Imaging 3D Anisotropic Subduction Zone Structure with Teleseismic P-waves: Method and Application to the Western United States

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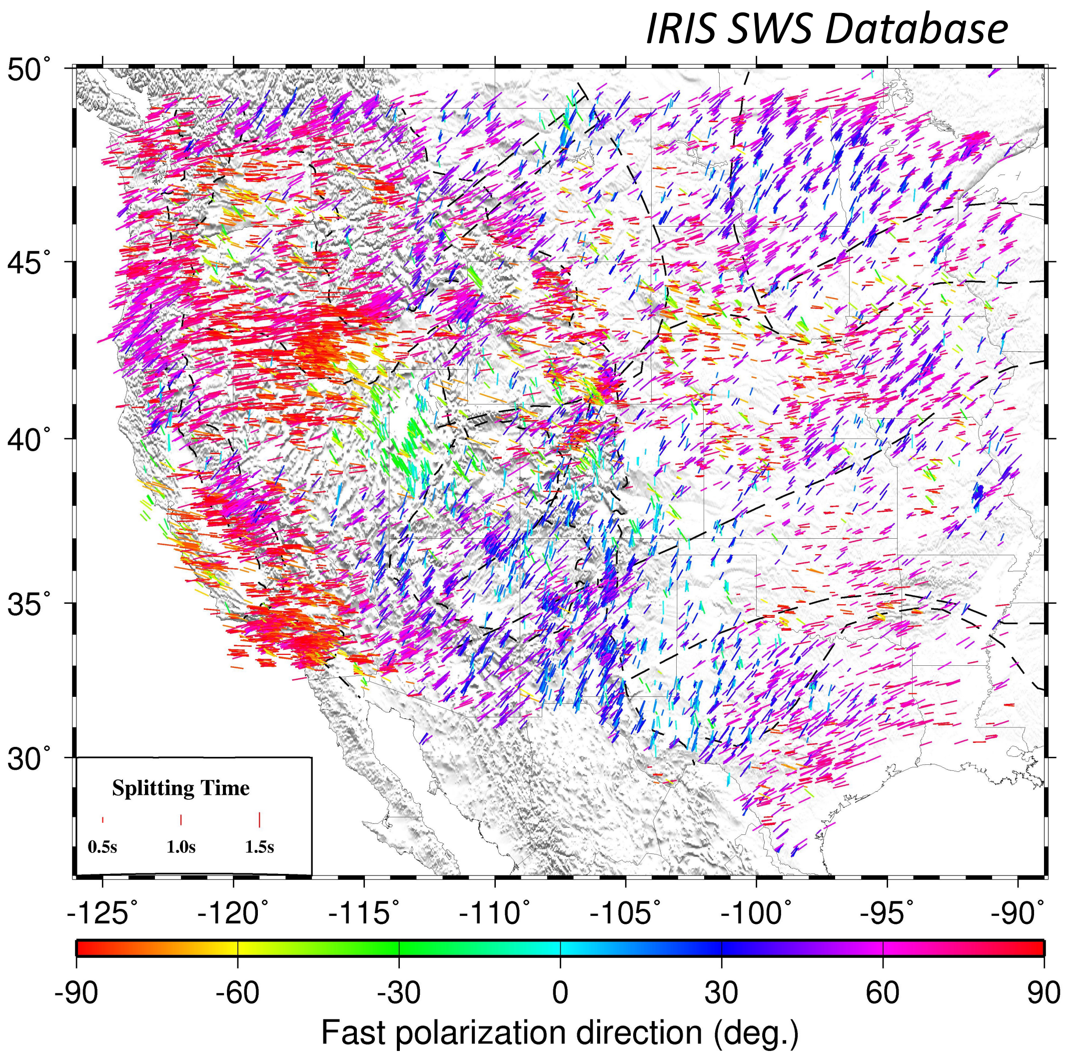
Motivation

- Contradictory assumptions regarding analysis of teleseismic wavefield
  - Shear wave splitting used to infer anisotropic structure
  - But we often ignore anisotropy in constructing tomographic models
- Neglecting anisotropy in teleseismic tomography generates significant artefacts
  - E.g., Blackman & Kendall, 1997; Sieminski et al., 2007; Lloyde & van der Lee, 2008; Bezada et al., 2016
- Anisotropy can easily be included in travel-time imaging and doing so improves models of the subsurface



Outline

1. Brief review of anisotropic imaging method
   a) Parameterization of anisotropy—including dip is key!
   b) Inclusion of approximate Born kernels
   c) For further details see VanderBeek & Faccenda GJI 2021

