Episodic fluid flow in an active fault

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ABSTRACT

We present a reconstruction of episodic fluid flow over the past ~250 k.y. along the Malpais normal fault, which hosts the Beowawe hydrothermal system (Nevada, USA), using a novel combination of the apatite (U-Th)/He (AHe) thermochronometer and a model of the thermal effects of fluid flow. Samples show partial resetting of the AHe thermochronometer in a 40-m-wide zone around the fault. Numerical models using current fluid temperatures and discharge rates indicate that fluid flow events lasting 2 k.y. or more lead to fully reset samples. Episodic fluid pulses lasting 1 k.y. in result partially reset samples, with 30–40 individual fluid pulses required to match the data. Episodic fluid flow is also supported by an overturned geothermal gradient in a borehole that crosses the fault, and by breaks in stable isotope trends in hydrothermal sinter deposits that coincide with two independently dated earthquakes in the past 20 k.y. This suggests a system where fluid flow is triggered by repeated seismic activity, and that seals itself over ~1 k.y. due to the formation of clays and silicates in the fault damage zone. Hydrothermal activity is younger than the 6–10 Ma age of the fault, which means that deep (~5 km) fluid flow was initiated only after a large part of the 230 m of fault offset had taken place.

INTRODUCTION

Fault-hosted transient fluid flow and hydrothermal activity play an important role in a wide range of geologic processes, including metasomatism (Weis et al., 2012), oil migration (Boles et al., 2004), fault mechanics, and metamorphism (Magee and Zoback, 1993). The time scale of fluid flow is important because the longer fluid flow is active, the more it changes subsurface temperatures and alters the rock matrix. Long-term changes in fluid flow and permeability in fault zones are driven by the competition between mineral precipitation (Lowell et al., 1993) and the creation of new flow paths by fault movement and the creation of connected fractures in fault damage zones (Sibson, 1981; Eichhubl et al., 2009). While field evidence of hydrothermal minerals precipitating in faults is common (Fisher et al., 2003; Eichhubl et al., 2009), the time scale at which new flow paths are opened by fault activity and closed by cementation is largely unknown (Woodcock et al., 2007). Data on changes in permeability or the duration of fluid flow in faults are rare, especially over geological time scales (104–107 yr) (Ingebritsen and Gleeson, 2017).

Determining the duration of fluid flow in hydrothermal systems is often difficult because not all hydrothermal systems generate mineral deposits that can be dated, and because the uncertainty in dating hydrothermal minerals may exceed the duration of short hydrothermal events (Skinner, 1997). Several studies of fossil hydrothermal systems have demonstrated that low-temperature thermochronology offers new opportunities to date fluid flow by quantifying the thermal history of rocks in or adjacent to fluid conduits (Luijendijk, 2012; Gorynski et al., 2014; Hickey et al., 2014).

Here, we present a new approach to quantify the history of fluid flow in the active Beowawe hydrothermal system in the Basin and Range province (Nevada, United States), based on a combination of low-temperature thermochronology at high spatial resolution with a new model of conductive and advective heat flow (Luijendijk, 2019) that allows testing different hypotheses on the history of hydrothermal activity. Previous work suggests that fluid flow in the Beowawe system may have been episodic. Variations in trace elements in sinter and salinities in fluid inclusions indicate changes in fluid sources over time (Leatherman, 2010). 14C ages and stable isotope data of hydrothermal sinter deposits show a change from a light to heavy δ18O signature that coincides with an independently dated earthquake along the Malpais fault at 7500 yr B.P. (Howard et al., 2015). The most likely explanation is that the earthquake led to an increase in permeability, the opening of new flow paths, and the incorporation of new isotopically heavy fluid source that is in equilibrium with a 5-km-deep carbonate formation (Howard et al., 2015). The 4C and stable isotope record of fluid flow goes back 20 k.y. Our objective is to quantify the long-term (>20 k.y.) history of hydrothermal activity.

