# Episodic fluid flow in an active fault

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**ABSTRACT**

We present a 250 ky record of episodic fluid flow along the Malpais fault which hosts the Beowawe hydrothermal system, Nevada, USA. Samples show partial resetting of the apatite (U-Th)/He thermochronometer in a 40 m wide zone around the Malpais fault. Numerical models indicate that, using current fluid temperatures and discharge rates, fluid flow events lasting 2000 years or more would lead to fully reset samples. Episodic fluid pulses lasting 1000 years resulted in partially reset samples, with ~36 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 last 20 ky. This suggests a system where fluid flow is triggered by repeated seismic activity and seals itself over ~1000 years due to formation of clay minerals and silicates in the fault damage zone. Hydrothermal activity is younger than the 6-10 Ma age of the fault. This suggests that the onset of deep (~5 km) fluid flow was initiated only after a large part of the total of 230 m offset took place.

## INTRODUCTION

Fault hosted transient fluid flow and hydrothermal activity plays an important role in a wide range of geologic processes, including metalogenesis (Weis et al., 2012), oil migration (Boles et al., 2004), fault mechanics and metamorphism (Magee and Zoback, 1993). The timescale of fluid flow is important because the longer fluid flow is active, the more pronounced it changes subsurface temperatures and alters the rock matrix. Transient changes in fluid flow and pore pressure also affect fault movement and seismic activity (Evans, 2005; Manga et al., 2012; Person et al., 2012). However, data on the duration of fluid flow in faults are rare, especially over geological timescales ($10^4$-$10^7$ years).

Direct observations of fluid flow responses to earthquakes last on the order of days to months (Rojstaczer and Wolf, 1992; Manga et al., 2012, 2016). Responses over longer timescales are the result of changes in driving forces or the permeability of faults. In contrast to the relatively slow changes in driving forces, such as changes in groundwater recharge or discharge over thousands to millions of years, changes in permeability can generate more dynamic responses of flow systems, such as the episodic release of overpressures that generates a short-lived flow systems lasting 100s of years (Ge and Garven, 1994; Roberts et al., 1996; Wang and Xie, 1998). Fluid pulses that move in the order of several 100s of meter per year have been interpreted using seismic data from sedimentary basins (Haney et al., 2005). Changes in permeability are driven by the competition between mineral precipitation in fault zones (Lowell et al., 1993), which reduces permeability and can seal hydrothermal systems and the creation of new flow paths by seismic or aseismic fault movement and the creation of connected fractures in fault damage zones (Sibson, 1981; Eichhubl et al., 2009). Model experiments of the sealing of faults by silica show that the timescale varies strongly, from 1 to $10^5$ years (Lowell et al., 1993). In geothermal systems, boreholes can become clogged over timescales of years (Gunnarsson and Arnórsson, 2005). While field evidence of hydrothermal minerals precipitating in faults is common (Fisher et al., 2003; Eichhubl et al., 2009), data on changes of fault permeability over longer timescales are rare.

Determining the duration of fluid flow in hydrothermal systems by dating hydrothermal minerals is often difficult because not all hydrothermal systems generate mineral deposits. Dating the most common hydrothermal minerals calcite and silica is hampered by low concentrations of datable isotope systems and recrystallization and because the uncertainty in dating these minerals may exceed the duration of short hydrothermal events (Skinner, 1997). Dating of clays in faults is often used as an indicator of fault activity (van der Pluijm et al., 2001) and clay mineral transformation driven by hydrothermal fluid flow (Morton et al., 2012), but their relation with fluid flow is often uncertain (Solum et al., 2005). 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 of the history of fluid flow in an active hydrothermal system based on a combination of low-temperature thermochronology at high spatial resolution with a new inverse model of conductive and advective heat flow. We apply this approach to quantify the history of fluid flow in the Beowawe hydrothermal system and geyser field in the Basin and Range Province. The results provide a novel record of episodic fluid flow activity in a fault over a timescale of ~250,000 years.

## THE BEOWAWE HYDROTHERMAL SYSTEM

The Beowawe hydrothermal system is an amagmatic hydrothermal system located in north-central Nevada, USA, southwest of the town of Elko (Fig.1). The area had the second greatest concentration of active geysers in the USA, second only to Yellowstone National Park. However, in 1960 geyser activity ceased due to geothermal development (White, 1998). The geysers, hot springs and fumaroles were located in the hanging wall of the Malpais fault, an active normal fault that formed when extension in this part of the Basin and Range Province rotated to a northwest to southeast direction around 10 to 6 Ma (Zoback et al., 1981; Watt et al., 2007). Hydrothermal activity has generated an up to 65 m thick and 1600 m long sinter deposit, consisting predominantly of opal, at the footwall of the fault (Zoback, 1979). The sinter terrace is underlain by Middle Miocene volcanic rocks, including dacite, basaltic andesite and basalt flow sequences that overlie Ordovician sedimentary rocks (Struhsacker, 1980). Pervasive hydrothermal alteration of the volcanic host rock and formation of clay minerals was observed in boreholes that cross the Malpais fault (Cole and Ravinsky, 1984). Prior to 1960 the total fluid discharge was 0.018 $m^3$ $sec^{-1}$ of which around one third discharged through the geysers and hot springs and two thirds contributed to diffuse 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 (Howald et al., 2015). Low $^3He/^4He$ ratios suggests that there is no magmatic heat source (Banerjee et al., 2011). Geothermometers and $\partial^{13}C$ concentration indicate that fluids were in contact with a carbonate reservoir at temperatures averaging 230°C at a depth of approximately 5 km (Rimstidt and Cole, 1983; Day, 1987; John et al., 2003). As a result of hydrothermal activity heat flow around the Beowawe sinter terrace is elevated to an average of 235 mW $m^{-2}$ compared to a background heat flow of 118 mW $m^{-2}$ (Smith, 1983).

## METHODS

We collected seventeen surface rock samples of Middle Miocene pyroxene dacites along the Malpais fault in the vicinity of the Beowawe sinter terrace (Fig. 1B). The rocks were dated using the apatite (U-Th)/He thermochronometer (AHe), which is sensitive to temperatures ranging from 40°C to 70°C (Reiners et al., 2005). For four samples the crystallization age was dated using the zircon U-Pb method. See Data Repository[1] section DR1.1-DR1.5 for description of the sampling and dating methods.

We used an advective and conducive heat flow model (Luijendijk, 2018) to quantify the thermal effects of fluid flow near the Malpais fault. We first quantified the timescale of present-day (pre-1960) fluid flow system by calibrating fluid flow to borehole temperature record from the 1680 m deep well 85-18 (Iovenitti and Epperson, Jr., 1981) that is located near the western edge of the sinter terrace (Fig. 1A). We then ran models of continuous and episodic hydrothermal activity. The modeled thermal histories were used to calculate AHe ages, which were compared to observed values. The modeled fluid flux was equal to the observed flux in the system of 0.018 $m^3 s^{-1}$ (Olmsted and Rush, 1987) and flowed upward from a carbonate formation at 5 km depth. The background geothermal gradient was based on an undisturbed gradient of 0.04 ˚C $m^{-1}$ in well Collins-1 (Jones, 1983). A more detailed description of the model setup can be found in Data Repository section DR1.6.

## RESULTS

### Short-lived fluid flow deduced from borehole temperatures

The temperature-depth profile in well 85-18 shows a bulge where the borehole crosses the Malpais fault at 550 m below the surface, with a small decrease in temperatures below the

Malpais fault (Fig. 2G). Overturned geothermal gradients indicate transient hydrothermal flow, because over long timescales conductive heat flow would dissipate the overturned geothermal gradient (Ziagos and Blackwell, 1986). The model results provide the best match to the observed temperature data for a duration of fluid flow of 3000 years (Fig. 2). Longer runtimes at present-day fluid fluxes would heat the system too much and would also not match the overturned geothermal gradient. In addition, a positive and negative inflection of the temperature profile can be observed above the Malpais fault at a depth of up to 500 m (Fig. 2G), which is caused by lateral flow of hydrothermal fluids from the fault into permeable tuff or basalt layers in the volcanic host rock and shallow alluvial aquifer or vice versa. The location and rate of lateral flow were calibrated manually to get a good fit to the temperature data, with the best fit provided by a flux of 80 $m^2$ $a^{-1}$ towards the fault at 510 m below the surface to 180 m below the surface and an upper one with a flux of 150 $m^2$ $a^{-1}$ flowing out of the fault between 80 and 10 m below the surface. The results suggest that there may be a convective loop below the sinter terrace, with warm water entering shallow alluvial aquifer levels from the fault, and cool water flowing into the fault through deeper permeable tuff or basalt layers (Olmsted and Rush, 1987).

**Long-term history of fluid flow using low-temperature thermochronology**

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, which is slightly younger than previously reported K-Ar ages of the same unit (Struhsacker, 1980). Samples at distances of more than 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 approximately 70 °C since their deposition in the Miocene. In contrast, most samples that are close to the

Malpais fault show a small but consistent decrease in AHe ages that is likely the result of heating by hydrothermal fluids (Fig. 1B). Interestingly, the AHe data suggests that over long timescales hydrothermal activity was focused on the Malpais fault. However, while fluid flow originated in the Malpais fault, historically the surface discharge was focused on a line of fumaroles and former geysers on top of the sinter terrace, approximately 70 m north of the Malpais fault (Fig. 1B). The focus of hydrothermal activity around the Malpais fault is however consistent with the location of the oldest generation of sinter deposits that have been found close to the fault (White, 1998).

We quantified the duration of hydrothermal activity by comparing a model of advective and conductive heat flow to measured AHe ages along a cross-section perpendicular to the fault (Fig. 3E-H). We first modeled the effects of continuous hydrothermal activity. The best fit suggests hydrothermal activity started about 70,000 years ago (Fig. 3E), which is shorter than the approximately 210,000 years that are required to deposit the volume of sinter at current fluid discharge rates and silica concentrations (Zoback, 1979). The results also indicate that the high fluid temperatures in the system would result in full resetting (AHe age=0 Ma) of the AHe thermochronometer a 13 m zone around the fault bounded by a 5 m zone with partially reset samples after 70,000 years. For a duration of 200,000 years fully reset samples would cover a zone of 45 m. However, even though the sampling was relatively dense, we did not find a single fully reset apatite (Fig. 1B and Data Repository table DR6). This suggests that models of continuous hydrothermal activity underestimate AHe ages and overestimate heating time and/or temperatures.

We explored the effects of transient hydrothermal activity using model experiments with repeated cycles of hydrothermal activity and thermal recovery, with fluid flow pulses lasting 500, 1000 or 2000 years followed by thermal recovery of 2000 to 9000 years. The results show that periodic heating followed by thermal recovery would result in only partially reset AHe ages around the fault and no fully reset samples (Fig. 3C). The best fit as obtained by 36 cycles of heating of 1000 years followed by 9000 years of thermal recovery (Fig 3C). A model run with heating of 2000 years resulted in full resetting, whereas 500 years would not be sufficient to reduce AHe ages to their observed values (Data Repository Fig. DR9). This suggests that the individual fluid pulses lasted longer than 500 but less than 2000 years. The duration of thermal recovery is not well constrained, any value of 6500 years or more provided a good fit. This means that the hydrothermal system must have been at least 255,000 years old.

The modeled effects of hydrothermal activity on AHe ages are dependent on modeled background exhumation rates. The reason is that land surface temperatures are buffered by air temperatures, and exhumation rates need to be high enough to bring up rocks from deeper levels that have undergone sufficient heating to affect AHe ages. Our model experiments assumed a background exhumation rate of $1 \times 10^{-4}$ m $a^{-1}$, which is an average of reported regional values of $3 \times 10^{-5}$ m $a^{-1}$ to $5 \times 10^{-3}$ m $a^{-1}$ (Gosse et al., 1995; Riebe et al., 2000; Stockli et al., 2002; Jungers and Heimsath, 2016) and is in accordance with relatively high erosion rates due to proximity to an active fault with a major fault scarp. Model sensitivity analysis (Data Repository Fig. DR6) shows that exhumation rate and duration are linearly correlated. Halving the exhumation rate would double the modeled duration of hydrothermal activity.

## DISCUSSION AND CONCLUSIONS

### Episodic fluid flow

In addition to the comparison of the thermal model with borehole temperature records and low-temperature thermochronometers presented here, two additional lines of evidence indicate that fluid flow in the Beowawe system occurred episodically over geological time scales. Variations in trace elements in sinter and differences of salinities in fluid inclusions indicate changes in fluid sources over time (Leatherman, 2010). Carbon-14 ages in pollen trapped in sinter deposits and stable isotope data of sinter deposits showed stable isotope values equal to present-day values around 8500 years ago, followed by an isotopically heavy $\delta^{18}O$ signature that is 20‰ higher at 7000 years BP and a slow decrease to meteoric values up to the present (Howald et al., 2015). The rapid change from light to heavy isotope signature coincides with an earthquake along the Malpais fault at 7450 years BP, that was dated by offset alluvial sediments around 12 km northeast of the sinter terrace (Wesnousky et al., 2005). The most likely explanation for the observed trend is a seismically induced increase in permeability, the opening of new flow paths and the incorporation of a new isotopically heavy fluid source that is in equilibrium with a 5-km-deep carbonate formation. This was followed by a steady incorporation of more light meteoric water into the hydrothermal system over time (Howald et al., 2015). The much better fit of episodic fluid flow models to the AHe data (Fig. 3C) means that either fluid flow ceased in between the 1000 year-long fluid pulses, or that overall fluid flow in the Beowawe system was continuous but shifted location every ~1000 years. The last explanation is favored by the distribution of $^{14}C$ ages of hydrothermal sinter deposits (Howald et al., 2015) that suggests relatively constant fluid discharge over the last 20,000 years.

**Relation between fluid flow and tectonic activity**

The reconstructed duration of hydrothermal activity of ~250,000 years in the Malpais fault is much shorter than the duration of tectonic activity of this fault. Extension in this part of the Basin and Range started around 17.5 Ma ago (Dickinson, 2006) and regional extension rates may have increased around 12 Ma (Colgan et al., 2006). The Malpais fault is likely to have formed due to rotation of extension to a northwest-southeast direction between 10 and 6 Ma (Zoback et al., 1981; Watt et al., 2007). The net fault offset of the Malpais fault is approximately 230 m (Fig. 1). Seismic activity on the Malpais fault has been quantified by dating offsets in alluvial sediments along the fault scarp, with two dated earthquakes at 7450 years BP and 18701 years BP and vertical offsets of 0.7 and 2 m, respectively (Wesnousky et al., 2005). This is in line with the average slip rates on faults of 0.1 to 0.3 mm $a^{-1}$ over the last 100 ka reported for this part of the Basin and Range Province (Koehler and Wesnousky, 2011). Regional late-Pleistocene extension rates in the Basin and Range system are approximately 1.0 mm $a^{-1}$ and are consistent with current geodetic extension rates (Koehler and Wesnousky, 2011).

One explanation for the relatively recent appearance of the Beowawe hydrothermal system may be that the fault was tectonically active for much longer, but continuous fault movement may have gradually increased permeability of the fault damage zone over time and permeability and fracture connectivity only reached a threshold value that was sufficient to channel hydrothermal fluids along the fault from around 5 km depth around 250,000 years ago. The formation of connected pathways in the fault damage zone would have also been slowed by the extensive hydrothermal alteration around the fault, which has resulted in an alteration zone that is rich in clay minerals and has a low permeability (Cole and Ravinsky, 1984; Leatherman, 2010), and by the clogging of the fault zone with silica precipitated by hydrothermal fluids.

An alternative explanation for the relatively short period of hydrothermal activity may be that it coincides with an increase in rate of fault movement along the Malpais fault. Although there is no data available for the long-term rate of motion along the Malpais fault, Pérousé and Wernicke (2017) have recently suggested that normal faults in the Basin and

Range may alternate between periods of increased activity of 50,000 years and longer periods of slow deformation. Assuming that the Malpais fault has had a recent period of increased activity, the increased rates in fault activity may have been sufficient to keep permeability high enough for deep fluid flow to be channeled through the Malpais fault. In periods with lower fault activity the fault would have been sealed by the formation of clay and silica minerals in the fault damage zone.

Although the stable isotope record by Howald et al. (2015) provides clear indication of the effects of earthquakes on opening new flow paths, not all changes in fluid flow can be attributed to earthquakes. The borehole temperature record of well 85-18 provides evidence for the opening of a new flow path along the Malpais fault around 3000 years ago (Fig. 2), whereas the latest earthquake was dated as 7450 BP (Wesnousky et al., 2005). In addition, the relocation of flow paths every 1000 years suggested by the thermochronological data exceeds the earthquake recurrence cycle. This matches findings by Eichhubl and Boles (2000) who report that the number of fluid pulses that led to cementation exceeded the number of brecciation events and earthquakes in a fault zone in California. Our findings suggests that, in addition to earthquakes on the Malpais fault, new flow paths may be opened by permeability changes induced by earthquakes in nearby faults and the resulting changes in stress (Caskey and Wesnousky, 2000).

**Quantifying fluid flow using low-temperature thermochronology**

The combination of low-temperature thermochronology and numerical models of hydrothermal systems presented here potentially opens new avenues of research on the history of active hydrothermal systems. The method can be used where fluid temperatures are warm enough to affect the apatite (U-Th)/He thermochronometer (>40 ˚C) and where exhumation rates and age of the system are sufficient to bring up rocks from a depth of a few meters that have not been buffered by air temperatures. The method is highly sensitive to exhumation rates, and in strongly exhuming terranes like mountain belts the thermal signal may be much larger and easier to quantify than at the moderate exhumation rates of the area in the Basin and Range Province presented here.

