Statistical Relations Among Earthquake Magnitude, Surface Rupture Length, and Surface Fault Displacement

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ABSTRACT

In order to refine correlations of surface-wave magnitude, fault rupture length at the ground surface, and fault displacement at the surface by including the uncertainties in these variables, the existing data were critically reviewed and a new data base was compiled. Earthquake magnitudes were redetermined as necessary to make them as consistent as possible with the Gutenberg methods and results, which necessarily make up much of the data base. Measurement errors were estimated for the three variables for 58 moderate to large shallow-focus earthquakes. Regression analyses were then made utilizing the estimated measurement errors.

The regression analysis demonstrates that the relations among the variables magnitude, length, and displacement are stochastic in nature. The stochastic variance, introduced in part by incomplete surface expression of seismogenic faulting, variation in shear modulus, and regional factors, dominates the estimated measurement errors. Thus, it is appropriate to use ordinary least squares for the regression models, rather than regression models based upon an underlying deterministic relation with the variance resulting from measurement errors.

Significant differences exist in correlations of certain combinations of length, displacement, and magnitude when events are qrouped by fault type or by region, including attenuation regions delineated by Evernden and others. Subdivision of the data results in too few data for some fault types and regions, and for these only regressions using all of the data as a group are reported.

Estimates of the magnitude and the standard deviation of the magnitude of a prehistoric or future earthquake associated with a fault can be made by correlating M with the logarithms of rupture length, fault displacement, or the product of length and displacement.

Fault rupture area could be reliably estimated for about 20 of the events in the data set. Regression of M_s on rupture area did not result in a marked improvement over regressions that did not involve rupture area. Because no subduction-zone earthquakes are included in this study, the reported results do not apply to such zones.

INTRODUCTION

Many correlations have been made among the variables fault rupture length, fault displacement at the earth's surface, and earthquake magnitude. Bolt (1978) pointed out that the correlations of length and magnitude published up to 1978 did not take into account the errors in the variables, especially in reported rupture length, and suggested that the uncertainties be assessed. Following that suggestion, we have estimated the measurement errors in surface rupture length, displacement, and earthquake magnitude for historic surface faulting, and present new correlations among the variables. Published and unpublished data on over 100 historical fault-events that occurred on land were examined, and those events for which the errors in reported length or displacement could be estimated were selected for revision of earthquake magnitudes and for regression analysis. Primary responsibility for the results rests with Bonilla for the rupture lengths and displacements and for estimating their errors, with Lienkaemper for determining the earthquake magnitudes and errors, and with Mark for the statistical analyses.

The faulting was classified into five principal types based on the relative importance and sense of the strike-slip and dip-slip components of displacement using the classification of Bonilla and Buchanan (1970). The five types are a simplified grouping of the 12 fault types shown on Figure 1. The value of the cotangent of angle a (strike-slip component divided by dip-slip component) together with the normal or reverse sense of displacement gives the five principal types of faults (Table 1).

SURFACE RUPTURE LENGTH AND DISPLACEMENT

Events were selected for the data set primarily on the basis of whether the measurement errors could be estimated satisfactorily. Some events are excluded because the reported surface ruptures have a doubtful relation to the faulting that produced the earthquake. In determining surface rupture length and displacement there are several possible sources of error or ambiguity in both the field investigation and in interpreting the published reports.

For determination of rupture length, the sources of uncertainty include: 1) fault enters water and no subaqueous work done; 2) terminal areas not examined; 3) end points examined in reconnaissance only; 4) end points obscured by landslides, landspreads, desiccation cracks, vegetation, or materials that could absorb and conceal fault ruptures; 5) displacement dies out gradually and ends are indefinite; 6) local decrease in displacement along fault incorrectly interpreted as dying out at end of fault; 7) surface rupture trace dies out but reappears beyond area examined; 8) difficulty in distinguishing between main fault and subsidiary faults; 9) inclusion or exclusion of irregularities in fault geometry such as curves, jogs, and overlaps; 10) text of source report gives different length than distance scaled on map; 11) map scale not correctly determined (e.g., bar scale different from actual map scale); and 12) mistakes in making map measurements.

Maximum displacement for each event was compiled because very few reports give enough information to determine average displacement; furthermore an estimate of the maximum displacement commonly is needed for engineering design of critical structures. Sources of error or ambiguity in determining maximum displacement include: 1) entire rupture trace was not examined and therefore maximum may have been missed; 2) maximum may have occurred where good measurements could not be made (e.g., reference lines for measurement of strike slip may be absent); 3) maximum may be obscured by landslides, vegetation, local bodies of water, or other entities; 4) separation, scarp height, or vertical component reported instead of slip; 5) nontectonic effects such as local slope movements not separated from tectonic effects; 6) displacement partly absorbed by distributed fracturing, flexing, intergranular movements, or other process; 7) afterslip of unknown amount has increased the displacement; 8) rounding of measurements upward (or downward) by field investigator; and 9) mistakes in making and recording measurements.

Many of the sources of error listed above can be evaluated or minimized; some cannot be quantitatively evaluated but are judged to a) have such a small effect that they can be disregarded or b) have a large effect, in which case the associated events were excluded from the data set. The nature of the basic data is such that a rigorous method of estimating errors cannot he applied but instead the best limiting values for length and maximum displacement were selected. The error was then taken to be one-half of the difference between the limiting values. The methods used in selecting the limiting values are listed in Table 2 and given identifying numbers. In determining the errors in length, methods numbered 1, 2, 3, 4, 5, and 7 were each applied to 10 or more events, and methods 6, 8, and 9 were each applied to three or fewer events. In determining the errors in displacement, methods numbered 1, 2, 3, and 4 were each applied to 15 or more events and method 10 was applied to 3 events. The list of surface rupture lengths and displacements (Table 3) indicates which method was applied to each event.

SURFACE-WAVE MAGNITUDE

All values of surface-wave magnitude shown in Table 3 and the associated estimates of error are uniformly derived from amplitude data as described by Lienkaemper (written commun., 1984). The magnitudes are as consistent as possible with those in Gutenberg and Richter (1954) and the average values of M_s in *Preliminary Determination of Epicenters*, published by the U.S. Geological Survey. Lienkaemper (written commun., 1984) has demonstrated that the observed distribution of single-station residuals about the mean may be reasonably modeled as a normal Gaussian error function. However, tests for fit to normal distribution were made on sums of residuals about the mean for many events with various mechanisms, rather than for a single event. Thus the validity of assuming normally distributed residuals is not explicitly proven for each individual event.

Because error estimates of the mean M_s (Table 3, $\sigma/\sqrt{n}$) are only about 0.1 unit of magnitude, the accuracy of these estimates appears to be greater than the accuracy of magnitude as a measure of energy. For example, Von Seggern (1970), using a point-source model, showed that average M_s, derived from sampling theoretically expected single-station M_s evenly with respect to azimuth, may differ by an entire unit of magnitude for sources of identical size, but with differing slip orientations. If such a model even roughly describes the actual effect of source variability on mean M_s then the source dependent effect could dwarf observational error in estimating mean M_s. Hence the separation of events by fault type in regression against surface-rupture lengths and displacements should improve correlation to mean M_s.

STATISTICAL CORRELATIONS

The correlations among earthquake magnitude and surface rupture length and displacement are well known. Many ordinary-least-squares (OLS) regression lines have been published (e.g., Bonilla and Buchanan, 1970; Slemmons, 1977; Mark and Bonilla, 1977), but little consideration has been given to the underlying statistical model and the appropriate choice of a regression model (e.g., Mark, 1977, 1979; Bolt, 1978).

A unique (single-valued), functional relationship does not exist between earthquake magnitude and either surface rupture length or displacement taken individually or jointly, due to the many variables which are not and perhaps cannot be considered. These variables include shape of rupture surface, relation of the rupture surface to the earth's surface, the stress drop, the shear modulus, the type of faulting, and so forth. For this reason, the relationships among magnitude, length, and displacement are stochastic in nature; moreover, there are measurement errors associated with these variables.

The purpose of our regression modeling is prediction; that is, given the value of one or more variables, we wish to estimate the expected value of another variable.

If the measurement errors dominate the stochastic variance (i.e., the points would fall approximately on a straight line were it not for measurement error) then models appropriate for a functional relationship may be used (e.g., York, 1966; Brooks et al., 1972). If the stochastic variance dominates the measurement errors, then the OLS model is appropriate. If both are comparable, analysis becomes more difficult.

For this analysis we have used only those events for which measurement errors could be estimated and for which these errors were not excessive. We have limited the regression analyses to those events for which M ≥ 6. Smaller events are less likely to be adequately observed, and the surface rupture is less likely to be representative of the source rupture.

The main focus of the analysis is on regression models relating M_s, log length, and log displacement. These variables appear to be linearly related. The data set was divided into logical subsets based upon type of faulting, region, and tectonic setting. OLS regressions were calculated among the three pairs of variables, and those subsets yielding t-statistics significant at the 95% confidence level were subjected to further analysis. Table 4 reports these results.

The next step in the analysis was to compare the variance about each regression line with the corresponding measurement error variance (Table 5). The mean ratio of error variance to variance about regression lines is 8% (median = 4%). Thus, the stochastic variance is dominant and therefore OLS is an appropriate model. In the two cases where this ratio is high, it is because the variance about the regression line is very low (r^2 • 1). In those cases, the result is insensitive to the statistical model selected.

For heuristic comparison we also report weighted least-squares (WLS) models (Table 4), with weights (W_i) selected as a relative measure of the quality of each data point:

$$W_i = \left(\frac{SD(x)}{ER(x_i)} \right)^2 + \left(\frac{SD(y)}{ER(y_i)} \right)^2$$

where SD(x) is the standard deviation of variable x, ER(x_i) is the measurement error associated with x_i, and so on.

The comparison of the OLS models and the WLS models can be seen in Figures 2-4 and Table 4. The differences are generally small.

DISCUSSION

In this section some of the factors other than measurement errors that may affect the magnitude-length-displacement relations are discussed, as are other types of relations and the significance and use of the correlations.

Incomplete surface expression of the seismogenic rupture.

Many seismogenic ruptures are deep and do not extend to the ground surface. One would expect a gradation from no surface expression to complete or nearly complete surface expression of the rupture length, depending primarily on the depth of the rupture compared to its dimensions. Even for shallow events such as those in our data set, ruptures with small dimensions might have considerably shorter surface lengths than subsurface lengths. This tendency cannot be evaluated quantitatively with the data at hand, but for steeply dipping faults we judge that it is probably unimportant for rupture lengths greater than about two times the downdip rupture width. Based on limited aftershock focal depths of varied quality, we estimate that more than 80 percent of the surface rupture lengths in our data set are two or more times greater than the corresponding rupture widths, and adequately represent the subsurface lengths.

Other ways in which subsurface faulting can be incompletely expressed at the ground surface include folding, and absorption by intergranular movement or distributed faulting (Bonilla, 1970, 1979). These processes can decrease both the rupture length and displacement that might be expected at the surface for an earthquake of particular size.

Source parameters that are estimated using geophysical methods are also subject to uncertainty, and estimates of subsurface fault parameters made by various workers using geodetic or seismologic data often differ greatly for the same event. An example is the 1971 San Fernando, California, earthquake. For this event the derived average fault displacements ranged from 0.45 m (Wyss and Hanks, 1972) to about 1.7 m (average of Sylmar and Tujunga segments, from Jungels and Frazier, 1973), and derived maximum displacements ranged from about 3.5 m (Heaton, 1982) to about 8 m (Jungels and Frazier, 1973). Heaton (1982) discusses many of the difficulties in using the seismologic method, with particular application to the 1971 California faulting. Fault parameters obtained by direct measurement at the surface and those estimated from geophysical data both have shortcomings; when possible, both methods should be used and the results compared.

Saturation of M_s.

For large events, surface-wave magnitude may saturate (increase very slowly or remain nearly constant as the size of the event increases) and thus not correctly represent large earthquakes. Saturation of M_s has been variously estimated to occur in the range M_s 8.3 through M_s 8.7 (Howell, 1981). Although only one of the events in our data set, California, 1906, lies in that magnitude range, moment-magnitudes, which are not subject to the saturation problem, were determined for all events with published seismic moments that were not based on rupture length. The formulas of both Hanks and Kanamori (1979) and Singh and Havskov (1980) were used to convert seismic moments to magnitude. The moment-magnitudes for the Mongolia 1957 and the China 1931 events are larger than the corresponding M_s, values but are counterbalanced by the moment-magnitudes for California 1906, which are considerably smaller than M_s. In general the moment-magnitudes show a good correlation with M_s, especially using the Singh and Havskov (1980) conversion, and saturation effects apparently do not affect the correlations for the magnitude range of our data.

Shear modulus.

