Appendix B

The Seismogenic Scaling Factor, R

William H. Bakun

Elastic waves are generated by slip on a fault. Far away from the causative slip, the amplitude of the elastic waves increases with the velocity of the slipping points on the fault (Aki and Richards, 1980). If slip is rapid, then detectable elastic waves are generated, and an "ordinary" earthquake occurs. If the slip is slow (a *slow earthquake*), then the energy propagated to distant points is small, and damage is minimal. If the slip is very slow (*a silent earthquake*), then no detectable seismic waves are generated (*aseismic slip*) and damage is limited to deformation of structures built across the trace of the slipping fault.

Louderback (1942) notes that geologists have long speculated on the possibility of the slow yielding of crustal rocks such that elastic strain that might result in earthquakes was not accumulated. Such aseismic slip, or *fault creep*, was first recognized in 1956 (Steinbrugge, 1957) on the trace of the San Andreas fault south of Hollister near the south end of the WG99 study area. Fault creep events at the earth's surface are a near-surface soil failure phenomena driven by deeper fault slip (Johnston and Linde, 2001). Fault creep at the surface has since been documented on the Hayward, Calaveras, San Andreas, and Concord faults in the San Francisco Bay region, on the Garlock, Banning, San Andreas, Coyote Creek, Superstition Hills, and Imperial faults in southern California (Louie and others, 1985), and on the Anatolian fault in Turkey (Ambraseys, 1970; Aytun, 1980).

Too important to ignore

Slow earthquakes have been detected in many tectonic settings. Kanamori and Hauksson (1992) described a shallow $M_L = 3.5$ earthquake associated with oil-field operations near Santa Maria in southern California in which the radiated energy was 1-2 orders of magnitude smaller than that of an ordinary earthquake. Slow earthquakes associated with spreading centers along mid-ocean ridges have been discussed by Beroza and Jordan (1990), and a deep slow earthquake was recently detected on the Cascadia subduction zone (Dragert and others, 2001). Closer to home, slow earthquakes have been detected on borehole strainmeters and associated with slip at depth on the Hayward fault and on the San Andreas fault in the SFBR (Linde and others, 1996; Johnston and Linde, 2001). The slow earthquake in December 1992 on the San Andreas fault near San Juan Bautista was associated with small earthquakes (aftershocks?) that outlined a crescent shape on the fault extending from a few kilometers depth to about 8 kilometers (Johnston and Linde, 2001). The aseismic moment inferred for this slow earthquake was equivalent to an **M** 5.1 ordinary earthquake, but the seismic moment was more than 100 times smaller (Johnston and Linde, 2001). That is, there is convincing evidence that aseismic slip extends to seismogenic depths for faults in the SFBR that are characterized by WG99. Aseismic slip at depth occurs *in lieu* of slip during ordinary earthquakes so that a proper accounting of the extent and amount of aseismic slip at depth is essential for accurate estimates of the probability of future damaging earthquakes.

We don’t know what causes a fault to creep. Field evidence suggests that the distribution of weak materials such as serpentinite and the presence of carbon dioxide-rich fluids may be important (Irwin and Barnes, 1975, 1980). Laboratory experiments (e.g., Byerlee and Summers, 1976; Reinen and others, 1994) indicate that the presence of serpentinite, high temperatures, high pore pressures, and a thick zone of fault gouge tend to promote fault creep. In any case, we cannot map these fault attributes at depth, but must estimate the regions of aseismic slip from remote observations. Our primary indicator of the presence of aseismic slip at depth is the observation of surficial fault creep (e.g., Galehouse, 1995). If surficial fault creep is not observed, there is little reason to suspect that it is a significant fault attribute at seismogenic depths. If surficial fault creep is observed, aseismic slip may extend to seismogenic depths beneath that section of that fault and can account for a significant portion of the plate-motion slip rate available for earthquake generation.

How much aseismic slip?

