

SEISMICITY AND THE SUBDUCTION PROCESS *

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There is considerable variation between subduction zones in the largest characteristic earthquake within each zone. Assuming that coupling between downgoing and upper plates is directly related to characteristic earthquake size, we have tested for correlations between variation in coupling and other physical features of subduction zones: the lateral extent and penetration depth of Benioff zones, age of subducting lithosphere, convergence rate, and back-arc spreading. Using linear multivariate regression, coupling is correlated with two variables: convergence rate and lithosphere age. Secondary correlations within the data set are penetration depth versus lithosphere age, and lateral extent versus convergence rate. An important additional correlation is that back-arc spreading is found to be associated with subduction zones where coupling is low (those characterised by small earthquakes). Taken together, the observed correlations suggest a simple qualitative model where convergence rate and lithosphere age determine the horizontal and sinking rates, respectively, of slabs: these parameters influence the seismic coupling in the subduction zone. In the limit of a fast sinking rate and slow convergence rate, back-arc spreading occurs and thereby appears to be a passive process.

1. Introduction

Since the advent of the plate tectonics model, trench–island arc systems and seismic Benioff zones have been interpreted as features related to the subduction of oceanic lithosphere. Understanding the mechanics and dynamics of the subduction process in view of these observed features has proved to be difficult. As one approach to this problem, various models have been concerned with modeling the features of a composite subduction zone which combines the pertinent features. Another method is to compare the subduction zones of the world noting the similarities and differences in the essential features. We have employed the latter method and include the strength of coupling at plate boundaries as one of the essential features. We find that there is

a correlation between Benioff zone geometry, convergence rate, age of the subducting slab, strength of coupling, and formation of marginal (back-arc) basins.

In a global view of subduction zones, two key discriminating physical features are the extent and geometry of the Benioff zone, and the presence or absence of a marginal basin (Uyeda, 1977). The Benioff zone geometry relates to the behavior of the subducted lithosphere within the mantle, while marginal basin formation presumably results from the interaction of the slab with the surrounding mantle and crust. Therefore, these features should be at least partially diagnostic of the mechanics of subduction. There is considerable variation in these two features between subduction zones: the slab penetration depth varies from 100 to 700 km and the slab dip angle ranges from nearly horizontal to vertical. Also, marginal basin activity ranges from active formation to the absence of any back-arc spreading.

Studies attempting to relate these observed fea-

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tures to causal parameters have had some success. In particular, there appears to be a correlation between the maximum depth of the continuous Benioff zone and the age of the subducting oceanic lithosphere (Vlaar and Wortel 1976, Wortel and Vlaar 1978). An approximate relationship between the down-dip lengths of slabs and lithospheric convergence rates was found by Isacks et al. (1968). This relationship has been further elaborated by a proposed correlation between the total lengths of subducted slabs and the products of lithosphere ages and convergence rates (Molnar et al., 1979). Luyendyk (1970) investigated variations in dips of down-going plates, and proposed a relation between dip and convergence velocity which assumed a constant vertical velocity for slabs. With regard to marginal basin formation, Kanamori (1977a) proposed that the Philippine Sea plate might have been formed by a complete decoupling of the slab from the upper plate, leading to a fast retreat of the trench line. (See also Wu, 1972; Uyeda and Kanamori, 1979.) Molnar and Atwater (1978) suggested that some relationship exists between marginal basins, convergence rates and oceanic lithosphere ages. The results of this paper substantiate and combine the above suggestions.

Another key feature of subduction zones is their seismic character, indicated by the size of the largest, shallow, thrust earthquakes. The variation in this property for the northwestern Pacific was pointed out by Kanamori (1971), and related to the nature of the mechanical coupling between the oceanic and continental plates and the formation of the Philippine Sea plate. The size of large earthquakes was also treated by Kelleher et al. (1974) who proposed a correlation between earthquake size and the width of the contact zone. The world-wide variation in seismic character is indeed significant, from the South America and Alaska regions in which great earthquakes occur, to the Mariana and Izu-Bonin subduction zones which lack comparably large interplate thrust events. This contrast in regional seismic character, which represents more than two orders of magnitude in the characteristic energy release of subduction earthquakes, has not been fully appreciated. These differences are interpreted as representing significant variations in coupling between plates in subduction zones. Uyeda and Kanamori (1979) conducted a global survey of subduction zone features

and recognized the importance of these variations in seismic coupling. In this paper, we have parameterized the coupling strength and have sought a quantitative relationship between the physical features of subduction zones.

2. Large earthquakes and strength of coupling

The relative size of earthquakes is typically described by a magnitude scale, with the 20-second surface wave magnitude, M_s , commonly used for the larger earthquakes. This magnitude scale is inadequate for the largest earthquakes however, as the scale saturates above $M_s \sim 8$, thereby not truly representing the entire energy release of large events. A more accurate measure of the total energy release is the seismic moment $M_0 = \mu Ad$, where μ is the rigidity, A the fault area, and d the average displacement. In order to remedy the saturation problem of the M_s scale, Kanamori (1977b) devised a new magnitude scale for large events, denoted by M_w , in which the magnitude is determined by the seismic moment, and which smoothly connects to the M_s scale at magnitude ~ 8 . As the moments of the largest instrumentally recorded earthquakes have been determined (see Kanamori, 1977b), the M_w scale allows us to compare the relative sizes of these large earthquakes. The locations and magnitudes of the largest events are shown in Fig. 1.

One feature apparent in Fig. 1 is the variation in the size of the largest event occurring within the various subduction regions, as pointed out by Uyeda and Kanamori (1979). For example, while South America is characterized by very large events, other regions such as the Marianas or the Scotia arc appear to be relatively quiescent. This scale of variation in seismic behavior will be included in our global view of the subduction process.