Some of the scatter in plots of earthquake magnitudes against rupture length or displacement can be the result of differences in shear modulus from place to place. Very commonly, a value of 3×10^{11} dyne/cm^2 has been used for shallow events with surface faulting. Some variations from this generalization are the use of 3.4×10^{11} dyne/cm^2 for the 1943 Japan faulting (Kanamori, 1972) and the shear modulus estimates for the 1979 Imperial Valley, California, faulting. For the upper 10 km of section involved in the 1979 faulting Archuleta (1982, p. 1953) estimated an average shear modulus of 1.7×10^{11} dyne/cm^2. An average modulus of 2.2×10^{11} dyne/cm^2 was obtained for the upper 11 km of the same section by weighted averaging, using the detailed S-wave velocity and density structure listed in table 2 of Olson and Apsel (1982), and $\mu = \rho V^2$ where μ is shear modulus, ρ is density in g/cm^3 , and V is shear wave velocity in cm/s. An extreme case is the shear modulus of only 1×10^9 dyne/cm^2 that was determined by field measurement of S-wave velocity for diatomite in which surface faulting occurred in 1981 (Yerkes *et al.*, 1983).

Laboratory determinations of shear modulus show considerable differences among various types of rocks. Shear wave velocities determined at a pressure of 1 kilobar for various types of igneous and metamorphic rocks (Press, 1966, Table 9-3) yield shear modulus values ranging from 2.1 to 7.1×10^{11} dyne/cm^2. Stewart and Peselnick (1977) measured P-wave velocities at various pressures and temperatures for graywackes from the widespread Franciscan Complex. Using their densities and velocities for pressures of 2 to 4 kilobars and temperatures between

130° and 290°C and P/S ratios ranging from 1.69 (Peselnick and Stewart, 1975, Figure 4) to 1.73, the calculated shear modulus for normal graywackes ranged from 2.3 to 3.4 x 10^{11} dyne/cm^2 and for metamorphosed graywackes from 3.6 to 4.2 x 10^{11} dyne/cm^2 From the limited survey outlined above it is clear that the modulus applicable to surface faulting could range from 2 x 10^{11} dyne/cm to 3.4 x 10^{11} dyne/cm a factor of 1.7, and may have a greater range. Shear modulus μ is part of the definition of seismic moment: $M_o = \mu dLW$, where d is average fault displacement, L is rupture length, and W is rupture width (downdip dimension). From the seismic moment definition it follows that, for a given moment, a factor of 1.7 difference in shear modulus would also permit a difference in fault displacement or length or width inversely by a factor of 1.7*. Because seismic moment can be related to earthquake magnitude (Hanks and Kanamori, 1979; Singh and Havskov, 1980) the preceding statement applies to earthquake magnitude as well as moment; that is, differences in shear modulus from place to place probably explain some of the observed variation in surface rupture length and displacement associated with a given magnitude.

Effect of fault type on the correlations.

When sufficient data were available, Bonilla and Buchanan (1970), Slemmons (1977), and Mark and Bonilla (1977) reported differences in magnitude-length-displacement relations for different types of faults. The present data set is too small to consider each of the five principal fault types separately but three groupings of types can be compared: 1) Normal and normal-oblique-slip; 2) reverse- and reverse-oblique-slip; and 3) strike-slip faults. Because the purpose of the regression models is prediction rather than estimating the parameters of a physical model, we have not made statistical comparisons of the regression coefficients. We do, however, discuss below some of the more apparent differences in the models for different fault types and, in a following section, for different regions.

For the length-magnitude relations, reverse- and reverse-oblique-slip faults have similar moderate coefficients of determination (r^2) as the strike-slip faults, but the normal and normal-oblique-slip faults have a low coefficient of determination (Figure 5). The normal and normal-oblique-slip group has a higher standard deviation of magnitude on length but a lower standard deviation of length on magnitude than the other two fault-type groups (Figure 5; Table 4); however, the normal- and normal-oblique-slip group has such a low coefficient of determination and such poor t-statistics that use of that regression is not recommended and is not included in Table 4.

Two groups of fault types can be compared in the correlation between surface displacement and earthquake magnitude. The regressions for the strike-slip faults have lower coefficients of determination and higher standard deviations than the group of normal- and normal-oblique-slip faults (Figures 3B, 3C, 6; Table 4). The correlation between surface displacement and earthquake magnitude for reverse- and reverse-oblique-slip faults is too poor to make valid comparisons (Figure 6).

The coefficient of determination for the displacement-length relation is moderate for strike-slip faults but so low for the other two fault-type groups that comparisons are of little or no value (Figure 7).

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* Inasmuch as fault displacement varies with rupture length, both length and displacement would change by a factor somewhat less than 1.7.

Regional variation in the correlations.

Using primarily aftershock data, Acharya (1979) found that the relation between rupture length and earthquake magnitude differs from region to region. Because our data set is small and restricted to on-land faulting, only a few regional comparisons can be made.

Differences are apparent in the length-magnitude regression lines for events in Turkey compared to events in western North America. Not only do the slopes and intercepts differ (Figures 2D, 2E), but the coefficients of determination are higher and the standard deviations are lower for the Turkish events (Figure 5; Table 4). Length-magnitude data points for other geographic regions are too sparse to make valid comparisons.

Regional differences in length-magnitude relations are also apparent within the United States. Evernden et al. (1981) have divided the U.S. into regions with distinctive crustal properties defined by the attenuation of seismic waves. Length-magnitude data points for events in their attenuation region k=1.75 (CA06, CA40, CA68, CA71, and CA79 of Table 3) form a remarkably coherent group (Figure 2F) and have a very high coefficient of determination (99%) and a low standard deviation (0.1 for M_s; see Figure 5 and Table 4). In contrast, events in attenuation region k=1.5 (NVI5, CA52, NV54A-C, and MT59) have a moderate coefficient of determination (54%) and a high standard deviation (0.4 for M_s) (Figure 5). More importantly, for a given rupture length greater than 10 km, the indicated earthquake magnitude is larger in region k=1.5 than in region k=1.75; however, this comparison must be viewed cautiously because the t-statistic for the U.S. k=1.50 set of events is significant only at the 10% level.

The concept that regional differences in attenuation of seismic waves has some bearing on length-magnitude correlations is supported by the addition of events in China. The Chinese events CH31, CH32, CH70, and CH73 are in attenuation region k=1.75 (Evernden, 1983). When length-magnitude data for these events are added to the data for U.S. k=1.75 events, the combination also forms a coherent group with a high coefficient of determination (Figures 2G, 5; Table 4).

The data are sufficient to compare length-magnitude relations of events on plate margins with events within plates. Events on the North Anatolian fault in Turkey, the Motagua fault in Guatemala, and the San Andreas and Imperial faults in the U.S. were considered to be on plate margins, and all other events in plate interiors. The plate margin events form the more coherent group and the regression lines for the two groups are different both in slope and in intercept (Figures 2H, 2I; Table 4).

Regressions of maximum surface displacement on M_s or on surface rupture length show some possible regional differences; however, the t-statistics show that the regressions for some regional groupings are not significant at the 5% level (Figures 6 and 7) and the comparisons are of doubtful validity.

Correlation of magnitude with log LD.

The regression of M_s on the logarithm of the product of surface rupture length and maximum surface displacement for all events with $M_s \geq 6$ yields a higher coefficient of determination, 56%. (Table 6), than the regression of M_s on either surface rupture length or displacement alone, 44% and 40%, respectively (Table 4). Similarly, the standard deviation of M_s regressed on log LD is lower (0.27) than the standard deviation of M regressed on either logarithm of surface rupture length or displacement alone, 0.31 and 0.32, respectively. Using all the events with M>4 for the regression of M on log LD improves the coefficient of determination to 73% but increases the standard deviation to 0.35 (Table 6).

Correlation of magnitude with logarithm of fault rupture area.

The physical theory of the earthquake process indicates that magnitude should be correlated more strongly with the logarithm of the rupture surface area than with the logarithm of length alone (Wyss, 1979; Singh et al., 1980. Unfortunately, accurate estimates of rupture area can be made for only a minority, 21 of 48, of the events with better known surface rupture lengths where M_s was greater than or equal to 6.0.

The most accurate data on downdip widths of fault rupture derive from aftershock studies, which among themselves vary considerably in the accuracy of focal depth determination. In this group are JA27, JA43, CA52, CA68, CA71, GU76, CA75, IR78, CA79, and AL80 of Table 3. Next in accuracy are carefully located microearthquake focal-depth values from the vicinity of the mainshock rupture, but occurring years after the mainshock; these include CA06, JA30, CA40, JA45, CH51, CA52, NV54C, MX56, MT59, and TK67. Using the aftershock and microearthquake data, we have estimated the rupture widths on the assumption that a small percentage of the aftershocks and microearthquakes will he deeper, or calculated to he deeper, than the actual seismogenic rupture, and by taking into account the dips of the faults. The rupture widths for events of $M_s \geq 6$ estimated in this way ranged from 8 to 18 km (Table 3).

Width data for the remaining (majority) of events are from a variety of methods: 1) deformation model; 2) teleseismic model; 3) macroseismic model; 4) depths extrapolated from microearthquakes a considerable distance from the event; and 5) regional crustal models. These methods are generally not sufficiently accurate to either prove or disprove for the events in our study with $M_s \geq 6$, that any of the widths lie outside of the range of 8 to 18 kilometers.

Linear regression, by ordinary least squares of M_s on rupture area using the estimated rupture widths and surface rupture lengths for the 21 events with $M_s \geq 6$ yielded $M_s = 4.96 + 0.82 \log LW$, where L (length) and W (width) are in kilometers (Table 6). The coefficient of determination is 46% and the standard deviation of M_s is 0.34 for this regression. Both of these measures have about the same value as in the regression of M_s vs. surface rupture length alone for the set of 45 events with $M_s \geq 6$, which yielded 44% and 0.31 respectively. Using all the events (M > 4) for the regression of M on log LW improves the coefficient of determination to 67%, but increases the standard deviation to 0.36 (Table 6). Thus, if the expected rupture widths are not extreme (i.e., beyond the range of about 10 to 20 km) our data indicate no practical advantage in using rupture area rather than rupture length to estimate earthquake magnitude.

Geometric moment.

The geometric moment (King, 1978) is the seismic moment divided by the shear modulus, and equals the area of rupture times the average fault displacement. Our data include maximum, rather than average, fault displacement, but with that modification, we correlated geometric moment with M_s using surface rupture lengths and the rupture widths discussed above and listed in Table 3. The linear regression, using ordinary least squares, for 19 events with $M_s \geq 6$, yields $M_s = 5.65 + 0.51 \log LWD$ in which L and W are in kilometers, and D (maximum surface displacement) is in meters. The coefficient of determination is 52%, considerably higher than for our regressions of M_s versus rupture area or M_s versus rupture length, 46% and 44%, respectively, but the standard deviation of M_s is 0.32, about the same as for M_s versus rupture area and M_s versus rupture length, 0.34 and 0.31, respectively. The regression of M_s on log LWD for $M_s \geq 6$ compares unfavorably with M_s vs. log LD in that it has a somewhat smaller coefficient of determination, 52% vs. 56%, and a somewhat higher standard deviation, 0.32 vs. 0.27 (Table 6). Using all of the events (M > 4) for the regression of M on log LWD increases the coefficient of determination to 75% and lowers the standard deviation to 0.31 (Table 6).

Estimation and exceedance probability.

In using the regression equations to estimate the modeled variables it is important that the appropriate regression (i.e., x regressed on y or y regressed on x) be used. For example, if the length of a prehistoric surface rupture is measured, the magnitude of the associated earthquake can be estimated from the regression of M_s on log L, which is found in the row in Table 4 where M_s is listed in the "For" column. Conversely to estimate surface rupture length given M_s the regression of log L on M_s should be used; this is found in the row in Table 4 where log L is listed in the "For" column. In these equations, L is in kilometers and D is in meters. For some practical problems more than one of the regressions listed in Tables 4 and 6 and shown in Figures 2-4 may be applicable. Using those ordinary least squares regressions ("OLS" in the tables) that are applicable to a particular problem, several estimates of the required parameters can be made and compared. The selection of the estimate or range of estimates to be adopted requires the use of judgment, which may be based in part on the examination of the actual data plots and the statistical measures given in Table 4, but we can offer no general suggestions except to urge caution in the use of regressions that are based on very few data points. The weighted least-squares regressions ("WLS" in tables and figures) are for purposes of heuristic comparison and not intended for practical applications. The regressions should not be extrapolated beyond the range of the data sets or applied to subduction zone faulting.

Although regression models of magnitude on log L can be used to estimate the most likely magnitude for a given maximum rupture, it must be stressed that such an estimate is not a maximum magnitude, but rather the magnitude that could be expected to be exceeded in 50% of the earthquakes associated with that rupture length.

