Using $^{40}\text{Ar}/^{39}\text{Ar}$ ages of intercalated silicic tuffs to date flood basalts: precise ages for Steens Basalt Member of the Columbia River Basalt Group

Gail A. Mahood^{*,a} and Thomas R. Benson^a

^aDepartment of Geological Sciences, Stanford University, Building 320, 450 Serra Mall, Stanford, CA 94305-2115, USA

*Corresponding author: mahood@stanford.edu

ABSTRACT

To establish causality between flood basalt eruptions and extinction events and global environmental effects recorded by isotopic excursions in marine sediments, highly accurate and precise ages for the flood basalts are required. But flood basalts are intrinsically difficult to date. We illustrate how $^{40}\text{Ar}/^{39}\text{Ar}$ feldspar ages for silicic tuffs intercalated with and overlying sections of Steens Basalt, the earliest lavas of the Middle Miocene Columbia River Basalt Group in the northwestern United States, provide high-precision ages that, for the first time, make it possible to resolve age differences with stratigraphic position within a section of these flood lavas. The stratigraphically lowest rhyolitic tuff, a fall deposit, yielded an age of 16.592 ± 0.028 Ma (FCs = 28.02), and the uppermost, the alkali rhyolite ignimbrite Tuff of Oregon Canyon, is 16.468 ± 0.014 Ma. The argon and stratigraphic data indicate that Steens Basalt eruptions occurred from ~16.64 to 16.43 Ma in the southern end of its distribution. We estimate that the Steens Mountain geomagnetic reversal occurred at 16.496 ± 0.028 Ma (± 0.18 Ma total error). Our estimates of the timing for initiation of volcanism and volumetric eruptive rates do not seem

to support volcanic forcing by the initial stages of Columbia River Basalt Group eruptions as an explanation for the abrupt warming and carbonate dissolution at the beginning of the Miocene Climatic Optimum.

HIGHLIGHTS

- Precise ages for flood basalts obtained from $^{40}\text{Ar}/^{39}\text{Ar}$ feldspar ages for intercalated silicic tuffs.
- Estimated eruptive interval of Steens Basalt is 16.64 ± 0.05 to 16.43 ± 0.03 Ma.
- Initiation of Miocene Climatic Optimum appears to precede eruption of Steens Basalt.
- Steens Mountain geomagnetic reversal occurred at 16.496 ± 0.028 Ma (± 0.18 Ma total error).

Keywords: $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, Steens Basalt, geomagnetic reversal, Miocene Climatic Optimum, flood basalts

1. Introduction

Flood basalts represent arguably the most impactful volcanism on Earth, with cumulative volumes of 10^5 - 10^6 km³ of basalt erupting within short periods of time (Bryan and Ernst, 2008). Increasingly, there is evidence that the volumes of basalt erupted and intruded during the main pulses of volcanism are large enough to result in global environmental degradation through the release of CO₂, sulfur gases, and toxic metals by exsolution from the magma and by breakdown of sulfate-, carbonate-, and coal-rich sediments by associated gabbroic intrusions (e.g., Van de Schootbrugge and Wignall (2016) and references therein). To establish causality between flood basalt eruptions and major extinction events or less dramatic global environmental effects recorded by isotopic excursions in marine sediments, such as the Miocene Climatic Optimum, highly accurate and precise ages for flood basalts (and corresponding stratotype sections) are required. Flood basalt lavas are difficult to date with accuracy and precision because zircon for

U-Pb dating is sparse or absent, and they are challenging candidates for argon dating because the plagioclase phenocrysts have low concentrations of K₂O and the groundmasses are easily altered.

Voluminous silicic volcanism is a ubiquitous component of flood basalt provinces (Bryan et al., 2002). By analyzing rhyolitic ash layers interbedded with flood basalts, it is possible to obtain ages with precisions an order of magnitude greater than those obtainable on the basalts. For example, U/Pb ages on zircon in silicic ashes intercalated with the Siberian Traps and Deccan Traps have established the synchronicity of these flood basalts with the end-Permian and end-Cretaceous biotic crises (Burgess et al., 2015; Schoene et al., 2015), and ages on silicic ashes above and below the Emeishan flood basalts implicated in the Late Guadalupian mass extinction indicate that the duration of basaltic eruptions was <1 Ma (Huang et al., 2016). In this study we demonstrate how precise and accurate ages for flood basalt lavas can be obtained by performing ⁴⁰Ar/³⁹Ar analyses of feldspar phenocrysts in intercalated silicic tuffs. We do this for the Steens Basalt, the earliest flood lavas of the Middle Miocene Columbia River Basalt Group (Fig. 1), by analyzing tuffs that are part of the ~3,900 km³ of silicic volcanic rocks spatially and temporally associated with the most voluminous outpourings of flood basalt lavas (Coble and Mahood, 2012).

2. Methods

Samples of mafic, trachytic, and alkali rhyolitic lavas and tuffs were collected during 1:100,000-scale mapping and reconnaissance studies of Middle Miocene volcanic centers along the Oregon/Nevada border (Fig. 2). We collected samples in the steep main fault scarp that bounds the eastern side of the southern Pueblo Mountains (Main Scarp section in Fig. 3), as well as in canyons cut into the dip slope (Bog Hot Springs and East Creek sections) of the 20°W-dipping range. The Rosebriar Creek, Cottonwood Creek, and Aspen Spring sections were

collected in steep canyons cut through Steens Basalt and outflow ignimbrites of the McDermitt Volcanic Field (Fig. 3).

Pumice lapilli from fall deposits and nonwelded ignimbrites and whole-rock samples of lavas and densely welded ignimbrites were analyzed by energy-dispersive XRF in order to apply compositional names and correlate tuffs from far-flung exposures. In the text and in stratigraphic columns in Fig. 3, mafic rocks of Steens Basalt proper (basalt, trachybasalt, and trachybasaltic andesite) have <2.5 wt.% K₂O; this corresponds to the ~900 ppm Ba upper bound for the most evolved of the “Upper Steens Basalt” chemical type of Camp et al. (2013). Rocks with 2.5-4.0 wt% K₂O and 2-6 wt% CaO are classified as intermediate rocks (trachyandesite and trachyte); alkali rhyolites are those with >4.0 wt% K₂O and <2 wt% CaO.

