Slab geometry and a diffuse plate boundary beneath Sumatra: constrained using a new receiver function analysis method

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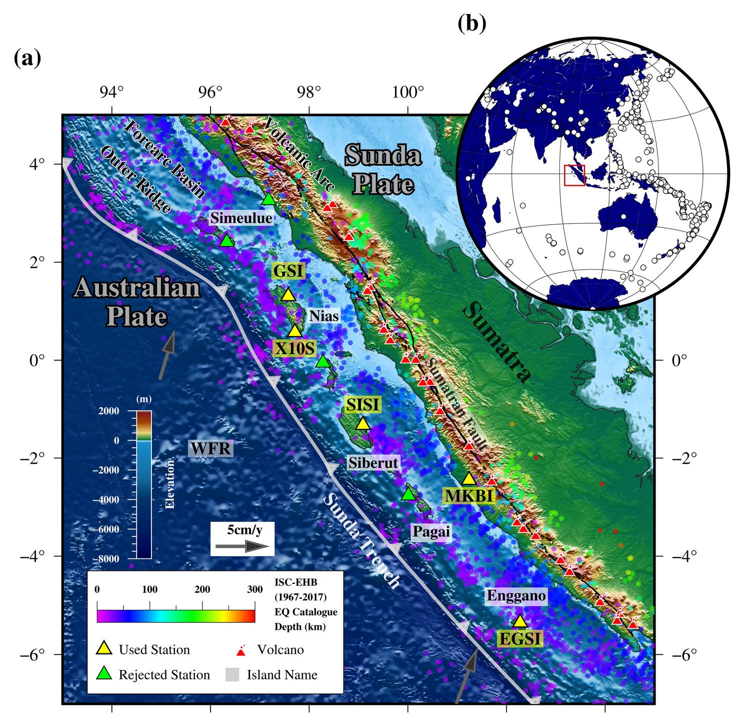
Key points

- A dip direction searching (DDS) method is developed to constrain the geometry of subducting slab-related discontinuities using teleseismic receiver functions (RFs).
- A dipping low velocity layer (LVL) is imaged at the subducting plate boundary in Sumatra using the DDS method. The LVL is much thicker than a normal oceanic crust (10-14 km vs. ~6-7 km), and its upper and lower boundaries are parallel in northwestern and southeastern Sumatra, but have different dip directions in central Sumatra (by up to 23°).
- The dipping LVL is interpreted as the oceanic crust overlain by a low-velocity serpentinized mantle layer, indicating a diffuse plate boundary caused by slab dehydration.

The Sumatran subduction zone is characterized by a strongly coupled slab discontinuity and intensive arc volcanism



- Previous seismic studies reveal subducting seamounts and strong slab deformation, both of which govern the features of earthquake rupture and magma generation associated with slab dehydration and mantle wedge hydration (e.g., Singh et al., 2011; Liu et al., 2021).
- However, detailed slab geometry and the "slab dehydration - mantle hydration" processes remain poorly constrained.

Figure 1: *(a) The Sumatran subduction zone is between the Indo-Australian and Sunda plates, where the Indo-Australian plate obliquely subducts toward the Sunda plate. The "WFR" label marks the location of Wharton Fossil Ridge. Yellow and green triangles show the stations with and without a clear pair of negative-positive targeting phases in RFs, respectively. The white dots in subplot **(b)** show locations of tele-seismic earthquakes used in this study.*

