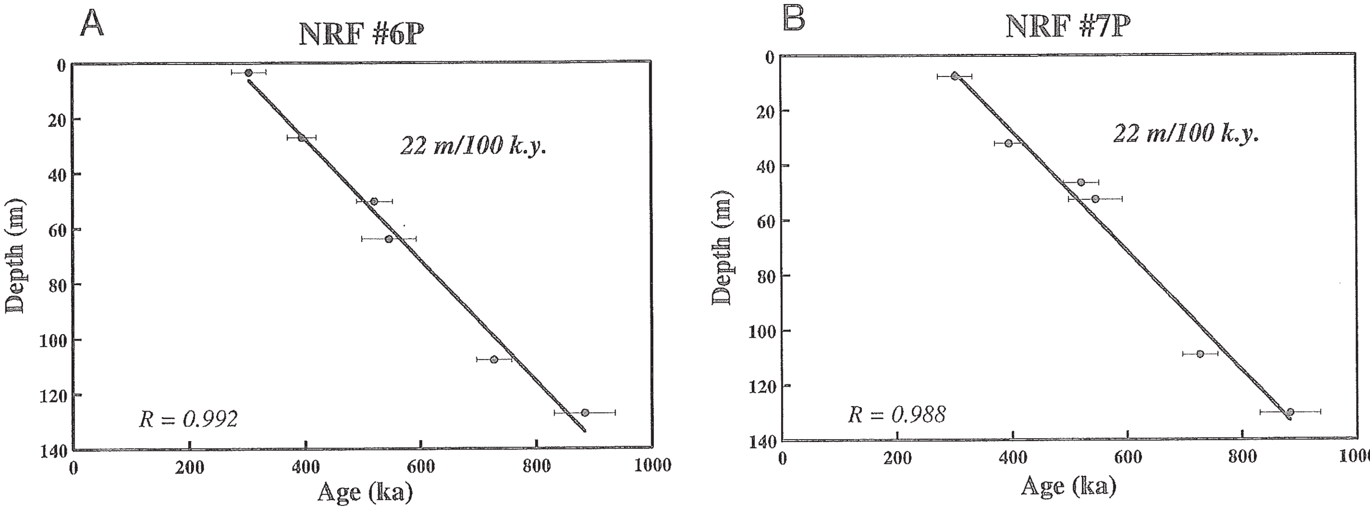

Figure 10. A: Graph of ages of lava flows plotted against depths to flow tops in core hole NRF #6P from Naval Reactor Facility (NRF) of Idaho National Engineering and Environmental Laboratory. B: Graph of ages of lava flows plotted against depths to flow tops in core hole NRF #7P. Data are as in Figure 4.

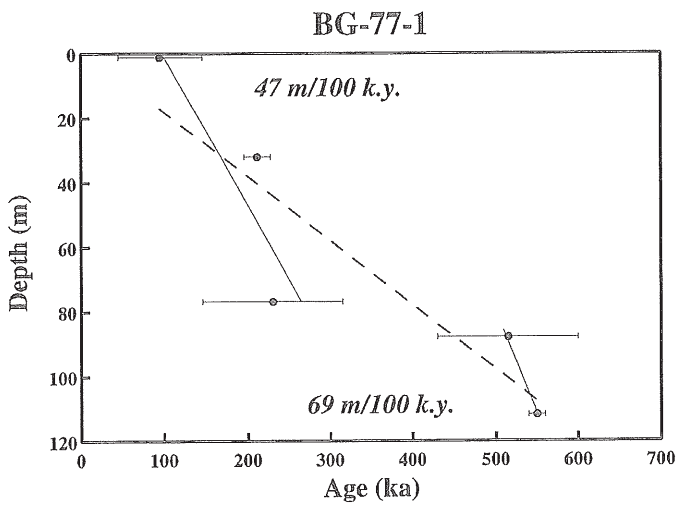

Figure 11. Graph of ages of lava flows plotted against depths to flow tops in core hole BG-77-1 at the Radioactive Waste Management Complex. Accumulation rate calculated without consideration of a hiatus between flows 4 and 5 shown as dashed line, accumulation rates calculated with a hiatus between those flows shown as two solid lines. Data shown as in Figure 4.

