Upper Mantle Deformation Patterns beneath Northeast India from Shear-Wave Splitting Analysis

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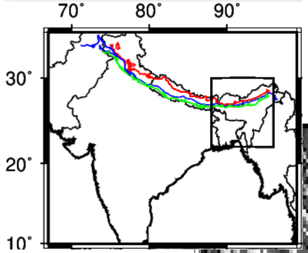
Introduction

Study Region:Northeast India

- This study investigates the deformation of the Earth's crust and upper mantle from Northeast India.
- The region bounded between Eastern Himalaya foothills from north, Indo-Burman subduction ranges from the east, and Bengal basin from the south.
- The Indian plate collision with Eurasia gave rise to the most spectacular tectonic event on Earth i.e. formation of Himalaya, with this study we, therefore, gain unprecedented insight on the structure of NE fringe of Himalaya along with other surrounding entities.

Distance range	80º-130º
Magnitude range	6 and above
Total No. of events	341
Data Duration	2016-2019



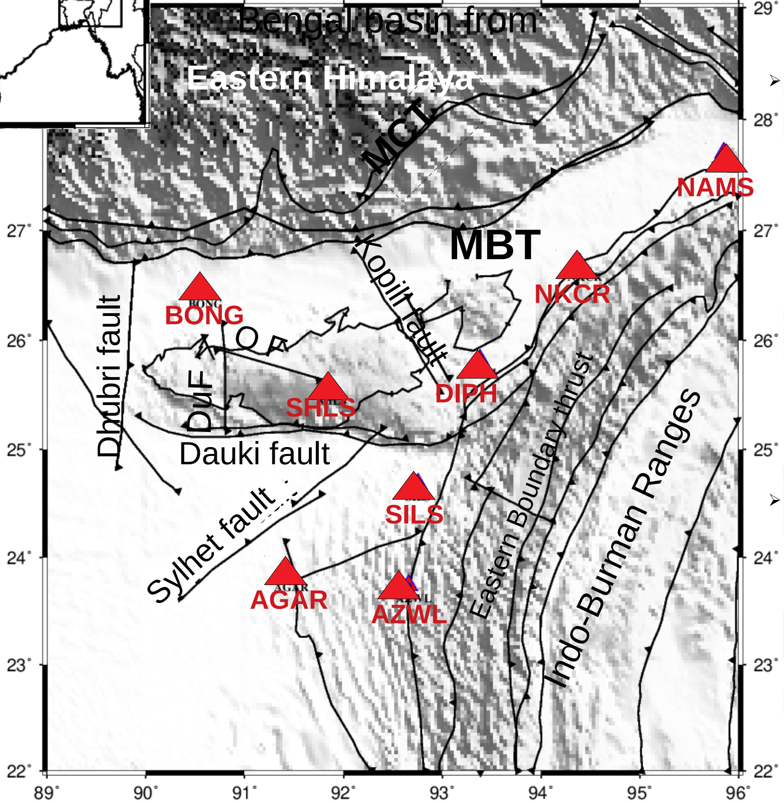


Figure:The topographic map of Northeast India showing major tectonic units. Red rectangles are the stations used in this study operated by IIG Mumbai

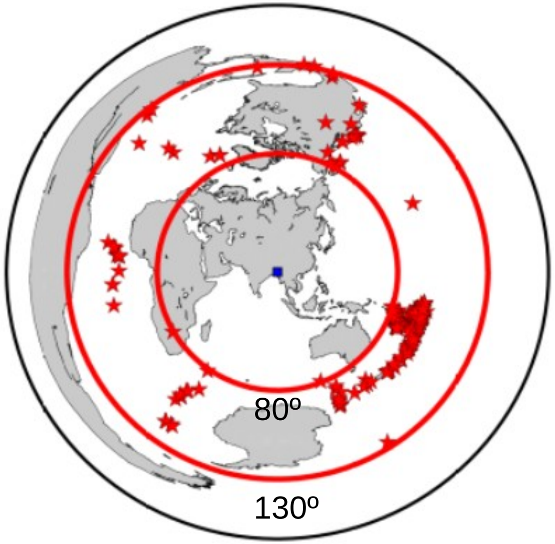
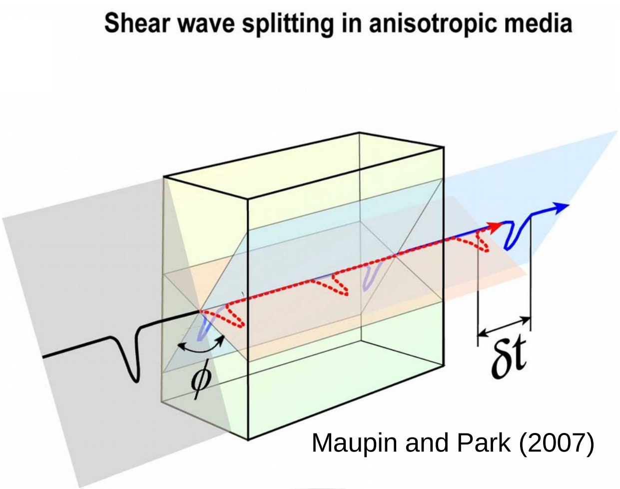
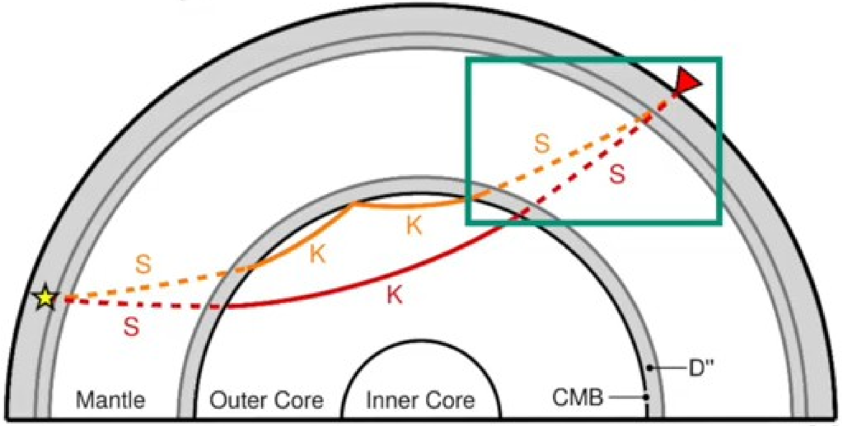