The characterization of subduction regions must be done with some reserve, due to the possibility that the largest earthquake in a particular region may not have been recorded, considering the limited period of observation. For subduction zones where the historical data of the past several hundred years are available (e.g., Japan, Kuriles, South America), the instrumental records from 1900 onwards appear to be representative of the seismic activity of the respective

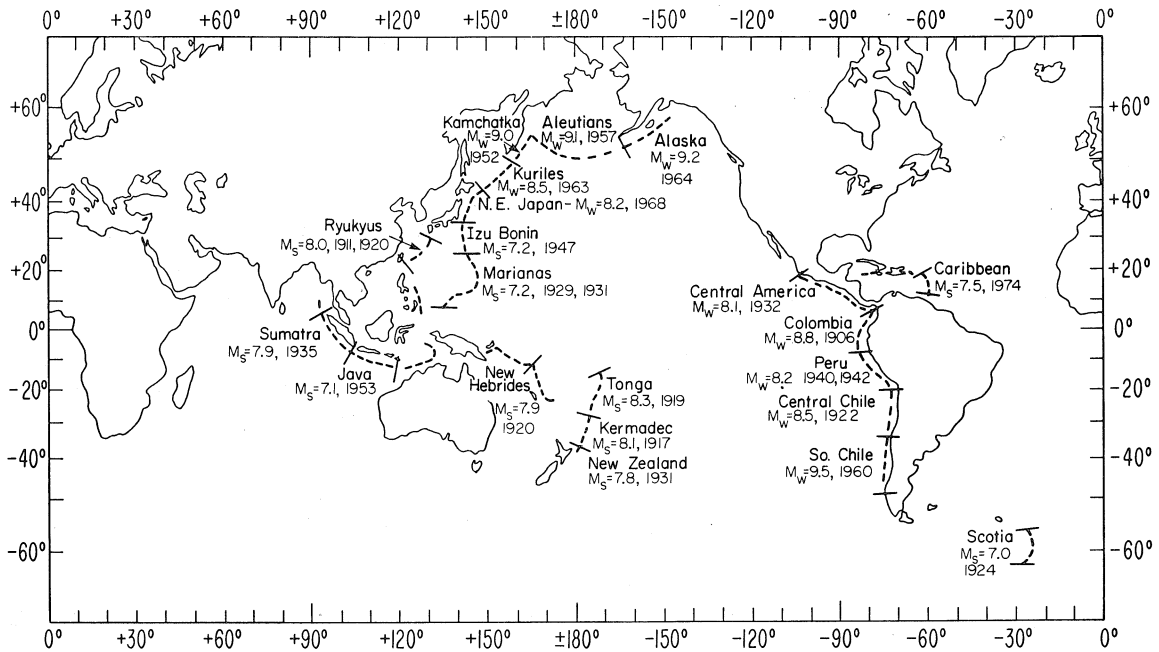


Fig. 1. Subduction regions used in this study. The date and M_s or M_w value of the largest event within each subduction region are shown.

regions: at least one typical large event has occurred since 1900 in each region. For subduction zones with an incomplete historical record and no occurrences of great earthquakes since 1900 (e.g., Izu–Bonin, Marianas, Java), the instrumental record may underestimate the seismic activity. However, historical tsunami data and an anomalously low frequency of earthquakes below magnitude 7 indicate that seismic activity is indeed low in these regions (see Kelleher and McCann, 1976). Though the particular M_w values that we assign to the subduction zones may be modified by an additional 100 years of observations, we conclude that the presently available values provide a basic representation of the varying seismic character of these zones.

The strength of coupling between upper and downgoing plates may be determined as the product of the area of contact and the average stress on the contact zone. Since large thrust earthquakes along subduction zones represent a stress release on these contact zones, the seismic moment (and therefore M_w) can be related to the strength of coupling. The provi-

sion of an explicit relationship between earthquake moment and strength of coupling would be difficult due to many complications, and the result would certainly be model-dependent. Consequently, we will use the observed variation in M_w as a representation of the variation in the strength of coupling.

Thus, we have taken the largest earthquake occurring in a subduction region as measured by M_w , as a characteristic property of that region, and relate the varying seismic character to a varying strength of coupling between the respective plates. An alternate measure would be to take the cumulative seismic moment (or its logarithm) instead of the moment of the largest earthquake. However, the contribution from the largest earthquake usually dominates the cumulative moment. In Appendix A, the cumulative seismic moment is calculated and corrected for subduction zone length along the trench axis. The effective M_w for a few subduction zones does change; however, the conclusions remain the same. For simplicity, we use the maximum M_w in the following discussion.

TABLE I

Subduction zones and parameters used in this study

Zone	Seismicity (M_w)	Depth (km)	Length (km)	Age (My)	Rate (cm y^{-1})
Marianas	7.2	700	300	150	4.0
Java	7.1	650	550	135	7.1
Izu-Bonin	7.2	550	500	150	6.1
N.E. Japan	8.2	600	1200	130	9.7
Tonga	8.3	650	600	120	8.9
Kermadec	8.1	570	400	120	6.4
Kuriles	8.5	625	800	100	9.3
Kamchatka	9.0	625	800	80	9.3
New Zealand	7.8	350	270	120	5.5
New Hebrides	7.9	270	170	60	2.7
Ryukyus	8.0	280	380	60	5.6
Aleutians	9.1	280	200	60	7.5
Sumatra	7.9	200	400	80	6.6
Alaska	9.2	140	450	40	5.9
Central America	8.1	200	200	45	8.0
Central Chile	8.5	250	550	50	11.0
S. Chile	9.5	160	500	20	11.1
Peru	8.2	200	700	45	10.0
Caribbean	7.5	250	280	100	2.0
Scotia arc	7.0	180	200	65	2.0
Colombia	8.8	150	220	20	7.7

3. Data and correlation

In order to use a systematic method to establish correlations between the physical features of subduction zones, linear multi-variable regression was applied to the data from the subduction zones for which we could reliably determine the parameters, as listed in Table I. The ages of subducting oceanic lithosphere are mostly from deep-sea drilling data and are consistent with values used elsewhere (Vlaar and Wortel, 1976; Molnar and Atwater, 1978). "Depth" refers to the maximum depth of a continuous Benioff zone. Hence, the deep and isolated zones of seismicity below South America and the Fiji Plateau are not considered to be related to the recently subducted lithosphere at the South America and New Hebrides trenches. The "length" is the distance from the trench line to the furthest lateral extent of the continuous Benioff zone.

