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Intermediate depth earthquakes controlled by incoming plate hydration along bending-related faults

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Key Points:

- Global survey demonstrates a correlation between bending faults in the incoming plate and the seismicity rate of intermediate depth earthquakes
- Fault throw provides a proxy for overall fault damage and the ability of water to penetrate and hydrate the incoming plate
- A mechanical parameter based on the incoming plate faulting controls the seismicity rate of intermediate depth earthquakes

Abstract

Intermediate depth earthquakes (focal depths 70 – 300 km) are enigmatic with respect to their nucleation and rupture mechanism, and the properties controlling their spatial distribution. Several recent studies have shown a link between intermediate depth earthquakes and the thermal-petrological path of subducting slabs in relation to the stability field of hydrous minerals. Here we investigate whether the structural characteristics of incoming plates can be correlated with the intermediate depth seismicity rate. We quantify the structural characteristics of 17 incoming plates by estimating the maximum fault throw (MFT) of bending-related faults. MFT exhibits a statistically significant correlation with the seismicity rate. We suggest that the correlation between fault throw and intermediate depth seismicity rate indicates the role of hydration of the incoming plate, with larger faults reflecting increased damage, greater fluid circulation, and thus more extensive slab hydration.

Plain Language Summary

In subduction zones, one tectonic plate plunges beneath another into the Earth's interior. Some of the earthquakes that occur at subduction zones are unusual due to their occurrence at depths of 70 to 300 km ("intermediate depths"), deeper than the expected limit of brittle failure. In this study, we evaluate whether the faults that form when a plate bends as it enters a subduction zone can explain the occurrence of these deep earthquakes. Sea water penetrates deep into these faults and forms new, hydrous minerals, but these new minerals are not stable deeper in the subduction zone. Laboratory experiments show that breakdown of these hydrous minerals can cause seismicity at depths of 70 – 300 km (intermediate depths). Here we examined a set of 17 subduction zone segments around the globe and found that the seismicity is correlated with the faults that formed due to plate bending. This observation can be explained if the amount of faulting prior to subduction controls the amount of hydrous mineral formation, which subsequently determines the intensity and rate of subduction zone related intermediate depth earthquakes.

1 Introduction

Intermediate depth earthquakes, defined as seismic events at depths of 70 – 300 km, are a unique feature of subduction zones, delineating the upper crust and mantle of the subducting slab in what is often referred to as the Wadati-Benioff zone [*Benioff*, 1963; *Wadati*, 1928]. The dehydration of hydrous minerals in the subducted slab is the most commonly invoked mechanism to explain events at these depths, where conditions of high temperature and pressure should inhibit dynamic fracture or frictional sliding [*Green and Houston*, 1995; *Hirth and Guillot*, 2013; *Meade and Jeanloz*, 1991; *Yamasaki and Seno*, 2003]. Rheological instabilities in some hydrous minerals deformed under high pressures (> 1 GPa) have been observed experimentally [*Ferrand et al.*, 2017; *Jung et al.*, 2004; *Jung et al.*, 2009; *Okazaki and Hirth*, 2016; *Proctor and Hirth*, 2016; *Raleigh and Paterson*, 1965]. However, there is still ambiguity regarding the specific mechanism(s) through which hydrous minerals can generate seismic events. Additionally, there is considerable uncertainty about the degree of hydration of the incoming plate, particularly for the oceanic upper mantle, which should be largely anhydrous due to extraction of water during mid-ocean ridge melting [e.g., *Hacker*, 2008].