Figure 2: Red stars are the events used in the study.

Shear-Wave Splitting



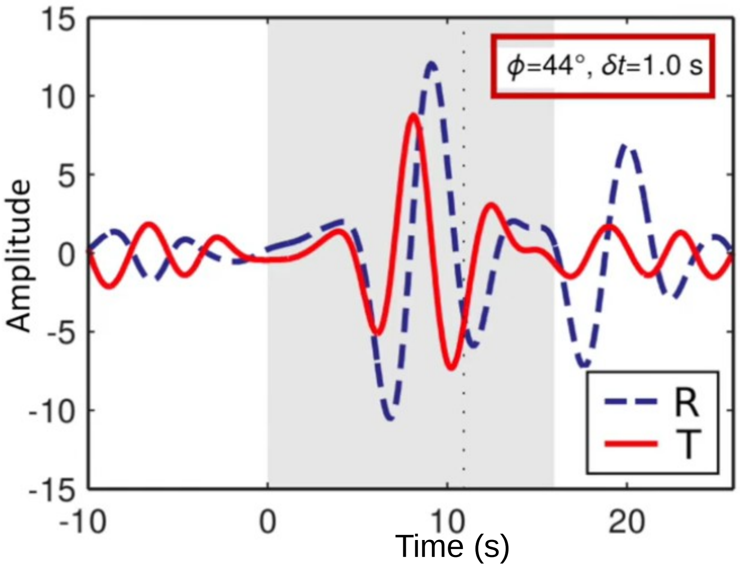
Maupin and Park (2007)



Grund and Barth (2019)

Fast polarization direction (FPD)(ϕ): Polarization direction of the medium in which S-wave travels faster.

Delay time (δt): Time difference between fast and slow travelling S-waves



Grund and Barth (2019)

Ref: Basic Geophysics: Shear Wave Splitting, https://www.youtube.com/watch?v=T2zhwg8kgpM

