Variations in Creep Rate along the Hayward Fault, California, Interpreted as Changes in Depth of Creep

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Abstract. Variations in surface creep rate along the Hayward fault are modeled as changes in locking depth using 3D boundary elements. Model creep is driven by screw dislocations at 12 km depth under the Hayward and other regional faults. Inferred depth to locking varies along strike from 4-12 km. (12 km implies no locking.) Our models require locked patches under the central Hayward fault, consistent with a **M**6.8 earthquake in 1868, but the geometry and extent of locking under the north and south ends depend critically on assumptions regarding continuity and creep behavior of the fault at its ends. For the northern onshore part of the fault, our models contain 1.4-1.7 times more stored moment than the model of Bürgmann et al. [2000]; 45-57% of this stored moment resides in creeping areas. It is important for seismic hazard estimation to know how much of this moment is released coseismically or as aseismic afterslip.

Introduction

The Hayward fault, a strand of the San Andreas fault system to the east of San Francisco Bay, creeps aseismically at the Earth's surface and yet is known to fail in major earthquakes. Creep rates, measured over decades using alinement arrays, offset cultural features, and creepmeters range from 3–10 mm/yr along the 70-km onshore length of the fault [*Bilham and Whitehead*, 1997; *Lienkaemper et al.*, 2001]. One large earthquake is known from the historic record—a **M**6.8 event in 1868 [*Yu and Segall*, 1996; *Bakun*, 1999]. Older events have been discovered in paleoseismic trenching investigations, the penultimate large event on the northern part of the fault probably occurring between 1640 and 1776 [*Hayward Fault Paleoearthquake Group*, 1999].

Savage and Lisowski [1993] presented a quantitative explanation for the seemingly paradoxical behavior of a creeping fault producing major earthquakes. They used a 2D dislocation model incorporating the Hayward, San Andreas, and Calaveras faults to demonstrate that a surface creep rate of ~5 mm/yr on the Hayward fault could be explained by a creeping zone extending from the surface to about 5 km depth with a locked zone below extending to 10 km depth. The three faults were assumed to slip aseismically below 10 km at long-term rates of 9, 20, and 9 mm/yr, respectively. Elastic stresses generated by this deep slip are transmitted around the locked zone to drive observed surface creep. About 35% of the total stress acting on the creeping zone came from deep slip on the San Andreas and Calaveras faults.

3D Model Geometry

Our 3D boundary element model (BEM) consists of two parts. The first, representing the upper creeping and seismogenic sections of the Hayward fault, is an 83-km long by 12-km tall grid of 1×1-km square elements, reaching from 13.5 km north of Point Pinole to south of Fremont (Figure 1). (12 km represents an average depth to which seismicity extends under the fault.) The second part of the model is composed of ~10-km long, vertical driving dislocations under the major fault traces in the Bay region, extending from 12 to 10,000 km depth and forced to slip at long-term rates.

It is not known how, or whether, the Hayward fault connects in the subsurface with the Rodgers Creek fault or other faults, and we have assumed that the Hayward fault simply ends 13.5 km north of Point Pinole. Unfortunately, fault terminations and discontinuities have a strong effect on boundary element results [*Bilham and Bodin*, 1992], and this assumption is an important one. To the south of San Pablo Bay, we constructed our model directly under the creeping trace of the fault, even though seismicity appears to splay to the east along the Mission fault trend connecting eventually with the Calaveras fault [*Andrews et al.*, 1993; *Waldhauser and Ellsworth*, 2001].

The deep driving part of our model is consistent with the driving mechanism of Savage and Lisowski [1993], although alternate models involving deformation on horizontal detachments or weak lower crustal layers under San Francisco Bay have been proposed [*Furlong et al.*, 1989; *Kenner and Segall*, 1999]. Seismic results seem to support vertical extension of the Hayward fault at least into the lower crust [*Parsons*, 1998].

Savage and Lisowski [1993] proposed a friction model for the creeping zone, but discovered that the parameters of the friction model did not appear in their final results. We have assumed that the 1×1-km elements forming the Hayward part of the fault model are either locked, or completely free to slip so as to reduce the shear stress acting on them to zero. In steady-state, this assumption produces results closely approximating the slip distribution of Savage and Lisowski [1993].

