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Global Prevalence of Double Benioff Zones

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Double Benioff zones provide opportunities for insight into seismogenesis because the underlying mechanism must explain two layers of deep earthquakes and the separation between them. We characterize layer separation inside subducting plates with a coordinate rotation to calculate the slab-normal distribution of earthquakes. Benchmark tests on well-established examples confirm that layer separation is accurately quantified with global seismicity catalogs alone. Global analysis reveals double Benioff zones in 30 segments, including all 16 subduction zones investigated, with varying subducting plate ages and stress orientations, which implies that they are inherent in subducting plates. Layer separation increases with age and is more consistent with dehydration of antigorite than chlorite.

Despite the passage of nearly 30 years since the discovery of double Benioff zones (DBZs) (*1*), the nature of these parallel planes of seismicity in a subducting plate remains enigmatic (*2*–*5*). Benioff zones represent internal deformation of actively sinking lithosphere as inclined zones of seismicity connecting shallow earthquakes near the trench with earthquakes deep in the mantle. The mechanism for any seismicity below ~70-km depth is a matter of ongoing debate because of the need to overcome high confining pressure that would otherwise prohibit the sudden release of strain as earthquakes [e.g., (*6*)]. The existence of DBZs presents an important opportunity for gaining insight into earthquakes at intermediate depths of 70 to 300 km, because a hypothesis for such seismogenesis must explain the presence of the two layers and the separation between them. In general terms, earthquakes require two conditions: the presence of sufficient deviatoric stress to generate shear deformation and an adequate mechanism to store and release strain in a seismogenic way. Proposed mechanisms for triggering intermediate-depth seismogenesis that may account for DBZs center around dehydration of hydrothermally altered oceanic lithosphere, with a variety of hydrated rocks being suggested as contributors (e.g., serpentine, chlorite, and gabbro) (*5*, *7*–*13*). Likewise, several mechanisms have been proposed to explain the stress conditions in DBZs, including unbending of the slab [e.g., (*14*, *15*)], thermoelastic stress [e.g., (*16*)], and sagging of the plate [e.g., (*17*)]. An open question that would provide a key constraint on models for seismogenesis is: Are DBZs common in subduction zones globally as a result of a ubiquitous mechanism, or are they rare because of special conditions present in only a few situations? This study provides a preliminary answer to this question: DBZs are relatively widespread.

DBZs have been most successfully characterized in regions where local seismic networks provide adequate coverage to yield relatively high-precision earthquake hypocenters (*18*–*23*). We can use such locally "calibrated" DBZs to test the ability of global seismicity catalogs to identify the presence of DBZs and estimate the layer separation. Despite increased location scatter in global catalogs compared with local-network catalogs, a benchmark test described below indicates that global catalogs are sufficient for characterizing DBZs. In this study, we investigated (i) whether DBZs are prevalent globally and (ii) potential relationships between DBZ layer separation and subducting-plate properties, with special attention to thermal parameters (Fig. 1). The overall prevalence and regularity of DBZs on a global basis will characterize the conditions at depth, both seismic and petrologic, that reveal how a plate evolves after subduction.

We have developed a straightforward method for determining the separation between layers of a DBZ that can also assess the existence of a DBZ. This technique determines the distribution of events in the slab-normal direction for a given slab segment such that seismic layers appear as peaks in earthquake histograms. We use the dip test to establish whether the distribution is multimodal (*24*); if it is, we calculate the separation between modes and the associated uncertainty using a multiple Gaussian fit (*25*). Further details on data and analysis are in the Supporting Online Material.

To evaluate the performance of our method for determining DBZ separation with the slab-normal distribution, we applied the technique to what is arguably the best-characterized DBZ—northeastern Japan—using hypocenters relocated with the advanced double-difference tomography method and local network data (*19*). In this case, DBZ separation was easily seen before coordinate rotation due to high-precision event locations (Fig. 2A, top panel), and it has been established to be ~30 km (*1*, *19*). After rotation of the events into down-dip and slab-normal directions (Fig. 2A, bottom), we found that the distribution is bimodal at >99.99% confidence level ($P < 0.0001$) and that the peak-to-peak separation is 31 km.

