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SOURCE PARAMETERS OF SMALL EARTHQUAKES RECORDED AT 2.5 KM DEPTH, CAJON PASS, SOUTHERN CALIFORNIA: IMPLICATIONS FOR EARTHQUAKE SCALING

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Abstract. A 2.5 km deep triaxial seismometer at Cajon Pass in southern California has recorded several hundred earthquakes $<M_L4.0$ occurring within the San Andreas fault system. At 2.5 km seismic background noise is below amplifier sensitivity and the 2-250 Hz spectral range of recorded seismic motion is wider and higher than that of most natural event catalogs. Compared with downhole recorded motion, seismic amplitudes at the surface are amplified below 10 Hz and severely attenuated above 30 Hz. We estimate that Q_S is at least 1000 for wave motion at 2.5 km and below and Q_P is over 2000. The range of source dimensions in the downhole recorded catalog is ~10 m to ~70 m (M_L~-2.0, M_o~10^8 Nm to M_L~2.7, M_o~10^{13} Nm). The plot of log(source-radius) vs log(moment) has a straight line trend compatible with earthquake scaling at constant stress drop; inferred stress drops are scattered between 1 and 500 bars. There is no evidence in the catalog for the proposed minimum source dimension at ~100 m. When the Cajon Pass borehole catalog, containing some of the smallest recorded natural earthquakes, is combined with 800 larger events from previous studies, the moment-radius trend suggests that natural earthquakes are self-similar over a magnitude range M~-2 to ~8. We suggest that inferences of minimum source dimension are more likely due to bias in bandlimited individual catalogs than to properties of the seismic crust.

Introduction

Seismic rupture and associated seismic radiation are observed to have strong similarities over a great range of source volume. The range of observed source volumes spans 24 orders of magnitude: < 1 mm^3 (laboratory induced failure, *Hirata et al.* [1987]), 1 to 1000 cm^3 (mine-by experiments, *Gibowicz et al.* [1992], and rock bursts, *Spottiswoode & McGarr* [1975]), 1 to 1000 m^3 (large scale hydraulically induced failure, *Fehler & Phillips* [1991], *Pearson* [1982]), to 1 to 10^6 km^3 (local and regional seismicity, *Kagan* [1992]). Throughout the 10^{24} range of scale volume seismic events show spatial clustering, a power law relation between number of events and event size, and a constant power law relation between event radius inferred from high frequency radiation and seismic moment inferred from low frequency radiation.

The similarity of seismic event size and spatial distribution over a wide range of scale volumes is consistent with scale independent static fracture populations observed *in situ* [*Leary* 1991] and with computer simulations of the spatial and size distributions of brittle fracture failure [*Kagan* 1992]. Scaling similarity in seismic radiation associated with fracture failure follows more or less logically from the integral expression relating radiated seismic displacement to the slip velocity field within the source volume [Eq. 14.7, *Aki & Richards* 1980]. That is, if the mean sliding velocity of rock during elastic rebound across a rupture surface is independent of the size of the rupture surface, then the seismic radiation accompanying an earthquake simply scales with the dimensions of the rupture [*Aki & Richards* 1980]. Scale invariance of the seismic rupture process is equivalent to the observation that the ratio of seismic moment (proportional to event volume) to event radius is a power law with exponent 3, and that earthquakes have a (nearly) constant stress drop.

Compilations of seismic moments and source radii assembled over several orders of magnitude in source radius from separate seismic catalogs support the cubic relation between source radius and earthquake moment [*Pearson* 1982; *Scholz* 1990], and indicate that crustal earthquakes have average stress drops in the range 1 to 1000 bars. To date, however, the smallest events included in the compilations are induced (hydrofractures and mine tremors) and may not be strictly similar to small natural earthquakes at active major faults. Furthermore, several studies of small earthquakes (~ 1-4 M_L) have been interpreted as evidence for breakdown in constant stress drop scaling below about magnitude 3 [*Archuleta et al.* 1982; *Guo et al.* 1992]. In these studies, ~3 M_L events and smaller appear to have a minimum source dimension of a few hundred meters, and stress drop appears to decrease with decreasing seismic moment. The apparent breakdown in earthquake self-similarity observed could be due simply to confusing attenuation of frequencies above 10 Hz with spectral amplitude decay at or about 10 Hz [*Anderson* 1986]. The severest attenuation occurs in the upper few hundred meters of the crust where it can affect the high seismic frequency contents of most catalogs.

