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Subducting passive continental margins with crustal (ultra)mafic intrusions: An underappreciated mechanism for recycling water back into the mantle

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Key Points:

- High outer rise seismicity coincides with passive margins that exhibit crustal (ultra)mafic intrusions.
- Crustal (ultra)mafic intrusions increase the seismogenic layer thickness, promoting lithospheric fracturing and plate hydration.
- Subducting passive margins with crustal (ultra)mafic intrusions transport considerable water flux into the mantle.

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Abstract: It is well known that outer rise bending-assisted oceanic plate hydration is an important mechanism for transporting substantial amounts of water into the mantle. A key question is: Are there other equally or more important water transport mechanisms? Here we propose, for the first time, that subducting passive continental margins, particularly those with crustal (ultra)mafic intrusions, play a critical role in recycling water back into the mantle. Evidence for this mechanism is the exceptionally high outer rise seismicity observed in a subducting passive continental margin (i.e., the northeastern South China Sea continental margin) near the northern Manila trench, characterized by a high-velocity lower crust that has been attributed to (ultra)mafic intrusions. Our interpretation of this correlation between high outer rise seismicity and lower crust (ultra)mafic intrusions is that (ultra)mafic intrusions alter the crustal rheology and increase brittle deformation in the lower crust in this region, thereby promoting lithospheric fracturing and plate hydration, which is evidenced by increased outer rise seismicity.

Keywords: (ultra)mafic intrusion; passive margin; lithospheric fracturing; outer rise; plate hydration

1. Introduction

Water transported by subducting slabs into the mantle at subduction zones has profound implications for magmatism, earthquakes, and the deep-water cycle (He XB et al., 2022; Wang DJ et al., 2022; Zhao H and Leng W, 2023). Hydration of the oceanic slab determines the amount of water transported from the Earth's surface into its interior. Hydration occurs first at mid-ocean ridges in response to the high porosity and permeability caused by various processes, such as hydrothermal activity, fissuring, and volume decrease due to thermal contraction (e.g., Iyer et al., 2010). It is also well documented that outer rise bending of oceanic plates promotes hydration by causing extension and normal faulting in the upper, brittle part of a slab (e.g., Ranero et al., 2003; Faccenda et al., 2009; Cai C et al., 2018; Wan KY et al., 2019; Zhu GH et al., 2021). Note that lithospheric strength depends largely on a slab's structure; strength is key to the degree of faulting and depth of faults, which determines the hydration state (e.g., Korenaga, 2017). Knowledge of a subducting plate's rheology structure (i.e., its strength) is thus key to understanding the deep-water cycle.

Outer rise bending-related faulting plays a critical role in plate hydration; subduction of seamounts is also thought to transport a considerable water flux into the mantle (He XB et al., 2022). However, whether there are other important water transport mechanisms has remained mostly unaddressed. Here we suggest a new mechanism by demonstrating that subducting passive continental margins, when their lower crust is intruded by (ultra) mafic materials, can transport a great amount of water into the mantle. Our principal evidence for this novel mechanism is the observation of very high outer rise seismicity at the northeastern South China Sea continental margin, where a high-velocity body attributed to (ultra)mafic intrusions is found in the lower crust.

Thus, the purpose of this paper is to: (1) characterize the depth distribution of outer rise seismicity at a variety of subduction settings, (2) anatomize the cause of the exceptionally high outer rise seismicity observed at the northeastern South China Sea continental margin, and (3) emphasize the importance, for understanding the deep-water cycle, of subduction of continental margins with crustal (ultra)mafic intrusions.

