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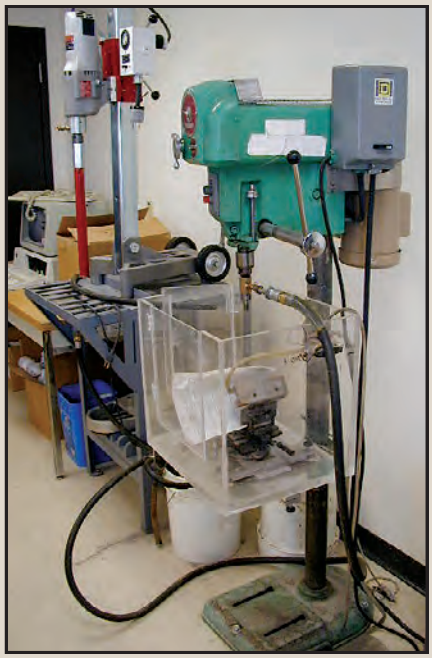

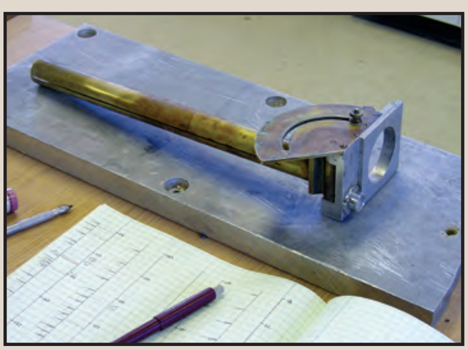

Scientific Investigations Report 2011–5049

U.S. Department of the Interior
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Cover: Photographs (top, left to right) of box of drill core, drill press, sub-core being drilled with the drill press; (bottom left to right) paleomagnetic sub-core orienting device, oriented sub-cores, and cryogenic magnetometer with sample changer. (Photographs courtesy of the U.S. Geological Survey Idaho National Laboratory Project Office.)

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U.S. Department of the Interior
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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Conversion Factors, Datums, and Abbreviations and Acronyms

Conversion Factors

Multiply	By	To obtain
centimeter (cm)	0.3937	inch (in.)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
cubic meter (m^3)	35.3145	cubic foot (ft^3)
foot (ft)	0.3048	meter (m)
kilometer (km)	0.6214	mile (mi)
meter (m)	3.2808	foot (ft)
mile (mi)	1.609	kilometer (km)
square kilometer (km^2)	0.3861	square mile (mi^2)
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F= (1.8×°C) +32.$$

Datums

Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

Abbreviation or acronym	Definition
AF	Alternating field
ATRC	Advanced Test Reactor Complex (formerly known as RTC, Reactor Technology Complex, and TRA, Test Reactor Area)
AVZ	Axial Volcanic Zone
CFA	Central Facilities Area
DOE	Department of Energy
ESRP	Eastern Snake River Plain
ICPP	Idaho Chemical Processing Plant
INEL	Idaho National Engineering Laboratory (1974–97)
INEEL	Idaho National Engineering and Environmental Laboratory (1997–2005)
INL	Idaho National Laboratory (2005–present)
INTEC	Idaho Nuclear Technology and Engineering Center
IRM	Isothermal remanent magnetization
K_2O	potassium oxide
ka	Thousand years
Ma	Million years
MFC	Materials and Fuels Complex
NRF	Naval Reactors Facility
NRTS	National Reactor Testing Station (1949–74)
RWMC	Radioactive Waste Management Complex
TAN	Test Area North
USGS	U.S. Geological Survey

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By Duane E. Champion, Mary K.V. Hodges, Linda C. Davis, and Marvin A. Lanphere

Abstract

Paleomagnetic inclination and polarity studies have been conducted on thousands of subcore samples from 51 coreholes located at the Idaho National Laboratory. These studies are used to paleomagnetically characterize and correlate successive stratigraphic intervals in each corehole to similar depth intervals in adjacent coreholes. Paleomagnetic results from 83 surface paleomagnetic sites, within and near the INL, are used to correlate these buried lava flow groups to basaltic shield volcanoes still exposed on the surface of the eastern Snake River Plain. Sample handling and demagnetization protocols are described as well as the paleomagnetic data averaging process. Paleomagnetic inclination comparisons between coreholes located only kilometers apart show comparable stratigraphic successions of mean inclination values over tens of meters of depth. At greater distance between coreholes, comparable correlation of mean inclination values is less consistent because flow groups may be missing or additional flow groups may be present and found at different depth intervals. Two shallow intersecting cross-sections, *A–A'* and *B–B'* (oriented southwest-northeast and northwest-southeast, respectively), drawn through southwest Idaho National Laboratory coreholes show the corehole to corehole or surface to corehole correlations derived from the paleomagnetic inclination data.

From stratigraphic top to bottom, key results included:

- The Quaking Aspen Butte flow group, which erupted from Quaking Aspen Butte southwest of the Idaho National Laboratory, flowed northeast, and has been found in the subsurface in corehole USGS 132.
- The vent 5206 flow group, which erupted near the southwestern border of the Idaho National Laboratory, flowed north and east, and has been found in the subsurface in coreholes USGS 132, USGS 129, USGS 131, USGS 127, USGS 130, USGS 128, and STF-AQ-01.
- The Mid Butte flow group, which erupted north of U.S. Highway 20, flowed northwest, and has been found in the subsurface at coreholes ARA-COR-005 and STF-AQ-01.
- The high $K_2$0 flow group erupted from a vent that may now be buried south of U.S. Highway 20 near Middle Butte, flowed north, and is found in the subsurface in coreholes USGS 131, USGS 127, USGS 130, USGS 128, USGS 123, STF-AQ-01, and ARA-COR-005 ending near the Idaho Nuclear Technology and Engineering Center.
- The vent 5252 flow group erupted just south of U.S. Highway 20 near Middle and East Buttes, flowed northwest, and is found in the subsurface in coreholes ARA-COR-005, STF-AQ-01, USGS 130, USGS 128, ICPP 214, USGS 123, ICPP 023, USGS 121, USGS 127, and USGS 131.
- The Big Lost flow group erupted from a now-buried vent near the Radioactive Waste Management Complex, flowed southwest to corehole USGS 135, and northeast to coreholes USGS 132, USGS 129, USGS 131, USGS 127, USGS 130, STF-AQ-01, and ARA-COR-005.
- The AEC Butte flow group erupted from AEC Butte near the Advanced Test Reactor Complex and flowed south to corehole Middle 1823, northwest to corehole USGS 134, northeast to coreholes USGS 133 and NRF 7P, and south to coreholes USGS 121, ICPP 023, USGS 123, and USGS 128.

Evidence of progressive subsidence of the axial zone of the ESRP is shown in these cross sections, distorting the original attitudes of the lava flow groups and interbedded sediments. A deeper cross-section, *C–C'* (oriented west to east), spanning the entire southern Idaho National Laboratory shows correlations of the lava flow groups in the saturated part of the ESRP aquifer.

Areally extensive flow groups in the deep subsurface (from about 100–800 meters (330–2,625 feet) below land surface) can be traced over long distances. In cross-section *C–C*', the flow group labeled "Matuyama" can be correlated from corehole USGS 135 to corehole NPR Test/W-02, a distance of about 28 kilometers (17 miles). The flow group labeled "Matuyama 1.21 Ma" can be correlated from corehole Middle 1823 to corehole ANL-OBS-A-001, a distance of 26 kilometers (16 miles). Other flow groups correlate over distances of up to about 18 kilometers (11 miles).

Introduction

The U.S. Atomic Energy Commission [now the U.S. Department of Energy (DOE)] established the National Reactor Testing Station (NRTS) on 2,315 km^2 (890 mi^2) of the ESRP in southeastern Idaho in 1949. The NRTS was established to develop peacetime atomic energy, nuclear safety research, defense programs, and advanced energy concepts. The name of the laboratory has been changed to reflect changes in the research focus of the laboratory. Names formerly used for the laboratory, from earliest to most recent, were National Reactor Testing Station (NRTS, 1949 to 1974), Idaho National Engineering Laboratory (INEL, 1974 to 1997), and Idaho National Engineering and Environmental Laboratory (INEEL, 1997 to 2005). Since 2005, the laboratory has been known as the Idaho National Laboratory (INL) (fig. 1).

U.S. Geological Survey (USGS) scientists have been studying the geology and hydrology of the eastern Snake River Plain (ESRP) for more than 100 years beginning with Russell (1902). Studies of the geologic framework of the ESRP at and near the INL intensified in 1949, when feasibility studies for siting of the NRTS began. Studies included evaluation of hydraulic properties of the aquifer, seismic and volcanic hazards, facility design and construction, and the evolution of basaltic volcanism on the ESRP.

Wastewater containing chemical and radiochemical wastes was discharged to ponds and wells, and solid and liquid wastes were buried in trenches and pits excavated in surficial sediments at the INL. Some wastewater continues to be disposed to infiltration and evaporation ponds. Concern about subsurface movement of contaminants from these wastes increased the number and variety of studies of subsurface geology and hydrology in order to provide information for conceptual and numerical models of groundwater flow and contaminant transport (Anderson, 1991; Anderson and Bartholomay, 1995; Anderson and Bowers, 1995; Ackerman and others, 2006; 2010).

Accumulations of basaltic lava flows, eruptive fissures and vents, and fluvial and eolian sediments differ greatly in hydraulic conductivity, and the three-dimensional distribution of these materials controls groundwater movement in the Snake River Plain aquifer (Welhan and others, 2002). Lava flows comprise more than 85 percent of the volume of the subsurface of the ESRP (Kuntz and others, 1992). Sedimentary interbeds comprise the rest. Paleomagnetic inclination and polarity studies on samples from subsurface drill cores and surface samples provide valuable data that can help constrain the age and extent of basaltic lava flow groups. Data from paleomagnetic studies at and near the INL (Champion and Greeley, 1978; Champion and others, 1981; Champion and others, 1988) also have been used to document paleomagnetic secular variation (Hagstrum and Champion, 2002) during late Pliocene to Holocene time. The Big Lost Reversed Polarity Cryptochron (formerly referred to as the Big Lost Reversed Polarity Subchron [Champion and others, 1988]) of the Brunhes Normal Polarity Chron was first identified in subsurface ESRP basalts at the Idaho National Laboratory (Champion and others, 1981; 1988).

Purpose and Scope

Knowledge about the surface and subsurface geologic framework of the ESRP is needed to aid in refining conceptual and numerical models of groundwater flow and contaminant transport at and near the INL. Paleomagnetic data were used to correlate surface and subsurface stratigraphy, determine relative ages, and, in conjunction with previous studies (table 1), determine the absolute age of certain basalt flows. Samples from 83 surface sites (fig. 2) and from 51 coreholes (fig. 1) at and near the INL were collected and analyzed for this study. Surface samples were selected from outcrops that had little alteration and in low-lying areas, where possible, to avoid the secondary magnetic effects of lightning strikes. Samples were collected from coreholes at depths of a few meters to 1,143 m (3,750 ft). Drill core samples were selected from individual lava flows based on identification of flow tops and bottoms in the coreholes. In this report, correlations were made using paleomagnetic inclinations; methods used by other investigators were only used to confirm or reject paleomagnetic inclination correlations.

Previous Investigations

Numerous geologic, paleomagnetic, and stratigraphic investigations on surface and subsurface basalts at and near the INL and the ESRP have been conducted. Table 1 summarizes selected previous investigations and the areas of investigation. Paleomagnetic data records the magnetic field at the time of eruption and is not unique. Other data such as lithology, petrology, geophysical logs, and geochemistry must be used in conjunction with paleomagnetic and age data to confirm or reject correlations.

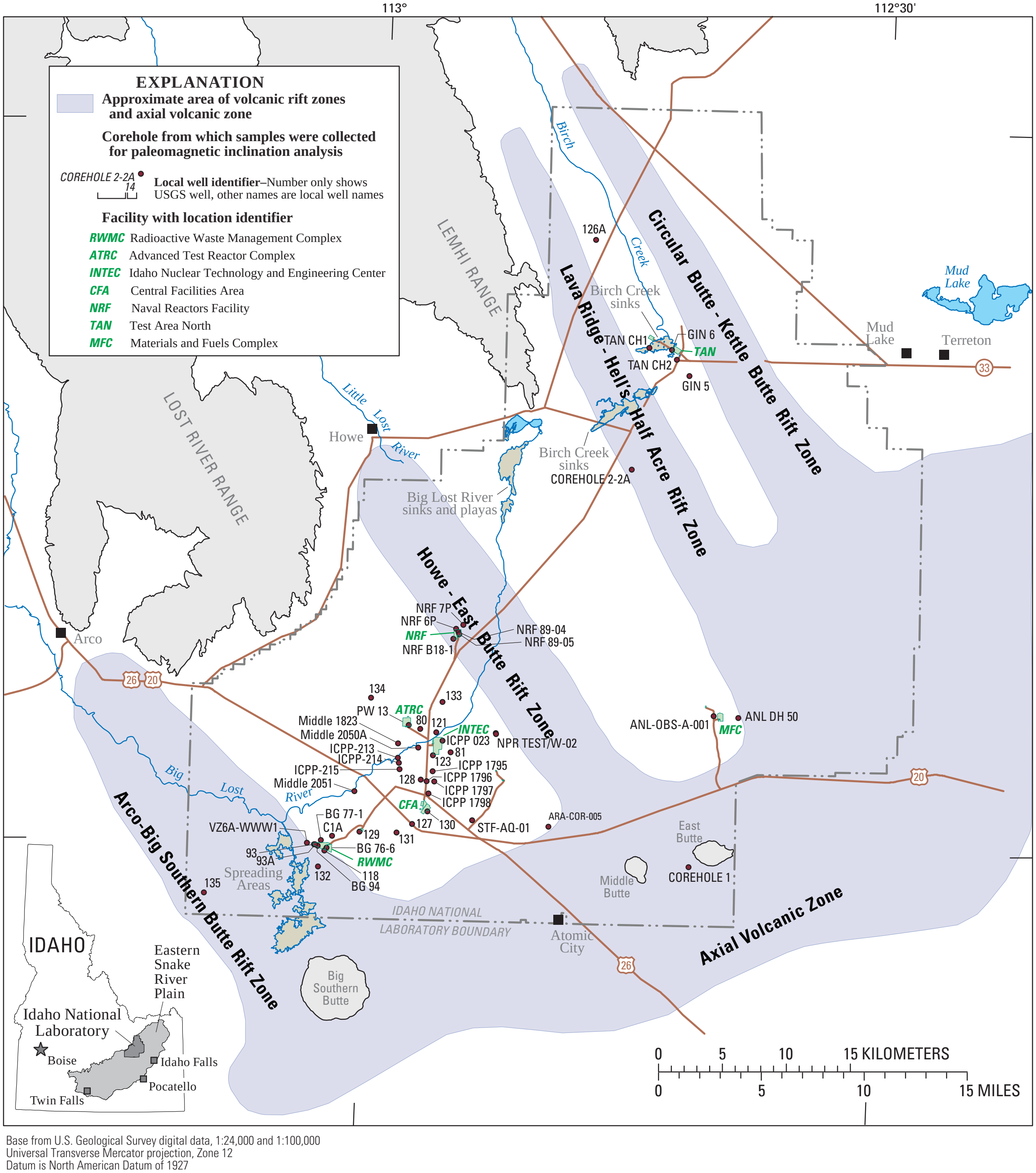


Figure 1. Location of selected facilities, the Axial Volcanic Zone and volcanic rift zones, and coreholes for which data are presented, Idaho National Laboratory, Idaho.

