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A Reappraisal of Large Earthquake Scaling

by C. H. Scholz

Abstract Twelve years ago I pointed out that observations indicate that the slip in large earthquakes scales with their length, rather than their width, as expected from the canonical model. Romanowicz (1992) has recently argued that more recent data show that the opposite is true, which has obliged me to re-examine the question. I point out here a defining flaw in her analysis, in that she allowed M_0^*, the moment at the cross-over from small to large earthquakes, to be a free variable in her curve fitting, whereas this parameter can be defined independently. When this parameter is independently fixed, I find that the updated data set confirms my earlier conclusion that for large crustal earthquakes M_0 scales with L^2.

A little over a decade ago I pointed out that observations indicate that the slip in large earthquakes scales with their rupture length (Scholz, 1982). Several subsequent papers provided additional data supportive of this view (Chen and Molnar, 1983; Shimazaki, 1986; Scholz *et al.*, 1986). Large earthquakes are defined in this context as those that rupture the entire seismogenic thickness W_0 and are thus constrained to propagate farther in a horizontal direction only. For crustal earthquakes, W_0 is nearly constant ~15 km; so this scaling conflicts with conventional models of earthquakes, such as dislocation models, because they predict that slip scales with width, which is invariant for these earthquakes. I offered two alternative ways to interpret these observations. One is that such conventional W models are correct but that stress-drop could no longer be regarded as scale-invariant but must scale with fault length. As an alternative, I suggested the possibility of what I termed an L model, in which slip intrinsically scales with fault length.

This created a minor crisis in seismology, which has yet to be resolved. It is no exaggeration to say that my L model suggestion has not attracted a noticeable coterie of admirers, nor has my other suggestion, and there has been no other model proposed in the interim that explains the observed L scaling [although Heaton (1990) has suggested a way in which length may scale with stress-drop, a variation of my W model scaling alternative]. In the face of this, an alternative is to question the observations, which is what Romanowicz (1992) has recently chosen to do. In her interpretation of an updated data set, she concluded that seismic moment, M_0, scales linearly with rupture length L for large earthquakes, which is consistent with W models and implies that slip, u, is scale invariant for large crustal earthquakes. This great discrepancy with the earlier result, she implies, is due to the presence of superior modern measurements in the updated data set. This issue has major implications, both practical and theoretical, and merits some debate. Here I present my own reappraisal of the data, in which the conclusions are very different.

Reappraisal of the Data

Romanowicz's conclusions were based on a log-log plot of M_0 versus L for a data set of strike-slip earthquakes. She showed that the data in this figure could be better fit by two straight lines, one with slope 3 in the lower scale range and one with slope 1 in the upper scale range, than with a single line of slope 2. For small earthquakes, which grow in both dimensions with $L \approx W$, M_0 should scale with L^3. For large earthquakes, where W has saturated at W_0 and growth only occurs in the L direction, M_0 should scale with L according to conventional models; hence the problem produced by my observation that M_0 scales with L^2 for those events. Superficially, then, it appears that she has resolved the issue. The problem, however, is that she has allowed the cross-over length, L^*, which separates small from large earthquakes, to be a free variable in her curve-fitting exercise. She thus obtains a cross-over moment of 0.6 to 0.8×10^{20} N-m, which is appropriate for a rupture length of 60 to 70 km. By adding an additional free parameter to the curve fitting, one would expect a much better fit to be achieved; the question is whether such a step is justified. If small earthquakes grow with $L \approx W$, then the transition to large earthquakes (defined as an event that ruptures the entire seismogenic thickness) would be $L^* \approx W_0 \approx 10$ to 20 km for the data being studied. This may be checked observationally; because large earthquakes almost invariably nucleate near the base of the seismogenic layer (Das and Scholz, 1983), it follows that the transition to large earthquakes is at the length at which one begins to consistently see surface ruptures. Inspection of the earthquakes in Romanowicz's (1992) Figure

1 and Figure 1 of the present article shows this to be at about 20 km, in agreement with the above argument. It is at this length that the geometry of earthquakes change and we might expect to see a scaling change; there is no characteristic dimension at 60 to 70 km at which we should expect a change in scaling relation. All of the earthquakes shown in Romanowicz's (1992) Figure 1 have $L \geqq 20$ km, so they are all large earthquakes. Hence she asked the wrong question. The correct question is: which *single* line of integer slope best fits these data?

