Bulletin of the Seismological Society of America, Vol. 97, No. 6, pp. 1833–1840, December 2007, doi: 10.1785/0120070048

Scaling of Fault Parameters for Continental Strike-Slip Earthquakes

by Geoffrey C. P. King and Steven G. Wesnousky

Abstract The long-standing conflict between the predictions of elastic dislocation models and the observation that average coseismic slip increases with rupture length is resolved with application of a simple displacement-depth function and the assumption that the base of the seismogenic zone does not result from the onset of viscous relaxation but rather a transition to stable sliding in a medium that remains stressed at or close to failure. The resulting model maintains the idea of self-similarity for earthquakes across the entire spectrum of earthquake sizes.

Introduction

Slip and rupture length are the most readily observed parameters used to describe an earthquake source whether determined by direct measurement in the field or from instrumental studies. Although real earthquake rupture is known to be associated with complex slip patterns, the simple parameters of average fault slip (D), fault length (L), and down depth width (W) are commonly at the heart of discussions of the physics of earthquake rupture (e.g., Scholz, 1982). Ignoring a shape factor close to unity, elastic models indicate that the slip on a fault in a uniformly stressed elastic medium should be proportional to the smallest fault dimension and that earthquake stress drops should be scale independent (Fig. 1 and, e.g., Kanamori and Anderson [1975]). This is commonly observed for smaller and moderate earthquakes (Hanks, 1977) and led to the proposition that little earthquakes are models for the behavior of large, less frequent, and more devastating ones (e.g., Scholz, 1990). However, the prediction has been complicated by the inconvenient observation that, for large continental strike-slip earthquakes, coseismic slip steadily increases as a function of earthquake rupture length (Fig. 2). Because it is generally assumed that the shortest dimension is the thickness of the seismogenic layer, which extends to a relatively constant depth of ~15 km, the increase in slip that accompanies growth in rupture length L requires that large earthquakes have increasingly higher stress drops than lesser ones and should consequently radiate proportionally more high-frequency energy. No evidence for this has been published. We here put forward a model that resolves the conflict within the context of static dislocation theory and a recognition that coseismic slip during large earthquakes may extend below the base of the seismogenic layer.

Slip Distribution as a Function of Depth

The general characteristics of observed seismic slip as a function of depth in continental strike-slip regions are illustrated in Figure 3. The histogram in Figure 3a provides an example of the observation that seismic slip of smaller earthquakes is typically concentrated at mid-seismogenic depths of 6 to 10 km and systematically decreases to zero above and below those depths. The same is broadly true when one views the coseismic slip distributions of large earthquakes. The examples of the 1992 Landers and 1999 Hector Mine earthquakes are shown in Figure 3b and c. Areas of maximum slip are observed to occur at mid-seismogenic depths. While studies of individual earthquakes may differ substantially and the behavior of one earthquake can differ from another, greatest values of slip are usually in the middle of the seismogenic zone. Over the long term of numerous earthquake cycles, slip at greater and lesser depths must be accommodated by aseismic motion.

The observed distribution of seismic slip with depth can be explained by changes in frictional behavior with depth. The simplest view is to consider that earthquakes can initiate only in unstable zones where dynamic friction is less than static friction, a condition often referred to as slip weakening (Dieterich, 1972; Scholz *et al.*, 1972). Rupture once initiated can propagate indefinitely into a stressed region where static and dynamic friction are equal and no dissipation occurs. In practice, slip is attenuated in such regions by plastic processes referred to as velocity strengthening (Ruina, 1983). Except when subject to an abrupt stress increase, slip in these stable regions occurs as aseismic creep (Tse and Rice, 1986). The way in which slip as a function of depth during earthquakes relates the frictional characteristics is shown in Figure 4. Events smaller than M ~6 rarely break the surface, and slip is limited to mid-seismogenic depths. Larger events with more displacement commonly propagate to the surface and also propagate below the depth at which earthquakes can initiate.

Modeling Geodetic Displacements

Two simplified displacement-depth slip profiles are illustrated in Figure 5. The first of these is a simple box. The second, referred to for convenience as tapered, is designed to emulate the character of the displacement-depth profiles