Feldspar was separated from rhyolitic and trachytic units for ⁴⁰Ar/³⁹Ar analysis in the Noble Gas Laboratory at Stanford University. Inverse isochron ages (Table 1) were calculated using an age of 28.02 Ma for Fish Canyon sanidine (Renne et al., 1998), a decay constant of 5.543⁻¹⁰a⁻¹ (Steiger and Jaeger, 1977), and an atmospheric air ⁴⁰Ar/³⁶Ar ratio of 298.56 (Lee et al., 2007). We report an *analytical error* in which random errors associated with the following parameters are propagated: zero-time peak heights, detector baseline, ion counter dead time, procedural blank and instrumental mass fractionation interpolated to the time of measurement, and ³⁹Ar normalization to calculate ratios. In order to compare our results with previously published ⁴⁰Ar/³⁹Ar ages (all recalculated to FCs = 28.02 Ma) and to calculate preferred ages as weighted mean averages of aliquots from different irradiations, we also report a *model error* that, in addition to the foregoing random errors, includes systematic errors that change for each irradiation: correction factors for K-derived nucleogenic ⁴⁰Ar and Ca-derived nucleogenic ³⁷Ar and ³⁹Ar, and fitting errors in J-factor curves. It is model dependent because it assumes an age of

28.02 Ma for Fish Canyon sanidine. In order to compare our results to U-Pb zircon ages, it is necessary to calculate a *total error* that also propagated the uncertainties for constants that apply to all $^{40}\text{Ar}/^{39}\text{Ar}$ analyses: ^{40}Ar decay constant, $^{40}\text{Ar}/^{36}\text{Ar}$ of atmospheric air, and the age of the standard used to calculate the J factor. Because this is dominated by the uncertainty in the age of the standard, the 1σ *total errors* for all samples reported here are ~0.17 Ma (0.167-0.185 Ma). In the text we report 2σ *model errors*.

Argon and XRF analytical procedures are summarized in Appendix A. Supplementary material, where we also provide the ED-XRF and $^{40}\text{Ar}/^{39}\text{Ar}$ raw data¹.

3. Regional Geology

3.1. Steens Basalt

Steens Basalt lavas cover an area of 53,000 km² in southeastern Oregon and northern Nevada (Fig. 1), and total ~31,800 km³ of mafic lavas (Camp et al. (2013). The type section is at Steens Mountain (Fig. 2), where a section of flood lavas ~1 km thick is exposed in a Basin-and-Range fault scarp that bounds the eastern side of the Steens and Pueblo Mountains (Fuller, 1931; Walker and Reppening, 1965). At the type locality the Steens Basalt has been divided into Lower Steens that is dominated by olivine tholeiite and Upper Steens that is compositionally more variable and includes transitional basalt and trachybasalt (Johnson et al., 1998; Camp et al., 2013). A capping section of thicker, platy flows originally mapped separately as “basaltic andesite” or “andesite” (Mankinen et al., 1985; Johnson et al., 1998) consists of trachybasaltic andesite lavas now considered part of the Steens Basalt (Camp et al., 2013).

¹ Supplementary material related to this article can be found on-line at <http://dx.doi.org/10.1016/j.epsl.201x.xx.xxx>.

Our study area lies ~80 km to the south, along the Oregon/Nevada border (Fig. 2), where normal faults expose thick sections of Steens Basalt overlying Mesozoic metasediments and granitoids and Oligocene to Early Miocene volcanic rocks in the central Pueblo Mountains and northern Pine Forest Range (Tower, 1972; Colgan et al., 2010). In the Trout Creek, Oregon Canyon, and southern Pueblo Mountains (Fig. 2), the base of the Steens Basalt is not exposed. As at Steens Mountain, thick, platy, Fe-rich lavas at the tops of the basalt sections were originally mapped as a separate “andesite” unit (Tower, 1972; Greene, 1976; Rytuba et al., 1983), but these trachybasaltic andesite lavas have been included in Steens Basalt proper in recent work completed in the study area (Jarboe et al., 2008, 2010, 2011; Camp et al., 2013).

3.2. Silicic tuffs intercalated in Steens Basalt sections

The occurrence of silicic pyroclastic rocks within and overlying sections of Steens Basalt near the Oregon/Nevada border has been known for some time. In the original description of the Steens Basalt, Fuller (1931) was no doubt referring to fused tuffs when he described “obsidian sills” intruding the basaltic lavas. Many of the units we have analyzed from the southernmost Pueblo Mountains--fall deposits and ignimbrite interbedded with the Steens Basalt and, above the basaltic lavas, a thick, highly brecciated rhyolitic lava and four ignimbrites--were mapped and described in early mapping studies (e.g., Rowe, 1971; Tower, 1972; Roback et al., 1987), and noted by Hart et al. (1989) in the first petrologic study of the basaltic lavas of the Pueblo Mountains, which are now considered correlative with Steens Basalt. Rowe (1971) and Tower (1972) observed that in the central Pueblo Mountains north of the study area, where the Steens Basalt section is thickest and the base is exposed, intercalated tuffs occur in the upper 2/3 of the section.

The Tuff of Oregon Canyon in sections of the Steens Basalt in the western Trout Creek

and northern Bilk Creek Mountains (Fig. 2) was a key element in detailed studies of the Steens Mountain geomagnetic reversal (Mankinen et al., 1987; Jarboe et al., 2010, 2011). Rytuba and McKee (1984) were the first to take advantage of the relatively precise K-Ar ages that could be obtained on sanidine-bearing tuffs to improve upon the low-precision ages that were then available from the Steens Basalts, suggesting an age of “about 16.1 Ma” for the flood lavas based on a K-Ar age of 16.1 ± 0.8 Ma obtained on the Tuff of Oregon Canyon. This study explores the capacity of the order-of-magnitude improvement in precision of $^{40}\text{Ar}/^{39}\text{Ar}$ ages in the subsequent 30 years to produce high-precision ages for alkali feldspar from silicic tuffs, that, when combined with an understanding of the regional stratigraphy, can further constrain the age and duration of Steens Basalt volcanism.

4. Results

We use the lithologic term “tuffs” for ash-rich deposits intercalated within and overlying sections of Steens Basalt lavas. The tuffs we dated are primary fall deposits and ignimbrites ranging in thickness from 0.3 to 12 m. We did not analyze additional tuff horizons that are volcaniclastic deposits that were reworked alluvially. The lower and upper contacts are conformable or slightly disconformable with the basalts, with the thicknesses of some flow units varying along strike due to filling topography on the surfaces of basalt lava flows (Fig. 4).

Some of the thin ash-fall tuffs were entirely fused by the heat and load of the overlying basaltic lavas, producing dense, black vitrophyres in which primary stratification and stratabound variations in grain size and phenocryst abundance are still evident (Fig. 4). Fused tuffs were found in the Cottonwood and Rosebriar Creek sections and in the Main Scarp section of the Pueblo Mountains. In some of the thicker tuffs in the Main Scarp section, the upper parts were fused, with a gradual lessening of the degree of flattening downward. Some of the tuffs show

narrow, cm-scale red, baked bands immediately below the basalt lavas (Fig. 4). The fusing and oxidation indicate that the tuffs were deposited subaerially.