2. Present results from synthetic tests conducted using an elastically anisotropic geodynamic model of subduction
   a) Demonstrate how different assumptions (e.g. isotropic, azimuthally anisotropic) affect the image
   b) For details see VanderBeek & Faccenda GJI 2021

3. Present preliminary P-wave anisotropic images of the Western US

Methods: Anisotropy Parameterization

- Sinusoidal approximation for P-wave anisotropy in hexagonally symmetric medium:

slowness

anisotropic magnitude

symmetry axis azimuth

symmetry axis elevation

$$u = \bar{u}\left[1 \pm f\left(2\left[\cos(\theta)\cos(\gamma)\cos(\phi - \psi) + \sin(\theta)\sin(\gamma)\right]^2 - 1\right)\right]^{-1}$$

mean slowness

ray azimuth

ray elevation

Inversion for spherical anisotropic parameters can be problematic (Munzarovà et al., 2018)

- Vectoral representation of sinusoidal anisotropy

$$u = \bar{u}\left[1 \pm \left(\left[(n_1^2 - n_2^2)\cos(2\phi) + 2n_1n_2\sin(2\phi)\right]\cos^2(\theta) - (n_1^2 + n_2^2)\sin^2(\theta)\right.\right.$$
$$\left.\left. - n_3^2\cos(2\theta) + 2n_3\left[n_1\cos(\phi) + n_2\sin(\phi)\right]\sin(2\theta)\right)\right]^{-1}$$

Magnitude & orientation of azimuthal anisotropy

Anisotropic Inversion Parameters
$A = (n_1^2 - n_2^2)$
$B = 2n_1n_2$
$C = n_3$
$\bar{u}$

Fabric dip parameter

Methods: Approximate Born Kernels

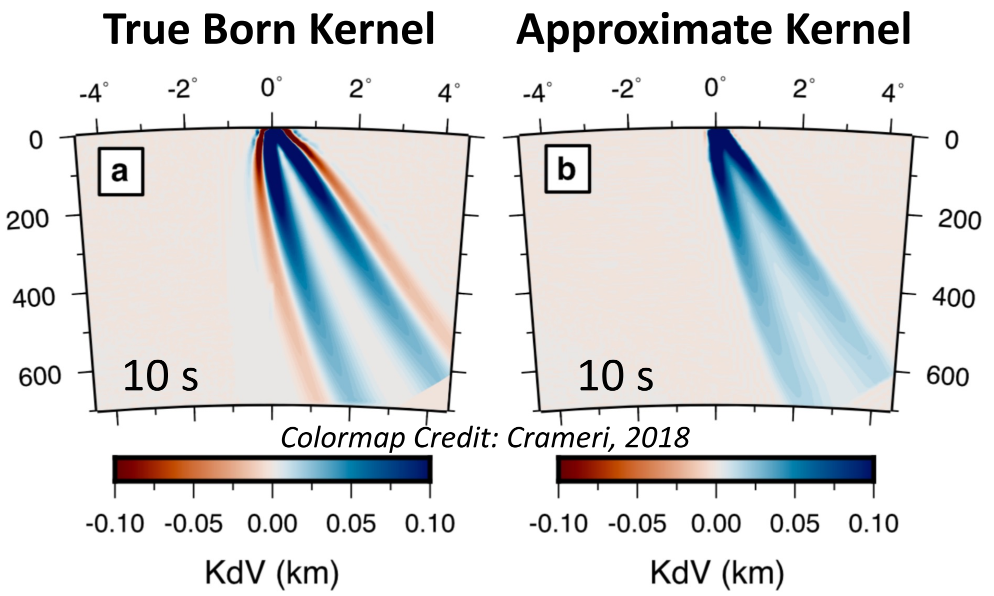
- Finite-frequency travel-time from Dahlen et al. (2000)

$$t = t' + \int_V (u - u')K\,dV$$

- Kernel approximation from Schmandt & Humphreys (2010)

$$K(x,r) = \frac{Q}{\pi R_f^2(x)} \sin\left(\pi \frac{r^2}{R_f^2(x)}\right)$$

- Treat anisotropic heterogeneity as isotropic scatters using slowness in direction of propagation
  - *dt/dm = Kdu/dm; m =* $A, B, C, \bar{u}$



