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SCALING DIFFERENCES BETWEEN LARGE INTERPLATE AND INTRAPLATE EARTHQUAKES

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ABSTRACT

A study of large intraplate earthquakes with well determined source parameters shows that these earthquakes obey a scaling law similar to large interplate earthquakes, in which $M_0 \propto L^2$ or $u = \alpha L$, where L is rupture length and u is slip. In contrast to interplate earthquakes, for which $\alpha \approx 1 \times 10^{-5}$, for the intraplate events $\alpha \approx 6 \times 10^{-5}$, which implies that these earthquakes have stress-drops about 6 times higher than interplate events. This result is independent of focal mechanism type. This implies that intraplate faults have a higher frictional strength than plate boundaries, and hence that faults are velocity or slip weakening in their behavior. This factor may be important in producing the concentrated deformation that creates and maintains plate boundaries.

INTRODUCTION

Differences in the source parameters of intraplate and interplate earthquakes have often been remarked on. Kanamori and Anderson (1975), for example, concluded that in general the former have higher stress-drops than the latter. While this conclusion is unlikely to be incorrect, it seems worthwhile to study differences between these two types of earthquakes in more detail. This is because there is some disagreement as to the definition of intraplate earthquakes, and there may as well be some other reasons, such as a difference in focal mechanism, which lead to stress-drop differences. Furthermore, the earthquakes studied by Kanamori and Anderson (1975) were all large events, and as the scaling laws for large earthquakes have been more recently refined (Scholz, 1982) it would be of interest to see if large intraplate earthquakes also scale in a similar way.

DEFINITIONS AND DATA

Although the terms intraplate and interplate are in common use in describing earthquakes, their usage varies somewhat with different authors and although these differences in usage are usually clear in context they need stricter definition here. An earthquake that occurs on a well defined plate boundary such as, say, the San Andreas fault, is clearly an interplate earthquake, and one that occurs in a mid-plate region far from any known plate boundary is clearly intraplate. Yet there is a large class of earthquakes intermediate in both their frequency of occurrence and their tectonic environment from those simple extreme cases. These are those earthquakes that occur either in a diffuse zone surrounding a plate boundary and which contribute, secondarily, to the deformation associated with the plate boundary, or those which occur within plate boundaries which are altogether diffuse. We therefore suggest three categories of earthquakes, as indicated in Table 1, in which a distinction is made between two types of intraplate events, the latter mentioned type, which we call the plate boundary related type, and what might be considered a 'true' intraplate earthquake, which we call the mid-plate type. We distinguish these types roughly on the basis of the slip rate of the faults they occur on, their recurrence time, and their tectonic environment. Even this classification has gray areas in between since it is recognized that any such classification which does not recognize a continuum of types is artificial. Nevertheless, for practical purposes it can be used without a great deal of ambiguity in most cases. We introduce this classification for clarification because most if not all of the earthquakes called intraplate by Kanamori and Anderson (1975) are of the class II, plate boundary related, type. The earthquakes used in the present study are also all of this type since insufficient data presently exist to make a comparable study of mid-plate events. Nevertheless, as we shall show, these earthquakes are systematically different from interplate events.

In making our comparison, we also restrict ourselves to large earthquakes, e.g., those which rupture the entire seismogenic layer (Scholz, 1982), since such earthquakes sample the same depth range and provide an average response to the mechanical properties of that entire layer. From these we eliminated subduction zone interface events, since those have much greater down-dip widths and extend to considerably greater depths than other shallow tectonic earthquakes. Thus, all the earthquakes we study have essentially the same width, 20±10 km and vary only in their length and seismic moment, which are the parameters that we have chosen for study.

The earthquakes we have included all have very well determined source parameters. Their seismic moments have usually been determined by both seismological and geological methods and are considered reliable to about a factor of 2. Fault lengths were usually estimated from both surface rupture lengths and the length of the aftershock zone; they are considered reliable to within 20%. The interplate earthquakes are from the list of Scholz (1982). Since subduction zone events have been eliminated, these turn out to be all strike-slip earthquakes. Although this may bias our results, we shall show later that this does not seem to be a serious problem. Intraplate earthquakes from Japan are taken from the list compiled by Wesnousky et al. (1982), which was updated with the parameters for the 1983 Japan Sea earthquake (Satake, 1985). These earthquakes are about half strike-slip and half reverse faulting events. A list of parameters for intraplate earthquakes from the western U.S. was compiled and is presented in Table 2. These events are mostly normal faulting type with some thrust events.