The convergence rates are taken from Model AM1 (Minster et al., 1974). We have used the convergence rates determined by Seno (1977) for the Mariana and

Ryukyu subduction zones. Also, we have used a convergence rate for the New Hebrides which assumes that the Fiji Plateau is decoupled from the Pacific plate (Isacks et al., 1969). This results in a rather large reduction of the New Hebrides convergent velocity.

We have included as many subduction zones as possible since we wish to include the full range of subduction behavior. The Philippines and New Britain-Solomon Islands regions are excluded from this analysis. These two regions are quite complex and involve the interaction of more than two plates, possibly combined with subduction polarity changes. Other zones not considered are the Andaman Sea region and the Mediterranean deep seismic zone, as these tectonic settings are rather unique. The former includes highly oblique subduction and unusual back-arc spreading (Eguchi et al., 1979), and the latter a continent-continent subduction zone.

The correlation coefficients, r_{ij} , indicate the correlation between any two variables. The correlation between three or more variables can be tested with

TABLE II

Absolute values of the correlation coefficients using the data in Table I. The variables are: *S*, seismicity, *D*, depth, *L*, length, *A*, age, and *R*, rate. The coefficients are symmetric about the diagonal

	<i>S</i>	<i>D</i>	<i>L</i>	<i>A</i>	<i>R</i>
<i>S</i>		0.287	0.209	0.627	0.629
<i>D</i>	0.287		0.505	0.837	0.118
<i>L</i>	0.209	0.505		0.278	0.631
<i>A</i>	0.627	0.837	0.278		0.229
<i>R</i>	0.629	0.118	0.631	0.229	

TABLE III

The multiple correlation coefficients with seismicity as the dependent variable, and combinations of the other variables as the independent variables. The abbreviations are the same as in Table II. Significance at the 99% level corresponds to a value of 0.633

$r'_{S,AR}$	$r'_{S,AD}$	$r'_{S,AL}$	$r'_{S,RD}$	$r'_{S,RL}$	$r'_{S,DL}$
0.802	0.763	0.743	0.727	0.675	0.500

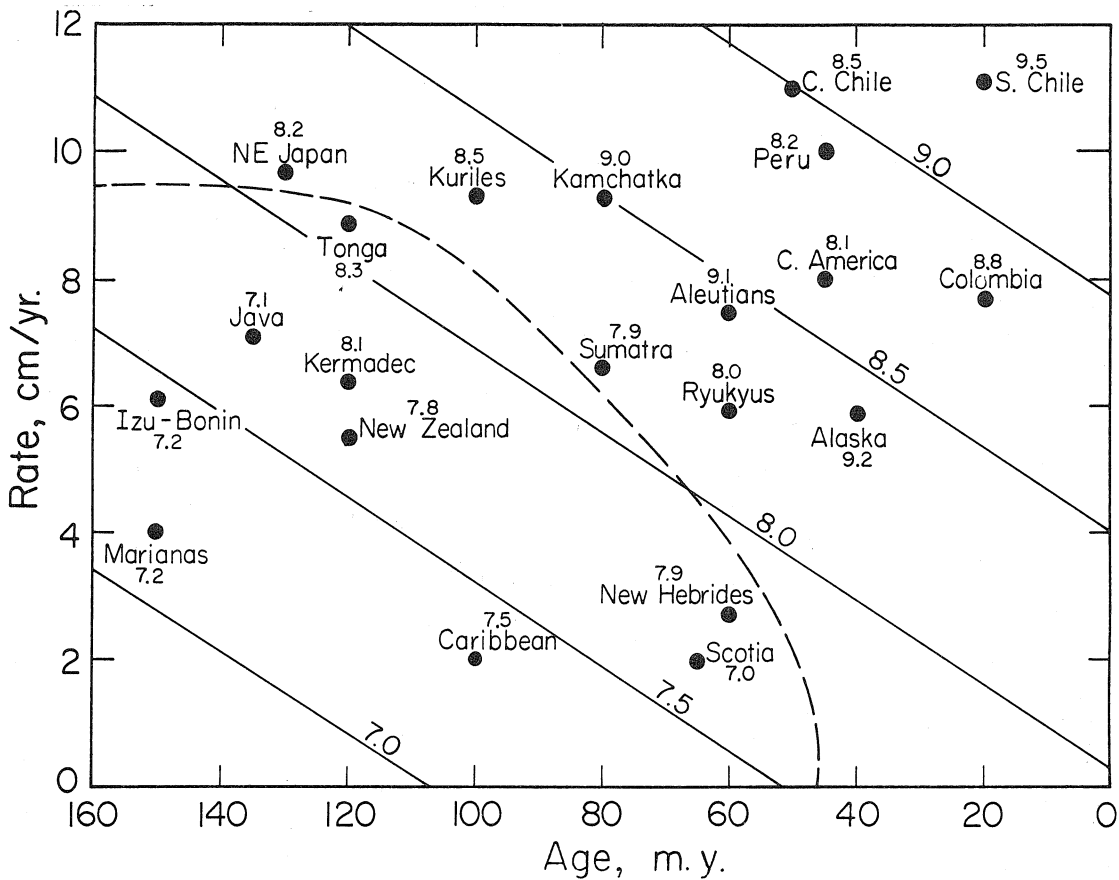


Fig. 2. The relationship of seismicity to the two variables: convergence rate and age of the subducting oceanic lithosphere. The number at each subduction zone is the associated M_w , and the contours of constant M_w define the resultant plane from the regression analysis. The broken line in the lower left corner delimits the subduction regions where there is either confirmed or suspected back-arc spreading.

