Multi-Proxy Approach to Robustly Capture Earthquake Temperature Rise at the Punchbowl Fault, California

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MULTI-PROXY APPROACH TO ROBUSTLY CAPTURE EARTHQUAKE TEMPERATURE RISE AT THE PUNCHBOWL FAULT, CALIFORNIA

by

Emma M. Armstrong

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in

Geology

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ABSTRACT

Multi-proxy approach to robustly capture earthquake temperature rise at the Punchbowl fault, California

by

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Utah State University, 2021

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During an earthquake, work done to overcome fault friction along localized fault surfaces is dissipated as heat. However, coseismic temperature rise, critical for identifying past earthquakes, is difficult to accurately quantify in the rock record. To address this issue, we compare two fault-slip paleothermometers: thermal maturation of organic matter (biomarkers) and low-temperature thermochronometry. Recent work using biomarkers demonstrates coseismic temperature rise of ~465-1065 °C along localized principal slip zones (PSZs) in the Punchbowl fault (PF), CA (Savage & Polissar, 2019, Geochemistry, Geophysics, Geosystems). We reoccupied previous sample sites and acquired high-spatial resolution zircon (U-Th)/He (ZHe) thermochronometry.
data, which may be sensitive to short-duration, high temperatures characteristic of earthquakes. ZHe data from the PF PSZ and gouge, as well as the adjacent crystalline basement and Punchbowl Formation, define a positive ZHe date-eU trend from ~10-60 Ma and ~20-700 ppm eU with a plateau at ~65 Ma at >700 ppm eU. This pattern suggests the PSZ and gouge share a similar thermal history to material outside the PF.

Complementary apatite (U-Th)/He dates from the Punchbowl Formation are ~4 Ma over ~30-150 ppm eU, implying rapid cooling at that time due to PF activity. Limited apatite fission track data suggest grains are partially reset and did not experience temperatures >110 °C since ~12 Ma. We leverage zircon damage-diffusivity relationships with a suite of numerical models that consider coseismic temperature rise and that collectively indicate peak temperatures on the PF are <600-750 °C. Results support spatio-temporal variability in temperatures along the PF and lower frictional energy than previously estimated during large earthquakes.

Ongoing outreach and education activities focus on scientific drilling along the San Andreas fault and complement fault zone research. Activities include an interactive poster, lecture series, and an informational video with an associated assignment. Outreach increases awareness and engagement with the geosciences, scientific drilling, and fault studies for distinct audiences, including Cache Valley residents, and non-geoscience-major students at USU and USU Blanding.
PUBLIC ABSTRACT

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temperature rise at the Punchbowl

fault, California

Emma M. Armstrong

Earthquakes produce heat along a fault surface from friction created as two blocks of rock move past each other. The amount of heat generated depends on a variety of factors, including rock type, stresses, and thickness of the fault zone. Identifying evidence for and quantifying this earthquake (coseismic) temperature rise are essential for identifying past earthquakes in the rock record. Indirect methods, such as textures and geochemical signatures that change with temperature, can serve as paleothermometers. Here we compare two paleothermometers, biomarkers and thermochronometry, from two transects across the Punchbowl fault (PF), California. The PF is an ancient fault strand of the San Andreas fault system and is similarly a strike-slip fault that experienced past earthquakes. Biomarkers are organic materials in rocks whose chemical character changes with temperature, such as coseismic friction-generated heat. On the PF, biomarkers indicate temperature rise of \(\sim460-1060 \, ^\circ\text{C}\) (Savage & Polissar, 2019, *Geochemistry, Geophysics, Geosystems*). Minerals such as zircon are amenable to \((\text{U-Th})/\text{He}\) thermochronometry, where He is produced from the radioactive decay of isotopes of U and Th and can escape zircon crystals as a function of temperature.

\((\text{U-Th})/\text{He}\) results, reported as dates, from zircon crystals extracted from the PF itself and dates away from a fault are similar, \(\sim10\) to 65 million years old, and define similar
patterns between date and mineral chemistry. This implies that temperatures in the fault zone were insufficient to cause He loss from zircon crystals. These results, together with numerical models, refine the temperature rise estimates to less than 600-750 °C. Our data imply there is variable temperature rise on the PF in space and time. Due to the abundance of zircon crystals in fault rocks, thermochronometry methods are potentially useful for quantifying coseismic temperatures in other fault zones worldwide.

Ongoing outreach and education activities related to scientific drilling along the San Andreas fault complement PF research. Activities include an interactive poster, lecture series, and an informational video with an associated assignment targeted for distinct audiences, including Cache Valley residents, and non-geoscience-majors. The objective of these activities is to increase awareness of geosciences, fault zone research, and scientific drilling.
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I. Introduction

Friction-generated heat, or the energy to overcome friction, is thought to be the largest sink (~90%) in the earthquake energy budget (Lachenbruch & McGarr, 1990; McGarr, 1999; Scholz, 2002). Coseismic temperature rise along a fault occurs because heat generation outpaces conductive heat dissipation along localized slip surfaces (Lachenbruch, 1986; Rice, 2006). Temperature rise activates dynamic weakening mechanisms that affect mechanical fault strength, rock properties, and chemical reactions within a fault zone and promote earthquake rupture (Scholz, 2002; Di Toro et al., 2004; Wibberley & Shimamoto, 2005; Reches & Lockner, 2010; Di Toro et al., 2011). Documenting temperature rise on a fault fingerprints past earthquakes in the rock record and is critical for understanding the in situ physics of earthquakes and slip histories, which in turn can inform future earthquake patterns.

Fault rock chemistry and textures can be used to identify coseismic temperature rise to subsolidus temperatures (e.g., Rowe & Griffith, 2015, and references therein). Textures and mineral reactions that inform fault slip temperatures include decarbonation (McIntosh et al., 1990; Collettini et al., 2013), thermal decomposition of clays (Kameda et al., 2011), serpentine dehydration (Kohli et al., 2011), hematite textural and oxidation state transformations (Evans et al., 2014; Ault et al., 2015), and biomarkers (Savage & Polissar, 2019). Biomarkers are organic molecules in sedimentary rocks that alter as a function of temperature, and certain biomarkers are sensitive to coseismic heating (Polissar et al., 2011; Savage et al., 2014; Sheppard et al., 2015; Rabinowitz et al., 2017;
Savage & Polissar, 2019). However, applications of these paleothermometers may be limited by poor preservation and overprinting deformation (Rowe & Griffith, 2015).

Zircon (U-Th)/He (ZHe) thermochronometry is a tool nominally used to constrain low temperature processes, such as cooling due to tectonic or erosional exhumation (Reiners et al., 2004; Reiners, 2005; Shirvell et al., 2009; Singleton et al., 2014; Ault et al., 2019, and references therein). ZHe has a broad temperature sensitivity owing to radiation damage in a grain and variable intrasample damage accumulation (Guenthner et al., 2013; Ault et al., 2018). This system is also sensitive to short-duration, high temperature events (Reiners, 2009), such as wildfires (Mitchell & Reiners, 2003) or shear heating during fault slip (Maino et al., 2015).

To robustly capture coseismic temperatures and overcome individual method limitations, comparison of two fault slip paleotemperature proxies with different kinetics is useful. Here, we conduct a multi-method comparison of two paleothermometers: biomarkers and ZHe thermochronometry, to refine peak coseismic temperatures along the Punchbowl fault (PF), CA. The PF is an ancient, exhumed strand of the San Andreas fault (SAF), with a localized, discrete principal slip zone (PSZ), that developed during past earthquakes (Chester & Logan, 1987; Chester & Chester, 1998). Recent biomarker analyses shows evidence of concentrated friction-generated heat along the PF during fault slip (Savage & Polissar, 2019). Biomarkers indicate ~465-1065 °C temperature rise in the PSZ of the PF for a slip zone half-width of 50 µm to 10 mm.

In this study, we re-occupy some sample sites of Savage and Polissar (2019) at Devil’s Punchbowl Natural Area (Fig. 1) and compare existing biomarker data with newly acquired ZHe thermochronometry data from a location with a well-defined PSZ.
and a location characterized by a broader zone of fault core gouge, as well as adjacent crystalline basement and Punchbowl Formation (Fm). We also acquired apatite (U-Th)/He (AHe) and apatite fission-track (AFT) thermochronometry for comparison with our ZHe results. We use thermal history modeling to constrain the long-term thermal history of material within and outside the PF, and employ a suite of fault slip heating models to refine maximum coseismic temperatures along the PF.

Punchbowl fault research activities are complemented with outreach activities centered on the SAF and continental drilling across this structure in the San Andreas Fault Observatory at Depth (SAFOD). Utahns may have limited exposure to geosciences and scientific drilling projects. It is crucial to increase engagement in these topics to (1) increase interest in the geosciences to expand and diversify the future STEM workforce and (2) promote appreciation of the natural world. To make inroads on these objectives, three related activities were created for different target audiences (Appendix A, B). The first activity targets the general public in Cache Valley, Utah, and involves an interactive poster and informational fliers about fault rocks collected in the SAFOD, presented at the USU Geoscience Department Rock and Fossil Day. The second activity is aimed toward Native American students attending the USU Blanding Campus (a two-year college) for the USU-hosted Native American Science Mentoring Program. For this program, a week-long set of activities and lectures were used to increase understanding of earthquakes and the scales at which fault rocks are studied and to foster interest in geoscience research techniques. The final activity focuses on the importance of scientific drilling and the creeping section of the SAF and will be implemented in the USU Natural Disasters class.
II. Background

2.1 Geologic Framework

The PF is an inactive, abandoned strand of the SAF (Chester & Chester, 1998). The PF is parallel to and located ~3.5 km southwest of the SAF, adjacent to the San Gabriel Mountain section of the Transverse Ranges (Fig. 1). The PF was likely seismogenic because the adjacent strand of the current SAF produces earthquakes and the PF exhibits textural and geochemical evidence of friction-generated heat associated with coseismic slip (Chester & Chester, 1998; Savage & Polissar, 2019). The PF accommodated more than 40 km of strike-slip displacement from Miocene through Pleistocene time, but the exact timing of slip and seismogenesis is poorly constrained (Chester et al., 1993; Chester & Chester, 1998). Two leading interpretations for the timing of displacement along the PF exist. First, faulting occurred in two distinct phases with half of the displacement before deposition of the Punchbowl Fm and the remaining displacement in the Plio-Pleistocene (~6-1 Ma) following deposition of the entire Punchbowl Fm (Woodburne, 1975; Meisling & Alexander, 1993; Chester & Chester, 1998). Alternatively, all of the slip was accommodated in the last 5 Ma (Schulz & Evans, 1998, 2000; Coffey, 2015; Coffey et al., 2019b). Present-day fault exposures reflect ~2-4 km of exhumation, exposing the upper end of the seismogenic zone where earthquakes either nucleated or propagated (Chester, 1983; Chester & Logan, 1986; Savage & Polissar, 2019). At our study site in Devil’s Punchbowl Natural Area, two strands define the PF. Here, we focus on the northern strand, which is more continuous and easier to identify (Chester & Chester, 1998).
The PF juxtaposes the Mio-Pliocene Punchbowl Fm to the northeast against Mesozoic and older gneissic crystalline basement to the southwest (Fig. 1). In the study area, basement rocks are variably mapped as Precambrian crystalline basement, Mesozoic and older crystalline rock, or Mesozoic Wilson Diorite (Barth, 1990; Chester & Chester, 1998; Coffey, 2015; Coffey et al., 2019b). Although some crystalline basement rocks in the San Gabriel Mountains have well-constrained crystallization ages, the age of the gneiss at our specific sample sites is unknown. Apatite fission-track (AFT) thermochronometry dates from nearby basement rocks are ~9 Ma and ~4 Ma (Blythe et al., 2000), supporting exhumation associated with PF activity.

Figure 1. Simplified geologic map modified from California Geological Survey overlaid on DEM showing the Punchbowl fault (PF) in the Devil’s Punchbowl Natural Area, San Gabriel Mountains, CA. Biomarker (Savage & Polissar, 2019) and thermochronometry (this study) sample locations and are shown.
The Punchbowl Fm is a syntectonic sedimentary deposit in the Punchbowl block, an inferred pull-apart basin formed by offset along the PF (Chester & Chester, 1998). The Punchbowl Fm is 1500 m-thick and unconformably overlies the Paleogene San Francisquito Fm. The Punchbowl Fm comprises fluvial to alluvial conglomerate and sandstone that were deposited ~12.5-8.5 Ma (Woodburne, 1975; Liu, 1990). The basal unit is a conglomerate that is distinct from the main Punchbowl Fm and is cut by, and overlies, the PF (Chester, 1995). Detrital zircon U-Pb age spectra from the Punchbowl Fm include peaks at ~70-100 Ma, ~150-160 Ma, ~210-260 Ma, ~1400 Ma, and ~1700 Ma (Ingersoll et al., 2013; Hoyt et al., 2018). Prior work suggests the provenance for zircon in the Punchbowl Fm is the distal Mojave region located northeast of the present location of the Punchbowl Fm (Woodburne, 1975; Meisling & Alexander, 1993; Barth et al., 1997; Coffey et al., 2019b). Preliminary AFT dates from the Punchbowl Fm are ~15-7 Ma (Kirschner, 2004).

In the vicinity of Devil’s Punchbowl Natural Area, the PF architecture is well-characterized with a PSZ, fault core, and broader damage zone (Chester & Logan, 1986; Schulz & Evans, 1998, 2000). The PF PSZ is an archetypal example of a highly localized slip zone caused by strain localization (Chester & Logan, 1987; Chester & Chester, 1998). The PSZ is observed in some PF exposures and is a narrow (<1 cm-wide) layer of clayey fault gouge, with a distinctively different color (brown to yellow) than the surrounding fault core (Chester & Logan, 1986). The fault core surrounding the PSZ is ~0.5-1 m wide, olive-black or dark yellow to brown, and is composed of comminuted rock material including fault gouge, ultracataclasite, and cataclasite (Chester & Logan, 1986; Chester et al., 2005). The materials comprising the fault core on either side of the
PSZ are derived from their respective, adjacent host rocks and limited mixing is inferred across the PSZ (Chester & Chester, 1998; Savage & Polissar, 2019). The broader fault damage zone is ~140 m wide and minimally fractured (Chester & Logan, 1986; Schulz & Evans, 1998, 2000; Wilson et al., 2003; Dor et al., 2006).

