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New Argon-Argon (^{40}Ar/^{39}Ar) Radiometric Age Dates from Selected Subsurface Basalt Flows at the Idaho National Laboratory, Idaho

Scientific Investigations Report 2015–5028

U.S. Department of the Interior
U.S. Geological Survey

Cover: Foreground—Core laid out for sampling at the Idaho National Laboratory Lithologic Core Storage Library. (Photograph taken by Heather Bleick, U.S. Geological Survey, summer 2014.)
Background—Shield volcano Mid Butte, Bingham County, Idaho, looking west-northwest from Highway 20. (Photograph taken by M.K.V. Hodges, U.S. Geological Survey, March 4, 2015.)

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

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Contents

Abstract 1
Introduction 1
  Previous Age Dating Investigations at the Idaho National Laboratory 4
  Purpose and Scope 4
Geologic Setting 8
  Geochemistry of Eastern Snake River Plain Olivine Tholeiite Basalts 9
    Basalt Flow Labeling Conventions 9
  Paleomagnetism of Basalt Flows in the Southern Idaho National Laboratory 9
Argon-Argon ($^{40}Ar/^{39}Ar$) Dating Methods 11
  Results of Argon-Argon ($^{40}Ar/^{39}Ar$) Dating Experiments 15
    Quaking Aspen Butte Basalt Flow—60 ± 16 Thousand Years Ago 15
    Vent 5206 Basalt Flow—63 ± 9 Thousand Years Ago 16
    Mid Butte Basalt Flow—195 ± 39 Thousand Years Ago 16
    West of Advanced Test Reactor Complex Basalt Flow—270 ± 15 Thousand Years Ago 17
    High K_2O Basalt Flow—289 ± 8 Thousand Years Ago 17
    South Central Facilities Area Buried Vent(s) Upper Basalt Flow—309 ± 13 Thousand Years Ago 18
    "D3" Basalt Flow—456 ± 15 Thousand Years Ago 18
    South Central Facilities Area Buried Vent(s) Lower Basalt Flow—452 ± 88 Thousand Years Ago 18
    "E" Basalt Flow—550 ± 33 Thousand Years Ago 18
    Big Lost Basalt Flow—560 ± 4 Thousand Years Ago 19
    Central Facilities Area Buried Vent Basalt Flow—536 ± 63 Thousand Years Ago 19
    State Butte Basalt Flow—621 ± 9 Thousand Years Ago 20
Summary 20
References Cited 20
Appendix A. Analytical Data—Plateau and Isochron Plots 25

Figures

1. Maps showing locations of coreholes and Axial Volcanic Zone, volcanic rift zones, inferred caldera complex outlines, and geologic features; and study and geographic areas, Idaho National Laboratory, Idaho 2
2. Map showing locations of surface basalt flows, vents, and coreholes, Idaho National Laboratory, Idaho 5
3. Pleistocene-Pliocene Geomagnetic Time Scale, polarity chrons, subchrons, and cryptochrons 10

Tables

1. Selected previous investigations on geology and radiometric dating of basalts in the eastern Snake River Plain and Idaho National Laboratory, Idaho 6
2. Selected corehole names used in this report and aliases used in previous publications at the Idaho National Laboratory, Idaho 7
3. Results of $^{40}Ar/^{39}Ar$ age dating experiments for basalt samples from Idaho National Laboratory, Idaho...12

Conversion Factors

[Inch/pound to International System of Units]

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (m)	1.60934	kilometer (km)
	Area	
square mile (mi^2)	2.58999	square kilometer (km^2)

[International System of Units to inch/pound]

Multiply	By	To obtain
	Length	
micron (μ)	0.000039	inch (in.)
millimeter (mm)	0.0393701	inch (in.)
meter (m)	3.28082	foot (ft)
kilometer (km)	0.621371	mile (m)
	Area	
square kilometer (km^2)	0.386102	square mile (mi^2)
	Volume	
cubic kilometer (km^3)	0.239912759	cubic mile (mi^3)

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

$$°F=(1.8\times°C)+32.$$

Datums

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

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

Abbreviations

$^{40}Ar/^{39}Ar$	argon 40/argon 39
ATR Complex	Advanced Test Reactor Complex
Ar	argon
AVZ	Axial Volcanic Zone
BLS	below land surface
CFA	Central Facilities Area
DOE	U.S. Department of Energy
ESRP	eastern Snake River Plain
IIP	Isochron Intercept Plateau
INEL	Idaho National Engineering Laboratory
INEEL	Idaho National Engineering and Environmental Laboratory
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
K_2O	potassium oxide
K-Ar	potassium-argon
NRF	Naval Reactors Facility
NRTS	National Reactor Testing Station
QAB	Quaking Aspen Butte
RWMC	Radioactive Waste Management Complex
USGS	U.S. Geological Survey

New Argon-Argon ($^{40}Ar/^{39}Ar$) Radiometric Age Dates from Selected Subsurface Basalt Flows at the Idaho National Laboratory, Idaho

By M.K.V. Hodges[1], Brent D. Turrin[2], Duane E. Champion[1], and Carl C. Swisher III[2]

Abstract

In 2011, the U.S. Geological Survey, in cooperation with the U.S. Department of Energy, collected samples for 12 new argon-argon radiometric ages from eastern Snake River Plain olivine tholeiite basalt flows in the subsurface at the Idaho National Laboratory. The core samples were collected from flows that had previously published paleomagnetic data. Samples were sent to Rutgers University for argon-argon radiometric dating analyses.

Paleomagnetic and stratigraphic data were used to constrain the results of the age dating experiments to derive the preferred age for each basalt flow. Knowledge of the ages of subsurface basalt flows is needed to improve numerical models of groundwater flow and contaminant transport in the eastern Snake River Plain aquifer. This could be accomplished by increasing the ability to correlate basalt flow from corehole to corehole in the subsurface. The age of basalt flows also can be used in volcanic recurrence and landscape evolution studies that are important to better understand future hazards that could occur at the Idaho National Laboratory.

Results indicate that ages ranged from 60 ± 16 thousand years ago for Quaking Aspen Butte to 621 ± 9 thousand years ago for State Butte.

Introduction

In 1949, the U.S. Atomic Energy Commission (now the U.S. Department of Energy [DOE]) established the National Reactor Testing Station (NRTS) on 890 mi^2 (2,315 km^2) of the eastern Snake River Plain (ESRP) in southeastern Idaho. 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, 1949–74), Idaho National Engineering Laboratory (INEL, 1974–97), and Idaho National Engineering and Environmental Laboratory (INEEL, 1997–2005). Since 2005, the laboratory has been known as the Idaho National Laboratory (INL; fig. 1).

Beginning with Russell (1902), U.S. Geological Survey (USGS) scientists have studied the geology and hydrology of the ESRP. 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 (Mann and Beasley, 1994; Cecil and others, 1998; Bartholomay and others, 2000). Some wastewater continues to be discharged to infiltration and evaporation ponds. Concern about the 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; Ackerman and others, 2010; Fisher and Twining, 2011; Twining and Fisher, 2012).

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 basalt and sediment controls groundwater movement in the Snake River Plain aquifer (Welhan and others, 2002). Basalt flows comprise more than 85 percent of the volume of the subsurface of the ESRP (Kuntz and others, 1992). Sedimentary interbeds comprise the rest.

[1] U.S. Geological Survey

[2] Rutgers University

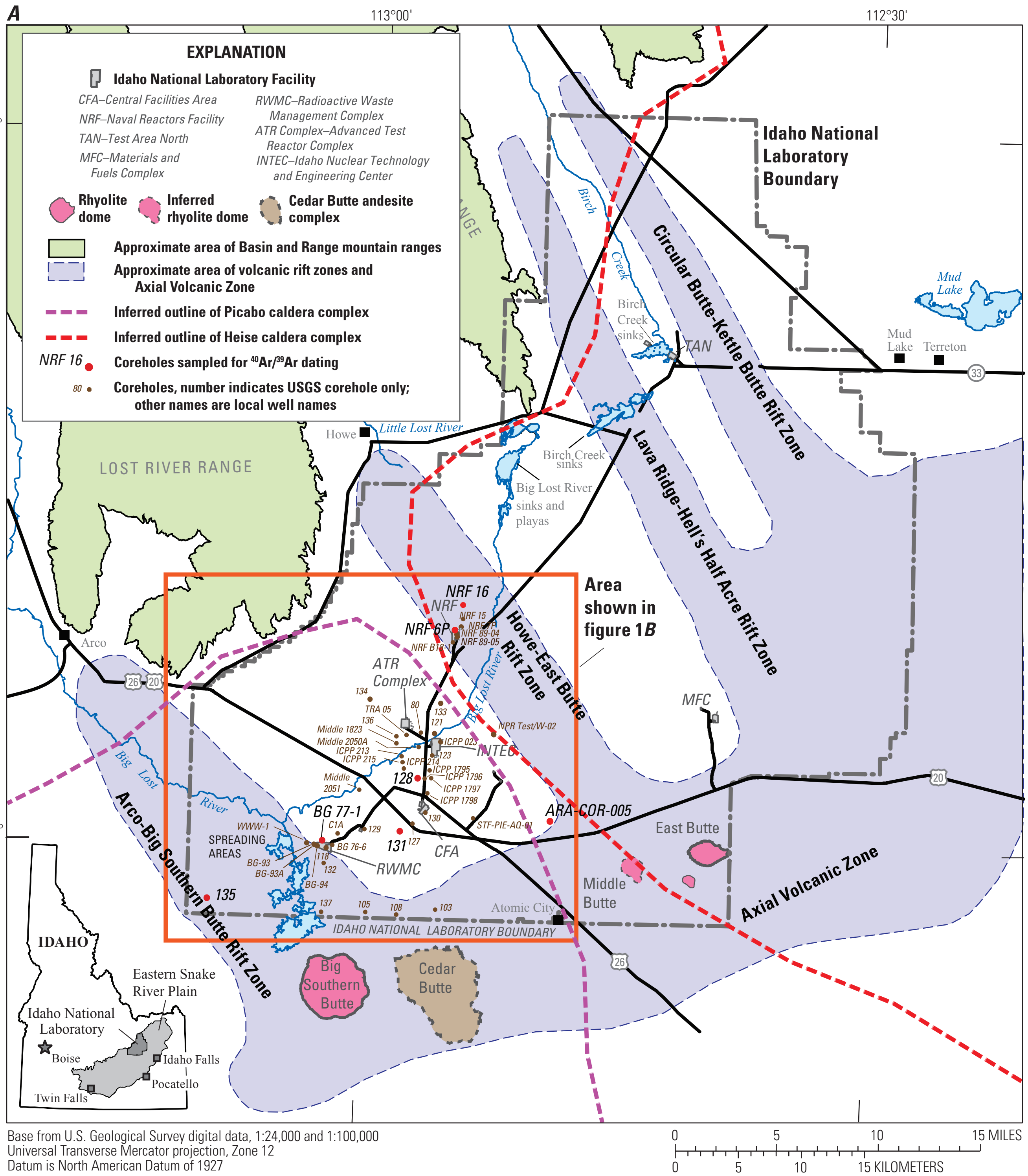

Figure 1. Locations of coreholes and (*A*) Axial Volcanic Zone, volcanic rift zones, inferred caldera complex outlines, and geologic features; and (*B*) study and geographic areas, Idaho National Laboratory, Idaho.