Most of the intercalated tuffs we studied are probably sourced nearby, as silicic eruptions of the appropriate age occurred at four volcanic centers along the Oregon/Nevada border (Fig. 2): 16.6 to 15.4 Ma at McDermitt Volcanic Field (Henry et al., 2016; Benson et al., in revision), 16.6 to 15.7 Ma at High Rock Caldera Complex (Coble and Mahood, 2016), ca. 16.5-16.3 Ma at Hawks Valley—Lone Mountain center (Wypych et al., 2011), and ca. 16.4-15.5 Ma at Santa Rosa—Calico Volcanic Field (Brueseke et al., 2007a). Some of the tuffs we studied could be subplinian fall deposits associated with emplacement of trachytic lavas that occur sporadically within the upper part of the Steens Basalt section in the Pueblo and Trout Creek Mountains (Tower, 1972; Benson et al., in revision; this study).

4.1. Stratigraphy and $^{40}\text{Ar}/^{39}\text{Ar}$ Ages of Regionally Significant Ignimbrites

Five ignimbrites bear on the age of the Steens Basalt in the study area. The youngest three are known to have erupted from McDermitt Volcanic Field (Rytuba and McKee, 1984; Benson et al., in revision). The two oldest ignimbrites may have erupted from the nearby Hawks Valley—Lone Mountain volcanic center (H in Fig. 2), given that lavas and ignimbrites of similar age, metaluminous composition, and biotite-bearing phenocryst assemblage occur there (Wypych et al., 2011; Mahood, Benson, and Witter, unpublished data).

(1) A nonwelded trachyrhyolite ignimbrite is exposed within the Steens Basalt section in the dip slope along the western side of the southern Pueblo Mountains in the canyon of East Creek (Fig. 3). This *Tuff of East Creek* also forms the thickest (~12 m) and most conspicuous yellowish-white tuff band in the 283-m-high Main Scarp section (Fig. 4). Pumice lapilli contain ~3% small phenocrysts of feldspar > mafic phases including biotite.

We obtained an age of 16.513 ± 0.120 Ma on ignimbrite sampled in East Creek, and 16.499 ± 0.104 Ma on ignimbrite in the Main Scarp (Tuff #3). An ash-fall deposit that directly overlies it in the Main Scarp (Tuff #4 in Figs. 3, 4) has similar chemistry and mineralogy, suggesting they are from the same eruptive episode, yielded a preferred weighted mean age of 16.490 ± 0.090 Ma (Table 1).

(2) The *Tuff of Monument Basin*, which we name informally for hoodoo exposures in an eponymous basin on the dip slope of the southern Pueblo Mountains, is a nonwelded, vapor-phase-altered, cavernous-weathering, trachyrhyolite ignimbrite that lies above Steens Basalt in the southern Pueblo Mountains. Pumice lapilli in this unit are of two types: gray with 2-4% phenocrysts of feldspar > biotite, and tan with 7-10% phenocrysts of feldspar > biotite. In the Bog Hot Springs section (Figs. 2, 3) this ~10-m-thick ignimbrite is separated from the top of the basalt section by a few meters of volcanoclastic sediments and trachytic fall deposits. In East Creek it overlies a trachytic tuff overlying a trachyte lava flow that caps the Steens section.

We obtained an age of 16.479 ± 0.042 Ma for the Tuff of Monument Basin in the Bog Hot Springs section (Table 1). This age is consistent with its stratigraphic position directly beneath the 16.468 Ma Tuff of Oregon Canyon (Benson et al., in revision) at this locality.

(3) The *Tuff of Oregon Canyon* is the key unit in the stratigraphy because it occurs in most of the Steens Basalt sections we studied (Fig. 3). It is the oldest ignimbrite erupted from the McDermitt Volcanic Field (Rytuba and McKee, 1984), with a source caldera in the northern part of the field (Fig. 2) (Benson et al., in revision). Zoned from high-silica alkali rhyolite to low-silica alkali rhyolite with ~10% phenocrysts of sanidine > quartz > arfvedsonite, it is typically densely welded throughout, lithic-poor, and bluish-grey in outcrop.

The weighted mean of $^{40}\text{Ar}/^{39}\text{Ar}$ inverse-isochron ages for eight samples of the Tuff of Oregon Canyon from widespread localities is 16.468 ± 0.014 Ma (Benson et al., in revision). Jarboe et al. (2010) obtained a slightly older age of 16.548 ± 0.050 Ma based on the weighted mean of eight single-crystal sanidine total fusions (CP01 in their Table 1) for a sample collected at the top of the Catlow Peak section (Fig. 3). Resampling the locality, Benson et al. (in revision) obtained an age of 16.494 ± 0.017 Ma.

(4) The *Tuff of Trout Creek Mountains* (Rytuba and McKee, 1984) is also sourced from a caldera in the northern part of the McDermitt Volcanic Field (Fig. 2) (Benson et al., in revision). This ignimbrite is typically green or bluish-green in outcrop, densely welded, with abundant phenocrysts (15-30 vol.%) of blocky chatoyant sanidine > quartz > alkali amphibole.

The weighted mean age of 16.415 ± 0.015 Ma for seven samples (Benson et al., in revision) is consistent with its occurrence above the 16.468 Ma Tuff of Oregon Canyon and below the 16.328 Ma Tuff of Long Ridge.

(5) The *Tuff of Long Ridge* is sourced from the McDermitt Caldera in the southern part of McDermitt Volcanic Field (Rytuba and McKee, 1984; Henry et al., 2016) (Fig. 2). In the study area, the light bluish-gray to pink, alkali rhyolite outflow sheet is lithic-poor, phenocryst-poor (2-5 vol.%), and commonly rheomorphic.

The weighted mean of ages for four samples is 16.328 ± 0.022 Ma (Benson et al., in revision), consistent with it overlying the 16.415 Ma Tuff of Trout Creek Mountains widely in the Trout Creek and Oregon Canyon Mountains (Figs. 2, 3). Henry et al. (2016) report a slightly younger preferred age of 16.25 ± 0.03 Ma for the McDermitt Tuff, their proposed name for the caldera-forming unit for McDermitt Caldera.

