A PHYSICAL MODEL FOR THE EVALUATION OF THE SLIP RATES OF CRUSTAL FAULTS IN JAPAN

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ABSTRACT:

Constructing regional seismic hazard models often requires estimating the long term slip rates of active crustal faults and estimating the recurrence intervals of the related characteristic earthquakes. This is a difficult task. Paleoseismic studies and kinematic models based on GPS data play a critical role in providing this information. However, for many faults, paleoseismic and detailed GPS data are either not complete or not available. In such situations and when there is reasonable understanding of the causative tectonic environment, physical models can be used to simulate regional stress/strain accumulation and release across faults. These simulations can be used to evaluate the possible long term slip rates of faults under different tectonic settings. It is the objective of this study to construct such a physical model for Japan in order to evaluate the long term slip rates of the regional crustal faults.

KEYWORDS:

Physical Model, Dynamic Model, Block Model, Fault Interaction, Slip Rate, Recurrence Interval

1. INTRODUCTION

In 2005, the Headquarter for Earthquake Promotion (HERP, 2005), in Japan, released the a new national hazard report. The report provides detail information on the magnitudes and rates of the characteristic earthquakes on all major subduction zones, as well as 98 well-studied faults along with about 178 active faults. The recurrence intervals of the majority of the crustal faults in the HERP report are a few thousand years. Although HERP has compiled many detailed studies on those crustal faults, paleoseismic data are still very limited, and there are large uncertainties in interpreting carbon dating data. In view of this, we can benefit from physical models that simulate regional tectonic stresses on faults to gain insight into their possible ranges of long term slip rates. Such physical models can only be constructed if we understand the dominant causative tectonic forces responsible for straining the crustal region. The tectonic history of Japan is dominated by the subduction of the Philippine Sea plate beneath the Amurian plate in the south and the Pacific plate beneath the Okhotsk plate in the north. Figure 1 shows the main subduction zones and the distribution of the crustal faults. As is seen in this figure, all crustal faults are within about three hundred kilometers of the subduction zone. Considering the proximity and scale of the subduction zone with down-going plates that spread beneath Japan, it can be argued that the present state of stress is dominated by the regional subduction environment. Based on this assumption, Japan and adjacent areas, within few hundred kilometers, are considered to be a large block that is undergoing regional straining in response to the interaction between the Philippine Sea, Amurian, Pacific, and Okhotsk plates.

Using the concept of the block model for capturing the regional response to tectonic forces is not new. Numerous studies have used a variety of this concept in conjunction with the regional GPS and earthquake data to estimate convergence rates and coupling strength of regional subducting plates (e.g., McCaffrey, 2002;

McCaffrey, 2005; Meade et al., 2002). In this study, we use the block model concept to construct a physical model to simulate the state of stress on regional faults in response to large scale tectonic forces. We calculate the cumulative normal and shear stresses on faults due to regional tectonic forces as a function of time. A fault rupture model, based on Coulomb stress failure, is constructed to translate the accumulated stresses on different faults into rupture scenarios using time predictable or slip predictable models. The effects of faults interaction are considered by accounting for rupture related shear and normal stress changes on all regional faults. Theoretical equations (Keilis-Borok, 1959) are used to translate stress drops into seismic moments. Based on these assumptions and information, the physical model is used to simulate 100,000 years of stress accumulation and release over the subduction zones and crustal faults within the greater Japan area. The results are used to estimate the long term mean recurrence intervals and slip rates on faults.