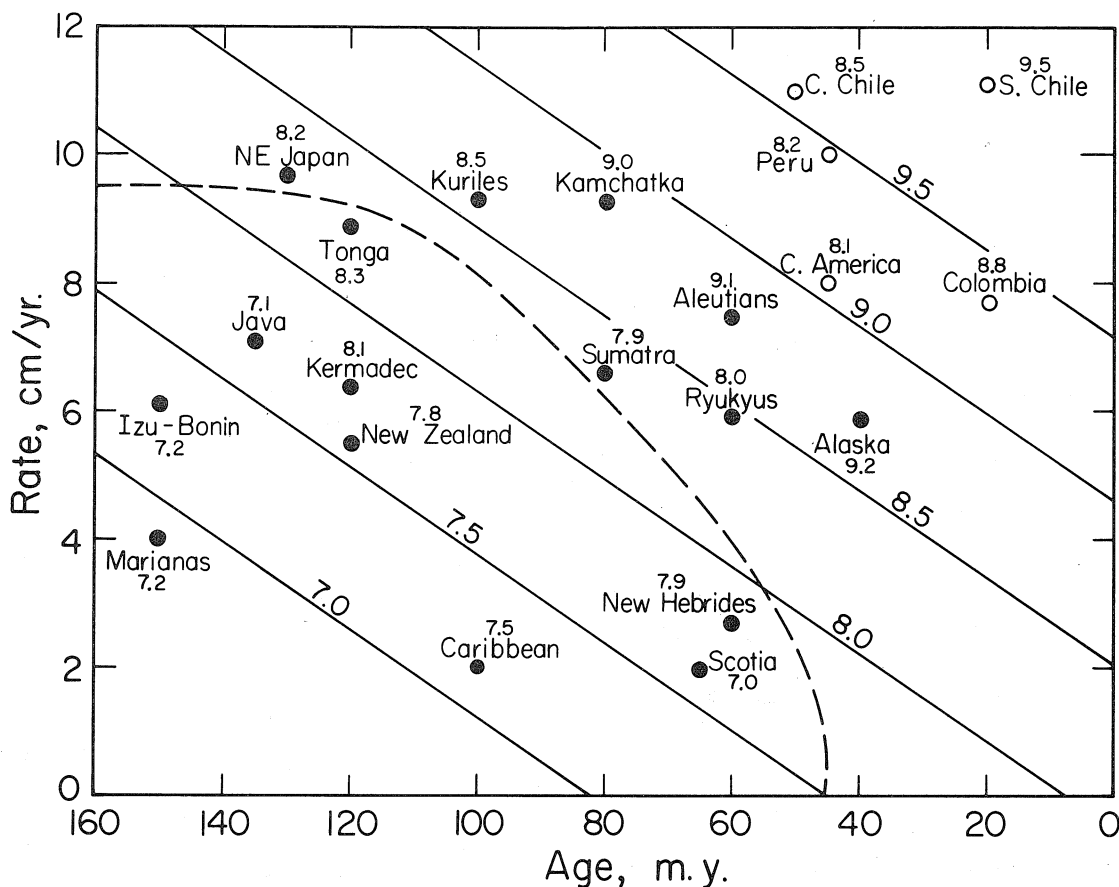


Fig. 3. As Fig. 2 except that the South and Central American points are not included in the regression analysis. The remaining 16 subduction zones conform quite well to the regression plane.

multivariate regression. The correlation is given by the multiple correlation coefficient, $r_{1,mn\dots}$ where 1 is the dependent variable with m, n , and any additional variables treated as independent variables. The correlation coefficients between the variables listed in Table I are shown in Table II. For the number of data points used in the analysis, significance at the 99% level corresponds to the absolute value of $r_{ij} = 0.549$ (i.e. the probability is 1% that the variables i and j are independent). Pairs of variables that correlate above this level are: age and depth, rate and length, seismicity and age, and seismicity and rate. The correlation coefficients for seismicity and rate, and seismicity and age are nearly equal, indicating that the combination of rate and age would better explain the variation in seismicity. This is verified by the multiple cor-

relation coefficient in Table III. By using both age and rate, the correlation with seismicity is improved from ~ 0.630 to 0.802 . There are other high values of the multiple correlation coefficient in Table III; however, these coefficients include either age or rate as one of the independent variables. The regression analysis determined that age and rate are the only significant variables in explaining the variation in seismicity. The correlation between these three variables is shown in Fig. 2, where the subduction zones are plotted with respect to the independent variables, age and rate. The correlation is indicated by the best fit regression plane. The general trend is for low seismicity to correlate with the combination of older oceanic lithosphere and smaller convergence rates, while younger lithosphere and larger convergence