2.2 Biomarker evidence for coseismic temperature rise on the PF

Biomarker data patterns support friction-generated temperature rise in the PF PSZ (Savage & Polissar, 2019). Biomarkers are organic materials that are present in some rocks, and whose molecular composition alters as a function of temperature (Peters et al., 2007; Sheppard et al., 2012; Sheppard et al., 2015). The relative alteration of different organic molecules, such as phenanthrenes and methylphenanthrenes, is calculated as an index. An increased index signals increased thermal alteration (Radke, 1988; Polissar et al., 2011; Sheppard et al., 2015). Kinetic reactions associated with a particular index and ambient temperature are used to quantify the temperature rise. In general, biomarker alteration records the maximum temperatures that samples experience; biomarkers are insensitive to subsequent lower temperatures, and they do not have retrograde reactions (Peters et al., 2007; Coffey et al., 2019a). The index relevant to the present study, the MPI-4 index, is sensitive to short-duration, high temperatures associated with earthquakes, when the ambient temperature is ~110 °C (Polissar et al., 2011; Sheppard et al., 2012; Savage et al., 2014; Savage et al., 2018; Savage & Polissar, 2019).

The MPI-4 values reported in Savage and Polissar (2019) suggest coseismic temperature rise of ~465-1065 °C along the PF PSZ. Variability in inferred temperatures reflects different assumptions about the thickness of the deforming zone, as well as
uncertainty in kinetic parameters. Modeled peak temperatures of ~465-620 °C are calculated with a 10 mm slip zone and ~815-1065 °C are commensurate with a 50 μm slip zone (Savage & Polissar, 2019). MPI-4 values decrease with increasing distance from the PSZ, indicating PSZ-perpendicular thermal gradients. Data patterns imply that the Punchbowl Fm-side ultracataclasite is made of reworked and transported PSZs that experienced prior coseismic temperature rise (Savage & Polissar, 2019), indicating that friction-generated heat does not penetrate beyond the PSZ at the studied location on the PF (cf. Coffey et al., 2019a).

2.3 Zircon (U-Th)/He thermochronometry

Low-temperature thermochronometry has the potential to constrain the thermal history of fault rocks (Ault, 2020, and references therein). The ZHe system, for example, is nominally used to decipher slow, low-temperature processes of rocks transiting the upper ~8 km, such as exhumation (Reiners et al., 2004; Reiners, 2005; Shirvell et al., 2009; Singleton et al., 2014; Ault et al., 2019, and references therein). The ZHe closure temperature (T_c), or the temperature range over which the system transitions from open to closed behavior (i.e., He loss to retention), is 25-200 °C, assuming a 10°C/Ma cooling rate (Guenthner et al., 2013). Apatite (U-Th)/He (AHe) and apatite fission track (AFT) thermochronometry can provide complementary thermal history information (e.g., Armstrong et al., 2003; Ehlers & Farley, 2003). The AHe and AFT T_c are 30-90 °C and 60-120 °C, respectively, assuming a 10 °C/Ma cooling rate (Gallagher, 1995; Flowers et al., 2009; Gautheron et al., 2009).
The dominant control on ZHe $T_c$ is radiation damage accumulation in a zircon crystal (Reiners & Brandon, 2006; Guenthner et al., 2013; Ketcham et al., 2013). Radiation damage accumulation is a function of a grain’s Th and U content and thermal history (Guenthner et al., 2013). Metamict zircon crystals are easily identified with a stereoscope, appearing brown-opaque in plane-polarized light (Ault et al., 2018).

Radiation damage, or metamictization, forms because actinide decay disrupts the crystal lattice and it anneals as a function of increasing temperature (Holland & Gottfried, 1955; Woodhead et al., 1991; Nasdala et al., 1995). Provided grains share a common thermal history, a grain’s eU (effective uranium, $eU=[U]+0.235*\text{[Th]}$) serves as a proxy for accumulated damage. Accumulated damage controls He diffusion, and thus a grain’s $T_c$ and ZHe date. At low eU and accumulated damage, zircon is more retentive with respect to He and the $T_c$ increases with increasing damage. Above a percolation threshold where damage becomes interconnected, zircon He retentivity and $T_c$ decrease (Nasdala et al., 2004; Guenthner et al., 2013; Ketcham et al., 2013). For certain thermal histories, patterns between ZHe date and eU develop because of the relationship between damage and He retentivity. For example, samples that experience a protracted thermal history can exhibit a positive and/or negative ZHe date-eU trend (Guenthner et al., 2013; Orme et al., 2016; Powell et al., 2016; Johnson et al., 2017; Ault et al., 2018; DeLucia et al., 2018; Flowers et al., 2020). Uniform dates across a wide range of eU values, or a ZHe date-eU “pediment” or “plateau”, may reflect a phase of rapid cooling at that time (e.g., Ault et al., 2018; DeLucia et al., 2018).

The ZHe system is also sensitive to short-duration, high temperature pulses (Mitchell & Reiners, 2003; Reiners, 2009), such as frictional heat produced by an earthquake (Ault
et al., 2015; Maino et al., 2015). The temperatures required to induce substantive He loss from zircon crystals over a range of geologic conditions are inversely and logarithmically proportional to the duration of heating over a range of geologic conditions (Reiners, 2009). The temperature sensitivities of the ZHe system may be within observed and calculated temperature rise due to coseismic friction-generated heat (Lachenbruch, 1986; Reiners, 2009; Savage & Polissar, 2019); thus, the ZHe system has the potential to serve as a fault slip paleotemperature proxy.
III. Sampling approach and analytical methods

Samples were collected in Devil’s Punchbowl Natural Area, CA, where semi-continuous exposures of the PF are preserved (Fig. 1, 2a, 2b; Table D.1). Sample locations replicate some sites of Savage and Polissar (2019) because their sites exhibit biomarker evidence for increased temperature rise along the PSZ. The structural and microtextural analysis of our selected sites are well-characterized by previous work (Chester & Logan, 1986, 1987; Chester et al., 1993; Chester & Chester, 1998).

We collected samples in two high-spatial resolution transects perpendicular to the trace of the PF separated by ~10 m along strike, sites EA20-1 and EA20-2 (Figs. 2a, 2b, 3a, 3b). At each site, we collected crystalline basement, Punchbowl Fm, and PF fault materials over a distance of ~15 cm. The basement rocks form a sharp, nearly vertical, contact with the fault gouge (Figs. 2a, 2b), mirroring the overall orientation of the PF. Fault rocks are highly comminuted and friable. Individual layers of gouge were isolated with a knife and collected with a flat trowel. Basement and Punchbowl Fm samples were removed with a hammer and chisel.

The structural architecture of the fault zone is distinct at each site. At site EA20-1, we sub-sampled fault rocks based on previous characterization (Chester & Chester, 1998; Savage & Polissar, 2019) because sub-units could be distinguished by color (Fig. 2a). Here, fault core domains include: basement-side (black) ultracataclasite (1A), the PSZ (1B), and Punchbowl Fm-side (brown) ultracataclasite (1D). The fault architecture at site EA20-2 was comparatively homogeneous and lacked obvious sub-domains, so we collected a single fault core gouge (hereinafter referred to as gouge) sample (2B; Fig. 2b).
Crystalline basement samples (1C and 2A; Fig. 2a) were slabbed with a water-cooled saw perpendicular to the fault core contact at 1-cm intervals to create subsamples at <1 cm, 1-2 cm and >2 cm away from the gouge interface (samples 1C-1, 1C-2, 1C-3, and 2A-1, 2A-2, and 2A-3, respectively). Sample 3A consists of undeformed Punchbowl Fm ~100 m north of the PF (Fig. 1).

Accessory phases were isolated using standard crushing methods including mortar and pestle for more friable samples, and magnetic and density separation techniques in the USU Mineral Microscopy and Separation Lab (M²SL). Whole zircon grains and apatite fragments were present in each sample, but whole apatite grains were only present in Punchbowl Fm sample 3A. We target a subset of samples for ZHe thermochronometry including the PSZ (1B), gouge (2B), basement (1C-1, 1C-3, 2A-1, 2A-3), and Punchbowl Fm (1E, and 3A). These samples were targeted for thermochronometry because of inferences about the presence and absence of friction-generated heat from biomarker data (Savage & Polissar, 2019). Zircon grains were selected following the approach of Ault et al. (2018) to encapsulate the range of visual metamictization in each sample. Most samples yield limited zircon quantities, and we chose the most metamict zircon crystals possible from each sample.

Target zircon and apatite grains were imaged and measured using a stereoscope and Leica software, and loaded into 1 mm Nb tubes in the M²SL. Grains were analyzed for U, Th, and He, and Sm (apatite only) at Arizona Radiogenic Helium Dating Lab (ARHDL) at the University of Arizona following standard apatite and zircon degassing, spiking, and dissolution protocols. Apatite fragments from samples 1C-2, 1B, 1D, 1E, 2A-3, 2A-2,
2A-1, and 2B were analyzed for AFT thermochronometry at the Arizona FT Lab. ZHe, AHe, and AFT analytical details are provided in Appendix C.1.
IV. Thermochronometry results

We acquired 45 individual zircon ZHe dates from eight samples (Figs. 2, 3, D.1; Table 1), six individual AHe dates from one sample (Fig. 3; Table 2), and AFT dates from eight samples (Table D.2). For ZHe and AHe thermochronometry samples with single-grain dates <20% standard deviation of the mean, we report the unweighted sample mean and 1σ standard deviation of the mean. For samples with single-grain dates with >20% standard deviation of the mean, we report the range of individual dates with 2σ analytical error (Flowers & Kelley, 2011). We report AFT dates as the central date ±1σ standard deviation (Galbraith, 1990). Across the whole dataset, zircon grains selected for ZHe analysis range from faceted, clear grains to honey to brown opaque, rounded grains (Fig. 3c). It is difficult to evaluate the relationship between visual metamictization and eU concentration in our samples because there is limited intra- and inter-sample eU variability and, with a few exceptions, most grains exhibit low damage (Fig. 3c).

Mean ZHe dates from basement samples are 23.7 ± 1.1 Ma (1C-3, n=5) with 136-239 ppm eU and 25.1 ± 3.5 Ma (2A-3, n=5) with 97-316 ppm eU (Figs. 2c, 2d, 3a). Samples 1C-1 and 2A-1 have individual ZHe dates of 14.7 ± 0.5 Ma - 29.0 ± 0.8 Ma (1C-1, n=6) over 119-212 ppm eU, and 10.7 ± 0.3 Ma – 28.4 ± 0.8 Ma (2A-1, n=6) over 97-386 ppm eU, respectively (Figs. 2c, 2d, 3a). The Th/U ratio ranges for all basement samples are the highest of the data set, ranging from 0.41-0.66, with two outliers of 0.29 in sample 1C-3 and 0.74 in sample 1C-1 (Fig. 2e, 2f).
Punchbowl Fm samples yield individual ZHe dates of 28.6 ± 0.9 Ma – 64.1 ± 1.9 Ma (1E, n=5) and 20.5 ± 0.4 Ma – 60.1 ± 0.9 Ma (3A, n=5) (Figs. 2c, 3a). These samples have broader eU ranges of 298-948 ppm and 182-1945 ppm, respectively (Fig. 3a). Zircon grains in Punchbowl Fm sample 1E have a narrow and low range of Th/U ratios of 0.10-0.14 and sample 3A yields a Th/U ratio of 0.16-0.66 (Fig. 2e).

Individual ZHe dates from PSZ sample 1B range from 17.4 ± 0.5 Ma to 84.6 ± 2.5 Ma (n=7), with a broad eU concentration range of 345-1102 ppm. Fault gouge sample 2B yields a mean date of 36.1 ± 6.0 Ma (n=6), with a narrow eU range of 128-417 ppm (Figs. 2c, 2d, 3a). The Th/U ratios for fault gouge samples 1B and 2B are 0.10-0.38 and 0.15-0.32, respectively (Fig. 2e, 2f). There are no obvious intrasample trends between ZHe dates and equivalent spherical radius (Rs), a proxy for zircon grains size and another potential source of date variation data (Fig. D.2.a).

ZHe data from all samples collectively define a positive ZHe date-eU trend from ~10-60 Ma and ~20-700 ppm eU with a date plateau at ~65 Ma at >700 ppm eU (Fig. 3a). There is, however, minor variability in the dates over equivalent eU ranges. For example, there are differences in the approximate slope of the ZHe date-eU pattern in the 150-200 ppm eU range (Fig. 3a).