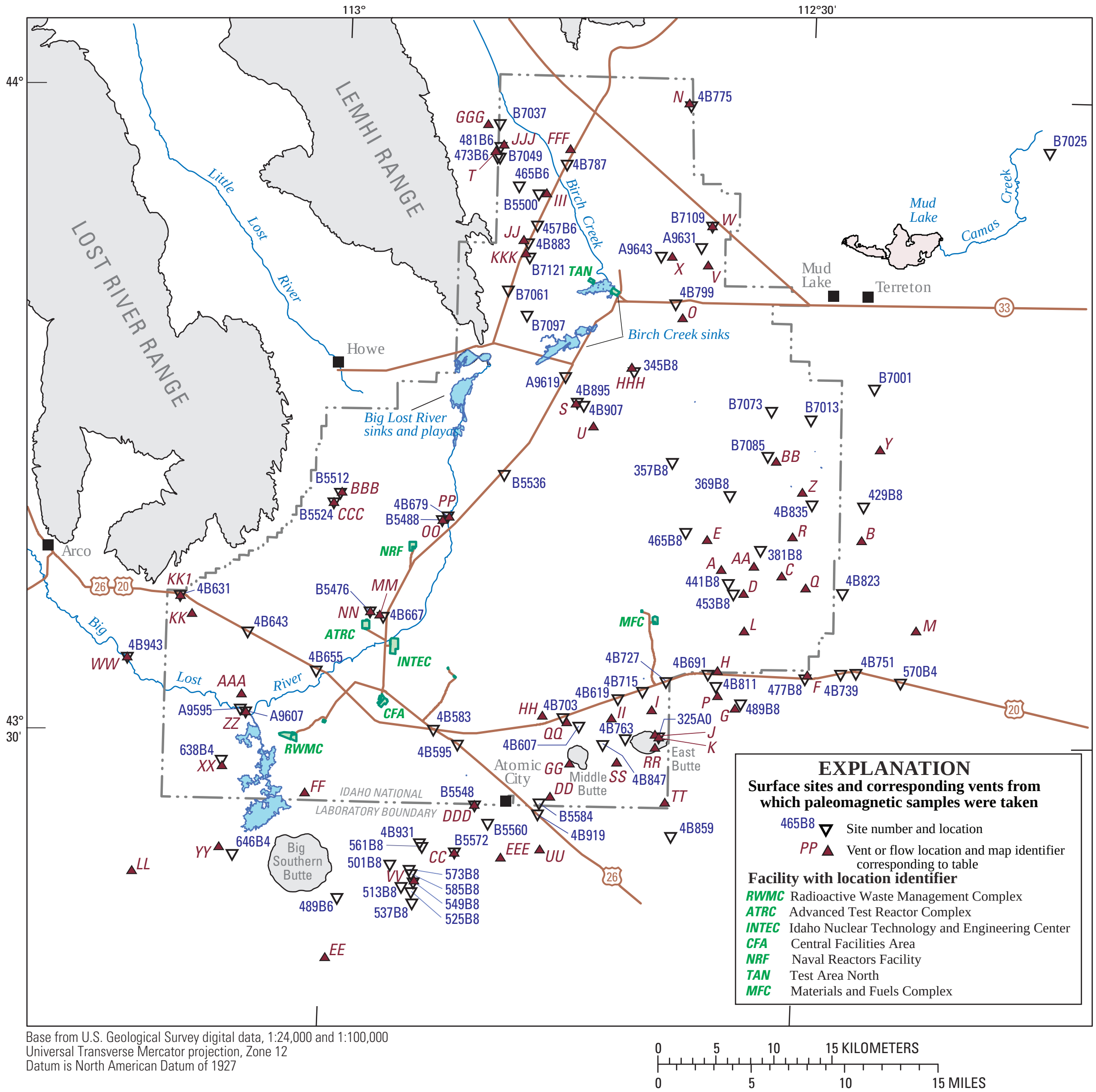


Figure 2. Surface paleomagnetic sample sites and associated vents at and near the Idaho National Laboratory, Idaho.

Map identifier	Site No.	Vent/flow identifier	Map identifier	Site No.	Vent/flow identifier	Map identifier	Site No.	Vent/flow identifier	Map identifier	Site No.	Vent/flow identifier
A	369B8	Vent 5305 (Eastern INL)	*T*	B7049	Vent 5305 (Northern INL)	*KK*	4B643	Crater Butte	*XX*	638B4	Coyote Butte
B	429B8	Vent 5316	*U*	A9619	Vent 4853	*KK1*	4B631	Crater Butte	*YY*	646B4	Vent 5244
C	441B8	Vent 5298		4B907	Vent 4853	*LL*	4B655	Quaking Aspen Butte	*ZZ*	A9595	small qbc South of Lavatoo
D	453B8	Vent 5271 SE	*V*	A9631	Vent 4957 (Antelope Butte)	*MM*	4B667	AEC Butte	*AAA*	A9607	Lavatoo Butte
E	465B8	Vent 5171	*W*	B7109	Antelope Butte	*NN*	B5476	AEC Butte west	*BBB*	B5512	Knob VABM
F	477B8	Vent 5315	*X*	A9643	Vent 4862	*OO*	B5488	State Butte Flow	*CCC*	B5524	South of Knob VABM
G	489B8	Little Butte	*Y*	B7001	Vent 5181	*PP*	4B679	State Butte Vent	*DDD*	B5548	Borrow Pit West of Atomic City
H	4B691	Microwave Butte	*Z*	B7013	Tanner Butte	*QQ*	4B703	Vent 5252	*EEE*	B5560	Vent 5212
	B5536	Microwave Butte	*AA*	B7073	Vent 5313 (Topper Butte)	*RR*	4B763	Moonshiner's Cave	*FFF*	B7025	Richard Butte
I	4B715	Vent 5415 (Twin)		381B8	Vent 5313	*SS*	4B847	Vent 5551	*GGG*	B7037	Vent 5450
J	4B727	Vent 5561	*BB*	B7085	Vent 5007	*TT*	4B859	Vent 5183		4B787	Vent 5450
K	325A0	Vent 5742	*CC*	B5572	Borrow Pit near Cerro Grande	*UU*	4B919	Table Legs Butte	*HHH*	345B8	Vent 4812
L	4B739	Vent 5454 (Deuce Butte)	*DD*	B5584	Vent 5119	*VV*	4B931	Cedar Butte	*III*	465B6	Vent 5110
	357B8	Vent 5454	*EE*	489B6	Vent 5494		501B8	Cedar Butte		B5500	Vent 5110
M	4B751	Kettle Butte (Pinhead Butte)	*FF*	4B583	Vent 5206		513B8	Cedar Butte	*JJJ*	481B6	Vent 5262
	570B4	Kettle Butte	*GG*	4B595	Vent 5398		525B8	Cedar Butte	*KKK*	B7121	Vent 4976
N	4B775	Vent 4925	*HH*	4B607	Mid Butte Vent		537B8	Cedar Butte			
O	4B799	Circular Butte	*II*	4B619	Vent 5350		549B8	Cedar Butte		473B6	Unknown Vent
P	4B811	Radio Facility Butte	*JJ*	457B6	Vent 5044		561B8	Cedar Butte			
Q	4B823	Vent 5410		4B883	Vent 5044		573B8	Cedar Butte			
R	4B835	Vent 5148		B7061	Vent 5044		585B8	Cedar Butte-Trimodal Dyke			
S	4B895	Teat Butte		B7097	Vent 5044	*WW*	4B943	Box Canyon flow			

Figure 2. Continued.

Table 1. Summary of selected previous investigations on geology, paleomagnetism, and stratigraphy of the eastern Snake River Plain and Idaho National Laboratory, Idaho.

[**Abbreviations:** INL, Idaho National Laboratory; ESRP, eastern Snake River Plain; INTEC, Idaho Nuclear Technology and Engineering Center (also known as ICPP (Idaho Chemical Processing Plant); CFA, Central Facilities Area; RWMC, Radioactive Waste Management Complex; TAN, Test Area North; NPR, New Production Reactor; NRF, Naval Reactors Facility; SRP, Snake River Plain; USGS; U.S. Geological Survey]

Reference	Area of investigation	Reference summary
Anders and Sleep, 1992	ESRP	Thermal and mechanical effects of the Yellowstone hotspot
Anderson and Liszewski, 1997	INL	INL unsaturated and ESRP aquifer stratigraphy, based on core and natural gamma logs
Anderson and others, 1996a	INL	INL stratigraphy based on natural gamma logs
Anderson and others, 1996b	INL	INL surficial sediment thickness
Anderson and others, 1999	ESRP, INL, and vicinity	Geologic controls on hydraulic conductivity
Bestland and others, 2002	INL, Big Lost Trough	Sedimentary interbeds in the Big Lost Trough, corehole 2-2A
Braile and others, 1982	ESRP	Seismic profiling of ESRP
Champion and others, 1981	INL	Radiometric ages and paleomagnetism at corehole Site E (NPR Test)
Champion and others, 1988	INL	Radiometric ages and paleomagnetism at corehole Site E (NPR Test), description of Big Lost cryptochron
Champion and Herman, 2003	INL, INTEC area	Paleomagnetism of basalt from drill cores
Champion and others, 2002	INL and vicinity; ESRP	Accumulation and subsidence based on paleomagnetism and geochronology
Geslin and others, 2002	Big Lost Trough, INL	Pliocene and Quaternary river drainage and sediment
Grimm-Chadwick, 2004	INL, CFA	Stratigraphy, geochemistry, and descriptions of high K_2O flow in cores
Hackett and Smith, 1992	ESRP	Description of ESRP volcanism including development of Axial Volcanic Zone
Kuntz, 1978	INL, RWMC	Geology of RWMC area
Kuntz and others, 1980	INL, RWMC	Radiometric dating, paleomagnetism on cores from RWMC
Kuntz and others, 1986	ESRP	Radiocarbon dates on Pleistocene and Holocene basalt flows
Kuntz and others, 1992	ESRP	ESRP basaltic volcanism, including eruption styles, landforms, petrology, and geochemistry
Kuntz and others, 1994	INL	Geologic map of INL, including radiometric ages and paleomagnetism
Lanphere and others, 1994	INL, TAN cores	Petrography, age and paleomagnetism of basalt flows at and near TAN
Lanphere and others, 1993	INL, at and near NRF	Petrography, age and paleomagnetism of basalt flows at and near NRF
Mazurek, 2004	Central INL	Genetic alteration of basalt in SRP aquifer
Miller, 2007	INL, RWMC	Geochemistry, and descriptions of the B flow, and stratigraphy of corehole USGS 132
Morse and McCurry, 2002	INL	Base of the aquifer, alteration in basalts
Pierce and Morgan, 1992	ESRP	Age progression of Yellowstone hot spot
Pierce and others, 2002	ESRP	Age progression of Yellowstone hot spot
Reed and others, 1997	INL, ICPP	Geochemistry of lava flows in cores at ICPP
Rightmire and Lewis, 1987	INL, RWMC	Unsaturated zone geology, geochemistry of sediment and alteration products
Russell, 1902	Snake River Plain and aquifer	Geology and water resources of the Snake River Plain
Scarberry, 2003	INL, RWMC cores	Geochemistry of the F flow (now referred to as the Big Lost Reversed Polarity Cryptochron flows) and distribution in several coreholes at the INL
Shervais and others, 2006	INL, TAN cores	Cyclic geochemical variations in basalt in TAN drill cores
Stroup and others, 2008	INL	Statistical stationarity of sediment interbed thickness
Tauxe and others, 2004	SRP	Paleomagnetism of the Snake River Plain
Twining and others, 2008	INL	Construction diagrams, lithological, and geophysical logs for coreholes
Walker, 2000	ESRP	Volcanology of the Snake River Plain
Welhan and others, 2002	INL, ESRP	Morphology of inflated pahoehoe flows
Welhan and others, 2007	INL	Geostatistical modeling of sediment abundance
Wetmore and Hughes, 1997	INL	Model morphologies of subsurface lava flows
Wetmore and others, 1999	INL	Axial Volcanic Zone construction

Geologic Setting

The ESRP developed when the North American tectonic plate moved southwestward over a fixed upper mantle-melting anomaly beginning about 17 million years ago (Pierce and Morgan, 1992; Pierce and others, 2002; Morgan and McIntosh, 2005). Thermal disruption resulted in a time transgressive series of silicic volcanic fields, characterized by positive geoid anomalies, rhyolitic resurgent caldera eruptions, emplacement of a mid-crustal mafic sill, and subsidence with later basaltic plains magmatism (Braile and others, 1982; Anders and Sleep, 1992; Peng and Humphries, 1998; Rodgers and others, 2002; Shervais and others, 2006). The part of the ESRP now occupied by the INL was the site of resurgent caldera activity, which formed the Picabo volcanic field from 10.2 ± 0.06 million years ago (Ma) to 7.9 ± 0.4 Ma (Kellogg and others, 1994; McCurry and Hughes, 2006), and the Heise volcanic field from 7.05 ± 0.04 Ma to 4.43 ± 0.08 Ma (Pierce and Morgan, 1992; Morgan and McIntosh, 2005; McCurry and Hughes, 2006).

The ESRP is subsiding in the wake of the Yellowstone hot spot calderas (Braile and others, 1982; Anders and Sleep, 1992; McQuarrie and Rodgers, 1998; Rodgers and others, 2002). The ESRP subsided as it was filled, first with silicic material from the caldera eruptions, then later with tholeiitic basalt, and to a minor degree with fluvial sediments washed out onto the ESRP. The total volume of basalt fill of the ESRP is estimated to be 4 x 10^4 km^3 (9,600 mi^3) (Kuntz, 1992).

The ESRP is the type example of basaltic plains volcanism (Greeley, 1982). This form of basaltic volcanism is intermediate in style between flood basalts, such as the Columbia River Basalt Group, and shield volcano eruptions, such as those found in Hawaii and Iceland. Basaltic eruptions on the ESRP generated a land surface formed from coalesced shield volcanoes that produced voluminous tube-fed pahoehoe flows and fissure eruptions (Greeley, 1982). Basaltic plains volcanism is characterized by relatively low effusion rates, long recurrence intervals, low total volumes of lava erupted, and the prevalence of monogenetic volcanoes (Kuntz, 1992). ESRP shield volcanoes produce flows that range from about 1 to 40 m (3 to 131 ft) thick. The extent of most ESRP flows may be as large as 400 km^2 (155 mi^2). Lava flows may be up to 35 km (22 mi) long, and the accumulated volume of a shield volcano may be as large as 7 km^3 (1.7 mi^3) (Kuntz and others, 1992). The flank areas of typical ESRP low shield volcanoes have slopes that average less than 1 degree, whereas summit and vent areas have slopes of approximately 5 degrees (Greeley, 1982). Large, old vents are sometimes preserved as hills surrounded by flows from younger vents; a good example is AEC Butte (Kuntz and others, 1994).

More than 95 percent of the total volume of basalt in the ESRP is composed of tube-fed pahoehoe flows erupted from monogenetic shield volcanoes and lava cones (Kuntz and others, 1992). Basaltic lava fields, partially mantled with loess, cover the ESRP. The greatest numbers of eruptive centers are in the Axial Volcanic Zone (AVZ) (fig. 1) (Hackett and Smith, 1992). The AVZ is a constructional volcanic highland that parallels the long axis of the ESRP (Hackett and Smith, 1992; Kuntz and others, 1992, 1994; Anderson and Liszewski, 1997; Anderson and others, 1999; Hughes and others, 1999; Wetmore and others, 1999).

Basaltic eruptions have occurred on the ESRP an average of every 32,000 to 140,000 years over the entire INL (Champion and others, 2002). Eruptions in the northern part of the INL occur at longer intervals, and the shortest recurrence interval eruptions occur on or near the axis of the ESRP in the AVZ. Accumulation rates also are highest in and around the AVZ (fig. 1) (Champion and others, 2002).

Most ESRP basalts are olivine tholeiites, the result of small quantities of magma that rise to the surface from subcrustal sources over short periods of time without significant fractionation or crustal contamination (Kuntz and others, 1992). Most basaltic lava flows at the INL are petrographically similar and contain olivine, plagioclase, clinopyroxene, ilmenite, magnetite, glass, and accessory apatite (Kuntz, 1978). Extrusive rocks of more evolved compositions also are found on the ESRP, but the volume of these rocks is small in comparison with the volume of olivine tholeiite basalts. Evolved composition lavas are exposed on the surface at the Cedar Butte eruptive center in the southern part of the INL and are found at depth in coreholes to the north and east of Cedar Butte (fig. 2) (Anderson and others, 1996a).

Lava flow groups and vents on the surface in the southern part of the INL have normal polarity. These lava flow groups and vents were erupted during the Brunhes Normal Polarity Chron (less than 0.78 Ma). Some surface lava flow groups and vents in the northern part of the INL have reversed magnetic polarity and erupted during the Matuyama Reversed Polarity Chron (2.581–0.78 Ma) (fig. 3) (Gradstein and others, 2004). A young, reversed polarity lava flow group is found at 99 to 233 m (324 to 765 ft) depths in coreholes RWMC BG 77-1, C1A, ARA-COR-005, STF-AQ-01, NPR Test/W-02, and USGS 127, 129, 130, 131, 132, and 135 in the southern INL area, and was named as the Big Lost Reversed Polarity Subchron (565 ± 14 thousand years [ka]) by Champion and others (1988). This flow group has since been reclassified as the Big Lost Reversed Polarity Cryptochron, and has been referred to as the “F” flows in previous studies (Anderson and others, 1996a; Scarberry, 2003).

Historically, official corehole names have been shortened or otherwise modified in various publications or documents by different authors. Table 2 shows some variations and aliases of corehole names previously used. The corehole names used in this report are shown in the first column.