THE BEOWAWE HYDROTHERMAL SYSTEM

The Beowawe hydrothermal system is located in north-central Nevada (Fig. 1A), southwest of the town of Elko. The area was once the second-most active geyser field in the United States, after Yellowstone National Park. However, in C.E. 1960, geyser activity ceased due to geothermal development (White, 1992). The geyser and hot springs were located in the hanging wall of the Malpais fault, an active normal fault that formed when extension rotated to a northwest-southeast direction at ca. 10–6 Ma (Zoback et al., 1981). The offset of the Malpais fault is ~230 m (Fig. 1C). Alluvial sediments along the fault document vertical offsets of 0.7 and 2 m caused by earthquakes at 18,700 and 7500 yr B.P., respectively (Wensnousky et al., 2005). Hydrothermal activity has generated a 1600-m-long sinter deposit at the footwall of the fault with a relatively constant thickness of 65 m, consisting predominantly of opal (Zoback, 1979). The sinter terrace is underlain by middle Miocene

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volcanic rocks, including dacite, basaltic andesite, and basalt, that overlie Ordovician sedimentary rocks (Struhacker, 1980). Prior to 1960, the total fluid discharge was 0.018 m$^3$ s$^{-1}$, of which one-third discharged through the geysers and hot springs and two-thirds contributed to lateral discharge through alluvial sediments (Olmsted and Rush, 1987). The low salinity of hydrothermal fluids and their stable isotope composition point to a meteoric origin. The system is recharged at a topographic high northwest of the geysers and is driven by both topography and thermal convection (Olmsted and Rush, 1987; Howald et al., 2015). Low $^3$He/$^4$He ratios suggest that there is no magmatic heat source (Banerjee et al., 2011). Geothermometers and $^{13}C$ concentration indicate that fluids were in contact with a carbonate reservoir at temperatures averaging 230 °C at a depth of ~5 km (Rimstidt and Cole, 1983; Day, 1987; John et al., 2003).

**METHODS**

We collected 17 surface rock samples of middle Miocene dacites along the Malpais fault in the vicinity of the Beowawe sinter terrace (Fig. 1B; Fig. DR1 in the GSA Data Repository$^1$; Table 1). For four samples, the crystallization age was dated using the zircon U-Pb method. Theapatite (U-Th)/He thermochronometer (AHe) was used to constrain the post-formation thermal history. For more detailed information on the methods used in this study, see the Data Repository.

We used a new advective and conductive heat flow model called Beo (Luijendijk, 2019: https://github.com/ElcoLuijendijk/beov), which is based on the finite-element model code *escript* (Gross et al., 2007a, 2007b), to simulate the thermal effects of upward fluid flux in a single fault zone and lateral flow into a connected alluvial aquifer (Fig. 1D). The modeled temperature history was combined with a helium diffusion model (Meesters and Dunai, 2002a, 2002b) to calculate AHe ages. AHe ages equal crystallization age if the apatite grains have remained at low temperatures, but will tend toward zero if temperatures have exceeded 55–80 °C over long (thousands of years) time scales (Reiners et al., 2005). The model simulates only the part of the hydrothermal system where upward fluid flow and discharge take place. Flow starts at 5 km depth in a carbonate formation that is the likely origin of upward flow. The flow rate is imposed and is based on a reconstruction of the present-day fluid discharge at the surface and the flux along the fault (Olmsted and Rush, 1987). The temperature at the lower model boundary at 8 km depth was fixed at 330 °C, based on measured regional geothermal gradients (Zoback, 1979; Howald et al., 2015). We first quantified the age of the latest episode of fluid flow in this system by calibrating the model to a temperature record from Chevron–U.S. Department of Energy exploratory well 85-18 (Iovenitti and Epperson, 1981) near the western edge of the sinter terrace (Fig. 1A). We then ran models of continuous and episodic hydrothermal activity and compared modeled and measured AHe ages. Because hydrothermal activity may have varied temporally and spatially along the Malpais fault, the AHe samples were grouped along three profiles (Figs. 1A and 1B; Table 1). A number of different model experiments were conducted to test the effects of the duration of advective heating and thermal recovery on modeled AHe ages, with heating durations ranging from 0.5 to 2 k.y. and thermal recovery ranging from 2 to 9.5 k.y.

**RESULTS**

Comparison of the modeled and measured borehole temperatures (Fig. 2G) constrains the age of the latest stage of the hydrothermal activity along the Malpais fault. The model results provide the best match to the observed temperatures for a fluid flow duration of 3 k.y. (Fig. 2) using flow rates that are based on reconstructions of fluid discharge along the fault (Olmsted and Rush, 1987). Longer run times would result in too much heating of the system and would also not reproduce the overturned geothermal gradient.