AHe and AFT analyses from a subset of samples provide a comparison to ZHe results. Individual AHe dates from the Punchbowl Fm sample 3A are 3.0 ± 0.8 Ma – 5.5 ± 0.8 Ma (n=5) with 17-157 ppm eU (Table 2). These dates are uniform over a broad range in eU (Fig. 3b). There are no obvious trends between AHe dates and Rs (Fig. D.2.b). Samples analyzed for AFT thermochronometry are plagued by low apatite yield and analyzed grains have minimal tracks, which results in large individual analysis and
sample level uncertainties. Our AFT data can still inform general thermal histories by exploiting intra- and inter-sample data pattern scatter. We report eight AFT central dates (Table D.2). The central date for sample 1C-2 is 18.1 ± 13.2 Ma (n=4), 1B is 18.4 ± 7.2 Ma (n=3), 1D is 9.0 ± 9.1 Ma (n=5), 1E is 12.2 ± 1.5 Ma (n=18), 2A-3 is 8.7 ± 8.8 Ma (n=4), 2A-2 is 10.1 ± 4.2 Ma (n=10), 2A-1 is 16.5 ± 17.0 Ma (n=2), and 2B is 25.2 ± 16.7 Ma (n=5) (Table D.2).
Figure 2. (A, B) Field photos and schematic diagrams of sample transects at sites EA20-1 (A) and EA20-2 (B). (C, D) Zircon (U-Th)/He (ZHe) dates for EA20-1 and EA20-2 as a function of distance from the center of the fault zone. Date error bars are 2σ analytical uncertainty. (E, F) Zircon Th/U ratios at EA20-1 and EA20-2 as a function of location as in C and D.
Figure 3. (A) Individual ZHe date as a function of eU, classified by sample. eU concentration calculated based on grain dimensional mass. Date error bars are $2\sigma$ analytical uncertainty. (B) Apatite (U-Th)/He (AHe) date as a function of eU for Punchbowl Formation (Fm) sample 3A. eU concentration calculated from the Ca-based mass (Guenthner et al., 2016). Error bars are $2\sigma$ analytical uncertainty. (C) Plane-polarized light stereoscopic images of zircon and apatite grains analyzed in this study.
### Table 1. Zircon (U-Th)/He data

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**EA20-2B, gouge**

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\(^a\) Zr-based mass calculated from Zr measurement, stoichiometry (Guenthner et al., 2013)

\(^b\) Equivalent spherical radius

\(^c\) \(r = \) prism half-width

\(^d\) \(l = \) length

\(^e\) \(eU = \) calculated as \([U] + 0.235 \times [Th]\)

\(^f\) \(F_t = \) alpha ejection correction of Hourigan et al. (2005); Reiners (2005)

\(^g\) Error - 1σ analytical uncertainty propagated from the U, Th, Zr, He and grain length measurements
Table 2. Apatite (U-Th)/He data.

<table>
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<tr>
<th>Sample</th>
<th>Mass $^a$ (µg)</th>
<th>$R_s$ $^b$ (µm)</th>
<th>$r^c$ (µm)</th>
<th>$l^d$ (µm)</th>
<th>$U$ (ppm)</th>
<th>$Th$ (ppm)</th>
<th>$eU$ (with Sm)</th>
<th>$4He$ (nmol/g)</th>
<th>$Ft^e$</th>
<th>Raw date (Ma)</th>
<th>Corr. Date (Ma)</th>
<th>Error $^f$ (Ma)</th>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>0.68</td>
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</table>

$^a$ Ca-based mass  
$^b$ Equivalent spherical radius  
$^c$ $r$ = prism half-width  
$^d$ $l$ = length  
$^e$ Ft-alpha ejection correction of Farley (2002)  
$^f$ Error - 1σ analytical uncertainty propagated from the U, Th, He and grain length measurements
V. Discussion

5.1 Preliminary zircon (U-Th)/He thermochronometry data interpretations

Zircon (U-Th)/He data from all samples define a positive date-eU trend from ~10-60 Ma and ~20-700 ppm eU with a plateau at ~65 Ma at >700 ppm eU (Fig. 3a). Across all samples, most zircon grains have generally low (<500 ppm) to moderate (<500-1200 ppm) eU values, and low visual metamictization (Fig. 3c; cf. Ault et al., 2018). In the absence of Raman spectroscopy and detailed knowledge of the thermal history, the low to moderate eU and limited visual metamictization support the interpretation that these grains likely have low accumulated radiation damage. In addition, the positive ZHe date-eU pattern is characteristic of grains with low accumulated damage (Guenthner et al., 2013). This indicates that basement and Punchbowl Fm zircon grains, and PSZ grains sourced from these units, are likely Phanerozoic in age. If grains were Proterozoic or Archean, we might anticipate an inverse ZHe date-eU relationship at low to moderate eU values reflecting the antiquity of the grains and long duration(s) at temperatures low enough for damage to accumulate (Guenthner et al., 2013; Ault et al., 2018). Although we do not know the crystallization age of the basement, prior detrital zircon U-Pb geochronology of Punchbowl Fm grains indicates the presence and dominance of Phanerozoic zircon in the Punchbowl Fm (Ingersoll et al., 2013; Hoyt et al., 2018; Coffey et al., 2019b).

Data from the PSZ and gouge do not deviate from the overall ZHe date-eU pattern. For example, ZHe dates within the PSZ at site EA20-1 are ~18 to ~85 Ma, which overlap with Punchbowl Fm samples 1E and 3A ZHe dates of ~20 to ~64 Ma over similar eU
values (Figs. 2a, 3a). This relationship suggests that PSZ and gouge zircon grains shared a common thermal history with material outside the PF, and that the low-moderate radiation damage grains in the PF were not thermally reset by coseismic friction-generated heat. Although basement zircon crystals yield a restricted range of low eU values (<400 ppm), their ZHe dates are similar to Punchbowl Fm ZHe dates at similar eU, which supports that these units shared elements of a similar thermal history (Fig. 3a). If correct, the ZHe date-eU pattern defined by all samples implies some Punchbowl Fm grains could be sourced from the adjacent basement or units of similar age.

Punchbowl Fm AHe thermochronometry data provide important constraints on the thermal history of the PF and Punchbowl Fm. AHe dates from sample 3A are uniform at ~4 Ma over ~180 ppm spread in eU, indicating rapid cooling of the Punchbowl Fm adjacent to the PF at that time (Fig. 3b). Assuming this phase of exhumation is related to transpression on the PF, these dates may represent the best new timing constraint of PF activity. Robust interpretation of AFT results is hindered by low apatite and track yields (Table D.2). Limited AFT dates show intrasample scatter and sample central dates that do not pass the $X^2$ test, suggesting different AFT date populations reflect partial resetting. The lack of complete track annealing in sample 1E indicates the Punchbowl Fm did not experience temperatures >110 °C since ~12 Ma, constraining the magnitude of burial in the Punchbowl basin since that time. This peak temperature is consistent with biomarker-derived estimates of burial temperatures of the Punchbowl basin (Polissar et al., 2011).

Zircon Th/U values are useful for documenting the source of material in the PSZ and gouge. Th/U values of PSZ and gouge grains from samples 1B and 2B, respectively, support mixing of material from both sides of the PF (Fig. 2c, 2d; Table 1). Punchbowl
Fm samples (1E, 3A) yield Th/U values of 0.10-0.16 and >0.52, with a notable gap in between these Th/U ranges. Basement samples (1C-1, 1C-3, 2A-1, 2A-3) have Th/U >0.29. The Th/U ratio of four grains from PSZ sample 1B zircon overlap with values from Punchbowl Fm sample 1E (~0.1-0.2). The other three sample 1B grains have Th/U values that overlap with those of basement samples (~0.3-0.5), and thus must be basement derived. Results require that the PSZ comprises material from both the Punchbowl Fm and the basement. Interestingly, at site EA20-2, the Th/U of gouge grains (2B) do not overlap with those of adjacent basement samples (2A-3, 2A-1). If grains within gouge are derived solely from immediately-adjacent wall rock, then the Punchbowl Fm is the source of material at site EA20-2. This is consistent with the greater fracture intensity and erodibility of the Punchbowl Fm (Dor et al., 2006). Alternatively, these Th/U values reflect m-scale lateral translation of basement material along the PF during fault slip.

5.2 Characterization of the Punchbowl formation long-term thermal history

5.2.1 Modeling approach and setup

We leverage our ZHe and AHe date-eU patterns to broadly constrain the long-term history of the Punchbowl Fm and PF fault rocks using thermal history modeling. We focus on the Punchbowl Fm and not the crystalline basement because more independent information that can inform thermal history models exists for the Punchbowl Fm including potential zircon crystallization ages and detailed constraints on the thermal history since ~12 Ma. In addition, Punchbowl Fm samples also have a broader zircon eU range than basement samples, allowing us to better utilize ZHe date-eU relationships.
Because the PSZ (1B) and gouge (2B) ZHe results define the same date-eU pattern as the Punchbowl Fm (1E, 3A) and Th/U data suggest some zircon grains are derived from the Punchbowl Fm, models also inform the long-term thermal history of the PSZ and gouge.

We employ the forward modeling capabilities of HeFTy (Ketcham, 2005) and the diffusion kinetics of the zircon and apatite radiation damage accumulation and annealing models (ZRDAAM and RDAAM, respectively; Flowers et al., 2009; Guenthner et al., 2013). We use the ZRDAAM of Guenthner et al. (2013) and note model outcomes are not likely to differ if the Ginster et al. (2019) annealing kinetics are applied for the types of time-temperature (tT) histories investigated here (Guenthner, 2021). We pose candidate tT paths to generate ZHe and AHe dates over a range of eU comparable to the range observed in analyzed grains. Models apply the mean grain size or equivalent spherical radius (Rs) for the Punchbowl Fm zircon (62 µm) and apatite (42 µm).

We consider end-member tT scenarios based on available geologic constraints and inferences from our observed date-eU patterns. Figure 4a shows our five candidate tT paths (1=pink, 2=blue, 3=green, 4=orange, 5=purple). The paths begin at 150 Ma (paths 2, 3) or 65 Ma (paths 1, 4, 5), owing to the likely crystallization ages of our zircon grains from observed minimal visual metamictization and peaks in detrital zircon U-Pb age data (Ingersoll et al., 2013; Hoyt et al., 2018). The Punchbowl Fm ZHe date-eU plateau at ~60-65 Ma suggests grains cooled rapidly through ~160-200 °C at that time. For simplicity, paths 2-5 cool rapidly to near-surface temperatures at ~65 Ma, but we also explore the scenario in which the zircon grains monotonically cool from crystallization to 0 °C at 12 Ma (path 1). To evaluate the role of reheating events in development of the observed positive ZHe date-eU pattern, paths 3 and 5 include a reheating event prior to
12 Ma and paths 2 and 4 do not. Paths 3 and 5 are characterized by reheating to 150 °C, constrained by the inference of inherited He in Punchbowl Fm grains, symmetric around ~35 Ma. All paths are at the surface (0 °C) at 12 Ma, reflecting the unconformity between the San Francisquito Fm and Punchbowl Fm and deposition of the Punchbowl Fm at ~12.5-8.5 Ma (Liu, 1990). Temperatures peak at 110 °C at 5 Ma for all paths, representing Punchbowl basin burial, consistent with our partially reset AFT data and prior biomarker work (Polissar et al., 2011). Finally, all paths cool after 5 Ma, representing Punchbowl Fm exhumation during the time the PF is thought to be active.

5.2.2 Model outcomes and implications

Modeled ZHe and AHe date-eU patterns from thermal history forward models are compared with observed Punchbowl Fm (1E, 3A), PSZ (1B), and gouge (2B) ZHe data and Punchbowl Fm (3A) AHe data (Fig. 4). Paths with two reheating events best predict the observed ZHe and AHe date-eU patterns. For example, tT histories with two reheating events (paths 3, 5) reproduce the observed steep positive ZHe date-eU trends at <700 ppm eU, the ZHe date plateau at ~60-65 Ma at >700 ppm eU, and uniform ~4 Ma AHe dates regardless of eU. In contrast, paths 2 and 4, which remain at surface temperatures between 65 and 12 Ma, predict uniform ~65 Ma ZHe dates at >100 ppm eU, older than what is observed, and predict markedly older AHe dates at high eU, inconsistent with predicted AHe results. Monotonic cooling since formation (path 1) is unlikely because the predicted ZHe date-eU plateau is too young relative to observed data. Additionally, it is geologically unlikely that detrital Punchbowl Fm grains were not exposed at the surface since the time of crystallization. Thus, model outputs suggest that
detrital grains comprising the Punchbowl Fm, PSZ, and gouge experienced an initial Eocene-Oligocene reheating event prior to deposition of the Punchbowl Fm and reheating during Punchbowl basin development.

Thermal history models also support the assumption that zircon grains from the Punchbowl Fm, PSZ, and gouge are likely Phanerozoic. It is challenging to reproduce the observed ZHe date-eU pattern if the grains are Precambrian and experienced prolonged residence at near-surface conditions (Fig. D.3). If analyzed grains were Precambrian, it would require that they resided at >200-500 °C, temperatures where they would not accumulate radiation damage to be compatible with the lack of visual metamictization (Guenthner et al., 2013; Ault et al., 2018; Ginster et al., 2019), for a substantial period of geologic time before 65 Ma. However, prior thermochronometry studies, together with the development of the Great Unconformity, indicate most Proterozoic and Archean crystalline basement in the North American Cordillera has been previously exhumed, making it unlikely that ancient zircon grains resided at >200-500 °C from crystallization to ~65 Ma (Orme et al., 2016; Johnson et al., 2017; Ault et al., 2018; DeLucia et al., 2018; Jensen et al., 2018; Flowers et al., 2020).

Thermal history models imply that the PF fault rocks broadly share the same long-term thermal history as the Punchbowl Fm. The general overlap of the basement ZHe date-eU trend with this pattern also suggests the basement shares elements of a common thermal history with the Punchbowl Fm. However, basement samples lack a broad span of eU values to evaluate this. More work, including double-dating basement zircon with U-Pb geochronology and ZHe thermochronometry, is required to constrain the crystallization age of these rocks and the corresponding long-term tT history.
Figure 4. (A) Representative time-temperature (tT) paths for the Punchbowl Fm. (B) Predicted ZHe date-eU curves of Punchbowl Fm grains with colors corresponding to tT paths in (A) and observed ZHe date-eU patterns for the Punchbowl Fm (samples 1E, 3A), principal slip zone (PSZ, sample 1B), and gouge (sample 2B). (C) Predicted AHe date-eU curves and observed AHe date-eU patterns for Punchbowl Fm sample 3A.
5.3 Refining peak temperature rise with numerical models

Thermochronometry data patterns and thermal history models suggest friction-generated heat from past seismic slip on the PF was insufficient to reset ZHe dates in the PSZ at EA20-1 and in gouge at EA20-2. Numerical models that couple temperature-sensitive kinetic reactions, based on biomarker MPI-4 values, with bulk fault surface temperature rise indicate peak temperatures of 465-620 °C for a 10 mm half-width of the deforming zone up to 815-1065 °C for 50 µm half-width. (Savage & Polissar, 2019). Multi-method comparison of systems with different kinetics allows us to compare systematics and refine coseismic temperature estimates. Here we use a suite of numerical modeling approaches to bracket peak temperatures associated with coseismic temperature rise on the PF leveraging the ZHe date-eU pattern from the PSZ and gouge samples, inferences of low to moderate accumulated radiation damage, and associated He loss in these zircon grains.