Extensional faulting due to plate bending provides a conduit for fluids into the crust and uppermost mantle. Slab hydration and fluid circulation associated with plate bending-related faults have been observed in seismic and electromagnetic studies [*Cai et al.*, 2018; *Grevemeyer et al.*, 2007; *Key et al.*, 2012; *Nedimović et al.*, 2009; *Van Avendonk et al.*, 2011; *Worzewski et al.*, 2011]. Numerical models suggest that stress and pressure changes during slab bending and slab unbending can induce circulation of fluid through the fault zones into the lithospheric mantle [*Faccenda et al.*, 2009; *Faccenda et al.*, 2012]. Subducting slabs have been inferred to contain a significant amount of water, with hydration of the crust and mantle deduced from seismic surveys [*Abers*, 2000; *Cai et al.*, 2018; *Faccenda et al.*, 2008; *Peacock*, 1990; *Pozgay et al.*, 2009; *Zhao et al.*, 2007] and from chemical enrichments observed in arc magmas [e.g., *Plank and Langmuir*, 1998; *Stern*, 2002].

This wide range of observations for incoming plate hydration, together with the experimental evidence for embrittlement of hydrous minerals at high pressures, leads to an expected relationship between incoming plate bending faults, amount of slab hydration, and intermediate depth seismicity [*Ranero et al.*, 2005]. A correlation between the hydration state of the incoming plate and the seismicity rate in the subducted slab has been established regionally [*Shillington et al.*, 2015]. However, a previous attempt to find a worldwide relationship based on the predicted water flux due to mineral dehydration did not find a correlation [*Barcheck et al.*, 2012]. Here, we show that incoming plate faults, which may control the extent of hydration pathways in the subducted slab, correlates globally with the off-trench intermediate depth earthquakes. We postulate that the global distribution of intermediate depth earthquakes is controlled by the extent of faulting and fracturing on the incoming plate, and thus that hydration is inherited through the brittle deformation history of the incoming plate.

2 Methods

2.1 Seismicity rate for intermediate depth earthquakes

In order to quantify the seismic productivity of intermediate depth earthquakes, we used the International Seismological Centre (ISC) Bulletin earthquake catalog (http://www.isc.ac.uk). The ISC Bulletin is the most complete and comprehensive teleseismic earthquake catalog available and includes documentation of globally recorded earthquake hypocenters, phases, magnitudes, and other pertinent earthquake data [e.g., *Di Giacomo et al.*, 2015].

The intermediate depth events used in this study were chosen based on three criteria: (1) focal depth of 70 – 300 km, (2) magnitude of $m_b \geq 4.5$, and (3) occurrence between 1964 to 2015. Although the ISC catalog contains events beginning in 1900, global monitoring of earthquakes for these magnitudes became effective only in the 1960s. We define the seismicity rate as the number of events normalized by the trench length (km) and time (year).

We estimated the seismicity rate for 17 subduction zone segments (Fig. 1) with trench lengths of 210 – 1450 km (Table S1). For each segment, the increasing focal depth of intermediate depth events away from the trench trace the descending slab. Maps of each subduction zone showing the trench segments are provided in the supplementary material (Fig. S1).