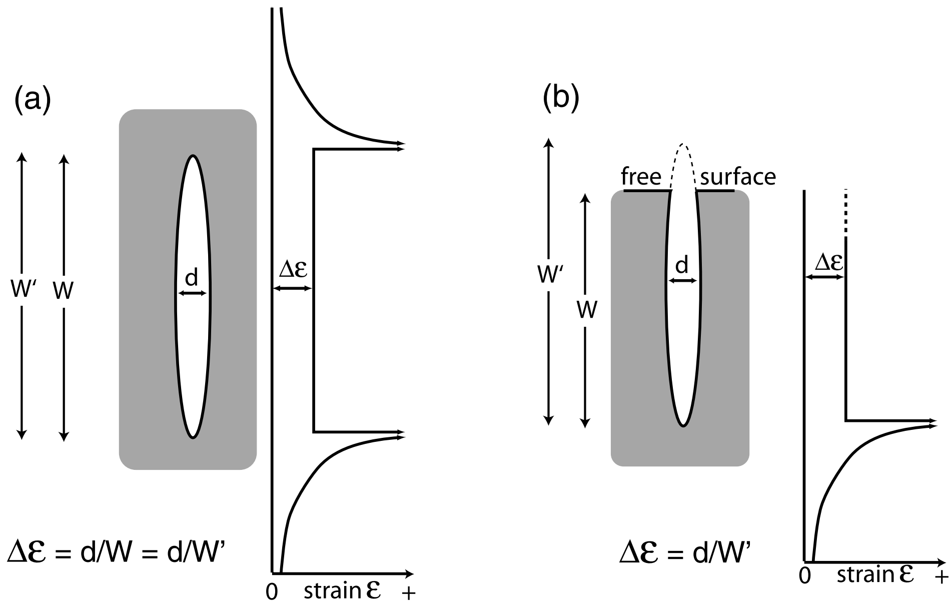

Figure 1. Strain profiles for dislocation surfaces (a) entirely and (b) partially in an elastic medium (shaded) on which an elliptical slip distribution has been imposed for each. Surfaces are of infinite length into page. Strain drop $\Delta\varepsilon$ for each is almost identical and equal to d/W', where d is the maximum displacement and W' is the width (shortest dimension) of the surface. Small differences in constant strain drop (dashed line) will occur near the surface for case (b). For case (b) where the crack intersects the free surface, W' is greater than the portion W of crack embedded in the medium. By analogy W is the depth to which a fault extends into the earth's crust, and the end member cases $W = W'$ and $W' = 2W$ correspond to the definition of small and large earthquakes by Scholz (1982).

shown in Figure 4. The slip is maximum at a depth of 6 km with constant reductions of slip both above and below. The displacement fields at the surface (such as those measured by the Global Positioning System [GPS] or Interferometric Synthetic Aperture Radar [InSAR]) resulting from the two displacement-depth profiles are constructed with the formulas of Okada (1992) and provided in Figure 5c. Displacements from the tapered slip function are displayed by circles while those from the box are indicated as a line. The two very different slip functions produce the same displacement field. In other words the same displacement field can be produced by distinctly differing slip functions. Differences between the displacement fields do occur very close to the fault and result from near surface differences in the two slip functions but are scarcely measurable in the field and do not concern establishing the form of the slip distribution at depth.

We take the same approach in Figure 6, where a series of tapered displacement functions are shown and labeled a–g, respectively. As in Figure 5, the maximum slip for each is placed at 6 km and decreases at a constant rate above and below, and in this sense the tapered slip functions are self-similar and, as explained in Figure 1, have the same stress drop. The maximum slip for each ranges from about 2 to 8 m, and the surface slip ranges from 0 to 6 m. Associated with each tapered slip function is a box slip distribution like that shown in Figure 5 that produces the same surface deformation field, and similarly labeled a–g. It is not necessary that the tapered slip function is a particularly

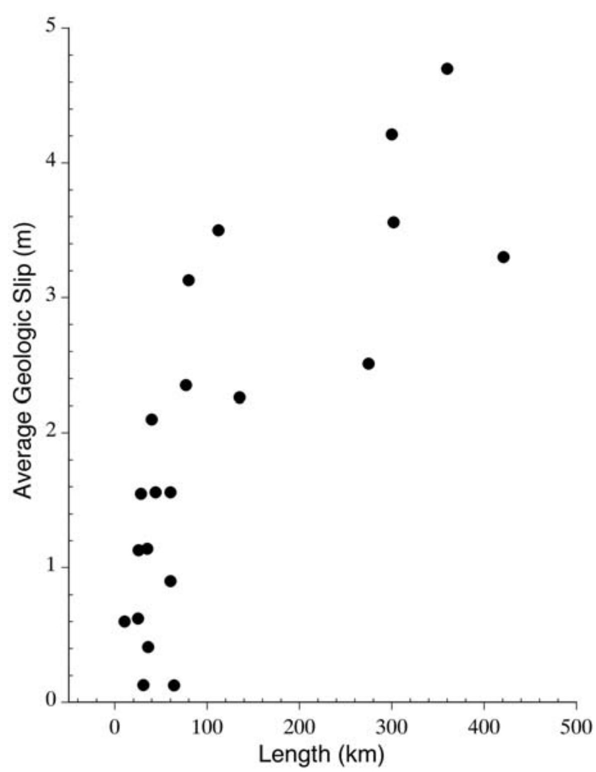

Figure 2. Average surface displacement is an increasing function of rupture length for continental strike-slip earthquakes. Adapted from S. G. Wesnousky (unpublished manuscript, 2007).

