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STRIKE-SLIP EARTHQUAKES ON QUASI-VERTICAL TRANSCURRENT FAULTS: INFERENCES FOR GENERAL SCALING RELATIONS

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Abstract. The recent occurrence of several large strike-slip earthquakes provides the opportunity to review and complement available data on the scaling of seismic moment (M_0) with length of rupture (L) for large earthquakes, depending on their tectonic setting and mechanism. For strike-slip earthquakes on quasi-vertical transcurrent faults, the M_0 versus L relation has a significant change of slope around $M_0 \sim (0.6\text{-}0.8)*10^{20}$ N-m, and for larger earthquakes, M_0 scales linearly with L. This is compatible with models where slip is controlled by the width of the fault. Also, it appears to be easier to categorize large earthquakes by their mechanism (strike-slip on vertical transcurrent fault, versus pure thrust/normal) than their tectonic setting (interplate/ intraplate).

Introduction

Many investigators have described the remarkable scaling relation, linking M_0 to fault area S for large earthquakes (e.g. Aki, 1972; Abe, 1975; Hanks, 1977):

$$Mo = k\, S^{3/2} \qquad (1)$$

where k is a constant. This self-similarity relation implies that static stress drop $\Delta\sigma$ is approximately constant for large earthquakes worldwide and falls in the range 10-100 bars. These inferences are made within the framework of dislocation theory, on the assumption of a fault of comparable dimensions in length (L) and width (W). In fact, it has also been documented (Abe, 1975; Purcaru and Berckhemer, 1982) that, over a wide moment range, L~2W for circum pacific subduction zone earthquakes.

On the other hand, it has also been reported that for large interplate strike-slip earthquakes, L is consistently larger by a factor of 2 or 3 than that of thrust or intraplate ones of comparable size (e.g. Kanamori and Allen, 1986; Aki, 1991). This indicates lower stress-drop for interplate strike-slip earthquakes. Also, for large strike-slip earthquakes on quasi-vertical faults, the width of the fault zone is narrow and limited to the thickness of the brittle portion of the crust, inferred to be, from analysis of aftershock locations and geodetic data, on the order of 15-25 km at most. For large strike-slip earthquakes, the width of the rupture zone therefore must saturate, and S then grows only as L. One would therefore expect scaling relations for large strike-slip earthquakes to depart in a systematic fashion from those of other earthquakes, reflecting the saturation of W, much as Shimazaki (1986) has documented a kink in the M_0 versus L curve for intraplate earthquakes in Japan. However, relatively little attention has been given so far to characterize better these departures. This is mainly due to the fact that large strike-slip earthquakes occur more rarely than large thrust and normal fault events in convergent plate boundaries, so that fewer independent reliable estimates of both M_0 and L are available.

In what follows, we review the available data for large earthquakes, depending on their tectonic setting and mechanism. We rely primarily on 3 recent compilations (Wesnousky, 1986; Kanamori and Allen, 1986; Purcaru and Berckhemer, 1982), and low frequency surface wave measurements of M_0 (Romanowicz and Monfret, 1986) for recent large strike-slip events. Only those events for which there are independent measurements of L and M_0, are considered here. We limited our selection to two classes of events: strike-slip ones occurring on quasi-vertical transcurrent faults (not necessarily on plate boundaries) and thrust or normal fault events occurring in a variety of tectonic settings. We have excluded thrust/normal events with a significant strike-slip component and strike-slip earthquakes occurring on non-vertical faults (e.g Gobi-Altai,1957 earthquake).

Strike-slip earthquakes on quasi-vertical transcurrent faults

Figure 1 shows the M_0 versus L relation obtained for strike-slip earthquakes. The data are listed in Table I. Two observations are clear in Figure 1: first, given the scatter in the data, there is no obvious difference between strike-slip earthquakes occurring on the San Andreas fault system and other transcurrent faults. Second, and most important, there is a definite change in slope or "kink" in the curve, at moment values between 0.6 and $0.8*10^{20}$ N-m.