The large volume of hydrothermal sinter deposits indicates that the system must have been active much longer, ~210 k.y. (Zoback, 1979). To quantify the long-term history of fluid flow, we used low-temperature thermochronology on surface samples close to the Malpais fault. The crystallization age of the volcanic host rock of the Beowawe hydrothermal system was dated using the zircon U-Pb method as 15.6 Ma (Table DR5 in the Data Repository). Samples at distances of >40 m from the Malpais fault show AHe ages that are equal to the U-Pb age (Fig. 1B), which signifies that they have not undergone heating of temperatures exceeding ~55–80 °C since their deposition in the Miocene. In contrast, most samples that are close to the Malpais

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$^1$GSA Data Repository item 2019334, description of the sampling, dating, and modeling methods and additional model sensitivity analyses and model-data comparisons, is available online at http://www.geosociety.org/datarepository/2019/; or on request from editing@geosociety.org.
Table 1. Locations and minimum, maximum and average single grain AHe ages for the surface outcrop samples used in this study

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Longitude (WGS84) (°W)</th>
<th>Latitude (WGS84) (°N)</th>
<th>Distance and direction from fault (m)</th>
<th>Cross-section</th>
<th>Minimum age (m.y.)</th>
<th>Maximum age (m.y.)</th>
<th>Average age (m.y.)</th>
<th>Average Error (m.y.)</th>
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<tr>
<td>B1</td>
<td>116.59235</td>
<td>40.5606</td>
<td>56 N</td>
<td>A</td>
<td>14.7</td>
<td>16.8</td>
<td>15.8</td>
<td>2.2</td>
</tr>
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<td>B2</td>
<td>116.53728</td>
<td>40.5601</td>
<td>40 N</td>
<td>A</td>
<td>5.4</td>
<td>10.7</td>
<td>8.9</td>
<td>0.9</td>
</tr>
<tr>
<td>B3</td>
<td>116.59175</td>
<td>40.56384</td>
<td>15 N</td>
<td>A</td>
<td>8.1</td>
<td>10.9</td>
<td>10.0</td>
<td>1.1</td>
</tr>
<tr>
<td>B4</td>
<td>116.59018</td>
<td>40.56114</td>
<td>48 N</td>
<td>No data</td>
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<td></td>
<td></td>
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<td>B5</td>
<td>116.59878</td>
<td>40.560716</td>
<td>7 S</td>
<td>B</td>
<td>10.6</td>
<td>18.0</td>
<td>14.1</td>
<td>1.6</td>
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<tr>
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<td>40.5623</td>
<td>35 N</td>
<td>C</td>
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<td>17.7</td>
<td>15.0</td>
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</tr>
<tr>
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<td>40.5619</td>
<td>18 N</td>
<td>C</td>
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<tr>
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<td>116.59032</td>
<td>40.56115</td>
<td>20 N</td>
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<td>10.1</td>
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</tr>
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<td>B9</td>
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<td>40.56115</td>
<td>17 N</td>
<td>B</td>
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<td>13.4</td>
<td>8.6</td>
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<td>15 N</td>
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<td>40.561964</td>
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<tr>
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<td>40.562094</td>
<td>8 S</td>
<td>C</td>
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<td>17.8</td>
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<tr>
<td>B13</td>
<td>116.58876</td>
<td>40.560984</td>
<td>4 S</td>
<td>B</td>
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<tr>
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<tr>
<td>B15</td>
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<td>40.560344</td>
<td>37 S</td>
<td>B</td>
<td>12.4</td>
<td>17.0</td>
<td>14.0</td>
<td>2.2</td>
</tr>
<tr>
<td>B16</td>
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<td>40.5623</td>
<td>19 N</td>
<td>C</td>
<td>11.4</td>
<td>19.7</td>
<td>15.9</td>
<td>3.4</td>
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<td>40.561134</td>
<td>242 N</td>
<td>Discarded</td>
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</table>

Note: More details on the analysis and single grain ages can be found in Table DR5 (see text footnote 1).

