Single-crystal laser-probe $^{40}\text{Ar}/^{39}\text{Ar}$ dating of 133 grains of sanidine and plagioclase has enabled us to resolve the eruption ages of the Upper Basin Member rhyolites — the lava flows and related tuffs that erupted within the Yellowstone Caldera shortly after its collapse 630 ky ago on eruption of the Lava Creek Tuff. Two lavas and a tuff that erupted from the eastern ring-fracture zone yield an eruptive age of $481 \pm 8$ ka, whereas two flows from the western ring-fracture zone yield eruptive ages of $516 \pm 7$ and $198 \pm 8$ ka. Most of the units contain old xenocrysts, explaining why previous attempts at dating these earliest post-caldera units by the conventional K–Ar method yielded poorly resolved and, in some cases, anomalous ages. The tuff shows the most severe contamination. Grains from a single pumice lapilli in the tuff show as large an age range as those from bulk vitrophyre, indicating that the xenocrysts were incorporated in the magma prior to its near-surface explosive fragmentation. Diffusion calculations indicate that the xenocrysts could not have remained in the magma for more than a few years without degassing and giving ages indistinguishable from the phenocrysts. Thus, the contamination represented by the xenocrysts probably occurred during fracturing and conduit propagation, rather than during caldera collapse, which took place more than 100 ky earlier. The apparent ages of xenocrysts and their compositions as determined by electron microprobe suggest that the Eocene Absaroka volcanics are the main contaminant, with a single xenocryst probably coming from Precambrian basement rocks. Most of the xenocrysts are difficult to distinguish optically or chemically from feldspar phenocrysts, illustrating the necessity of single-crystal analysis to date many young volcanic rocks accurately.

Keywords: Snake River plain; rhyolites; absolute age; Ar-$^{40}$/Ar-$^{39}$; laser methods; magma contamination

1. Introduction

The problem of xenocrystic contamination in radiometric dating of young volcanic rocks, particularly pyroclastic rocks, is well known. In recent years, the $^{40}\text{Ar}/^{39}\text{Ar}$ technique has enabled workers to eliminate or at least minimize contamination and/or excess $^{40}\text{Ar}$ by several different methods. Step-heating has been useful in identifying the presence of excess $^{40}\text{Ar}$ (e.g. [1,2]), although interpretations of release spectra can be ambiguous. Because the $^{40}\text{Ar}/^{39}\text{Ar}$ method allows much smaller samples than conventional K–Ar and does not require complete extraction of Ar, or that a separate aliquot of sample be analyzed for K, single crystals may be analyzed. Single-crystal dating can eliminate the
problem of contamination by older xenocrysts. This technique has proven successful in overcoming problems of xenocrystic contamination in dating young pyroclastic rocks, in which small amounts of contamination can strongly affect the determined age [3–6]. Xenocrysts may be difficult to identify visually, particularly in the case of long-lived silicic volcanic systems, where younger units erupt through thick piles of compositionally and mineralogically similar material.

Although it is well known that ignimbrites and ash-fall deposits are prone to contamination, anomalously old K–Ar ages have also been obtained on post-caldera rhyolite lavas in a number of systems, including the Sierra La Primavera [7], Yellowstone [8], Long Valley [9] and the Valles caldera [10]. Recent single-crystal 40Ar/39Ar dating by Spell and Harrison [11] of the post-Valles Caldera rhyolites established a more precise chronology there and presented evidence for xenocrystic contamination.

In the Yellowstone Plateau volcanic field, contamination associated with or following caldera collapse, resulting from eruption of the Lava Creek Tuff, is particularly striking. Attempts at dating the earliest of the post-caldera units by conventional K–Ar techniques yielded poorly resolved and, in some cases, anomalously old apparent ages [8]. Isotopic ratios of these units demonstrate that caldera collapse led to major interaction of magma remaining in the chamber with crustal fluids or rocks, but no obvious xenocrysts were identified [12,13].

We used laser-fusion 40Ar/39Ar dating of individual sanidine and plagioclase grains to establish more accurate eruption ages for the post-caldera units and to identify the sources of the anomalous ages. We also conducted electron microprobe analyses on splits of feldspar grains to see if it was possible to identify feldspar populations distinct in composition from the phenocrysts as a means of determining the nature of xenocrystic contamination.

2. Geological background

The Yellowstone Plateau volcanic field, located at the apex of the eastern Snake River Plain, is an enormous center of associated rhyolitic and basaltic volcanic activity spanning the last 2.2 My [14,15]. Three main eruptive cycles at Yellowstone are each marked by the early eruption of rhyolite lavas, voluminous climactic ignimbrite eruptions, and subsequent caldera collapse and eruption of numerous rhyolite lavas and tuffs in and around each caldera (Fig. 1; [16]). The first and largest of the ignimbrites is the Huckleberry Ridge Tuff (~2500 km3); the second and smallest is the Mesa Falls Tuff (~300 km3); and the youngest is the Lava Creek Tuff (LCT; ~1000 km3). The early post-caldera lavas and tuffs associated with the eruption of the Lava Creek Tuff are the focus of this study. Collectively, these units are referred to as the Upper Basin Member of the Plateau Rhyolite [14] and represent the best-preserved and best-exposed post-caldera sequence of the three volcanic cycles. In addition, the age range of this cycle is great enough to yield amounts of 40Ar* sufficient for good analytical precision yet young enough that relatively small amounts of extraneous argon can be resolved.

