



ABSTRACT

The causes of seismic anisotropy are still under debate, e.g., to which degree it is due to more **recent geodynamic activities in the asthenosphere**, or to **frozen-in deformation in the lithosphere**. We show that these two endmember cases can in principle be distinguished using shear-wave splitting observations from SKS waves. This is illustrated by the simple example of pure olivine with horizontal a-axis, and differing orientations of the other two axes, namely vertical b (b-up) and vertical c (c-up). The azimuthal dependence of shear-wave splitting measurements is described by two parameters, which can provide additional information about subsurface deformation. In particular the **oscillation parameter d_1 constrains the orientation of foliation**. We demonstrate that shear-wave splitting in Western and Central United States indeed shows the predicted azimuthal dependence, related to a mainly subhorizontally-oriented flow plane of deformation in the upper mantle. This has important implications for asthenospheric flow.

SHEAR-WAVE SPLITTING APPROACH

A frequently used approach to quantify azimuthal anisotropy, generated by lattice-preferred orientation of upper mantle minerals like olivine, is the investigation of shear-wave splitting (SWS) measurements (Vinnik *et al.*, 1984, 1989; Silver and Chan, 1988, 1991). If a planar S-wave passes through an anisotropic media, it will split into two quasi S-waves with mutually-perpendicular polarization (Fig. 1 left), similar to optical birefringence.

- **Phases used:** SK(K)S $\Rightarrow$ S- to P-wave conversion at Core-Mantle-Boundary $\Rightarrow$ source-side anisotropy effects are eliminated
- **Distance required:** $\sim 90^\circ - 130^\circ \Rightarrow$ nearly vertical ray path incidence
- **Parameters determined:** Fast orientation ϕ and delay time Δt
- **Depth resolution:** Anisotropy cause not determinable $\Rightarrow$ **Simple Asthenospheric Flow (SAF)** or **Vertical Coherent Deformation (VCD)**

NON-VERTICAL SHEAR-WAVE SPLITTING

Davis (2003) introduced an approximate solution to the Christoffel equation, valid for incidence (θ) near an axis of crystal symmetry. This lead to Eq. 1 & 2, where ϕ oscillates ($\delta\phi$) around the fast orientation for vertical incidence (ϕ_0) with a 180° periodicity in azimuth (z):

$$\phi = \phi_0 + \delta\phi \quad (1)$$

$$\phi = \phi_0 + d_1 \sin(2z)\theta^2 \quad (2)$$

The polarity and amplitude of ϕ are controlled by the oscillation parameter d_1 , defined by the stiffness tensor. Comparing b- and c-up olivine orientation, which can be associated with SAF (Fig. 1 top) and VCD (Fig. 1 bottom) case, the backazimuthal (baz) variations show a phase shift in ϕ (shaded intervals) and differ in the Δt amplitude.