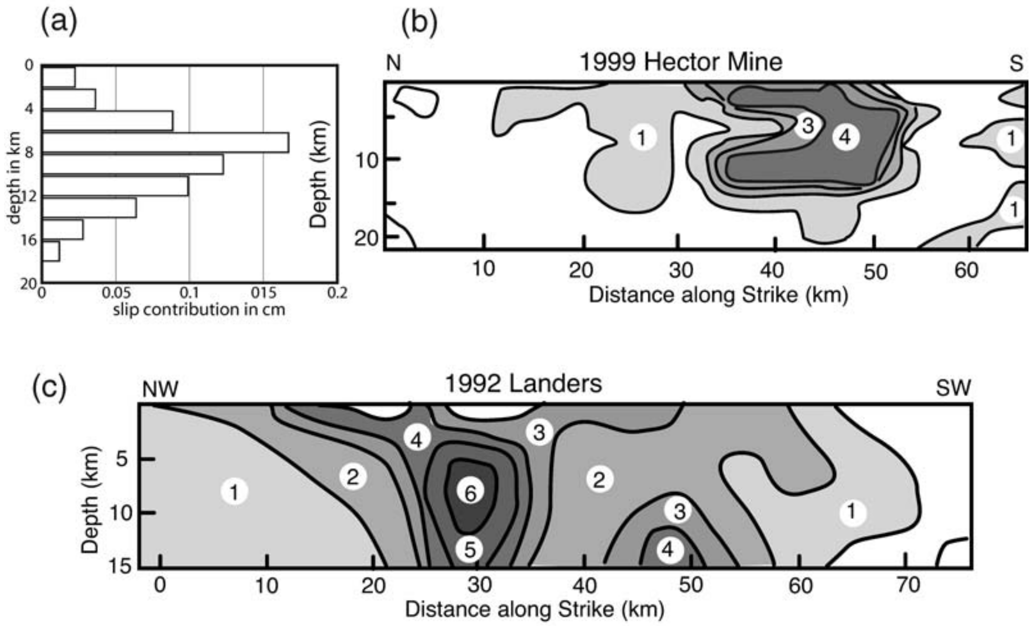

Figure 3. (a) Histogram of total slip contributed by small earthquakes as a function of depth for background seismicity recorded between 36.4° N and 38.0° N and 121.0° E and 123.0° E in California during the period of 1969 to 1994 (adapted from King *et al.* [1994]). Coseismic slip distributions on (b) the 1999 Hector Mine and (c) the 1992 Landers earthquake fault plane determined from teleseismic body waves and displacement waveforms, respectively, modified from Wald and Heaton (1994) and Kaverina *et al.* (2002). Contours are in meters.

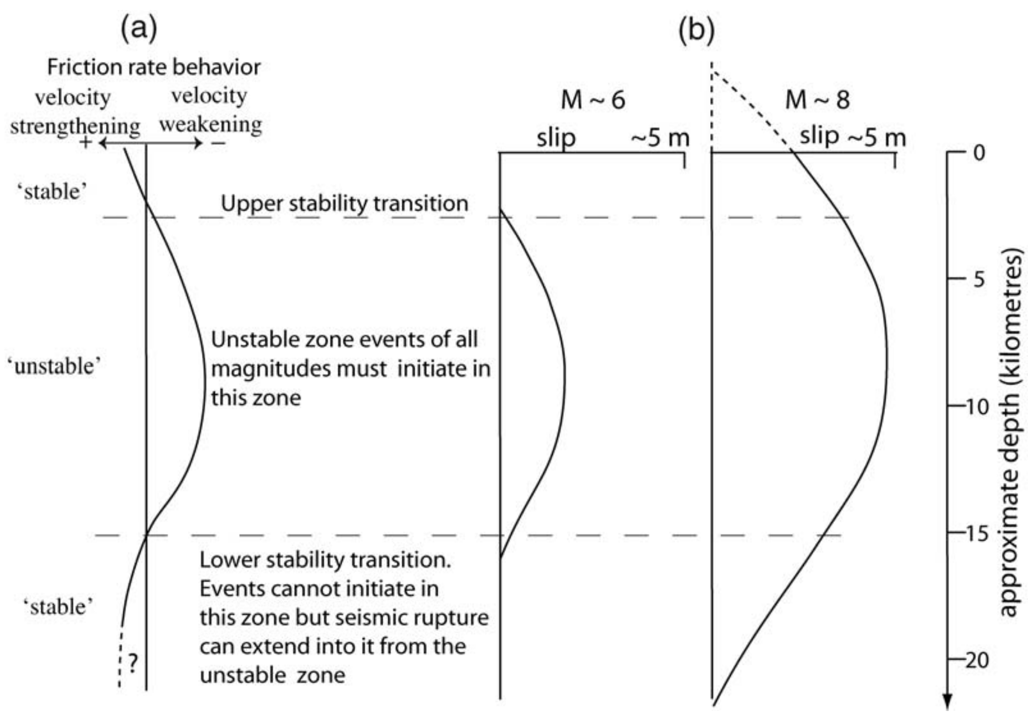

Figure 4. (a) Conceptual model for frictional characteristics with depth. Earthquakes may only initiate in mid-crustal depths in the unstable zone, where dynamic friction is less than static friction (velocity weakening). Slip may not initiate above or below, where static friction is equal to or greater than dynamic friction (velocity strengthening). (b) Generalized depiction of expected coseismic slip distribution with depth for a moderate M ~6 and large M ~8 earthquake. Maximum slip for each is at mid-crustal level. Only the largest events propagate far into the stable zones.

