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Predicted reversal and recovery of surface creep on the Hayward fault following the 1906 San Francisco earthquake

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[1] Offset cultural features suggest that creep rates along the Hayward fault have remained constant since 1920 until the 1989 Loma Prieta earthquake despite evidence in the earthquake record of an enduring stress shadow after 1906. We re-construct the stressing history on the Hayward fault in order to predict when creep, assumed to have slowed, likely resumed at historical rates. The resumption of creep is dependent on the stressing history imposed from postseismic processes. Basic viscoelastic models produce stress histories that allow creep to resume within a couple decades. A detachment zone model for the Bay Area predicts that creep would not resume for 70+ years after the 1906 earthquake, in disagreement with historical creep observations. The recovery of creep is also advanced by potential left-lateral slip that could have been induced by the 1906 earthquake. Calculations for a friction-less fault suggest that 30–210 mm of left-lateral slip could have occurred. **Citation:** Schmidt, D. A., and R. Bürgmann (2008), Predicted reversal and recovery of surface creep on the Hayward fault following the 1906 San Francisco earthquake, *Geophys. Res. Lett.*, *35*, L19305, doi:10.1029/2008GL035270.

1. Introduction

[2] Faults that exhibit surface creep are known to change their creep rate following large earthquakes on neighboring faults due to a change in the state of stress. Modern examples of induced changes in surface creep were documented on several Bay Area faults, such as the creeping sections of the San Andreas, Calaveras, and Hayward faults, following the $\mathbf{M}_w$ 6.9 Loma Prieta earthquake in 1989 [i.e., *Galehouse*, 1997]. For this event, *Lienkaemper et al.* [1997] find that a $\sim$0.1 MPa reduction in right-lateral shear stress is enough to alter the creep rate along the southern Hayward fault and produce a temporary reversal in slip. A larger coseismic event and postseismic response, such as the 1906 San Francisco earthquake ($\mathbf{M}_w$ 7.8), is expected to induce an even greater response on adjacent faults including a reduction or increase in surface creep rates. The resulting stress shadow is generally used to explain the reduction in seismicity rates in the San Francisco Bay region since 1906 (for events with $M > 5.5$) [*Harris and Simpson*, 1998; *Bakun*, 1999; *Kenner and Segall*, 1999; *Parsons*, 2002]. However, observations suggest that creep rates along the Hayward fault were not significantly reduced in the decades following the 1906 event.

[3] No direct observations of the surface creep response on the Hayward fault were documented in the decade immediately following the 1906 earthquake on the San Andreas fault. However, *Lienkaemper and Galehouse* [1997] reconstruct the surface creep history over the ensuing decades on the Hayward fault using offset cultural features, such as curbs and other man-made structures. Sites that contain multiple measurements over varying time periods suggest that time-averaged creep rates have remained constant for much of the twentieth century (Figure 1). If creep rates were reduced, fault creep must have recovered by the early 1920's. The quick recovery to the contemporary creep rates is surprising given that moment release rates did not recover to pre-1906 values for nearly 70 years [*Bakun*, 1999].

[4] The record of surface creep along the southern Hayward fault following Loma Prieta provides an informative example of how a fault can respond to a nearby earthquake (Figure 2a). Following the 1989 Loma Prieta earthquake, a reduction in creep was observed along the southern Hayward fault which historically exhibits surface creep $\sim$9 mm/yr [*Lienkaemper et al.*, 1997]. Alignment array data of fault creep at one site indicate a subtle left-lateral trend that lasted $\sim$3 years before returning to a right-lateral sense of slip. A discrete creep event was observed about the time that the fault resumed right-lateral slip at a time-averaged rate of $\sim$6 mm/yr. This lower rate may suggest that the background loading rate that drives creep remains low from post-Loma Prieta relaxation and the creep rate is still climbing to pre-Loma Prieta levels. We hypothesize that a similar reversal and recovery occurred after the 1906 San Francisco earthquake. Using the information learned from the Loma Prieta response, we attempt to explain how creep rates could recover on the Hayward fault following the 1906 San Francisco earthquake by reconstructing the coseismic and postseismic stress history.