What part of the plate-motion slip rate is accounted for by aseismic slip? It appears that most, if not all, of the plate motion is accommodated by fault creep along the relatively simple section of the San Andreas fault in central California just south of the SFBR (Savage and Burford, 1973). In contrast, 3-10 mm/year of fault creep has been measured since the 1970s along the trace of the south Hayward fault segment, precisely where the Hayward fault slipped in the **M** 6.8 earthquake of October 21, 1868. Clearly this amount of fault creep on the southern Hayward fault cannot extend through the seismogenic depth range. In fact, the inferred depth extent of creep varies along strike from 4 km to the bottom of the seismogenic zone (Simpson and others, 2001). Their models require locked patches under the central Hayward fault, consistent with the earthquake in 1868, but the geometry and extent of locking under the north and south ends of the Hayward fault depend critically on assumptions of fault geometry. Bürgmann and others (2000) suggested from InSAR data and the presence of repeating micro-earthquakes that a 20-km-long section of the northern Hayward fault may be creeping at all depths, precluding the initiation of any large earthquake under that section of fault. Simpson and others’ (2001) models contain 1.4-1.7 times more stored moment along this stretch of the Hayward fault than does the model of Bürgmann and others (2000). That is, there is considerable uncertainty regarding the relative importance of aseismic slip on the Hayward fault, and on the other faults characterized by WG99.

WG99’s method of accounting for aseismic slip

WG99 accounts for aseismic slip through a seismogenic scaling factor *R* which varies from R = 0, where all of plate-motion slip rate is accounted for by aseismic slip, to R = 1, where all of plate-motion slip rate is accounted for by earthquakes. The values of R used in USGS Open-file Report # 99-517 (see Table) were based on the consensus opinion of an expert group of geologists and geophysicists. The expert group subsequently decided that regional tectonic models based on geodetic observations collected in the SFBR in the last few decades should be the primary basis for the R values used in the final WG99 calculations. The revised R values (see Table above) that are used in this report are based on results of modeling the geodetic data (see Geodetic Modeling Section below), modified in cases by additional information. The rationale for each of the recommended R values is given below.

Fault Segment	**USGS OFR 99-517**		**Revised (23 August 2001)**	
	R	**Weights**	**R**	**Weights**
SAS	1	-	0.8/ 0.9 /1.0	.2/.6/.2
SAP	1	-	0.9/ 1.0 /1.0	.2/.6/.2
SAN	1	-	0.9/ 1.0 /1.0	.2/.6/.2
SAO	1	-	0.9/ 1.0 /1.0	.2/.6/.2
HS	0.6/ 0.8 /1.0	.1/.8/.1	0.4/ 0.6 / 0.8	.2/.6/.2
HN	0.3/ 0.6 /0.9	.2/.4/.4	0.4/ 0.6 / 0.8	.2/.6/.2
RC	1	-	0.9/ 1.0 /1.0	.2/.6/.2
CS	0.1/0.4/0.7	.1/.8/.1	0.0/ 0.2 /0.4	.2/.6/.2
CC	0.1/0.4/0.7	.1/.8/.1	0.1/ 0.3 /0.5	.4/.5/.1
CN	0.8/0.9/1.0	.2/.6/.2	0.7/ 0.8 /0.9	.2/.6/.2
CON	0.0/.5/1.0	thirds	0.2/ 0.5 /0.8	thirds
GVS	0.0/.5/1.0	thirds	0.2/ 0.5 /0.8	thirds
GVN	0.0/.5/1.0	thirds	0.2/ 0.5 /0.8	thirds
SGS	1	-	0.8/ 0.9 /1.0	.2/.6/.2
SGN	1	-	0.8/ 0.9 /1.0	.2/.6/.2
GS	1	-	0.8/ 0.9 /1.0	.2/.6/.2
GN	1	-	0.8/ 0.9 /1.0	.2/.6/.2