2. MODEL FORMULATION

Various criteria have been used to model failure in rocks. One of the most widely used model is the Coulomb failure criterion (Jaeger & Cook, 1979; Scholz, 1990; Harris, 1998). The Coulomb failure stress is defined as

$$CF = |\tau| + \mu * (\sigma + p) - S \tag{1}$$

where τ is the shear traction on the fault surface, σ is the normal traction (positive for tension), p is the fluid pressure, μ is the coefficient of friction, and S is the cohesion. Assuming that the values of μ and S do not vary greatly over time (except during and a short period after the rupture), the change in the Coulomb's stress can be written as

$$\Delta(CF) = \Delta |\tau| + \mu * (\Delta\sigma + \Delta p) \tag{2}$$

Equation 2 has been used by different authors to study the stress triggering effects of earthquakes on their neighboring faults, and to calculate the potential shifts in faults rupture clocks (e.g., Harris and Simpson, 1992; King et al., 1994; Simpson and Reasenbert, 1994; Stein and Lin, 2006; Lin and Stein, 2006). Within the block model concept, Equation 2 can also be used to monitor the changes in the Coulomb stress on a fault due to regional tectonic forces. For example, after a large earthquake with a complete stress drop, the level of the shear stress on the fault is reduced by the amount of the stress drop. We consider this state as the state of equilibrium for the fault. In time, the fault is stressed due to the regional tectonic forces and from large regional earthquakes. The changes in the shear and normal stresses on the faults due to these effects are estimated using the block model concept and a dislocation model for stress analysis (Okada, 1985). Using Equation 2, the changes to the stresses are translated into excess Coulomb stress, beyond the fault's state of equilibrium, available for rupturing the fault. The excess Coulomb stress is then checked against the expected level of stress drop on the fault to initiate its next rupture. This procedure, certainly, cannot provide the real time to the next rupture on any fault without knowing its present state of the stress. However, because our objective is to estimate the long term rupture intervals on faults, we need to rupture each fault many times to statistically estimate its mean moment release and recurrence interval. For this reason, not knowing a fault's present state of the stress for the next immediate rupture is not important. We can simply randomize the present state of stress deficit to initiate the process. Accordingly, the initial state of Coulomb stress on each fault is randomized. Faults are stressed in response to regional tectonic forces and brought to the rupture point using either the slip-predictable or the time predictable model.

3. MODEL TECTONIC SETTING

The dominant tectonic structures that shape Japan's seismicity are the Philippine Sea and the Pacific Plate subduction zones. A number of studies provide long term relative convergence rates between Philippine Sea and Amurian plates and between Pacific and Okhotsk plates (Wei and Seno, 1998; Heki et al., 1999; Miyazaki and Heki, 2001). However, as the historic data has shown, not all the long term convergence rates are seismogenic. Japan has a rather long history of earthquake records that goes back to about 679 A.D. These data provide valuable information on the magnitudes and recurrence intervals of large earthquakes on subduction zones. In fact, the recent HERP report provides such detail information for all subduction segments. Using this information, we construct a regional tectonic model and formulate a physical model for simulating the rupture of the subduction zones and crustal faults in order to estimate the long term recurrence intervals of their corresponding characteristic earthquakes. We calibrate the model by adjusting the frictional coefficients on all segments of the subduction zones, those that are defined as causative tectonic forces, in such a way that the simulated long term recurrence intervals of their corresponding characteristic earthquakes are compatible with the time independent recurrence intervals given in the HERP report. Using this tectonic system as the regional driving force that stresses the crustal faults, the rates of shear and normal stress changes on all faults are calculated.

We use HERP's delineation and depth distribution of the interface subduction zones and faults to define the geometry of all seismic sources. Each segment of the subduction zone is defined by two planes, one represents the subduction interface segment that can rupture and create earthquakes, and the other is a parallel close-by plane that represents the down-going slab. Figure 2 shows a schematic diagram of these planes. A third plane is also defined to represent the deep down-going slab with partial coupling. This scenario can be used to model more complex situations. However, for this study only a single shallow down-going slab is considered.

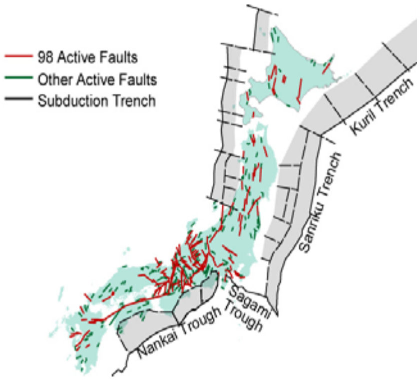

Figure 1. The plot shows the Philippine Sea and Pacific subduction zones segments, eastern Japan Sea convergence front and the active and potentially active crustal faults.

