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$^{40}Ar/^{39}Ar$ and paleomagnetic constraints on the age and areal extent of the Picabo volcanic field: Implications for the Yellowstone hotspot

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ABSTRACT

The Picabo volcanic field is one of the key silicic volcanic fields in the time-transgressive track of the Yellowstone hotspot. The Picabo volcanic field is also one of the most poorly defined volcanic fields along the track of the Yellowstone hotspot. Determining the age and areal extent of the Picabo volcanic field ignimbrites is one of the primary objectives of this study. In our effort to correlate ignimbrites within the Picabo volcanic field as well as identify those from the neighboring Twin Falls and Heise volcanic fields, we present new petrographic, $^{40}Ar/^{39}Ar$, and paleomagnetic data. With these data, we correlated several ignimbrites within the Picabo volcanic field. In some cases, we correlate units previously thought to be in the Picabo volcanic field to older volcanic fields. This includes the Picabo Tuff, which we suggest originates from the Twin Falls volcanic field rather from its namesake volcanic field. The first and best documented major silicic eruption of the volcanic field, the Arbon Valley Tuff, is also the largest ignimbrite in the Picabo volcanic field. There is disagreement as to whether the Arbon Valley Tuff is the result of a single ignimbrite eruption or multiple eruptions. We previously have suggested that the Arbon Valley Tuff is the result of two eruptions, one at 10.41 ± 0.01 Ma and the other at 10.22 ± 0.01 Ma (Anders et al., 2014). Those combining radiometric dates into a single eruption age report ages of 10.2 Ma, 10.27 ± 0.01 Ma, 10.34 ± 0.03 Ma, and 10.44 ± 0.27 Ma. We also suggest the final eruption of the Picabo volcanic field was the tuff of American Falls dated at 7.58 ± 0.02 Ma. Estimates of the location of Picabo volcanic field have been used to mark a major change in the migration rate of the Yellowstone–Snake River Plain silicic volcanic system. Based on our new data, we found only minor changes of the boundaries of the Picabo volcanic field from previous studies. Using the age of the Arbon Valley Tuff (10.41 Ma), we calculated an extension-corrected migration rate of 2.27 ± 0.2 cm/yr between the position of the Picabo volcanic field and that of the Yellowstone volcanic field over the past ~10 m.y. This estimate is close to the extension corrected 2.38 ± 0.21 cm/yr value based on the migration of the hotspot deformation field. These rates are consistent with independent estimates of North American plate velocity over the past 10 m.y. and therefore consistent with a fixed reference frame for the Yellowstone hotspot. These results stand in contrast with several recent models for the evolution of the Yellowstone–Snake River Plain volcanic system.

We also discovered a new ignimbrite from the Heise volcanic field, the 4.37 ± 0.08 Ma tuff of Birch Creek Sinks, in core from the U.S. Geological Survey (USGS) borehole 2-2A, which now represents the youngest outflow ignimbrite of the Heise volcanic field. Although recently, several intracaldera ignimbrites younger than 4 Ma have been identified in the volcanic field, the age range of outflow ignimbrites from the Heise volcanic field is now extended from 6.66 Ma to at least 4.37 Ma.

INTRODUCTION

The Twin Falls, Picabo, Heise, and Yellowstone volcanic fields (Fig. 1) are the last four of a series of time-transgressive silicic volcanic centers associated with the Yellowstone–Snake River Plain volcanic system. The origin of the Yellowstone–Snake River Plain volcanic system has long been associated with the track of the North American plate over a hotspot (Morgan, 1971; Suppe et al., 1975; Armstrong et al., 1975; Anders et al., 1989; Anders and Sleep, 1992; Pierce and Morgan, 1992; Smith and Braile, 1994; Shervais and Hanan, 2008; Smith et al., 2009; Obrebski et al., 2010; Anders et al., 2014). Recently workers have alternatively suggested the origin of the track is related to upper-mantle upwelling associated with a subducted plate (Saltzer and Humphreys, 1997; Humphreys et al., 2000; Christiansen et al., 2002; Faccenna et al., 2010; James et al., 2011). There are also some hybrid models involving the interaction of a deep-sourced hotspot plume and the down-going Juan de Fuca plate (Geist and Richards, 1993; Pierce et al., 2002). Key to assessing these various models is the geographic position and timing of the Picabo volcanic field with respect to the other eruptive centers along the track. Assuming, as many do (e.g., Pierce and Morgan, 1992), that the silicic track begins with the first eruptions associated with the McDermitt volcanic center at ca. 16 Ma, the rate of the track progression from 16 Ma to Yellowstone is higher (e.g., 4.5 cm/yr; Smith and Braile, 1994) than estimates for the North America plate overriding a fixed hotspot position. Recent work by Benson and Mahood (2016) suggests the trends of the volcanic centers of the High Rock caldera complex (Coble and Mahood, 2016), McDermitt, and Lake Owyhee volcanic fields are due to the intersection of large flood basalt dikes resulting from a plume head rather

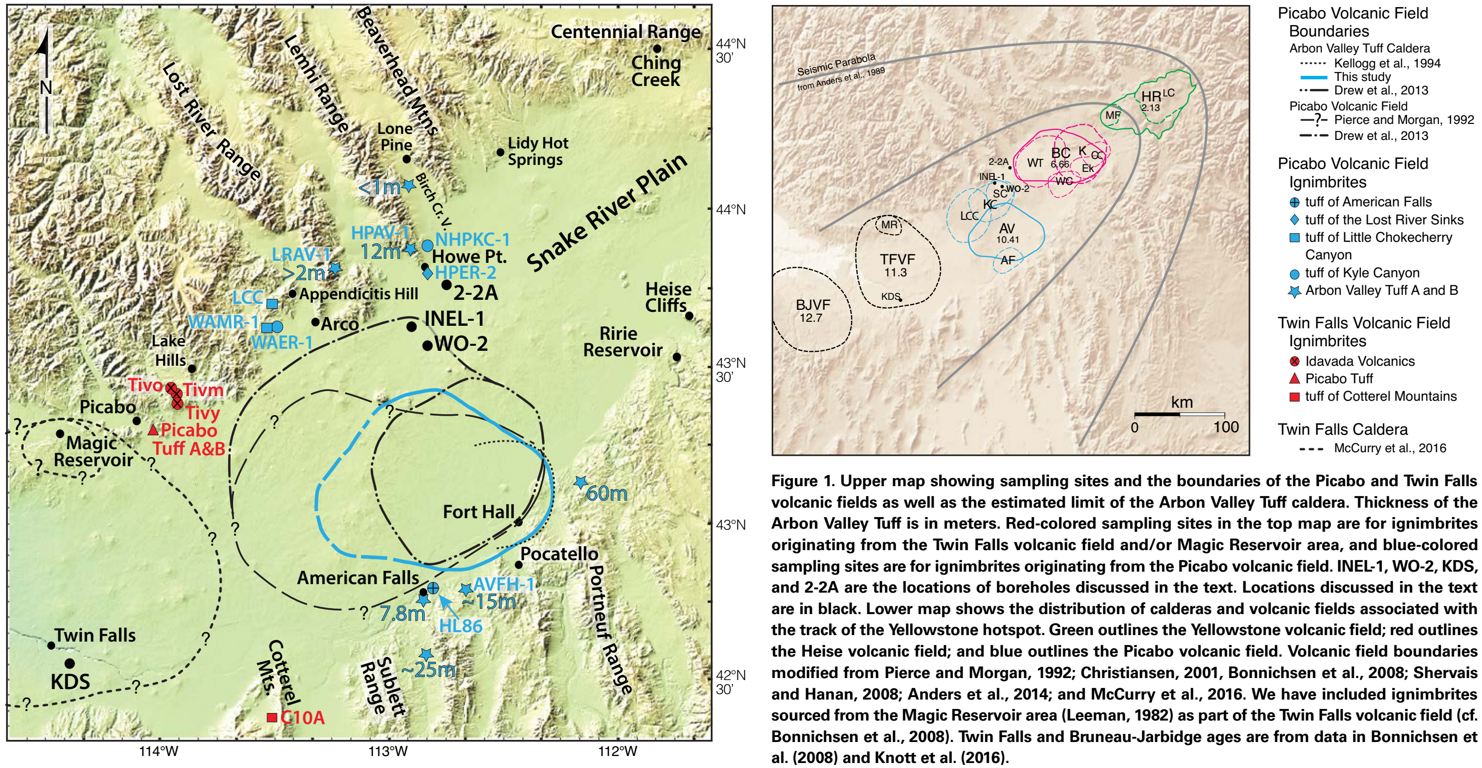


Figure 1. Upper map showing sampling sites and the boundaries of the Picabo and Twin Falls volcanic fields as well as the estimated limit of the Arbon Valley Tuff caldera. Thickness of the Arbon Valley Tuff is in meters. Red-colored sampling sites in the top map are for ignimbrites originating from the Twin Falls volcanic field and/or Magic Reservoir area, and blue-colored sampling sites are for ignimbrites originating from the Picabo volcanic field. INEL-1, WO-2, KDS, and 2-2A are the locations of boreholes discussed in the text. Locations discussed in the text are in black. Lower map shows the distribution of calderas and volcanic fields associated with the track of the Yellowstone hotspot. Green outlines the Yellowstone volcanic field; red outlines the Heise volcanic field; and blue outlines the Picabo volcanic field. Volcanic field boundaries modified from Pierce and Morgan, 1992; Christiansen, 2001, Bonnichsen et al., 2008; Shervais and Hanan, 2008; Anders et al., 2014; and McCurry et al., 2016. We have included ignimbrites sourced from the Magic Reservoir area (Leeman, 1982) as part of the Twin Falls volcanic field (cf. Bonnichsen et al., 2008). Twin Falls and Bruneau-Jarbidge ages are from data in Bonnichsen et al. (2008) and Knott et al. (2016).

than a hotspot tail as previously suggested (e.g., Pierce and Morgan, 1992). This may mitigate some of the velocity discrepancy but not all of it. However, Anders (1994) and Anders et al. (2014) have shown from ca. 10 Ma to the present, the rate is consistent with a fixed mantle plume or tail with respect to independent estimates of the North American plate. This work was based on velocity estimates using the migratory pattern of the thermally activated deformation field (see Rodgers et al., 1990) rather than the location of volcanic centers. Here we will present evidence that the migration rate of silicic volcanism based on the timing and location of the Picabo volcanic field is also consistent with independent estimates of North American plate velocity.

Each of the major volcanic fields of the Yellowstone–Snake River Plain track, including the Yellowstone, Heise, Picabo, Twin Falls, and Bruneau-Jarbidge volcanic fields, initiates with a large silicic eruption that marks the sublithospheric arrival of the Yellowstone hotspot (e.g., Suppe et al., 1975; Anders and Sleep, 1992, Pierce and Morgan, 1992; Smith and Braile, 1994; Humphreys et al., 2000; Perkins and Nash, 2002; Shervais and Hanan, 2008; Watts et al., 2011; Wotzlaw et al., 2014; Drew et al., 2016; cf. Brueseke et al., 2014). Other eruptions may be younger than the first eruption in the progression due to delayed magma migration through the lithosphere or downstream plume flow (Anders and Sleep, 1992; Ribe and Christensen, 1999; Lowry et al., 2000; Obrebski et al., 2010; cf. Humphreys et al., 2000). Therefore, it is only the first large eruption that is critical to establishing whether the hotspot source is fixed with respect to the motion of the North American plate. The first and largest eruption of the Yellowstone volcanic field is the 2.135 ± 0.006 Ma Huckleberry Ridge Tuff A (Ellis et al., 2012), and the first and the largest eruption of the Heise volcanic field is the 6.66 ± 0.01 Ma Blacktail Creek Tuff (Pierce and Morgan, 1992; Anders et al., 2014). There are other ages for both the Huckleberry Ridge Tuff and the Blacktail Creek Tuff (see Morgan and McIntosh, 2005 and Rivera et al., 2014); however, we chose to use the Anders et al. (2014) and Ellis et al. (2012) $^{40}Ar/^{39}Ar$ ages for consistency. Of the known Picabo volcanic field ignimbrites that we studied, only the tuff of American Falls is found exclusively along the southern margin of the eastern Snake River Plain. We investigated whether two other previously described ignimbrites found south of the Snake River Plain originate from the Picabo volcanic field. One ignimbrite is located in the Cotterel Mountains (we called this ignimbrite C10A) and is described in Konstantinou et al. (2013; C10 in Table 1). We analyzed this ignimbrite and referred to it as the tuff of Cotterel Mountains. The other ignimbrite is the tuff of Cedar Knoll (7.0 ± 0.2 Ma; Williams et al., 1982), which we interpreted, based on field observations discussed below, as a rhyolite lava rather than an ignimbrite.