WG99’s method of accounting for aseismic slip using the revised R values can be explained by consideration of Oppenheimer and others’ (1990) model for earthquake occurrence on the central and south segments of the Calaveras fault. Oppenheimer and others (1990) model the Calaveras fault as a collection of stuck and creeping patches. All of the slip on the Calaveras fault occurs as fault creep at depths less than 4 kilometers and greater than about 10 kilometers. Ambient microseismicity and aftershocks extend from 4 kilometers depth to about 10 km and defines zones where 1) the slip occurs as small earthquakes and fault creep, or 2) usually aseismic zones. Hypocenters of the $5 < \mathbf{M} < 6\,{}^{1}/_{4}$ main shocks occur at depths of 8-9 kilometers near the base of the zone of ambient microearthquakes within the usually aseismic zones. The usually aseismic zones are stuck patches that slip infrequently only during main shocks. Oppenheimer and others’ (1990) partition of the 4-10 km seismogenic depth range into a shallow zone where aseismic slip prevails and a 2-km-thick deeper zone where seismic slip prevails might be represented by a value of R of about 1/4 to about 1/3.

WG99 uses R to reduce the width W (depth extent) of the seismogenic zone to that fraction that fails only in “characteristic” or “floating” earthquakes. Since the area of slip =W * length L, R has the effect of scaling the area. Since **M** is calculated from the area, R scales **M**. Less frequent events with larger M are necessary to satisfy the geologic slip rate, so the average recurrence time T decreases with decreasing R. That is, a decrease in R on a fault segment decreases the mean magnitude and the mean recurrence time for segment-rupturing earthquakes.

A different model and method of accounting: R scaling the geologic slip rate

Other models can be devised to account for aseismic slip. Rather than the Oppenheimer and others (1990) model described above, consider a fault that creeps everywhere, but the aseismic slip rate is less than the long-term geologic slip rate. In this model, the difference between the geologic and aseismic slip rates would be accounted for by slip in infrequent segment-rupturing earthquakes. Given this model, R might be used to scale the long-term geologic slip rate, and while the mean magnitude would not change, the mean recurrence time would increase with decreasing R.

For comparison purposes, we calculated a SFBR earthquake model and 30-year conditional probabilities accounting for aseismic slip by scaling the slip rate rather than W. Scaling the slip rate results in larger magnitude earthquakes (more W and more area) and greater recurrence times, both because there is more slip per event for larger events and because there is less slip available to produce earthquakes. The conditional 30-yr probabilities are significantly greater with slip rate scaling. For the Poisson model, the conditional 30-yr probability of at least one M≥6.7 earthquake in the SFBR is 69.9% rather than the 60.6% that is calculated in this report.

Rationale for the R values for fault segments

San Andreas North Coast (SAN). The SAN is the simplest segment of the SAF for which dense relevant geodetic observations are available. There are no significant nearby tectonic structures to complicate the interpretation of the model results for SAN, and there is no known seismic activity or surface creep on SAN since 1906. The recommended R values reflect the model results that imply a fully locked SAN segment. Note that the 0.2 weight for R = 0.9 allows for the possibility of both precursory aseismic slip and creep following a segment-rupturing earthquake (*afterslip*).

San Andreas Offshore (SAO). Like the SAN segment, there is no known seismic activity or surface creep since 1906 on SAO. Since there is no reason to differentiate the SAN and SAO segments, we assume that SAO is a continuation of SAN with the same R.

San Andreas Peninsula (SAP). Creep is not observed on the Peninsula segment (SAP) and small to moderate earthquakes are located within a few kilometers of the fault trace, but appear to be associated with tectonic processes off the SAF trace (Zoback and others, 1999). Unlike the SAN segment, the interpretation of the geodetic observations are complicated by the nearby San Gregorio fault. Also, the calculated R tradeoff with the loading rates assumed for the SAP segment (see Geodetic Modeling section below). Since there is no convincing basis for differentiating the SAP and SAN segments, we assume that SAP is a continuation of SAN with the same R.

San Andreas Santa Cruz Mtns (SAS). The SAS is different from the SAF segments to the northwest. Surface creep is clearly observed near San Juan Bautista along the southeast 10% of the SAS segment. Also, there are repeating clusters of microearthquakes on the SAS segment near San Juan Bautista (Rubin and others, 1999), and repeating clusters of microearthquakes have been suggested as a diagnostic of creep on a fault at depth (Nadeau et al, 1995). The interpretation of the models of the geodetic data is complicated by creep on the nearby Sargent fault. Also, the depth to the base of the seismogenic zone is significantly greater in the northwest part of the SAS than in the southeast, and the model results are likely to underestimate R since they assume a constant intermediate depth. The recommended R reflects a locked SAS, but with creep in the southeast most 10% of the segment.

