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# SUPPLEMENTAL MATERIAL

# History of earthquakes along the creeping section of the San Andreas fault

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Materials and methods



**Fig S1.** Biomarker thermal maturity parameters sensitive to coseismic temperature rise at SAFOD conditions. Panels shows the stable (red) and unstable (blue) isomers of each

biomarker. A) Methylphenanthrene structural isomes and the methylphenanthrene index (MPI-4). B) C29 Steranes  $\alpha$  and  $\beta$  isomers and the sterane index (SI).  $\alpha\alpha\alpha$  -Ster: 20S + 20R  $5\alpha(H), 14\alpha(H), 17\alpha(H)$  C<sub>29</sub> regular sterane,  $\alpha\beta\beta$ -Ster: 20S + 20R  $5\alpha(H), 14\beta(H), 17\beta(H)$  C<sub>29</sub> regular sterane.



**Fig S2.** Plot of sterane index along the core, includes replicate measurements of samples split prior to crushing and extraction. Purple shaded regions are the actively creeping Southern and Central deforming zones. The grey shaded zone represents the background maturity of steranes at SAFOD. Due to the higher source dependence of steranes, the high values in the sandstone at 3152 m is likely an effect of different lithology.



**Fig S3.** *n*-alkane carbon preference index (CPI,  $C_{26} - C_{35}$ ) measurements made on the first sampling round of SAFOD samples. Purple shaded regions are the SDZ (top) and CDZ (bottom). CPI decreases with increasing temperature. CPI is low in SAFOD samples, mostly hovering around 1, indicating they have reached maximum maturity and therefore show no thermal maturity anomaly.



**Fig S4.** Alkane distribution index (ADI) measurements made on the first sampling round of SAFOD samples. Purple shaded regions are the SDZ (top) and CDZ (bottom). ADI decreases with increasing temperature. Samples are at or approaching the maximum value (~1.5) for ADI\ and therefore show no thermal maturity anomaly.



**Fig S5.**  $17\alpha(H)$ ,  $21\beta(H)$ -homohopane 22SR ratio (22S/[22S+22R]) measurements made on the first round of SAFOD samples. This ratio increases with increasing thermal maturity. All samples along the core are approaching maximum for the  $C_{31}$  22SR hopane index (~0.6, dashed lines) from burial heating, therefore no thermal maturity anomaly is present.



**Fig S6.** *C*<sub>31</sub> hopane/moretane index (hopanes/[hopanes + moretanes]) measurements made on the first sampling round of SAFOD samples. This parameter decreases with increasing thermal maturity. Most samples are approaching their maximum value (0.1, dashed line), therefore no thermal maturity anomaly is present. Hopanes are (22S + 22R)  $17\alpha(H)$ , 21  $\beta(H)$ -homohopanes (*C*<sub>31</sub> hopanes) and moretanes are (22S+22R)  $17\beta(H)$ , 21  $\alpha(H)$ -homohopanes (*C*<sub>31</sub> moretanes).



**Fig S7.**  $C_{29}$  SR-sterane index (20S/20S+20R) measurements made on the first sampling round of SAFOD samples. This ratio increases with increasing temperature. Most samples are at or approaching the maximum value of 0.5 for this particular sterane ratio, therefore no thermal maturity anomaly is present. 20SR sterane index calculated from the 20S and 20R  $5a(H), 14a(H), 17a(H) C_{29}$  regular steranes.



**Fig S8.** Thickness information from and west of the BFR. A) Thickness with distance along the core. B) thickness distribution calculated using measurements and applied in temperature models.



**Fig S9.** Maximum temperature histograms for each sample that were modeled using biomarker thermal maturities. These reflect the uncertainties in MPI4 reaction kinetics, slip layer thickness, friction, and event displacement.



Fig S10. Experimental set up for laser heating experiments.



**Fig S11.** Schematic demonstrating the three different pathways that can lead to a measured *K/Ar* age. 1) Temperature is high enough that complete resetting occurs, this results in a zero age immediately after heating. The measured *K/Ar* age in this case reflects the time since the earthquake. Scenarios 2) and 3) reflect partial resetting resulting in a non-zero age immediately after the earthquake. In these cases, the measured age is older than the earthquake.



**Fig S12.** average friction during sliding plotted against displacement for a range of normal stresses with hydrostatic pore pressure. At larger normal stress and displacement, the thermal breakdown distance is small relative to displacement and the average friction is low. Average friction for SAFOD normal stress conditions (49 MPa) is shown in red.

**Table S1** – Parameters used to model SAFOD earthquake displacements and apparent ages resulting from thermal resetting. The range of friction values used is consistent with steady-state friction values measured from Di Toro et al. (2011) and with calculations of average friction for sliding at SAFOD (see supplementary methods and Fig. S14). Slip layer thicknesses represent the distribution of localized layers throughout the BFR.