North of the Snake River Plain, we identified three Picabo volcanic field ignimbrites that are not found along the southern margin of the Snake River Plain. The three are the tuff of Lost River Sinks, the tuff of Kyle Canyon, and the tuff of Little Chokecherry Canyon. These units were determined to be part of the Picabo volcanic field based on their mineralogy, distribution patterns, and radiometric ages (see McBroome, 1981; Pierce and Morgan, 1992; Snider, 1995; Anders et al., 2009; Anders et al., 2014). There are three ignimbrites in the Lake Hills (Fig. 1) deposited one on top of another called Idavada "older" (Tivo; Fig. 2A), "middle" (Tivm), and "younger" (Tivy) as described by Michalek (2009). These all yield ages consistent with the nearby Picabo volcanic field and the Twin Falls volcanic field (see Bonnichsen et al., 2008). The corrected ages of Michalek (2009) are 9.22 ± 0.02 Ma, 9.27 ± 0.18 Ma for the "older" ignimbrite, 8.44 ± 0.54 for the "middle" ignimbrite, and 8.82 ± 0.38 Ma for the "younger" ignimbrite (a discussion of

TABLE 1. IDAHO FALLS VOLCANIC FIELD IGNIMBRITES $^{39}Ar/^{40}Ar$ ISOTOPIC AGES

Sample	Ca/K	37/39	36/39	40*/39	%Rad	Age	Error	Irradiation	J†	J error
Tivo (Lake Hills, Idaho: N43.38752, W113.91515)										
17425-03A	6.8285	3.4840	0.0911	3.1447	73.2	9.21	1.17	USGS51E	0.0018107	3.68E-06
17425-04A	7.1623	3.4839	0.0044	3.1485	98.2	9.36	0.98	USGS51E	0.0018107	3.68E-06
17425-05A	8.5659	3.6542	0.0012	3.0946	98.1	9.75	1.64	USGS51E	0.0018107	3.68E-06
Oldest ignimbrite of the Lake Hills					Average: 9.38 ± 0.64 Ma					
PVT-2 (Picabo, Idaho; Queen's Crown: N43.28315, W113.99232)										
17029-01A	5.6280	3.1258	0.0001	2.8714	36.5	9.18	0.14	USGS46B	0.0018124	3.87E-06
17029-02A	5.0868	3.2425	0.0013	2.5953	93.5	8.55	0.26	USGS46B	0.0018124	3.87E-06
18385-01A	4.7949	3.4709	0.0025	2.6245	84.3	9.37	0.68	USGS58E	0.0018333	3.26E-07
18385-02A	5.8856	3.4721	0.0031	2.9306	80.7	8.98	0.49	USGS58E	0.0018333	3.26E-07
18385-03A	6.1642	3.3990	0.0036	2.8083	76.2	8.30	0.73	USGS58E	0.0018333	3.26E-07
18385-04A	5.6223	3.0141	0.0016	2.5970	91.7	8.85	0.60	USGS58E	0.0018333	3.26E-07
18385-05A	6.1756	2.5517	0.0002	2.7684	107	8.79	1.04	USGS58E	0.0018333	3.26E-07
Picabo Tuff B					Average: 9.02 ± 0.11 Ma					
PVT (Picabo, Idaho: N43.27386, W114.01019)										
17417-05A	5.9518	3.0366	0.0006	5.5898	80.0	10.25	2.10	USGS51E	0.0018107	3.68E-06
17417-06A	5.8631	2.9913	0.0005	5.5604	79.5	10.80	0.94	USGS51E	0.0018107	3.68E-06
17417-08A	5.9089	3.0147	0.0002	5.5616	80.2	9.31	0.16	USGS51E	0.0018107	3.68E-06
17025-03A	5.6490	3.4839	0.0027	2.7178	98.7	8.86	0.29	USGS46B	0.0018124	3.87E-06
18383-03A	4.5316	2.3120	0.0009	2.6679	94.0	9.33	0.24	USGS58E	0.0018333	3.26E-07
18383-05A	4.8899	2.4949	0.0013	2.8288	100.7	10.59	0.47	USGS58E	0.0018333	3.26E-07
18383-10A	5.8691	2.9907	0.0012	2.8117	97.7	9.27	0.45	USGS58E	0.0018333	3.26E-07
18383-11A	5.0060	2.5541	0.0021	2.8271	88.0	9.31	0.63	USGS58E	0.0018333	3.26E-07
18383-01A	4.5316	2.3120	0.0009	2.6679	97.2	8.79	0.14	USGS58E	0.0018333	3.26E-07
18385-01A	4.7949	2.4464	0.0025	2.9306	84.0	9.66	0.71	USGS58E	0.0018333	3.26E-07
18385-02A	5.8856	3.0028	0.0030	2.8083	80.7	9.25	0.51	USGS58E	0.0018333	3.26E-07
18385-04A	5.6222	2.8684	0.0016	2.7683	91.7	9.12	0.62	USGS58E	0.0018333	3.26E-07
Picabo Tuff A					Average: 9.12 ± 0.08 Ma					
C10A (Cotterel Mountains: N42.33504, W113.49326)										
17422-06A	7.9276	4.0446	0.0017	2.8039	94.3	9.07	0.17	USGS51E	0.0018107	3.68E-06
17422-04A	6.5533	3.3435	0.0621	2.6732	74.6	8.65	0.92	USGS51E	0.0018107	3.68E-06
17422-02A	8.1712	4.1690	0.0038	2.7524	77.8	8.91	1.17	USGS51E	0.0018107	3.68E-06
17422-01A	6.5092	3.3210	0.0049	2.6130	68.5	8.45	1.02	USGS51E	0.0018107	3.68E-06
17027-02A	6.0529	3.0881	0.0150	2.6839	38.7	8.69	0.25	USGS46B	0.0018124	3.87E-06
17027-01A	6.7318	3.4345	0.0053	2.6885	67.3	8.70	0.45	USGS46B	0.0018124	3.87E-06
Tuff of Cotterel Mountains					Average: 9.05 ± 0.13 Ma					

†J values were calculated based on the Fish Canyon Tuff with an age of 28.201 Ma.

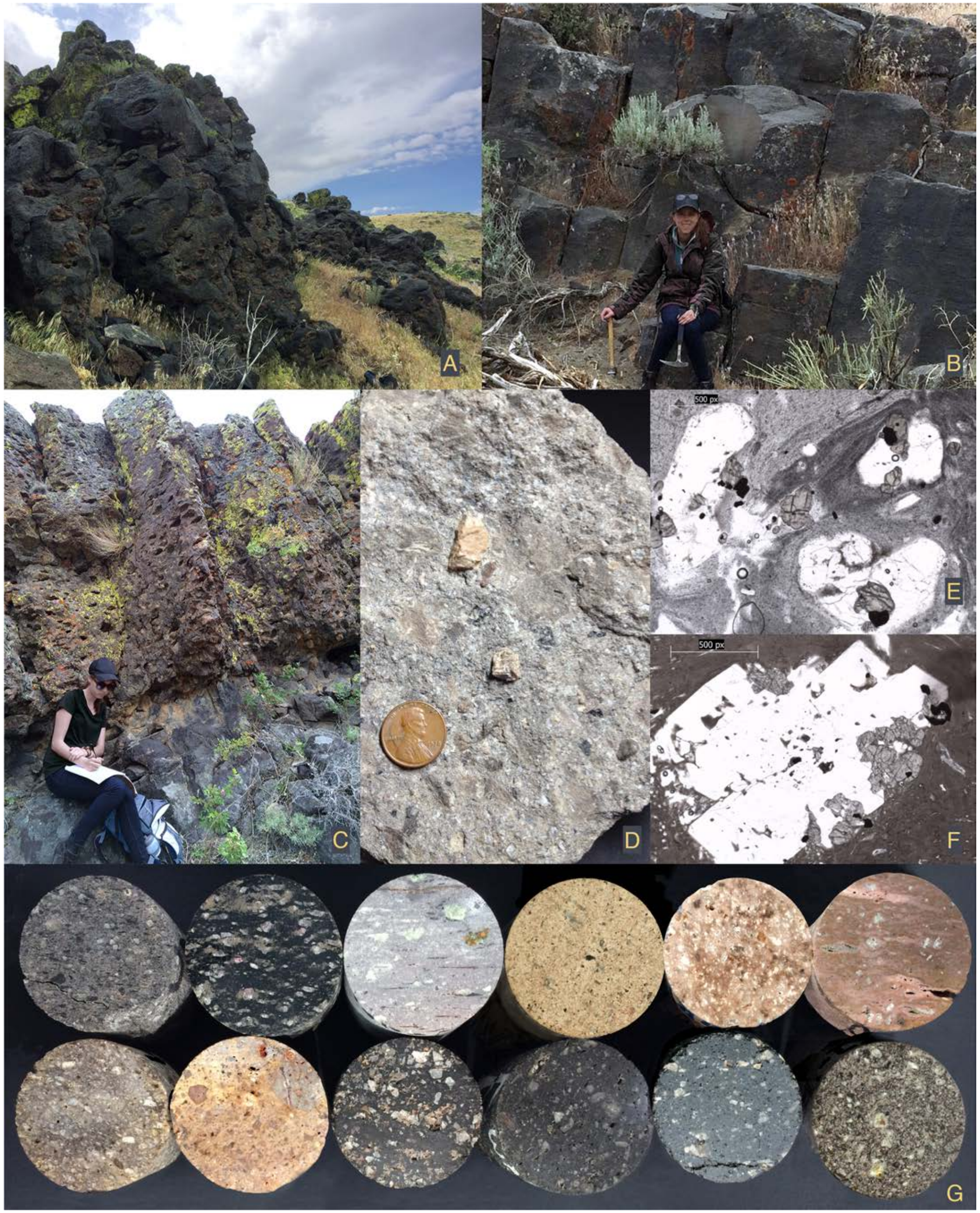


Figure 2. (A) Lake Hills ignimbrite (Tivo, N43.38752, W113.91515); (B) Picabo Tuff A (PVT—N43.27386, W114.01019); (C) tuff of Little Chokecherry Canyon (LCC—N43.69632, W113.50945); (D) tuff of American Falls (TAF, N42.78514, W112.83860); (E) Lake Hills ignimbrite Tivo thin section (clinopyroxene-pigeonite)/plagioclase cluster); (F) Picabo Tuff A thin section (clinopyroxene-pigeonite/plagioclase cluster). (G) Cores from top row left to right; tuff of Little Chokecherry Canyon (LCC—basal vitrophyre); upper cooling unit of oldest Idavada ignimbrite of the Lake Hills (Tivo—lithophysal zone); INEL-1 rhyolite flow (from depth 1119.8 m/3674 ft); tuff of Kyle Canyon (NHPKC from Howe Point, N43.85390, W112.85864), tuff of Kyle Canyon (WAMR—west of Arco, Idaho; Anders et al., 1993); tuff of Cotterel Hills (C10 from Konstantinou et al., 2013; N42.33504, W113.49326). Cores from bottom row, left to right: tuff of Little Chokecherry Canyon (LCC—lithophysal zone); tuff of Cedar Knoll (rhyolite flow TCK, N42.17944, W113.42167); tuff of American Falls (TAF); tuff of Little Chokecherry Canyon (WAER—basal vitrophyre; Anders et al., 1993), Picabo Tuff A (PVT—lowest cooling unit); Picabo Tuff B (PVT2—highest cooling unit, locally called Queen's Crown).

correction procedure is presented in the Methods section). The substantial error in the "middle" ignimbrite and the nominal age being out of stratigraphic order suggest that although it falls within the range of precision overlap of Tivo and Tivy, it has limited determinative value. As will be discussed below, we suggest, as was argued by Michalek (2009), that the Lake Hills ignimbrites are not part of the Picabo volcanic field, in spite of their proximity, mineralogy, and age (Fig. 1). Also, as we discuss below, the Picabo Tuff, which is the namesake of the Picabo volcanic field, actually originates from the Twin Falls volcanic field. Other possible Picabo volcanic field ignimbrites may be found in the INEL-1 borehole (Fig. 1). McCurry and Rodgers (2009) discussed these units found in INEL-1 and provided U/Pb dates for some of them, but they did not indicate whether they were ignimbrites or lava flows. Drew et al. (2013) described one of the units found in INEL-1 as ignimbrite 3686 (1123 m); Doherty et al. (1979) described this unit as a "welded tuff" and described the volcanic rocks at sample site 3686 as part of longer interval of "welded tuff" extending from 764 m to 2469 m. As we discuss below, we also found it difficult to distinguish between the recovered core being a rhyolite lava or an ignimbrite (see Bonnichsen and Kauffman, 1987; Brueseke et al., 2014). However, based on our study of the core, we believe that units encountered below 764 m are rhyolite lavas.

The location and ages of the Heise volcanic field have been interpreted in various ways (e.g., Morgan, 1992; Pierce and Morgan, 1992; Morgan and McIntosh, 2005; Bindeman et al., 2007; Anders et al., 2009, Anders et al., 2014). Since publication of Anders et al. (2014), we have discovered a new outflow ignimbrite that reduces the temporal gap between the age of the Heise volcanic field and that of the Yellowstone volcanic field. Previously, the age of the last known outflow ignimbrite erupted from the Heise volcanic field (Kilgore Tuff) was 4.61 ± 0.01 Ma (Anders et al., 2014). We discovered a new ignimbrite near the top of borehole 2-2A (Fig. 1; Table 2); we refer to this ignimbrite as the tuff of Birch Creek Sinks. Originally this unit was thought to be the uppermost Kilgore Tuff (McBroome, 1981); however, the younger age and our discovery that the ignimbrite has a normal polarity, as opposed to the reverse polarity of the Kilgore Tuff (Anders et al., 1989; Morgan, 1992; Morgan and McIntosh, 2005; Anders et al., 2014), suggest this core is from a newly discovered outflow ignimbrite of the Heise volcanic field.

