GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L15S16, doi:10.1029/2003GL019407, 2004

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

A. E. Blythe
Department of Earth Sciences, University of Southern California, Los Angeles, California, USA

M. A. d'Alessio
Department of Earth and Planetary Science, University of California, Berkeley, California, USA

R. Bürgmann
Department of Earth and Planetary Science, University of California, Berkeley, California, USA

Received 31 December 2003; revised 12 February 2004; accepted 19 February 2004; published 24 June 2004.

[1] 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 (SAF) near Parkfield, California. In order to evaluate the burial and exhumation history of the site and its relationship to the kinematics and mechanics of the SAF, we use 15 apatite fission-track (FT) and 5 (U-Th)/He analyses from pilot hole samples to document their thermal history. Sample ages decrease with depth: FT and (U-Th)/He ages range from ~60 and ~31 Ma, respectively, in the upper 800 m of the hole to ~3 and 1 Ma at the base of the hole (2.2 km depth, 93°C).Thermal modeling of the distribution of FT 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. *INDEX TERMS:* 5418 Planetology: Solid Surface Planets: Heat flow; 8110 Tectonophysics: Continental tectonics—general (0905); 8150 Tectonophysics: Plate boundary—general (3040). **Citation:** Blythe, A. E., M. A. d'Alessio, and R. Bürgmann (2004), Constraining the exhumation and burial history of the SAFOD pilot hole with apatite fission track and (U-Th)/He thermochronometry, *Geophys. Res. Lett.*, *31*, L15S16, doi:10.1029/2003GL019407.

1. Introduction

[2] The San Andreas Fault Observatory at Depth (SAFOD) provides a unique opportunity to study one of the world's major active faults by acquiring measurements and samples from seismogenic depths. Here, we present a study of the low-temperature thermal history of the samples from the SAFOD pilot hole to gain insight into the long-term fault kinematics (block uplift and exhumation) and mechanics (frictional heating) of the San Andreas fault (SAF) near Parkfield. Since heat flow observations are fundamental in constraining the frictional strength of the fault, it is crucial to understand how the long-term thermal evolution affects present thermal observations. We use a combination of apatite fission track (FT) and (U-Th)/He thermochronometry on 16 samples recovered from the pilot hole drilled during the summer of 2002 to determine the thermal history of the SAFOD site and interpret it in the context of the geologic history of the region.

2. SAFOD Setting

[3] 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 by *Rymer et al.* [2003]. In the pilot hole, 768 m of Tertiary-age sediments overlie Salinian granodiorites of ~110 Ma age [*Kistler and Champion*, 1986] which were transported northward alongside the SAF 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 (Figure 1a) [*Naeser and Ross*, 1976; *Bürgmann et al.*, 1994] 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 SAF transform motion.

3. Samples and Thermochronometry Results

[4] During June and July 2002, borehole cuttings were collected from the pilot hole, which extended to a depth of 2160 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 five (U–Th)/He analyses of these samples (Figure 2 and Tables 1 and 2[1]) and an additional FT sample from a nearby granitic outcrop (BARN on Figure 1b).

[5] Fission tracks are linear zones of damage in the crystal lattice that form as the result of the spontaneous fission of ^{238}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 FT 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

---

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL019407.

0094-8276/04/2003GL019407$05.00

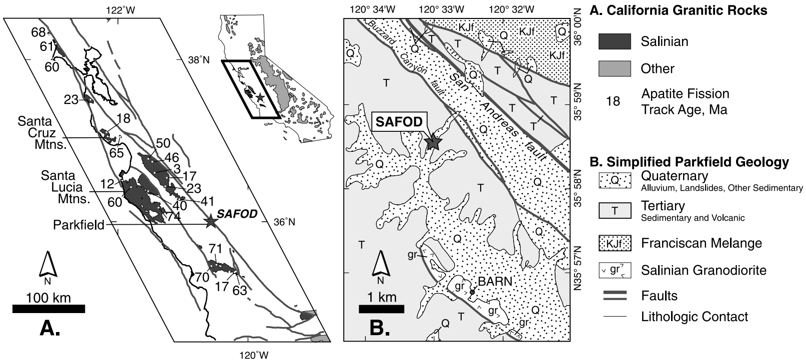

Figure 1. Location maps for study: A. Simplified tectonic map of central California, showing the locations of granitic terrains and major faults. Fission track ages from *Naeser and Ross* [1976] and *Bürgmann et al.* [1994]. B. Simplified geologic map for the SAFOD site near Parkfield, CA (after M. Rymer, personal communication, based on *Dibblee* [1971]). See color version of this figure in the HTML.