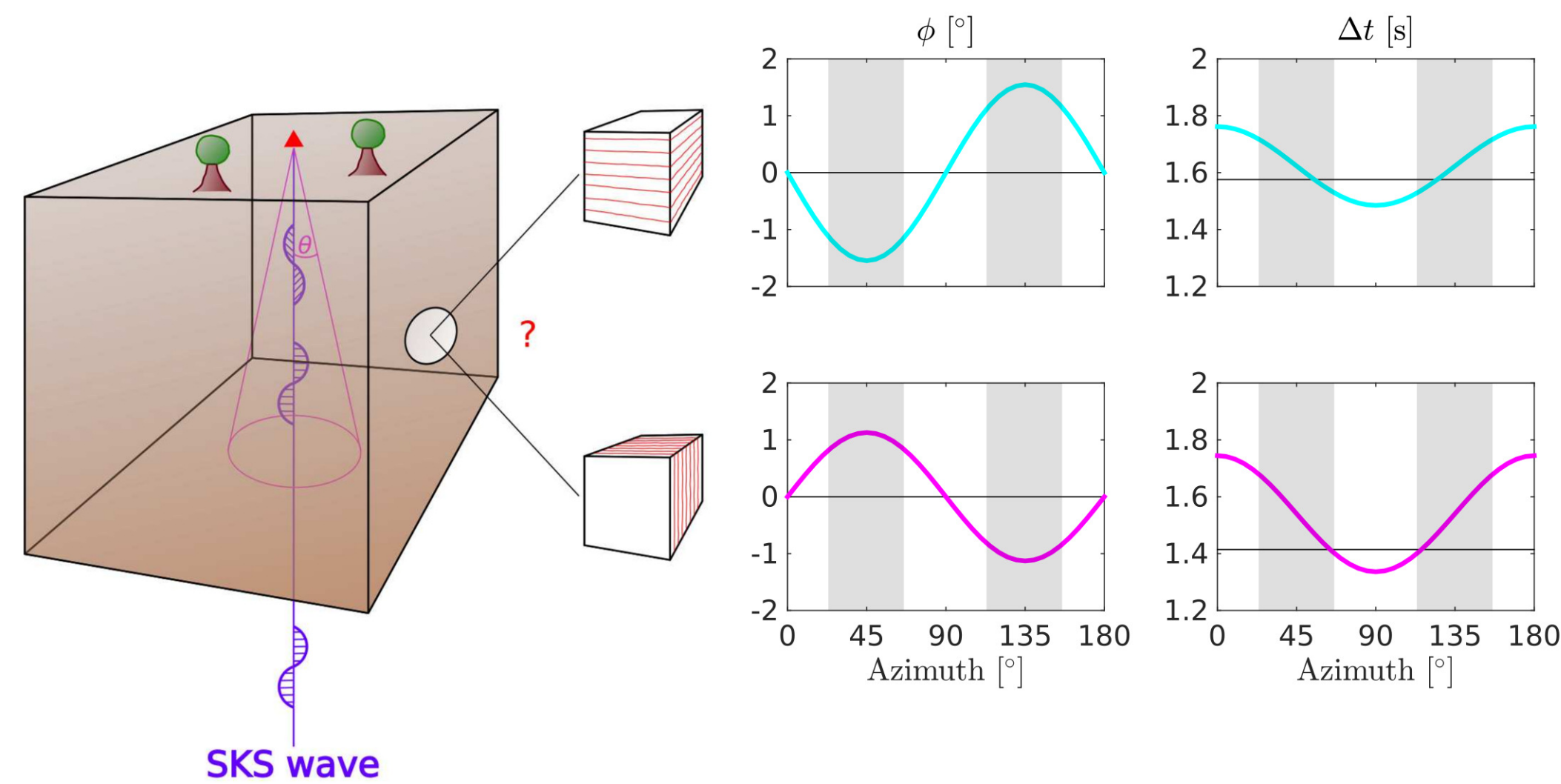


Fig. 1: (left) Ray geometry of SKS waves along the upper mantle. (center) The SAF model (top), horizontal oriented foliation planes, and the VCD (bottom), steeply oriented foliation planes. (right) Azimuthal variations of ϕ and Δt in comparison to a vertical incidence case (black lines), assuming a mantle of 70% b-up ($d_{1b} \sim -0.70$) or c-up ($d_{1c} \sim 0.51$) olivine.

INDIVIDUAL SHEAR-WAVE SPLITTING MEASUREMENTS

The effect of non-vertical SWS is difficult to investigate at individual stations, as it is not large, assumes single-layer anisotropy, and requires a wide baz range of recorded earthquakes. Our study instead takes advantage of the high amount of measurements in dense arrays to determine the polarity of d_1 , analyzing the SWS-DB-MST dataset (Fig. 2) put online by Liu *et al.* (2014).