Signals related to the subducting plate boundary are observed in RFs

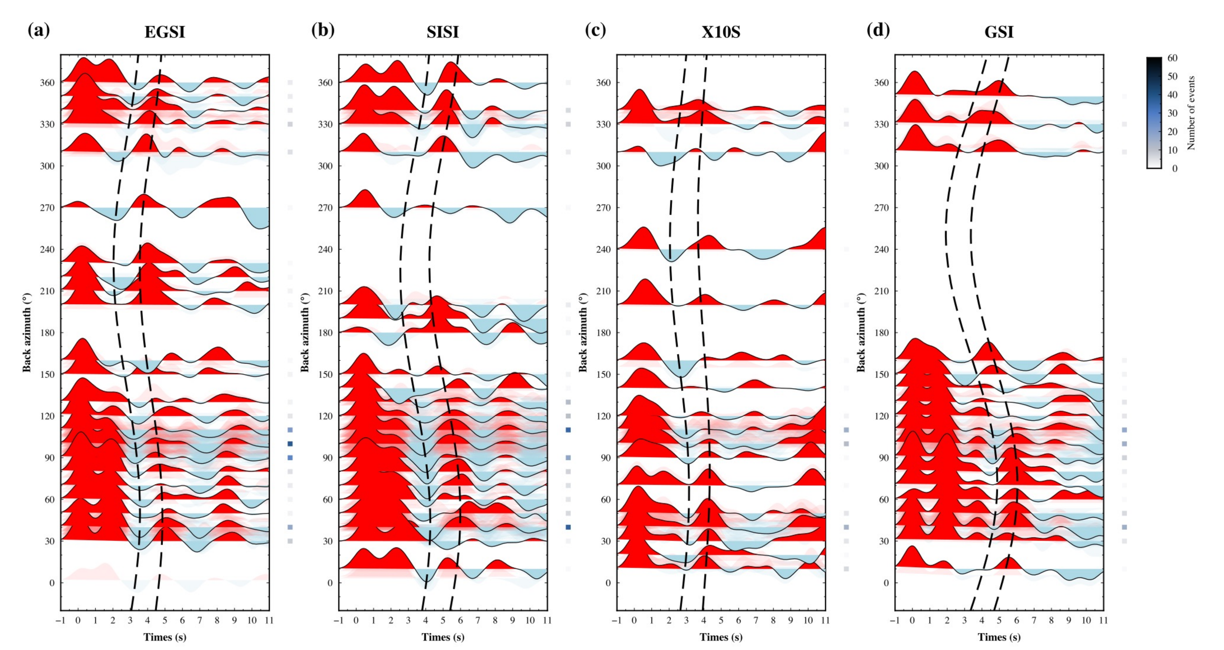


Figure 2: *(a-d) The dash lines mark a pair of negative-positive phases with clear back azimuthal variations, which are revealed as signals associated with the subducting oceanic crust in global subduction zones (e.g., Yuan et al, 2000). The pair of phases provides a precise opportunity to study the geometry and structure at the subducting plate boundary.*

Dip direction searching: A new method

Fitting RF back azimuthal variation to estimate dip directions

- Back azimuthal (α) variation of P-to-s conversion phases in P-wave RFs at dipping interfaces are considered as a harmonic function (e.g., cosine function) in which phase shifts (θ) indicate dip directions:

$$T(\alpha) = T_0 + A\cos(\alpha - \theta)$$

A and T_0 are amplitude and central arriving time of the cosine function, respectively.