Given the well known relation (e.g. Aki, 1972):

$$Mo = \mu\, \bar{u}\, S = \mu\, \bar{u}\, L\, W \qquad (2)$$

where μ is rigidity, and $\bar{u}$ is the average displacement on the fault, we test a relationship of the form:

$$M_0 = a\, L^{n} \qquad (3)$$

where n=3 would be expected if $\Delta\sigma$ is constant and if W and L increase in a proportional manner. In Figure 1, we have drawn three pairs of bounding lines, each with equal intercept interval, corresponding to n=1,2,3. We observe that, for earthquakes of $M_0 < 0.6*10^{20}$ N-m, n ~ 3 gives a reasonable fit. In fact, for these earthquakes, L grows very slowly with M_0. On the other hand, for $M_0 > (0.6\text{-}0.8)*10^{20}$ N-m, the trend is well described by n=1. The exponent n=2 requires an intercept interval twice as wide to contain the data. More quantitatively, we have performed a regression on the data for $Mo>0.6*10^{20}$ N-m, excluding earthquakes that occurred prior

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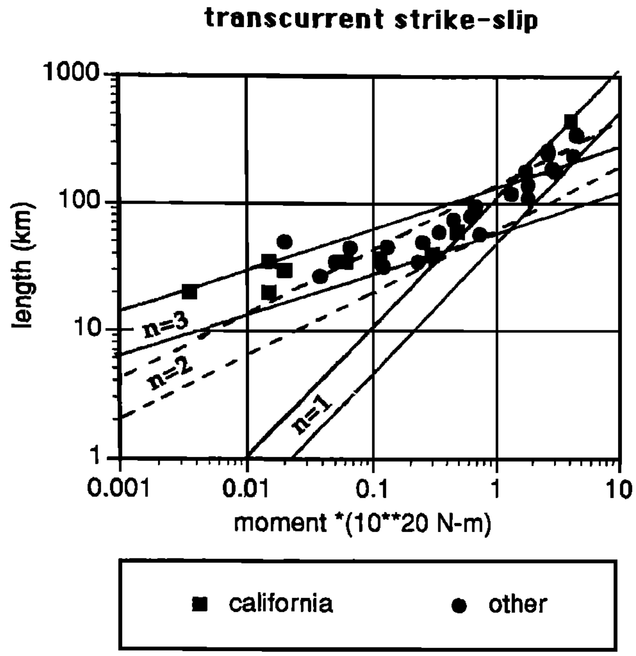

Fig. 1. Moment-length relation for large strike-slip earthquakes on quasi-vertical transcurrent faults. The solid lines are bounding curves for n=3 and n=1 in equation (1), the broken line is for n=2. All three types of curves span the same intercept in length axis

to 1960, assuming a uniform 20% error on both M_0 and L.We obtain a slope of 0.99± 0.12.

The value of n is critical for our understanding of the dynamic rupture process. Indeed, if we assume that the "kink" in Figure 1 occurs when $W=W_0$, where W_0 is the thickness of the brittle zone (averaged globally), the observations of Figure 1 have the following implications:

1) for large strike-slip earthquakes, defined as those for which $W=W_0$, the average slip on the fault is approximately constant (equation 2), which also implies that $\bar{u}$ is governed by W and not L. This is consistent with theoretical modelling (Madariaga, 1976), and in particular the recently proposed "healing pulse" concept (Heaton, 1990), but not with linear increase of $\bar{u}$ with L, as proposed on the basis of surface breakage measurements (Scholz, 1982; Sykes and Quittmeyer, 1981;Scholz et al., 1986), from which one would expect n=2 in relation (3) for large earthquakes.

2) In order to obtain a slope closer to n=2 in Figure 1, we need to include earthquakes of moment down to at least 0.2 10^{20} N-m, and then the standard deviation on the slope is at least double. We also point out that our interpretation (n=1 and a kink at ~0.6*10^{20} N-m) matches what is expected from the relation for surface strike-slip earthquakes (Aki, 1972):

$$M_0 = \pi/2\, \Delta\sigma\, W^2 L \qquad (4)$$

Let us assume $\Delta\sigma$ ~ 10-30 bars, as commonly obtained for smaller strike-slip earthquakes in California, and W_0 = 15-25 km, worldwide. Then the domain spanned in Figure 1 by the 2 extreme lines thus defined from equation (4) practically coincides with the bounding curves drawn for n=1.

