Appendix C: R-factors Inferred from Geodetic Modeling

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17 July 2000

Summary

In assigning final R-factors to the faults, the working group combined geologic and geodetic estimates of fault slip and other information about the behavior of the segments. In this section we summarize the geodetic results.

Using geodetic data, we have estimated values for the R-factors on San Francisco Bay area faults. The geodetically estimated R-factors are summarized and compared to the Working Group 99 Report (USGS Open-File 99-517, 1999) in Table 1.

Table 1. Geodetically inferred R-Factor estimates.

Name	*Code*	*WG99 Open-File 99-517*			*Suggested by this study*	
		R	*2-sigma*	*Wgts*	*R*	*2-sigma*
SAF - Santa Cruz Mtns	SAS	1.0	-	-	0.9	0.2
SAF - Peninsula	SAP	1.0	-	-	0.8	0.2
SAF - North Coast	SAN	1.0	-	-	1.0	0.1
SAF - Offshore	SAO	1.0	-	-	1.0	0.1
Hayward South	HS	0.8	0.2	.1/.8/.1	0.5	0.8
Hayward North	HN	0.6	0.3	.2/.4/.4	0.7	0.6
Rodgers Creek	RC	1.0	-	-	0.9	0.4
Calaveras South	CS	0.4	0.3	.1/.8/.1	0.1	0.5
Calaveras Central	CC	0.4	0.3	.1/.8/.1	0.6	0.3
Calaveras North	CN	0.9	0.1	.2/.6/.2	0.9	0.4
Concord	CON	0.5	0.5	thirds	1.0	0.3
Green Valley South	GVS	0.5	0.5	thirds	1.0	0.2
Green Valley North	GVN	0.5	0.5	thirds	1.0	0.2
San Gregorio South	SGS	1.0	-	-	0.7	0.8
San Gregorio North	SGN	1.0	-	-	0.7	0.8
Greenville South	GS	1.0	-	-	0.7	1.0
Greenville North	GN	1.0	-	-	0.7	0.9
Mount Diablo Thrust	MTD	1.0	-	-	-	-

Notes: The central R-factors are taken from Table 3 below, with the R-factors rounded to 0.1 unit. The 2-sigma uncertainties shown here are twice those shown in Table 3.

For the San Andreas, Calaveras, Rodgers Creek faults, the geodetically estimated R-factors are consistent with the WG99 Open-File. For the remaining faults, the values and/or the uncertainties suggested by this study are somewhat different than the WG99 Open-File. These differences are discussed in more detail below, but part of the explanation is that the geodetic observations require higher-than-geologic slip rates on the deep portions of some of the faults.

Introduction

Using geologic data (dated offset features), Working Group 1999 (WG99) arrived at a consensus geologic rate for 18 fault segments in the San Francisco Bay Area. In addition WG99 estimated the fraction of the geologic slip that occurs through seismic processes and, by implication, what fraction is released by other mechanisms (creep, inelastic deformation). WG99 refers to this ratio as the R-factor and tabulates an estimate of R-factors and their distribution for the WG99 faults. An R-factor of 1.0 implies that a fault is completely locked between seismic events and that all of the geologic slip occurs during seismic events.

We have used a set of geodetic observations from the San Francisco Bay area to provide an independent estimate of these R-factors. The relation is simple in principle:

$$\mathbf{R = 1 - b_s/b_l}$$

b_s= slip rate at seismogenic depths ("s" for seismogenic slip),
b_l = slip rate at greater depths ("l" for lower slip).

Our original strategy was to estimate b_s from the geodetic data and use the WG99 geologic rates for b_l. However, the geodetic data and the geologic data appear inconsistent for some faults, and these definitions led to unlikely values for some R-factors. Thus, instead we estimated both b_s and b_l from the geodetic data. Both sets of values are given below, the geodetic/geologic set in Table 2 and the geodetic/geodetic set in Table 3. The values in the summary table come from the geodetic/geodetic set.