METHODS

Feldspar separates were handpicked and then soaked in dilute HF acid for 5 min. If there were signs of glass mantling after the acid treatment, a second treatment was done. Few samples required a second application of HF, and none needed a third application. Samples were washed in alcohol and dried

TABLE 2. HEISE VOLCANIC FIELD IGNIMBRITES (BOREHOLE 2-2A) $^{39}Ar/^{40}Ar$ ISOTOPIC AGES

Sample	Ca/K	37/39	36/39	40*/39	%Rad	Age	Error	Irradiation	J†	J error
2-2A (borehole 2-2A, depth 2526.5 ft)										
17418-01A	2.3249	1.1861	0.0015	1.3458	79.5	4.39	0.47	USGS51E	0.0018107	3.68E-06
17418-02A	2.3168	1.1821	0.0010	1.3095	85.4	4.27	0.53	USGS51E	0.0018107	3.68E-06
17418-03A	2.6960	1.3755	0.0043	1.2644	51.8	4.13	0.45	USGS51E	0.0018107	3.68E-06
17418-04A	3.4659	1.7683	0.0039	1.3336	56.7	4.35	0.64	USGS51E	0.0018107	3.68E-06
17418-05A	2.3298	1.1887	0.0046	1.4271	52.7	4.66	1.85	USGS51E	0.0018107	3.68E-06
Tuff of Birch Creek Sinks						Average: 4.26 ± 0.25 Ma				
2-2A (borehole 2-2A, depth 2530 ft)										
17420-01A	2.8496	1.4539	0.0324	1.3688	82.0	4.46	1.03	USGS51E	0.0018107	3.68E-06
17420-02A	0.1160	0.0592	0.1134	1.3308	91.7	4.34	0.10	USGS51E	0.0018107	3.68E-06
17420-03A	0.1931	0.1932	0.0006	1.3648	88.7	4.45	0.67	USGS51E	0.0018107	3.68E-06
17420-04A	0.0781	0.1002	0.0007	1.3671	86.9	4.46	0.15	USGS51E	0.0018107	3.68E-06
Tuff of Birch Creek Sinks (2526.5 ft + 2530 ft)						Average: 4.37 ± 0.08 Ma				
Tuff of Birch Creek Sinks						Average: 4.38 ± 0.09 Ma				
2-2A (borehole 2-2A, depth 2552 ft)										
17419-01A	0.1109	0.0566	0.0077	1.3743	37.7	4.49	0.87	USGS51E	0.0018107	3.68E-06
17419-03A	0.0847	0.0433	0.0003	1.4840	94.2	4.83	0.77	USGS51E	0.0018107	3.68E-06
17419-05A	0.0868	0.0443	0.0005	1.5346	90.2	5.00	0.98	USGS51E	0.0018107	3.68E-06
17419-06A	0.0781	0.0399	0.0006	1.3874	88.6	4.52	0.45	USGS51E	0.0018107	3.68E-06
Kilgore Tuff§						Average: 4.63 ± 0.33 Ma				

†J values were calculated using a standard of the Fish Canyon Tuff at 28.201 Ma.
§Anders et al. (2014) dated the Kilgore Tuff at 4.61 ± 0.01 Ma based on 43 individual single-crystal analyses from seven locations.

and then loaded in disks with a standard. Samples were then co-irradiated with Fish Canyon sanidine (28.201 ± 0.046; Kuiper et al., 2008) for 8 h at the USGS TRIGA reactor in Denver. Individual grains of monitors and unknowns are degassed with a CO_2 laser, and gases released from the heating of samples are scrubbed of reactive gases such as H_2O, CO_2, CO, and N_2 by exposure to Zr-Al sintered metal alloy getters at 2 A. The remaining inert gases, principally Ar, are then admitted to the mass spectrometer, and the Ar-isotopic ratios are determined using automated data collection software (MassSpec). Measurements are made on a VG5400 noble gas mass spectrometer using an electron multiplier in analog mode. Frequent measurements of the background and air pipette are used to correct for background and discrimination, respectively.

It is important to note that all of the $^{40}Ar/^{39}Ar$ dates in this paper were corrected to account for the evolution in the age of standards used and were reported with errors of two sigma. For example, there has been an evolution in the accepted Fish Canyon Tuff age that we used to establish our J value; this age is different in different laboratories at different times. Therefore, we corrected all $^{40}Ar/^{39}Ar$ ages to a common age of 28.201 Ma for the Fish Canyon Tuff standard. We made this correction for all our analyses in this study and corrected all J values for $^{40}Ar/^{39}Ar$ ages we used that are taken from the various publications we have cited.

Sampling for paleomagnetic analysis was accomplished by a combination of oriented drill cores and oriented block samples in the field and laboratory sampling of USGS 2-2A (Table 3) and INEL-1 core (data from INEL-1 are only available in the Supplemental Material[1]). Field-oriented cores were obtained using a Pomeroy gas-powered drill and block samples. All field samples were oriented with a Brunton compass. Five to ten oriented samples were collected per site. Three specimens were collected from each of three segments in the USGS 2-2A and INEL-1 cores in the laboratory using a drill press; the cores were drilled at right angles to the vertical core. Since 2-2A and INEL-1 cores are unoriented with respect to declination, only the magnetic inclination information is meaningful for comparison. All sample measurement and demagnetization were performed in the Paleomagnetics Laboratory at Lamont-Doherty Earth Observatory of Columbia University. Natural remnant magnetization (NRM) was measured for all samples, and most samples were then subjected to progressive alternating field (AF) demagnetization up to peak alternating fields as high as 100 mT. Magnetic component directions were calculated by principal component analysis (Kirschvink, 1980) of linear segments chosen by inspection from orthogonal plots (Zijderveld, 1967). Mean directions were calculated using standard Fisher (1953) statistics.

■ RESULTS

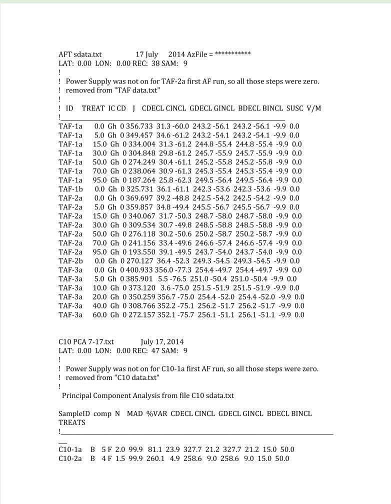
$^{40}Ar/^{39}Ar$ Analyses

The results of our $^{40}Ar/^{39}Ar$ analyses are typical of our analysis of other ignimbrites, in which plagioclase crystals yielded higher errors (e.g., Anders

TABLE 3. PALEOMAGNETIC RESULTS

Sample	NS	MAD	%VAR	Decl	Incl
Tuff of Cotterel Mountain (N42.33504, W113.49326)					
C10A-01b	5	6.9	98.6	331.0	45.0
C10A-02a	4	5.2	99.2	329.1	44.9
C10A-03a	4	2.2	99.9	212.9	4.6
C10A-04a	5	3.0	99.7	332.5	32.5
C10A-05a	5	3.0	99.7	328.0	37.7
C10A-06a	6	2.4	99.8	336.8	25.2
C10A-07a	4	4.7	99.3	344.9	27.6
C10A-08a	4	2.0	99.9	335.5	27.4
C10A-09a	5	2.6	99.8	340.0	27.8
C10A-10a	5	2.1	99.9	335.7	27.8
Mean	N	k	α_{95}	Decl	Incl
C10A	9	13.8	5.7	335.2	30.6
Tuff of American Falls (N42.78574, W112.83876)					
TAF-2a	5	1.7	99.9	248.1	–57.9
TAF-3a	3	1.2	100.0	257.0	–51.1
TAF-1a	5	2.5	99.8	240.2	–54.6
TAF-4a	4	6.4	98.8	275.5	–66.0
TAF-5b	5	5.8	99.0	246.7	–56.1
Mean	N	k	α_{95}	Decl	Incl
TAF	5	85.6	8.3	252.2	–57.6
Sample	N	k		Decl	Incl
Tuff of Little Chokecherry Canyon (N43.69632, W113.50945)					
LCC1	1	-		334.6	56.4
LCC2	4	456.9		154.6	–22.9
LCC3	2	2687.1		344.4	53.2
LCC4	2	620.2		325.4	55.6
LCC5	2	36.9		351.2	50.8
LCC6	3	1872.2		336.2	46.9
LCC7	4	145.0		65.7	53.5
Mean	N	k	α_{95}	Decl	Incl
LCC	5	131.8	6.7	338.6	52.9
Sample	N	k	α_{95}	Decl	Incl
USGS 2-2A core, tuff of Birch Creek Sinks (4.37 ± 0.08 Ma)					
2526.1	2	245.8		283.3	67.7
2526.2	2	165.0		277.8	66.1
2526.3	2	99.8		276.9	69.3
2526	3	1538.0	3.1	279.4	67.7
2530-1a				60.8	72.2
2530-2a				77.1	63.3
2530-3a				52.1	75.3
2530	3	114.1	11.6	65.9	70.6
2526-2530	6	241.6	4.3	360.0	69.1
USGS 2-2A core, Kilgore Tuff (4.63 ± 0.33 Ma)					
2552-1a				324.0	–46.9
2552-2a				340.3	–52.5
2552-3a				315.9	–52.7
2552	3	93.9	12.8	326.6	–51.1