It is possible to use the regression models to estimate the magnitude, as a function of length, that could be expected to be exceeded in a given proportion ($1 - \alpha$) of surface-rupture occurrences using a one-sided confidence limit (Wonnacott and Wonnacott, 1972; Mark, 1977):

$$M_\alpha(L) = M(L) + t_{1-\alpha}\, s \left[\frac{1}{n} + 1 + \frac{(\log L - \overline{\log L})^2}{\sum_{i=1}^{n} (\log L_i - \overline{\log L})^2} \right]^{1/2},$$

where M(L) is the regression value, $t_{1-\alpha}$ is the critical value of the t distribution with (n - 2) degrees of freedom, s is the standard deviation of the regression, L_i is the rupture length of the *i*th earthquake occurrence in the sample of n earthquakes, and $\overline{\log L}$ is the mean of log L. That is, the curve $M_\alpha(L)$ is the locus of points such that for a particular L, I - α is the probability that the magnitude will exceed M_α. Note that the regression line M (L) is equivalent to $M_{0.5}(L)$. The last term within the brackets is generally small compared to 1 and can be neglected. For example, using the regression for all faults of M_s on log L (Table 4):

$$M_s(L) = 6.04 + .708 \log L \qquad s = .306 \qquad n = 45.$$

The magnitude which would be expected to be exceeded in 5% of ruptures of length L is given by:

$$M_{.95} \approx M_S(L) + t_{.05}\, s[1/n + 1]^{1/2} .$$

For 43 degrees of freedom, $t_{.05} \approx 1.68$ (Crow et al., Table 3, 1960; Wonnacott and Wonnacott, 1972, p. 591).

Therefore

$$M_{0.95} \approx M_S(L) + (1.68)(.306)(1.01)$$

$$\approx M_S(L) + 0.52.$$

For a fault length of 50 km:

$$M_S\ (50\ \text{km}) = 7.24$$

$$M_{.95}\ (50\ \text{km}) = 7.24 + 0.52 = 7.76.$$

These results should be compared with other applicable regressions given in Table 4. Exceedance probabilities can also be estimated for regressions involving displacement-magnitude and displacement-length by making appropriate substitutions in the equation given above, bearing in mind that these regression equations are for the log variables.

For the reasons given previously, the fault displacement value used in our correlations is the maximum recorded for each event. Thus, using our regressions to obtain surface displacement from expected earthquake magnitude or rupture length yields an estimate of the most likely value of maximum surface displacement. For some applications an estimate of average surface displacement may be more appropriate. Although few events have been studied in detail, the available data suggest that for most events the average surface displacement has been about 30 percent of the maximum surface displacement (Bonilla, unpublished data).

SUMMARY AND CONCLUSIONS

Published and unpublished data on fault rupture length at the ground surface, maximum displacement at the surface, and surface-wave magnitude of the associated earthquakes were critically reviewed and the measurement errors in each variable were estimated where possible.

Regression analysis shows that the variance resulting from errors in measurement of length, displacement, and magnitude is dominated by stochastic variance resulting from other factors, some of which have been discussed. The stochastic nature of the relations among length, displacement, and magnitude indicates that the ordinary least-squares regression model rather than the weighted least-squares model is the appropriate one to use for correlations of these variables. Use of the estimated errors in measurement as a weighting factor has only a small effect on the regressions (Figures 2-4, Table 4).

Some of the factors that affect the stochastic variation are incomplete surface expression of the seismogenic faulting, variation in stress drop and shear modulus, type of faulting, the region in which the faulting occurs, and relation of the faulting to plate boundaries. Shear modulus can vary from place to place by a factor of 1.7 or more and probably explains some of the variation in rupture length or displacement associated with a given earthquake magnitude. The type of faulting and the region in which it occurs apparently can have an important effect on the correlations (Figures 5-7), but only a few reliable comparisons can be made because of the limited number of data points. The data suggest that subdivision of regions according to the rate of attenuation of seismic waves can improve the correlation of M_s with rupture length, and the concept deserves further study.

Ms was regressed on the logarithms of LD, LW, and LWD, where L is surface rupture length, D is maximum surface displacement, and W is downdip width (Table 6). A comparison of these regressions with the regressions of M_s on log L or log D is shown in Figure 8. Of the five correlations, log LD gives the highest coefficient of determination and t-statistic and the lowest standard deviation. The ranking among the remaining four correlations varies depending on whether a high coefficient of determination, high t-statistic, or low standard deviation is considered most important, but the differences are not great.

Estimates of the magnitude, and the standard deviation of the magnitude, of prehistoric or future earthquakes associated with a fault can be made by correlating M_s with log L, log D, or log LD. Displacement can he estimated from geologic evidence of past displacements, including possible characteristic displacement (Swan et al., 1980), or from geologic slip rate (slip rate multiplied by time since last displacement).

The data indicate that for faults with moderate down-dip width, within the range of about 10 to 20 km, use of fault rupture area does not greatly improve the correlations (Figure 8); however, rupture area is no doubt an important factor when dealing with subduction-zone faulting. Better estimates of earthquake size can probably be made in all tectonic settings using seismic moment estimated from geologic data, provided that the local shear modulus and rupture width, and their associated errors, can be estimated.

The regression equations given in Tables 4 and 6 can be used to estimate the modeled variables. The resulting estimates, however, are not maxima; they are expected values which could be exceeded 50% of the time. The equations should not be extrapolated beyond the range of the data sets or applied to subduction zone faulting.

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TABLE 1

CLASSIFICATION OF FAULT TYPES

	Fault type	Angle a (degrees)	Cotangent of a	Movement of hanging wall
A	Normal slip	90 to 60	0 to 0.577	Down*
B	Reverse slip	90 to 60	0 to 0.577	Up
C	Normal oblique slip	<60 to 30	>0.577 to 1.732	Down*
D	Reverse oblique slip	<60 to 30	>0.577 to 1.732	Up
E	Strike slip	<30	>1.732	-

* If the fault surface was reported as vertical or nearly vertical, vertical slip was treated as normal slip unless strong evidence of compression was found, in which case it was treated as reverse slip or reverse oblique slip.

TABLE 2

METHODS USED IN SELECTING LIMITING VALUES

Both length and displacement

1. Values from 2 or more reports
2. At least one limiting value taken directly from a report.
3. Calculation, measurement, or estimate from data in a report.
4. At least one value based on calculations, measurements, or estimates where our judgment is significant.

Length only

5. Smaller value for solid line on map, or known extent; larger value for solid plus dashed line, or inferred extent.
6. Larger value includes stepover distance between subparallel non- overlapping traces; smaller value does not.
7. Larger limiting value includes distance to point where faulting was known (or reasonably inferred) not to have occurred.
8. Larger value includes curves in fault; smaller value is straight-line distance.
9. Larger value includes possible subsidiary ruptures.

Displacement only

10. Error assumed to be one-half of nearest unit given in report (i.e., if value given to nearest 10 cm., error taken as ± 5 cm).

TABLE 3
SURFACE RUPTURE DATA, EARTHQUAKE MAGNITUDE, AND RUPTURE WIDTH

Event No.	Symbol	Yr. Mo. D.	Country	Faul t type	Length (km)	Length error km	Method	Displ[a] m	Displ. error m	Method	Mean magnitud e M_s	Magnitude error σ	$\sigma/\sqrt{n}$ [b]	Width, downdip km
I	CA857	1857.01.09	U.S.A.	E	358.0	65.0	3,4	9.4	1.0	3	--[c]	--	--	
2	JA891	1891.10.28	Japan	E	81.0	1.0	2,3	8.0	0.3	1,2,3	--	--	--	
3	GR894	1894.04.27	Greece	A	57.0	2.0	1,2,3	1.7	0.2	1	--	--	--	
4	JA896	1896.08.31	Japan	B	49.0	12.0	1,4	4.4	0.2	2,3				
5	CA06	1906.04.18	U.S.A.	E	444.0	20.0	1,4	6.1	0.2	2,4	8.32[d]	0.29	0.08	13
6	NV15	1915.10.03	U.S.A.	A	61.0	1.0	3,4	6.6	0.1	3,4	7.61	0.30	0.08	
7	JA27	1927.07.07	Japan	E	29.0	4.0	1,4,5	2.9	0.1	1	7.65	0.32	0.12	16
8	KE28	1928.01.06	Kenya	A	28.0	4.0	1	2.9	0.5	1	6.96	0.26	0.08	
9	BG28A	1928.04.14	Bulgaria	A	54.0	10.0	7	0.4	0.1	2,4	6.57	0.26	0.09	
10	BG28B	1928.04.18	Bulgaria	A	50.0	3.0	1	3.0	1.0	1	6.94	0.21	0.06	
11	IR29	1929.05.01	Iran	?	60.0	10.0	5,7				7.27	0.21	0.08	
12	NZ29	1929.06.16	N. Z.	B				5.1	0.2	1,2	7.75	0.16	0.06	
13	IR30	1930.05.06	Iran	D	23.0	7.0	1,2,3	5.0	0.5	3,4	7.40	0.19	0.06	
14	JA30	1930.11.25	Japan	E	24.0	2.0	4,5	3.5	0.1	1	7.28	0.24	0.08	12
15	CH31	1931.08.10	China	E	173.0	7.0	1,2,3				7.94	0.21	0.07	
16	CH32	1932.12.25	China	B	116.0	6.0	2,3,4,7	4.0	1.0	1,3	7.69	0.16	O.06)	
17	CH35N	1935.04.20	China	B	18.0	3.0	1,2,3,4	3.0	0.2	1,3	--	--	--	
18	CH35S	1935.04.20	China	E	17.0	3.0	1,2,3,4	1.7	0.3	1	--	--		
19	TK38	1938.04.19	Turkey	E	14.0	2.0	1,2,3				6.77	0.29	0.08	
20	TK39	1939.12.26	Turkey	E	365.0	5.0	1,3	3.7	0.3	4	7.77	0.23	0.06	
21	CA40	1940.05.19	U.S.A.	E	63.0	3.0	4,5	5.9	0.1	1	7.17	0.32	0.09	8
22	TK42	1942.12.20	Turkey	E	45.0	5.0	1	1.75	0.2	2,4	7.23	0.19	0.07	
23	JA43	1943.09.10	Japan	E	11.0	3.0	2,3,4,5	1.5	0.1	2,4	7.42	0.22	0.06	13
24	TK43	1943.11.26	Turkey	E	288.0	8.0	2,3				7.54	0.30	0.11	
25	TK44	1944.02.01	Turkey	E	177.0	8.0	3,4				7.52	0.35	0.12	
26	JA45	1945.01.12	Japan	B	31.0	5.0	1,4	2.2	0.2	1,3	6.84	0.30	0.09	14
27	CH46	1946.12.04	China	E				2.1	0.05	3	6.68	0.48	0.17	
28	CA50	1950.12.14	U.S.A.	A	8.7	0.2	5,7	0.6	0.15	3	5.65[e]	0.25	0.13	
29	CH51	1951.11.24	China	D	43.0	1.0	1,2,3	2.1	0.1	3,4	7.44	0.36	0.10	17
30	CA52	1952.07.21	U.S.A.	B	52.0	1.0	4,5	1.2	0.2	1,3	7:66[f]	0.30	0.04	15
31	TK53	1953.03.18	Turkey	E	64.0	6.0	1,3,4	4.3	0.05	2,10	7.24	0.25	0.09	
32	NV54A	1954.07.06	U.S.A.	A	20.0	2.0	3,7	0.3	0.05	2,4	6.34	0.26	0.12	14
33	NV54B	1954.08.24	U.S.A.	A	26.0	5.0	3	0.76	0.05	2,4	6.95	0.28	0.11	14
34	NV54C	1954.12.16	U.S.A.	C	48.0	5.0	3,4,5	5.6	0.2	1,3,10	7.24	0.22	0.07	14
35	NV54D	1954.12.16	U.S.A.	A	47.0	4.0	3,7	2.7	0.6	1	--	--	--	
36	MX56	1956.02.09	Mexico	D	22.0	2.0	4,7	0.9	0.05	3	6.94	0.23	0.09	15
37	MG57	1957.12.04	Mongolia	E	245.0	5.0	1,3	9.2	0.3	1,2,4	7.88	0.25	0.10	
38	MT59	1959.08.18	U.S.A.	A	26.0	2.0	3,8	5.5	0.3	2,4	7.57	0.40	0.14	15
39	IR62	1962.09.01	Iran	B	80.0	23.0	1,2,3	0.8	0.2	1,3	7.16	0.28	0.09	
40	MG67	1967.01.05	Mongolia	E	36.0	2.0	3,7				7.45	0.13	0.04	
41	TK67	1967.07.22	Turkey	E	58.0	4.0	3,4,9	1.9	0.2	2,4	7.41	0.21	0.05	15
42	CA68	1968.04.09	U.S.A.	E	31.0	1.0	3,6	0.38	0.01	1,4	6.83	0.19	0.06	11
43	IR68	1968.08.31	Iran	E	74.0	6.0	1,2,3,4	4.5	0.1	1,2	7.13	0.34	0.11	
44	AT68	1968.10.14	Australia	B	36.0	1.0	2,3	3.5	0.1	3,4	6.89	0.30	0.08	10
45	CH70	1970.01.04	China	E	47.0	1.0	2,3	2.7	0.05	3	7.51	0.27	0.10	
46	AT70	1970.03.10	Australia	B	3.4	0.2	2,3	0.7	0.37	2,3,4	4.98	0.27	0.06	
47	TK70	1970.03.28	Turkey	A	38.0	1.0	1,3,4,5	2.4	0.2	3,4	7.07	0.17	O.04	
48	CA71	1971.02.09	U.S.A.	D	16.0	1.0	6,8	2.1	0.1	1,2,3,4	6.53	0.23	0.06	18
49	CH73	1973.02.06	China	E	89.0	2.0	3	3.6	0.05	10	7.30	0.31	0.07	
50	CA75	1975.05.31	U.S.A.	E	6.6	0.1	3,7	0.015	0.003	1,2,3	5:30[g]	0.14	0.10	3
51	GU76	1976.02.04	Guatemala	E	235.0	5.0	4,5	3.3	0.1	1,2,3,4	7.46	0.27	0.09	13
52	TK76	1976.11.24	Turkey	E	55.0	5.0	1,4,5	3.5	0.2	1	7.32	0.15	0.04	
53	IR77	1977.12.19	Iran	E	19.5	0.2	3,4,8	0.2	0.02	4	5.82	0.27	0.09	
54	IR78	1978.09.16	Iran	B	80.0	14.0	3,4				7.48	0.28	0.06	17
55	CA79	1979.10.15	U.S.A.	E	30.1	0.3	3,5,7				6.66	0.38	0.08	8
56	IR79A	1979.11.14	Iran	E	20.0	1.0	3,5	1.0	0.1	1,3,4	6.69	0.31	0.08	
57	IR79B	1979.11.27	Iran	D	63.0	3.0	1	3.7	0.4	1,3,4	7.15	0.32	0.10	
58	AL80	1980.10.10	Algeria	B	33.0	2.0	1,3,4	4.9	1.7	1,3	7.25	0.27	0.08	16

