FINAL TECHNICAL REPORT

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HEAT-FLOW CONSTRAINTS OF SEISMOGENIC FAULTING FROM THERMOCHRONOLOGY STUDIES OF APATITES, ZIRCONS, AND K-FELDSPARS IN TWO EXHUMED FAULTS OF THE SAN ANDREAS SYSTEM

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Technical Abstract

There has been a longstanding debate regarding the strength of the San Andreas fault and other large faults in the San Andreas system. Some field- and laboratory-derived data are consistent with these faults being anomalously weak, while other data are consistent with these faults having normal strength. One of the most widely accepted and oft-quoted data in support of weak faults is the absence of anomalously high heat flow in the vicinity of these faults. Friction in a normal-strength fault should produce significant amounts of heat, resulting in elevated heat flow in and adjacent to the fault. The discrepancy between expected strength of the San Andreas fault and lack of significant heat flow in the fault has been called the "stress / heat-flow" paradox. To date, the only heat flow data collected along the San Andreas fault and other large faults in the San Andreas system has come from boreholes measurements made primarily within a kilometer of the land surface. Because the data have been obtained at depths where flowing groundwater might advect (disperse) the heat away from the fault, the reliability of this data to accurately document heat generated by seismogenic faults has been questioned.

Thermochronology data have been / are in the process of being obtained from the San Gabriel and Punchbowl faults, which are two large-displacement, quiescent faults in the San Andreas fault system. Samples have been collected along four traverses across these faults, resulting in a total of approximately 100 samples having been collected. Apatites and zircons have been successfully separated from approximately 40 samples. To date, fission-track (FT) data have been obtained from 8 zircon samples. The remaining data (both fission-track and U/Th-He) will be obtained in the coming year.

The eight fission-track dates, combined with the apatite FT results of a similar study by d'Alessio and others, provide insight into the thermal history of the faults. The zircon ages range from 40 to 60 Ma, though they do not monotonically young toward the fault. Instead, the FT dates on the SW-side of the fault are younger in the damage zone of the fault and are older in the core of the fault. Conversely, the FT dates on the NE-side of the fault are older in the damage zone of the fault, and are younger in the core of the fault. This asymmetrical distribution of FT ages and trends across the fault are not easily understood in terms of a simple younging model of ages towards a planar source of heat. One potential explanation is that systematics of the FT system have been altered (e.g., fluid-enhanced track annealing, leaching of uranium) by locallized fluid-rock interaction in the core and/or damage zone of the fault. We will not know until the FT results of all samples have been completed for the other three localities whether the variable trends in FT dates are of fundamental importance for these two faults, or whether most of the data will be consistent with a simple model of heat production at the fault surface.

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Non-Technical Summary

It is important to know the strength of large-displacement faults in the San Andreas system in order to better understand the processes involved in seismogenic faulting and model/predict the occurrence of potentially damaging earthquakes. There has been a longstanding debate, however, regarding the strength of the San Andreas fault and other large faults in the San Andreas system. Some field- and laboratory-derived data are consistent with these faults being anomalously weak, while other data are consistent with these faults having normal strength. One of the most widely accepted and oft-quoted data in support of weak faults is the absence of anomalously high heat flow in the vicinity of these faults. Friction in a normal-strength fault should produce significant amounts of heat, resulting in elevated heat flow in and adjacent to the fault. The discrepancy between expected strength of the San Andreas fault and lack of significant heat flow in the fault has been called the "stress / heat-flow" paradox. To date, the only heat flow data collected along the San Andreas fault and other large faults in the San Andreas system has come from boreholes measurements made primarily within a kilometer of the land surface. Because the data have been obtained at depths where flowing groundwater might advect (disperse) the heat away from the fault, the reliability of this data to accurately document heat generated by seismogenic faults has been questioned.