Input data

All of the input data files are listed in the appendix and accessible on the web. The data consisted of:

- Trilateration data collected between, roughly, 1971 and 1991;
- GPS data collected between, roughly, 1992 and 1999;
- Creep rates (Lienkaemper, pers comm.):

HN & HS	4.5 mm/yr
CS & CC	15.0 mm/yr
CN	1.5 mm/yr
CON	3.5 mm/yr
Other faults	0.0 mm/yr

- 18 fault segments as given by WG99 with three locations for each end of each segment;
- 3 depth ranges for each fault segment, 0-3 km, 3-W km, W-5000 km, where width, W, is variable and sampled from WG99 distribution;
- 15 additional faults extending outside the primary area of WG99 interest;

- 10,000 samples of segment endpoints, and widths drawn from the WG99 distribution (only the first 100 have been used);
- 10,000 samples of geologic slip rates for each of the segments drawn from the WG99 distribution (only the first 100 have been used).

In addition, the following assumptions were imposed on the solution:

- Slip in the shallowest layer for all segments was constrained to the estimated creep rate;
- Slip on the north and south pieces of many segments were constrained to be the same;
- Conservation of the Burgers vector was weakly imposed at fault triple junctions (e.g., where the San Gregorio fault merges with the San Andreas fault);
- In one of the two models discussed below, slip in the deepest layer is constrained to geologic rates; in the other slip is free in both the seismogenic and deep layer.

Results

The results are most easily summarized with tables:

Table 2. Slip rate estimates and R-factors when deep slip is constrained to geologic rates.

Name	*Code*	*La1Slp*	*La1Std*	*La2Slp*	*La2Std*	*R*	*Rstd*
		mm/yr	mm/yr	mm/yr	mm/yr		
SAF - Santa Cruz Mtns	SAS	4.62	1.68	17.12	0.20	0.73	0.10
SAF - Peninsula	SAP	3.58	1.54	17.12	0.20	0.79	0.09
SAF - North Coast	SAN	0.54	0.62	24.09	0.20	0.98	0.03
SAF - Offshore	SAO	0.54	0.71	24.09	0.20	0.98	0.03
Hayward South	HS	7.18	2.10	8.82	0.20	0.19	0.24
Hayward North	HN	8.22	2.21	8.82	0.20	0.07	0.25
Rodgers Creek	RC	11.10	2.60	8.92	0.20	-0.24	0.29
Calaveras South	CS	20.92	2.99	14.67	0.20	-0.43	0.20
Calaveras Central	CC	14.54	2.08	14.67	0.20	0.01	0.14
Calaveras North	CN	6.81	2.57	5.78	0.20	-0.18	0.45
Concord	CON	10.83	3.38	4.06	0.20	-1.67	0.84
Green Valley South	GVS	14.05	2.59	5.14	0.20	-1.73	0.51
Green Valley North	GVN	14.06	2.59	5.19	0.20	-1.71	0.51
San Gregorio South	SGS	1.19	1.60	4.24	0.20	0.72	0.38
San Gregorio North	SGN	1.20	1.61	5.52	0.20	0.78	0.29
Greenville South	GS	6.11	3.02	1.85	0.20	-2.30	1.67
Greenville North	GN	6.11	3.02	1.85	0.20	-2.30	1.67
Mount Diablo Thrust	MTD	0.00	0.13	0.00	0.04		

Notes: Estimated Slip in seismogenic layer (La1) from 3 km depth to about 12 km depth (exact depth to the bottom varies with segment and sample). The entries are the average over 100 samples. Also shown is the average geologic slip rate (La2). In this solution, La2 was strongly constrained. All standard deviations are one sigma.

Table 3. Slip rate estimates and R-factors when deep slip is estimated from geodetic data.