The method may be more suitable to date fluid flow in exhumed fossil hydrothermal systems, because the thermal footprint of fluid flow is much larger at depth than close to the surface. However, the advantage of studying an active hydrothermal system is that the fluid discharge and temperatures are known. For fossil hydrothermal systems there is a potential tradeoff between fluid temperatures and duration of heating, with short heating at high temperatures providing the same thermal signal in adjacent rocks as long heating at lower temperatures. However this could be remedied when fluid temperatures can be estimated independently from for instance fluid inclusion data. Alternatively, the use of multiple thermochronometers could provide constraints on timing because of the difference sensitivity to heating time of each thermochronometer (Reiners, 2009).

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# FIGURES

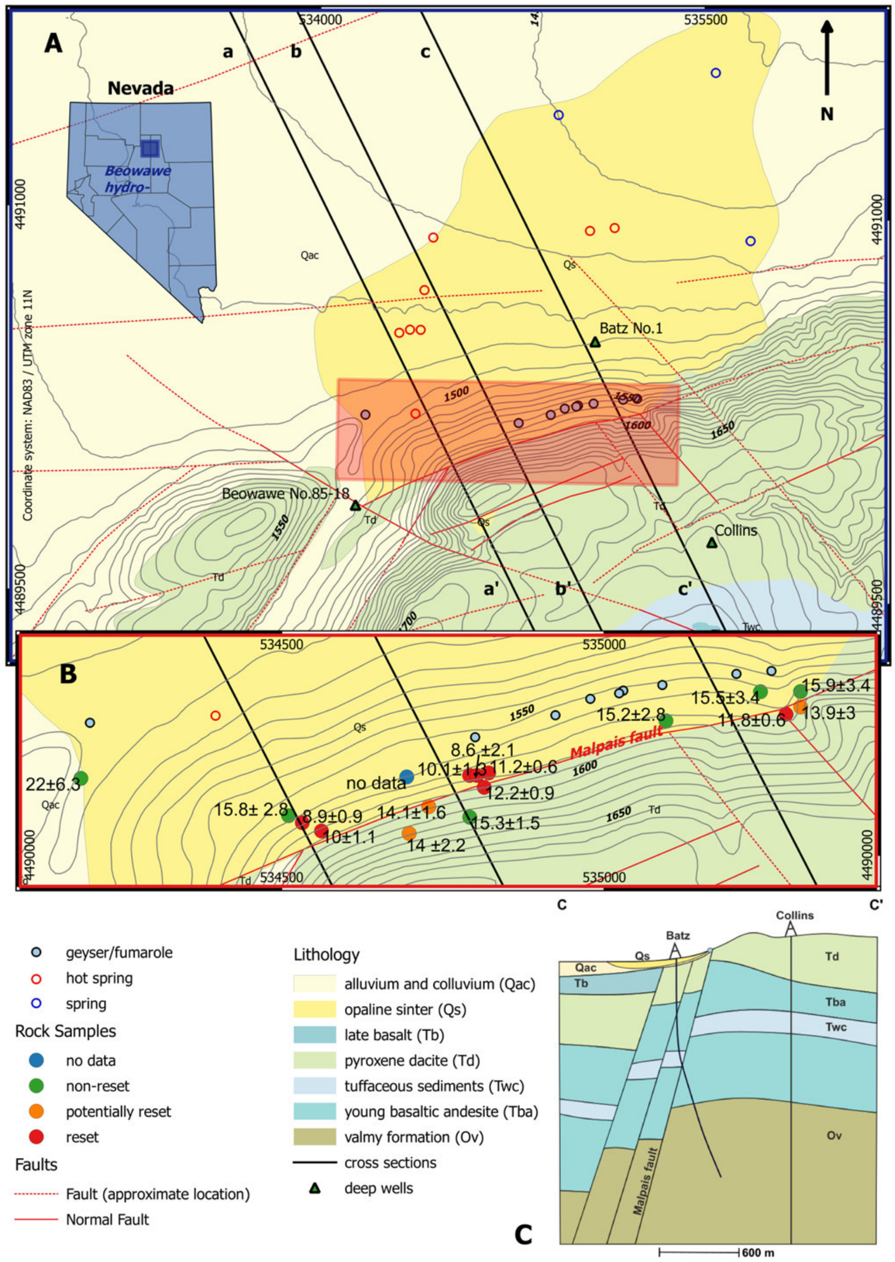


Figure 1. (A) Geological map of the Beowawe geothermal area, locations of wells and the geysers and hot springs that were active prior to geothermal development in the 1960s. (B) Close-up of the hydrothermally active Malpais fault, the sample locations and apatite (U-Th)/He ages and their uncertainty. (C) Geologic cross-section showing the Batz and Collins wells relative to the Malpais fault zone.

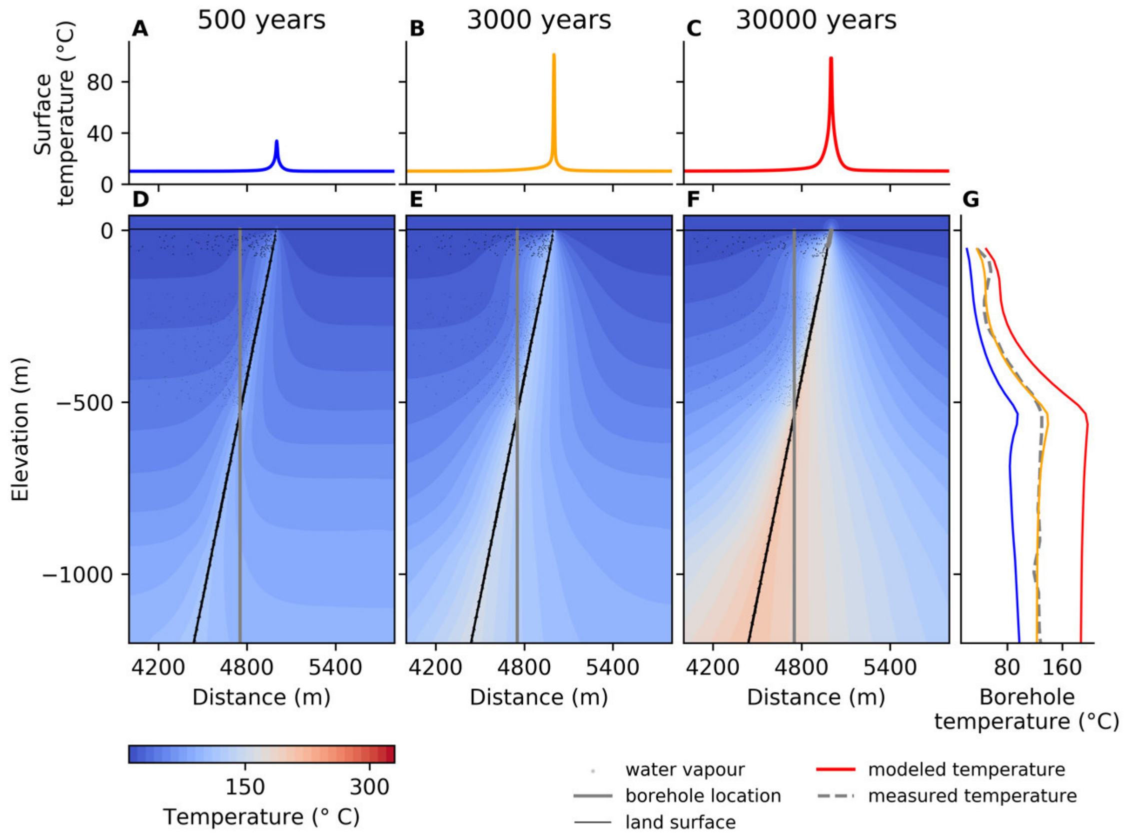


Figure 2. Comparison of modeled temperatures over time and borehole temperature record for borehole 85-18 indicates that fluid flow in this section of the fault is around 3000 years old (panel G). Panels A, B, and C show the surface temperature over time, panels D, E and F show the modeled temperature field and the location of the borehole. The measured borehole temperature data and the modeled temperatures for three time-slices are shown in panel G.

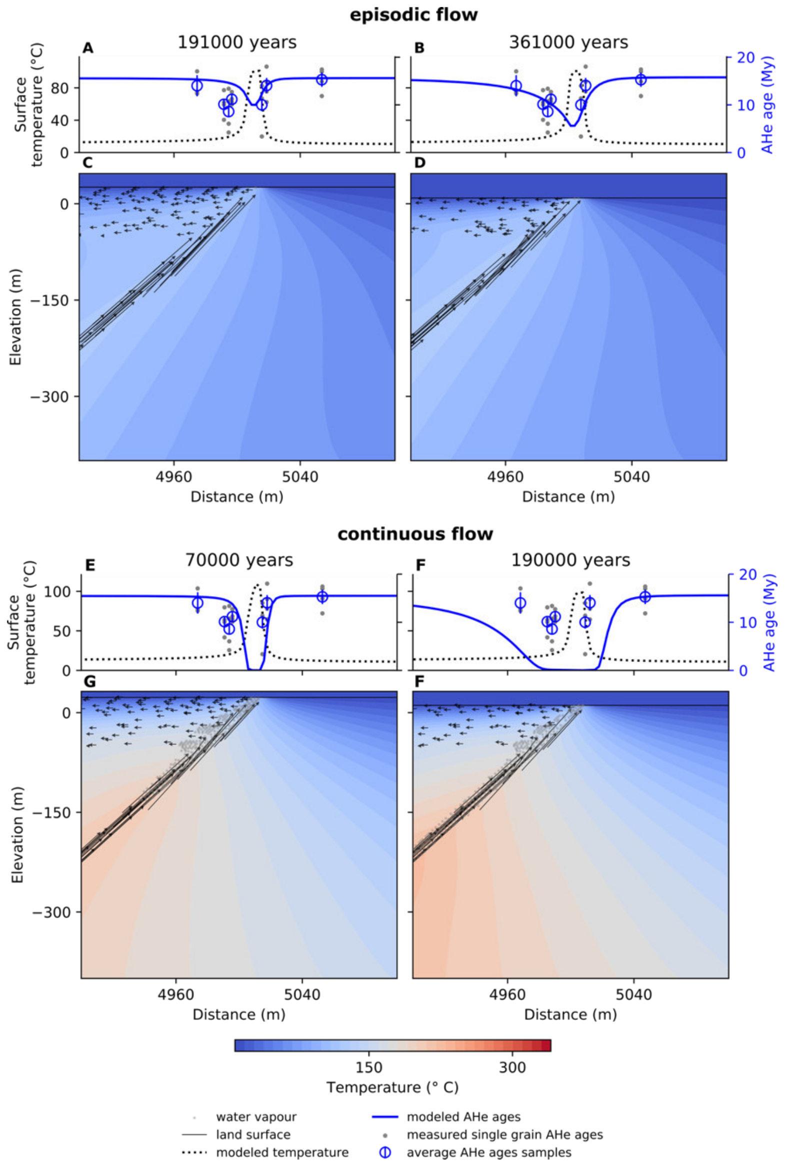


Figure 3. Modeled temperatures over long (ka) timescales around the Malpais fault and a comparison with measured apatite (U-Th)/He samples for episodic flow with 1000 years of fluid flow followed by 9000 years of thermal recovery (A-D), and continuous fluid flow (E-H). Panels A, C, E and G show a comparison between observed and modeled AHe ages for rocks at the surface. Panels B, D, F, and H show modeled temperatures in a slice of the model domain around the Malpais fault. The best fit for episodic activity is reached after 36 cycles of 1000 years of heating (C), with shorter heating times showing an overestimation of AHe data (A). The best fit for a model of continuous heating is reached after 70,000 years, but the fit is worse than for episodic heating, and the model predicts a relatively large zone where AHe ages are 0, which has not been found in our study.

Episodic fluid flow in an active fault

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**DR1: METHODS**

**DR1.1: Sampling and sample preparation**

We collected seventeen surface rock samples of Middle Miocene pyroxene dacites along the Malpais fault in the vicinity of the Beowawe sinter terrace. All of them were taken at a different distance from the Malpais fault (Figure DR1, Table DR1). The samples were crushed and sieved. Apatite and zircon crystals were separated using a wet shaking table, dissolution of carbonates in 5% acetic acid, density separation using a lithium polytungstate solution and magnetic separation. Apatites and zircons were hand-picked from concentrates under an Olympus SZX7 microscope.

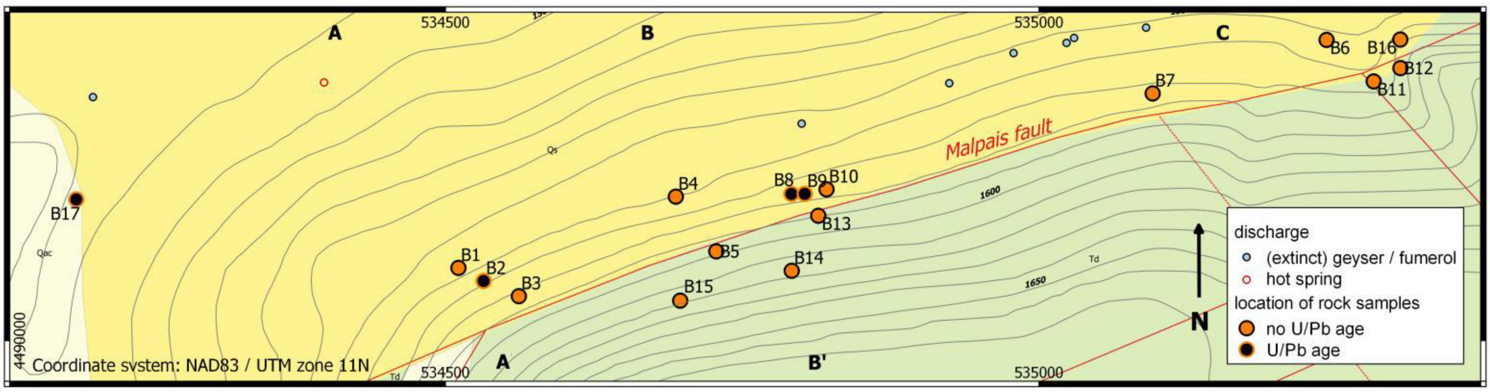



***Figure DR1** The location of rock samples around the Malpais fault*

*Table DR1* *Locations of samples and their distance to the Malpais fault.*

| Sample ID | Latitude (WGS84) | Longitude (WGS84) | Distance to Fault (m) |
|---|---|---|---|
| B1 | -116.59235 | 40.560600 | 56 N |
| B2 | -116.59210 | 40.560500 | 40 N |
| B3 | -116.59175 | 40.560384 | 15 N |
| B4 | -116.59018 | 40.561134 | 48 N |
| B5 | -116.58978 | 40.560717 | 7 S |
| B6 | -116.58370 | 40.562300 | 35 N |
| B7 | -116.58543 | 40.561900 | 18 N |
| B8 | -116.58903 | 40.561150 | 20 N |
| B9 | -116.58890 | 40.561150 | 17 N |
| B10 | -116.58868 | 40.561184 | 15 N |
| B11 | -116.58323 | 40.561984 | 10 S |
| B12 | -116.58296 | 40.562084 | 8 S |
| B13 | -116.58876 | 40.560984 | 4 S |
| B14 | -116.58903 | 40.560567 | 42 S |
| B15 | -116.59014 | 40.560344 | 37 S |
| B16 | -116.58296 | 40.562300 | 19 N |
| B17 | -116.59615 | 40.561134 | 242 N |

## DR1.2: Zircon U-Pb geochronology

The hand-picked zircon crystals from samples B-2, B-8, B-9 and B-17 were fixed on a double-side adhesive tape attached to a thick glass plate and embedded in a 25 mm diameter epoxy mount. The crystal mounts were lapped by 2500 mesh SiC paper and polished by 9, 3 and 1 µm diamond suspensions. For all zircon samples and standards used in this study cathodoluminescence (CL) images were obtained using a JEOL JXA 8900 electron microprobe to study their internal structure and to select homogeneous parts for the in-situ

age determinations. The carbon coating used for CL imaging was later removed with a brief hand polish on a 1 μm diamond cloth. The in-situ U-Pb dating was performed by laser-ablation single-collector sector-field inductively coupled plasma mass spectrometry. The method employed for analysis is described in detail by Frei & Gerdes (Frei and Gerdes, 2009). A Thermo Element 2 mass spectrometer coupled to a Resonetics Excimer laser ablation system was used. All age data presented here were obtained by single spot analyses with a laser beam diameter of 33 μm and a crater depth of approximately 10 μm. The laser was fired at a repetition rate of 5 Hz and at nominal laser energy output of 25 %. Two laser pulses were used for pre-ablation. The carrier gas was He and Ar. Analytes of $^{238}U$, $^{235}U$, $^{232}Th$, $^{208}Pb$, $^{207}Pb$, $^{206}Pb$, mass 204 and $^{202}Hg$ were measured by the ICP-MS. The data reduction is based on the processing of ca. 50 selected time slices (corresponding ca. 14 seconds) starting ca. 3 sec. after the beginning of the signal. The age calculation and quality control are based on the drift- and fractionation correction by standard-sample bracketing using GJ-1 zircon reference material (Jackson et al., 2004). For further control the Plešovice zircon (Sláma et al., 2008), the 91500 zircon (Wiedenbeck et al., 1995) and the FC-1 zircon were analyzed as "secondary standards". The age results of the standards were consistently within 2σ of the published ID-TIMS values. Drift- and fractionation corrections and data reductions were performed by our in-house software (UranOS; (Dunkl et al., 2008)). The level of Hg-corrected $^{204}Pb$ signal was very low, thus no common lead correction was required. The number of single-grain ages per sample ranges between 20 and 47. Concordia plots (Figure DR5) were constructed by the help of Isoplot/Ex 3.0 (Ludwig, 2012).
The dated zircon crystals have significantly lower radiation damage density, than the zircon reference materials used for correction of the fractionation ($1.7 \times 10^{16}$ in the samples and 6.1, 7.4 and $3.1 \times 10^{17}$ alpha decay/g in the GJ1, Plešovice and 91500 zircons, respectively). The increasing radiation damage density has an impact on the ablation rate of zircons (Marillo-Sialer et al., 2014) and it needs a correction that is based on the offset between the TIMS ages and laser ablation ages detected on a series of reference material having different degree of metamictization (Sliwinski et al., 2017). These RDC (radiation damage corrected) ages can be considered as the most reliable approximation of the crystallization age of zircons.

