

Reply Letter

Mantle Deformation Patterns Beneath the Central India Tectonic Zone: Evidence from SK(K)S Splitting Measurements in the Satpura Gondwana Basin and Adjacent Areas

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We would like to thank the Editor and reviewers for their insightful and constructive comments, which helped us in improving the quality of the paper. We have prepared the revised version of the manuscript by carefully taking into account the suggestions and comments from the reviewers. Below, we provide specific responses to the queries and concerns expressed by the reviewers and list the corresponding modifications made to the manuscript for the revised version.

Comments from Reviewer 1

Comment 1: I'm not very convinced by the reasons to associate the source of anisotropy with lithospheric and asthenospheric contribution. What I see in Figure 10 and what you explain in the text is that FPD, APM and GPS velocity are in agreement, and what I could think is that the deformation could occur on the entire volume from crust to upper mantle. This, in my opinion, is reasonable, but it is not clear why you associate so strictly the litho and asthenospheric contributions if all the directions are in agreement. How can you say that the deformation doesn't occur entirely in the asthenosphere? or completely in the lithosphere? How could you distinguish between these contributions only by comparing the vectors' direction? I think that a more detailed motivation and analysis about this issue could strengthen the whole interpretation of the results, which I would repeat, seems to be reasonable for me too.

Response: We appreciate the reviewer emphasizing this point. SK(K)S splitting measurements at any seismic station provide the integrated seismic anisotropy of the crust and upper mantle. The

origin of the anisotropy in SK(K)S splitting studies is commonly thought to originate in the upper mantle given the dominance of the dislocation creep deformation mechanisms there, which creates LPO of the intrinsically anisotropic minerals olivine and orthopyroxene. Typically, olivine aligned along the shearing direction is considered to be the major contributor to mantle anisotropy (Silver, 1996). Crustal anisotropy (e.g., Silver & Chan, 1991; Boness & Zoback, 2006), anisotropy in the transition zone (e.g., Tong et al., 1994; Fouch & Fischer, 1996), and anisotropy in the D'' layer (e.g., Vinnik et al., 1995; Kendall & Silver, 1996; Garnero & Lay, 1997) of the lower mantle also contribute to the measured SK(K)S wave splitting, but their potential contribution is usually negligible in comparison to the upper mantle anisotropy. Seismological and petrological findings suggest that most of the anisotropy is limited to the olivine stability field (i.e., down to about 400 km depth) and is most prominent above about 200 km depth (e.g., Karato, 1987; Karato et al., 1995; Meade et al., 1995).

Typical splitting delay time values for crustal regions documented so far do not exceed 0.3 s (Barruol & Mainprice, 1993), which is significantly lower than the SK(K)S-derived average split delay times for the study region. Barruol & Mainprice (1993) quantitatively constrained the crustal contribution to SK(K)S delay times by modeling the elastic properties of typical crustal compositions and petrofabrics, and establishing that even strongly foliated crustal rocks contribute no more than 0.1 s per 10 km of anisotropic path. A typical crustal thickness of ~40 km under the CITZ (as constrained by receiver function studies in the region) results in a maximum crustal contribution of ~0.3-0.4 s.

Furthermore, Silver & Chan (1991) reported that the lithospheric mantle alone would cause a delay time of 0.04-0.2 sec. The observed delay times at our stations, which exceed 1.0 s at several stations, therefore cannot be attributed only to the lithosphere. This establishes a strong lower limit, implying that the excess delay time, which cannot be explained only by the crust and lithosphere mantle, necessitates a contribution from the sub-lithospheric layer.

Additionally, pure asthenospheric flow is also insufficient on its own, because if the anisotropy were entirely asthenospheric (i.e., purely APM-driven), the FPDs would be expected to align uniformly and exactly with the APM direction across all stations (Vinnik et al., 1992), which is not the case. At 5 out of 9 stations, angular deviations between FPD and APM exceed 10°, reaching up to ~35° at stations located near major geological boundaries of the CITZ. Seismological studies have indicated that the deviation in the FPD from the APM direction may reflect deformation originating within the lithosphere, particularly in regions with layered anisotropy corresponding to multiple deformation episodes (Link & Rumpker 2023).

The correlation between seismic anisotropy and geodetic measurements (APM and GPS vectors) provides an indirect indicator for comprehending deformation mechanisms in the crust and upper mantle. GPS measurements are related to upper crust deformation (Chen et al., 2013), whereas APM primarily concerns the upper mantle (Kreemer, 2009). The discrepancies between SK(K)S-wave-derived FPDs and GPS data imply that deformation patterns vary across the crust and upper

mantle. The absolute difference between FPDs and APM directions accounts for frozen-in lithospheric anisotropy and the mantle flow pattern related to the shearing of the asthenosphere at the base of the lithospheric plate. Overall, we conclude that the APM velocity of the Indian plate mostly aligns with the splitting parameter to the best approximation; however, some discrepancies remain in the FPD orientation and Indian plate APM direction. Their similarities and discrepancies suggest that seismic anisotropy is associated with both lithospheric and sub-lithospheric dynamics.

We have modified our discussion section in the revised manuscript accordingly.

Comment 2: In several parts of the paper, the authors attest to the complexity of the anisotropic structure of the area (for example, line 184 "the splitting data may indicate a multilayered anisotropic structure"). These sentences should be justified through complex-layer modelling or classical FPD versus BAZ plots that software such as SplitLab could execute, but in no part of the paper is this shown or discussed. Apart from the software, there are several techniques to analyse the data trying to understand the presence of two anisotropic layers beneath a station, as the analysis of Fresnel Zones, the orientation of FPD based on back-azimuth or the comparison with other data as Pn data (sampling anisotropy in the shallower part of the upper mantle) and so on, just to be more precise on what you are saying in the interpretation.

Response: We thank the reviewer for this critical and valuable suggestion. We agree that rigorous two-layer anisotropy modelling will be effective in demonstrating our interpretation. However, as shown in Figure 7c, our splitting measurements are primarily concentrated within a backazimuthal range of 90° to 120° , a constraint imposed by India's geographic position relative to the global distribution of large teleseismic earthquakes at appropriate epicentral distances. This narrow window is a well-documented limitation of SK(K)S splitting studies on the Indian subcontinent (Rao et al., 2013; Roy et al., 2014).

The backazimuthal variance of individual FPDs seen at all seismic sites (Figure 7c in the revised paper) suggests the presence of two-layer anisotropic layers. However, the quantity of high-quality SKS observations per station in our dataset is relatively limited. Our backazimuthal coverage has also been limited (Figure R4) (Supplementary Figure S2 in the revised manuscript). Constructing meaningful XY backazimuth plots necessitates dense and well-distributed backazimuthal sampling, ideally covering at least 180° with enough event density in each bin, which we don't have across all stations in our network. Splitting parameters for two layers of anisotropy modeling, whether at individual stations or station groups, may only be read correctly if their variation with backazimuth follows a distinct 90° periodicity (Silver & Savage, 1994; Savage, 1999). Ritter et al. (2022) and Frohlich et al. (2024) have explicitly demonstrated that when measurements are concentrated in a narrow backazimuthal range, layered models produce statistically indistinguishable fits (which we have also encountered when we tried doing it), making unique

structural determination impossible. Presenting such plots for stations with sparse or uneven backazimuthal coverage increases the risk of over-interpreting artifacts arising from poor sampling rather than genuine anisotropic complexity. Therefore, two- or multilayer anisotropic models cannot be robustly applied to our dataset, and we acknowledge this as a fundamental limitation.

It is well understood that SK(K)S splitting measurements have poor depth resolution. Furthermore, to add depth constraints to the observed SK(K)S splitting parameters, we performed a Fresnel zone analysis using the spatial coherency analysis of the high-quality SK(K)S splitting data (Liu & Gao, 2011; Gao & Liu, 2012). In the case of steep incident angles (SKS and SKKS phases), the ray-path data is used to compute the ray-piercing point at any imagined depth of the anisotropic layer. The mean splitting information is then computed within the Fresnel zone, with the ray-piercing point at the center. Figure R6 (Supplementary Figure S4 in the revised manuscript) shows the piercing spots at 50, 100, 200, and 300 km depths. The spatial distribution of ray-piercing points exhibits progressive lateral migration with increasing depth, which is consistent with the expected geometry of steeply incident SK(K)S raypaths. The variation factor is computed as the weighted sum of the circular mean of the FPDs and the arithmetic mean of the splitting time delays. The depth value with the lowest variation factor was chosen as the best depth of anisotropy. The variation factor was calculated at each depth for block sizes ranging from 0.05° to 4.0° , with an incremental interval of 0.05° . Figure R7 (Figure 11 in the revised manuscript) depicts the variation factor with varying anisotropic depth for block sizes of 0.30 and 0.35, indicating that 235 km represents a promising average depth of anisotropy. This depth range is consistent with a sublithospheric, asthenospheric source of anisotropy, suggesting that mantle flow at asthenospheric depths, rather than frozen lithospheric fabric, is the primary driver of the observed shear-wave splitting. Our study found that the variation factor curve gradually flattens beyond ~ 235 km, indicating that the technique's sensitivity decreases as depth increases and ray-piercing point separations become larger than the spatial scale of anisotropy variations.

We have now revised the texts accordingly.