5.3.1 Fractional He loss in variably damaged zircon

First, we constrain the peak coseismic temperatures by coupling heating for different magnitudes and durations with He diffusion in zircon grains with variable radiation damage levels. Figure 5 is a “pseudo-Arrhenius” diagram with contours of zircon fractional (90%) He loss calculated as a function of time and temperature from a square-pulse heating event, where the magnitude and duration of heating are inversely related (Reiners, 2009). Here, we use experimentally-derived diffusion kinetic parameters (activation energy, \(E_a\), and frequency factor, \(D_0\)) from zircon grains encapsulating a range of accumulated radiation damage from no damage (Reiners et al., 2004) to low, medium,
high, and very high (amorphous) damage (Table 3; Guenthner et al., 2013), and a Rs of 30-60 µm that encompasses the range of most analyzed zircon grains. Diffusion experiments were conducted using prograde-retrograde heating schedules of 10 to 15 90-minute at 150 to 500 °C (Reiners et al., 2004; Guenthner et al., 2013)

We consider the temperatures required to induce He loss at earthquake timescale durations (10-60 s), consistent with heating durations inferred in Savage and Polissar (2019). Our grains are low accumulated radiation damage analogous to Mudtank diffusion kinetics, based on dominantly low eU values, likely Phanerozoic age, and limited metamictization (blue line, Fig. 5) (Guenthner et al., 2013). At earthquake timescales and this damage level, temperatures required to induce 90% He loss are ~600-750 °C. PSZ and gouge ZHe data do not deviate from the ZHe date-eU pattern defined by the host rocks implying coseismic temperatures did not exceed these values. Ambient conditions during PF activity were <110 °C, well below the nominal Tc for low damage zircon at these geologic conditions. Thus, evidence of superimposed coseismic temperature rise, manifest as additional He loss from low eU grains, should be reflected in the ZHe data if temperatures were >600-750 °C.

Although prior biomarker analyses from these same rocks suggest temperature rise range from 465-1065 °C (depending on the imposed slip zone width), ZHe data and pseudo-Arrhenius relationships indicate peak temperatures did not exceed ~600-750 °C. If grains are characterized by moderate damage (analogous to B231 of Guenthner et al., 2013) then they would require temperatures >750 °C to induce appreciable He loss (purple line, Fig. 5). In order to induce He loss at temperatures <600 °C, zircon kinetics require effectively amorphous (i.e., very high damage analogous to N17; black line, Fig.
5; Guenthner et al., 2013) grains that exhibit high eU and are Archean or Paleoproterozoic, which we do not observe in our dated aliquots.
Figure 5. Zircon 90% fractional He loss contours as a function of the inverse of temperature (T) and time (t) calculated from a square-pulse heating event. Calculations use $E_a$ and $D_0$ values from grains with no damage (green), low damage (blue), medium damage (purple), high damage (red to orange), and very high damage (grey to black) from Reiners et al. (2004) and Guenthner et al. (2013). For each contour, $R_s$ varies from 30µm (light color) to 60 µm (dark color). Bottom panel shows a zoomed in portion of top diagram, highlighting the relationships of 90% He loss contours at earthquake timescales (10-60 s, brown shaded region).
Table 3. Diffusion kinetic reaction parameters.

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<th>Ea (kj/mol)</th>
<th>D0</th>
<th>Fluence (alpha/g)</th>
<th>Source</th>
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</table>
5.3.2 Shear heating model

We next explore fault slip conditions that produce temperatures hot enough to induce He loss in low radiation damage zircon grains with a coupled shear heating-He diffusion model. This model calculates bulk surface temperature rise using an isotropic square heat pulse associated with an individual earthquake and corresponding zircon fractional He loss (Appendix C.2; Fechtig & Kalbitzer, 1966; Lachenbruch, 1986; McDermott et al., 2017). We use model parameters similar to those of Savage and Polissar (2019) and diffusion kinetic parameters for low damage zircon (Table 3; Guenthner et al., 2013). We calculate the 90% and 10% zircon He loss contours because they define the partial retention zone for ZHe (Wolf et al., 1998).

We consider four models that each predict peak temperature over a range of slip velocities (V) and displacements (D), for prescribed slip zone half-width (h) and coefficient of friction (μ). We focus on the temperature at the slip interface (z=0). The range in V (0.01-1 m/s) and D (0.1-5 m) are within the expected range for large earthquakes and are similar to values used in Savage and Polissar (2019). Models 1 and 2 use h of 1 cm and 5 cm, respectively, reflecting the observed PSZ width of 2 cm at EA20-1 and gouge width of 10 cm at EA20-2. The μ for models 1 and 2 is 0.12, which is the measured value for PF gouge material (Kitajima et al., 2010). Models 3 and 4 use h of 1 cm and μ is varied to 0.3 and 0.6, illustrating a range of μ from clay-like materials to Byerlee’s coefficient of friction (Byerlee, 1978; Moore & Lockner, 2008). Values and reasoning for parameters are listed in Table D.5.

Model outcomes show calculated temperatures on the fault surface as a function of V and D and temperature-dependent 90% and 10% He fractional loss contours (Fig. 6).
Analogous to prior work (e.g., Lachenbruch, 1986; Coffey et al., 2019b; Savage & Polissar, 2019), temperature rise is sensitive to \( h \) and \( \mu \) but there is a tradeoff between \( \mu \) and \( D \). At an \( h \) of 1 cm, for any given \( D \), \( V > 0.2 \) m/s yields uniform peak temperatures because at these conditions heat production outpaces heat dissipation (Lachenbruch, 1986). For any \( V \) and \( D \), a thinner deforming zone yields higher temperatures than a wider deforming zone (compare model 1 (\( h = 1 \) cm) with model 2 (\( h = 5 \) cm); Fig. 6a, b), and the model predicts a temperature rise of only \( \sim 250 \) °C and no corresponding He loss at EA20-2. Increasing \( \mu \) from 0.12 to 0.6 (while holding \( h \) constant) yields higher peak temperatures (Fig. 6a, c, d).

Shear heating model results have implications for peak temperature, as well as \( h \), \( \mu \), and displacement, during earthquake activity on the PF. Shear heating models indicate that 90% He loss is achieved at temperatures \( > 750 \) °C, slightly higher than inferred temperatures derived from pseudo-Arrhenius calculations (Fig. 6a, 6c, 6d). Models 1 and 2, which apply slip zone thicknesses relevant for PSZ and gouge at sites EA20-1 and EA20-2, respectively, illustrate that a narrow PSZ is required to generate temperatures hot enough to induce He loss and that if the thickness of the gouge approximates the width of the deforming zone, then it is insufficient to cause even 10% He loss. Because there is no He loss in PSZ and gouge zircon data it is likely that the \( \mu \) of the PF was closer to 0.12 (Kitajima et al., 2010) during PF activity. Additionally, the absence of substantive coseismic He loss in the PSZ in conjunction with model 1 outcomes indicates that displacement per event likely did not exceed 4 m.
Figure 6. Shear heating model results showing peak temperature rise (color scale at right) at fault surface with 10% and 90% fractional He loss contours (black lines) calculated from shear heating (Lachenbruch, 1986) and fractional He loss (Fechtig & Kalbitzer, 1966) equations. Velocity (x-axis) and displacement (y-axis) are 0.1-1 m/s and 0.01-5 m, respectively, for each model. (A) Model 1 slip zone half-width is 1 cm (representing observed PSZ width of 2 cm at EA20-1) and coefficient of friction is 0.12. (B) Model 2 slip zone half-width is 5 cm (representing observed gouge width of 10 cm at site EA20-2) and coefficient of friction is 0.12. Note temperature scale is 0-500 °C in B and calculated temperatures are insufficient to induce He loss in this model. (C) Model 3 slip zone half-width is 1 cm; coefficient of friction is 0.3. (D) Model 4 slip zone half-width is 1 cm; coefficient of friction is 0.6.
5.3.3 Thermal history with superimposed temperature rise

We also quantify coseismic temperature rise along the PF by modeling the effect of theoretical earthquake friction-generated heat on ZHe date-eU trends (Fig. 7). To accomplish this, we superimpose temperature spikes at 5 Ma, or the time the PF was active, on the best representative long-term tT path (path 3 in section 5.2) and use HeFTy to model predicted ZHe dates over a range of eU. We apply the inferred tT path for the Punchbowl Fm to the PSZ and gouge grains because the data from both units broadly define the same ZHe date-eU pattern and Th/U data indicate some fault material is sourced from the Punchbowl Fm. As a thought experiment, models incorporate 100 earthquake events, which are represented by 100 ~30 s temperature spikes to 500, 600, 700, 800, or 900 °C, occurring 1000 years apart, and beginning at 5 Ma. The temperature pulses last ~30 s because that is the minimum time interval HeFTy can resolve. The 1000-year recurrence interval allows the model to return to ambient temperature following each temperature spike. Models use the ZRDAAM (Guenthner et al., 2013) and an Rs of 37 µm and an eU range of 0-1200 ppm, consistent with PSZ and gouge grains. Although the shear heating model holds zircon diffusion kinetics constant (Fig. 5), the ZRDAAM allows radiation damage accumulation and annealing and He diffusion to evolve as a function of time and temperature.

Model outcomes exhibit variable ZHe date-eU patterns depending on the magnitude of temperature rise (Fig. 7). To first order, 500 °C, 600 °C, and 700 °C models yield positive ZHe date-eU trends and associated date-eU plateaus similar to the observed data pattern. The 800 °C model yields a positive date-eU trend, but it is a different shape and yields younger dates at every given eU than the lower temperature models. The 900 °C
model predicts uniform ~5 Ma dates regardless of eU because coseismic temperatures are hot enough to induce complete He loss from grains at that time.

For the models with temperature spikes >700 °C, the predicted and observed ZHe date-eU patterns diverge because PF temperatures induce excess He loss. This comparison implies coseismic temperatures likely were <700 °C, consistent with the outcomes of our two other modeling exercises. He loss is greater in lower eU grains in each of our temperature spike models, reflecting that low eU grains are more sensitive to short-duration high temperatures than moderate damage grains, consistent with results in the pseudo-Arrhenius diagram (Fig. 5). We note that one PSZ ZHe date differs from the broader date-eU trend (700 ppm, ~20 Ma), and overlaps the 800 °C temperature curve. This date may reflect the spatial variability in coseismic temperatures and that these grains experienced ~800 °C or the effects of U and Th zonation, but more data is needed to discriminate between these possibilities.
Figure 7. Predicted ZHe date-eU curves for PSZ and gouge grains with hypothetical temperature “spikes” simulating coseismic friction-generated heat events superimposed on the best representative tT path (path 3 in Fig. 4). 100 earthquake events are represented as 100 ~30 second temperature spikes that are 1000 years apart beginning at 5 Ma. The temperature spikes in each model are 500 °C, 600 °C, 700 °C, 800 °C, or 900 °C (dark grey to light grey, respectively). The predicted ZHe date-eU curve with no earthquake temperature rise (black) is shown for reference.
5.4 Intermethod comparison and implications for Punchbowl fault evolution

Thermochronometry data patterns together with pseudo-Arrhenius calculations, shear heating models, and forward models with superimposed short-duration reheating events refine the peak temperature rise along the PF. Prior work provides a backdrop to interpret our data and model outcomes. Biomarker results suggest coseismic temperature rise ranges from 465-1065 °C depending on the thickness of the slip zone. PSZ and gouge data define the same ZHe date-eU pattern as samples from outside the PF, indicating coseismic temperatures did not induce He loss in the PSZ and gouge superimposed on the long-term thermal history. Thus, our ZHe data provide an upper bound on peak temperatures. Collectively, model outcomes suggest coseismic temperature rise is <600-750 °C, even though each model has different assumptions.

Differences between inferred peak temperatures from the biomarker and ZHe systems reflect several factors related to method systematics and fault zone characteristics through time. First, biomarker data, or the MPI-4 index, has a lower $E_a$ (22.4; Sheppard et al., 2015; Savage & Polissar, 2019) than the ZHe system, regardless of the damage level (71-170 kJ/mol; Table 3; Guenthner et al., 2013). This means biomarkers are more easily altered than He is lost from zircon for a given thermal history characterized by frictional heating. Biomarker reaction kinetics are sensitive to coseismic temperatures based on prior high velocity friction experiments (Savage et al., 2018), as well as to maximum coseismic temperatures (Savage & Polissar, 2019). In the ZHe system, the He budget in a zircon grain reflects accumulated radiation damage (Guenthner et al., 2013) and the integrated thermal history. Thus, the peak temperatures of coseismic reheating events
matter, but also the duration and amount of time between temperature spikes – all
parameters that are inferred in our models – influence He loss.

Second, the conditions and mechanics of slip along the PF likely evolved since the
fault initiated. This results in different coseismic temperatures due to spatio-temporal
differences in $h$ and $\mu$. Our observation of variable fault-zone width and presence/absence
of a PSZ, in conjunction with shear heating model results, imply that the temperature rise
can vary substantially on the meter-scale along strike. Shear heating model results
indicate that a wider slip zone (analogous to EA20-2) produces lower temperature rise
than a narrow slip zone (EA20-1). Third, differences in ZHe and biomarker-derived
temperature estimates may reflect disparate fault slip paleotemperatures in space and
time. Although we reoccupied the same sites as Savage and Polissar (2019), we sampled
different volumes of rock that experienced different thermal conditions in three
dimensions. This complements inferences from Savage and Polissar (2019), who
observed different MPI-4 values within and across different sites, indicative of variations
in temperature rise along and across strike from variable slip zone width and localized
variations in earthquake properties.