2. Modeling of Fault Creep Recovery

[5] In our attempt to better understand the response of the Hayward fault to the 1906 earthquake, it is instructive to develop a frictional model that can reproduce the time-dependent features of the Loma Prieta response. The response of the fault to a stress perturbation can be approximated using a simple spring-slider system governed by a rate-and-state constitutive law. The evolution of slip as a function of time is calculated using the iterative, numerical method of *Dieterich* [1992]. During each time step, the slip rate is determined such that the driving stress and the frictional resistance are balanced. The state variable depen-

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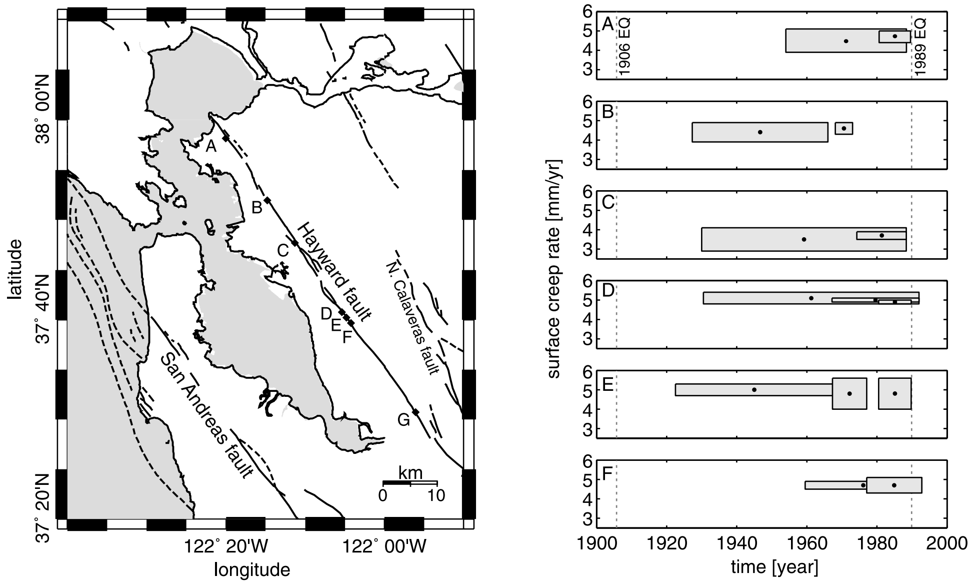

Figure 1. (left) A map of the San Francisco Bay Area shows the location of major faults. The epicenter of the Loma Prieta earthquake is located along the San Andreas fault just south of the region shown. The 1906 earthquake ruptured a 400 km segment of the San Andreas fault, including the segment shown. Letters A-F along the Hayward fault mark the location of time-averaged creep measurements shown to the right. Location G marks the observation point for the data in Figure 2. (right) Time-averaged creep rate data are measured from offset cultural features by *Lienkaemper and Galehouse* [1997]. Each gray box represents one observation where the height of the box signifies the error of the measurement and the width of the box designates the time period over which the displacement is averaged. The data suggest that surface creep rates along the Hayward fault have remained constant despite a lingering stress shadow. Historical creep rates are $\sim$5 mm/yr along most of the fault, except on the southern end where rates are $\sim$9 mm/yr.

dence on normal stress is evaluated between time steps [*Linker and Dieterich*, 1992]. Given the left-lateral creep on the Hayward fault in the first three years after Loma Prieta (Figure 2a), the numerical algorithm of *Dieterich* [1992] has been modified to allow for a temporary reversal in the slip direction. The creeping fault is represented as a vertical array of 10 sub-faults extending from the surface to a depth of 300 meters embedded in an elastic half-space.