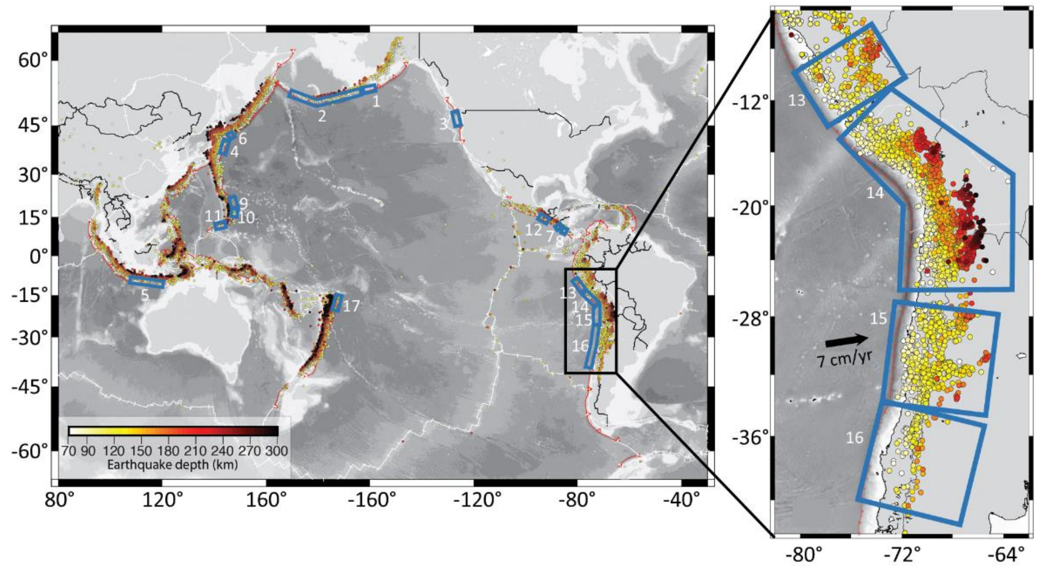

Figure 1. Left: Global map showing the subduction zone segments used in this paper (segment numbers correspond to IDs in Table S1). Intermediate depth earthquakes are delineated by circles colored by the hypocenter depth. Right: enlargement of the South-America trench, subdivided into 4 segments of different seismicity rates.

2.2 Bending-related fault throw

Slab flexure and the resulting tensional stresses generate normal faulting [e.g., *Ludwig* et al., 1966; *Parsons and Molnar*, 1976; *Ranero* et al., 2003]. The bending-related normal faults, manifested in horst and graben features, are a common characteristic of subduction zones and can be seen in seismic reflection images and bathymetric maps up to about 100 km seaward of the trench axis [e.g., *Chapple and Forsyth*, 1979; *Hilde*, 1983].

We quantified the vertical component of fault displacement (i.e., fault throw) in the incoming plate using a compilation of previously published bathymetry data from seismic reflection imaging and ship-based multibeam mapping [Table S2]. In regions with sparse or no data for bending fault offset, we used bathymetric data from the Global Multi-Resolution Topography (GMRT) [*Ryan* et al., 2009] accessed with GeoMapApp (http://www.geomapapp.org/). Topographic profiles orthogonal to both fault strike and the trench were manually selected and used to calculate the vertical fault throw on distinct seaward facing normal faults (Fig. 2 and Fig. S2). We quantified the maximum fault throw (MFT) for each region as a representation of the regional faulting intensity. Here we focus on MFT calculated as the average of the largest 10% of fault throw measurements for each region, but we also evaluated MFT based on the largest 5%, 20%, and 30% of fault throw measurements (Fig. S3).