Notes: NS—number of demagnetization steps used for principal component analysis; MAD—maximum angular deviation about component direction; %VAR—percent variation from chosen vector; N—number of samples used to calculate the mean direction; k—Fisher's precision parameter; α95—radius of 95% cone of confidence about mean direction; Directions: Decl—mean declination; Incl—mean inclination; USGS—U.S. Geological Survey.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!   removed from "TAF data.txt"
!
!  ID     TREAT  IC CD    J    CDECL CINCL  GDECL GINCL  BDECL BINCL  SUSC  V/M
!_____________________________________________________________________
TAF-1a      0.0  Gh  0 356.733  31.3 -60.0  243.2 -56.1  243.2 -56.1  -9.9  0.0
TAF-1a      5.0  Gh  0 349.457  34.6 -61.2  243.2 -54.1  243.2 -54.1  -9.9  0.0
TAF-1a     15.0  Gh  0 334.004  31.3 -61.2  244.8 -55.4  244.8 -55.4  -9.9  0.0
TAF-1a     30.0  Gh  0 304.848  29.8 -61.2  245.7 -55.9  245.7 -55.9  -9.9  0.0
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TAF-1a     95.0  Gh  0 187.264  25.8 -62.3  249.5 -56.4  249.5 -56.4  -9.9  0.0
TAF-1b      0.0  Gh  0 325.731  36.1 -61.1  242.3 -53.6  242.3 -53.6  -9.9  0.0
TAF-2a      0.0  Gh  0 369.697  39.2 -48.8  242.5 -54.2  242.5 -54.2  -9.9  0.0
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TREATS
!_____________________________________________________________________
___
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C10-2a    B   4 F  1.5  99.9  260.1   4.9  258.6   9.0  258.6   9.0  15.0  50.0
```

[1]Supplemental Material. Includes the individual paleomagnetic data used to construct Figures 2 and 3. It also includes the paleomagnetic results from the INEL-1 borehole briefly discussed in the text. Please visit https://doi.org/10.1130/GES01589.S1 or access the full-text article on www.gsapubs.org to view the Supplemental Material.

et al., 2009; Anders et al., 2014). This required measuring multiple samples of plagioclase to account for the variability (Tables 1 and 2). We used Taylor (1982) statistics that weighted the results based on the error, and the error is inversely correlated with the percent radiogenic argon and abundance of $^{40}Ar^*$. Hence, the older ages with higher error had a smaller effect on the ages of the samples where feldspar populations were dominated by plagioclase, as is the case for the Picabo Tuff A and B, Lake Hills ignimbrite (Tivo), and the tuff of Cotterel Mountains. For example, in Table 1, there are three dates for sample PVT that are >10 Ma. The large associated error with these three samples led to their having little effect on the final age we determined. On sample PVT, we performed step heating that produced results that were of no value, and we chose not to include them. The one exception to the relationship between feldspar chemistry and error is the Kilgore Tuff in borehole 2-2A (4.63 ± 0.33 Ma; Table 2). Although all of the crystals analyzed were sanidine, the error bars were large in comparison to the error typically found for the Kilgore Tuff (e.g., 4.51 ± 0.05 Ma, corrected from Morgan and McIntosh, 2005; 4.61 ± 0.01 Ma from Anders et al., 2014; and secondary ion mass spectrometry [SIMS] U/Pb zircon age of 4.4876 ± 0.0023 Ma, Wotzlaw et al., 2014). We suspect this is due to alteration of feldspars in other Snake River Plain boreholes (Anders et al., 2014) and our small sample population. Analyses of the Lake Hills ignimbrites proved difficult for us as well as for analyses by Michalek (2009). Analyses by Michalek (2009) produced an age for the middle ignimbrite (Tivm) that is out of stratigraphic order, but given their 2σ overlap, their ages could be considered to represent proper stratigraphic order. We produced an age with a large precision error for the oldest of the Lake Hills ignimbrites, Tivo—9.38 ± 0.64 Ma (Table 1)—similar to Michalek's (2009) results for Tivm, and our 2σ values overlap with their age determinations of 9.22 ± 0.2 and 9.27 ± 0.18 for Tivo. Our large error for the age of Tivo is similar to other large precision errors we acquired from low-potassium plagioclase grains in this study.

Paleomagnetic Analyses

Ten oriented cores were collected from the tuff of Cotterel Mountain (C10A in Fig. 3). NRM directions are somewhat scattered with northerly declinations and downward inclinations (Fig. 3). Progressive AF demagnetization removes low-stability spurious magnetizations and yields stable characteristic magnetization directions. Nine of the ten cores yield northwest and moderately down, normal-polarity magnetizations. One core gives an anomalous southeast and shallow direction that was omitted from calculation of the paleomagnetic mean direction (Table 3). Five oriented cores were collected from the tuff of American Falls. NRM directions are fairly well grouped (TAF in Fig. 3). Principal component directions are well grouped, west-northwesterly with negative inclination, reverse-polarity magnetization after AF removal of low-stability magnetizations. Seven oriented block hand samples were collected in the tuff of Little Chokecherry Canyon (Fig. 2C). One to four specimens were analyzed from each block. AF demagnetization showed stable magnetizations after removal of weak low-stability magnetizations. Five of the seven blocks yielded well-grouped, northwest and downward, normal-polarity magnetization (Fig. 3). Two of the blocks yielded stable, but anomalous directions and were omitted from calculation of the site mean direction (Table 3). Samples from each of the three segments of the borehole 2-2A core yielded well-grouped NRM directions (Fig. 4). After AF demagnetization, the sample at 777.9 m (2552 ft) depth in 2-2A (Kilgore Tuff) displays a moderate inclination, reverse-polarity magnetization of –51.1°, matching the –50.4° found for that unit by Anders et al. (2014). The sample from 2-2A at 770.1 m (2526.5 ft) and 771.1 m (2530 ft) depths (tuff of Birch Creek Sinks) contains moderately steeply inclined normal-polarity magnetization (Fig. 4). The 770.1 m (2526.5 ft) and 771.1 m (2530 ft) directions (six specimens) were combined by arbitrarily rotating each segment mean direction to north. The combined specimens yield a mean inclination of 69.1 (α_{95} = 4.3) (Table 3).

Picabo Volcanic Field

The boundaries of the Picabo volcanic field are difficult to define because the calderas are all buried under several kilometers of younger basalt, which is the case for most of volcanic fields of the Yellowstone–Snake River Plain volcanic system. The boundaries are defined by the proximity of volcanic deposits, very limited geophysical data, and a limited number of boreholes (see Pierce and Morgan, 1992; Bonnichsen et al., 2008; Anders et al., 2009; McCurry and Rodgers, 2009; Anders et al., 2014; McCurry et al., 2016). Proximity is based on relative outcrop thickness, lithic and/or pumice size, and character of the welding. Although the boundaries of calderas are poorly constrained, our contention is that the caldera centroid of the volcanic field's first major eruption is a better estimate of the position of the hotspot at any given time. By using proximal deposits, we can define a centroid location within a few kilometers. We use the centroid of the first major eruption of each respective volcanic field to estimate rates. It is our view that the first major volcanic eruption in a volcanic field marks the arrival of a sublithospheric heat source (the hotspot tail), whereas later eruptions within the direct area of the first eruption, or eruptions to the southwest, do not define the deep mantle hotspot source. In our view, the delayed eruptions located at the initial eruption site or downstream are a result of the deflection of the plume downstream (Anders and Sleep, 1992; Ribe and Christensen, 1999; Lowry et al., 2000) or in delays in magma ascension through the lithosphere (Drew et al., 2013). Evidence of this downstream deflection can be seen in the sublithospheric thermal structure reported from seismic studies (Obrebski et al., 2010).

Some of the Yellowstone–Snake River caldera boundaries were previously defined in Anders et al. (2009) and differ from those defined by Pierce and Morgan (1992). With the exception of the Arbon Valley Tuff, the first major eruption of the Picabo volcanic field, we have not identified a Picabo volcanic field ignimbrite that is present on both sides of the eastern Snake River Plain. Here we will briefly identify those units we suggest originate from the Picabo volcanic field and those units that were previously assigned to the Picabo

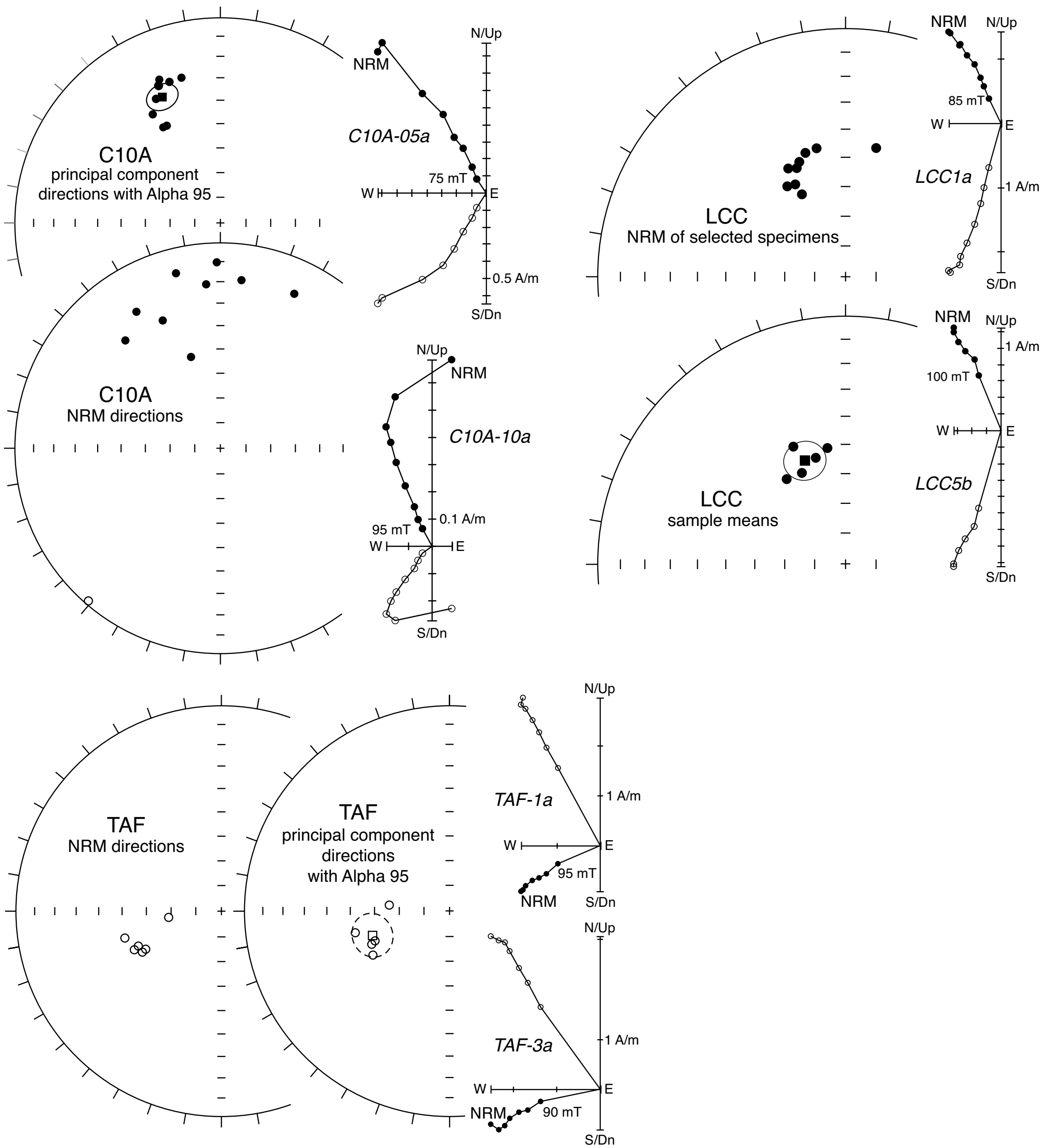

Figure 3. Paleomagnetic results from three ignimbrites discussed in the text. LCC—tuff of Little Chokecherry Canyon (9.46 ± 0.03 Ma); C10A—tuff of Cotterel Mountains (9.05 ± 0.13 Ma); and TAF—tuff of American Falls (7.58 ± 0.01 Ma). NRM—natural remnant magnetization. Demagnetization plots are shown on the right side of each diagram. Solid circles are normal polarity, and open circles are reversed polarity. Circles with square in the center are the α_{95}s.

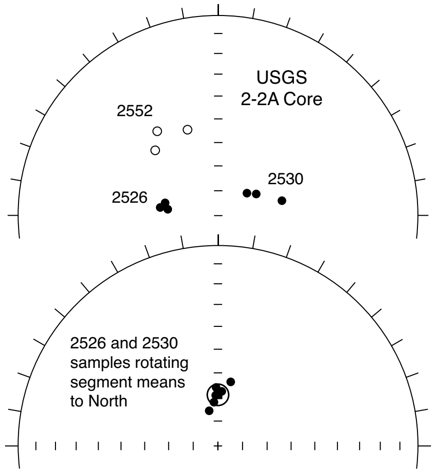

Figure 4. Paleomagnetic results from core recovered from borehole 2-2A (Fig. 1). There was no declination recorded for the vertical core. The grouping of three magnetic directions is from a section of continuous core. Normal-polarity paleomagnetic orientations are for the uppermost two sampling depths of the tuff of Birch Creek Sinks that we dated at 4.37 ± 0.08 Ma (Table 2). The reverse polarity is for the Kilgore Tuff recovered core that we dated at 4.63 ± 0.33 Ma (Table 2). Anders et al. (2014) dated the Kilgore Tuff at 4.61 ± 0.01 Ma based on 43 dates from seven different locations. The lower plot is the result of a vertical axis rotation of the tuff of Birch Creek Sinks to a common declination to show consistency of inclination.

volcanic field and that we now believe originate from the Twin Falls volcanic field based on mineralogy, location, age and previously published data. Our emphasis is on silicic ignimbrites, although we will also discuss a limited number of rhyolite lavas.

Tuff of American Falls

The tuff of American Falls (Anders et al., 2009; Drew et al., 2013; Anders et al., 2014) has a limited areal extent since we found only a single ~4-m-thick exposure along the southern margin of the Snake River Plain, ~2 km east of the town of American Falls, Idaho (Fig. 1). Where exposed, the unit has a significant population of lithic and volcanic fragments, some of which are over a cm in diameter (Fig. 2D). There is a thick basal vitrophyre with abundant feldspars (~15%) that are dominated by mm-sized sanidines (Fig. 2G). The limited extent of outcrops and size of fragments suggest this unit is due to a local caldera eruption. As seen in Figure 3 and in Table 3, the tuff of American Falls has a reversed magnetic polarity. The tuff of American Falls was dated by $^{40}Ar/^{39}Ar$ at 7.58 ± 0.01 Ma (Anders et al., 2014) and U/Pb at 7.91 ± 0.16 Ma (Drew et al., 2013). This age is similar to the Snake River Plain basalts found in Birch Creek Valley on the northern side of the Snake River Plain (Rodgers and Anders, 1990) and ashfall deposits found in Grand Valley, Idaho (Anders et al., 2009). Although Anders et al. (2009) suggested the possibility that this unit was the first eruption of the Heise volcanic field, we now place it as the last silicic eruption of the Picabo volcanic field. This again is based on its mineralogy; the cm-size lithic and pumice fragments suggest a proximal source and its location with respect to the Heise and Picabo volcanic fields (~2 km east of American Falls, Idaho; Fig. 1).

Tuff of Lost River Sinks

Like the tuff of American Falls, the tuff of Lost River Sinks (McBroome, 1981) is only found at one location at the southern tip of the Lemhi Range (Fig. 1). Less than a meter of the unit is exposed at this location. It is reddish-tan in color with pervasive lithophysae cavities. Based on the size of flattened pumice (<1 cm), petrography, age, and its location, it is most likely sourced from the Picabo volcanic field. This unit was first dated at 12.4 Ma by McBroome (1981) using zircon fission track. However, Anders et al. (2014) dated this unit using $^{40}Ar/^{39}Ar$ at 8.87 ± 0.16 Ma. Drew et al. (2013) dated this unit by U/Pb at 7.05 ± 0.13. In a footnote in Drew et al. (2013, p. 66), they commented that "The tuff of Lost River Sinks we sampled was likely the Blacktail Creek Tuff." We agree with this statement because from our experience in working at this location (Howe Point and the southernmost tip of the Lemhi Range; Fig. 1), it can be difficult to separate these two units. Anders et al. (2014) dated the Blacktail Tuff, which directly overlies the tuff of Lost River Sinks, at 6.66 ± 0.01 Ma (n = 23). The tuff of Lost River Sinks yields a normal polarity of declination 2.5° and inclination of 69° (Anders et al., 2014). Like the tuff of American Falls, sanidine is the dominant feldspar. Although the paleomagnetic signal from rhyolites in INEL-1 (in Supplemental Material [see footnote 1]) closely matches the results from the tuff of Lost River Sinks, the age of the tuff of Lost River Sinks is older (8.87 ± 0.16 Ma) than the INEL-1 rhyolites (U/Pb ages of 8.27 ± 0.27 Ma, 8.04 ± 0.10 Ma, and 8.35 ± 0.24 Ma; McCurry and Rodgers, 2009). Moreover, a correlation is unlikely because we interpreted the INEL-1 rhyolites as lavas, not ignimbrites.