Splittings Results

Null Results

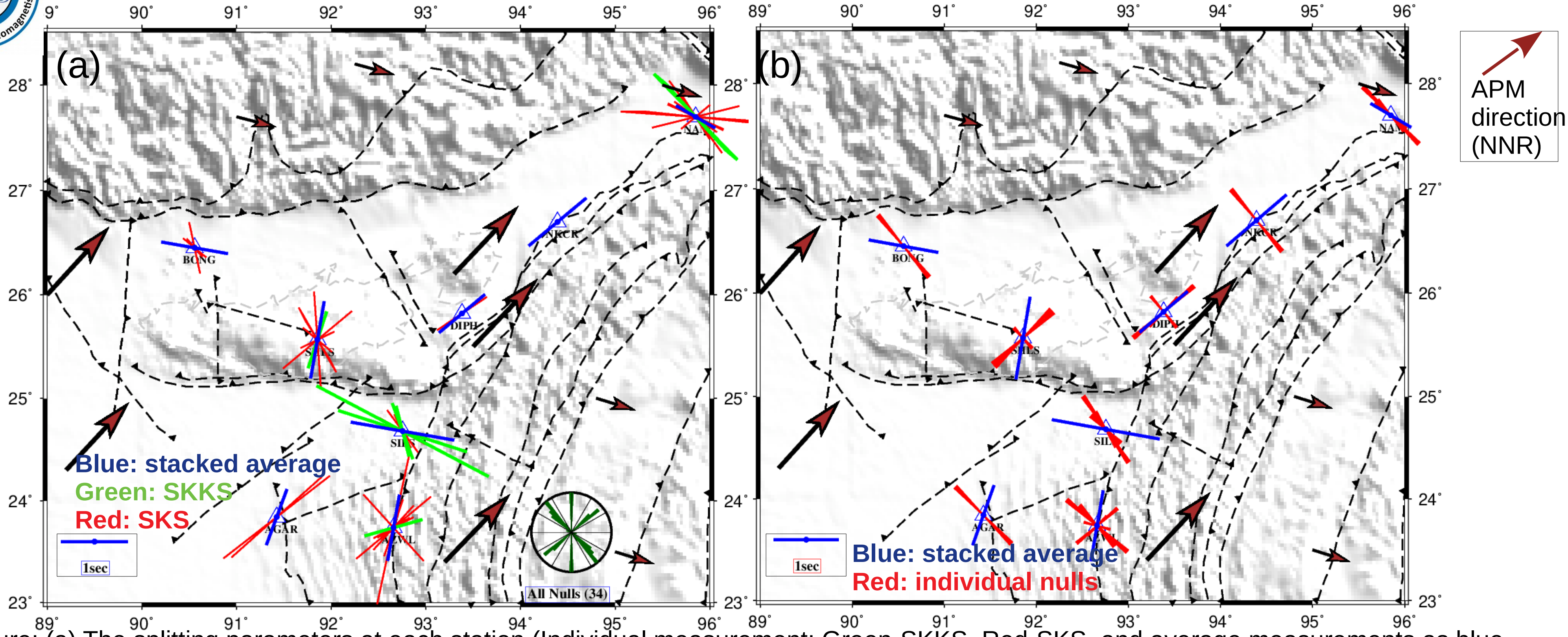
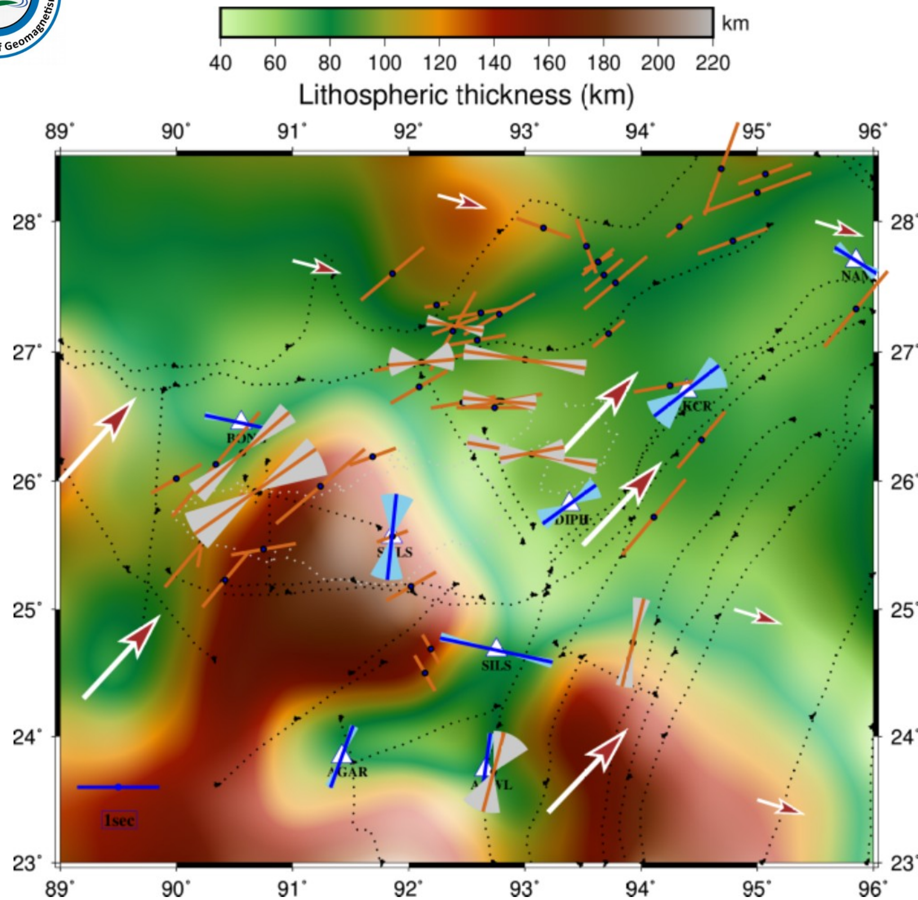
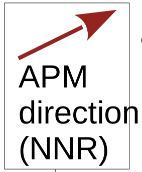


Figure: (a) The splitting parameters at each station (Individual measurement; Green-SKKS, Red-SKS, and average measurements as blue bars) Each bar is oriented along the fast polarization direction (FPD) and its length is proportional to the amount of delay time. (b)The station wise null measurements plotted as red bars. Station averaged splitting results (blue bars) are also plotted over the station to ease the comparison of splitting and null results. Various regional thrust/faults are plotted as dotted lines with triangles. Arrows represents the APM (absolute plate motion) directions in a no-net-rotation (NNR) frame (NUVEL-1A, DeMets et. al.,1994).