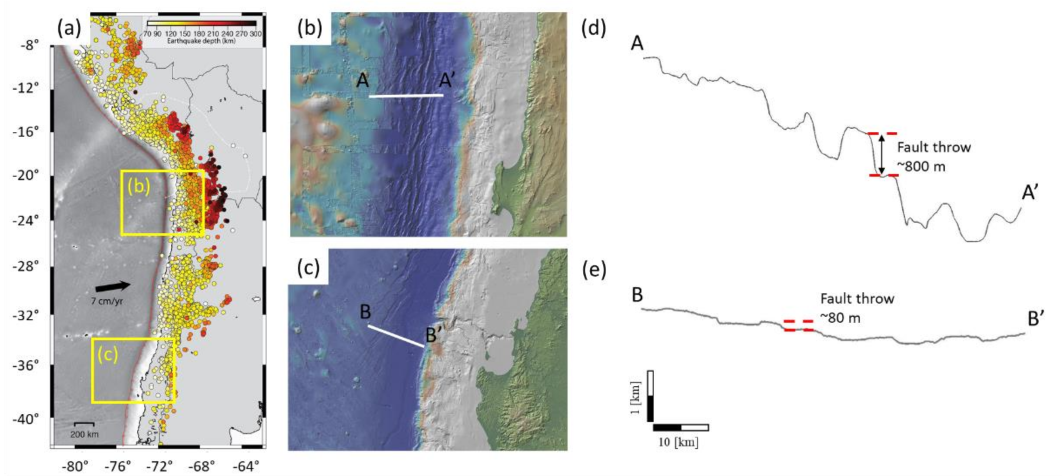

Figure 2. Bathymetry and incoming plate roughness due to bending faults. (a) The South-American coast with intermediate depth earthquakes (from Fig. 1). Yellow boxes show the locations of the zoomed-in bathymetry images shown in b and c. (b and c) Bathymetric maps (GRMT) where A-A' and B-B' indicate the cross sections d and e, respectively, showing the rough central (b) and conversely smooth southern (c) bathymetry off South America.

Fault throw represents fault displacement when a small variation in dip angle is assumed. We use it here to represent fault intensity on the assumption that this provides a proxy for hydration of the incoming plate. We therefore omit bathymetry related to seamounts and focus on bathymetry related to plate faulting. Topographic fault scarps and fault throw estimates have often been used to infer regional stress state, tectonics, and deformation rates where direct field studies are not possible, such as is in other submarine environments and planets [*Schultz et al.*, 2006; *Wilkins et al.*, 2002].

3 Results

3.1 Comparison of incoming plate properties with seismicity rate

The co-variation of the bathymetric expression of faults (as represented by MFT), and the intermediate depth seismicity rate for the 17 trench segments is shown in Figure 3. This correlation suggests a general trend, where the largest fault throws are associated with an increase in intermediate depth seismicity. For example, the bathymetry of Cascadia presents low fault throw values of less than 50 m [*Masson*, 1991] and no intermediate depth earthquakes have been recorded at this subduction zone. On the other hand, the highly faulted slab at the Tonga trench has the highest seismicity rate of our dataset (46.2 10^{-3} km^{-1} $year^{-1}$). Regional data show a similar trend. For example, we divided the Nazca plate, which subducts beneath South America, into four parts according to the bathymetric texture (Fig. 1). Along the northern part of the South America trench, the bathymetry is rough with MFT ~ 800 m, whereas the ocean-floor becomes smoother towards the south with MFT ~ 80 m (Fig. 2). The seismicity rate follows this trend, with higher seismicity rates corresponding to regions with rougher fault scarps. To test possible variations in the magnitude completeness of the ISC seismic catalog, we compared the seismicity rate with a threshold of $m_b \geq 4.5$ and threshold of $m_b \geq 5.6$ [*Di Giacomo* et al., 2015]. We found no significant statistical difference in the seismicity rate between the two thresholds (Fig. S4).