The Lava Creek Tuff comprises more than 1000 km3 of non-welded to densely welded high-silica rhyolite. Thicker than 300 m in some sections, the Lava Creek Tuff consists of a basal ashfall and overlying ignimbrite. The ignimbrite consists of two members that welded as a single cooling unit; Christiansen [15,17] showed the ignimbrite to have erupted through two ring-fracture zones along which roof segments of the magma chamber initially collapsed and later underwent resurgent uplift. The most abundant phenocrysts in the Lava Creek Tuff are quartz and sanidine; plagioclase, fayalite, amphibole (in the first erupted tuff only), and clinopyroxene are present in lesser amounts. Pre-eruptive magma temperatures, based on compositions of coexisting Fe–Ti oxides, lie in the range 820–900°C [12].

Field relations suggest that eruption of all of the Upper Basin Member rhyolites post-dated initial resurgence of both structural domes (Fig. 2; [14]) but that faulting on the western dome continued or resumed long after emplacement of the early lavas. Large portions of the Upper Basin flows were buried by subsequent eruption of the much more voluminous and highly evolved Mallard Lake and Central Plateau Members of the Plateau Rhyolite.

2.1. Rhyolites of the Upper Basin Member

Two flows of the Upper Basin Member of the Plateau Rhyolite erupted from the western ring-frac-
Fig. 1. Generalized geologic map of post-Lava Creek Tuff rhyolites of the Yellowstone caldera (from [15,16]). Roman numerals indicate successive calderas: III is the Yellowstone Caldera.

Fig. 2. Schematic diagram showing stratigraphic relations and \(^{40}\)Ar/\(^{39}\)Ar and K–Ar ages for the third-cycle rhyolite units. Results of this study are in bold print; others by Obradovich [6].

Fig. 2. Schematic diagram showing stratigraphic relations and \(^{40}\)Ar/\(^{39}\)Ar and K–Ar ages for the third-cycle rhyolite units. Results of this study are in bold print; others by Obradovich [6].

The Upper Basin units are among the least evolved rhyolites in the entire volcanic field. Quartz and sanidine are much less abundant than in the Lava

6-

p!

2-

01

Ba

0.7

0.5

0.3

0.1

Age (Ma)

Fig. 3. Plot of $\delta^{18}\text{O}_{\text{w}}$ vs. age of Yellowstone units based on [12], using revised dates from this paper and from [8]. BB = Biscuit Basin flow; TSC = Tuff of Sulphur Creek; CF = Canyon flow; SCP = Scaup Lake flow.

Creek Tuff and younger members of the Plateau Rhyolite, and sanidine is absent in the Dunraven Road flow. Oligoclase is the dominant feldspar in most of the Upper Basin units except the Scaup Lake flow, which has both abundant sanidine and oligoclase. The more evolved nature of the Scaup Lake flow is supported by its calculated pre-eruptive Fe–Ti-oxide equilibration temperatures of 850–880°C, akin to the rhyolites of the Central Plateau Member, but lower than the 900–920°C obtained on the other flows of the Upper Basin Member [12].

Major and trace element chemistry [12,13] indicate that the Lava Creek Tuff and earliest Upper Basin flows tapped progressively deeper levels of a large, zoned magma chamber. Sr, Nd, Pb, and O isotopic ratios [12,13,19], however, changed dramatically between eruption of the ignimbrite and the earliest post-caldera lavas (Fig. 3), indicating interaction of the magma remaining in the chamber with rocks and/or hydrothermal fluids in the subsided cauldron block [12,13,20]. Hildreth et al. [12,13] reported that the Upper Basin flows do not have significant xenocrystic contamination, contrary to what would be expected if the magmas assimilated enough crustal material to so drastically change the isotopic composition of the magma.

Eruption of the Scaup Lake flow and the subsequent Central Plateau flows document a gradual recovery toward pre-collapse compositions. Progressive influx of new magma into the chamber, as well as eruption of the most contaminated roofward magma, may explain the change of trace element and isotopic compositions back toward more 'normal', pre-collapse values.

3. Previous geochronological work

The Huckleberry Ridge Tuff, Mesa Falls Tuff and Lava Creek Tuff were first dated at 2110 ± 8, 1270 ± 3 and 617 ± 4 ka, respectively, by Obradovich [8], using conventional K–Ar analysis of sanidine and glass. Sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 600 ± 10 and 610 ± 10 ka [21], and 660 ± 10 and 670 ± 10 ka [22] were also recently obtained for the Lava Creek Tuff. For the purposes of this paper we have used 631 ka, a simple average of all reported ages, as the age of the Lava Creek Tuff. We have no basis to evaluate whether the higher or lower ages are more accurate, and neither would change any of our results or interpretations, except to vary the time between caldera collapse and post-caldera eruptions.

