Forum Reply

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Constraining the maximum depth of brittle deformation at slow- and ultraslow-spreading ridges using microseismicity

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We thank Schlindwein (2020) for continuing the discussion on the depth of seismic faulting at slow- and ultraslow-spreading ridges. We (Grevemeyer et al., 2019) investigated micro-seismicity of the Mid-Cayman Spreading Center and compiled maximum depths of brittle deformation of ten additional slow- and ultraslow-spreading ridges. Our approach included the re-localization of an earthquake catalogue from the Southwest Indian Ridge (SWIR) between 13°E and 14°E (Schlindwein and Schmid, 2016). The original SWIR analysis found unusually deep earthquakes with maximum depth of faulting of up to 35 km and absence of seismicity between 5 km (east) and 15 km (west) below the seafloor. In contrast, we estimated maximum hypocentral depths of 17 km and minimum depth of faulting of ~4 km (east) and 1 km (west). Schlindwein (2020) agrees in her comment that a shallower maximum depth of faulting of <20 km is a robust feature, but suggests that an 8 km thick aseismic domain may occur in the uppermost lithosphere.

Earthquake locations are particularly uncertain due to a trade-off with onset times and limited constraints on Earth's velocity structure. In addition, station distribution and the distance of stations to the focal area are critical to provide reliable estimates of hypocentral depth. Schlindwein (2020) closely followed our technical approach, but used a different data selection strategy. We used the criteria defined by Husen and Hardebeck (2010): (i) gap < 180° of well-constrained earthquakes; (ii) at least eight (which we relaxed to six) travel time arrivals, of which one (or more) being a S-wave arrival, and at least one onset time reported from a station within an focal depth's distance from the epicenter; (iii) one S-wave arrival recorded within 1.4 focal depth's distance to the epicenter, providing reliable constraint on focal depth (Gomberg et al. 1990). Unfortunately, for some shallow events, the last criterion was not always met (poor station coverage) and thus shallow faulting cannot always be well constrained. We included 470 events recorded at eight stations; initial large delays of S-arrivals disappear while iteratively updating station terms automatically. As a measure of quality, we used a cross plot of P-arrival time versus S-arrival time, showing a compact distribution, supporting appropriate station corrections and average P-wave to S-wave velocity (Vp/Vs) ratios of ~1.8 (Fig. 1).

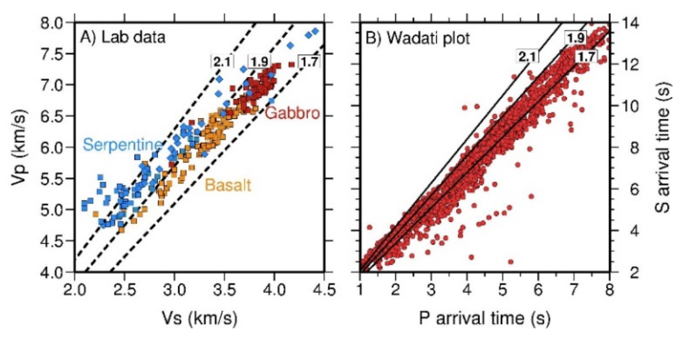

Figure 1. (A) P-wave and S-wave velocity of different lithologies, revealing that different rock types can be discriminated by the Vp/Vs ratio (modified from Grevemeyer et al., 2018); (B) Modified Wadati diagram derived from P- and S-wave onset times for the SWIR deployment (data from Fig. DR7B of Grevemeyer et al., 2019), supporting Vp/Vs ratios smaller than 1.9 at the SWIR.

Schlindwein (2020) used 202 events and excluded S-arrivals at the four stations SWE05, 06, 08, and 09 (four out of eight stations) as they sat on sediment ponds within the median valley. However, three of these were the only stations located above the observed seismicity. By excluding them, the minimum epicentral distance of recorded S-arrivals increases to at least 20–40 km, violating the third criterion for shallow earthquakes recommended to yield focal depth (e.g., Gomberg et al., 1990; Husen and Hardebeck, 2010). Therefore, we suggest that the discrepancy in the depth distribution of micro-earthquakes might arise by rejecting S-arrivals within or close to focal depth's distance. Yet, we believe that by not omitting any reliable S-arrivals our depth estimates are robust and more accurate than any approach excluding S-arrivals at short epicentral distance as station terms correct biased travel times caused by sediments and local heterogeneities. Unfortunately, the data set from the SWIR suffered from failure of two instruments and hence sparse station distribution. Therefore, the available data are far from being well-suited to close the controversy for the onset of shallow seismic faulting at the SWIR.

Conceptually, Schlindwein (2020) suggests that the aseismic region at the top of the lithosphere might be controlled by hydration of ultramafic rocks. However, seismic data from the Cayman Trough (Grevemeyer et al., 2018) and the Tyrrhenian Sea (Prada et al., 2016) suggest that strongly serpentinized mantle, which may support aseismic behavior, generally occurs at <3–4 km below seafloor, but does not reach as deep as 8 km. Therefore, her conceptual model might need observational corroboration. Yet, the seismological travel time data reveal that the SWIR is characterized by Vp/Vs ratios <1.9 (Fig. 1), while laboratory data suggest that serpentinized mantle has a Vp/Vs ratio of >1.9 (e.g., Christensen, 2004; Grevemeyer et al., 2018), reaching up to 2.2 for strongly altered mantle (Carlson and Miller, 1997). Therefore, we conclude that the bulk of crust or mantle along the SWIR might not be sufficiently hydrated to support widespread aseismic behavior.

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