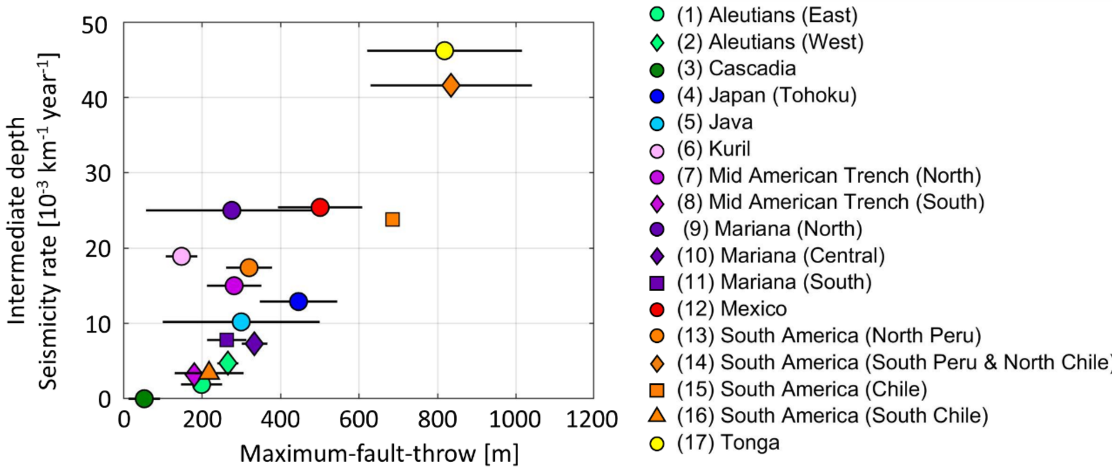

Figure 3. The seismicity rate of intermediate depth earthquakes against the incoming plate maximum fault throw (MFT). MFT error bars are the standard deviation of the averaged 10% fraction largest fault throws, except Java, which is estimated to be 100 – 500 m by *Masson* [1991]. Error bars for segment 15 are smaller than the symbol size.

Syracuse et al. [2010] defined several slab properties and the correlation of these properties with seismicity rate is shown in Figure 4; slab age (Fig. 4a), convergence velocity (Fig. 4b), dip angle (Fig. 4c), and thermal parameter (Fig. 4d). In contrast to the positive trend between MFT and seismicity rate, none of these parameters show a clear correlation with intermediate depth earthquake intensity. In particular, the thermal parameter (φ), defined as the product of slab age and convergence velocity perpendicular to the trench [*Kirby* et al., 1996], where higher values of φ correspond to cooler slabs. This parameter provides a proxy for slab temperature, assuming that heating of the subducting lithosphere is by conduction [*Molnar* et al., 1979]. The thermal state of a subduction zone has been assumed to control deep seismicity due to temperature-dependent mineral breakdowns reactions [*Kirby* et al., 1991], yet φ is not correlated with seismicity rate (Fig. 4d).

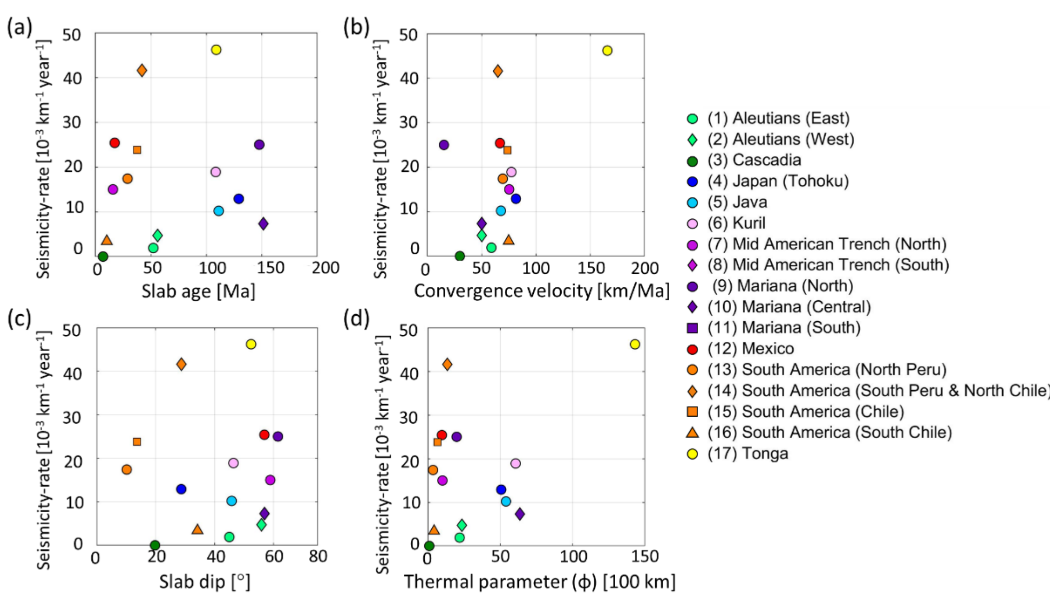

Figure 4. The seismicity rate of intermediate depth earthquakes plotted against slab properties from *Syracuse* et al., [2010]: (a) age, (b) convergence velocity, (c) dip angle, and (d) thermal parameter.