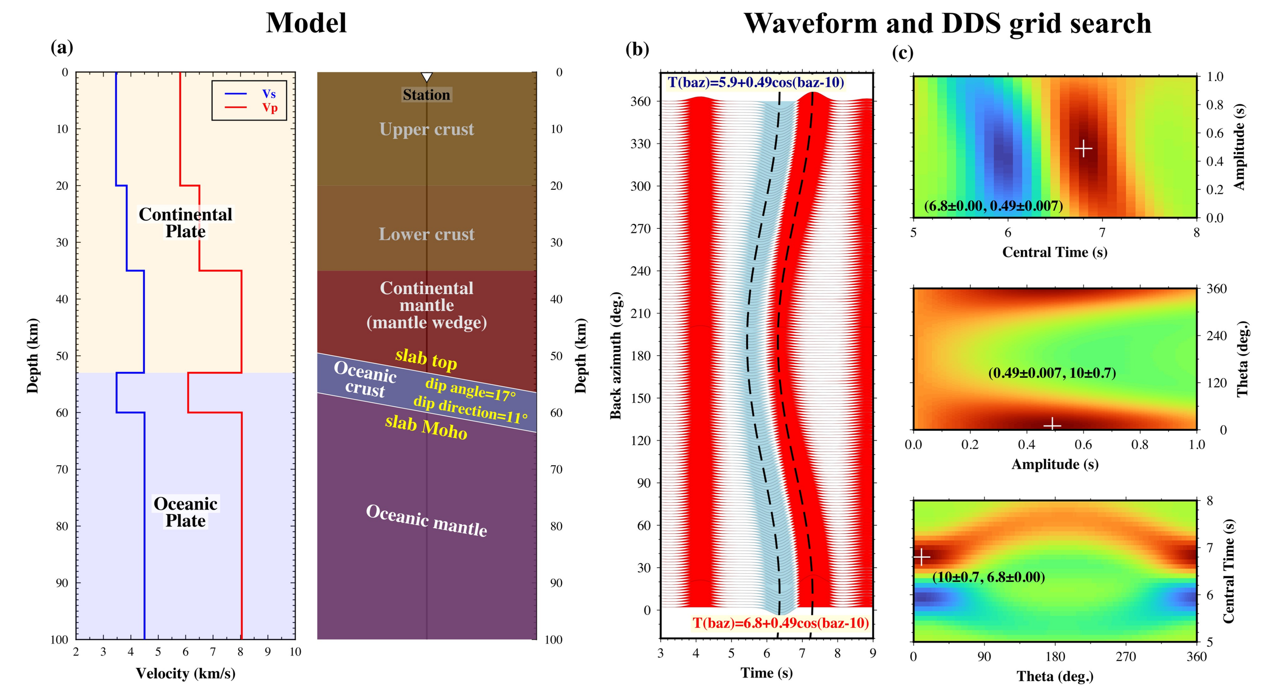
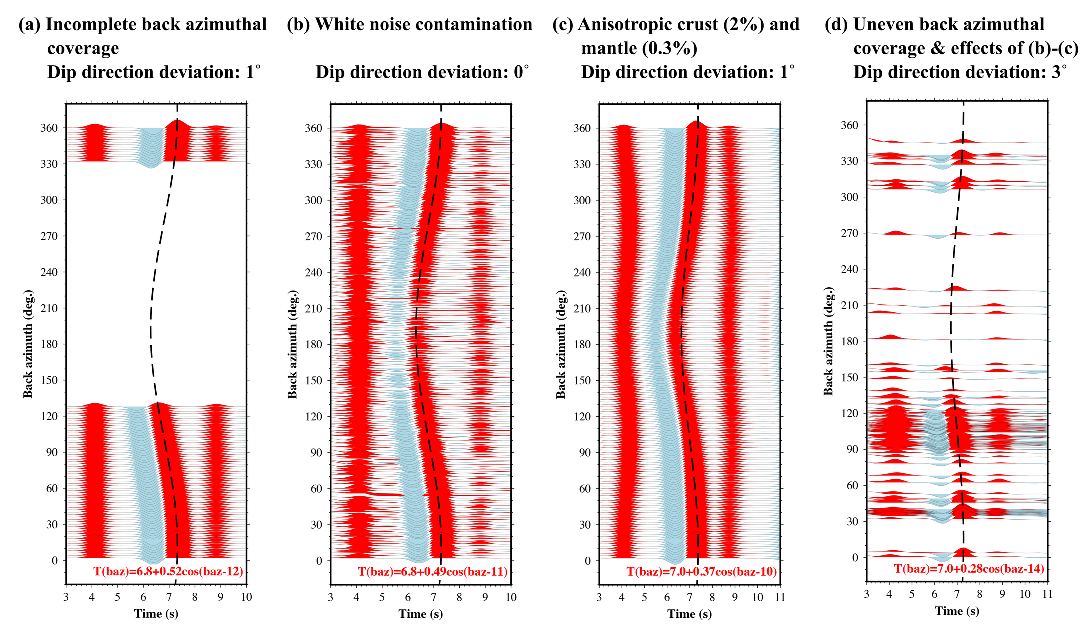


Figure 3: *(a) Synthetic model of subducting oceanic crust. **(b)** Synthetic RF waveforms and the best fitting harmonic functions. **(c)** Grid search works well to estimate the dip direction, with deviation of only 1°.*