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.

[6] A nearby surface sample (BARN) from the Salinian bedrock yielded an apatite FT 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.

[7] In the pilot hole, samples from the shallow Tertiary-age sediments have apatite FT ages of 49.2 ± 5.8, 28.0 ± 3.0, and 59.6 ± 4.9 Ma. These ages probably reflect the ages of their source rocks. The apatite FT 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 2160 m, respectively and temperatures of ~93°C [*Williams et al.*, 2004]).

[8] (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 [*Wolf 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 granodiorite (depth of 792 m) and yielded replicate ages of 32 and 19 Ma. Replicates for the rest of the samples overlapped more closely, and ages consistently decreased with depth (Figure 2). The two deepest samples (at current temperatures of ~93°C) yielded He ages of ~1.7 and 1 Ma. These two non-zero sample ages immediately signal a somewhat complicated thermal history for the pilot hole, as 93°C is substantially hotter than the helium closure temperature (for pilot hole samples that have mean crystal radii of 60 ± 10 μm, we expect closure temperatures of ~66° for a 10°C/Myr cooling rate [*Farley*, 2000]). In a study of Otway Basin borehole samples, *House et al.* [1999] obtained similarly young (U-Th)/He ages at ambient temperatures of >80°C. They attribute these ages to complexities in the long-term thermal history, and possibly helium diffusivities of the borehole apatite crystals that differ slightly from laboratory values.

4. Apatite Fission Track Length Analysis and Thermal Model

[9] The kinetics of FT annealing and He loss depend strongly on temperature and have been well characterized in the laboratory [e.g., *Laslett et al.*, 1987; *Wolf et al.*, 1998]. We use the FT 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 temper-

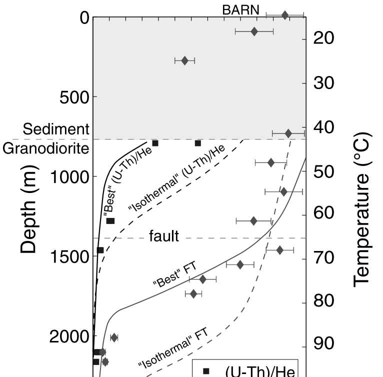

Figure 2. Apatite fission track and (U-Th)/He ages plotted with respect to depth and temperature. The location of the granite/sediment contact is shown as is the location of a fault of unknown importance. Dashed lines show predicted ages for the samples if they had resided at their present-day temperature for the last 60 Myr. Solid curves show ages predicted from the best fit thermal history derived from track lengths (Figure 3) and assuming no change in the local geothermal gradient (Table 3). See color version of this figure in the HTML.

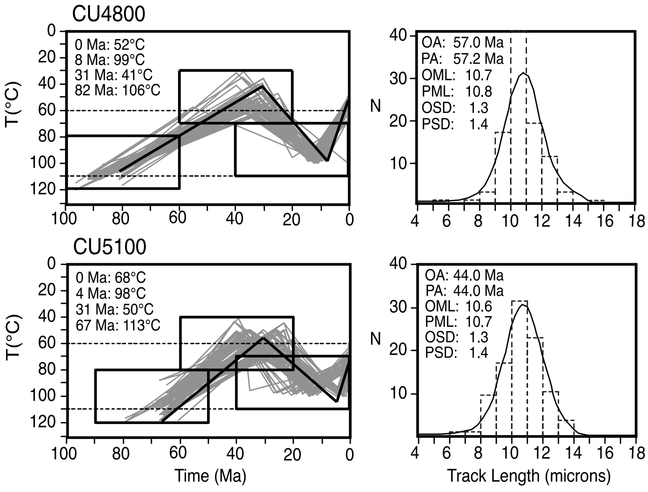

Figure 3. Modeled thermal histories for samples CU4800 and CU5100 are shown on the left-hand side. These were obtained using the modeling program MonteTrax [*Gallagher*, 1995] on measured FT age and length distributions for each sample. The thermal models were obtained using forward modeling (4 time 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 annealing model of *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.

atures of ~70 and 72°C, respectively. The third, CU300, was a near-surface sample from the Tertiary sedimentary sequence. The single crystal FT ages from this sample indicate the presence of more than one population of ages, most likely from two or more source terrains, making it inappropriate for thermal modeling.