To reexamine this question, a similar plot is shown in Figure 1 of the data set of crustal earthquakes, by which is meant all nonsubduction zone events. W_0 is in the range 10 to 20 km for these events, and so they can be sensibly compared on a plot of this type, whereas subduction zone events cannot because they have widely varying W_0 values. There is no need to limit the data to strike-slip earthquakes, as Romanowicz did, because previous work has shown little dependence on focal mechanism type (Scholz *et al.*, 1986). On the other hand, a strong difference between interplate and intraplate earthquakes has been noted, so these need to be differentiated (Scholz *et al.*, 1986; Kanamori and Allen, 1986). In any case, the reader may judge; different symbols are used for the different types of earthquakes in the figure.

The data in Figure 1 are the same as used by Romanowicz (1992) in her Figures 1 and 2, with the addition of normal fault events from Scholz *et al.* (1986), the deletion of events of $L < 15$ km from Shimazaki's (1986) list, deletion of the subduction zone events, and a few changes as listed in Table 1. The fit of Romanowicz (1992) is shown by the light lines. One can see, in the strike-slip data, the feature that may have led her to make this fit, although, for reasons given above, this fit is not valid. The eye may be drawn, in this regard, to several of the data points at the lower end of the magnitude range, but be aware that these values are among the poorest determined on a log-log plot like this. For example, two of these data points are for the Parkfield earthquakes of 1934 and 1966, whose relative moments and fault lengths are still quite uncertain in spite of extensive study (Segall and Du, 1993).

Because all the earthquakes in Figure 1 have $L \geqq 15$ km, they are all large. Hence, to investigate scaling of large earthquake, we seek the best single line that best fits these data. We can see, by extrapolating the two branches of Romanowicz's fit, that neither slope 1 nor slope 3 will be satisfactory. Instead, we find that the data is bracketed by two lines of slope 2, with ratios of slip to length of 10^{-5} and 10^{-4}. Notice that the intraplate earthquakes are systematically lower on the plot than the interplate events of the same moment. This plot, and the conclusions made from it, are essentially indistinguishable from that presented in Scholz *et al.* (1986). The addition of the new data has filled in the earlier plot without changing the conclusions that were made then. There is no separation of the new data from the old.

Three earthquakes shown in Figure 1 deserve special mention. The 1989 Loma Prieta earthquake (labeled 1) falls far off the trend of other San Andreas earthquakes and lies within the field of intraplate earthquakes, its position on the plot shows it also to be a crucial point for the Romanowicz interpretation. It is somewhat dubious to classify this earthquake as an interplate strike-slip event,

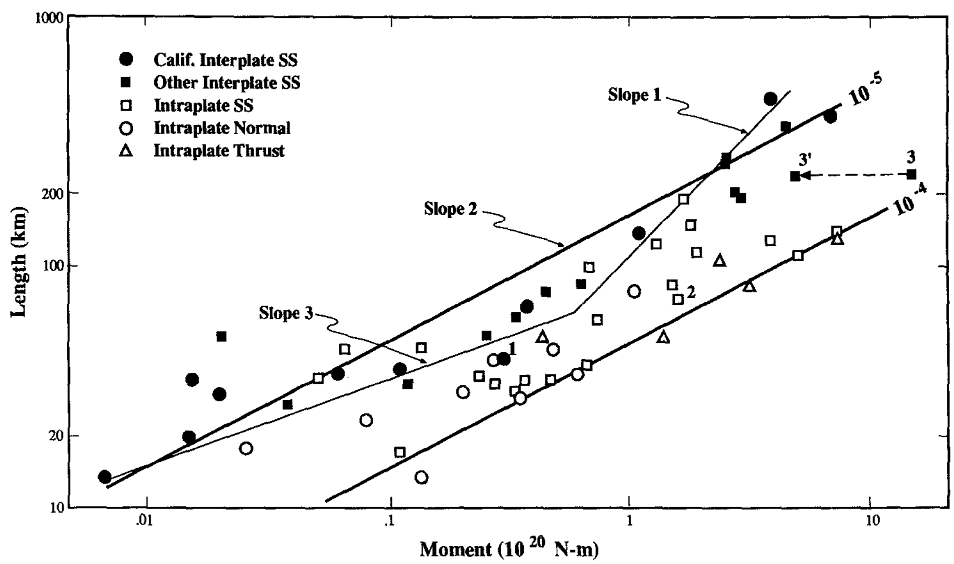

Figure 1. A log-log plot of length versus moment for large crustal earthquakes. The light lines are the fit of Romanowicz (1992) to the strike-slip data. The two lines of slope 2 that bracket the data indicate slip-to-length ratios of 10^{-5} and 10^{-4} for averaged widths of 15 km. See text for a discussion of numbered events.

however, because it had a large component of reverse slip and was considerably deeper than other San Andreas events. An even odder interpretation was made by Segall and Lisowski (1990), who suggested that this earthquake did not occur on the San Andreas fault, but on a nearby, slower moving fault. Although probably not provable, if their hypothesis were true then this earthquake would be properly classified as an intraplate event; the classification criterion used in Figure 1 is based solely on the geological slip rate of the causative fault (Scholz *et al.*, 1986; Scholz, 1990, p. 304–8).