**DR1.3: Apatite (U-Th)/He thermochronology**

Apatite crystals were hand-picked under a binocular microscope. Selected crystals had a minimum width of 60 μm, euhedral shape and equal widths in all directions perpendicular to the c-axis. To secure intact shape and exclude minerals with inclusions and cracks, further selection was done using a polarizing microscope. Four apatite crystals per sample were analyzed. The mineral grains were enclosed in a pre-cleaned platinum capsule of ~1x1 mm size. The Pt capsules were heated in the full-metal extraction line by an infra-red laser for 2 minutes in high vacuum. The extracted gas was purified using a SAES Ti-Zr getter while being kept at 450°C. The chemically inert noble gases and a minor amount of other rest gases were then expanded into a Hiden triple-filter quadrupole mass spectrometer equipped with a positive ion counting detector. Beyond the detection of helium, the partial pressures of some rest gases were continuously monitored ($H_2$, $CH_4$, $H_2O$, $N_2$, Ar and $CO_2$). Crystals were checked for degassing of He by sequential reheating and He measurement. The amount of He extracted in the second runs are usually below 1%. Following degassing, samples were retrieved from the gas extraction line, spiked with calibrated $^{230}$Th and $^{233}$U solutions. The apatite crystals were dissolved in a 4% $HNO_3$ + 0.05% HF acid mixture in Savillex teflon vials. Spiked solutions were analyzed by isotope dilution method using a Perkin Elmer Elan DRC II ICP-MS or a Thermo iCAP Q mass spectrometer. The (U-Th)/He ages were calculated by the Taylor Expansion Method (Braun et al., 2006). (U-Th)/He ages were corrected for alpha ejection ($F_T$ correction) (Farley, 2000).

**DR1.4: Determination of internal zoning of actinide elements in the apatite crystals**

The correction of alpha ejection assumes homogeneous distribution of alpha-emitting elements within the dated crystals. Zonation of U and Th would affect the correction of alpha ejection, resulting underestimation or overestimation of ages (Meesters and Dunai, 2002a). To describe the internal distribution of actinide elements in the apatite samples we performed laser ablation trace element determination along lines across polished half-crystals perpendicular to the c-axis. Laser ablation cross profiling was performed with a 10 µm beam diameter, with a speed of 3 µm $s^{-1}$.

**DR1.5: Quantitative sample analysis using XRD and Rietveld method**

To determine the rock composition and look for secondary minerals we conducted x-ray diffraction (XRD) on five samples (B-4, B-5, B-8, B-9, B-14) using a Philips X'Pert MPD and a PW 3050/10 goniometer. The sieved sample fraction <250µm was mixed with the internal standard zinc oxide (ZnO) at a ratio of 8/2 respectively. The mixture was then back loaded on a powder mount with a diameter of 27mm. Measurement settings are summed up in the table below (Table DR2). The diffractogram was analyzed qualitatively using the software X'pert High Score by PANAlytical. Qualitative analysis was performed with the Rietveld method (Young, 1995).

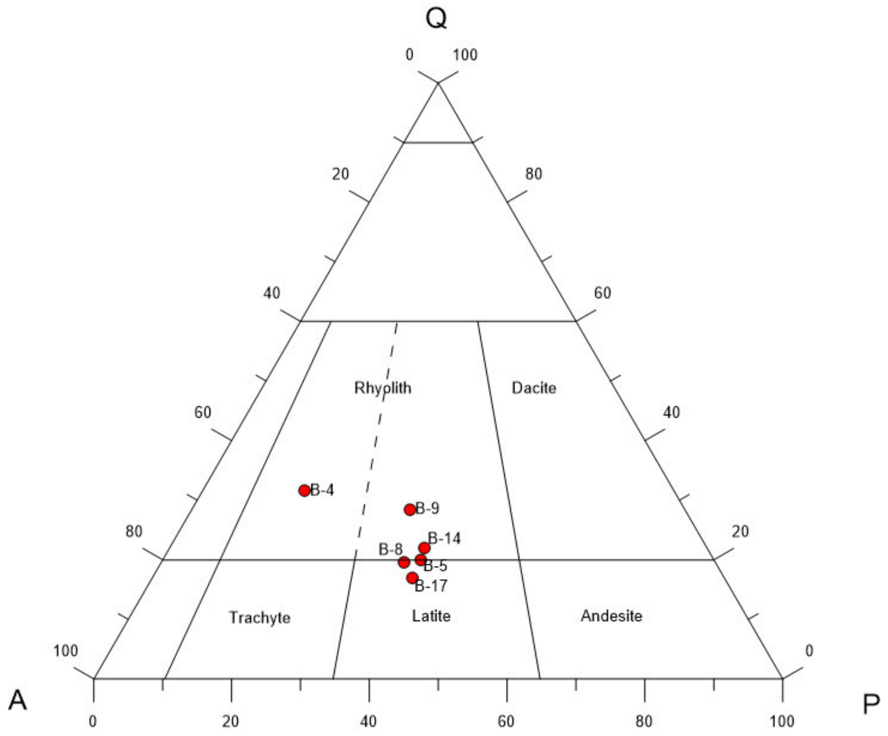



***Figure DR3*** *Streckeisen diagram showing the total weight percentage of all quartz, potassium feldspar and plagioclase mineral phases in the analyzed samples.*

The crystal phases of all six samples were determined using the Rietveld method (after Young (1995)). The total weight percentage of all quartz, potassium feldspar and plagioclase mineral phases were added up respectively and normalized to 100%. Results were plotted into a Streckeisen diagram (Figure DR3, Table DR2 and DR7). Contradicting the geological map of Stuhsacker, the majority of samples plotted into the lower ryolith field of the Streckeisen diagram. Sample B-17 contains less Quartz and its zircons contain more U and Th than most other samples. It plots into the latite field. Thus, sample B17 is most likely from a different lithology than the other samples, but it does not explain the anomalously old AHe age.

***Table DR2*** *XRD settings*

| | |
|---|---|
| Anode material of x-ray tube | Copper (Cu) |
| Voltage | 40 kV |
| Current | 30 mA |
| Mask | 17.20 mm |
| Divergent slit angle | 0.5° |
| Distance of divergent slit to sample | 140 mm |
| Anti-scatter slit angle | 0.5° |
| Height of receiving slit | 0.2 mm |
| Scan range | 4.0° – 69.5° |
| Step size | 0.02° |
| Counting time | 10 sec |

**DR1.6: Thermal model**

We used a new inverse 2D thermal model code, Beo (Luijendijk, 2018), to simulate the temperature history of the rocks surrounding a hydrothermal system. The model code simulates advective and conductive heat transfer and uses the modeled temperature history to model apatite (U-Th)/He ages of synthetic rocks samples. Beo uses the generic finite element code Escript (Gross et al., 2007b, 2007a; Poulet et al., 2012) to solve the heat advection and conduction equation. The model setup and boundary conditions are shown in Figure DR2. The fluid flux term (q) is a fixed value in a single fault zone and one or two horizontal aquifers connected to this fault. A fixed temperature is assigned to the lower model boundary that is based on the regional geothermal gradient. No heat flow is allowed over the left and right hand model boundary. The upper model boundary consists of a layer of 10 m of air overlying the land surface. The top boundary is assigned a specified temperature that corresponds to the average annual air temperature of 10˚C. Heat transfer between the surface and the atmosphere is modeled as conductive heat flow. A variable and artificially high value of thermal conductivity of the air layer is calculated following equations for sensible and latent heat flow by Bateni and Entekhabi (Bateni and Entekhabi, 2012) to account for the relatively efficient heat transport at the land surface. The reason for using this boundary condition is that it provides a physically realistic heat flux at the land surface, and it avoids applying a fixed temperature or heat flux, which would skew the model results because both temperature and heat flux at the surface vary over time. The thermal conductivity in the subsurface was dependent on lithology. The model does not take into account the presence of an unsaturated zone away from the hot spring area, where thermal conductivities may be lower than below the water table. Apatite (U-Th)/He ages are calculated using the modeled thermal history following a helium diffusion model by Meesters and Dunai (2002b, 2002a), with helium diffusivity calculated as a result of radiation damage following the RDAAM model (Flowers et al., 2009). See Luijendijk (2018) for more details on the model code. Beo is an open source code and is available at https://bitbucket.org/ElcoLuijendijk/beo.

In this study, the thermal history was calculated for three cross-sections perpendicular to the Malpais fault (A-A', B-B' and C-C', Figure DR1). The samples closest to either cross section were interpolated onto the profile. The three cross sections were chosen because the thermal conditions vary along the sinter terrace as evidenced by different borehole temperatures at the western and eastern part of the sinter terrace (Garg et al., 2007). In addition, hydrothermal activity may have shifted its locus over time (Leatherman, 2010), which may result in different temperature histories and AHe data for each cross-section. Profile length and width of the model domain are 8000 m and 2000 m respectively. The model contains a single normal fault, the Malpais fault. The subsurface consists of different lithologies that show an offset between the hanging wall and the foot wall of the Malpais fault. For our model setup we chose the lithology of the deep well Collins 76-17 (Sibbett, 1983). According to Zoback (Zoback, 1979), the net offset between the top of the volcanic sequence of the Malpais rim and the subsidiary block is 230 m. Grid size varied between 250 m for the grid cells away from the fault zone, 2 m for the cell size in the air layer, 2.5 m within the fault damage zone and 500 m at the model base.

The fixed parameters for the thermal model were taken from previous studies on the Beowawe system. The geology was based on a profile by Hoang et al. (Hoang et al., 1987) and information from deep wells (Chevron Resource Company, 1979) (Figure DR2). Bulk thermal conductivities of volcanic and intrusive rocks were determined at ~2 W $m^{-1}$ $K^{-1}$ with exceptions of significantly lower conductivities for basalt and tuffaceous sediments, which were assigned a thermal conductivity of 1.6 and 1.33 – 1.65 W $m^{-1}$ $K^{-1}$, respectively (Smith, 1983). Modeled present-day temperatures were compared with borehole temperatures recorded by Iovenitti And Epperson, Jr. (Iovenitti and Epperson, Jr., 1981) in borehole 85-18 that is located at 250 m NW of the Malpais fault (Figure 1).

The modeled fluid fluxes were based on a previously published groundwater budget of the area (Olmsted and Rush, 1987). The total fluid flux of the hydrothermal system is 380 $m^2$ $a^{-1}$. Deflections in the temperature-depth profile of wells Beowawe 85-18 suggests that lateral flow occurs at low depth. According to Olmsted and Rush (Olmsted and Rush, 1987) the up to 50 m thick quaternary alluvium that underlies the sinter terrace and extends into the valley channels 2/3 of the total fluid flux from the Malpais fault towards the valley. The remaining 1/3 of the fluid flux is discharged as spring flow near the fault. All variable parameters are set to their base values as described in Table DR3 and Table DR4.

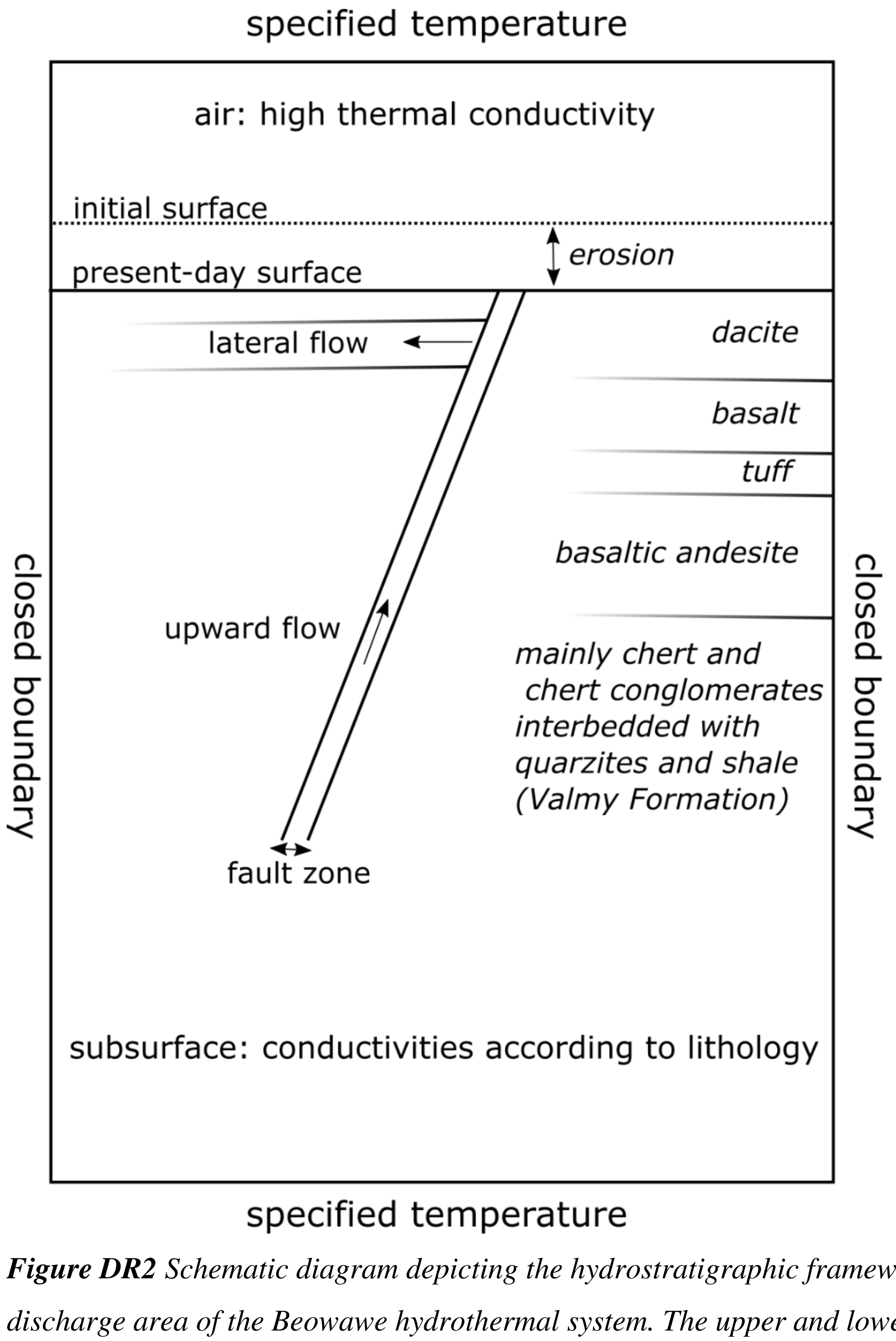



***Figure DR2*** *Schematic diagram depicting the hydrostratigraphic framework model of the discharge area of the Beowawe hydrothermal system. The upper and lower boundary conditions were assigned a specified temperature according to the average annual air temperature and the regional geothermal gradient. No heat flow is allowed over the left and right hand model boundary. Fluid flows upwards along a single fault zone, part of the flux* *contributes to lateral flow in one or more aquifers that are connected to the fault. The remaining fluid discharges at the surface. The bottom of the fault is located above the lower boundary of the model domain to avoid interference of the boundary with modeled fluid temperatures. Heat transfer between the surface and the atmosphere is modeled as a conductive heat flow. Heat transfer in the subsurface is determined by the specific thermal conductivities of the local lithologies. The land surface is lowered in steps of 1 m to account for erosion over longer timescales.*

**DR1.7: Borehole temperature data**

We compared modeled temperatures with borehole temperature data from hydrothermal exploration programs from the deep well Beowawe 85-18 (Figure 2). Beowawe 85-18 was drilled and completed from February 22$^{nd}$ 1980 to June 2$^{nd}$ 1980. Temperature-depth profiles were conducted in five separate runs on May 10$^{th}$ and 11$^{th}$ 1980 (Iovenitti and Epperson, Jr., 1981).