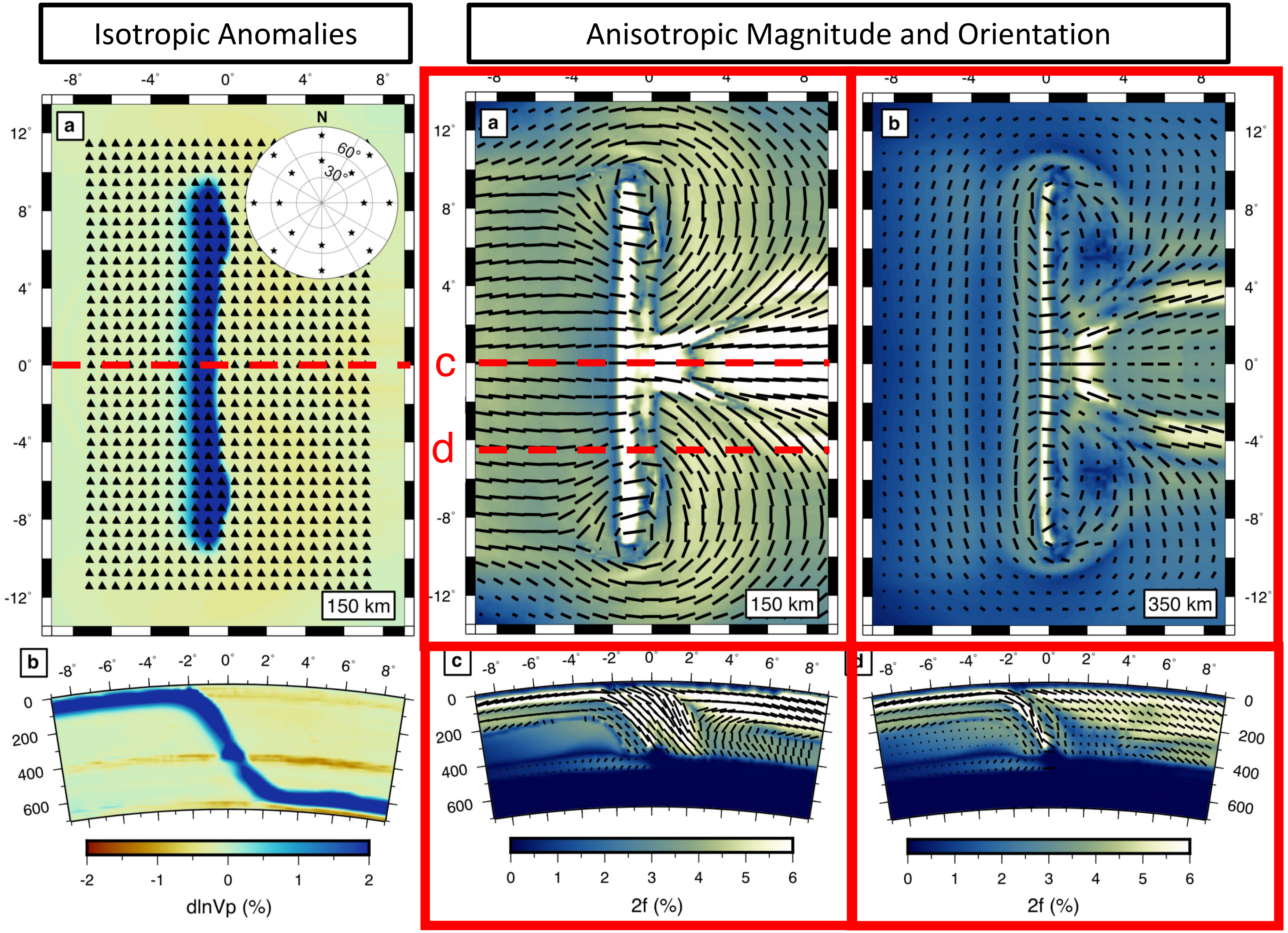
Colormap Credit: Crameri, 2018

- Verified anisotropic kernel approximation via SPECFEM
  - RMS travel-time errors: 325 ms (ray theoretical) and 165 ms (approximate kernels) relative to cross-correlated delay time measurements

Synthetic Subduction Zone Model

Realistic synthetic dataset is independent from inversion algorithm

- Anisotropic elastic model from geodynamic model of subduction (Faccenda, 2014)
- Model teleseismic wavefield with SPECFEM + AxiSEM (includes P, S, and SKS phases; Monteiller & Long, 2013; Nissen-Meyer et al., 2014)
- 770 receivers spaced 75 km apart record teleseismic wavefield from 16 sources evenly distributed in back azimuth