Our data and model results have implications for the earthquake energy budget. Prior
work suggests frictional energy along the PF was at least an order of magnitude more
than the fracture energy (Savage & Polissar, 2019). However, if the coseismic
temperatures along the PF locally did not exceed 600-750 °C, then less energy was
consumed to overcome fault friction. Lower relative frictional energy implies that either
the ambient strength of the fault was less, suggesting that more displacement along the
PF was accommodated aseismically, or that the magnitude of displacement per event was
lower. Studies show that faults weaken through time (e.g., Chester et al., 1993), so it is possible that the strength of PF has evolved.
VI. Conclusions

Robustly quantifying coseismic temperatures on fault surfaces requires intermethod comparison of paleothermometers with different kinetics. Here we leverage prior biomarker evidence for friction-generated heat, newly acquired ZHe data and complementary apatite low-temperature thermochronometry, and numerical models to constrain the coseismic temperature rise on the PF. We infer that analyzed grains are low accumulated radiation damage because of their limited visual metamictization, low to moderate eU, and likely Phanerozoic age. Zircon grains entrained within the PSZ and gouge are derived from both the crystalline basement and Punchbowl Fm adjacent to the PF and share a common thermal history with material outside the PF characterized by multiple reheating and thus burial and unroofing events. Thermochronometry data patterns suggest friction-generated heat from past seismic slip on the PF was insufficient to reset ZHe dates in the PSZ and gouge. Combined model results in conjunction with ZHe date-eU patterns suggest the temperature rise along the PF was <600-750 °C. Temperatures required to induce He loss in zircon across a spectrum of accumulated damage must be higher than those needed to thermally alter organic material. Differences in calculated coseismic temperature rise reflect disparate reaction and diffusion kinetics between the two systems, as well as the thermal and mechanical evolution of the PF in space and time. Parallel outreach and education activities promote engagement in geosciences, through activities centered on scientific drilling through active faults.
VII. References


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APPENDICES
APPENDIX A. OUTREACH AND BROADER IMPACTS ACTIVITIES

A.1. Preface

Work presented here comprises two completed outreach activities that provide the groundwork and scaffolding for a third outreach activity. Each activity has different but related objectives, audiences, and products. The third activity will continue through my PhD studies at USU, which will allow me to better develop outcomes and findings.

A.2. Introduction

The San Andreas Fault (SAF) is a transform plate boundary that borders nearly 800 miles of the western margin of North America and poses earthquake threats to a large portion of California’s population. Geologists can study exhumed, ancient strands of the SAF, such as the Punchbowl fault (PF; Chester & Chester, 1998) to learn more about past and future SAF behavior. However, to investigate in situ processes associated with faults at depth, geologists examine subsurface samples and downhole logging measurements obtained from scientific drilling projects. Earthscope’s San Andreas Fault Observatory at Depth (SAFOD) drilling project (Zoback et al., 2010; Earthscope.org; NSF-EAR 1829465) allows geologists to study in situ physical, chemical, and mechanical processes controlling active faulting and seismicity (Hickman et al., 2007).

SAFOD is a scientific drilling project drilled through the creeping section of the San Andreas Fault, near Parkfield, California (Hickman et al., 2007; Zoback et al., 2010). The drill site location was selected along the SAF because the SAF is a major plate boundary and has been extensively studied, allowing ground-truthing of fault properties observed at
the surface. The borehole reaches ~2500 m depth and crosses the fault at nearly a 90˚ angle. Using recovered core and borehole geophysical data, geologists identified two major strands of the SAF that are actively deforming; the central deforming zone and southern deforming zone (CDZ and SDZ, respectively; Boness & Zoback, 2004; Hickman & Zoback, 2004; Zoback et al., 2010; Jeppson & Tobin, 2015). Cuttings and core show that materials at the CDZ and SDZ are altered and serpentinized (Bradbury et al., 2007; Springer et al., 2009; Bradbury et al., 2011; Holdsworth et al., 2011). The low coefficient of friction and Poisson’s ratio of serpentine may be why the SAF is creeping in this section (Carpenter et al., 2015; Jeppson & Tobin, 2015). SAFOD findings are crucial to our understanding of fault-related rocks and processes at depth.

My thesis research incorporates a component of outreach education that directly contributes to Broader Impact goals of the NSF-EAR 1829465 Project, *Integration of the Physical and Chemical Rock Properties, Structure, and Permeability of the San Andreas Fault, San Andreas Fault Observatory at Depth Borehole, California*. Herein, I provide a description of these public outreach efforts and online learning modules developed for undergraduate non-major students based on the Earthscope SAFOD scientific drilling project (Hickman et al., 2007; Zoback et al., 2010). The primary objectives for the participants in these outreach activities are: 1) to foster an appreciation scientific drilling and earthquake geology, and 2) to inspire interest in non-geoscience majors and the general public, potentially motivating a geology-related career path. This STEM learning opportunity is in alignment with several NSF agency directives (https://www.nsf.gov/pubs/2018/nsf18045/nsf18045.pdf)
I have implemented public outreach and learning activities with >1300 community members of all ages at the Department of Geosciences Rock and Fossil Day, with two non-major students from USU Blanding, and nine geoscience-major students in the USU Communicating Geosciences course. Over the next year, final implementation of the learning activities are anticipated to reach >5000 people, including members of the local community and non-major students within USU’s Natural Disaster’s courses.

**Figure A.1.** (A) Seismicity (black dots) and population density in the state of Utah are coincident. From [https://quake.utah.edu/2017](https://quake.utah.edu/2017). (B) Location of San Andreas fault (black line), earthquakes associated with the SAF (grey circles), and SAFOD location (red star).
A.3. Motivation

Earth Science is relevant to our daily lives, especially in seismically active regions such as the Intermountain Seismic Belt (ISB) in northern Utah. Most Cache Valley (where USU is located) residents live along or in close proximity to the Wasatch fault or the East and West Cache Fault zones, which are part of the ISB (Fig. A.1a). However, in Utah most K-12 students are not directly exposed to the Earth sciences or the topic of earthquake hazards, thus they are not aware of the potential risks associated with these hazards. Additionally, schools may lack teachers who specialize in geoscience education or there is significant lack of diverse or female role models within the geosciences (e.g., Bernard & Cooperdock, 2018; Ranganathan et al., 2021). These factors all contribute to an overall lack of engagement amongst underrepresented and underserved groups, including women in the geosciences (Ranganathan et al., 2021). In the state of Utah, developing STEM identity in women, K-12, and broadening participation of marginalized populations is critical for growth and diversity within the STEM work force and a scientifically-literate society (Ranganathan et al., 2021; https://www.uvu.edu/uwlp/docs/2019.uwlp.briefn-14.pdf). Remote learning assignments can also provide greater accessibility (especially in a pandemic) and an increase in potential engagement from student’s living in rural communities throughout Utah.

The societal and scientific impacts of scientific drilling projects are also not widely appreciated by the general public. Misconceptions may exist surrounding scientific drilling because it is commonly confused with commercial drilling or oil and gas drilling, which may lead to a destruction of the surrounding natural environment or induced seismicity (Suckale, 2009; Ellsworth, 2013). However, scientific drilling is specifically
focused on increasing understanding of Earth systems and typically involves only a few
drillholes per project and extensive planning to minimize impacts. Scientific drilling is a
form of technology in research and is interdisciplinary in nature; it requires experts in
geo sciences, physics, engineering, and math; and it is expensive and time consuming.
Education about the differences in drilling types and benefits of scientific drilling is
important to create a positive perception of scientific drilling.

Engagement in scientific drilling projects and geology has the potential to motivate
future interest in a broad range of geoscience topics. To increase engagement and build
the next generation of geoscientists, students need to be exposed to the topic, and earlier
in their education is better, such as in K-12 schools or as undergraduate students (Eagan
Jr et al., 2013). Here I use SAFOD and the SAF as a case study for investigating
scientific drilling, earthquake hazards, and fault zones as a way to introduce these topics
to a broad range of target audiences. The SAF has similar seismic risk to the ISB, thus
students can transfer this knowledge to further their understanding of fault zones and
associated earthquake hazards in their region.

A.4. Outreach Efforts

The outreach efforts presented here are both formal and informal and aimed at
different populations including students and the general public. The activities include an
interactive poster, a week-long learning module with hands-on activities, and an
informational video and class assignment. Activities are designed for transportability to a
variety of audiences and specifically target non-geoscience majors and the general public.
For some of the activities, students utilize integrated, multi-scale datasets, such as
SAFOD rock core, thin-section observations, and geophysical data. SAFOD provides an opportunity to share an interesting tool that geologists use to learn about Earth, faults, earthquake hazards, and demonstrates to students and the public how fault studies and scientific drilling projects are conducted. In these outreach lessons, I focus on earthquake geology, thus enhancing Earthscope’s outreach efforts and legacy.

The purpose of these outreach activities is to give the general public, college, and Native American two-year college students (Table A.1) an authentic learning experience based on the investigation of SAFOD fault rocks and the purpose of scientific drilling within the field of geology. An overarching goal of the activities is to engage participants with a broader understanding of earthquakes and how fault behavior might directly impact the participant’s lives. Using the scientific method and guided learning practices allows the students to take ownership of their learning and to construct and reflect upon their own ideas. Additionally, by disseminating complex aspects of earthquake research more simply through these outreach efforts, I am building effective geoscience communication skills and aim to inspire the next generation of earthquake scientists.
Table A.1. Activities and target groups for SAFOD outreach.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Date(s)</th>
<th>Target group; number of participants reached</th>
<th>Implementation methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock and Fossil Day</td>
<td>February 23, 2020</td>
<td>Logan-area general public, specifically K-12 students; &gt;1300</td>
<td>Interactive poster, fliers</td>
</tr>
<tr>
<td>USU’s Native American Science Mentoring Program (NASMP)</td>
<td>June 1-5, 2020</td>
<td>Non-geoscience-major students at a two-year college; 2</td>
<td>Online learning modules, 4 days of activities</td>
</tr>
<tr>
<td>USU Communicating Geoscience class (GEO 3400)</td>
<td>Spring 2021</td>
<td>Geoscience undergraduate students; 9</td>
<td>Presentation, assignment, and survey</td>
</tr>
<tr>
<td>USU Natural Disasters class (GEO 3100)</td>
<td>Summer 2021</td>
<td>Non-geoscience-major students; ~100</td>
<td>Learning module, one activity in class</td>
</tr>
</tbody>
</table>

A.4.1. Rock and Fossil Day 2020

Rock and Fossil Day is an annual free-choice informal learning event for the general public hosted by USU’s Geosciences department. The event serves community members from ages 4-90, with an emphasis on student populations because Utah students have limited engagement with and thus struggle to connect with Earth science. More than 1300 community members attended the 2020 Rock and Fossil Day, hosted on February 23. The products and activity that I created for this event include a poster with actual SAFOD rock samples and informative fliers (Figs. A.2, B.1, B.2, B.3). The poster depicts a cross-section view of the SAFOD bore hole path with generalized rock units and descriptions. Within the ‘borehole’ there are Velcro patches where participants could place the appropriate rock sample (with attached Velcro) corresponding to the geology. The fliers (Figs. B.2, B.3) provided more information about the findings of SAFOD and the creeping portion of the SAF. I plan to present this poster at future Rock and Fossil Days
as well. This poster can also be presented by my advisor, Kelly Bradbury, in subsequent years when I am no longer at USU.

The first-order learning objectives for the audience at Rock and Fossil Day were to gain knowledge of fault zones, fault rocks, SAFOD, fault types, and scientific drilling benefits (see appendix B.1.1. for learning objectives). The interactive part of the poster allowed the audience to synthesize the rock types presented and analyze why certain rock types are present in particular locations. My second-order objectives (for students who were older and/or more engaged) were to demonstrate to students that fault rocks may be serpentinized (and thus be green) and that rock properties may be an influential or controlling factor for why the SAF creeps in this section. With this, the participants learned that there are damaged rocks along the deforming zones (the fault), and that there are different rock types on either side of the plate boundary. In addition, for learners who were particularly engaged, I connected the SAF to faults in the Logan area, and that there may even be a fault under their homes.

The results from the first presentation at Rock and Fossil Day were well-received. Students of all ages were interested in the poster, and many had preliminary knowledge of faults and earthquakes, allowing them to connect with the material on a deeper level. The poster also engaged students and their parents together effectively, indicated by the numerous parents who were surprised to learn that there are many faults within Cache Valley and the area surrounding USU. This of free-choice learning event allow participants to feel more comfortable asking questions and to make observations and interpretations on their own. This supports their curiosity and provides a positive interaction that we hope stimulates future interest in STEM fields. Another positive
outcome of the Rock and Fossil Day activity was that I gauged interest and understanding of fault zones by general audience in Cache Valley, which was helpful for subsequent related outreach activities.

Figure A.2. Rock and Fossil Day poster, rock samples, and student interactions.

A.4.2. NASMP 2020

The Native American Science Mentoring Program (NASMP, https://www.usu.edu/mesas/nasmp/index) is a program that brings students from the USU Blanding campus (near the Navajo Nation) to the Logan main campus to experience a larger campus and have research-like experiences with various science groups. The USU Blanding campus is a small, 2-year college with limited research activities on campus, and therefore students have minimal interaction with science and likely little to no experience with scientific drilling. This leads to few role models, contributing to Native
American students not connecting to and not pursuing geology. The main goal for our participation in NASMP was to increase awareness and exposure of the field of Earth Sciences, specifically Earthquake geology, as Indigenous students continue to be one of the most underrepresented groups in the geosciences (Bernard & Cooperdock, 2018). Ideally, students may even consider becoming geoscience majors at USU. In a typical year, the NASMP program is taught in person, however the 2020 NASMP activities were administered remotely due to COVID-19.