The research funded by this grant has taken a different approach to documenting the amount of heat generated by seismogenic faulting and the strength of two large-displacement (currently inactive) faults in the San Andreas system -- the Punchbowl and San Gabriel faults. The time-temperature history has been be constrained partly by fission-track and U/Th-He dating of apatites and zircons. These thermochronometers are proven monitors for documenting the heating and cooling histories of rocks between the temperature interval of ~70 and 240 °C. Many samples were collected in traverses across each fault; some of the analyses have been completed already. The “ages” recorded by these minerals do get monotonically younger with proximity to the faults, as would be expected if the faults had been significant sources of heat during seismogenic faulting. Rather the ages recorded by the minerals appear to be partly the product of fluid-rock interactions in / adjacent to the fault zones. More data are in the process of being obtained across these faults in order to identify processes responsible for the age variations and the extent of thermal heating during seismogenic faulting.

The results of this study have much potential for providing information that has not yet been obtained for faults in the San Andreas system. These results will help resolve the long-standing stress / heat-flow paradox,and provide important information needed to better understand the mechanics of faulting and better model/predict the occurrence damaging earthquakes in the San Andreas system.

Main body of report:

It is important to know the strength of large-displacement faults in the San Andreas system in order to understand the processes involved in seismogenic faulting and to better model/predict the occurrence of potentially damaging earthquakes. Experimental and field-based observations, coupled with theoretical arguments and modelling, have been used to delimit the strength of these faults. Two opposing conclusions have been reached. One conclusion is that the San Andreas fault has normal strength (*ca.* 50 to 100 MPa depth-averaged shear stress) and is consistent with a coefficient of friction, m, ranging between 0.6 and 0.7. The other conclusion is that the San Andreas fault is anomalously weak with an average shear stress of less than *ca.* 20 MPa. There is no consensus based on the data and observations listed in Table 1 whether the San Andreas fault is 1) uniformly weak along its entire length, 2) weak only along particular segments of the fault, or 3) uniformly normal in strength. The original and widely-quoted argument in favor of a weak San Andreas fault is based on heat flow. The following discussion will focus on heat flow in the fault.

Initial arguments made in favor of a weak San Andreas fault were based on the apparent absence of anomalously elevated heat flow adjacent to the fault. These researchers argued that frictionally generated heat produced during seismogenic slip should result in elevated heat flow that would be discernable from heat flow measurements made in boreholes in and adjacent to the fault. Surface heat flow values 1.6 times greater than regional heat flow values were predicted for the San Andreas fault, assuming 1) a normal strength for the fault that increases linearly with depth, 2) Byerlee's Law and hydrostatic pore fluid pressure, and 3) the conduction of heat away from the fault (Figure 1; *e.g.,* Lachenbruch and Sass, 1973).

There have been a large number of heat-flow measurements collected along the entire length of the San Andreas fault to document the heat flow in and adjacent to the fault (*e.g.,* Henyey, 1968; Lachenbruch and Sass, 1980; Sass *et al.,* 1997). There is no correlation between heat flow[1] and distance from the fault. On the basis of these results, Brune and others (1969) and Henyey and Wasserburg (1971) proposed that the upper boundary on the average frictional stress along the San Andreas fault was less than 20 MPa. This value is much lower than that predicted for normal strength faults and the disparity between observed versus predicted values has been called the stress / heat-flow paradox. At least eleven models have been proposed in response to the stress / heat-flow paradox to account for a weak San Andreas fault. These hypotheses can be grouped into three classes: 1) weakening due to intrinsically weak fault rocks; 2) weakening due to elevated fluid pressures; 3) weakening due to dynamic processes that are activated during coseismic slip.

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[1] The regional heat flow is high (~70 mW/m2) relative to heat flow over most of North America. The cause of the anomalously high regional heat is not well understood. Lachenbruch and Sass (1973) suggested that it was related to mid-crustal detachment of the seismogenic upper crust from the aseismic lower crust.

No definitive conclusion(s) has been reached regarding the strength of the San Andreas fault and other faults in the San Andreas system -- are the faults anomalously weak or do the faults have normal strength? Most recently, Scholz (2000) has argued that the San Andreas fault has normal strength, similar to most faults in continental crust. He interprets the orientation and magnitudes of the maximum and minimum horizontal stresses for the San Andreas fault to be related to transpressional plate-boundary motion especially adjacent, and north of, the Mojave Desert. In regard to heat flow, Scholz (2000) does not discount the fact that heat is generated by seismic slip on the fault. Rather, he suggests that *"....the heat-flow model is flawed, probably in its assumption that all heat transfer is governed by conduction*." Advection of heat away from the fault by fluids would decrease the heat flow immediately over the fault and potentially produce locallized upwellings of warm water and irregular distribution of high and low heat-flow values at the land surface (similar to what has been documented for heat flow in mid-ocean ridges).