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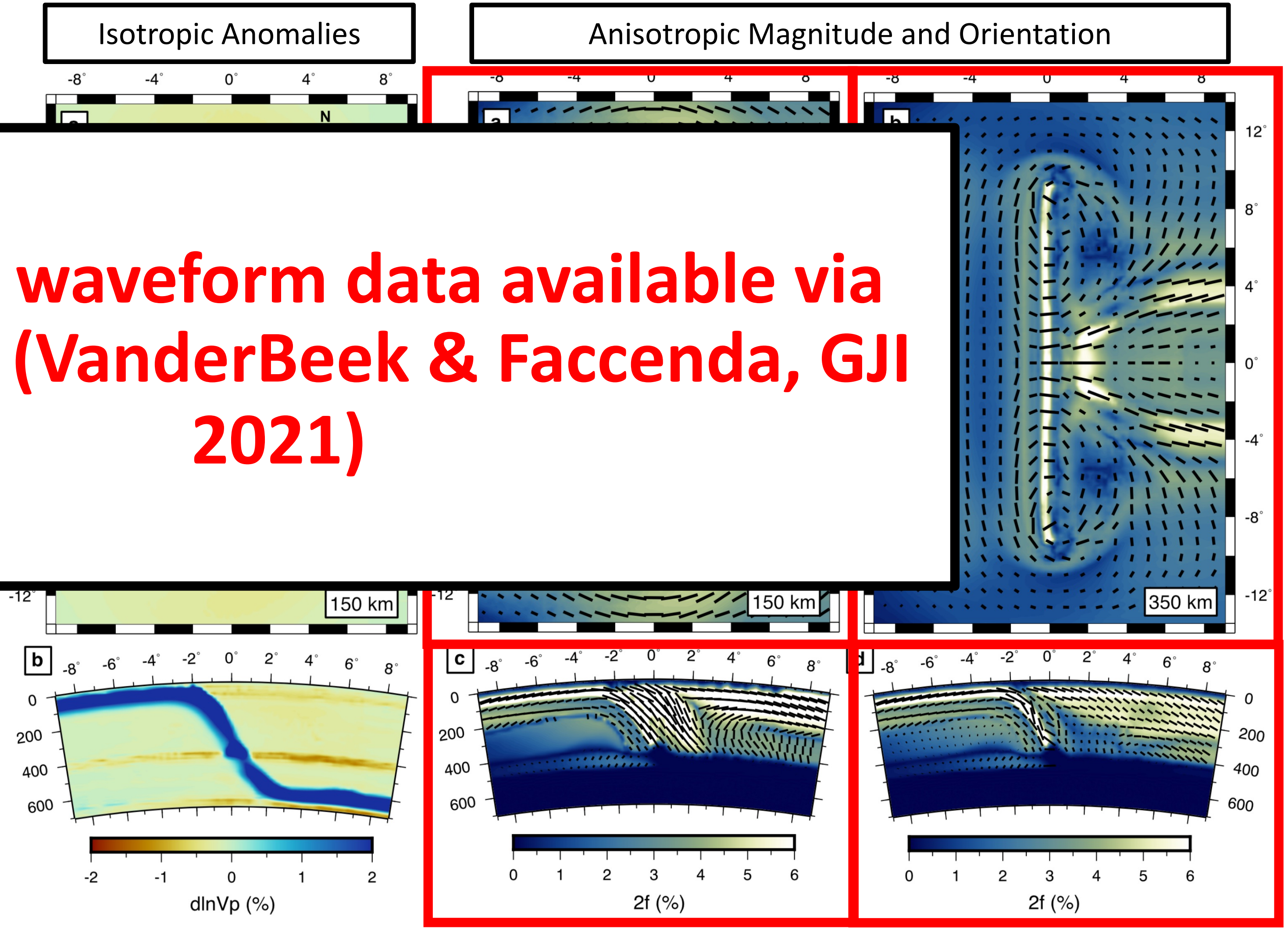
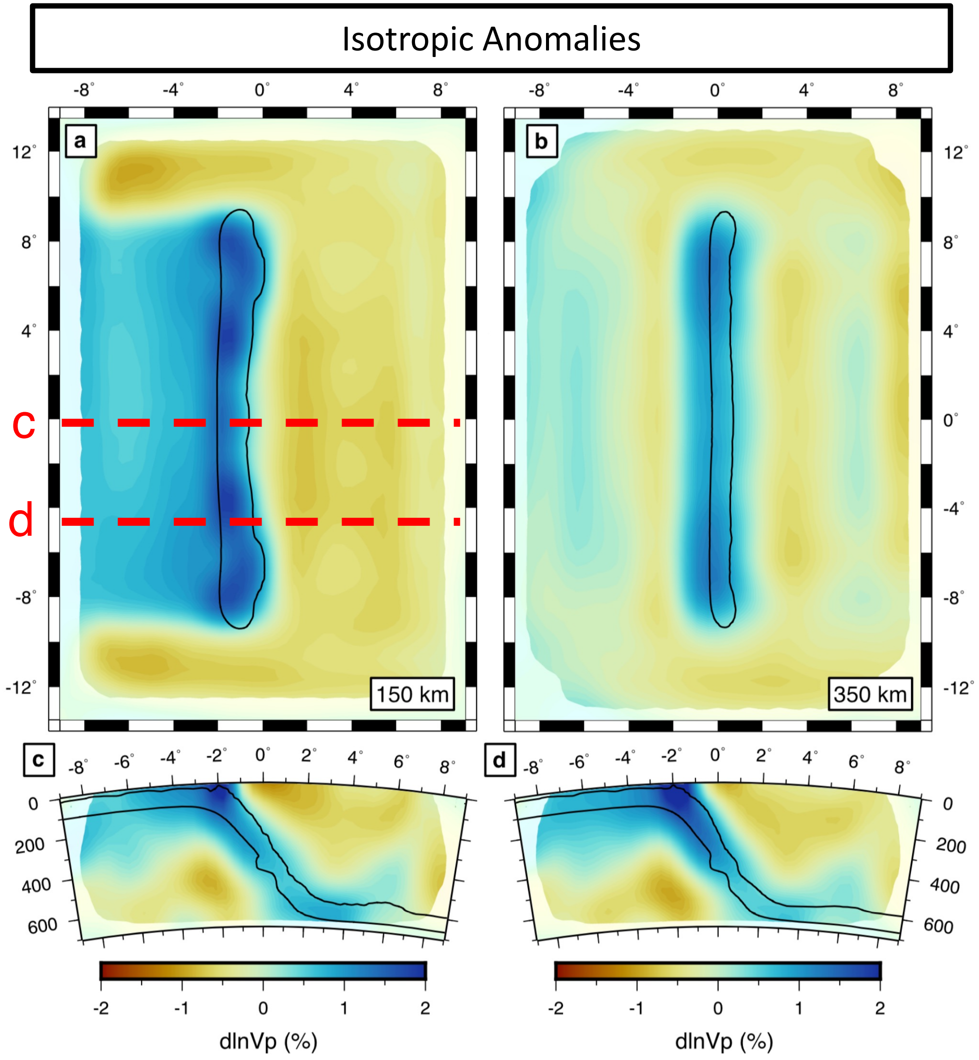