Name	*Code*	*La1Slp*	*La1Std*	*La2Slp*	*La2Std*	*R*	*Rstd*
		mm/yr	mm/yr	mm/yr	mm/yr		
SAF - Santa Cruz Mtns	SAS	2.34	1.69	23.24	4.50	0.90	0.08
SAF - Peninsula	SAP	2.56	1.68	15.38	3.23	0.83	0.11
SAF - North Coast	SAN	0.24	0.85	21.65	2.17	0.99	0.04
SAF - Offshore	SAO	0.24	0.98	21.65	2.18	0.99	0.05
Hayward South	HS	3.39	2.20	7.27	3.89	0.53	0.39
Hayward North	HN	2.38	2.48	8.79	3.23	0.73	0.30
Rodgers Creek	RC	1.66	2.84	14.89	2.85	0.89	0.19
Calaveras South	CS	16.70	2.84	19.60	4.08	0.15	0.23
Calaveras Central	CC	8.40	2.47	19.23	3.14	0.56	0.15
Calaveras North	CN	1.77	2.15	12.32	5.05	0.86	0.18
Concord	CON	0.00	2.50*	16.64	3.18	1.00	0.15
Green Valley South	GVS	0.00	2.50*	20.18	2.23	1.00	0.12
Green Valley North	GVN	0.00	2.50*	20.20	2.23	1.00	0.12
San Gregorio South	SGS	1.84	2.18	5.91	2.54	0.69	0.39
San Gregorio North	SGN	1.86	2.18	5.91	2.54	0.69	0.39
Greenville South	GS	1.59	2.31	5.32	3.47	0.70	0.48
Greenville North	GN	1.60	2.30	5.32	3.47	0.70	0.47
Mount Diablo Thrust	MTD	0.00	0.16	0.00	0.08		

Notes: Estimated Slip in seismogenic layer (La1) from 3 km depth to about 12 km depth (exact depth to the bottom varies with segment and sample). The entries are the average over 100 samples. Also shown is the estimated slip in the deeper layer from about 12 km to infinity essentially. Entries with 0 slip and standard deviation were forced to 0 to avoid negative slip values. All standard deviations are one sigma. (*) indicates assumed values; since slip was constrained to zero, no uncertainty is calculated.

Discussion

Tables 2, 3, and 4 contain three estimates of the R-factors and their uncertainties. In Table 2, the R-factor displayed for each fault is calculated from the mean value of 100 calculations for geodetic fault slip in the seismogenic layer with the deep slip constrained to the geologic rate. The standard deviation in Table 2 is mean of the standard deviation calculated for each of the 100 cases. These standard deviations reflect the uncertainties in the observations (trilateration and GPS) and the ability of the model to resolve fault slip. The R-factors and standard deviations in Table 3 are similar, except that in this case both the seismogenic and deep slip are estimated from the geodetic data. In Table 4, the R-factors are calculated slightly differently. Rather than calculate a mean slip over 100 cases and then turn that into a single R-factor, we calculate the R-factor for each case for each fault. Table 4 contains the median values for these R-factors and a standard deviation computed from the 100-sample distribution.

Fig.1 is a histogram of these R values over 100 cases, and Fig. 2 illustrates the variation of the R-factors with slip rate in the lower layer. From Fig.2 it is apparent that for some faults the R-factor correlates strongly with the slip rate in the deep layer and for some faults it does not. Along the San Andreas and San Gregorio fault segments, there is little or no correlation (Fig. 2) between R and deep slip; while, for the other faults, there is usually a strong correlation. Another way of

Table 4. Median R-factor and standard deviations estimated from variation with model geometry and rate.

Name	*Code*	*R*	*Rstd*
SAF - Santa Cruz Mtns	SAS	0.91	0.03
SAF - Peninsula	SAP	0.87	0.04
SAF - North Coast	SAN	1.0	0.02
SAF - Offshore	SAO	1.0	0.02
Hayward South	HS	0.5	0.12
Hayward North	HN	0.66	0.09
Rodgers Creek	RC	0.89	0.03
Calaveras South	CS	0.18	0.08
Calaveras Central	CC	0.46	0.07
Calaveras North	CN	0.84	0.07
Concord	CON	0.96	0.01
Green Valley South	GVS	0.95	0.01
Green Valley North	GVN	0.95	0.01
San Gregorio South	SGS	0.77	0.12
San Gregorio North	SGN	0.76	0.13
Greenville South	GS	0.76	0.05
Greenville North	GN	0.76	0.05
Mount Diablo Thrust	MTD		

Notes: These R-factors and their standard deviations were calculated from the variation of R over the 100 cases. See the Discussion Section for a fuller description. All standard deviations are one sigma.

saying the same thing is that to note that, for the western faults, the deep slip rate and the seismogenic slip rate are positively correlated, so that R (which is essentially a ratio between the seismogenic and deep slip) is uncorrelated with either. Whereas, for the eastern faults, the seismogenic and deep slips tend to be negatively correlated. Low deep slip rates correspond to higher seismogenic slip rates and visa-versa.