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2. Data and Analyses

The strength (or the seismogenic layer thickness) of the subducting plate determines the seismic activity of the outer rise in response to lithospheric bending, whereas the focal depth spectrum directly reflects the regional seismogenic layer thickness at various outer rises. To characterize the focal depth spectrum in a variety of subduction settings, we collected outer rise seismicity data ($M > 4.5$) from 1990 to 2022 from the International Seismological Centre (ISC). Specifically, we focus mainly on the northeastern South China Sea continental margin near the Manila trench. Still, we compare outer rise seismicity in six other settings, including the Kurile, Izu–Bonin, Mariana, Tonga, Kermadec, and Philippine subduction zones (Figure 1). The subducting plate at the Manila trench is affiliated with the continental lithosphere. In contrast, the rest of the plates are affiliated with the oceanic lithosphere. Our collections are limited to outer rise events that were abundantly clustered; events that occurred near the trench are largely excluded to avoid ambiguity induced by interplate and overriding plate events. It is challenging to differentiate the interplate from the overriding plate earthquakes without a precise relocation process when they occur near the trench.

2.1 Outer Rise Seismicity in the Manila Subduction Zone

Two outer rise seismicity groups along the Manila trench are selected (Figure 2a). The depth spectrum in the north is distinct from that in the south. Specifically, the north is much more abundant in seismicity than the south; the cut-off depth in the north is ~35 km (Figure 2b), deeper than the ~23 km cut-off depth in the south (Figure 2c); both have a similar peak of the spectrum at a depth of ~15 km. The cause of the regional north–south difference in the seismicity depth spectrum will be explored in the Discussion section.

2.2 Outer Rise Seismicity in the Philippine and Kurile–Kermadec Subduction Zones

The outer rise seismicity is limited to six subduction zones ranging from the Philippines to the Kurile–Kermadec (Figure 3). The most striking signature of the spectrums is that they mostly have a cut-off depth of ~27 km (except the Izu–Bonin's, the cut-off of which is as great as ~40 km) and a similar peak at ~15–20 km depth (Figure 4). Each spectrum also has some individual features. For instance, that observed at the Philippine trench shows a slightly shallow cut-off depth at ~20 km, and the Izu–Bonin outer rise not only has a deeper cut-off depth but is also more abundant in seismicity than the other subduction zones studied.

3. Discussion

Comparing the eight depth spectrums, it is very clear that the broadest depth spectrum of seismicity occurs in the north group at the Manila trench and the Izu–Bonin trench, ranging from ~5 to 35 km depth; both areas are also very abundant in seismicity. It is evident (see Figure 3f) that the high seismicity at Izu–Bonin is associated with seamount subduction, and our recent study (He XB et al., 2022) has argued that, due to the bathymetric anomaly, seamount subduction will promote extensive plate hydration, and thereby increase seismicity in response to outer rise bending. Therefore, in the following, we will mainly explore the cause of the outer rise seismicity north of the Manila trench.

As we documented above, the depth range of seismicity is determined by (or proportional to) the seismogenic layer thickness of the subducting lithosphere; outer rise seismicity is a result of brittle failure in response to plate bending. Therefore, the fact that the broadest depth range is observed in the northern Manila trench suggests that there is where the subducting plate must have its thickest brittle part within the lithosphere. By contrast, although