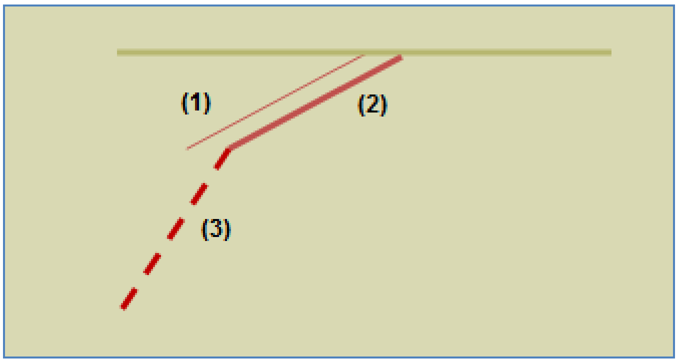

Figure 2. A schematic diagram showing the geometry of the subduction zone as is used in the model. Plane 1 is the subduction interface rupture plane, plane 2 represents the shallow down-going slab with a constant slip rate, and plane 3 represents deep down-going slab with constant slip rate but partially coupled.

For stress analysis, the surfaces of faults are divided into grids of 4x4 km^2, Figure 3. Okada's (1985) inclined dislocation model in a homogeneous elastic half space is used to calculate stress tensors over faults at the defined grid points from the motion of the down-going slabs and from the rupture of the subduction zones and crustal faults. The input data for both situations are the displacements of the dislocation plane (in one case, the yearly displacement of the down-going slab and in the other case the displacement from the fault rupture). To account for the nonlinear nature of the regional stress transfer from the fault rupture zone to its surrounding areas, an exponential term is defined to capture this effect empirically. Such nonlinear consideration is important for studying the effects of real time fault interactionfor predicting the next ruptures. However, it is not very critical for calculating the long term mean recurrence interval and slip rate since simulation goes through many rupture cycles and such effects from different faults smooth each other out.

The convergence vectors for the Philippine Sea and Pacific plates are used as a guide to quantify the along-strike and along-dip effective slip rates for the subducting slabs. We calculate seismic coupling coefficients for different segments from magnitudes and recurrence intervals of the characteristic earthquakes and convergence rates on plate boundaries. Magnitudes and recurrence intervals are from HERP report, and convergence rates are from published literatures (e.g. Wei and Seno, 1998; Heki et al., 1999; Miyazaki and Heki, 2001).For each segment, we calculate the effective convergence rates, compatible with its observed historic data. The frictional coefficients for the subduction zones are optimized, through trial and error, in such a way that the model simulates approximately the observed recurrence intervals for the characteristic earthquakes on faults.

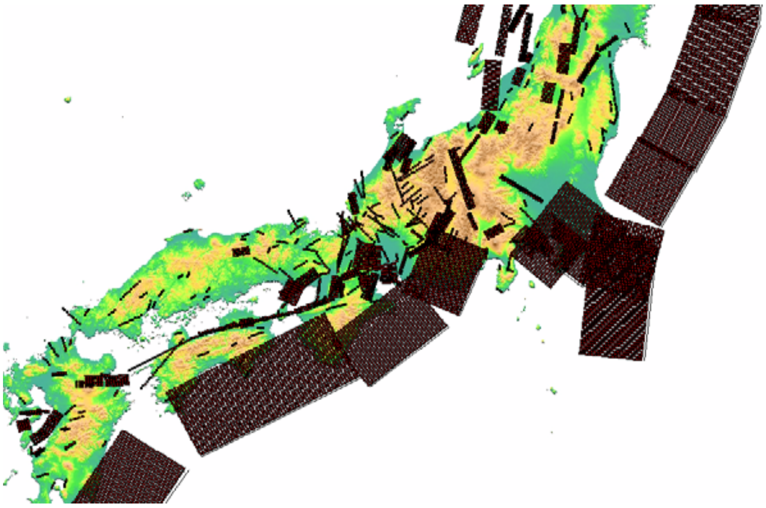

Figure 3. Plot of the distribution of grid points used to calculate shear and normal stresses from the down going slabs or from regional subduction zone or fault rupture.