All seismic waveform data available via publication (VanderBeek & Faccenda, GJI 2021)

Colormap Credit: Crameri, 2018

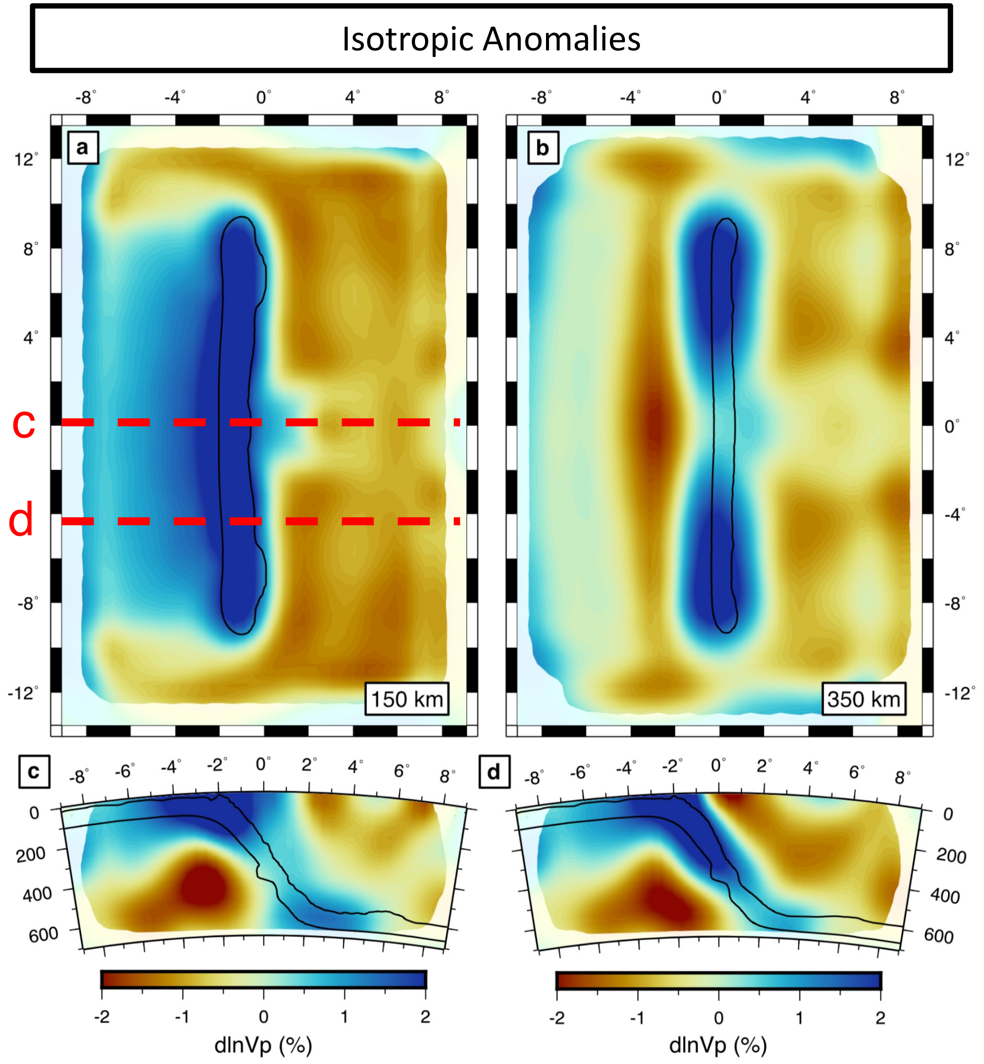
Isotropic Inversion of Isotropic Data



Colormap Credit: Crameri, 2018

- In this case, inverting teleseismic data created with isotropic model