If the Hayward fault were free to creep from top to bottom everywhere, surface creep of up to 11 mm/yr near the center of the fault would be expected (Figure 2, '12-km free'

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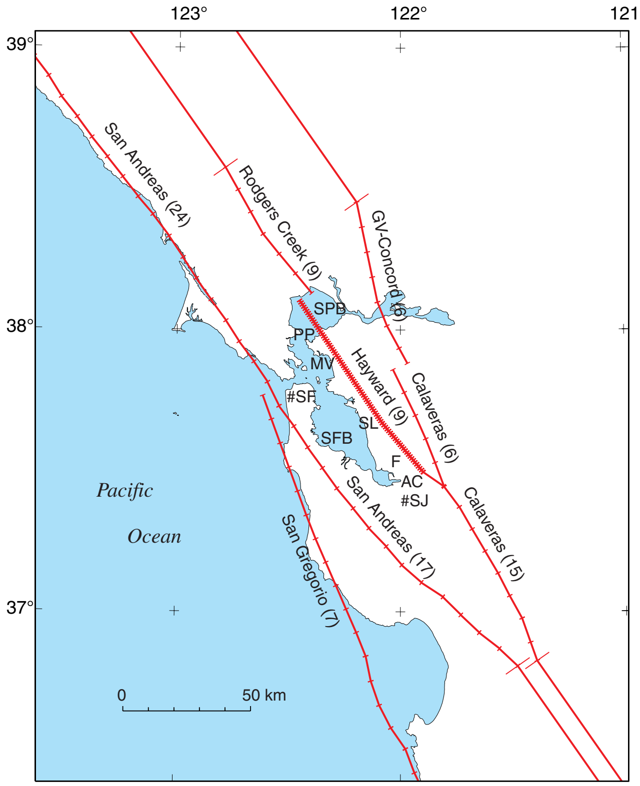

Figure 1. Major faults in the San Francisco Bay region used in this study, showing model geometry. Assumed deep slip rates (mm/yr) are listed in parentheses after the fault name. Rates have been adjusted from those preferred by WG99 [1999] in order to avoid discontinuous slip rates. Hachures along the faults indicate ends of model elements (see text for details). Also shown are long segments used to extend the major faults so as to reduce end effects. AC = Agua Caliente, F = Fremont, MV = Mira Vista, PP = Point Pinole, SF = San Francisco, SFB = San Francisco Bay, SJ = San Jose, SL = San Leandro, SPB = San Pablo Bay.

model). This is greater than the assumed long-term rate of 9 mm/yr at depth and is explained by additional driving force coming from deep slip under the San Andreas and Calaveras faults. This excess slip would presumably disappear when earthquakes on these neighboring faults produce left-lateral stress changes on the Hayward fault, which would retard or reverse creep as happened after the 1989 Loma Prieta earthquake [*Lienkaemper et al.*, 1997].

If the fault were free to creep to a uniform depth of 5 km (Figure 2), the 3D model predicts creep rates less than observed, especially at the north end of the fault. This is caused by assumed long-term creep rates smaller than those used by Savage and Lisowski, and by the northward divergence of the Calaveras fault from the Hayward: as the faults separate, slip at depth under the Calaveras cannot as effectively drive creep on the Hayward. This deficit of driving stress at the northern end can be countered by a greater depth to the bottom of the creeping zone. A good fit to an average uniform rate of 4.6 mm/yr requires slip down to 6-8 km, with deeper slip toward the north (Figure 2).

Iteration Scheme and Model Results

Reliable surface creep observations (Figures 2 and 3) were fitted by a piecewise continuous polynomial curve with rates interpolated at every kilometer along the fault [*Lienkaemper et al.*, 2001, Figure 3]. Starting with an evenly spaced, smoothed version of the data made the iterative modeling scheme described below feasible. In spite of numerous difficulties associated with collecting and interpreting creep observations, we have used only the most reliable data to construct the interpolated curve and its 2σ confidence region shown in Figure 3. It is our best judgment that variations in creep rate along the fault are significant, representing real changes in rate, and that our confidence envelope puts reasonable bounds on the uncertainties.

The iterative process began with a locked zone extending from 5 to 12 km everywhere. The slip rate predicted by this geometry was compared with the smoothed average creep rate (center of gray region, top of Figure 3). If, at some distance along the fault, the calculated slip rate was higher than the observed (within a tolerance of 0.2 mm/yr), then the depth to the locked zone was decreased by 1 km (i.e., one element height). If the calculated slip rate was lower, then the depth to locking was increased by 1 km. The depth to

