

Talc-bearing serpentinite and the creeping section of the San Andreas fault

Diane E. Moore¹ & Michael J. Rymer¹

The section of the San Andreas fault located between Cholame Valley and San Juan Bautista in central California creeps at a rate as high as 28 mm yr^{-1} (ref. 1), and it is also the segment that yields the best evidence for being a weak fault embedded in a strong crust^{2–5}. Serpentinized ultramafic rocks have been associated with creeping faults in central and northern California^{6–8}, and serpentinite is commonly invoked as the cause of the creep and the low strength of this section of the San Andreas fault. However, the frictional strengths of serpentine minerals are too high to satisfy the limitations on fault strength, and these minerals also have the potential for unstable slip under some conditions^{9,10}. Here we report the discovery of talc in cuttings of serpentinite collected from the probable active trace of the San Andreas fault that was intersected during drilling of the San Andreas Fault Observatory at Depth (SAFOD) main hole in 2005. We infer that the talc is forming as a result of the reaction of serpentine minerals with silica-saturated hydrothermal fluids that migrate up the fault zone, and the talc commonly occurs in sheared serpentinite. This discovery is significant, as the frictional strength of talc at elevated temperatures is sufficiently low to meet the constraints on the shear strength of the fault, and its inherently stable sliding behaviour is consistent with fault creep¹¹. Talc may therefore provide the connection between serpentinite and creep in the San Andreas fault, if shear at depth can become localized along a talc-rich principal-slip surface within serpentinite entrained in the fault zone.

The SAFOD drillsite is located 14 km northwest of Parkfield in central California (Fig. 1), along the creeping section of the San

Andreas fault (SAF). In 2005, drilling successfully crossed the active trace of the SAF at $\sim 3 \text{ km}$ vertical depth¹², where the measured temperature is $\sim 112 \text{ }^\circ\text{C}$ (ref. 13). The drillhole terminated in sedimentary rocks of the Great Valley Sequence (K. McDougall, personal communication) east of the fault. Since then, a portion of the well casing has been actively deforming in response to creep on a fault strand¹². Serpentine was identified in X-ray diffraction patterns of cuttings¹⁴ collected at the eastern margin of the zone of active deformation (Supplementary Fig. 1). Aeromagnetic surveys¹⁵ indicate the presence of a flat-lying slab of serpentinite at $>3 \text{ km}$ depth on the northeast side of the fault (Fig. 1). This body may be $\geq 2 \text{ km}$ thick, and it abuts the fault for 50–60 km (ref. 15). The serpentinite slab is probably part of the Coast Range ophiolite, the oceanic basement on which the sediments of the Great Valley Sequence were deposited. Serpentinized ultramafic rock has a relatively low density compared to the overlying rock column, and a fault intersecting such a rock unit provides the pathway for the migration of serpentinite to shallower depths¹⁶. The Table Mountain serpentinite¹⁷ east of Parkfield (Fig. 1) is an extrusive body that formed as a result of the diapiric rise of low-density serpentinite from the deeply buried slab along faults that served as ‘fissure feeders’¹⁷. The serpentinite associated with the active trace in the SAFOD drillhole¹⁴ and outcrops of serpentinite^{18,19} fault gouge (Fig. 1) suggest that the same process is occurring along the SAF.

Serpentinite has been suggested as a possible cause of creep, because of its close association with creeping faults in central and northern California^{6–8}. The SAF creeping section coincides with the