- Stations having **equivalent** null and fast polarisation directions: NAMS, NKCR, DIPH, AGAR
- Stations having a **difference** between null and fast polarisation directions: SHLS, BONG, SILS, AZWL

Apparent (Composite) Splitting Results along with Prior Anisotropic Studies





- Composite splitting results were calculated using the Wolfe and Silver (1998) stacking method.

Figure: Composite results; our results are as a blue bar with sky blue fan as their associated errors. Others are composite splitting results (brown bars) from Singh et. al. (2006), Roy et. al. (2014), and Saikia et. al. (2018) with available error information (gray fans).

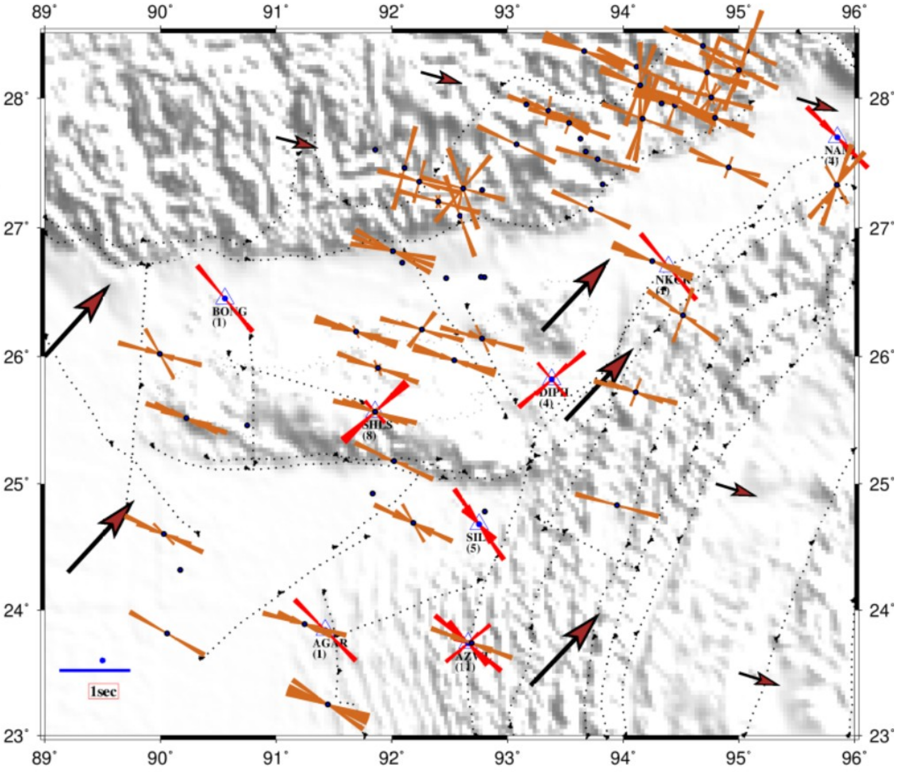
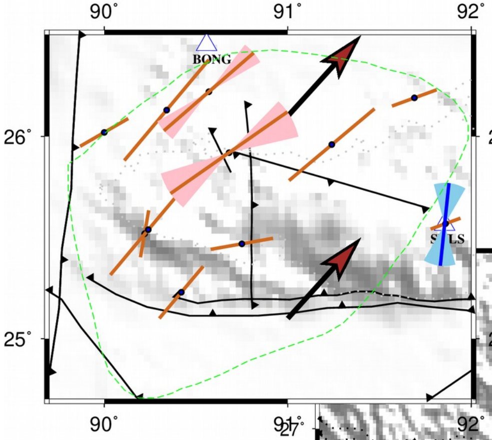


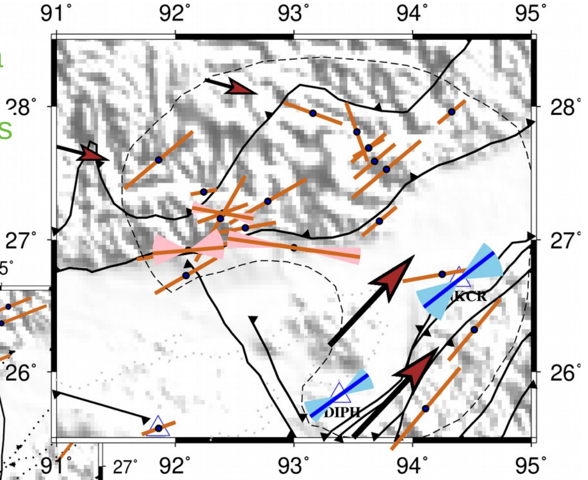
Figure: Nulls were plotted from Roy et. al. (2014), and Saikia et. al. (2018) as brown bars, our null measurements are as red bars.