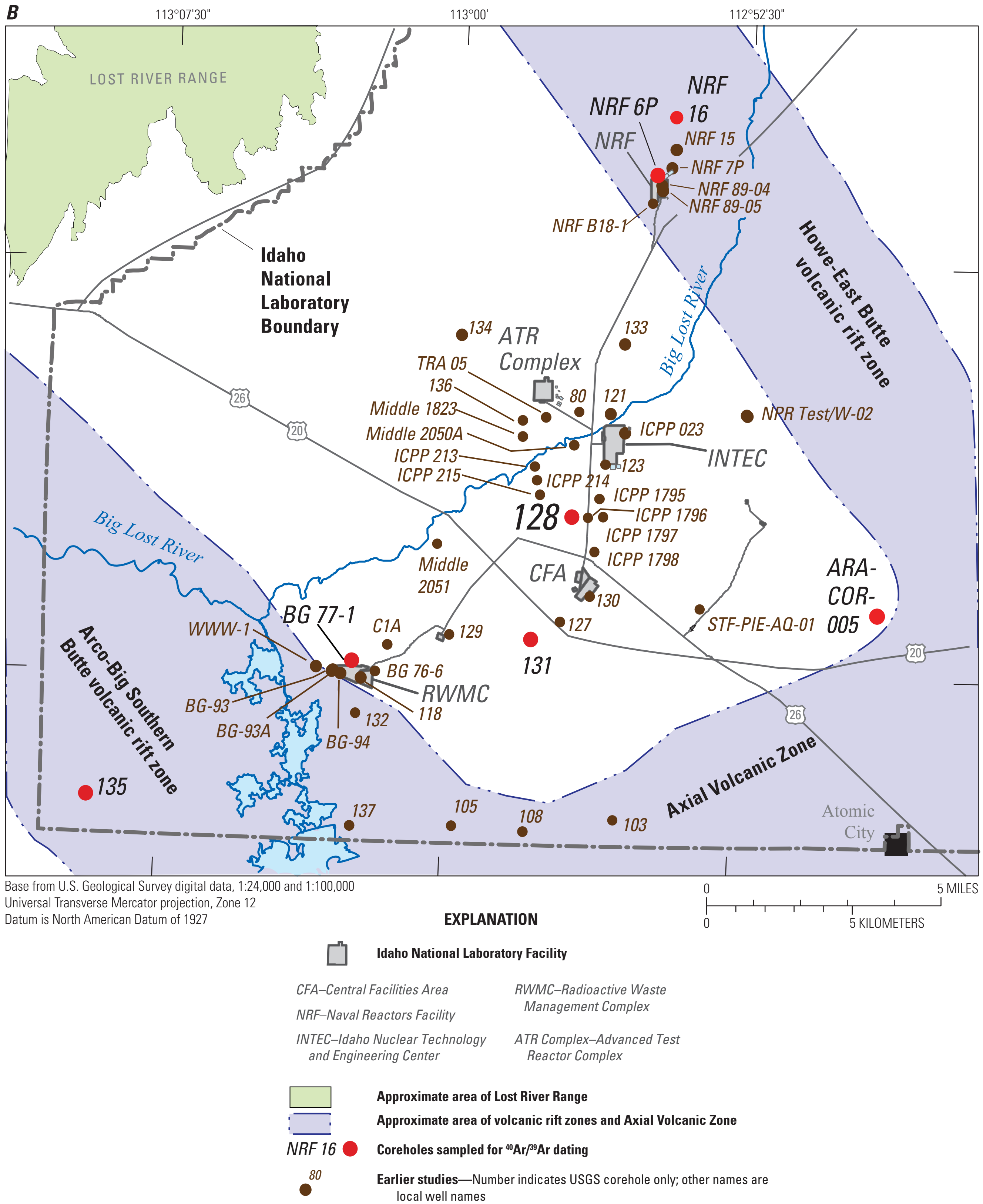

Figure 1.—Continued.

Basalt flows at the INL are mostly tube-fed pahoehoe. The exterior surfaces of basalt flows fracture as they cool, and, in an aquifer, these fracture zones may form preferential pathways for groundwater. Fracture networks on the exteriors of basalt flows may extend for miles. Basalt flows exposed at the surface in and near the study area include Crater Butte, Sixmile Butte, Lavatoo Butte, Tin Cup Butte, Teakettle Butte, Quaking Aspen Butte, Vent 5206, Microwave Butte, Mid Butte, Vent 5119, Cerro Grande, and State Butte (fig. 2). Samples from Quaking Aspen Butte, Vent 5206, Mid Butte, and State Butte (fig. 1) were dated and results are published in this report.

Successions of many thin basalt flows, which have a greater proportion of fractured surfaces, allow more rapid groundwater flow than thick basalt flows that have massive, relatively unfractured interiors. Sedimentary interbeds in the subsurface at the INL, almost all of which are fine-grained, impede groundwater flow (Fisher and Twining, 2011).

Tracing the distribution of basalt flows in the subsurface at the INL is done mostly by correlating subsurface flows through their paleomagnetic remanent inclination values because many ESRP olivine tholeiite basalt flows of all ages are so similar in appearance and chemical composition that they often cannot be distinguished from one another. Cores drilled at the INL are not oriented, so obtaining paleomagnetic declination values is not possible.

The depth and sequence of paleomagnetic inclinations and the depth, presence, and thickness of sedimentary interbeds in a corehole are used to identify basalt flows in the subsurface and their associated sedimentary interbeds and to help determine their extents in the subsurface. These geologic data were used to help interpret the data reported here, resulting in the preferred ages.

Paleomagnetic remanent inclination values are non-unique, so independent data, especially radiometric ages, are valuable for distinguishing basalt flows with similar paleomagnetic inclinations from one another. Paleomagnetic inclination and polarity data from well cores have been used to construct cross sections of the subsurface in the southern INL (Champion and others, 2011) and near the Naval Reactors Facility (NRF; Champion and others, 2013). Previous age dating studies have contributed to landscape development studies, volcanic eruption frequency and extent studies, and volcanic hazard studies.

This study was done in cooperation with the U.S. Department of Energy, by the U.S. Geological Survey and the Department of Earth and Planetary Sciences, Rutgers, State University of New Jersey, Wright-Rieman Laboratories.

Previous Age Dating Investigations at the Idaho National Laboratory

Basalt flows at and near the Idaho National Laboratory have been dated by the radiocarbon method (Kuntz and others, 1986), the potassium-argon (K-Ar) method (Kuntz and others, 1980; Champion and others, 1981; Champion and others, 1988; Lanphere and others, 1993; Lanphere and others, 1994), and the $^{40}Ar/^{39}Ar$ method (Champion and Lanphere, 1997). Previous work is summarized in table 1, and corehole names and aliases are in table 2.

Purpose and Scope

This report provides results of a study done to determine the ages of subsurface basalt flows at the Idaho National Laboratory. Improved age control will help define the subsurface stratigraphy by allowing discrimination between basalt flows that are similar in paleomagnetic inclination and chemistry but different in age. Improved age control will help researchers understand the recurrence interval of basalt eruptions.

Twelve new radiometric age dates from subsurface ESRP olivine tholeiite basalt flows were obtained from argon-argon ($^{40}Ar/^{39}Ar$) radiometric age dating analyses performed in the Wright-Riemann Laboratory of the Department of Geology at Rutgers University, New Jersey. Samples were selected from basalt flows that had well-documented paleomagnetic and stratigraphic data, and from hand specimens that had minimal glass, no carbonate, and no oxidation. Samples were crushed, prepared, and separated into splits by using a hand magnet and a Frantz magnetic separator. Each split was analyzed for $^{40}Ar/^{39}Ar$ age dating using methods developed by Turrin and others (2008, 2010) that differ from other methods in that mass discrimination is monitored for variation during the course of the incremental-heating experiments, with corrections for mass discrimination variation applied to the resulting data.

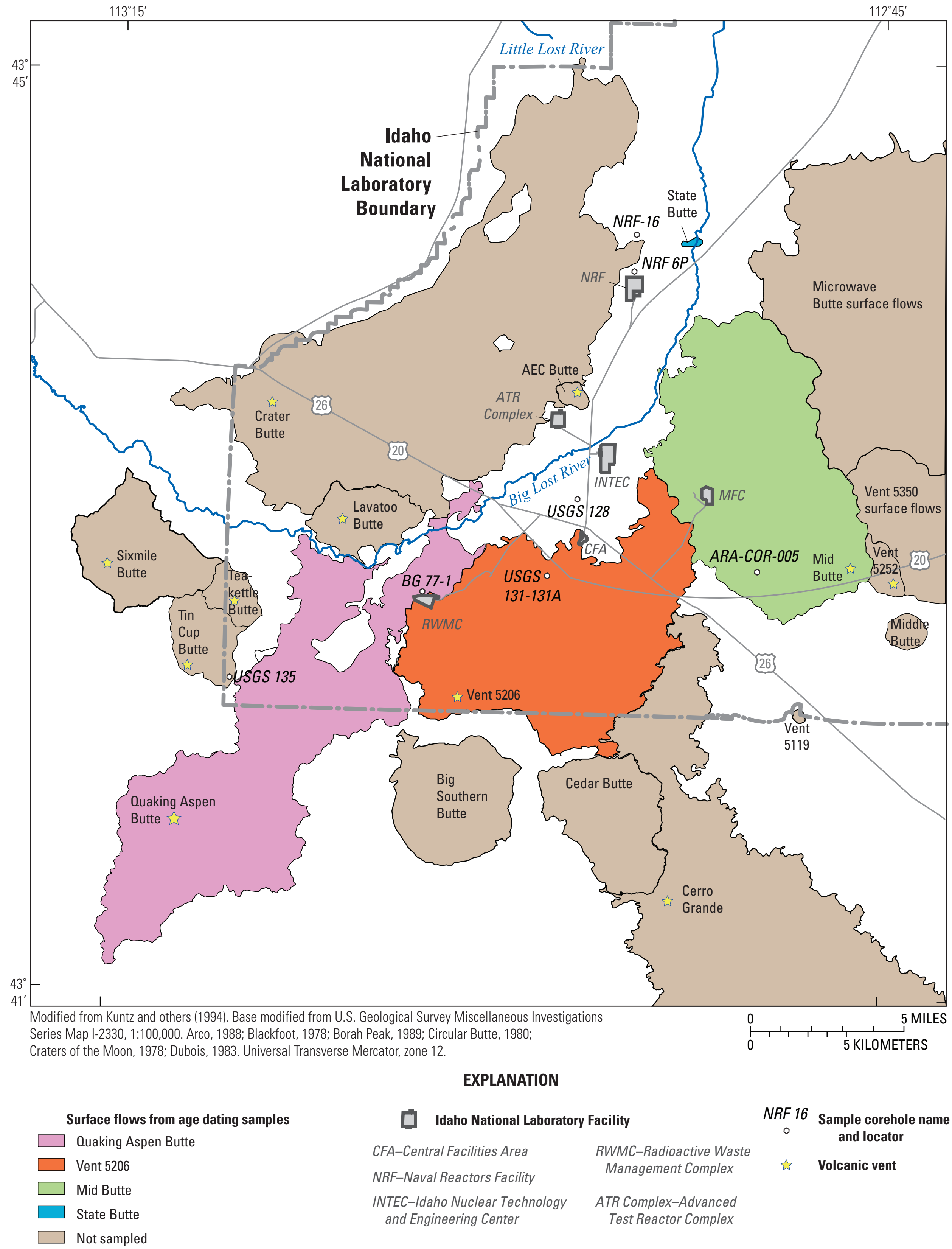

Figure 2. Locations of surface basalt flows, vents, and coreholes, Idaho National Laboratory, Idaho. Modified from Kuntz and others (1994).