The Upper Basin Member rhyolites were also dated by Obradovich [8] using conventional K–Ar analysis. The Biscuit Basin and Scaup Lake flows, exposed in the western ring-fracture zone, yielded sanidine ages of 542 ± 42 and 275 ± 11 ka, respectively. Ages obtained for the eastern post-caldera rhyolites were highly problematic. Only one plagioclase separate from the Canyon flow produced a plausible age of 613 ± 11 ka. All of the reported ages on plagioclase and glass from the Dunraven Road flow were imprecise and anomalously old. The Tuff of Sulphur Creek gave impossibly old sanidine and plagioclase ages, ranging from 0.95 to 2.9 Ma [8].

4. Methods

4.1. $^{40}\text{Ar}/^{39}\text{Ar}$ analyses

We analyzed samples collected by R.L. Christiansen and W. Hildreth from the five earliest post-caldera rhyolite units. For the Tuff of Sulphur Creek, samples of both whole-rock welded tuff and a single large pumice block were used; the other samples were glassy lavas. Samples were carefully crushed using mortar and pestle or a small jaw crusher, and
the mafic minerals were removed by a Frantz magnetic separator. Sanidine and plagioclase grains were carefully hand picked from the separates to avoid grains containing any visible glass or mineral inclusions. Grains with adhering glass were cleaned in 5% HF for 5–10 min, prior to cleaning in acetone and distilled water in an ultrasonic cleaner, each for 10 min. Samples were packed into quartz glass tubes with a sanidine monitor (27.92 Ma Taylor Creek Rhyolite, sample 85G003 of [23]) and irradiated for 45 min at the Oregon State University TRIGA Reactor in the CLICIT (cadmium-lined) facility.

Samples were analyzed at Stanford University using a Spectra-Physics 2016 continuous argon-ion laser with a maximum output power in multi-line mode of 6.0 W. Each grain was fused individually using degassed basalt flux to aid fusion. The extracted gas was purified using SAES Zr–Al getters and released into a Mass Analyzer Products 216 model mass spectrometer with Baur Signer ion source and an electron multiplier. The laser extraction line blank was measured every fourth or fifth run. Typical background values for the extraction line were around $1.5 \times 10^{-18}$ mol $^{36}$Ar and $1-2 \times 10^{-16}$ mol $^{40}$Ar. Mass discrimination in the spectrometer was monitored by measuring purified air several times each day, yielding an average $^{40}$Ar/$^{36}$Ar ratio of 292.1 ± 1.5 over the time the samples were run.

Raw data were reduced and statistically analyzed by the computer program ‘EyeSoreCon’ (or ‘ESC’) written by Brad Hacker. Decay constants used were after Steiger and Jäger [24]. Errors are reported at 1σ. Isochrons were regressed according to the least squares method described by York [26]. A goodness of fit parameter, the mean square weighted deviation (MSWD), was used to evaluate the sources of scatter in the data. A MSWD value that exceeds the critical value $(1 + 2/(n - 2))^{1/2}$ for $n$ points, e.g. [27]) indicates a greater than 95% probability that the scatter cannot be explained by analytical error alone. In these cases there must be some geologic reason for the observed heterogeneity.

4.2. Electron microprobe analyses

Splits of the feldspar separates used for $^{40}$Ar/$^{39}$Ar dating were mounted in Crystal Bond epoxy on glass slides and polished. Chemical compositions were determined using the JEOL 733 electron microprobe in the Center for Materials Research at Stanford University. The operating conditions were 20 s peak counting times, 15 kV accelerating voltage, 15 nA beam current and a beam diameter of 10 μm. Data reduction was done using the CITZAF matrix correction program. Natural silicate minerals and a NBS glass were used as standards: orthoclase (K), albite (Si, Al), jadeite (Na), wollastonite (Ca), hematite (Fe) and NBS ‘W’ glass (Ba). Standards were analyzed at the beginning, middle and end of the run sessions to correct for machine drift. Measurements were made on cores and rims of many grains. Analytical errors are ±1–5% for major elements and ±10–50% for Ba.

5. $^{40}$Ar/$^{39}$Ar results

$^{40}$Ar/$^{39}$Ar total-fusion ages were determined on a total of 133 individual sanidine and plagioclase grains from six samples of rhyolite from the Upper Basin Member (Table 1). Contaminating xenocrysts significantly older than the underlying Lava Creek Tuff (i.e., greater than two standard deviations from the mean age: 631 ± 62 ka) are readily identifiable and can be eliminated from calculating the ages of the units. Detecting more subtle contamination, presumably from incompletely outgassed xenocrysts, is a trickier problem.