Comment 3: Another issue that I would raise in this review is the use of the single shear wave splitting result. Why didn't you use or plot the null measurements? Especially where you have an asthenospheric upward, the amount of nulls should be consistent since the waves don't split horizontally, so this information could be useful in the region where the dykes occur. On the other hand, the discrepancy between SKS and SKKS directions should be an indication of a deformation that possibly occurs in the deeper part of the mantle, so a comparison of them could help the authors to discriminate better the source of anisotropy, confirming/not confirming their hypothesis.

Response: Thank you for this valuable suggestion. We have now rigorously checked our dataset for null measurements and found just 6 null measurements (4 at SG02 and 2 at SG09) for the entire dataset.

Null splitting measurements, which show negligible tangential (SH) energy, may occur in three situations. The first occurs when no anisotropy is encountered and the initial SV polarization of the SK(K)S phases is unaffected by anisotropy. It appears practically impossible that any tectonic plate is isotropic in nature. Second, if the region is isotropic in nature due to complex anisotropy (multiple horizontal anisotropic layers with different fast polarization directions). Third, if the initial SV polarization is similar to that of the slow/fast anisotropy axis, the shear wave will not be split into two quasi-S waves (Saltzer et al., 2000; Barruol et al., 1997; Wusterfeld et al., 2008). Figure R2 (Figure 6 in the revised manuscript) shows an example of a null measurement at the SG02 seismic station, in which particle motion before and after correction coincides and aligns linearly with the back-azimuth. In such cases, the energy of the transverse component is at a minimum.

We observed six null measurements in our dataset, four at the SG02 seismic station and two at SG09. The observed null measurements can be explained by the anisotropic fabric preserved from past orogenic events during the Mesoproterozoic era, substantial magmatism during the Cretaceous period, and northward movement of the Indian plate, which caused shear at the base of the lithosphere. The combined effect of all of these is most likely to result in a vertical anisotropic heterogeneity, which produces the reported null measurements. However, due to inadequate back-azimuthal coverage and a restricted number of SK(K)S splitting measurements, we are unable to model the region's real 3D anisotropy orientation.

Station SG02 has the lowest δt (0.74 sec) value. The lower δt (0.74 sec) and 4 null measurements in the Pachmarhi region (SG02 seismic station) could be attributable to significant magmatism during the Cretaceous era in the Narmada and Tapti graben areas, as evidenced by the presence of dykes near the SG02 station (Shukla et al., 2022). Station SG09 is located close to the DVP. The lower δt (0.74 sec) and 2 null measurements at SG09 may be linked to mantle plume upwelling during the upper Cretaceous to early Paleocene (Krishnamurthy, 2020). Figure R3 (Supplementary Figure 1 in the revised manuscript) depicts a rose diagram of the backazimuthal coverage for the splits (in black) and the nulls (in red) for the SG02 and SG09 stations, demonstrating that the null and split measurements are obtained from different backazimuths, but their numbers are limited, so detailed modelling is the fundamental limitation of this study.

Regarding SKS-SKKS comparisons, we agree that discrepancies between these phases can reveal deeper mantle deformation. However, due to limitations in the number of good splitting measurements and backazimuthal distribution, a systematic comparison was not feasible for our dataset.

We have updated the texts in the revised manuscript accordingly.

Comment 4: In my version of the manuscript, I didn't find any supplementary material. I would encourage the authors to add at least a table with all the measurements obtained to reproduce the results, even for the seismological community working in the area or interested in the use of these data.

Response: Thank you for this insightful suggestion. We have now included Supplementary Table S1, which contains detailed information about the earthquake events (event date, time, longitude, depth, and magnitude), station name, phase information, and shear wave splitting parameters with associated error (ϕ or FPD, FPD error, δt , and δt error) for each splitting measurement.

Minor Corrections:

Comment 5: Line 4 and 104-109: If you don't use the results obtained in the Rotation Correction method, I think you can also remove the description of the method itself. I know that SplitLab calculates in the same run, both the results but at the end, you use only one of the TEM techniques, so you can focus the description only on this. Alternatively, you can also decide to use only the results that give similar results in both cases, strengthening your final dataset with objective choices.

Response: Thank you for your constructive suggestions. We have now revised the texts in the amended manuscript. We included a concise overview of the rotation-correlation (RC) approach for thoroughness but emphasized that our final interpretation relies on the results of transverse energy minimization (TEM). We only used splitting data with consistent splitting parameters (ϕ and δt) across RC, eigenvalue, and TEM methods, with ϕ agreeing within 10° and δt within 0.2 seconds.

Comment 6: What is the hypothesis that the authors prefer? Double-sided subduction? I suppose this from the cartoon in Figure 12, but in the text is not motivated properly.

Response: We thank the reviewer for pointing this out. The SK(K)S splitting observations at any seismic station provide the integrated seismic anisotropy of the crust and upper mantle. Since we did not undertake two-layer or multilayer anisotropy modeling because of the low number of individual splitting data and limited backazimuthal coverage, the SK(K)S splitting observations alone cannot indicate subduction polarity reversal. We already stated in the last paragraph of the

discussion that the current investigation of seismic anisotropy does not provide confirmation of the slab break-off hypothesis. To obtain comprehensive information regarding the detached remnants slab, slab breakoff, and polarity reversal, additional seismological investigations (such as seismic tomography, splitting intensity tomography, receiver function analysis, etc.) are required to elucidate the detailed tectonic framework of the CITZ and the surrounding adjacent regions.

We have now clarified that Figure 12 is a conceptual interpretation based on past tectonic models together with our SK(K)S splitting observations rather than a direct confirmation of the subduction geometry from splitting data alone. In addition, we have included a question mark sign in the conceptual model to indicate the possibility of subduction polarity reversal.

We have now revised the manuscript accordingly.

Comment 7: Lines 85-91: This paragraph seems out of place, but this is only my opinion.

Response: Thank you for the suggestions. We have revised the manuscript accordingly.

Comment 8: Lines 159-160: the presence of complex mantle deformation should be examined in a better way; you can't attest it just in one phrase. The same applies to the presence of lithospheric strain and mantle flow relationships.

Response: Thank you for the constructive suggestion. The discussion on complex mantle deformation and lithosphere-asthenosphere interaction has been expanded and now better clarified in the revised manuscript.

Comment 9: Lines 183-186: As in the previous comment, the presence of the multilayered anisotropic structure should be justified better.

Response: Thank you for the suggestions. The statement concerning multilayered anisotropy has been updated to reflect a more circumspect interpretation, as previously mentioned in the comment. The statement regarding multilayered anisotropy has been revised to reflect a more cautious interpretation in the revised manuscript.

Comment 10: Line 200: DVP states for?

Response: The acronym DVP stands for Deccan Volcanic Province. It is already defined on line 183 of the manuscript.

Comment 11: Lines 200-202: The presence of the mantle plume could also be corroborated by the presence of null measurements.

Response: Thank you for the suggestions. The null measurements that support plume-related interpretations have now been incorporated into the revised manuscript.

Comment 12: Line 209: double citation of SG08

Response: Thank you for pointing this out. The duplicate citation of SG08 has been removed from the revised manuscript.

Comments on Figures:

Comment 13: Figure 1: Please cite the DOI of the NCS network or some references about it. Have the 9 seismic stations recorded with a different DOI?

Response: Thank you for the suggestions. We have now added appropriate references (Roy et al., 2014; Roy et al., 2024). Our nine stations were recorded using different DOIs. Currently, there is no peer-reviewed paper related to this research, and two papers containing this seismic dataset are undergoing review in a peer-reviewed journal. Consequently, we have not yet provided a DOI or paper reference for our nine seismic stations. Table 1 of the manuscript contains the details of each seismic station.

We have modified the figure caption in the amended manuscript.

Comment 14: Figures 2, 8, and 9: In my opinion, these figures are a bit "bare". Filling them with the names of the stations and the faults could help. I think it could also be useful to trace the region where the plumes are present.

Response: Thank you for your constructive suggestions. We have now modified the figures accordingly.

Comment 15: Figure 10: The word "inclination" should be "orientation", don't it?

Response: Thank you for pointing this out. The term “inclination” has been changed to “orientation.”

Comments from Reviewer2:

Comment 1: Tectonic context visualization: The manuscript discusses the CITZ as a major suture between northern and southern Indian cratons, but the figures don't really show this clearly. Figure 1 doesn't explicitly indicate the CITZ or the craton boundaries, so it's hard to see how the sutures or faults relate to the tectonic story. Figure 2 shows a lot of local lithology, supracrustals, granitoids, basins, supergroups, but it's hard to place that in the larger craton-scale context. A wider, simpler, regional tectonic map showing the two cratons, the CITZ, and major faults would help readers connect the field observations to the bigger tectonic picture.

Response: Thank you for your constructive suggestions. We have now modified Figure 1 in the revised manuscript (Figure R1) to illustrate the Craton boundaries and the CITZ suture zone. Figure 2, which displays additional geological features, has been eliminated from the revised manuscript, as it contributed to the complexity of the large-scale tectonic context without effectively communicating it. These modifications improve the connection between seismic observations and the broader tectonic framework.