4.2. $^{40}\text{Ar}/^{39}\text{Ar}$ Ages for Intercalated Ash Fall Deposits Older than the Tuff of Oregon Canyon

We found fused ash-fall deposits in five of the Steens Basalt sections studied. The Main Scarp section of the southernmost Pueblo Mountains contains the largest number of ashes, including the oldest dated, Tuff #1, which occurs in the lower quarter of the exposed section (Fig. 4). This 16.592 ± 0.028 Ma tuff is fused throughout its 30-cm thickness. It is alkali rhyolite, the most evolved of the ash-fall tuffs analyzed, and the only one that contains conspicuous quartz phenocrysts. Fall units intercalated successively above it yielded ages of 16.606 ± 0.034 Ma (trachytic Tuff #2 in Fig. 4 and Table 1, up to 90 cm thick), 16.490 ± 0.090 Ma (~150-cm-thick trachyrhyolitic Tuff #4, and ~275-cm-thick 16.495 ± 0.048 Ma (low-silica alkali rhyolite Tuff #5).

A low-silica alkali rhyolite ash fall intercalated within the Rosebriar Creek section (Fig. 3) is fused through its entire ~60-cm thickness. It is a chemical match for Tuff #5 in the Main Scarp section, and yielded an analytically indistinguishable age of 16.532 ± 0.046 Ma.

A 50-cm-thick, densely fused, trachyte ash fall intercalated in the Steens Basalt in the Cottonwood Creek section (Fig. 3) yielded an age of 16.475 ± 0.054 Ma. An analytically indistinguishable age of 16.474 ± 0.042 Ma was obtained on a thin, poorly exposed, nonwelded, trachytic ignimbrite that directly overlies a trachyte lava capping Steens Basalt north of the East Creek section in the southern Pueblo Mountains (Fig. 3).

5. Discussion

5.1. Significance of the Feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ Ages

Many of the dated samples were sintered to fully compacted vitrophyres collected from tuffs that had been fused by the heat and load of the overlying basalt lava flows. This setting raises the possibility of the feldspars having experienced Ar loss due to this transient heating. Whether Ar loss occurred depends upon the diffusion properties of the feldspar and the magnitude and duration of heating produced by the basalt. Samples yield calculated MSWD values (Table 1) that indicate homogeneous age distributions, and provide ages that are in correct stratigraphic order within 2σ uncertainty. Partial argon loss is unlikely to produce such systematic age data; hence, the two remaining interpretations of the data are: (1) eruption ages of phenocrysts from primary tuffs (i.e., quantitative Ar retention) or (2) ages of the overlying basaltic lavas (i.e., quantitative Ar loss, regardless of whether the alkali feldspar crystals are primary or reworked).

The magnitude of the thermal pulse experienced by a tuff overridden by a basalt flow is a function of the lava emplacement temperature, whereas the duration scales with the thickness of the lava. Steens Basalt typically consists of inflated, compound pahoehoe flows or a'a flows meters to a few tens of meters thick (Bondre and Hart, 2008; Camp et al., 2013). Modeling of the cooling of mafic lava flows (Basu et al., 2012) similar to the relevant situation (50-m-thick flow, emplacement temperature of 1140-1200°C, conductive heating of the substrate) shows that the *maximum* temperatures reached by a substrate is ~700°C at the contact, ~500°C at ~2 m depth (corresponding to the thickest fused zone observed in the study area), and falling off to ~300°C (the approximate closure temperature for alkali feldspar) at a depth of 5 m. These calculated maximum temperatures are similar to glass transition temperatures (Giordano et al., 2005), above which ash compacts rapidly, on time scales of hours (Friedman et al., 1963; Grunder et al., 2005). For example, Boyd (1961) and Friedman et al. (1963) show that dense welding in alkali

rhyolite tuffs requires temperatures of 635-685°C under a superincumbent load in the presence of water vapor. The thermal modeling shows that the substrate remains at these maximum temperatures for much less than the several years required for solidification of the basalt lavas. Indeed, such temperatures could not have been sustained long, given that the fused tuffs remain vitric and the experimental results of Lofgren (1971) show that rhyolitic glass partially devitrifies if held at 500-700°C for periods of 20-40 days.

Figure 5 shows the extent of Ar loss predicted for a 500-μm-diameter anorthoclase crystal as a function of temperature and heating duration based upon experimentally determined diffusion parameters for sample TB-124 (Table 1). Given that the heating duration must have been shorter than ~40 days for the tuffs to remain vitric, and that maximum temperatures attained in the fused zones were ~700°C, the maximum possible $^{40}\text{Ar}^*$ loss is <25%. Hence, it seems impossible that the feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ ages could have been reset by transient heating related to basalt emplacement. Instead, heating durations on the order of days most likely resulted in <10% loss of the Ar generated in the interval between eruptions of the tuff and the basalt flow and thus favor the interpretation that the reported ages are representative of the eruptive ages of the tuffs. Shortening the interval between the silicic eruption and the emplacement of the overlying basalt lava flow progressively produces a situation where the tuff will always date the basalt flow regardless of how much ^{40}Ar is lost.

5.2. *Precisions of $^{40}\text{Ar}/^{39}\text{Ar}$ Ages*

The analytical error for feldspar total-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ ages is inversely proportional to Ca/K, which in turn is determined by magma type: plagioclase with high Ca/K in trachytes, anorthoclase with low Ca/K in low-silica alkali rhyolites, and sodic sanidine with very low Ca/K in high-silica alkali rhyolites (Fig. 6). The best precision attainable would be in metaluminous

rhyolites, which contain sanidine with even lower Ca/K values. In this study, inverse isochron analysis of plagioclase yields 1σ analytical errors of 25-80 ka (see also sample CP02 in Jarboe et al., 2010), slightly better than the best results obtainable with plateau ages for Steens Basalt lavas (Jarboe et al., 2010; Baksi, 2013). Anorthoclase analyses yield errors of 10-20 ka, whereas lower Ca/K sodic sanidines yield even more precise results with 1σ errors of 6-13 ka for these Mid-Miocene grains. Pooling model ages from several co-irradiated samples of a sodic-sanidine-bearing unit can routinely yield a calculated 1σ analytical error smaller than 10 ka. At this level of precision it is possible to resolve age differences among K-poor basaltic lavas based upon sanidine ages from intercalated rhyolitic tuffs.

5.3. Age of Steens Basalt

We report 13 new precise $^{40}\text{Ar}/^{39}\text{Ar}$ analyses for six different rhyolitic to trachytic tuffs that range in age from 16.59 to 16.47 Ma (Table 1), and are intercalated with Steens Basalt lavas, indirectly providing precise ages for the Steens Basalt. These ages also appear to be accurate, based on reproducibility on multiple samples from several sections, consistency with stratigraphic position (Figs. 3, 7), and comparison to other workers' results.