It is apparent that corrections for attenuation, such as by forming ratios of the seismic spectra of large and small events from the same general crustal volume, with the expectation that attenuation effects along the common ray path divide out [eg. *Mori & Frankel* 1990], or by a theoretical Q correction [e.g. *Lindley & Archuleta* 1992] lead to ambiguity. However, the low background noise levels in deep boreholes allow smaller, higher characteristic frequency earthquakes to be recorded, extending the magnitude range of catalog events and avoiding near surface attenuation. The 3.5 km deep Cajon Pass borehole, 4 km from the San Andreas fault in southern California, provides an opportunity to record natural earthquakes at seismogenic depths in a major fault zone.

Data and Instrumentation

The 3-component set of high temperature 10 Hz geophones was installed at 2.5 km in the Cajon Pass scientific drill hole in 1991 (Figure 1). The drill hole rock column consists of 500 m of sediment and 200 to 300 m of highly fractured granite followed by largely uninterrupted intact crystalline granite [*Geophys. Res. Lett. 15*, 1988; *Leary* 1991). Triggered recording of the downhole sensor at 500 samples per second started in 1991. About 10% of the typical background seismicity (10 to 15 earthquakes a day) are large enough to be recorded by the Southern California Seismographic Network (SCSN), which is estimated to be complete down to about 1.8 M_L. The seismic noise at this depth is undetected below instrumental noise (10 to 50 times lower than background noise at the wellhead). The high frequency limit is about twice that of most surface small

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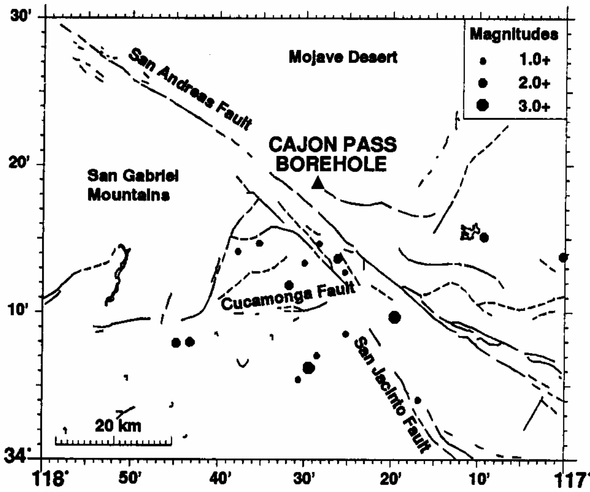

Fig. 1. Location of the Cajon Pass borehole and the epicenters of our sample earthquakes large enough to trigger the SCSN.

earthquake studies and up to three times that of most regional networks. The forty earthquakes presented here were selected for their high signal to noise ratio and their small hypocentral distances (all within 45 km, 2/3 within 15 km; Figure 1). Approximately half were large enough to trigger the SCSN. They have focal depths between 5 and 18 km but shallower earthquakes are recorded in the area.