Dip direction searching shows high robustness

Figure 4: *DDS is valid in the cases of incomplete or uneven back azimuthal coverage, white noise, crustal and mantle anisotropy (<~5-10%), and their compound effects. DDS provides high resolution of dip direction estimations with biases of only several degrees.*



Application in the Sumatran subduction zone

A dipping low velocity layer with dip directions constrained by DDS

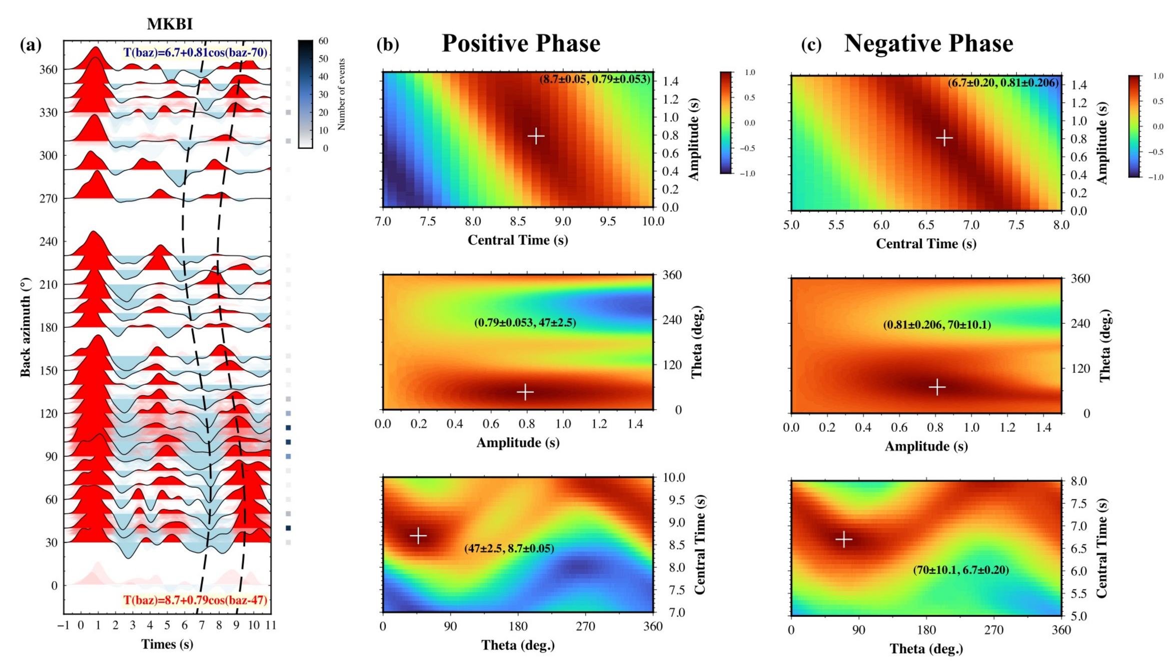


Figure 5: **(a)** A pair of negative-positive phases are well fitted by a harmonic function beneath five broadband seismic stations, indicating *a dipping low velocity layer (LVL)*. MKBI is a representative station. **(b-c)** The harmonic variations provide dip direction estimations for two dipping interfaces reflected by the pair of phases.