**DR1.8: Model sensitivity analysis**

A sensitivity analysis was performed to test the influence of model parameters on the thermal overprint of AHe data in surface samples adjacent to the hydrothermally active Malpais fault. The parameters and their ranges are listed in Table DR3. A first model run was performed with the initial base values that were taken from earlier studies on the Beowawe hydrothermal system. For each parameter listed in Table DR3, a range of values were tested by changing the parameter in each model run while keeping all other parameters fixed to their initial base values.

No direct measurements of the Malpais damage zone width were performed. However, studies on fault zone architecture show that there is a positive correlation between fault damage zone (or fault thickness) and displacement (Caine et al., 1996; Childs et al., 2009; Bense et al., 2013). Based on these studies we derived an estimate of the fault damage zone for the Malpais fault. With a displacement of ~230 m and a crystalline bed rock we used fault zone thickness values varying between 10 and 30 m for our parameter range (Table DR3).

We used a background geothermal gradient of 0.04°C m$^{-1}$ (Howald et al., 2016). This is in accordance with Zoback's (Zoback, 1979) reported reservoir temperature of 210-230°C. The deep reservoir is located in a carbonate layer of the Valmy Formation at depth of ~5 km.

Smith (Smith, 1983) reports a general background heat flow of 110 mW $m^{-2}$ in this part of the Battle Mountain heat flow high. With thermal conductivities varying between 1.6 and 4.4 W $m^{-1}$ $K^{-1}$ for the different lithologies, the geothermal gradient could vary between 0.02 and 0.07°C $m^{-1}$.

The exhumation rate was varied between $1\times10^{-3}$ and $7.5\times10^{-5}$ m $a^{-1}$. Estimates of erosion and exhumation rates in the Basin and Range vary widely. Low temperature thermochronology indicates long-term (millions of years) exhumation rate of 6 x $10^{-4}$ m $a^{-1}$ for the Wassuk range in the eastern part of the Basin and Range (Stockli et al., 2002). Surface exposure dating using cosmogenic nuclides suggests relatively high short-term erosion rates of 5 x $10^{-3}$ m $a^{-1}$ in the Yucca mountains (Gosse et al., 1995). In contrast, a cosmogenic nuclide study in SE-Arizona by Jungers & Heimsath (2016) suggested much lower erosion rates of 3 x $10^{-5}$ to 6 x $10^{-5}$ m $a^{-1}$. In the Sierra Nevada, west of the Basin and Range, exhumation varies between 1 x $10^{-5}$ to 3 x $10^{-4}$ m $a^{-1}$, with a strong correlation of the rate of exhumation and the proximity to active faults (Riebe et al., 2000). Given the high activity of the Malpais fault as shown by the prominent fault scarp and two dated earthquakes over the last 20,000 years (Wesnousky et al., 2005) we adopt a exhumation rate of 1 x $10^{-4}$ m $a^{-1}$ over the last 500,000 years as a base case. Given the large uncertainty of this value we explore a wide range of exhumation rates using sensitivity analysis. We also tested the effects of relatively high exhumation rates of 1 $\times10^{-3}$ m $a^{-1}$ that reflect rates in active mountain belts (Herman et al., 2013).

Based on a detailed study on the hydrogeology of the Beowawe geothermal system by Olmsted and Rush (1987), the pre-developmental discharge rate at the Beowawe hydrothermal system was estimated to have been ~380 $m^2$ $s^{-1}$. This value is based on recent hydrogeological activity. However, this value may have changed over geological timescales. Nolan and Anderson (1934) reported that hydrothermal discharge varied seasonally, indicated by more energetic activity during the winter months. Both Howald et al. (2015) and Banerjee et al. (2011) suggest a transient and episodic fluid flow for the Beowawe system, with changes over a timescale of approximately 7000 years. To quantify the effect of changing fluid fluxes we included values ranging between 100 and 600 $m^2$ $s^{-1}$ in the sensitivity analysis.

***Table DR3*** *Parameters used for modeling and ranges of values tested in sensitivity analysis.*

| Parameter | Base Value | Range | Unit |
|---|---|---|---|
| Exhumation rate | 0.0001 | $1\times10^{-3}$ - $7.5\times10^{-5}$ | M $a^{-1}$ |
| Geothermal gradient | 0.04 | 0.02 - 0.07 | C° $m^{-1}$ |
| Fault width | 10 | 10 – 40 | m |
| Fault flux | 400 | 100 – 600 | $m^2$ $s^{-1}$ |
| Width of model domain | 2000 | | m |
| Depth of model domain | 8000 | | m |
| Cell size | 250 | | m |
| Cell size air layer | 10 | | m |
| Cell size fault zone | 2.5 | | m |
| Cell size at land surface | 100 | | m |
| Cell size base | 500 | | m |
| Fault angle | 65 | | ° |
| Fault bottom | 5000 | | m BGS |
| Air temperature | 10 | | °C |
| Aerodynamic resistance | 80 | 20 - 140 | s $m^{-1}$ |
| Crystallization age host rock | 15.7 | | Ma |
| Stopping distance of alpha particle | $2.10\times10^{-5}$ | | m |

***Table DR4*** *Depth and properties of the different lithologies. The depth of lithologies of the footwall taken from deep well Collins* (Sibbett, 1983)*, thermal conductivity was based on Smith* (Smith, 1983) *and porosity on Freeze and Cherry* (Freeze and Cherry, 1979).

| Lithology | Bottom of layer (footwall) (m BGS) | Porosity (dimensionless) | Thermal conductivity (W $m^{-1}$ $K^{-1}$) |
|---|---|---|---|
| dacite | 370 | 0.08 | 2 |
| basalt | 550 | 0.05 | 1.6 |
| tuff | 720 | 0.2 | 1.58 |
| basaltic andesite | 950 | 0.05 | 2.26 |
| Valmy formation | | 0.05 | 4.44 |

## DR2: RESULTS

### DR2.1: U-Pb geochronology

The average zircon U-Pb age of four dacite  samples was determined to be 15.6 Ma (Table DR5, Fig. DR5), which is slightly younger than previously reported K-Ar ages of the same volcanic unit (Struhsacker, 1980).

***Table DR5*** *Results of U-Pb analysis. Ages are shown in Ma including their decay constant errors. For samples B-2, B-8 and B-9 a total of 15 crystals were analyzed and for samples B-17 17 crystals were analyzed. Unc. is uncertainty, prob. denotes probability and corr. denotes corrected.*

| Sample | Dated crystals | N crystals | Concordia age (Ma) | Unc. (Ma) | MSWD | Prob. | U (µg $g^{-1}$) | Th (µg $g^{-1}$) | Log alpha Density $(alpha/g)^{-1}$ | Corr. Age (Ma) | Unc. (Ma) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B-2 | 15 | 13 | 15.25 | 0.11 | 0.07 | 0.79 | 1358 | 1985 | 16.9 | 15.6 | 0.3 |
| B-8 | 15 | 14 | 15.23 | 0.10 | 0.18 | 0.68 | 1283 | 1329 | 16.9 | 15.6 | 0.3 |
| B-9 | 15 | 15 | 15.02 | 0.11 | 2.80 | 0.10 | 1253 | 1057 | 16.9 | 15.4 | 0.3 |
| B-17 | 17 | 17 | 15.47 | 0.05 | 0.01 | 0.91 | 1959 | 3231 | 17.1 | 15.7 | 0.3 |

### DR2.2: Apatite (U-Th)/He data

Table DR6 summarizes the results of (U-Th)/He analysis. The map in Figure DR1 shows the surface samples along the Malpais fault. Single grains that significantly are out of line with the others are excluded from the average age (marked grey in Table DR6), but they are still included in the comparison between the modeled ages and the measured ages. These outliners can be the result of tiny inclusions or zoning in the actinide content of the dated apatite crystal. The unweighted average age of six samples (B-1, B-6, B-7, B-14, B-16, B-17) show AHe ages similar to the U-Pb age of the host rock. These samples have not experienced detectable thermal overprint since their crystallization. Most of them are located at distances of approximately 50 m away from the main fault. Samples B-16 and B-7 are located at distances of ~15 m to ~20 m to the fault respectively. Two samples are potentially partially reset (B-5 and B-12), which means that these samples have a younger AHe age than the crystallization age but their uncertainty is in the range of the U-Pb age. Both are within a distance of about 10 m from the Malpais fault. The remaining 7 samples are younger than the emplacement age, showing a thermal overprint on their AHe age (B-2, B-3, B-8, B-9, B-10, B-11, B-13). These samples are within a distance of only a few m to up to ~40 m from the hydrothermally active normal fault. Sample B-17 shows older AHe ages than its U-Pb age. This is most likely due to submicroscopic fluid or mineral inclusions.

To assess the impact of zonation of alpha-emitting element in the apatite crystals on the measured AHe ages, the actinide concentrations in single crystals were imaged using laser ablation (Fig. DR4). The laser ablation line measurement has shown variable patterns in actinide concentration, with both core and rim-zoned crystals for a number of 24 grains from 7 samples (B-1, B-2, B-5, B-7, B-8, B-9, B-13). For most grains the actinide concentration is about 15% in the outer most 10 µm. Following the He-diffusion model HeFTy (Ketcham, 2005), the difference in modeled ages between the homogeneous assumption and rim zoned grains is approximately 100 to 200 ka for typical grain properties found in this study (radius: 70 µm, U: 6 ppm, Th: 17 ppm, Sm: 370 ppm). Given the relatively small magnitude of the error induced by zonation, we assumed homogeneous U-Th-Sm distributions for calculating AHe ages using alpha ejection ($F_T$) correction and all further model-data comparison.

***Table DR6*** *Results of (U-Th)/He analysis.*

| Sample | Sphere radius [µm] | He vol. [ncc] | He 1s [%] | U238 mass [ng] | U238 1s [%] | U238 conc. [ppm] | Th232 mass [ng] | Th232 1s [%] | Th232 conc. [ppm] | Th/U ratio | Sm mass [ng] | Sm 1s [%] | Sm conc. [ppm] | Ejection correct. (Ft) | *Uncorr. He-age [Ma]* | Ft-Corr. He-age [Ma] | 2s [Ma] | 2s [%] | Sample unweighted aver. ± 1 s.e. [Ma] | [Ma] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B-1 a1 | 39.5 | **0.018** | 4.5 | **0.006** | 14.0 | 3.5 | **0.022** | 3.0 | 13.7 | 3.92 | **0.550** | 8.4 | 336 | **0.59** | *9.6* | **16.3** | 3.1 | 19.0 | | |
| B-1 a2 | 40.9 | **0.023** | 4.1 | **0.005** | 17.8 | 1.5 | **0.015** | 3.2 | 4.3 | 2.92 | **0.511** | 8.4 | 147 | **0.59** | *14.7* | **24.8** | 5.2 | 20.9 | | |
| B-1 a3 | 52.7 | **0.030** | 3.4 | **0.009** | 9.3 | 4.0 | **0.027** | 2.9 | 12.3 | 3.12 | **0.731** | 8.3 | 328 | **0.69** | *11.7* | **16.8** | 2.4 | 14.4 | | |
| B-1 a4 | 56.7 | **0.032** | 3.4 | **0.010** | 8.2 | 3.0 | **0.030** | 2.8 | 9.0 | 2.98 | **0.945** | 8.3 | 283 | **0.72** | *10.6* | **14.7** | 2.0 | 13.8 | **15.8** | 2.2 |
| B-1 a5 | 68.6 | **0.127** | 1.8 | **0.031** | 3.0 | 5.3 | **0.096** | 2.5 | 16.4 | 3.08 | **2.200** | 8.2 | 377 | **0.77** | *14.6* | **19.1** | 1.8 | 9.4 | | |
| B-2 a1 | 94.9 | **0.024** | 3.8 | **0.017** | 5.1 | 4.3 | **0.070** | 2.5 | 17.5 | 4.10 | **1.303** | 8.2 | 328 | **0.83** | *4.4* | **5.4** | 0.6 | 10.9 | | |
| B-2 a2 | 106.5 | **0.044** | 2.8 | **0.016** | 5.4 | 2.9 | **0.046** | 2.7 | 8.6 | 2.94 | **1.637** | 8.2 | 302 | **0.85** | *9.0* | **10.7** | 1.1 | 10.0 | | |
| B-2 a3 | 104.1 | **0.087** | 2.0 | **0.028** | 3.3 | 7.7 | **0.226** | 2.4 | 63.1 | 8.16 | **1.498** | 8.2 | 418 | **0.84** | *7.7* | **9.2** | 0.7 | 7.4 | | |
| B-2 a4 | 81.7 | **0.025** | 3.5 | **0.010** | 8.1 | 4.7 | **0.032** | 2.8 | 14.7 | 3.14 | **0.812** | 8.3 | 371 | **0.81** | *8.4* | **10.3** | 1.2 | 12.0 | **8.9** | 0.9 |
| B-3 a1 | 59.7 | **0.108** | 2.0 | **0.046** | 3.5 | 6.8 | **0.209** | 2.5 | 30.9 | 4.57 | **2.675** | 2.2 | 396 | **0.729** | *7.61* | **10.44** | 1.01 | 9.7 | | |
| B-3 a2 | 90.0 | **0.033** | 3.2 | **0.017** | 8.9 | 2.9 | **0.054** | 2.7 | 9.4 | 3.22 | **1.362** | 2.2 | 239 | **0.834** | *6.77* | **8.11** | 0.89 | 11.0 | | |
| B-3 a3 | 71.6 | **0.042** | 3.1 | **0.019** | 7.9 | 3.6 | **0.054** | 2.7 | 10.2 | 2.83 | **1.188** | 2.2 | 224 | **0.795** | *8.36* | **10.52** | 1.19 | 11.3 | | |
| B-3 a4 | 78.0 | **0.031** | 3.5 | **0.013** | 11.4 | 2.7 | **0.039** | 2.9 | 8.1 | 2.98 | **0.952** | 2.2 | 201 | **0.792** | *8.61* | **10.87** | 1.46 | 13.4 | **10.0** | 1.1 |
| B-5 a1 | 72.7 | **0.114** | 1.9 | **0.043** | 2.3 | 6.5 | **0.126** | 2.5 | 19.0 | 2.91 | **2.553** | 2.8 | 384 | **0.78** | *10.0* | **12.8** | 1.0 | 8.0 | | |
| B-5 a2 | 67.5 | **0.047** | 2.7 | **0.013** | 5.5 | 6.3 | **0.063** | 2.6 | 30.2 | 4.78 | **0.815** | 3.8 | 392 | **0.76** | *11.3* | **14.8** | 1.5 | 10.1 | | |
| B-5 a3 | 90.5 | **0.011** | 5.3 | **0.004** | 24.7 | 2.2 | **0.013** | 3.5 | 7.5 | 3.50 | **0.439** | 4.8 | 256 | **0.82** | *8.7* | **10.6** | 2.2 | 21.1 | | |
| B-5 a4 | 67.9 | **0.071** | 2.2 | **0.017** | 4.5 | 4.9 | **0.056** | 2.6 | 15.7 | 3.19 | **1.372** | 3.1 | 387 | **0.78** | *14.1* | **18.0** | 1.6 | 9.0 | **14.1** | 1.6 |
| B-6 a1 | 46.7 | **0.024** | 3.5 | **0.009** | 17.3 | 2.3 | **0.026** | 3.0 | 6.8 | 2.98 | **0.510** | 2.2 | 131 | **0.658** | *10.36* | **15.75** | 3.12 | 19.8 | | |
| B-6 a2 | 46.8 | **0.036** | 3.4 | **0.012** | 13.1 | 2.8 | **0.036** | 2.9 | 8.9 | 3.11 | **0.629** | 2.2 | 155 | **0.664** | *11.73* | **17.67** | 2.98 | 16.9 | | |
| B-6 a3 | 47.0 | **0.009** | 5.9 | **0.004** | 36.4 | 1.2 | **0.013** | 3.0 | 3.7 | 3.02 | **0.321** | 2.2 | 93 | **0.681** | *7.63* | **11.20** | 3.76 | 33.6 | | |
| B-6 a4 | 52.4 | **0.027** | 3.6 | **0.008** | 21.1 | 2.2 | **0.024** | 3.1 | 6.3 | 2.88 | **0.537** | 2.2 | 143 | **0.709** | *12.45* | **17.57** | 3.80 | 21.6 | **15.5** | 3.4 |
| B-7 a1 | 55.9 | **0.042** | 2.7 | **0.014** | 9.9 | 2.9 | **0.045** | 2.8 | 9.3 | 3.16 | **0.979** | 2.2 | 204 | **0.712** | *10.68* | **15.00** | 1.99 | 13.2 | | |
| B-7 a2 | 51.6 | **0.018** | 4.3 | **0.005** | 30.9 | 1.5 | **0.016** | 3.1 | 4.8 | 3.23 | **0.406** | 2.2 | 118 | **0.710** | *12.13* | **17.09** | 4.70 | 27.5 | | |
| B-7 a3 | 61.3 | **0.038** | 3.1 | **0.013** | 11.0 | 2.7 | **0.043** | 2.8 | 8.6 | 3.24 | **1.047** | 2.2 | 210 | **0.738** | *9.95* | **13.47** | 1.81 | 13.4 | **15.2** | 2.8 |
| B-7 a4 | 38.3 | **0.020** | 4.1 | **0.005** | 27.9 | 1.4 | **0.015** | 3.2 | 4.2 | 2.94 | **0.469** | 2.2 | 127 | **0.575** | *12.77* | **22.20** | 5.96 | 26.8 | | |
| B-8 a1 | 74.0 | **0.052** | 2.7 | **0.026** | 3.2 | 7.9 | **0.071** | 2.5 | 21.7 | 2.75 | **1.465** | 3.4 | 449 | **0.78** | *7.9* | **10.1** | 0.9 | 9.2 | | |
| B-8 a2 | 57.2 | **0.033** | 3.3 | **0.013** | 5.7 | 7.4 | **0.038** | 2.7 | 21.9 | 2.94 | **0.822** | 4.2 | 471 | **0.72** | *9.4* | **13.1** | 1.6 | 12.1 | | |
| B-8 a3 | 73.7 | **0.017** | 4.3 | **0.011** | 7.2 | 4.7 | **0.034** | 2.7 | 14.0 | 2.98 | **0.924** | 3.9 | 383 | **0.78** | *5.3* | **6.9** | 0.9 | 12.6 | | |
| B-8 a4 | 59.1 | **0.058** | 2.5 | **0.027** | 2.9 | 5.8 | **0.086** | 2.5 | 18.1 | 3.14 | **1.819** | 3.1 | 382 | **0.73** | *7.7* | **10.5** | 1.0 | 10.0 | **10.1** | 1.3 |
| B-9 a1 | 72.6 | **0.009** | 5.9 | **0.011** | 7.4 | 8.6 | **0.031** | 2.8 | 24.9 | 2.89 | **0.575** | 5.4 | 461 | **0.78** | *3.3* | **4.2** | 0.6 | 15.4 | | |
| B-9 a2 | 74.8 | **0.023** | 3.9 | **0.018** | 4.4 | 5.8 | **0.052** | 2.6 | 17.0 | 2.94 | **1.165** | 3.5 | 384 | **0.79** | *4.8* | **6.0** | 0.7 | 11.0 | | |
| B-9 a3 | 63.5 | **0.050** | 2.8 | **0.023** | 3.3 | 4.8 | **0.069** | 2.5 | 14.7 | 3.03 | **1.495** | 3.7 | 319 | **0.75** | *8.0* | **10.7** | 1.1 | 10.2 | | |
| B-9 a4 | 45.7 | **0.030** | 3.2 | **0.013** | 5.3 | 5.8 | **0.034** | 2.7 | 14.6 | 2.53 | **0.869** | 3.7 | 373 | **0.65** | *8.7* | **13.4** | 1.8 | 13.4 | **8.6** | 2.1 |
| B-10 a1 | 61.9 | **0.041** | 2.9 | **0.017** | 4.5 | 4.9 | **0.053** | 2.6 | 15.2 | 3.08 | **1.355** | 3.5 | 391 | **0.73** | *8.2* | **11.2** | 1.2 | 10.9 | | |
| B-10 a2 | 92.2 | **0.024** | 3.9 | **0.010** | 7.7 | 4.6 | **0.032** | 2.8 | 14.8 | 3.20 | **0.756** | 3.9 | 350 | **0.83** | *8.4* | **10.1** | 1.2 | 11.5 | | |
| B-10 a3 | 89.8 | **0.122** | 1.8 | **0.040** | 2.4 | 4.1 | **0.204** | 2.4 | 20.7 | 5.06 | **3.298** | 2.4 | 334 | **0.82** | *8.7* | **10.6** | 0.8 | 7.1 | | |
| B-10 a4 | 57.2 | **0.045** | 2.7 | **0.016** | 4.5 | 5.6 | **0.060** | 2.6 | 20.8 | 3.75 | **1.261** | 3.0 | 435 | **0.71** | *9.1* | **12.7** | 1.4 | 10.9 | **11.2** | 0.6 |
| B-11 a1 | 76.2 | **0.036** | 2.8 | **0.013** | 5.5 | 4.2 | **0.036** | 2.7 | 11.7 | 2.78 | **0.922** | 3.8 | 298 | **0.79** | *10.1* | **12.8** | 1.3 | 10.0 | | |
| B-11 a2 | 83.6 | **0.038** | 3.0 | **0.016** | 4.8 | 7.8 | **0.038** | 2.7 | 18.5 | 2.37 | **0.744** | 3.7 | 364 | **0.81** | *10.3* | **12.7** | 1.3 | 9.8 | | |
| B-11 a3 | 75.3 | **0.018** | 4.1 | **0.010** | 7.4 | 8.4 | **0.023** | 2.9 | 20.8 | 2.46 | **0.417** | 4.3 | 370 | **0.79** | *8.2* | **10.5** | 1.4 | 12.9 | | |
| B-11 a4 | 106.5 | **0.046** | 2.7 | **0.019** | 4.0 | 7.1 | **0.051** | 2.6 | 18.5 | 2.61 | **0.987** | 3.6 | 361 | **0.85** | *9.7* | **11.4** | 0.9 | 8.2 | 11.8 | 0.6 |