In young, thermally unperturbed volcanic rocks such as these, argon loss is far less likely than inherited or excess $^{40}$Ar, particularly given the abundance of much older xenocrysts apparent from the data. Thus, we feel it is geologically justified to analyze the data so as to counteract statistically the natural bias toward higher ages. We have used an approach suggested by C. Hall (personal communication, 1996) and similar to that recently used by Bogaard [6]. The data are ordered with increasing apparent age, and a running weighted average and MSWD is calculated (Table 1, Fig. 4). If the scatter in ages is due only to analytical precision, the MSWD should approach 1. For most of these units, the total weighted average age results in a high MSWD, indicating that there is geologic scatter in the data. Our preferred eruptive age is taken where the MSWD
Table 1

$^{39}$Ar/ $^{39}$Ar analytical data, sorted with increasing apparent age

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Age (Ma)</th>
<th>Running wtd average (Ma) ± 1σ</th>
<th>Mineral</th>
<th>Age (Ma)</th>
<th>Running wtd average (Ma) ± 1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biscuit Basin Flow (81YH-90)</td>
<td></td>
<td></td>
<td>Tuff of Sulphur Creek, vitrophyre (9YCY-491A and B)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p</td>
<td>0.428 ± 0.053</td>
<td>0.428 ± 0.053</td>
<td>s</td>
<td>0.442 ± 0.023</td>
<td>0.442 ± 0.023</td>
</tr>
<tr>
<td>p</td>
<td>0.487 ± 0.166</td>
<td>0.434 ± 0.051</td>
<td>s</td>
<td>0.450 ± 0.018</td>
<td>0.447 ± 0.014</td>
</tr>
<tr>
<td>s</td>
<td>0.483 ± 0.019</td>
<td>0.477 ± 0.018</td>
<td>s</td>
<td>0.480 ± 0.028</td>
<td>0.454 ± 0.013</td>
</tr>
<tr>
<td>s</td>
<td>0.509 ± 0.026</td>
<td>0.487 ± 0.015</td>
<td>s</td>
<td>0.482 ± 0.042</td>
<td>0.456 ± 0.012</td>
</tr>
<tr>
<td>s</td>
<td>0.511 ± 0.037</td>
<td>0.490 ± 0.014</td>
<td>s</td>
<td>0.483 ± 0.042</td>
<td>0.458 ± 0.012</td>
</tr>
<tr>
<td>s</td>
<td>0.512 ± 0.023</td>
<td>0.496 ± 0.012</td>
<td>s</td>
<td>0.484 ± 0.046</td>
<td>0.460 ± 0.011</td>
</tr>
<tr>
<td>s</td>
<td>0.512 ± 0.014</td>
<td>0.503 ± 0.009</td>
<td>s</td>
<td>0.485 ± 0.026</td>
<td>0.464 ± 0.010</td>
</tr>
<tr>
<td>s</td>
<td>0.516 ± 0.014</td>
<td>0.507 ± 0.008</td>
<td>p</td>
<td>0.523 ± 0.221</td>
<td>0.464 ± 0.010</td>
</tr>
<tr>
<td>s</td>
<td>0.533 ± 0.026</td>
<td>0.511 ± 0.008</td>
<td>s</td>
<td>0.524 ± 0.018</td>
<td>0.479 ± 0.011</td>
</tr>
<tr>
<td>s</td>
<td>0.544 ± 0.017</td>
<td>0.516 ± 0.007</td>
<td>s</td>
<td>0.533 ± 0.014</td>
<td>0.495 ± 0.012</td>
</tr>
<tr>
<td>s</td>
<td>0.549 ± 0.013</td>
<td>0.522 ± 0.007</td>
<td>p</td>
<td>0.548 ± 0.106</td>
<td>0.495 ± 0.011</td>
</tr>
<tr>
<td>s</td>
<td>0.553 ± 0.016</td>
<td>0.526 ± 0.007</td>
<td>s</td>
<td>0.550 ± 0.015</td>
<td>0.506 ± 0.012</td>
</tr>
<tr>
<td>s</td>
<td>0.561 ± 0.019</td>
<td>0.528 ± 0.007</td>
<td>s</td>
<td>0.560 ± 0.039</td>
<td>0.508 ± 0.011</td>
</tr>
<tr>
<td>p</td>
<td>0.568 ± 0.033</td>
<td>0.529 ± 0.007</td>
<td>s</td>
<td>0.564 ± 0.049</td>
<td>0.509 ± 0.011</td>
</tr>
<tr>
<td>s</td>
<td>0.570 ± 0.019</td>
<td>0.532 ± 0.007</td>
<td>s</td>
<td>0.603 ± 0.034</td>
<td>0.512 ± 0.011</td>
</tr>
<tr>
<td>s</td>
<td>0.573 ± 0.032</td>
<td>0.533 ± 0.007</td>
<td>s</td>
<td>0.606 ± 0.023</td>
<td>0.519 ± 0.012</td>
</tr>
<tr>
<td>s</td>
<td>0.575 ± 0.016</td>
<td>0.537 ± 0.007</td>
<td>s</td>
<td>0.632 ± 0.156</td>
<td>0.519 ± 0.012</td>
</tr>
<tr>
<td>s</td>
<td>0.577 ± 0.018</td>
<td>0.539 ± 0.007</td>
<td>Best wtd. ave. (n = 9, MSWD = 1.44): 0.479 ± 0.010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>0.580 ± 0.015</td>
<td>0.543 ± 0.007</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>0.587 ± 0.015</td>
<td>0.546 ± 0.007</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Best wtd. ave. (n = 10, MSWD = 1.09): 0.516 ± 0.007

