Depth Dependent Rupture Properties in Circum-Pacific Subduction Zones

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Depth dependence of the source rupture duration of interplate thrust earthquakes is examined for seven subduction zones around the Pacific to explore variations in faulting properties. Multi-station deconvolutions of teleseismic P waves for moderate size earthquakes yield estimates of the source time function and centroid depth for each event. Analysis of 17 to 75 earthquakes in each region reveals a consistent trend of decreasing source duration (inferred from the source time functions, after correction for differences in total energy release) with increasing depth. Rupture duration patterns vary somewhat between subduction zones as well as along strike within a given zone, and the data have large scatter, implying significant variation in rupture processes along the interplate megathrusts, but the depth dependence appears to be robust. The rupture duration variations prompt consideration of two end-member models: 1) depth-dependent rupture velocity is caused by variations of rigidity of materials in the fault zone, while static stress drop is constant, and 2) static stress drop varies with depth while material properties and rupture velocity are constant. For the first model, the volumetrically averaged rigidity of the fault zone must increase with depth in each region by a factor of 5 between depths of 5 to 20 km. If rupture velocity is constant, the stress drop must increase by an order of magnitude over the same depth range. This systematic variation in rupture behavior with depth may reflect spatial variations in the amount, compaction and porosity of sediment in the fault zone, topography on the subducting plate, phase transitions in the fault zone materials, thermal structure of the megathrust, and varying presence of fluids in the fault zone. Such physical variations appear to control the physics of rupture propagation, leading to intrinsic dependence of rupture velocity on materials and fluids within the fault zone.

INTRODUCTION

Approximately 90% of global seismic energy release occurs in subduction zone earthquakes, primarily involving thrusting motions on the interplate megathrust faults [Pacheco et al., 1993]. Variations in earthquake rupture complexity and total energy release have been related to gross properties of subduction zone geometry and kinematics, with the underlying premise that earthquake faulting varies with the megathrust environment [Ruff and Kanamori, 1980; Lay et al., 1982; Kanamori, 1986; Ruff, 1992]. While some intriguing general associations have become evident, we are far from a detailed understanding of what controls faulting
in subduction zones. It is becoming increasingly well documented that frictional properties of the megathrust are very complex, and the entire spectrum of convergent motions must be considered. For example, some regions experience large amounts of slip occurring over periods as long as one year after large thrust events. This has been observed in Japan, where Heki et al. [1997] used geodetic measurements to detect postseismic slip equal to the amount of coseismic slip in the year following the December 24, 1994 Sanriku-oki event. Similarly, significant postseismic slip has been observed for the 1992 Sanriku-oki event in Japan [Kawasaki et al., 1995].

Several subduction zones have also experienced destructive tsunami earthquakes, which produce a larger tsunami than expected given their seismic magnitude [Kanamori, 1972]. These events commonly release seismic waves that are depleted in high frequency energy, apparently as a result of having unusually slow rupture propagation [Pelayo and Wiens, 1990; Kanamori and Kikuchi, 1993; Satake, 1994; Tanioka and Satake, 1996; Johnson and Satake, 1997; Ihmlé et al., 1998]. The distinctive seismic wave spectra of these events has even served as a basis for near real-time detection of tsunami earthquakes involving calculation of spectral energy ratios [Newman and Okal, 1998; Shapiro et al., 1998]. The observation that tsunami events rupture at very shallow depths where weak sediments are likely to be present in the fault zone has prompted speculation that rupture in low rigidity materials causes slow rupture velocities and results in a larger faulting displacement for a given seismic moment. These factors can explain the spectral characteristics and enhanced tsunami excitation of tsunami earthquakes [e.g., Kanamori and Kikuchi, 1993]. If this is correct, one might expect shallower thrust events in the interplate thrust zone to have longer rupture durations than deeper events, and relatively long duration ruptures should be observed in regions where significant sediment is subducting compared to regions where no sediment is present. It is not clear what to expect in terms of complexity of rupture, other than the possibility that the shallow environment is intrinsically more heterogeneous in material properties and stress than the deeper portion of the interplate thrust zone.