Source Parameters

Displacement amplitude spectra of *P* and *S* waves for two-second time windows of the downhole seismograms (e.g. Figure 2) were fit to the logarithm of the functional form [Brune 1970]. The best fit to the variables low frequency asymptote (Ω_0) high frequency decay rate (n) and corner frequency (f_c) is found by a non-linear, least squares simplex algorithm. The source parameters seismic moment, source radius and stress drop were then calculated following *Brune* [1970], *Madariaga* [1976] and *Kanamori & Anderson* [1975] respectively. The mean radiation pattern is assumed [*Aki & Richards* 1980]. The two decade frequency bandwidth and low background noise increase the reliability of the corner frequency and high frequency decay rate measurements over those from more narrow band studies. The *P* wave corner frequencies are approximately equal to those of the *S* waves plus 8 Hz. Amid the scatter, the ratio of *P* to *S* corner frequencies is also compatible with the theoretical value of 1.5 [*Madariaga* 1976]. For the majority of the spectra $1.5 \leq n \leq 3$, with no significant dependence on hypocentral distance. The straight line decay on the log(amplitude) vs log(frequency) plot in Figure 2 indicates a power law fall off of amplitude rather than an exponential decay characteristic of attenuation. When the entire source-receiver ray path is deeper than 2.5 km, attenuation is negligible for the hypocentral distances represented in the catalog. To affirm that significant correction for intrinsic attenuation is not necessary for the downhole spectra, source parameters and Q values are calculated by fitting a standard ω^{-2} source model to spectra of earthquakes at a range of hypocentral distances. The fits produced minimum possible values of Q of ~1000-2000 for *S* waves and twice that for *P* waves in the frequency range 2 to 200 Hz. These Q values are similar to those found by *Hough & Anderson* [1988] in crust deeper than 5 km at Anza. Correcting for attenuation with Q ~ 1000-2000 produces less than 10% differences in seismic moment and source radius, with corrections not systematic for hypocentral distance or event magnitude.

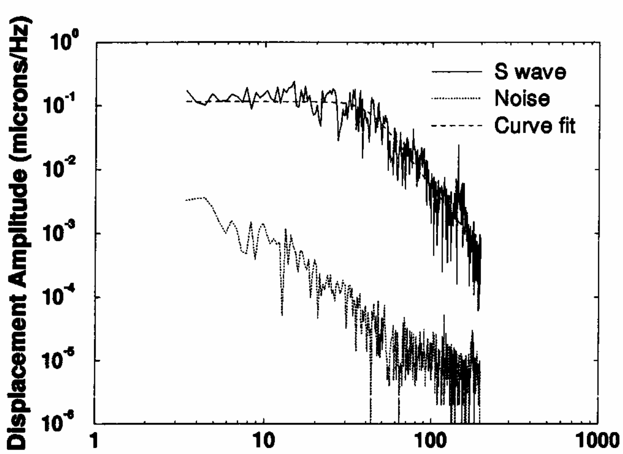

Fig. 2. Displacement amplitude spectrum of a magnitude 1.7 earthquake, showing the curve fitted to determine source parameters (f_c = 39.6 Hz, Ω_0 = 0.12 microns/Hz, n = 3.3).

Near Surface Attenuation

Several of the earthquakes in our downhole catalog were large enough to be recorded by the Cajon Pass surface receiver over surface background noise. Comparison of uphole and downhole recordings of these events determines the near surface attenuation. Figure 3 compares the spectra of a 12 km deep earthquake near the borehole as recorded at the surface and downhole. Uphole *P* and *S* corner frequencies determined by curve fitting with an ω^{-2} model are 36 Hz and 5 Hz respectively, with the average whole path Q ~ 500. The uphole *S* wave corner frequency is substantially lower than the 40 Hz for *S* waves downhole, casting doubt on the ability of simple theoretical attenuation corrections to compensate for near-surface attenuation. Curve fitting of the spectral ratios of surface and downhole recordings in the Cajon Pass catalog yield mean near-surface Q_S ~25 and Q_P ~ $2Q_S$.

Earthquake Source Scaling

Figure 4 plots log(seismic moment) vs log(source radius) for the 40 event Cajon Pass catalog. The events are entirely

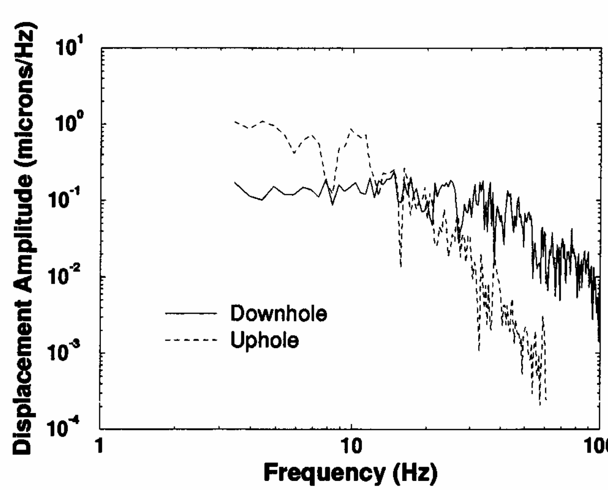

Fig. 3. Displacement spectra of the *S* waves of the same earthquake as in Figure 2, as recorded downhole and at the wellhead, showing the amplification of the lower frequencies and attenuation of the higher frequencies at the surface with respect to downhole.