Canyon Flow (81Y-225)

| p | 0.330 ± 0.073 | 0.330 ± 0.073 |
| p | 0.466 ± 0.354 | 0.336 ± 0.032 |
| s | 0.434 ± 0.036 | 0.414 ± 0.032 |
| s | 0.490 ± 0.038 | 0.446 ± 0.028 |
| s | 0.499 ± 0.016 | 0.483 ± 0.018 |
| p | 0.507 ± 0.393 | 0.483 ± 0.016 |
| p | 0.540 ± 0.180 | 0.484 ± 0.015 |
| s | 0.550 ± 0.035 | 0.493 ± 0.014 |
| s | 0.550 ± 0.025 | 0.504 ± 0.015 |
| s | 0.561 ± 0.052 | 0.507 ± 0.015 |
| s | 0.573 ± 0.044 | 0.510 ± 0.014 |
| s | 0.581 ± 0.039 | 0.515 ± 0.014 |
| p | 0.582 ± 0.219 | 0.515 ± 0.014 |
| p | 0.605 ± 0.286 | 0.515 ± 0.013 |
| p | 0.652 ± 0.244 | 0.516 ± 0.013 |

Best wtd. ave. (n = 7, MSWD = 1.23): 0.484 ± 0.015

Tuff of Sulphur Creek, pumice block (9YCY-492B)

| s | 0.400 ± 0.069 | 0.400 ± 0.069 |
| s | 0.404 ± 0.036 | 0.403 ± 0.032 |
| s | 0.420 ± 0.039 | 0.410 ± 0.025 |
| p | 0.431 ± 0.139 | 0.411 ± 0.020 |
| p | 0.431 ± 0.033 | 0.418 ± 0.020 |
| p | 0.570 ± 0.240 | 0.419 ± 0.020 |
| s | 0.591 ± 0.051 | 0.441 ± 0.024 |
| s | 0.620 ± 0.030 | 0.489 ± 0.036 |
| p | 0.637 ± 0.109 | 0.492 ± 0.034 |
| p | 0.657 ± 0.153 | 0.494 ± 0.032 |

Best wtd. ave. (n = 7, MSWD = 1.79): 0.441 ± 0.024

Best wtd. ave. (n = 12, MSWD = 0.06): 0.486 ± 0.042

Scaup Lake Flow (78YH-69)

Dunraven Road Flow (78YH-48)
5.1. Eruption ages of Upper Basin flows

Among the analyzed grains from the western ring-fracture zone, only one obvious xenocryst, with an apparent age of 2.8 Ma, was found, in the Scaup Lake flow. Applying the technique described above, however, the data show that many of the grains from both the Biscuit Basin and Scaup Lake flows and have some inherited $^{40}$Ar, accounting for the difference between the K–Ar ages of Obradovich [8] and the results of this study. For the Biscuit Basin flow, we obtained a preferred eruption age of 516 ± 7 ka (MSWD = 1.09) versus a maximum average age of 546 ± 7 ka (MSWD = 2.89). The isochron age of 519 ± 10 ka agrees very well with the preferred average age. The Scaup Lake flow yielded a significantly younger preferred eruption age of 198 ± 8 ka (MSWD = 1.78) and an isochron age of 201 ± 13 ka. Even the maximum average age for this flow, 241 ± 8 ka (MSWD = 7.37), is lower than the published K–Ar age, suggesting that this cryptic contamination may be more significant than previously suspected.

The eastern ring-fracture units were more heavily contaminated, and thus we were able to improve their ages greatly with single-crystal dating. We obtained preferred average eruption ages of 441 ± 24 ka (MSWD = 1.79) and 479 ± 10 ka (MSWD = 1.44) on the Tuff of Sulphur Creek pumice and vitrophyre samples, respectively. Their isochron ages are the same within 1σ error. Several young ages from the Tuff of Sulphur Creek pumice (Table 1; Fig. 6) may reflect the loss of some radiogenic argon during contact with meteoric or hydrothermal water percolating through the permeable pumice, explaining why the vitrophyre gives ages more consistent with (i.e., not younger than) the units above it. Many of the older grains from this unit have a very large atmospheric argon component, which may also be due to water infiltration. Therefore, we use the preferred age of the vitrophyre, 479 ± 10 ka, as the best eruption age for the unit.
**Western Units**

- **Scaup Lake flow**
  - \( \frac{^{40}Ar}{^{36}Ar} = 294.5 \pm 3.1 \)
  - Age = 201 ± 13 ka
  - MSWD = 2.24 (< 2.41)

- **Biscuit Basin flow**
  - \( \frac{^{40}Ar}{^{36}Ar} = 297.1 \pm 10.4 \)
  - Age = 519 ± 10 ka
  - MSWD = 1.53 (< 1.94)