Pure thrust and normal fault events

In Figure 2, we compare the events described above to other large earthquakes: interplate thrust events (Purcaru and Berckhemer, 1982), several thrust earthquakes in the western U.S. (Wesnousky, 1986), and also intraplate Japanese events from Shimazaki (1986). While the scatter is large, and there may be fine structure, the data for these events are well contained between parallel lines corresponding to n=3 in equation (2), in good agreement with Aki, 1972; Abe, 1975). We note, that for this global collection of earthquakes, there is no obvious saturation of W, since Wo can vary widely from one subduction zone to another.

Table 1: List of strike-slip earthquakes and source parameters as displayed in Figures (1) and (2). References are as follows: (1) Wesnousky(1986); (2) Purcaru and Berckhemer (1982); (3) Kanamori and Allen (1986); (4) Kanamori and Satake(1990); (5) Scheel and Ruff (1989); (6) CMT solution (Dziewonski et al.,1981); (7) Moment from moment tensor inversion (Romanowicz and Monfret (1986) and length from aftershock distribution as given in the NEIC bulletins; (8) Ekstrom and Romanowicz (1990); (9) Okal (1976).

Event	Date	Moment (10^{20}N-m)	ref.	length (km)	ref.
California					
San Francisco	04/18/1906	4.0	(1)	450	(1)
Parkfield	06/07/1934	0.015	(1)	20	(1)
Parkfield	06/07/1934	0.015	(1)	20	(1)
Imperial Val.	05/19/1940	0.48	(1)	60	(1)
Parkfield	06/27/1966	0.015	(1)	35	(1)
Borrego Mtn	04/09/1968	0.11	(1)	37	(1)
Coyote Lake	08/06/1979	0.0035	(1)	20	(1)
Imperial Val.	10/15/1979	0.06	(1)	35	(1)
Eureka	11/08/1980	1.12	(7)	130	(7)
Morgan Hill	04/24/1984	0.02	(1)	30	(1)
Loma Prieta	10/17/1989	0.3	(4)	40	(5)
Other transcurrent faults					
Turkey	12/26/1939	4.5	(1)	350	(1)
Turkey	12/20/1942	0.25	(1)	50	(1)
Turkey	11/26/1943	2.6	(2)	265	(2)
Turkey	02/01/1944	2.8	(1)(2)	190	(1)
Turkey	03/18/1953	0.73	(1)	58	(1)
Alaska	07/10/1958	4.4	(2)	350	(2)
N. Atlantic	08/03/1963	0.12	(2)	32	(2)
N.Atlantic	11/17/1963	0.038	(2)	27	(2)
Aleutian	07/04/1966	0.23	(2)	35	(2)
Gibbs f.z.	02/13/1967	0.34	(2)	60	(2)
Turkey	07/22/1967	0.62	(1)(2)	80	(1)(2)
Iran	08/31/1968	0.67	(1)	95	(1)
Sitka,Alas.	07/30/1972	3.	(6)	180	(6)
Luhuo	02/06/1973	1.8	(3)	110	(3)
Yunnan	05/10/1974	0.065	(2)	45	(2)
Gibbs f.z.	10/16/1974	0.45	(1)(2)	75	(1)(2)
Gulf of Calif.	07/08/1975	0.02	(2)	50	(2)
Guatemala	02/04/1976	2.6	(2)	250	(2)
Yunnan	05/29/1976	0.05	(1)	35	(1)
Tangshan	07/27/1976	1.8	(1)	140	(1)
Daofu	01/23/1981	0.13	(1)	46	(1)
Soudan	05/20/1990	1.3	(7)	120	(7)
Iran	06/20/1990	1.7	(7)	180	(7)
Philippines	07/17/1990	4.2	(7)	240	(7)
Unusual strike-slip					
Alaska	11/30/1987	7.3	(6)	88	(7)
Alaska	03/06/1988	4.9	(6)	70	(7)
Macquarie	05/23/1989	22.	(8)	140	(7)