There have been several investigations of earthquake rupture duration variations with depth in subduction zones, primarily focused on intraplate events within the subducted slab. Vidale and Houston [1993] stacked short period $P$ waveforms to estimate source duration of 160 intermediate to deep events (depth > 100 km). They found evidence for a decrease of source duration with increasing depth accompanied by enhanced scatter in duration for intermediate depth events. Bos et al. [1998] and Houston et al. [1998] stack broadband records for events from 100 to 650 km deep, finding a weak trend of decreasing source duration with increasing depth that can be completely accounted for by the expected increase in shear wave velocity with depth. Houston et al. [1998] find evidence of asymmetry and complexity in the stacked time functions for events from 350-550 km depth. Campus and Das [Comparison of the rupture and radiation characteristics of intermediate and deep earthquakes, submitted, J. Geophys. Res.] do not detect any unusual depth dependence for intermediate and deep focus events for events in Fiji and Japan. Overall, no dramatic depth dependence of rupture properties has been revealed within the intraplate environment of intermediate and deep focus earthquakes.

Many studies of earthquake rupture have been made for individual or suites of events on the megathrust zones, and some have focused on depth dependent systematics. Tichelaar and Ruff [1991, 1993] examined variations in maximum depth of interplate thrust events to assess controls on seismic coupling. Zhang and Schwartz [1992] analyzed the depth distribution of moment release in different zones to assess variations in thermal structure and stress. Ekström and Engdahl [1989] determined source parameters for many earthquakes in the central Aleutian Islands to examine variations in stress distribution, and Tanioka et al. [1996] considered lateral variations in earthquake rupture and slab morphology along the Japan trench. Bilek and Lay [1998, 1999a] focus on earthquake rupture duration variations for shallow events in the Japan and Middle America subduction zones, finding that the shallowest events have anomalously long source durations in both subduction zones. Bilek and Lay [1999b] show evidence for similar behavior in other regions, and propose several possible mechanisms to account for this observation, involving physical attributes of the subduction zone such as roughness of the subducting plate, amount and type of sediment being subducted, thermal structure, and fluid processes in the fault zone. Earthquake behavior in the interplate seismogenic zone can thus guide interpretations of the thermal and petrological structure of subduction zones [e.g., Peacock, 1993; Hyndman et al., 1997; Oleskevich et al., 1999]. This study extends the examination of depth dependent variations of earthquake rupture duration in seven subduction zones: Japan, Kuriles, Alaska-Aleutian Islands, Mexico, Middle America, Peru, and Chile.
The subduction zones around the Pacific that we analyze (Figure 1) are selected primarily on the basis of abundant shallow interplate seismicity. Our focus is on frictional and faulting processes along the megathrust zones, and several criteria are used to select events located on the main thrust fault. Earthquakes are initially selected based on (1) close proximity to the main thrust zone of interest, (2) having a faulting mechanism (from the Harvard Centroid Moment Tensor (CMT) catalog) with strike, dip, and rake consistent with underthrusting of the subducting plate (typically, events have a strike within 20-30° of the local strike of the trench, a dip of 30°-35°, and a rake of 90°±30°), (3) having a moment magnitude (Mw) of 5.0-7.5, and (4) availability of at least 4 good quality broadband teleseismic P wave recordings that are well distributed azimuthally from the source (between 7 and 15 P wave recordings are used for most events). These criteria are similar to those used by other authors in earlier studies of depth dependence of subduction zone properties [e.g., Zhang and Schwartz, 1992; Tichelaar and Ruff, 1991, 1993].