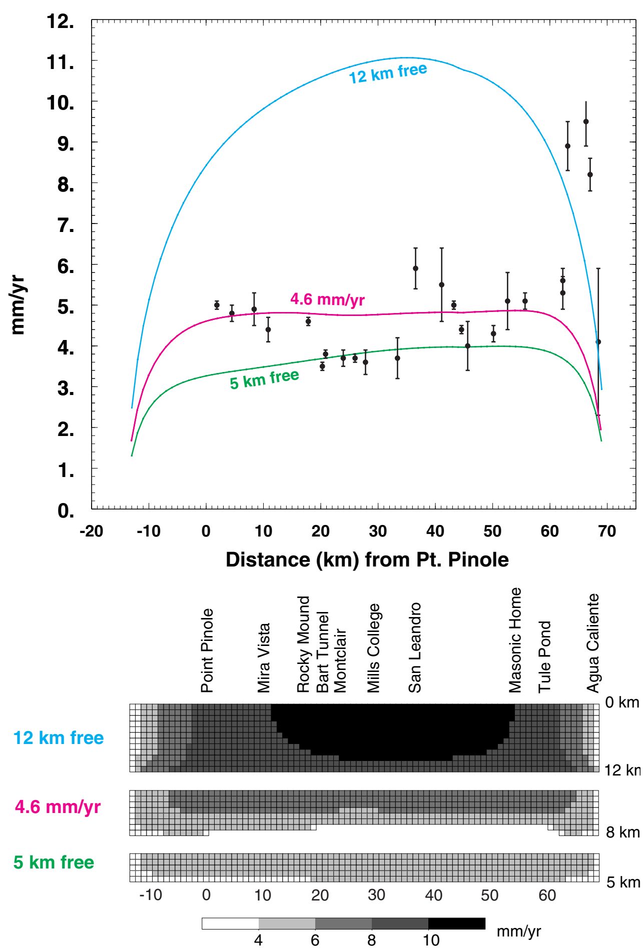

Figure 2. Points with $\pm 2\sigma$-error bars indicate observed creep rates along the Hayward fault. Upper curve is predicted surface creep rate if model fault is free to slip to 12 km (no locked patches). Lower curve is surface creep rate if top 5 km of the Hayward fault are free to slip. Middle curve shows result of a model which attempts to match a steady 4.6 mm/yr rate along the entire fault. The cross-sections at bottom show the distribution of slip at depth. Small squares are 1×1-km dislocation patches.

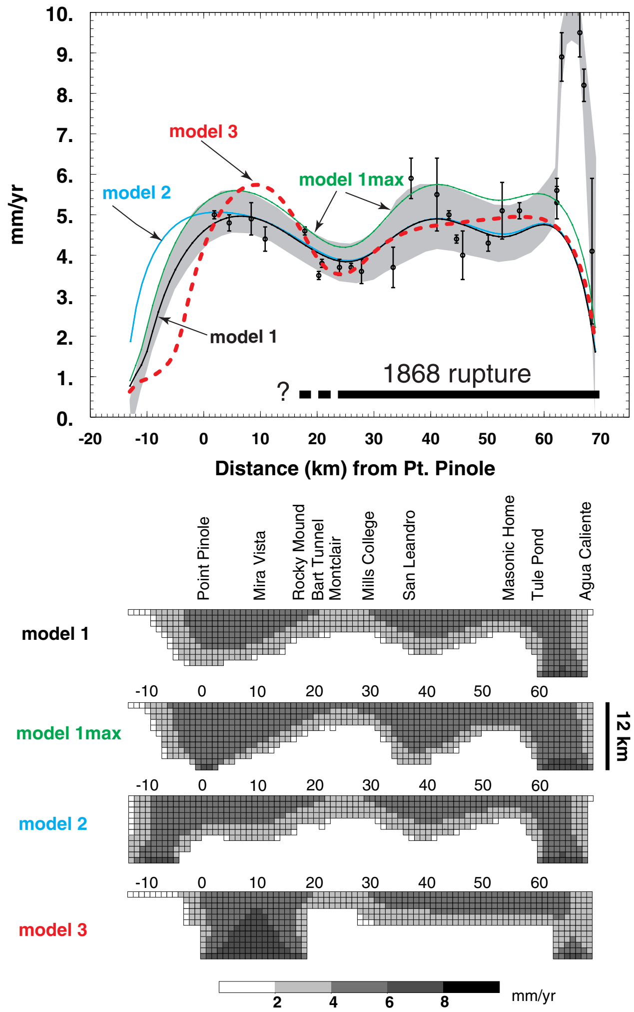

Figure 3. Gray area at top defines the $\pm 2\sigma$ region around a piecewise polynomial fit to the best creep observations. Curves at top show the surface slip predicted by four models described in the text. Cross-sections at bottom show the inferred distributions of slip at depth for the four models.

locking was not permitted to exceed 12 km, or to shrink to less than 1 km (because creep is observed along the entire onshore length of the fault). When this adjustment was completed along the entire length of the fault, slip values were recalculated for the new geometry and compared again with observed values.