Figure 2. Comparison of modeled temperatures over time and borehole temperature record for Chevron–U.S. Department of Energy exploratory well B-18 (Lowenstein and Epperson, 1981) near Malpas fault (Nevada, USA), indicating that fluid flow in this section of the fault is ~3 k.y. old (panel G). (A–C) Surface temperature over time. (D–F) Modeled temperature field and location of borehole. G: Measured borehole temperature data and modeled temperatures for three time slices shown in panels A–C. Distance refers to the distance to the left-hand side of the model domain.

Discussion and Conclusions

The much better fit of episodic fluid flow models to the AHe data (Fig. 3C) compared to models of continuous fluid flow means that either fluid flow in the Beowawe system ceased between the 1-k.y.-long fluid pulses or that overall fluid flow in the Beowawe system was continuous but shifted location every ~1 k.y. The latter explanation is favored by the distribution of 13C ages of hydrothermal sinter deposits (Howald et al., 2015), which suggests relatively constant fluid discharge over the past 20 k.y.

The 1 k.y. length of fluid pulses suggested by the AHe data is shorter than the 3 k.y. age of the latest fluid pulse based on modeled borehole temperatures. The difference may be resolved if one assumes higher flow rates at the start of the last fluid pulse and decreasing permeability and flow rates over time instead of constant rates. This would have increased subsurface temperatures and reduce the reconstructed age of the last fluid pulse. At shallow levels, temperatures are limited by the boiling temperature, and higher flow rates would therefore not have affected AHe ages and the reconstructed duration of fluid pulses of 1 k.y.

The reconstructed start of hydrothermal activity of ~250 k.y. is much younger than the 10–6 Ma age of tectonic activity of the Malpas fault. One explanation for the relatively recent appearance of the Beowawe hydrothermal system may be that continuous fault movement has gradually increased permeability of the fault damage zone, and permeability and fracture.
connectivity reached a threshold value that was sufficient to channel fluids along the fault from ~5 km depth 250 k.y. ago. The formation of connected pathways in the fault damage zone would have been slowed by the formation of a clay-rich alteration zone with low permeability (Cole and Ravinsky, 1984), and by the sealing effects of earthquakes on opening new flow paths, as noted by Person et al. (2015) provides a clear indication of the effects of earthquakes on opening new flow paths, as noted by Person et al. (2015). However, while the seismicity record shows that earthquakes have played a role in the permeability changes, not all changes in fluid flow can be attributed to earthquakes. Comparison of the modeled heat flow and the temperature record of well 85-18 suggests that the temperature record of well 85-18 is not a direct indicator of hydrothermal fluid flow.

Although the stable isotope record of Howald et al. (2015) provides a clear indication of the effects of earthquakes on opening new flow paths, not all changes in fluid flow can be attributed to earthquakes. Comparison of the modeled heat flow and the temperature record of well 85-18 provides evidence for the opening of a new flow path along the Malpais fault ~3 k.y. ago (Fig. 2), whereas the latest earthquake was dated as 7500 yr B.P. (Wensoulsky et al., 2005). One explanation may be simply that there has been more recent earthquake activity on the Malpais fault than the seismicity record shows. However, the model results suggest that the effect of earthquakes on opening new flow paths may have been induced by hydrothermal fluid flow revealed by thermal halos around giant gold deposits: Implications for Carlin-type gold systems: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 109, p. 1461–1487, https://doi.org/10.1016/j.geologe.2013.11.018.

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REFERENCES CITED

Figure 3. Modeled temperatures over long (thousands of years) time scales around Malpais fault (Nevada, USA) and comparison with measured apatite (U-Th)/He (AHe) samples for a continuous flow lasting 70 k.y. (A,D) and 200 k.y. (B,E), and 35 cycles of episodic flow with each cycle consisting of 1 k.y. of fluid flow followed by 9 k.y. of thermal recovery (C,F). Panels A–C show comparison between observed and modeled AHe ages for rocks at the surface. Error bars represent the ± 2 standard error of the AHe age. Panels D–F show modeled temperatures in the slice of model domain around Malpais fault. Panel G depicts mean absolute error (MAE) of modeled and measured single-grain AHe ages for several model experiments of continuous and episodic hydrothermal activity. Results are shown for profile B-B’ (see Fig. 1 for location), which had the highest density of AHe data. “1000/9000” denotes 1000 yr of fluid flow followed by 9000 yr of thermal recovery. Red stars show model error of model outputs shown in panels A, B, and C. Distance refers to the distance to the left-hand side of the model domain.