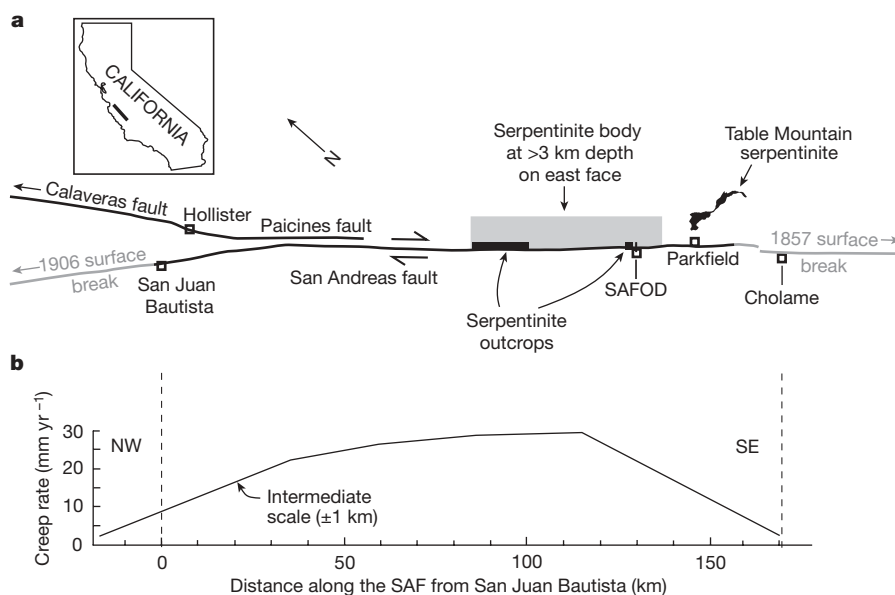


Figure 1 | Distribution of serpentinite along the SAF creeping section. **a**, The creeping section lies between areas of the fault that ruptured during great earthquakes in 1857 and 1906. Serpentine occurs in rare surface exposures of the fault^{18,19} and in the probable active trace of the fault encountered at $\sim 3 \text{ km}$ vertical depth in the SAFOD drillhole^{12,14}. The extrusive serpentinite at Table Mountain¹⁷ is derived from the same serpentinite body that abuts the fault on the northeast side at $>3 \text{ km}$ depth¹⁵. **b**, Recently updated creep rates measured at distances of 10 m to 1 km from the fault¹. Total offset rates along the San Andreas system in the creeping section are considered to be between 28 and 34 mm yr^{-1} (ref. 1).

¹US Geological Survey, 345 Middlefield Road, Mail Stop 977, Menlo Park, California 94025, USA.

is most abundant in the 3,325 m MD sample, which also contains nearly all of the sheared talc-bearing grains identified thus far. Talc is only a minor component of the serpentinite ($\leq 2\text{--}3\%$), although this soft mineral may have been preferentially lost during drilling (Fig. 3d).

Talc compositions (Supplementary Table 1) are consistent with those of talc in other low-temperature hydrothermal environments²⁷. The talc typically contains 4.0–5.5 wt% FeO and as much as 1.5 wt% NiO. In contrast, talc takes up only minor amounts of Al, and the Mg-rich smectite clay mineral saponite, with $\sim 5.0\text{--}7.5$ wt% Al_2O_3 (Supplementary Table 1), replaces serpentinite that has been mixed with feldspathic sediments.

The presence of talc in the active trace of the SAF is significant because talc has a very low shear strength in the temperature range 100–400 °C (Fig. 2). Talc may be the only mineral that can satisfy the conditions for a weak SAF over the entire depth range of the seismogenic zone without the need to invoke additional weakening mechanisms such as fluid overpressures. It is also characterized by inherently stable, velocity-strengthening behaviour¹¹. In rocks of appropriate composition, talc is stable at temperatures ranging from surficial to nearly 800 °C (ref. 27). The frictional strength of water-saturated smectite clay is comparable to that of talc at room temperature²⁸. However, the smectite clay saponite begins to break down at temperatures slightly above 100 °C (ref. 29), transforming to chlorite the water-saturated frictional strength of which²⁸ is close to that of lizardite. As with chrysotile (Fig. 2), saponite cannot explain the low apparent strength of the creeping section at depths greater than 3–4 km.