My research group created a weeklong set of lectures and activities for NASMP students. These activities highlighted the rock cycle, plate tectonics, Earth system science, fluid-rock interactions, and the scientific method, (see Appendix B.1.2 for learning objectives). Because this event is usually in person where students get to visit the USU campus and experience lab activities, we also emphasized the analytical techniques that we use in research in order to increase interest and show a holistic view of what we really do. We organized and created a variety of activities to present to the three NASMP students in our group. Before NASMP week, I coordinated meetings with our team to distribute responsibilities for each activity. We shipped a box of selected materials to enhance the participants’ experiences that included rock samples (Fig. B.4), a geologic notebook, various pens and pencils, printed materials to create fault block models, and Oreos to for an activity demonstrating fault types.

When NASMP week began, we lectured remotely (Fig. A.3) each day and provided time for the students to complete our provided activities and ask questions. Each day focused on a different theme relating to fault studies: (1) Earth systems science overview, the rock cycle and rock descriptions, (2) macroscale studies, (3) microscale studies, (4)
borehole geophysics, and (5) wrap-up. See Table B.1 for the NASMP week itinerary. My task for day 1 was to create and present lectures about the rock cycle and rock descriptions, as well as to demonstrate how the students would complete their at-home assignments using their geologic notebooks. For day 2, I highlighted the scientific method, demonstrated fault types with a paper fault block model, and introduced scientific drilling. For day 3, I created and presented a video about mineral separation techniques. For day 4, while I did not have any specific presentation responsibilities, I helped with the delivery of the online learning content. On day 5, we held a wrap-up session where we provided a short overview and the students provided feedback.

NASMP activities were well-received, especially with the given circumstances. We had many difficulties with synchronous meetings and student internet connection, and it was hard to gauge interest and understanding because of the remote delivery. However, one student said that our activities were her favorite, and presented a positive poster regarding our activities (Fig. B.5). Importantly, I learned how to better engage students remotely, which was critical for the final activity I created.
A.4.3. Scientific drilling and SAFOD video and assignment

The final product of SAFOD-related outreach activities is a video and companion assignment to be implemented in USU’s Department of Geosciences Natural Disasters course (GEO 3100). The video consists of demonstration of fault rock studies on SAFOD samples. For each rock sample in the borehole, the video examines a different technique to investigate fault processes. For example, for the sample in the central deformation zone (CDZ), the video demonstrates the uses and purpose of using a Raman to identify micro-scale structures in the fabric of the sample. The assignment consists of three parts in which students (1) review plate tectonics and plate boundaries and understand that the SAF is the plate boundary, (2) learn about scientific drilling, SAFOD, and geoscience
analyses, and (3) the SAF is creeping in some locations because of serpentine. Students use context clues from the video and from suggestions in the assignment to interpret the reason the SAF is creeping (see Appendix B.1.3 for learning objectives). The assignment was created in Canvas, an online learning management system that is used in many universities. The content in the assignment and video is sourced from the Rock and Fossil Day poster and NASMP activities. We partnered with USU Senior Lecturer Blair Larsen and Instructor Amy Hochberg to assist in developing appropriate instructional materials for undergraduate non-major students and to conduct learning assessments on the proposed learning module.

To develop the assignment associated with the video further, I presented a preliminary version of the activity (Appendix B.2) to the USU Communicating Geoscience class (GEO 3400), an undergraduate Geoscience-major class. When I presented this activity to the Communicating Geoscience class, the video was not yet finalized, so I presented a lecture describing the background and aims of the video and assignment. This was reasonable because the students were geoscience majors so they had some preliminary background knowledge about earthquakes and fault studies. The students then completed the assignment and provided feedback in a survey, allowing me to gauge the effectiveness of the activity as well as consider how the assignment could be improved. The survey responses were positive with helpful ideas on how to improve the online assignment (Fig. B.6).

The implementation of the video and assignment will be in the Natural Disasters class over the next few semesters. This is a non-major class that is offered via traditional face-to-face instruction on USU’s Logan main campus, online, hybrid-online, and
broadcast to 11 regional campuses throughout Utah. Enrollment in this class for the Summer 2017-Spring 2018 period exceeded 2000 students (Table B.2). As a result of the COVID-19 pandemic, there were increases in online enrollment, thus there was a need for relevant online education modules such as this.

For this assignment, a major challenge is to engage a large number of students who do not have a strong interest in geology. Another challenge for the assignment is it was required to be self-contained and auto-graded in order to alleviate extra work on the instructors administering the assignment. These limitations restricted the creativity and thinking questions delivered to students but are crucial to make the activity more applicable to the large-enrollment Natural Disasters classes.

A.5. Future outreach efforts

Future work involves implementing the video and assignment in the USU Natural Disasters class during my PhD studies at USU during the 2021 school year. Based on feedback from the class, I will continue to modify and improve the assignment, then publish the assignment and video to be available for public use. The video and activity will be available on USU’s Department of Geosciences outreach webpage (https://geo.usu.edu). We will also pursue open-access availability of these activities through a variety of STEM and geoscience teaching websites such as: 1) the National Association of Geoscience Teachers (NAGT, https://nagt.org/index.html). 2) IRIS; and 3) the Science Education Resource Center at Carleton College (SERC, https://serc.carleton.edu/index.html). The activities will have an associated DOI (digital object identifier, or link to a web version). Thus, the activities have the potential to create
an accessible and long-term learning opportunity for a much broader and diverse range of scientists, community members, policy makers, educators, and students.

As a future educator, I aim to communicate science to the general public, with an emphasis in earthquake geology to increase exposure and engagement within this field. Using the SAFOD scientific drilling project as the central focus to examine fault rocks, plate boundaries, and earthquake hazards across a variety of learning levels and/or events, I’ve refined and developed critical outreach skills that will ultimately inform and motivate future implementation of effective and fun learning activities.
A.6. References


APPENDIX B. OUTREACH AND BROADER IMPACTS

SUPPLEMENTAL MATERIALS, FIGURES, AND TABLES

B.1. Learning objectives for all activities.

B.1.1. For all activities:
- Develop knowledge of fault zones and fault rocks
- Associate the SAF and SAFOD, identify the type of fault
- Interpret why scientific drilling is necessary and useful
- Identify where the San Andreas Fault is located
- Explain what SAFOD is and importance of its location
- Identify and locate fault rocks

B.1.2. For NASMP:
- All of the above plus:
  - Identify three types of plate boundaries
  - Identify and describe three types of faults, interpret a fault’s orientation and sense of motion
  - Identify where earthquakes occur in the world
  - Identify changes in geophysical properties from well logs and align these changes with other geological datasets
  - Investigate the scales of study completed on fault rocks

B.1.3. For Natural Disasters assignment:
- all of the above plus:
  1. Gain a basic understanding of the subject
     a. Plate boundaries
     b. Fault zones
        i. Recognize that a fault zone is where earthquakes occur, and that there is not just one fault, but rather it is a ‘zone’
     c. Scientific drilling
        i. Define scientific drilling
        ii. Identify the purpose of scientific drilling
        iii. List types and applications of scientific drilling
     d. Serpentine or Serpentinite (the rock comprised of serpentine minerals)
        i. Mineral is green
        ii. A physical property=slippery
  2. Solve spatial and temporal problems
  3. Read various types of graphs
  4. Gain broader understanding of intellectual activity
a. Wholistic activity: students use data and samples from SAFOD to gain a deeper understanding of why the fault is creeping at depth.
b. Students appreciate the importance and challenges of scientific drilling.

5. Apply course/activity material
6. Highlight USU lab spaces
B.2. Canvas assignment and video

Link to Canvas assignment:
https://lor.instructure.com/resources/e3853106b6744ac2972594be149d3684?shared

Link to YouTube Video: https://youtu.be/7y6xxeXGLXI

PDF version of Canvas quiz:
Instructions: Stimulus is the information provided before the questions are answered. The question answer choices are listed as bullet points, and the correct answer is bolded.

**Stimulus: Plate tectonics Overview**

**Question 1:**
Match the plate boundary type to the location on the map. One boundary has two answers (matching)

- transform boundary  **answer: location A**
- convergent boundary  **answer: location C**
- divergent boundary  **answers: location B, D**

**Question 2:**
What type of plate boundary is closest to Logan, Utah (star on map)

- transform
- divergent
- convergent

**Stimulus: Video [insert link to video]**
**Question 3:**
Watch the video and click done when the video is complete.
- video is complete.

**Stimulus: Where does the San Andreas fault show evidence of creep?**
Each circle on this map represents an earthquake that occurred between 1769-2015 in the state of California. Notice that there are less earthquakes near the star which represents the SAFOD Scientific Drilling site. Recall that where a fault is creeping, earthquakes are uncommon because the motion is accomplished with sliding rather than large magnitude earthquake events with intense ground shaking.

Another piece of evidence that the fault is creeping near SAFOD is shifted roads and fences. The average creep rate is 21-26 mm/year which is 2.6-2.8 m/100 years (Titus et al., 2006).

Notice how both of these photos show a shifted curb. This did not occur because of an earthquake, but rather because of creep. An earthquake would probably cause the curb to break not bend. Note that this is a photo in segment A in the map above, showing the Calaveras fault near Berkeley, California which is a branch of the San Andreas fault system.
Question 4:
Based on the map to the left, select the two locations where the San Andreas fault is probably creeping as shown by a general lack of significant earthquakes.

- segment A
- segment B
• segment A
• segment D

**Question 5:**
Based on what you heard in the video, what is the hypothesis about why the fault is creeping?
• Serpentinite (a rock made of serpentine minerals) is present
• Quartz is present
• the water table is very shallow there
• the ground is composed of loose sand

**Stimulus: What is scientific drilling and who does it benefit?**
We want to know more about why the fault is creeping near SAFOD. The rocks at the surface tell us a lot, but we want to know MORE. Such as what rock types or features are controlling the fault motion at depth. We can use rock samples and data collected from scientific drilling projects to increase our understanding of what is going on at depth. Other applications of scientific drilling include: paleoclimate studies using ice core and determining the age of sea floor sediments.

While the same technologies are used for both scientific and oil and gas exploration drilling, scientific drilling is different than drilling for oil and gas because scientific is for public interest and oil and gas is for specific corporations.

The reason drilling rocks at depth can be more useful than collecting rocks at the surface, is because they are *in situ*, meaning they are the rocks that are at depth and currently experiencing and influencing fault activity. If we can get our hands on these samples and learn more about their properties, we can get a better idea of what is going on at depth at the earthquake focus. However, scientific drilling is very expensive and challenging to carry out and can take years of careful planning.

The San Andreas Fault Observatory at Depth, or SAFOD, took >10 years of planning before the main borehole was drilled, and cost ~ $25 million for on-site operations. Taxpayers benefit from scientific drilling because it helps us to understand how earthquakes form and impact the landscape. We can use findings from scientific drilling to create more realistic seismic risk models and to mitigate the potential damaging effects of earthquakes.

**Question 6:**
What are the benefits of scientific drilling
• it is a simple, inexpensive tool
• obtain samples of unweathered rock
• ground-truth surface measurements
• collect oil and natural gas for profits

**Stimulus: Where exactly is the fault creeping?**
Calipers are the finger-like instruments that are put down the borehole to measure *in situ* movement of the crust. Here is a photo of a caliper that was sent down the hole to measure motion.
40-arm caliper logging tool (PMIT)
Source: Photographic core atlas (2011)

The graphs below illustrate motion along the fault over a certain time period. Where the line strays the most from horizontal is where the crust is moving the most. This is a key observation from SAFOD because other we have not drilled across other active faults, thus we don’t have this type of data from other faults. Drillers typically don’t drill across faults because it is risky- if an earthquake occurs when the instruments are in the drill hole, the drillers may lose machinery, instrumentation, and data and may cause damage to the surrounding infrastructure.

**Caliper log data**

Southwest Deforming Zone (SDZ)  
Central Deforming Zone (CDZ)

Source: modified from Photographic core atlas (2011)

As a reminder, here is the cross-section view of the SAFOD drill path and the faults that it intersected. Both the SDZ and CDZ sections are part of the San Andreas fault.
Question 7:
Which zone has the most deformation? (Hint: look at the caliper log data in the second image)
- Central Deforming Zone (CDZ) (~3300 m)
- Southwest Deforming Zone (SDZ) (~3192 m)

Stimulus: Do certain minerals cause the fault to creep?
Now let’s figure out why the fault is creeping in the SDZ and CDZ. Remember from the video that the rock sample near the SDZ is green – this is exciting since no other rock samples collected are olive green and have a waxy texture.

Let’s look at the mineral contents of the rocks from SAFOD to figure out which mineral is responsible for making the rocks appear olive green and to see if this mineral has anything to do with the creeping behavior. The below shows mineral contents at certain depths.
Presence of prominent quartz and serpentine in SAFOD drill core. Modified from Bradbury et al. (2011).

**Question 8:**
At what depths is the serpentine content the highest? Select all that apply. Note that the depth ranges also overlap with deformation zones (CDZ and SDZ).
- ~3181 - 3191 m
- ~3200 - 3292 m
- ~3292 - 3302 m
- ~3302 - 3308 m
Stimulus: What rock type is present in the active part of the fault?

modified from Zoback et al. (2011)
Question 9:
Which rock type is from the SDZ? (Hint: it is greenish)

- granite
- black fault rock
- block in matrix (BIM) rock
- andesite
- serpentine
- silicate
**Stimulus: Why do certain minerals cause the fault to creep?**
We have learned that serpentine is prominent in both of the actively creeping fault segments (the SDZ and CDZ), but is not prominent elsewhere in the borehole. This result supports the hypothesis that the fault could be creeping due to the presence of serpentine.