Comment 2: The authors report performing SKS splitting analyses using both RC and TEM methods. However, the only measurements presented are in Table 1, which shows station-averaged values without uncertainties, making it difficult to assess the quality of the final results. In SKS studies, and generally as best practice, it is expected that all individual measurements be provided. Since the authors used two methods, even if only one forms the basis of their interpretation, the individual measurements, associated uncertainties, and earthquake metadata should be included. Providing these details is essential for evaluating the quality, reproducibility, and reliability of the results and would greatly enhance the transparency and rigor of the study.

Response: Thank you for your insightful suggestion. We have now included Supplementary Table S1, which contains detailed information about the earthquake events (event date, time, longitude, depth, and magnitude), station name, phase information, and shear wave splitting parameters along with associated error (ϕ or FPD, FPD error, δt , and δt STD error) for each splitting measurement.

Comment 3: I strongly suggest that the authors plot individual SKS measurements, similar to what is done for other stations in Figure 3, perhaps using color or symbol size to represent delay times. While rose diagrams (Fig. 8) are valuable, they emphasize quantity and can obscure the actual measurement values and variability. Plots of individual measurements, potentially at chosen piercing points (50, 100 or 200 km for example), could provide insight into the depth and lateral extent of the anisotropy. For example, if two nearby stations record different fast directions from the same earthquake, the overlap of the SKS Fresnel zones can constrain the minimum depth of the anisotropy source (e.g. Alsina and Snieder). Exploring this type of lateral and depth coherence would greatly improve understanding of the anisotropic structure beneath the network.

Response: Thank you for this valuable suggestion. Individual SKS measurements have now been plotted on the top of the spatial delay time map (Figure R5; Figure 8 in the revised manuscript), replacing the rose diagram that almost shows similar results. Figure R6 (Supplementary Figure S4 in the revised manuscript) demonstrates the piercing points at 50, 100, 200, and 300 km depth. The spatial distribution of ray-piercing points exhibits progressive lateral migration with increasing depth, which is consistent with the expected geometry of steeply incident SK(K)S raypaths.

It is well-known that SK(K)S splitting measurements have poor depth resolution. Furthermore, to add depth constraints to the observed SKS splitting parameters, we conducted a Fresnel zone analysis based on the spatial coherency analysis of the high-quality SK(K)S splitting measurements (Liu & Gao, 2011; Gao & Liu, 2012). In the case of steep incident angles (SKS and SKKS phases), the ray-path information is used to calculate the ray-piercing point at any assumed depth of the anisotropic layer. The mean splitting information is thus computed within the Fresnel zone, with the ray-piercing point as the center. The search for anisotropy depth was carried out at 5 km intervals within the depth range of 0-400 km. The variation factor is calculated as the weighted sum of the circular mean of the FPDs and the arithmetic mean of the splitting time delays. The depth value with the least variation factor was chosen as the optimal depth of the anisotropy. The variation factor was calculated at each depth for block sizes ranging from 0.05° to 4.0° , with an incremental interval of 0.05° . The optimum number of splitting measurements and spatial consistency in each block affect the variation factor. Both block-size configurations ($dx = 0.30^\circ$ and $dx = 0.35^\circ$) show consistent behavior, with the variation factor declining steeply from near-surface values (~ 0.95 - 1.0) down to a broad minimum in the 200-250 km depth range before stabilizing at ~ 0.3 - 0.4 for greater depths. Figure R7 (Figure 11 in the revised manuscript) depicts the variation factor with varying anisotropic depth for block sizes of 0.30 and 0.35, indicating that 235 km represents a promising average depth of anisotropy. This depth range is consistent with a sub-lithospheric, asthenospheric source of anisotropy, suggesting that mantle flow at asthenospheric depths, rather than frozen lithospheric fabric, is the primary driver of the observed shear-wave splitting. Our study found that the variation factor curve gradually flattens beyond

~250 km, indicating that the technique's sensitivity decreases as depth increases and ray-piercing point separations become larger than the spatial scale of anisotropy variations. Individual Fresnel zone analysis for each seismic station was attempted, but the split measurements were insufficient to produce an acceptable result.

We have now updated the texts in the revised manuscript accordingly.

Comment 4: Station orientation and horizontal component alignment can influence SKS measurements. Even small misalignments can rotate the observed particle motion, affecting both the fast-axis direction and the split time, potentially introducing systematic errors. The authors could note whether any checks or corrections for station misalignment were applied and discuss how such uncertainties might impact their results. If station misalignment was not assessed prior to SKS splitting results, I believe this can even be done by comparing SKS source polarization with theoretical backazimuths of analyzed earthquakes (like the shown example), so it could be a good post-analysis check as well.

Response: We thank the reviewer for this advantageous suggestion. We performed a post-analysis verification of station orientation using the polarization characteristics of SKS phases. For each event, we manually checked the particle motion before and after splitting correction. In particular, we compared the corrected radial component particle motion to the theoretical backazimuth of the incoming wave.

After applying the splitting correction, the particle motion is expected to align with the source polarization direction, which coincides with the backazimuth (Liu & Gao, 2013; Eakin et al., 2018; Eakin et al., 2019). For all final split datasets, the corrected particle motion projected onto the radial-transverse plane consistently aligns with the theoretical backazimuth (as indicated by the black dotted lines in the third column of Figure 5), confirming that the stations are properly oriented. Any significant misalignment would result in a systematic deviation between the corrected particle motion and the backazimuth as well as increased scatter in the measured fast polarization directions. However, we observe a good agreement between the measured polarization angles and the event backazimuths across all stations, implying that orientation errors are negligible.

We recently evaluated the performance of all broadband seismic stations using power spectral density analysis (PSD) (the related paper is currently being reviewed in the Journal of Seismology). The PSD analysis for all frequency bands reveals that noise levels at all stations consistently meet global noise standards, confirming the quality of recordings.

The magnetic body nearby, sensor installation, and human error in declination calibration primarily influence the orientation of seismic sensors. However, according to the most recent World

Magnetic Model, the magnetic declination value for our study region is minimal (maximum 0.4°) ([NCEI Geomagnetic Calculators](#)). As a result, if there is some error in sensor misorientation, the estimated anisotropy parameters will have small errors. Its impact is expected to be limited to the uncertainty estimate for the splitting measurements.

Comment 5: It would be valuable to incorporate existing estimates of lithospheric and crustal thickness beneath the stations, for example, from previous geophysical studies, to visualize how much the lithosphere could contribute to the observed SKS delay times. Cratons are generally very thick, and depending on crustal thickness, the lithospheric contribution to δt could range from roughly 0.04-0.2 s (Barruol & Mainprice, 1993). Plotting or summarizing this information alongside the SKS measurements would help assess the relative contributions of lithospheric versus deeper mantle anisotropy and provide context for interpreting the splitting results.

Response: We thank the reviewer for this fruitful suggestion. We have now updated the manuscript to include previously published research articles that discussed the crustal and lithospheric structure of the CITZ, which is critical for determining the relative contributions of crustal, lithospheric, and asthenospheric sources to the recorded delay times. Deep seismic sounding profiles along the Hrapur-Mandla transect over the NSL restrict the Moho depth to 40-44 km beneath the study region (Murty et al., 2004; Kaila, 1986), with local thickening to ~52 km eastwards near the Narmada paleo-rift zone (Kumar et al., 2015). The lithospheric thickness beneath central India, affected by the reunion plume interaction, has been estimated to be between 160 and 220 km (Kumar et al., 2013; Maurya et al., 2016; Kumar & Mohanty, 2025). We recently performed receiver function analysis on our dataset to assess the crustal architecture beneath the study area; the corresponding publication is now being prepared. According to the study, the moho depth varies from 30 to 48 km in the study region.

The quantitative method of Barruol & Mainprice (1993) states that the crustal contribution to delay times is around 0.1 s per 10 km of anisotropic crust. Based on this, a 40 km thick crust would contribute approximately 0.4 sec to the observed SK(K)S delay times. The additional contribution to SK(K)S delay times comes from the lithospheric mantle layer. The remaining delay times of SK(K)S split measurements that cannot be accounted for by the lithosphere alone need an asthenospheric contribution, which is consistent with present-day plate motion-driven olivine LPO alignment (Vinnik et al., 1989; Roy et al., 2014). This supports our notion of a twofold contribution from frozen lithospheric anisotropy and ongoing asthenospheric flow.

We have now revised the texts in the amended manuscript.

Comment 6: The authors link lower delay times values to mantle plume upwelling and Cretaceous magmatism, but could a plume formed millions of years ago could still influence present-day SKS measurements? Since India has drifted north since the Cretaceous, the spatial relationship between the original magmatism and the current station location should be addressed. Also the authors invoke the presence of dykes as evidence for magmatism which they relate directly to lower delay times. However, crustal features such as dike intrusions or aligned fabrics could contribute to the observed delay times and fast axes in different ways, potentially producing different signatures from crustal LPO or SPO compared with mantle LPO (see articles by Fouch and Rondenay (2006), Meissner et al. (2002), Mainprice & Nicolas (1989) and others by Karato, Zoback, Ribe, Crampin, Long).