We determined ages for five tuffs intercalated with Steens Basalt lavas in the Main Scarp section (Figs. 3, 7), including the oldest age determined on an intercalated tuff. There is a resolvable difference between the ages for the stratigraphically lowest and highest intercalated tuffs, 16.592 ± 0.028 Ma and 16.495 ± 0.048 Ma, respectively. During this interval of ~97 ka (21-173 ka at the 95% confidence level), 24 lavas of Steens Basalt totaling ~230 m of section were emplaced. That is equivalent to the eruption of a lava flow on average of every 4 ka, and an accumulation rate of 2.4 m ka^{-1} ($1.3 - 11 \text{ m ka}^{-1}$ at the 95% confidence level).

The base of the Steens Basalt is not exposed in our study area. We can, however, estimate when eruptions began, based on the observation of Rowe (1971) and Tower (1972) that in the central Pueblo Mountains, where the base of the section *is* exposed, the tuffs occur in the upper 2/3 of the section. The time interval between the oldest intercalated tuff (16.592 ± 0.028 Ma) and the low-silica alkali rhyolite lava that caps the Main Scarp section (16.485 ± 0.028 Ma) is ~ 107 ka (51 - 163 ka at 2σ uncertainty). Making the assumption that the lower 1/3 of the section accumulated at the same rate, this makes the base of the Steens Basalt section ~ 53 ka older than the oldest tuff, or ~ 16.64 Ma.

It is hard to know whether tuffs are absent in the lower third of the Steens Basalt section because silicic eruptions were not yet occurring nearby or because it accumulated more rapidly, making it less likely that tuffs would be intercalated. If the accumulation rate was greater at the earliest stages of volcanism, then the onset of Steens Basalt volcanism would be slightly later than the estimated 16.64 Ma; however, it can be no later than 16.56 Ma, taking into account the 2σ uncertainty on the age of Tuff #1, the oldest dated intercalated tuff.

A minimum age for the youngest Steens Basalt lavas in the study area is provided by the age of 16.415 ± 0.015 Ma for the Tuff of Trout Creek Mountains. We have not observed Steens Basalt or intermediate lavas on top of the Tuff of Trout Creek Mountains. Near Aspen Spring (Fig. 3) the tuff lies conformably on intermediate composition lavas above ~ 90 m of Steens Basalt lavas that lie above the 16.468 Ma Tuff of Oregon Canyon. Assuming that this 90 m of Steens Basalt accumulated at the same rate as calculated for the Main Scarp section, 2.4 m ka^{-1} , it took 38 ka to accumulate, making the top of the section ~ 16.43 Ma.

Based on these calculations, our best estimate for the interval of Steens Basalt volcanism in the study area, which lies at the southern end of the distribution of the Steens Basalt lavas, is

16.64 to 16.43 Ma. Taking account of the model-dependent error of the $^{40}\text{Ar}/^{39}\text{Ar}$ analyses and uncertainties that result from underlying geologic assumptions, we estimate that there is an uncertainty of about 0.05 Ma on the onset and 0.03 Ma on the cessation.

5.5. Duration of Steens Basalt Eruptions

The estimated 210-ka duration (130-290 ka taking into account uncertainties) of Steens Basalt volcanism in the study area may be a minimum estimate for the total duration of flood lava eruptions throughout its distribution if eruptions began before or persisted longer in more northerly sections. The stratigraphic relationships with tuffs and lavas indicate that Steens Basalt volcanism ceased diachronously in the study area. In the Oregon Canyon Mountains, the ignimbrite is overlain by up to ~90 m of Steens Basalt (Fig. 2; Rytuba and Curtis, 1983; Camp et al., 2013). At Catlow Peak, the Tuff of Oregon Canyon lies conformably on an intermediate lava that is conformable with the Steens Basalt section. In the southernmost Pueblo Mountains, it is separated from the Steens Basalt section by a thick, capping, low-silica alkali rhyolite lava that yielded an age of 16.485 ± 0.028 Ma (Table 1), overlain with slight disconformity by a thin section consisting of ash and pumice falls and minor volcanoclastic sediments, and by the 16.48 Ma Tuff of Monument Basin (Figs. 3, 7).

These stratigraphic relationships are determinative because, in contrast to younger members of Columbia River Basalt Group, there is no evidence for individual lavas of Steens Basalt being far-traveled. Instead, lavas were derived from local vents, given the presence of scoria falls and phreatomagmatic deposits within sections, and feeder dikes in the Pine Forest Range, Trout Creek Mountains, the southern and central Pueblo Mountains, and the Mickey Hot Springs area (Tower, 1972; Hook, 1981; Mankinen et al., 1987; Hart et al., 1989; Colgan et al., 2010; this study).

Even though our 210 ka estimate for the duration of flood basalt volcanism in the study area may be a minimum for the total duration of Steens Basalt eruptions regionally, it is considerably longer than estimates obtained from paleomagnetic studies. Jarboe et al. (2008) concluded that the upper 250 m of the Steens Basalt lavas in the Pueblo Mountains erupted in only ~2.5 ka based on secular variation behavior. Jarboe et al. (2011) calculated maximum lava accumulation rates of 85-120 m ka⁻¹ from rates of secular variation during the transition recorded in the section at Catlow Peak in the Trout Creek Mountains (Fig. 3). These are larger than the rates calculated for the type section at Steens Mountain: 20-43 m ka⁻¹, which equate to durations of Steens Basalt volcanism of 2 to 50 ka (Watkins, 1969; Mankinen et al., 1985; Jarboe et al., 2008; summarized in Camp et al., 2013). Camp et al. (2013) adopted the more conservative rate to calculate an overall time span of 47.5 ka, which equates to an effusion rate of 0.67 km³ a⁻¹ for the entire 31,800 km³ of Steens Basalt. The accumulation rate we calculate for our study area at the southern end of the Steens Basalt distribution, 2.4 m ka⁻¹, is more than an order of magnitude smaller, and the duration is more than four times longer. Estimates based on paleomagnetic secular variation can be erroneously large if there is episodicity or hiatuses in eruptions (Jarboe et al., 2011; Camp et al., 2013). The fact that lavas ceased erupting earlier in the southwest than in the northeast in the study area makes gaps in the geomagnetic record a possibility.

5.6. Implications for the Age of the Steens Mountain Geomagnetic Reversal

Jarboe et al. (2010, 2011) established that the Steens Mountain geomagnetic reversal occurred shortly before eruption of the Tuff of Oregon Canyon, based on detailed work on a ~400 m section in a canyon near Catlow Peak (Fig. 3). They measured ~182 m of reverse polarity lavas overlain by ~115 m of lavas with transitional directions, overlain by 67 m constituting ~11 lavas with normal polarity, overlain by a thick trachyandesite lava and the Tuff

of Oregon Canyon, which also have normal polarity.

