Constraining the exhumation and burial history of the SAFOD pilot hole at Parkfield, California, with apatite fission track and (U-Th)/He thermochronometry

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Abstract

The San Andreas Fault Observatory at Depth (SAFOD) pilot hole traverses the upper 2 km of a site 1.8 km west of the San Andreas fault near Parkfield, California. We use 15 apatite fission-track (FT) and 5 (U-Th)/He analyses from pilot hole samples to document their thermal history in order to evaluate the burial and exhumation history of the site. Pilot hole FT and (U-Th)/He sample ages decrease with depth: FT ages range from ~60 Ma at the surface to ~3 Ma at the base of the hole (at 2.2 km depth and current temperature of 90°C). (U-Th)/He ages at the base of the hole are ~1 Ma. Thermal modeling of the distribution of measured fission track lengths indicates three events in the last 80 Ma: 1) cooling and exhumation of >60°C that culminated at ~30 Ma, 2) reheating of ~50°C from ~30 to 8-4 Ma, probably as the result of basin subsidence and burial by 1-1.5 km of sediments, and 3) cooling of ~30°C and estimated Coast Range exhumation of ~1 km since 8-4 Ma.
Introduction

The San Andreas Fault Observatory at Depth (SAFOD) provides a unique opportunity to study one of the world’s major active faults by collecting geophysical measurements and samples from a drillhole that crosses the fault at significant depths. In anticipation of a future rupture, the Parkfield site has become the most thoroughly instrumented fault site in the world, with the hopes of obtaining significant results on the rupture dynamics of a major plate boundary strike-slip fault. However, in order to fully understand the conditions and mechanics of faulting at Parkfield, the complete geological and thermal history of the site must be documented. Here, we present a study of the low-temperature thermal history of the samples from the SAFOD pilot hole. We use a combination of apatite FT and (U-Th)/He thermochronometry on 16 samples recovered from the pilot hole drilled during the summer of 2002.

SAFOD setting

The SAFOD site is located in the Coast Ranges of central California, 1.8 km southwest of the San Andreas fault (SAF) near Parkfield (Figure 1). The geology near Parkfield is complex and is discussed elsewhere in this volume (see Rymer). In the pilot hole, 768 m of Tertiary-age sediments overlie Salinian granites of ~110 Ma age (Kistler and Champion, 2001) which were transported northward alongside the San Andreas fault from their original emplacement as part of the southern Sierra Nevada batholith. Previous low-temperature dating studies of surface Salinian samples from throughout central California (Naeser and Ross, 1976; Bürgmann et al. 1994; Figure 1A) indicate a relatively heterogeneous cooling history. Only a few places appear to have been cooled by >100 °C (and thus exhumed by more than 2-3 km) in the last 30 Ma; i.e., since initiation of San Andreas transform motion.
Samples and Thermochronometry Results

During June and July 2002, borehole cuttings were collected from the pilot hole, which extended to a depth of 2164 m. The SAFOD team extracted 20 samples for our analyses, at downhole intervals of approximately 100 m. Here we present fifteen apatite FT analyses and 5 (U-Th)/He analyses from pilot hole samples (see Tables 1 and 2 in the electronic supplement and Figure 2) and an additional FT sample from a nearby granitic outcrop (BARN on Figure 1B).

Fission tracks are linear zones of damage in the crystal lattice that form as the result of the spontaneous fission of $^{238}\text{U}$. The tracks are unstable at higher temperatures and the crystal lattice anneals or heals itself. At moderate geologic cooling rates, the closure temperature (Dodson, 1973) for fission track annealing in F-rich apatites is ~110°C (Green et al., 1986). Track length annealing, however, occurs at slower rates at lower temperatures also, and therefore a range of temperatures from ~110 to 60°C is referred to as the partial annealing zone, or PAZ (Gleadow and Fitzgerald, 1987). The length distribution of fission tracks in individual samples can be used to reconstruct the thermal history of the sample through the PAZ (Gleadow et al., 1986): long tracks indicate a short residence time and short tracks a long residence time within the PAZ.

A nearby surface sample (BARN) from the Salinian bedrock yielded an apatite fission track age of 60.2 ± 6.0 Ma. This 60 Ma age can be interpreted to indicate that the sample has not been buried or exhumed >2.5-3 km since that time, if the present-day geotherm of ~35 °C/km is assumed.