Using these calibrated slip rates, the annual rates of stress changes over all sub areas defined by grid points are calculated and are used to accumulate excess stresses over faults to bring them to the point of rupture. As the cumulative stress on any fault exceeds the prescribed stress drop, the fault ruptures. We consider stress droprange of 30 to 100 bars for faults. This is consistent with the results of numerous studies that have shown that earthquakes with a broad range of magnitudes have rather stable stress drops within a narrow range of about 10 to 100 bars (e.g., Aki, 1972; Hanks, 1977). The mode of rupture is defined by the time predictable or slip predictable model assumptions. However, the results presented here are based on the assumption of complete stress drop. The released stress drops are translated into displacements, using theoretical moment stress drop equations for different faulting mechanisms. These rupture-related displacements are used to calculate the corresponding shear and normal stresses on all regional faults. The calculated rupture-related stresses are imposed on each fault using an empirical relation to account for the potential nonlinear stress propagation effects. This will increase or decrease stresses on faults and shift their rupture clocks forward or backward. This cycle of events continues over the simulation time and provides a sequence of ruptures for each fault from which the mean and standard deviation of error for the fault recurrence interval are calculated. The magnitudes of the simulated earthquakes for each fault can be uniform or varied, depending on the assumption made on the stress drop for different rupture scenarios.

4. RESULTS AND DISCUSSIONS

Based on the HERP's recurrence intervals for the major subduction zone segments, the model is calibrated for the frictional coefficient of 0.2 on all subduction zone segments. For this study, we conducted three sets of simulation for three different set of friction coefficients (0.2, 0.3, and 0.4) on crustal faults. As was discussed, each simulation provides estimates of the mean and standard deviation for the recurrence intervals. Considering the total number of faults in Japan, it is difficult to discuss all details of the analysis. We limit the discussion here to the distribution of the mean recurrence intervals and the regional moment release by crustal faults from these simulations against HERP's corresponding values. Figures 4a, 4b, and 4c show the distribution of the faults with recurrence intervals less than 1000 years, between 1000 and 2000 years, and between 2000 and 5000 years, respectively, for the case of friction coefficient of 0.2. The figures show the fault distributions for both HERP and this study.

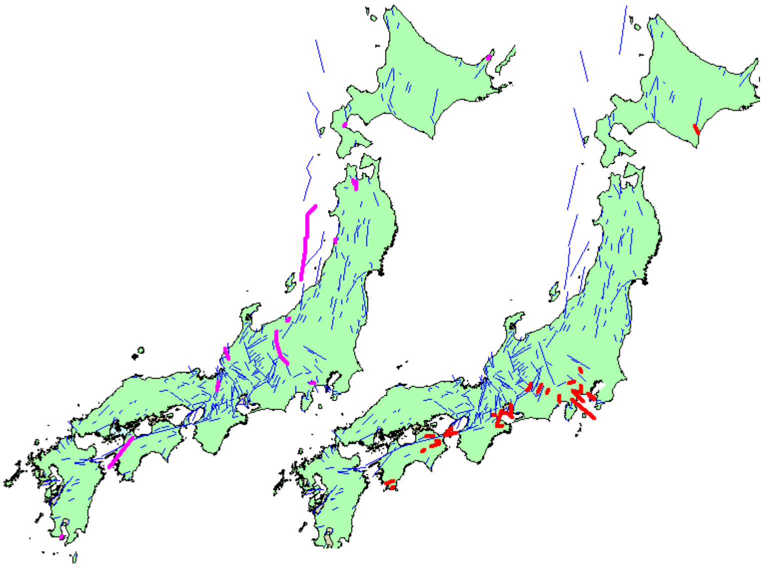

Figure 4a. Plots of crustal faults with recurrence intervals less than 1000 years for HERP, left figure, and this study, right figure. The thick pink lines in the left map represent faults with recurrence intervals less than 1000 years in HERP report, and the thick red lines in the right map indicate faults with recurrence intervals less than 1000 years from this study. The thin blue lines in both maps indicate 98 well-studied faults along with over 178 active faults reported by HERP.