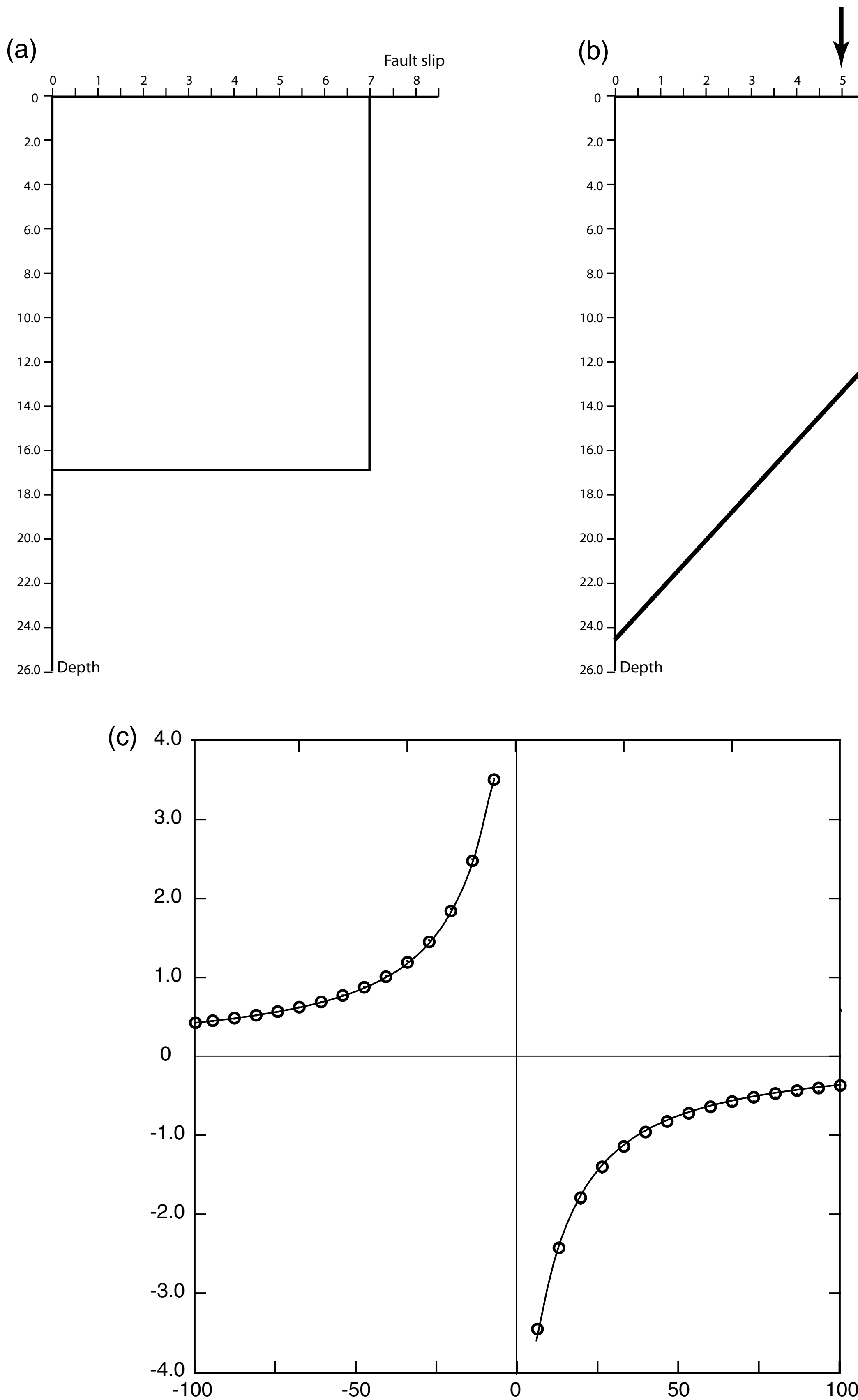

Figure 5. The (a) box and (b) tapered displacement functions produce (c) the same deformation field (circles and lines) at the earth's surface. The vertical axis is meters of surface displacement, and the horizontal axis is distance in kilometers from the fault. The downward pointing arrow indicates the average value of slip for the tapered function.