[6] The stressing history imposed on the fault must be specified in order to predict the slip response. Using the source model of *Árnadóttir and Segall* [1994] for Loma Prieta, we calculate a coseismic shear stress change of -0.11 MPa (positive right-lateral) and a change in normal stress of -0.09 MPa (positive compresssional) on the shallow Hayward fault near site G on Figure 1 (see auxiliary material[1] for additional information on elastic modeling). *Lienkaemper et al.* [2001] infer 2.1 ± 1.6 cm of dynamically triggered right-lateral creep by resurveying a nearby curb at Camellia drive. It is unknown whether this initial response also included left-lateral creep from the coseismic static stress change. We assume that the initial shear stress on the fault is reduced to zero at the time of the coseismic event by some combination of induced slip. Thus, the coseismic stress reduction, the timing of the switch from left-lateral to right-lateral slip, and the timing of the creep event help to constrain the initial state of stress on the fault. The stressing history from postseismic processes are parameterized by calculating the shear and normal stressing rate imposed on the Hayward fault using the postseismic afterslip model of *Segall et al.* [2000] for the three years following the 1989 Loma Prieta earthquake. Following the postseismic afterslip, we assume that the shear loading rate quickly recovers to the interseismic rate of 0.015 MPa/yr [*Parsons*, 2002]. While there are many assumptions made in constructing this stress history and parameterizing the frictional model, our objective is to explore the first-order time-dependent recovery of a creeping fault to a stress perturbation.

[7] Based on the pre-defined stressing history, the model qualitatively reproduces the creep event and the recovery of stable sliding (Figure 2b). Left-lateral slip is also predicted by the simulation and is driven by the stress imposed by the afterslip model. However the slip rate is an order of magnitude smaller in the simulation than what is observed and is not readily discernible in Figure 2.

[8] After compensating for the creep event, the time-averaged steady-state slip resumes 5.4 years after Loma Prieta. The creep simulation illustrates that sliding at a near constant right-lateral rate resumes when the ratio of shear stress to normal stress on a fault patch is equal to a steady-state value (Figure 2c). The time frame for recovery is identical to that predicted using a standard Coulomb failure stress calculation. The reduction in normal stress on the fault means that a lower shear stress is required to attain the steady-state coefficient of friction. Therefore, it is possible to predict the time frame for creep rates to recover if the time dependent stressing history is known.

3. Creep Recovery Following 1906

[9] In order to predict how the Hayward fault would respond to the 1906 earthquake, its full stressing history

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL035270.

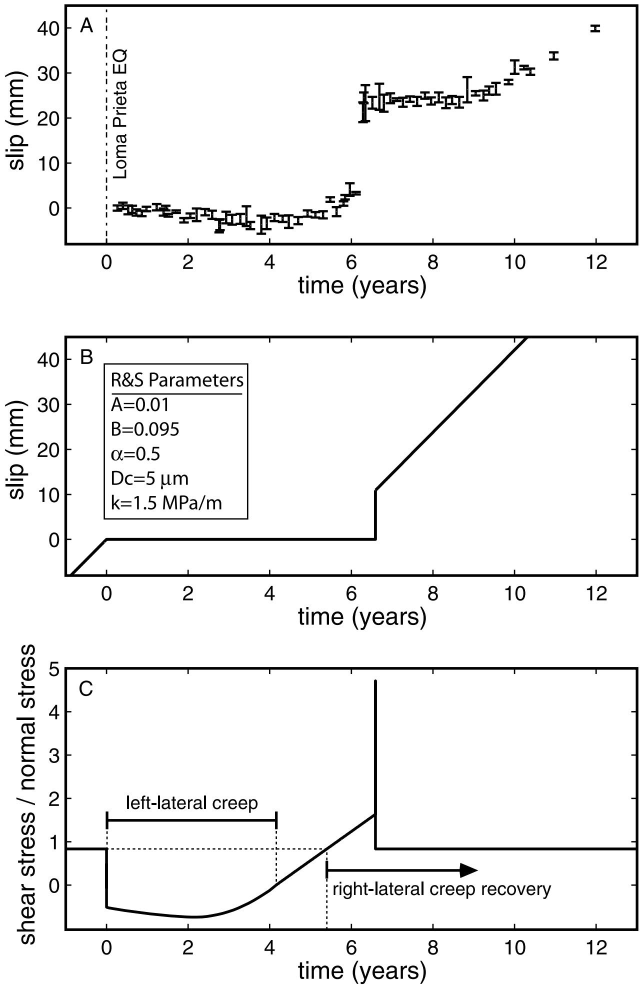

Figure 2. (a) The surface creep response on the southern Hayward fault following the 1989 Loma Prieta earthquake. The alignment array data were collected at location G in Figure 1 by *Lienkaemper et al.* [1997]. (b) The simulated creep response is calculated using a rate-and-state constitutive law on a creeping fault. The rate-and-state constitutive parameters used in the simulation are indicated in the inset: *A* and *B* are laboratory fit parameters, α defines the state variable's dependence on normal stress, D_c is the critical slip distance, and *k* is the fault stiffness. (c) Steady-state slip resumes when the ratio of the shear to normal stress reaches the initial ratio prior to a stress perturbation.