Table 1. Selected previous investigations on geology and radiometric dating of basalts in 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; Ma, million years; Ar/Ar, argon-argon]

Reference	Area of investigation	Summary
Armstrong, R.L., Leeman, W.P., and Malde, H.E., 1975, K-Ar dating, quaternary and neogene volcanic rocks of the Snake River Plain, Idaho: American Journal of Science, v. 275, p. 225–251.	Snake River Plain	Potassium-argon dating and paleomagnetic data on surface basalt and rhyolite rocks of the Snake River Plain
Champion, D.E., Dalrymple, G.B., and Kuntz, M.A., 1981, Radiometric and paleomagnetic evidence for the Emperor reversed polarity event at 0.46 ± 0.05 m.y. in basalt lava flows from the eastern Snake River Plain, Idaho: Geophysical Research Letters, v. 8, no. 10, p. 1,055–1,058.	INL, RWMC	Potassium-argon dating and paleomagnetic data from RWMC basalt cores indicate a 0.46 Ma magnetic reversal
Champion, D.E., Lanphere, M.A., and Kuntz, M.A., 1988, Evidence for a new geomagnetic reversal from lava flows in Idaho—Discussion of short polarity reversals in the Brunhes and late Matuyama polarity chrons: Journal of Geophysical Research, v. 93, no. B10, p. 11,667–11,680.	INL, RWMC	Radiometric ages and paleomagnetism at corehole Site E (NPR Test), description of Big Lost cryptochron
Champion, D.E., Lanphere, M.A., Anderson, S.R., and Kuntz, M.A., 2002, Accumulation and subsidence of late Pleistocene basaltic lava flows of the eastern Snake River Plain, Idaho, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colo., Geological Society of America Special Paper 353, p. 175–192.	ESRP, INL	Accumulation and subsidence based on paleomagnetism and selected core data
Champion, D.E., Davis, L.C., Hodges, M.K.V., and Lanphere, M. A., 2013, Paleomagnetic correlation and ages of basalt flow groups in coreholes at and near the Naval Reactors Facility, Idaho National Laboratory, Idaho: U.S. Geological Survey Scientific Investigations Report 2013-5012 (DOE/ID-22223), 48 p.	NRF	Paleomagnetism and radiometric ages for basalt flows at NRF
Hackett, W.R., and Smith, R.P., 1992, Quaternary volcanism, tectonics, and sedimentation in the Idaho National Engineering Laboratory area, *in* Wilson, J.R., ed., Field guide to geologic excursions in Utah and adjacent areas of Nevada, Idaho, and Wyoming: Utah Geological Survey Miscellaneous Publication 92-3, p. 1–18.	ESRP	Description of ESRP volcanism including development of Axial Volcanic Zone
Hughes, S.S., McCurry, M., and Geist, D.J., 2002, Geochemical correlations and implications for the magmatic evolution of basalt flow groups at the Idaho National Engineering and Environmental Laboratory, *in* Link, P.K., and Mink, L.L., eds., Geology, hydrogeology, and environmental remediation—Idaho National Engineering and Environmental Laboratory, Eastern Snake River Plain, Idaho: Boulder, Colo., Geological Society of America Special Paper 353, p. 151–173.	INL, TAN	Ar/Ar ages from cores near TAN and corehole 2-2A
Kuntz, M.A., Dalrymple, G.B., Champion, D.E., and Doherty, D.J., 1980, An evaluation of potential volcanic hazards at the Radioactive Waste Management Complex, Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Open-File Report 80-388, 63 p., 1 map.	INL, RWMC	Radiometric dating, paleomagnetism on cores from RWMC
Kuntz, M.A., Spiker, E.C., Rubin, M., Champion, D.E., and Lefebvre, R.H., 1986, Radiocarbon studies of latest Pleistocene and Holocene lava flows of the Snake River Plain, Idaho—Data, lessons, interpretations: Quaternary Research, v. 25, p. 163–176.	ESRP	Radiocarbon dates on Pleistocene and Holocene basalt flows
Kuntz, M.A., Skipp, Betty, Lanphere, M.A., Scott, W.E., Pierce, K.L., Dalrymple, G.B., Champion, D.E., Embree, G.F., Page, W.R., Morgan, L.A., Smith, R.P., Hackett, W.R., and Rodgers, D.W., 1994, Geologic map of the Idaho National Engineering Laboratory and adjoining area, eastern Idaho: U.S. Geological Survey Miscellaneous Investigations Series I-2330, scale 1:100,000.	INL	Geologic map of INL, including radiometric ages and paleomagnetism
Lanphere, M.A., Kuntz, M.A., and Champion, D.E., 1994, Petrography, age, and paleomagnetism of basaltic lava flows in coreholes at Test Area North (TAN), Idaho National Engineering Laboratory: U.S. Geological Survey Open-File Report 94-0686, 49 p.	TAN	Petrography, age and paleomagnetism of basalt flows at and near TAN
Lanphere, M.A., Champion, D.E., and Kuntz, M.A., 1993, Petrography, age, and paleomagnetism of basalt lava flows in coreholes Well 80, NRF 89-04, NRF 89-05, and ICPP 123, Idaho National Engineering Laboratory: U.S. Geological Survey Open-File Report 93-0327, 40 p.	NRF	Petrography, age and paleomagnetism of basalt flows at and near NRF

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

Corehole name	Alternate name	Alias 1	Alias 2	Alias 3
ARA-COR-005	ARA-005	ARA 1		
C1A	C-1A	C1A	C1-A	
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 Test1	NPR-Test	Site E	NPR-E	
[1]W-02	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		
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	
USGS 80	USGS 80	USGS-080		
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 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 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.

Geologic Setting

The ESRP developed when the North American tectonic plate started moving southwestward over a fixed upper-mantle-melting anomaly beginning about 17 million years (Ma) 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 that formed the Picabo volcanic field from 10.2 ± 0.06 to 7.9 ± 0.4 Ma (Kellogg and others, 1994; McCurry and Hughes, 2006), and the Heise volcanic field from 7.05 ± 0.04 to 4.43 ± 0.08 Ma (fig. 1*A*) (Pierce and Morgan, 1992; Morgan and McIntosh, 2005; McCurry and Hughes, 2006; Anders and others, 2009; Anders and others, 2014).

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 eolian and fluvial sediments. The total volume of basalt fill of the ESRP is estimated to be 9,600 mi^3 (4×10^4 km^3) (Kuntz, 1992).

The ESRP is an 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 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; Champion and others, 2002). 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 produced flows that range from about 1 to 40 m (3 to 131 ft) thick. The extent of some ESRP flows might be as large as 400 km^2 (155 mi^2). Lava flows might be as long as 35 km (22 mi), and the accumulated volume of a shield volcano may be as large as 7 km^3 (1.7 mi^3) (Kuntz and others, 1992). Fracture networks form on the outer surfaces of basalt flows as they cool and contract, and these fracture networks form preferential pathways for groundwater movement in the part of the Snake River aquifer that underlies the Idaho National Laboratory. The flank areas of typical ESRP low shield volcanoes have slopes that average less than 1 degree; summit and vent areas have slopes of approximately 5 degrees (Champion and Greeley, 1978; Greeley, 1982). Large, old vents are sometimes preserved as hills surrounded by flows from younger vents; a good example is AEC Butte (fig. 2), which is surrounded by younger basalt flows, and by wind- and water-borne sediment (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, 1992; Kuntz and others, 1992). Basaltic lava fields, partially mantled with loess, cover the eastern Snake River Plain. 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 roughly parallel to the long axis of the ESRP (Hackett and Smith, 1992; Kuntz, 1992; Kuntz and others, 1992; Kuntz and others, 1994; Anderson and Liszewski, 1997; Anderson and others, 1999; Hughes and others, 1999; Wetmore and others, 1999).

ESRP basaltic eruptions have occurred somewhere on the INL, on average, every 32,000–140,000 years, with hiatuses in volcanic activity of several hundred thousands of years (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 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 (Champion and Shoemaker, 1977; 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 and Kork, 1978; Kuntz and others, 1980). Extrusive rocks of more evolved compositions also are found on the ESRP, but the volume of these rocks is small compared with the volume of olivine tholeiite basalts. Such 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. 1; Anderson and others, 1996).

Geochemistry of Eastern Snake River Plain Olivine Tholeiite Basalts

ESRP olivine tholeiite basalts are similar in major- and minor-element geochemistry and mineralogy (Kuntz and others, 1992). Within a narrow range, however, some basalt flows may exhibit a range of compositions and others might have consistent chemistry (Geist and others, 2002). In some cases, variations in major and trace element composition can be used to correlate some basalt flows over short distances (Reed and others, 1997), but over long distances, other stratigraphic data, such as paleomagnetic inclinations and radiometric ages, must be used to avoid false correlations (Hughes and others, 2002).

Most ESRP olivine tholeiite basalts have less than 1 weight percent potassium oxide (K_2O; Stout and Nicholls, 1977, table 9). Low-potassium, geologically young, olivine tholeiites present $^{40}Ar/^{39}Ar$ dating challenges, partly because the small amount of K_2O present in the magma is partitioned into the matrix of the basalt, as none of the mineral phases present in olivine tholeiite basalts readily incorporate potassium (K). Argon inherited from magma is also found in the matrix, where it may contribute to “excess argon,” which can increase the complexity of results of $^{40}Ar/^{39}Ar$ and K-Ar experiments (Kelley, 2002).

Basalt Flow Labeling Conventions

Champion and others (2011, 2013) used the term “basalt flow groups” to describe the eruptive products of a single monogenetic volcano, which have the same or related average paleomagnetic inclinations. However, the North American Stratigraphic Code states that “A flow is the smallest formal lithostratigraphic unit of volcanic flow rocks. A flow is a discrete, extrusive, volcanic body distinguishable by texture, composition, order of superposition, paleomagnetism, or other objective criteria” (North American Commission on Stratigraphic Nomenclature, 2005, p. 1,569). Therefore, this report will follow the terminology recommended by the Commission and use the term “basalt flow.”

Basalt flows are labeled for their vents, such as “Mid Butte” (fig. 2), where a basalt flow can be traced from a vent exposed on the surface to core in the subsurface. Where surface to subsurface correlations are not possible, flows are labeled for chemical, spatial, or paleomagnetic identifiers. For example, a flow that has relatively large amounts of potassium oxide is labeled “high K_2O,” the reversed polarity flow that records the Big Lost Reversed Polarity Cryptochron is labeled “Big Lost,” and a subsurface basalt flow that is thickest in the Central Facilities Area (CFA) is labeled the “CFA buried vent basalt flow” (modified from Champion and others, 2011).