Dip directions are consistent with Slab2 and estimates of other methods

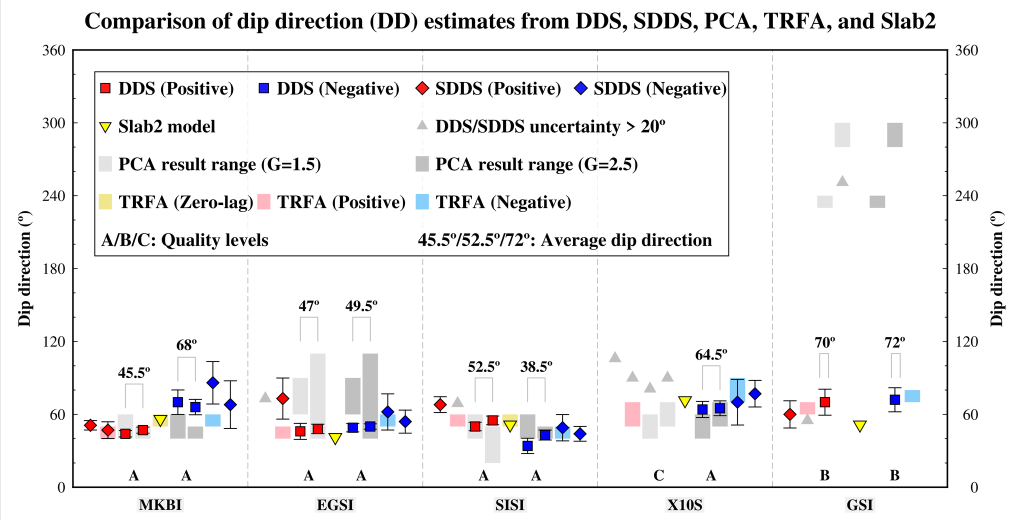
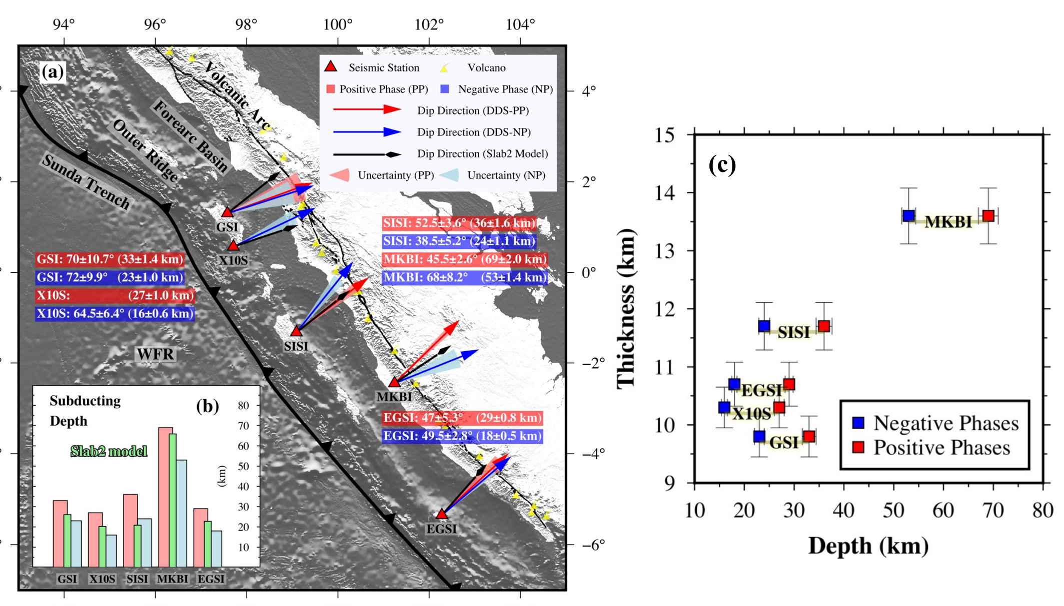


Figure 6: Dip directions estimated using the negative and positive phases are consistent with the Slab2 model (Hayes et al, 2018), suggesting the LVL is associated with the subducting slab. The DDS estimates are also consistent with dip directions estimated using other approaches (i.e., transverse RF analysis (TRFA) and principal component analysis (PCA); Zhang et al., 2019) and DDS estimates using different frequency and different stacking strategy. Post-stacking dip direction searching (SDDS) is DDS applied to RFs stacked in back azimuthal bins.

Unparallel boundaries and abnormally large thickness are found at the dipping low velocity layer

Figure 7: **(a)** The upper and lower boundaries of the LVL are parallel in northwestern and southeastern Sumatra, but unparallel in central Sumatra, with a discrepancy of dip directions of ~14-23°. **(b)** Slab top surface (from Slab2) is located almost between the LVL boundaries. **(c)** The LVL thickness is estimated at 10-14 km, which is larger than the thickness of a normal oceanic crust (~6-7 km). The LVL thickness increases with the increase of subduction depth.