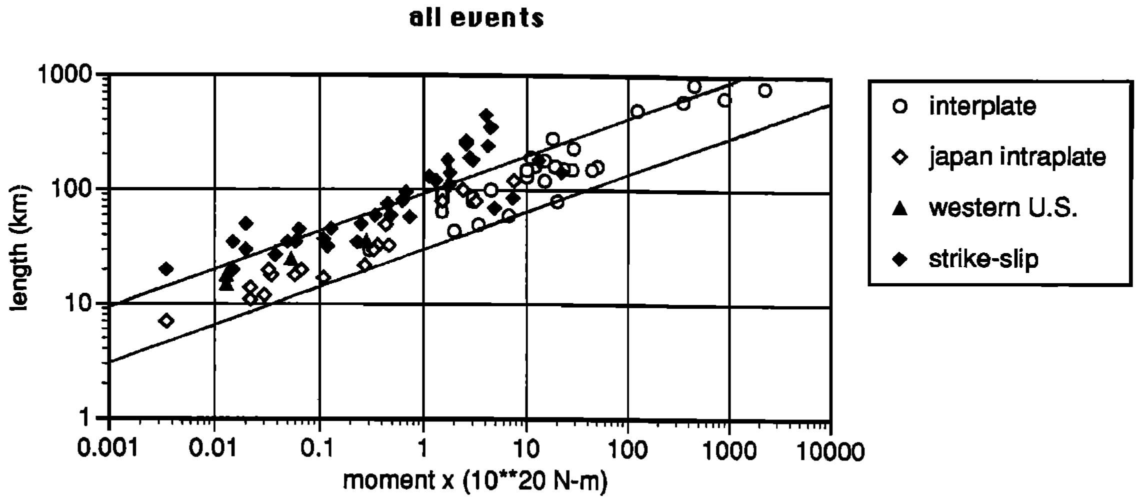

Fig. 2. Comparison of moment-length relations for large earthquakes of "pure" mechanism. We distinguish interplate thrust/normal events, from the collection of Purcaru and Berckhemer(1982), leaving out those with significant strike-slip component, thrust/normal events in western U.S. (Wesnousky, 1986) and the japanese "intraplate" collection of Shimazaki (1986). Several "unusual" large strike-slip earthquakes are also added (Table 1).

We also show, in Figure 2, several "unusual" strike-slip events, in particular the Macquarie earthquake of May 23, 1989, a strike-slip earthquake, and the largest earthquake in the past 14 years, whose unusual nature has been noted (Tichelaar and Ruff, 1990; Satake and Kanamori, 1990; Ekstrom and Romanowicz, 1990). Indeed, with a particularly short length for its size (Table 1), its scaling is consistent with that of large subduction zone events, confirming that it occurred in an unusual portion of the plate boundary, where the initiation of subduction has been conjectured (Ruff et al., 1989). To be consistent with relation (1), this implies W>50km for this earthquake, in agreement with the centroid depth obtained from low frequency surface waves (Ekstrom and Romanowicz, 1990). Other unusual strike-slip earthquakes are those which occurred in Alaska (11/17/87; 11/30/87; 03/06/88) and are clearly not associated with the North American transform fault system, and the large South Indian Ridge earthquake of 1942, whose rupture must have involved a much thicker zone than usually assumed for oceanic crustal earthquakes (Okal and Stein, 1987).

Further inferences

Further inferences can be made on the basis of the observations presented here. First, if for large strike-slip events, M_0 is proportional to L, an estimate of M_0 for large historical earthquakes in California could be obtained based on information on L only. For example, for the Fort Tejon earthquake of 1857, the length is relatively well known (360-400 km) (Sieh, 1978). On the basis of this study, we infer a moment of $(4 \pm 1)*10^{20}$ N-m, on the lower side of estimates found in the literature (Wesnousky, 1986).