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 Advanced Test Reactor Complex (ATR Complex), and may be designated “West of ATR Complex.” Other subsurface flows are labeled with capital letters, such as the “E” and “D3” flows, following the terminology of scientists who first investigated subsurface basalt cores at the INL, such as Kuntz and others (1980) and Anderson and Lewis (1989).

Paleomagnetism of Basalt Flows in the Southern Idaho National Laboratory

Basalt flows and vents on the surface in the southern part of the INL have normal polarity. These basalt flows were erupted during the Brunhes Normal Polarity Chron (0.78 million years ago [Ma]–present). Some surface lava flows and vents in the northern part of the INL have reversed magnetic polarity and erupted during the Matuyama Reversed Polarity Chron (0.78 –2.581 Ma; fig. 3) (Gradstein and others, 2004).

A young, reversed inclination polarity, basalt flow was detected at 324–765 ft (99–233 m) depths in coreholes BG 77-1, C1A, Middle 2051, ARA-COR-005, STF-PIE-AQ-01, NPR Test/W-02, and USGS 103, 105, 108, 127, 129, 130, 131, 132, and 135 in the southern INL area (figs. 1*A* and 1*B*). The Big Lost basalt flow was originally called the “F” flow (Anderson and others, 1996; Scarberry, 2003), and was labeled the “Big Lost basalt flow group” by Champion and others (2011). The term “basalt flow group” has been replaced with “basalt flow,” in accordance with the North American Stratigraphic Code (2005). The Big Lost reversed magnetic polarity cryptochron occurred during the Brunhes Normal Polarity Chron (780 ka–present). The event recorded in the Big Lost basalt flow was named the Big Lost Reversed Polarity Subchron (565 ± 14 ka) by Champion and others (1988). It has since been reclassified as the Big Lost Reversed Polarity Cryptochron (Gradstein and others, 2004), and the age is now 560 ± 4 ka (fig. 3). The Big Lost basalt flow is a significant marker in the INL subsurface because it is a large flow, paleomagnetically identifiable in core, and widespread in the southern part of the INL. The Big Lost basalt flow also is at or near the water table where it occurs.

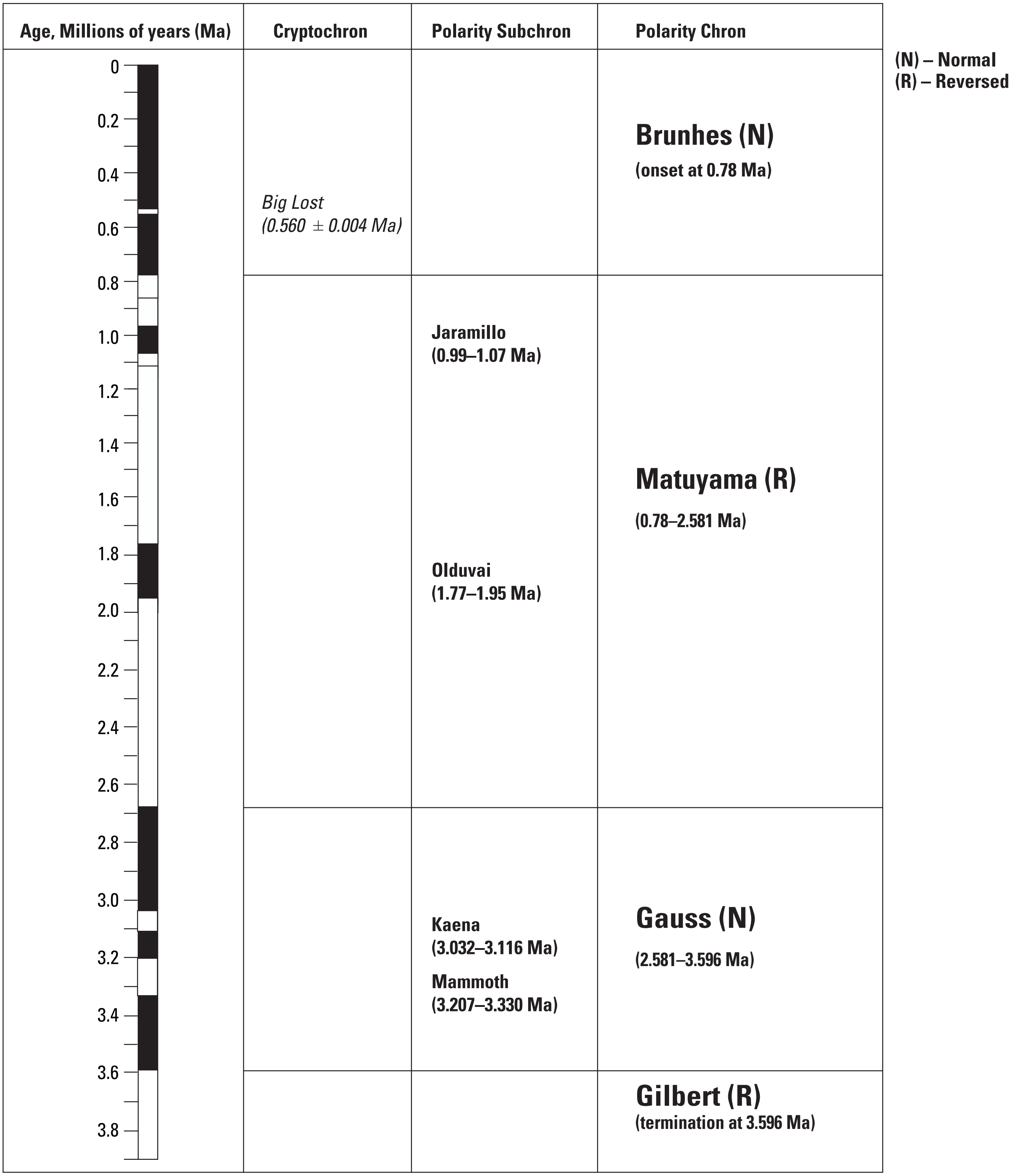

Figure 3. Pleistocene-Pliocene Geomagnetic Time Scale, polarity chrons, subchrons, and cryptochrons. Periods when the global magnetic polarity is the same as at present are defined as "normal"; periods when global magnetic polarity is the opposite of what they are at present are defined as "reversed." Ages are reported in millions of years in accordance with Ogg and Smith (2004).

Argon-Argon ($^{40}Ar/^{39}Ar$) Dating Methods

The $^{40}Ar/^{39}Ar$ measurements of basalt core samples used in this study were done at the $^{40}Ar/^{39}Ar$ Dating Laboratory at Rutgers University, Piscataway Township, New Jersey, using methods similar to those of Turrin and others (2008). Samples were selected from basalt flows, which were stratigraphically significant in terms of position, unique chemical or paleomagnetic properties, and distribution in the subsurface. Corehole locations are shown in figures 1 and 2 and sample depths are shown in table 3.

Four samples, Quaking Aspen Butte basalt flow, Vent 5206 basalt flow, Mid Butte basalt flow, and State Butte basalt flow were selected from basalt flows that could be traced from the surface to the subsurface, and which were identified by paleomagnetic inclination studies and that previously had been dated by other methods (Kuntz and others, 1986; Kuntz and others 1980; Champion and others, 1988; Lanphere and others, 1993; Kuntz and others, 1994).

Four samples, the "D3" basalt flow, West of ATR Complex basalt flow, High K_2O, and Big Lost basalt flows, were selected because the basalt flows from which they were collected are at or near the top of the stratigraphic section, which could mean that they came from vents exposed on the surface, and (or) because they are important stratigraphic markers.

The remainder of the samples were collected from basalt flows that are in close proximity to the Big Lost flow, three of which, South CFA Upper and Lower, and CFA Buried Vents, are at or near the top of the water table. The South CFA Upper and Lower flows were initially thought to be one very thick flow, and were sampled for dating to determine if it should be divided stratigraphically into two different basalt flows.

Samples collected for $^{40}Ar/^{39}Ar$ age determinations were evaluated in hand specimen, and samples were selected that had no oxidation and minimal glass and interstitial carbonate. The samples were then crushed, sieved to 180–500 µ size range, washed in distilled water in an ultrasonic bath, and dried in an oven at 50–80 degrees Celsius (°C). The prepared material was then magnetically separated into three to four splits using a hand magnet and a Frantz magnetic separator. The splits are described as hand magnet, which is the most magnetic fraction, more magnetic (from Frantz magnetic separation), and less magnetic (from Frantz separation). In some cases, magnetic splits were run in duplicate.

Approximately 100 mg of the prepared splits were loaded into aluminum irradiation disks along with the monitor mineral, sanidine from the rhyolite of Alder Creek (Turrin and others, 1994). The aluminum sample disks were wrapped in aluminum foil and encapsulated in cadmium foil for neutron irradiation. The samples were irradiated for 0.33 hours in the USGS TRIGA Reactor.

The irradiated sample splits were transferred into 6-mm-diameter sample wells milled into an approximately 60-mm-diameter stainless steel disk and loaded into the extraction system. The extraction system was baked overnight at 180–200 °C. A 40-watt carbon dioxide laser passing through a faceted lens that produces a 6 × 6 mm beam was used as the thermal source for the incremental-heating experiments. The power gradient across this beam is "flat" with little variation, providing uniform heating of the material illuminated by the 36-mm^2 beam. Additionally, the sample chamber is "jogged" in a diamond pattern, thus moved at a uniform rate so that the 6-mm round sample pit is evenly heated by the laser beam. Samples were heated incrementally, through step-wise increases in laser wattage output, from approximately 200 to 1,400 °C, or until the samples were fused into glass balls and minimal Ar was measurable above background values. Typically, Ar extractions included 10 incremental steps.

Ar isotopic ratios were measured on a MAP™-215-50 mass spectrometer. Data collection and data reduction were performed using the software "MassSpec" (Deino, 2014). Typical extraction line blanks for the Rutgers University system at the mass-to-charge ratios of the pertinent Ar isotopes are $M/e_{40} = 2 \times 10^{-16}$ mol, $M/e_{39} = 4 \times 10^{-19}$ mol, $M/e_{38} = 5 \times 10^{-19}$ mol, $M/e_{37} = 4 \times 10^{-18}$ mol, and $M/e_{36} = 2 \times 10^{-18}$ mol.

The neutron fluence parameter "J" for the sample irradiation was determined using an age of 1.204 Ma for sanidine from the rhyolite of Alder Creek, California (Turrin and others, 1994). Interfering neutron reactions from calcium (Ca) and K (Brereton, 1970; Dalrymple and others, 1981) were corrected for using the following values $(^{36}Ar/^{37}Ar)_{Ca} = (2.81 \pm 0.06 \times 10^{-4}$; $(^{39}Ar/^{37}Ar)_{Ca} = (7.11 \pm 0.05) \times 10^{-4}$ (Renne and others, 1998; Deino and McBrearty, 2002). Age calculations were made using the current accepted decay constants and isotopic abundances: $\lambda\varepsilon = 5.81\ 10^{-11}\ yr^{-1}$, $\lambda\beta = 4.962 \times 10^{-10}\ yr^{-1}$, $^{40}K/K_{total} = 1.167 \times 10^{-4}$ (Steiger and Jager, 1977).