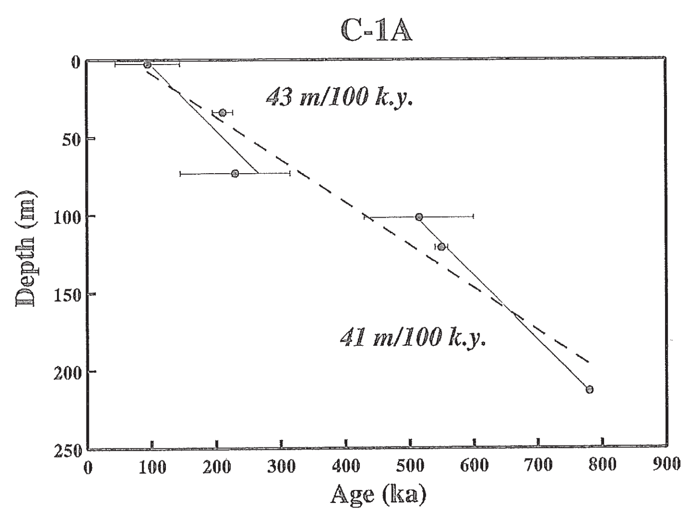

Figure 12. Graphs of ages of lava flows plotted against depths to flow tops in core hole C-1A at Radioactive Waste Management Complex. Accumulation rate calculated without consideration of hiatus between flows 4 and 6 is shown as dashed line; accumulation rates calculated with hiatus between those flows is shown as two solid lines. Data are as in Figure 4.

separate regression lines above and below the hiatus. Data from core hole C-1A define accumulation rates of 41 m/100 k.y. and 43 m/100 k.y. below and above the hiatus interval, respectively (Fig. 12).

TCH #1

The stratigraphy, petrography, age, and paleomagnetic inclination stratigraphy of core hole TCH #1 were reported by Lanphere et al. (1994), who described 14 lava flows of reversed polarity to a depth of 183 m (Fig. 13; Table 4). Similar mean-inclination values and the absence of intercalated sediments indicate that the number of flows in the core hole is fewer than earlier reported, based on the presumption that a feature observed in the cores represents multiple flow units within each of several eruptive events. An accumulation rate of 14 m/100 k.y. is derived from the six dated flows in the core hole, but the regression coefficient of 0.95 suggests that this should be considered an apparent accumulation rate. Thus, rates of 24 m/100 k.y. calculated for the periods before and after a hiatus of 420

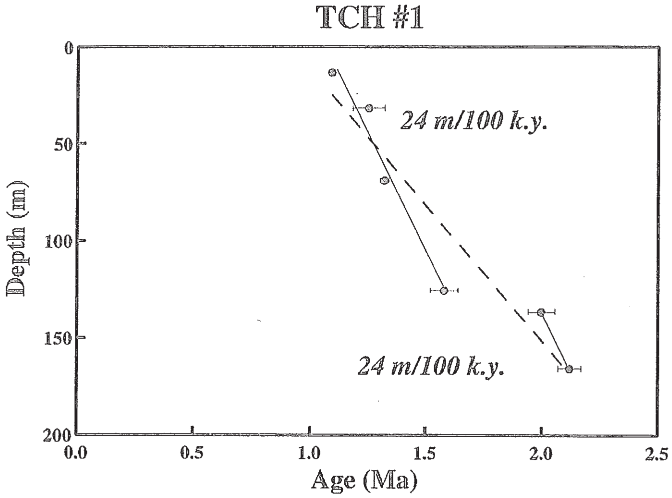

Figure 13. Graphs of age of lava flows plotted against depths to flow tops in core hole TCH #1 at Test Area North. Accumulation rate calculated without consideration of hiatus between flows 5 and 6 is shown as dashed line; accumulation rates calculated with hiatus between those flows are shown as two solid lines. Data are as in Figure 4.

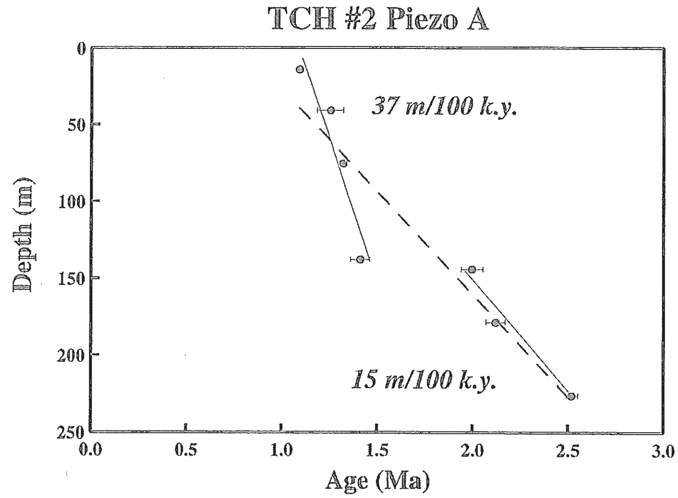

Figure 14. Graphs of ages plotted against depths to flow tops in core hole TCH #2 Piezo A at Test Area North. Accumulation rate calculated without consideration of hiatus between flows 5 and 6 is shown as dashed line; accumulation rates calculated with hiatus between those flows are shown as two solid lines. Data are as in Figure 4.

k.y. at a depth of ~137 m might be more realistic (Fig. 13). No flows of Brunhes age, younger than 780 ka, are known in the immediate TAN area. Normal polarity flows located just north of "TCH #1" and on top of the 1.09 Ma reversed polarity flows of Circular Butte are likely to have been erupted during the Jaramillo Normal Polarity Subchron of the Matuyama Reversed Polarity Chron, 1.07–1.0 Ma. It is unclear that the accumulation rates of the northern (TAN) INEEL area can be directly compared to the younger sections to the south.