**Eastern Units**

- **Dunraven Road flow**
  - \( \frac{^{40}Ar}{^{39}Ar} = 297.8 \pm 31.8 \)
  - Age = 477 ± 146 ka
  - MSWD = 0.06 (< 1.89)

- **Canyon flow**
  - \( \frac{^{40}Ar}{^{39}Ar} = 299.3 \pm 1.8 \)
  - Age = 482 ± 15 ka
  - MSWD = 1.02 (< 1.94)

- **Tuff of Sulphur Creek-vitrophyre**
  - \( \frac{^{40}Ar}{^{39}Ar} = 291.7 \pm 5.3 \)
  - Age = 477 ± 22 ka
  - MSWD = 0.48 (< 2.07)

- **Tuff of Sulphur Creek-pumice**
  - \( \frac{^{40}Ar}{^{39}Ar} = 297.1 \pm 0.8 \)
  - Age = 438 ± 24 ka
  - MSWD = 1.74 (< 2.15)
The Canyon flow yielded a preferred average age of \(484 \pm 15\) ka (MSWD = 1.23) and isochron age of \(482 \pm 15\) ka, nearly identical to that of the Tuff of Sulphur Creek, giving support to the assertion that they may have been the explosive and effusive phases of the same eruption [12,14]. The overlying Dunraven Road flow gave a much less precise age of \(486 \pm 42\) ka (MSWD = 0.06), which was determined only from analysis of plagioclase grains, due to the absence of sanidine in this flow. It is, within analytical error, indistinguishable from the two underlying flows. Fitting an isochron to the data for the Dunraven Road flow (477 ± 146 ka) creates a particular problem because of clustering of points with large errors. In cases such as this, the isochron method is not the most appropriate means of analyzing the data, and the weighted average must be relied upon.

All three of the eastern post-caldera units had yielded conventional K–Ar ages older than or indistinguishable from the Lava Creek Tuff and, as a result, had previously been thought to have erupted very soon after caldera collapse [12]. It now appears that all three were erupted around 480 ka, about 150 ky after the eruption of the Lava Creek Tuff.

5.2. Anomalous ages from xenocrysts

Single-crystal \(^{40}\text{Ar}/^{39}\text{Ar}\) dating of the eastern ring-fracture units reveals severe xenocrystic contamination in two of the units, explaining why reasonable conventional K–Ar ages were difficult or impossible to obtain. There is a wide range in the apparent ages of unambiguously xenocrystic grains (Figs. 6 and 7), from 0.7 Ma to 370 Ma. Most are plagioclase, but xenocrystic K-feldspar is present as well. There is no obvious clustering of dates that could indicate a direct source, other than a group of five large sanidine grains from the Tuff of Sulphur Creek pumice block, which gave ages between 1.2 and 1.6 Ma. Most of the anomalous ages are younger than 10 Ma; only five are older. Partial degassing in the magma has probably affected many or all of these xenocrysts.

As might be expected, the most explosively emplaced unit, the Tuff of Sulphur Creek, shows the most xenocrystic contamination. There is no significant difference, however, between the age distributions of grains from a sample of agglutinated vitrophyre and grains from a block of pumice (Fig. 7). If anything, the oldest ages were obtained from the pumice. This may be a function of small sampling size or, possibly, of continued feldspar degassing during the slower cooling of the vitrophyre. The fact that all the larger (> 0.1 cm) plagioclase grains in the vitrophyre and all the larger sanidine and plagioclase grains in the pumice give anomalously old ages supports this hypothesis. In any case, the occurrence of xenocrysts in pumice lapilli indicates that they were incorporated in the magma before vesiculation and explosive disruption of the magma and, therefore, were not simply incorporated in the vent during eruption.

The wider distributions of ages from the Tuff of Sulphur Creek than from the Canyon flow suggest several possibilities. A straightforward interpretation of the distributions is that explosive eruptions incorporate more material from their conduits than effusive eruptions. It is also possible that xenocryst incorporation occurs mostly during dike propagation and vent opening (but still before explosive disruption of the magma) and that there is less contamination as the eruption proceeds. The lesser contamination of the Canyon flow could also be apparent, as the thick lava flow may have taken longer to cool than the fallout deposit, resulting in more thorough post-eruptive outgassing of xenocrysts.