| Sample | Sphere radius [µm] | He vol. [ncc] | He 1s [%] | U238 mass [ng] | U238 1s [%] | U238 conc. [ppm] | Th232 mass [ng] | Th232 1s [%] | Th232 conc. [ppm] | Th/U ratio | Sm mass [ng] | Sm 1s [%] | Sm conc. [ppm] | Ejection correct. (Ft) | *Uncorr. He-age [Ma]* | Ft-Corr. He-age [Ma] | 2s [Ma] | 2s [%] | Sample unweighted aver. ± 1 s.e. [Ma] | [Ma] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B-12 a1 | 51.2 | **0.039** | 2.9 | **0.010** | 17.4 | 2.3 | **0.040** | 2.8 | 9.2 | 4.03 | **0.807** | 2.2 | 185 | **0.687** | *12.25* | **17.84** | 3.04 | 17.0 | | |
| B-12 a2 | 67.6 | **0.012** | 5.0 | **0.006** | 25.9 | 1.6 | **0.019** | 3.3 | 4.6 | 2.93 | **0.576** | 2.2 | 141 | **0.798** | *6.17* | **7.73** | 1.83 | 23.7 | | |
| B-12 a3 | 45.8 | **0.029** | 3.4 | **0.010** | 15.9 | 2.5 | **0.034** | 2.9 | 8.8 | 3.53 | **0.644** | 2.2 | 168 | **0.646** | *10.45* | **16.16** | 2.93 | 18.1 | | |
| B-12 a4 | 41.0 | **0.011** | 5.3 | **0.005** | 34.5 | 1.3 | **0.016** | 3.1 | 4.6 | 3.49 | **0.342** | 2.2 | 100 | **0.605** | *8.33* | **13.78** | 4.34 | 31.5 | **13.9** | 3.0 |
| B-13 a1 | 67.7 | **0.028** | 3.6 | **0.013** | 6.4 | 7.1 | **0.033** | 2.7 | 17.9 | 2.52 | **0.674** | 4.8 | 364 | **0.76** | *8.6* | **11.4** | 1.4 | 12.3 | | |
| B-13 a2 | 61.5 | **0.069** | 2.4 | **0.025** | 3.2 | 5.8 | **0.079** | 2.5 | 18.7 | 3.19 | **1.561** | 4.0 | 369 | **0.73** | *10.2* | **14.0** | 1.4 | 10.1 | | |
| B-13 a3 | 49.1 | **0.015** | 4.8 | **0.008** | 11.5 | 3.5 | **0.017** | 3.2 | 8.0 | 2.29 | **0.625** | 4.2 | 289 | **0.66** | *7.4* | **11.3** | 2.0 | 17.4 | **12.2** | 0.9 |
| B-13 a4 | *38.4* | **0.005** | 1.8 | **0.010** | 8.2 | 5.8 | **0.031** | 2.8 | 17.9 | 3.06 | **0.598** | 5.0 | 346 | **0.56** | *1.9* | **3.4** | 0.5 | 15.6 | | |
| B-14 a1 | *84.9* | **0.070** | 2.3 | **0.021** | 4.1 | 7.9 | **0.073** | 2.5 | 27.6 | 3.49 | **1.214** | 8.3 | 460 | **0.81** | *12.1* | **14.9** | 1.3 | 9.0 | | |
| B-14 a2 | 103.4 | **0.053** | 2.8 | **0.018** | 4.7 | 6.2 | **0.063** | 2.6 | 21.7 | 3.49 | **1.196** | 8.3 | 410 | **0.85** | *10.1* | **11.8** | 1.1 | 9.1 | | |
| B-14 a3 | 70.8 | **0.066** | 2.4 | **0.013** | 6.0 | 3.8 | **0.076** | 2.5 | 21.6 | 5.72 | **1.144** | 8.3 | 326 | **0.77** | *13.4* | **17.4** | 1.8 | 10.2 | | |
| B-14 a4 | 80.1 | **0.052** | 2.7 | **0.012** | 6.8 | 2.9 | **0.038** | 2.7 | 9.0 | 3.14 | **1.270** | 8.3 | 302 | **0.80** | *13.6* | **17.0** | 1.9 | 11.0 | **15.3** | 1.5 |
| B-15 a1 | 62.3 | **0.030** | 3.4 | **0.011** | 16.6 | 2.7 | **0.037** | 2.8 | 8.9 | 3.24 | **0.720** | 2.2 | 172 | **0.760** | *9.41* | **12.37** | 2.13 | 17.2 | | |
| B-15 a2 | 44.2 | **66.851** | 5.6 | **0.020** | 7.9 | 4.7 | **0.191** | 2.5 | 46.4 | 9.81 | **0.821** | 2.2 | 199 | **0.629** | *5967.96* | **9489.89** | 1579.42 | 16.6 | | |
| B-15 a3 | 42.6 | **0.407** | 1.5 | **0.299** | 1.9 | 76.1 | **0.010** | 3.0 | 2.7 | 0.03 | **0.498** | 2.2 | 127 | **0.647** | *11.01* | **17.02** | 1.97 | 11.6 | | |
| B-15 a4 | 41.3 | **0.019** | 4.1 | **0.008** | 18.8 | 2.0 | **0.035** | 2.9 | 8.9 | 4.39 | **0.532** | 2.2 | 135 | **0.610** | *7.71* | **12.64** | 2.55 | 20.1 | **14.0** | 2.2 |
| B-16 a1 | 46.9 | **0.032** | 3.2 | **0.010** | 16.9 | 2.6 | **0.038** | 2.8 | 9.8 | 3.77 | **0.591** | 2.2 | 154 | **0.657** | *11.28* | **17.19** | 3.16 | 18.4 | | |
| B-16 a2 | 41.1 | **0.020** | 4.0 | **0.005** | 44.6 | 1.5 | **0.021** | 3.1 | 6.0 | 3.86 | **0.431** | 2.2 | 125 | **0.603** | *11.88* | **19.69** | 7.14 | 36.2 | | |
| B-16 a3 | 59.0 | **0.060** | 2.6 | **0.018** | 8.0 | 3.5 | **0.067** | 2.6 | 13.1 | 3.75 | **1.260** | 2.2 | 246 | **0.728** | *11.24* | **15.44** | 1.80 | 11.7 | | |
| B-16 a4 | 61.1 | **0.032** | 3.2 | **0.013** | 12.1 | 3.2 | **0.049** | 2.8 | 12.5 | 3.87 | **0.710** | 2.2 | 181 | **0.770** | *8.81* | **11.45** | 1.58 | 13.8 | **15.9** | 3.4 |
| B-17 a1 | 47.7 | **0.027** | 3.7 | **0.010** | 15.7 | 2.6 | **0.040** | 2.8 | 10.9 | 4.12 | **0.680** | 2.2 | 184 | **0.660** | *8.93* | **13.54** | 2.36 | 17.5 | | |
| B-17 a2 | 50.9 | **0.039** | 3.0 | **0.008** | 18.3 | 2.1 | **0.031** | 3.0 | 8.1 | 3.85 | **0.618** | 2.2 | 159 | **0.682** | *15.78* | **23.14** | 4.17 | 18.0 | | |
| B-17 a3 | 36.6 | **0.028** | 3.6 | **0.006** | 25.6 | 1.7 | **0.021** | 3.0 | 6.2 | 3.67 | **0.403** | 2.2 | 121 | **0.562** | *17.07* | **30.35** | 7.62 | 25.1 | | |
| B-17 a4 | 49.5 | **0.014** | 5.3 | **0.003** | 60.5 | 1.1 | **0.010** | 3.0 | 3.3 | 3.00 | **0.252** | 2.2 | 81 | **0.695** | *14.69* | **21.15** | 11.07 | 52.3 | **22.0** | 6.3 |

*Table DR7* XRD results.

| | |
|---|---|
| Device | Philips X'Pert MPD |
| Rietveld software | AutoQuan 2.8.0.1 |
| Tube | Cu Kα |
| Voltage [kV] | 40 |
| Current [mA] | 30 |
| Soller slit [rad] | 0.04 |
| Divergence slit [°] | 0.5 |
| Mask [mm] | 20 |
| Anti Scatter slit [°] | 0.5 |
| Reciving slit [mm] | 0.2 |
| Scan mode | step scan |
| Step (°2Theta) | 0.02 |
| Time/step [s] | 10 |
| Internal Standard | 20 wt% ZnO |

| $SiO_2$ (Quarz) [%] | K-Fsp [%] | Plagioclase [%] |
|---|---|---|
| 20 | 46 | 34 |
| 6 | 21 | 73 |
| 7 | 27 | 66 |
| 22 | 23 | 54 |
| 20 | 17 | 63 |
| 19 | 19 | 62 |

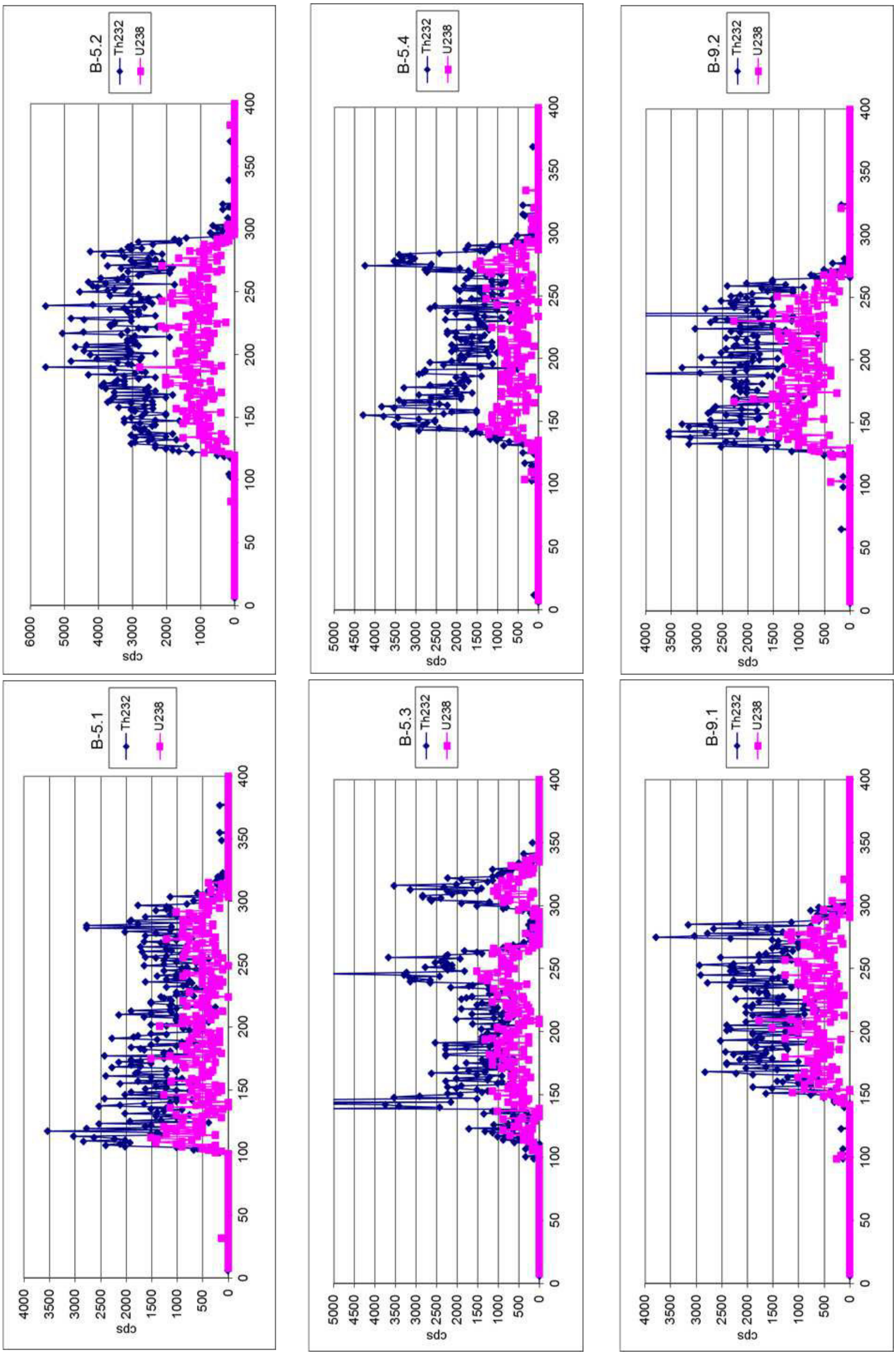
| Batch 1 | | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ |
|---|---|---|---|---|---|---|---|
| Probe | Qualitätsparameter (1-rho) [%] | amorph content | | Cordierite | | Cristobalite | |
| SL-B-4 | 0.76 | 5.20 | 4.20 | | | 6.26 | 1.23 |
| SL-B-5 | 0.63 | 8.37 | 2.91 | 2.86 | 0.42 | 2.32 | 0.81 |
| SL-B-8 | 0.66 | 4.20 | 3.30 | | | 2.74 | 0.63 |
| SL-B-9 | 0.76 | 2.90 | 4.80 | | | 11.14 | 2.85 |
| SL-B-14 | 0.68 | 5.20 | 3.30 | 0.75 | 0.33 | 9.74 | 2.04 |
| SL-B-17 | 0.75 | 5.40 | 3.30 | 0.20 | 0.28 | 9.20 | 0.99 |