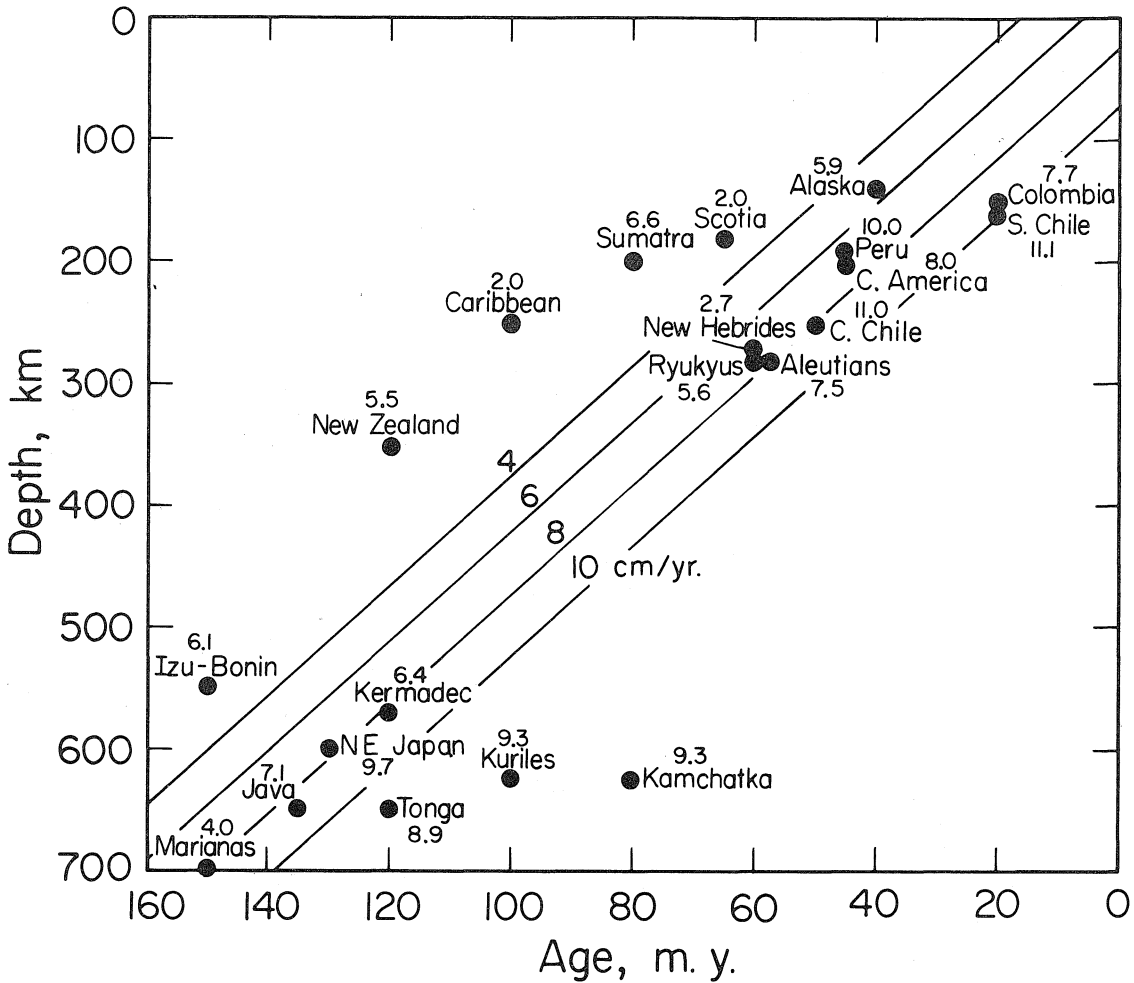


Fig. 4. Depth versus age plot for the different subduction zones. (Treating the penetration depth of the Benioff zones as the independent parameter, the lithospheric age is the most significant variable.) Parallel lines show the regression solution for various values of the convergence rate. These contours do not appear to substantially explain the data, thus the convergence rate should be considered as an accessory correlation. Though there is a significant linear trend between depth and age, a bimodal distribution of penetration depths is also a good characterization of the data.

rates are associated with great earthquakes.

The most notable exceptions to this trend are the M_w values for Peru and Central America. As shown in Appendix A, the moment sum M_w is somewhat larger than the single event M_w for these two regions. Also the South American points which plot in the upper right-hand corner of Fig. 2 are not quite on the trend of the others points. Figure 3 plots the results when the Central and South American points are removed from the regression analysis. It is interesting to note that the Central and South American subduc-

tion zones are east-dipping. The only other east-dipping zones are the New Hebrides and Sumatra. This apparent bias between east and west dipping zones was attributed to a global mantle flow by Uyeda and Kanamori (1979), but other explanations are certainly admissible. We will not pursue this apparent bias further, as the main interest here is the establishment of basic trends.

There are other significant correlations within the data set. Depth of penetration is strongly correlated with lithosphere age (see Table II). This correlation

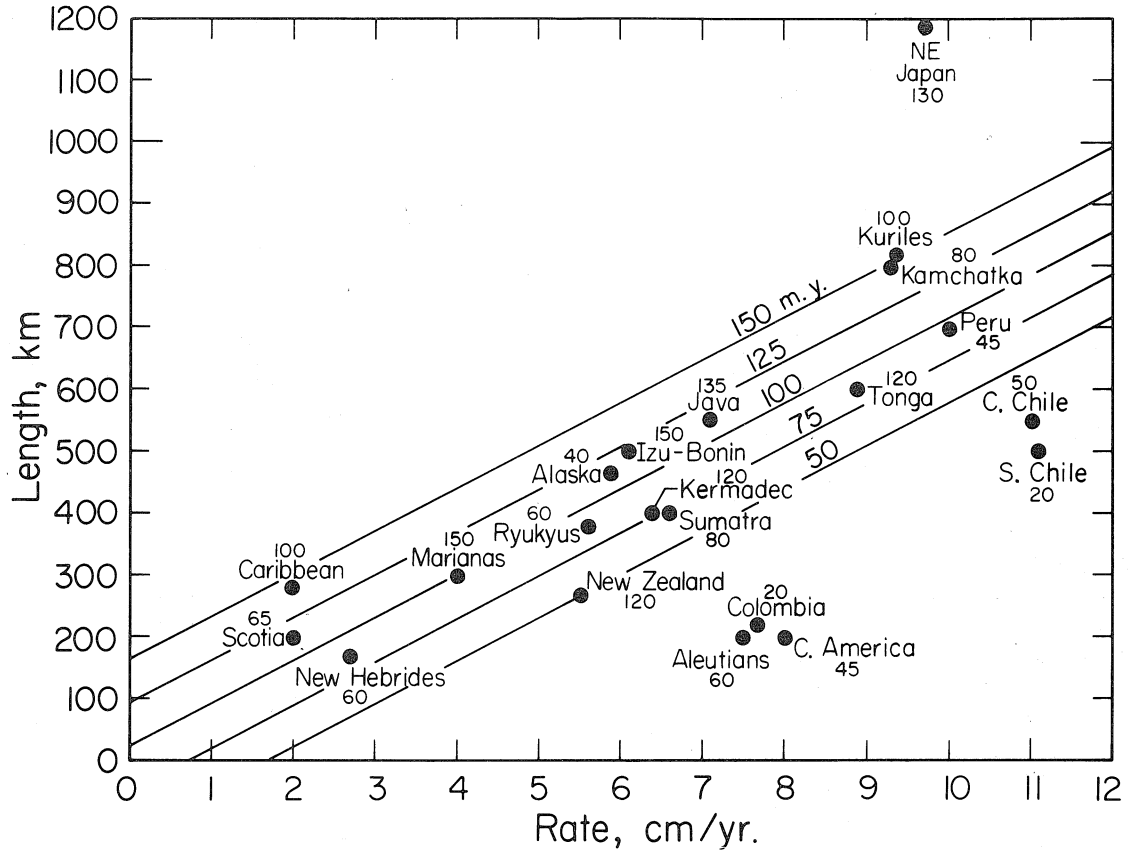


Fig. 5. Plots of the subduction zone lengths versus convergence rates. (With the horizontal length of the slab as the independent variable, the convergence rate is the most significant variable, with the lithosphere age having secondary importance.) The linear correlation is given by the parallel lines, different lines corresponding to different values for lithosphere age (My).