Finally, the behavior of large strike-slip earthquakes described here may have some bearing on the global moment-frequency relation, which is known to have a change of trend at a magnitude of ~7.4 (M_0 ~$1.2*10^{20}$ dyne-cm). Using arguments of self-similarity (e.g. Rundle, 1989), it is easy to show that, if we consider a 2D fault that can be filled with earthquakes whose dimensions grow both in L and W, from relation (2) with n=3, we infer a slope of b'=2/3 in the frequency-moment relation:

$$\text{Log } N = a - b'\text{Log } M_0 \quad (6)$$

in good agreement with the "b-value" of 1, when using the established moment-magnitude relation (Hanks and Kanamori, 1979). When the earthquakes reach the saturation width W_0, the fault zone can only be filled by earthquakes whose surface is proportional to length, leading to N proportional to 1/L, and given n=1 in relation (2), this leads to b'= 1. If only strike-slip earthquakes are considered, this implies a change of slope from 2/3 to 1 in equation (6), indicating fewer large strike-slip earthquakes.

If relation (6) is considered worldwide, the sum of transform fault strike-slip and "other" will produce a change of slope from 2/3 to a value between 2/3 and 1. According to our observations, this kink should occur at a moment on the order of $(0.6\text{-}1.0)*10^{20}$ N-m, consistent with the change of slope in the observed frequency-magnitude relation (Gutenberg and Richter, 1954; Pacheco et al., 1991). If only the largest earthquakes are considered worldwide ($M_0 >$ 6-8 10^{20}N-m), which excludes transcurrent fault ones, a "b-value" of 1 is expected, which has been documented (Davison and Scholz, 1985). Finally, the regional variations in the moment-magnitude relation (Ekstrom and Dziewonski, 1988) could also in part be due to this saturation effect, given the regional variations in predominent source mechanisms.

Discussion and Conclusions

The results presented here apparently contradict the observations reported in the literature which support the idea that $\bar{u}$ is governed by L (Scholz, 1982). However, these measurements of slip rely primarily on surface measurements, which may result in biased estimates of the average slip $\bar{u}$: recent tomographic models of large earthquake sources have shown that the distribution of slip over the rupture surface can be very inhomogenous. Also, the linear relation between Mo and L advocated in this paper, implies an approximately constant slip, on the order of 3-5 m, for the largest strike-slip earthquakes, which is not inconsistent with measurements reported in the literature, given the large uncertainties in the data. As for thrust events, since W_0 is much larger and varies from one region to another, one would expect to see $\bar{u}$ grow with L (Scholz, 1982), the saturation of W is not as readily observed in a heterogeneous global dataset..

The data shown here support a mechanism whereby $\bar{u}$ is governed by W, at least for strike-slip earthquakes on vertical faults, in agreement with theoretical models. The data for thrust earthquakes in subduction zones do not contradict such a model, at least when considered globally. Figure 2 also indicates that large earthquakes can be distinguished on the basis of their mechanism (strike-slip on vertical faults versus pure thrust/normal) more easily than according to their tectonic setting (intraplate/interplate). Given the large errors in the measurements of M_0, L and $\bar{u}$, especially for older events, we must await the occurrence of several more strike-slip earthquakes of $M_0 > 2*10^{20}$ N-m to further confirm or modify this interpretation.

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References

Abe, K., Reliable estimation of the seismic moment of large earthquakes, Phys. Earth Planet. Int., 23, 381-390 (1975).

Aki, K., Earthquake mechanism, Tectonophys., 13, 423-446 (1972).

Aki, K., Higher order interrelations between seismogenic structures and earthquake processes, Tectonophys., in press (1991).

Davison, F.C. and C.H. Scholz, Frequency moment distribution of earthquakes in the aleutian arc: a test of the characteristic earthquake model, Bull. Seism. Soc. Am., 75, 1349-1361 (1985).

Dziewonski, A.,M., G. Chou and J.H. Woodhouse, Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, J. Geophys. Res., 86, 2825-2852 (1981).

Ekstrom, G. and A.M. Dziewonski, Evidence of bias in estimations of earthquake size, Nature, 332, 319-323 (1988).