Table 3. Results of $^{40}Ar/^{39}Ar$ age dating experiments for basalt samples from Idaho National Laboratory, Idaho.

[All ages are in thousands of years. Shading indicates preferred ages, with uncertainties. Bold values indicate usable ages. **SEM:** Standard error of the mean. **MSWD:** Mean square of weighted deviates. **Abbreviations:** ATR Complex, Advanced Test Reactor Complex; 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; mag, magnetic; USGS; U.S. Geological Survey; Ar, argon; ft, foot; K_2O, potassium oxide]

			Atmospheric intercept plateau											Isochron intercept plateau					
Sample No.	Laboratory identifier	Material	Plateau age	±1 SEM	^{39}Ar plateau (percent)	Number of steps	Integrated age	±1 SEM	Isochron age	±1 SEM	$^{40}Ar/^{36}Ar$ initial	±1 SEM	MSWD	Plateau age	±1 SEM	^{39}Ar plateau (percent)	Number of steps	Integrated age	±1 SEM
Quaking Aspen Butte—BG-77-1 (25-ft depth)																			
	21486	hand mag	(no plateaus)				310	24	279	27	295.6	1.1	5.9	(no plateaus)					
	21492	more mag	89	20	65	4	206	28	50	21	300.6	1.5	1.2	47	20	65	4	133	29
	21487	less mag	136	27	49	3	143	25	61	33	300.4	1.8	0.7	84	27	49	3	87	25
									67	**11**	**300.0**	**0.8**	**1.7**	**60**	**16**	**(2)**			
									(combined isochron age and intercept)					(weighted mean plateau age)					
									53	**18**	**(2)**								
									(weighted mean isochron age)										
Vent 5206—USGS 131 (66-ft depth)																			
	21473	hand mag	15	18	87	7	16	23	23	13	298.3	1.4	0.6	23	18	87	7	28	23
	21474	more mag	95	22	50	3	16	23	66	27	300	2.0	2.3	66	20	65	4	-44	23
	21475	less mag	33	18	100	9	33	24	19	7	299	1	0.9	19	18	100	9	16	24
			42	**11**					**63**	**9**	**298.0**	**0.6**	**1.8**	**34**	**11**				
			(weighted mean plateau age)						(combined isochron age and intercept)					(weighted mean plateau age)					
Mid Butte—ARA-COR-005 (37-ft depth)																			
	21489	hand mag	224	16	77	6	174	22	198	61	299.7	2.8	0.5	198	16	77	6	135	22
	21490	more mag	216	22	60	5	107	27	190	110	299.8	7.0	0.5	186	22	60	5	60	27
	21488	less mag	(no plateaus)				1,235	28	315	95	297.5	3.5	0.3	(no plateaus)					
									195	**39**	**300.2**	**2**	**0.7**						
									(combined isochron age and intercept)										
West of ATR Complex—NRF #6P (64-ft depth)																			
	21476	hand mag	144	25	62	6	-58	30	131	51	298.9	3.4	1.4	250	26	62	6	-78	30
	21477	more mag	223	29	70	7	52	42	240	120	298.3	4.0	0.2	294	28	70	7	67	42
	21478	less mag	193	24	59	4	-30	28	230	120	297.4	5.5	0.8	269	24	59	4	33	28
			184	**15**					**272**	**46**	**296.1**	**0.1**	**1.0**	**270**	**15**				
			(weighted mean plateau age)						(combined isochron age and intercept)					(weighted mean plateau age)					
High K_2O flow—USGS 128 (173-ft depth)																			
	21450-01	hand mag	250	15	85	6	258	23	292	24	297.1	0.8	0.7	307	14	85	6	345	22
	21450-02	hand mag	246	17	75	9	127	40						284	18	51	6	215	40
	21460	more mag	237	21	73	8	15	29	268	57	297.5	2.2	0.9	289	21	73	8	103	28
	21466-01	less mag	218	25	52	4	36	31	367	40	293.0	1.4	0.9	264	25	52	4	125	30
	21466-02	less mag	236	22	54	6	24	27						277	20	74	7	112	27
			241	**9**					**289**	**19**	**296.7**	**0.7**	**1.1**	**289**	**8**				
			(weighted mean plateau age)						(combined isochron age and intercept)					(weighted mean plateau age)					

Table 3. Results of $^{40}Ar/^{39}Ar$ age dating experiments for basalt samples from Idaho National Laboratory, Idaho.—Continued

[All ages are in thousands of years. Shading indicates preferred ages, with uncertainties. Bold values indicate usable ages. **SEM:** Standard error of the mean. **MSWD:** Mean square of weighted deviates. **Abbreviations:** ATR Complex, Advanced Test Reactor Complex; 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; mag, magnetic; USGS; U.S. Geological Survey; Ar, argon; ft, foot; K_2O, potassium oxide]

			Atmospheric intercept plateau												Isochron intercept plateau					
Sample No.	Laboratory identifier	Material	Plateau age	±1 SEM	^{39}Ar plateau (percent)	Number of steps	Integrated age	±1 SEM	Isochron age	±1 SEM	$^{40}Ar/^{36}Ar$ initial	±1 SEM	MSWD	Plateau age	±1 SEM	^{39}Ar plateau (percent)	Number of steps	Integrated age	±1 SEM
South CFA Buried Vent(s)—Upper flow – USGS 128 (272-ft depth)																			
	21501	hand mag	315	18	82	6	331	21	312	31	299.0	0.9	1.2	318	18	82	6	336	21
	21502	more mag	297	22	70	4	344	24	338	39	297.9	1.3	2.1	301	22	70	4	349	24
	21491	less mag	296	29	83	5	349	35	291	74	298.7	1.8	0.3	300	29	83	5	354	33
			306	**13**					**320**	**23**	**298.5**	**0.6**	**1.0**	**309**	**13**				
			(weighted mean plateau age)						(combined isochron age and intercept)					(weighted mean plateau age)					
D3 flow—USGS 135 (225-ft depth)																			
	21515	hand mag	422	31	89	6	382	42	451	45	297.3	1.2	1.2	472	30	100	8	478	41
	21516	more mag	423	24	91	6	317	34	451	44	296.7	2.5	1.2	453	24	91	6	379	34
	21517	less mag	417	26	74	5	449	29	427	63	298.0	3.7	0.9	449	26	74	5	492	29
			421	**15**					**454**	**22**	**296.6**	**0.9**	**1.2**	**456**	**15**				
			(weighted mean plateau age)						(combined isochron age and intercept)					(weighted mean plateau age)					
South CFA Buried Vent(s)—Lower flow – USGS 128 (312-ft depth)																			
	21499	hand mag	506	33	59	5	346	34	763	86	292.1	1.9	1.1	758	28	82	6	711	34
	21500	more mag			(no plateaus)		501	32	440	280	303.8	8.3	0.2		(no plateaus)			207	32
	21505	less mag	464	37	61	6	364	39	520	150	297.1	4.3	0.5	495	33	84	7	442	39
			487	**25**					**452**	**88**	**302.0**	**3.5**	**1.0**						
			(weighted mean plateau age)						(combined isochron age and intercept)										
"E" flow—BG-77-1 (320-ft depth)																			
	21461-01	hand mag	38	91	100	11	0	120	560	140	291.0	2.4	0.3	561	89	100	11	580	120
	21461-02	hand mag	65	63	80	9	-3	71						553	56	100	10	569	70
	21462-01	more mag	100	150	100	11	140	200	540	150	292.4	3.5	0.5	510	140	100	11	610	200
	21462-02	more mag	72	97	100	9	60	120						553	95	100	9	590	110
	21463-01	less mag	170	140	99	7	100	170	550	120	290.0	2.6	0.8	540	150	80	7	670	170
	21463-02	less mag	77	66	75	5	-7	74						550	63	81	7	516	72
									507	**71**	**291.6**	**1.5**	**0.5**	**550**	**33**				
									(combined isochron age and intercept)					(weighted mean plateau age)					
									550	**78**									
									(weighted mean isochron age)										

Table 3. Results of $^{40}Ar/^{39}Ar$ age dating experiments for basalt samples from Idaho National Laboratory, Idaho.—Continued

[All ages are in thousands of years. Shading indicates preferred ages, with uncertainties. Bold values indicate usable ages. **SEM:** Standard error of the mean. **MSWD:** Mean square of weighted deviates. **Abbreviations:** ATR Complex, Advanced Test Reactor Complex; 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; mag, magnetic; USGS; U.S. Geological Survey; Ar, argon; ft, foot; K_2O, potassium oxide]

			Atmospheric intercept plateau											Isochron intercept plateau					
Sample No.	Laboratory identifier	Material	Plateau age	±1 SEM	^{39}Ar plateau (percent)	Number of steps	Integrated age	±1 SEM	Isochron age	±1 SEM	$^{40}Ar/^{36}Ar$ initial	±1 SEM	MSWD	Plateau age	±1 SEM	^{39}Ar plateau (percent)	Number of steps	Integrated age	±1 SEM
Big Lost flow—BG-77-1 (427, 473, and 534-ft depths)																			
427-ft	21447-01	hand mag	584	14	87	8	688	21	570	37	299.0	1.1	0.7	570	14	87	8	670	21
	21448-01	more mag	540	29	93	7	478	35	620	47	295.9	1.7	0.4	610	28	93	7	565	35
	21448-02	more mag	554	17	93	7	533	29						623	17	100	9	621	29
	21449-01	less mag	549	34	100	9	542	45	564	62	297.7	2.2	0.7	557	35	81	6	575	45
	21449-02	less mag	532	28	69	5	492	40						556	28	69	5	525	40
473-ft	21453-01	hand mag	537	13	100	9	553	17	555	14	296.3	1.6	1.3	552	13	96	7	579	17
	21453-02	hand mag	545	9	80	5	575	14						556	9	93	7	608	14
	21452-01	more mag	537	17	92	7	576	24	550	15	297.6	2.1	1.4	543	17	92	7	587	23
	21452-02	more mag	539	9	84	6	587	13						545	9	84	6	598	12
	21451-01	less mag	584	30	96	8	618	39	560	20	298.1	2.2	1.3	587	30	96	8	624	39
	21451-02	less mag	557	14	99	8	585	53						559	14	98	7	596	53
534-ft	21503-01	hand mag	532	40	68	5	261	47	564	98	298.2	1.0	0.4	564	40	68	5	304	47
	21504-01	more mag	561	33	47	5	172	36	564	98	298.6	1.6	0.9	564	33	47	5	176	36
	21514-01	less mag	(no plateaus)				223	36	623	110	298.1	1.9	0.1	(no plateaus)				270	36
			548	**4**					**558**	**9**				**560**	**4**				
			(weighted mean plateau age)						(weighted mean isochron age)					(weighted mean plateau age)					
CFA Buried Vent flow—USGS 128 (596-ft depth)																			
	21513	hand mag	(no plateaus)				50	50	1,212	94	285.7	1.0	0.8	1,213	30	90	5	1,283	44
	21512	more mag	[1]*550*	[1]*52*	[1]*(24)*	[1]*5*	-71	46	1,344	84	283.4	1.0	1.4	693	41	45	6	271	46
	21518	less mag	560	60	47	4	340	70	540	260	298.9	5.4	1.1	536	63	47	4	309	65
														536	**63**				
														(Frantz less magnetic plateau age)					
State Butte flow—NRF-16 (187-ft depth)																			
	21464	hand mag	590	14	75	6	549	17	654	30	294.6	1.6	0.4	654	14	75	6	632	16
	21465	more mag	560	20	66	6	550	20	598	51	295.4	3.5	0.6	598	21	66	6	610	24
	21479	less mag	616	16	92	7	655	20	591	45	300.3	2.8	1.2	594	16	96	8	620	20
			592	**9**					**627**	**22**				**621**	**9**				
			(weighted mean plateau age)						(weighted mean isochron age)					(weighted mean plateau age)					

[1] Values indicate a weak interpretation due to the small amount of ^{39}Ar released (24 percent).