Response: We appreciate this insightful comment. Yes, a plume generated millions of years ago might still have an effect on current SKS readings, albeit to a small extent. The SK(K)S splitting observations at any seismic station reflect the cumulative seismic anisotropy of the crust and upper mantle, which serves as an indicator of overall deformation caused by contemporary mantle flow and the prior tectonic history of the region. As per Silver & Chan (1991) and Savage (1999), the LPO of olivine developed during deformation can be frozen into the lithosphere and retained for billions of years. This fossilized anisotropy can influence SK(K)S delay times regardless of the plate's subsequent motion. During the Cretaceous period, plume upwelling occurred in the CITZ region, modifying the lithospheric fabric beneath it (Ghosh et al. 2026). The reunion plume triggered not only the Deccan traps but also major lithospheric thinning and anisotropic fabric alterations (Barruol et al., 2019). This modified lithosphere still exists beneath the Indian plate today, contributing to the observed anisotropy patterns. While the Indian plate has moved northward, the plume-induced lithospheric fabric is still entrenched in the continental lithosphere (Silver & Chan 1991, Fouch & Rondenay 2006). The reunion hotspot remained active, influencing the Indian plate as it migrated. The track runs from the Deccan Traps south to what is now Reunion Island (Barruol et al., 2019). This continuous thermal influence has resulted in a regionally coherent anisotropic signature. The existence of this plume activity is further supported by a continental-scale body wave tomography investigation of the Indian subcontinent (Singh et al., 2014).

Crustal anisotropy typically contributes only 0.1 - 0.3 sec to delay times (δt) (Silver & Chan, 1991; Barruol & Mainprice, 1993). The measured δt values at SG02, the lowest δt (0.76 sec) at all seismic stations, exceeded expected crustal contributions, indicating a dominant mantle source. Crustal anisotropy from dykes would cause shape preferred orientation (SPO) effects, which have different seismic signatures from mantle LPO (Mainprice & Nicolas, 1989). Crustal anisotropy is commonly attributed to LPO in mica-rich minerals such as biotite and amphibole, as well as SPO in cracks, fractures, and compositional layering formed during deformation (Crampin, 1984; Mainprice & Nicolas, 1989; Meissner et al., 2002; Fouch & Rondenay, 2006; Brownlee et al.,

2017). Mantle anisotropy is primarily attributed to the strain-induced LPO of anisotropic minerals such as olivine, orthopyroxene, and clinopyroxene, which results from the dislocation creep deformation mechanism, which is characterized by the creeping motion of crystal dislocations caused by mantle flow and tectonic stresses at plate boundaries due to past and ongoing deformations (Nicolas & Christensen 1987; Karato 1987; Barruol & Mainprice 1993; Mainprice et al. 2000). The FPD at SG02 aligns with the regional mantle flow patterns rather than the strike of dykes (which trend ~E-W) (Shukla et al. 2022).

In addition to lower δt , we also found null measurements at stations near the mantle plume activity, with counts of four at SG02 and two at SG09. Station SG02 has the lowest δt value (0.74 sec). The lower δt (0.74 sec) and 4 null measurements in the Pachmarhi region (SG02 seismic station) could be attributable to significant magmatism during the Cretaceous era in the Narmada and Tapi graben zones, as evidenced by the presence of dykes near the SG02 station (Shukla et al., 2022). Station SG09 is located close to the DVP. The lower δt (0.95 sec) and 2 null measurements at SG09 may be linked to mantle plume upwelling during the upper Cretaceous to early Paleocene (Krishnamurthy, 2020).

We have now expanded the discussion section in the revised manuscript accordingly.

More line-by-line comments:

Comment 7: L27: The CITZ is not clearly shown in Figure 1. It is unclear whether it is meant to represent a collection of sutures and faults shown in the figure, or if it is delimited by some other feature. This should be clarified. If CITZ is an important suture between the northern and southern cratons, the boundaries of these cratons should also be indicated in Figure 1.

Response: Thank you for the suggestion. Figure 1 in the revised manuscript (Figure R1) has been adjusted to clearly highlight the CITZ and craton borders.

Comment 8: L33: "The northern Indian craton subducting beneath the southern Indian craton." Since the CITZ formed during the Mesoproterozoic (~1.6–1.0 Ga), possibly before modern-style plate tectonics was fully established, and given that cratons are thick and buoyant, it may be clearer to describe this as underthrusting or collisional interactions along craton margins, rather than full-scale subduction, while acknowledging that the polarity and details of these collisions remain debated.

Response: Thank you for your valuable suggestion. We have modified the texts in the revised manuscript.

The statement has been amended as follows: Some hypotheses propose that the southern Indian craton underthrusts northward beneath the northern Indian craton (Roy & Prasad, 2003; Mall et al., 2008; Mandal et al., 2013; Chattopadhyay et al., 2017), while others propose the opposite, with southward-directed underthrusting of the northern Indian craton beneath the southern Indian craton (Yedekar et al., 1990; Acharyya, 2003; Bora & Kumar, 2015).

Comment 9: L55: The manuscript briefly mentions anisotropy may be due to mantle LPO, but given that the preceding paragraphs focus on crustal and lithospheric structures, it would be helpful to also discuss potential sources of anisotropy within the crust. For example, lattice-preferred orientation (LPO) of crustal minerals such as biotite, and shape-preferred orientation (SPO) of aligned grains or foliation, can influence shear-wave splitting in different ways. References such as Fouch and Rondenay (2006), Meissner et al (2002), and Mainprice & Nicolas (1989) provide detailed examples, though the authors should also consider additional established studies (for example by authors like Karato, Zoback, Ribe, Crampin, Long) to give a broader perspective. Including these sources would strengthen the link between observed anisotropy and deformation in both the crust and upper mantle.

Response: Thank you for your valuable suggestion. SK(K)S splitting measurements at any seismic station provide the integrated seismic anisotropy of the crust and upper mantle. We have now updated the Introduction part of the revised manuscript to emphasize the crust and upper mantle contributions to seismic anisotropy.

The revised version of the introduction paragraph is as follows:

“Seismic anisotropy, caused by the directional dependence of seismic wave velocities, can be used to effectively define crustal and upper mantle deformation (Bowman & Ando, 1987; Vinnik et al., 1989; Silver & Chan, 1991; Savage, 1999). Seismic anisotropy can be explained by two main deformation mechanisms: shape preferred orientation (SPO) and lattice preferred orientation (LPO) (e.g., Savage, 1999; Fouch & Rondenay, 2006). Crustal anisotropy is commonly attributed to LPO in mica-rich minerals such as biotite and amphibole, as well as SPO in cracks, fractures, and compositional layering formed during deformation (Crampin, 1984; Mainprice & Nicolas, 1989; Meissner et al., 2002; Fouch & Rondenay, 2006). Upper crustal anisotropy is primarily caused by structural features such as faults, layering, flat mineral alignment, and consistently oriented cracks in the upper crust (Crampin, 1981; Mainprice et al., 2000, 2006; Brownlee et al.,

2017). The LPO of mica or amphibole minerals can explain anisotropy below the crack closure depth in the mid- to lower crust (Brownlee et al., 2017).

Upper mantle seismic anisotropy is primarily attributed to the strain-induced LPO of anisotropic minerals, like olivine, orthopyroxene, and clinopyroxene, arising from the dislocation creep deformation mechanism, which is characterized by the creeping motion of crystal dislocations caused by mantle flow and tectonic stresses at the plate boundaries due to past and ongoing deformations (Nicolas & Christensen 1987; Karato 1987; Barruol & Mainprice 1993; Mainprice et al. 2000). Anisotropy in subduction zones may reflect fossilized fabrics in the overriding plate or stress-aligned crack systems influenced by slab dehydration and fluid migration, whereas in collisional orogens it is frequently associated with ductile shearing and lithospheric shortening, which produce coherent mineral fabrics parallel to orogenic trends (Savage, 1999; Long & Silver, 2009). In contrast, rift settings show anisotropy linked with extensional strain fields, with vertically aligned cracks and dike intrusions producing different anisotropic signatures.”

Comment 10: L60: "moves parallel to it" - not always (see the references above).

Response: Thank you for pointing this out. We have now modified the texts in the revised manuscript.

Comment 11: L80: This is the first mention of a mantle plume. I suggest first describing it in the earlier tectonic paragraphs rather than mentioning it so briefly at the end of a paragraph about seismic anisotropy studies in India.

Response: Thank you for the suggestion. We have now added a small description of mantle plumes related to the CITZ context in the second part of the introduction section of the revised manuscript.

Comment 12: L130: "The rose diagram for each split measurement (Figure 8) illustrates the variance and predominant orientation of FPDs at each seismic station." This statement should be interpreted cautiously. The apparent “predominant orientation” does not necessarily represent the true fast-axis direction, as it can be biased by the uneven distribution of earthquakes, which may

preferentially sample only part of the anisotropic signal. At the same time, the large variability in measurements in Fig 7c,d is noteworthy and deserves careful exploration. I suggest that the authors report individual measurements with associated uncertainties and discuss how both earthquake distribution and potential multilayer or complex anisotropy contribute to the observed variance.

Response: Thank you for your comment. We have now included Supplementary Table S1, which contains detailed information about the earthquake events (event date, time, longitude, depth, and magnitude), station name, phase information, and shear wave splitting parameters with associated error (ϕ or FPD, FPD error, δt , and δt error) for each splitting measurement. The revised manuscript now places a greater emphasis on individual measurements and variability.

As discussed in comment no. 20, modelling two layers of anisotropy with hexagonal or orthorhombic symmetry approximations requires broad azimuthal coverage and substantial splitting measurements, both of which are lacking from all stations in our dataset. As a result, we have decided not to proceed with two-layer anisotropic modeling.