For the selected events, we obtain all available teleseismic vertical component broadband recordings from the IRIS data center with time windows appropriate for the direct P phase and associated depth phases (pP, sP) needed for accurate source depth determination. Ground displacement traces are obtained by deconvolving the instrument response, and the P wave onsets are manually picked on each record. A multistation deconvolution method is then used to determine the source time function that represents the time history of seismic moment release from the source [Kanamori and Ruff, 1983; Ruff, 1989; Tichelaar and Ruff, 1991; Ruff and Miller, 1994]. The deconvolution method is based on computing synthetic P wave Green's functions for each event using the best double couple of the Harvard CMT solution for a model with a water layer over a uniform half space with a P wave velocity of 6.0 km/s. We deconvolve the P waves by Green's functions generated for a range of 15-25 point source depths, obtaining source functions at each trial depth. The depth at which the deconvolution minimizes the misfit between the data and synthetic seismograms is preferred. While simultaneous inversion for a revised focal mechanism may reduce some uncertainties, it is not viable for most of our events given the limitations of the available P wave data. In general, tradeoffs between source mechanism and either source depth or source time function are not too severe for shallow thrusting events, and the CMT solutions are probably fairly robust for most of our events. The general processing sequence is shown in Figure 2 for an event in the Aleutian Islands region. The stations used are well-distributed azimuthally from the source, which ensures a range of wave shapes and corresponding Green's functions that reduces the severe trade-offs between depth and source function. From the deconvolution procedure, performed for 23 depths in Figure 2, we determine an optimal depth of 31 km based on the minimum in the misfit curve. The corresponding source function has a simple trapezoidal shape with a duration of 7 s, followed by some low amplitude oscillations. The latter oscillations are highly variable, and represent instabilities caused by accumulating inaccuracies in the Green's functions with lapse time into the signal. This event and the associated P wave signals are well characterized by the strong trapezoidal pulse, although there is intrinsically some subjectivity as to when the true source radiation was finished.

Figures 3-9 show final source time functions for all events in the 7 subduction zones. The panel for each event shows the source time function for the optimal source depth and our preferred depth and source duration. In some cases, the depth determination is robust, with a single distinct minimum in the misfit curve. However, in other cases, there are double or multiple minima in the misfit curves, or a range in depths with relatively uniform misfit. For these cases, we examine the source time function produced for each depth, and choose the depth which yields the simplest time function, with most of the moment released early in the signal [Christensen and Ruff, 1985].
Figure 2. Example of data processing for $M_w=6.49$ event in the Aleutian Islands region. (a) Focal mechanism of the event taken from the Harvard CMT catalog. The event was chosen because of its underthrusting mechanism (strike 262$^\circ$, dip 24$^\circ$, rake 114$^\circ$), close proximity to the trench, and moderate magnitude. (b) Error or misfit as a function of depth for the deconvolutions. We perform the deconvolution for 23 different depths to minimize the misfit between the data and synthetics. Minimum occurs at 31 km depth. (c) Source time function for deconvolution at 31 km depth. On left is source time function, on right is source time function with misfit bounds in gray dashed lines. Source duration is measured from the first large peak of the source time function; the black bar indicates the measured duration of 7 s. (d) Data (solid black lines) and synthetic seismograms (dashed) shown with the station code and azimuth from the event.

The point-source time functions in Figures 3 to 9 further illustrate the difficulties intrinsic to measuring the time interval of source energy release. As in Figure 2, the deconvolutions sometimes show significant amplitude oscillations after the main pulse of moment rate, or significant negative overshoot following the primary pulse. For the largest events, unparameterized spatial finiteness may contribute to these features, but their sensitivity to source depth suggests that inaccuracy of the later portions of the Green's functions is the primary
culprit. This is not unexpected given possible errors in the focal mechanism and the very simple velocity model assumed in computing the Green's functions. Until realistic near-surface and wedge velocity structure is known_t in each region and fully three-dimensional Green's functions can be computed for such structures, it will be hard to improve the accuracy of the time function estimates. The time function complexity makes it difficult
to define the cessation of coherent energy release from the source, and in some cases there may be isolated secondary pulses of source radiation. However, every case shown does have a primary pulse of moment rate in the early part of the signal that accounts well for the predominant features of the teleseismic $P$ waves. We proceed by measuring the duration of the primary positive pulse of the source time function, which usually suffices to characterize the energy release history. We attempt to be consistent in measuring the width of this
pulse, defining the end as when the pulse returns to a baseline level. We incorporate error bars on the duration estimates to subjectively reflect the difficulties in measuring the time function duration.