As mentioned above, all these intraplate earthquakes are of the plate boundary related type. This data set is not meant as an exhaustive list of all known intraplate events, but it is large enough, containing 30 earthquakes, to be a representative sample, and it contains an almost equal representation of strike-slip, reverse, and normal faulting events.

OBSERVATIONS

The source parameters for these earthquakes are presented in Figure 1 as a plot of log moment vs. log length. The lines drawn through the data have slopes of 1/2 indicating a relation $M_o \propto L^2$. This is equivalent to the simple scaling, $u=\alpha L$, found earlier (Scholz, 1982). Data from both types of earthquakes follow this trend quite well, but it is clear than the intraplate events fall systematically lower on the plot, indicating a higher value of α. The interplate earthquakes fall close to the $\alpha=1\times10^{-5}$ line; a best fitting line with this trend for the intraplate earthquakes indicates a value of $\alpha=6\times10^{-5}$ (dashed line). Thus, large intraplate earthquakes obey the same scaling law as interplate events, but on average have about 6 times greater slip than interplate earthquakes of the same length.

A somewhat surprising result is that the data do not show, among the intraplate earthquakes, any significant difference between normal faulting, reverse faulting, and strike-slip earthquakes. Thus, although the interplate earthquakes are all of the strike-slip type, a difference in focal mechanism type does not explain the observed differences with intraplate earthquakes.

Estimating stress-drops for these earthquakes is problematical, since the observation that slip scales with length produces interpretive difficulties with this model dependent parameter (Scholz, 1982). However, if we consider that, crudely, stress-drop is proportional to slip per unit area, then we would conclude that the stress-drops for the intraplate earthquakes are systematically about 6 times greater than of interplate earthquakes, a conclusion similar to that of Kanamori and Anderson (1975).

DISCUSSION

We have observed that large intraplate earthquakes obey the same length proportional scaling law as large interplate earthquakes, but that they exhibit stress-drops that are systematically greater by about a factor of 6. Within the resolution of the data these results do not depend on the focal mechanism type: they apply equally to the strike-slip and reverse faulting regimes of SW and NE Japan, to reverse faulting earthquakes in California, and to normal faulting events in the Basin and Range province. This stress-drop difference, then, is a robust result, and suggests that intraplate faults have systematically higher frictional strengths than do plate boundaries.

There are a number of possible mechanisms that could lead to such a difference in fault strength. Intraplate faults differ in a number of important aspects from plate boundaries: a) they have slip rates typically one to two orders of magnitude slower than plate boundaries, b) total slip on them is typically of the order of 1-10 km, as opposed to 100's of km for plate boundaries, and c) they have finite lengths and are not continuous features. It is unlikely that a difference in crustal structure could result in this strength difference, since the earthquakes in our data set are from a variety of regions, and frictional strength is almost independent of lithology (Byerlee, 1979) and temperature (Stesky et al., 1974).

Laboratory studies have shown that the frictional strength of rock has a negative dependence on sliding velocity and increases with time of stationary contact (Dieterich, 1972; Scholz et al., 1972). These results suggest that faults with lower slip rates and longer recurrence times should have higher frictional strengths. Kanamori and Allen (1985) have attempted to relate stress-drop with earthquake repeat time, and although there is too much scatter in the data to determine a clear relationship, both their data and the data presented here support a rough trend of this type. The effect observed in the laboratory produces about a 5% change in strength per decade change in stationary contact time and is therefore much smaller than the effect observed for the earthquakes, which is on the order of a factor of 5 change in stress-drop per decade change in recurrence time. In nature, however, it is quite likely that other mechanisms than those studied in the laboratory, such as chemical healing of faults, may come into play and may augment this effect.