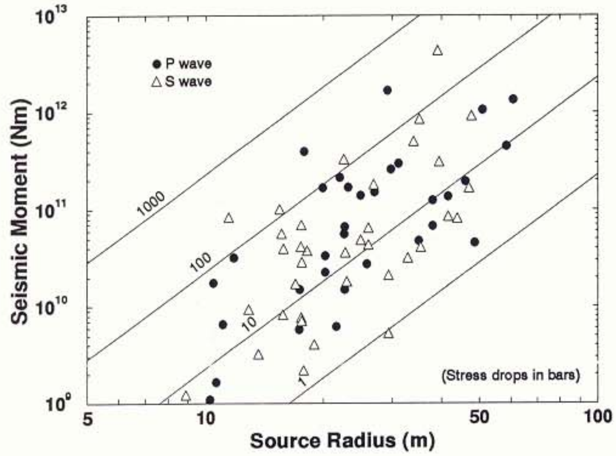

Fig. 4. Source parameters for 40 sample earthquakes determined from borehole recordings. The lines of constant stress drop are calculated following *Kanamori & Anderson* [1975].

compatible with a "constant stress drop" slope of 3 (slope of least squares regression is 2.7). The larger events for which SCSN magnitudes are available fit the typical relationship between seismic moment and magnitude of small (≤3 M_L) Californian earthquakes [*Pearson* 1982; *Archuleta et al.* 1982]. Extrapolation of the moment-magnitude relationship to moments having no SCSN magnitude implies that earthquakes down to about magnitude -2 are in the borehole event catalog. Seismic moments determined from the downhole recordings at ~5 Hz agree with moments determined from 20 to 30 s surface waves for events recorded by the TERRAscope network [*H-K. Thio,* 1992 *per. comm.*] .

In compilations of seismic events of magnitude -6 to 6 [e.g. *Pearson* 1982] the smallest tectonic earthquakes had source dimensions of a hundred meters. A 100 m source dimension has been suggested by *Archuleta et al.* [1982], *Aki,* [1987] and *Hough et al.* [in prep.] to be a constant minimum rupture dimension. Figure 4, containing tectonic events with source radii < 100 m, does not support this conclusion as a general feature of crustal earthquakes. Figure 5 shows the results from the Cajon Pass borehole combined with those from 12 other studies covering a moment range of 20 orders of magnitude. Although all authors do not use exactly the same method of determining the stress drop, any systematic differences between studies are likely to be negligible in comparison to the large errors in an individual stress drop measurement (proportional to corner frequency) and the scatter within individual studies. The combined results over the range 0.1 to 10^5 m source dimension are compatible with constant stress drop scaling. The Cajon Pass events, the smallest natural earthquakes analyzed to date, extend the minimum source dimension observed for natural earthquakes down to less than 10 m.

Discussion

A closer look at Figure 5 shows two points worthy of note. The first is that although earthquakes as a whole are broadly self-similar, the induced seismic events (the lowest moments studied) have lower average stress drops than the smallest