There are several trade-offs in determining the source duration and depth parameters. Source time function duration and depth have particularly strong trade-offs for individual stations [e.g., Christensen and Ruff, 1985]; however, by performing the deconvolution for many well distributed stations, the ability to separate these parameters is greatly improved. Additionally, there are trade-offs between velocity model and source depth. The choice of a half space velocity of 6.0 km/s undoubtedly biases our depth estimates. Tests using a different average velocity show that a 10% change in average velocity leads to a corresponding 8-12% change in source depth (approximately 3-4 km), similar to the results of Tichelaar and Ruff [1991]. Given the likelihood of low velocities in the sedimentary wedge above the thrust plane, we probably overestimate true depths by several kilometers, particularly for the shallowest events. Our depth estimates still tend to be shallower than those in the CMT catalog (Figure 10), partly due to the higher average crustal and upper mantle velocity of the Preliminary Reference Earth Model (PREM) [Dziewonski and Anderson, 1981] structure used in the CMT inversion. There are also differences caused by the practice of fixing CMT depths at either 15 km or 33 km for shallow earthquakes when the depth resolution is not good. Holding the focal mechanism constant is another source of possible error in the depth determinations, but tests of the effects of focal mechanism uncertainty indicate that the depth estimates are not very sensitive to small focal mechanism changes. The error bars that we assign to the depth estimates reflect these sources of error. The point-source assumption explicit in our deconvolutions clearly results in some averaging of spatial finiteness effects that may bias our source duration estimates. Estimation of source radiation duration from the source time functions involves an approximation that there is a simple rupture process that yields negligible directivity effect. As most of our events are of moderate size, and the deconvolution process emphasizes wave periods longer than 1 or 2 s, the directivity effects in teleseismic P waves are likely to be below the resolution of our measurements in almost all cases. The good fit of the point source synthetics to the observations gives direct support for this assertion. The residual waveform mismatch error varies somewhat, but not in a fashion simply linked to the shape of the source time functions or the event moment (see Figure 2). As a first-order approximation, we take the duration of the main pulse of the source time function as an estimate of the actual rupture duration. We correct the rupture duration estimates for the effect of varying seismic moment (\(M_o\)) as it has been empirically shown that the duration is proportional to the cube root of \(M_o\) [Kanamori and Anderson, 1975; Houston et al., 1998; Campus and

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Figure 4. Continued
Das, 1999]. Each duration estimate is divided by the cube root of the associated $M_0$ from the Harvard CMT catalog, normalized to a moment magnitude ($M_w$) 6.0 event. The CMT moments are used for scaling rather than the moments determined from the deconvolution process, as we feel the CMT moments are more stable estimates because they are derived from large numbers of long-period data. Our deconvolution moments tend to underpredict the values found by Harvard, in part due to the velocity model used, and possibly due to
RESULTS

Figure 11c shows normalized duration estimates as a function of source depth for the entire dataset, representing 354 events. We include 68 events from a
study of maximum coupling depth in subduction zones [Tichelaar and Ruff, 1991; Tichelaar and Ruff, 1993], which provided depth and duration estimates by the same general procedure used here. Those duration estimates are also scaled using cube root of moment scaling. The trend of decreasing duration with increasing depth is very clear, even in this composite plot which combines data from subduction zones with different regional characteristics. A source duration of about 3 s is typical of an $M_w = 6.0$ event, but scaled durations as long as 18 s are found for events shallower than 15 km depth. With typical error bars being $\pm 1.5$ s, the long duration estimates appear to be real anomalies.

Figure 12 shows the same data, subdivided by geographic region and with error bars on depth and duration values. The trend of decreasing source duration with increasing depth is apparent for each region, although some subduction zones have stronger patterns than others. For instance, data for the Alaska-Aleutian Islands region show a very dramatic decrease in duration down to a depth of 15-20 km, then a flatter distribution at depths deeper than 20 km. The Kuriles,
Mexico and Peru show similar abrupt changes at depths shallower than 25 km, but these three regions have fewer events than the Alaska-Aleutian Islands region. The South American zones have slightly shorter duration plateaus at depths greater than 20 km than do Japan and the Aleutians, which may reflect differences in crustal structure overlying the subduction zones. Central America displays the weakest variation with depth, with events less than 10 km deep showing some increase in duration. The scatter in duration is

Figure 7. Source time functions for Central America events, in same format as Figure 3.
comparable between regions for depths greater than 10 km, and indicates the intrinsic variability in earthquake rupture processes and errors in duration estimation.