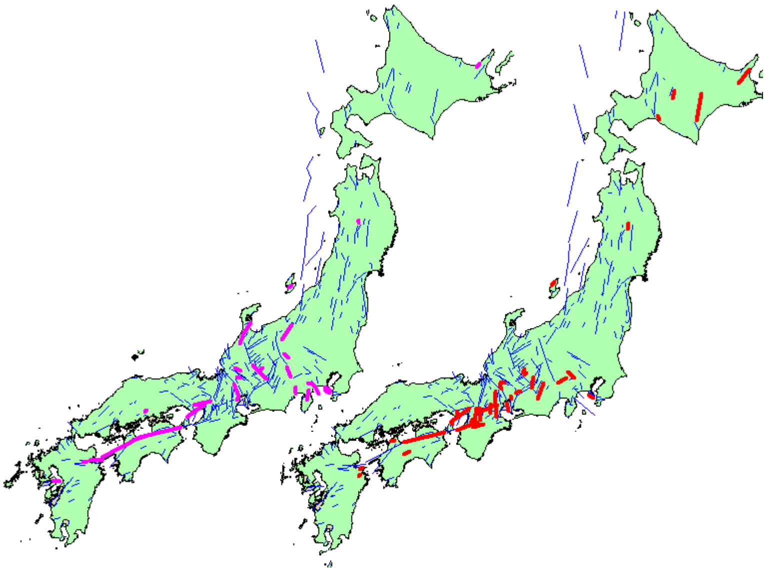

Figure 4b. Plots of crustal faults with recurrence intervals between 1000 to 2000 years for HERP, left figure, and this study, right figure. The meanings of thick pink, thick red, and think blue lines are the same as in Figure 4a, except that they are for recurrence intervals between 1000 to 2000 years.

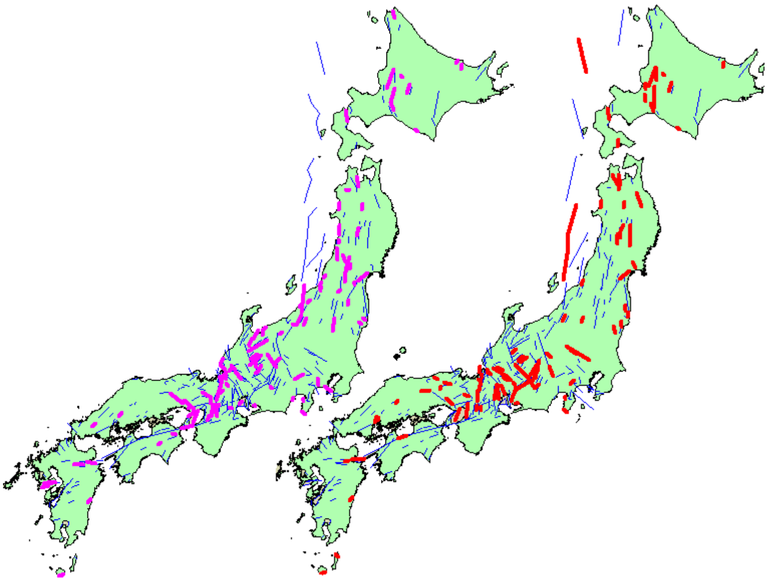

Figure 4c. Plots of crustal faults with recurrence intervals between 2000 and 5000 years for HERP, left figure, and this study, right figure. The meanings of thick pink, thick red, and think blue lines are the same as in Figure 4a, except that they are for recurrence intervals between 2000 to 5000 years.