A stable geometry was attained within 8 iterations (Figure 3, model 1). The model result fits the smoothed creep data everywhere to within 0.2 mm/yr except at the south end of the fault where there is an abrupt change in rate near km_63 to about 9 mm/yr. This is the region in which creep essentially stopped after the 1989 Loma Prieta earthquake, only to suddenly resume in 1995-1996 [*Lienkaemper et al.*, 1997; *Bürgmann et al.*, 1998]. Our models in their present form cannot address this anomaly which requires a near-surface source.

Model 1 contains stored moment equivalent to two **M**6.7 earthquakes per century for the entire length of the fault. (Stored moment is estimated from the slip deficit occurring in and around locked areas, compared to a long-term slip rate of 9 mm/yr.) In model 1-max (Figure 3) we used the $+2\sigma$ bounding curve in order to estimate deepest bounds for the locking depth. In this case, the creep just south of Point Pinole is driven to 12-km depth to fit the data. Model 1-max contains stored moment equivalent to two **M**6.6 earthquakes per century.

Because the smoothed observed values in models 1 and 1-max were constrained to drop to less than 1 mm/yr at the north end of the model (13.5 km north of Point Pinole), there is an abrupt northward decrease in the depth to creep in these models. Little is known about the northward extension of the Hayward fault under San Pablo Bay. Information north of Point Pinole bearing on creep rate was a single geodetic line crossing the bay [*Lienkaemper et al.,* 1991, Figure 6], suggesting an upper bound of 1.4 ± 1.0 mm/yr on creep. However, this line does not offer a very robust constraint.

If no limit is placed on the creep rate north of Point Pinole, more slip at depth appears in the model below San Pablo Bay (Figure 3, model 2). The onshore observations are still well fit, but less slip is required under the northern segment (0_km to 20_km), permitting a deep locked zone under that region. The behavior of the fault under San Pablo Bay appears to be critical to understanding the geometry and extent of locked patches under the onshore northern part of the fault.

Bürgmann et al. [2000] proposed that InSAR observations and repeating micro-earthquakes indicate that a 20-km long segment of the northern Hayward fault may be creeping from top to bottom, with no locked zone capable of initiating earthquakes under that section of the fault. To evaluate if this finding was consistent with surface creep data, they used a similar 3D BEM model approach to estimate the surface creep rates resulting from a freely slipping northern Hayward fault. Model 3 (Figure 3), which approximates their geometry, predicts creep rates in excess of our $+2\sigma$ bound, possibly because our long-term slip rates differ from theirs. Models 1, 1-max, and 2 (Figure 3) have 1.7, 1.4, and 1.7 times the stored moment of model 3 under the northern onshore 20 km length of the fault. For model 3, the stored moment in this distance is equivalent to a **M**6.3 earthquake per century.

Discussion

Inferred depths to the top of a Hayward fault locked zone vary along strike from 4-12 km. Although the true geometry of locked patches on the Hayward fault is undoubtedly far more complex than our model results, it seems inescapable that there are locked regions on this fault. (Variations in the lower locking depth as well as upper depth are likely to exist; locked asperities might be scattered on the fault surface, rather than forming continuous non-slipping areas.)

If our inferred depth-to-locking values offer a guide to the degree of locking under different parts of the fault, then all models find that locked patches exist under the central part of the fault in the region of the 1868 earthquake. Models 1 and 2 show two areas of shallow depth to locking separated by a reach near San Leandro with deeper locking. In model 1-max, this reach defines two separate locked patches.

Surface creep observations by themselves cannot determine the geometry of locked patches under the northern Hayward fault. The behavior of the fault under San Pablo Bay is critical, because the location of the northern termination of creep at depth greatly influences the locus of creep at the north end.

Bürgmann et al. [2000] suggested that the presence of repeating micro-earthquakes under the northern Hayward fault requires slip at all depths in this region. Waldhauser and Ellsworth [2001] proposed that these repeating earthquakes may mark the top and bottom boundaries of locked patches, rather than indicating the absence of locked patches. In either case, the creeping regions of the various models store moment comparable to that stored in locked regions by virtue of creep retarded relative to the long term slip rate. For the north onshore 20 km of the Hayward fault, moment is stored in the creeping regions at a rate equivalent to a **M**6.2-6.3 earthquake every century for all models (Figure 3). This represents 45-83% of the total stored moment in this 20-km length for the four models. For purposes of seismic hazard assessment, it will be important to know how much of the moment stored in creeping sections is released coseismically when nearby locked patches fail and how much is released as postseismic afterslip.

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