Tuff of Kyle Canyon

The tuff of Kyle Canyon is located at the southern tip of the Lemhi Range and on the northern margin of the Snake River Plain southwest of Arco (Fig. 1). McBroome (1981) first described this unit as two ignimbrite cooling units—an upper >50-m-thick unit and a lower ~1-m-thick unit with a basal vitrophyre. The upper unit exhibits platy partings as well as a vapor phase. This unit is densely welded, brown to reddish-brown in color, and crystal poor. Phenocrysts are

~3%–5% and comprise mostly <1 mm sanidine crystals, with minor quartz and augite (Fig. 2G, top row; second from right).

At the location southwest of Arco, Anders et al. (1993) identified the unit as the Blacktail Creek Tuff (the same unit then called the tuff of Edie School). However, Anders et al. (2014) later identified this outcrop as the tuff of Kyle Canyon, thus making two locations where this ignimbrite is found. McBroome (1981) reported a fission-track age of 9.91 ± 0.90 Ma. Anders et al. (2014) determined a $^{40}Ar/^{39}Ar$ age of 9.28 ± 0.01 for the tuff of Kyle Canyon. The polarity of the tuff of Kyle Canyon is normal with an orientation of I = 73.5°, D = 359.2°, and α_{95} = 5.7°, overlapping the α_{95}s of the tuff of Little Chokecherry Canyon (see figure 4 of Anders et al., 2014).

Tuff of Little Chokecherry Canyon

Anders et al. (2014) previously dated the tuff of Little Chokecherry Canyon at 9.46 ± 0.03 Ma. Snider (1995) dated the same unit at a different location at 9.52 ± 0.04 Ma (corrected for a common standard). The tuff of Little Chokecherry Canyon is a dark-brown and gray to black densely welded ignimbrite (Fig. 2C). Where sampled, it ranges from 4 m to 5 m thick. It has two distinct cooling units with the lower one consisting of 20% crystals (Fig. 2G, upper row, left-hand side) that are dominantly sanidine and plagioclase, with minor quartz, augite, and opaque minerals. The basal vitrophyre has fist-sized, rounded masses of dark-brown vitrophyric ignimbrite that is similar in character to the upper cooling unit. The upper cooling unit has ~10% crystals equally sanidine and plagioclase with minor amounts of quartz, augite, and biotite (Fig. 2G, lower row, left-hand side). The upper lithophysal zone has cavities averaging 20 cm × 6 cm in dimension. Anders et al. (2014) reported a normal polarity D = 5.8°, I = 71.9°, and α_{95} = 3.4° for the tuff of Little Chokecherry Canyon (WAER-1 in their figure 4). This is different from the tuff of Little Chokecherry Canyon site sampled for the present study (D = 338.6°, I = 52.9°, α_{95} = 6.7°, LCC; Table 3 and Fig. 3). However, Anders et al. (1993) showed the tilts in the mountains north of the eastern Snake River Plain were sufficient to account for most of the difference in the magnetic directions between the tuff of Little Chokecherry Canyon site that we sampled and that sampled by Anders et al. (1993). The overlap of radiometric error and similar paleomagnetic orientations support this interpretation. Moreover, both locations have similar mineralogy and meter-thick black basal vitrophyres overlain by a brown lithophysal zone with large cavities (e.g., Fig. 2C). However, the possibility exists that the tuff of Little Chokecherry Canyon is the same unit as the tuff of Timbered Dome and the tuff of Appendicitis Hill discussed in Anders and Hemming (2004) and Anders et al. (2009).

Arbon Valley Tuff

The Arbon Valley Tuff is the largest and first eruption of the Picabo volcanic field (Kellogg et al., 1994). The Arbon Valley Tuff is distinctive among eastern Snake River Plain volcanic eruptions in that it has a significant content of biotite. In the area around the Cove (labeled 60 m in Fig. 1), there are two distinct zones: the lower is poorly welded, and the upper is densely welded (Kellogg et al., 1994; Drew, 2013; Drew et al., 2016). Thicknesses are extremely variable where found north and south of the eastern Snake River Plain as shown in Figure 1. Where the zonation is present, the lower zone is a white crystal-rich ground-surge deposit that is poorly welded to ashy in character (Drew, 2013). The densely welded upper ignimbrite has a crystal density of 25%–35%, of which 40%–50% are quartz crystals. Of the crystals, 25%–30% are plagioclase, 15%–20% are sanidine, and both are typically from 1 mm to 2 mm in length. Biotite is as much as 5%–8%, and clinopyroxene crystals comprise ~1%–2%. Distal outcrops of the Arbon Valley Tuff are typically poorly welded and have higher biotite content (see Kellogg et al., 1994 and Drew et al., 2013, 2016 for more details of the chemistry of the Arbon Valley Tuff). Ashfall deposits have been recognized as far as 150 km from its source (Anders et al., 2009). No densely welded locations have been identified on the northern side of the Snake River Plain. However, in the southern Snake River Plain, in and around the Fort Hall Indian Reservation, there are abundant outcrops of densely welded ignimbrite. In that area, paleomagnetic analysis yields a normal polarity with a mean site orientation of D = 304.5°, I = 57.5°, and α_{95} = 7.3° (Anders et al., 2014). At these locations, the Arbon Valley Tuff has a gray and in places a pink appearance and is 60 m to 70 m thick with a welded upper section up to 40 m thick in some places (Drew et al., 2013). A thin, <1 m unwelded pumice-dominated layer caps the units, and at some locations, such as the Cove (see Drew, 2013), there appears to be a missing section at the top (M. McCurry, 2018, personal commun.). Drew et al. (2013) dated the upper welded parts of the tuff at 10.44 ± 0.27 Ma.

There has long been confusion over whether there are one or two ignimbrite eruptions associated with the Arbon Valley Tuff. Kellogg et al. (1994) first presented an averaged $^{40}Ar/^{39}Ar$ age of 10.20 ± 0.06 Ma for the unit. However, there is a clear bifurcation in ages between ca. 10.2 Ma and ca. 10.4 Ma in Kellogg et al.'s (1994) data. For example, their step-heating result yields a 10.18 ± 0.04 Ma age, and another sample is dated at 10.38 ± 0.06 Ma. It should be noted that Kellogg et al. (1994) used the MMhb-1 standard, whereas Morgan and McIntosh (2005) and Anders et al. (2014) use the Fish Canyon Tuff as a standard, the age for which has been in flux (see Anders et al., 2014 for further discussion). On the shores of the Palisades Reservoir, Anders et al. (2009) identified two ashfall horizons that had a high percentage of biotite and yield an $^{40}Ar/^{39}Ar$ age of 10.41 ± 0.02 Ma on one horizon. Anders et al. (2014) identified two populations within the various outcrops of the Arbon Valley Tuff (Fig. 1) and determined ages of 10.41 ± 0.01 Ma and 10.22 ± 0.01 Ma. Morgan and McIntosh (2005) determined a single $^{40}Ar/^{39}Ar$ age of 10.34 ± 0.03 Ma (corrected for a common Fish Canyon Tuff standard age of 28.201 Ma) for the Arbon Valley Tuff. Curiously, there is only one individual age determination of the 85 made by Morgan and McIntosh (2005) that is 10.34 Ma, and only 24 determinations fall within their 0.03 Ma error. This could mean either there is a significant skewing of a single eruption event, or as Anders et al. (2009) interpreted, there is more than one eruption associated with the Arbon Valley Tuff. Kellogg et al. (1994) observed two clearly defined zones at the Cove area (location marked as 60 m in Fig. 1) and referred to both of them as the Arbon Valley Tuff Member of the Starlight Formation (M. McCurry [2018, personal commun.] indicated he has looked for a location with two cooling units around the Cove location of Drew [2013] and Kellogg et al. [1994] and found only evidence of a single cooling unit). However, Trimble and Carr (1976) described two cooling units in the Arbon Valley Tuff in the Deep Creek Mountains, ~10–15 km southeast of American Falls, Idaho (Fig. 1). Drew et al. (2016) identified two distinct groupings in the Arbon Valley Tuff based on chemistry and quartz phenocryst zoning characteristics and concluded there were two distinct eruptions that comprised the Arbon Valley Tuff. They suggest that there was an initial shallow-sourced eruption followed by a more deeply sourced eruption that they referred to as "lower" and "upper" eruptions. As discussed above, Drew et al. (2013) dated the upper horizon at the Cove section of the Arbon Valley Tuff at 10.44 ± 0.27 Ma using U/Pb analysis. We prefer to use a somewhat younger $^{40}Ar/^{39}Ar$ age of 10.41 ± 0.01 Ma from Anders et al. (2014) over the slightly older age of 10.44 ± 0.27 Ma used by Drew et al. (2013) because from our experience, the zircon U/Pb ages from the eastern Snake River Plain generally come in a little bit older than the sanidine $^{40}Ar/^{39}Ar$ ages (see Drew et al., 2013; Anders et al., 2014; and Rivera et al., 2014 for further discussion).

Twin Falls Volcanic Field

Here we discuss only those units that we suspect could have originated from the Picabo volcanic field but are generally thought to originate from the Twin Falls volcanic field. These units were investigated due to their age overlap with Picabo volcanic field age range and/or their spatial position relative to the boundary of the Picabo volcanic field (Fig.1).

Tuff of Cedar Knoll

Williams et al. (1982) reported a fission-track age of 7.0 ± 0.2 Ma, which places it clearly in the range of ages from the Picabo volcanic field. Although defined as an ignimbrite by Williams et al. (1982) and Konstantinou et al. (2013, we determined it to be a rhyolite flow based on a lack of glass shards layering of viable thickness with numerous thin glass layers similar in character to lavas described by Brueseke et al. (2014). This rhyolite lava (Fig. 2G; bottom row, second from left) could be related to either the Picabo or the Twin Falls volcanic fields. The paleomagnetic results were scattered in orientation and generally reversed in polarity but close to equatorial. This unit, like the rhyolite flows that make up the majority of the Cotterel Mountains as well as the Rhyolite of Hawley Spring and the West Pocatello Rhyolite (Drew et al., 2013; Anders et al., 2014), has little influence on our definition of the boundaries of the various volcanic fields because the rhyolite lavas often occur well after the passage of the Yellowstone hotspot.

Picabo Tuff

The Picabo Tuff was mapped as a single unit by Garwood et al. (2011), but we, like Honjo et al. (1986) and Schmidt (1962), identified an upper and lower division called Picabo Tuff A and Picabo Tuff B. Schmidt (1962, p. 27) described the boundary as a "thick layer of white tuffaceous sediment which is poorly exposed." He also commented on there being several cooling units in both A and B as well as possible individual ignimbrites. Both divisions of the Picabo Tuff have highly weathered plagioclase with sanidine and rare euhedral quartz. Picabo Tuff A forms a black to purple, densely welded basal vitrophyre (Fig. 2B) with a crystal density of ~15% (Fig. 2G; bottom row, second from right). There is a pervasive subhorizontal rheomorphic flow pattern in Tuff A that in places is overprinted with crude columnar jointing (Fig. 2B). Picabo B is also densely welded but has a slightly less crystal density (Fig. 2G; bottom row, right side) and is gray to dark-brown in color where we sampled. Both Picabo A and B have a crystal content that is dominated by plagioclase formed in clusters with clinopyroxenes (Fig. 2E). Analyses of the pigeonite by Honjo (1990) yield ~10 wt% magnesium. Honjo et al. (1986) dated the Picabo Tuff A at 8.98 ± 0.12 Ma by K/Ar. Our best estimates on the ages of the lowermost and uppermost lithographic divisions of the Picabo Tuff yield ages of 9.12 ± 0.08 Ma and 9.02 ± 0.11 Ma, respectively (Table 1). Leeman (1982) reported that the Picabo Tuff had two different paleomagnetic polarities with the upper unit being reversed and the lower unit being normal. However, Bonnichsen et al. (2008) reported both the upper and lower units (Picabo Tuff A and Picabo Tuff B) have normal polarity. Neither Leeman (1982) nor Bonnichsen et al. (2008) indicated how their results were achieved. However, we took seven cores from A and B each. Several of the samples were erroneously inverted. However, after demagnetization, sample PVT2 (Picabo Tuff B) yielded six cores with normal polarity and one core with reverse polarity, and PVT (Picabo Tuff A) yielded five cores with reversed polarity and two cores with normal polarity. From this, we concluded that Picabo A was reversed polarity and Picabo B was normal polarity. Our demagnetized orientation results were relatively poor and did not yield useful paleomagnetic declination and inclination data from these units.