Having established that the technique can reproduce a DBZ spacing with precisely located events, we compared results for northeastern Japan using the global hypocentral catalogs of Engdahl *et al.* (EHB) (*26*, *27*, and subsequent updates) and the Preliminary Determination of

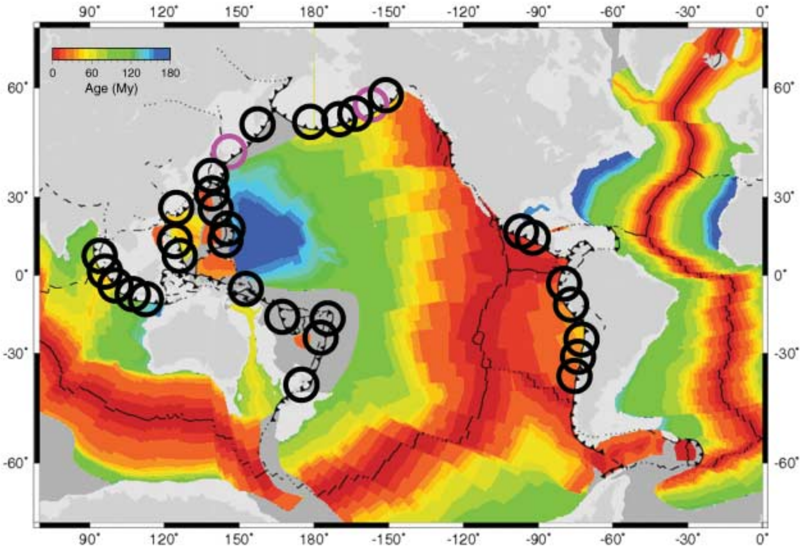

Fig. 1. Subduction-zone segments analyzed, with color scale illustrating seafloor age (*28*) before being consumed at trenches (barbed lines). Black circles indicate areas with a multimodal distribution of events in the slab-normal direction (pink circles indicate cases with confidence < 95%), demonstrating that DBZs are globally prevalent.

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Fig. 2. Analysis of DBZ separation using slab-normal distributions. (**A**) Results for northeastern Japan using relocated, local-network hypocenters (*19*). Top panel shows events (crosses) in typical cross-section view (gray areas not analyzed), and bottom panel shows events after rotation into down-dip and slab-normal locations. This provides the benchmark for comparison with results using global hypocentral catalogs of (**B**) EHB (*26*, *27*) and (**C**) PDE. Similar estimates of DBZ separation among the three data sets at several other subduction zones confirm that global catalogs are sufficient to characterize DBZs. (**D**) Histograms showing slab-normal distribution of EHB events for all segments analyzed, sorted by subducting plate age. DBZ separation is estimated by multiple Gaussian fits shown in green, and dashed linear best fit highlights a significant increase with age.