- Illustrates recovery of isotropic heterogeneity in absence of complications due to anisotropy
- Relative nature of teleseismic data requires that the fast slab be balanced by low velocity perturbations
- Low-velocity zones are small in amplitude and evenly distributed

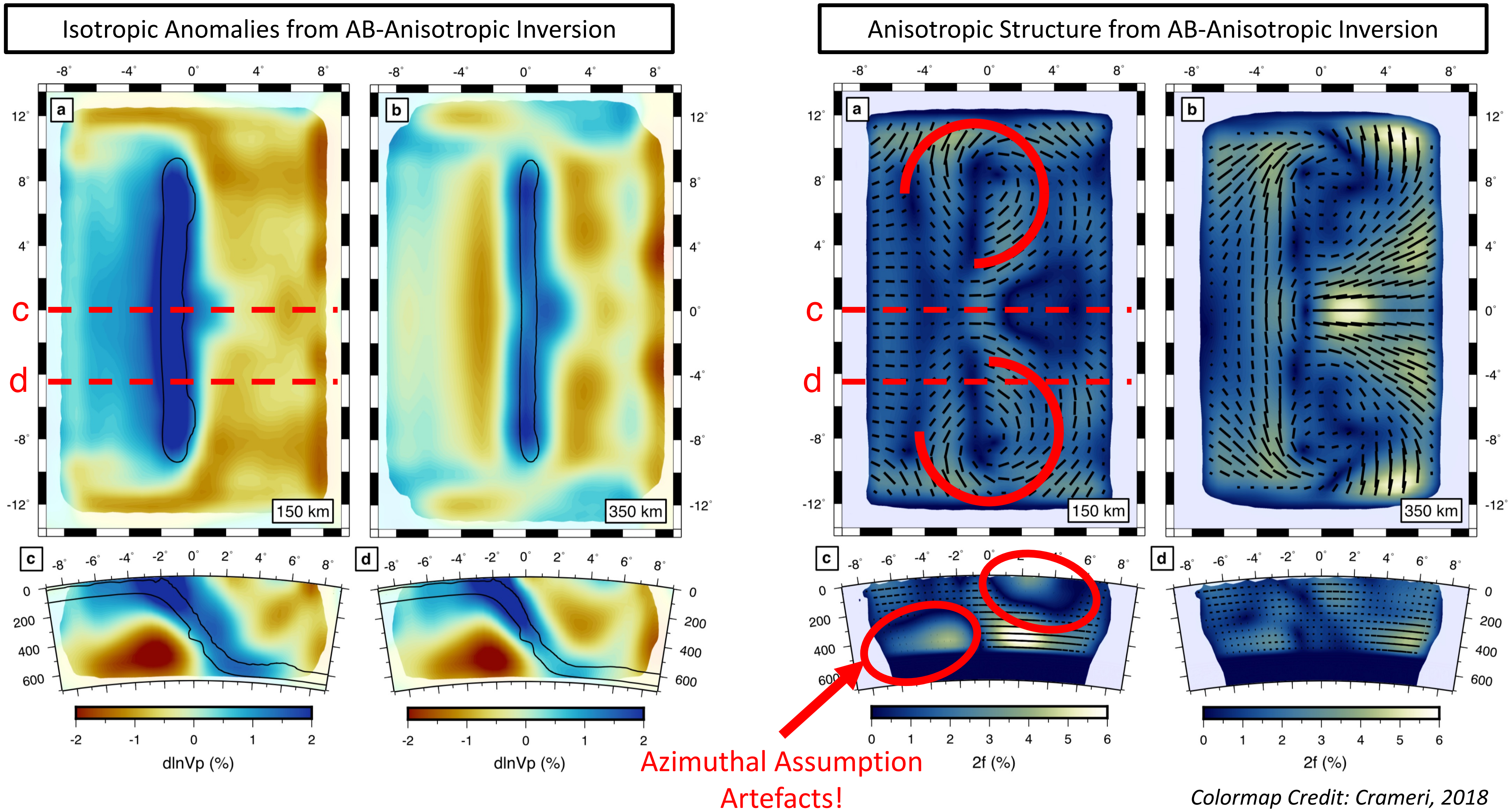
Anisotropic Structure Creates Strong Isotropic Artefacts