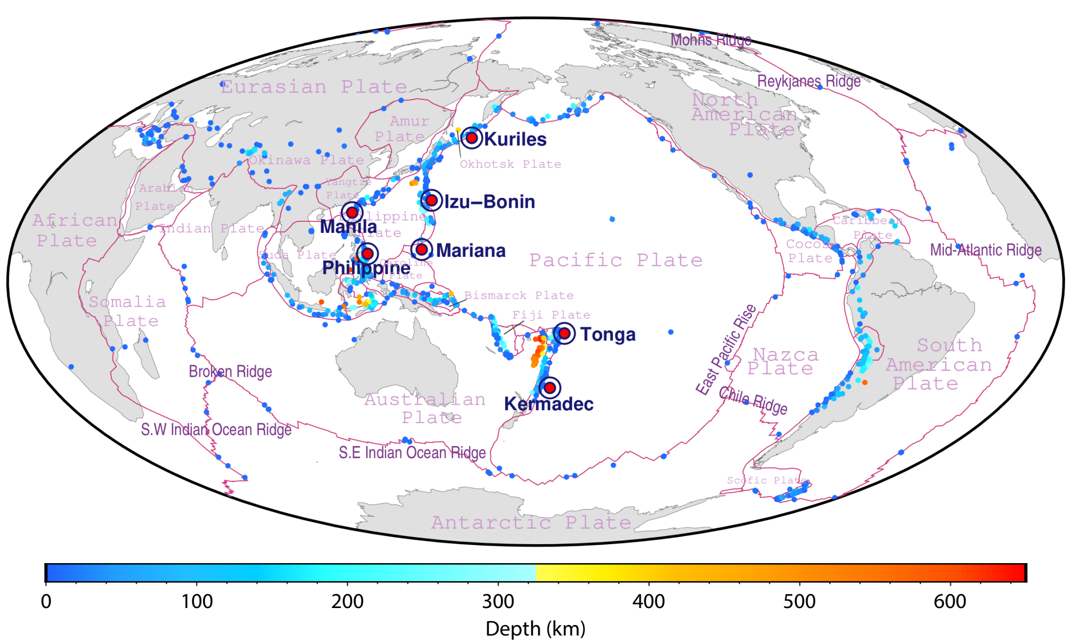

Figure 1. Distribution of locations of outer rise seismicity observations analyzed in this study. A big open circle with a small solid red circle indicates each location. Colored dots show $M > 4.5$ seismicity observations worldwide from April 7 to May 7, 2022. The color scale for the focal depths is shown at the bottom. The plate boundaries are taken from the model by Bird (2003).