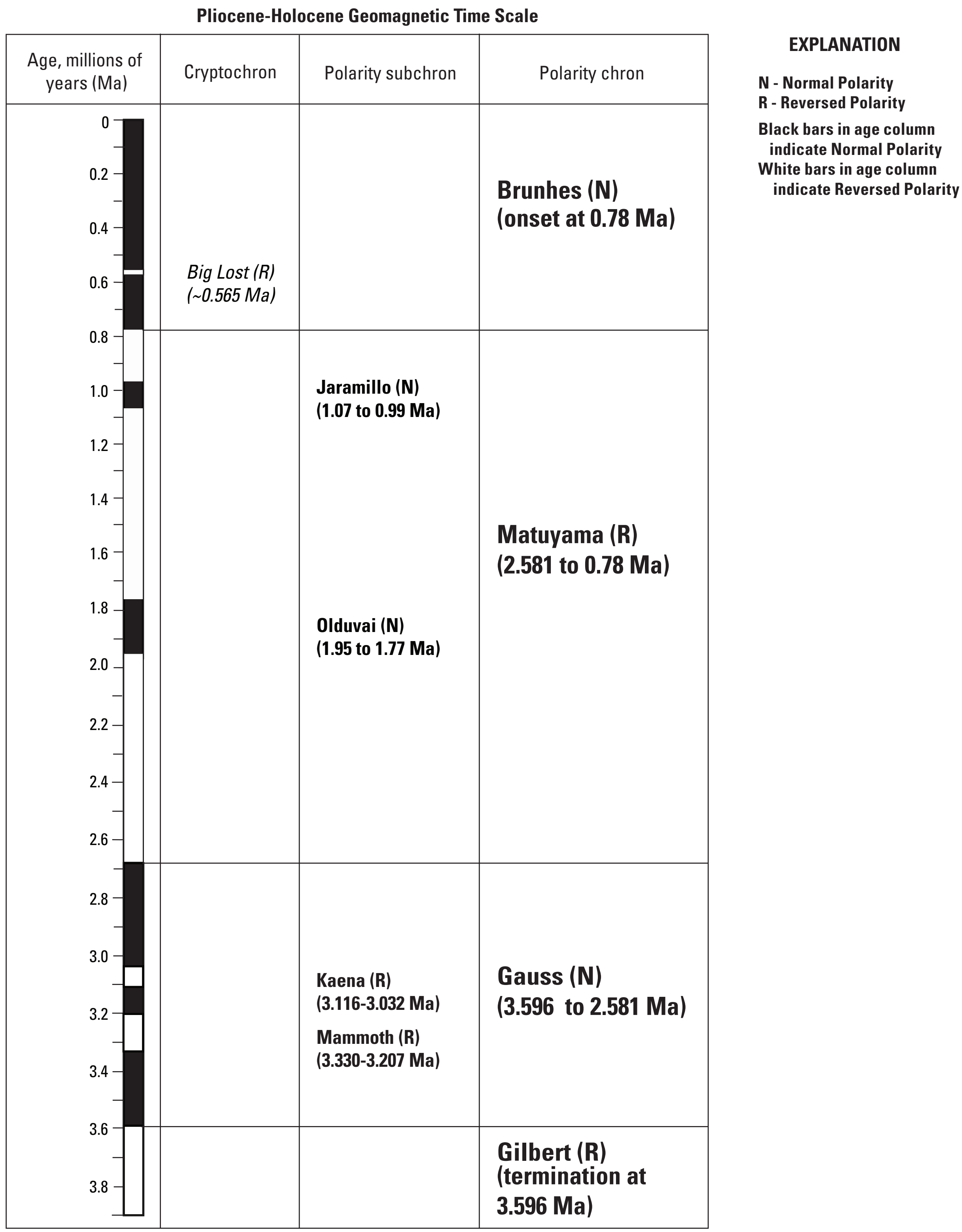


Figure 3. Pliocene-Holocene geomagnetic time scale.

Table 2. Selected corehole names used in this report and aliases used in previous publications.

Corehole name used in this report	Alternate corehole name	Alias 1	Alias 2	Alias 3
ANL DH 50	ANL DH-50	DH 50		
ANL-OBS-A-001	ANL-OBS-AQ-014	ANL-1	CH1	Argonne Deep Core
ARA-COR-005	ARA-005	ARA 1		
C1A	C-1A	C1A	C1-A	
Corehole 1	Corehole 1	CH-1		
Corehole 2-2A	Corehole 2-2A	2-2A	Corehole 2A	
GIN 5	GIN 5	GIN-05		
GIN 6	GIN 6	GIN-06		
ICPP 023	ICPP-COR-A-023	CPP-CH-AQ-01	ICPP-023	
ICPP 213	ICPP-SCI-V-213			
ICPP 214	ICPP-SCI-V-214			
ICPP 215	ICPP-SCI-V-215			
ICPP 1795	ICPP-1795			
ICPP 1796	ICPP-1796			
ICPP 1797	ICPP-1797			
ICPP 1798	ICPP-1798			
Middle 1823	Middle-1823			
Middle 2050A	Middle-2050A			
Middle 2051	Middle-2051			
NPR Test[1]	NPR-Test	Site E	NPR-E	
W-02[1]	NPR W-02	NPR-W-02	W02	W02 (deepened)
NRF 6P	NRF 6P	NRF #6P		
NRF 7P	NRF 7P	NRF #7P		
NRF 89-04	NRF 89-04			
NRF 89-05	NRF 89-05			
NRF B18-1	NRF B18-1	B18-1		
PW 13	PW-13			
BG 76-6	RWMC BG-76-6	BG-76-1	76-6	
BG 77-1	RWMC BG-77-1	BG-77-1	77-1	
STF-AQ-O1	STF-PIE-AQ-O1	STF-PIE-A-001	STF-1001	
TAN CH1	TAN CH1	TCH-1	TCH #1	
TAN CH2	TAN CH2	TCH-2	TCH #2 Piezo A	
TRA 5	TRA 05	TRA-05A	TRA 05/PZ1	
TRA 6	TRA 06	TRA-06A		
USGS 80	USGS 80	USGS-080		
USGS 81	USGS 81	USGS-081		
BG 93A	USGS 93A	USGS-93A	USGS-093A	BG-93A
BG 94	USGS 94	USGS-94	USGS-094	BG-94
USGS 118		USGS-118		
USGS 121	USGS 121	ICPP 121	USGS-121	
USGS 123	USGS 123	ICPP 123	USGS-123	
USGS 126A	USGS 126A	USGS-126A	USGS-OBS-A-126A	
USGS 127	USGS 127	USGS-127	USGS-OBS-A-127	USGS MON-A-127
USGS 128	USGS 128	USGS-128	CFA LF 3-11A	LF 3-11A
USGS 129	USGS 129	USGS-129		
USGS 130	USGS 130	USGS-130		
USGS 131	USGS 131	USGS-131		
USGS 132	USGS 132	USGS-132		
USGS 134	USGS 134	USGS-134		
USGS 135	USGS 135	USGS-135		
VZ6A-WWW1	VZ6A	WWW1	WWW-1	

[1]Coreholes NPR Test and W-02 are located near each other. Corehole NPR Test was cored from the 2.1 to 185.6 meters (6.8 to 609.2 feet) below land surface, and corehole NPR W-02 was cored from 189 to 1,523 meters (620.0 to 4,995.7 feet) below land surface. These two holes together form a composite stratigraphic record of the subsurface in the area.

Geomagnetic Framework

The remanent magnetization recorded by ferrimagnetic minerals in basalt lava flows aligns with the geomagnetic field vector as the basalt crystallizes and cools. The local geomagnetic field vector varies with an average angular motion of 4 to 5 degrees per 100 years in latest Pleistocene and Holocene basalt flows, with extreme variance from 0 to 10 degrees per 100 years (Champion and Shoemaker, 1977). Snake River Plain monogenetic volcanic fields with volumes of 4 km^3 (0.96 mi^3) or more record a single direction of remanent magnetization, indicating that individual lava flows belonging to that flow group erupted in a sufficiently brief period of time such that any change in the local geomagnetic field vector was too small to detect (less than 100 years). Each volcano most likely erupted for only a few days to a few decades of time. Paleomagnetic inclination and declination can be measured from samples collected from surface flows because the original orientation of the field core sample can be measured at the surface. The subcore plugs taken from drill cores and used in this study only yield inclination data because the original declination was not preserved in the drill cores during drilling.

Sampling and Analytical Techniques

The drill cores investigated for this study were carefully logged and sampled using INL Lithologic Core Storage Library protocols described in Davis and others (1997). Prior to sampling, the core material was described and the tops and bottoms of lava flows were identified. A lava flow is defined here as the minimum subdivision of a lava flow group, possessing quenched bottom and top surfaces, and typically part of a nearly contemporaneous group of other lava flows. Depths were measured by tape from known marks recorded on wooden plugs or footage marked on the cores in the core boxes at the drill site. The wooden plugs are placed, or marks on cores are made by the drillers at the time of coring, and record the measured depths logged at the end of each core run.

Attempts were made to take seven paleomagnetic samples from each identified lava flow when enough core material allowed. Using a drill press with a diamond-coring bit, a 2.5-cm (1 in) diameter core plug was drilled at right angles to the vertical axis of the original core. This plug was drilled almost through the original core slug to maximize the amount of material to work with and to preserve the orientation and the precision of labeling of the plug. The drill cores are assumed to be vertical in their original drilling orientation to facilitate paleomagnetic study. Gyroscopic deviation logs of most wells were made at 3 m (10 ft) intervals. They typically document less than one degree of corehole deviation from vertical, and thus, the deviations are no impediment to paleomagnetic remanent inclination interpretations. When deviations were greater than one degree, and occurred in a N-S vertical plane, corrections to the data were applied (appendix A).

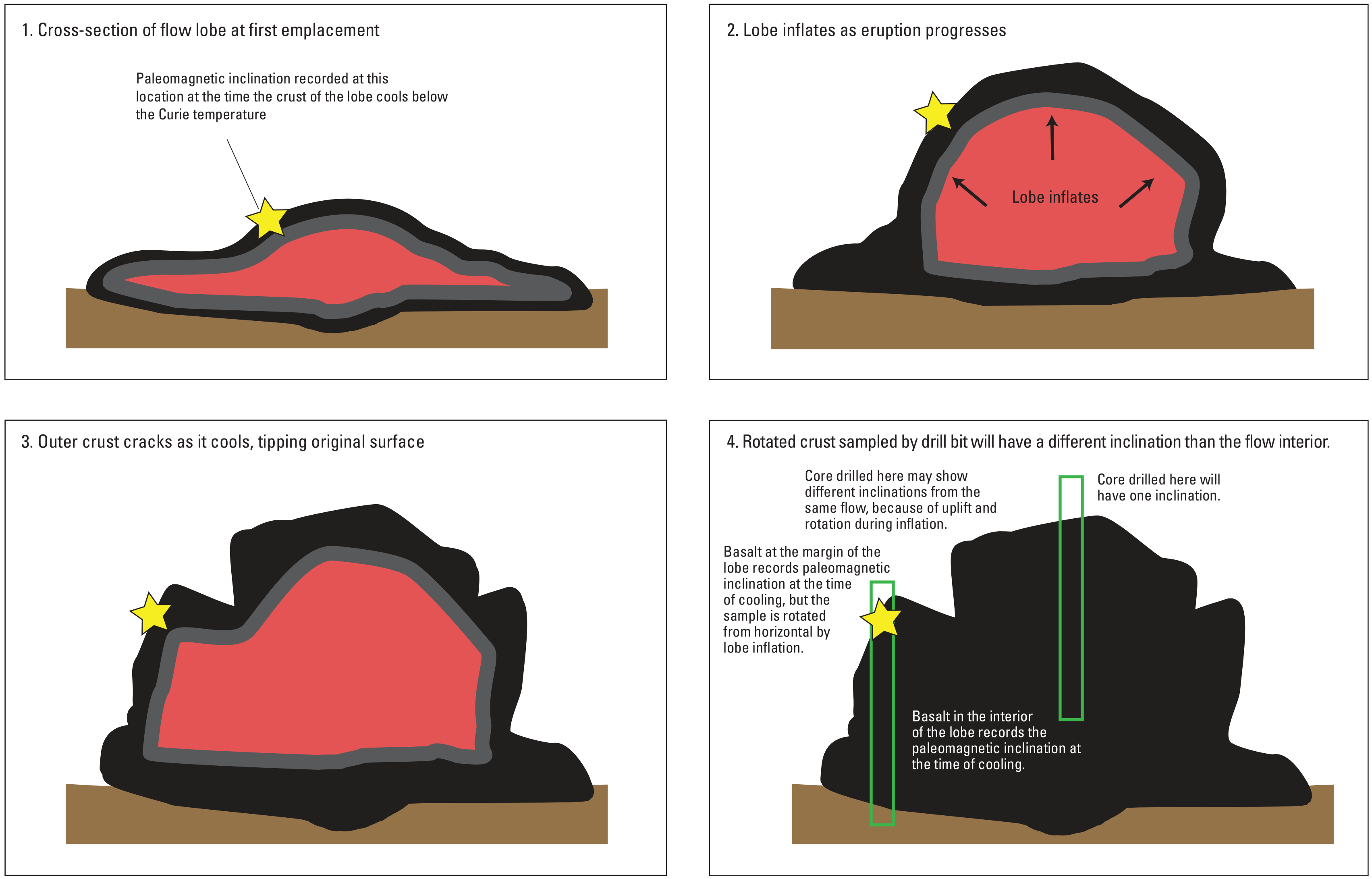
The core plugs were trimmed to 2.2-cm (0.87 in) lengths, and the inclination, unoriented declination, and intensity of magnetizations were measured with a cryogenic magnetometer. Progressive alternating-field (AF) demagnetization using a commercial tumbling demagnetizer was performed on one sample from each core plug to remove any components of secondary magnetization. A common secondary magnetization is found on many core plugs, imparted by the original drill string as a weak vertical downward isothermal remanent magnetization (IRM) and is easily removed. Very rare instances of a much stronger IRM imparted by a lightning strike to a previously exposed surface near the future corehole location also are observed. This secondary magnetization can penetrate 3 m (10 ft) or more along the vertical line of the corehole, and frequently cannot be removed. Mean inclination values for each lava flow and 95 percent confidence limits about the mean value were calculated using the method of McFadden and Reid (1982).

Following the protocols and procedures above, individual sample inclinations commonly are within ±5 degrees of the mean value of a single lava flow or flow groups of the same age. Above or below this depth interval, the inclination values obtained typically shift to center around a different steeper or shallower value. Notable exceptions to this common data distribution rule occur with samples from the uppermost parts of some lava flows as they are encountered with increasing depth. Samples with disparate inclination values typically are discarded and not included in the mean inclination value of the lava flow group(s) (appendix A).

The choice of the location to drill a suite of surficial field cores for paleomagnetic analysis on the ESRP is extremely important because the exposed uppermost surface of a lava flow may record anomalous remanent magnetic directions because of endogenous inflation of pahoehoe flows at the time of emplacement and cooling. This is a common physical process within ESRP basalt flows, which lifts and rotates the solid upper crust of the flow after it has acquired most or all of its remanent magnetic character (fig. 4). Surficial sample locations were evaluated in the field to minimize the possibility that a rotated surface domain was sampled. About 50 percent of a flow's surface should be suitable for paleomagnetic field sampling in order to avoid sampling a rotated surface and obtaining anomalous results.

It is likely that the top of an underlying flow found in a drill core may have been deformed, rotated, or both during emplacement, rendering the uppermost part of the flow unsuitable for paleomagnetic analysis (fig. 4). The depth range of samples near flow surfaces that need to be discarded is typically less than 1 to 2 m (3.2 to 6.5 ft).

The remanent magnetization of the top of any subsurface flow may be thermally remagnetized by subsequent eruption and emplacement of the overlying flow. Anomalous magnetizations because of this process are uncommon but



Modified from Self and others (1998).

Figure 4. Inflation and rotation of lava flow surfaces and implications for paleomagnetic inclination values.

may be mistaken for rotation of the upper surface of a flow, as previously described. Thermal remagnetization of flows is a minor process, probably because although molten basalt is erupted at about 1,100°C, it will heat the surface of the underlying flow to half of this temperature (550°C), below the 585°C Curie temperature of magnetite. Additionally, depending on the amount of time between eruptive events, even 0.3 m (1 ft) of loess accumulation on the surface of the underlying flow may provide sufficient insulation to limit thermal remagnetization.

Thermal remagnetization frequently is detected on the contacts between flows of opposing polarity. Since 2000, the demagnetization protocol changed such that several samples below polarity boundaries were routinely thermally demagnetized. Formerly, samples were demagnetized using the AF protocol. Thermal demagnetization better separates the original magnetization from the secondary one imposed by the overlying flow.

Every specimen taken from any flow recording the Big Lost Reversed Polarity Cryptochron was thermally demagnetized to remove the weak drill string IRM and to assess the relative declination orientations of overlying and underlying normal polarity flows, because they overprint and are overprinted, respectively, by subsequent flows. Assuming the bracketing normal polarity flows have declinations near zero degrees, an assessment of the declination of the Big Lost Reversed Polarity Cryptochron may be made. Champion and others (1988) provide further details of this analysis.

Correlation Techniques

Following the protocol and procedures above, it is possible to subsample any drill core, obtain characteristic inclination and polarity data, and average that data for any depth interval. The mean inclination value may represent just a few flows over as little as 3 m (10 ft) of depth, or represent data from a dozen or more flows over more than about 90 m (300 ft) of depth. In this report, the term “flow” refers to a single sheet of lava, and the term “flow group” refers to a package of flows from the same eruptive event (Kuntz and others, 1980). Each drill core can be characterized for polarity and inclination over its entire length. Nearby drill cores (100’s of meters to a few kilometers) may be correlated at similar depth intervals having the same polarity and inclination values.

The subsurface of the INL is “layercake,” with each successive low-relief flow group overlapping the edges of previous eruptions by as much as kilometers. Correlation is more difficult when coreholes are farther apart because flow group similarities may be difficult to identify. Flow groups may pinch out before reaching the next drill core, or additional flow groups(s) may be present in that drill core. At distances of about 10 km (6 mi) or greater, it may still be possible to correlate lava flow groups if they have the same petrography, polarity, and mean inclination values, but the depths at which they correlate may be significantly different (about ±15 to 30 m [50 to 100 ft]) because of topographic or structural controls or both on flow groups during and after emplacement. Supporting data such as geophysical logs, geochemical analyses, and age dating experiments are necessary to make correlations when coreholes are far apart.