If advection is responsible for the dissipation of heat away from the fault, then it most likely occurs close to the land surface where fluids are most readily able to move through interconnected pores and fractures. Unfortunately, most of the heat-flow data has been collected close to the land surface where the potential for groundwater flow and heat advection are greatest. Williams and Narasimhan (1989) showed that groundwater flow across the San Andreas fault could effectively disperse any fault-generated, heat flow anomaly near the fault. In order to minimize the potential dispersion of heat by groundwater, it will be necessary to get heat flow data from deep boreholes. This will be possible, for example, in the proposed deep drillhole near Parkfield, which is an attempt in part to obtain heat flow data and fluid flow information directly in the San Andreas fault that will help to resolve the stress / heat-flow paradox. In the funded research of this project, we have used thermochronology data from two exhumed faults in the San Andreas fault system to help resolve the paradox.

Rational For Using Thermochronology

Thermal pulses generated by individual earthquakes will dampen rapidly away from the fault and become indistinquishable by direct measurement within a couple of months after faulting (McKenzie and Brune, 1972; Lachenbruch, 1986). Depending on the ambient temperature and amount of heat generated during an individual seismic event, the absolute temperature rise experienced by the fault rocks and adjacent host rocks can increase drastically, even to the level needed to partially melt the rock. Although melt products are not ubiquitous in faults, they are common enough in quartzofeldspathic fault rocks in the mid-crust to indicate that seismically induced transient temperature increases of hundreds of degrees Celsius do occur in some faults. If the recurrence interval of seismic events is short relative to the characteristic length scale for thermal diffusivity, then an anomalous temperature increase will develop adjacent to the fault with increasing number of seismic events (Lachenbruch and Sass, 1980).

The transient and/or long-term rise in temperature adjacent to the fault could result in partial or complete resetting of the U/Th-He and fission track ages of apatite and/or zircons. The extent to which the ages are affected depend on the kinetics of noble gas diffusion and fission track annealing in the minerals. The temperatures over which these systems are affected vary among the systems and by combining analyses of these differents systems in this study, I will be able to delimit the thermal history of the rocks in the temperature range of approximately 70 to 240 °C

This approach to documenting anomalous heat flow adjacent to seismogenic faults has been attempted recently by Tagami and others (2001) for the Nojima fault, Japan. They obtained apatite and zircon fission track ages from samples collected in a 500-meter-deep borehole that crossed the fault. Apatites had relatively young ages and did not vary with distance from the fault due to partial or complete resetting / annealing. Conversely, the fission track lengths of zircons did vary such that those samples closest to the fault had the shorter tracks. Tagami and others (2001) interpreted this track-length variation to a localized source of heat along the fault due either to frictionally generated heat and/or advection of hot fluids in the fault. Apart from the importance these results might have for the "stress / heat-flow" paradox, Tagami and others' study demonstrates the importance of using several thermochronometers in this type of study. Unless there had been an high heat flow anomaly centered about the fault trace, it would have been difficult to predict *a priori* that apatite fission tracks would be so thoroughly reset and zircons tracks partially affected from samples collected at such shallow depths in the drill hole. Consequently, I have chosen to use several systems to bracket any thermal anomaly associated with the San Gabriel and Punchbowl faults.

Geologic Setting

Samples for fission-track and U/Th-He analyses were collected at three localities along the San Gabriel fault and one locality on the Punchbowl fault. These faults were chosen because they are the most deeply exhumed large-displacement faults in the San Andreas system (*e.g.*, Anderson *et al.*, 1983; Chester *et al.*, 1993). They were the main components of the San Andreas transform system in the central Transverse Ranges of southern California during the Miocene and Pliocene. Miocene (12 to 5 Ma) faulting on the main strand of the San Gabriel fault accounted for 42 to 60 km of right-lateral separation. After the late Miocene, most of the transform displacements in the central Transverse Ranges occurred 30 km northeast on the Punchbowl fault and on the presently active trace of the San Andreas fault. Total right-lateral separation on the Punchbowl fault is approximately 44 km.