Given that our depth estimates differ from both the CMT values and earthquake bulletin values, we seek to confirm that the events are truly on the megathrust, and not intraplate ruptures. Plate I shows our depth and duration data plotted as a function of distance perpendicular to the regional trench axis. This distance was measured using bathymetry maps to track the trench axis. Events located within the dashed gray boxes are considered likely to lie on the main plate interface, which may itself involve multiple thrust planes, within a ±5-10 km region. Those events which lie outside the box may either be mislocated (laterally or in depth), are intraplate earthquakes with thrust mechanisms similar to underthrusting at the plate boundary, or are thrust events occurring in the accretionary wedge above the seismogenic zone. The events define dipping plate interfaces in each region, with some of the scatter attributable to changes in plate geometry. The distributions are much tighter than provided by either the CMT or earthquake bulletin locations, so our depth estimation process generally appears to have succeeded. In regions that exhibit a lot of scatter and where there is significant along-strike geometry change, we binned the data to ensure that we include only events that are confidently identified as interplate thrust events. The data still show a decrease in source duration with increasing depth along the plate interface for each region.
Figure 9. Source time functions for Chile events, in same format as Figure 3.

mainly because very few of the shallowest events have been excluded.

ALASKA-ALEUTIAN ISLANDS DATASET

The strong pattern and large number of data in Figure 12 for the Alaska-Aleutian Islands region prompted a more detailed look at the seismic parameters for events in this area. There have been many great earthquakes as well as tsunami earthquakes in this region, which emphasizes the importance of understanding the nature of the seismogenic zone here. Figure 13a shows the locations of the events analyzed for the Alaska-Aleutian Islands region; a total of 74 earthquakes from 1989 to 1997. We consider the patterns in the data in both depth and along-strike bins.
Figure 10. Comparison of depths as listed by the Harvard CMT catalog and depths determined in this study. Our depths tend to be more shallow than the Harvard CMT depths, and our depths do not show any bias towards certain depths, such as the large grouping of Harvard CMT depths of 15 km and 33 km.

Figure 13b shows the average source time functions along the entire Alaska-Aleutian arc for four depth bins of 0-10 km (20 events), 10-20 km (26 events), 20-30 km (10 events), and 30-40 km (18 events). Both the seismic moment rate amplitudes and the source durations were scaled to remove the effects of varying seismic moment, following the procedure of Houston et al. [1998], prior to binning the events and averaging the time functions. The time scales were divided by $\sqrt{M_o}$, normalized by the reference $M_w$ 6.0 event ($M_o$ 1.16x10^{25} dyne-cm). The moment rate amplitudes were divided by the event $M_o^{2/3}$ in order to maintain the relationship between moment and area under the time function. Individual time functions were set to 0 prior to the beginning of the large pulse of energy in the source time function, and 0 after our pick of the termination point of the faulting radiation. The stacked source functions for each depth range have been scaled so that the area beneath each curve is equal to 1.16x10^{25} dyne-cm, to facilitate comparison. The most obvious feature is the dramatic difference in the shape of the source time function for the 0-10 km bin, as this visually demonstrates the general trend of decreasing source duration with increasing depth. The time function for the 0-10 km bin has a duration of 16.4 s while the time function for events greater than 30 km has the shortest duration of 7.0 s. The average source function for the shallow events suggests evidence of greater rupture complexity as well, although the subevent features are highly variable from event to event.

We also consider along-strike variations in the source time functions of the Alaska-Aleutian Islands events. The along-strike bins are based on distinct tectonic blocks as described by Geist et al. [1988]. Initially we considered all events in each spatial bin, but this was problematic due to the distinct shape of the time functions for the shallowest events. The shallowest events in each region display qualitatively similar broadening, but the total numbers are too small to average just the shallowest events. For this reason, we stack only events deeper than 10 km in the along-strike bins shown in Figure 13a using the same procedure as described above. Figure 13c shows the average source time functions for each subregion, plotted on same scale to facilitate comparison between regions. Four of the six bins look remarkably similar, but events in the Unimak Block and Shumagin Block differ somewhat from the others. There may still be some depth effect in these stacks, as events in the Unimak Block have mainly 10-20 km depths while events in the Shumagin Block have mainly 30-40 km depths. The cause of these variations is unclear at this point, but lateral variations along the arc are certainly less pronounced than the common depth variation.