- **No Uniform alignments of FPDs.**
- **Effect of local geology is evident on FPDs**

Lithospheric Thickness and FPDs

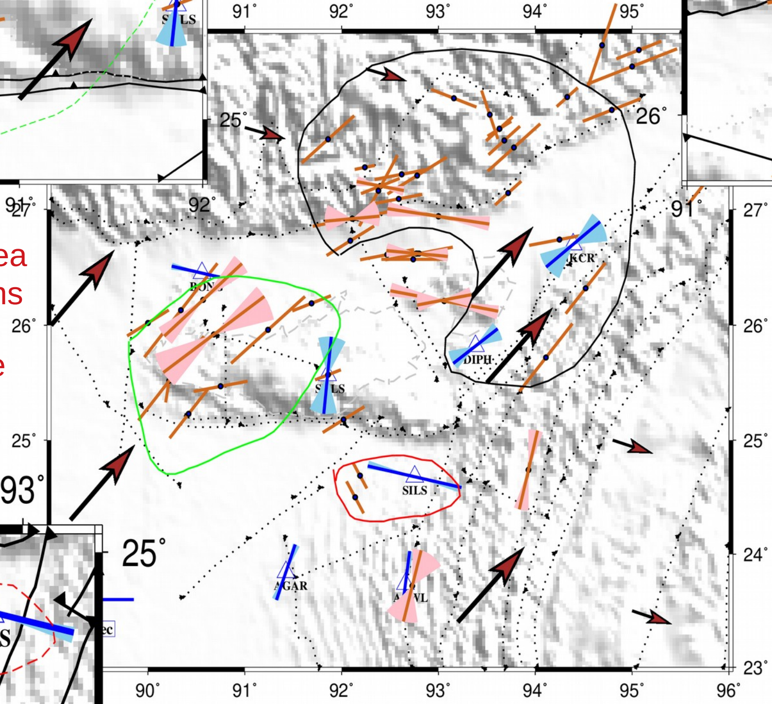


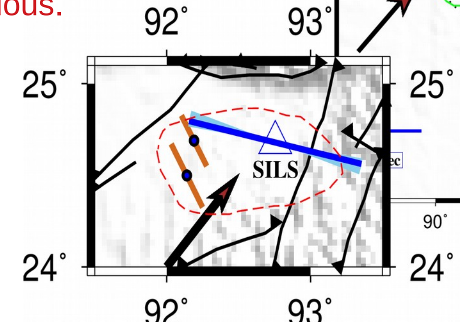
Green line polygonal area lithospheric thickness is deep (~180 km) and FPDs are following APM direction.



Black line polygonal area this has shallow lithosphere (~70-80 km) and FPDs are following the local geological units.

The Geomagnetism area marked by Red line polygons are the transition zone between deeper lithosphere and shallower lithosphere and FPDs direction are ambiguous.





Black line polygon: FPDs are following the direction of local geological features (thrust and faults).
Green line polygon: FPDs are following the APM directions.
Red line polygon: FPDs are neither in APM direction nor in the direction of local tectonic units.

- **Various deformation processes active in different regions**

Results

- The study provides a piece of evidence for the complex deformation pattern of the upper mantle in Northeast India.

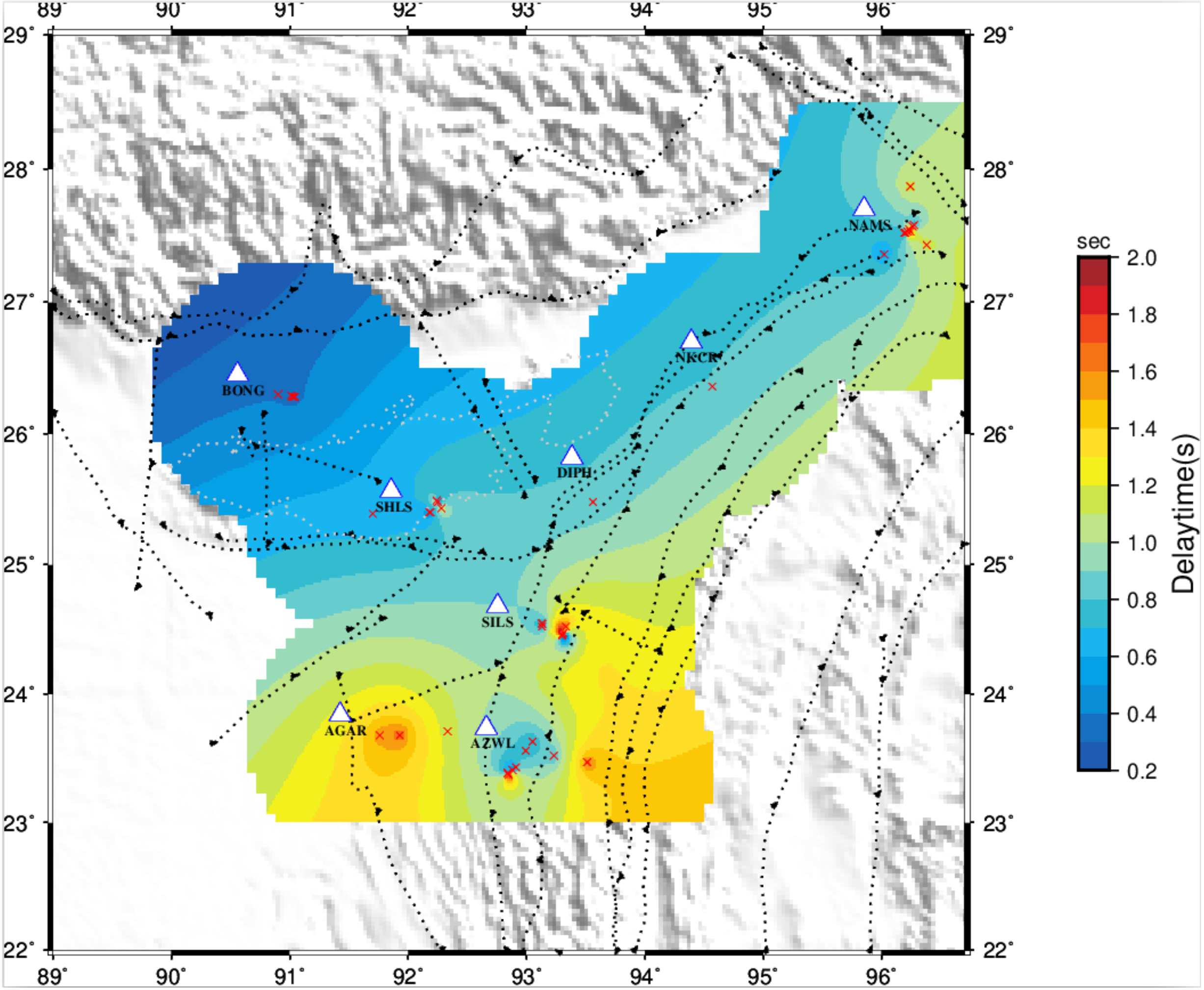
- The direction of anisotropy is nearly E-W at BONG, NE-SW in the Indo-Burman subduction zone, nearly N-S on Shillong plateau and NW-SE at eastern syntaxis of the Himalaya.