This discovery reinstates serpentinite as a possible explanation for fault creep, although indirectly through its association with talc; testing this hypothesis may prove challenging. The collection of core from the active trace of the SAF planned for 2007 at SAFOD may provide some answers, although, as noted previously, chrysotile and smectite clays have comparable frictional properties to talc at ~ 3 km depth. The small amount of talc found in the cuttings raises the question of whether enough talc could be present at greater depths to influence fault behaviour. However, along the Punchbowl fault, an exhumed former strand of the SAF in southern California, offset became extremely localized to a single fracture surface within a narrow (0.15–0.55 m) fault core³⁰. For such a fault geometry, only enough talc to line a fracture surface in serpentinite would be needed. Shear of laboratory samples of serpentinite and talc is typically highly localized^{9–11} along shear planes similar to the one in the Punchbowl fault. The talc-forming reaction should also be enhanced at depths >3 km, because of faster reaction rates and the ability of higher-temperature ground waters to introduce larger amounts of dissolved silica to the serpentinite.

Received 6 March; accepted 3 July 2007.

- Titus, S. J., DeMets, C. & Tikoff, B. Thirty-five-year creep rates for the creeping segment of the San Andreas fault and the effects of the 2004 Parkfield earthquake: Constraints on alignment arrays, continuous global positioning system, and creepmeters. *Bull. Seismol. Soc. Am.* **96** (4B), S250–S268 (2006).
- Provost, A.-S. & Houston, H. Orientation of the stress field surrounding the creeping section of the San Andreas fault: Evidence for a narrow mechanically weak fault zone. *J. Geophys. Res.* **106**, 11373–11386 (2001).
- Hickman, S. & Zoback, M. Stress orientations and magnitudes in the SAFOD pilot hole. *Geophys. Res. Lett.* **31**, L15512, doi:10.1029/2004GL020043 (2004).
- Chéry, J., Zoback, M. D. & Hickman, S. A mechanical model of the San Andreas fault and SAFOD Pilot Hole stress measurements. *Geophys. Res. Lett.* **31**, L15513, doi:10.1029/2004GL019521 (2004).
- Williams, C. F., Grubb, F. V. & Galanis, S. P. Jr. Heat flow in the SAFOD pilot hole and implications for the strength of the San Andreas Fault. *Geophys. Res. Lett.* **31**, L15514, doi:10.1029/2003GL019352 (2004).
- Allen, C. R. in *Proc. Conf. on Geologic Problems of San Andreas Fault System* (eds Dickinson, W. R. & Grantz, A.) 70–80 (Stanford University Publications in the Geological Sciences Vol. 11, Stanford University, Stanford, California, 1968).
- Hanna, W. F., Brown, R. D. Jr, Ross, D. C. & Griscom, A. Aeromagnetic reconnaissance and generalized geologic map of the San Andreas fault between San Francisco and San Bernardino, California. *US Geol. Surv. Geophys. Investig. Map GP-815* (1972).
- Irwin, W. P. & Barnes, I. Effect of geologic structure and metamorphic fluids on seismic behavior of the San Andreas fault system in central and northern California. *Geology* **3**, 713–716 (1975).
- Moore, D. E., Lockner, D. A., Ma, S., Summers, R. & Byerlee, J. D. Strengths of serpentinite gouges at elevated temperatures. *J. Geophys. Res.* **102**, 14787–14801 (1997).
- Moore, D. E., Lockner, D. A., Tanaka, H. & Iwata, K. in *Serpentine and Serpentinites: Mineralogy, Petrology, Geochemistry, Ecology, Geophysics, and Tectonics* (ed. Ernst, W. G.) 525–538 (International Book Series Vol. 8, Geological Society of America, Boulder, Colorado, 2004).