[10] We model the FT length distributions of samples CU4800 and CU5100 to derive time-temperature histories experienced by those samples (Figure 3; the methodology is briefly explained in the caption). The two models are consistent with each other and with the known geologic record, however, they are poorly constrained at temperatures outside the PAZ and a wide range of solutions (lighter gray lines, Figure 3) fit the observed data. The solutions with the best statistical fit to the observed FT analyses (solid black lines) indicate three distinct phases (Figure 3): The earliest phase is one of slow cooling from ~80 until ~31 Ma. During this phase, both samples cooled fully through the PAZ, reaching temperatures of 40–50°C. 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 30–47°C to their present-day temperatures.

[11] If we adopt the simplifying assumption that the geothermal gradient of the site did not change, we can use forward modeling to predict both FT and (U-Th)/He ages as a function of depth. This test allows us to verify that the thermal history derived in an 'inverse' sense from two samples using FT alone (Figure 3), is consistent with the entire suite of data. For reference, the dashed curves in Figure 2 ("Isothermal") show the theoretical age profiles for the pilot hole for the hypothetical case 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 curves in Figure 2 ("Best Fit") show the expected FT and (U-Th)/He ages for samples that experienced the thermal history shown in Figure 3 (also Table 3). Heating of 48°C between 31 and 8 Ma does an excellent job of fitting the age-depth data, corresponding to ~1.3 km of burial. Overall, the thermal history derived from FT length modeling of two samples predicts FT and (U-Th)/He age distributions that are consistent with the observations throughout the borehole.

5. Interpretation

[12] 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.*, 2003]. 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.

[13] 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 1–1.5 km of Tertiary sediment. Heat flow in the Coast Range may have evolved significantly over time related to the transition from subduction to transform faulting [*ten Brink et al.*, 1999; *Guzofski and Furlong*, 2002], we cannot detect changes in the geothermal gradient with our current data. It is possible that some component of this heating could be from frictional heat generation on the SAF, however, the existing mantle of nearly 800 m of overlying late Cenozoic 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.

[14] 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 FT 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 ~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 SAF.

[15] The exhumation rate in the final phase of cooling for the best fitting model is 0.1–0.2 mm/yr, removing about 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 caused by uplift – allowing extrapolation of the present-day geotherm to the target depth of the main SAFOD hole.

6. Conclusions

[16] 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 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 SAF 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 over the last 5 Ma [*Sims*, 1993], only ~1 km of vertical motion (up and down) occurred during the last 60 Ma.

[17] **Acknowledgments.** We thank Mihai Ducea and Demian Saffer for their constructive reviews. This material is based on work supported by the National Science Foundation Grant No. EAR-0207306 and EAR-0207388. Lindsey Hedges assisted with the He thermochronometry in Ken Farley's laboratory at Caltech. Berkeley Seismological Laboratory Contribution No. 04-04.

References

Atwater, T., and J. Stock (1998), Pacific North America plate tectonics of the Neogene southwestern United States: An update, *Int. Geol. Rev.*, *40*, 375–402.

Blake, M. C., R. H. Campbell, T. W. Dibblee, D. G. Howell, T. H. Nilsen, W. R. Normark, J. C. Vedder, and E. A. Silver (1978), Neogene basin formation in relation to plate-tectonic evolution of San Andreas fault system, California, *Am. Assoc. Petrol. Geol. Bull.*, *62*, 344–372.

Bürgmann, R., R. Arrowsmith, T. Dumitru, and R. Mclaughlin (1994), Rise and fall of the southern Santa Cruz mountains, California, from fission tracks, geomorphology, and geodesy, *J. Geophys. Res.*, *99*, 20,181–20,202.

Crouch, J. K., S. B. Bachman, and J. T. Shay (1984), Post-Miocene compressional tectonics along the California margin, in *Tectonics and Sedimentation Along the California Margin*, vol. 38, edited by J. K. Crouch and S. B. Bachman, pp. 37–54, Pac. Sect., Soc. of Econ. Paleontol. and Mineral, Los Angeles, Calif.

Dibblee, T. W. (1971), Geologic maps of seventeen 15-minute quadrangles (1:62,500) along the San Andreas fault in the vicinity of King City, Coalinga, Panoche Valley, and Paso Robles, California, *U.S. Geol. Surv. Open File Rep.*, *71*.

Dodson, M. H. (1973), Closure temperature in cooling geochronological and petrological systems, *Contrib. Mineral. Petrol.*, *40*, 259–274.

Ducea, M., M. A. House, and S. Kidder (2003), Late Cenozoic denudation and uplift rates in the Santa Lucia mountains, California, *Geology*, *31*, 139–142.