can be seen in Fig. 4. Applying multivariate regression, rate enters the correlation at the 95% significance level. The multiple correlation coefficient with depth as the dependent variable and age and rate as the independent variables is $r_{D,AR} = 0.895$. This value is not appreciably larger than the simple correlation coefficient between depth and age, i.e. $r_{DA} = 0.837$. Therefore, there is only a weak dependence of depth upon rate. For completeness, this dependence is plotted in Fig. 4 for different values of the convergence rate. The strong correlation between depth and age agrees with the results of Vlaar and Wortel (1976).

The other significant correlation in Table II is horizontal length and convergence rate, and these two variables are plotted in Fig. 5. Using multivariate

regression with length as the dependent variable, age enters the correlation at the 95% significance level, with $r_{L,RA} = 0.766$. It appears that this dependence is largely due to the outlying point of northeast Japan. There are no other significant (at 95%) multivariate correlations amongst the variables.

Figures 4 and 5 suggest that the penetration depth and horizontal length essentially depend on single variables, the lithosphere age and convergence rate respectively. On the other hand, Fig. 2 indicates that two variables, age and rate, are required to explain the variation in the coupling strength. This is verified quantitatively by the simple and multiple correlation coefficients.

4. Discussion

We have sought the simplest explanation relating the strength of coupling to the properties of subducting slabs, though recognizing that other interpretations are possible. The fact that both coupling strength and Benioff zone horizontal and vertical extents depend upon two parameters, lithosphere age and convergence rate, suggests that there is a common mechanism affecting both Benioff zone geometry and coupling. Vlaar and Wortel (1976) explained the correlation between lithospheric age and penetration depth by the higher density of older slabs, which should therefore penetrate further into the mantle when subducted. This explanation seems reasonable if the intrinsic density of a subducted slab contributes to its downward penetration. As various types of evidence support this idea (e.g., McKenzie, 1969), it appears reasonable that initial density differences could affect both the rate of sinking and the level at which thermal assimilation occurs (Vlaar and Wortel, 1976). In view of this, the correlation of convergence rate and horizontal extent is related to the dependence of the horizontal velocity of a subducted slab on the convergence rate at the trench.

The preferred trajectory of subducting lithosphere in the mantle is then determined by two factors, lithospheric age and convergence velocity. Deviations from the preferred trajectory can be caused by other factors which influence the geometry. The horizontal and vertical rates should directly affect the dip of a subducting plate, with the total length of the slab dependent on the time scale of assimilation. As proposed by Molnar et al. (1979), this time scale may be mostly determined by the product of lithospheric age and convergence rate, hence a coupling between the age and rate upon the length and depth of the Benioff zone. The resolution of the slab's trajectory into horizontal and vertical rates is depicted in Fig. 6.

There is an apparent bimodal distribution in the penetration depths in Fig. 4. The absence of slabs terminating between 300 and 500 km was attributed by Vlaar and Wortel (1976) to difficulty in penetrating the phase change (presumably the 450 km discontinuity). Another possibility, suggested by the relative aseismicity of this depth range in slabs which extend to below 600 km (Abe and Kanamori, 1979), is that

once slabs penetrate below 300 km they can rapidly descend to ~600 km (Anderson, 1979). We defer from a detailed discussion of this distribution, since for our present purposes we are concerned only with the basic trends.

The correlation of seismicity with convergence rate and lithospheric age implies a relationship between the strength of coupling and either slab geometry, or lithospheric age and convergence rate in some other manner. As the strength of coupling is dependent upon three factors: stress normal to the fault plane, the coefficient of friction, and the area of contact, there would seem to be more than one explanation. There may be differences in the fault

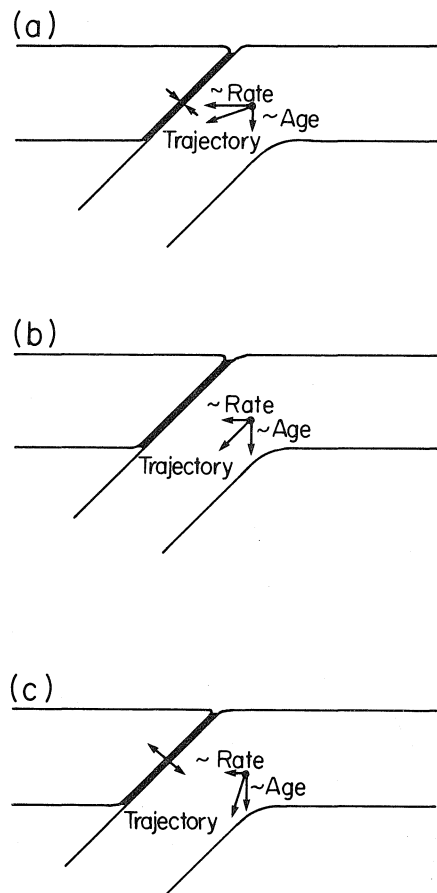


Fig. 6. Schematic representation of how particular combinations of lithospheric ages and convergence rates might cause subducting slabs to have preferred trajectories, thereby affecting Benioff zone geometry. The preferred instantaneous trajectory of a slab is most certainly affected by other influences, such as the global mantle flow.

plane normal stress due to changes in the applied tectonic stress as slab geometry changes (Fig. 6). Possibly the coefficient of friction changes systematically with convergence rate and age. Also, the area of coupling could change due to either a reduction in the cross-section as the slab dip angle becomes more vertical, or by a degradation of the upper plate's fault surface (Kanamori, 1971). Perhaps these different effects upon coupling strength operate in some combination, with one mechanism being dominant in certain subduction zones. In the next section on marginal basins it is suggested that the behavior of the downgoing plate could be the most important effect on coupling.