Hayward South (HS). The 52-km-long HS segment has been creeping at the surface at average long-term rates of 3-10 mm/yr for as long as careful observations have been made, with a 5-6 year slowdown at the south end following the 1989 Loma Prieta earthquake (Lienkaemper and others, 2001). The geodetic models (see Geodetic Modeling Section below) suggest R = 0.50 ± 0.2. Savage and Lisowski (1993) presented a two-dimensional model of the Hayward fault with a 5-km tall creeping zone over a 5-km tall locked zone. The creeping zone was driven by 10-km deep horizontal screw dislocations representing deep slip under the Hayward, Calaveras, and San Andreas faults. In their model, 50% of the area is strictly locked, but retarded creep in the creeping zone accounts for an additional 20-30% of the moment budget, for a total stored moment of 70-80%. Three-dimensional models (Bürgmann and others, 2000; Simpson and others, 2001) of a creeping zone over locked regions yield similar results. Approximately 40% of the area in these models is strictly locked, but 70-80% of the total moment budget is stored in locked areas or areas of retarded creep. The key unknown is how much of the moment stored as retarded creep is released coseismically as opposed to postseismically as afterslip. If all the stored moment were released as afterslip, R = 0.8, whereas if only the strictly locked regions contribute, R=0.4. Since the truth is probably somewhere in between, the panel chose R=0.6 as the central value.

Hayward North (HN). The 35-km long HN segment was assigned R values identical to HS. Geodetic models (see report below) suggest R = 0.66 ± 0.2. Bürgmann and others (2000) have proposed that a 20-km long part of the HN has no locked regions, but creeps from top to bottom. There are locked regions in their model to north and south of this part, however, and the locked-area percentages for HS models are slightly smaller than for HN models, but not significantly so, rounding to identical values as for HN. Given the uncertainties, the panel decided to use R values for HN identical to HS.

Rodgers Creek (RC). Although microearthquakes are located along the RC fault, there is no evidence of surface creep on the fault. There is geologic evidence for surface-rupturing earthquakes on the RC fault and the southern end of the segment is a likely location for the 31 March 1898 **M**6.3 “Mare Island” earthquake (Bakun, 1999). The models of the geodetic data for the RC fault imply a loading rate significantly greater than the long-term geologic rate used in the WG99 calculation sequence. The recommended R reflects a locked Rodgers Creek fault.

Calaveras South (CS). The19-kilometer-long CS segment is characterized by surface creep (14 mm/yr) and frequent small- and moderate-size earthquakes. There have been no significant historical earthquakes and there is no evidence for or against paleoearthquakes on the CS segment. Several studies have concluded that observed strain in the crust near the CS segment is consistent with rigid block motion with steady slip on the CS segment at the plate-motion rate. Although microearthquakes occur along the nearby Quien Sabe fault, this fault is not characterized by WG99 so that the interpretation of the models of the geodetic data for the CS segment is complicated by un-modeled slip on the nearby Quien Sabe fault. The recommended R for the CS segment is appropriate for a creeping fault with a possibility of infrequent segment-rupturing earthquakes.

Calaveras Central (CC). Observed surface creep decreases northward along the Calaveras fault from 14 mm/yr in the CS segment and southern CC segment to a few mm/yr near the northern end of the CC segment. Several **M** < 6.5 historical earthquakes (**M**6.3 on 20 June 1897, **M**6.2 on 1 July 1911, **M**5.9 on 6 August 1979, and **M**6.2 on 24 April 1984) have occurred on the CC segment (Bakun, 1999). There is some geologic evidence for **M**7 earthquakes on the CC segment. The recommended R for the CC segment is appropriate for a fault with both creeping and locked patches at seismogenic depth as suggested by Oppenheimer and others (1990) that fails infrequently in **M**7 events associated with rupture of CN.