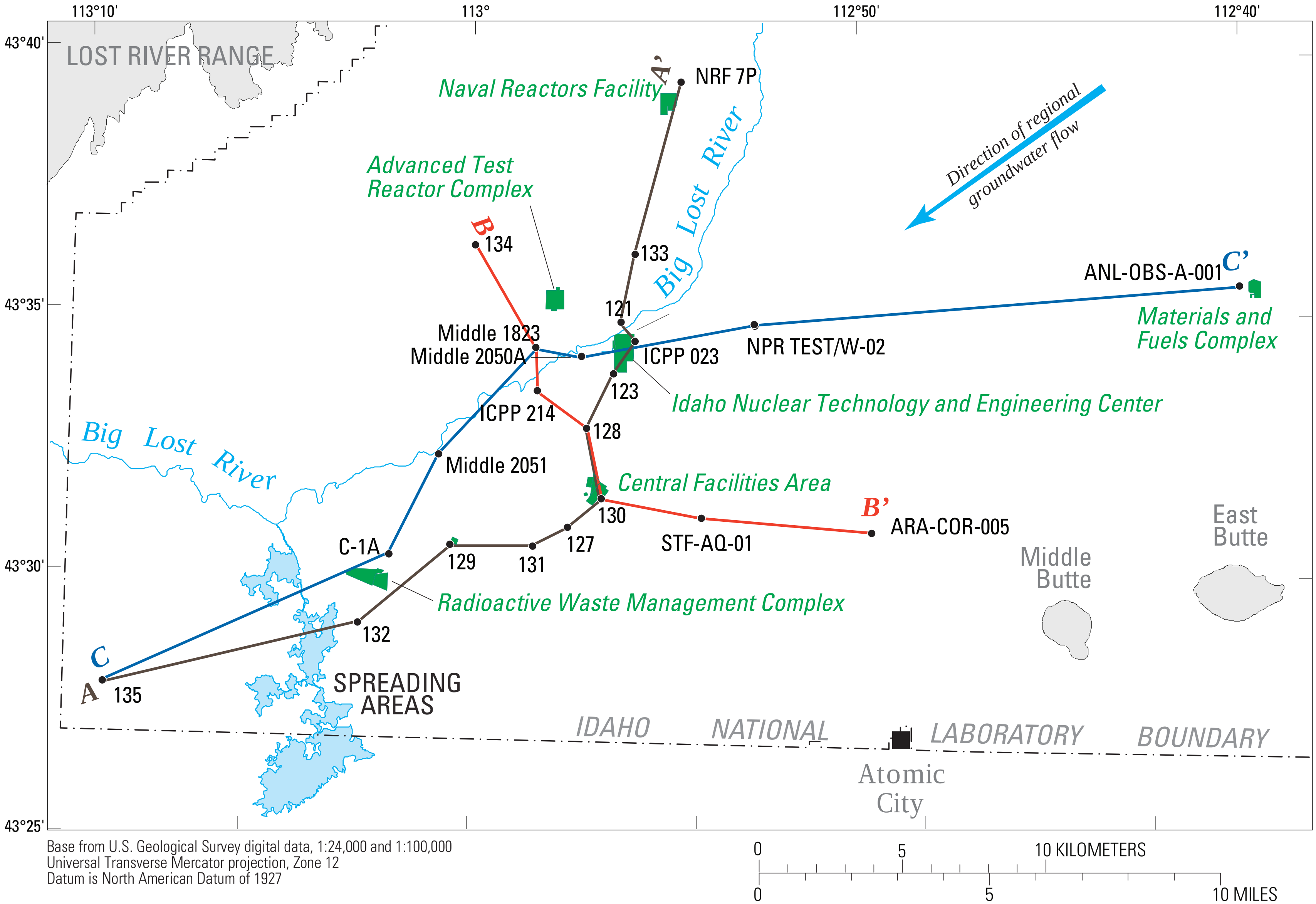
Lava Flow Group Labeling Conventions

Flow groups are labeled for their vents, such as “AEC Butte” and labeled as such on cross sections where surface to subsurface correlations are possible. Where surface to subsurface correlations are not possible, flow groups are labeled for chemical, spatial, or paleomagnetic identifiers. For example, a flow group that has relatively large amounts of potassium oxide is labeled “high K_2O,” and the reversed polarity flow group that records the Big Lost Reversed Polarity Cryptochron is labeled “Big Lost.”

Many volcanoes on the ESRP do not have formal names. Informal names have been adopted for these vents, some of which have been in use at the INL and among ESRP researchers for many years. Some names came from spot elevations on 7.5’ topographic maps, such as “vent 5206.” Other names were derived from proximity to INL facilities, such as the Advance Test Reactor Complex (ATRC) and may be designated “west of ATRC.” Other subsurface flow groups are labeled with capital letters, such as the “E” and “G” flow groups, following the terminology of workers who first investigated subsurface basalt cores at the INL, such as Kuntz and others (1980) and Anderson and Lewis (1989).

Cross Sections

Correlation of lava flow groups was established using subsurface cross sections through different areas of the INL. Stratigraphic units on the cross-section illustrations represent similar paleomagnetic inclinations for lava flows in that flow group. The blocks only represent a mean inclination value of a flow group; they do not represent the number or thickness of individual flows in a flow group. A southwest to northeast cross-section line, *A–A’* (fig. 5 and pl. 1), begins at corehole USGS 135 southwest of the Radioactive Waste Management Complex (RWMC), passes through coreholes USGS 132, USGS 129, USGS 131, USGS 127, USGS 130, USGS 128, USGS 123, ICPP 023, USGS 121, USGS 133, and ends at corehole NRF 7P, north of the Naval Reactors Facility (NRF). A northwest to southeast section line, *B–B’* (fig. 5 and pl. 1), begins at corehole USGS 134 west of the ATRC, passes through coreholes Middle 1823, ICPP 214, USGS 128, USGS 130, STF-AQ-01, and ends at corehole ARA-COR-005 located 10 km (6 mi) east of the Central Facilities Area (CFA), crossing section *A–A’* at USGS 128 to USGS 130 at a high angle. These cross sections represent the stratigraphy in the unsaturated zone and upper part of the ESRP aquifer.



Base from U.S. Geological Survey digital data, 1:24,000 and 1:100,000
Universal Transverse Mercator projection, Zone 12
Datum is North American Datum of 1927

Figure 5. Lines of cross-sections *A–A'*, *B–B'*, and *C–C'* and coreholes intersected in each section, Idaho National Laboratory, Idaho.

Another southwest to northeast cross-section, *C–C'* (fig. 5 and pl. 1), representing the stratigraphy of deeper sections of coreholes in the southern part of the INL, shows the stratigraphy of the lava flow groups at and below the Brunhes-Matuyama Polarity Boundary. Cross-section *C–C'* begins at corehole USGS 135, passes through coreholes C1A, Middle 2051, Middle 1823, Middle 2050A, NPR Test/W-02, and ends at ANL-OBS-A-001 at the Materials and Fuels Complex (MFC), formerly known as Argonne National Laboratory-West (ANL-W). The top of this cross section ranges from about 180 to 215 m (600 to 700 ft) depth below land surface in the comprising coreholes. In the coreholes shown in cross-section *C–C'*, the strata containing the majority of the lava flows emplaced during the Brunhes Normal Polarity Chron are excluded. Cross-section *C–C'* is intended to show the stratigraphy through which groundwater passes in the saturated zone.

Cross-Section *A–A'*

Cross-section *A–A'* (fig. 5 and pl. 1) intersects as many as 15 different lava flow groups and numerous interbedded sediments. This discussion proceeds from land surface to the bottom of the coreholes, southwest to northeast, and describes the lava flow groups that have important corehole to corehole correlations. The top few flow groups in cross-section *A–A'* correlate to flow groups that are exposed at the surface and have been mapped geologically by Kuntz and others (1994). Paleomagnetic samples have been taken at sites in these surface flows, and the data from these sample sites are listed in table 3. Surface sample sites have completely oriented directions of remanent magnetization and subsurface corehole inclination means agree with the surface site inclination data for flow groups that can be traced from surface to subsurface.

Table 3 contains data for 83 paleomagnetic surface sites located at and near the INL, and has been divided into 5 subsets representing different areas of the INL. The subsets are designated as:

- Northern INL (Lava Ridge volcanic rift zone – Test Area North [TAN] area)
- Eastern INL (Hells Half Acre volcanic rift zone)
- Southeastern INL (along U.S. Route 20)
- South of southern INL boundary
- Western INL (RWMC and CFA areas)

The majority of lava flows at the surface of the INL have normal polarity acquired during the Brunhes Normal Polarity Chron. Lava flow groups in the TAN area mostly have reversed polarity remanent directions, and are older than the onset of the Brunhes Normal Polarity Chron (0.78 Ma) (fig. 3).

Quaking Aspen Butte Flow Group

The youngest flow group (Kuntz and others, 1994) in cross-section *A–A'* (pl. 1) is only found in corehole USGS 132, has a mean inclination of 60 degrees, and correlates to a surface site with a 63.6-degree inclination in the Quaking Aspen Butte (QAB) flow group (fig. 2, vent ID LL; table 3, Site 4B655). The QAB flow group comes from Quaking Aspen Butte, a large, young (95 ± 50 ka) (Kuntz and others, 1980) shield volcano located southwest of the INL. Quaking Aspen Butte flows cross the western boundary of the INL just to the north of the RWMC. At the RWMC, QAB flows disappear into the thick sediments of the south-central part of the INL (Rightmire and Lewis, 1987) and terminate somewhere to the northeast.

Vent 5206 Flow Group

The vent 5206 flow group is found in coreholes USGS 132, USGS 129, USGS 131, USGS 127, USGS 130, and USGS 128 in the middle of cross-section *A–A'* (pl. 1). Vent 5206 is located north of Big Southern Butte (fig. 2, vent ID FF; table 3, site number 4B583) and is older than 95 ± 50 ka and younger than 190 ka (Kuntz and others, 1980). The vent 5206 surface paleomagnetic site has an inclination of 63.9 degrees, which corresponds well with inclination values in coreholes that range from 62 to 66 degrees. The vent 5206 flow group is thickest in corehole USGS 129, pinches out to the north and east under the thick surficial central INL sediment layer, and against flows from Mid Butte (fig. 2, vent ID HH). To the south, vent 5206 flows are overlain by flows from the eruption of the Cerro Grande basalt shield (fig. 2, near vent ID CC). The Cerro Grande basalt shield erupted about 13.38 ± 0.35 ka (carbon-14 date, Kuntz and others, 1986).

Mid Butte Flow Group

Mid Butte (fig. 2, vent ID HH; table 3, site number 4B607) is just north of Highway 20 and 3.2 km (2 mi) northwest of Middle Butte. The Mid Butte flow group is 233 ± 34 ka (Champion and others, 1988) and has a mean inclination of 52 degrees. This value matches the inclinations of the flow group in coreholes USGS 128, USGS 123, and ICPP 023 (pl. 1) that have values ranging from 51 to 53 degrees.

East of Middle Butte Unknown Vent Flow Group

In coreholes USGS 129, USGS 131, USGS 127, and USGS 130, lava flow groups with mean inclinations near 60 degrees underlie vent 5206 flows and overlie Lavatoo Butte flows (pl. 1). No surface source has been identified for these flows, but there are surface vents east of Middle Butte (fig. 5) that have mean inclination values near 60 degrees that may correlate with this subsurface flow group.

Table 3. Paleomagnetic data for surface sample sites at and near the Idaho National Laboratory, Idaho.

[Shading delineates the sample sites averaged. **Vent/flow identification:** map reference name, or the altitude of the vent (in feet) producing the lava flow. **Site**: alphanumeric identifier of the paleomagnetic sampling site. Sites and Vents are shown in figure 2. **Lat.** and **Long.:** Sampling site location in latitude degrees (north), and longitude degrees (west). **N/no:** Number of cores used compared with the number originally taken at the site. **Exp.:** Strength of the peak Alternating Field demagnetization field in milliTesla; + symbol indicates that the peak field strength was at least as high as the given number, in milliTesla; Li and Pl, are lines and planes solutions, respectively, using principal component analysis of Kirschvink (1980). **I:** Remanent inclination in degrees, positive for downward inclinations and negative for upward inclinations. **D:** Remanent declination in degrees east of north. **α95:** Radius of the 95-percent confidence limit about the mean direction. **k:** Estimate of the Fisher (1953) precision parameter. **R:** Length of the resultant vector; —, no R value available for planes (Pl) solutions. **Plat.** and **Plong.:** Location in latitude degrees (north) and longitude degrees (east) of the virtual geomagnetic pole (VGP) calculated from the mean direction of the sampling site. **Abbreviations:** °, degree; INL, Idaho National Laboratory; TAN, Test Area North; RWMC, Radioactive Waste Management Complex; CFA, Central Facilities Area]

Vent/flow identification	Site	Lat.	Long.	N/no	Exp.	I	D	α95	k	R	Plat.	Plong.
Northern INL - (Lava Ridge Volcanic Rift Zone - TAN Area)												
Vent 4957 (Antelope Butte)	A9631	43.885°	112.613°	12/12	30+	65.4°	328.4°	2.3°	361	11.96951	67.8°	177.9°
Antelope Butte	B7109	43.819°	112.602°	12/12	Pl	64.4°	334.9°	3.0°	236	—	72.2°	173.9°
Antelope Butte average		**43.85°**	**112.61°**	**2/2**		**64.9°**	**331.7°**	**6.4°**	**1,528**	**1.99935**	**70.0°**	**176.2°**
Vent 5450	B7037	43.978°	112.832°	11/12	Pl	-53.0°	157.8°	1.5°	1,263	—	-69.9°	313.5°
Vent 5450	4B787	43.948°	112.759°	12/12	40+	-47.2°	158.5°	2.1°	434	11.97463	-66.8°	302.2°
Vent 5450 average		**43.96°**	**112.8°**	**2/2**		**-50.1°**	**158.2°**	**12.7°**	**388**	**1.99742**	**-68.4°**	**307.3°**
Vent 5110	B5500	43.924°	112.789°	11/12	30+	-56.0°	201.0°	2.4°	360	10.9722	-72.5°	174.9°
Vent 5110	465B6	43.930°	112.810°	8/8	Pl	-56.0°	200.3°	1.6°	1,034	—	-72.9°	175.8°
Vent 5110 average		**43.93°**	**112.80°**	**2/2**		**-56.0°**	**200.7°**	**0.9°**	**84,733**	**1.99999**	**-72.7°**	**175.3°**
Vent 5044	4B883	43.886°	112.799°	12/12	30+	-50.6°	203.1°	1.7°	676	11.98372	-67.9°	184.0°
Vent 5044	B7061	43.849°	112.819°	10/12	30+	-50.5°	203.9°	1.0°	2305	9.99609	-67.4°	183.0°
Vent 5044	B7097	43.830°	112.799°	11/12	30	-52.2°	202.4°	1.1°	1657	10.99396	-69.4°	182.0°
Vent 5044	457B6	43.900°	112.790°	8/8	Pl	-47.9°	203.0°	1.7°	931	—	-66.4°	188.7°
Vent 5044 average		**43.87°**	**112.80°**	**4/4**		**-50.3°**	**203.1°**	**2.1°**	**1,978**	**3.99848**	**-67.8°**	**184.6°**
Circular Butte	4B799	43.841°	112.640°	8/12	Pl	-67.6°	189.8°	2.8°	1,065	—	-80.6°	108.9°
Vent 4925	4B775	43.995°	112.627°	9/12	40+	-75.3°	223.7°	1.9°	705	8.98866	-59.0°	105.8°
Vent 4862	A9643	43.878°	112.656°	10/12	Pl	58.8°	328.1°	1.9°	630	—	66.0°	158.1°
Richard Butte	B7025	43.963°	112.759°	12/12	30+	-65.8°	194.0°	2.1°	426	11.97421	-79.4°	129.3°
Vent 5262	481B6	43.960°	112.831°	8/8	Pl	-48.1°	166.9°	2.1°	614	—	-71.9°	286.7°
Vent 5305 (Northern INL)	B7049	43.952°	112.831°	9/12	Pl	-77.7°	199.0°	2.5°	481	—	-65.3°	85.3°
Unknown vent	473B6	43.952°	112.834°	8/8	40	-50.9°	210.9°	2.1°	726	7.99036	-62.8°	173.7°
Vent 4976	B7121	43.875°	112.797°	12/12	Pl	-71.9°	161.1°	2.2°	568	—	-72.4°	31.3°

Table 3. Paleomagnetic data for surface sample sites at and near the Idaho National Laboratory, Idaho.—Continued