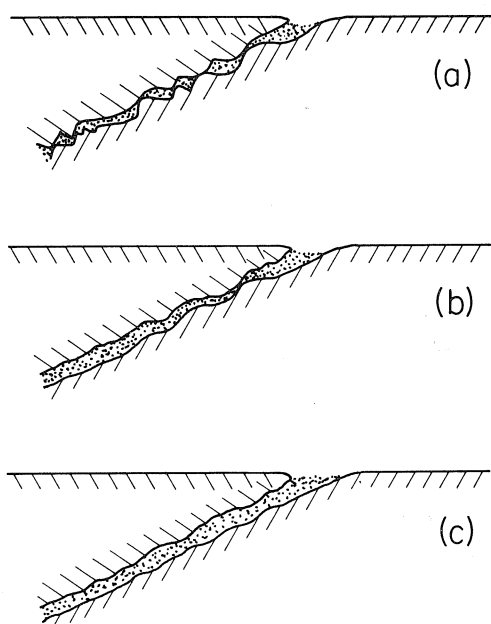


Fig. 7. Schematic representation of three different asperity distributions. The dotted region between the upper and lower fault surfaces represents a low strength material. The tectonic stress is mostly distributed over the total area of asperity contact, with (a) representing a large area of asperity contact, thereby strong coupling. In (b) the tectonic stress is concentrated at one asperity and therefore the tectonic stress level achieved before a seismic event would be lower than in case (a). (c) illustrates the case when tectonic stress is transmitted through the low-strength material. In this case the tectonic stress level will be the lowest, and the relative displacement will be mostly aseismic with occasional small seismic events corresponding to the breaking of asperities of a size scale smaller than those considered in these diagrams.

As a brief departure from the main topic, the relationship between moment and coupling strength will now be considered in more detail. From the discussion concerning tectonic stress, one might expect larger earthquakes to have a higher stress drop, in addition to a larger fault area and displacement. The stress drops of earthquakes appear to be approximately equal over a large range of magnitudes (see, for example, Kanamori and Anderson, 1975). This constancy of stress drop, despite different levels of tectonic stress can be explained by an asperity fault model (Fig. 7).

The asperity model stipulates that instead of smooth planar fault surfaces, most of the coupling is confined to the contact between irregularities of the fault surfaces. The tectonic stress is communicated across a smaller area than the total fault area, and so the stress at the asperities is in general higher than the tectonic stress. If there is a uniform characteristic rock strength, then the breaking stress will be approximately equal. A larger asperity area increases the contact area so that a higher tectonic stress is required to exceed the asperity breaking stress. Figure 7(c) shows that an aseismic weakly coupled configuration results as a limit to a smaller asperity contact area.

4.1. Marginal sea formation

The consequences of the partial decoupling of plates as depicted in Fig. 6(c) could be marginal sea formation. If the preferred trajectory of a slab becomes steep enough, there would be a tendency for the oceanic plate to separate from the overlying plate. If this occurs, the trench line will migrate oceanward, material must be removed from in front of the sinking plate, and material must be supplied behind the moving trench.

The details of the oceanic-plate bending process are not known and the contribution of the upper plate cannot be fully assessed. However, as the assumed cause of the plate bending is the gravitational sinking of the slab, the plate should still bend if it is uncoupled from the upper plate. Removal of material in front of the slab does not appear to present serious difficulties. With regard to the supply of material behind the slab, kinematic models of the subduction process indicate that there is an induced

corner flow due to viscous coupling of the oceanic plate with the surrounding mantle (e.g., Sleep and Toksöz, 1971; Andrews and Sleep, 1974; Toksöz, and Hsui, 1978). This result precludes the possibility of material flowing updip along the slab. However, horizontal transport seems capable of supplying adequate material to the corner region, as illustrated in Fig. 8. Therefore, it appears reasonable that a weakly coupled contact zone could result in marginal basin formation.

We would therefore anticipate that low seismic coupling should be correlated with active marginal basin formation. The broken line in Fig. 2 delimits the subduction zones in which active marginal basin formation is either known or suspected (see Karig, 1971; Uyeda and Kanamori, 1979; for reviews). The region of marginal basin activity is in the corner of lower convergence rates and older lithosphere, where coupling is weak in our model. We consider this result supportive of our seismic coupling model. It also emphasizes the fact that marginal basins are not currently forming behind subduction zones with great earthquakes. It should be noted that, even when the trench line is retreating, there is still relative motion across the contact zone due to the downgoing plate. Therefore, there can still be occasional shallow thrust earthquakes, though not of great size. This supports the view of Kanamori (1977a) that aseismic subduction is the cause of diminished seismicity in certain regions, as opposed to suggestions that subduction

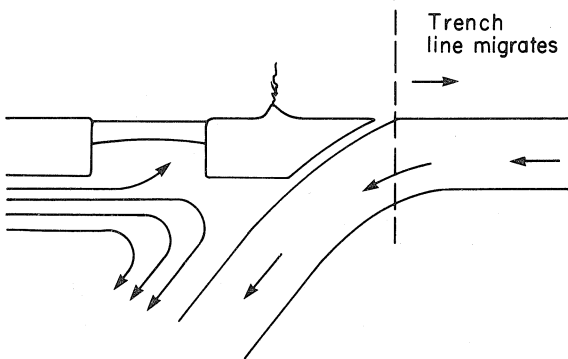


Fig. 8. Back-arc spreading as a passive process. If the subducting slab bends and sinks such that there is a tendency for the trench line to migrate oceanward, then material must be supplied behind the volcanic arc. The proposed corner flow could possibly transport the necessary material to the island arc. Other studies have proposed that the corner flow itself forces the island arc to push the trenchline oceanward.

has ceased due to the presence of buoyant "gravity ridges" on the oceanic lithosphere.

Thus, in our view, marginal basin formation is inherently a passive process (Elsasser, 1971; Molnar and Atwater, 1978). This result is in contrast to models of back-arc spreading derived from considerations of the induced corner flow (e.g., Toksöz and Hsui, 1978), in which back-arc spreading implies horizontal compression in the upper plate.