Tables 3 and 4 provide similar estimates of the R-factors. The standard deviations in Table 4 are smaller than the data- and model-driven standard deviations in Table 3. In the summary to this writeup, Table 1, we used the common R-factors from Tables 2/3 and the standard deviations from Table 3. However, in assigning final R-factors to the faults, the working group took into account the distribution of R-factors for each fault, Fig.1, and the correlation with slip rate, Fig. 2, as well as other factors (see the Aseismic Slip section).

San Andreas and San Gregorio faults (SAS, SAP, SAN, SAO, SGS, SGN)

For the west bay faults, the results of geodesy and the geology seem fairly consistent. The geodetic models give low rates of slip in the seismogenic zone (La1Slp). And the deep slip rates (La2Slp) in Table 3, where this is a free parameter, are in reasonable agreement with the corresponding values in Table 2, where La2Slp is the geologic estimate. R-factors determined geodetically agree very well with WG99 estimates. Note that the uncertainty for the R-factor is driven by the fractional uncertainty in the slip rates. For slowly slipping faults like the San Gregorio, the uncertainty in the R-factor is large because the slip rate is low compared to its standard deviation.

Hayward fault (HS and HN)

If the geologic rates are assumed to be correct, Table 2, then the seismogenic layer of the Hayward fault is slipping at nearly the geologic rate giving an R-factor near 0, and implying an absence of strain accumulation. However, a free solution, Table 3, produces nearly the geologic rate for the deep layer, but about 1/3 of that rate for the seismogenic layer, implying R = 1/3.

Calaveras South segment (CS)

The geodetic data prefer a slightly higher than geologic rate. If the deep layer is constrained to geologic values, Table 1, the geodetic model puts the extra slip in the seismogenic layer. In the free solution, Table 3, the deep slip is slightly higher than the geologic rate with most of it occurring aseismically (R = 0.15).

Calaveras Central and North Segments (CC and CN)

The constrained model, Table 2, slip in the seismogenic layer is about equal to the geologic rates, giving R-factors near 0. In the free model, Table 3, the slip pattern is more complex. In the deep layer, the slip rate is more-than-geologic along the central Calaveras and less-than-geologic along the northern Calaveras. In this free case, seismogenic layer slip is significantly less than deep slip giving R-factors of about 2/3.

Rodgers Creek fault (RC)

Along this fault, the geodetic model is mildly unhappy with the geologic rate. If forced to follow the geologic rate in the deep layer, Table 2, the model infers that the seismogenic layer is also slipping at the geologic rate (R = 0). But the geodetic data would prefer to approximately double the geologic rate in the deep layer, Table 3, and then keep slip near zero in the seismogenic layer. Thus producing an R-factor near 1.

Concord and Green Valley faults (CON, GVS and GVN)

Along this fault, the geodetic model is really not happy with the geologic rate. If forced to follow the geologic rate in the deep layer, Table 2, the model infers that the seismogenic layer is also slipping at 3 times the geologic rate (R = -2). But the geodetic data would prefer to quadruple the geologic rate in the deep layer, Table 3, and then keep slip near zero in the seismogenic layer. Thus producing an R-factor near 1. These are the only faults where a non-negative constraint was required to produce right-lateral slip. A pure least-square solution (not shown) produces left-lateral slip at about 8 mm/yr in the seismogenic layer and right lateral slip at rates about 5 mm/yr higher than those in Table 3.

Greenville fault (GS and GN)

Along this fault, the geodetic model prefers slightly more slip than the geologic rate. If the deep slip is constrained to geologic rates, Table 2, the seismogenic slip is 3 times that rate (R = -2). However, a free solution, Table 3, is happy with about double the geologic rate for the deep layer and about the geologic rate in the seismogenic layer. Thus, R = 0.7

Mount Diablo Thrust fault (MTD)

This fault was constrained to zero slip at all depths.