Jarboe et al. (2008, 2010) measured reverse polarities on all the basalt sampled from the Pueblo Mountains (Figs. 7 and 8), and did not locate any normal polarity flows in additional reconnaissance work. Two of their measured reversed basaltic lavas occur low in the Main Scarp section. Our lowest dated tuff, Tuff #1, with an age of 16.592 Ma, occurs meters above their upper lava. The 16.495 ± 0.048 Ma age of Tuff #5, the tuff intercalated highest in that reverse-polarity section (Tuff 5 in Table 1, Figs. 3, 4, 7), is nominally older than the 16.468 ± 0.014 Ma age for the stratigraphically younger, normal-polarity Tuff of Oregon Canyon (Fig. 8), but is not statistically different.

Jarboe et al. (2008, Sample 03PMA in Table 3; 2010, PM in Table 1) reported a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 16.404 ± 0.042 Ma and a reverse polarity for the thick rhyolitic unit at the top of the Main Scarp section in the southernmost Pueblo Mountains (Figs. 3, 4, 7, 8), and suggested that it is the Tuff of Trout Creek Mountains. Based on this correlation, they assigned this flow and its age to the next reverse chron, C5Cn.2r, *above* the C5Cn.3n chron they assigned to the normally magnetized Tuff of Oregon Canyon. This sparsely porphyritic, low-silica alkali rhyolite is neither a chemical nor petrographic match for the strongly porphyritic Tuff of Trout Creek. Moreover, it is overlain by both the Tuff of Oregon Canyon and the Tuff of Trout Creek on the western dip slope of the southern Pueblo Mountains, consistent with the older age of 16.485 ± 0.028 Ma we obtained on it (Fig. 7). Hence, we suggest that this rhyolitic unit capping the Main Scarp section, which we interpret as a lava flow, belongs to the same reversed chron as the Steens Basalt lavas of the Pueblo Mountains section. Where sampled by Jarboe et al. (2008) at the southern end of the Main Scarp fault, this rhyolitic lava is silicified and shattered; we

speculate that their sample may have lost argon due to alteration, resulting in an anomalously young age.

Based on the foregoing age constraints and the small number of normal polarity flows found by Jarboe et al. (2010) beneath the Tuff of Oregon Canyon in the Catlow Peak section (Fig. 3), we conclude that the age of the Steens Mountain geomagnetic reversal is only slightly older than the age for the Tuff of Oregon Canyon, 16.468 ± 0.014 Ma. Using the calculated accumulation rate for the Main Scarp section, 2.4 m ka^{-1} , we estimate that it would have taken $\sim 28 \text{ ka}$ for the 67 m of normally polarized section below the tuff to accumulate. Taking into account uncertainties in the argon ages and geologic assumptions, this yields an estimated age for the top of the transitional section and the Steens Mountain geomagnetic reversal of 16.496 ± 0.028 Ma. This age is ~ 0.1 Ma younger than the Bayesian best estimate of $16.62 \pm 0.13 / -0.08$ Ma preferred by Jarboe et al. (2010) for the Steens Mountain geomagnetic reversal (and the end of chron C5Cr) (Fig. 8), and ~ 0.1 Ma older than the 16.41 Ma age adopted by Baksi (2013).

5.7. Implications for the Miocene Climatic Optimum

The Miocene Climatic Optimum is an interval in the Middle Miocene during which long-term Cenozoic global cooling associated with expansion of southern hemisphere glaciers was interrupted for more than 2 Ma (Savin et al., 1985). It has been proposed that sustained intense volcanic degassing by the Columbia River Basalt Group countered the cooling trend by CO_2 loading of the atmosphere (Hodell and Woodruff, 1994). Holbourn et al. (2015) present a high-resolution $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ record that reveals a rapid global warming and/or polar ice melting event at ca. 16.8 Ma that was accompanied by a massive increase in carbonate dissolution, which persisted for $\sim 80 \text{ ka}$. These authors pointed out that the existing ages for initiation of Steens

Basalt volcanism indicated that the volcanism postdated this event. Our new 16.64 Ma estimate does not substantively improve the temporal match (Fig. 9).

Even if this mismatch were attributed to an offset between orbitally tuned ages and the isotopic record, the eruption of the entire Columbia River Basalt Group can account for only a small part of the Middle Miocene 3-8°C warming relative to preindustrial values (You et al., 2009), even with a generous allowance for degassing of related intrusions and unspecified carbon-bearing host rocks (Armstrong McKay et al., 2014). Hence, this relatively small flood basalt episode is unlikely to have caused the Miocene Climatic Optimum, but the CO₂ it emitted could have helped intensify it and delay reglaciation of Antarctica (Armstrong McKay et al., 2014; Holbourn et al., 2015). The combination of the short-term cooling effects triggered by degassing of SO₂ and the formation of sulfate aerosols (Self et al., 2005) and the long-term heating effects of CO₂ emitted during eruptions superimposed onto cycles of primary productivity, silicate weathering, and carbon sequestration may account for the large-amplitude δ¹⁸O and δ¹³C variations observed during the Miocene Climatic Optimum (Holbourn et al., 2015). Interestingly, Ebinghuas et al. (2015) found no signal of the Miocene Climatic Optimum reflected in the biome composition of terrestrial flora local to the Columbia River Basalt Group eruptions; instead, the palynological record shows shifts due to rearrangement of drainage systems by the emplacement of lavas flows, and the strong effects of deposition of silicic ashes erupted from the Yellowstone/Snake River Plain trend in stalling seral succession.

6. Conclusions

The high-precision ⁴⁰Ar/³⁹Ar ages reported here for silicic units intercalated with Steens Basalt in the southern part of its distribution near the Oregon/Nevada border are within the 2σ analytical uncertainties of *all* recently published ages for Steens Basalt (Brueseke et al., 2007b;

Jarboe et al., 2008, 2010; Camp et al., 2013; Baksi, 2013), regardless of locality or stratigraphic position. This is because the greatest precision achievable for $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages on Middle Miocene flood basalts is about 0.10 Ma (Jarboe et al., 2010; Baksi, 2013), and most of the individual samples in recent studies yielded results with analytical errors significantly larger. High-precision determinations on alkali feldspar from silicic units provide $^{40}\text{Ar}/^{39}\text{Ar}$ ages with precisions an order of magnitude better than can be obtained by dating the enclosing basalts, making it possible to resolve the age differences between the bottom and top of flood lava sections. The stratigraphically lowest rhyolite intercalated in the basalts, a fall deposit, yielded an age of 16.592 ± 0.028 Ma, and the uppermost, the Tuff of Oregon Canyon, yielded 16.468 ± 0.014 Ma, requiring that Steens Basalts erupted for *at least* ~80 ka. Our best estimate for the eruptive interval in the southern part of its distribution is 16.64 ± 0.05 Ma to 16.43 ± 0.03 Ma. The resulting calculated duration of ~210 ka is considerably longer than previous estimates based on geomagnetic data. Assuming a duration of 210 ka, the resulting effusion rate of ~0.15 $\text{km}^3 \text{a}^{-1}$ is only ~10% of the estimated effusion rate of $1.3 \text{ km}^3 \text{a}^{-1}$ for the largest flood basalt province on Earth, the Siberian Traps (Renne et al., 1995), but exceeds the $0.10 \text{ km}^3 \text{a}^{-1}$ rate at Pu'u O'o, the ongoing, longest-lived, most voluminous historic eruption of Kilauea Volcano in Hawaii (Garcia et al., 2000).