We have now revised the manuscript accordingly.

Comment 13: L141: Which absolute plate motion (APM) model did the authors use for this analysis? The resulting trench-parallel and trench-perpendicular components can vary depending on the chosen global model (e.g., Nuvel-1A, MORVEL) or reference frame (e.g., no-net-rotation, Eurasia-fixed, hotspot). Clarifying the specific model and reference frame is important, I think.

Response: Thank you for this valuable question. In the discussion section of the manuscript, we have already mentioned the APM model and the source from which we calculated the APM velocity vectors.

The APM velocities were estimated using the GAGE Plate Motion calculator (<https://www.unavco.org/software/geodetic-utilities/plate-motion-calculator/plate-motion-calculator.html>) with the ITRF2020 model (Altamini et al., 2023). The APM direction is calculated in the no-net-rotation frame of reference. We have now modified the texts in the revised manuscript accordingly.

Comment 14: L170: 'the measured δt s varies from 0.74 seconds at station SG02 to 1.4 seconds" this should be shown and/or added as a dataset in the SI.

Response: Thank you for suggestions. This is already illustrated in Table 1. We have now included a supplementary Table S1 providing detailed information of individual splitting measurements at each seismic station.

Comment 15: L188: "The lithosphere-asthenosphere boundary (LAB)" It would be very good to add a map of the LAB here to support the text.

Response: Thank you for the insightful suggestion. Because of the scarcity of seismic data, there has been no seismological study in this area to estimate LAB depth. In a broader sense, Kumar et al (2013) used the receiver function inversion, and Maurya et al (2016) used surface wave dispersion to create a LAB depth map for India. However, the dataset is not available in the public domain, and all we have is the spatial map of the LAB. Kumar & Mohanty (2025) recently produced a LAB depth map for India using potential field modeling and thermal analysis, which is consistent with previous seismological works for the CITZ region. We have now added the LAB map, as modified by Kumar & Mohanty (2025), for our study region as a supplementary Figure S3 in the revised manuscript (Figure R8). We have now expanded the paragraph related to the LAB in the revised manuscript.

Comment 16: L193: 'maybe located in locations with thicker lithosphere' adds a value.

Response: Thank you for pointing this out. We have now explicitly added the lithospheric thickness values and included the relevant citation in the amended paper.

Comment 17: L200-205: The paragraph links lower dt at SG02 to mantle plume upwelling and Cretaceous magmatism, but this raises a few points worth exploring further. If the mantle plume formed in the Cretaceous, could its effects still influence present-day SKS measurements, or would the signal primarily reflect frozen-in anisotropy? Considering that the Deccan plume (Reunion hotspot, if I m not mistaken?) is now far south in the western Indian Ocean and India has drifted north since the Cretaceous, how might the original location of magmatism relate to current station positions? Finally, given the potential influence of crustal features, including dike intrusions or aligned fabrics, it may be valuable to consider the different signatures of crustal LPO and SPO

versus mantle LPO (i.e. see my earlier comment about other articles the author should engage with).

Response: Thank you for your valuable suggestion. We have now expanded the discussion on plume influence and crustal anisotropy sources in the revised manuscript, as previously discussed (Reply of significant comment nos. 9 and 6).

Figure comments

Comment 18: Figure 1. I strongly suggest adding a wider tectonic figure here showing the cratons and the suture zones between them investigated with SKS in this study.

Response: Thank you for the insightful suggestions. We have modified Figure 1 (Figure R1) to include craton boundaries and CITZ.

Comment 19: Figure 2 shows range of petrological regions, but it mixes many terms like supergroups, supracrustals, sediments, basins, traps, groups, granitoids. For a seismologist who may not be familiar with the local tectonic framework, it is quite confusing and hard to connect all these lithological regions with the tectonic context described in the main text. Where are the limits of the Southern cratons in this figure? What is the area of the Satpura Gondwana Basin (or mobile belt?) here? Perhaps also add the recognized limits of the CITZ here as well.

Response: Thank you for your suggestions. We have now removed Figure 2 from the revised manuscript since it contributed to the complexity of the large-scale tectonic context without effectively communicating it. We have modified Figure 1 in the revised manuscript (Figure R1) to illustrate the Craton boundaries and the CITZ suture zone. These modifications strengthen the connection between seismic observations and the broader tectonic framework.

Comment 20: Figure 7. This shows a large range of values for the same backazimuth. I wonder how it looks like for individual stations (rose diagrams such as the ones in Fig 8 are also representative but seeing the values in xy baz plots can even tell about 2D layer variabilities. Such a high variation in values of the same baz seems indicative of multiple layers to me).

Response: Thank you for the constructive suggestion. The backazimuthal variation of individual FPDs observed at all seismic stations (Figure 7c in the revised manuscript) indicates the existence of multiple anisotropic strata. However, the number of high-quality SKS measurements per station in our dataset is relatively limited. Our backazimuthal coverage has also remained limited. Constructing meaningful XY backazimuth plots requires dense and well-distributed backazimuthal sampling, ideally spanning at least 180° with adequate event density in each bin, which is not uniformly achievable across all stations in our network. Presenting such plots for stations with sparse or uneven backazimuthal coverage increases the risk of over-interpreting artifacts arising from poor sampling rather than genuine anisotropic complexity. Splitting parameters for two layers of anisotropy modeling, whether at individual stations or station groups, can only be interpreted reliably when the variation of splitting parameters with backazimuth demonstrates a clear 90° periodicity (Silver & Savage, 1994; Savage, 1999). Modeling two layers of anisotropy with hexagonal or orthorhombic symmetry approximations necessitates broad azimuthal coverage and substantial splitting measurements, which are missing across all stations in our dataset. Therefore, we have chosen not to proceed with two-layer anisotropy modeling. Instead, we present results of single-layer anisotropy derived from SK(K)S splitting measurements.

We have now clarified the text in the amended manuscript accordingly.

Comment 21: Figure 12. The elevation profile appears to differ from the cross section shown below. What time frame does the sketch represent? If this region shifted northward or eroded over time, how did the topographic high develop in the backarc region relative to the subduction front? It would also be helpful to indicate the craton boundaries and thick roots on this section. Given that subduction along the CITZ occurred in the Mesoproterozoic, while magmatism related to the Deccan plume occurred in the Cenozoic, how should present-day SKS delay times be interpreted in the context of mantle upwelling?

Response: We thank the reviewer for this observation. The SK(K)S splitting observations at any seismic station provide the cumulative seismic anisotropy of the crust and upper mantle, serving as an indicator of overall deformation due to contemporary mantle flow and the prior tectonic history of the region. In Figure 12, the conceptual model aims to emphasize the frozen anisotropy resulting from prior Mesoproterozoic orogeny and cretaceous mantle plume activity, alongside the APM direction of the Indian Plate.

The elevation profile at the top of Figure 12 illustrates the present-day topography along the A-A' transect, while the schematic cross-section below depicts the Mesoproterozoic collisional era ($\sim 1.55\text{--}0.85$ Ga), specifically capturing the subduction polarity reversal and N-directed subduction of the SIC and possible subduction polarity reversal, as well as mantle plume activity during the

late Cretaceous to early Paleocene. We acknowledge that this temporal juxtaposition was not clearly labeled previously. In the revised manuscript, we have now added explicit time-frame annotations for both panels in the revised figure 12 caption to avoid confusion.

The present-day topography in the central part of the profile is not a direct result of Mesoproterozoic orogeny. Instead, it reflects post-collisional crustal thickening, isostatic adjustment, and subsequent tectonic and erosional processes of the Phanerozoic Eon. The northward movement of the Indian plate and differential erosion of the Deccan Plateau have further altered the topography. The revised manuscript now clarifies that the present-day topography should not be interpreted as a direct analog of the Mesoproterozoic relief, and that the current elevation of the backarc region is indicative of long-term post-orogenic evolution rather than contemporaneous arc-related uplift.