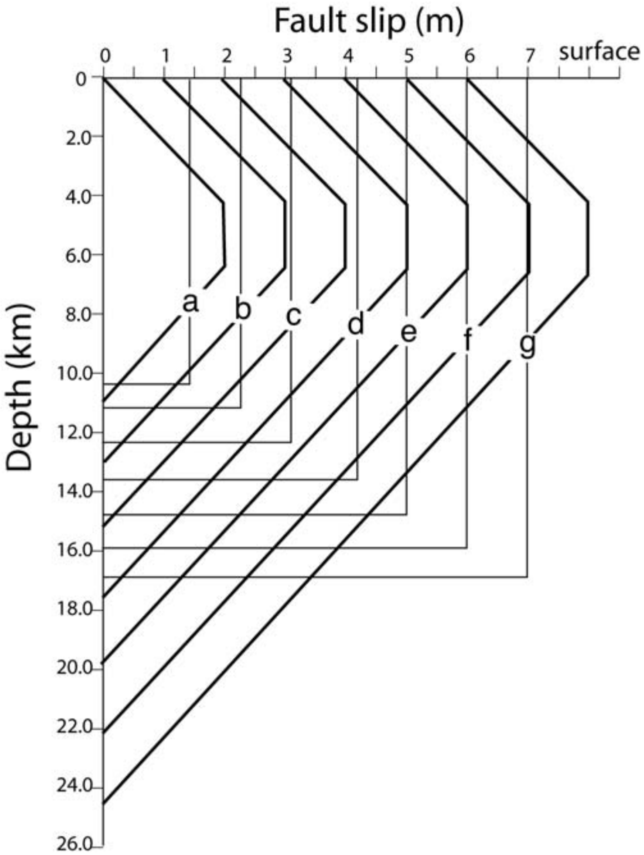

Figure 6. Paired box and tapered displacement-depth profiles are labeled a–g. The respective pairs produce the same deformation field at the Earth's surface.

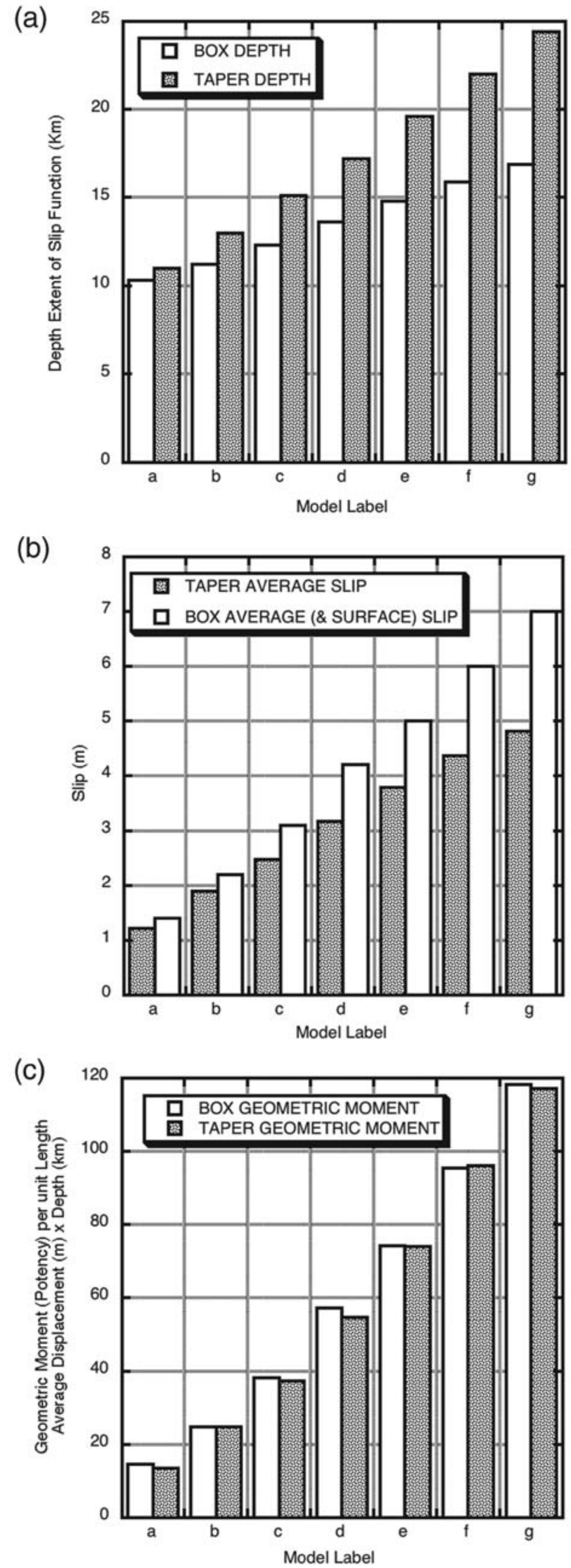

Figure 7. Comparison of (a) depth extent, (b) average displacement, and (c) the geometric moment for the paired box and tapered displacement-depth profiles shown in Figure 6.

accurate depiction of the slip as a function of depth. We suggest only that it is much more reasonable than a box. Independent of details the exercise illustrates how poorly slip as a function of depth is constrained and that more plausible profiles can fit the same data.