Uplift and erosion of the San Gabriel Mountains have exhumed the Punchbowl and San Gabriel faults to provide excellent exposures of the products of faulting at 2 to 5 km depth. Uplift of the San Gabriel Mountains since the Pliocene is largely a result of dip-slip motion on the northward-dipping Sierra Madre-Cucamonga thrust system and by regional arching of the Transverse Ranges (Oakeshott, 1971; Ehlig, 1975; Morton and Matti, 1987). The uplift rate of the Sierra Madre- Cucamonga thrust system is approximately 0.5 to 5 mm/yr (Oakeshott, 1971; Bull, 1987; Morton and Matti, 1987). Microstructures and mineral assemblages of the fault rocks from the San Gabriel and Punchbowl faults are consistent with faulting at several kilometers depth (Anderson *et al.*, 1983; Chester *et al.*, 1993).

For each sample locality, 20 to 30 samples (10 to 15 samples on each side of fault) were collected along a traverse oriented orthogonal to the strike the fault. Sampling density decreased exponentially with distance from the fault to a distance of hundreds of meters

(Table 1). Apatites and zircons were separated successfully from forty nine samples at Saint Louis University using standard techniques of crushing, grinding, sieving, Wilfley table washing, magnetic separating, and settling in heavy liquids. To date, fission-track data for 8 zircon samples were collected in the laboratory of Dr. John Garver, Union College. Fission-track data for the rest of the samples are in the process of being obtained.

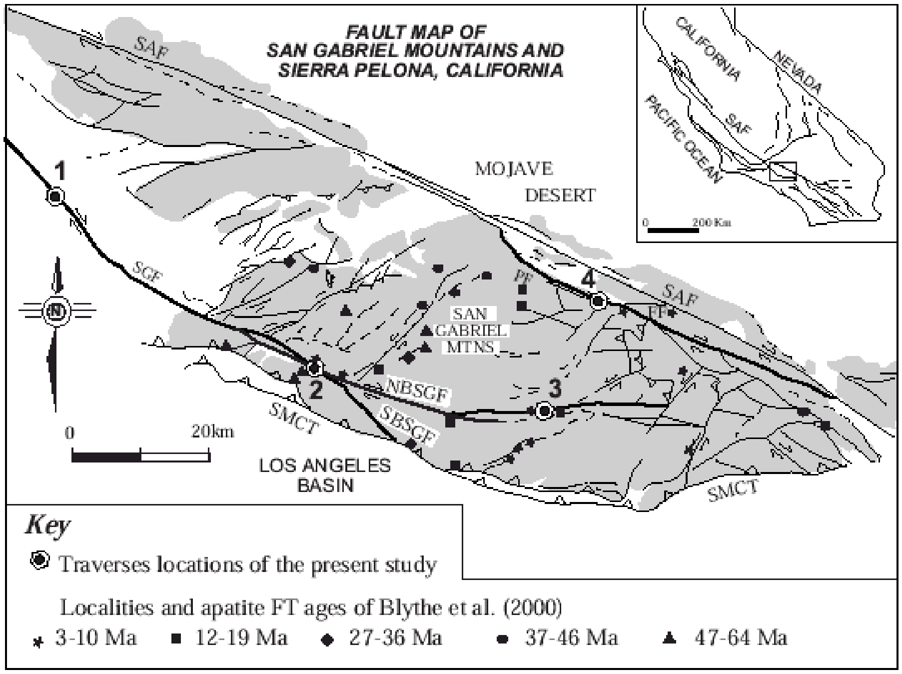

Figure 1 - Generalized geologic map of San Gabriel Mountains and four sample locations of this study (map reproduced from Chester and Logan, 1987). Solid pattern represents crystalline rocks. Symbols include SGF - San Gabriel fault (NBSGF - north branch; SBSGF - south branch); SMCT - Sierra Madre-Cucamonga thrust; VT - Vincent thrust; SAF - San Andreas fault; PF - Punchbowl fault. FT age data from Blythe *et. al.*, 2000.