The main advantage of the $^{40}Ar/^{39}Ar$ incremental-heating method is the information obtained on the internal distribution of K relative to Ar within a whole-rock or mineral system over the temperature range of approximately 400 °C to fusion. In an "ideal" system, in which K is homogeneously distributed relative to radiogenic argon ($^{40}Ar^*$) produced by the radioactive decay of ^{40}K , $^{40}Ar/^{39}Ar$ results should meet the criteria put forth by Fleck and others (1977) and Dalrymple and Lanphere (1969, 1974). These criteria are summarized as follows:

1. A plateau is defined by a minimum of three consecutive steps that together comprise at least 50 percent of the total $^{39}Ar_K$ released from the sample (where $^{39}Ar_K = {}^{39}Ar$ produced from ^{39}K) and for which no difference in age can be detected between two adjacent fractions at the 95 percent confidence level.

2. When the isotopic data are plotted on an isotope correlation diagram, they should form a linear array that defines a mixing line between the trapped component and the "age" component. The mean square of weighted deviates of this line should be less than 2.5. In the original criteria set forth in Fleck and others (1977), it is not clear whether all of the data or just the plateau data are considered.

3. The trapped $^{40}Ar/^{36}Ar$ component, as indicated by the isotope correlation diagram analysis, should be analytically indistinguishable from the accepted atmospheric ratio at the 95 percent confidence level.

4. The isochron age should be analytically indistinguishable from the plateau age at the 95 percent confidence level.

5. The integrated (total-fusion) age should be analytically indistinguishable from the plateau and isochron ages at the 95 percent confidence level.

The improved measurement precision now possible with ion-pulse counting detectors (Turrin and others, 2010) and tight temporal monitoring of mass spectrometer mass fraction (Turrin and others, 2008) warrant a reevaluation of the third criterion stated above, for the following reasons:

1. A detectable increase in the atmospheric $^{40}Ar/^{36}Ar$ ratio over the last 800 ka has been documented (Bender and others, 2008).

2. Studies of the Devonian Rhynie Chert (Cadogan, 1977) suggest that since the Devonian, the degassing of radiogenic ^{40}Ar has increased the atmospheric $^{40}Ar/^{36}Ar$ ratio from 294.1 relative to today's value of 298.6 (Lee and others, 2006; Valkiers and others, 2010).

3. Non-atmospheric $^{40}Ar/^{36}Ar$ ratios for the "trapped" component in volcanic rocks have been presented in Takaoka and others (1989); Matsumoto and others (1989); and Matsumoto and Kobayashi (1995). Sub-atmospheric $^{40}Ar/^{36}Ar$ values correlated with $^{38}Ar/^{36}Ar$, consistent with kinetic mass fractionation.

The studies discussed above bring into question the validity of assuming atmospheric $^{40}Ar/^{36}Ar$ ratio for the trapped component for calculating the apparent ages used in determining plateau ages for samples.

Because these studies indicate that there may be variability in the "trapped" component, the data evaluation procedure was changed. After all of the corrections (such as blanks, reactor corrections, mass discrimination) have been applied, the data are plotted on an isotopic correlation diagram, and the $^{40}Ar/^{36}Ar$ ratio of the trapped component is derived from the data. This value and its associated error are then used to determine the apparent step ages. These "apparent" ages are then applied to criterion 1 to determine a plateau age for the sample. The replotted plateau is referred to as an Isochron Intercept Plateau (IIP).

Results of Argon-Argon ($^{40}Ar/^{39}Ar$) Dating Experiments

Each age dating experiment on a sample split may yield more than one age. Ideally, all the plateau and isochron ages from all splits of each sample will be the same at the 95 percent confidence level, but ages from low-potassium, geologically young olivine tholeiite basalts often yield different plateau and isochron ages. Characteristic patterns, especially in the plateau diagrams of the data, may indicate potential interpretation problems such as excess argon or various analytical failures. Geological data, such as paleomagnetic inclination data, map relations, and stratigraphy, are of considerable aid in interpreting age data that may not be straightforward. Ages derived from $^{40}Ar/^{39}Ar$ age dating experiments interpreted in light of other geologic data are referred to as "preferred ages."

Preferred ages for the samples reported here were interpreted by using the results of the $^{40}Ar/^{39}Ar$ age experiments merged with existing geologic data. Analytical data and plots for the experiments are presented in appendix A. Geographic distribution of coreholes from which samples were collected is shown in figures 1*A* and 1*B*, and corehole names and aliases are presented in table 2.

Shading in table 3 indicates the preferred ages. Appendix A presents the data from which the preferred ages were derived and the plateau and isochron diagrams for the experiments that yielded isochron and plateau diagrams.

Quaking Aspen Butte Basalt Flow—60 ± 16 Thousand Years Ago

The Quaking Aspen Butte (QAB) basalt flow (fig. 2) is the youngest basalt flow in the southwest part of the INL, and is so labeled because it can be traced from the QAB vent to the subsurface (fig. 2). The QAB vent is exposed on the surface about 4.3 mi (7 km) southwest of the southwest corner of the INL boundary. The QAB basalt flow was originally described by Kuntz and others (1980), and identified in the subsurface by Anderson and Lewis (1989). It is found in coreholes BG 77-1, WWW-1, and USGS 132 (figs.1*A* and 1*B*), and is exposed on the surface in the RWMC area (fig. 2). The QAB basalt flow overlies the Vent 5206 basalt flow at the surface and in the subsurface in coreholes WWW-1, BG-77-1, and USGS 132 (Champion and others, 2011). The QAB sample was collected from corehole BG-77-1 (fig. 2), about 25 ft (7.6 m) below land surface (BLS). Latest Pleistocene (Marine Isotope Stage 2) gravels from the 21.9 ± 2.1 ka Big Lost River glacial outburst flood are on top of the surface lava flows of QAB, so the QAB basalt flow is at least older than 21.9 ± 2.1 ka (Cerling and others, 1994). Kuntz and others (1986) attempted to date the QAB surface flow by the radiocarbon method and obtained values that suggest that the QAB basalt flow is older than about 40 ka (M. Ruben, U.S. Geological Survey, written commun., 1977). Kuntz and others (1980) obtained a K-Ar weighted mean age of 95 ± 50 ka for the QAB.

Three magnetic splits from the QAB sample from corehole BG-77-1 (fig. 1*A*) were analyzed. Fusion ages from the splits trend towards ages that are too old to be reasonable, and the hand magnet split failed to produce a plateau. The ^{40}Ar release for individual steps in the QAB experiments typically is less than 2 percent, indicating that this experiment is difficult to interpret.

The isochron ages produced from the three splits involve the fewest assumptions, and two average ages can be suggested from that data. An isochron from the combined data of the three splits yields an age of 67 ± 11 ka, with a ^{40}Ar/^{36}Ar intercept of 300.0 ± 0.8. A weighted mean isochron age of the two least magnetic splits yields an age of 53 ± 18 ka. The combined isochron intercept value generates two new IIPs from the two least magnetic splits, but did not generate an IIP plateau for the hand magnetic split. The weighted mean age of 60 ± 16 ka from the two new IIP plateaus is the preferred age of this sample (table 3).

Vent 5206 Basalt Flow—63 ± 9 Thousand Years Ago

The Vent 5206 lava flow is the surface lava flow on the southwest part of the INL, with vents near the southern INL border, north of Big Southern Butte (fig. 2). The Vent 5206 basalt flow is found in coreholes WWW-1, BG-94, BG77-1, BG 76-6, USGS 118, USGS 132, USGS 137-137-A, C1A. USGS 129, USGS 131, USGS 127, USGS 130, STF-PIE-AQ-01, USGS 128, USGS 80, ICPP 215, and USGS 121 (figs. 1*A*, 1*B*, and 2; Champion and others, 2011). The Vent 5206 sample was collected from corehole USGS 131-131A (131 in fig. 1*A*), approximately 66 ft (20.1 m) below land surface. The sample was separated into three magnetic splits, and all produced young plateaus and total fusion ages, but the isochrons for these experiments were not easily interpreted. The plateau diagrams show relatively large quantities of ^{39}Ar released, despite having individual step ^{40}Ar radiogenic percentages generally less than 2 percent. The initial age estimate for this sample is the weighted mean plateau age of 42 ± 11 ka. However, the QAB flow overlies the Vent 5206 basalt flow, and the QAB ^{40}Ar/^{39}Ar preferred age from this report is 60 ± 16 ka.

Morphologically, the surface flow field of Vent 5206 appears older than the surface of Quaking Aspen Butte. In coreholes BG 77-1 and USGS 132 (figs. 1*A* and 1*B*), where QAB and Vent 5206 are both present, they are separated by sediment, which generally indicates that the two basalt flows are separated by some time. The QAB (60 ± 16 ka, this study) and the 13.2 ka latest Pleistocene Cerro Grande lava fields (fig. 2; Kuntz and others, 1986) overlie the Vent 5206 basalt flow, which overlies the Lavatoo Butte, Mid Butte, and the unknown vent East of Middle Butte basalt flow (Champion and others, 2011, pl. 1). Kuntz and others (1980) sampled the Vent 5206 basalt flow from BG 76-6 (figs. 1*A* and 1*B*) for K-Ar age experiments and obtained ages of less than 240 ka (sample 76-6-64), less than 200 ka (sample 77-1-126), and less than 190 ka (sample 76-6-90).

The weighted mean IIP plateau age from the splits of this sample is 34 ± 11 ka, which is younger than the preferred age of the overlying QAB basalt flow. The preferred age of the Vent 5206 basalt flow is therefore the combined isochron age, 63 ± 9 ka (table 3).

Mid Butte Basalt Flow—195 ± 39 Thousand Years Ago

The Mid Butte vent is exposed at the surface of the southeast part of the INL (Kuntz and others, 1994). The Mid Butte basalt flow is exposed at the surface (fig. 2), and is also found in the subsurface in coreholes ARA-COR-005, STF-PIE-AQ-01, USGS 80, USGS 128, ICPP 214, NPR Test/W-02 (fig. 1*A*), and Middle 2052A (figs. 1*A* and 1*B*; Champion and others, 2011). Vent 5206 (63 ± 9 ka, this study) overlies the Mid Butte basalt flow, and the West of ATR Complex, High K_2O, and Vent 5252 (350 ± 40 ka; K-Ar; Champion and others, 1988) basalt flows underlie the Mid Butte basalt flow near the CFA (fig. 1*A*). Champion and others (1988) sampled the Mid Butte basalt flow in corehole NPR-Test from 23 and 82 ft (7 and 25 m) BLS for age dating by the K-Ar method and obtained an age of 233 ± 34 ka. Lanphere and others (1993) sampled a basalt flow that may be part of the Mid Butte basalt flow in corehole USGS 80 at 44 ft (13.4 m) BLS, and obtained a K-Ar age of 419 ± 33 ka. The Mid Butte flow sample analyzed in this study was collected from corehole ARA-COR-005 (fig. 2), from about 37 ft (11.3 m) BLS.