Tuff of Cotterel Mountain

The tuff of Cotterel Mountain sample C10A was sampled from the same location as C10 in Table 1 of Konstantinou et al. (2013). Konstantinou et al. (2013) describe this unit as a "welded ignimbrite" and provided the GPS coordinates that we used. This unit is sandwiched in between lavas in the southern Cotterel Mountains on the southern margin of the Snake River Plain. Thin-section analysis of this unit suggests a high degree of welding and yields evidence of significant rheomorphic flow. This unit is brown in color with a crystal density from 5% to 10% (Fig. 2G; top row, right side), and plagioclase is the dominant feldspar. Paleomagnetic analysis shows this unit has a normal polarity with I = 30.6°, D = 335.2°, and α_{95} = 5.7° (Table 3; Fig. 3). This orientation is significantly different from those of Konstantinou et al.'s (2012) Unit 6, which Knott et al. (2016) correlated with the Castleford Crossing member and which has a magnetic orientation of D = 3.1°, I = 66°, α_{95} = 4.6° (David Finn, 2018, personal commun.). We dated this unit at 9.05 ± 0.13 Ma (Table 1), which is also older than the age estimate of Knott et al. (2016) based on dating of the unit overlying the Castleford Crossing member of 8.117 ± 0.46 Ma (corrected to common $^{40}Ar/^{39}Ar$ standard) and the underlying unit dated at 8.20 ± 0.14 Ma (corrected to common $^{40}Ar/^{39}Ar$ standard).

Idavada Ignimbrites of the Lake Hills

Michalek (2009) identified three Lake Hills ignimbrite units (Fig. 1) that he identified as Tivo (oldest), Tivm (middle), and Tivy (youngest). The Idavada ignimbrites are located 12 km northeast of the uppermost Picabo Tuff (Queen's Crown). The ages of these units as reported in Michalek (2009) are 9.16 ± 0.20 Ma, 9.21 ± 0.18 Ma (two age determinations for Tivo), 8.39 ± 0.54 Ma (Tivm), and 8.76 ± 0.38 Ma (Tivy). However, as we mentioned above, correcting for the age of the Fish Canyon standard used in Anders et al. (2014), we get an age of 9.22 ± 0.20 Ma, 9.27 ± 0.18 Ma for (Tivo), 8.44 ± 0.54 Ma (Tivm), and 8.82 ± 0.38 Ma (Tivy). We only sampled Tivo and found two flow units; the lower one was ~20 m thick, and the upper one was ~40 m thick. The lower flow was black and platy in character with crystal density of up to 20%. The upper flow is a black vitrophyre, also with up to 20% crystals (Fig. 2G; upper row, second from left) and has an extensive lithophysal zone with cavities of 6 cm or more in diameter (Fig. 2A). The dominant crystal content is plagioclase in both flows with crystals averaging from 1 to 3 mm. Also a large percentage of crystal content of both was clinopyroxene and an opaque mineral (magnetite?). Minor or trace mineralogy of both flows included quartz, sanidine, zircon, and apatite. Many of the feldspar crystals formed clusters with pyroxenes (Fig. 2F) similar to that found in the Picabo Tuff. Our $^{40}Ar/^{39}Ar$ analysis of Tivo yields an age of 9.38 ± 0.64 Ma for the upper of the two flows of Tivo. Although Michalek (2009) reported that age determinations were on sanidine for the Lake Hills ignimbrites, he reports that the dominant feldspar is plagioclase in all three ignimbrites. The age of Tivo is close to that of the tuff of Little Chokecherry Canyon (9.46 ± 0.03 Ma; Anders et al., 2014) and the tuff of Kyle Canyon (9.28 ± 0.01 Ma). However, the high content of plagioclase and clinopyroxene and minor sanidine content in Tivo compared to the high content of sanidine, minor plagioclase, and limited pyroxenes in both the tuff of Little Chokecherry Canyon and the tuff of Kyle Canyon means a correlation is unlikely.

Boreholes in the Picabo, Twin Falls, and Heise Volcanic Fields

Two cores from boreholes drilled into the Picabo volcanic field (Fig. 1) penetrated into the silicic volcanic rocks. These cores—INEL-1 and WO-2—were drilled for the Idaho Engineering Laboratory (now called Idaho National Laboratory) of the U.S. Department of Energy. Only one of these cores, WO-2, encountered Heise volcanic field rock at its maximum depth (Anders et al., 1997; Anders et al., 2014). A third borehole, 2-2A, was drilled into the northern margin of the Picabo volcanic field (Fig. 1; Doherty et al., 1979; McBroome, 1981; Morgan et al., 1984). We analyzed 2-2A core for paleomagnetism and $^{40}Ar/^{39}Ar$ analysis and did not find evidence of Picabo volcanic field units. However, during the course of our work, we discovered a new Heise volcanic field outflow ignimbrite, which we named the tuff of Birch Creek Sinks (Anders et al., 2016). Borehole INEL-1 encountered numerous rhyolite lava rocks that McCurry and Rodgers (2009) interpreted as caldera fill of the Picabo volcanic field. Another borehole recently drilled for the Snake River Plain Scientific Drilling Project (HOTSPOT) (Shervais et al., 2013, labeled KDS in Fig. 1) yields important data on the Twin Falls volcanic field but encounters no units from the Picabo volcanic field (see Knott et al., 2016).

Borehole 2-2A

Doherty et al. (1979) first reported two ignimbrites in borehole 2-2A. The upper ignimbrite is 1.6 m thick, and the lower ignimbrite is 10 m thick (Fig. 5). We dated the ignimbrites at three depths: 770.1 m (2526.5 ft), 771.1 m (2530 ft), and 777.9 (2552 ft). The top of the upper ignimbrite was dated by $^{40}Ar/^{39}Ar$ at 4.26 ± 0.25 Ma (Table 2), and the bottom of the upper ignimbrite was dated at 4.38 ± 0.09 Ma (Table 2). Combining the top and bottom of the ignimbrites yields a $^{40}Ar/^{39}Ar$ age of 4.37 ± 0.08 Ma (Table 2), and the lowest ignimbrite in the 2-2A core yields an age of 4.63 ± 0.33 Ma (Table 2). Paleomagnetic analysis at the top and bottom of the upper ignimbrite at 770.1 m (2526.5 ft) and 771.1 m (2530 ft) resulted in a normal polarity with an inclination ranging from 63.3° to 75.3° (Fig. 3; declination could not be assessed because the core was not marked for direction). Paleomagnetic analysis at depth 777.9 m (2552 ft) yields an inclination range of from I = –46.9° to –52.7° (Fig. 3). Anders et al. (2014) dated the Kilgore Tuff with $^{40}Ar/^{39}Ar$ at 4.61 ± 0.01 Ma, and they determined the paleomagnetic unit mean inclination for the Kilgore Tuff to be I = –50.4° with α_{95} = 7.7°. The age, similarity to surface exposures, and reversed polarity at depth 777.9 m suggest the 10-m-thick unit correlates with the Kilgore Tuff. McBroome (1981) and Morgan et al. (1984) dated what we defined as the tuff of Birch Creek Sinks at depth 765.7 m (2512 ft) at 4.2 ± 0.3 Ma by fission track and determined it to be the Kilgore Tuff. The discovery of this new ignimbrite extends the age of the outflow ignimbrites of the Heise volcanic field from 6.66 Ma to 4.37 Ma and reduces the gap between the Heise and Yellowstone volcanic field silicic ignimbrite eruptions from 2.48 m.y. to 2.24 m.y. As discussed below, Ellis et al. (2017) suggest the gap may be even less by ~275,000 years based on their dating of intracaldera units in the Sugar City core (Embree et al., 1978) recovered from within the boundaries of Kilgore Caldera (Fig. 1). With the exception of the Huckleberry Ridge Tuff A, units younger than 4.37 Ma recovered from the Sugar City core yielding ages as young as 3.74 ± 0.15 Ma (U/Pb SIMS age) are not found outside the boundaries of the Caldera. However,

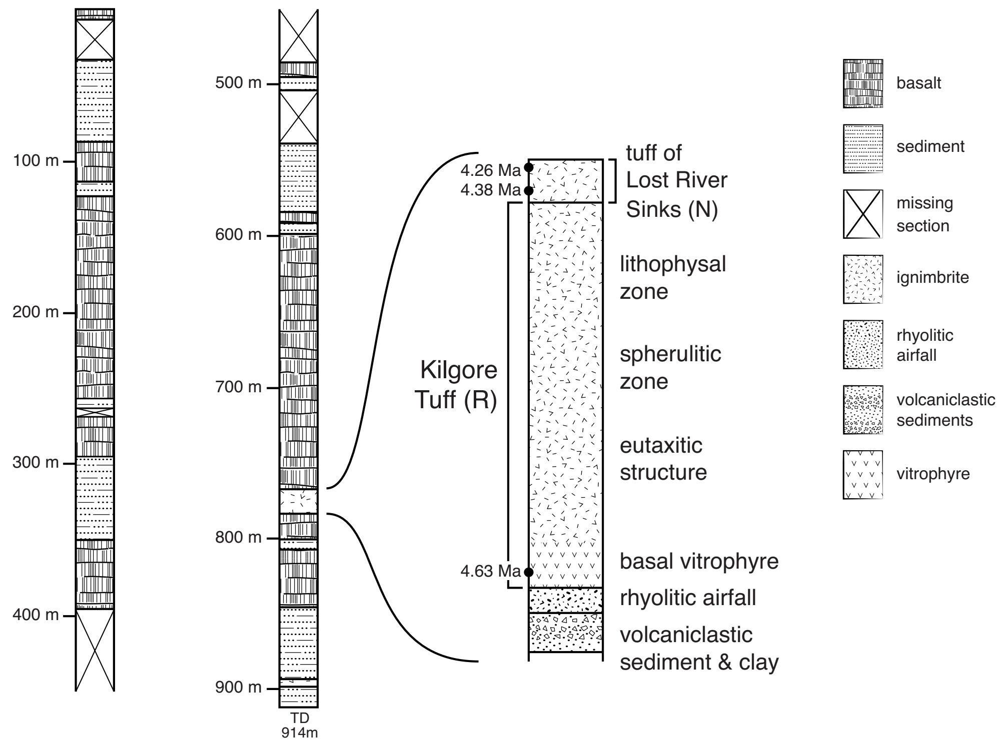

Figure 5. Description of core recovered from borehole 2-2A from the Snake River Plain (location on Fig. 1). Modified from Doherty (1979). Enlarged area is the location of the Kilgore Tuff and the overlying tuff of Birch Creek Sinks discussed in the text. The locations for $^{40}Ar/^{39}Ar$ dates are marked and are also the sites of paleomagnetic sampling.

as we will discuss below, it is possible the outflow tuff of Birch Creek Sinks is also found near the base of the Sugar City borehole.

Borehole WO-2

As discussed in detail in Anders et al. (2014), the WO-2 borehole bottoms out within the oldest unit of the Heise volcanic field, the 6.66 Ma Blacktail Creek Tuff. Neither the 4.61 Ma Kilgore Tuff nor the younger 4.37 ± 0.08 Ma tuff of Birch Creek Sinks is found in WO-2. Given the proximity of the WO-2 and 2-2A boreholes, it is reasonable to assume these units were eroded prior to deposition of the overlying basalt at the WO-2 location.

Borehole INEL-1

Morgan et al. (1984) suggested core recovered from borehole INEL-1 included ignimbrites from the Heise volcanic field. They identified the Kilgore Tuff, the Walcott Tuff, and the Blacktail Creek Tuff from core in the interval of 0.76–1.2 km and in cuttings from 1.3 to 1.36 km. McCurry and Rodgers (2009) dated three sections of recovered core using U/Pb and reported ages of 8.27 ± 0.27 Ma (1.123 km), 8.04 ± 0.1 Ma (1.481 km), and 8.35 ± 0.24 Ma (3.159 km). McCurry and Rodgers (2009) did not distinguish between ignimbrites and lava flows. However, the lowermost sections of core have been interpreted as rhyolite lavas, and the upper sections of the INEL-1 core could be either ignimbrites or lava flows (M. McCurry, 2018, personal commun.). We also had difficulty distinguishing between a lava flow and an ignimbrite below 764 m in INEL-1. Although based on our work on Snake River Plain core WO-2 (Anders et al., 2014), the INEL-1 core below 764 m appears to us to be a lava flow. We sampled the rhyolite in the core for paleomagnetism matches between the core and ignimbrites that are found at the surface in the Heise, Twin Falls, or Picabo volcanic fields (see Supplemental Material [footnote 1] for this paleomagnetism data) and found none. As is shown in the Appendix, we identified six separate units for which none of the sequences match those of either volcanic field found by Anders et al. (2014). Given that recovered core represents less than 5% of the length of the core, the possibility exists there are ignimbrites not recovered by drilling.

Boreholes Kimberly and Kimana

As part of the HOTSPOT scientific drilling program, two boreholes were drilled into the estimated location of the Twin Falls volcanic field (Christiansen et al., 2013; Shervais et al., 2013). The Kimana borehole bottomed out in the basalt. However, the Kimberly borehole (KDS in Fig. 1) drilled through three rhyolitic units, at the bottom of which is an ignimbrite sequence over 600 m thick. Christiansen et al. (2013) interpreted this sequence as the tuff of McMullen Creek. Knott et al. (2016) interpreted the Kimberly borehole-thick section to be what they are calling the Castleford Crossing member of the Cassia Formation.

DISCUSSION AND CONCLUSIONS

The Picabo volcanic field is one of the least understood volcanic centers marking the track of the Yellowstone hotspot. Among the first attempts to understand the volcanic rocks of the Picabo volcanic field were those by Drew (2013), Drew et al. (2013), and Drew et al. (2016), who focused on the geochemistry of the volcanic field. We have followed on their work, focusing on correlating ignimbrites in the volcanic field and assessing which ignimbrites are sourced from the Heise volcanic field to the northeast or the Twin Falls volcanic field to the southwest. Since to some extent the track of the Yellowstone hotspot can be considered a continuum, a defined source area can be difficult to establish. Moreover, using geographic criteria alone is prone to error because ignimbrite fields can overlap, be buried, or be removed by erosion, thus disguising their point of origin. The timing and location of these eruptive events are also important because they are among the main criteria for assessing the migration rate of volcanism and, by inference, the velocity of the North American plate (Armstrong et al., 1975; Suppe et al., 1975; Anders et al., 1989; Rodgers et al., 1990; Pierce and Morgan, 1992; Anders, 1994; Smith and Braile, 1994; Nash et al., 2006; Shervais and Hanan, 2008; Anders et al., 2014).