A number of other observations related to Figure 6 have a bearing on the question of whether or not large earthquakes differ in a fundamental sense from small ones. The surface slip for the box functions is consistently ~1 m greater than for the respective tapered function (Fig. 6). The depth to which slip extends ranges from ~12 to ~25 km for the tapered function, while the box models extend only to ~11 to ~17 km (Fig. 7a). While the average value of slip for the box and tapered functions is about the same at lesser magnitudes, the average value of slip of the box functions systematically increases over the respective tapered functions as the magnitude of the pairs increases (Fig. 7b). Finally, although the respective box and tapered distributions are of distinctly different form, they produce the same surface deformation field at the surface but are characterized by almost the same geometric moment (potency) (Fig. 7c). From this it appears that while geodesy may be robust in estimating earthquake size (moment) from a particular deformation field, the shape of the causative slip function is poorly resolved.

Each of the box and tapered slip distribution pairs in Figure 6 may also be characterized by the average strain and, hence, stress drop (Fig. 8). The strain drop is proportional to Dmx/W for the box and tapered slip functions when slip is confined to the subsurface (small earthquakes). In the case of slip functions that break the surface, the strain drop is Dmx/W' for the tapered function and $Dmx/2W$ for the box. The factor of 2 in the expression for the box includes the effect of the free surface. The value of W' for the tapered slip function approaches $2W$ as displacement Dmx increases. The calculation of strain drop for each slip function pair shows that the box function implies a steady increase of stress drop with increasing slip whereas strain drop remains constant for the tapered model.

Discussion

In 1982 Scholz proposed that for large earthquakes rupture would end at the base of the seismogenic layer that could be determined from the aftershock depth distribution. Thus, in the context of elastic dislocation theory earthquakes above some magnitude should have the same surface slip independent of length. This has been termed the *W* model and, in light of independent observations suggesting earthquakes share an approximately constant stress drop, is in conflict with the observed increasing slip with length for large strike-slip earthquakes. In response he posed an alternative referred to as the *L* model assuming the base of the seismogenic zone was unconstrained such that length became effectively the shortest dimension. The mechanical explanation of such a model has not been straightforward and conflicts with elastic dislocation theory. The conundrum has been addressed by evoking dynamic explanations that subsequently formed the basis of discussion over many years (Scholz, 1982; Heaton, 1990; Romanowicz, 1994; Bodin and Brune, 1996; Shaw and Scholz, 2001; Manighetti *et al.*, 2007).

More recently it has become clear that neither a *W* nor an *L* model is appropriate. Slip does not increase linearly with rupture length for large earthquakes, nor does it saturate for rupture lengths greater than ~15 km. Rather, the rate of increase of strike-slip offset appears to continually decrease with rupture length without reaching a plateau (Fig. 2). The observation removes the premise of either the *L* or *W* model and the contradictions that were the most difficult to explain. We pose here a model that is neither *W* nor *L* but retains the simplicity of the constant stress drop of the original *W* model being based on simple dislocation theory and is consistent with current understanding of fault behavior with depth. Constant stress drop is achieved by assuming a slip function that tapers with depth and can extend below the seismogenic depth. It is consistent with geodetic observation and does not appear to violate applications of inverse methods to waveform data used in estimating seismic slip distributions on faults. The latter permit considerable latitude in the depth to which slip can extend (e.g., Beresnev, 2003), and some authors simply limit or clip the depth of the grid used for the inversions and thus require that slip does not extend below the seismogenic zone (P. Somerville, unpublished manuscript, 2006), effectively dismissing the possibility of the latter as unimportant. The effect is evident in the slip distribution for the 1992 Landers earthquake shown in Figure 3c, where the abrupt cutoff of large values of slip at the base of the model are likely to be artificial and actual slip extends deeper.

Consequently, it seems that, within the resolution of the data available to us at present, static models adequately describe in a general way the geometric character of the earthquake rupture surface and slip distribution for events of all sizes. This is not to suggest that dynamic processes are not important. They obviously are, and models such as Shaw and Scholz (2001) imply the extension of slip below the seismogenic depth that we propose. However, neither dynamic processes nor assumptions that large earthquakes are mechanically different from smaller ones need be invoked to