Figures:

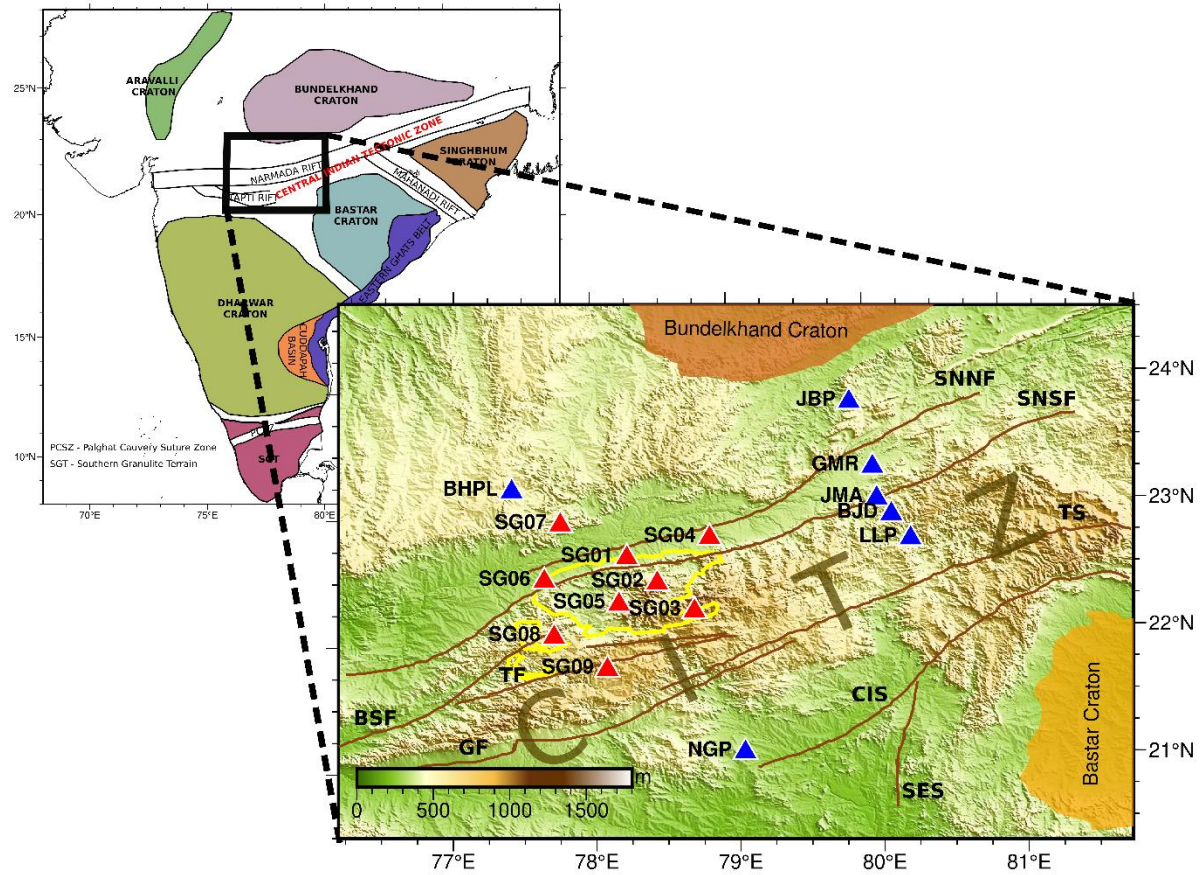


Figure R1: Tectonic and topographic map of the Central Indian Tectonic Zone across the Satpura Gondwana Basin. Red triangles denote the temporary seismic stations installed in and around the Satpura Gondwana Basin, whereas blue triangles indicate the seismic stations reported by Roy et al. (2014) and Roy et al. (2024). The fault lines shown in brown and the yellow curved lines denoting the boundary of the Satpura Gondwana Basin are adopted from Singh et al. (2015). Top Left: Regional geological and tectonic setting of Peninsular India, highlighting the distribution of Archean cratonic blocks and Proterozoic mobile belts (modified after Groves and Santosh, 2021). BSF: Barwani Sukta Fault; CIS: Central Indian Suture; GF: Gavligarh Fault; SNNF: Son Narmada North Fault; SNSF: Son Narmada South Fault; TF: Tapti Fault; TS: Tan Shear; SES: Sakoli East Shear.

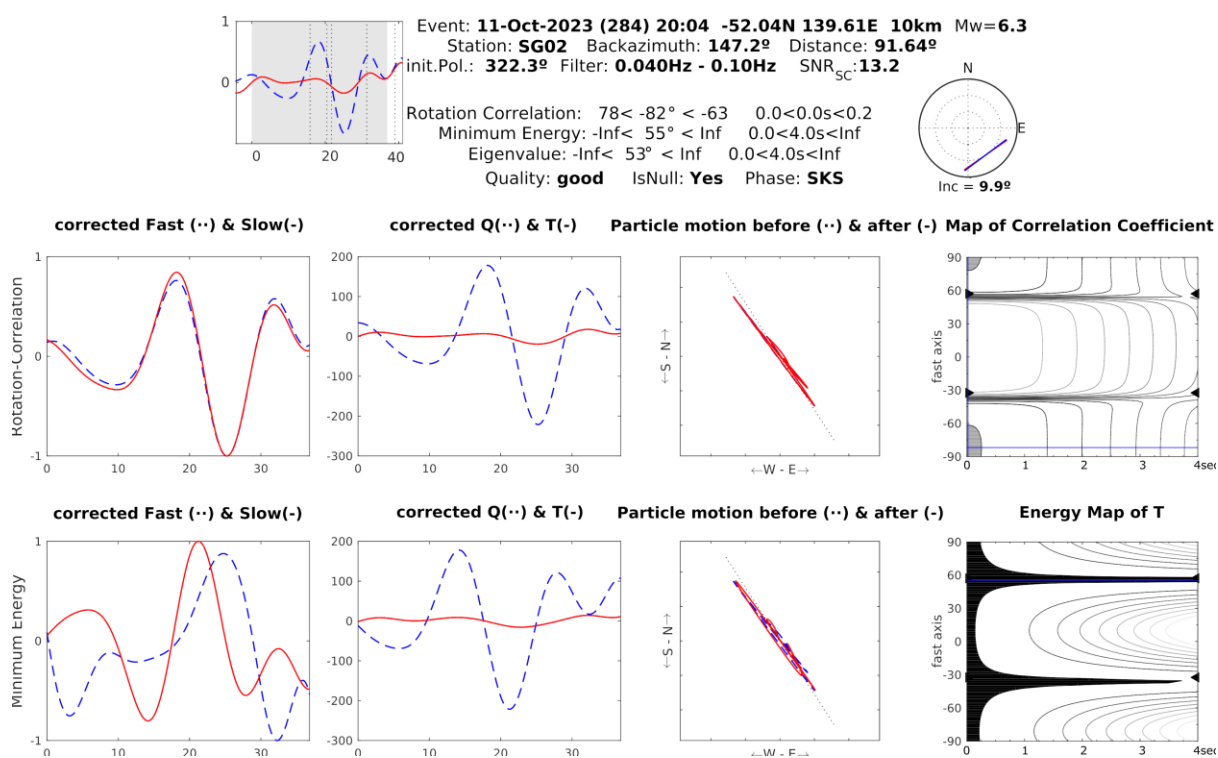


Figure R2: An example of null measurement at SG02 seismic station.

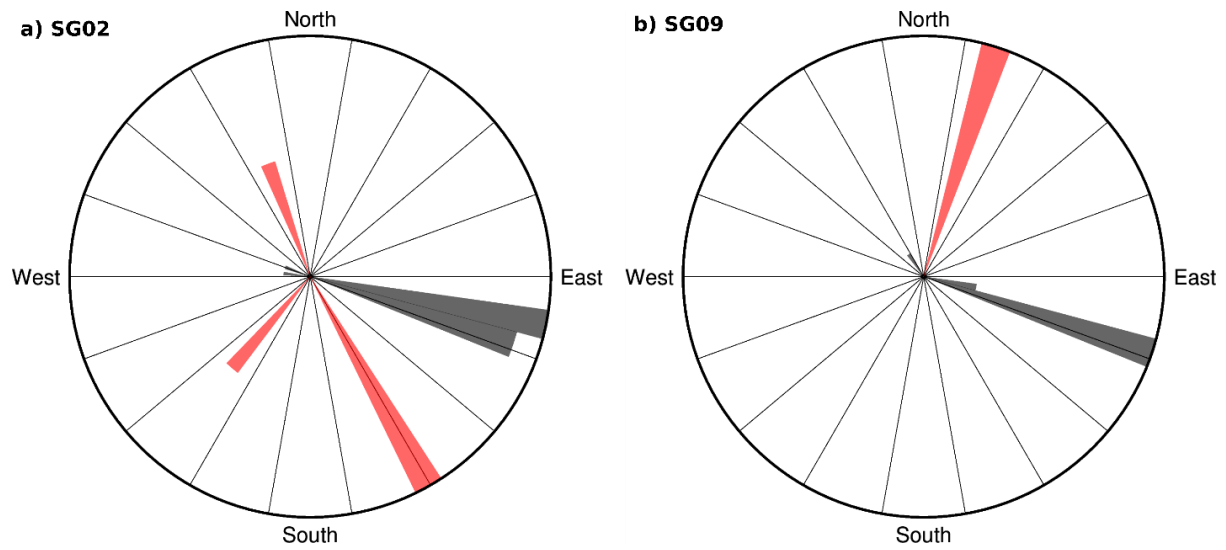


Figure R3: Rose diagram illustrating the backazimuthal coverage for the splits (depicted in black) and the nulls (shown in red) for the SG02 and SG09 seismic stations.