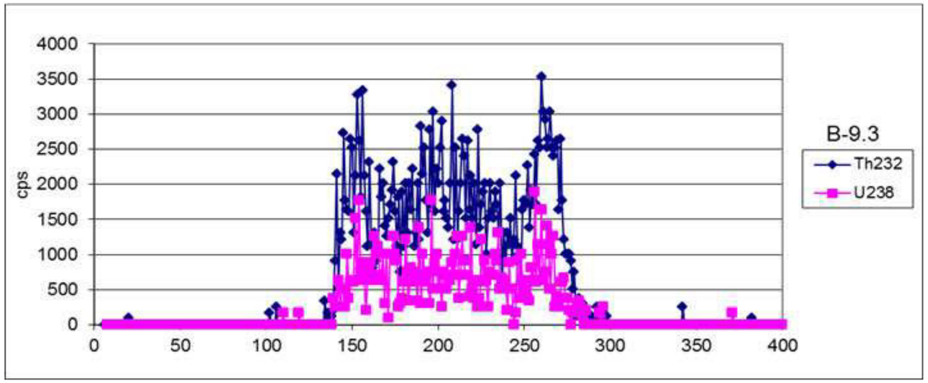
| Batch 1 | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ |
|---|---|---|---|---|---|---|---|---|
| Probe | Tridymite | | Diopside | | Garronite | | Goethite | |
| SL-B-4 | 9.85 | 0.84 | | | 1.55 | 1.11 | 1.75 | 0.81 |
| SL-B-5 | 9.80 | 1.32 | | | | | 5.79 | 0.96 |
| SL-B-8 | 9.56 | 1.44 | | | | | 3.19 | 0.84 |
| SL-B-9 | 10.52 | 0.72 | | | 0.88 | 1.08 | 0.72 | 0.96 |
| SL-B-14 | 4.19 | 1.26 | | | | | 4.62 | 1.17 |
| SL-B-17 | 3.29 | 1.92 | 1.91 | 0.72 | | | 6.24 | 1.08 |

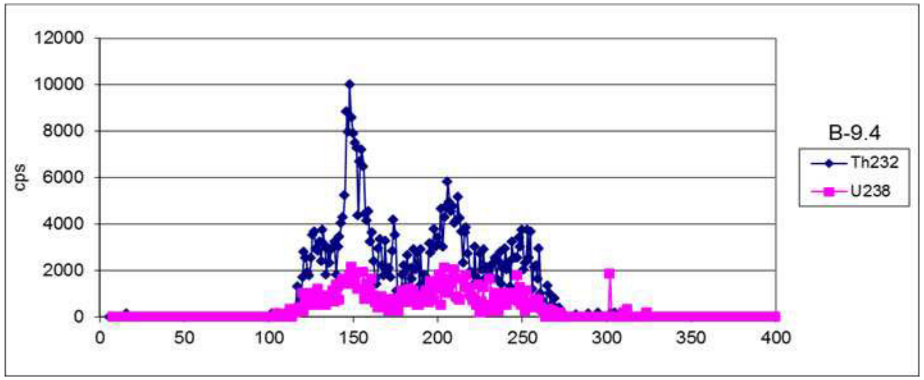
| Batch 1 | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ |
|---|---|---|---|---|---|---|---|---|
| Probe | Hematite | | Kaolinite | | Microcline | | Albit | |
| SL-B-4 | 2.28 | 0.45 | 6.75 | 1.11 | 14.16 | 3.81 | 2.68 | 2.31 |
| SL-B-5 | 1.17 | 0.22 | | | 7.93 | 2.01 | 2.04 | 0.69 |
| SL-B-8 | 1.51 | 0.25 | 1.68 | 0.75 | 11.43 | 2.76 | 4.89 | 1.41 |
| SL-B-9 | 2.27 | 0.39 | | | 11.56 | 4.05 | 3.40 | 2.19 |
| SL-B-14 | 1.65 | 0.21 | | | 8.02 | 1.89 | 9.17 | 1.77 |
| SL-B-17 | 1.09 | 0.17 | | | 9.13 | 1.95 | 7.37 | 1.47 |

| Batch 1 | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ | Mineral Phase [wt%] | ±3σ |
|---|---|---|---|---|---|---|---|---|
| Probe | Andesine | | Quartz | | Sanidine | | Smectite | |
| SL-B-4 | 7.70 | 1.74 | 6.02 | 0.45 | 23.37 | 2.73 | 12.40 | 3.30 |
| SL-B-5 | 26.25 | 1.41 | 2.92 | 0.19 | 24.11 | 1.59 | 6.43 | 1.20 |
| SL-B-8 | 23.04 | 1.47 | 3.17 | 0.27 | 24.38 | 1.56 | 10.14 | 1.68 |
| SL-B-9 | 23.49 | 1.59 | 2.52 | 0.36 | 22.30 | 2.85 | 8.75 | 2.85 |
| SL-B-14 | 21.38 | 1.56 | 4.28 | 0.21 | 25.81 | 1.80 | 5.18 | 1.05 |
| SL-B-17 | 22.81 | 1.68 | 1.10 | 0.14 | 27.16 | 1.71 | 5.16 | 1.41 |

***Figure DR4*** *Laser ablation profiling perpendicular to the c-axis.*




B-9.3
Th232
U238
cps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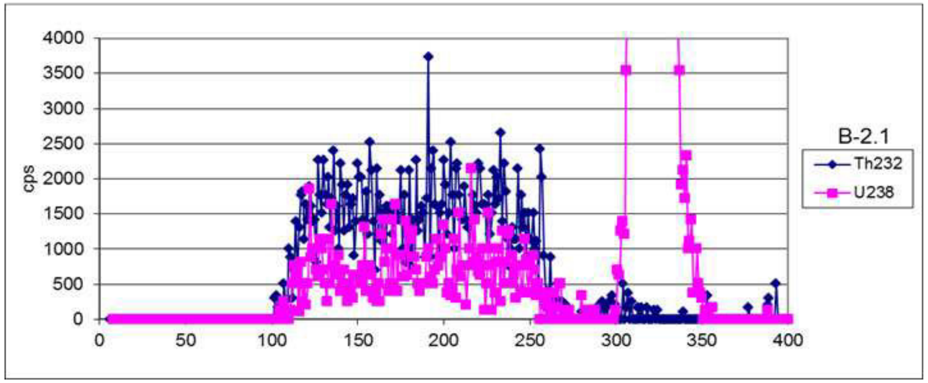
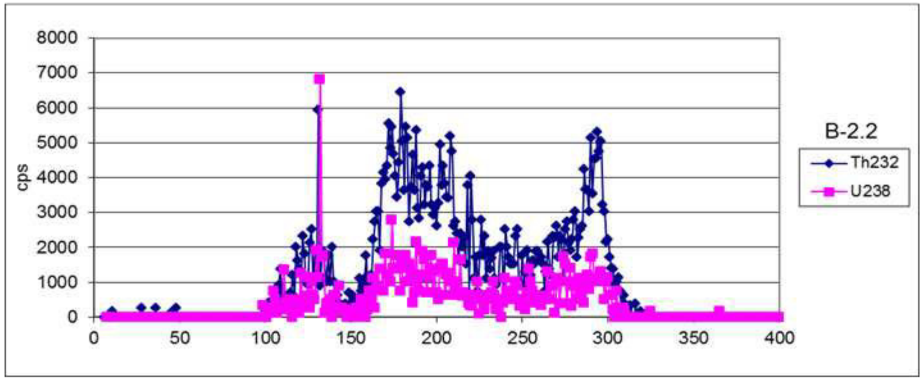
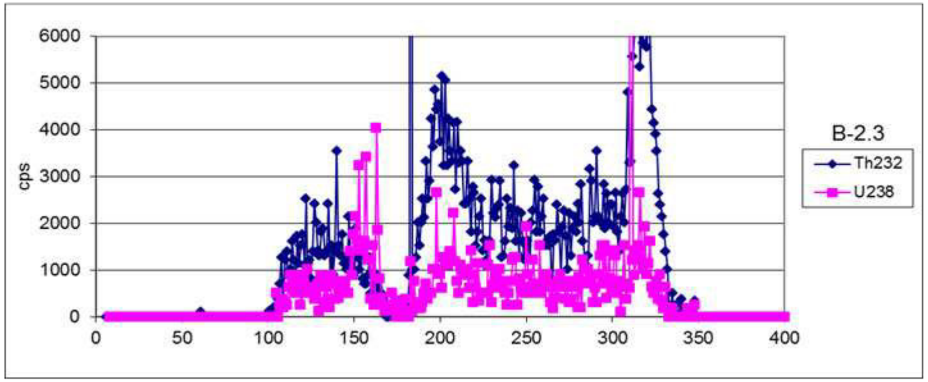
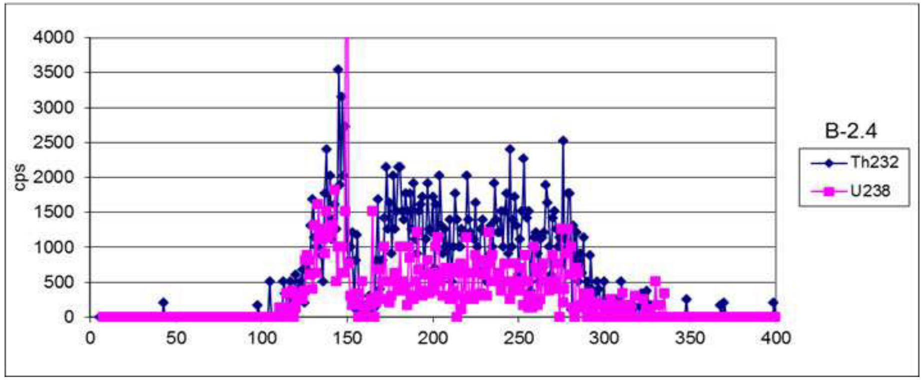
Th232
U238
cps


B-2.1
Th232
U238
cps


B-2.2
Th232
U238
cps


B-2.3
Th232
U238
cps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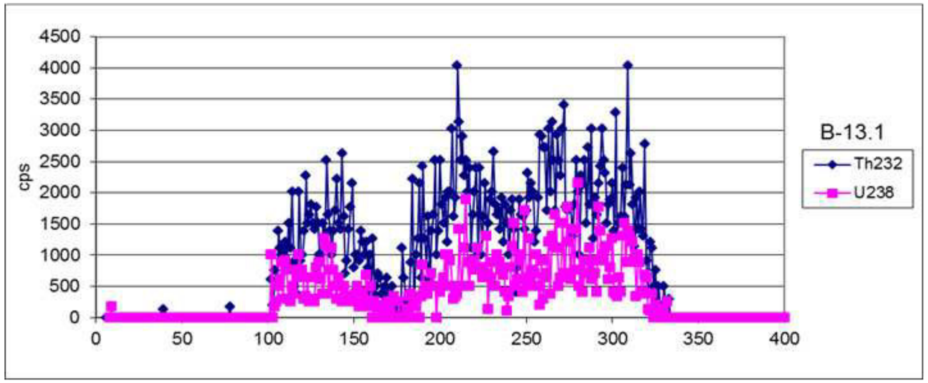
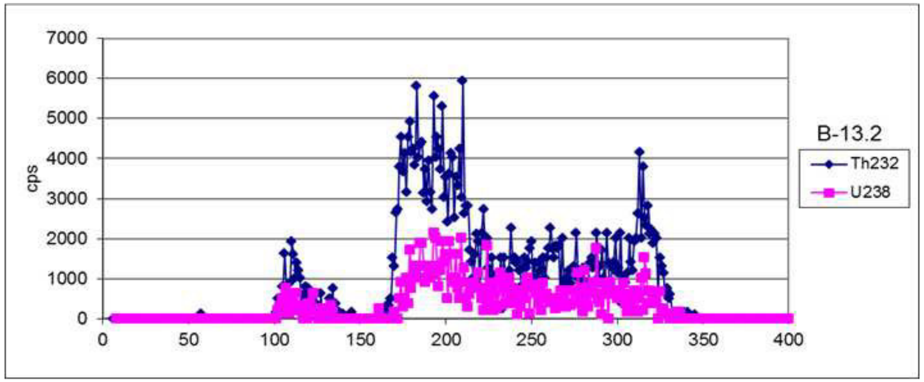
Th232
U238
cps


B-13.1
Th232
U238
cps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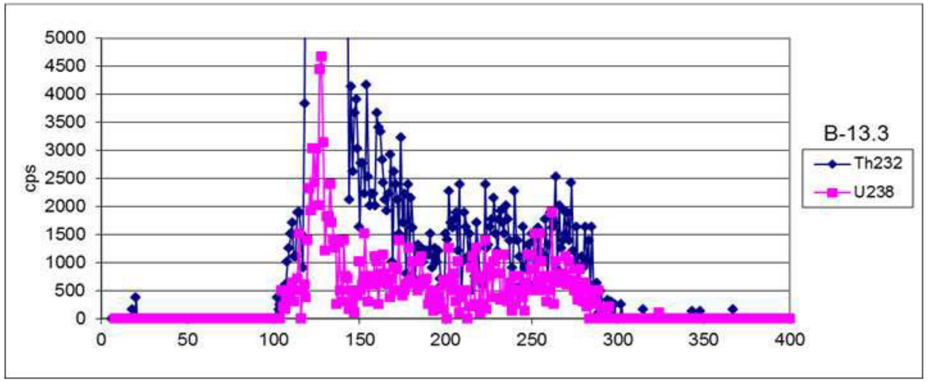
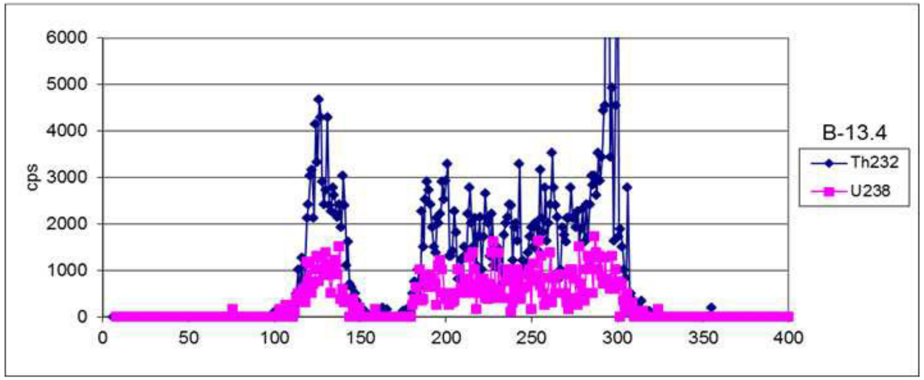
Th232
U238
cps