must be defined. We use the 1906 coseismic slip model of *Thatcher et al.* [1997] to calculate the coseismic stress change resolved onto the Hayward fault. We calculate a right-lateral, shear stress change of −0.3 MPa and a −0.1 MPa change in compressional normal stress on the shallow southern Hayward fault. Because the postseismic response is expected to play an important role in driving regional deformation following a large earthquake, we incorporate the postseismic shear stressing histories calculated by *Kenner and Segall* [1999] for the 1906 event. *Kenner and Segall* [1999] use an anti-plane finite element model to calculate the stress imposed on Bay Area faults as a function of time for various rheological scenarios (Figure 3). The crustal fault model represents an elastic layer over a Maxwell viscoelastic half-space. The shear zone model includes vertical, low-viscosity shear zones beneath the San Andreas, Hayward, and Calaveras faults. The detachment model connects the three vertical shear zones at a depth of 15 km with a horizontal zone of viscoelastic material. In addition to the stress perturbation from postseismic processes, a shear rate of 0.015 MPa/yr is added for tectonic loading.

[10] Steady creep resumes when the ratio of shear to normal stress equals the pre-1906 value (Figure 3d). For the crustal fault model, steady state creep should resume in 13–18 years following the 1906 earthquake. The range in recovery times corresponds to a range of friction values from 0.9 to 0.1, respectively. The shear zone model and the detachment model predict that creep resumes in 21–27 and 70–77 years, respectively. Given the insignificant postseismic relaxation in the crustal fault model, fault creep resumes within two decades. The inclusion of vertical shear zones

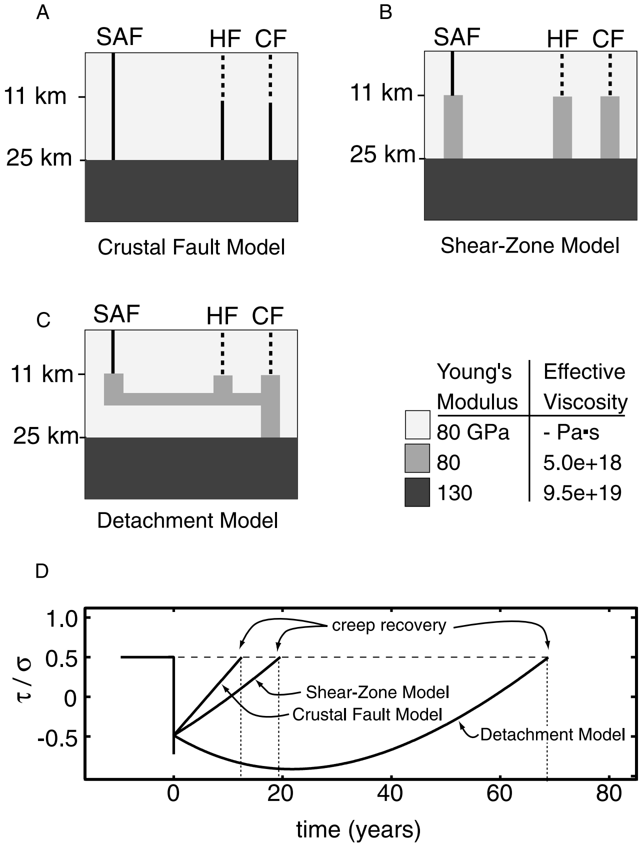

Figure 3. The postseismic stressing history imposed on the shallow Hayward fault following the 1906 San Francisco earthquake is calculated by *Kenner and Segall* [1999] for three rheological models: (a) an elastic layer over a viscoelastic mantle, (b) an elastic layer with vertical viscoelastic shear zones beneath the San Andreas (SAF), Hayward (HF), and Calaveras (CF) faults, and (c) an elastic layer with vertical and horizontal shear zones. (d) The stress histories for these models are used to predict when creep resumes on the Hayward fault by tracking the ratio of shear to normal stress. For this plot, an initial ratio of 0.5 is used along with a left-lateral stress reduction from 30 mm of induced left-lateral slip (see section 3).

beneath the three major faults in the Bay Area acts to extend the recovery of creep as viscous relaxation redistributes more stress in the crust. As discussed by *Kenner and Segall* [1999], the horizontal shear zone acts to transfer additional left-lateral stress to the Hayward and Calaveras faults. This produces a more intense and drawn out postseismic response delaying the recovery of creep for 3/4 of a century.