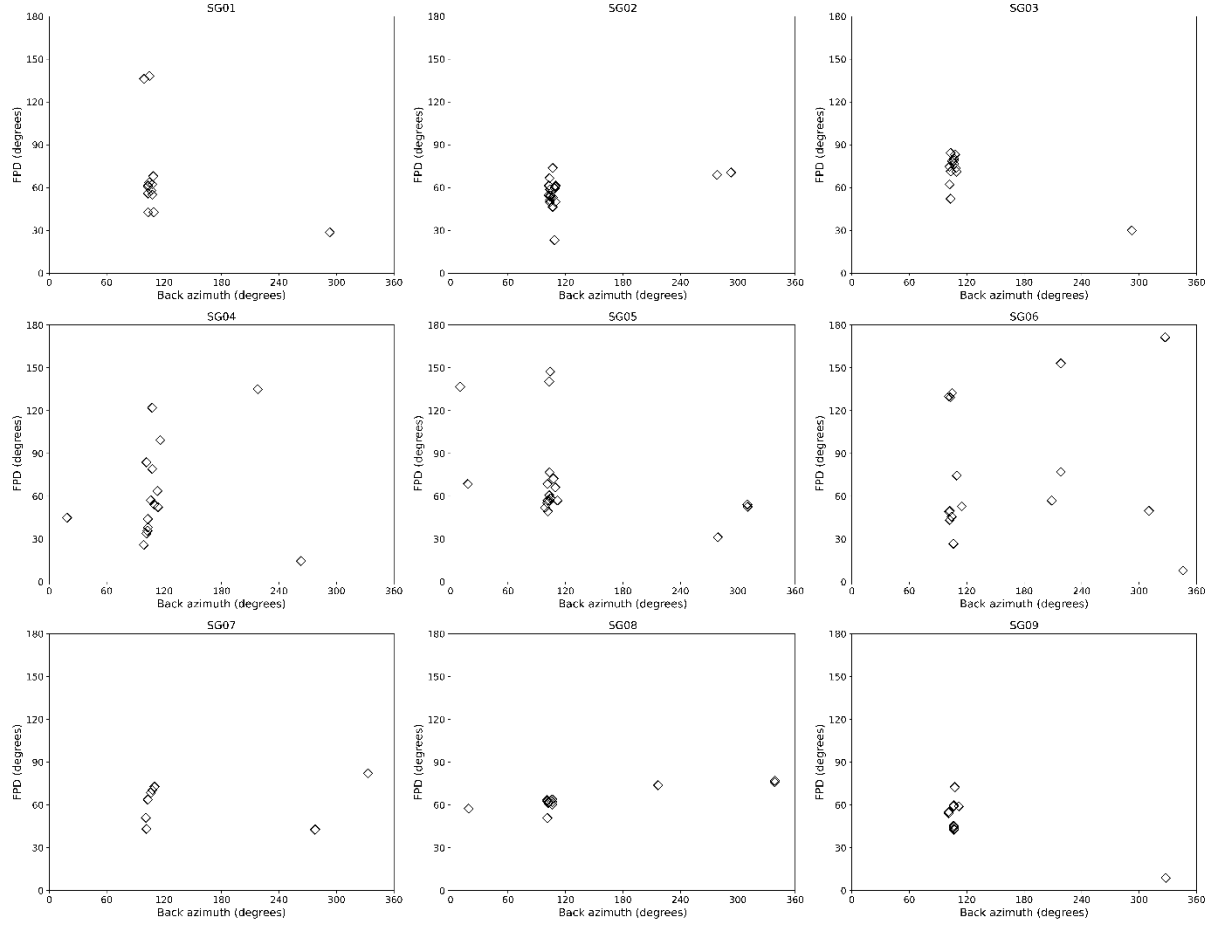


Figure R4: Backazimuthal variation of the individual fast polarization directions (FPDs) for all nine seismic stations.

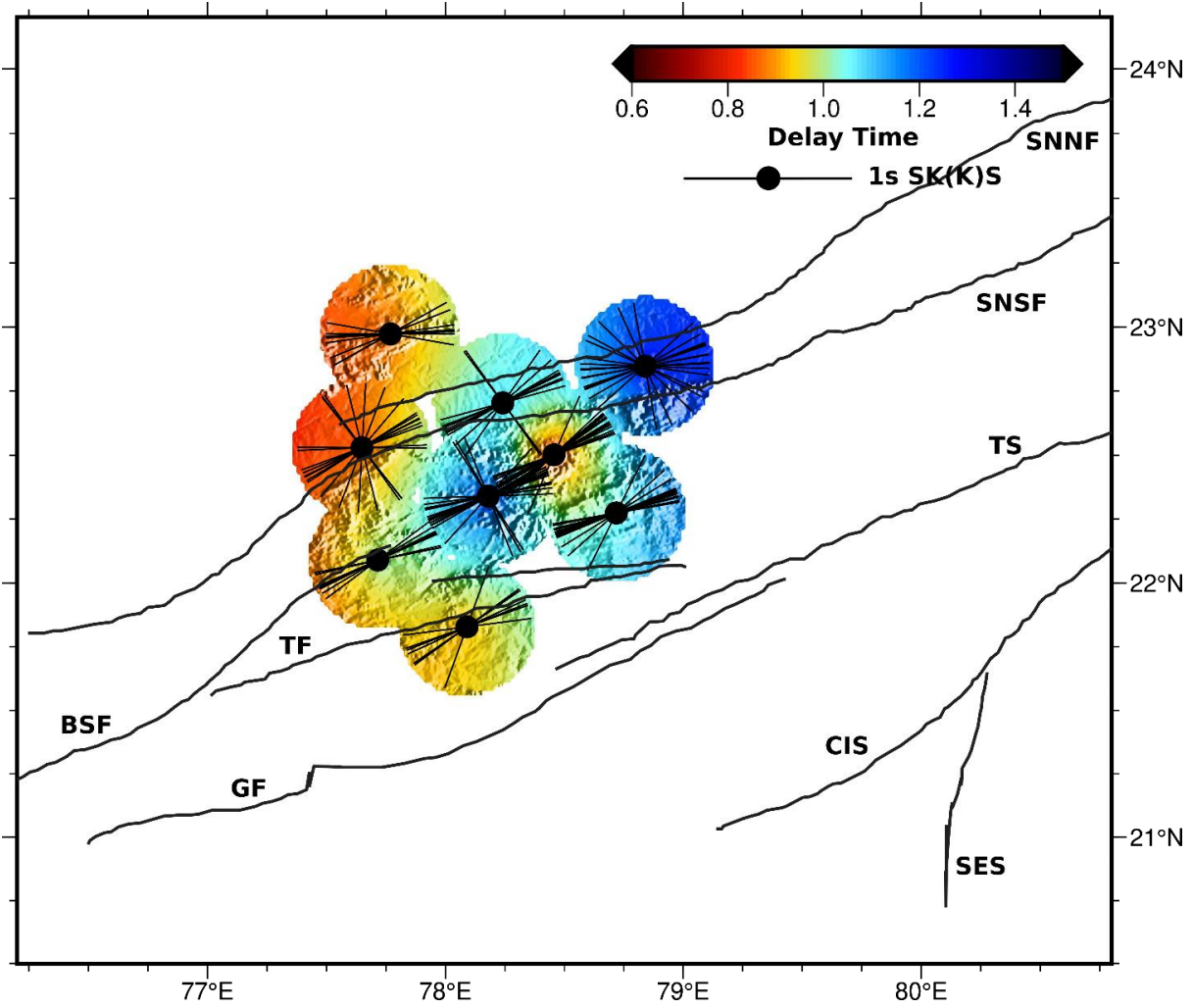


Figure R5: The tectonic map of the study area, which depicts the fast polarization direction (FPD) of individual SK(K)S splitting at each seismic station. The azimuth of the black bars denotes the individual FPDs of the obtained splitting parameters. The interpolated station-averaged split delay time at each seismic station is presented in a color-coded format to illustrate lateral variations in delay times. The black circles indicate the seismic stations used in this study.

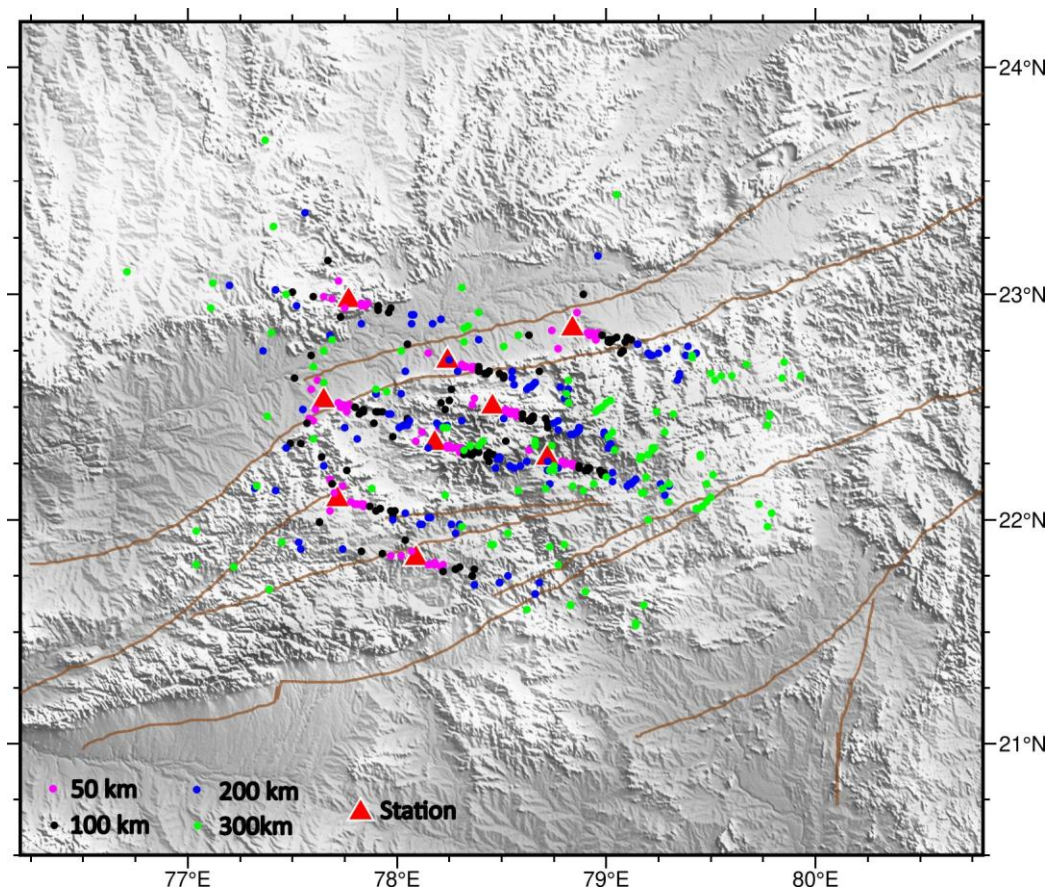


Figure R6: Piercing points of SKS and SKKS phases at depths of 50, 100, 200 and 300 km.