SPATIAL DISTRIBUTION AND DATA PARAMETERS

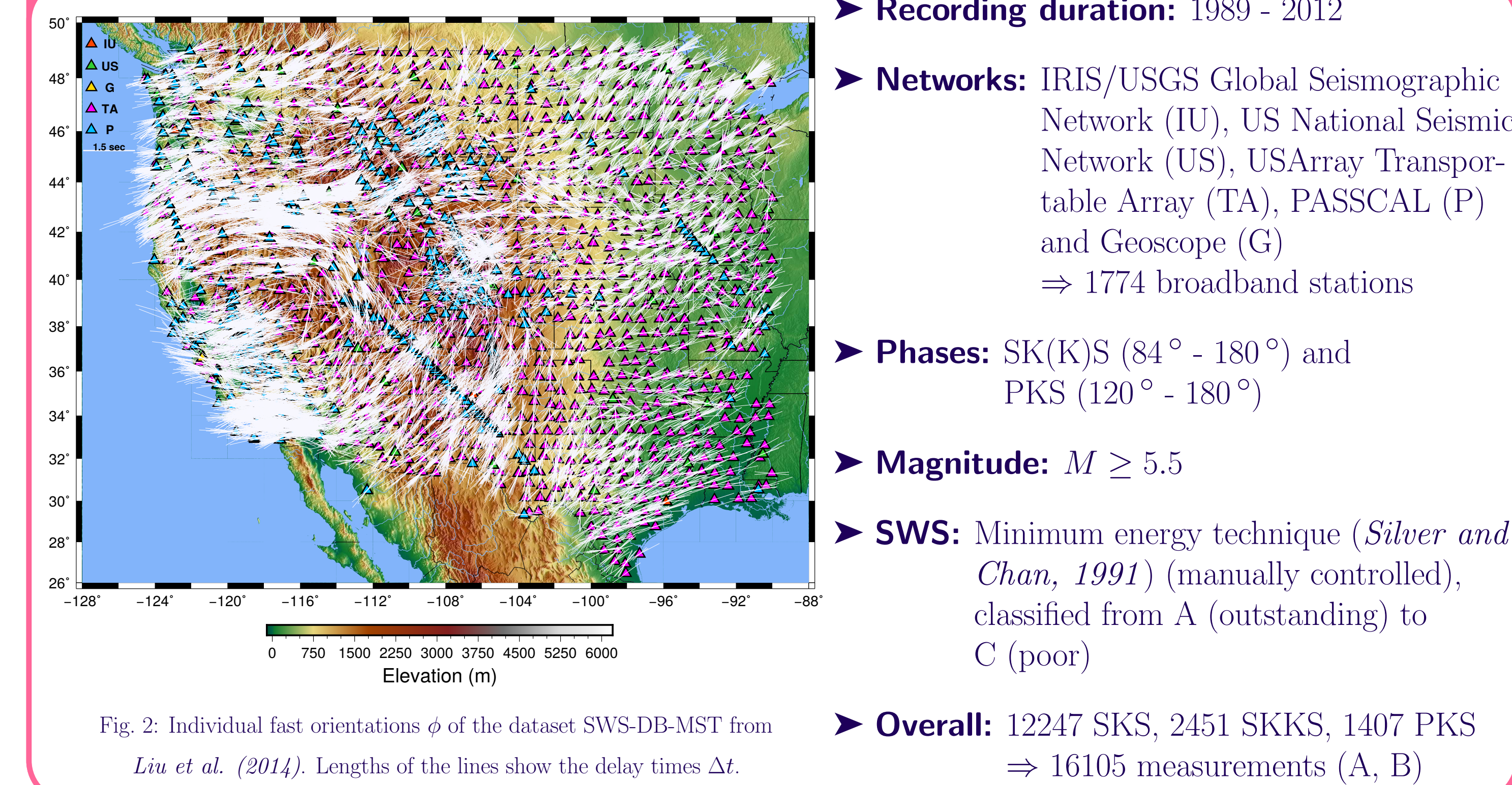


Fig. 2: Individual fast orientations ϕ of the dataset SWS-DB-MST from Liu *et al.* (2014). Lengths of the lines show the delay times Δt .