The difference in total slip between intraplate faults and plate boundaries may also play a role in the greater strength of intraplate faults. Since faulting is a wear process there is a general increase in the amount of wear particles, as indicated by the thickness of the gouge zone, with total slip. Thus, intraplate faults, which have total slips typically of 1-10 km, usually have gouge zones only 1-10 m in width, whereas plate boundary faults, such as the San Andreas fault and Alpine fault, often have gouge zones of crushed rock 100-1000 m in width. Since laboratory studies are all conducted at very small total slip, they offer little corroboration for a weakening with the development of a wide gouge zone. Such an effect is suggested, however, by the general observation that crustal deformation is a strain softening process since progressive deformation tends to be concentrated in limited, narrow zones.

The absence of a correlation of stress-drop with focal mechanism type was surprising, since a simple friction consideration (Sibson, 1974) would suggest that the frictional strength would be greatest for thrust faults, least for normal faults, and intermediate for strike-slip faults. In terms of stress-drops, such an effect would be expected to be reduced by gravitational work, which would reduce the stress-drop for reverse faulting and increase the stress-drop for normal faulting relative to strike-slip faulting. A comparison of subduction zone thrust events with strike-slip interplate events

(Scholz, 1982) did show, however, a slight effect, with $\alpha=2\times10^{-5}$ for the former as opposed to 1.25×10^{-5} for the latter. This is a relatively minor effect, however, and would not be resolvable within the scatter in the intraplate earthquake data shown here.

Whatever the mechanisms that produce this effect, the observation that intraplate faults have higher frictional strengths than plate boundaries means that, in a long term sense, that faults are either velocity or slip weakening (or both). Thus deformation of the seismogenic layer will be expected to concentrate on slip of a few master faults as opposed to being evenly distributed over a broad zone. This overall strain-softening behavior is, of course, one of the principal observations of tectonics of the earth, since it would lead to the creation and maintenance of the plate boundaries.

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FIGURE CAPTIONS

Figure 1. Log fault length vs. log moment for large interplate and intraplate earthquakes.

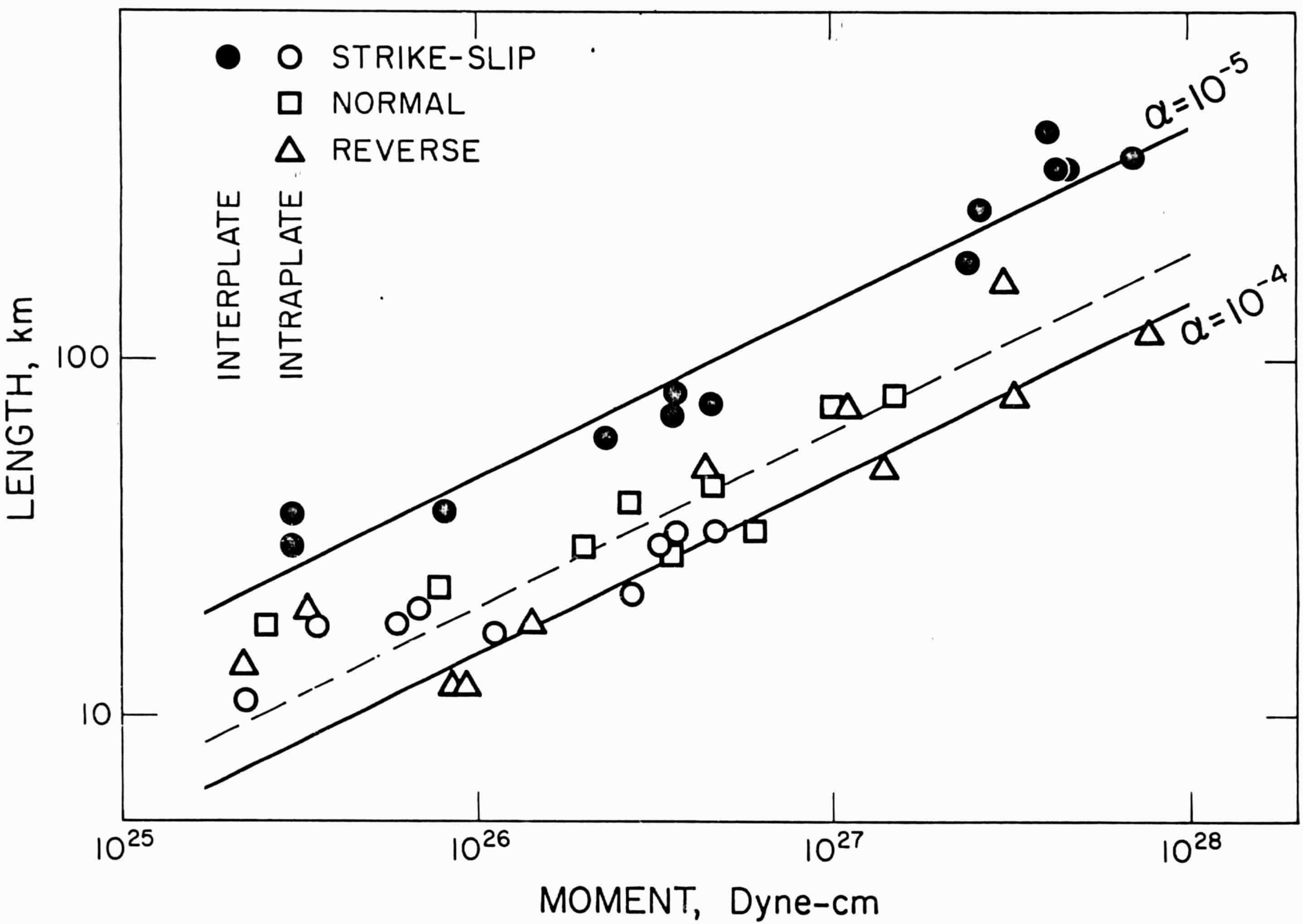
TABLE 1. Classification of Tectonic Earthquakes