There are reasonable agreements between the distributions of faults from HERP and this study for the cases of 1000 to 2000 and 2000 to 5000 years recurrence intervals. Considering that, we have not done any exhaustive attempt to fine tune the model for any particular fault, we find this agreement encouraging. It should also be noted that there are strong uncertainties in the recurrence intervals posted in HERP report due to the scarcity of the paleoseismic and historic earthquake data on most crustal faults. This does not imply that we should trust the results of this simulation more than HERP's values. However, the results of studies like this can be used to gain insight and possibly put constraints on the inferred recurrence models based on the paleoseismic and historic data.

Table 1. The moment release ratios, this study over the corresponding HERP values, for crustal faults for the zones shown on Figure 5 for three different friction coefficients.

Zone ID	f=0.2	f=0.3	f=0.4
1	0.66	0.60	0.54
2	46.32	45.82	45.31
3	0.48	0.41	0.34
4	2.12	1.93	1.76
5	0.35	0.26	0.17
6	0.74	0.60	0.49
7	0.55	0.52	0.50
8	0.33	0.31	0.30
9	1.11	0.95	0.81

We also evaluated the general regional moment release by faults from HERP and our study. Table 1 shows the ratios of moment release on faults from this study over those from HERP report for the zones shown on Figure 5 for three different friction coefficients of 0.2, 0.3, and 0.4. For most zones, the model predicts lower seismic moment rate than that of HERP. One contributing source to this difference is the way that magnitudes of the simulated earthquakes are calculated. The magnitudes in this study are estimated using theoretical equations that relate seismic moment to stress drop. The HERP's magnitudes for crustal faults are based on magnitude-length empirical equations. All magnitudes in this study are lower than the corresponding HERP magnitudes. The magnitude differences do not affect the estimates of the recurrence intervals, however, they will affect the estimates of the moment rates. If we adjust for the magnitude differences, the regional moment release from HERP and this study will be closer. Table 1 shows a big difference in the moment release for zone 2. This zone is dominated by earthquake activity related to the interactions between the Philippine Seaand Pacific plates, as well as the inland area. HERP defines a number of special interface and intra-slab seismic sources in this region. These sources are not specifically identified in our model. In Table 1, because we compare only the crustal moment rates, all the interface and intra-slab sources from the HERP data set are removed. Some of these sources are captured in our model and this is the source of the large difference in moment release.

The physical model that is formulated here provides a practical tool for evaluating possible regional fault rupture scenarios and examining the effects of different tectonic hypothesis on regional seismicity. Such tools can help seismologists to better evaluate paleoseismic and historic earthquake data and constrain faults long term slip rates for the purpose of seismic hazard analysis.

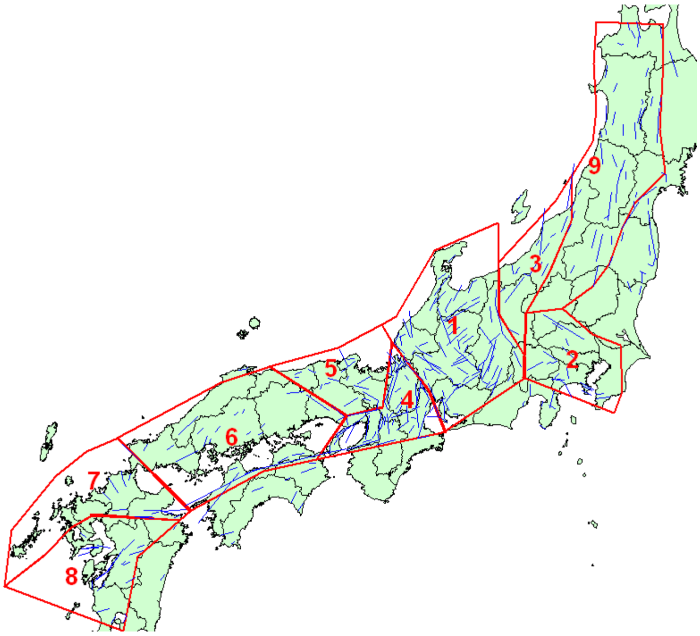

Figure 5. Plots of zones used to compare crustal fault moment release.