Based on Liu *et al.* (2014) and Hongsresawat *et al.* (2015) ϕ is in general aligned with North America's absolute plate motion. In any case, there are strong deviations from that direction with the most striking one being the circumferential pattern in the Great Basin (e.g. Eakin *et al.*, 2010). Considering only SK(K)S phases ϕ is **mainly oriented ENE-WSW** and the number of Δt measurements **peaks at ~ 1.2 s**. For stations with at least five measurements, ϕ and Δt show average uncertainties of $\sim 8^\circ$ and 0.2 s - 0.3 s.

ANGULAR DISTRIBUTION

The baz distribution of selected SWS parameters is widely spread, reflecting the diversity of anisotropy at large scale (Fig. 3 left). Further an uneven distribution of earthquakes is unveiled. To investigate stations jointly, we calculate the variation $\delta\phi$ and $\delta\Delta t$ per measurement with respect to the station means (Fig. 3 right). The corresponding **relative frequencies give indications for variations of both parameters**.

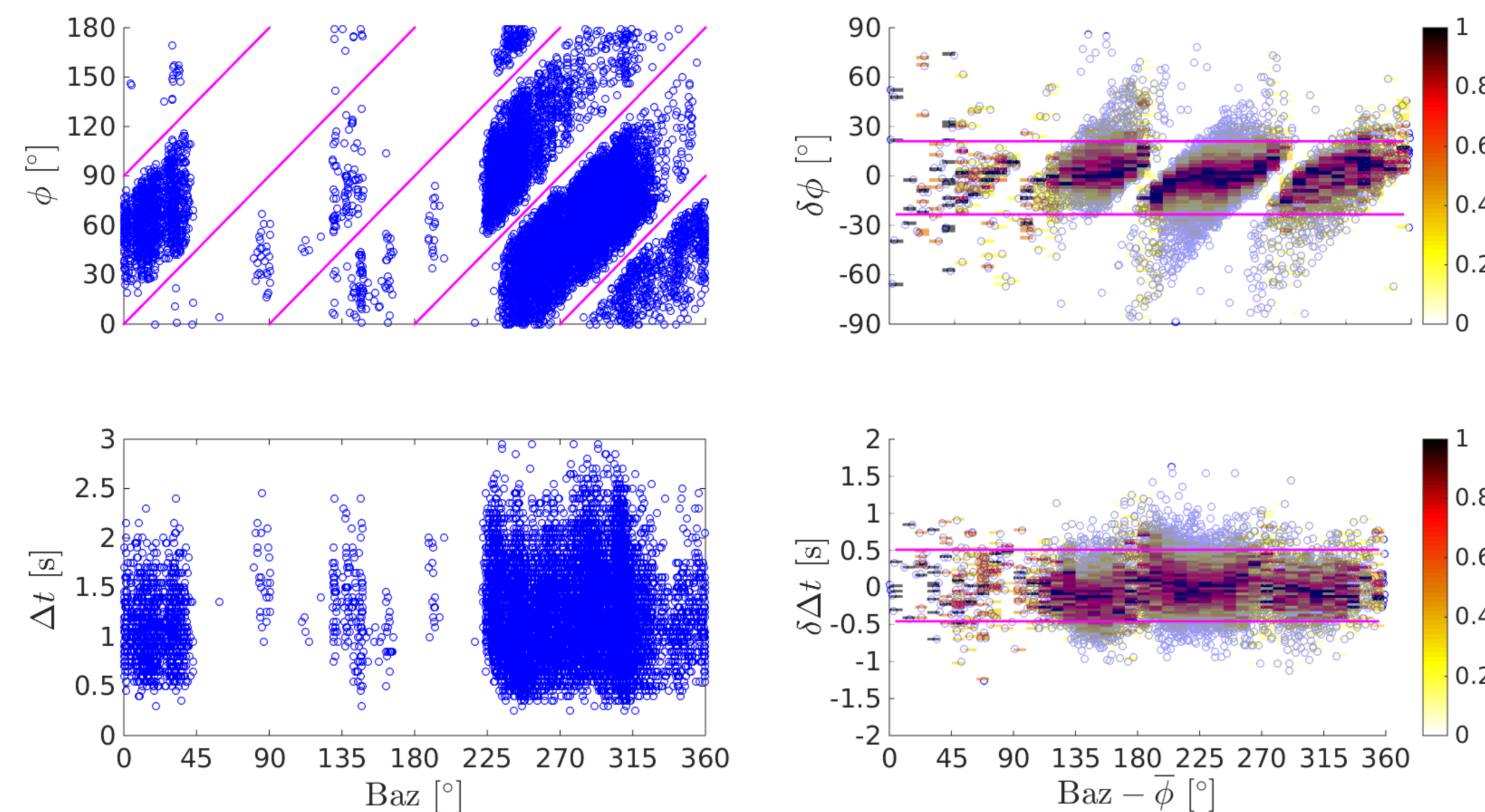


Fig. 3: Backazimuthal distribution of shear-wave splitting parameters. (left) Fast orientations ϕ and delay times Δt from all SK(K)S arrivals (magenta lines: Null directions). (right) Overlay of variations $\delta\phi$ and $\delta\Delta t$ corrected for the different fast orientation per station $\bar{\phi}$ (selected stations have at least five observations), and their relative frequencies (magenta lines: thresholds for $\delta\phi$ and $\delta\Delta t$).

RESULTS

To reduce the influence of outliers and more complex anisotropy, we constrain the data point selection introducing thresholds [5% and 95% quantile (Fig. 3 right, magenta lines)]. Since the station-correction still displays a biased distribution, we focus on intervals of $\pm 15^\circ$ around 45° , 135° , etc., the angles, where the difference between b-up and c-up olivine is clearest in $\delta\phi$ (Fig. 1 right, gray shaded intervals). Fig. 4 shows the final selection (left) of $\delta\phi$ (top), $\delta\Delta t$ (bottom), and their averages in comparison (right) with the expected baz variations of the upper configuration from Fig. 1 (right), the b-up case.