Although the $^{40}\text{Ar}/^{39}\text{Ar}$ ages provided by intercalated tuffs can provide accurate ages and estimates of the overall duration that can be used to calculate overall volumetric eruption rates, the paleomagnetic record is superior for measuring the durations of packets of flows that can be demonstrated through field or petrologic studies to be closely related, and, as such, is better for calculating *instantaneous* accumulation rates and volumetric eruptive rates that bear on estimates of the short-term effects of flood basalt eruptions. The main value of $^{40}\text{Ar}/^{39}\text{Ar}$ ages on alkali

feldspar from intercalated silicic units is to provide high precision ages (± 15 ka) that, if replicated to ensure accuracy, can be “spikes” on which to hang a stratigraphic framework and provide absolute age constraints for astronomically tuned isotopic and geomagnetic chronologies. Precise ages on alkali rhyolitic units immediately preceding and postdating the Steens Mountain geomagnetic reversal tightly constrain its age to 16.496 ± 0.028 Ma (± 0.18 Ma total error).

Our estimates of volumetric eruptive rates and 16.64 Ma for the initiation of Columbia River Basalt Group volcanism do not seem to support volcanic forcing as an explanation for the abrupt warming and carbonate dissolution at the beginning of the Miocene Climatic Optimum at 16.8 Ma. Nevertheless, the combination of the long-term heating effect of CO_2 , which could have intensified the warming, and the short-term cooling effects of S gases emitted by particularly voluminous eruptive episodes could have contributed to the large-amplitude $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ variations observed in sedimentary records.

Voluminous rhyolites erupt contemporaneously with basalts in many flood basalt provinces. Rhyolitic and trachytic fall deposits and ignimbrites intercalated with flood basalts, by virtue of containing feldspar phenocrysts relatively enriched in potassium, can provide accurate and precise $^{40}\text{Ar}/^{39}\text{Ar}$ ages for these otherwise difficult-to-date lava sequences.

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FIGURE CAPTIONS

Figure 1. Location map for Middle Miocene volcanic rocks of the northwestern United States (after Benson and Mahood, 2016). The Middle Miocene Steens Basalt is the oldest member of the Columbia River Basalt Group. During the main phase of Steens and Columbia River flood basalt eruptions, 16.5 to 15 Ma, nearly 4,000 km³ of silicic magma erupted from centers spread across northern Nevada, southeastern Oregon, and western Idaho, with about 90% of the volume erupted from three caldera centers: McDermitt Volcanic Field, High Rock Caldera

Complex, and Lake Owyhee Volcanic Field. Smaller Middle Miocene silicic centers shown by yellow dots. NNR – Northern Nevada Rift. Isopleths of 0.704 and 0.706 $^{87}\text{Sr}/^{86}\text{Sr}_i$ after Benson and Mahood (2016) and references therein. [1.5 column width; color on-line and print]

Figure 2. Location map of study area and nearby Middle Miocene rhyolitic centers. The study area lies ~80 km south of the type section of Steens Basalt at Steens Mountain. Four nearby Middle Miocene rhyolitic volcanic centers erupted during the appropriate interval: McDermitt Volcanic Field, High Rock Caldera Complex, the Santa Rosa—Calico volcanic field (S), and the Hawks Valley/Lone Mountain center (H). [1 column width; B&W on-line and print]

Figure 3. Stratigraphic columns for tuff-bearing sections of Steens Basalt. The Main Scarp section is exposed in the fault scarp that bounds the eastern side of the southern Pueblo Mountains, and the Bog Hot Springs and East Creek sections are in canyons cut into the dip slope of the range. The other sections are in steep canyons cut through Steens Basalt and outflow sheets associated with calderas of the McDermitt Volcanic Field. Caldera sources for regionally important ignimbrites are outlined. Ages are from this study and Benson et al. (in revision). In Catlow Peak stratigraphic column, geomagnetic polarity data are from Jarboe et al. (2011). [2-column/full-page width; color on-line and print]

Figure 4. Photographs of tuffs intercalated with Steens Basalt in the Main Scarp section of the southern Pueblo Mountains. (A) Main Scarp section exposed in a 283-m-high normal fault scarp. Positions of dated tuffs and lavas indicated. (B) Tuff #1. Densely fused fall deposit that is baked red at the top. Vesicular Steens Basalt lava is above and below. (C) Tuff #2 drapes topography on surface of basaltic lava. Degree of fusion and compaction decreases downward from upper contact with basalt lava. (D) Tuff #3, the Tuff of East Creek is nonwelded ignimbrite overlain by fused Tuff #4. (E) Tuff #4 consists of fall deposits conformably above the Tuff of

East Creek. It is similar in composition to the Tuff of East Creek and yields an analytically indistinguishable $^{40}\text{Ar}/^{39}\text{Ar}$ age, suggesting they are related eruptive episodes. Note sharp transition from uncompacted fall at the base to fused layers above. [2-column/full-page width; color on-line and print]

Figure 5. Calculated argon loss for a 500- μm -diameter anorthoclase crystal as a function of temperature and duration of transient heating. Based on a one-domain diffusion model assuming spherical geometry, using the fractional loss expressions in McDougall and Harrison (1999), the "short-time" solution for $f \leq 0.85$ and the steady-state solution for $f > 0.85$. The Arrhenius parameters used ($E = 41185 \text{ cal mol}^{-1}$, $D_0 = 0.00197 \text{ cm}^2 \text{ s}^{-1}$) are based on step-heating experiments conducted on Sample TB-124 (Table 1). The closure temperature for these Arrhenius parameters is 311°C for a cooling rate of 10°C Ma^{-1} . Feldspar in the fused tuffs loses little ^{40}Ar because the transient heating imposed by the overlying basalt is so short relative to the million-year time scale for monotonic cooling. Thermal modeling yields a maximum temperature at the basalt-tuff interface of about 700°C , and for the fused tuffs to remain vitric and not devitrify, the thermal pulse cannot last more than 40 days; hence, $<10\%$ of $^{40}\text{Ar}^*$ in feldspar in the tuffs is likely to have been lost on being fused by an overlying basalt lava flow. [1-column width; B&W on-line and print]