Type	Description	Slip Rate of Causative Fault	Recurrence Time
I	Interplate	$v>1$ cm yr^{-1}	$\approx 10^2$ yrs
II	Intraplate (plate boundary related)	$.01<v<1$ cm yr^{-1}	$\approx 10^3-10^4$ yrs
III	Intraplate	$v<.01$ cm yr^{-1}	$>10^4$ yrs

TABLE 2

Source Parameters, Western U.S. Intraplate Earthquakes

EARTHQUAKE	TYPE	LENGTH (km)	MEAN SLIP (cm)	MOMENT (10^{19} N-m)	REFERENCE
21 Jul 1952, Kern Co., California	SS & Thrust	75	214	11	Stein & Thatcher (1981)
3 May 1887, Sonora Mexico	Normal	76	190-380	6.9-13.8	Hurd & McMasters (1982)
2 Oct 1915, Pleasant Valley, Nevada	Normal	30-40	150-460	2.9-8.8	Ryall (1977) Page (1935)
6 Jul 1954, Fallon, Rainbow Mtn., Nevada	Normal	18	31	.25	Ryall & Van Wormer (1980) Tocher (1956)
23 Aug 1954, Fallon, Stillwater Nevada	Normal	23	76	.79	Tocher (1956)
16 Dec 1954, Fairview Peak, Nevada	Normal & ss	45	250-290	4.4-5.1	Savage & Hastie (1967) Slemmons (1957)
16 Dec 195 Dixie Valley, Nevada	Normal	40	150	2.7	Ryall (1977) Slemmons (1957)
17 Aug 1959, Hebgen Lake Montana	Normal	24-32	280	3.0-4.0	Witkin (1964) Savage & Hasties (1966) Doser (1984)
9 Feb 1971, San Fernando California	Thrust & ss	13.5	126	1.3	Allen et al. (1975) Sharp (1975)
28 Mar 1975, Pocatello Valley Utah	Normal			.06-.07	Arabasz et al. (1979)
28 Oct 1983, Borah Peak, Idaho	Normal	30 30	100-150	1.6-1.7 1.6-2.7	Boatwright (pers. comm., 1984


STRIKE-SLIP
NORMAL
REVERSE
INTERPLATE
INTRAPLATE
$\alpha=10^{-5}$
$\alpha=10^{-4}$
LENGTH, km
100
10
10^{25}
10^{26}
10^{27}
10^{28}
MOMENT, Dyne-cm