5.3. Degassing of xenocrysts

The extent to which contaminating grains might have degassed in the magma prior to eruption is impossible to determine from their total-fusion ages. We can, however, calculate degassing times for xenocrystic feldspars in magma (Fig. 8) by assuming that simple bulk-volume diffusion is the rate-controlling process and assuming spherical diffusion [28] and its solutions described in Lee [29]. For our calculations, we assumed a temperature of 900°C.
Western Units

Scaup Lake Flow

- Weighted average ± 2σ: 198 ± 16 ka
- Age (ka): 2824

Biscuit Basin Flow

- Weighted average ± 2σ: 516 ± 14 ka

Eastern Units

Dunraven Road Flow

- Weighted average ± 2σ: 486 ± 84 ka

Canyon Flow

- Weighted average ± 2σ: 484 ± 30 ka

Tuff of Sulphur Creek

(best dates only)

- Weighted average ± 2σ: 479 ± 20 ka

Whole-Rock Vitrophyre

- Age (ka): 24960 ka
- Age (ka): 1856 ka
Tuff of Sulphur Creek: Whole-Rock Vitrophyre

Weighted average ± 2σ
479 ± 20 ka

Tuff of Sulphur Creek: Single Pumice Block

Weighted average ± 2σ
441 ± 48 ka

Fig. 7. Comparison of distributions of $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages from a single pumice block and whole-rock vitrophyre from the Tuff of Sulphur Creek.

Fig. 6. Distributions of $^{40}\text{Ar}/^{39}\text{Ar}$ apparent ages from the rhyolites of the Upper Basin Member displaying preferred weighted averages of each unit and their relations to the age of the Lava Creek Tuff. Error bars on individual data points are ±1σ. For the Tuff of Sulphur Creek only geologically reasonable ages are plotted; the full data are given in Fig. 7.
(based on Fe-Ti-oxide temperatures of 880–920°C for the Upper Basin units [12]), a diffusion radius (here assumed equal to grain radius) of 0.05 cm, and a diffusion coefficient of $5 \times 10^{-11}$ cm$^2$/sec and activation energy of 45 kcal/mol, based on experimentally derived values for sanidine [30,31]. Diffusion coefficients for $^{40}$Ar in plagioclase have not been established experimentally, so the degassing times calculated here will probably be maxima, as structural inhomogeneities in plagioclase would tend to enhance diffusion by creating smaller effective diffusion radii [32,33]. The calculations (Fig. 8) show that, after only several years in the magma, even xenocrysts 1000 my old would produce ages indistinguishable from magmatic phenocrysts. Thus, the grains showing anomalous ages probably had not been in the magma for more than a few months prior to eruption.

6. Feldspar chemistry

We undertook electron microprobe analyses of splits of the feldspar separates to determine whether distinct populations of xenocrysts could be identified and, if so, to use the compositions to suggest potential sources. None of the feldspars analyzed show obvious microscopic exsolution, although some sanidine grains from the Lava Creek Tuff appear chatoyant in hand specimen. Previous work establishing the range of feldspar compositions in the combined Upper Basin units and the Lava Creek Tuff [12] is in close agreement with our results and is shown for comparison in Figs. 9 and 10. We did not detect xenocrysts while hand picking the grains, and it is even difficult to distinguish xenocrysts chemically from true phenocrysts.

Feldspar compositions from the western ring-fracture units and the Dunraven Road flow (Fig. 9) are tightly clustered and show little or no variation between core and rim compositions of individual grains. The analyzed sample of the Biscuit Basin flow contains only sodic sanidine, whereas the Scape Lake flow has more K-rich sanidine coexisting with An$_{24}$ plagioclase. The sanidine in both units is rich in Ba, containing around 2% celsian component. The Dunraven Road flow contains only oligoclase of a limited compositional range.

The units with the largest proportions of anomalous ages, the Tuff of Sulphur Creek and the Canyon flow, also have the widest range of feldspar compositions (Fig. 9). The Tuff of Sulphur Creek contains plagioclase that ranges up to the most calcic compositions (An$_{48}$) observed in the rhyolites of the Upper Basin Member. Three sanidine grains have cores of apparently plutonic K-feldspar. The Canyon flow feldspars are less heterogeneous than those from the Tuff of Sulphur Creek, but still show a wider spread than the other units. All sanidine grains from these two units have high Ba contents (2–4% celsian component), with the exception of the three outlying very high-K core analyses, which have negligible Ba, although their corresponding rims have Ba contents similar to the other sanidine analyses.

The most calcic plagioclase compositions observed in the Tuff of Sulphur Creek and the Canyon flow would not be expected in rhyolites, particularly high-silica rhyolites such as most of these units. The isothermal solvi and tie lines of coexisting feldspars, as predicted by the model of Fuhrman and Lindsley [34], shown in Figs. 9 and 10, indicate that only plagioclase less calcic than An$_{30}$ is likely to be in equilibrium with the sanidine compositions obtained from the Yellowstone rhyolites. Thus a significant proportion of the plagioclase grains from the Tuff of Sulphur Creek appear to be xenocrystic.

Feldspar compositions from the Upper Basin units do not significantly overlap compositions of feldspars.
Fig. 9. Electron microprobe analyses of feldspars from the western and eastern rhyolite flows of the Upper Basin Member. Pairs of core–rim analyses showed no significant differences except for the Tuff of Sulphur Creek (pumice block and vitrophyre shown together), for which core compositions are shown in gray. The solid outlined areas show the combined data of Hildreth et al. [12] on all Upper Basin feldspars. Dashed lines are the isothermal solvi and tie-lines of coexisting feldspars at 900°C, 0.5 kbar and 825°C, 1 kbar from Fuhrman and Lindsley [34].
from the Lava Creek Tuff. Plagioclase and sanidine from the Lava Creek Tuff have a lower An content than Upper Basin feldspars (Fig. 10), reflecting the lower temperatures and higher H₂O concentrations of the Lava Creek magma. Lava Creek Tuff sanidine grains also have negligible Ba concentrations, easily distinguishing them from Upper Basin sanidine. There is, therefore, no evidence that either sanidine or plagioclase xenocrysts were incorporated from intracaldera Lava Creek Tuff.