**Question 10:**
Serpentinite is a rock composed of serpentine minerals. Serpentine is a similar mineral to clay or talc. Talc is used in baby powder because it prevents chaffing on a baby’s bottom. Therefore, what physical property of serpentine might make the fault creep?
- slippery
- hard
- rough
- bouncy

**Question 11:**
Serpentine and talc are minerals that have low friction and slide easily. Therefore the reason the fault is creeping here is because of the presence of:
- serpentine
- quartz
- calcite
- salt

**Stimulus: Do other faults creep and are there other important uses of scientific drilling?**
The Wasatch fault (located on the Wasatch front, Utah) doesn’t have creeping sections because rocks nearby do not contain the mineral serpentine, and for other more complex reasons like stresses within the crust and pore-fluid pressures that are beyond the scope of this assignment.

**Question 12:**
What are other use/application of scientific drilling?
- analysis of seafloor sediments
- geothermal resource evaluation
- dating/chemistry of ice cores
- all of the above

**Stimulus: Resources and references**
Websites:
https://www.icdp-online.org/projects/world/north-and-central-america/san-andreas-fault-
usa/details/
2011, Photographic Atlas of the SAFOD Phase 3 Cores (version 5). (http://www.earthscope.org/ http://www.icdp-
online.org/contenido/icdp/front_content.php?idcat=896)

Journal articles:


CAN YOU IDENTIFY FAULT ROCKS?

1. Read rock descriptions
2. Identify the rock that matches the description
3. Place the rock in its location on the cross section
4. You identified which rock is the fault rock!

**Fault rocks from active San Andreas Fault Zone**
- numerous fractures (cracks)
- ultracataclasite (black)
- serpentinite (green)
- scaly clay fault gouge (brown)
- shiny, reflective slip surfaces
- creep rate = 4.8 cm/year

**Sedimentary bedrock**
- North American rocks are sedimentary
- sandstones, siltstones, shales (grey, reddish-brown, tan)
- undeformed

**Crystalline bedrock**
- Pacific plate rocks are granite
- crystalline
- white, black, and pink speckles

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**Figure B.1.** Rock and Fossil Day poster
The goal of this project was to find what kinds of minerals define the fault at depth, why it is creeping in this section, and to make geophysical observations near the fault zone.

**why**

The SAFOD borehole is drilled along the Parkfield segment of the San Andreas fault, at the transition between creeping and locked portions of the fault.

**where**

Scientists, engineers, and drillers teamed up to create a drill rig that could dig 2 kilometers into Earth, then turn 45° to cross the fault. In order to grind through hard rocks, large drill bits are covered with a coating that contains diamonds!

**how**

SAFOD is a scientific borehole drilled through the San Andreas fault zone. There was a pilot hole and three main phases of drilling to collect rock samples and in-hole measurements. The project was formulated in 1992 and finished the last portion of drilling in 2007.

**what**

Serpentine-rich scaly clay fault gouge from the San Andreas fault zone

**when**

SAFOD borehole

*Figure B.2. Rock and Fossil Day flier 1.*
The San Andreas Fault is creeping!

How do we know?
On the surface of Earth, there is evidence of continuous, slow motion of the plates sliding, or creeping, past each other.

Scientists drilled a hole that crosses the San Andreas Fault (called San Andreas Fault Observatory at Depth), and use an instrument called a caliper logging tool to record creep (the wavy lines on the graph).

Why is this happening?
This is debated, but we now know from scientific drilling that there are weak, ‘slippery’ serpentinite clay minerals that are along the fault that allow the rocks to slide past each other without creating earthquakes.

In some sections of the San Andreas Fault, the North American Plate is sliding past the Pacific Plate at a rate of 4.8 cm/year, but there are no big earthquakes.

Figure B.3. Rock and Fossil Day flier 2.
Figure B.4. Rock samples sent to NASMP students.
Figure B.5. NASMP student poster.
Scientific drilling and SAFOD assignment feedback

9 responses

Publish analytics

On a scale of 1 to 5, how well did you understand the questions?

9 responses

On a scale of 1 to 5, how much did you learn from the reading associated with the questions?

9 responses

https://docs.google.com/forms/d/1ek31qFXMxcC1zZzWmMyGiSfD8zAK_t0DeBt8yY3s/viewanalytics
What did you feel were the main takeaways from the reading and questions?
9 responses

They were associated with the questions, and were made to help understand the relationship between fault activity and more “slip” minerals such as serpentine

Applying knowledge of San Andreas fault to other fault systems makes this project worth it

Faults are cool

The importance of the drill core. What the faults are made of.

Drilling is important for hazard analysis

Learning about the San Andreas fault zone and drill core.

The warping of the rock at the fault due to the nature of the fault.

My main takeaways from the video were mostly information about how the samples from the drill core were prepared and analyzed. From the reading and questions I mainly
Given what the students know before watching the video, do you think there are enough context clues in the assignment to answer the questions?

9 responses

Yes

Assuming that this material was also discussed in a lecture, I feel like it should be enough information, assuming the questions are completed (since it looks like there are some placeholder answers for some of the options, etc). I think the one where the drill data was representing the amount of serpentine at depth from the core (I forget the question #) I think being able to read that data might not come as easily for non-majors, so maybe like a different key or legend with it.

yes

I think there is enough

When watching the entire video then most likely.

Yes, I think there are enough clues.

I think there was enough context but some of the questions were pretty confusing.
Suggestions for improvement. Please provide any suggestions for the questions, answer choices, or text.

9 responses

Just updating/completing the questions, and perhaps a section in this survey for things that are done well, because so far things look really good. Very simple and straightforward.

Few questions with typos (chart scale on question 7), option C and D got redundant and obviously the incorrect answer.

Turn off that randomize, fix typos, fix viewing, include the segments.

I understand that they are for students who know nothing about Geology. There were some questions where it was like. There are snakes there, option D, option C, or creeping. I just felt like having only 1 answer like that was a little to easy for them. I think it would be nice for non-majors to know the depth of drilling, just so they might know better how deep deformation and faulting occurs.

One of the questions gave a clue about a green mineral (serpentine) but in the images associated with the question the mineral doesn't display to be very green.
Do you wish there were more information about a certain topic? Explain
9 responses

Nothing in particular, I'm sure when the video is complete it will have more on this, but I think taking a bit more about the benefits of scientific drilling in the video.

Compare data learned to other fault systems. Is it similar or different to other popular fault zones, or is this experiment the one-and-only of its kind?

yes I think that everything needs a little more info associated with it, but I think once the video is finished it will add a lot more

I thought that there was enough information presented

More information on why faulting leads to earthquakes, if I'm not a geology student I might not know.

No

I felt satisfied with the content provided

Figure B.6. Communicating Geoscience class survey and responses.
# Table B.1. NASMP itinerary.

Zoom meeting times may not be at specified times, will not last the full 3 hours

Zoom link (same for every day): https://us02web.zoom.us/j/81631575993?pwd=bTJOOTNwSkdlVHJEUKZRZTVNZHVzdz09

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<td>Kelly</td>
<td>watch /ask questions if possible; Oreo Demo</td>
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<td>Rock cycle/rock descriptions</td>
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<td>watch /ask questions if possible</td>
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<td>Assignment 1a - plate tectonics</td>
<td>Notebook, videos</td>
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<td>Watch plate tectonics video, answer questions</td>
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<td>Assignment 1b - rock type</td>
<td>Notebook, samples</td>
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<td>Fill in which sample is associated with which rock type</td>
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<td>Assignment 1c - rock description</td>
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<td>Write 2-3 bullet points for a rock description of each rock</td>
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<tr>
<td>Scientific method</td>
<td>Video</td>
<td>Ema</td>
<td>Watch video and answer questions</td>
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<td>Faults</td>
<td>Zoom, Powerpoint (or youtube video), Fault block model</td>
<td>Kelly, Anna, Ema</td>
<td>Watch video about faults, do paper block model with Anna</td>
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<td>Fault zone architecture and fault rocks</td>
<td>Powerpoint</td>
<td>Kelly</td>
<td>watch /ask questions if possible</td>
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<td>Issues of scale - Outcrop studies</td>
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<td>watch sample processing video</td>
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<td>Core studies</td>
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<td>Assignment 2a</td>
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<td>Watch drawing video, make your own sketch of a rock sample or a view. Make interpretations about how rock/outcrop formed.</td>
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<td>Assignment 2b</td>
<td>Video, notebook</td>
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<td>Watch SAFOD videos, complete SAFOD activity</td>
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### Day 3: Wednesday, June 3 9:30 am - 12:30 pm

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<td>watch/ask questions if possible</td>
<td>Develop knowledge of fluid related alteration processes in fault zones</td>
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<td>Mineralogical alteration and fluid-rock interactions</td>
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<td>Develop knowledge of petrography</td>
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<td>Petrography</td>
<td>Video</td>
<td>Kayla</td>
<td>watch video</td>
<td>Brief intro to x-ray methods (handout). Video of pXRF in process and graphs of spectra associated with samples that were sent.</td>
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<td>XRF and pXRF</td>
<td>Video, handout</td>
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<td>watch video</td>
<td>Recognize different elements exhibit different spectra</td>
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<td>Geominutes video</td>
<td>Ema</td>
<td>watch video</td>
<td>Recognize that sample processing takes many forms and is a lengthy process</td>
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<td>Visualize the lab spaces at USU</td>
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<td>Assignment 3a</td>
<td>Handout</td>
<td>Anna/Kelly</td>
<td>pXRF - identify elements associated with spectra for select samples</td>
<td>Recognize different elements exhibit different spectra</td>
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<td>Jared</td>
<td>Measure spring constant for two springs. Measure yield point for 4 rubber bands. Identify linear and nonlinear elasticity.</td>
<td>Describe elasticity, plasticity, and fracture, and observe these deformation behaviors using force vs. extension graphs.</td>
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<td>Intro to borehole geophysics</td>
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<td>Jared</td>
<td>Match changes in elastic moduli to changes in the lithology/structure in the SAFOD borehole.</td>
<td>Identify changes in geophysical properties from well logs and align these changes with other geological datasets.</td>
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### Day 5: Friday, June 5 9:30 am - 11 am

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APPENDIX C. THERMOCHRONOMETRY METHODS AND SHEAR HEATING MODEL SET UP

C.1. Thermochronometry methods

C.1.1. Zircon and apatite (U-Th)/He methods

Zircon and apatite were isolated using standard crushing methods including mortar and pestle for more friable samples, and magnetic and density separation techniques in the USU Mineral Microscopy and Separation Lab (M^2SL) at Utah State University. Apatite and zircon were extracted from bedrock samples using standard magnetic and density separation techniques at the Mineral Microscopy and Separation Laboratory at Utah State University. Whole zircon grains and apatite fragments were present in each sample, but whole apatite grains suitable for (U-Th)/He analysis were only present in Punchbowl Formation (Fm) sample 3A. We target a subset of samples for ZHe thermochronometry including the PSZ (1B), gouge (2B), basement (1C-1, 1C-3, 2A-1, 2A-3), and Punchbowl Fm (1E, and 3A). Mineral separates were examined under stereoscope and target apatite crystals selected on the basis of morphology, clarity, and lack of inclusions and target zircon crystals were selected following the visual metamictization approach described in detail in Ault et al. (2018). Final grains were imaged, their dimensions measured, and loaded into Nb packets.

U-Th-He (as well as Sm for apatite) analyses were conducted at the Arizona Radiogenic Helium Dating Laboratory at the University of Arizona. To measure He, aliquots were heated with a diode laser to ~900-1300°C for 18-20 minutes and four minutes for zircon and apatite, respectively. One or more gas re-extract (lasing) for 20-21 minutes at higher temperatures was performed for zircon grains and no gas re-extract
were done for apatite grains. Extracted He was spiked with $^3$He, purified using cryogenic and gettering methods, and measured with a quadrupole mass spectrometer. A known amount of $^4$He was measured every 8th sample to monitor instrument variability drift.

Degassed apatites were retrieved, spiked with a $^{233}$U-$^{229}$Th-$^{147}$Nd-$^{42}$Ca tracer, dissolved in HNO$_3$, and analyzed on an Element 2 high-resolution inductively-coupled plasma mass spectrometer (HR-ICP-MS). Following addition of a $^{233}$U-$^{229}$Th-$^{90}$Zr spike, equilibration, and dissolution in HF in dissolution in a Parr bomb, the U, Th, and Zr isotopes of zircon aliquots were measured on an Element 2 HR-ICP-MS. Grain masses were used to calculate U, Th, Sm, and He concentrations. For apatite grains, the mass was calculated from Ca measurements and stoichiometry following the protocols of Guenther et al. (2016). For zircon analyses, we report the dimensional mass calculated from morphological measurements following the protocols of Hourigan et al. (2005) to be consistent across all data. Durango apatite and Fish Canyon Tuff zircon were used as standards to assess dissolution protocols and HR-ICP-MS analyses. Blank-corrected (U-Th-Sm)/He and (U-Th)/He dates were calculated with propagated analytical uncertainties from U, Th, Sm, and He measurements. An alpha-ejection correction was applied using grain measurements and assuming apatite and zircon are unzoned with respect to U, Th, and Sm (Farley et al., 1996; Hourigan et al., 2005).