[11] It is likely that the Hayward fault exhibited left-lateral surface creep due to the 1906 event given the large shear stress imposed. A simple elastic model where the southern Hayward fault is allowed to slip freely from the surface to a depth of 1 km predicts 30 mm of left-lateral slip. This slip would act to advance the resumption of surface creep by at least 3 years for the crustal fault model and 5 years for the detachment model. Reverse slip driven by postseismic processes would further advance recovery. A friction-less fault that extends to 10 km would produce 210 mm of left-lateral slip on the southern Hayward fault which would effectively erase the entire coseismic stress perturbation.

4. Discussion

[12] Different rheological models for the San Andreas fault system produce observable differences in the surface creep response on the Hayward fault following the 1906 San Francisco earthquake. Time-averaged creep rates can be estimated by assuming that a fault resumes creep at the steady-state rate after the recovery time, as is observed with the rate-and-state simulation. For an assumed steady-state creep rate of 5 mm/yr (Figure 1e) and 30 mm of left-lateral slip, the crustal fault model would produce an average creep rate of 5 mm/yr and the shear zone model would produce a rate of 4.4–4.9 mm/yr for the time period of 1922 to 1989. These rates are consistent with observations from offset cultural features for the longest post-1906 record (Figure 1e). The detachment model predicts a time-averaged creep rate of 0.8–1.3 mm/yr. Our stress reconstructions suggests that the detachment zone model of *Kenner and Segall* [1999] does not agree with the time-averaged slip rate data. Thus, observations of surface creep can be used not only for fault monitoring, but also as a tool to discriminate between crustal models.

[13] A 1965 survey of the railroad tracks built across the southern Hayward fault in 1869 (near site G, Figure 1) provides a time-averaged creep rate estimate of >8.5 ± 0.6 mm/yr, which is consistent with pre-Loma Prieta slip rate measurements [*Lienkaemper and Galehouse*, 1997]. While this is the only estimate that extends through 1906, the cumulative slip includes an unknown amount of afterslip from the 1868 earthquake (**M** 6.8) on the Hayward fault. Therefore, it is impossible to extract definitive information about the creep response in the 16 years immediately following the 1906 event. If it is assumed that no creep occurred from 1906 to 1922 and that the creep rate was >8.5 mm/yr after 1922, then a minimum time-averaged rate of 12 mm/yr is required between 1869 and 1906, a period likely dominated by post-1868 afterslip. Any induced left-lateral creep following 1906 would require additional post-1868 right-lateral afterslip to offset the cumulative slip.

[14] It should not be surprising that no observations of 1906 induced left-lateral creep on the Hayward fault exist given the minimal cultural development that extended across the Hayward fault in the early part of the twentieth century. The greatest potential for a documented observation would exist in the deformation of railroad tracks that crossed the Hayward fault in Fremont. *Cluff and Steinbrugge* [1966] and *Bonilla* [1966] summarize the information obtained from records detailing the repair of railroad tracks during the first half of the twentieth century. There exists no specific mention of left-lateral movement across the tracks along the southern Hayward fault in 1906. However, *Forbes* [1914] mentions that deformation of an undefined nature was observed along the fault.

[15] One implication of a significant left-lateral response is that the displacement history on the fault will lag the far-field displacement history across the plate boundary. For the displacement record on the Hayward fault following the Loma Prieta earthquake, *Lienkaemper et al.* [2001] find that a permanent slip deficit persists after a full decade of observations. This slip deficit can be explained by the coseismic stress change and the depressed loading rate that exists in the years following the coseismic event.