7. Potential sources of contamination

It is possible to constrain the potential sources of contamination in these rocks, although the data do not allow a unique provenance determination for individual contaminating xenocrysts. The microprobe data enable us to identify xenocrysts of apparently plutonic K-feldspar, as well as intermediate plagioclase most likely of volcanic origin. In addition, the ⁴⁰Ar/³⁹Ar dating puts some limits on the ages of the units that may be contributing xenocrysts.

The microprobe data of Hildreth et al. [12] show no overlap between compositions of Upper Basin Member and Lava Creek Tuff pyroxenes, supporting this conclusion.

The Absaroka volcanic field, beneath the eastern portion of the caldera, is probably the source for most of the old plagioclase grains. The more calcic plagioclase compositions in the Tuff of Sulphur Creek (Fig. 9) would be consistent with feldspars from

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Fig. 10. Electron microprobe analyses of feldspars from the Lava Creek Tuff. Dashed lines as in Fig. 7. The solid outlined areas show the combined data of Hildreth et al. [12] on feldspars from the Lava Creek Tuff.
dacitic to andesitic magma, such as are found in the Absaroka volcanic rocks. The eastern ring-fracture units have vents within a kilometer or two of the caldera wall and are adjacent to exposures of andesitic Absaroka rocks, whereas the western units erupted closer to the center of the caldera [18]. This may explain why xenocrystic plagioclase is found only in the eastern units. The oldest xenocryst age (~370 Ma) is most likely derived from partially degassed Precambrian basement rocks.

The inherited $^{40}$Ar identified in the western units may not be of a strictly xenocrystic origin. The

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**Fig. 11.** Simplified map of the regional geology exposed around the Yellowstone Plateau volcanic field (from [13]). Outline of Yellowstone National Park shown for reference.
tightly clustered sanidine compositions instead suggest that these lavas may have reincorporated crystals that were formed, separated and cooled earlier in the history of the same magma body. Thus, it is possible that the maximum ages calculated for these units may represent a minimum age of the magma batches themselves. This subtle self-contamination is more difficult to distinguish in the eastern units due to the overwhelming presence of xenocrysts.

8. Conclusions

Laser-probe dating of single crystals has enabled us to refine the timing of events following the eruption of the 630 ka Lava Creek Tuff and to begin to identify the major contaminants present in the post-caldera rhyolites. Our results indicate that timescales of recovery of this large, integrated magmatic system following a catastrophic eruption, involving mixing with new magma batches and continued differentiation, may be on the order of a few hundred thousand years. The drastic $^{18}$O depletion that is recorded in the Upper Basin units [12] is greatest in the oldest unit, the Biscuit Basin flow. The available data do not allow us to determine whether the $^{18}$O depletion was a sudden event or whether it took place over the full 100 ky between eruption of the Lava Creek Tuff and the Biscuit Basin flow. If any older post-caldera lavas exist, they have been buried by younger flows. By the time the eastern units erupted, ~50 ky later, there had been partial recovery toward normal ratios, and, 300 ky later, the Scaup Lake flow erupted with an $^{18}$O ratio similar to the youngest flows of the Plateau Rhyolite [12].

The scarcity of xenocrystic ages and tightly clustered feldspar compositions indicate that western ring-fracture units had little interaction with older crustal rocks immediately before and during eruption, despite having erupted through thick intra-caldera fill. The isotopic signature of crustal interaction documented by Hildreth et al. [12], therefore, must have been acquired long before eruption. The location of the vents for the eastern ring-fracture rhyolites close to the caldera rim, where brecciated and faulted country rock are exposed, may be responsible for the greater degree of xenocrystic contamination present in these units. In the eastern ring-fracture zone rhyolites we can document contamination from the Eocene Absaroka volcanic rocks as well as from old basement gneiss.

Diffusion calculations give a maximum for residence time of xenocrysts in magma of several years, whereas the presence of xenocrysts in a single pumice block gives a minimum time of incorporation (i.e., before explosive disruption). These limits indicate that the xenocrysts we detected by $^{40}$Ar/$^{39}$Ar dating are most likely not related to the contamination documented, via Sr, Nd, and O isotope data, to have occurred during or immediately following caldera collapse. What this study does make clear, however, is that crustal contamination in long-lived silicic caldera systems can be extremely difficult to detect and that $^{40}$Ar/$^{39}$Ar single-crystal dating, combined with careful assessment of the apparent ages, is necessary to obtain accurate ages on some young lavas, as well as on pyroclastic rocks.

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