Parameter	Value	Source	
Friction, µ	0.1 - 0.2	Measured ( <i>Caroenter et al. 2011; Di Toro</i> al. 2011; Lockner et al. 2011)	
Slip layer thickness (mm)	0.1 – 18	Measured, this study	
Background MPI4	0.488	Measured, this study	
Starting age (Ma)	63	Measured, this study	
Displacement (m)	0.2 – 15	Modeled, this study	
Slip velocity (ms <sup>-1</sup> )	1	Modeled (Heaton, 1990)	
Effective normal stress (MPa)	49	Measured (Hickman & Zoback, 2004)	

Depth (m)	3000	Measured (Hickman & Zoback, 2004)		
Ambient temperature (°C)	100	Measured (Hickman & Zoback, 2004)		
Heat capacity (Jkg <sup>-1</sup> K <sup>-1</sup> )	910	Siltstone measurements (Di Toro et al. 2011)		
Thermal diffusivity (m <sup>2</sup> s <sup>-1</sup> )	1x10 <sup>-6</sup>	Siltstone measurements (Di Toro et al. 2011)		
Heat capacity (Wm/K)	2400	Measured (Erkan & Blackwell, 2008)		
Density (kgm <sup>-3</sup> )	2600	Measured (Jeppson et al. 2010)		
Activation energy (kcalK <sup>-</sup> <sup>1</sup> mol <sup>-1</sup> )	$22.4\pm2.7$	Measured (Savage et al. 2018)		
Frequency factor (s <sup>-1</sup> )	$1.6 \times 10^4 \pm 11.0$	Measured (Savage et al. 2018)		

Table S2. parameters used in calculation of friction during slip

Parameter	Value	Source		
Steady state shear stress	10.6 MDa	From measured friction (Di Toro		
$( au_{ss})$	19.0 WFa	<i>et al. 2011</i> )		
Peak shear stress ( $\tau_p$ )	40.08 MPa	From measured friction		
	4.9 - 9.8 WIF a	(Carpenter et al. 2011)		
Normal stress $(\sigma_n)$	40 MBa	Measured (Hickman & Zoback,		
	49 IVIF a	2004)		
Coefficient, a	0.39	Measured (Di Toro et al. 2011)		
Coefficient, b	0.97	Measured (Di Toro et al. 2011)		
Thermal breakdown	8 am	Calculated, this study		
distance $(D_{th})$	o chi			
Accumulated slip ( $\delta$ )	Accumulated slip ( $\delta$ ) 0.1 – 20 m			

Position		Mean maximum temperature (°C)	95% CI	Mean	95% CI apparent	Highest	Range of possible
along core	MPI4		temperature	frictional work	frictional work	probability EQ	earthquake ages
(m)			bounds (Ma)	(MJ/m <sup>2</sup> )	bounds (MJ/m <sup>2</sup> )	age (Ma)	(Ma)
3188.4	0.5241	700	480-1110	15.1	9.1 – 23	15.8	0-18.4
3191.9	0.5357	730	490 - 1140	15.5	9.1 - 23.8	12.7	0 - 13.1
3192.8	0.5369	730	490 - 1140	15.5	9.2 - 23.8	11.1	0 - 16.1
3193.4	0.5677	770	500 - 1180	16.3	9.3 - 25.7	14.7	0 - 15.1
3196	0.5904	810	510 - 1210	16.8	9.4 - 26.9	4.1	0 - 4
3195.9	0.6052	810	510 - 1230	17.1	9.6 - 27.6	4	0 - 4
3195.9	0.6055	810	510 - 1230	17.2	9.6 - 27.6	4	0 - 4
3195.9	0.609	810	510 - 1230	17.2	9.7 - 27.8	4	0 - 4
3196.1	0.6154	840	510 - 1240	17.4	9.7 - 28.2	3.6	0-5.6
3193	0.6259	840	520 - 1250	17.6	9.8 - 28.6	6.5	0 - 7.7
3193.4	0.6369	850	520 - 1270	17.8	9.8 - 29.1	8.9	0 - 10
3193.5	0.643	890	520 - 1280	17.9	9.9 – 29.3	9.9	0 - 10.4
3196.4	0.6502	890	520 - 1290	18.1	9.9 - 29.7	4.2	0 - 5.5
3196.4	0.6518	890	520 - 1290	18.1	9.9 - 29.8	3.3	0 - 5.9
3195.1	0.6554	890	520 - 1290	18.2	9.9 - 30	3.6	0 - 4.6
3194	0.6578	890	520 - 1300	18.2	9.9 - 30.2	4.3	0-5
3194	0.6641	890	520 - 1300	18.3	9.9 - 30.3	3.9	0-5.3