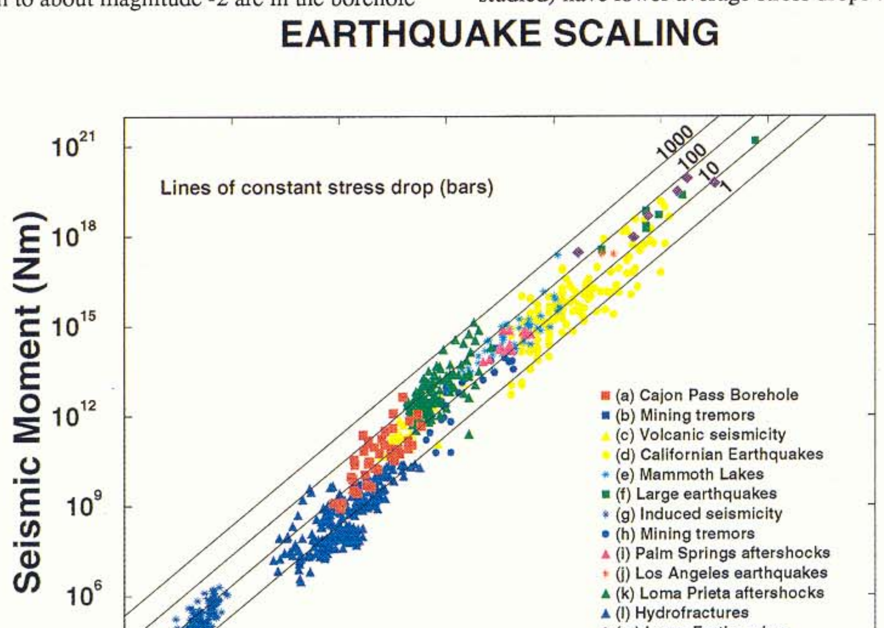

Fig. 5. Composite plot showing the results of 13 source parameters studies over a very wide magnitude range. Only studies in which the effects of attenuation were taken into account are included. Lines of constant stress drop as in Figure 4. (a) Cajon Pass, the smallest tectonic earthquakes; (b) Mining tremors [*McGarr et al.* 1990]; (c) Volcanic seismicity [*Del Pezzo et al.* 1987]; (d) Mammoth Lakes (large events), California [*Archuleta et al.* 1982]; (e) California earthquakes [*Thatcher & Hanks* 1973]; (f) Large earthquakes, including 1985 Michoacan, [*Heaton* 1990]; (g) induced seismicity [*Gibowicz et al.* 1991]; (h) Mining tremors [*Spottiswoode & McGarr* 1975]; (i) Palm Springs, California, aftershocks [*Mori & Frankel* 1990]; (j) Los Angeles earthquakes [*D. Dreger, pers. comm.*]; (k) Loma Prieta, aftershocks [*Guo et al.* 1992]; (l) Hydrofractures [*Fehler & Phillips* 1991], (m) recent earthquakes [*D.Wald, pers. comm.* 1993].

natural earthquakes. The mean stress drop in both this study and that of *Guo et al.* [1992] is about 50 bars, whereas that of the induced events is about 5 bars. *Fehler & Phillips* [1991] suggest that hydrofractures may have lower average stress drops due to heterogeneous slip, presumably along less well developed or previously non-existing fractures. We favor the possibility that, because artificial conditions locally disturb the *in situ* stress levels, fluid-induced (or mining induced) seismic events can occur in areas of lower tectonic stress than characterizes natural seismicity. Attributing differences in stress drop between induced and natural earthquakes to different levels of crustal stress is consistent with the scale invariance of the brittle failure process in crustal rock suggested by the fractal distribution of fractures seen in deep borehole logs [*Leary* 1991].

The second observation of note is that whereas composite studies are compatible with a constant stress drop (in fact if induced events are excluded they show a slight increase in stress drop with decreasing moment) some individual study catalogs show a decrease in stress drop with decreasing moment. This trend could be due to the frequency band limited nature of each study combined with the large errors in the stress drop measurements (stress drop $\propto f_c^3$). If the trend toward lower stress drop with smaller moment is real, we suggest that it is more likely to be due to local structure [*Hough et al.*, in prep.] than a fundamental aspect of the crustal brittle failure process. In order to test this, individual catalogs covering a greater range of source dimensions (greater frequency bandwidth) are needed.

Conclusions

The natural earthquake seismograms recorded at 2.5 km at Cajon Pass near the San Andreas fault zone provide evidence that non-scaling source structure (f_{max}, breakdown of seismic scaling or strongly decreasing stress drop with decreasing moment) reported in recent studies of small, surface-recorded earthquake catalogs is an artifact of the severe near surface attenuation. We find no evidence for a breakdown in earthquake self-similarity in natural seismicity to a source radius of 10 m.

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