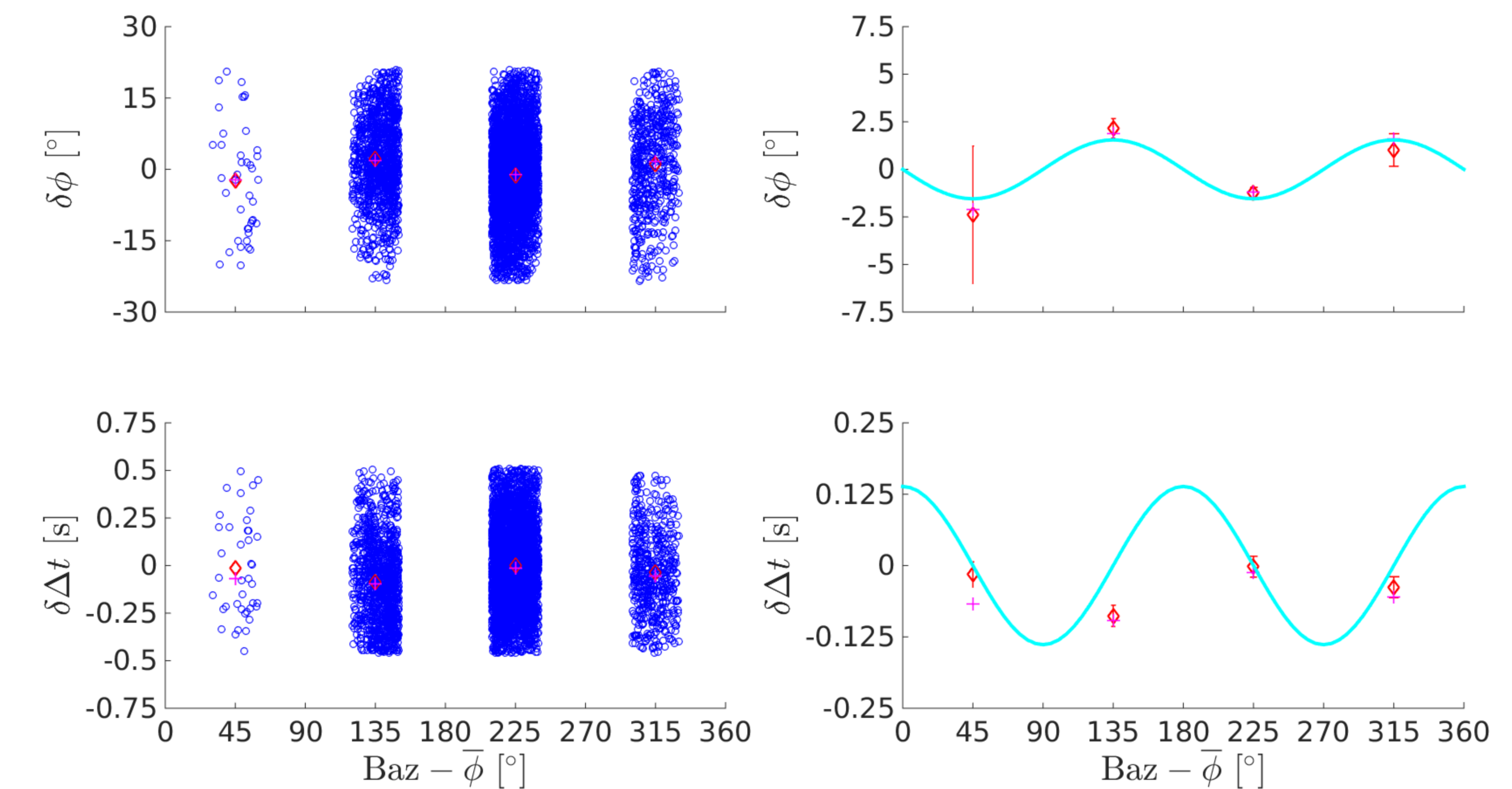


Fig. 4: Backazimuthal changes of shear-wave splitting parameters. (left) Mean (diamond) and median (plus) $\delta\phi$ and $\delta\Delta t$ of selected values. (right) Comparison of means (errorbar: 2σ of the mean) and medians with expected variations (Fig. 1) for a b-up olivine (cyan line).

The very good agreement with this case suggests **the main source of observed anisotropy is related to a horizontal orientation of the rock foliation (and flow) plane**, which would be in line with **subsurface deformation being primarily in the asthenosphere** and coherent with the SAF model. The value of the d_1 -parameter for the b-up model (-0.7) can therefore be considered as an average value for Western and Central United States. The splitting delay for that same crystallographic model would be around 1.6 s, as shown for vertical incidence in Fig. 1 (right, black lines).

CONCLUSION

We introduced and tested a new approach to better understand seismic anisotropy and subsurface deformation in the upper mantle from shear-wave splitting, based on the non-vertical incidence of SKS waves. We have considered two scenarios of upper mantle anisotropy related to a lithospheric or asthenospheric origin, and shown that **both endmember models can be distinguished in real data**, by using the backazimuthal variation of SKS splitting measurements. Investigating shear-wave splitting results in the Western and Central United States, **the derived variations of individual measurements per station ($\delta\phi$, $\delta\Delta t$) unveiled the predicted variations, expected from Simple Asthenospheric Flow**, and $\delta\phi$ constrained the polarity of the oscillation parameter d_1 .

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