3.2 Statistical significance of the MFT correlation with seismicity rate

We use three different statistical measures to evaluate the correlations between MFT and properties of the incoming plate (Table S3): (1) the Pearson product-moment correlation coefficient, (2) the Kendall rank correlation coefficient, and (3) the Spearman rank correlation coefficient. The Pearson's coefficient is used to explore the linear dependence between two variables. The other two coefficients provide a measure of how well the relationship between the two variables can be described by a monotonic function. In other words, they test the extent to which the positive/negative relationship between two variables is systematic without the necessity of a linear relationship. We also calculated the p-value to test the significance of the correlations, where p varies between 0 and 1 and a small p-value indicates evidence against the null hypothesis. In our analyses, the null hypothesis is that no correlation exists between the two variables. We consider a correlation to be significant when $p \ll 0.05$ and the correlation coefficients are higher than ~ 0.6.

Our analysis reveals high, statistically significant correlations between seismicity rate and MFT for all three statistical tests (Fig. S5). The correlation between seismicity rate and MFT (average of the top 10% of fault throws) shows values of 0.86, 0.6 and 0.74 for the Pearson, Kendall and Spearman coefficients, respectively (Table S3). In contrast, none of the four other parameters (slab age, velocity, dip, and thermal parameter) show a significant correlation, with coefficients < 0.54, 0.21, and 0.32 for the Pearson, Kendall and Spearman coefficients, respectively (Fig. S4). We also tested different definitions for MFT, using both higher (20% and 30%) and lower (5%) percentages of the total fault throw to calculate MFT. The correlation of seismicity rate with MFT is statistically significant for all definitions although using a higher percentage (20 or 30% of the largest faults throws) results in slightly lower correlations.

The rank correlation coefficients (Kendall and Spearman) give slightly lower correlations than the linear correlation coefficient (Pearson), because they are less sensitive to extreme values. The high value of the Pearson coefficient partly stems from the high MFT and seismicity rate values Tonga and South Peru-North Chile. Nevertheless, the fact that the rank dependence coefficients also show significant correlations supports our finding of a positive relationship between MFT and seismicity rate.

4 Discussion

Our results indicate that bending-related faulting of the incoming plate may be a significant control on the seismicity rate of intermediate depth earthquakes. This relationship between shallow incoming plate faults and intermediate depth seismicity rate was previously shown for the Nazca and Cocos plates and was interpreted as fault reactivation [*Ranero* et al., 2005]. However, *Warren* et al., [2007, 2008] found that rupture directivity of intermediate depth earthquakes was inconsistent with the orientation of outer-rise normal faults. Thus, the correlation that we observe may instead be explained by hydration along these faults, with subsequent embrittlement of the hydrated regions at >70 km, in accordance with nucleation mechanisms for intermediate depth earthquakes.

4.1 Fault-zone damage leads to slab hydration

Bending faults provide a pathway for fluid circulation and deep hydration within the downgoing plate [*Emry and Wiens*, 2015; *Grevemeyer* et al., 2007; *Iyer* et al., 2012; *Key* et al., 2012; *Nishikawa and Ide*, 2015; *Ranero and Sallares*, 2004; *Ranero* et al., 2003; *Tilmann* et al., 2008]. The damage associated with faulting leads to channels of increased permeability that allow deep fluid penetration into the oceanic lithosphere [e.g., *Naif* et al., 2015] and these fluids react with the host rock to form hydrous minerals [e.g., *Andreani* et al., 2007]. The ability of fluids to penetrate and react deep in the lithosphere is governed by properties such as fracture density, permeability, and porosity, which are enhanced by faulting [*Sibson*, 2000]. Importantly, these physical properties are expected to evolve through progressive displacement on faults.