**C.1.2. Apatite fission track methods**

Selected apatite fragments were mounted in epoxy, polished and etched with 5.5M HNO$_3$ at 20-21°C for 20 seconds (Donelick et al., 2005) to reveal spontaneous fission tracks. The samples were irradiated in a reactor and analyzed with the external
detector method (Gleadow, 1981). Track lengths, track densities, and Dpar values (or the diameter of etched spontaneous fission-tracks measured parallel to the crystallographic c-axis, used to characterize grain chemistry, which impacts annealing kinetics) were measured under a microscope using FT software by Stuart Thomson at the University of Arizona FT Lab. Central ages and 1σ uncertainties are calculated with a zeta-calibration approach against Durango apatite standards (e.g. Gallagher, 1995; Carlson et al., 1999; Gleadow et al., 2002).
C.2. Shear heating model set up

Here we apply and modify the coupled thermomechanical-He diffusion model of McDermott et al. (2017). This model first quantifies slip surface temperatures using the bulk fault temperature rise equations of Lachenbruch (1986) and Cardwell et al. (1978):

\[
T(z, t) = \frac{\tau V}{2 \rho C h} \left[ \left( 1 - 2i^2 \text{erfc} \frac{h - z}{\sqrt{4 \alpha t}} \right) - 2i^2 \text{erfc} \frac{h + z}{\sqrt{4 \alpha t}} \right] \left( t - t^* \right)
\]

\[
\frac{2i^2 \text{erfc} \frac{h - z}{\sqrt{4 \alpha (t-t^*)}} - 2i^2 \text{erfc} \frac{h + z}{\sqrt{4 \alpha (t-t^*)}}}{2i^2 \text{erfc} \frac{h - z}{\sqrt{4 \alpha (t-t^*)}}} + T_{\text{amb}}
\]

(C.1)

where \( T \) is temperature, \( z \) is distance from the fault surface (or shear zone depth), \( t \) is time, \( \tau \) is shear stress, \( V \) is slip velocity, \( \rho \) is density of the slipping material, \( C \) is the specific heat capacity, \( h \) is the half-width of the deforming zone, \( i^2 \text{erfc} \) is the second integral of the complementary error function, \( \alpha \) is the thermal diffusivity, \( t^* \) is the duration of slip, and \( T_{\text{amb}} \) is the ambient fault temperature. Model input values are based on relevant material properties; see Table D.5 for model input values and reasoning.

Using the calculated temperature rise from equation (C.1), the He diffusion rate for each timestep is calculated. He diffusion can be represented by the Arrhenius equation:

\[
\frac{D}{r^2} = \frac{D_0}{r^2} e^{\frac{-E_a}{RT}}
\]

(C.2)

where \( D \) is the diffusion coefficient, \( D_0 \) is the frequency factor, \( r \) is the diffusion length scale, \( E_a \) is the activation energy, \( R \) is the gas constant, and \( T \) is the temperature. The integrated thermal history can be represented as “reduced time” (Fechtig & Kalbitzer, 1966), where equation (C.2) is integrated from 0 to \( t \) for each time step:

\[
\tau_r(T, t) = \frac{D_0}{r^2} \int_0^t e^{\frac{-E_a}{RT}} dt'
\]

(C.3)
where $t_r$ is the reduced time for each time step. Temperature, $T$, is from equation (C.1) and time, $t$, is the current time step. The diffusion length scale is based on observed grain size, and other parameter inputs are typical values for He diffusion from zircon.

We calculate the fractional loss of He for each timestep using the paired fractional loss equations of Fechtig and Kalbitzer (1966):

$$
F \approx \frac{6}{\pi^2} \left[ \sqrt{\pi^2 t_r} - \frac{3}{\pi^2} (\pi^2 t_r) \right] \quad F \leq 0.85 \tag{C.4}
$$

$$
F \approx 1 - \frac{6}{\pi^2} e^{-\pi^2 t_r} \quad F \geq 0.85
$$

where $F$ is the fractional loss for each time-temperature step, assuming a spherical domain. The reduced time for each time step, $t_r$, is from equation (C.3).
C.3. References


APPENDIX D. SUPPLEMENTAL FIGURES AND TABLES
FOR THERMOCHRONOMETRY AND SHEAR HEATING MODELS

Figure D.1. (U-Th)/He date vs. eU for individual samples with plain-polarized stereoscope images of each grain.
Figure D.2. (U-Th)/He date vs. equivalent spherical radius for (A) zircon and (B) apatite.
Figure D.3. Forward model results for grains with Archean crystallization ages.
Figure D.4. Forward model results with a single temperature spike at 5 Ma.
<table>
<thead>
<tr>
<th>Site ID</th>
<th>Latitude, Longitude</th>
<th>Outcrop number in Savage and Polissar (2019)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA20-1</td>
<td>34°23'53.5&quot;, -117°49'55.1&quot;</td>
<td>1</td>
</tr>
<tr>
<td>EA20-2</td>
<td>34°23'53.5&quot;, -117°49'54.0&quot;</td>
<td>1</td>
</tr>
<tr>
<td>EA20-3</td>
<td>34°23'56.2&quot;, -117°49'54.1&quot;</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Table D.2. Apatite fission track central dates.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of grains</th>
<th>Ns</th>
<th>Ni</th>
<th>Ng</th>
<th>Dpa</th>
<th>ρs</th>
<th>ρi</th>
<th>ρs / ρi</th>
<th>U ppm</th>
<th>Central Date</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>basement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A20-1C-2</td>
<td>4 2 30 96 1.70</td>
<td>4</td>
<td>1.19E+0</td>
<td>1.19E+0</td>
<td>0.0667</td>
<td>4.6</td>
<td>18.1</td>
<td>13.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EA20-2A-3</td>
<td>4 1 30 1.176</td>
<td>4</td>
<td>2.25E+0</td>
<td>3.58E+0</td>
<td>0.0333</td>
<td>3.5</td>
<td>8.7</td>
<td>8.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EA20-2A-2</td>
<td>10 6 155 6 1.72</td>
<td>4</td>
<td>5.82E+0</td>
<td>5.82E+0</td>
<td>0.0387</td>
<td>5.7</td>
<td>10.1</td>
<td>4.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EA20-2A-1</td>
<td>2 1 16 64 1.73</td>
<td>4</td>
<td>3.91E+0</td>
<td>3.91E+0</td>
<td>0.0625</td>
<td>3.8</td>
<td>16.5</td>
<td>17.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fault gouge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EA20-1B</td>
<td>3 7 104 0 1.83</td>
<td>4</td>
<td>8.13E+0</td>
<td>8.13E+0</td>
<td>0.0673</td>
<td>7.6</td>
<td>18.4</td>
<td>7.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EA20-2B (corr)</td>
<td>5 5 25.5 0 2.22</td>
<td>3</td>
<td>5.28E+0</td>
<td>5.28E+0</td>
<td>0.0333</td>
<td>1.5</td>
<td>9.0</td>
<td>9.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Punchbowl Fm.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EA20-1E</td>
<td>18 76 3 0 1.84</td>
<td>5</td>
<td>2.71E+0</td>
<td>2.71E+0</td>
<td>0.0457</td>
<td>26.1</td>
<td>12.2</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table D.3. Data inputs and constraints for thermal history forward model simulations.

**1. Thermochronometry data.**
Model predicted ZHe and AHe date-eU relationships are visually compared with observed ZHe and AHe date-eU trends, respectively.

**ZHe data are from 2 samples***
Punchbowl Fm samples: EA20-1E, EA20-3A

**AHe data are from 1 sample***
Punchbowl Fm sample: EA20-3A

*All data necessary for modeling is reported in Table 1.

**2. Time-temperature constraints for models in section 5.2.1.**
See main text for complementary details.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Explanation and data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paths 1-5</td>
<td>&gt;600 °C at ~150 Ma or ~65.1 Ma</td>
</tr>
<tr>
<td>Archean modeled to investigate old grains (paths 6 and 7 in Appendix Fig. D.3)</td>
<td>&gt;600 °C at ~1700 Ma</td>
</tr>
<tr>
<td>Paths 2-5</td>
<td>Surface at ~65 Ma</td>
</tr>
<tr>
<td>Paths with reheating event prior to 12 Ma (paths 3 and 5)</td>
<td>150 °C at ~30 Ma</td>
</tr>
<tr>
<td>All paths</td>
<td>Surface at ~12.5 Ma</td>
</tr>
<tr>
<td>Peak temperature of 110 °C at ~5 Ma</td>
<td>Timing based on PF activity (Woodburne, 1975; Meisling &amp; Alexander, 1993; Chester &amp; Chester, 1998). Peak temperature based on AFT data (this study) show incomplete track length shortening since before 12 Ma (indicating temperatures ≤ 110 °C), biomarker alteration indicate temperatures ≤ 110 °C since 12 Ma, and exhumation amount (2-4 km; Chester &amp; Chester, 1998) combined with inferred geotherm of region (Bostick et al., 1978).</td>
</tr>
<tr>
<td>Surface temperature of 0 °C at 0 Ma</td>
<td>Near-present day temperatures.</td>
</tr>
</tbody>
</table>

**3. System- and model-specific parameters**

*He kinetic model: ZRDAAM (Guenthner et al., 2013) for ZHe simulations, RDAAM (Flowers et al., 2009) for AHe simulations.*

*Modeling code: Forward modeling approach that uses HeFTy v.9.3 algorithms (Ketcham, 2005) Modeling approach can be replicated in HeFTy.*

*Model inputs: Time-temperature path (see section 2 above for constraints); synthetic zircon eU; mean equivalent spherical radius (Rs, a proxy for grain size) for all Punchbowl Fm zircon grains (Rs=62 µm) and apatite grains (Rs=42 µm).*

*Model outputs: Synthetic zircon He dates for a range of eU with mean equivalent spherical radius.*

*IT path characteristics: Linear and based on section 2 inputs.*
Table D.4. Data inputs and constraints for thermal history forward model simulations with superimposed temperature spikes.

1. Thermochronometry data. Model predicted ZHe date-eU relationships are visually compared with observed ZHe date-eU trends.

ZHe data are from 2 samples*
PSZ sample: EA20-1B
Gouge sample: EA20-2B

*All data necessary for modeling is reported in Table 1.

2. Time-temperature constraints for models in section 5.2.1. Note these models incorporate constraints for path 3 in Table D.3. See main text for complementary details.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Explanation and data source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>For 100 temperature spikes model (Fig. 7)</strong></td>
<td>We simulate 100 earthquakes with 100 temperature spikes. Each temperature spike lasts ~30 seconds because that is the minimum resolution that HeFTy can resolve. The 1000-year time interval allows temperatures to cool to ambient conditions between each temperature spike. The temperatures are created to represent different earthquake conditions.</td>
</tr>
<tr>
<td>100 temperature spikes that last ~30 seconds are 1000 years apart and begin at 5 Ma. Peak temperature for each spike is either 500 °C, 600 °C, 700 °C, 800 °C, or 900 °C.</td>
<td></td>
</tr>
</tbody>
</table>

| **For 1 temperature spike model (Fig. D.4)**     | We simulate 1 earthquake with 1 temperature spike. The temperature spike lasts ~30 seconds because that is the minimum resolution that HeFTy can resolve. The temperatures are created to represent different earthquake conditions. |
| 1 temperature spike that lasts ~30 seconds at 5 Ma. Peak temperature for spike is either 500 °C, 600 °C, 700 °C, 800 °C, or 900 °C. |                                                                                                                                                             |

3. System- and model-specific parameters

He kinetic model: ZRDAAM (Guenthner et al., 2013) for ZHe simulations, RDAAM (Flowers et al., 2009) for AHe simulations.
Modeling code: Forward modeling approach that uses HeFTy v.9.3 algorithms (Ketcham, 2005) Modeling approach can be replicated in HeFTy.
Model inputs: Time-temperature path (see section 2 above for constraints); synthetic zircon eU; mean equivalent spherical radius (Rs, a proxy for grain size) for PSZ and gouge grains (Rs=37 µm).
Model outputs: Synthetic zircon He dates for a range of eU with mean equivalent spherical radius.
TT path characteristics: Linear and based on section 2 inputs.
### Table D.5. Shear heating model inputs

*All values are similar to those used in Savage and Polissar (2019).*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source, reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear stress, $\tau$</td>
<td>4.29 Mpa</td>
<td>Calculated from $\tau=\mu(\sigma-p)$.</td>
</tr>
<tr>
<td>Slip velocity, $V$</td>
<td>0.001-10 m/s</td>
<td>Varies in model.</td>
</tr>
<tr>
<td>Density, $\rho$</td>
<td>2575 kg/m$^3$</td>
<td>Based on density values of ultracataclasite.</td>
</tr>
<tr>
<td>Heat capacity, $C$</td>
<td>953 J/kg K</td>
<td>Based on heat capacity values of ultracataclasite.</td>
</tr>
<tr>
<td>Half width of deforming zone, $h$</td>
<td>0.15-10 mm</td>
<td>Varies in model.</td>
</tr>
<tr>
<td>Time</td>
<td>0-3000 s</td>
<td>Varies in model.</td>
</tr>
<tr>
<td>Shear zone depth, $z$</td>
<td>3 km</td>
<td>Average of 2-4 km depth of faulting from Chester and Logan (1986).</td>
</tr>
<tr>
<td>Thermal diffusivity, $\alpha$</td>
<td>9.1x10^-7 m$^2$/s</td>
<td>Based on thermal diffusivity values for clay rich ultracataclasite in Di Toro et al. (2011).</td>
</tr>
<tr>
<td>Duration of slip, $t^*$</td>
<td>0.0001-100 s</td>
<td>Varies in model, calculated from slip/V.</td>
</tr>
<tr>
<td>Ambient temperature, $T_{amb}$</td>
<td>110 °C</td>
<td>Based on biomarker evidence from Polissar et al. (2011), surface temperature combined with borehole geotherm temperature (Bostick et al., 1978) at 3 km depth (average of 2-4 km depth from Chester &amp; Logan, 1986).</td>
</tr>
<tr>
<td>Coefficient of friction, $\mu$</td>
<td>0.12-0.6</td>
<td>Based on $\mu$ values of Punchbowl Fm gouge in Kitajima et al. (2010).</td>
</tr>
<tr>
<td>Displacement, $D$</td>
<td>0.001-10m</td>
<td>Varies in model.</td>
</tr>
<tr>
<td>Normal stress, $\sigma_n$</td>
<td>64.7 MPa</td>
<td>$\rho g h$</td>
</tr>
</tbody>
</table>
D. 1. References