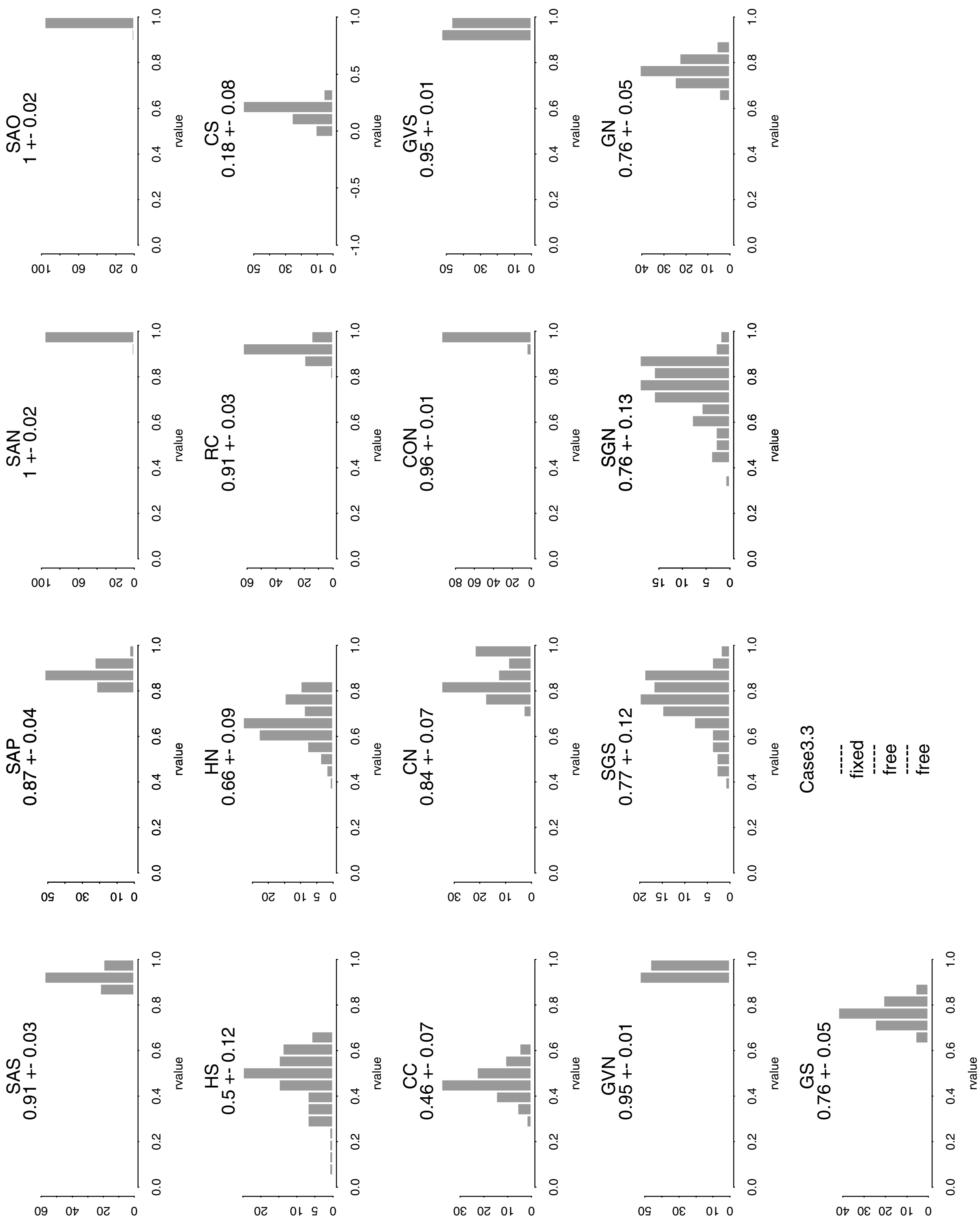

Figure 1. Histograms of R-factors for fault segments. Slip from 0 to 3 km is fixed at the surface creep rate. Slip in the seismogenic layer and in the deep layer are estimated, and R is calculated. Histograms show the values of R obtained for 100 samples of fault end points and depth-to-boundary between seismogenic and deep layer.