- The Source of anisotropy in the Himalaya collision boundary is the result of lithospheric deformation due to finite strain induced by collision. Small delay times in these regions also indicate the strain in the lithosphere

- In the Shillong plateau and Indo-Burman subduction boundary, the source of anisotropy seems to be the asthenospheric flow-related strain which is also in harmony with the absolute plate motion (APM) of the Indian plate in a no net reference frame. Higher delay time indicates the anisotropy from the asthenosphere.

- Strong back azimuth dependence and difference between null and apparent directions indicate more than one layer of anisotropy.

Delay times distribution at pierce point (200 km)



- The Region is characterized by variable delay times, ranging from 0.2s to ∼1.8 s, implying the presence of a well-developed anisotropy within the study area.
- Larger values of delay time are close to the complex regional fault/thrust systems at and around the Indo-Burman folds.

Figure: Map of linear interpolation of delay time plotted as a continuous surface plotted on the topographic map of the region with various fault/shear zones. The red crosses are ray piercing points plotted above the 200km.

Depth of Anisotropic Layer

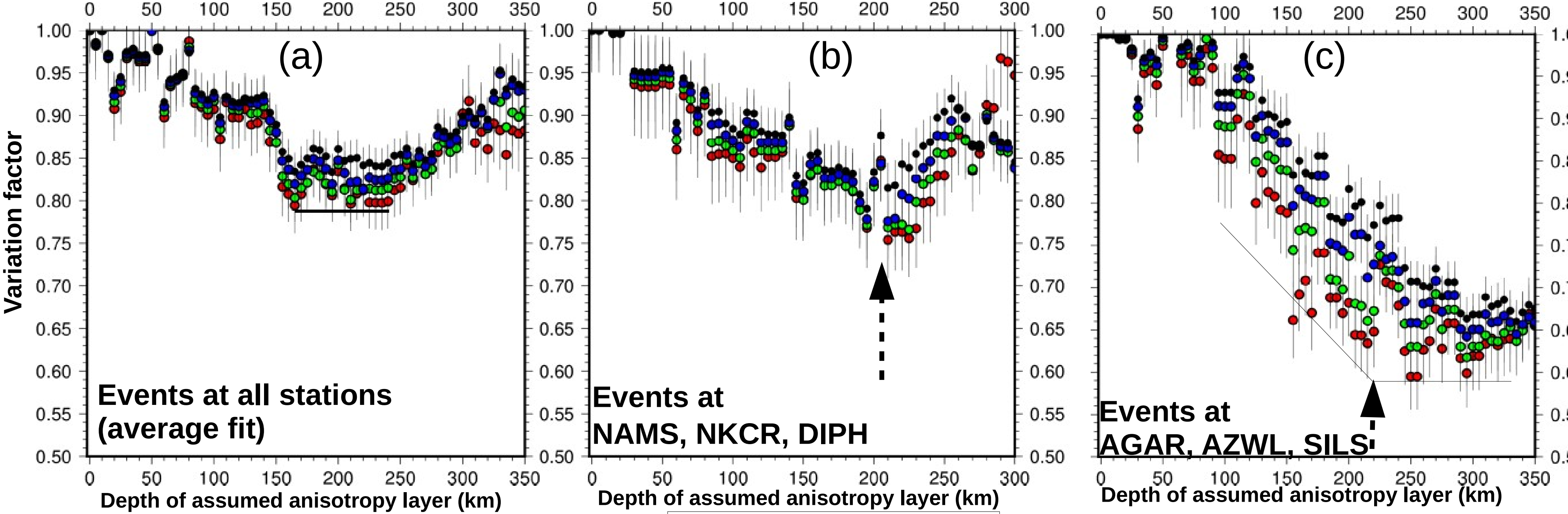