REFERENCES

Aki, K. (1972). Scaling law of earthquake source time-function. *Geophysical Journal International* **31:1-3**, 3-25, 1972.
Hanks, T.C. (1977). Earthquake stress drops, ambient tectonic stresses and stresses that drive plate motions. *Pure and Applied Geophysics* **115:1-2**, 441-458.

Harris R. (1998). Introduction to special section: Stress triggers, stress shadows, and implications for seismic hazard. *J. Geophys. Res.* **103: B10**, 24,347-24,358.

Harris, R. A., and Simpson, R. W. (1992). Changes in static stress on southern California faults after the 1992 Landers earthquake, *Nature*, **360**, 251-254.

Heki, K., Miyazaki S., Takahashi H., Kasahara M., Kimata F., Miura S., Vasilenko N.F., Ivaschenko A., and An K.-D. (1999). The Amurian plate motion and current plate kinematics in eastern Asia. *J. Geophys. Res.* **104**, 29,147–29,1559.

Headquarters for Earthquake Research Promotion (HERP). (2005). National Seismic Hazard Maps for Japan (2005). Http://www.jishin.go.jp/main/index-e.html.

Jaeger, J. C. and Cook N. W. G. (1979). Fundamentals of Rock Mechanics. Chapman and Hall, New York, third edition.

Keilis-Borok, V. (1959). On estimation of the displacement in an earthquake source and of source dimensions. *Annali di Geofisica*, **12**, 2,205–2,214.

King G. C. P., Stein R. S. and Lin J. (1994). Static stress changes and the triggering of earthquakes, *Bull. Seismol. Soc. Amer.*, **84**, 935-953.

Lin J. and Stein R.S. (2006). Seismic constraints and Coulomb stress changes of a blind thrust fault system, 1: Coalinga and Kettleman Hills, California. *U.S. Geological Survey, Open-File Report*, **2006-1149**, 17 p.

McCaffrey, R. (2002). Crustal Block Rotations and Plate Coupling, in Plate Boundary Zones. Geodynamics Series 30, S. Stein and J. Freymueller, editors, 101-122, AGU.

McCaffrey, R. (2005). Block kinematics of the Pacific - North America plate boundary in the southwestern US from inversion of GPS, seismological, and geologic data. *J. Geophys. Res.* **110: B07401**, doi:10.1029/2004JB003307.

Meade, B.J., Hager B.H., McClusky S.C., Reilinger R.E., Ergintav S., Lenk O., Barka A., and Ozener H. (2002). Estimates of seismic potential in the Marmara Sea region from block models of secular deformation constrained by Global Positioning System measurements. *Bull. Seis. Soc. Am.* **92**, 208-215.

Miyazaki, S. and Heki K. (2001). Crustal velocity field of Southwest Japan: subduction and arc-arc collision. *J. Geophys. Res.* **106**, 4305-4326.

Okada, Y. (1985). Surface deformation to shear and tensile faults in a half-space. *Bull. Seism. Soc. Am.* **75:4**, 1135-1154.

Okada, Y. (1992). Internal deformation due to shear and tensile faults in a half-space. *Bull. seism. Soc. Am.* **82**, 1018–1040.

Scholz, C. H. (1990). The mechanics of earthquakes and faulting. Cambridge University Press, Cambridge.

Stein R.S. and Lin J. (2006). Seismic constraints and Coulomb stress changes of a blind thrust fault system, 2: Northridge, California. *U.S. Geological Survey, Open-File Report*, **2006-1158**.

Wei, D., and Seno T. (1998). Determination of the Amurian plate motion, in Mantle Dynamics and Plate Interactions in East Asia, Geodyn. Series, vol. **27**, edited by M. F. J. Flower et al., pp. 337–346, AGU, Washington, D. C.