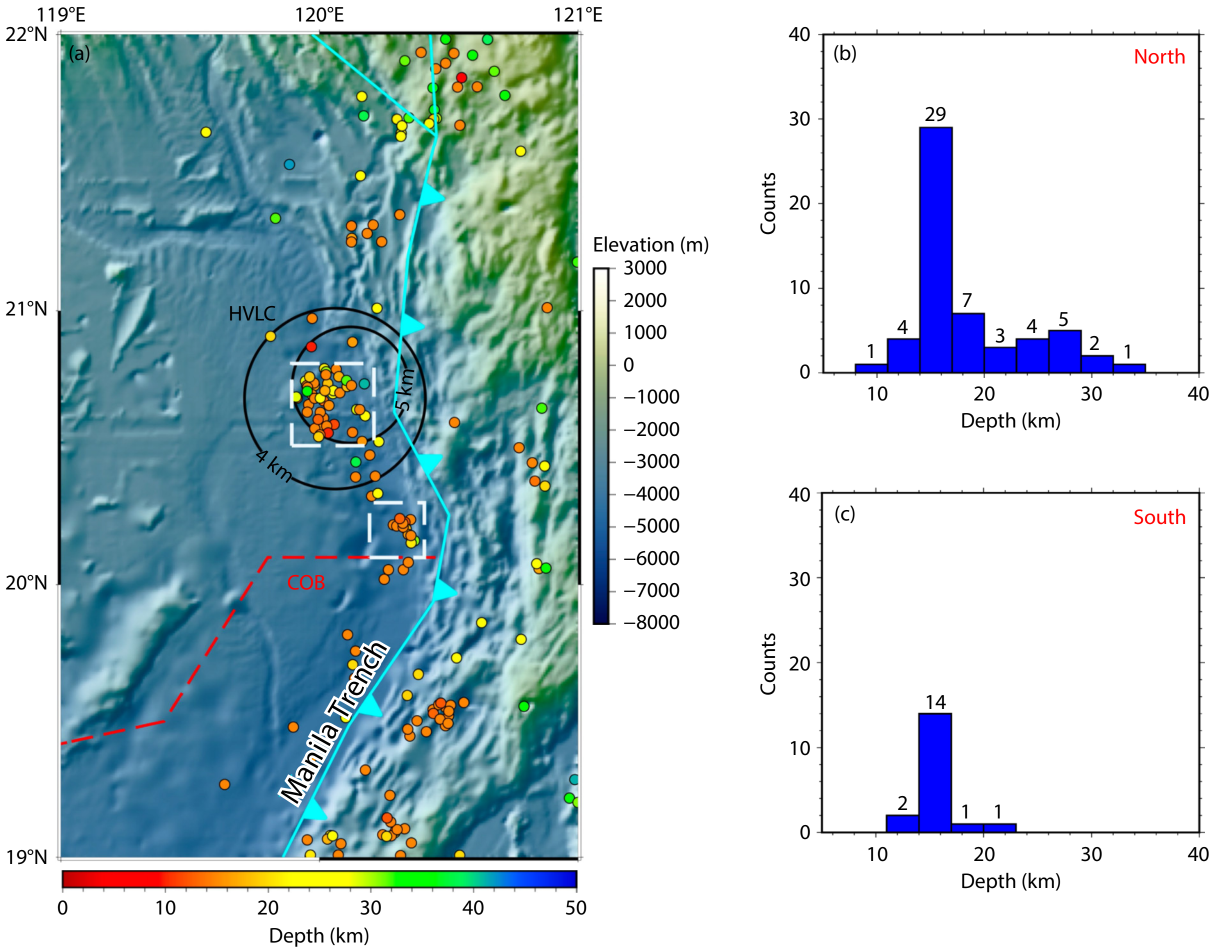

Figure 2. (a) Distribution of seismicity (colored dots) along the northern Manila Trench. The red dashed line denotes the COB. Black circles show the thickness contours of the HVLC. White dashed squares indicate the two outer rise seismicity groups collected in this study in the north and south. Histograms of the focal depths of the outer rise events in the north (b) and the south (c). HVLC: High-velocity lower crust; COB: Continent-ocean boundary. The data of the COB and HVLC are provided by Cheng JH et al. (2021).

the subducting plate in the south is also affiliated with a continental lithosphere, it has a much narrower depth spectrum (~11–23 km depth range), suggesting a relatively thin brittle lithosphere.

We attribute the difference in depth spectrum to structural heterogeneity, particularly in the lower crust, because we find no evidence for other factors, such as trench curvature and temperature variations across the two groups, that might influence the lithosphere strength. Also, a previous study has suggested that structural heterogeneity occurs in the subducting plate along the northern Manila Trench (Chen CX et al., 2015). More importantly, the north region is characterized by a high-velocity lower crust (Figure 2a), which is interpreted to be the product of mafic and ultramafic intrusions, associated with either the paleo-Pacific subduction or post-rift magmatic activity (Cheng JH et al., 2021). Experiments have suggested that (ultra)mafic intrusions significantly affect the rheological properties of the lithosphere, rending the lower crust transition into a brittle regime (at least in part) and thereby increasing the thickness of the brittle lithosphere (Figure 5b; Burov, 2011). It is thus evident that the difference in depth spectrum can be largely explained by variations of rheological properties of the lithosphere, in particular those of the lower crust. In the southern part, which was not intruded by (ultra)mafic materials, the brittle upper crust has decoupled from the mantle lithosphere, leading to difficulty in stress transmission from the surface to the mantle lithosphere (Figure 5a). This structural difference thus explains the narrow depth range and shallow cut-off depth of the depth spectrum observed in the south part.