[Shading delineates the sample sites averaged. **Vent/flow identification:** map reference name, or the altitude of the vent (in feet) producing the lava flow. **Site**: alphanumeric identifier of the paleomagnetic sampling site. Sites and Vents are shown in figure 2. **Lat.** and **Long.:** Sampling site location in latitude degrees (north), and longitude degrees (west). **N/no:** Number of cores used compared with the number originally taken at the site. **Exp.:** Strength of the peak Alternating Field demagnetization field in milliTesla; + symbol indicates that the peak field strength was at least as high as the given number, in milliTesla; Li and Pl, are lines and planes solutions, respectively, using principal component analysis of Kirschvink (1980). **I:** Remanent inclination in degrees, positive for downward inclinations and negative for upward inclinations. **D:** Remanent declination in degrees east of north. **α95:** Radius of the 95-percent confidence limit about the mean direction. **k:** Estimate of the Fisher (1953) precision parameter. **R:** Length of the resultant vector; —, no R value available for planes (Pl) solutions. **Plat.** and **Plong.:** Location in latitude degrees (north) and longitude degrees (east) of the virtual geomagnetic pole (VGP) calculated from the mean direction of the sampling site. **Abbreviations:** °, degree; INL, Idaho National Laboratory; TAN, Test Area North; RWMC, Radioactive Waste Management Complex; CFA, Central Facilities Area]

Vent/flow identification	Site	Lat.	Long.	N/no	Exp.	I	D	α95	k	R	Plat.	Plong.
Eastern INL - (Hells Half Acre Volcanic Rift Zone)												
Teat Butte	4B895	43.763°	112.743°	10/12	20+	42.9°	11.4°	1.5°	1,104	9.99185	69.0°	37.2°
Vent 4853	4B907	43.761°	112.736°	11/12	30+	38.3°	4.8°	0.8°	3,318	10.99699	67.4°	55.5°
Vent 4853	A9619	43.783°	112.756°	12/12	20+	40.9°	6.0°	1.4°	1,041	11.98944	69.0°	51.7°
Vent 4812	345B8	43.788°	112.683°	10/12	Pl	44.3°	5.9°	2.1°	737	—	71.6°	50.3°
Vent 5171	465B8	43.664°	112.624°	11/12	Pl	41.0°	2.8°	5.4°	65	—	69.7°	60.0°
Vent 5313 (Topper Butte)	B7073	43.759°	112.535°	12/12	30+	42.5°	8.4°	1.3°	1,135	11.99031	69.7°	45.0°
Vent 5313 (Topper Butte)	381B8	43.651°	112.544°	11/12	Pl	46.8°	2.4°	2.8°	253	—	74.3°	59.6°
Vent 5271 SE	453B8	43.617°	112.572°	11/12	30+	43.5°	5.7°	1.1°	1,693	10.99409	71.2°	51.2°
Vent 5315	477B8	43.552°	112.494°	11/12	30+	42.5°	1.8°	1.7°	710	10.98592	71.0°	62.6°
average		**43.6°**	**112.6°**	**9/9**		**42.6°**	**5.5°**	**2.1°**	**614**	**8.98698**	**70.5°**	**52.3°**
Tanner Butte	B7013	43.753°	112.493°	12/12	20+	64.3°	30.1°	1.8°	595	11.98153	68.7°	320.5°
Vent 5007	B7085	43.724°	112.538°	9/12	40+	63.8°	28.7°	2.5°	442	8.98189	69.6°	322.5°
average		**43.73°**	**112.52°**	**2/2**		**64.1°**	**29.4°**	**1.7°**	**21,001**	**1.99995**	**69.1°**	**321.5°**
Vent 5454 (Deuce Butte)	4B739	43.556°	112.456°	11/12	30+	64.5°	13.0°	1.7°	746	10.98659	80.4°	316.1°
Vent 5454 (Deuce Butte)	357B8	43.718°	112.640°	12/12	Pl	62.3°	13.2°	2.0°	975	—	80.5°	333.5°
Vent 5305 (Eastern INL)	369B8	43.693°	112.578°	12/12	Pl	64.5°	12.7°	3.3°	166	—	80.7°	316.5°
average		**43.6°**	**112.6**	**3/3**		**63.8°**	**13.0°**	**1.9°**	**4,039**	**2.9995**	**80.6°**	**321.8°**
Kettle Butte (Pinhead Butte)	4B751	43.557°	112.440°	12/12	30+	38.4°	357.3°	2.2°	375	11.97069	68.0°	74.3°
Kettle Butte	570B4	43.550°	112.392°	7/8	30+	44.7°	358.8°	1.9°	997	6.99398	72.7°	71.4°
Kettle Butte average		**43.55°**	**112.42°**	**2/2**		**41.6°**	**358.0°**	**14.0°**	**321**	**1.99688**	**70.3°**	**73.0°**
Vent 5410	4B823	43.619°	112.456°	11/12	40	61.6°	344.8°	1.2°	1,352	10.99261	78.9°	158.3°
Vent 5298	441B8	43.625°	112.528°	12/12	Pl	65.3°	5.0°	2.2°	373	—	84.9°	288.7°
Vent 5148	4B835	43.687°	112.490°	6/12	Li	53.4°	316.8°	4.8°	193	—	55.4°	156.1°
Vent 5316	429B8	43.686°	112.435°	12/12	Pl	75.7°	8.3°	3.8°	165	—	70.1°	258.7°
Vent 5181	B7001	43.778°	112.425°	12/12	Pl	60.1°	355.9°	1.4°	893	—	85.9°	116.5°

Table 3. Paleomagnetic data for surface sample sites at and near the Idaho National Laboratory, Idaho.—Continued

[Shading delineates the sample sites averaged. **Vent/flow identification:** map reference name, or the altitude of the vent (in feet) producing the lava flow. **Site**: alphanumeric identifier of the paleomagnetic sampling site. Sites and Vents are shown in figure 2. **Lat.** and **Long.:** Sampling site location in latitude degrees (north), and longitude degrees (west). **N/no:** Number of cores used compared with the number originally taken at the site. **Exp.:** Strength of the peak Alternating Field demagnetization field in milliTesla; + symbol indicates that the peak field strength was at least as high as the given number, in milliTesla; Li and Pl, are lines and planes solutions, respectively, using principal component analysis of Kirschvink (1980). **I:** Remanent inclination in degrees, positive for downward inclinations and negative for upward inclinations. **D:** Remanent declination in degrees east of north. **α95:** Radius of the 95-percent confidence limit about the mean direction. **k:** Estimate of the Fisher (1953) precision parameter. **R:** Length of the resultant vector; —, no R value available for planes (Pl) solutions. **Plat.** and **Plong.:** Location in latitude degrees (north) and longitude degrees (east) of the virtual geomagnetic pole (VGP) calculated from the mean direction of the sampling site. **Abbreviations:** °, degree; INL, Idaho National Laboratory; TAN, Test Area North; RWMC, Radioactive Waste Management Complex; CFA, Central Facilities Area]

Vent/flow identification	Site	Lat.	Long.	N/no	Exp.	I	D	α95	k	R	Plat.	Plong.
Southeastern INL - (along U.S. Route 20)												
Microwave Butte	4B691	43.554°	112.598°	11/12	30	66.1°	343.2°	1.7°	687	10.98545	77.4°	186.1°
Microwave Butte	B5536	43.706°	112.819°	11/12	30+	62.1°	342.4°	1.3°	1,276	10.99216	77.2°	161.5°
Microwave Butte average		**43.6°**	**112.7°**	**2/2**		**64.1°**	**342.8°**	**8.8°**	**815**	**1.99877**	**77.6°**	**173.7°**
Vent 5742	325A0	43.505°	112.649°	10/12	Pl	61.7°	2.9°	2.4°	363	—	87.8°	352.8°
Moonshiner's Cave	4B763	43.503°	112.684°	8/12	30+	61.6°	6.0°	1.7°	1,103	7.99366	85.6°	344.9°
Unit average		**43.50°**	**112.67°**	**2/2**		**61.7°**	**4.5°**	**3.2°**	**6,031**	**1.99983**	**86.7°**	**347.5°**
Little Butte	489B8	43.532°	112.562°	12/12	Pl	50.2°	33.1°	1.5°	805	—	61.1°	352.0°
Mid Butte Vent	4B607	43.512°	112.774°	12/12	30+	52.3°	340.9°	2.5°	302	11.9636	71.7°	128.2°
Vent 5350	4B619	43.534°	112.693°	12/12	20+	62.7°	352.8°	2.1°	442	11.97513	84.8°	165.9°
Vent 5561	4B727	43.548°	112.642°	10/12	30+	59.9°	7.6°	2.1°	542	9.98339	83.7°	0.9°
Vent 5252	4B703	43.518°	112.751°	9/12	30+	71.2°	358.9°	0.9°	3,229	8.99752	77.8°	244.3°
Vent 5398	4B595	43.496°	112.863°	11/12	30+	52.9°	350.1°	1.7°	723	10.98617	77.4°	108.0°
Vent 5551	4B847	43.498°	112.708°	12/12	Pl	62.0°	355.4°	2.1°	373	—	86.6°	150.6°
Radio Facility Butte	4B811	43.545°	112.589°	8/12	30+	69.6°	14.3°	1.4°	1,679	7.99583	76.4°	286.2°
Vent 5415 (Twin)	4B715	43.540°	112.667°	10/12	40+	68.6°	305.4°	2.3°	457	9.98033	53.3°	190.2°
South of southern INL Boundary												
Cedar Butte andesite	4B931	43.419°	112.901°	11/12	40+	62.2°	352.7°	1.6°	851	10.98825	84.7°	159.6°
Cedar Butte	501B8	43.402°	112.932°	11/12	Pl	62.6°	359.7°	2.2°	368	—	89.4°	226.2°
Cedar Butte	513B8	43.385°	112.920°	11/12	Pl	60.1°	357.1°	5.1°	78	—	86.8°	110.2°
Cedar Butte	525B8	43.381°	112.909°	11/12	Pl	59.7°	356.1°	4.5°	134	—	86.0°	114.1°
Cedar Butte	537B8	43.372°	112.908°	11/12	Pl	61.9°	351.6°	3.2°	213	—	83.9°	157.6°
Cedar Butte	549B8	43.388°	112.907°	12/12	Pl	54.3°	355.9°	4.1°	140	—	80.9°	88.8°
Cedar Butte	561B8	43.416°	112.899°	12/12	Pl	62.6°	359.1°	2.3°	355	—	89.2°	197.7°
Cedar Butte	573B8	43.398°	112.911°		(Cleans to anomalous directions)							
Cedar Butte-Trimodal Dyke	585B8	43.394°	112.909°	12/12	Pl	62.0°	356.5°	3.7°	155	—	87.5°	154.8°
Cedar Butte average		**43.4°**	**112.91°**	**8/9**		**61.6°**	**356.1°**	**1.4°**	**1,908**	**6.99868**	**87.1°**	**146.1°**

Table 3. Paleomagnetic data for surface sample sites at and near the Idaho National Laboratory, Idaho.—Continued

[Shading delineates the sample sites averaged. **Vent/flow identification:** map reference name, or the altitude of the vent (in feet) producing the lava flow. **Site**: alphanumeric identifier of the paleomagnetic sampling site. Sites and Vents are shown in figure 2. **Lat.** and **Long.:** Sampling site location in latitude degrees (north), and longitude degrees (west). **N/no:** Number of cores used compared with the number originally taken at the site. **Exp.:** Strength of the peak Alternating Field demagnetization field in milliTesla; + symbol indicates that the peak field strength was at least as high as the given number, in milliTesla; Li and Pl, are lines and planes solutions, respectively, using principal component analysis of Kirschvink (1980). **I:** Remanent inclination in degrees, positive for downward inclinations and negative for upward inclinations. **D:** Remanent declination in degrees east of north. **α95:** Radius of the 95-percent confidence limit about the mean direction. **k:** Estimate of the Fisher (1953) precision parameter. **R:** Length of the resultant vector; —, no R value available for planes (Pl) solutions. **Plat.** and **Plong.:** Location in latitude degrees (north) and longitude degrees (east) of the virtual geomagnetic pole (VGP) calculated from the mean direction of the sampling site. **Abbreviations:** °, degree; INL, Idaho National Laboratory; TAN, Test Area North; RWMC, Radioactive Waste Management Complex; CFA, Central Facilities Area]

Vent/flow identification	Site	Lat.	Long.	N/no	Exp.	I	D	α95	k	R	Plat.	Plong.
South of southern INL Boundary—Continued												
Vent 5183	4B859	43.428°	112.634°	11/12	40+	59.7°	317.8°	2.8°	267	10.96255	58.9°	166.8°
Vent 5119	B5584	43.452°	112.775°	12/12	30+	57.6°	12.7°	1.6°	706	11.98441	79.1°	1.5°
Table Legs Butte	4B919	43.443°	112.776°	12/12	20	51.9°	23.4°	1.4°	993	11.98892	68.7°	0.2°
Borrow Pit west of Atomic City	B5548	43.449°	112.843°	12/12	30	48.0°	13.9°	1.4°	1,020	11.98921	71.8°	25.1°
Vent 5212	B5560	43.435°	112.829°	12/12	30+	65.1°	355.5°	1.5°	839	11.98689	85.1°	208.5°
Borrow Pit near Cerro Grande	B5572	43.412°	112.864°	10/12	Pl	59.4°	0.5°	2.4°	391	—	86.8°	60.3°
Vent 5494	489B6	43.375°	112.988°	8/8	30+	51.7°	359.6°	2.2°	627	7.98883	79.0°	68.8°
Vent 5244	646B4	43.407°	113.100°	8/8	Pl	66.0°	7.6°	3.1°	265	—	82.8°	291.4°
Western INL - (RWMC and CFA areas)												
State Butte Vent	4B679	43.673°	112.879°	12/12	Pl	74.6°	18.0°	3.3°	159	—	69.5°	272.3°
State Butte Flow	B5488	43.670°	112.884°	9/12	Pl	75.4°	26.9°	2.1°	740	—	65.6°	277.5°
State Butte average		**43.672°**	**112.88°**	**2/2**		**75.0°**	**22.3°**	**5.3°**	**2,214**	**1.99955**	**67.6°**	**275.1°**
AEC Butte	4B667	43.594°	112.945°	9/12	40+	53.5°	359.0°	1.6°	986	8.99188	80.4°	72.0°
AEC Butte west	B5476	43.598°	112.959°	10/12	20+	53.3°	359.3°	2.5°	371	9.97577	80.2°	70.5°
AEC Butte average		**43.59°**	**112.95°**	**2/2**		**53.4°**	**359.2°**	**0.6°**	**182,395**	**1.99999**	**80.3°**	**71.3°**
Crater Butte	4B643	43.580°	113.090°	9/12	30+	60.5°	345.8°	1.2°	1,764	8.99546	79.3°	150.4°
Crater Butte	4B631	43.607°	113.162°	12/12	30+	63.1°	342.1°	1.6°	784	11.98597	77.1°	167.4°
Crater Butte average		**43.59°**	**113.13°**	**2/2**		**61.8°**	**344.0°**	**6.8°**	**1,339**	**1.99925**	**78.4°**	**159.6°**
Lavatoo Butte	A9607	43.520°	113.095°	12/12	10+	54.8°	354.7°	1.3°	1,069	11.98971	80.8°	95.2°
South of Lavatoo Butte	A9595	43.518°	113.089°	11/12	10+	56.1°	357.5°	1.5°	908	10.98899	82.9°	83.4°
Lavatoo Butte average		**43.52°**	**113.09°**	**2/2**		**55.5°**	**356.1°**	**4.5°**	**3,120**	**1.99968**	**81.9°**	**90.0°**
Knob VABM	B5512	43.689°	112.994°	9/12	Pl	-50.7°	184.6°	3.6°	215	—	-77.2°	229.0°
South of Knob VABM	B5524	43.682°	113.001°	11/12	Pl	55.3°	359.8°	1.2°	1,467	—	82.2°	68.2°
Quaking Aspen Butte	4B655	43.551°	113.015°	12/12	20+	63.6°	344.8°	1.1°	1,493	11.99263	79.0°	170.9°
Vent 5206	4B583	43.507°	112.889°	12/12	30+	63.9°	12.6°	1.1°	1,655	11.99335	80.8°	319.7°
Coyote Butte	638B4	43.480°	113.114°	8/8	Pl	63.1°	0.8°	1.8°	1,338	—	88.8°	274.2°
Box Canyon flow	4B943	43.558°	113.217°	10/12	20	50.4°	348.2°	1.2°	1,541	9.99416	74.5°	107.6°

Lavatoo Butte Flow Group

The Lavatoo Butte (fig. 2, vent ID ZZ) flow group is 211 ± 16 ka (Champion and others, 2002) and has a mean inclination value of 55 degrees, which matches the inclinations of flows in coreholes USGS 132, USGS 129, USGS 131, and USGS 127 that have values in the mid-50 degrees (pl. 1). This flow group is 15 to 30 m (50 to 100 ft) thick and underlies vent 5206 flows. Stratigraphy in this depth interval seems to place the East of Middle Butte and Mid Butte flow groups (fig. 2, vent ID HH) over the Lavatoo Butte lava flow group. The Mid Butte flow group is 233 ± 34 ka (Champion and others, 1988) and the Lavatoo Butte flow group is 211 ± 16 ka (Champion and others, 2002). The discrepancy in ages is insignificant in light of the uncertainties in the age dates.