Figure: Spatial variation factors plotted against the assumed depth of anisotropy for shear wave splitting measurements (a) including data from all stations. When considering data from all stations, no clear minima (black bar at (a)) was found for variation factor value, because it averaged out all the different geological provinces. Therefore stations are grouped according to different geological condition, (b) group 1, areas around stations AGAR, AZWL, and SILS, arrow indication clear minima around 205 km, (c) group 2, areas around stations DIPH, NAMS, and NKCR, local minima is at around 220 km and variation factor values follow L-shaped curve.

- **Single layer seismic anisotropy seems to have originated at asthenosphere depth**

- The depth of the anisotropic layer was calculated using the spatial Coherency of splitting parameters (Liu and Gao 2011).
- The optimal depth of the anisotropic layer corresponds to the minimum Variation factor.
- The resulting optimal depth of the anisotropic layer is 205 km in the areas beneath the stations' AGAR, AZWL, and SILS at Bengal-basin and adjoining part of Indo-Burman folds, and 220 km for the DIPH, NKCR, and NAMS stations at Indo-Burman folds and Eastern Himalayan syntaxis.

Test results for two-layer anisotropy

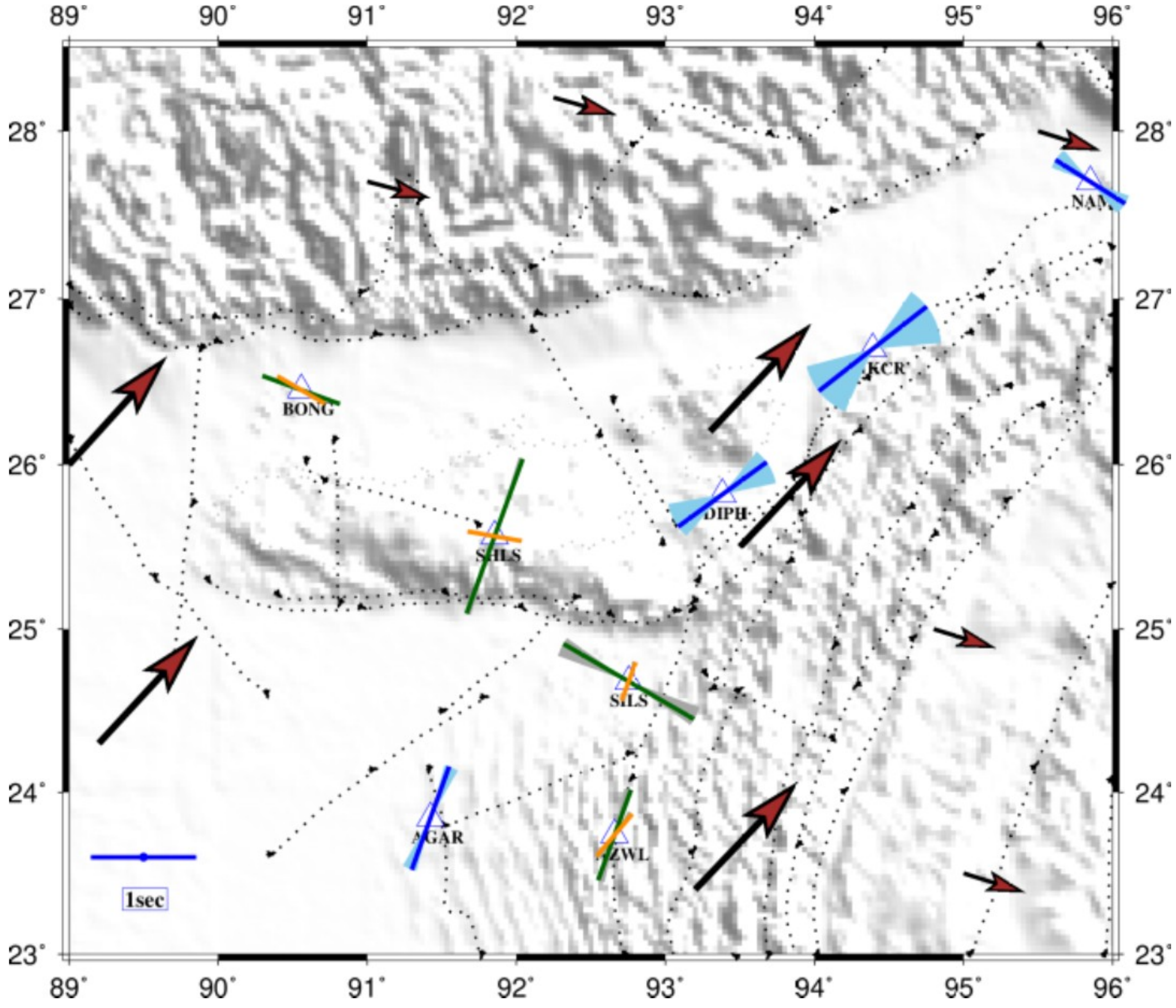
Station	Apparent (ϕ, δt)	Lower-layer (ϕ_L, δt_L)	Upper-layer (ϕ_U, δt_U)
BONG	(-78±3.5, 0.8±0.2)	(-69, 0.6)	(-60, 0.3)
AZWL	(8±2, 0.9±0.1)	(15±3, 0.7)	(35±5, 0.4)
SHLS	(6±15, 1.05±0.3)	(18, 1.2)	(-84, 0.4)
SILS	(-78±1.5, 1.4±0.2)	(-63±5, 1.1±0.1)	(18±5, 0.3±0.1)