Compared with continental lithospheric rheology, the oceanic plate is characterized by relatively simple rheological properties (Figure 5c; Kohlstedt et al., 1995; Burov, 2011). This rheological simplicity is evidenced by the depth spectrums of outer rise seismicity presented in this study, mostly showing a cut-off depth of ~27 km and a depth peak of 15–20 km; both are slightly deeper than those observed in the south part at the Manila trench because the stress can more readily transfer from the surface to the subcrustal mantle in response to oceanic plate bending, facilitating a deep brittle failure. At the outer rise, previous studies have also suggested that some earthquakes are likely to cut >20 km deep into the lithosphere, promoting the reaction between the seawater and the underlying lithospheric mantle (e.g., Christensen and Ruff, 1988; Hasegawa et al., 1994). The common features among the six depth spectrums can thus be

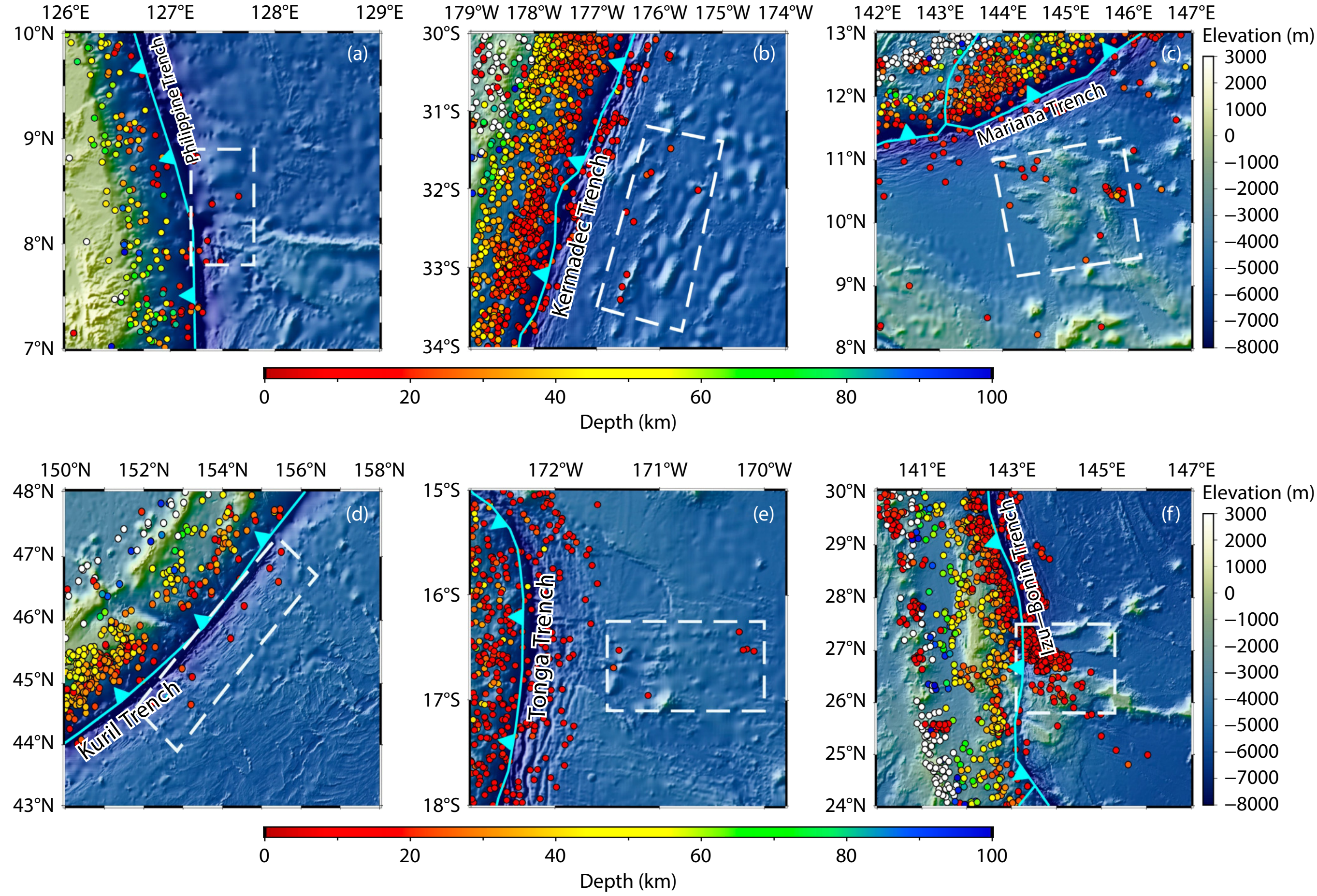

Figure 3. Distribution of the collected outer rise seismicity at six different subduction zones, including (a) Philippine subduction zone, (b) Kermadec subduction zone, (c) Mariana subduction zone, (d) Kuril subduction zone, (e) Tonga subduction zone, and (f) Izu–Bonin subduction zone. The dashed white-line rectangles indicate the selected outer rise areas.

attributed to rheological simplicity (Figure 5c). In contrast, the individual characteristics can be attributed to other factors, such as plate age and proximity to seamounts (Burov, 2011).

In addition, the abundance of seismicity (or high seismicity) in the north of the Manila trench may reflect that the subducting plate has been subjected to extensive fracturing and hydration; this may, in turn, suggest that the (ultra)mafic intrusions play a role in enhancing the fracture density, thereby increasing the degree of hydration. To summarize, (ultra)mafic intrusions significantly contribute to plate hydration by increasing (1) fracture density and (2) the depth extent of brittle failures. More importantly, (ultra) mafic intrusions occur widely in a passive