West of ATRC Flow Group

The next oldest lava flow group in cross-section *A–A'*, labeled "west of ATRC" (pl. 1), appears in laterally separated depth intervals beneath the Lavatoo Butte lava flow group in corehole USGS 129, and beneath a sediment layer in coreholes USGS 121, USGS 133, and NRF 7P. This lava flow group records 74 to 76 degree paleomagnetic inclinations, and has an age of 303 ± 30 ka (D.E. Champion, U.S. Geological Survey, unpub. data). The vent for this flow group is not known with certainty, but a likely candidate is a nearly buried vent located about 4.8 km (3 mi) northwest of the ATRC in the northeastern corner of section 4., T3N, and R29E (fig. 2). The "west of ATRC" vent is almost buried by young lava flows (292 ± 58 ka) (Skipp and others, 2009) from the huge basalt shield volcano, Crater Butte (fig. 2, vent ID KK). Crater Butte flows dominate the surface of the western INL (Kuntz and others, 1994). The subsurface distribution of the"west of ATRC" lava flows is consistent with the location of the "west of ATRC" vent. These flows are thickest in coreholes USGS 133 and 134 (cross-sections *A–A'* and *B–B'*, pl. 1), which are the nearest coreholes to the vent. The "west of ATRC" flows are at the surface throughout the NRF area (fig. 5; pl. 1). Lava flows from the "west of ATRC" vent also extend southwest to northern RWMC area coreholes (C1A, BG 76-6, BG 77-1, VZ6A, and BG 94) (fig. 1; appendix A).

High K_2O Flow Group

The high K_2O flow group is the next deepest correlative sequence of lava flows and is found in coreholes USGS 131, USGS 127, USGS 130, USGS 128, and USGS 123. The high K_2O flow group has paleomagnetic inclinations of 49 to 54 degrees, is enriched in K_2O compared to most ESRP olivine tholeiites (Reed and others, 1997; Grimm-Chadwick, 2004), and is relatively easy to distinguish in natural gamma logs. The high K_2O flow group is aphanitic and aphyric, making it fairly easy to identify it in hand specimen. The vent for the high K_2O flow group is unidentified but may be at the surface to the south and east of cross-section *B–B'* (fig. 5).

Vent 5252 Flow Group

The vent 5252 flow group is in coreholes USGS 131, USGS 127, USGS 130, USGS 128, USGS 123, and ICPP 023 (cross-section *A–A'*, pl. 1). Vent 5252 is located on the northwestern margin of the AVZ northwest of Middle Butte (fig. 2, vent ID QQ), and its flows run downhill to the northwest. Vent 5252 flows have a mean inclination of 71 degrees and are 350 ± 40 ka old (Champion and others, 1988).

Tin Cup Butte Flow Group

Corehole USGS 135 spuds into a sequence of lava flows with low 70 degree mean inclinations that erupted from Tin Cup Butte (cross-section *A–A'*, pl. 1). The Tin Cup Butte, State Butte, and AEC Butte lava flow groups are the oldest in cross-section *A–A'* (pl. 1) for which a surface vent can be identified (Kuntz and others, 1994) (fig. 2). Most deeper correlative intervals probably do not have vents still exposed at the surface. Despite being fairly close to the RWMC area, USGS 135 does not sample any of the young sequences in RWMC coreholes in that area (cross-section *A–A'*, pl. 1). The next two deeper flow groups in corehole USGS 135 with mean inclinations of 51 and 60 degrees do not correlate to any flow groups in other coreholes in cross-section *A–A'*.

ATRC Unknown Vent Flow Group

The next oldest flow group in cross-section *A–A'* is labeled the ATRC unknown vent (pl. 1). This lava flow group has 51 to 55 degree mean inclinations and is found in coreholes ICPP 023, USGS 121, and USGS 133. An age of 376 ±81 ka (Champion and others, 2002) in corehole USGS 121 provides some age control for this flow group. This 51 to 55 degree mean inclination flow group may correlate to the second flow group in corehole NRF 7P, which is close to the same age (395 ± 25 ka), but that flow group has a steeper mean inclination value of 57 degrees, and thus does not match well to the 51 to 55 degree sequence in coreholes ICPP 023, USGS 121, and USGS 133. No gyroscopic deviation log exists for corehole NRF 7P, so there is more uncertainty in paleomagnetic inclination measurements in this corehole than in other coreholes.

South CFA Buried Vent(s) Flow Group

The next oldest flow group, labeled the South CFA buried vent(s), have mean paleomagnetic inclinations ranging from 57 to 64 degrees (cross-section *A–A'*, pl. 1). In most of the coreholes in which this flow group is found, steeper inclinations are found above shallower indicating either dynamic variation of the geomagnetic field during the eruption of this flow group, or that this flow group is composed of two stratigraphically overlapping flow groups. This flow group is found in coreholes USGS 129, USGS 131, USGS 127, USGS 130, USGS 128, and USGS 123. This flow group is thickest in coreholes USGS 131, USGS 127, and USGS 130, so the vents for this flow group may be close to those coreholes. No age experiments have been performed on any sample from a corehole in this flow group, but Champion and others (2002) estimated ages for the flows of about 376 and 406 ka, based on the inference of the linear accumulation rate in corehole USGS 123.

North INTEC Buried Vent Flow Group

The North INTEC buried vent flow group underlies the South CFA buried vent(s) flow group in coreholes USGS 128 and USGS 123. It underlies the ATRC unknown vent flow group in coreholes ICPP 023, USGS 121, USGS 133, and possibly in corehole NRF 7P (cross-section *A–A*', pl. 1). This lava flow group has mean inclinations between 53 to 57 degrees, and is thickest in coreholes ICPP 023 and USGS 121 such that the buried vent is probably near those coreholes beneath the north INTEC area. The age of this flow group is uncertain; results of age dating experiments range from 441 ± 77 ka in NPR Test/W-02 (Champion and others, 1988) (fig. 5 and cross-section *C–C*', pl. 1), 466 ± 39 ka in USGS 123, to 543 ± 48 ka in USGS 121 (Champion and others, 2002). The weighted mean age and standard error of these ages is 489 ± 28 ka, which agrees with argon ages from flows bounding this sequence.

The 57-degree mean inclination flow group located between 32 to 46 m (105 to 151 ft) depths in corehole NRF 7P also may correlate to this sequence, despite that flow group having an argon age of 395 ± 25 ka (Champion and others, 2002). This is younger than the ages obtained for this flow group from coreholes USGS 121, USGS 123, and NPR Test/W-02.

Low K_2O Flow Group

The low K_2O flow group is the next oldest sequence of flows found in coreholes USGS 123, ICPP 023, and USGS 121 (cross-section *A–A*', pl. 1). This flow group is a sequence of thin lava flows that have relatively low K_2O values (Reed and others, 1997), are olivine phyric, and have mean inclinations of 60 to 62 degrees. The low K_2O flow group might be an important chemostratigraphic marker; however, in coreholes drilled to date, the low K_2O flow group has limited lateral extent. The low K_2O flows do not seem to be correlative to the low K_2O "E" flows near the RWMC discussed below because their paleomagnetic inclinations do not match.

"E" Flow Group

The "E" flow group (Anderson and Lewis, 1989) is found in coreholes USGS 135 and USGS 132 in cross-section *A–A*' (pl. 1) and is the next oldest flow group with an age of 515 ± 85 ka (Kuntz and others, 1980). The "E" flow group has 67 to 68 degree mean inclination values in a thick lava flow group widely distributed in the subsurface of the southern RWMC area (coreholes BG 94, BG 77-1, and USGS 118) (fig. 1, appendix A). The "E" flow group is not found in coreholes to the north or east of cross-section *A–A*'.

Big Lost Flow Group

The Big Lost flow group is in coreholes USGS 135, USGS 132, USGS 129, USGS 131, USGS 127, and USGS 130 (cross-section *A–A*', pl. 1). The Big Lost flow group is an important marker in the subsurface correlation of the southern INL because it has anomalous shallow reversed polarity mean inclinations (-47 to -30 degrees) and is 565 ± 14 ka in age (Champion and others, 1988). In cross-section *A–A*', the Big Lost flow group is thickest in coreholes USGS 129 and USGS 131. The thickness of the Big Lost flow group in coreholes USGS 118, BG 77-1, and RWMC C1A (fig. 1 and appendix A) indicates that the Big Lost vent is likely buried near the RWMC. Its lava flows probably filled the valley of a former course of the Big Lost River that flowed past and to the east of the RWMC. Miller (2007) made a geochemical correlation between lava flows from Lavatoo Butte and the Big Lost flow groups, but the mean paleomagnetic inclination, polarity, and age of the Lavatoo Butte flow group does not match that of the Big Lost flow group. Geochemically, the Lavatoo Butte flow group is very similar to the Big Lost flow group because their magmas erupted under similar conditions and in close proximity (Mel Kuntz, U.S. Geological Survey [retired], oral commun., 2010).

Generally, in coreholes with more than one Big Lost flow, each overlying younger flow has a shallower reversed polarity inclination. Inferred internal tielines, dashed in the Big Lost flow group in cross-section *A–A*', represent time boundaries within the Big Lost flow group.

At the time of the Big Lost eruptions, the paleovalley of the Big Lost River passed close to coreholes USGS 132 and USGS 131 and early lava accumulation (-44 and -42 degree mean inclinations) occurred there. The youngest lava flows (-30 and -32 degree mean inclinations) were emplaced at the periphery of the Big Lost lava field. An example is found in corehole USGS 130 (cross-section *A–A*', pl. 1). The relatively "early" -40 degree mean inclination found for a thin sequence of Big Lost flows in corehole USGS 135 is at a higher altitude than older, thicker, and more steeply inclined reversed inclination flows in coreholes in the immediate RWMC area. The simplest explanation for this observation is different relative subsidence of the USGS 135 area and the RWMC area since about 565 ka ago.

"G" Flow Group

The "G" flow group (Anderson and Lewis, 1989) is the next oldest lava flow group and is found in coreholes USGS 135 and USGS 132 (cross-section *A–A*', pl. 1). A thick sequence of 58 to 60 degree mean inclination lava flows in USGS 135 that thins to a single 58 degree lava flow in corehole USGS 132. The "G" flow group is also found in coreholes C1A and BG 77-1 (fig. 1 and appendix A) in the subsurface of the RWMC area but is not found in coreholes east of the RWMC.

CFA Buried Vent Flow Group

The next sequence, labeled the CFA buried vent flow group, is found in coreholes USGS 132, USGS 129, USGS 131, USGS 127, USGS 130, USGS 128, USGS 123, ICPP 023, USGS 121, USGS 133, and perhaps in NRF 7P (cross-section *A–A*', pl. 1). The CFA buried vent flow group records mean inclination values ranging from 65 to 69 degrees, with the exception of one flow in corehole USGS 123, which has a mean inclination of 61 ± 7.3 degrees, a much larger than usual uncertainty. The flow group is thickest between coreholes USGS 129 and USGS 121 suggesting a vent south of the CFA. Age experiments on samples from this interval in coreholes USGS 121, USGS 123, and NPR Test/W-02 (fig. 5) yielded a weighted mean age of 617 ± 22 ka (Champion and others, 2002). Corehole NRF 7P has 67 degree flows in approximately the same stratigraphic position, but those flows are 521± 31 ka in age (Champion and others, 2002) and, therefore may be too young and not correlated (cross-section *A–A*', pl. 1).

State Butte Flow Group

Corehole NRF 7P contains a thick 73 degree mean inclination flow group that is also found in NRF 89-04, NRF 89-05, NRF B18-1, and NRF 6P (fig. 1; cross-section *A–A*', pl. 1; and appendix A). Surface samples from State Butte, located near NRF (fig. 2, vent ID PP, site numbers 4B679 and B5488), have a mean inclination of 75 degrees, which is a reasonable match for the 73-degree mean inclination of this flow group in corehole NRF 7P. The age of this flow group is 546 ± 47 ka in corehole NRF 6P, which is located just southwest of NRF 7P (Champion and others, 2002), and the State Butte surface outcrop has an age of 579 ± 130 ka (Kuntz and others, 1994) further supporting a correlation.

AEC Butte Flow Group

The AEC Butte lava flow group in coreholes USGS 128, USGS 123, ICPP 023, USGS 121, USGS 133, and NRF 7P (cross-section *A–A*', pl. 1) records mean inclinations of 50 to 58 degrees. It correlates to surface lava flows from AEC Butte (fig. 2, vent IDs MM and NN, table 3, site numbers 4B667 and B5476) that have a mean inclination of 53 degrees. AEC Butte is 637 ± 35 ka in age (Champion and others, 2002) and has very limited surface expression, but its flows are found in many coreholes in south-central INL (appendix A). The AEC Butte flow group is also found in coreholes USGS 134, Middle 1823, NPR Test/W-02, Middle 2050A, and USGS 80 (fig. 1; cross-section *B–B*', pl. 1; and appendix A). In cross-section *A–A*', the AEC Butte flow group is thickest in USGS 133, the closest corehole to the AEC Butte vent at the surface. The AEC Butte flow group extends northeast to corehole NRF 7P, south to USGS 121, ICPP 023, USGS 123, and USGS 128. The AEC Butte flow group pinches out to the south of USGS 128.

Basal Brunhes Chron Flow Groups

Three different flow groups mark the base of the Brunhes Normal Polarity Chron. On cross-sections *A–A*' and *B–B*', they are labeled Early, Middle, and Late Basal Brunhes flow groups because they are all found in stratigraphic order in corehole Middle 1823 above the boundary that separates the Brunhes Normal Polarity Chron and the Matuyama Reversed Polarity Chron (cross-sections *A–A*' and *B–B*', pl. 1). The Early Basal Brunhes flow group is thickest in the Big Lost Trough, the Middle Basal Brunhes flow group is thickest in the southern part of the INL, and the Late Basal Brunhes flow group is thickest in the west-central part of the INL (fig. 1, pl. 1).

Late Basal Brunhes Flow Group

The Late Basal Brunhes flow group is beneath the AEC Butte flow group and has mean inclinations ranging from 62 to 66 degrees (cross-section *A–A*', pl. 1). This flow group is present in coreholes ICPP 023, USGS 121, USGS 133, and NRF 7P and thickens to the southwest before pinching out somewhere southwest of corehole ICPP 023. In coreholes USGS 133 and NRF 7P, these are the basal lava flows of the Brunhes Normal Polarity Chron (cross-section *A–A*', pl. 1).

Middle Basal Brunhes Flow Group

The Middle Basal Brunhes flow group is the oldest that can be correlated between coreholes USGS 135, USGS 132, USGS 129, USGS 131, USGS 130, and USGS 128 in the lava flows of the Brunhes Normal Polarity Chron (cross-section *A–A*', pl. 1). This interval has mean inclination values between 64 to 66 degrees, and underlies the AEC Butte lava flows. The Middle Basal Brunhes flow group underlies the previously described CFA buried vent flow group and is separated from it in most coreholes by a sediment layer. In coreholes USGS 135, USGS 132, and USGS 129, this is the basal lava flow group of the Brunhes Normal Polarity Chron. Similarity in mean inclination values suggests the possibility that the Late Basal Brunhes and Middle Basal Brunhes flow groups may be correlative units.

Early Basal Brunhes Flow Group

The Early Basal Brunhes flow group is found in coreholes USGS 128, USGS 123, ICPP 023, and USGS 121 (cross-section *A–A*', pl. 1) and has mean inclinations of 55 to 58 degrees. In corehole USGS 121 at the INTEC, the

Early Basal Brunhes flow group was dated at 759 ± 12 ka (Champion and others, 2002), which is close to the 0.78 Ma transition from the Matuyama Reversed Polarity Chron to the Brunhes Normal Polarity Chron (fig. 3).

The deepest flow groups in corehole USGS 131 have mean inclinations of 68 and 54 degrees. They do not correlate to flow groups in adjacent coreholes in part because those wells were not deep enough. The deepest flow group in corehole USGS 131, with 54 degree mean inclination, is likely correlative to the Early Basal Brunhes flow group. Cross-section *A–A'* shows this tentative correlation, with the Brunhes-Matuyama polarity boundary just below it. The approximate magnetic polarity boundary is represented as a dashed red line in the middle of cross-section *A–A'* just below the cored intervals (pl. 1). The magnetic polarity boundary is well-defined in coreholes USGS 135, USGS 132, and USGS 129. In coreholes USGS 133 and NRF 7P, the change in magnetic polarity occurred during the accumulation of the sediment layer between the Late Basal Brunhes and North Late Matuyama flow groups.

Matuyama Chron Flow Groups

Five flow groups, four with reversed polarity and one with normal polarity, erupted during the Matuyama Reversed Polarity Chron. These Matuyama flow groups are shown on cross-section *A–A'* (pl. 1). One of these flow groups, labeled “Matuyama” is found in coreholes USGS 135, USGS 132, and USGS 133 and probably underlies the entire line of cross section. Two younger flow groups, labeled the South Late Matuyama and North Late Matuyama flow groups, are found in the southern and northern part of the cross section, respectively (cross-section *A–A'*, pl. 1). An older flow group underlies the Matuyama flow group in USGS 135 and USGS 132. It is labeled the Post-Jaramillo (Matuyama) flow group because it is between the Matuyama flows and the underlying normal polarity Jaramillo (Matuyama) flow group found in USGS 132.