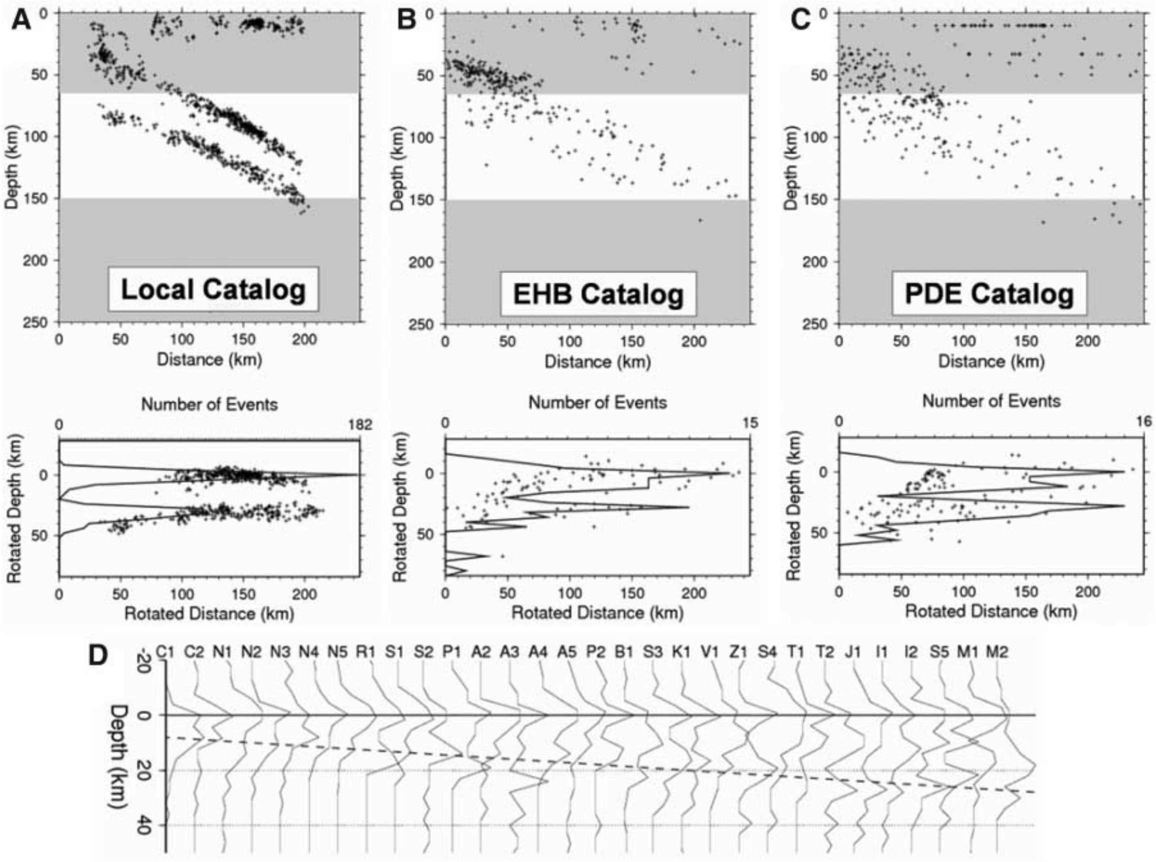
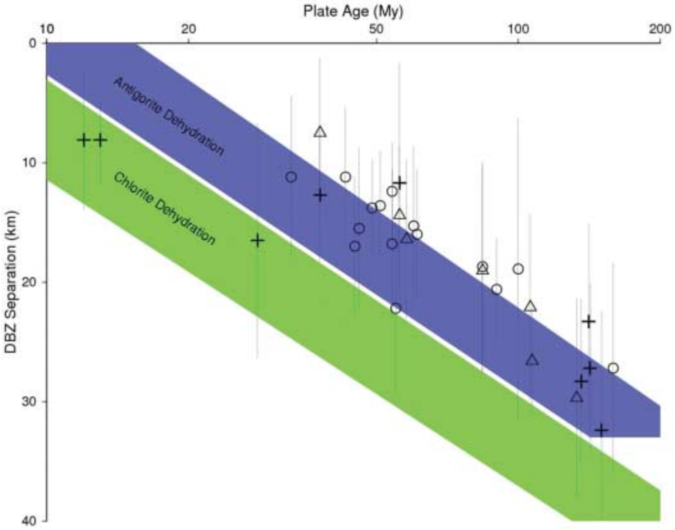


Fig. 3. DBZ separation versus subducting plate age for each segment analyzed, including 1-SD uncertainties from Gaussian fits. Predictions of DBZ separation due to the lower zone resulting from ultimate dehydration of antigorite (blue) and chlorite (green) are shown based on Hacker *et al.* (*9*). Antigorite dehydration is consistent with all observed DBZ separations, whereas chlorite dehydration might explain only a few cases. Separations are not correlated with stress orientations, shown as triangles for typical down-dip compression overlying down-dip extension, circles for a different pattern, and crosses when the pattern is unknown.



Epicenters (PDE). The catalogs are constructed only from hypocenters determined using globally reported arrival times and do not include hypocenter solutions from dense local networks. In these cases, the DBZ separation is more difficult to see in a typical cross-sectional view because of the increased scatter in event location and depth, presumably due to the increased effects of subduction zone lateral heterogeneity on global arrival-time data combined with arrival-time pick inaccuracy (Fig. 2, B and C, top). Nevertheless, the slab-normal distribution after coordinate rotation shows two prominent peaks (Fig. 2, B and C, bottom), the dip test for multimodality is easily satisfied ($P < 0.01$), and the separations between the Gaussian peak fits are 30 km for EHB and 29 km for PDE.

Comparing the EHB catalog and other available local network locations, we found excellent agreement for the DBZ separation (*18*, *20*, *21*, *23*). For example, in the case of New Zealand (*22*), we determined the slab-normal distribution of EHB and local catalog data, finding DBZ separations of 21 km for each. With the successful benchmark tests in hand, our method allows a new global investigation of DBZ prevalence and patterns in the DBZ separation. We investigated 16 different subduction zones (Alaska, Aleutians, Central America, Kurile-Kamchatka, Izu-Bonin, Japan, Mariana, Nazca, New Britain, New Hebrides, New Zealand, Philippines, Ryukyu, Sumatra, Sunda, and Tonga) that account for a range of subducting plate ages [~10 to 160 million years (My)] (Fig. 1) (*28*) and slab dips (~0 to 70°) (table S1).