continental margin due to various processes, such as post-rift magmatic activity, plate subduction, and the arrival of plumes. These intrusions are often seen in a magma-rich rifted margin (Thybo and Artemieva, 2013). The long-term influence on the deep-water cycle associated with the subduction of passive continental margins during the Earth's evolutionary history should thus be given greater consideration. Figure 6 schematically illustrates that when the lower crust is intruded with (ultra)mafic materials, mantle hydration of subducted continental lithosphere occurs at the outer rise in response to plate bending.

The slightly shallower cut-off depth (i.e., a shallow brittle failure) of outer rise seismicity observed at the Philippine trench may be attributed to its younger age compared to the western Pacific plate. Moreover, uncertainties in ISC data relevant to the focal depths of outer rise events limit our ability to characterize the seismogenic structure of the lithosphere further; future re-determination of these important focal depths is thus needed to improve our understanding of the brittle behavior of plates. However, the depth spectrums presented in this study should be meaningful statistically. In addition, quantitative estimation of the amount of water carried in the continental margin lithosphere is also important for evaluating to what extent this water transport mechanism has contributed to the deep-water cycle.

4. Summary

In this contribution, we propose a new mechanism, employing the subduction of passive continental margins with (ultra)mafic intrusions in the lower crust that may be responsible for transporting a considerable water flux into the mantle. The foundation of this mechanism lies in the observed correlation between the high outer-rise seismicity observed in the northeastern South China Sea continental margin and its lower crustal high-velocity anomaly due to (ultra)mafic intrusions. We attribute this spatial correlation to lower crustal brittle deformation favored by (ultra) mafic intrusions. In contrast, brittle deformation, in turn, promotes