TCH #2 Piezo A

The stratigraphy, petrography, age, and paleomagnetic inclination stratigraphy of core hole TCH #2 Piezo A were reported by Lanphere et al. (1994), who described 20 lava flows of reversed polarity to a depth of 340 m (Fig. 14; Table 4). Again, owing to similar mean-inclination values and the absence of intercalated sediments, fewer flows in the core have been interpreted on the presumption that some multiple flow units formed within each of several eruption events. A regression coefficient of 0.93 suggests that an accumulation rate of 13 m/100 k.y. derived from seven dated flows in the core hole (Fig. 14) is an apparent rate. Thus, a rate of 37 m/100 k.y., after a hiatus of 590 k.y. at a depth of ~137 m, preceded by a rate of 15 m/100 k.y. deeper in the core, are probably more realistic values (Fig. 14).

Core hole 2-2A

There is no detailed report on the stratigraphy, petrography, age, and paleomagnetism of the 915 m core hole 2-2A in the north-central part of the INEEL (Fig. 3). A general description of the stratigraphy of the core hole was produced by Doherty (1979). Core hole 2-2A is unique among the longer core holes at the INEEL in that more than one-third of the section consists of fine-grained lake and playa sediments that can span 100 m. The large amount of sediment in this core hole complicates the lava accumulation rate for the core hole. Preliminary paleomagnetic studies have designated 26 lava flows within the upper 604 m of the core. Paleomagnetic studies below this depth have been more cursory. Preliminary determination of flow thicknesses and depths to tops of flows are listed (Table 4). An accumulation rate for the top two-thirds of core hole 2-2A has been derived from a combination of four K-Ar ages on four lava flows within the core, the ages of flows correlated to the core hole, and the depths of magnetic polarity boundaries between lava flows (Fig. 15). These 11 points of age control yield an accumulation rate of 20 m/100 k.y., and a correlation coefficient of 0.998. This calculation of accumulation rate is different from that of the other data sets of this report in that the reported depths may have considerable error, whereas the ages may constitute proportionately a lower source of error. This results from the age being assigned to the top of a lava flow, so that for a thick flow the assigned depth may have a considerable uncertainty; instead of knowing that accumulation proceeded to a certain depth, we know that a polarity change of the magnetic field occurred at a particular time (±0.01 m.y.), but that no lava accumulation occurred between flows or while sediments accumulated. The accumulation rate for this core must be considered an apparent rate, averaging accumulation bursts and hiatuses into a longer term rate. It is remarkable, however, that the accumulation of lavas at this location progressed rather smoothly for nearly 5 m.y.

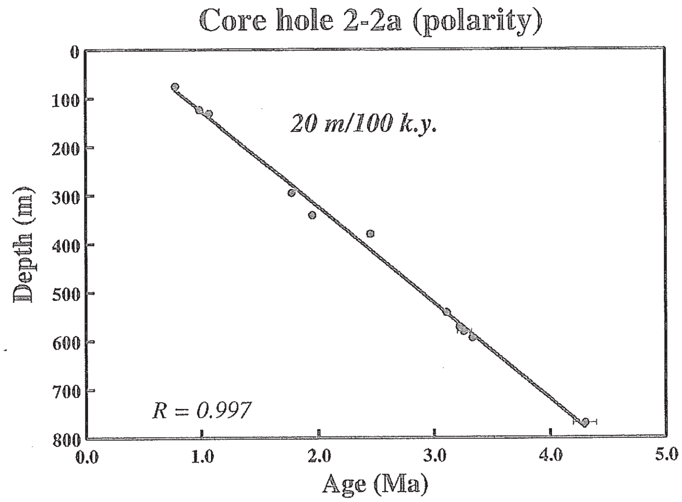

Figure 15. Graph of ages of lava flows plotted against depths to flow tops in core hole 2-2A in north-central part of Idaho National Engineering and Environmental Laboratory. See text for discussion of error sources.

RESULTS

Accumulation rate

The accumulation rates found in drill cores vary by a factor of 4, from 16 m/100 k.y. to 67 m/100 k.y. Regression coefficients of age versus depth plots are typically greater than 0.98 (Table 5). The graphical representations of accumulation rates are compelling and suggest a regular and controlled process of lava flow accumulation for the eastern Snake River Plain. This is well shown by those core holes for which complete or nearly complete K-Ar and $^{40}Ar/^{39}Ar$ age data are available.