South Late Matuyama Flow Group

At the southwest end of cross-section *A–A'*, coreholes USGS 135 and USGS 132 contain paired sequences of -61 to -62 degree mean inclination lava flows overlying -59 to -60 degree mean inclination lava flows, together comprising the South Late Matuyama flow group. Only the deeper sequence is found in corehole USGS 129 but pinches out to the northeast of that corehole (pl. 1). It is possible that these flows with similar mean inclinations are part of a single time sequence. Despite their similar, steepening mean inclination values, this lava flow group may be two separate lava flow groups.

North Late Matuyama Flow Group

At the northeastern end of cross-section *A–A'*, coreholes USGS 133 and NRF 7P have -47 and -46 degree mean inclination lava flows, respectively, near their bases (pl. 1). This flow group is only found in the northern part of the cross section in two different NRF area coreholes (NRF 6P and NRF 7P [appendix A]), and in corehole USGS 133. It has been dated at 884 ± 53 ka in corehole NRF 7P (Champion and others, 2002).

Matuyama Flow Group

In corehole USGS 133, the Matuyama flow group underlies the North Late Matuyama flow group and has two lava flows with steep mean reversed inclination values near -70 degrees (cross-section *A–A'*, pl. 1). Similar steep inclination values are found in thick sequences in the deeper portions of coreholes USGS 135 and USGS 132. This lava flow group is found in the subsurface in the entire southwestern and south-central parts of the INL and is an important correlative flow group for cross-section *C–C'*, which is discussed below.

Post-Jaramillo (Matuyama) Flow Group

The Post-Jaramillo (Matuyama) flow group has a -66-degree mean inclination in corehole USGS 135, and a -64-degree mean inclination in corehole USGS 132. A deeper -71-degree flow group is found in corehole USGS 135 and does not correlate to any other coreholes.

Jaramillo (Matuyama) Flow Group

The deepest flow group in corehole USGS 132 is labeled the Jaramillo (Matuyama) flow group and has normal polarity with a 52-degree mean inclination value. This flow group was emplaced during the Jaramillo Normal Polarity Subchron (fig. 3), about 1.045 ± 0.012 Ma (B. Turrin, Rutgers University, written commun., 2010).

Cross-Section *B–B'*

Cross-section *B–B'* (fig. 5 and pl. 1), starts in the northwest at corehole USGS 134 and passes through coreholes Middle 1823 (the upper 152 m (500 ft) of corehole Middle 1823 were not cored), ICPP 214, USGS 128, USGS 130, STF-AQ-01, and ends at ARA-COR-005. Cross-section *B–B'* is oriented northwest to southeast generally perpendicular to the direction of groundwater flow of the ESRP aquifer. The speed and direction of groundwater flow may be affected by the thickness, degree of fracturing, orientation, and distribution of lava flows and flow groups. Cross-section *B–B'* samples most of the flow groups present in cross-section *A–A'* (pl. 1) and several that are not in cross-section *A–A'*. Coreholes USGS 128 and USGS 130 appear in both lines of section.

Vent 5206 Flow Group

The youngest (less than 190 ka) (Kuntz and others, 1980) flows in cross-section *B–B'* (pl. 1) are from vent 5206, which is located north of Big Southern Butte (fig. 2, vent ID FF). Lava flows from vent 5206 flowed downhill to the northeast and are in coreholes USGS 128, USGS 130, and STF-AQ-01 and have 65 degree mean inclinations. These flows pinch out south and east of corehole ICPP 214 and north and west of corehole ARA-COR-005.

Crater Butte Flow

Corehole USGS 134 is the only corehole in cross-section *B–B'* (pl. 1) that contains a flow from Crater Butte (fig. 2, Vent/flow ID KK and KK1). The huge, 292 ± 58 ka (weighted mean of two potassium-argon sample ages, Skipp and others, 2009) Crater Butte shield volcano is more than 16 km (10 mi) northwest of the CFA, and its lava flows cover much of the surface of the western INL. In corehole USGS 134, the Crater Butte flow is thin and has a paleomagnetic inclination of 59 degrees. Surface paleomagnetic sites in Crater Butte lavas (table 3, site numbers 4B643 and 4B631) have a mean inclination value of 62 degrees and agree with the corehole USGS 134 inclination within the margin of error. Crater Butte lava flows overlie the 303 ± 30 ka flows from the "west of ATRC" vent.

Mid Butte Flow Group

The Mid Butte flow group has paleomagnetic inclinations ranging from 52 to 58 degrees and underlies vent 5206 flows in STF-AQ-01. In the southeastern part of cross-section *B–B'*, this flow group is present at the top of corehole ARA-COR-005. Map relations suggest that the 52 degree and 53 degree flows in ICPP 214 and USGS 128 may also be from Mid Butte (Kuntz and others, 1994). The flow group pinches out near corehole ICPP 214, may or may not be found in the uncored part of corehole Middle 1823, and slightly thickens to the southeast toward corehole USGS 128. It does not seem to correlate to the thick East of Middle Butte Unknown Vent flow group found at the same depth interval in corehole USGS 130.

East of Middle Butte Unknown Vent Flow Group

In corehole USGS 130, vent 5206 flows overlie a thick 60-degree mean inclination flow, labeled "East of Middle Butte Unknown Vent flow group" (cross-section *B–B'*, pl. 1). Stratigraphic relations between this unit and the Mid Butte flows are unclear. No surface source has been identified for this flow group, but there are surface vents east of Middle Butte (fig. 5) that have mean inclination values near 60 degrees that may correlate with this subsurface flow group.

West of ATRC Flow Group

Lava flows from a vent labeled "west of ATRC" have mean inclinations of 77 degrees and are 303 ± 30 ka (D.E. Champion, U.S. Geological Survey, unpub. data). This flow group is in coreholes USGS 134 and ICPP 214, possibly in corehole Middle 1823, and pinches out southeast of corehole ICPP 214 (cross-section *B–B'*, pl. 1). An interpreted correlation of these flows was made to the upper part of corehole Middle 1823 (queried on cross-section *B–B'*, pl. 1) based on correlation to the southeast in nearby corehole ICPP 213 (fig. 1 and appendix A) because the upper 152 m (500 ft) of corehole Middle 1823 was not cored. The thickness and identity of the flows from land surface to 152-m depth in corehole Middle 1823 is speculative. Beneath the "west of ATRC" flow group, lava flows with a mean inclination of 54 degrees, labeled the "ATRC unknown vent" appear only in corehole USGS 134 in cross-section *B–B'*.

High K_2O Flow Group

The high K_2O lava flow group in coreholes ICPP 214, USGS 128, USGS 130, STF-AQ-01, and ARA-COR-005 has mean inclination values ranging from 49 to 59 degrees. The higher mean inclination value for the high K_2O flow group in corehole ICPP 214 for this interval is because of residual thermal overprinting to a steeper inclination value from the overlying 77-degree inclination of the west of ATRC lava flow group. Alternating-field demagnetization was unable to remove the effects of this magnetic overprinting. Natural gamma geophysical logs of corehole Middle 1823 do not show the distinctive kick of the high K_2O flows in the uncored upper interval of corehole Middle 1823, which suggests that the high K_2O flow group did not reach corehole Middle 1823. The vent for the high K_2O flow group is unidentified but may be one of the surface vents south or east of cross-section *B–B'*, or it may be buried (fig. 2). Beneath the high K_2O flow group, a 6 m (20 ft) thick uncorrelated lava flow with a mean inclination of 61 degrees is found only in corehole STF-AQ-01. A 2-m (7 ft) lava flow with an inclination of 64 degrees for which an uncertainty cannot be calculated is found only in corehole ARA-COR-005.

Vent 5252 Flow Group

The vent 5252 flow group (fig. 2, vent ID QQ) has mean inclination values ranging between 69 and 71 degrees, is 350 ± 40 ka old (Champion and others, 1988), and is found in coreholes ICPP 214, USGS 128, USGS 130, STF-AQ-01, and ARA-COR-005 (cross-section *B–B'*, pl. 1). The vent 5252 flow group may be in the uncored upper part of corehole Middle 1823 based on its presence in nearby corehole ICPP-213 (fig. 1 and appendix A). Beneath the vent 5252 flow group, lava flows with a mean inclination value of 53 degrees are found only in corehole ARA-COR-005.

South CFA Buried Vent(s) Flow Group

The South CFA buried vent(s) flow group has mean inclinations of 59 to 64 degrees and underlies the vent 5252 flows (cross-section *B–B*', pl. 1). This flow group is present in all of the coreholes in cross-section *B–B*' and is thickest in corehole STF-AQ-01. The thickness of this flow group and variability of paleomagnetic inclinations suggest that multiple vents of similar age were near STF-AQ-01. This flow group thins and appears to flow uphill to the northwest. This appearance is likely because of differential subsidence of the ESRP to the southeast combined with thick accumulations of lava flows near the vents. Beneath this flow group, lava flows from the North INTEC Buried Vent are found only in corehole USGS 128.

Big Lost Flow Group

The Big Lost flow group is 565 ± 14 ka (Champion and others, 1988) and underlies the South CFA buried vents flow group in coreholes USGS 130, STF-AQ-01, and ARA-COR-005 (cross-section *B–B*', pl. 1). As discussed for cross-section *A–A*', shallower reversed polarity inclinations overlie steeper inclinations in this flow group. Two uncorrelated lava flows with mean inclinations of 45 and 60 degrees overlie the Big Lost flow group and are found only in corehole ARA-COR-005. Of the coreholes in cross-section *B–B*', corehole ARA-COR-005 is closest to the AVZ, where there are more volcanic vents and lava flows than the rest of the INL, and where subsidence toward the southeast and accumulation are more pronounced (Champion and others, 2002).

Uncorrelated 54 and 56 Degree Flows

A wedge of 54 and 56 degree mean inclination flows underlies the Big Lost flow group in coreholes STF-AQ-01 and ARA-COR-005 (cross-section *B–B*', pl. 1). This sequence is not found farther northwest in other coreholes in cross-section *B–B*' or *A–A*'. As discussed above, corehole ARA-COR-005 is the closest corehole to the AVZ, an area of greater lava flow accumulation and subsidence, and these flows seem to be an older stratigraphic interval.

CFA Buried Vent Flow Group

The CFA Buried Vent flow group has individual lava flows with inclinations ranging between 64 to 69 degrees, and is found in coreholes USGS 134, Middle 1823, ICPP 214, USGS 128, and USGS 130 (cross-section *B–B*', pl. 1). Age experiments on samples from this interval in coreholes NPR Test/W-02, USGS 121, and USGS 123 (fig. 5) yield a weighted mean age of 617 ± 22 ka (Champion and others, 2002). This flow group is thickest in coreholes to the north and west of the CFA (USGS 128, ICPP 214, Middle 1823, Middle 2050A, and Middle 2051 [appendix A]) and the vent may be located near there.

AEC Butte Flow Group

The AEC Butte flow group is found in coreholes USGS 134, Middle 1823, and USGS 128 and has mean inclination values ranging between 53 to 58 degrees (cross-section *B–B*', pl. 1). The AEC Butte flow group deepens from USGS 134 to the south and pinches out before reaching corehole USGS 130.

Basal Brunhes Chron Flow Groups

In cross-section *B–B*', as in cross-section *A–A*', the Late Basal Brunhes flow group (62 to 63 degree inclinations) underlies the AEC Butte flow group (pl. 1). In cross-section *B–B*', these flows are present in coreholes USGS 134 and Middle 1823. The Late Basal Brunhes flow group thickens toward corehole USGS 134, indicating that the vent for this flow group may be north or west of corehole USGS 134. The Late Basal Brunhes flow group overlies the Middle Basal Brunhes flow group (64 to 67 degree inclinations) in corehole Middle 1823. The Middle Basal Brunhes flow group is also found in coreholes USGS 128, USGS 130, and STF-AQ-01. The Early Basal Brunhes flow group (54 to 58 degree inclinations) underlies the Middle Basal Brunhes flow group in coreholes Middle 1823 and USGS 128, and underlies the Late Basal Brunhes flow group in corehole USGS 134. The Brunhes-Matuyama magnetic polarity boundary is shown as a red dashed line below the Basal Brunhes flow groups (cross-sections *A–A*' and *B–B*', pl. 1).

Matuyama Chron and Post-Jaramillo (Matuyama) Flow Groups

The stratigraphy of this interval is dominated by reversed polarity lava flows that have mean inclinations from -68 to -72 degrees labeled the Matuyama flow group (cross-section *B–B*', pl. 1). This interval overlies a sequence of reversed polarity lava flows labeled the Post-Jaramillo (Matuyama) flow group with -62 to -64 degree mean inclinations in corehole USGS 134. The Matuyama flow group is also in cross-section *A–A*' in coreholes USGS 135, USGS 132, and USGS 133 (cross-section *A–A*', pl. 1). The Matuyama flow group overlies the Post-Jaramillo (Matuyama) flow group in cross-section *A–A*' that has -64 and -66 degree mean inclinations and correlate to the -62- to -64-degree flows in corehole USGS 134 in cross-section *B–B*'. The Post-Jaramillo (Matuyama) flow groups may be present at depth throughout the western INL because they are found in coreholes USGS 135, USGS 132, and USGS 134 (figs. 5 and pl. 1).

Jaramillo (Matuyama) Flow Group

The Jaramillo (Matuyama) flow group is at the base of cross-section *B–B'* and is found in coreholes USGS 134 and Middle 1823 (pl. 1) and has mean inclinations ranging from 53 to 57 degrees. The Jaramillo (Matuyama) flow group is also in the bottom of USGS 132 in cross-section *A–A'* (pl. 1). These normal polarity flows likely erupted during the Jaramillo Normal Polarity Subchron (fig. 3) about 1.045 ± 0.012 Ma (B. Turrin, Rutgers University, written commun., 2010).

Cross-Section *C–C'*

Cross-section *C–C'* (fig. 5 and pl. 1) is about 45 km (28 mi) long, is nearly parallel to the topographic axis of the ESRP, and shows the stratigraphy of the most extensive older lava flows and flow groups and sediments that compose the saturated zone of the ESRP aquifer in the southern INL. Stratigraphic sequences for the unsaturated zone are shown in cross-sections *A–A'* and *B–B'*. Cross-section *C–C'* only includes stratigraphic sequences found below the approximate Brunhes-Matuyama polarity boundary. Cross-section *C–C'* starts at corehole USGS 135, passes through coreholes C1A, Middle 2051, Middle 1823, Middle 2050A, NPR Test/W-02, and ends at corehole ANL-OBS-A-001. Cross-section *C–C'* includes flow groups slightly younger than the beginning of the Brunhes Normal Polarity Chron (less than 0.78 Ma) to flows older than the onset of the Olduvai Normal Polarity Subchron of the Matuyama Reversed Polarity Chron (1.945 Ma, Gradstein and others, 2004) (pl. 1). Cross-section *C–C'* shows a “layer-cake” stratigraphy west to east across the INL. Despite distances up to 17 km (10.5 mi) between coreholes, individual flow groups can be correlated between two or more coreholes at similar depths. Some sediment layers more than about 15 m (50 ft) thick also correlate between some coreholes. Flows that comprise the deep section of the aquifer in this area do not show any significant evidence of differential subsidence. Basalt flows in section *C–C'* are described from youngest to oldest flows.

Basal Brunhes Flows

The Middle Basal Brunhes flows are in coreholes USGS 135 and C1A and have inclinations between 66 and 68 degrees (cross-section *C–C'*, pl. 1). The Early Basal Brunhes flows are in Middle 1823, Middle 2050A, and NPR Test/W-02 and have inclination values ranging from 52 to 55 degrees. It is likely that these flows correlate to the Early Basal Brunhes flows of cross-sections *A–A'* and *B–B'*. Corehole Middle 2051 has a 60-degree inclination Basal Brunhes flow, and ANL-OBS-A-001 has a 59-degree inclination Basal Brunhes flow that do not correlate with the Middle or Early Basal Brunhes flows in other coreholes in cross-section *C–C'*.

Matuyama Chron Flow Groups

The youngest reversed polarity Matuyama Chron flow group, labeled South Late Matuyama on all the cross sections, has mean inclinations ranging from -59 to -61 degrees, and is found in USGS 135 and C1A on cross-section *C–C'* (pl. 1).

The thick, reversed polarity, late Matuyama Chron flow group, labeled Matuyama on the cross sections, has mean paleomagnetic inclinations that range from -67 to -73 degrees and is found in coreholes USGS 135, C1A, Middle 2051, Middle 1823, Middle 2050A, and NPR Test/W-02. In cross-section *A–A'*, it is found in coreholes USGS 135, USGS 132, and USGS 133. In cross-section *B–B'*, it is found in coreholes USGS 134 and Middle 1823. This flow group occupies most of the remaining cored base of corehole USGS 135 and thins progressively to the east past corehole NPR Test/W-02. It is thickest in corehole USGS 135, indicating that the buried vent or vents for this flow group may be near or to the west of corehole USGS 135. Below the Matuyama flow group in corehole USGS 135 are two flows with inclinations of -66 and -71 degrees. The -66-degree flow group is part of the Post-Jaramillo (Matuyama) flow group shown on cross-sections *A–A'* and *B–B'* (pl. 1). The deeper -71-degree flow group is found in corehole USGS 135 and does not correlate to any other coreholes. Corehole Middle 2051 contains a late Matuyama Chron flow with a -63-degree inclination that correlates to other flows of the Post-Jaramillo (Matuyama) flow group in the coreholes in cross-sections *A–A'*, *B–B'*, and *C–C'*.