5. Conclusions

[16] Stress calculations illustrate how right-lateral surface slip rates could quickly recover on the Hayward fault following the 1906 San Francisco earthquake despite an enduring stress shadow and depressed seismic moment release rates. Low states of stress on sub-surface fault elements allow the fault to be highly responsive to a stress perturbation [e.g., *Mavko et al.*, 1985]. Creep can recover when the ratio of the shear to normal stress reaches a level equal to the initial steady-state value. Additionally, large negative stress perturbations can temporarily drive the shallow fault in reverse which can reduce the negative stress step and thereby advance the recovery time further. Such a response was observed following the 1989 Loma Prieta earthquake and likely occurred following the 1906 San Francisco earthquake as well. For the shallow Hayward fault, our estimates of when fault creep resumed are consistent with time-averaged slip rates measured from offset cultural features. The recovery of right-lateral creep signals when a fault first emerges from a stress shadow and can be used to constrain the evolution of the regional stress field. Refined postseismic models of the 1906 earthquake [i.e., *Parsons*, 2002] can then be used to estimate the time-dependent seismic hazard for the region.

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References

Árnadóttir, T., and P. Segall (1994), The 1989 Loma Prieta earthquake imaged from inversion of geodetic data, *J. Geophys. Res.*, *99*, 21,835–21,855.

Bakun, W. H. (1999), Seismic activity of the San Francisco Bay region, *Bull. Seismol. Soc. Am.*, *89*, 764–784.

Bonilla, M. G. (1966), Deformation of railroad tracks by slippage of the Hayward fault in the Nile District of Fremont, California, *Bull. Seismol. Soc. Am.*, *56*, 281–289.

Cluff, B., and K. V. Steinbrugge (1966), Hayward fault slippage in the Irvington-Niles Districts of Fremont, California, *Bull. Seismol. Soc. Am.*, *56*, 257–279.

Dieterich, J. H. (1992), Earthquake nucleation on faults with rate and state dependent strength, *Tectonophysics*, *21*, 115–134.

Forbes, H. (1914), Report on the underground waters of Niles cone, November 1913 to April 1914, *Water Resour. of Calif.*

Galehouse, J. S. (1997), Effect of the Loma Prieta earthquake on fault creep rates in the San Francisco Bay region, *U. S. Geol. Surv. Prof. Pap.*, *1550-D*, 193–207.

Harris, R. A., and R. W. Simpson (1998), Suppression of large earthquakes by stress shadows: A comparison of Coulomb and rate-and-state failure, *J. Geophys. Res.*, *103*, 24,439–24,451.

Kenner, S., and P. Segall (1999), Time-dependence of the stress shadowing effect and its relation to the structure of the lower crust, *Geology*, *27*, 119–122.

Lienkaemper, J. J., and J. S. Galehouse (1997), Revised long-term creep rates on the Hayward fault, Alameda and Contra Costa counties, California, *U. S. Geol. Surv. Open File Rep. 97-690*.

Lienkaemper, J. J., J. S. Galehouse, and R. W. Simpson (1997), Creep response of the Hayward Fault to stress changes caused by the Loma Prieta earthquake, *Science*, *276*, 2014–2016.

Lienkaemper, J. J., J. S. Galehouse, and R. W. Simpson (2001), Long-term monitoring of creep rate along the Hayward fault and evidence for a lasting creep response to 1989 Loma Prieta earthquake, *Geophys. Res. Lett.*, *28*, 2269–2272.

Linker, M. I., and J. H. Dieterich (1992), Effects of variable normal stress on rock friction: Observations and constitutive equations, *J. Geophys. Res.*, *97*, 4923–4940.

Mavko, G. M., S. Schulz, and B. D. Brown (1985), Effects of the 1983 Coalinga, California, earthquake on creep along the San Andreas fault, *Bull. Seismol. Soc. Am.*, *75*, 475–489.

Parsons, T. (2002), Post-1906 stress recovery of the San Andreas fault system calculated from 3-D finite element analysis, *J. Geophys. Res.*, *107*(B8), 2162, doi:10.1029/2001JB001051.

Segall, P., R. Bürgmann, and M. Matthews (2000), Time-dependent triggered afterslip following the 1989 Loma Prieta earthquake, *J. Geophys. Res.*, *105*, 5615–5634.

Thatcher, W., G. Marshall, and M. Lisowski (1997), Resolution of fault slip along the 470-km-long rupture of the great 1906 earthquake and its implications, *J. Geophys. Res.*, *102*, 5353–5367.

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