Although the rates of accumulation varied from core hole to core hole, a contour map of their values suggests a simple overall pattern (Fig. 16). Only rates of accumulation of lava flows erupted during the Brunhes Normal Polarity Chron are included in the map; the rates from older sections in wells farther north in the INEEL may vary broadly through time. The data suggest a northwest-southeast gradient; contour trends are broadly parallel to the axis of the eastern Snake River Plain, and accumulation rates are greater at sites closer to the axis of the plain. The accumulation rates (Fig. 16) would require that lava accumulates in the vicinity of the axis of the eastern Snake River Plain, unless some other process is involved. This process must be subsidence, because the eastern Snake River Plain generally is rather flat. The higher accumulation rates toward the axis of the plain are compatible with subsidence that compensates for the higher accumulation rates. Proximity to lava flow source vents along the axis of the eastern Snake River Plain could explain the faster accumulation and/or subsidence of these areas, with waning lava flow accumulation to the northwest (Fig. 17).

Within the overall gradient of accumulation rates, there is an abrupt increase to higher values, centered in the TRA and ICPP area. The anomaly near TRA and ICPP suggests a zone of relative structural movement, such as a monocline or a fault. A cross section drawn through core locations TRA 05/PZ1, USGS 80, USGS 121, and NPR Test/W-02 (Fig. 18) shows the structural effect on the otherwise nearly horizontal flat-bedded age horizons of the lava section of the INEEL. Although this cross section has a vertical exaggeration of 10 for clarity, the parallelism of surfaces between core locations TRA 05/PZ1 and USGS 80 and between USGS 121 and NPR Test/W-02 is striking, compared to the tilted west to east zone between USGS 80 and USGS 121, where successively older surfaces are dropped proportionately to greater depths. The only lava flow present in all four of the core holes TRA 05/PZ1, USGS 80, USGS 121, and NPR Test/W-02 is the 640 ka flow from a vent exposed at AEC Butte (Fig. 2). This upper surface of this flow pitches downward on the southeast side >100 m between USGS 80 and USGS 121. The differences in depth of this upper surface of the flow could be explained by a great thickness of AEC Butte flow units in the near-vent locations of core holes TRA 05/PZ1 and USGS 80, the next deeper flow having a more nearly horizontal surface. Anderson (1991) suggested that AEC Butte flows are possibly 75 m thick beneath core hole USGS 80, which is 1.3 km from the vent at AEC Butte. The AEC Butte flow units are only 16 m thick in TRA 05/PZ1 and 14 m thick in USGS 121, core holes that are 1.9 km and 2.0 km, respectively, from the vent. If the AEC Butte flow units represent a thick accumulation of basalt forming a shield near these core holes, it is necessary to explain how thin flows in examples between 400 and 500 ka overlapped the edge of the shield to an aggregate depth of 100 m so soon after eruption of AEC Butte lavas.

Thickness

Mean thicknesses of basalt lava flows at INEEL vary from 10 to 39 m per eruptive event (Table 5), each eruptive event being defined by a combination of paleomagnetic and petrographic criteria. A given event may be a single lava flow or several flow units that together constitute a single lava accumulation. Changes in thicknesses define a north-northwest–trending decreasing gradient (Fig. 19); thus lava flows are thicker close to the vent locations than farther away. The thickness gradient decreases toward the areas of ICPP and TRA (Fig. 2), where mean thickness values are <12 m. The gradient of decreasing flow thicknesses (Fig. 19) is similar to the pattern of accumulation rates (Fig. 16); the core holes having thinner flows generally yield lower accumulation rates (USGS 80, TRA 05/PZ1), whereas most core holes having thicker flows yield high accumulation rates (USGS 121, ICPP-COR-A-023, USGS 123). In the vicinity of AEC Butte, the average flow thickness is <12 m; Anderson et al. (1997) speculated that this is an area of possible uplift. Whether by uplift or by a slower rate of avg recurrence for all boreholes = 69 Ka, 1.4×10^{-5} yr^{-1}

"avg. of the avg." thickness = 20 m. (400 m / 20 meas. = 20 m)

TABLE 5. MEAN RECURRENCE INTERVALS, MEAN THICKNESSES, ACCUMULATION RATES, AND LINEAR REGRESSION COEFFICIENTS FOR CORED WELLS OF THE IDAHO NATIONAL ENGINEERING AND ENVIRONMENTAL LABORATORY

Well name	Recurrence interval (1 k.y.)	Mean thickness (m)	Accumulation rate (m/100 k.y.)	Regression coefficient
USGS 80	73 ± 84	11 ± 7	16	0.968
USGS 123	42 ± 28	15 ± 10	39	0.994
NPR Test/W-02	51 ± 22	20 ± 11	43	0.984
ICPP-COR-A-023	41 ± 56	14 ± 14	36	0.964
USGS 121	32 ± 46	12 ± 6	43	0.953
TRA 05/PZ1	84 ± 47	10 ± 7	16	0.994
STF-PIE-AQ-01	(54)	25 ± 21	50	(1.0)
ARA-COR-005	(36)	23 ± 17	67	(1.0)
ANL-OBS-AQ-014	(41)	21 ± 13	56	(1.0)
NRF 89-04	81 ± 51	18 ± 10	24	0.992
NRF 89-05	73 ± 38	18 ± 12	26	0.994
NRF B18-1	73 ± 38	19 ± 11	27	0.990
NRF #6P	116 ± 61	25 ± 11	22	0.993
NRF #7P	97 ± 55	19 ± 19	22	0.989
BG-77-1	43 ± 26	26 ± 18	47/69	0.878/(1.0)
C-1A	50 ± 41	20 ± 13	43/41	0.898/0.999
USGS 118	—	26 ± 19	—	—
TCH #1	122 ± 81	25 ± 18	24/24	0.981/(1.0)
TCH #2 Piezo A	140 ± 129	39 ± 33	37/15	0.938/0.979
Core hole 2-2A	—	(11 ± 6)*	20	0.998