East Matuyama Flow Group

The latest Matuyama Chron basalt flow that occurs in corehole ANL-OBS-A-001 has a paleomagnetic inclination of -48 degrees and is labeled the East Matuyama Upper flow group. It pinches out before corehole NPR Test/W-02 either below or above a thick sediment layer in that well. This flow group overlies the East Matuyama Middle flow group, which has a -41-degree mean inclination and may correlate to a flow in NPR Test/WO2 that has a mean paleomagnetic inclination of -38 degrees. The East Matuyama Middle flow group overlies a -54-degree mean inclination flow group present in coreholes ANL-OBS-A-001 and NPR Test/W-02, labeled the East Matuyama Lower flow group. The East Matuyama Middle and Lower flow groups are both thicker in corehole ANL-OBS-A-001, probably indicating a buried vent in the AVZ. The stratigraphic position of these flow groups, relative to flow groups to the west at this depth interval is unclear. The next deepest flow with a mean paleomagnetic inclination of -67 degrees is found only in corehole NPR Test/W-02. Again, its stratigraphic position relative to lava flow groups to the west at this depth interval is unclear.

Jaramillo (Matuyama) Flow Group

The Jaramillo (Matuyama) flow group is the product of at least four different eruptions, and thus includes at least four flows. The Jaramillo (Matuyama) flow group shown in cross-section *C–C'* has mean paleomagnetic inclinations that range from 44 to 58 degrees. The Jaramillo (Matuyama) flow group has normal polarity and was emplaced during the Jaramillo Normal Polarity Subchron of the Matuyama Reversed Polarity Chron (fig. 3). The Jaramillo (Matuyama) flow group is found in coreholes C1A, Middle 2051, Middle 1823, and Middle 2050A. A sample from a flow in corehole Middle 2051 is 1.045±0.012 Ma (B. Turrin, Rutgers University, written commun., 2010; Tom Wood, Battelle Energy Alliance, written commun., 2010). The Jaramillo (Matuyama) flow group thickens towards corehole C1A (fig. 1). The youngest lava flows of the Jaramillo (Matuyama) flow group have mean inclinations in the low- to mid-50 degrees, underlain by lava flows with inclinations of about 57 to 58 degrees in coreholes C1A, Middle 1823, and Middle 2050A. These flows are underlain by flows with inclinations between 49 and 53 degrees in coreholes Middle 1823 and Middle 2050A. The deepest flows in the Jaramillo (Matuyama) flow group in corehole Middle 2051 have inclinations of 44 and 45 degrees (cross-section *C–C'*, pl. 1).

The Jaramillo Normal Polarity Subchron is a relatively brief (80 ka, Gradstein and others, 2004) interval of normal magnetic polarity that occurred during later Matuyama Reversed Polarity Chron time. Transition from reversed to normal polarity and from normal to reversed polarity at the onset and termination of the Jaramillo Normal Polarity Subchron each took several thousand years.

The four flows emplaced during the Jaramillo Normal Polarity Subchron may be close to the same age. Inclination measurements span a mean inclination range of 14 degrees, which could be produced by geomagnetic secular variation in a few centuries.

Matuyama 1.21 Ma Flow

A 1.21 ± 0.04 Ma (Champion and Lanphere, 1997) flow with mean inclination values between -57 and -59 degrees underlies sediment and uncorrelated intervals beneath the Jaramillo (Matuyama) flow group in coreholes Middle 1823 and Middle 2050A. In corehole NPR Test/W-02, the Matuyama 1.21 Ma flow underlies sediment and an uncorrelated interval with a mean inclination of -67 degrees. In corehole ANL-OBS-A-001, the Matuyama 1.21 Ma flow underlies a sediment (cross-section *C–C'*, pl. 1). These flows thicken to the east.

Matuyama 1.256 Ma Flows

In corehole NPR Test/W-02, flows with anomalously shallow reversed inclination values of -23 degrees overlie normal polarity +5 degree inclination flows (cross-section *C–C'*, pl. 1). Age dates on both of these NPR Test/W-02 flows suggests an age of 1.256 ± 0.010 Ma (D.E. Champion, U.S. Geological Survey, unpub. data).

Corehole ANL-OBS-A-001 contains uncorrelated lava flows older than 1.21 Ma and younger than 1.44 Ma, with mean inclination values of -51 degrees that overlie flows with mean inclination values of -41 and -42 degrees, which overlie another -51 degree inclination flow. Correlations and relative stratigraphic positions between the anomalous polarity flows in NPR Test/W-02 and the flows in this depth interval in corehole ANL-OBS-A-001 are unclear.

Matuyama 1.37 Ma Flows

Coreholes C1A, Middle 1823, Middle 2050A, and NPR Test/W-02 contain the next oldest correlative flow (cross-section *C–C'*, pl. 1). This flow also is shown as continuous through corehole Middle 2051, however, the hole was not cored deep enough to confirm its presence. It has mean inclinations from -66 to -70 degrees, and has an age of 1.37 ± 0.18 Ma in corehole Middle 2050A (B. Turrin, Rutgers University, written commun., 2010).

Thick sediments underlie the 1.37 ± 0.18 Ma lava flow in C1A, Middle 1823, and Middle 2050A. These sediments also are shown as continuous beneath corehole Middle 2051, however, the hole was not cored deep enough to confirm their presence. These sediments have been referred to as "Olduvai lakebeds," which would have been deposited between 1.95 to 1.77 Ma ago (Blair, 2002). The proximity of these sediments to the overlying 1.37 Ma lava flow suggests that the descriptor "Olduvai" may be incorrect for these sediments. The Olduvai Normal Polarity Subchron lasted from 1.95 to 1.77 Ma (Gradstein and others, 2004) so the Olduvai ended at least 0.4 Ma prior to the emplacement of the overlying 1.37 ± 0.18 Ma lava flow.

Uncorrelated Lava Flows in Coreholes Middle 1823 and Middle 2050A

Corehole Middle 1823 has a thick sediment layer below the 1.37 ± 0.18 Ma flow (cross-section *C–C'*, pl. 1). An uncorrelated lava flow with mean inclination of -42 degrees underlies the sediment layer. Corehole Middle 2050A also has a thick sediment layer below the 1.37 ± 0.18 Ma flows and is in turn underlain by an interval of unrecovered sediment and basalt. The flow beneath the unrecovered interval has an anomalous mean inclination of 11 degrees in basalt that has significant chemical alteration and uncertain demagnetization characteristics. These flows with anomalous shallow normal polarity inclinations could be reversed polarity flows that have been significantly overprinted with normal polarity viscous or chemical secondary magnetizations or may indicate a time interval of odd remanent directions during later Matuyama Chron time.

Matuyama 1.44 Ma Flows

The next deepest and oldest flow is in coreholes NPR Test/W-02 and ANL-OBS-A-001. This flow has a -61-degrees mean inclination (cross-section *C–C'*, pl. 1) and has been dated at 1.44 ± 0.04 Ma (Champion and Lanphere, 1997). Below this flow is a -64-degree mean inclination flow that is part of the same flow group as the -61-degree flow in corehole ANL-OBS-A-001. These flows both correlate to the -61-degree flow in corehole NPR Test/W-02. Beneath the 1.44 Ma flows, a thin lava flow group with a mean inclination of -58 degrees is found in corehole ANL-OBS-A-001, and a much thicker flow group with a mean inclination of -55 degrees is found in corehole NPR Test/W-02. It is possible that these flows correlate to each other, but there is some uncertainty because of the large distance between the coreholes.

Post-Olduvai Flow Group

A flow group with -64 to -67 degree mean inclinations is at approximately the same depth in coreholes C1A, Middle 1823, NPR Test/W-02, and ANL-OBS-A-001 (cross-section *C–C'*, pl. 1). This flow group also is shown as continuous beneath coreholes Middle 2051 and Middle 2050A, however, the holes were not cored deep enough to confirm its presence. It underlies the uncorrelated -55 and -58 degree flows in coreholes NPR Test/W-02 and ANL-OBS-A-001. It is thickest in corehole C1A, suggesting a vent location to the west, and thins to the east past corehole NPR Test/W-02. This flow group may also correlate to a -64-degree flow in ANL-OBS-A-001. Corehole ANL-OBS-A-001 is about 30 km (19 mi) from corehole C1A, and flows of this length are very rare on the ESRP, so this correlation is tentative.

Beneath the Post-Olduvai flow group, correlation of flows and flow groups is difficult. Basal reversed polarity flows with mean inclinations of -63 and -49 degrees occur at the bottom of corehole C1A. Sediments are found at the base of corehole Middle 1823. Flows with reversed mean inclinations of -63 and -70 degrees, underlain by sediment, occur at 472 to 502 m (1,550 to 1,650 ft) below land surface in corehole NPR Test/W-02. In corehole ANL-OBS-A-001, flows with reversed mean inclinations of -56 and -53 degrees occur just above the base of the corehole. The distance between coreholes along this line of cross section and lack of any additional deep coreholes in the vicinity make correlation uncertain.

Olduvai Age Flows

Normal polarity 57 degree mean inclination lava flows are found at the base of corehole ANL-OBS-A-001, and 70 degree mean inclination lava flows are found at 518 m (1,700 ft) below land surface in corehole NPR Test/W-02 (cross-section *C–C'*, pl. 1). These flows and possibly the sediments above them were emplaced during the Olduvai Normal Polarity Subchron, though the flows clearly record two different eruptions. These flows represent the only Olduvai Normal Polarity Subchron eruptive events for which paleomagnetic data are available in the southern part of the INL. The Olduvai Subchron lasted approximately 180,000 years, enough time for many separate eruptions to have occurred (Champion and others, 2002; Gradstein and others, 2004). The thick sediments in corehole NPR Test/W-02, above and below the 70-degree normal polarity magnetic interval, are part of the "Olduvai" lakebeds (Bestland and others, 2002; Blair, 2002) (cross-section *C–C'*, pl. 1).

Pre-Olduvai Age Flows

In this study, deeper flows have only been cored in corehole NPR Test/W-02, beneath the "Olduvai" lakebeds. A sequence of flow groups below these lakebeds have mean inclination values of -61, -64, -64, and -66 degrees. They are pre-Olduvai Subchron in age, and therefore at least 2 Ma old. The similar mean inclination values indicate that the flow groups may be close in age. A sediment layer separates this sequence of flow groups from a deeper sequence of flow groups with mean inclination values of -55, -56, -57, and -46 degrees. Corehole NPR Test/W-02 was cored to 1,524 m (5,000 ft), however, it was not sampled for paleomagnetic analysis below 1,143 m (3,750 ft) because of increasing amount of alteration in the basalts and the transition from basalt to rhyolite with depth.

Summary and Conclusions

Paleomagnetic inclination and polarity studies on samples from subsurface drill cores and surface samples provide valuable data that can help constrain the age and extent of basalt lava flows and flow groups. Data from paleomagnetic studies were used to refine Pleistocene and Holocene stratigraphy at and near the Idaho National Laboratory (INL).

Samples from 83 surface sites and 51 coreholes at and near the INL were collected and analyzed for paleomagnetic inclination. Surface samples were selected from outcrops that had little alteration, and in low-lying areas where possible, to avoid the secondary magnetic effects of lightning strikes. Samples of individual lava flows from drill cores were collected in accordance with INL Lithologic Core Storage Library protocols. Paleomagnetic samples were collected from coreholes at depths from a few meters to 1,143 m (3,750 ft). Paleomagnetic inclination and polarity were determined and comparisons made between surface and corehole data.

Paleomagnetic inclination data were used to correlate surface and subsurface basalt stratigraphy, determine relative ages, and, in conjunction with other studies, determine the absolute age of some basalt flows. Results demonstrate that coreholes a few kilometers apart have stratigraphic successions that correlate over tens to hundreds of meters of depth. Correlations between coreholes separated by greater distances are less consistent because some stratigraphic sequences may be missing, added, or are at different depths.

Basalt shield volcanoes and their lava flow groups have a wide range of eruptive volumes and lateral extents. The topography present at the time of eruption controls flow emplacement. Correlative lava flows found in drill cores may be found at different depths. Large lava flow groups may be intersected by numerous coreholes; small lava flows may be found in only one corehole. Correlation of lava flows and flow groups was established using subsurface cross sections through different areas of the INL. One cross section represents the deep sections in the southern part of the INL, showing the stratigraphic sequences of the lava flows near and below the approximate Brunhes-Matuyama polarity boundary.

From stratigraphic top to bottom, key results include correlation of flows and flow groups along and among cross-sections *A–A*' and *B–B*'. Important correlations include:

- The Quaking Aspen Butte flow group erupted from Quaking Aspen Butte southwest of the INL, flowed northeast, and is found in the subsurface in corehole USGS 132.
- The vent 5206 flow group erupted near the southwestern border of the INL, flowed north and east, and is found in the subsurface in coreholes USGS 132, USGS 129, USGS 131, USGS 127, USGS 130, USGS 128, and STF-AQ-01.
- The Mid Butte flow group erupted north of U.S. Highway 20, flowed northwest, and is found in the subsurface at coreholes STF-AQ-01 and ARA-COR-005.
- The High K_20 flow group erupted from a vent south of Highway 20 near Middle Butte, flowed north, and is found in the subsurface in coreholes USGS 131, USGS 127, USGS 130, USGS 128, USGS 123, STF-AQ-01, and ARA-COR-005 ending near the Idaho Nuclear Technology and Engineering Center.
- The Vent 5252 flow group erupted just south of U.S. Highway 20 near Middle and East Buttes, flowed northwest and is found in the subsurface in coreholes USGS 131, USGS 127, USGS 121, ICPP 023, USGS 123, ICPP 214, USGS 128, USGS 130, STF-AQ-01, and ARA-COR-005.
- The Big Lost flow group erupted from a now-buried vent near the Radioactive Waste Management Complex, flowed southwest to corehole USGS 135, and northeast to coreholes USGS 132, USGS 129, USGS 131, USGS 127, USGS 130, STF-AQ-01, and ARA-COR-005.
- The AEC Butte flow group erupted from AEC Butte near the Advanced Test Reactor Complex and flowed south to corehole Middle 1823, northwest to corehole USGS 134, northeast to coreholes USGS 133 and NRF 7P, and south to coreholes USGS 121, ICPP 023, USGS 123, and USGS 128.

In cross-section *C–C*', the major correlative flow group is the labeled the Matuyama flow group, and can be correlated from corehole USGS 135 in the southwestern corner of the INL, as far as corehole NPR Test/W-02 near the INTEC. The Jaramillo (Matuyama) flow group is correlative from corehole C1A near the RWMC to corehole Middle 2050A located south of the ATRC. The Matuyama 1.21 Ma flows can be correlated over a long distance from corehole Middle 1823 to corehole ANL-OBS-A-001. Other correlations can be made between a few coreholes, but more extensive correlations are uncertain because of the long distances between coreholes in this cross section.

Subsidence of lava flows and flow groups is continuing with the axis of maximum rate of subsidence located south of the INL, under and parallel to the topographic axis of the ESRP. Cross-sections *A–A*' and *B–B*' show differential subsidence that make some correlated flows in the subsurface appear to have flowed "uphill." Cross-section *C–C*' is nearly parallel to the topographic axis of the ESRP and does not show evidence of differential subsidence.

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Appendix A. Paleomagnetic Inclination Data for Selected Coreholes at the Idaho National Laboratory, Idaho

Appendix A contains tables with depth and paleomagnetic inclination data from coreholes in cross-sections *A–A'*, *B–B'*, and *C–C'* presented in this report, and from 29 other coreholes at the Idaho National Laboratory (INL). Tables are organized alphabetically by corehole name.

Information in the tables includes sample depth and identification of sample groups that were used to determine the average inclination for flows and 95 percent uncertainty. Each sample has a characteristic remanent inclination in degrees and an alternating field demagnetization level in milliTeslas or an alternative demagnetization approach. Positive inclination values indicate normal paleomagnetic polarity, and negative inclination values indicate reversed paleomagnetic polarity.

Some coreholes are not vertical. In cases where the corehole deviates from vertical to the north or south, deviation correction values were obtained from geophysical deviation logs and applied to deviated samples to account for this variation from the vertical. Deviation corrections were applied to sample groups.

Petrographic boundaries denote a significant change in mineralogy in a flow. Unrecovered core and sediment intervals also were recorded in the depth column.

Some samples are labeled “NIIA,” which stands for “Not Included In Average.” NIIA samples may have been thermally overprinted by overlying flows, tilted by endogenous inflation, struck by lightning when on the surface, or otherwise had their orientations disturbed so that they do not yield usable paleomagnetic inclination data.

Some samples carry the notation “Diff. Vector,” which is the difference vector between sample magnetizations during the course of stepwise thermal demagnetizations. Stepwise thermal demagnetizations were only done on samples of particular interest.

The designation “TO” stands for “thermal overprinting.” Samples that are thermally overprinted may require extra processing to discover their original orientation. If thermal overprinting was extensive, the sample may not yield useful paleomagnetic data, and those samples were not included in averages. Measurements are in feet and milliTeslas because that is how the raw data were collected.

Appendix tables are available in Excel format for download at http://pubs.usgs.gov/sir/2011/5049/.

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