A key unit in the Picabo volcanic field is the Arbon Valley Tuff. This unit is the first ignimbrite emanating from the volcanic field and is the largest in volume. As we discussed above, our results support that the Arbon Valley Tuff involved two major eruptive events, one at 10.41 ± 0.01 Ma and the other at 10.22 ± 0.01 Ma (Anders et al., 2014). Correlating these two events from outcrop to outcrop is difficult, and not all workers have identified two events (Trimble and Carr, 1976; Morgan, 1992; Pierce and Morgan, 1992; Kellogg et al., 1994; Morgan and McIntosh, 2005, Drew, 2013, Drew et al., 2013; Drew et al., 2016). Part of the problem may lie in remixing of the older event material with younger event material. Remixing is made possible by reworking of poorly consolidated ash and pumice in the lower unit into the upper unit formed during a second eruption (Kellogg et al., 1994; Anders et al., 2009; Anders et al., 2014; Drew et al., 2016). The contact between these two eruptive events can be identified in only a few locations and must be determined by geochronology and geochemistry (Kellogg et al., 1994; Anders et al., 2009; Anders et al., 2014). Drew et al. (2016) came to the same conclusion that there are two distinct eruptions associated with the Arbon Valley Tuff, and they refer to these eruptions as "upper" and "lower." Anders et al. (2009) based their interpretation on the fact that there are two distinct ashfall deposits some 150 km from the source; both of these deposits have similar chemistry and age. Anders et al. (2014) based their interpretation on there being two groupings of $^{40}Ar/^{39}Ar$ age determinations on feldspars. These determinations yield ages of 10.22 ± 0.01 Ma and 10.41 ± 0.01 Ma. Drew et al. (2016) based their interpretation on there being two distinct populations of quartz zonation as well as differences in chemistry. Nevertheless, there seems to be no good outcrop where two well-defined cooling units are observable, and thus these interpretations are based on an assumption of mixing material from one eruption into that from a later eruption.

Ignimbrite Correlations

Below is our interpretation of units we studied that originate from the Picabo, the Twin Falls, and Heise volcanic fields and whether or not they correlate amongst one another within a particular volcanic field. This includes a discussion of newly identified ignimbrites and of ignimbrites that we suggest were misidentified with respect to their originating volcanic field.

Three of the ignimbrites of the Picabo volcanic field have only a limited distribution suggestive of volumetrically limited eruptions. These are the tuff of Lost River Sinks, the tuff of Kyle Canyon, and the tuff of American Falls. Of these three ignimbrites, only the tuff of Kyle Canyon is found at two locations (Fig. 1). McBroome (1981) suggested the tuff of Lost River Sinks was from a distal source. However, the cm-sized pumice cavities, 1–2 mm grain size, and the close timing of rhyolite caldera infill found in borehole INEL-1 are all suggestive of a local source. The cm-sized lithic and volcanic material in the tuff of Kyle Canyon and the tuff of American Falls suggests both are also sourced locally. This is further supported by the observation that the tuff of Kyle Canyon and tuff of Lost River Sinks are only found along the northern margin of the Snake River Plain, and the tuff of American Falls is only found along the southern margin of the Snake River Plain.

In order to correlate ignimbrites within the Twin Falls volcanic field and differentiate them from the Picabo volcanic field ignimbrites, we depended primarily on age dating, petrography, geochemistry, location, and paleomagnetism. We corrected all of the $^{40}Ar/^{39}Ar$ ages from different publications to a common reference standard of 28.201 Ma for the Fish Canyon Tuff (Kuiper et al. 2008). We did not correct K/Ar dates because none we cited are for dates older than the last change in decay constant. We also include U/Pb dates but realize they can sometimes be a poor way of correlating ignimbrites because the zircon population often reflects pre-eruption ages (e.g., Rivera et al., 2014; Wotzlaw et al., 2014) and can be different from $^{40}Ar/^{39}Ar$ ages for the same units (see Anders et al., 2014 for further discussion).

Many of these ignimbrites have different outcrop expressions that make correlation difficult (see Knott et al., 2016). For example, Leeman (1982) noted that the tuff of City of Rocks only has one cooling unit, compared to the Picabo

Tuff, which has several cooling units (Schmidt, 1961). The number of cooling units is problematic for correlating ignimbrite units because flow direction and timing of deposition can change from location to location (e.g., Ross and Smith, 1961). Therefore, this was not a determinant in our suggested correlations.

Here we will discuss possible correlations between the Picabo Tuff, the Lake Hills ignimbrites, and several units generally thought to originate in the Twin Falls volcanic field. The Picabo Tuff, the ignimbrites of the Lake Hills, the tuff of Cotterel Mountain, and the tuff of City of Rocks could all be correlative with the tuff of McMullen Creek, one of the largest eruption sequences of the Twin Falls volcanic field, based on similarities in chemistry, petrography, stratigraphy, and radiometric age (e.g., Wright, 1998; Wright et al., 2002). However, various authors have correlated these ignimbrites in differing combinations, and none argue they are all from the same source (e.g., Stearns et al., 1938; Stearns, 1955; Armstrong et al., 1980; Leeman, 1982; Nash et al., 2006; Bonnichsen et al., 2008; Ellis et al., 2010; Anders et al., 2014; Knott et al., 2016). For example, Bonnichsen et al. (2008, appendix 6) suggested that the Picabo Tuff and Lake Hills ignimbrites are the northern extent of the tuff of McMullen Creek. The tuff of McMullen Creek was described by Wright et al. (2002) as having five separate eruptive horizons. Ellis et al. (2010) referred to this unit as the McMullen Creek member of the Cassia Formation. Knott et al. (2016) referred to this unit as having three subdivisions they called the Dry Gulch member, the Indian Springs member, and the McMullen Creek member of the Cassia Formation. Wright et al. (2002) describe the source of these ignimbrites as from north of the Twin Falls, Idaho area and within the Twin Falls volcanic field (Fig. 1). Knott et al. (2016) make a convincing argument based on geochemical and paleomagnetic data that the tuff of City of Rocks is the Castleford Crossing member (called the Castleford Crossing ignimbrite by Bonnichsen et al., 1989) that originated from the Twin Falls volcanic field. However, to add further confusion, a 9.15 Ma K/Ar age (Honjo et al., 1986) for the tuff of City of Rocks is much older than the ca. 8 Ma age assigned by Knott et al. (2016).

One of the strongest arguments for the Picabo Tuff not being erupted from the Picabo volcanic field is the observation reported by Schmidt (1961, 1962), and repeated by Leeman (1982) and Anders et al. (2014), that the Picabo Tuff decreases in thickness from west to east, placing its origin to the west of the Picabo volcanic field. Leeman (1982) suggested the Picabo Tuff erupted from a center near the Magic Reservoir area (Fig. 1). Moreover, Hughes et al. (1996) argued, based on the similarity of the chemistry of the Picabo Tuff compared to that of the other Twin Falls units, the Picabo Tuff cannot have originated in the Picabo volcanic field.

Michalek (2009) suggested that the oldest of the three ignimbrites in the Lake Hills (Tivo) correlates with the tuff of City of Rocks, and the younger two ignimbrites of the Lake Hills correlate with the tuff of McMullen Creek. Honjo (1990) argues that the Lake Hills ignimbrites cannot correlate with the Picabo Tuff B because the pigeonite in that Tuff has a significantly higher concentration of magnesium than the pigeonites of the Lake Hills. The correlation between the tuff of City of Rocks and the Lake Hills ignimbrites does not seem reasonable to us because the content of magnesium of the tuff of City of Rocks as assessed by Honjo (1990) is almost twice that of the Lake Hills ignimbrites.

The age of the tuff of McMullen Creek or subdivisions of the Cassia Formation vary greatly (Bonnichsen et al., 2008; Knott et al., 2016). Perkins and Nash (2002) report ages ranging from 9.16 Ma to 8.60 Ma, for which we are unaware of the technique used or how their subdivisions of the tuff correlated to those of Knott et al. (2016). Nash et al. (2006) reported an age of 9.06 ± 0.07 Ma (corrected for a common standard age). Knott et al. (2016) report a U/Pb age of 9.0 ± 0.2 Ma and 9.0 ± 0.3 Ma on their subdivisions of the Cassia Formation; they call these subdivisions the McMullen Creek member and the Indian Springs member.

Michalek (2009) reported ages as corrected by us to be 9.27 ± 0.18 Ma and 9.22 ± 0.18 Ma for the oldest ignimbrite (Tivo), 8.44 ± 0.54 Ma for the middle unit (Tivm), and 8.82 ± 0.38 Ma for the youngest ignimbrite (Tivy). We determined a $^{40}Ar/^{39}Ar$ age of 9.38 ± 0.64 Ma for the oldest ignimbrite (Tivo). The relatively large errors on all the measurements leave open the possibility that the youngest Lake Hills ignimbrites (Tivy) correlate with the tuff of City of Rocks as suggested by Michalek and also correlated with the ca. 8 Ma Castleford Crossing member. However, the magnesium content of the pigeonite (from Knott et al., 2016) is twice that of the values determined by Honjo (1990), making the correlation unlikely. Tivo is also close in age to the 9.46 ± 0.03 Ma tuff of Chokecherry Canyon (Snider, 1995) and the 9.28 ± 0.01 Ma tuff of Kyle Canyon. However, all the Lake Hills ignimbrite mineralogy is similar to that of rocks from the Twin Falls volcanic field and dissimilar to the tuff of Kyle Canyon (Anders et al., 2014). Therefore, in our view, Michalek's (2009) Tivo does not correlate to any known Picabo or Twin Falls volcanic field ignimbrite, and more work is needed on these units.

Bonnichsen et al. (2008) suggested that the tuff of McMullen Creek, the Picabo Tuff, and the Lake Hills ignimbrites are all correlative. This is unlikely because as we will discuss below, the Picabo Tuff and Lake Hills do not correlate; rather, our interpretation is that some of the members of the Cassia Formation previously described as the tuff of McMullen Creek do correlate with the Picabo Tuff.

As discussed above, we dated Picabo Tuff A at 9.12 ± 0.08 Ma and Picabo Tuff B at 9.02 ± 0.11 Ma. Furthermore, we assessed the polarity of Picabo Tuff A as reversed and Tuff B as normal. Knott et al. (2016) determined the magnesium content of pigeonite as ~10–11 wt% for the McMullen Creek member, ~10–11 wt% for the Indian Springs member, and ~8–9 wt% for the Dry Gulch member. Although Ellis et al. (2010) published the magnesium content of clinopyroxenes from the Cassia Formation, there is no correlation of sampling sites between their work and that of the sites presented in Knott et al. (2016) and Honjo (1990). We assessed Honjo's (1990) content of magnesium as ~10 wt% for the Picabo Tuff B. All of the values determined by Honjo (1990) for the three Lake Hills ignimbrites were below ~7.4 wt% magnesium, suggesting that none correlated with the Knott et al. (2016) subdivisions of the Cassia Formation. However, the magnesium content of Picabo B is a close match to the values with the subdivisions of the Cassia Formation that Knott et al. (2016) called the McMullen Creek member and the Indian Springs member. Both these units have a normal polarity, and the unit directly below them, the Dry Creek member, has a reverse polarity. Assuming the out-of-stratigraphic-order dates Knott et al. (2016) give for the Dry Creek member (8.63 ± 0.5 Ma and 8.47 ± 0.19 Ma) are erroneous, the age dates are consistent with the McMullen Creek member (9.0 ± 0.2 Ma; 8.96 ± 0.04 Ma) and the Indian Springs member (9.0 ± 0.3 Ma) correlating with the Picabo B ignimbrite (9.02 ± 0.11 Ma; 8.98 ± 0.12 Ma; 9.06 ± 0.07 Ma) and Picabo A (9.12 ± 0.08 Ma) correlating with the Dry Gulch member of the Cassia Formation as defined by Knott et al. (2016). This interpretation is supported by the geochemistry, paleomagnetism, and geochronology as well as the physical descriptions of these units. Furthermore, there is a sedimentary layer deposited between the Dry Creek member and the Indian Springs member (Knott et al., 2016); the layer mirrors the sedimentary layer deposited between Picabo A and B (Schmidt, 1961). It is unclear how the McMullen Creek and Indian Springs members are divided within Picabo B, but there are numerous horizons that might appear as cooling units that could actually represent the boundary between the normal-polarity Indian Springs member and the normal-polarity McMullen Creek member. Also, the observation of thickening in an eastward direction of the Picabo Tuff from the Magic Reservoir area (Fig. 1) could be explained by a southwest location of the source of the subdivisions of the Cassia Formation or tuff of McMullen Creek as discussed in Wright et al. (2002).