Table S3. summary table of thermal maturity, temperature modeling, and age modeling results

# **MATERIALS AND METHODS**

#### **Biomarker thermal maturity analysis**

Samples were either subsampled if localized structures were present or processed whole. In the preliminary round of SAFOD sampling we separated and measured the biomarker maturity of the center and outside of a sample but found no difference in maturity between those aliquots. Samples were rinsed with dicholoromethane to remove any contamination and disaggregated using a mortar and pestle. Samples were extracted with a Dionex Accelerated Solvent Extractor (ASE-350) with 9:1 DCM:methanol at 1500 psi and a temperature of 100 °C for 3x5 minute static cycles to isolate the total lipid extract (TLE). A recovery standard consisting of  $5\alpha$ -androstane, 1-1' binapthyl, and stearyl stearate, was added to each TLE and the TLE was evaporated with nitrogen and transferred to 4 mL vials. The TLE was brought up in 0.5 ml of hexane and separated into aliphatic, aromatic/ketone, and polar fractions using 0.5 g silica gel (stored at 75 °C) in 5-inch Pasteur pipettes. The sample was loaded onto the columns in hexane, and the aliphatic fraction (F1) eluted with 4 ml of hexane, the aromatic/ketone fraction (F2) with 4 ml of dichloromethane, and the polar (F3) with 4 ml of methanol. The aliphatic and aromatic/ketone fractions were brought up in 0.25 mL of hexane and transferred to 2 mL high-recovery vials for analysis on an Agilent 7890A gas chromatograph with a 5975C mass selective detector (GC-MSD) equipped with a multi-mode inlet (MMI, deactivated single-taper liner with wool packing) and DB-5ms column (30 m length, 250 µm i.d., 0.25 µm phase thickness) at 1.0 ml/min helium flow. Samples were diluted in 100 to 500 µl hexane, depending upon their concentration, with an injection volume of 1 µl. The aromatic fraction containing phenanthrenes and methylphenanthrenes was analyzed in hybrid selected ion monitoring (SIM)/full scan mode (SIM/scan) with external calibration as described in Sheppard et al. (2015). The aliphatic fraction containing *n*-alkanes, steranes, and hopanes was analyzed in full scan mode. The sample in hexane was injected splitless into the MMI and the MMI temperature held at 60 °C for 0.1 minutes and then ramped to 320 °C at 15 °C/s and held for the remaining acquisition time. The oven temperature was held at 60 °C for 1.5 minutes, ramped to 150 °C at 15 °C/min and then to 320 °C at 4 °C/min where it was held for 10 minutes. The MSD ion source was held at 300 °C with an electron energy of 70 eV and a quadrupole temperature of 150 °C. The MSD was operated in full scan mode, scanning from 50 - 550 dalton with a cycle time of ~3 scans/s. Peaks were integrated with the Agilent Chemstation software, using extracted ion peak areas for *n*-alkanes (m/z 57), C<sub>29</sub> steranes (m/z 217), C<sub>31</sub> hopanes (m/z 205) and the recovery standard (5a-androstane, m/z 245). Concurrent analyses of a standard mixture of C<sub>8</sub> to C<sub>40</sub> *n*-alkanes plus 5a-androstane was used to calibrate the relative response ratio of each *n*-alkanes to the recovery standard daily. Individual ion peak areas were used to calculate sterane and hopane ratios without any further treatment.

#### K/Ar measurements

Argon measurements were made on samples after biomarker measurement. Bulk and  $< 2 \mu m$  grain size fractions were measured to assess whether measurements demonstrated any

grain size dependence. The  $< 2 \mu m$  fraction was isolated using gravitational settling techniques. Argon measurements were made using a VG 5400 mass spectrometer with a CO<sub>2</sub> laser extraction system, and potassium concentrations measured using inductively coupled plasma optical emission spectroscopy (ICP-OES). Replicates were measured for all samples. Ages were similar in age between each grain size fraction and thin section observations demonstrated no difference in grain size between unsettled and settled sediment fractions (this discrepancy may be due to clumping in the bulk fraction). As a result, we group the grain size fractions together and report the mean for each sample set.

To measure potassium, an open beaker total digest was performed using  $HNO_3/HF/HClO_4$  in order to achieve a complete digestion of the sample material. Due to the potential to form insoluble potassium perchlorate,  $HClO_4$  was used sparingly, and the samples were evaporated to dryness several times in the presence of nitric. Samples were taken up in ~3% nitric acid and brought to a final dilution of 3,000 - 10,000x. Replicate samples and a USGS certified reference material (SCo-1 Cody Shale) was prepared with each sample batch to evaluate reproducibility and precision. Samples were measured by Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES).