- Moore, D. E. & Lockner, D. A. Comparative deformation behavior of minerals in serpentinitized ultramafic rock: Application to the slab-mantle interface in subduction zones. *Int. Geol. Rev.* **49**, 401–415 (2007).
- Zoback, M. D., Hickman, S. & Ellsworth, W. Overview of SAFOD Phases 1 and 2: Drilling, sampling and measurements of the San Andreas Fault zone at seismogenic depth. *Eos* **86** (Fall Meet. Suppl.), abstr. T23E-01 (2005).
- Williams, C. F., Grubb, F. V. & Galanis, S. P. Heat-flow measurements across the San Andreas fault near Parkfield, California — Preliminary results from SAFOD. *Eos* **87** (Fall Meet. Suppl.), abstr. S33B-0241 (2006).
- Solum, J. G. et al. Mineralogical characterization of protolith and fault rocks from the SAFOD main hole. *Geophys. Res. Lett.* **33**, L21314, doi:10.1029/2006GL027285 (2006).
- McPhee, D. K., Jachens, R. C. & Wentworth, C. M. Crustal structure across the San Andreas Fault at the SAFOD site from potential field and geologic studies. *Geophys. Res. Lett.* **31**, L12503, doi:10.1029/2003GL019363 (2004).
- Coleman, R. G. Petrologic and geophysical nature of serpentinites. *Geol. Soc. Am. Bull.* **82**, 897–918 (1971).
- Dickinson, W. R. Table Mountain serpentinite extrusion in California Coast Ranges. *Geol. Soc. Am. Bull.* **77**, 451–472 (1966).
- Rymer, M. J. Geologic map along a 12 kilometer segment of the San Andreas fault zone, southern Diablo Range, California (scale 1:12,000). *US Geol. Surv. Open-File Rep.* 81-1173 (1981).
- Rymer, M. J. et al. Surface fault slip associated with the 2004 Parkfield, California, earthquake. *Bull. Seismol. Soc. Am.* **96** (4B), S11–S27 (2006).
- Robbins, S. L. Complete Bouguer gravity, aeromagnetic, and generalized geologic map of the Hollister 15-minute quadrangle, California (scale 1:62,500). *US Geol. Surv. Geophys. Investig. Map GP-945* (1982).
- Galehouse, J. S. & Lienkaemper, J. J. Inferences drawn from two decades of alignment array measurements of creep on faults in the San Francisco Bay region. *Bull. Seismol. Soc. Am.* **93**, 2415–2433 (2003).
- Brune, J. N., Henyey, T. L. & Roy, R. F. Heat flow, stress and rate of slip along the San Andreas fault, California. *J. Geophys. Res.* **74**, 3821–3827 (1969).
- Lachenbruch, A. H. & Sass, J. H. Heat flow and energetics of the San Andreas fault zone. *J. Geophys. Res.* **85**, 6185–6223 (1980).
- Mount, V. S. & Suppe, J. State of stress near the San Andreas fault: Implications for wrench tectonics. *Geology* **15**, 1143–1146 (1987).
- Zoback, M. D. et al. New evidence for the state of stress on the San Andreas fault system. *Science* **238**, 1105–1111 (1987).
- Blanpied, M. L., Lockner, D. A. & Byerlee, J. D. Frictional slip of granite at hydrothermal conditions. *J. Geophys. Res.* **100**, 13045–13064 (1995).
- Evans, B. W. & Guggenheim, S. in *Hydrous Phyllosilicates (Exclusive of Micas)* (ed. Bailey, S.W.) 225–294 (Reviews in Mineralogy Vol. 19, Mineralogical Society of America, Washington DC, 1988).
- Moore, D. E. & Lockner, D. A. Crystallographic controls on the frictional behavior of dry and water-saturated sheet structure minerals. *J. Geophys. Res.* **109**, B03401, doi:10.1029/2003JB002582 (2004).
- Inoue, A. & Utada, M. Smectite-to-chlorite transformation in thermally metamorphosed volcanoclastic rocks in the Kamikita area, northern Honshu, Japan. *Am. Mineral.* **76**, 628–640 (1991).
- Chester, F. M. & Chester, J. S. Ultracataclastic structure and friction processes of the Punchbowl fault, San Andreas system, California. *Tectonophysics* **295**, 199–221 (1998).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to D.E.M. (dmoore@usgs.gov).