Ekstrom, G. and B. Romanowicz, The 23 May 1989 Macquarie Ridge earthquake: a very broad band analysis, Geophys. Res. Lett., 17, 993-996 (1990).

Gutenberg, B. and C. F. Richter, Seismicity of the Earth and associated Phenomena, Princeton Univ. Press, Princeton, N.J. (1954).

Hanks, T. Earthquake stress drops, ambient tectonic stresses and stresses that drive plate motions, Pageoph., 115, 441-458 (1977).

Hanks, T. and H. Kanamori, A moment magnitude scale, J.Geophys.Res., 84, 2348-2350 (1979).

Heaton, T., Evidence for and implications of self healing pulses of slip in earthquake rupture, Phys. Earth Planet. Int., 64, 1-20 (1990).

Kanamori, H. and C. Allen, Earthquake repeat time and average stress drop, Earthquake Source Mechanics, Geophys. Monogr. 37, A.G.U., 227-236 (1986).

Kanamori, H. and K. Satake, Fault parameters and tsunami excitation of the May 23, 1989 Macquarie Ridge Earthquake, Geophys. Res. Lett., 17, 1179-1182 (1990).

Madariaga, R., Dynamics of an expanding circular fault, Bull. Seism. Soc. Am., 66, 639-666 (1976).

Okal, E.A., and S. Stein, The 1942 Southwest Indian ocean ridge earthquake: largest ever recorded on an oceanic transform, Geophys. Res. Lett., 14, 147-150 (1987)

Pacheco, J. F. and L.R. Sykes, Seismic moment catalog of large shallow earthquakes, Bull. Seism. Soc. Am, in press(1991).

Purcaru, G. and H. Berckhemer, Quantitative relations of seismic source parameters and a classification of earthquakes, Tectonophys., 84, 57-128 (1982).

Romanowicz, B. and T. Monfret, Source process times and depth of large earthquakes by moment tensor inversion of mantle wave data and the effect of lateral heterogeneity, Ann. Geophys., 4,B,3, 271-283 (1986).

Ruff, L. J., J.W. Given, C.O. Sanders, and C.M. Sperber, Large earthquakes in the Macquarie Ridge complex: transitional tectonics and subduction initiation, Pageoph., 129, 71-130 (1989).

Rundle, J., Derivation of the complete Gutenberg-Richter magnitude frequency relation using the principle of scale invariance, J. Geophys. Res., 94, 12337-12342 (1989).

Satake, K. and H. Kanamori , Fault parameters and tsunami excitation of the May 23, 1989, Macquarie Ridge earthquake, Geophys. Res. Lett., 17, 997-1000 (1990).

Scheel, M. and L. Ruff , Rupture of a seismic gap in souther Alaska: the 1972 Sitka earthquake (Ms 7.6), Phys. Earth Planet. Int., 54, 241-257 (1989).

Scholz, C., Scaling laws for large earthquakes and consequences for physical models, Bull. Seism. Soc. Am., 72, 1-14 (1982).

Scholz, C.H., C.A. Aviles and S.G. Wesnousky, Scaling differences between large interplate and intraplate earthquakes, Bull.Seism.Soc. Am., 76, 65-70 (1986).

Sieh, K., Slip along the San Andreas fault associated with the great 1857 earthquake, Bull. Seism.Soc. Am., 68, 1421-1448 (1978).

Shimazaki, K., Small and large earthquakes: the effects of the thickness of the seismogenic layer and the free surface, Earthquake Source Mechanics, Geophys. Monogr. 37, A.G.U., 209-216 (1986).

Sykes, L. and R. Quittmeyer, Repeat times of great earthquakes along simple plate boudaries, Earthquake Prediction, Maurice Ewing Series 3, A.G.U., 217-247 (1981).

Tichelaar, B.W. and L.J. Ruff, Rupture process and stress drop of the great 1989 Macquarie Ridge earthquake, Geophys. Res. Lett., 17, 1001-1004 (1990).

Wesnousky, S., Earthquakes, quaternary faults and seismic hazard in California, J. Geophys. Res., 91, 12587-12631 (1986).

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