In the pilot hole, samples from the shallow Tertiary-age sediments have apatite fission track ages of 49.2 ± 5.8, 28.0 ± 3.0, and 59.6 ± 4.9 Ma. These fission track ages appear to be unreset and probably reflect the ages of their source rocks. The apatite fission track ages in the underlying Salinian granites generally decrease with depth from 54.3 ± 4.8 Ma at a depth of 914 m to ages of 3.0 ± 0.8 and 3.8 ± 0.7 Ma from the two deepest samples (from 2103 and 2164 m, respectively and temperatures of >90°C).
(U-Th)/He thermochronometry, which is based on the release of He during the decay of U and Th, has a closure temperature of 70 - 75°C in apatite (Farley, 2000). The (U-Th)/He system in apatite has a partial retention zone (PRZ) which ranges from ~85 to 45°C (Wolfe et al., 1998). Six samples from the pilot hole were analyzed in Ken Farley’s laboratory at Caltech with two replicates obtained from each sample; results from five of these samples are presented here (the sixth sample had inclusions). The shallowest sample was from the top of the granite (depth of 792 m) and yielded replicate ages of 32 and 19 Ma. This spread in replicate ages is common in samples with a long residence time in the PRZ. Replicates for the rest of the samples overlapped more closely, and consistently decreased with depth (Figure 2). The two deepest samples (at current temperatures of ~90°C) yielded He ages of ~1.7 and 1 Ma. These two non-zero sample analyses immediately signal a somewhat complicated thermal history for the pilot hole, as 90°C is substantially hotter than the helium closure temperature and the hotter boundary of the PRZ, suggesting that these samples have not resided at this temperature for very long.

**Apatite fission track length analysis and thermal model**

We use the fission track length distributions to constrain the past thermal history of the site. Three of the samples yielded a sufficient number of track lengths for thermal modeling. Two of these samples, CU4800 and CU5100, were granitic rocks from depths of 1463 and 1554 m and current temperatures of ~70 and 72°C, respectively. The third, CU300, was a near-surface sample from the Tertiary sedimentary sequence. The single crystal fission track ages from this sample indicates the presence of more than one population of ages, most likely from two or more source terrains, making it inappropriate for thermal modeling.

The results of the modeling of length distributions for CU4800 and CU5100 are shown in Figure 3. The consistency of the two models with each other and with the known
geologic record is encouraging. However, caution should be used in interpreting the model results, which are poorly constrained at temperatures outside the PAZ. A wide range of solutions (lighter gray lines, Figure 30) fit the observed data. We discuss the solutions with the best statistical fit to the observed fission track analyses (solid black lines) below.

Three distinct phases are seen in the thermal models (Figure 3): The earliest phase is one of slow cooling that appears to have lasted from ~80 until ~30 Ma. During this phase, both samples cooled fully through the apatite PAZ, reaching temperatures of 40 - 50°C by 31 Ma. The second phase is a reheating of 48 - 58°C that occurred between 31 and 8-4 Ma. During the final phase, beginning between 8 and 4 Ma, samples cooled 30 to 47°C to their present-day temperatures.

The kinetics of FT annealing and He loss depend strongly on temperature and have been well characterized in the laboratory (e.g., Laslett, 1987; Wolf et al., 1998). Given a thermal history, we can therefore predict the FT and (U-Th)/He ages for a sample. The dashed curves in Figure 2 (“Isothermal”) show the theoretical age profiles for the pilot hole assuming that samples remained at present-day downhole temperatures for the last 60 Myr. The observed ages are consistently younger than the isothermal curve, implying that the borehole was exposed to temperatures hotter than the present-day. The solid curve in Figure 2 (“Best Fit”) shows the expected FT age for samples that experienced the best fitting thermal history shown in Figure 3. We adopt the simplifying assumption that the geothermal gradient of the site did not change, and evaluate the range of heating for samples in Figure 3 (48-58°C since 31 Ma). Heating of 48°C fits the age-depth data best, corresponding to ~1.3 km of burial at the present-day geothermal gradient. Overall, the thermal history derived from FT length modeling of two samples predicts FT ages consistent with observations throughout the borehole.
Interpretation

The initial phase of cooling from ~80 to 30 Ma is consistent with regional cooling ages of the Salinian block plutons (e.g., Mattinson, 1978; Naeser and Ross, 1976). This long period of cooling may well be attributable to multiple causes such as cooling and exhumation of granitic intrusions and Laramide cooling as the result of flat-slab subduction (Dumitru, 1989). Granitic rocks near the Salinian/sediment contact are weathered and this contact is interpreted to be a paleosurface exposed during part of the Tertiary (Rymer et al, this volume). Our best-fit thermal history has samples at the contact cooling to a temperature of less than 30°C and is consistent with this geologic interpretation.