## Laser heating experiments

Aliquots of a single background SAFOD sample were weighed out and wrapped in tantalum foil. The sample packets were folded over a type K thermocouple and placed in a diffusion cell for analysis. A schematic of this set up can be seen in *Fig S14*. Samples were heated to temperatures of 500 - 820 °C for 10s within diffusion cells (*Farley et al. 1999*) using a diode laser. Temperature was controlled by manipulating the power of the laser while recording the temperature output from the thermocouple. The amount of argon released during heating was measured, and the sample was then heated again to 900 °C for 3 minutes to completely degas it and the total argon measured. Suspending the samples on thin thermocouple wires in individual diffusion cells allows us to heat and cool the samples quickly enough to simulate earthquake conditions. We use the linear relationship between fraction degassed and temperature from these experiments to model the apparent age resulting from each possible SAFOD heating event for each sample.

## **Thermal modeling**

To constrain the temperature rise associated with a given high MPI4, heat generation and diffusion equations (*Fulton & Harris, 2012; Lachenbruch 1986*) for a fault are coupled with the reaction kinetics for MPI4 (*Sheppard et al. 2015*). The adiabatic temperature rise that occurs depends on properties of the fault zone are as follows

$$\Delta T(x < a, t) = \frac{\tau}{\rho c} \frac{v}{a} \left\{ t \left[ 1 - 2i^2 erfc \frac{a - x}{\sqrt{4\alpha t}} - 2i^2 erfc \frac{a + x}{\sqrt{4\alpha t}} \right] - H(t - t^*)(t - t^*) \left[ 1 - 2i^2 erfc \frac{a - x}{\sqrt{4\alpha (t - t^*)}} - 2i^2 erfc \frac{a + x}{\sqrt{4\alpha (t - t^*)}} \right] \right\}$$

$$\Delta T(x > a, t) = \frac{\tau}{\rho c} \frac{v}{a} \left\{ t \left[ 2i^2 erfc \frac{x-a}{\sqrt{4\alpha t}} - 2i^2 erfc \frac{x+a}{\sqrt{4\alpha t}} \right] - H(t-t^*)(t-t^*) \left[ 2i^2 erfc \frac{x-a}{\sqrt{4\alpha (t-t^*)}} - 2i^2 erfc \frac{x+a}{\sqrt{4\alpha (t-t^*)}} \right] \right\}$$

$$(3)$$

where  $\tau$  is shear stress,  $\rho$  is density, *c* is the heat capacity, *a* is the fault half width, v is slip velocity,  $\alpha$  is thermal diffusivity, *x* is distance from the slipping layer, and *t* is time. Temperature profiles are used to simulate biomarker reaction for different displacements, frictions, and slip layer thicknesses. MPI4 resulting from these scenarios are calculated using experimentally determined reaction kinetics (*Sheppard et al. 2015*) and the Easy%R\_0 method (*Sweeney & Burnham, 1990*). This allows identification of MPI4 profiles that best fit core measurements and the extraction of possible coseismic temperatures. Temperature rise and fault properties that fit our measurements are then, along with the kinetics of argon degassing used to model argon concentration and calculate the apparent ages expected for these conditions.

## Average friction calculation

Under the normal stress conditions at SAFOD, friction during sliding evolves from a peak value to steady state over a thermal weakening distance. Because the peak friction has a larger effect on the average friction for small earthquakes compared to large, we calculate the range of average friction for displacements used in our thermal model as follows.

Calculation of average friction and *Fig. S14* were done using the relationship for thermal breakdown distance  $(D_{th})$  and normal stress:

$$D_{th} = a\sigma_n^{-b}$$

where *a* and *b* are experimental constants and  $\sigma_n$  is normal stress (*Di Toro et al. 2011*). Fi<sup>4</sup>) this, friction was calculated using the following equation for stress ( $\tau$ ) established by fitting a shear stress curve to experimental data (*Seyler et al. 2020*):

$$\tau = \tau_{ss} + (\tau_p - \tau_{ss})e^{-\frac{D}{D_{th}}}$$

5)

where  $\tau_{ss}$  is the steady state shear stress,  $\tau_p$  is the peak shear stress, and  $\delta$  is the slip accumulated after  $D_{th}$ . Values used in this calculation for SAFOD are shown in the *Table S1*.

#### Earthquake magnitude scaling

We use the following scaling relationship developed by Ellsworth (2003) from a database of strike-slip earthquakes to estimate magnitude of these earthquakes identified at SAFOD.

$$M_w = 4.2 + \log_{10}(A) \tag{6}$$

where A is rupture area. We assume for earthquakes that do not rupture the entire seismogenic zone that A is equal to  $L^2$ , where is rupture length and the ratio of displacement to rupture length is 0.0001 (*Scholz 2002*).

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