a Displacement measured across a zone whose width was generally less than 10 m but for a few events (e.g. AT68 an AL80) the widths may have been several tens of meters. For strike-slip faults, maximum strike-slip component is listed unless one side was consistently uplifted; for these the greater of either the maximum strike-slip or maximum resultant slip is listed.

b Standard error of the mean, $\sigma/\sqrt{n}$, where σ is sample standard deviation and n is number in sample.

c Data are omitted where ambiguities could not be resolved.

d These numbers were used in the computations but if cited as individual Ms values they should be rounded to nearest tenth.

e Local magnitude, ML from Gutenberg's unpublished notes.

f Ms from special study by Gutenberg (1955).

g Local magnitude, ML, from Earthquake Data Report, EDR 37-75. U.S. Geological Survey (1975).

REFERENCES FOR TABLE 3

CA857 Sieh (1978), Wood (1955), Johnson (1905)
JA891 Matsuda (1974), Muramatu et al. (1964)
GR894 Skuphos (1894), Papavasiliou (1894a, 1894b)
JA896 Yamasaki (1900), Matsuda et al. (1980)
CA06 Lawson et al. (1908), Evernden et al. (1981), Lee (1971), W.H.K.Lee (1978, written commun.)
NV15 Wallace, 1984
JA27 Yamasaki and Tada (1928), Terada and Higasi (1928), Kanamori (1973), Watanabe and Sato (1928), Kunitomi (1930), Nasu (1929a, 1929b), Matsu'ura (1977)
KE28 Willis (1936), Ambraseys and Tchalenko (1968), Richter (1958)
BG28A Bonchev and Bakalov (1928), Jankof (1945)
BG28B Bonchev and Bakalov (1928), Jankof (1945), Kiroff (1935)
IR29 Tchalenko (1975)
NZ29 Henderson (1937), Berryman (1979, 1980)
IR30 Berberian (1976), Berberian and Tchalenko (1976), Ambraseys (1978b)
JA30 Central Meteorological Observatory (1930), Matsuda (1972), Tsumura et al. (1977)
CH31 Yang and Ge (1980), Beijing Review (1982)
CH32 Shih et al. (1974), Jiang and Gao (1976)
CH35N Otuka (1936), Earthquake Research Institute (1936), Bonilla (1975), Hsu and Chang (1979)
CH35S Otuka (1936), Earthquake Research Institute (1936), Bonilla (1975), Hsu and Chang (1979)
TK38 Arni (1938), Parejas and Pamir (1940)
TK39 Parejas et al. (1941), Ketin (1969)
CA40 J. P. Buwalda (1970, unpublished data), Richter (1958), Sharp (1982), Johnson and Hill (1982)
TK42 Blumenthal et al. (1943), Pamir (1952)
JA43 Tsuya (1944), Miyamura (1944), Kanamori (1972, 1973), Omote (1955)
TK43 Blumenthal (1945), Ketin (1969)
TK44 Pinar (1953), Ketin (1969), Allen (1969)
JA45 Tsuya (1946), Inouye (1950), Iida and Sakabe (1972), Ando (1974), Kobayashi (1976), Ooida and Yamada (1972)
CH46 Chang et al. (1947)
CA50 Gianella (1957)
CH51 Hsu (1962), Hsu and Chang (1979), Wang (1975)
CA52 Buwalda and St. Amand (1955), Cotton et al. (1976), Gutenberg (1955), Cisternas (1963), Southern Calif. Cooperative Seismic Network catalog (Calif. Institute Technology, Pasadena)
TK53 Ketin and Roesli (1953), Dilgan and Hagiwara (1956)
NV54A Tocher (1956), Mickey (1966), Westphal and Lange (1967), Ryall and Malone (1971)
NV54B Tocher (1956), Mickey (1966), Westphal and Lange (1967)., Ryall and Malone (1971)
NV54C Slemmons (1957, 1977), Slemmons et al. (1959), Mickey (1966), Smith et al (1972)
NV54D Slemmons (1957, 1977)
MX56 Shor and Roberts (1958), Johnson et al. (1976)
MG57 Florensov and Solonenko (1963), Lukianov (1965)
MT59 Witkind (1964), Myers and Hamilton (1964), Trimble and Smith (1975)

IR62 Ambraseys (1963, 1965, 1978a, 1978b), Mohajer and Pierce (1963)
MG67 Natsag-yum et al. (1971)
TK67 Ambraseys and Zatopek (1969), Crampin and Ucer (1975)
CA68 Allen et al. (1968), Clark (1972), Hamilton (1972)
IR68 Niazi (1968), Ambraseys and Tchalenko (1969), McEvilly and Niazi (1975)
AT68 Gordon and Lewis (1980), Fitch et al. (1973)
CH70 Zhang and Liu (1978)
AT70 Gordon and Lewis (1980)
TK70 Tasdemiroglu (1971), Ambraseys and Tchalenko (1972)
CA71 Kamb et al. (1971), U. S. Geological Survey (1971), Hanks et al. (1971), Barrows (1975), Barrows et al. (1974), Sharp (1975, 1981), Hanks (1974)
CH73 Tang et al. (1976)
CA75 Fuis (1976), Hill and Beeby (1977), G. Fuis (written commun., 1979)
GU76 Plafker (1976 and unpublished data, 1976), Plafker et al. (1976), Bucknam et al. (1978), Langer and Bollinger (1979)
TK76 Toksoz et al. (1977, 1978), Arpat et al. (1977)
IR77 Berberian et al. (1979), Ambraseys et al. (1979)
IR78 Berberian 1979, 1982)
CA79 Sharp et al. (1982), Johnson and Hill (1982)
IR79A Haghipour and Amidi (1980), Nowroozi and Mohajer-Ashjai (1981), Adeli (1981)
IR79B Haghipour and Amidi (1980), Nowroozi and Mohajer-Ashjai (1981)
AL80 Burford et al. (1981), Ouyed et al. (1981), Yielding et al. (1981), Ambraseys (1981)

TABLE 4
RESULTS OF REGRESSION ANALYSES FOR ORDINARY LEAST-SQUARES AND WEIGHTED LEAST-SQUARES MODELS

Set	n	Model	For	a	b	s	r^2 (%)	Standard error a	Standard error b	t ratio a	t ratio b
nml . dm	9										
		OLS	Ms	6.81	0.741	0.188	82.1	0.073	0.130	93.40	5.67
		WLS	Ms	6.81	0.728	-----	----	0.077	0.138	88.11	5.26
		OLS	log(d)	-7.51	1.109	0.230	82.1	1.376	0.195	-5.46	5.67
		WLS	log(d)	-7.38	1.096	-----	----	1.483	0.208	-4.98	5.26
nml.dl	12										
		WLS	log(l)	1.47	0.372	-----	----	0.086	0.116	16.97	3.21
		WLS	log(d)	-1.65	1.361	-----	----	0.734	0.425	-2.25	3.21
rv.lm	12										
		OLS	Ms	5.71	0.916	0.274	45.5	0.521	0.317	10.97	2.89
		WLS	Ms	5.13	1.324	-----	----	0.518	0.310	9.91	4.27
		OLS	log(l)	-1.96	0.497	0.202	45.5	1.239	0.172	-1.58	2.89
		WLS	log(l)	-1.92	0.488	-----	----	0.837	0.114	-2.29	4.27
ss.lm	23										
		OLS	Ms	6.24	0.619	0.293	49.8	0.255	0.136	24.42	4.56
		WLS	Ms	6.10	0.697	-----	----	0.247	0.132	24.75	5.28
		OLS	log(l)	-4.10	0.804	0.334	49.8	1.301	0.176	-3.15	4.56
		WLS	log(l)	-4.21	0.818	-----	----	1.144	0.155	-3.68	5.28
ss.dm	18										
		OLS	Ms	7.00	0.782	0.331	37.6	0.137	0.252	51.19	3.10
		WLS	Ms	7.07	0.698	-----	----	0.107	0.201	65.98	3.48
		OLS	log(d)	-3.09	0.481	0.260	37.6	1.140	0.155	-2.71	3.10
		WLS	log(d)	-4.13	0.617	-----	----	1.305	0.177	-3.16	3.48
ss.dl	22										
		OLS	log(l)	1.59	0.530	0.371	48.4	0.088	0.122	17.95	4.33
		WLS	log(l)	1.66	0.566	-----	----	0.103	0.156	16.18	3.63
		OLS	log(d)	-1.28	0.914	0.487	48.4	0.385	0.211	-3.33	4.33
		WLS	log(d)	-0.85	0.701	-----	----	0.384	0.193	-2.21	3.63
uc7.lm	9										
		OLS	Ms	4.94	1.296	0.193	91.0	0.291	0.154	17.01	8.41
		WLS	Ms	4.89	1.319	-----	----	0.245	0.131	20.00	10.05
		OLS	log(l)	-3.30	0.702	0.142	91.0	0.613	0.083	-5.39	8.41
		WLS	log(l)	-3.35	0.709	-----	----	0.516	0.071	-6.50	10.05
us7.lm	5										
		OLS	Ms	4.88	1.286	0.096	98.7	0.155	0.086	31.52	14.90
		WLS	Ms	4.92	1.272	-----	----	0.154	0.090	32.02	14.21
		OLS	log(l)	-3.72	0.767	0.074	98.7	0.367	0.051	-10.14	14.90
		WLS	log(l)	-3.79	0.775	-----	----	0.384	0.055	-9.86	14.21
us5.dl	9										
		OLS	log(l)	1.42	0.316	0.217	65.7	0.072	0.086	19.63	3.66
		WLS	log(l)	1.47	0.363	-----	----	0.073	0.090	20.28	4.04
		OLS	log(d)	-2.95	2.080	0.556	65.7	0.825	0.568	-3.58	3.66
		WLS	log(d)	-2.64	1.927	-----	----	0.823	0.477	-3.21	4.04
tky.1m	9										
		OLS	Ms	6.18	0.606	0.101	89.5	0.151	0.078	40.81	7.73
		WLS	Ms	6.13	0.645	-----	----	0.169	0.091	36.32	7.05
		OLS	log(l)	-8.93	1.478	0.157	89.5	1.400	0.191	-6.38	7.73
		WLS	log(l)	-8.10	1.359	-----	----	1.406	0.193	-5.76	7.05

TABLE 4 (continued)