Calaveras North (CN). There is no evidence for any fault creep on the CN segment, except near Calaveras Reservoir at the southern end of the CN segment. There is clear geologic evidence for paleoearthquakes on the CN segment and several moderate-size nineteenth-century earthquakes may have occurred on the CN segment. The models of the geodetic data for the CN segment are not appropriate because the geodetic data imply a loading rate significantly greater than the long-term geologic rate used in the WG99 calculation sequence. The recommended R for the CN segment is appropriate for a locked fault with some creep at the southern end of the segment.

Concord (CON). Although the M_L5.4 earthquake on 24 October 1955 apparently occurred on the Concord fault (Bolt and Miller, 1975), there is no evidence for or against surface-rupturing earthquakes on the Concord fault. Surface creep is observed on the Concord fault. The recommended R for the Concord fault is appropriate for a fault with both creeping and locked patches at seismogenic depth.

Green Valley South and North (GVS and GVN). There is evidence for both surface creep and for surface-rupturing earthquakes on the Green Valley fault. Since there is no basis for differentiating the Green Valley South segment (GVS) and the Green Valley North segment (GVN) segments, the recommended R for the GVS and GVN segments is appropriate for a fault with both creeping and locked patches at seismogenic depth.

San Gregorio South and North (SGS and SGN). There is no evidence of creep on either the San Gregorio South segment (SGS) or the San Gregorio North segment (SGN). While there are some small- and moderate-size earthquakes located near the SGS segment (e.g., two M_S 6.1 earthquakes in 1926), few earthquakes are located near the SGN segment except at its northern end where it merges into the SAF near the Golden Gate. There is some evidence for paleoearthquakes on the SGN segment. Since the San Gregorio fault is located almost entirely offshore, there is little geodetic control on the slip at depth so the geodetic models are not useful. Since there is no basis for differentiating the SGN and SGS segments, the recommended R for the SGS and SGN segments is appropriate for a primarily locked fault.

Greenville South and North (GS and GN). The **M**5.8 and **M**5.4 Livermore earthquakes in 1980 (Bolt and others, 1981) occurred on the Greenville North segment (GN), and there is evidence for surface-rupturing earthquakes on the Greenville South segment (GS) in the last 1000 years.

Afterslip (surface fault creep following an earthquake) was observed following the 1980 Livermore earthquakes. There is no other evidence of creep on the Greenville fault. The recommended R for the GN and GS segments is appropriate for a primarily locked fault.

Mount Diablo Thrust (MTD). There is no evidence for either earthquakes or fault creep on the blind MTD. The R =1 is an assertion that our characterization of the MTD is a valid source model for the generation of earthquakes.

References Cited

Aki, K., and Richards, P.G., 1980, Quantitative seismology: Theory and methods: San Francisco, W.H. Freeman.

Ambraseys, N.N., 1970, Some characteristic features of the Anatolian fault zone: Tectonophysics, v. 9, p. 143-165.

Aytun, A., 1980, Creep measurements in the Ismetpasa region of the North Anatolian fault zone, in Isakara, A.M., and Vogel, A., eds., Multidisciplinary approach to earthquake prediction 2: Braunschweig/Wiesbaden, Friedrich Vieweg & Sohn, p. 279-292.

Bakun, W. H., 1999, Seismic activity of the San Francisco Bay region: Seismological Society of America Bulletin, v. 89, p. 764-784.

Beroza, G., and Jordan, T., 1990, Evidence for slow earthquake rupture from 10 years of continuously-monitored normal-mode activity: Seismological Research Letters, v. 61, p. 27.

Bolt, B.A., and Miller, R., 1975, Catalogue of earthquakes in northern California, Jan 1. 1910 - Dec. 31, 1972: Seismographic Stations, Univ. of California, Berkeley, 567 p.

Bolt, B.A., McEvilly, T.V., and Uhrhammer, R.A., 1981, The Livermore Valley, California, sequence of January 1980: Seismological Society of America Bulletin, v. 71, p. 451-463.