Our data for the Alaska-Aleutian Islands events do suggest variations in maximum coupling depth for this region. Tichelaar and Ruff [1993] examined 11 events in the Aleutians region and 5 events near the Alaskan peninsula to determine an average maximum coupling depth for the Aleutians of 35-41 km and 37-41 km for Alaska. Our larger data set supports these averages of maximum coupling depth, although it appears that there is significant variation in the coupling depth along strike of the trench, with some sections of the seismogenic zone having much deeper coupling than other sections. Tichelaar and Ruff [1993] mention that the easternmost portion of the 1957 earthquake rupture zone may have shallower coupling; this region corresponds approximately to the Unimak Block bin, where we see earthquakes only down to 20 km depth. We also observe the possibility of shallower coupling around longitude 180° within the Rat and Delarof Block bins, with deeper coupling found on either side. We are only considering events with $M_w$ 5-7.7, so our results on coupling depth are appropriate for that magnitude range.
Plate 1. Normalized source duration and source depth as a function of distance from the respective trench. The color bar below indicates source duration for each symbol. Error bars show range in depth estimates from the range in misfit from the deconvolution processing. The dashed boxes enclose those events that define the plate interface, allowing for some scatter due to variation in the along-strike subduction zone geometry. Events which lie outside the box are likely either accretionary wedge or intra-plate events (gray symbols in Figure 12). Triangles represent events determined by Tichelaar and Ruff [1991, 1993].
As data accumulate, it may prove viable to map out lateral variations in faulting complexity and coupling depth in greater detail, but the present results indicate that rather subtle variations will be found.

**DISCUSSION**

Further mapping out of lateral variations in behavior of earthquake ruptures within each zone and between zones remains a desirable goal, but for the remainder of this study we focus on the common depth-dependence apparent in Figure 11c. Seismological analysis reveals only gross attributes of the source energy release, and there is substantial non-uniqueness when interpreting source time function characteristics in terms of dynamical behavior. We will consider several simple end-member possibilities to frame the problem. One possible explanation for the observed variations in source duration is systematic variation with depth of rigidity of the material in the seismogenic zone. This is an extension of the notion that tsunami earthquakes have slow rupture velocities because the slip occurs in low rigidity sediments at very shallow depths. Rigidity is a key material property that can be related to source duration through its direct influence on shear wave velocity. For a simple unilateral rupture model, source duration is inversely related to rupture velocity. The rupture velocity ($V_r$) is empirically found to be approximately equal to 80%±10% of the shear wave velocity ($\beta$) [Scholz, 1990],

$$\beta = \frac{\mu}{\rho}$$

where $\mu$ is the rigidity and $\rho$ is the material density. If we assume a constant static stress drop model for scaling, variations in the duration can be associated with variations in rigidity. The constant stress drop model appears valid for a range of earthquake magnitudes [e.g., Abercrombie, 1995], although we do expect scatter to result from variations in stress drop. Thus we can use our source duration measurements to estimate volume-averaged (over the range of large strain accumulation) rigidity variations with depth in the seismogenic zone.

In order to calculate the rigidity, we use a constant density of 2.7 g/cm$^3$. It is clear that the density will
Figure 12. Normalized source duration as a function of source depth for each of the analyzed regions. Open squares indicate events analyzed in a similar fashion by Tichelaar and Ruff [1991, 1993]. All of the 354 event source durations have been scaled using the cube root of seismic moment, normalized to a $M_w=6.0$ event. Gray symbols indicate those thrust events satisfying our initial criteria, but have depth estimates suggesting that they did not occur at the plate interface.
change somewhat with depth, but we use a constant density for simplicity. The other parameter needed to estimate rigidity is a source dimension, as the source duration ($\tau$) equals

$$\tau = \frac{\text{source dimension}}{V_r}.$$  \hspace{1cm} (2)

We assume a uniform source dimension of 10 km for our moment-scaled rupture durations. This dimension is consistent with the 3-4 s duration for a typical $M_w 6.0$ event, with a 3.0-3.5 km/s rupture velocity. This choice of a rupture dimension affects the baseline of the rigidity values, but not any systematic depth variations. It is not presently possible to independently determine the rupture dimensions for all of our events using directivity analysis because of their small magnitude. Since it is unlikely that they all rupture precisely (scaled) 10 km dimensions, we expect significant scatter to remain.