Two of the three magnetic splits analyzed for this basalt flow produced highly concordant age results in both plateau and isochron diagrams. The Franz least magnetic split failed to produce a plateau, has an old isochron, and yielded unreasonably old total fusion ages. The combined isochron age from all three splits yields the preferred age, 195 ± 39 ka, with a ^{40}Ar/^{36}Ar intercept of 300.2 ± 2.0 (table 3). Using that somewhat high intercept value allows the IIP plateau ages for the more magnetic splits to be recast, decreasing their ages from the initial plateaus by about 40 ka.

West of Advanced Test Reactor Complex Basalt Flow—270 ± 15 Thousand Years Ago

The West of ATR Complex basalt flow is prominent in the near surface stratigraphy of the central part of the INL. It is the youngest and uppermost basalt flow in coreholes USGS 133, NRF B18-1, NRF 89-05, NRF 6P, NRF 7P, NRF 15, and NRF 16 (Champion and others, 2013). The West of ATR Complex basalt flow underlies the Mid Butte flow in coreholes USGS 123, ICPP 214, USGS 80, and in Middle 2050A (Lanphere and others, 1993; Champion and Herman, 2003; Champion and others, 2011), and underlies the Crater Butte basalt flow in USGS 121, USGS 134, and USGS 136. The West of ATR Complex basalt flow overlies the High K_2O), the Idaho Nuclear Technology and Engineering Center (INTEC) buried vent, and the ATR Complex unknown vent basalt flow (Champion and others, 2011; Champion and others, 2013). The West of ATR Complex basalt flow is the uppermost basalt flow in the NRF area and thickens towards USGS 134 (figs. 1*A* and 1*B*); therefore, the West of ATR Complex vent likely is exposed on the surface, but it is one of the surface vents that has not yet been analyzed paleomagnetically. Lanphere and others (1993) sampled the West of ATR Complex basalt flow from corehole NRF 89-05 at 24 m BLS for K-Ar age dating and obtained a K-Ar age of 303 ± 30 ka. They also sampled the West of ATR Complex basalt flow in corehole USGS 80 at 98.8 and 127 ft (30.1 and 38.7 m) BLS, and obtained a K-Ar age of 461 ± 24 ka. The West of ATR Complex sample for this study was taken from corehole NRF 6P from approximately 64 ft (19.5 m) BLS (figs. 1*A*, 1*B*, and 2).

Three magnetic splits were analyzed. The three experiments yielded similar plateaus, isochrons and total fusion ages, but resulted in different ages. The total fusion ages are near zero, indicating that “excess” ^{36}Ar contaminates the lowest temperature steps. The near-zero total fusion ages may indicate a recoil effect, despite the short irradiation time used in this experiment, or there may have been excess argon in the magma itself. A recoil effect may occur during irradiation due to the kinetic energy of proton emission during the (n,p) reaction, which may cause loss or redistribution of ^{36}Ar, ^{37}Ar, and ^{39}Ar. Changes in the amount or distribution of argon isotopes will change the argon isotope values and yield anomalous ratios (McDougall and Harrison, 1999). Recoil effect may have also systematically affected the plateau steps.

The weighted mean plateau age, 184 ± 15 ka, is the most straightforward result, but it is not stratigraphically reasonable because the West of ATR Complex basalt flow underlies the Mid Butte basalt flow (195 ± 39 ka, this study; Champion and others, 2011, pl. 1) in coreholes ICPP 214, ICPP 248, Middle 2050A, and USGS 80 (figs. 1*A* and 1*B*). The West of ATR Complex basalt flow underlies the Crater Butte basalt flow (292 ± 58 ka; Skipp and others, 2009; Champion and others, 2011) in coreholes USGS 134 and USGS 121 (Champion and Herman, 2003; Champion and others, 2011, pl. 1; Champion and others, 2013, pl. 1). The combined isochron from the three splits has a low $^{40}Ar/^{36}Ar$ intercept and yields an age of 272 ± 46 ka. Recasting the data to three IIP plateau ages with the 296.1 ± 0.1 $^{40}Ar/^{36}Ar$ intercept value produces a new, weighted mean IIP plateau age of 270 ± 15 ka, which is the preferred age for the West of ATR Complex basalt flow (table 3).

High K_2O Basalt Flow—289 ± 8 Thousand Years Ago

The High K_2O basalt flow is so labeled because it has significantly greater amounts of K_2O than the average for ESRP olivine tholeiite basalts (Reed and others, 1997). The High K_2O basalt flow is overlain by the Mid Butte basalt flow and underlain by Vent 5252 basalt flow (fig. 2), both of which erupted from vents exposed on the land surface. The High K_2O vent may be exposed at the surface of the INL because it is near the top of coreholes in the southern INL above the Vent 5252 basalt flow, which is exposed at the surface. Like the Mid Butte basalt flow and the Vent 5252 basalt flow (Champion and others, 2011, pl. 1), the High K_2O basalt flow thickens towards the Axial Volcanic Zone (fig. 1), which may indicate that the High K_2O basalt flow erupted from an Axial Volcanic Zone vent. The High K_2O basalt flow is found in coreholes ARA-COR-005, STF-PIE-AQ-01, USGS 131-131A, USGS 130, USGS 128, USGS 127, USGS 123, USGS 121, ICPP 214, ICPP 023, and Middle 2050A (fig. 1*A*). The High K_2O basalt flow underlies the Vent 5206, Mid Butte, West of ATR Complex, East of Middle Butte unknown vent, and the Lavatoo Butte basalt flow, and overlies the Vent 5252 basalt flow (Champion and Herman, 2003; Champion and others, 2011, pl. 1). The High K_2O sample for this study was collected from corehole USGS 128 (fig. 2) from approximately 173 ft (52.7 m) BLS.

Two of the three High K_2O splits were run in duplicate. Total fusion ages from the different splits vary, with some ages near zero. The percentage of radiogenic ^{40}Ar from steps for the different experiments is about 4 percent, which was less than expected. Average ages were derived from atmospheric value assumptive plateau and isochron diagrams, and these ages did not statistically overlap. The initial $^{40}Ar/^{36}Ar$ ratio measured from the step-heating data of the Frantz less magnetic split is rather low at 293.0 ± 1.4, and the other $^{40}Ar/^{36}Ar$ intercepts are also less than 298.6, which probably indicates excess ^{36}Ar. Data from 38 steps from experiments on all three splits produce a combined isochron age of 289 ± 19 ka, with a $^{40}Ar/^{36}Ar$ intercept of 296.7 ± 0.7. This intercept was used to recalculate five IIP plateau ages, and their weighted mean age of 289 ± 8 ka is the preferred age for the High K_2O basalt flow (table 3).

South Central Facilities Area Buried Vent(s) Upper Basalt Flow—309 ± 13 Thousand Years Ago

Champion and others (2011) combined this basalt flow with one that immediately underlies it and labeled them the South CFA Buried Vent(s) (SCFABV) basalt flow (Champion and others, 2011). Age data from this study shows that the SCFABV basalt flow is actually two different basalt flows, from different monogenetic eruptions, separated in time by more than 200,000 years. Consequently, the upper unit is now labeled the South Central Facility Area buried vent(s) Upper (SCFABVU) basalt flow. The SCFABVU basalt flow is in coreholes USGS 123, USGS 127, USGS 128, USGS 129, USGS 130, USGS 131-131A, USGS 137-137A, Middle 2050A, Middle 2051, NPR-Test/W-02, ICPP 213, ICPP 214, and ICPP 215 (Champion and Herman, 2003; Champion and others, 2011, pl. 1 and app. A). It also may be present in the uncored interval of corehole Middle 1823. The SCFABVU sample was collected from corehole USGS 128 (fig. 2) from about 272 ft (82.9 m) BLS.

The three magnetic splits analyzed for this basalt flow produced age assessments from plateau, isochron, and total fusion age diagrams in significant conformity with each other. All three plateaus display a saddle pattern, which may indicate an excess ^{40}Ar component, so the initial weighted mean plateau age of 306 ± 13 ka probably is not accurate. The combined isochron age is 320 ± 23 ka, and the ^{40}Ar/^{36}Ar intercept value is 298.5 ± 0.6, which is close to the atmospheric value of 298.6. Recasting the IIP plateau ages to this near atmospheric value produces a new weighted mean age of 309 ± 13 ka, similar to the initial weighted mean ages using the atmospheric assumption. This sample demonstrates a null case situation where recasting might be unnecessary, but still allows use of measured IIP intercept and uncertainty values. The weighted mean IIP plateau age 309 ± 13 ka is the preferred age for the South CFABVU basalt flow (table 3).

"D3" Basalt Flow—456 ± 15 Thousand Years Ago

The "D3" basalt flow (Anderson and others, 1996) has only been identified in corehole USGS 135 (figs. 1*A* and 1*B*). In corehole USGS 135, the "D3" basalt flow is overlain by the Tin Cup Butte (fig. 2) basalt flow (352 ± 5 ka, Brent Turrin, Rutgers University, written commun., 2010), and an uncorrelated basalt flow that has an average paleomagnetic inclination of 51 degrees. The "D3" basalt flow overlies the "E" basalt flow (Anderson and others, 1996). The "D3" basalt flow sample was collected from corehole USGS 135 from about 225 ft (68.6 m) BLS (figs. 1*A*, 1*B*, and 2).

The three magnetic splits analyzed for this lava flow produced highly concordant age results in plateau and isochron diagrams. The combined isochrons for the 17 heating steps from the 3 plateau diagrams yield a ^{40}Ar/^{36}Ar intercept of 296.6 ± 0.9, slightly less than the atmospheric value of 298.6. The slightly older combined isochron age, 454 ± 22 ka, is in full accord with the weighted mean average of the three plateau ages, which is 421 ± 15 ka. Maximum radiogenic ^{40}Ar values for the three splits ranged from 9 to 11 percent, suggesting that these experiments are statistically strong. The preferred age for the "D3" basalt flow is the weighted mean IIP plateau age of 456 ± 15 ka (table 3).

South Central Facilities Area Buried Vent(s) Lower Basalt Flow—452 ± 88 Thousand Years Ago

The South CFA Buried Vent(s) Lower (SCFABVL) basalt flow underlies the SCFABVU (309 ± 13 ka; table 3), ATR Complex Unknown Vent (395 ± 25 ka; Champion and others, 2013), and the Vent 5252 basalt flow (350 ± 40 ka, Champion and others, 1988). It directly overlies the Big Lost, the North INTEC Buried Vent (489 ± 28 ka, Champion and others, 2002), and the CFA Buried Vent basalt flows (Champion and others, 2011, pl. 1). The SCFABVL sample was collected from corehole USGS 128 from about 312 ft (95.1 m) BLS (figs. 1*A*, 1*B*, and 2).