B-13.3
Th232
U238
cps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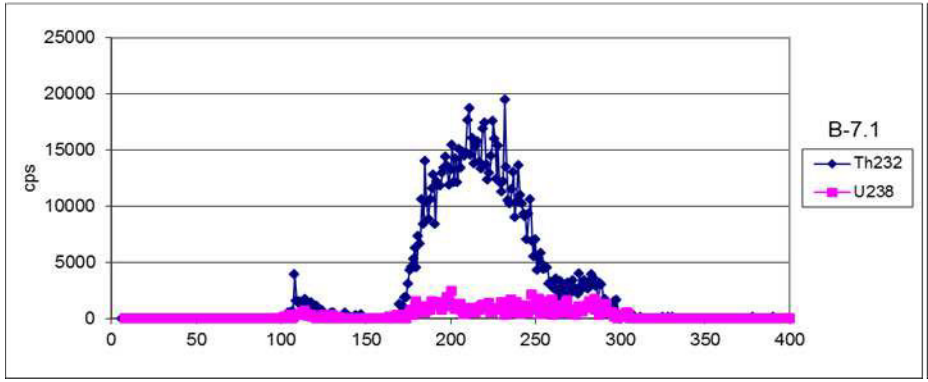
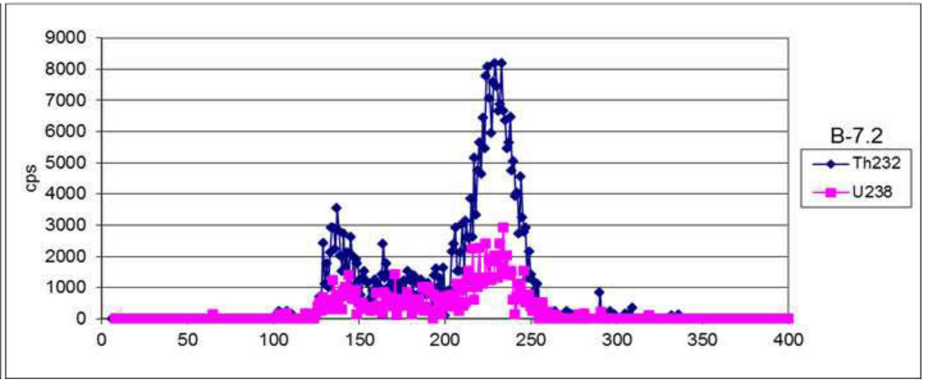
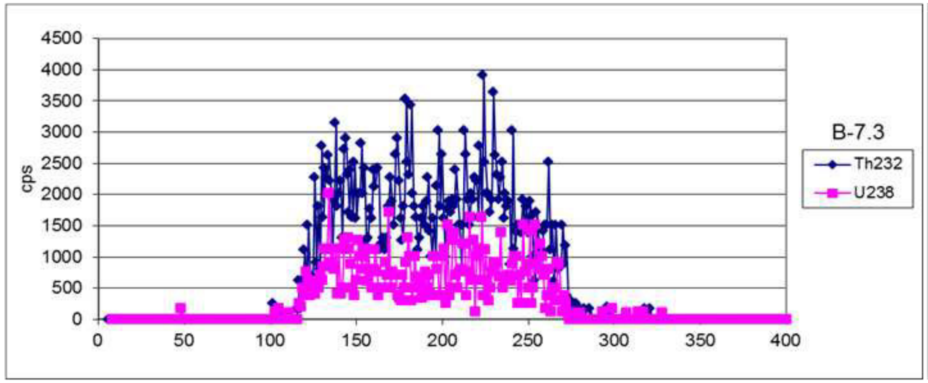
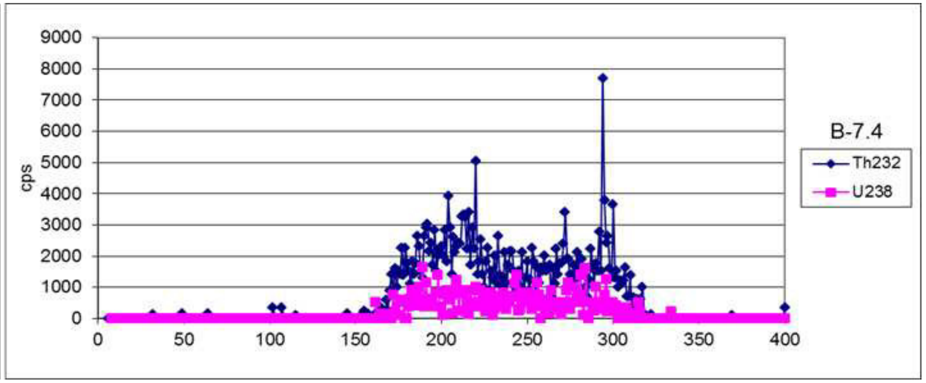
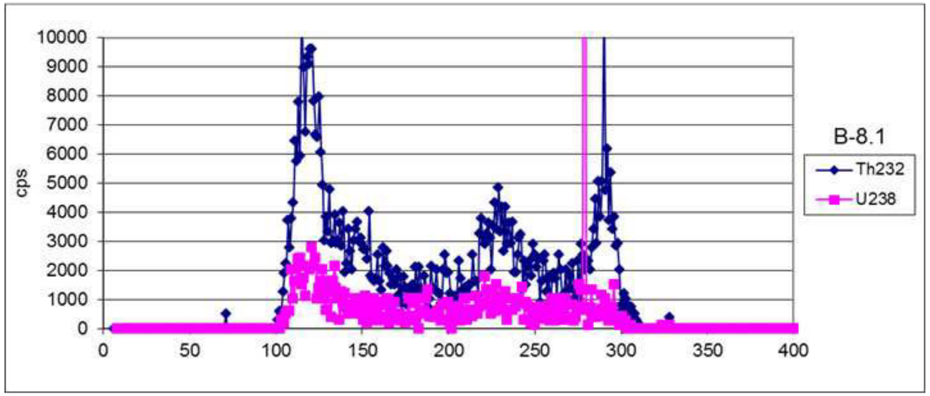
Th232
U238
cps

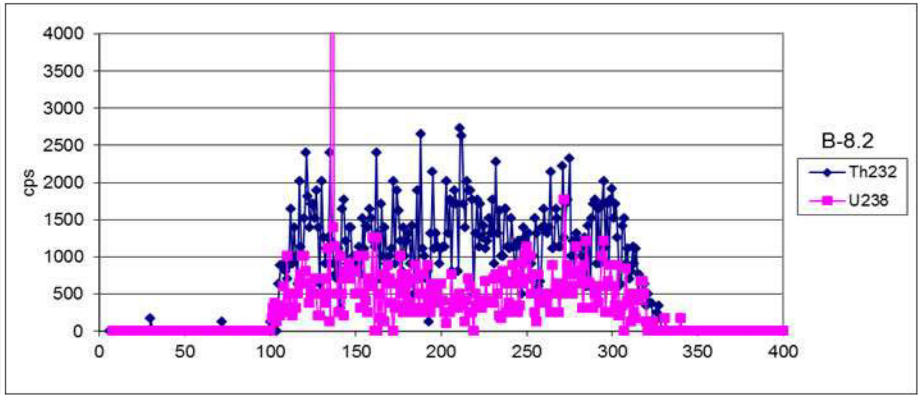

B-7.1
Th232
U238
cps


B-7.2
Th232
U238
cps


B-7.3
Th232
U238
cps


B-7.4
Th232
U238
cps


B-8.1
Th232
U238
cps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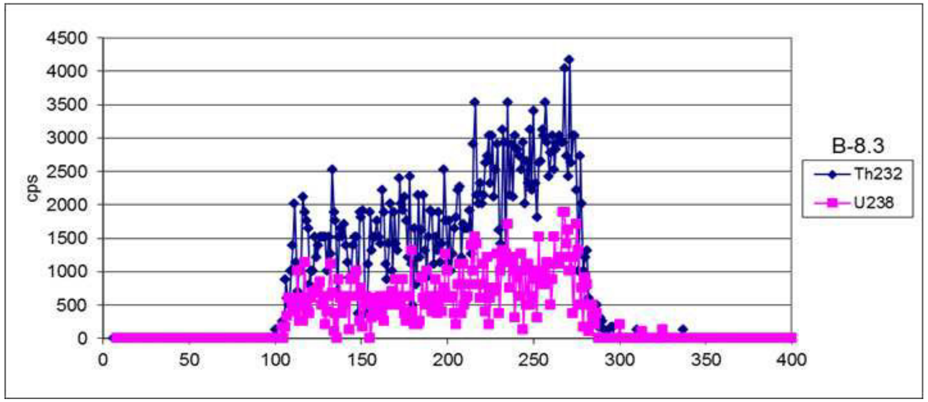
Th232
U238
cps


B-8.3
Th232
U238
cps

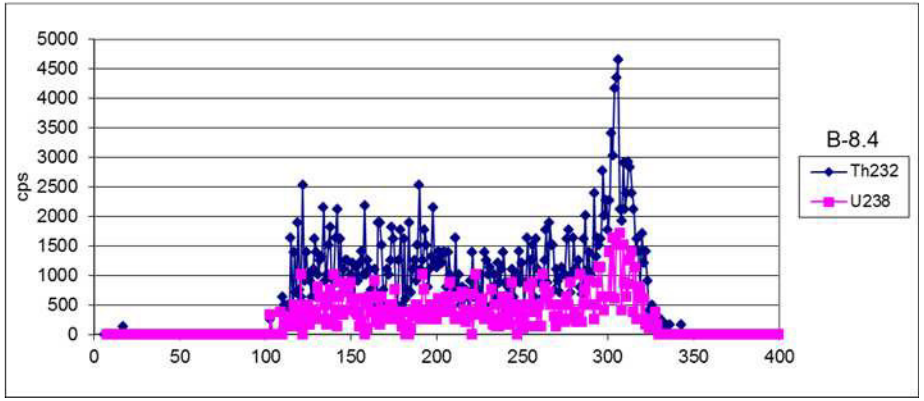
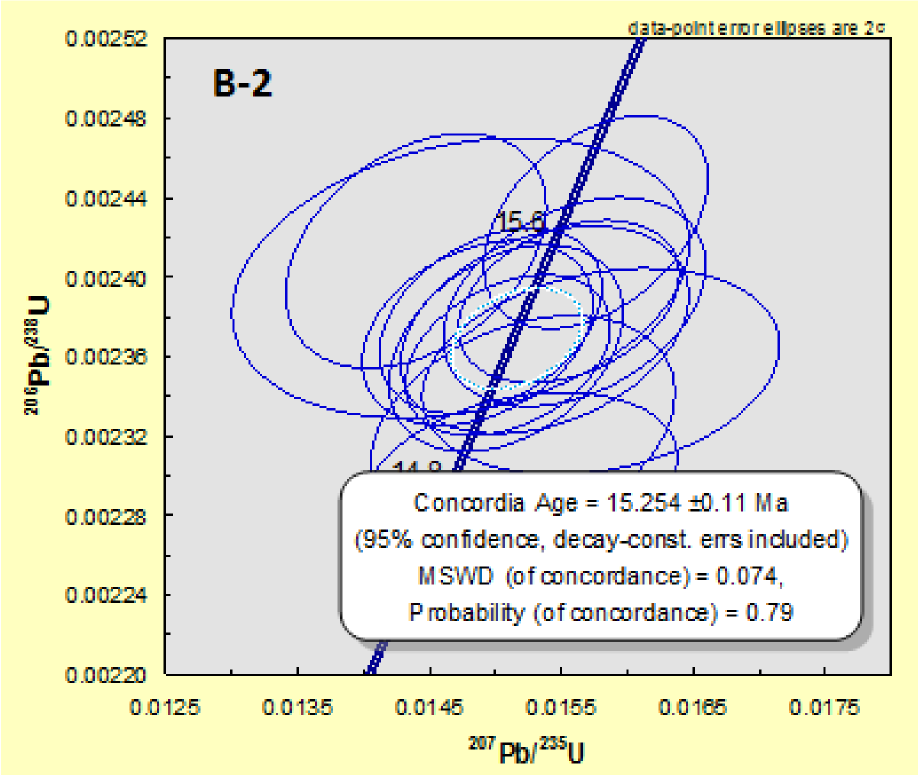
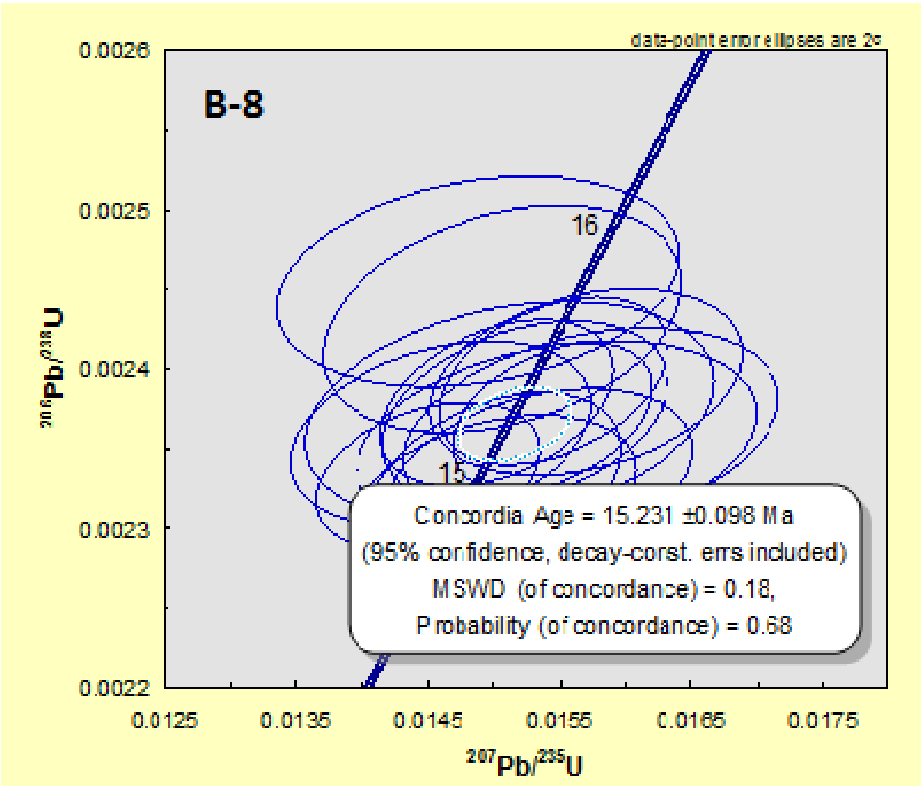
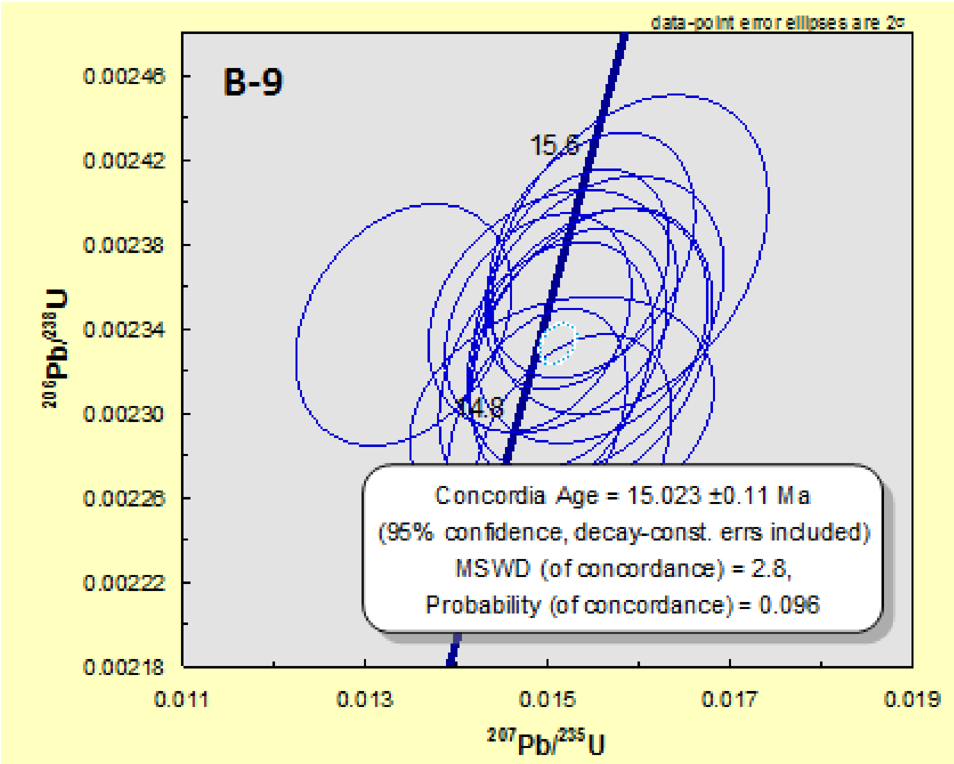

B-8.4
Th232
U238
cps

***Figure DR5*** *Concordia plots of U-Pb age of samples B-2, B-8 and B-9*




data-point error ellipses are 2σ
B-9
15.6
14.8
Concordia Age = 15.023 ±0.11 Ma
(95% confidence, decay-const. errs included)
MSWD (of concordance) = 2.8,
Probability (of concordance) = 0.096
0.00246
0.00242
0.00238
0.00234
0.00230
0.00226
0.00222
0.00218
0.011
0.013
0.015
0.017
0.019
206Pb/238U
207Pb/235U

**DR2.3: Model sensitivity analysis**

The sensitivity of the modeled AHe ages to specified vertical fluid flux, fault damage zone width, background thermal gradient, aerodynamic resistance, duration and exhumation rate were tested by changing one parameter at a time while keeping all other parameters at their base values. The impact of each parameter on the modeled width of the partial and full reset zone on one side of the Malpais Fault is shown in Figures DR6A, B and DR6C, D, respectively. The partial reset zone is the zone where modeled AHe ages at the surface are less than 75% of their crystallization age, and the full reset zone is the zone where AHe ages at the surface are 0.1 Ma or lower. Over long time scales, the host rock adjacent to the normal fault is heated due to conduction. This causes a rejuvenation of AHe ages in these rocks, with ages younger than the crystallization age referred to as partially reset and zero ages as fully reset.

As seen in Figure DR6, the partial and full reset zone increases with increasing hydrothermal activity. Fluid flux has a strong influence on the width of the partial reset zone perpendicular to the hydrothermally active fault for low flow rates. As fluid flux increases and reaches boiling temperatures at the surface, the differences become smaller. At high flow rates, this parameter becomes less sensitive. Same counts for background thermal gradient. Exhumation and duration of hydrothermal activity are highly sensitive parameters. In general, the relationship between the runtime and the partial reset zone is relatively linear. Notice the scale of the y-axis (Figure DR6C and D) in comparison to the y-axis of the parameters fluid flux, damage zone width, aerodynamic resistance and background thermal gradient. A relatively small increase in exhumation rates causes a large increase in the width of the partial reset zone to either side of a hydrothermally active area. The longer the hydrothermal system is active, the larger is the effect of exhumation on (U-Th)/He ages at a given thermal gradient. Thus, if there is hydrothermal activity on geological time scales, the area where AHe ages are rejuvenated becomes very large when exhumation or erosion take place at rates exceeding $1\times10^{-4}$ m $a^{-1}$. A similar relationship was found for duration. If a hydrothermal system is only active for a short time, the host rock is only slightly affected from thermal rejuvenation. However, if the hydrothermal system is active for a long time scale, the area of partially reset AHe ages in the host rock becomes very large. The reason for this is two-fold. First, heat conduction heats up rocks adjacent to the fault over time. The heating is strongest in the subsurface, where temperatures are not buffered by the relatively constant air temperature. Second, exhumation brings rocks to the surface that have not been buffered by air temperatures, the longer the duration, the deeper the origin of the rocks at the surface and the lower the effect of the buffering of air temperatures.