Bürgmann, R.D., Schmidt, R.M., Nadeau, M., d'Alessio, Fielding E., Manaker D., McEvilly T.V., and Murray, M.H., 2000, Earthquake potential along the northern Hayward fault: Science v. 289, p. 1178-1182.

Byerlee, J.D., and Summers, R., 1976, A note on the effect of fault gouge thickness on fault stability: Intl. J. Rock Mech. Min. Sci., v. 13, p. 35-36.

Dragert, H., Wang, K., and James, T.S., 2001, A silent slip event on the deeper Cascadia subduction interface: Science, v. 292, p. 1525-1528.

Galehouse, J.S., 1995, Theodolite measurements of creep rates on San Francisco Bay region faults: U.S. Geological Survey Open-file Report 95-210.

Irwin, W.P., and Barnes, I., 1975, Effect of geologic structure and metamorphic fluids on seismic behavior of the San Andreas fault system in central and northern California: Geology, v. 3 , p. 713-716.

Irwin, W.P., and Barnes, I., 1980, Tectonic relations of carbon dioxide discharges and earthquakes: Journal of Geophysical Research, v. 85, p. 3115-3121.

Johnston, M.J.S., and Linde, A.T., 2001, Implications of crustal strain during conventional, slow and silent earthquakes: Intl. Handbook of Earthquake and Engineering Geology, Academic Press, in press.

Kanamori, H., and Hauksson, E., 1992, A slow earthquake in the Santa-Maria Basin, California: Seismological Society of America Bulletin, v. 82, p. 2087-2096.

Lienkaemper, J.J., Galehouse, J.S., and Simpson, R.W., 2001, Long-term monitoring of creep rate along the Hayward fault and evidence for a lasting creep response to 1989 Loma Prieta earthquake: Geophysical Research Letters, v. 28, p. ???.

Linde A.T., Gladwin, M.T., Johnston, M.J.S., Gwyther, R.L., and Bilham, R., 1996, A slow earthquake sequence on the San Andreas fault: Nature, v. 383, p. 65-68.

Louderback, G.D., 1942, Faults and earthquakes: Seismological Society of America Bulletin, v. 32, p. 305-330.

Louie, J.N., Allen, C.R., Johnson, D.C., Haase, P.C., and Cohn, S.N., 1985, Fault slip in southern California: Seismological Society of America Bulletin: v. 75, p. 811-833.

Nadeau, R.M., Foxall, W., and McEvilly, T.V., 1995, Clustering and periodic recurrence of microearthquakes on the San Andreas fault at Parkfield, California: Science, v. 267, p. 503-507.

Oppenheimer, D.H., Bakun, W.H., and Lindh, A.G., 1990, Slip partitioning of the Calaveras fault, California, and prospects for future earthquakes: J. Geophys. Res., v. 95, p. 8483-8498.

Reinen, L.A., Weeks, J.D., and Tullis, T.E., 1994, The frictional behavior of lizardite and antigorite serpentinites: experiments, constitutive models, and implications for natural faults: Pageoph, v. 143, p. 317-358.

Rubin, A.M., Gillard, D., and Got, J.-L., 1999, Streaks of microearthquakes along creeping faults: Nature, v. 400, p. 635-641.

Savage, J.C., and Burford, R.O., 1973, Geodetic determinaton of relative plate motion in central California: Journal of Geophysical Research, v. 78, p. 832-845.

Savage, J.C., and Lisowski, M., 1993, Inferred depth of creep on the Hayward fault, Central California: Journal of Geophysical Research, v. 98, p. 787-794.

Simpson, R.W., Lienkaemper, J.J., and Galehouse, J.S., 2001, Variations in creep rate along the Hayward fault, California, interpreted as changes in depth of creep: Geophysical Research Letters, v. 28, p. 2269-2272.

Steinbrugge, K.V., 1957, Building damage on the San Andreas fault: report dated February 18, 1957, published by the Pacific Fire Rating Bureau for private circulation.

Zoback, M.L., Jachens, R.C., and Olson, J.A., 1999, Abrupt along-strike change in tectonic style: San Andreas fault zone, San Francisco Peninsula: Journal of Geophysical Research, v. 104, p. 10,719-10,742.