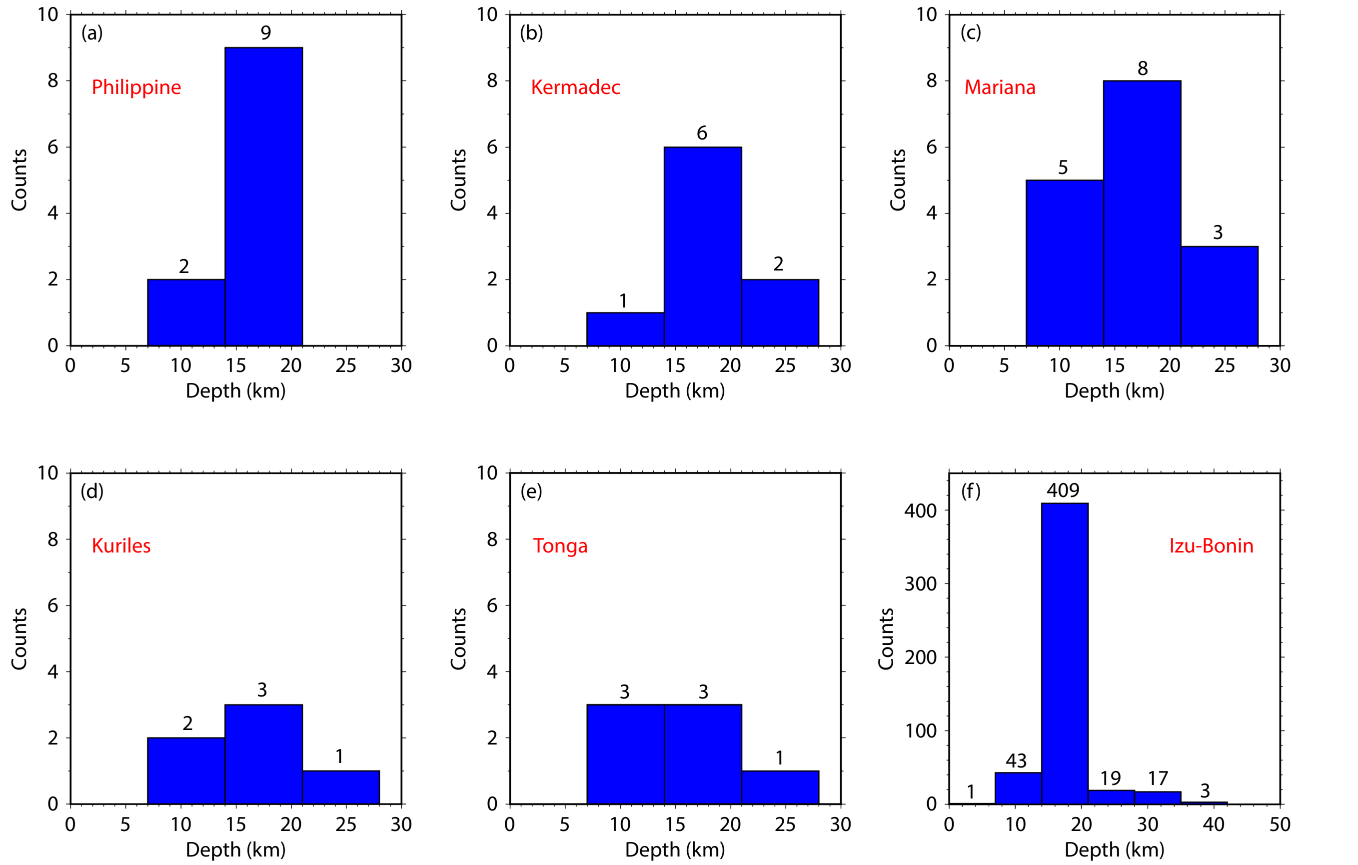

Figure 4. Histograms of focal depth of the outer rise seismicity that occurred at six different subduction zones.