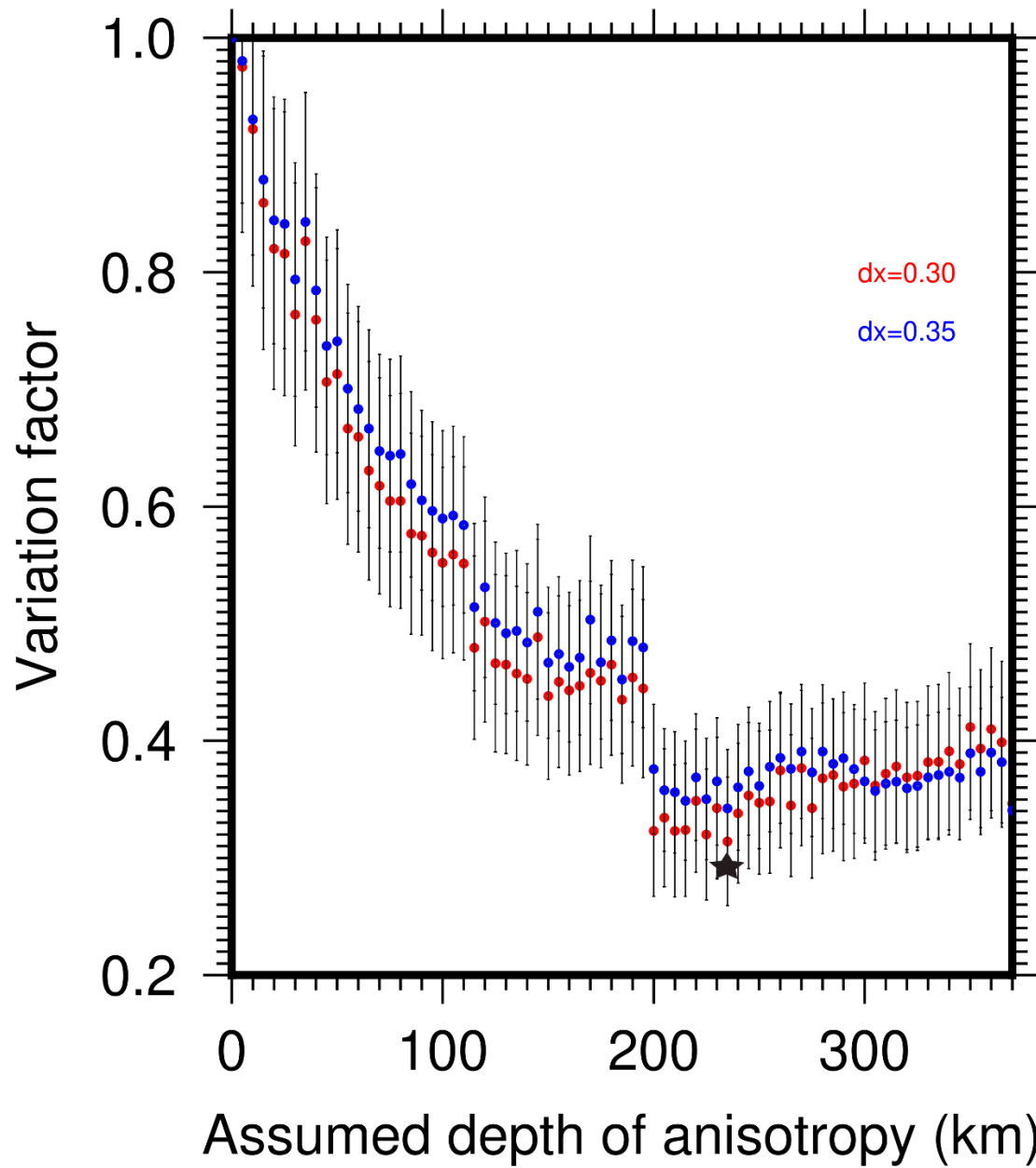


Figure R7: Depiction of the variation factor as a function of the presumed depth of anisotropy, calculated for block sizes of 0.30° and 0.35° . The variation factor is calculated as the weighted sum of the circular mean of the fast polarization directions and the arithmetic mean of the delay times.

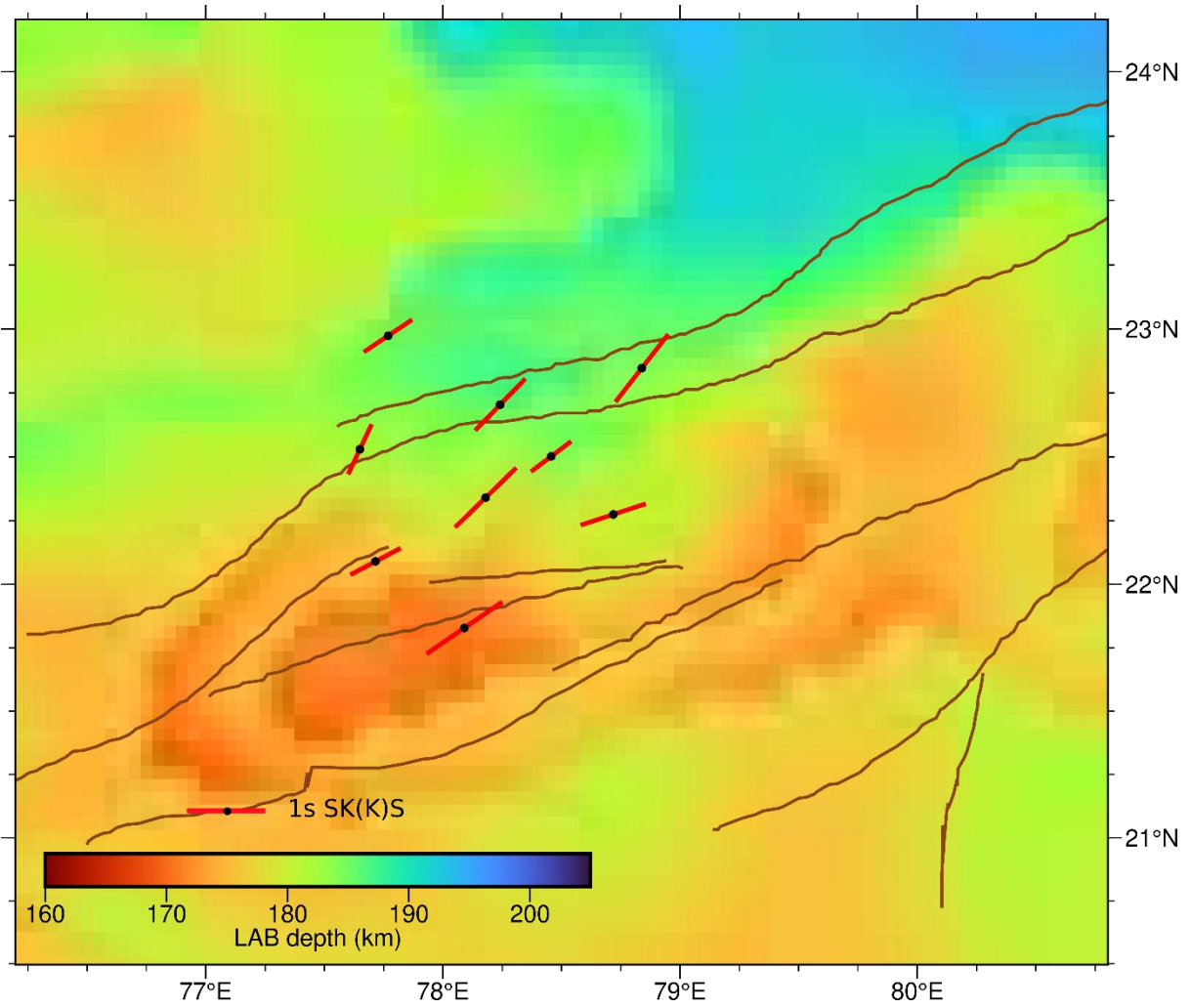


Figure R8: The figure shows the lithospheric-asthenospheric boundary (LAB) depth (from Kumar & Mohanty (2025)) in the study area, as well as the station-averaged splitting parameters for each seismic station. The black dots are the stations. The black dots denote the location of the stations. The inclination of each bar represents the fast polarization direction (FPD), while the length denotes the delay time (δt).

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