The 9.06 ± 0.07 Ma (Nash et al., 2006) or 9.0 ± 0.2 Ma (Knott et al., 2016) tuff of McMullen Creek member and the 9.05 ± 0.13 Ma tuff of Cotterel Mountain (Table 1) are likely correlative. The tuff of McMullen Creek has a magnetic inclination of between 50° and 60° (Christiansen et al., 2013). We determined an inclination of 30.6° NNE with a α_{95} of 5.7° for the tuff of Cotterel Mountains (Fig. 2 and Table 3), suggesting the two different units might not correlate. However, as discussed in Knott et al. (2016) and seen elsewhere along the margins of the Snake River Plain (McQuarrie and Rodgers, 1998), there is significant subsidence due to posteruptive basaltic loading (Anders and Sleep, 1992; McQuarrie and Rodgers, 1998) causing a tilting toward the center of the Snake River Plain. The 20° to 30° tilt difference could be due to the fact that the magnetic signal recovered from Kimberley borehole represents the sharp tilting experienced along the margins of the Snake River Plain in what Knott et al. (2016) called the Cassia Monocline.

Based on similarity in structure, petrology, and radiometric age, we suggest that the younger two Lake Hills ignimbrites (Tivm and Tivy) could correlate with the Lincoln Reservoir member of the Cassia Formation as defined by Knott et al. (2016). The ages of the Lincoln Reservoir member are 7.98 ± 0.30 Ma and 8.70 ± 0.90 Ma (corrected to a common standard). These ages fall within the error range of the younger two ignimbrites of the Lake Hills of 8.44 ± 0.54 and 8.82 ± 0.38 Ma. This leaves Tivo uncorrelated with any known ignimbrite. We calculated Honjo's (1990) magnesium concentration of pigeonite from the Tivm and Tivy as 7.4 wt%, which is close to the ~8.5 wt% estimate from Knott et al. (2016). Clearly this correlation scheme is somewhat speculative, and more work on this correlation is needed including refinement of ages, paleomagnetic orientations, chemistry, and petrography.

Correlation between the Tuff of Lost River Sinks and the Winnetou Tuff

Ellis et al. (2017) sampled an ignimbrite at Howe Point located at the southern tip of the Lemhi Range (Fig. 1). They "informally" called this ignimbrite the Winnetou Tuff and provided latitude and longitude in their repository. The published latitude and longitude are reported as N43.8073 and W112.84908 in Ellis et al. (2017). This location does not correspond to the Google Map latitude and longitude location of the Winnetou Tuff (B. Ellis, 2018, personal commun.). The location of this unit is actually in a Highway 33 road cut located ~300 m south of the location described in Ellis et al. (2017) using Google Map coordinates. Howe Point was first mapped by McBroome (1981) where she described an ignimbrite found in the same Highway 33 road cut as an "anomalously old age for an ash-flow sheet in this part of the eastern Snake River Plain", and where she determined the age to be 12.4 Ma using fission-track analysis. McBroome (1981) named this ignimbrite the tuff of Lost River Sinks. Kuntz et al. (2003) mapped Howe Point and also included the location of the tuff of Lost River Sinks in the road cut in Highway 33. As discussed above, this unit was sampled for paleomagnetics by Anders et al. (2014) and found to have a normal polarity. They also dated the tuff of Lost River Sinks by $^{40}Ar/^{39}Ar$ at 8.87 ± 0.16 Ma. Clearly, the $^{40}Ar/^{39}Ar$ dating showed the tuff of Lost River Sinks was significantly older than the 6.66 Ma age of the Blacktail Creek Tuff. As discussed above, Drew et al. (2013) mistook the lowest Blacktail Creek Tuff at Howe Point as the tuff of Lost River Sinks until their U/Pb age showed it to be the lowest Blacktail Creek Tuff. Drew et al. (2013, p. 66) state that they likely mistook the Blacktail Creek Tuff for the tuff of Lost River Sinks, stating: "The Tuff of Lost River Sinks we sampled was likely the Blacktail Creek Tuff." Moreover, Ellis et al. (2017, p. 117) pointed out that the "newly described Winnetou Tuff, ... differs geochemically and petrologically from the overlying Heise succession." We believe the "Winnetuo Tuff" is the tuff of Lost River Sinks, and its geochemistry and petrology should be different because this unit is part of the Picabo volcanic field and not the Heise volcanic field. As a result, we suggest the name "Winnetuo Tuff" should be abandoned.

Correlations between Ignimbrites in 2-2A and the Sugar City Cores

Ellis et al. (2017) reported four U/Pb ages for the rhyolites recovered from the Sugar City borehole, which is located within the boundaries of the caldera source of the Kilgore Tuff (see Embree et al., 1978). These are SIMS ages of 3.86 ± 0.15 Ma, 3.74 ± 0.15 Ma, and 4.10 ± 0.25 Ma, and an isotope dilution–thermal ionization mass spectrometry (ID-TIMS) age of 4.0248 ± 0.0011 Ma. The ID-TIMS age is from the lowest sampling of the recovered core (14 036 in Ellis et al., 2017), and the oldest SIMS date is from the same location. The two youngest ages (14 002 and 14 018) are out of stratigraphic order. The lowest two of these ages come from sampling locations that are described by Embree et al. (1978) and Jean et al. (2018) as lavas. As has been discussed with respect to the INEL-1 core, distinguishing between a lava and an ignimbrite in core or cuttings is difficult.

The 4.10 ± 0.25 Ma age is based on seven U/Pb SIMS analyses of the ten total zircon ages determined. Ellis et al. (2017) removed three zircon ages from the population because one of these ages is clearly from a different, much older event, and other two ages have high uranium content. The two removed zircon ages record the highest precision values (0.09 Ma and 0.11 Ma) of all ten. One of the remaining seven SIMS measurements also has the same high precision (0.09 Ma) and yields an age of 4.38 ± 0.09 Ma. Moreover, the two removed zircon samples have the highest radiogenic ^{206}Pb (89% and 99.5%). By not removing these high-precision samples, the age becomes 4.44 ± 0.05 Ma, and therefore the rhyolite lava at the base of the Sugar City core and the tuff of Birch Creek Sinks in 2-2A core are approximately the same age, with the possibility of the tuff of Birch Creek Sinks being younger than the oldest age determined from lava at the base of the Sugar City core. If the bottom sampling site 036 in Ellis et al. (2017) is older than 4.37 Ma, the next upsection age from Ellis et al. (2017) is their sampling site 14 018, which yields an age of 3.74 ± 0.15 Ma. Jean et al. (2018) report several ignimbrites within this interval in what they call units R4 and R3 (with R5 including the basal lava). One ignimbrite within R3 is as much as 72 m thick. It should be noted that the ID-TIMS results by Ellis et al. (2017) yield a much younger age of 4.0298 ± 0.0011 Ma for the basal lava than they found using a U/Pb SIMS dating technique. It is unclear why ID-TIMS data from the eastern Snake River Plain yield younger ages than U/Pb SIMS, K/Ar, and ^{40}Ar/^{39}Ar ages (Morgan and McIntosh, 2005; Drew et al., 2013; Anders et al., 2014; Szymanowski et al., 2016; and see Black et al., 2004 for further discussion of this topic). From the above discussion, there are two possibilities for the outflow tuff of Birch Creek Sinks being within the Kilgore Caldera. (1) One of the ignimbrites Jean et al. (2018) identified in their units R5, R4, and R3 correlated with the tuff of Birch Creek Sinks. This interpretation depends on whether the age of the basal lava recovered from the Sugar City borehole is 4.0248 ± 0.0011 Ma or 4.44 ± 0.05 Ma. (2) If the two U/Pb age determinations are excluded from the age estimate of the basal lava in the Sugar City borehole as suggested in Ellis et al. (2017), then the tuff of Birch Creek Sinks is either not found within the Kilgore Caldera or lies below the deepest penetration of the Sugar City borehole. We prefer the former interpretation over the latter; although, clearly, more data analysis of the units in R2–R5 of Jean et al. (2018), including paleomagnetic and radiometric dating, is needed to resolve this issue. Lately, another curious issue concerning the Sugar City core is why the tuff of Birch Creek Sinks is the only outflow ignimbrite following the eruption of the Kilgore Tuff. Jean et al. (2018) reported a 200-m-thick ignimbrite within their unit R2 in the Sugar City core; yet no ignimbrite younger than 4.37 Ma is found anywhere in the region surrounding the Kilgore Caldera.

Yellowstone Hotspot Migration Rate

Using the position and timing of the Picabo volcanic field is one of the two ways of estimating the position of the Yellowstone hotspot with respect to the motion of the North American plate for the past 10 m.y. Armstrong et al. (1975), Suppe et al. (1975), Pierce and Morgan (1992), Smith and Braile (1994), and Nash et al. (2006) used the position of the Yellowstone–Snake River Plain volcanic fields to estimate the migration rate of volcanism and, assuming a fixed mantle source, by inference, the North American plate velocity. Rodgers et al. (1990) and Anders (1994) used the migrating deformation field associated with the thermal perturbation caused by the hotspot to calculate velocity independent of volcanic eruptions. Here we assume, as did Anders et al. (2014), that the location and timing of the first major eruption of a volcanic field mark the sublithospheric location of the hotspot and can therefore be used to estimate the relation between plate motion and the hotspot source. Thus, the relative location of the hotspot in the Picabo volcanic field is defined by the largest and first eruption of the Arbon Valley Tuff. As we discussed above, the field mapping, geochemistry, and geochronology conducted by Trimble and Carr (1976), Kellogg et al. (1994), Anders et al. (2014), and Drew et al. (2016) on the Arbon Valley Tuff support two distinct eruptions. The combination of these studies has convinced us that the best representation of the oldest eruption of the Picabo volcanic field is the first eruption dated 10.41 ± 0.01 Ma (called Arbon Valley Tuff A in Anders et al., 2014). Therefore, in an apples-to-apples comparison, we use the oldest Arbon Valley Tuff ^{40}Ar/^{39}Ar age of 10.41 ± 0.01 Ma and the oldest Yellowstone volcanic field eruption age for the Huckleberry Ridge Tuff of 2.135 ± 0.006 Ma (Ellis et al., 2012) to calculate migration rates. We used the center of the caldera formed by the Huckleberry Ridge Tuff, as defined by Christensen (2001) and the center of the caldera of the first eruption of the Picabo volcanic field, the Arbon Valley Tuff, to define the distance. The center of the Arbon Valley Tuff caldera is determined by the locations and thicknesses of deposits north and south of the eastern Snake River Plain. Here we assume that the time lag between the initiation of sublithospheric heating of the lithosphere and eruptions at the surface is the same for both the Picabo and the Yellowstone volcanic fields. Using the age difference between the oldest eruptions and the distance between the centers of the respective calderas yields an extension-adjusted migration rate of 2.27 cm/yr (see Anders, 1994 for how extension is accounted for). We suggest this new calculation is a slight improvement to the estimate of velocity of 2.30 cm/yr calculated using the average age of the two Arbon Valley Tuff eruptions as presented in Anders et al. (2014). Both rates are well within the error of 0.2 cm/yr established by Anders (1994). Our migration rate results are consistent with previous estimates of North American plate velocity by Minster and Jordan (1978) and Gripp and Gordon (1990, 2002) of 2.4 cm/yr, 2.2 cm/yr, and 2.68 cm/yr, respectively. Our result of a migration rate of 2.27 cm/yr is consistent with the classical Hawaiian-type fixed plume tail model (Sleep, 1990), wherein, for the past 10 m.y., the track of silicic eruptions corresponds to a fixed mantle plume source with respect to the motion of the North American plate.

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