Note: Recurrence interval in parentheses are from incompletely studied core holes and preliminary; mean thickness for core hole 2-2A is preliminary due to insufficient data and an absolute minimum value; accumulation rates and regression coefficients separated by slash are for core holes with significant hiatuses in their sequence and represent before and after figures; regression coefficients in parentheses are on two-point lines and are unity by definition.

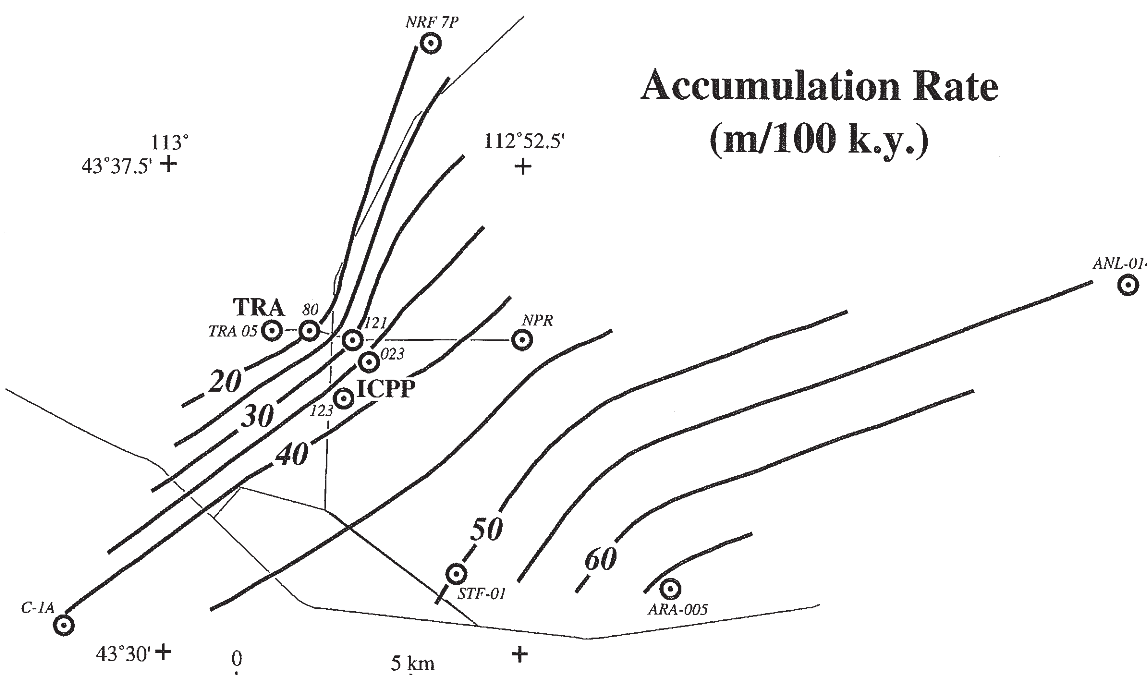

Figure 16. Contour map of basalt lava accumulation rates early to midway in Brunhes Normal Polarity Chron from core hole data in southern part of Idaho National Engineering and Environmental Laboratory. Values are in m/100 k.y., and contour interval is 5 m. Abbreviations: TRA, Test Reactor Area; ICCP, Idaho Chemical Processing Plant.

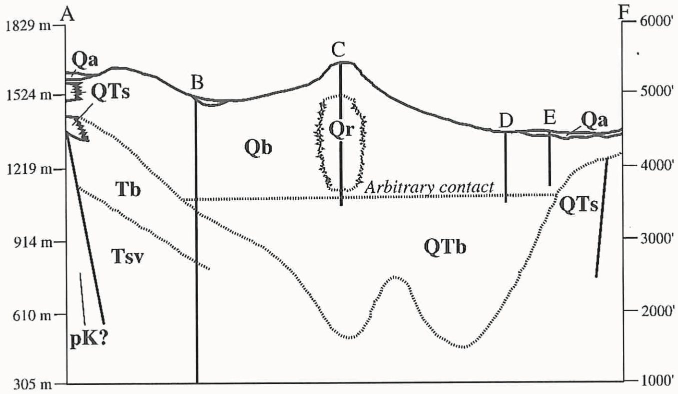

Figure 17. Northwest-southeast cross section showing subsidence of lava flows parallel to topographic axis of eastern Snake River Plain. Geologic units: Qa, Quaternary alluvium; Qr, Quaternary rhyolite; Qb, Quaternary basalt; QTs, Quaternary-Tertiary sediments; QTb, Quaternary-Tertiary basalts; Tb, Tertiary basalts; Tsv, Tertiary silicic volcanic rocks; pK, preCretaceous basement rocks. See Figure 2 for location of sections; after Whitehead (1992).

subsidence, the AEC Butte area seems to have served as a shoal for successive lava flow inundations.