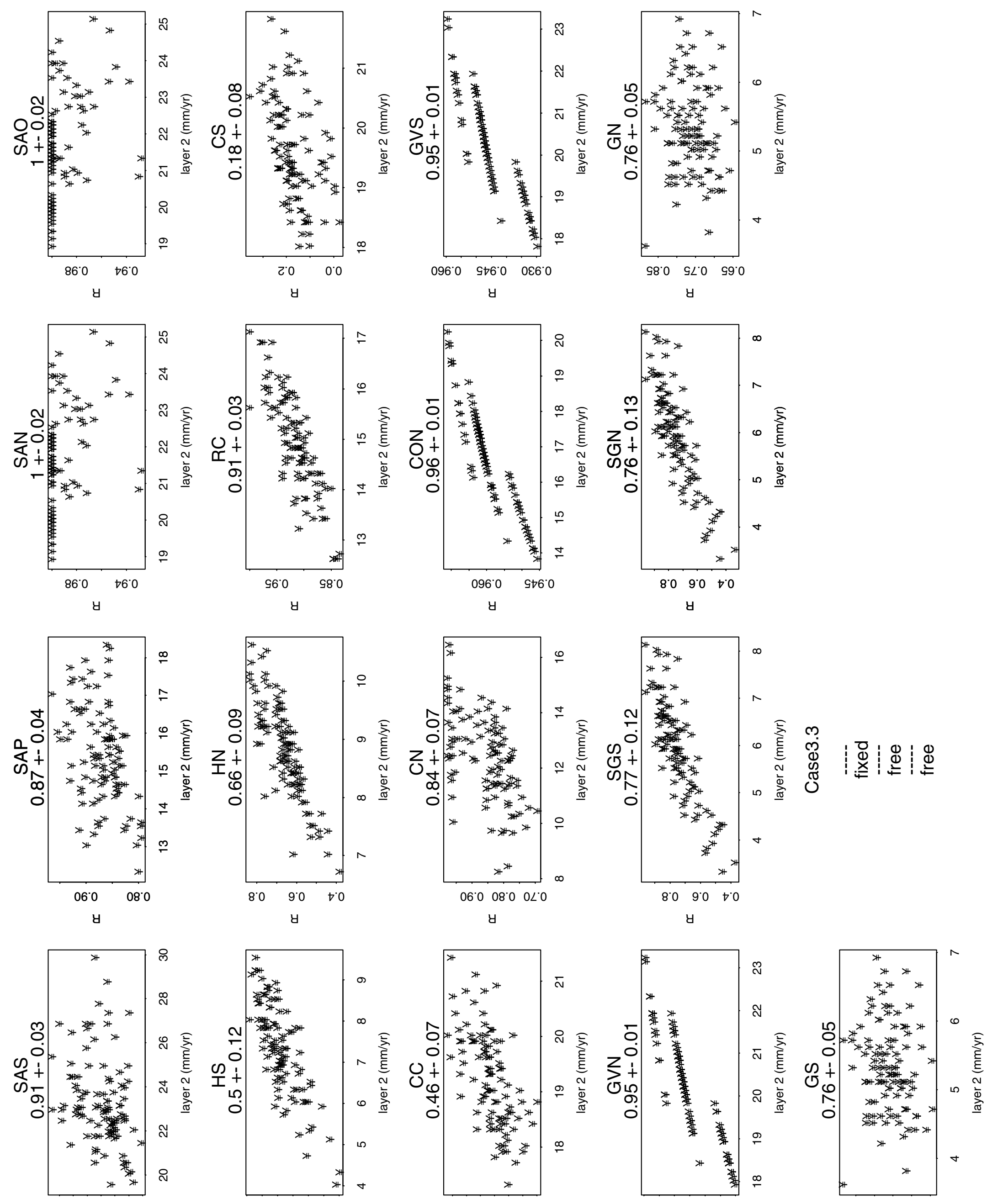

Figure 2. R-factors plotted against Layer 2 fault slip for fault segments. Slip from 0 to 3 km is fixed at the surface creep rate. Slip in the seismogenic layer and in the deep layer are estimated, and R is calculated. Plots show the values of R and slip obtained for 100 samples of fault end points and depth-to-boundary between seismogenic and deep layer.