Dumitru, T. A. (1989), Constraints on uplift in the franciscan subduction complex from apatite fission-track analysis, *Tectonics*, *8*, 197–220.

Farley, K. A. (2000), Helium diffusion from apatite: General behavior as illustrated by Durango flourapatite, *J. Geophys. Res.*, *106*, 2903–2914.

Gallagher, K. (1995), Evolving temperature histories from apatite fission-track data, *Earth Planet. Sci. Lett.*, *136*, 421–435.

Gleadow, A. J. W., and P. G. Fitzgerald (1987), Uplift history and structure of the Transantarctic mountains—New evidence from fission-track dating of basement apatites in the Dry Valleys area, southern Victoria Land, *Earth Planet. Sci. Lett.*, *82*, 1–14.

Gleadow, A. J. W., I. R. Duddy, P. F. Green, and J. F. Lovering (1986), Confined fission-track lengths in apatite—A diagnostic-tool for thermal history analysis, *Contrib. Mineral. Petrol.*, *94*, 405–415.

Green, P. F., I. R. Duddy, A. J. W. Gleadow, P. R. Tingate, and G. M. Laslett (1986), Thermal annealing of fission tracks in apatite; 1. A qualitative description, *Chem. Geol.*, *59*, 237–253.

Guzofski, C. A., and K. P. Furlong (2002), Migration of the mendocino triple junction and ephemeral crustal deformation: Implications for California Coast Range heat flow, *Geophys. Res. Lett.*, *29*(1), 1012, doi:10.1029/2001GL013614.

House, M. A., K. A. Farley, and B. P. Kohn (1999), An empirical test of helium diffusion in apatite: Borehole data from the otway basin, Australia, *Earth Planet. Sci. Lett.*, *170*, 463–474.

Kistler, R. W., and D. E. Champion (1986), Rb-Sr whole-rock and mineral ages, K-Ar, ^{40}Ar/^{39}Ar, and U-Pb mineral ages, and strontium, lead, neodymium, and oxygen isotopic compositions for granitic rocks from the Salinian composite terrane, *U.S. Geol. Surv. Open File Rep.*, *01-453*, 1–84.

Laslett, G. M., P. F. Green, I. R. Duddy, and A. J. W. Gleadow (1987), Thermal annealing of fission tracks in apatite, *Chem. Geol.*, *65*, 1–13.

Mattinson, J. M. (1978), Age, origin, and thermal histories of some plutonic rocks from the Salinian block of California, *Contrib. Mineral. Petrol.*, *67*, 233–245.

Naeser, C. W., and D. C. Ross (1976), Fission-track ages of sphene and apatite of Granitic rocks of Salinian block, Coast Ranges, California, *J. Res. U.S. Geol. Surv.*, *4*, 415–420.

Page, B. M., G. A. Thompson, and R. G. Coleman (1998), Late Cenozoic tectonics of the central and southern Coast Ranges of California, *Geol. Soc. Am. Bull.*, *110*, 846–876.

Rymer, M. J., R. D. Catchings, and M. R. Goldman (2003), Structure of the San Andreas Fault Zone as revealed by surface geologic mapping and high-resolution seismic profiling near Parkfield, California, *Geophys. Res. Abs.*, *5*, 13,523.

Sims, J. D. (1993), Chronology of displacement on the San Andreas fault in central California: Evidence from reversed positions of exotic rock bodies near Parkfield, CA, in *The San Andreas Fault System: Displacement, Reconstruction, and Geologic Evolution*, edited by R. E. Powell, R. J. I. Weldon, and J. C. Matti, *Mem. Geol. Soc. Am.*, *178*, 231–256.

ten Brink, U. S., N. Shimizu, and P. C. Molzer (1999), Plate deformation at depth under northern California: Slab gap or stretched slab?, *Tectonics*, *18*, 1084–1098.

Williams, C. F., F. Grubb, and S. P. Galanis (2004), Heat flow in the SAFOD pilot hole and implications for the strength of the San Andreas fault, *Geophys. Res. Lett.*, *31*, L15S14, doi:10.1029/2003GL019352.

Wolf, R. A., K. A. Farley, and D. M. Kass (1998), Modeling of the temperature sensitivity of the apatite (U-Th)/He thermochronometer, *Chem. Geol.*, *148*, 105–114.

A. E. Blythe, Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, USA. (blythe@earth.usc.edu)

R. Bürgmann and M. A. d'Alessio, Department of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767, USA.