Figure 14 shows the seismogenic zone rigidity estimates obtained for the seven subduction zones considered in this study. There is an order of magnitude
Figure 14. Plot of estimated rigidity variations along the megathrust for the entire dataset. Small black circles indicate rigidity values calculated from our measured source durations, triangles indicate rigidity estimates for the 68 events in the Tichelaar and Ruff [1991, 1993] datasets, and open circles are average rigidity values over a depth interval. The solid black line indicates the rigidity values estimated from PREM shear wave velocities and densities.

scatter in the data at all depths, but we find a general trend of increasing rigidity with increasing depth in the range of 5-50 km. Rigidity values estimated from PREM are included in the figure to provide a reference earth comparison for a layered crust/mantle intraplate oceanic environment. Our average values are very similar to PREM at depths of 20-40 km, but are lower than PREM by a factor of as much as 5 at depths shallower than 20 km. Given the likely contributions to error in the rigidity estimates from the factors described above, only the average trend should be considered, not the full range of values.

One concern inherent in these estimates is the use of Harvard CMT moments in scaling the source durations. These moments are calculated using the PREM structure for seismic wave excitation. If the rigidity variations in Figure 14 are correct, the excitation should be recomputed for a corresponding decrease of rigidity near the surface. Overestimating the rigidity in the modeling may have yielded seismic moments that are too small for shallow events, which would underestimate the corrections for moment scaling. A quantitative correction for this effect is very difficult, both because the rigidity is not independently known, and the excitation should be computed for a realistic three-dimensional model to obtain unbiased moments. We believe that the overall effect of such correction for moment scaling would be a slightly reduced range of rigidity values, but the general trend would be preserved.

Studies of tsunami earthquakes have inferred comparable (factor of 5 to 10) reductions of rigidity for the seismogenic zone necessary to reduce rupture velocities to about 1 km/s and to account for the enhanced slip needed to satisfy tsunami excitation given the observed seismic moments [Kanamori, 1972; Pelayo and Wiens, 1992; Kanamori and Kikuchi, 1993; Satake, 1994; Heinrich et al., 1998]. Thus, these calculations suggest that all subduction zones may have shallow regions with low rigidity properties that could enable large tsunami earthquakes to take place. Whether they do or not is likely to be a consequence of the slip history of the deeper portions of the seismogenic zone, along with the myriad factors that control the transition from stable sliding to stick-slip instabilities.

If the rupture velocity is decreased because of low shear velocities, a fairly thick zone of reduced rigidity must be present to affect the volumetric strain release during rupture. The rigidity estimates in Figure 14 would then be averaged over the seismogenic zones, and local properties right at the plate interface may vary even more. The fact that our rigidity estimates do not display any seismic moment dependence (especially when very large tsunami event results are included), indicates that the scale of the region of low rigidity may be substantial. Various factors could produce a distributed zone of low rigidity material near the fault zone. A thick zone of sediments both above and within the seismogenic zone is a likely candidate for significant reduction of rigidity relative to hard rock values. Lower rigidities can also be associated with increased water content in the material, which is abetted by having high porosity sediments. Increased water content can also be the result of phase transitions such as smectite to illite, and even basalt to eclogite, which can release water from the hydrous phase.

Other factors may be important. Previous studies have examined the depth dependence of moment release [Zhang and Schwartz, 1992], maximum coupling depth [Tichelaar and Ruff, 1991; 1993], stress drop and source durations for deep earthquakes [e.g., Ekström and Engdahl, 1989; Vidale and Houston, 1993; Bos et al., 1998; Houston et al., 1998], and lateral variations in earthquake occurrence [Tanioka et al., 1997]. These authors have invoked a number of possible factors for causing the variability in earthquake rupture, such as amount and types of sediment being subducted, thermal state, hydrologic effects, and changes in subducting plate roughness. Systematics in any of these factors is also a plausible cause for the depth dependence of the source duration and rigidity. However, with the current
data set, it is difficult to determine which is the most important cause of the variations. Figure 15 shows a schematic of the seismogenic zone indicating some of the possible processes likely involved in changing the material rigidity.