Table 1 - Samples prepared for analysis and some initial results. Apatite fission track data denoted with an "X" are in the process of being obtained. If a renewal proposal that is pending is funded, then the samples with an "O" symbol will be analyzed in ca. 2003 and 2004.

Sample #	**Position**	**Horiz. Dist. (m)**	**Orth. Dist. (m)**	**Elevation (m)**	**Apatite FT (Ma)**	**Zircon FT (Ma)**	**Apatite U - He**	**Zircon U - He**
Locality #1								
SG01-30	NE	3.73	3.66	1084	X		O	O
SG01-31	NE	6.84	6.71	1085	X		O	O
SG01-32	NE	12.7	12.5	1087	X		O	O
SG01-33	NE	14.9	14.6	1087	X		O	O
SG01-34	NE	23.3	22.9	1088	X		O	O

SG01-35	NE	27.0	26.5	1090	X		O	O
SG01-36	NE	81.7	80.2	1091	X		O	O
SG01-29	SW	0.15	0.15	1082	X		O	O
SG01-28	SW	0.86	0.85	1082	X		O	O
SG01-27	SW	3.07	3.0	1082	X		O	O
SG01-26	SW	7.1	7.01	1079	X		O	O
SG01-25	SW	25.0	24.7	1076	X		O	O
SG01-24	SW	117.0	114.6	1052	X		O	O
SG01-17	SW	367	360	1090	X		O	O
SG01-16	SW	495	486	1119	X		O	O
Locality #2								
SG00-28	NE	0.15	0.14	695	X		O	O
SG01-42	NE	1.15	1.13	696	X		O	O
SG00-29	NE	12.5	12.23	695	X		O	O
SG00-27	SW	0.15	0.15	695	X		O	too few
SG01-43	SW	0.80	0.79	696	X		O	too few
SG00-26	SW	9.5	9.27	695	X		O	too few
SG00-25	SW	73.0	71.6	690	X		O	too few
Locality #3								
SG01-62	NE	0.20	0.20	558	X		O	O
SG00-03	NE	0.98	0.97	558	X	42 ± 3.2	O	O
SG01-63	NE	1.00	0.99	558	X		O	O
SG00-04	NE	3.05	3.00	558	X	44.8 ± 3.0	O	O
SG00-05	NE	4.3?	4.3?	?	~19			
SG00-06	NE	37.0	36.0	558	~40	60.8 ± 4.6	O	O
SG00-08	NE	123.5	121.6	561	X	55.9 ± 4.6	O	O
SG01-60	SW	0.12	0.12	558	X		O	O
SG00-10	SW	0.36	0.36	558	X	45.5 ± 3.3	O	O
SG01-61	SW	0.81	0.80	558	X		O	O
SG00-11	SW	1.7	1.68	558	X		O	O
SG00-12	SW	19.8	19.5	558	X	39 ± 2.9	O	O
SG00-13	SW	55.8	55.0	552	X	40.1 ± 3.0	O	O
SG00-15	SW	213.4	210.0	552	X	39.7 ± 2.9	O	O
Locality #4								
PB01-51	NE	0.43	0.4	1494	X		O	O
PB01-50	NE	0.43	0.4	1494	X		O	O
PB01-49	NE	1.9	1.75	1494	X		O	O
PB01-48	NE	7.8	7.32	1494	X		O	O
PB01-47	NE	53.4	50.0	1504	X		O	O
PB01-46	NE	65.0	61.0	1501	X		O	O
PB01-52	SW	0.05	0.05	1494	X		O	O
PB01-53	SW	0.43	0.4	1494	X		O	O

PB01-54	SW	1.0	0.95	1497	X		O	O
PB01-55	SW	9.8	9.2	1506	X		O	O
PB01-56	SW	26.5	25.0	1535	X		O	O
PB01-57	SW	82.3	77.4	1545	X		O	O
PB01-58	SW	114.3	107.4	1547	X		O	O
PB01-59	SW	169.2	159.0	1551	X		O	O

Initial Results

The zircon data of this study for locality #3 and apatite fission track ages from d'Alessio and others (2001)[2] for locality #2 are shown in Figure 2. These data sets are similar in two ways. First, there are relatively sharp transitions in ages across the San Gabriel fault. And second, the relatively old ages of the host rocks are not significantly and uniformly younger in proximity to the fault, consistent with little fission track annealing during fault movement at 5 to 12 Ma. The 30 Ma and older ages are wide spread in the San Gabriels and have been interpreted to be related to metamorphic core-complex style extension and cooling of the Basin and Range (Blythe *et al.,* 2000).