After constructing histograms for the slab-normal distribution of events in the EHB catalog for each region (Fig. 2D), we found 30 different segments that have a bimodal or trimodal distribution that fulfills the dip test for multimodality (table S1). When the results for slab-normal distribution of events are sorted by age of subducting plate (Fig. 2D), the DBZ separation reveals a significant increase with plate age, from ~8 km for a ~12-My-old slab up to ~30 km for a ~160-My-old slab. A linear estimate for the DBZ separation versus age relationship is ~0.14 km/My, but the data can also be fit with a log-linear relationship.

Every subduction zone studied has at least one segment with a DBZ (Fig. 1), suggesting that DBZs are ubiquitous features. However, our method was not able to identify a DBZ in every section of every subduction zone. This is mainly due to difficulties constructing cross sections in areas with less seismicity, where wider cross sections raise problems with trench curvature or changes in slab dip. Two clear cross sections that did not meet the dip test for multimodality in Kurile-Kamchatka and Eastern Aleutians have been reported as transitions from a DBZ to a single Benioff zone, interpreted as situations where stresses are reduced (*4*, *29*). Moving from northeast to southwest in Kurile-Kamchatka, the decreasing compressive stress transmitted from greater depth is thought to control changes from single compressive zone to DBZ to single extensive zone.

Further evidence for the variable stress regime in DBZs globally can be seen in a survey of reported focal mechanisms (table S1), with several DBZs showing patterns different from the conventional compressive upper layer and extensive lower layer (*1*) (Fig. 3). This places new constraints on models for the source of stress in DBZs, which leads us to question the viability of each of the proposed models (thermoelastic, slab unbending, and sagging plate), which may have difficulty generating sufficient levels of stress for the wide range of slab temperatures, configurations, and focal mechanisms. The systematic variation in layer separation with plate age despite variations in stress orientations also suggests that the trend in layer separations is not controlled by intraplate stresses. Instead, the discovery of DBZs over a wide range of ages and focal mechanisms indicates that the conditions for seismogenesis can be met in two separate layers within plates at intermediate depths regardless of the slab thermal state and stress orientation. Thus, the triggering mechanism does not result from an unusual set of circumstances, but must be common in subduction zones.

The triggering mechanism for DBZs has typically been interpreted as due to the thermal-petrological evolution of the subducting plate [e.g., (*9*)]. One proposed mechanism for intermediate-depth seismogenesis that may account for DBZs is the breakdown of hydrous phases to produce a free fluid—and therefore zero effective pressure—allowing brittle faulting (e.g., *7*, *13*, *30*, *31*) (*32*). A variety of hydrous minerals have been suggested as contributors, with metamorphosed basalt near the top of the plate being the primary candidate for the upper zone of seismicity (*5*, *9*–*11*, *19*). Recently, the upper zone beneath northern Japan has been proposed to consist of two thin layers of seismicity with different focal mechanisms separated by a few kilometers (*33*). Although the global database used here is likely insufficient to see such a triple seismic zone, there are a few segments in this study (i.e., J1, T1, and T2) where a trimodal solution with a small separation between peaks in the upper layer provides a better fit than a bimodal solution.

Petrologic candidates that might explain the lower zone of DBZ seismicity as the result of dehydration include antigorite (*12*) and chlorite (*9*) in hydrous peridotite (*34*). The chlorite-dehydration reaction occurs at higher temperatures of 700 to 800°C (deeper within the plate), so the dipping seismic zone associated with this reaction would occur up to 10 km below that associated with antigorite dehydration at 600 to 650°C, generating a larger DBZ separation (*9*). Given this difference between the two dehydration reactions, we compared the results for DBZ separation versus subducting plate age found in this study with separations predicted for the dehydration of antigorite and chlorite based on the thermal-petrological models of Hacker *et al.* (*9*) (Fig. 3). Antigorite dehydration is consistent with all the observed DBZ separations, whereas chlorite dehydration can explain only a few cases. Given the variation of stress orientations in DBZs of our study areas, the lack of larger separations that would indicate chlorite dehydration is not due to stress limitations. This implies that the lower zone of earthquakes at intermediate depths is most likely associated with fluid released from antigorite breakdown. Given that serpentinized peridotite can store several times more water than chlorite-bearing peridotite (*9*), the amount of fluid released may be a key factor in generating earthquakes, which could be used to evaluate the seismogenic potential of other dehydration reactions [or perhaps phase changes that result in fluid-like material (*35*)].

Regardless of whether our inference about antigorite breakdown is correct, our finding that DBZs are found in all subduction zones worldwide requires that any triggering mechanism to explain DBZ seismicity (and hence intermediate-depth earthquakes in general) must be present in all subduction zones regardless of plate age, convergence rate, or stress orientation.

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Supporting Online Material

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Table S1
References

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