Fault displacement and length scaling relationships [*Cowie and Scholz*, 1992; *Schultz* et al., 2006] suggest that for greater fault displacement (and therefore greater fault throw), a larger volume of the incoming plate is damaged. This provides the potential for enhanced hydration on larger faults and thus more hydrous minerals would then be available at intermediate depths to cause dehydration embrittlement. Gouge thickness [*Scholz*, 1987] and damage zone thickness [*Faulkner* et al., 2011; *Savage and Brodsky*, 2011; *Shipton and Cowie*, 2001] increase with increased fault displacement. Hence, the ability of fluids to migrate through the rock is dependent on the damage-zone structure. Within the core of a fault, the permeability may be low due to the presence of fault gouge. However, in material adjacent to the fault core, the permeability can be an order of magnitude higher as a result of cracking in the region known as the damage-zone [*Caine* et al., 1996; *Evans* et al., 1997].

Mitchell and Faulkner [2012] showed that fracture density, damage-zone width, and fault displacement control overall damage zone permeability and that fault-related fracturing and permeability scale with fault displacement. The displacement (d) is scaled with the width of damage surrounding the fault (DW):

$$DW = \frac{a\,d}{b+d} \qquad (1)$$

where DW is in meters, and a and b are constants with values of 96.25 and 147.16, respectively [*Mitchell and Faulkner*, 2012; *Savage and Brodsky*, 2011] based on regression of fault-zone data [*Faulkner* et al., 2011]. Cowie and Scholz [1992] showed that the fault length (L) can be scaled with the displacement:

$$d/L \propto 0.01 \qquad (2)$$

Assuming Andersonian faults with 60° dip, displacement can be estimated from the fault throw. Using equations 1 and 2, the area of the damage-zone (DZ) due to faulting can be estimated:

$$DZ = L \cdot DW \qquad (3)$$

where DZ has units of m^2. The damage-zone associated with faulting increases the permeability around the fault and allows fluid infiltration and subsequent hydration [*Reynolds and Lister*, 1987; *Rüpke and Hasenclever*, 2017].

For the bending-faults in this study, the damage-zone width, estimated from the fault-throw, shows a quasi-linear relationship with the seismicity rate (Figure 5). As hydration kinetics are relatively fast [*Martin and Fyfe*, 1970], the limiting factor for slab hydration is the supply of water through brittle slab fractures and faults [*Rüpke* et al., 2013]. Although mineral production during hydration reactions has the potential to seal cracks [e.g., *Michibayashi*, et al., 2008], the reaction also results in a positive volume change that can generate additional fracturing and permeability [*Audet* et al., 2009; *Jamtveit* et al., 2009]. The relationship between mechanical faulting and the extent of plate hydration has been observed in extensional faults at continental rifts [*Pérez-Gussinyé and Reston*, 2001], where faults have been found to serve as fluid conduits for hydration. *Bayrakci* et al. [2016] used seismic tomography of a continental margin offshore from western Spain to determine that the volume of serpentine had a linear dependence with the amount of fault displacement, consistent with the linear relationship presented in this study (Fig. 5). We conclude that fault displacement controls the overall damage zone structure and permeability of the subducted plate and that bending faults function as conduits for fluid infiltration into the oceanic lithosphere. Therefore, maximum fault throw provides a proxy for the extent of hydration in the slab, which later leads to intermediate depth seismicity.