Set	n	Model	For	a	b	s	r^2 (%)	Standard error		t ratio	
								a	b	a	b
wna.lm	12										
		OLS	Ms	5.17	1.237	0.324	70.0	0.422	0.256	12.24	4.83
		WLS	Ms	5.04	1.346	-----	----	0.440	0.261	11.45	5.15
		OLS	log(l)	-2.44	0.566	0.219	70.0	0.841	0.117	-2.90	4.83
		WLS	log(l)	-2.27	0.539	-----	----	0.763	0.105	-2.97	5.15
wna.dm	11										
		OLS	Ms	6.98	0.742	0.442	45.4	0.155	0.271	45.20	2.74
		WLS	Ms	6.98	0.649	-----	----	0.170	0.301	41.05	2.15
		OLS	log(d)	-4.12	0.612	0.402	45.4	1.613	0.224	-2.55	2.74
		WLS	log(d)	-3.47	0.524	-----	----	1.752	0.243	-1.98	2.15
wna.dl	15										
		OLS	log(l)	1.51	0.462	0.367	50.4	0.097	0.127	15.62	3.64
		WLS	log(l)	1.56	0.365	-----	----	0.111	0.151	14.05	2.42
		OLS	log(d)	-1.58	1.093	0.565	50.4	0.498	0.300	-3.16	3.64
		WLS	log(d)	-0.95	0.852		----	0.627	0.352	-1.52	2.42
pm.lm	9										
		OLS	Ms	5.58	0.888	0.245	74.1	0.426	0.198	13.10	4.48
		WLS	Ms	5.68	0.858	-----	----	0.411	0.193	13.80	4.45
		OLS	log(l)	-4.11	0.835	0.237	74.1	1.391	0.186	-2.96	4.48
		WLS	log(l)	-4.35	0.862	-----	----	1.448	0.193	-3.00	4.45
int.lm	36										
		OLS	Ms	6.02	0.729	0.320	31.4	0.304	0.185	19.81	3.95
		WLS	Ms	5.60	1.000	-----	----	0.296	0.177	18.91	5.65
		OLS	log(l)	-1.49	0.431	0.246	31.4	0.788	0.109	-1.88	3.95
		WLS	log(l)	-1.86	0.485	-----	----	0.622	0.086	-2.99	5.65
int.dm	33										
		OLS	Ms	6.93	0.665	0.299	41.6	0.074	0.141	94.01	4.70
		WLS	Ms	6.97	0.604	-----	----	0.078	0.149	89.25	4.05
		OLS	log(d)	-4.12	0.626	0.290	41.6	0.957	0.133	-4.31	4.70
		WLS	log(d)	-3.73	0.572	-----	----	1.019	0.141	-3.66	4.05
int.dl	41										
		OLS	log(l)	1.44	0.364	0.287	32.7	0.050	0.084	28.64	4.35
		WLS	log(l)	1.51	0.466	-----	----	0.053	0.080	28A2	5.85
		OLS	log(d)	-1.11	0.897	0.450	32.7	0.324	0.206	-3.42	4.35
		WLS	log(d)	-1.23	1.002	-----	----	0.306	0.171	-4.02	5.85
all.lm	45										
		OLS	Ms	6.04	0.708	0.306	43.8	0.215	0.122	28.07	5.79
		WLS	Ms	5.87	0.818	-----	----	0.208	0.117	28.27	6.98
		OLS	log(l)	-2.77	0.619	0.286	43.8	0.777	0.107	-3.56	5.79
		WLS	log(l)	-3.00	0.649	-----	----	0.679	0.093	-4.41	6.98
all.dm	39										
		OLS	Ms	6.95	0.723	0.323	39.8	0.077	0.146	89.81	4.94
		WLS	Ms	6.98	0.686	-----	----	0.084	0.157	83.48	4.36
		OLS	log(d)	-3.58	0.550	0.282	39.8	0.806	0.111	-4.45	4.94
		WLS	log(d)	-3.18	0.495	-----	----	0.826	0.113	-3.85	4.36
all.dl	48										
		OLS	log(l)	1.48	0.469	0.352	33.1	0.059	0.098	24.90	4.77
		WLS	log(l)	1.58	0.486	-----	----	0.077	0.117	20.47	4.14
		OLS	log(d)	-0.83	0.706	0.431	33.1	0.249	0.148	-3.35	4.77
		WLS	log(d)	-0.48	0.559	-----	----	0.253	0.135	-1.90	4.14

Abbreviations for Table 4: nml, normal- and normal-oblique-slip faults; rv., reverse- and reverse-oblique-slip faults; ss, strike-slip faults; UC7, U.S. and China k=1.75 attenuation region; US7, U.S. k=1.75 attenuation region; US5, U.S. k=1.5 attenuation region; tky., Turkey; wna, western North America; pm, plate margins; int., plate interiors; all, all faults; d, maximum fault displacement at the ground surface; 1., rupture length at the ground surface; m and M , earthquake magnitude; n, number of events; OLS, ordinary least squares; WLS, weighted least squares; For, dependent variable Y, in Y = a + bX; s, standard deviation of the dependent variable about the regression line; r^2, coefficient of determination where r is the correlation coefficient; t ratio, coefficient of a or b divided by the corresponding standard error of a or b.

TABLE 5

COMPARISON OF MEASUREMENT AND REGRESSION VARIANCES AND OTHER STATISTICAL MEASURES FOR ORDINARY LEAST-SQUARES MODEL

Regression		n	t	Prob	S	ME	ME/S	$(ME/S)^2$
1	nml.md	9	5.67	0.001	0.188	0.093	0.493	0.243
2	nml.dm	9	5.67	0.001	0.230	0.072	0.313	0.098
3	rv.ml	12	2.89	0.016	0.274	0.078	0.285	0.081
4	rv.lm	12	2.89	0.016	0.202	0.063	0.313	0.098
5	ss.ml	23	4.56	0.000	0.293	0.084	0.285	0.081
6	ss.lm	23	4.56	0.000	0.334	0.038	0.115	0.013
7	ss.md	18	3.10	0.007	0.331	0.089	0.270	0.073
8	ss.dm	18	3.10	0.007	0.260	0.024	0.094	0.009
9	ss.ld	22	4.33	0.000	0.371	0.043	0.116	0.013
10	ss.dl	22	4.33	0.000	0.487	0.041	0.085	0.007
11	uc7.ml	9	8.41	0.000	0.193	0.076	0.393	0.154
12	uc7.lm	9	8.41	0.000	0.142	0.017	0.123	0.015
13	us7.ml	5	14.90	0.001	0.096	0.075	0.779	0.607
14	us7.lm	5	14.90	0.001	0.074	0.019	0.253	0.064
15	us5.ld	9	3.66	0.008	0.217	0.039	0.180	0.032
16	us5.dl	9	3.66	0.008	0.556	0.075	0.134	0.018
17	tky.ml	9	7.73	0.000	0.101	0.078	0.777	0.604
18	tky.1m	9	7.73	0.000	0.157	0.035	0.222	0.049
19	wna.ml	12	4.83	0.001	0.324	0.089	0.275	0.076
20	wna.lm	12	4.83	0.001	0.219	0.036	0.164	0.027
21	wna.md	11	2.74	0.023	0.442	0.090	0.203	0.041
22	wna.dm	11	2.74	0.023	0.402	0.035	0.087	0.008
23	wna.ld	15	3.64	0.003	0.367	0.039	0.107	0.011
24	wna.dl	15	3.64	0.003	0.565	0.060	0.106	0.011
25	pm.ml	9	4.48	0.003	0.245	0.086	0.351	0.123
26	pm.lm	9	4.48	0.003	0.237	0.023	0.096	0.009
27	int.ml	36	3.95	0.000	0.320	0.083	0.261	0.068
28	int.lm	36	3.95	0.000	0.246	0.054	0.220	0.048
29	int.md	33	4.70	0.000	0.299	0.089	0.297	0.088
30	int.dm	33	4.70	0.000	0.290	0.058	0.199	0.040
31	int.ld	41	4.35	0.000	0.287	0.053	0.184	0.034
32	int.dl	41	4.35	0.000	0.450	0.072	0.160	0.026
33	all.ml	45	5.79	0.000	0.306	0.084	0.275	0.076
34	all.lm	45	5.79	0.000	0.286	0.049	0.173	0.030
35	all.md	39	4.94	0.000	0.323	0.087	0.269	0.072
36	all.dm	39	4.94	0.000	0.282	0.055	0.194	0.038
37	all.ld	48	4.77	0.000	0.352	0.051	0.145	0.021
38	all.dl	48	4.77	0.000	0.431	0.068	0.157	0.025
	Mean							0.082
	Median							0.041

Abbreviations for Table 5: Prob, probability that t would be as high as or higher than the listed value if there were no linear correlation; ME, average measurement error for dependent variable; S, standard error of the regression; $(ME/S)^2$, the variance ratio. Other abbreviations are the same as in Table 4.

TABLE 6
RESULTS OF REGRESSION ANALYSES OF M ON VARIOUS COMBINATIONS OF SURFACE RUPTURE LENGTH, MAXIMUM SURFACE DISPLACEMENT, AND DOWNDIP WIDTH

Independent variable	n	a	b	s	r^2 %	Standard error a	Standard error b	t ratio a	t ratio b
log LD	37	6.22	0.492	0.272	55.5	0.161	0.074	38.62	6.61
	41	5.80	0.667	0.353	72.9	0.135	0.065	43.10	10.24
Log LW	21	4.96	0.823	0.342	45.6	0.568	0.206	8.73	3.99
	22	4.36	1.035	0.355	66.7	0.442	0.164	9.87	6.32
Log LWD	19	5.65	0.514	0.323	52.2	0.372	0.119	15.21	4.31
	20	5.66	0.512	0.314	75.4	0.210	0.069	27.00	7.44

Notes : Regressions are for M using ordinary least squares: M = a + bX, where X is the independent variable in first column; $M = M_s$ for $M_s \geq 6$, $M = M_s$ or M_L for $M < 6$. L, length, and W, width, are in km; D, maximum surface displacement, is in m. The number of data points is shown under "n". The smaller of the 2 numbers under n for each combination includes events with $M \geq 6$ and the larger is for all events. The t probability for the set Log LW, n = 21, is 0.001; all the others are 0.000.

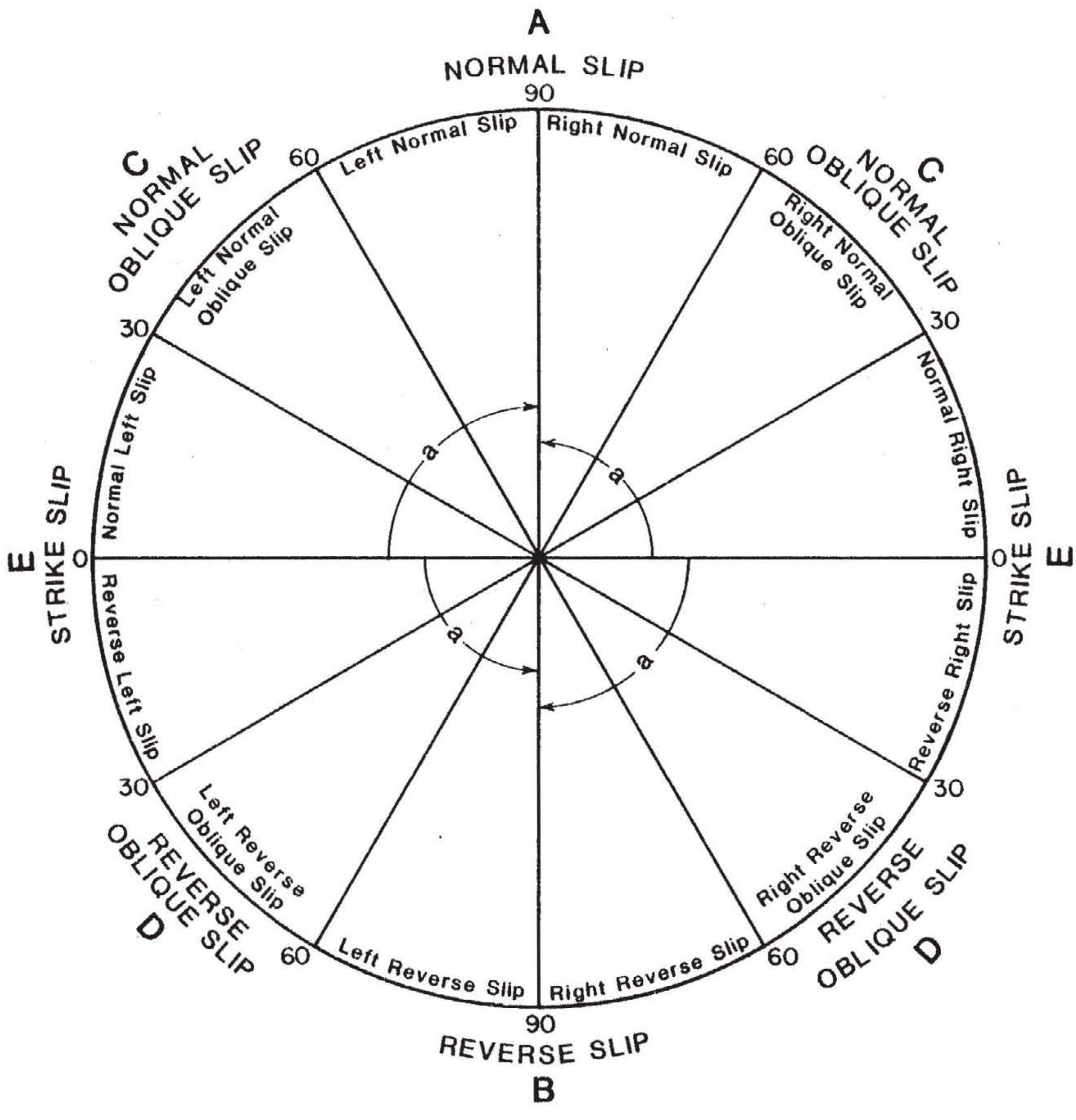


Figure 1. Diagram showing classification of fault types. The circle is in the plane of a fault dipping toward the observer; if a point originally at the center of the circle and on the far side of the fault is displaced to the rim of the circle, movement of the point generates a radial line that makes an angle a (measured in the plane of the fault) with the horizontal line. The radii that mark the boundaries between fault types make angles ("a") of 30°, 60°,and 90° above or below the horizontal line, which represents the strike of the fault.