The three magnetic splits analyzed for the SCFABVL basalt flow produced "climbing" age spectra, resulting in different age assessments. Early low and negative age steps hold the total fusion ages to generally low values. These same early steps force the isochrons to lower than atmospheric ^{40}Ar/^{36}Ar intercept values, and older ages. Weighted mean isochron ages for all three splits, or for the two Frantz magnetic splits, have unacceptably large uncertainties (greater than 100,000 years). The separate isochrons produced from the hand magnetic and least magnetic splits were used to recast new IIP plateau ages. The number of steps interpreted for the least magnetic split increases by one, and the span of ^{39}Ar released increases from 61 to 84 percent using this protocol. The combined isochron age and intercept 302.0 ± 3.5 from the recast data is 452 ± 88 ka, which is the preferred age for the SCFABVL basalt flow.

"E" Basalt Flow—550 ± 33 Thousand Years Ago

The "E" basalt flow (Anderson and others, 1996) is in the SW corner of the INL in coreholes USGS 135, BG-94, BG-77-1, USGS 118, USGS 132, USGS 137, and C1A (figs. 1*A* and 1*B*). The "E" basalt flow is overlain by the "D3" basalt flow (Anderson and others, 1996), and an unlabeled basalt flow that has an average paleomagnetic inclination of 51°, and the Tin Cup Butte basalt flow. The "E" basalt flow overlies the "Big Lost" basalt flow, which is an important INL stratigraphic marker because it was emplaced during the Big Lost Reversed Polarity Cryptochron and has reversed polarity inclination (Kuntz and others, 1980). The "E" basalt flow sample was collected from corehole BG 77-1 from about 320 ft (97.5 m) BLS (fig. 2).

The three magnetic splits analyzed for this lava flow were done in duplicate, producing six independent age experiments. This was fortunate, as the initial results indicated that this rock did not successfully equilibrate with the earth's $^{40}Ar/^{36}Ar$ atmospheric ratio of 298.6 at the time of its eruption and emplacement. Isochron diagrams using the atmospheric assumption had $^{40}Ar/^{36}Ar$ intercepts close to 291 and produced ages of about 550 ka, much older than the plateau diagram or total fusion age estimates. Previous argon dating work and stratigraphic depth data indicated that the "E" basalt flow should have an age near 500 ka, so the plateau diagrams were recast to the measured $^{40}Ar/^{36}Ar$ ratio of 291.6 ± 1.5 from the combined isochron in the calculations. The combined isochron for all six data sets suggests an age of 507 ± 71 ka, in full accord with the weighted mean average age of the IIP plateau diagrams at 550 ± 33 ka. The weighted mean isochron age calculated from each duplicated split is also in accord at 550 ± 78 ka. The preferred age for the "E" basalt flow is the weighted mean IIP plateau age of 550 ± 33 ka (table 3).

Big Lost Basalt Flow—560 ± 4 Thousand Years Ago

The Big Lost basalt flow is an important stratigraphic marker in the subsurface of the INL because it has reversed magnetic polarity and because it extends from the southern border of the INL to the CFA, a distance of about 28 km (Champion and others, 2011). The Big Lost basalt flow is found in coreholes USGS 137, USGS 132, USGS 129, USGS 131-131A, USGS 127, USGS 130, USGS 118, USGS 105, USGS 108, BG-77-1, C1A Middle 2051, NPR-Test-WO2, STF-AQ-01, and ARA-COR-005. Three samples were magnetically separated into 15 different splits and analyzed for argon ages. The Big Lost basalt flow is detected in many coreholes across the southern part of the Idaho National Laboratory. It directly underlies the "E" basalt flow (550 ± 33 ka, table 3) and the SCFABVL basalt flow (452 ± 88 ka, table 3), and overlies the CFA Buried Vent basalt flow (536 ± 63 ka, table 3) and the "G" basalt flow (Champion and others, 2011, pl. 1) in south-central Idaho National Laboratory. Kuntz and others (1980) sampled the Big Lost basalt flow for K-Ar dating, petrography, paleomagnetism, stratigraphy, and frequency of eruption in the RWMC area.

The Big Lost basalt flow samples were collected from corehole BG 77-1 from approximately 427, 473, and 534 ft (130.1 m, 144.2 m, and 162.8 m) BLS (figs. 1*A* and 1*B*). Three separate samples of the Big Lost basalt flow were collected, and divided magnetically into 15 splits, some of which were run in duplicate. All were analyzed for argon ages. The initial plateau ages using the atmospheric assumption are in reasonable accord with the separate split isochron ages. The $^{40}Ar/^{36}Ar$ intercept values on those isochron diagrams overlap the atmospheric value of 298.6, but those isochrons tend to be an older age within uncertainty. The integrated total fusion ages are also close to each other. The weighted mean IIP plateau age from the recast data from these 15 experiments is 560 ± 4 ka, which is the preferred age for the Big Lost basalt flow (table 3).

Central Facilities Area Buried Vent Basalt Flow—536 ± 63 Thousand Years Ago

The CFA Buried Vent (CFABV) basalt flow is widespread in the south and central parts of the INL and is thickest in the subsurface at the CFA (fig. 2). It extends north to corehole NRF 16, east to the corehole NPR-Test/W-02, south to the southern border of the INL, and west to corehole Middle 2051 (fig. 1*A*). The CFABV basalt flow is found in coreholes USGS 137, USGS 132, C1A, USGS 129, USGS 131-131A, USGS 127, USGS 130, USGS 128, USGS 123, ICPP 023, ICPP 213, ICPP 214, ICPP 215, ICPP 1795, ICPP 1796, ICPP 1797, ICPP 1798, USGS 121, NPR-Test/W-02, USGS 133, USGS 134, USGS 136, Middle 1823, Middle 2050A, Middle 2051, NRF B18-1, NRF 6P, NRF 7P, NRF 89-04, NRF 89-05, NRF 15, and NRF 16 (Champion and Herman, 2003; Champion and others 2011; Champion and others 2013). The CFABV basalt flow underlies the "G," Big Lost, SCFABVL, and North INTEC buried vent basalt flows and overlies the Middle Basal Brunhes, AEC Butte (637 ± 35 ka, K-Ar, Lanphere and others, 1993; 727 ± 31 ka, Champion and others, 2013), and State Butte basalt flows (Champion and others, 2011; Champion and others, 2013). The CFABV basalt flow sample was collected from corehole USGS 128 (figs. 1*A* and 1*B*) from about 596 ft (181.7 m) BLS.

The three magnetic splits analyzed for the CFA Buried Vent basalt flow produced variable and difficult-to-interpret ages. The total fusion ages from the three splits do not group and two are essentially zero, which is unreasonably young for a basalt flow at approximately 600 ft (183 m) depths. The isochron ages also do not group, and two of the isochrons suggest ages of about 1.3 Ma, which is unlikely because 1.3 Ma is much too old for a basalt flow with the normal polarity inclination between other normal polarity inclination lava flows at this depth.

The least magnetic split yielded the only age results that were reasonable, although the "all steps" isochron yielded an age greater than 1.0 Ma. A plateau derived from the least magnetic split isochron, with 47.2 percent of the ^{39}Ar released, yielded an age of 560 ± 60 ka. The associated "plateau steps only" isochron has an age of 540 ± 260 ka and a $^{40}Ar/^{36}Ar$ intercept value of 298.9 ± 5.4. The IIP plateau age calculated from this measured $^{40}Ar/^{36}Ar$ intercept is 536 ± 63 ka. The preferred age for the CFABV basalt flow is the Frantz less magnetic IIP age, which is 536 ± 63 ka (table 3).

State Butte Basalt Flow—621 ± 9 Thousand Years Ago

State Butte is exposed at the surface east of the NRF (fig. 2) and the State Butte basalt flow is found in coreholes NRF 89-04, NRF 6P, NRF 7P, NRF 15, and NRF 16. The State Butte basalt flow underlies the CFABV basalt flow (540 ± 60 ka, table 3) and overlies the AEC Butte basalt flow (637 ± 35 ka, K-Ar, Lanphere and others, 1993; 727 ± 31 ka, $^{40}Ar/^{39}Ar$, Champion and others, 2013). The State Butte surface flows were sampled for K-Ar dating by Kuntz and others (1994), who obtained an age of 579 ± 130 ka, and by Champion and others (2013), who obtained an $^{40}Ar/^{39}Ar$ age date of 546 ± 47 ka. The State Butte sample was collected from corehole NRF 6P (figs. 1*A* and 1*B*) from about 57 m BLS.

The three magnetic splits analyzed for this lava flow produced reasonably concordant age results in plateau or isochron diagrams. The two most magnetic splits produced “humped” spectra, which indicate relatively lower $^{40}Ar/^{36}Ar$ intercept values, whereas the least magnetic split is “saddled,” suggesting a high $^{40}Ar/^{36}Ar$ intercept value. This is pronounced in the “all steps” isochrons, but more muted in the “plateau steps only” isochrons, such that they are concordant at the 95 percent confidence level. The three splits produce a weighted mean isochron age of 627 ± 22 ka. These three separate isochrons produce the weighted mean IIP plateau age of 621 ± 9 ka, which is the preferred age for the State Butte basalt flow (table 3).

Summary

In 2011, the U.S. Geological Survey, in cooperation with the U.S. Department of Energy, collected samples for 12 new argon-argon ($^{40}Ar/^{39}Ar$) ages from eastern Snake River Plain olivine tholeiite basalt flows. The core samples were collected from basalt flows that had previously published paleomagnetic inclination data. Samples were sent to the Wright-Riemann Laboratory of the Department of Geology at Rutgers University, Piscataway Township, New Jersey, for $^{40}Ar/^{39}Ar$ radiometric dating analyses.

Knowledge about the ages of subsurface basalt flow is needed to improve numerical models of groundwater flow and contaminant transport in the eastern Snake River Plain aquifer. Age data will help correlate basalt flows from surface vents to the subsurface, and from corehole to corehole in the subsurface. The age of basalt flows also can be used in volcanic eruption frequency and recurrence studies and in landscape evolution studies. Paleomagnetic and stratigraphic data were used to constrain the results of the age dating experiments to derive the preferred age for each basalt flow.

Preferred ages of the basalt flows that resulted from the $^{40}Ar/^{39}Ar$ radiometric dating experiments, in stratigraphic order, from youngest to oldest, are Quaking Aspen Butte basalt flow, 60 ± 16 ka; Vent 5206 basalt flow, 63 ± 9 ka; Mid Butte basalt flow, 195 ± 39 ka; West of ATR Complex basalt flow, 270 ± 15 ka; High K_2O basalt flow, 289 ± 8 ka; South CFA buried Vent(s) Upper basalt flow, 309 ± 13 ka; “D3” basalt flow, 456 ± 15 ka; South CFA buried vent(s) Lower basalt flow, 452 ± 88 ka; “E” basalt flow, 550 ± 33 ka; Big Lost basalt flow, 560 ± 4 ka; CFA buried vent basalt flow, 536 ± 63 ka; State Butte basalt flow, 621 ± 9 ka.

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Appendix A. Analytical Data—Plateau and Isochron Plots

Appendix A contains a data table and isochron plots for all splits of all experiments. Appendix A is available for download as PDFs at http://pubs.usgs.gov/sir/2015/5028/.

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