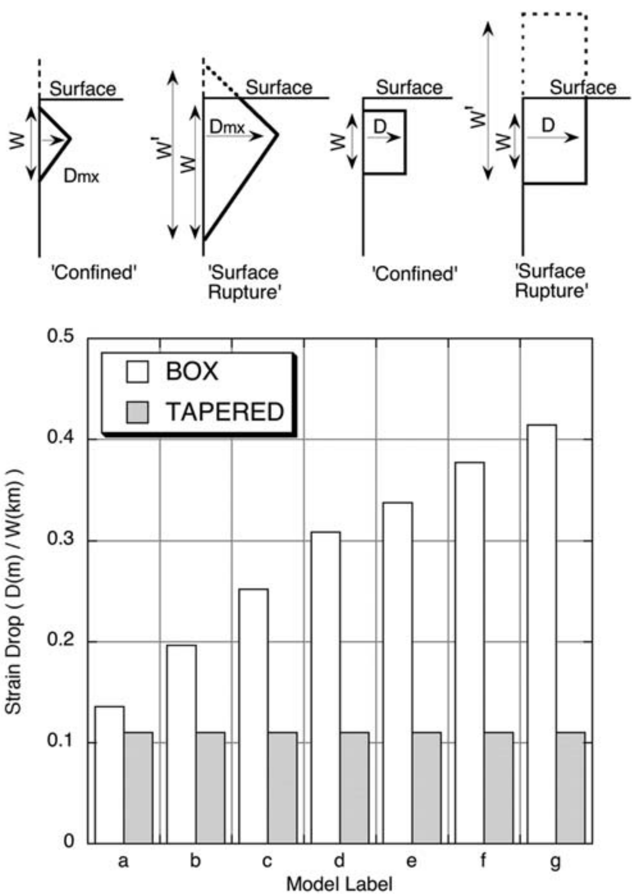

Figure 8. Comparison of values of strain drop for the paired box and tapered displacement-depth profile models in Figure 6. Strain drop increases with earthquake size for the box function but remains constant for tapered function. See text for further discussion.

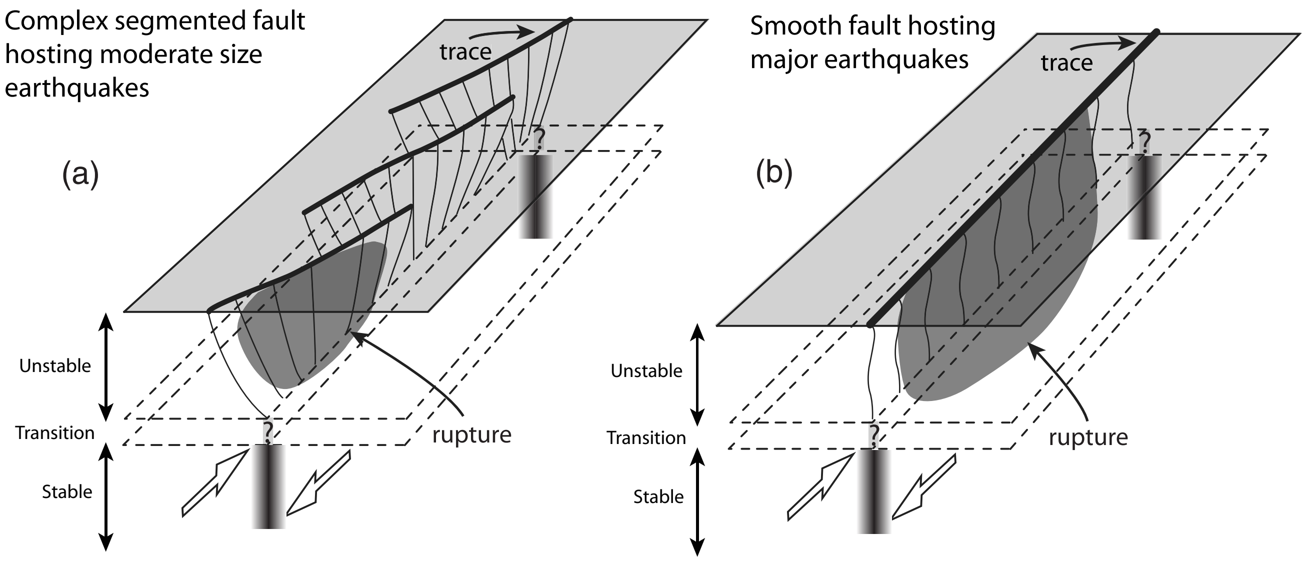

Figure 9. Conceptual model for the interaction of earthquake slip in the seismogenic zone and deformation in the lower crust. (a) Active strike-slip faults of low displacement tend to be structurally more complex and associated with relatively smaller earthquakes than faults of greater displacement. The complexity hinders rupture propagation both horizontally and vertically. (b) The accumulation of slip leads to geometrically simpler fault zones. The increasing simplification leads to a simpler geometric relation with the underlying shear zone and increasing capability for rupture to extend below the depth at which earthquakes can initiate.

explain the characteristics of surface slip associated with large earthquakes.