The model of rigidity variations is non-unique. We assumed that the scaled rupture area of the events is constant with volumetric material properties controlling the variations in duration. Another end member model involves a constant rupture velocity with a varying rupture area for each event. Such a model implies static stress drop variations with depth. We lack independent estimates of the fault area for each event, which is needed to resolve the trade-off between rupture area and rupture velocity [Vidale and Houston, 1993]. Instead we relate static stress drop to seismic moment through its relationship to fault displacement and area. For a circular crack model, static stress drop is

\[ \Delta \sigma = \frac{7\pi M_o}{16r^3} \tag{3} \]

where \( r \) is the radius of the circular fault area and \( M_o \) is the seismic moment [Kanamori and Anderson, 1975]. If we make a further assumption that the rupture velocity approximately equals the shear velocity, we can substitute the product of the shear velocity \( \beta \) and the measured source duration \( \tau \) for the fault radius, leaving

\[ \Delta \sigma = \frac{7\pi M_o}{16\beta^3 \tau^3} \tag{4} \]

for the static stress drop.

Figure 16 shows corresponding estimates of the static stress drop as a function of depth for each of the studied regions. For each calculation, we use the Harvard CMT catalog moments and a constant \( \beta = 3.5 \text{ km/s} \). The shear wave velocity will likely vary with depth because of rigidity variations with depth, but we use a constant value for simplicity for these calculations. This model predicts that stress drop increases with increasing depth ranging over an order of magnitude. This is certainly plausible, however, a study of dynamic stress drop for recent large earthquakes shows that the stress drop estimated from source time functions is basically constant for the events once the change in shear velocity (and therefore rigidity variations) with depth and region is taken into account [Ruff, 1998]. Efforts to improve our ability to estimate rupture dimensions for moderate size events are essential if we are to resolve the trade-off between fault area and rupture velocity variations.

The discussion above invokes very simple notions of earthquake mechanics, either with rupture velocity being controlled by volumetrically averaged rigidity and shear velocity variations, or with variable static stress drop resulting from depth-dependent changes in frictional behavior. It is likely that such effects could be coupled, with low rigidity regions tending to have larger fault areas, so that the true explanation lies in between. However, perhaps the most plausible model is one in which the micromechanical properties of the fault zone influence the macroscopic earthquake rupture. In particular, porous sediments at shallow depths in the seismogenic zone may be fluid saturated, with fluids playing a critical role in earthquake slip. Such a model is considered by Kanamori and Heaton [1999], who especially
emphasize the microscale interactions of frictional heating and fluid pressurization as key factors in the macroscopic behavior of faulting. Essentially, it may not be necessary to have large volumes of low rigidity material if the very presence of fluid rich sediments in the seismogenic zone can directly reduce rupture velocity intrinsically. Such models need further elaboration, but our observations provide key targets for explanation.

CONCLUSIONS

Earthquake source time functions for a large number of events in seven circum-Pacific zones indicate that moment-normalized source rupture duration decreases with increasing depth along the seismogenic zone. There are minor regional differences in details of this relationship that may be related to the tectonic environment, but the depth dependence appears to be robust. The Alaska-Aleutian Islands region has the most complete dataset, and shows dramatic differences in the shape of the source time functions with depth, with minor changes in time function shape along strike of the trench, indicating that the depth dependence is more than any along-strike variations for this region. Two end member models of earthquake rupture process are considered to explain the observations, one with varying volumetrically-averaged source zone rigidity and the other with variable static stress drop. For the first model, we find that rigidity increases by a factor of 5 over the depth range of 5 to 20 km. Low rigidity of the shallow portion of the seismogenic zone may result of sediments, high porosity, and weakly consolidated materials, all of which diminish in volume with depth. The variable stress drop model predicts an order of magnitude increase in stress drop with increasing depth. It is possible that the two scenarios are coupled, with material property variations influencing stress drop, but it may also be true that our observations reflect microscale influences of sediments and fluids in the fault zone on rupture propagation.

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