Both the oceanic crust and a partially serpentinized mantle layer compose the dipping low velocity layer, suggesting a diffuse plate boundary

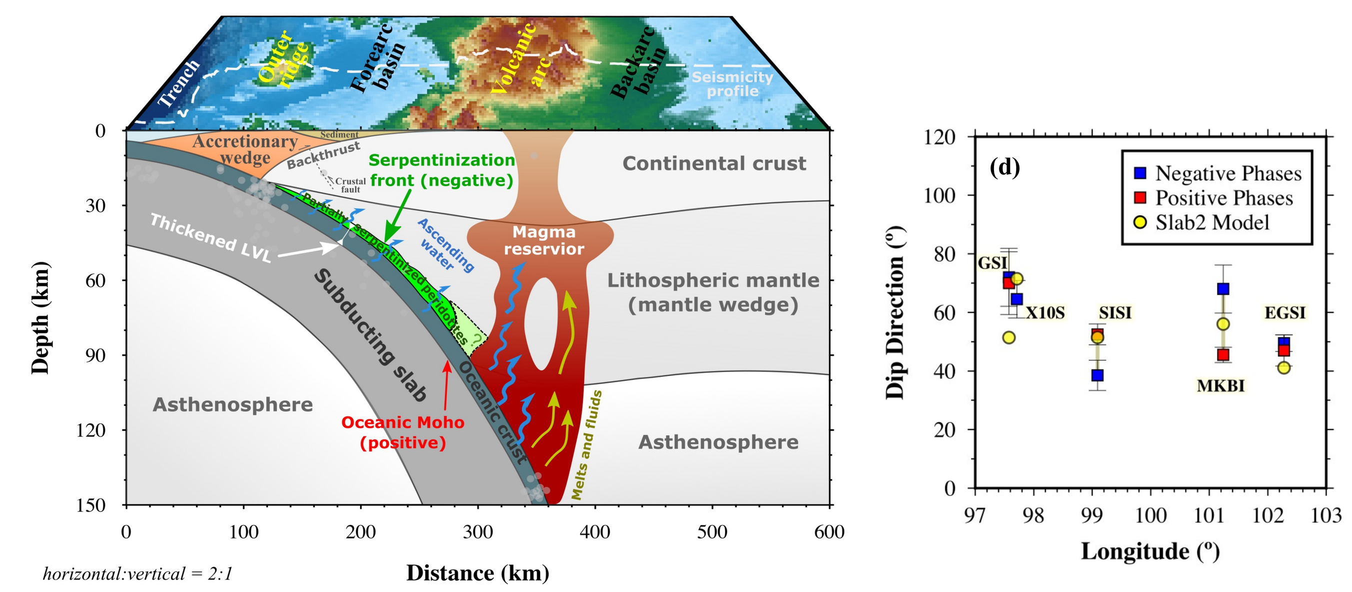


Figure 8: **(a)** The abnormally thick LVL is interpreted as both the oceanic crust and a serpentinized layer at the bottom of the mantle wedge. Partial serpentinization of peridotites makes the velocity contrast between the slab crust and the mantle wedge unsharp and unobservable in RFs. Thus, the positive and negative phases indicate the oceanic Moho and the front of mantle serpentinization, respectively. **(b)** The dip direction of the whole slab could be represented by the dip direction of the less deformed oceanic Moho, which gradually varies along the trench. This phenomenon suggests strong internal slab deformation, which would be caused by the oblique subduction or fossil ridge subduction.

Limitations and future studies

- While robust, DDS is applicable only when the back azimuthal variation pattern of RFs is clear, and when the crustal-mantle anisotropy is <~5-10%. For a better dip direction estimation, DDS should be combined with waveform modeling and harmonic decomposition.
- The LVL thickness is calculated using velocity models of a normal oceanic crust. Further studies will scrutinize the Vp/Vs of the LVL to better resolve the trade-off between the thickness and Vp/Vs.

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References: Singh et al., 2011, DOI: 10.1038/ngeo1119; Liu et al., 2021, DOI: 10.1029/2020JB020169; Yuan et al., 2000, DOI: 10.1038/35050073; Zhang et al., 2019, DOI: 10.1007/s11430-018-9341-9; Hayes et al., 2018, DOI: 10.1126/science.aat4723

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