ALL FIGURE 2A

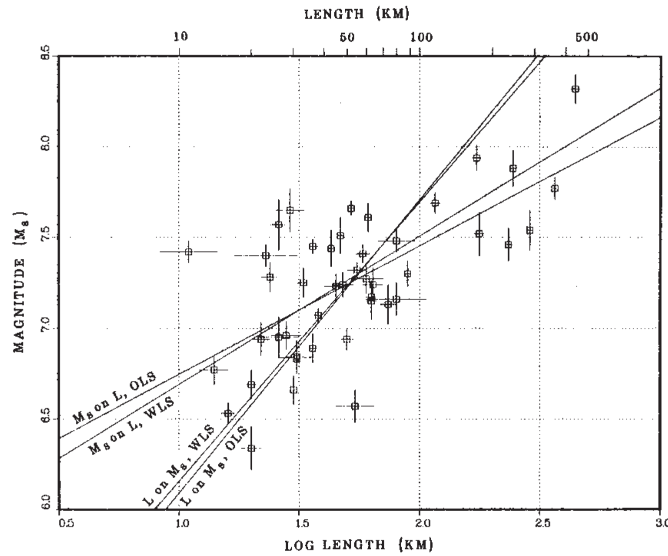


Figure 2. Length of surface rupture versus surface-wave magnitude, with regression lines for various fault groups. M_S on L, regression of magnitude on log length; L on M_S, regression of log length on magnitude; OLS, ordinary least squares; WLS, weighted least squares. Error bars are shown for each event.

2A	All faults
2B	Reverse- and reverse-oblique-slip faults
2C	Strike-slip faults
2D	Faults in Turkey
2E	Faults in western North America
2F	Faults in U.S. attenuation region k=1.75
2G	Faults in U.S. and China attenuation regions k=1.75
2H	Faults on plate margins
2I	Faults in plate interiors

FIGURE 2B

RV

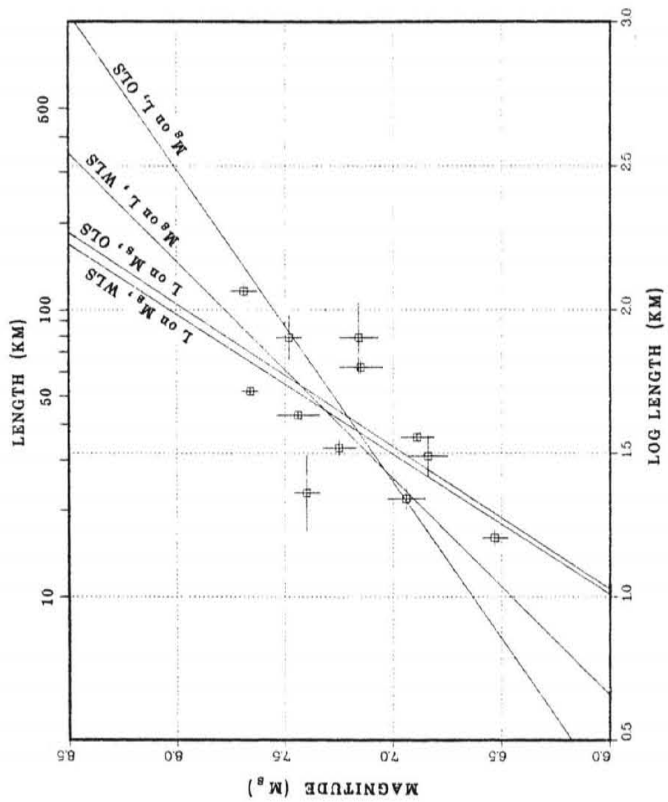
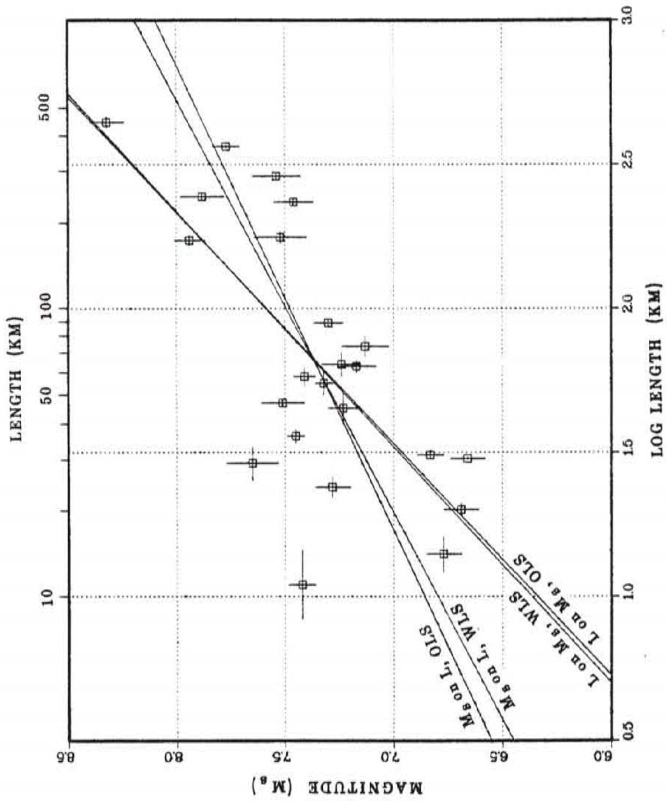
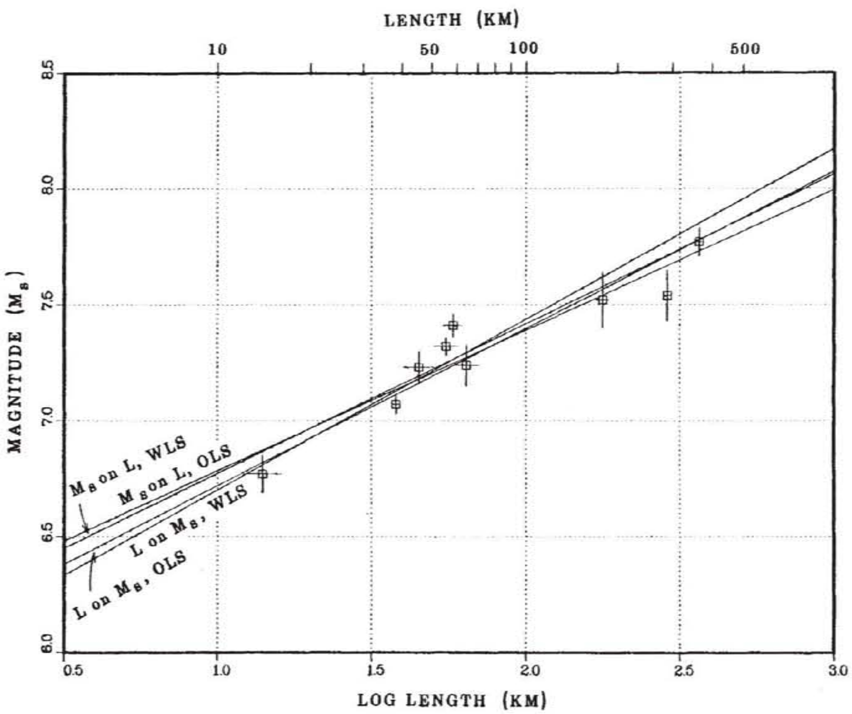