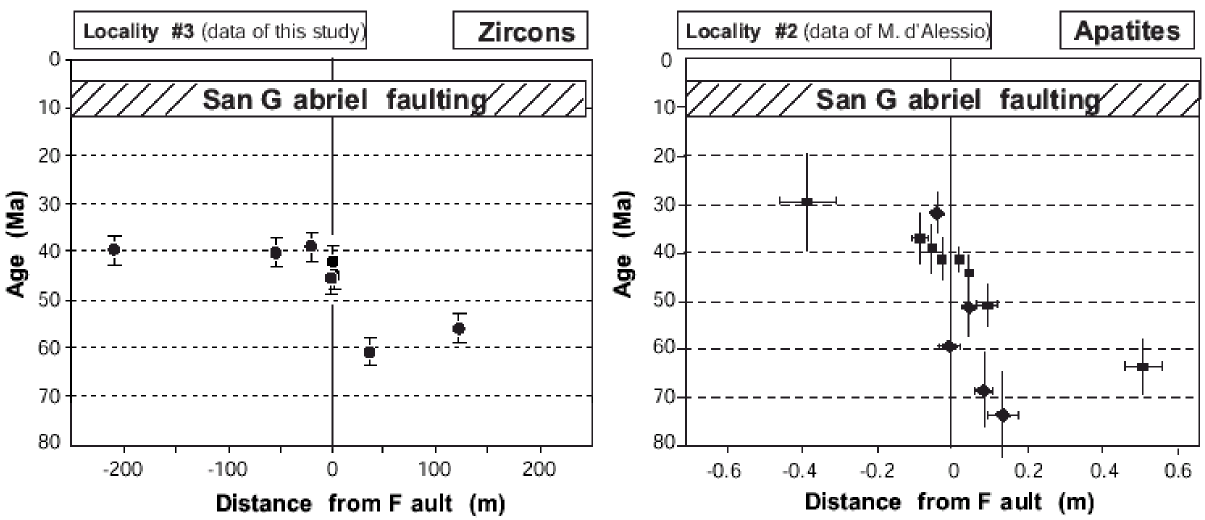

Figure 2 - Fission track ages for zircons at locality #3 (data of this study) and apatites at locality #2 (data of Matthew d'Alessio *et al.*, 2001/02 - figure reproducedwith minor modifications from his web site.).

These ages are consistent with the San Gabriel fault not having generated enough heat or channelizing sufficient quantities of hot fluids to raise the ambient temperature to partly or completely anneal the fission tracks in apatites at locality #2 or zircons at locality #3. That does not exclude the possibility, however, that there was enough heat to reset the lower temperature systems (*i.e,* U/Th-He ages of apatites at locality #2; U/Th-He ages of apatite and zircon, and fission tracks apatites at locality #3).

[2]A similar research project started independently in 2000/01 by Roland Burgmann, University of California Berkeley, and graduate student, Matthew d'Alessio. They have focused their attention on Anderson's "Earthquake Locality", which is also locality #2 in our study. Because of their work at this locality, we are focusing more attention on the three other localities in our study.

Continuation of project: The remainder of the 40 samples will be analyzed in 2003. Samples will then be chosen for U/Th-He analysis based on the results of the fission-track analyses. These analyses will most likely be completed in 2004. The results of this study will be published after all of the analyses are complete. This will result in one comprehensive article on the thermal history of these two faults and the implications this study has on the "stress-heat flow" paradox..

Near-term presentation of study's results:

Cuevas, D. Heat-flow constraints on the strength of seismogenic faulting using fission-track data from the San Andreas fault system, California. In process of writing MS thesis, Saint Louis University. (Expected graduation in May, 2003).

Results will also be presented in Fall 2003 AGU annual meeting.