The least sensitive parameters are aerodynamic resistance, which governs heat flux from the land surface, and the width of the fault damage zone. Since temperatures in the Beowawe system are limited by boiling temperatures, the heat flux from the surface is relatively constant. The width of the fault damage zone changes the size of the partial reset zone, but the change is proportional to the change in width. The parameters of the full reset zone behave similar to those of the partial reset zone regarding their sensitivities. It just takes a much longer time for the AHe system to be fully reset than for them being partially reset. They also differ in their slope. At first the full reset zone grows faster as hydrothermal activity continues. Over larger time scales the slope flattens and the full reset zone becomes wider at a slower rate.

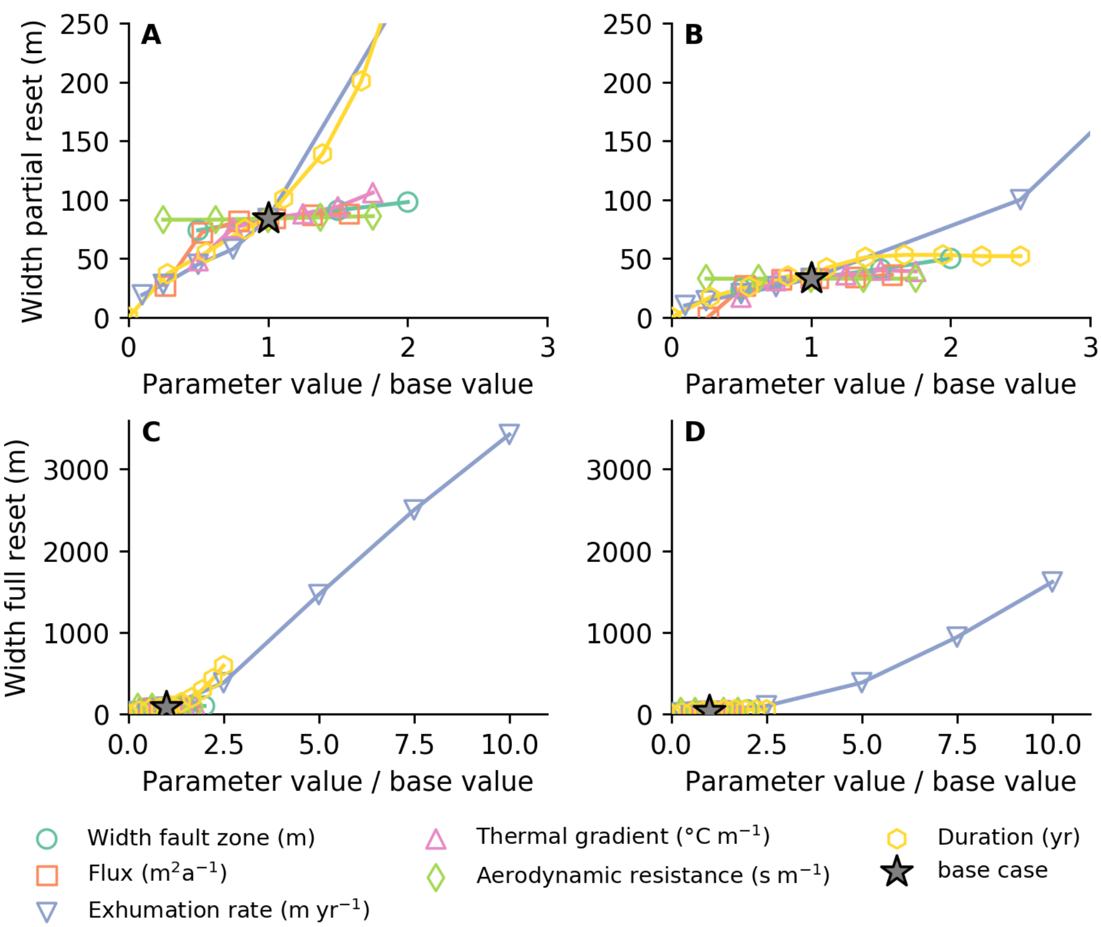


***Figure DR6:*** *Sensitivity of the size of the zone adjacent to one side of the hydrothermally active normal fault where AHe ages are partially reset. The analysis was performed for six parameters: duration, fluid flux, fault damage zone width, background thermal gradient, aerodynamic resistance and exhumation rate. For each line in the graph, one parameter was changed while all other parameters were set to their base values. Base values (star) are 400* $m^2\ a^{-1}$ *for the fluid flux, 10 m for the fault damage zone, 0.04 °C m-1 for the thermal gradient and* $1\times10^{-4}\ m\ a^{-1}$ *for the exhumation rate. Lateral flow in shallow layers connected to the fault was not taken into account. The most sensitive parameter is exhumation rate. An increase in exhumation rates leads to an exponential growth of the partial reset zone. The sensitivity for fluid flux, thermal gradient and fault damage zone are in a similar order of magnitude. Fluid flux and thermal gradient are more sensitive for small values and less sensitive for larger values. Fault damage zone and aerodynamic resistance are the least sensitive parameters.*

**DR2.4: Model-data comparison**

In addition to the results along profile B-B' that are show in the main manuscript we also modeled thermal history in profiles A-A' and C-C' as show in figure DR7 and DR8. These are models of continuous hydrothermal activity, and show comparable results to profile B-B' with the best fits for activity of 90,000 to 160,000 years in profile A-A/ and 70,000 to 100,000 years in profile C-C'.

We tested the effects of different durations of episodic fluid flow and recovery times, which are shown in Figure DR9. The results show that continuous fluid flow and episodic fluid flow with a duration of 2000 years would results in zero AHe ages near the Malpais fault (panel C) and a high mean absolute error between the modeled and measured AHe ages (panel B). In contrast, models with episodic fluid flow of 1000 years and a recovery time of 6500 or 9000 years result in a much better fit of the model to the AHe data.

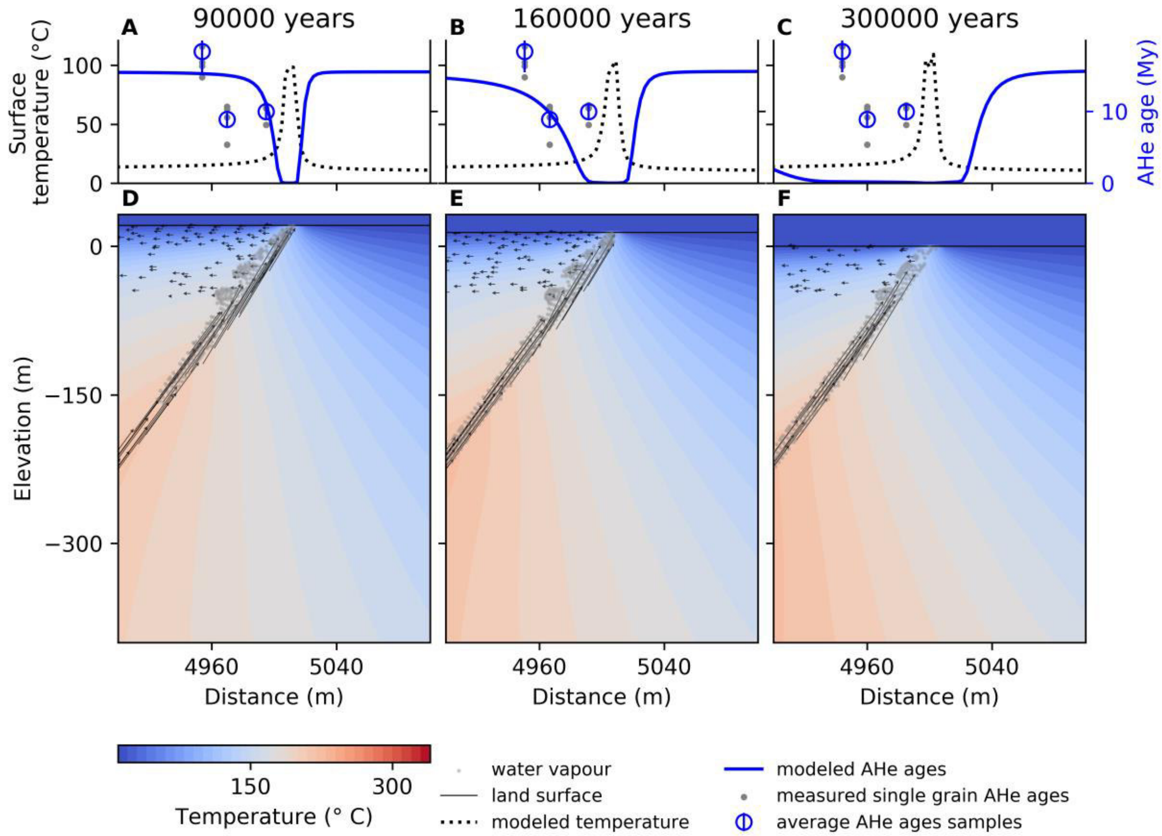



***Figure DR7:*** *Modeled temperatures over long (ka) timescales around the Malpais fault and a comparison with measured apatite (U-Th)/He samples at the surface for profile A-A' at the western part of the sinter terrace. Panel A to C show the modeled surface temperatures, modeled AHe ages and measured AHe ages for four time slices. The lower panels (D-F) show the modeled temperature field around the Malpais fault along with flow vectors and locations where the vapor pressure curve was exceeded. The best fit of the model was obtained for a duration of hydrothermal activity of 90,000 to 160,000 years (panels A and B). See figure DR1 for the location of profile A-A'.*

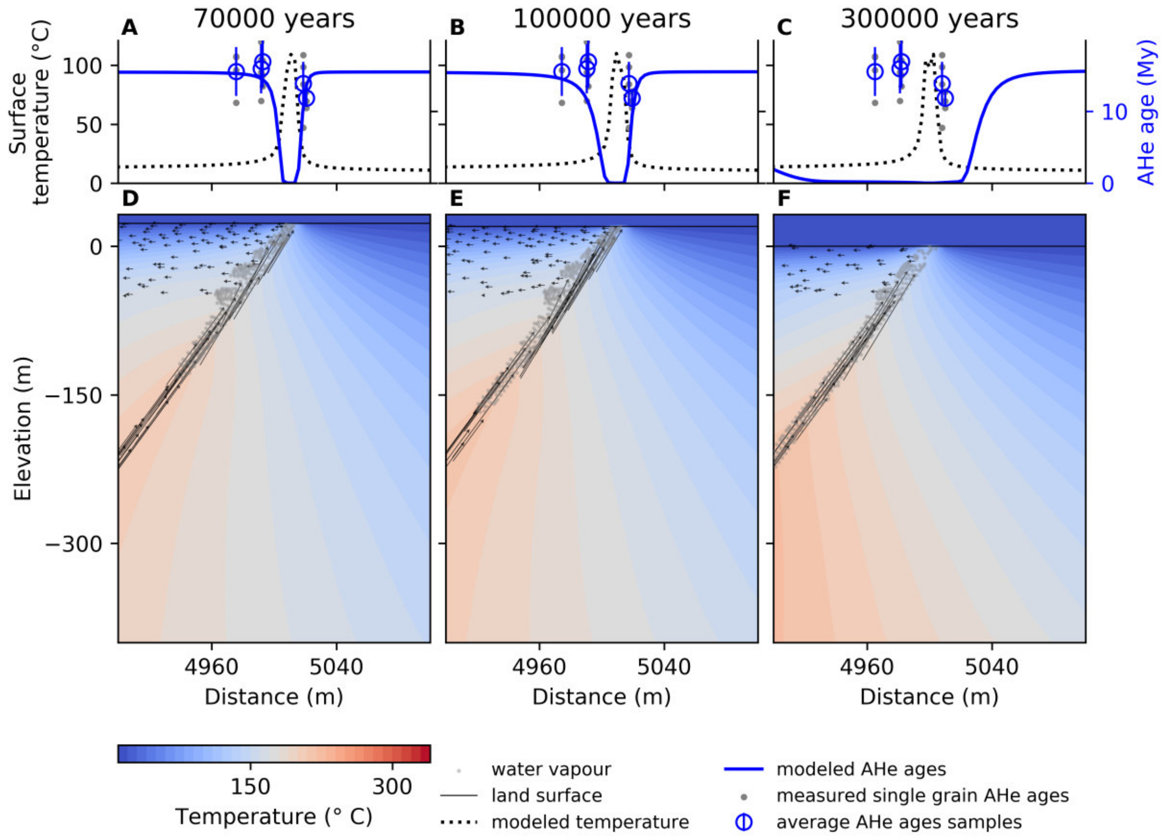



***Figure DR8:*** *Modeled temperatures over long (ka) timescales around the Malpais fault and a comparison with measured apatite (U-Th)/He samples at the surface for profile C-C' at the central part of the sinter terrace. The best fit of the model was obtained for a duration of hydrothermal activity of around 100,000 years (panels A and B).*

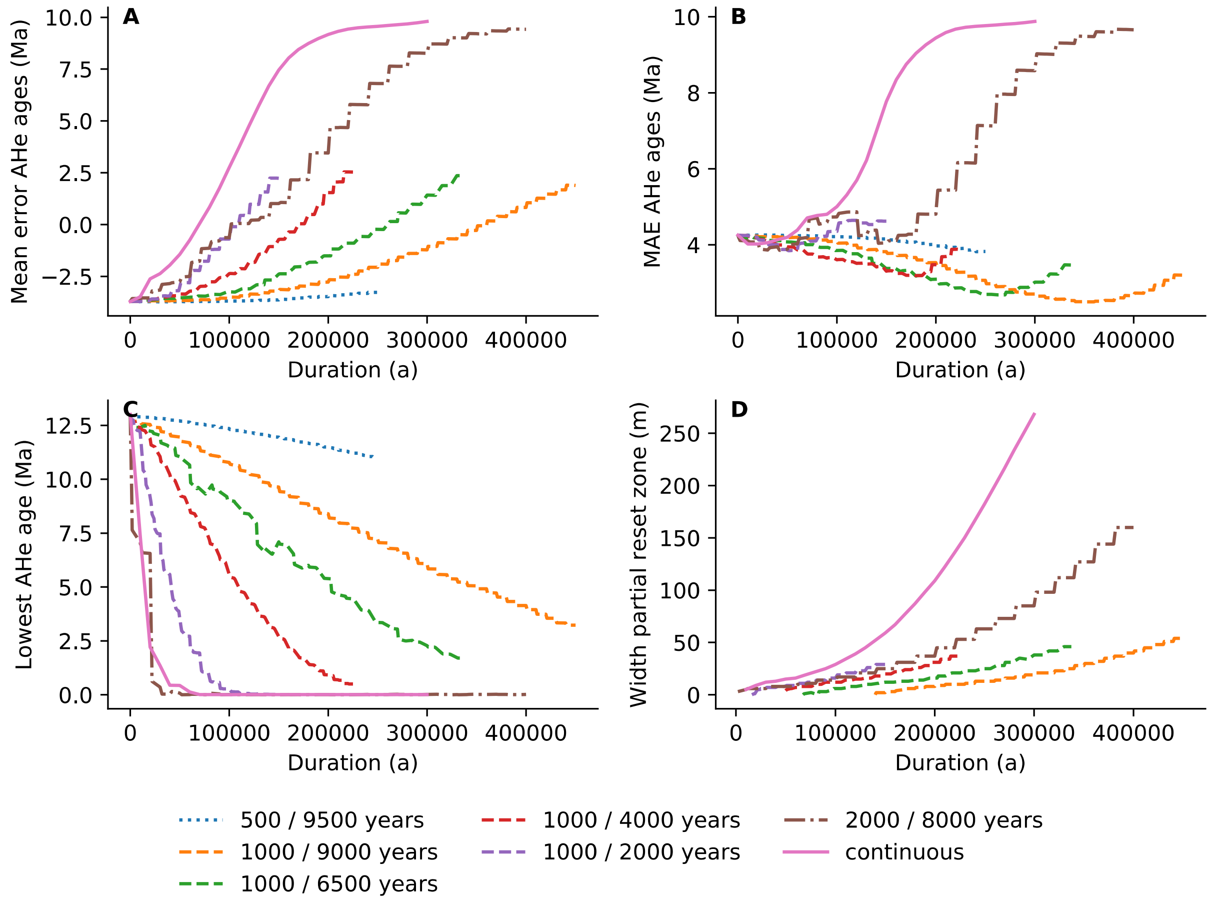



***Figure DR9:*** *Model runs for episodic fluid flow with various durations of fluid flow and recovery times, showing the lowest misfit between the modeled and measured AHe ages for episodic fluid flow with 1000 years of heating and 9000 years of recovery for a total duration of 360,000 years. 1000/9000 denotes 1000 years of fluid flow followed by 9000 years of thermal recovery.*

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