FIGURE 2C

SS



TKY FIGURE 2D



WNA FIGURE 2E

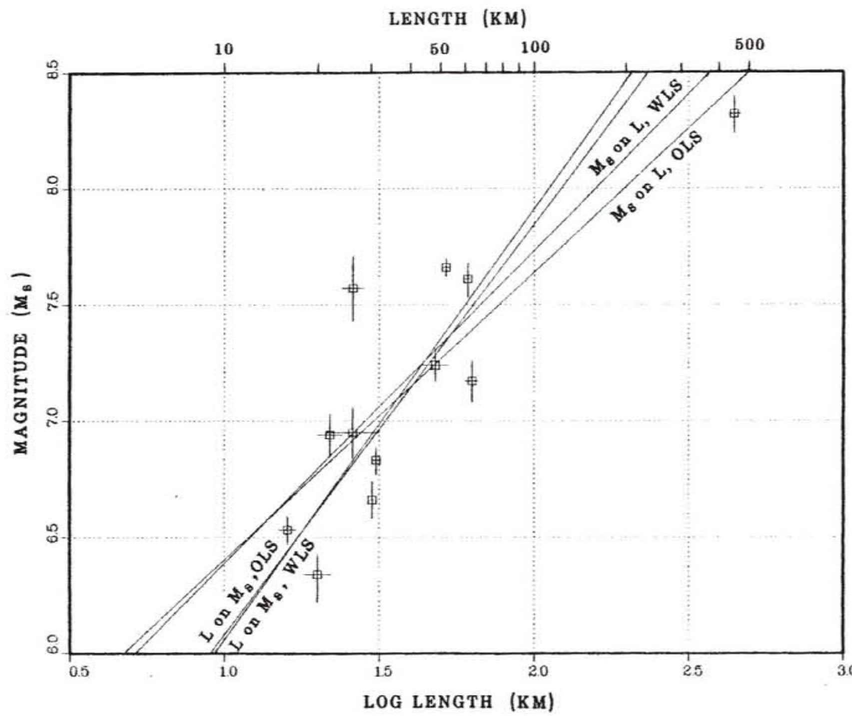


FIGURE 2F

US7

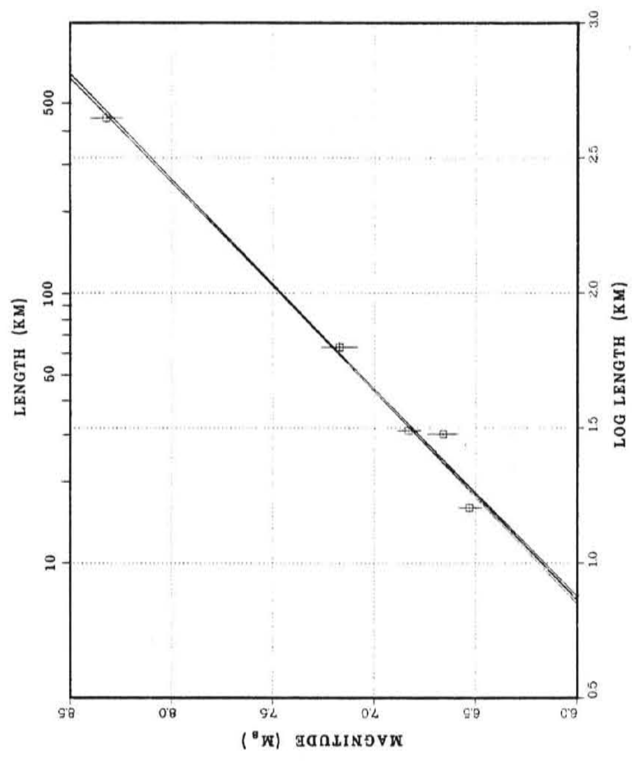


FIGURE 2G

UC7

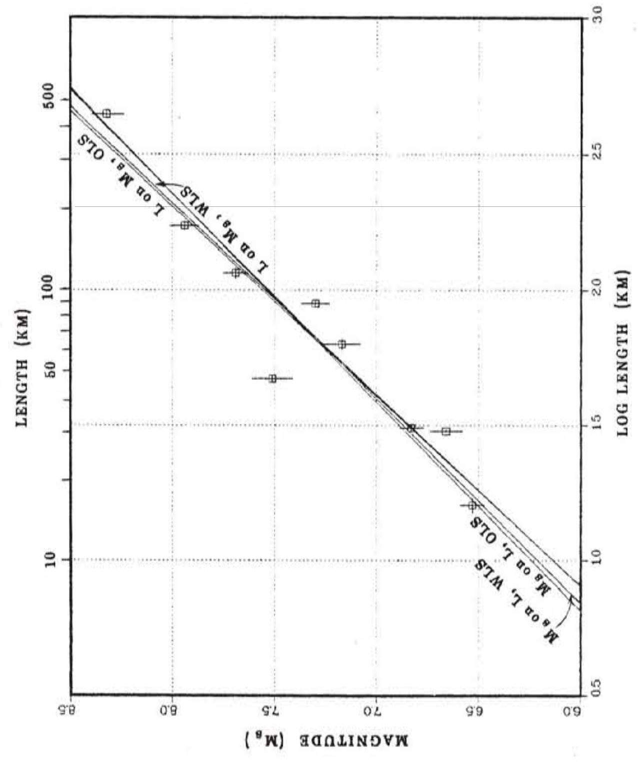


FIGURE 2I

INT

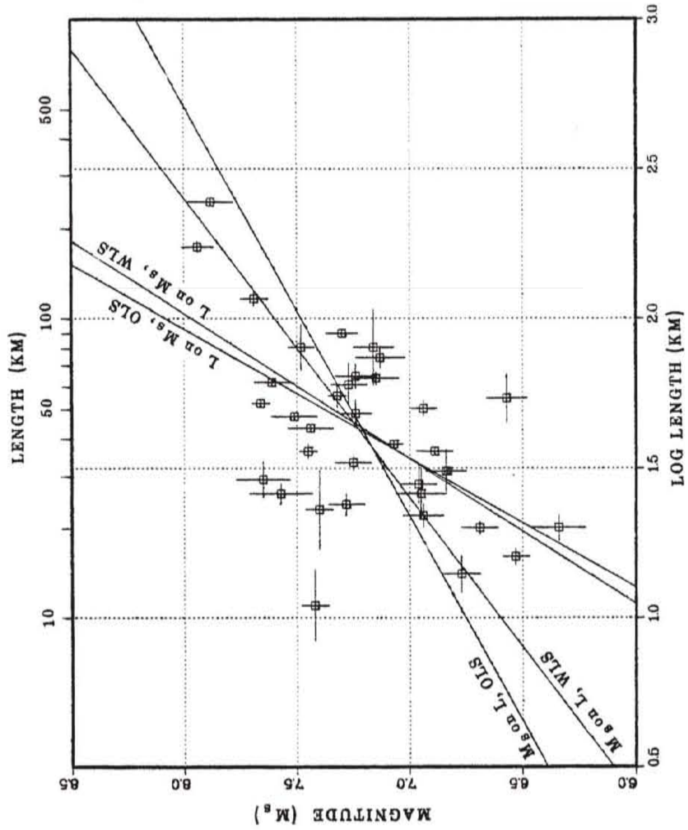
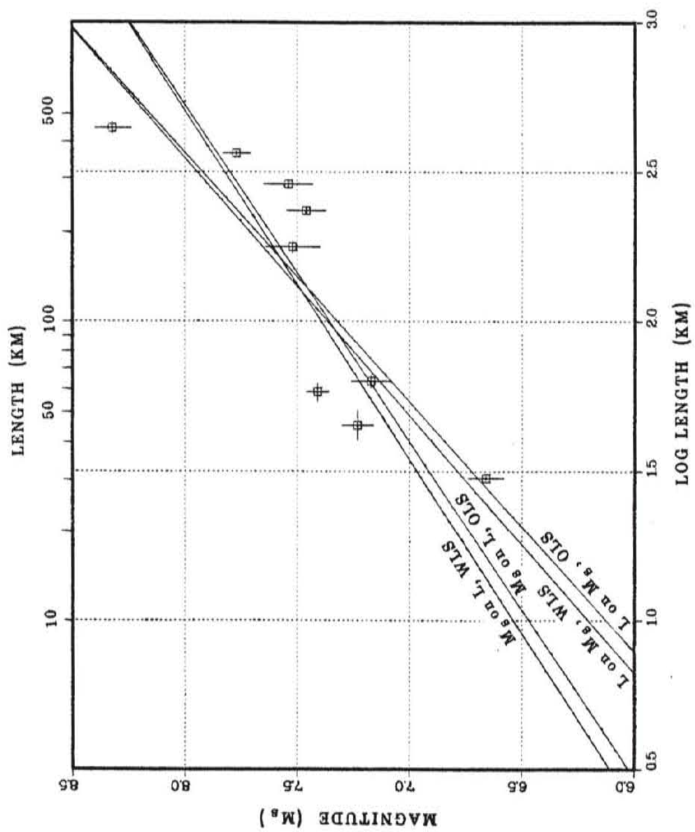
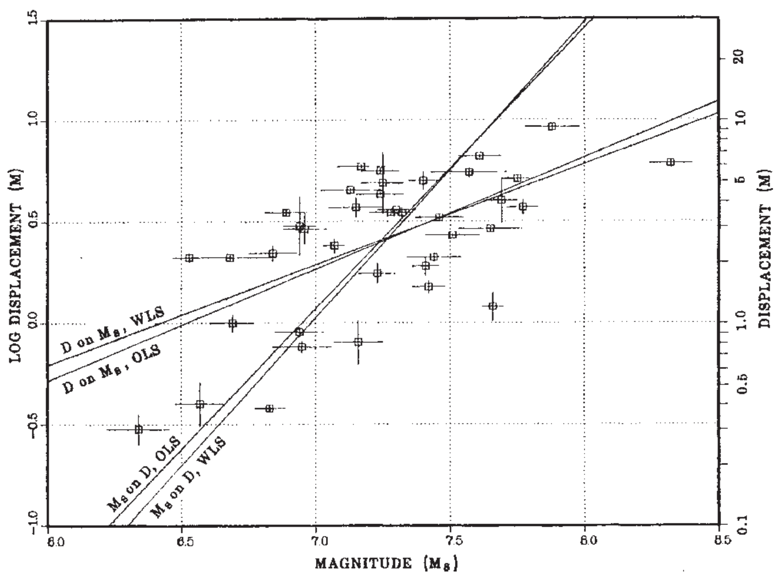


FIGURE 2H

PM



ALL FIGURE 3A



NML FIGURE 3B

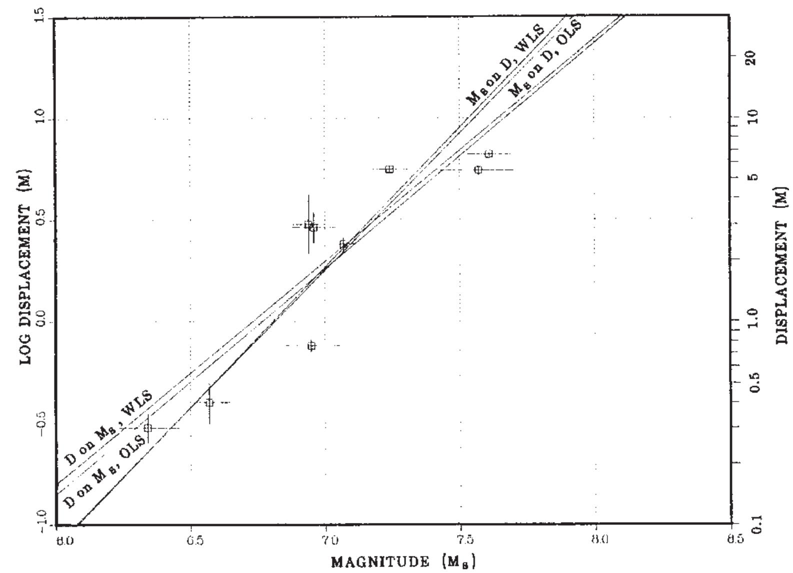


Figure 3. Surface-wave magnitude versus maximum fault displacement at surface, with regression lines for various fault groups. M_S on D, regression of magnitude on log displacement; D on M_S, regression of log displacement on magnitude; OLS, ordinary least squares; WLS, weighted least squares. Error bars are shown for each event.

- 3A All faults
- 3B Normal- and oblique-slip faults
- 3C Strike-slip faults
- 3D Faults in western North America

FIGURE 3C

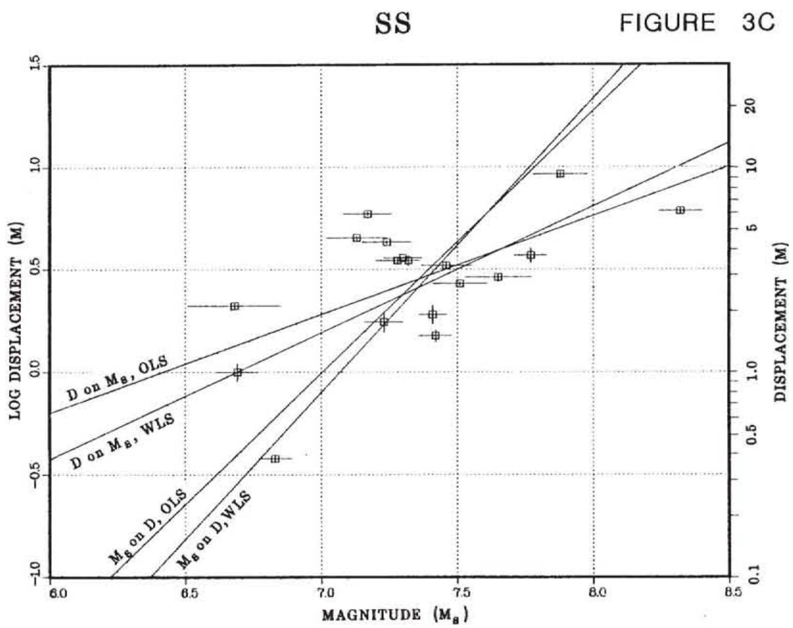
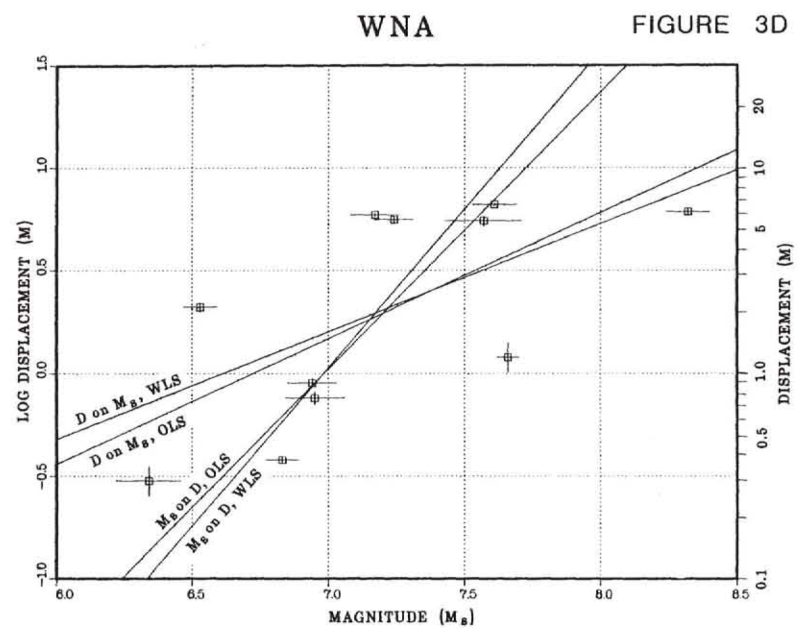