Recurrence interval

The recurrence rate for eruptions can be estimated if we assume a linear age versus depth relationship in combination with a given number of flows within each core hole (Table 5). The recurrence intervals vary by a factor of four, from an eruption every 32 k.y. at USGS 121, to an eruption every 140 k.y. at TCH #2 Piezo A. Uncertainties in the ages of flows in USGS 118, and of age and flow-unit groupings in core hole 2-2A, prevent the calculation of mean recurrence intervals in those core holes. Estimates of mean recurrence intervals in core holes ANL-OBS-AQ-014, ARA-COR-005, and STF-PIE-AQ-01 were made by dividing the time interval between dated lava flows by the number of independent lava flows.

The ages used to calculate recurrence intervals come from two assessment processes. If the lava flow was directly dated or correlated to a flow in an adjacent core hole that was directly dated, then that age was used to calculate the recurrence interval between successive flows. For a lava flow for which no ages have been measured, an age estimate (parentheses in Tables 1–4) was generated from the linear age versus depth relationship in that core hole. In well-studied core holes such as NPR Test/W-02, TCH #2 Piezo A, and USGS 123, the recurrence intervals vary. For incompletely studied core holes, such as USGS 121 and ICPP-COR-A-023, in which much of the age information is provided by correlation with other core holes, negative apparent recurrence intervals are paired with long positive recurrence intervals that immediately precede or follow the negative calculated intervals. Only the mean recurrence value is used in geologic interpretations; we believe that the errors of age assessment only increase the standard deviation of the mean recurrence interval and not the mean value itself.

The contour pattern of the mean recurrence intervals is broadly smooth and roughly parallels the axis of the eastern Snake River Plain (Fig. 20). One would expect the mean recurrence interval to be shorter close to vents in fast accumulation zones and longer at locations farther from vents in zones of lower accumulation rate. This pattern is approximated (Fig. 20) with the important additional feature that a sharp gradient in recurrence interval mimics the strong gradient in accumulation rate (Fig. 16). The higher accumulation rates of USGS 121, ICPP-COR-A-023, and USGS 123 arise in part due to short recurrence intervals compared to core holes USGS 80 and TRA 05/PZ1. The recurrence intervals to the east and southeast of the sharp gradient suggest an area of relatively uniform recurrence intervals between 40 and 50 k.y. Mean recurrence intervals vary significantly, typically by 50%–100% of the mean values, and clearly indicate that recurrence of lava flow inundation at a given locality is nonuniform. These recurrence intervals pertain to a time from early to midway in the Brunhes Normal Polarity Chron. It is important to note that most of the eastern Snake River Plain at or near the INEEL underwent a hiatus in lava flow accumulation for the past 200 ka. However, it is important to note that the limited data from core holes that capture hiatuses suggest that these same recurrence intervals would again exist when eruptions resume.

ca. 730 Ka to ~200 Ka generally

APPLICATION OF ACCUMULATION-RATE DATA TO VOLCANIC HAZARDS AT INEEL

The data on accumulation rates, mean thicknesses, and mean-recurrence intervals generated from the INEEL core holes present an opportunity to further assess the volcanic hazard to the INEEL. Volcanic hazards were discussed by Hackett and Smith (1994) and Hackett et al. (2000), mostly on the basis of geologic data derived from the geologic map of the INEL (Kuntz et al., 1994). Hackett and Smith (1994) estimated recurrence intervals using vent density, lava flow area, and lava flow age. They estimated recurrence intervals for core holes NPR Test and BG-77-1 of 45 k.y., in close agreement with the respective values of 51 ± 22 k.y. and 43 ± 26 k.y. calculated in this study. They assigned single values for recurrence interval to individual volcanic rift zones as defined by Kuntz et al. (1992) and expressed the belief that recurrence intervals increase northward in the northwest-trending volcanic rift zones with increasing distance from the axis of the eastern Snake River Plain and decreasing vent density.