5. Conclusions

We have introduced strength of coupling as measured by M_w as an important physical feature of subduction zones, and find that both Benioff zone geometry and strength of coupling are significantly correlated to two variables: age of subducting oceanic lithosphere and plate convergence rate. The dependence of Benioff zone geometry can be explained by a preferred slab trajectory, with the horizontal and vertical rates determined by the convergence rate and age of the subducting plate. The strength of coupling can be affected by lithospheric age and convergence rate by either reducing the effective contact area between the plates, or perhaps by the preferred trajectory which transmits a small tectonic stress to the contact zone between the plates which can either enhance or detract the plate coupling. In the limit of weak coupling, aseismic subduction and marginal sea formation will take place. Other features of subduction zones, such as differences in chemical composition, might be better understood in the context of the important physical features.

Appendix A

The purpose of this appendix is to investigate further the characterization of coupling strength. In the main text, we take the size of the largest earthquake as representative of the coupling strength. Perhaps it is better to use the cumulative seismic moment, though this introduces many problems. That is, a more appropriate measure of seismic coupling would be the cumulative moment per unit time per unit subduction zone trench length. While it is easy to correct for subduction zone trench length, the moment release per

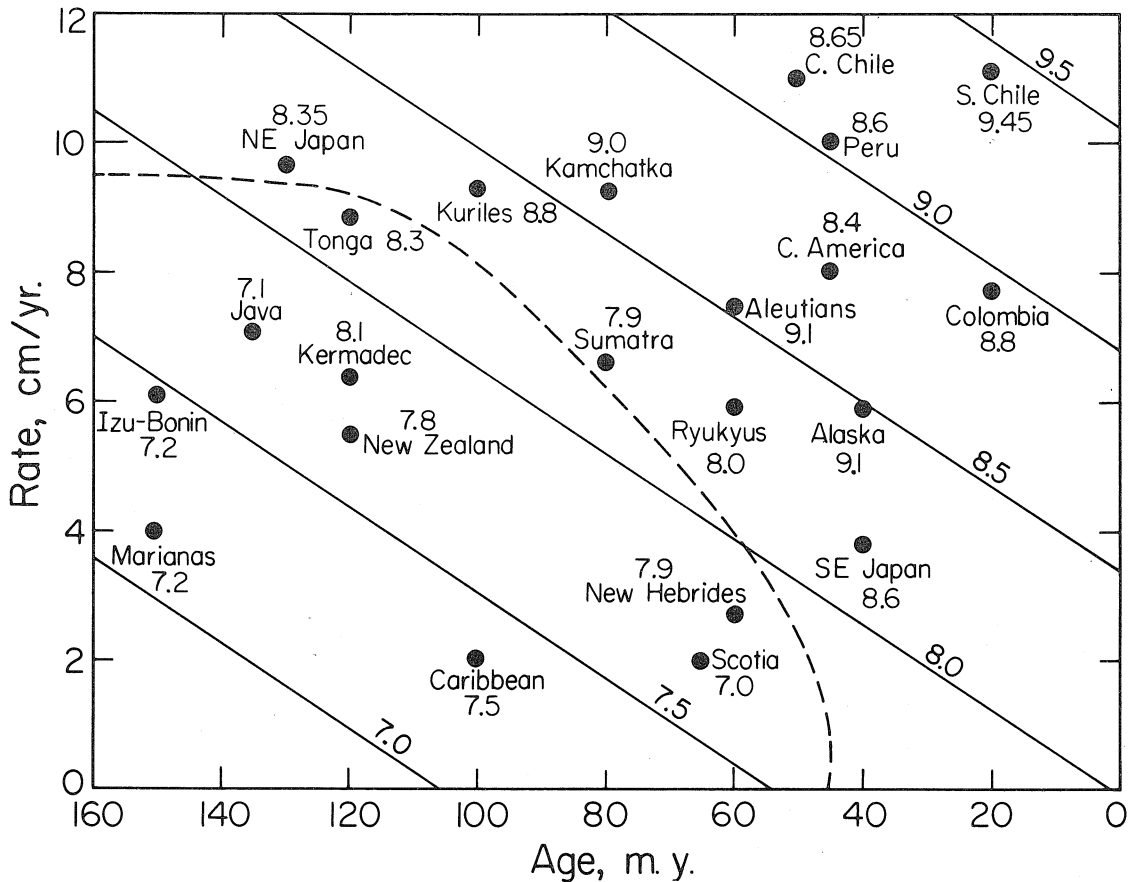


Fig. A1. As Fig. 2, except that the cumulative moment magnitude, M_W' , is used instead of the single event M_W . Also, the south-east Japan subduction zone has been added as the three variables: age, rate, and seismicity, can be determined. With seismicity represented by M_W' , the resultant regression plane fits the data slightly better than in Fig. 2.

unit time is difficult to estimate, as a regular recurrence interval and a complete sequence of events are required. The uncertainties in the recurrence intervals discourage any attempt to systematically apply corrections. If we were to normalize the seismic moment to a recurrence interval of 100 years, the zones that would be affected the most are those in the lower left-hand corner of Fig. 2. It is quite possible that the recurrence interval for some of these regions is ~ 1000 y or longer. Given these uncertainties, we are not able to apply corrections for the recurrence interval.

We use a cumulative moment M_W' , defined as $M_W' = (1/1.5) \log \Sigma 10^{1.5M_W}$, summed over the known events in one sequence and corrected to subduction zone trench length = 1000 km. The only zones in which the increase over the single event M_W is 0.3 units or larger are: Peru, Central America, and

Kuriles. These changes partially alleviate the low M_W values of Peru and Central America. The subduction zones and modified M_W' values are plotted in Fig. A1. As can be seen, the modified M_W' values tend to be more consistent with a plane fit, and the correlation coefficient, $r_{S,AR}$, is improved slightly to 0.844. In conclusion, Peru and Central America are more consistent with the general trend when using M_W' , though they are still low. These changes do not affect the conclusions in the main text.

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