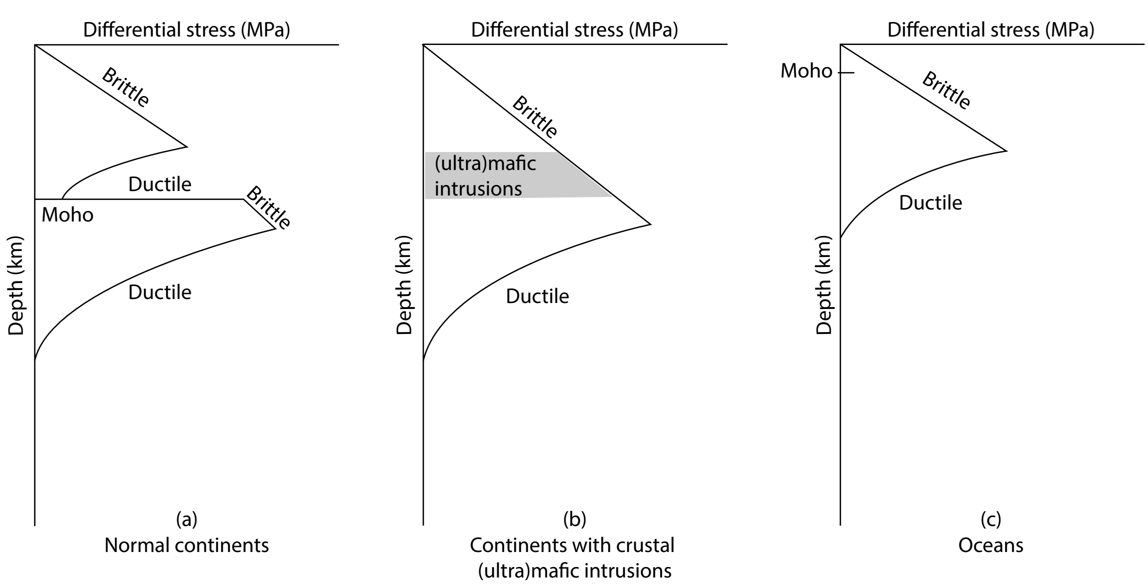

Figure 5. Schematic illustration of maximum rock strength (or rheological yield stress envelopes) as a function of depth for (from left to right) continents (a), modified continents by the (ultra)mafic intrusions (b), and oceans (c); modified from the models by Kohlstedt et al. (1995) and Burov (2011). Note that more complex variants due to varying thermo-tectonic age and multi-layered structure of the lithosphere are not considered here. Moreover, the middle (b) presents an end member in which (ultra)mafic intrusions have entirely replaced the lower crust; that is, the entire crust has transitioned to a brittle regime.

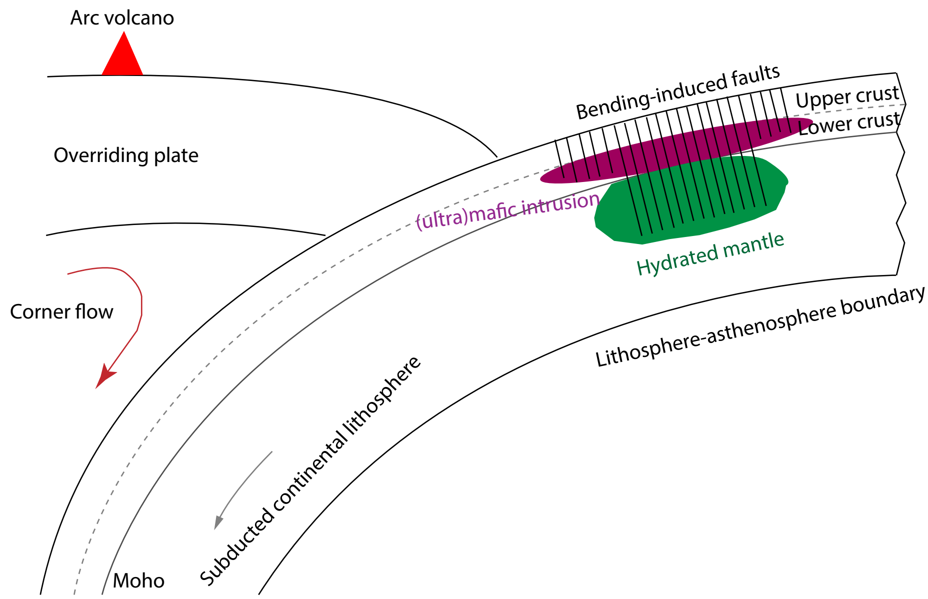

Figure 6. Schematic illustration of mantle hydration of subducted continental lithosphere at outer rise, facilitated with lower crust (ultra)mafic intrusion and plate bending.

plate fracturing and hydration at the outer rise, leading to increases in seismogenic layer thickness and seismicity.

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