From our study, recurrence intervals do not seem to be related to the northwest-trending volcanic rift zones, possibly due to the distribution of core holes we studied. However, recurrence intervals are relatively short near the axis of the eastern Snake River Plain and relatively long in the north part of the

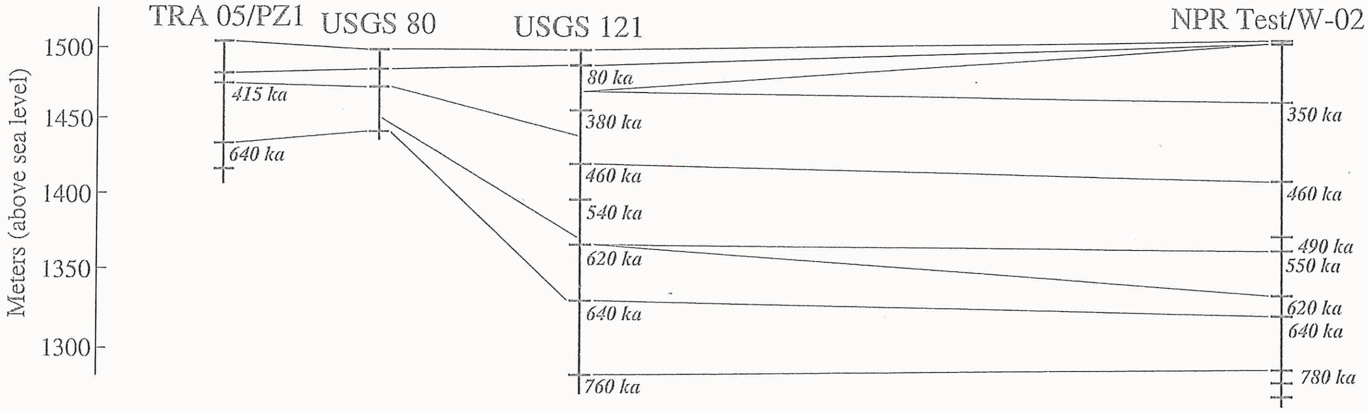

Figure 18. East-west vertical cross section between core holes TRA 05 and NPR Test/W-02 showing absolute depth position (in meters above sea level) of lava flows from AEC Butte (640 ka) and other dated flows correlated between these core holes. Gray halftone denotes surface sediment layer; numbers show age of horizons rounded to nearest 10 ka.

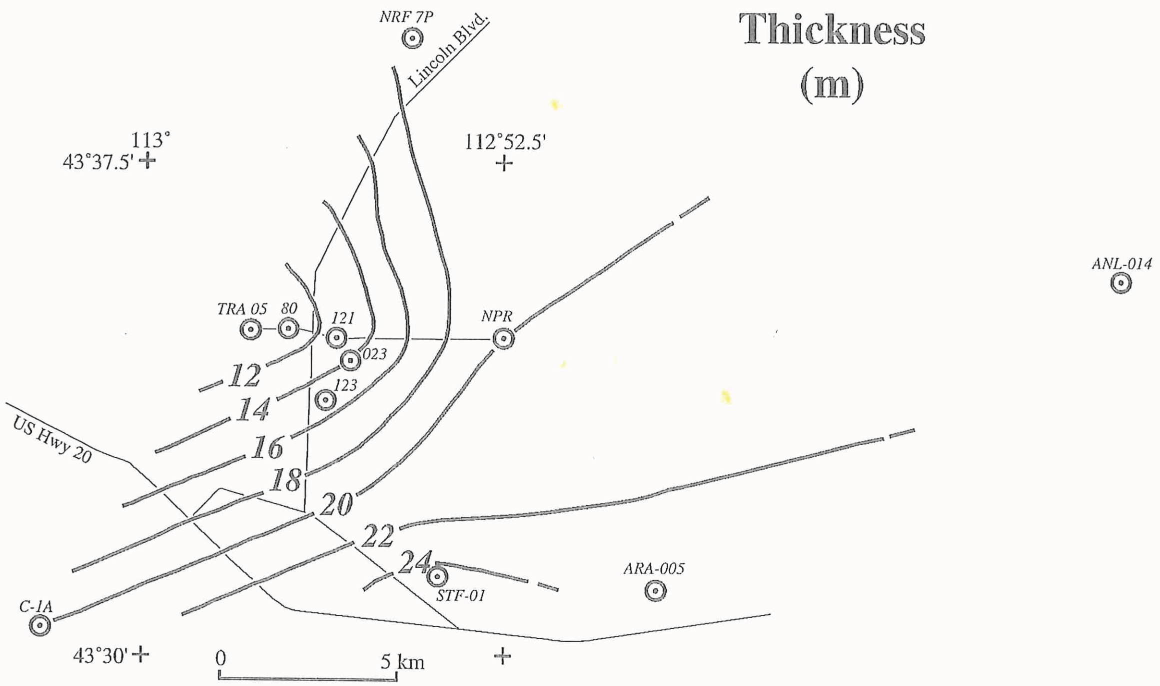

Figure 19. Contour map of average basalt lava flow thicknesses of lavas erupted early to midway in Brunhes Normal Polarity Chron, from core hole data in southern part of Idaho National Engineering and Environmental Laboratory. Values are in meters; contour interval is 2 m.

study area. Specific values computed from this study correspond to the 125 k.y. value estimated by Hackett and Smith (1994) only in the northern part of the Howe–East Butte, Lava Ridge–Hell's Half Acre, and Circular Butte–Kettle Butte volcanic rift zones, and generally for lava flows older than 780 ka. Appraisal of lava flow inundation hazards to sites on the INEEL must be viewed in light of the context that volcanic recurrence intervals are nonuniform, and that a hiatus of eruptions dominates the INEEL at present.