The 1992 Landers earthquake (labeled 2 on Fig. 1) was an intraplate strike-slip event, because it ruptured a series of faults with geological slip rates not greater than 1 mm/yr (Mori *et al.*, 1992; Wesnousky, 1986). As such, it plots in the correct place in Figure 1 and was not remarkable in its scaling properties. On the other hand, the Macquarie Ridge earthquake (labeled 3 in Fig. 1) plots in an unusual position for an interplate strike-slip earthquake. This earthquake is thought to have ruptured an unusual width of $W \approx 50$ km (Ekstrom and Romanowicz, 1990; Das, 1993). If that is the case, it cannot be directly compared with the other events in Figure 1, which all have $W \approx 15$ km; with three times the width it would be expected to have about three times the moment of an event with comparable length. If we do wish to compare it with the other events in Figure 1, we would have to divide its moment by three, which moves it to position 3′. Then its scaling becomes similar to the other interplate events, showing that its unusual character has only to do with its width. Finally, two intraplate strike-slip events in the Gulf of Alaska, called 'unusual' by Romanowicz (1992), turn out not to be unusual when the correct lengths, given by Lahr *et al.* (1988), are used.

Discussion

In my reappraisal of the data given above, I have reaffirmed my earlier conclusion that the appropriate scaling relation for large earthquakes is that M_0 scales with L^2. It is not apparent that the "new" data, obtained with modern seismological techniques, differ systematically from the "old" data based more on geological measurements. The scaling relations proposed by Romanowicz (1992) for strike-slip earthquakes have a scaling break within the field of large earthquakes, a phenomena for which there is no theoretical justification.

Romanowicz and Rundle (1993) have recently discussed this issue further. In particular they discuss it with regard to the cross-over in the size–frequency distribution observed by Pacheco *et al.* (1992). For crustal earthquakes (called 'transform' by them), Pacheco *et al.* found a change in b value from 1 to 1.5 at $M6$. Note that this corresponds to $L^* \approx 15$ km, as noted here, and not the cross-over value proposed by Romanowicz (1992), at about $M7.2$.

They are, however, correct to point out that Pacheco *et al.* were inconsistent in stating that this cross-over point corresponds to a change from L^3 to L^2 scaling of M_0, and at the same time that the observed b value change is consistent with a model of Rundle (1989). This is because, as they note, the Rundle model is based on a W model that is not consistent with L^2 scaling. As Romanowicz and Rundle (1993) point out, modifying the Run-

Table 1
Changes in Earthquake Data

Earthquake	M_0, 10^{20} N-m	Length, km	Modification	Reference
11/17/87 Alaska	0.66	40	added (intra-SS)	Lahr *et al.* (1988)
11/30/87 Alaska	7.3	140	changed (intra-SS)	Lahr *et al.* (1988)
3/6/88 Alaska	4.9	110	changed (intra-SS)	Lahr *et al.* (1988)
8/6/79 Coyote Lake	0.006	14	changed (Cal. inter-SS)	Bouchon (1982)
5/19/40 Imperial Valley	0.38	65	changed (Cal. inter-SS)	average of Trifunac (1972) and Doser and Kanamori (1987)
1/9/1857 Ft. Tejon	7	380	added (Cal. inter-SS)	Sykes and Quittmeyer (1981)
5/23/89 Macquarie Ridge	15	220	changed (other inter-SS)	Das (unpublished manuscript, 1993)
6/28/92 Landers	1.6	70	added (intra-SS)	Mori *et al.* (1992)
7/16/90 Philippines	3.9	120	changed (intra-SS)	Yoshida and Abe (1992)

dle (1989) tiling argument as an L model for large earthquakes predicts an incorrect b value for those events. I conclude that the casualty in this must be Rundle's model. There does not seem to be any general theoretical inconsistency between the change from L^3 to L^2 scaling corresponding with a b value change from 1 to 1.5, because this is predicted by the model of Sornette and Virieux (1992). Romanowicz and Rundle (1993), however, have challenged the applicability of the Sornette and Virieux model to this problem. Sornette and Sornette (1993) have written a comment regarding this point. I direct the reader to this exchange for clarification of the theoretical points being raised.

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