The reheating phase indicated by the thermal models from ~30 to 8 Ma is consistent with the onset of SAF movement, and burial of the site by up to 2 km of Tertiary sediment. While it is possible that some component of this heating could be from frictional heat generation on the SAF, the existing mantle of nearly 800 m of overlying sediments suggests that sediment burial, seen throughout central California at this time (e.g., Blake et al., 1978; Crouch et al., 1984), was the dominant source of heating.

The final phase of cooling seen in the thermal models, beginning between 8 and 4 Ma, is probably the result of ~0.8-1.3 km of exhumation, assuming the present-day geotherm of ~35°C/km. This event is consistent with the timing of Coast Ranges uplift seen in nearby ranges (Page et al., 1998). Apatite fission track analyses were used to document the onset of exhumation in the Santa Cruz Mountains at ~4 Ma (Bürgmann et al., 1994). For the Santa Lucia Mountains, Ducea et al. (2003) used (U-Th)/He analyses to document exhumation beginning at ~6 Ma. This uplift can be attributed to the increased convergence rate along the Pacific-North American plate boundary indicated at ca. 8 Ma by the reconstructions of Atwater and Stock (1998). Locally, Sims (1993) shows that the SAF achieved a geometry similar to its present-day configuration in Parkfield at 5 Ma and its slip rate accelerated from 10 mm/yr to 33 mm/yr. Active convergence and uplift in the region is continuing today, as evidenced by the seismically active thrust faults to
the northeast (e.g., 1984 Coalinga earthquake) and southwest (e.g., 2003 San Simeon earthquake) of the San Andreas fault.

The exhumation rate in the final phase of cooling for the best fitting model is 0.1-0.2 mm/yr, removing less than one kilometer of sedimentary cover since cooling began between 8 and 4 Ma. With such a low rate of exhumation, we would not expect significant disturbances in the geotherm at depth — allowing extrapolation of the present-day geotherm to the target depth of the main SAFOD hole.

Conclusions

The thermal history indicated by the pilot hole samples is consistent with previous studies of the general geologic history of central San Andreas fault. This includes evidence for a (1) a phase of gradual exhumation of the Salinian intrusives in the late Cretaceous and early Tertiary, (2) reburial by 1-1.5 km during the early phases of San Andreas transform faulting in the mid-Tertiary, and (3) exhumation related to regional Coast Ranges uplift in the late Cenozoic. What is remarkable is that given the complex tectonic history of these rocks, including lateral transport of 160 km (Sims, 1993) over the last 5 Ma, only ~1 km of vertical motion (up and down) occurred over the last 60 Ma.

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References


Figure Captions

**Figure 1.** Location maps for study: A. Simplified tectonic map of central California, showing the locations of granitic terrains and major faults. Fission track ages from Naeser and Ross (1976) and Bürgmann et al. (1994). B. Simplified geologic map for the SAFOD site near Parkfield, CA, after Rymer, pers. comm., based on Diblee (1971).

**Figure 2.** Apatite fission track and (U-Th)/He ages plotted with respect to depth and temperature. The location of the granite/sediment contact is shown as is the location of a fault of unknown importance. Dashed lines show predicted ages for the samples if the borehole has been at its present-day temperature for the last 60 Myr. Solid curve shows ages predicted from the best fit thermal history derived from track lengths (Figure 3).

**Figure 3.** Modeled thermal histories for samples CU4800 and CU5100 are shown on the left-hand side. These were obtained using the modeling program MonteTrax (Gallagher, 1995) on measured fission track age and length distributions for each sample. The thermal models were obtained using forward modeling (4 time temperature boundaries were specified) and a genetic algorithm approach (20 iterations of 100 solutions). A starting mean track length of 14.5 μm, a high-F apatite composition (Durango), and the Laslett annealing model (Laslett et al., 1987) were assumed. The dashed horizontal lines on each model represent the boundaries of the apatite PAZ. The black boxes are the specified input ranges of time and temperature. The lightly shaded lines are possible thermal histories that produced statistically acceptable fits to the observed data. The black line is the “best fit” solution and the ages and temperatures of its inflection points are in the upper left corners. Shown on the right-hand side are the measured track length distributions (histograms) and the modeled track length distribution (solid curves) for the best fit thermal history solution. OA - observed age, PA – predicted age, OML – observed mean length, PML – predicted mean length, OSD – observed standard deviation, PSD – predicted standard deviation.
Figure 1
Figure 2
Figure 3