- **Weak anisotropy in the Upper layer and strong anisotropy in the lower layer**
- **FPDs of the strong anisotropic layer are almost complying with apparent (composite) single layer FPDs.**

No fit found for below stations

	Apparent (ϕ, δt)
AGAR	(20±5, 0.8±0.1)
DIPH	(54±13, 0.8±0.1)
NKCR	(52±17, 0.8±0.4)
NAMS	(-58±10, 0.6±0.2)

Lithospheric deformation and/or asthenospheric flow?



- Two deformations processes are speculated to be operative at stations supporting two-layer anisotropy.
- Upper (Weak) layer, anisotropy in the lithospheric mantle.
- Lower (strong) layer; anisotropy in asthenospheric flow.

Figure: Shear wave splitting results supporting two layers of anisotropy beneath the stations; BONG, SHLS, SILS, and AZWL. At these stations, orientation and length of orange and dark green bars correspond to the upper layer and lower layer fast polarisation direction and delay times, respectively. Blue bars are the apparent station-averaged measurements supporting a single layer of anisotropy. The black arrows represent the APM (absolute plate motion) directions in a no-net-rotation frame (NUVEL-1A, DeMets et. al.,1994).

Conclusions

- Measurements in the Northeast Indian region reveal systematic spatial variations of splitting parameters.
- The Source of anisotropy is mostly in the upper asthenosphere or in the transition layer between the asthenosphere and lithosphere.
- At Indo-Burman arc the observed spatial pattern of anisotropy may be explained by trench/fault parallel flow in the mantle wedge driven by eastward subduction of the Indian plate.
- Measurements also support multiple anisotropic layers at stations located at Himalayan foothills, Shillong plateau, and SILS and AZWL stations at Indo-Burman arc.
- The anisotropic signature of the upper layers at these regions is may be due to structural induced fossil anisotropy from older episodes of deformations with weak anisotropic strength.
- While the lower layer supposed to be anisotropic due to the LPO of anisotropic minerals resulting from asthenospheric flow mantle.
- The upper layer seems to be dragged by the lower layer. The old LPO signature in the upper layer remains constant and active anisotropy is effective due to motion in the lower layer. The lower layer anisotropic fast directions exhibit the active plate motion direction.

References:

- DeMets, C., Gordon, R.G., Argus, D.F., Stein, S., (1994), Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. Geophys. Res. Lett. 21 (20), 2,191–2,194. https://doi.org/10.1029/94GL02118.
- Grund, M. & Barth, A., (2019), Basic Geophysics: Shear Wave Splitting. https://www.youtube.com/watch?v=T2zhwg8kgpM.
- Singh, A., Kumar, M.R., Raju, P.S., Ramesh, D., (2006), Shear wave anisotropy of the northeast Indian lithosphere. Geophys. Res. Lett. 33, L16302. https://doi.org/10.1029/2006GL026106.
- Saikia. D., Kumar. M. R., Singh. A., and Lyngdoh A.C., (2018), Mantle Deformation in the Eastern Himalaya, Burmese Arc and Adjoining Regions. Geochemistry, Geophysics, Geosystems, 19, 4420–4432. https://doi.org/10.1029/2018GC007691
- Roy, S., Kumar, M., Srinagesh, D., (2014), Upper and lower mantle anisotropy inferred from comprehensive SKS and SKKS splitting measurements from India. Earth Planet. Sci. Lett. 392, 192–206. https://doi.org/10.1016/j.epsl.2014.02.012.
- Liu, K.H., Gao, S.S., (2011) Estimation of the depth of anisotropy using spatial coherency of shear-wave splitting parameters. Bull. Seism. Soc. Am. 101 (5), 2,153–2,161. https://doi.org/10.1785/0120 100258.
- Silver, P., Savage, M., (1994), The interpretation of shear-wave splitting parameters in the presence of two anisotropic layers. Geophys. J. Int. 119 (3), 949–963. https://doi.org/10.1111/j.1365246X.1994.tb04027.x.
- Wolfe, C. J., and Silver, P. G., (1998), Seismic anisotropy of oceanic upper mantle: Shear wave splitting methodologies and observations, J. Geophys. Res., 103, 749 – 771.

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Thank you!