Figure 6. Typical results of $^{40}\text{Ar}/^{39}\text{Ar}$ analyses for plagioclase, anorthoclase, and sodic sanidine. Analytical precision is inversely proportional to feldspar Ca/K. In this study, inverse isochron analysis of plagioclase tends to yield 1σ analytical errors of $\sim 50\text{-}80 \text{ ka}$, slightly better than the best results obtainable with plateau ages for Steens Basalt lavas. Anorthoclase inverse isochron analysis tends to yield errors of $\sim 10\text{-}30 \text{ ka}$, whereas lower Ca/K sodic sanidines yield even more precise results with errors of $\sim 6\text{-}15 \text{ ka}$ for these Mid-Miocene grains. In nearly all

cases, inverse isochron analysis yielded a $^{36}\text{Ar}/^{40}\text{Ar}$ intercept within analytical error of the atmospheric ratio, and an age within error of the weighted mean of model ages of individual grains. [2-column width; color on-line; B&W print]

Figure 7. Composite stratigraphic section for southern Pueblo Mountains section of Steens Basalt and silicic tuffs. Paleomagnetic data from Jarboe et al. (2008, 2010), who found no evidence for normal-polarity basalt flows in the Pueblo Mountains. Our best estimate of 16.496 Ma for the age of the Steens Mountain geomagnetic reversal, derived from data from the Catlow Peak section (Fig. 3), is consistent with the age of the reverse-polarity capping rhyolite lava in the southern Pueblo Mountains. Ages for ignimbrites from McDermitt Volcanic Field from Benson et al. (in revision). Error bars are 2σ model errors. [1-column width; color on-line; B&W print]

Figure 8. New estimate of age of Steens Mountain geomagnetic reversal compared to ATNTS2012 geomagnetic reversal chronology and results of Jarboe et al. (2010). New $^{40}\text{Ar}/^{39}\text{Ar}$ ages for silicic tuffs and lavas and estimates of Steens Basalt accumulation rate provide tight constraints on timing of the reversal, indicating it occurred at $16.496\pm\pm 0.028$ Ma. This is consistent with the reversal occurring after emplacement of the reverse polarity $16.485\pm\pm 0.028$ Ma capping alkali rhyolite lava and before eruption of the overlying normal polarity 16.486 ± 0.014 Tuff of Oregon Canyon (age error bars subsumed by symbols on figure). Our estimate agrees well with the weighted mean age of four transitional-polarity lavas from Catlow Peak analyzed by Jarboe et al. (2010), but not with their Bayesian preferred age for the reversal. [1-column width; color on-line; B&W print]

Figure 9. Comparison of new estimate for age of Steens Basalt to the oxygen and carbon isotopic records for Mid-Miocene Climatic Optimum of Holbourn et al. (2015). In order to

724 compare our results to the isotopic record, which is consistent with an astronomically tuned age
725 of 28.201 Ma for the FCs (Kuiper et al., 2008), we adjusted the isotopic record to be consistent
726 with our use of FCs = 28.02 Ma. Given our best estimate of 16.64 Ma for the initiation of Steens
727 Basalt eruptions, Columbia River Basalt Group volcanism appears to start too late to be an
728 explanation for the abrupt warming and carbonate dissolution at the beginning of the Miocene
729 Climatic Optimum. [1-column width; color on-line; B&W print]

ATNTS2012

(= ATNTS2004 in this time interval)

Table 1: Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ data

Irr #	Sample #	Latitude	Longitude	# grains	grain type	Ca/K	rad. Ar %	$^{40}\text{Ar}/^{36}\text{Ar}$ trapped	$^{40}\text{Ar}/^{36}\text{Ar}$ 2 σ
<i>Tuff 1 in Main Scarp</i>									
10-06B	TB-124	41.91959	-118.73362	32/32	Anor	0.42	87.8	291.1	2.9
13-36B	TB-124	41.91959	-118.73362	31/31	Anor	0.52	85.6	297.1	1.3
								Weighted Mean:	
<i>Tuff 2 in Main Scarp</i>									
10-05B	TB-125	41.92007	-118.73415	22/22	Anor	0.73	84.6	265.1	4.1
13-35B	TB-125	41.92007	-118.73415	28/31	Anor	0.72	87.3	294.7	3.4
								Weighted Mean:	
<i>Tuff 3 in Main Scarp</i>									
13-33B	TB-128A	41.92049	-118.73509	21/22	Plag	14.7	81.1	300.3	11.1
<i>Tuff 4 in Main Scarp</i>									
10-04B	TB-128B	41.92049	-118.73509	41/41	Plag	18.0	49.0	292.2	3.0
13-32B	TB-128B	41.92049	-118.73509	32/32	Plag	16.2	55.2	294.7	2.1
								Weighted Mean:	
<i>Ignimbrite in East Creek (Tuff of East Creek)</i>									
13-41B	ML-316	42.06215	-118.72105	22/22	Plag	5.94	67.2	296.7	12.5
<i>Tuff 5 in Main Scarp</i>									
10-03B	TB-129	41.92060	-118.73528	27/27	Plag	1.68	82.3	293.2	1.8
<i>Tuff in Rosebriar Creek</i>									
10-11B	TB-382	42.16815	-118.37473	21/21	Plag	4.38	63.8	297.3	3.0
13-38B	TB-382	42.16815	-118.37473	29/32	Plag	6.53	72.6	289.2	3.2
								Weighted Mean:	
<i>Alkali rhyolite lava capping Main Scarp</i>									
10-02B	TB-130	41.92076	-118.73608	18/21	San	0.07	86.0	294.1	3.7
13-27B	TB-130	41.92076	-118.73608	19/22	San	0.07	93.8	294.0	2.7
								Weighted Mean:	
<i>Tuff capping Steens Basalt section in East Creek</i>									
13-40B	TB-397	42.05724	-118.73633	18/22	Plag	1.46	93.8	290.6	8.9
<i>Tuff in Cottonwood Creek</i>									
10-07B	TB-103A	42.05181	-118.43515	21/22	San	2.83	79.5	298.9	4.5
13-37B	TB-103A	42.05181	-118.43515	27/30	San	2.99	65.5	298.5	2.8
								Weighted Mean:	
<i>Tuff of Monument Basin</i>									
12-26C	TB-101	41.95643	-118.74502	17/22	San	0.04	63.9	292.7	1.4
McDermitt Ignimbrites (Benson et al., in revision)									
<i>Tuff of Oregon Canyon</i>									
<i>Tuff of Trout Ck Mtns</i>									
<i>Tuff of Long Ridge</i>									