While the analysis obviates the need for dynamics to explain the characteristics of surface slip with rupture length, it raises the question of the process that leads to a systematic increase in the depth to which rupture extends as rupture length grows. For this we allude to the idea that seismological characteristics of a fault evolve in concert with the accumulation of slip and structural characteristics of a fault (Wesnousky, 1988). Active strike-slip faults of low displacement and small earthquakes tend to be structurally more complex than those of greater displacement and host larger events. With time, however, the accumulation of slip leads to a geometrically simpler fault zone and a closer geometric relation with the underlying shear zone. For such faults rupture in large events can extend well below the depths where earthquakes can initiate (Fig. 9).

Conclusions

An old contradiction is resolved, and the behavior of small earthquakes can supply a model for large earthquakes. This is important for earthquake engineers and seismic hazard analysts. The model requires that a modest amount of rupture extends well below the seismogenic depth and that the base of the seismogenic zone does not result from the onset of viscous relaxation but rather a transition to stable sliding in a medium that remains stressed at or close to failure at all times.

Acknowledgments

Roland Burgmann, Paul Bodin, and Tom Hanks kindly provided reviews of the manuscript. The research of S.G.W. was supported in part by the Southern California Earthquake Center under NSF Cooperative Agreement Number EAR-0106924 and U.S. Geological Survey Cooperative Agreement Number 02HQAG008, NSF Award Number EAR-0509672, and U.S. Geological Survey Award Number 07HQGR0108. This paper is IPGP Number 2280, CNRS-INSU Number 389, SCEC Number 10964, and CNS Number 50.

References

Beresnev, I. A. (2003). Uncertainties in finite-fault slip inversions: to what extent to believe? (a critical review), *Bull. Seismol. Soc. Am.* **93,** 2445–2458.

Bodin, P., and J. N. Brune (1996). On the scaling of slip with rupture length for shallow strike-slip earthquakes: quasi-static models and dynamic rupture propagation, *Bull. Seismol. Soc. Am.* **86,** 1292–1299.

Dieterich, J. H. (1972). Time dependent friction in rocks, *J. Geophys. Res.* **77,** 3690–3697.

Hanks, T. H. (1977), Earthquake stress-drops, ambient tectonic stresses, and the stresses that drive plates, *Pure Appl. Geophys.* **115,** 441–558.

Heaton, T. H. (1990). Evidence for and implication of self-healing pulses of slip in earthquake rupture, *Phys. Earth Planet. Inter.* **64,** 10–20.

Kanamori, H., and D. Anderson (1975). Theoretical basis of some empirical relations in seismology, *Bull. Seismol. Soc. Am.* **65,** 1073–1096.

Kaverina, A., D. Dreger, and E. Price (2002). The combined inversion of seismic and geodetic data for the source process of the 16 October 1999 M_w 7.1 Hector Mine, California, earthquake, *Bull. Seismol. Soc. Am.* **92,** 1266–1280.

King, G., D. Oppenheimer, and F. Amelung (1994). Block versus continuum deformation in the western United States, *Earth Planet. Sci. Lett.*, **128,** 55–64.

Manighetti, I., M. Campillo, S. Bouley, and F. Cotton (2007). Earthquake scaling, fault segmentation, and structural maturity, *Earth Planet. Sci. Lett.* **253,** 429–438.

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

Romanowicz, B. (1994). Comment on "A reappraisal of large earthquake scaling" by C. Scholz, *Bull. Seismol. Soc. Am.* **84,** 1675–1676.

Ruina, A. L. (1983). Slip instability and state variable friction laws, *J. Geophys. Res.* **88,** 359–370.

Scholz, C. (1982). Scaling laws for large earthquakes: consequences for physical models, *Bull. Seismol. Soc. Am.* **72,** 1–14.

Scholz, C. (1990). *The Mechanics of Earthquakes and Faulting*, Cambridge U. Press, New York, 439 pp.

Scholz, C. H., P. Molnar, and T. Johnson (1972). Detailed studies of frictional sliding of granite and implications for the earthquake mechanism, *J. Geophys. Res.* **77,** 6392–6406.

Shaw, B. E., and C. H. Scholz (2001). Slip-length scaling in large earthquakes: observations and theory and implications for earthquake physics, *Geophys. Res. Lett.* **28,** 2991–2994.

Tse, S. T., and J. R. Rice (1986). Crustal earthquake instability in relation to the depth variation of frictional slip properties, *J. Geophys. Res.* **91,** 9452–9472.

Wald, D. J., and T. H. Heaton (1994). Spatial and temporal distribution of slip for the 1992 Landers, California, earthquake, *Bull. Seismol. Soc. Am.* **84,** 668–691.

Wesnousky, S. (1988). Seismological and structural evolution of strike-slip faults, *Nature* **335,** 340–342.

Laboratoire de Tectonique, Mecanique de la Lithosphere
Institut de Physique du Globe de Paris
4, place Jussieu
75252 Paris, Cedex 05, France
(G.C.P.K.)

Center for Neotectonic Studies
Mail Stop 169
University of Nevada, Reno
Reno, Nevada 89557
stevew@seismo.unr.edu
(S.G.W.)

Manuscript received 4 March 2007