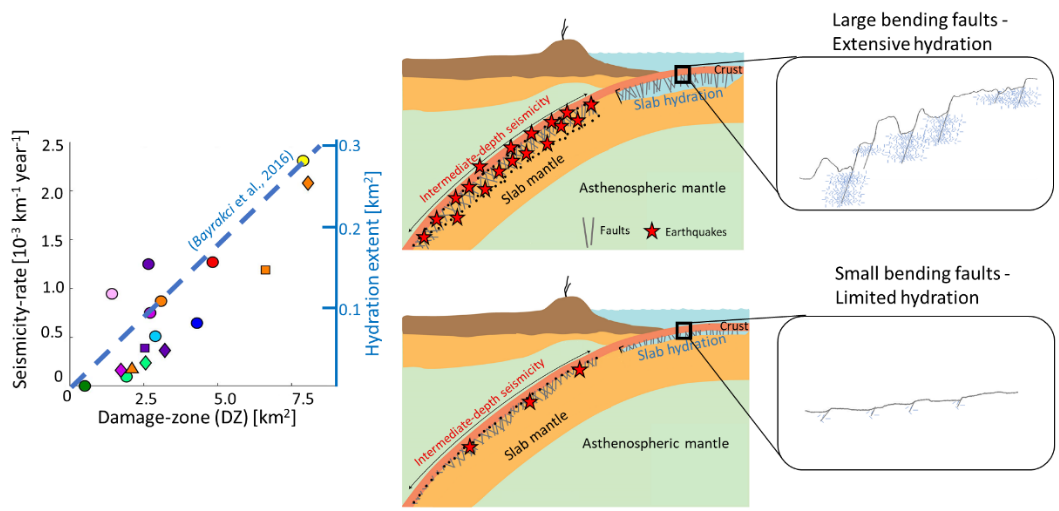

Figure 5. Left: seismicity rate plotted against damage-zone width estimated from fault displacements. Data from this study show a similar relationship to the estimated extent of hydration as a function of damage-zone width as determined from seismic data by *Bayrakci* et al. [2016] for the Iberia rifted margin. Right: schematic diagram of a subduction zone, illustrating the relationship between bending faulting, incoming plate hydration, and intermediate depth seismicity (modified from *Billen* [2009]).

4.2 The effect of incoming plate structure on intermediate depth earthquakes

Previous studies have investigated the relationship between the thermal structure of the slab, dehydration, and intermediate depth seismicity [*Abers et al.*, 2013; *Hacker et al.*, 2003; *van Keken et al.*, 2011; *Wei et al.*, 2017]. The premise behind such studies is that dehydration and breakdown of hydrous minerals cause intermediate depth seismicity, as the thermo-petrological state of the slab determines when mineral phase boundaries are crossed, controlling the depth of earthquakes [*Gorbatov and Kostoglodov*, 1997; *Hacker et al.*, 2003; *Peacock*, 2001]. Fracturing, elevated fluid pressure, and stress heterogeneities due to dehydration may all contribute to the nucleation of intermediate depth earthquakes [*Davies*, 1999; *Ferrand et al.*, 2017; *Gasc et al.*, 2017].

The correlation of thermal structure and slab age with intermediate depth seismicity suggests that the nucleation mechanism is temperature dependent [*Brudzinski et al.*, 2007]. This could be associated with the specific rheology of the hydrous minerals that have formed due to the brittle-ductile-brittle transitions characteristic of many hydrous minerals [*Brantut et al.*, 2011; *Jung et al.*, 2009; *Proctor and Hirth*, 2016; *Raleigh and Paterson*, 1965]. Alternatively, seismicity may result from dehydration embrittlement and the related change of fluid pressure and stress heterogeneities [*Ferrand et al.*, 2017; *Hirth and Guillot*, 2013; *Okazaki and Hirth*, 2016]. Although the pressure-temperature conditions in the slab are a first-order control on the release of fluids at intermediate depths, here we find that a mechanical parameter, fault throw, determines the net availability of fluids and therefore controls the intensity of intermediate depth seismicity.

5 Conclusions

We show a significant correlation between a global dataset of intermediate depth seismicity rates and the occurrence of shallow faulting caused by plate bending. Other parameters of the subducted slab such as plate age, convergence velocity, dip angle, and thermal parameter do not show a statistically significant correlation. Our results suggest that shallow processes associated with bending faults of the incoming plate have a strong control over intermediate depth seismicity rate. We propose that the hydration extent of the subducted slab, estimated from its faulting, exerts a primary control on the prevalence of intermediate depth seismicity. Thermo-petrological models that seek to describe intermediate depth earthquakes through mineral phase stability and breakdown of hydrous phases should also account for the extent of hydration within the slab.

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