CONCLUSIONS

Our studies show that the accumulation of basaltic lava flows at 20 studied core holes in the eastern Snake River Plain is uniform at a given locality over very long periods of time. We also find that adjacent core holes yield remarkably different accumulation rates for strata of the same age (Fig. 16). The accumulation rates are highest near the axis of the eastern Snake River Plain and near volcanic rift zones, and lowest near the

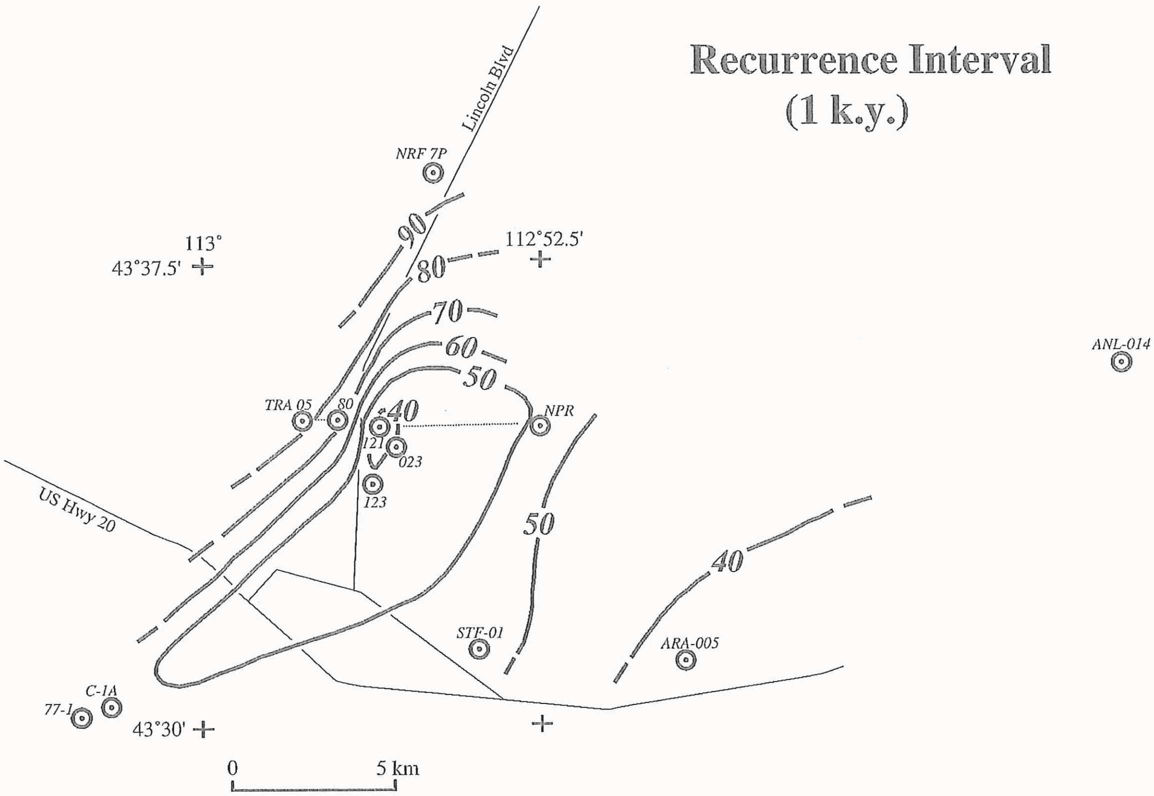

Figure 20. Contour map of average recurrence interval of basalt lava inundation during time period of early to midway through Brunhes Normal Polarity Chron from core hole data in southern part of Idaho National Engineering and Environmental Laboratory. Values are in k.y.; contour interval is 10 k.y.

margins of the eastern Snake River Plain and away from volcanic rift zones. In some core holes, the relatively steady accumulation history has been interrupted by hiatuses lasting several hundreds of thousands of years. When accumulation of flows began again at sites that underwent such a hiatus, the accumulation typically resumed at rates nearly identical to those before the hiatus.

These data provide strong evidence that basaltic volcanism in the eastern Snake River Plain is temporally and spatially predicable when viewed over hundreds of thousands or a few million years. Volcanism has occurred repeatedly along long-lived volcanic rift zones; areas away from the topographic axis of the eastern Snake River Plain and between volcanic rift zones have undergone fewer inundations by basaltic lava flows. The data can be used for long-term predictions about where and when future eruptions will occur and thus form a basis for volcanic-hazard evaluations for the INEEL area of the eastern Snake River Plain.

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