FIGURE 3D



ALL FIGURE 4A

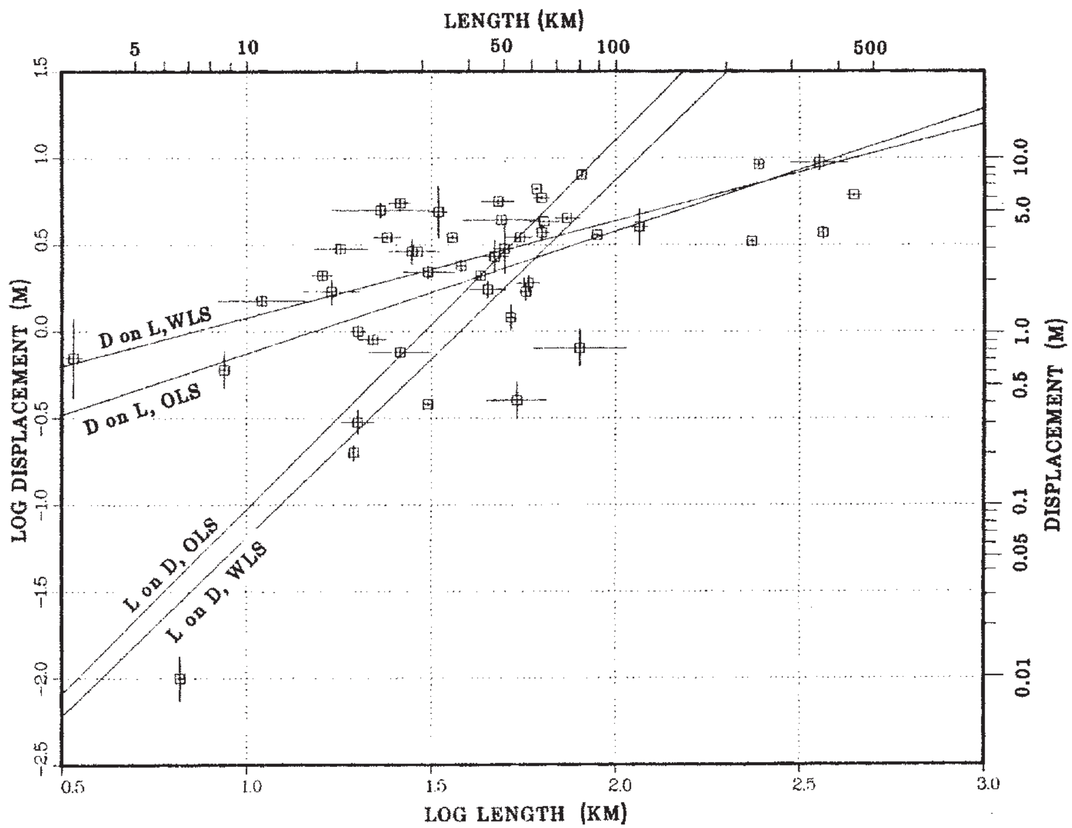
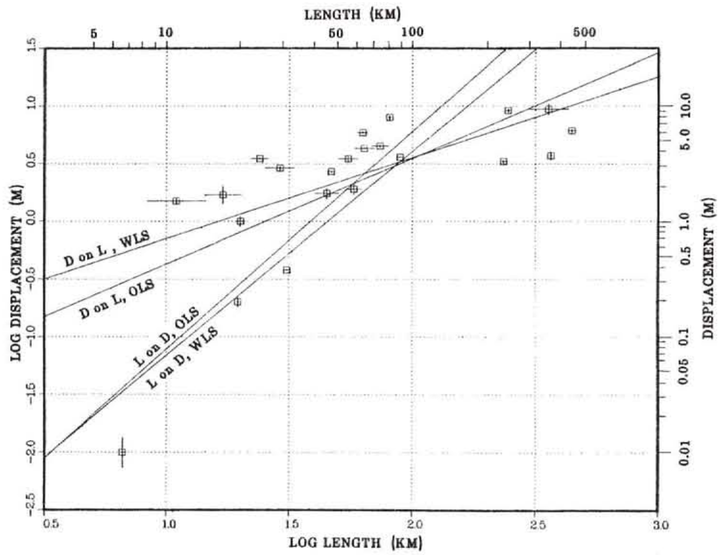


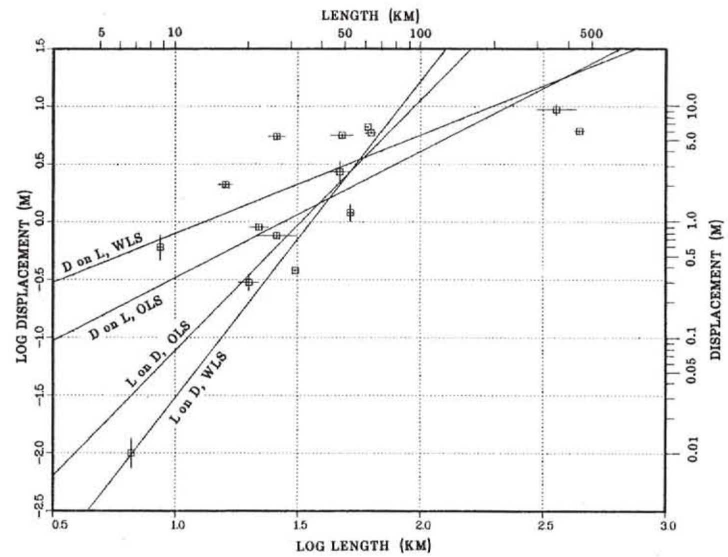
Figure 4. Maximum fault displacement at the surface versus length of surface rupture, with regression lines for various fault groups. D on L, regression of log displacement on log length; L on D, regression of log length on log displacement; OLS, ordinary least squares; WLS, weighted least squares. Error bars are shown for each event.

4A All faults
4B Strike-slip faults
4C Faults in western North America

SS FIGURE 4B



WNA FIGURE 4C



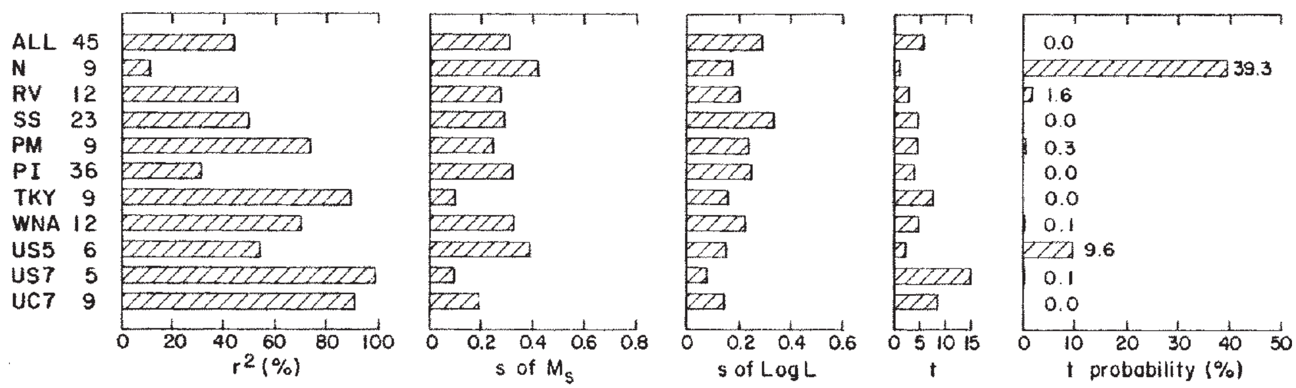


Figure 5. Bar graph showing coefficient of determination (r^2), standard deviation s of M_S regressed on logarithm of surface rupture length L and of log L on M_S (regression by ordinary least squares), t, and probability of t for various groups of events. Number of data points in each group is shown to right of name of each group. Abbreviations are: N, normal slip and normal-oblique slip; RV, reverse slip and reverse-oblique slip; SS, strike slip; PM, plate margins; PI, plate interiors; TKY, Turkey; WNA, western North America; US5, U.S. k=1.50 attenuation region; US7, U.S. k=1.75 attenuation region; UC7, U.S. and China k=1.75 attenuation regions.

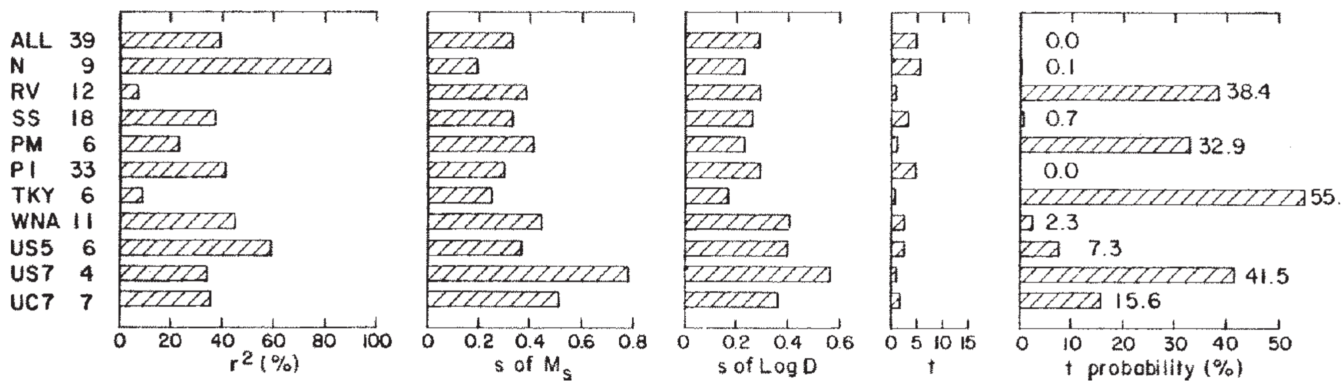


Figure 6. Bar graph showing coefficient of determination (r^2) and standard deviation (s) of M_S regressed on logarithm of maximum surface displacement D and of log D regressed on M_S by ordinary least squares, t, and probability of t. Number of data points in each group is shown to right of name of each group. Abbreviations same as in Figure 5.

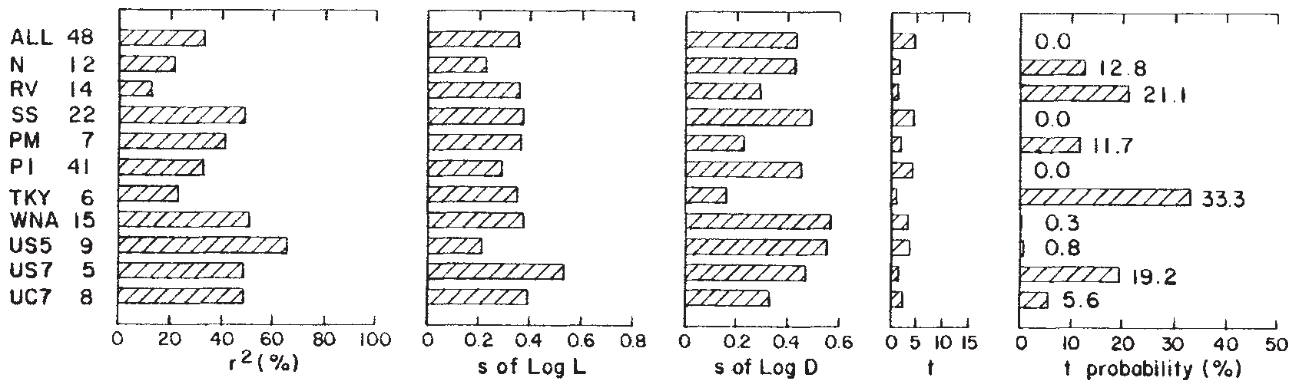


Figure 7. Bar graph showing coefficients of determination (r^2) and standard deviation (s) of logarithm of maximum surface displacement D regressed by ordinary least squares on logarithm of surface rupture length L and of log L regressed on log D, t, and probability of t. Number of data points in each group is shown to right of name of each group. Abbreviations same as in Figure 5.

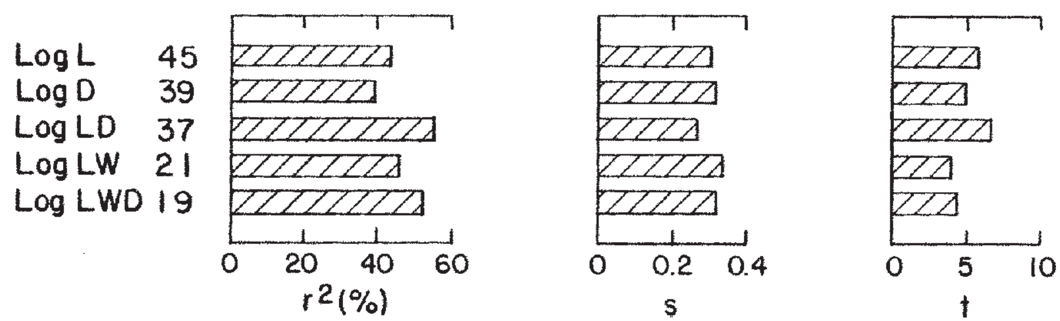


Figure 8. Comparison of correlations of M_S with various rupture parameters. Regressions are of M_S on the given parameter, using ordinary least squares, $M_S \geq 6$. Number of data points in each group is shown to right of parameter column. L, surface rupture length; D., maximum surface displacement; W, rupture width (downdip); r^2 , coefficient of determination, s, standard deviation of M_S; t, t-statistic. The t probability for the set Log LW is 0.001, and 0.000 for all the others.