Colormap Credit: Crameri, 2018

- Isotropic inversion of anisotropic data
- Significant distortion of slab geometry
- Significant increase in magnitude of low velocity artefacts
- Low velocity zones have stronger amplitude beneath the slab

Azimuthal Anisotropy is a Poor Assumption



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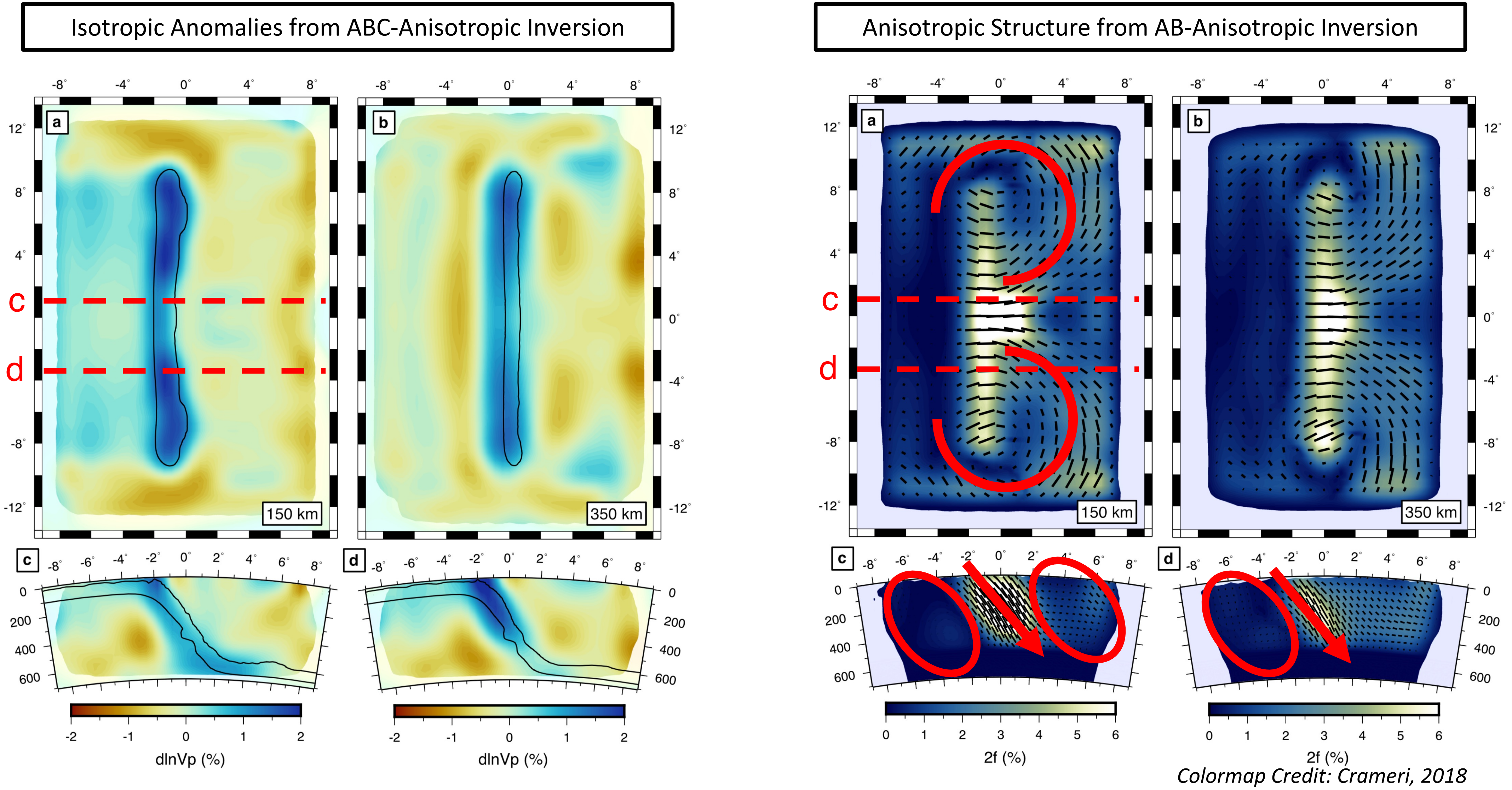
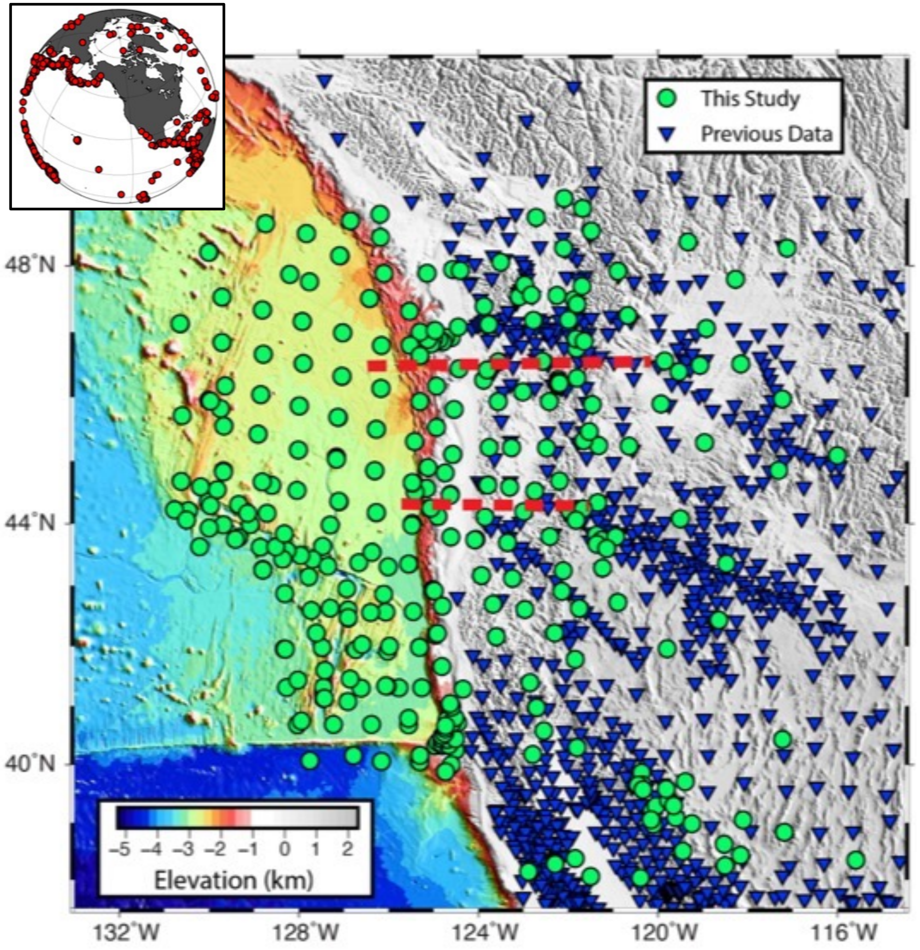
Accounting for Dip is Key to Improving Images



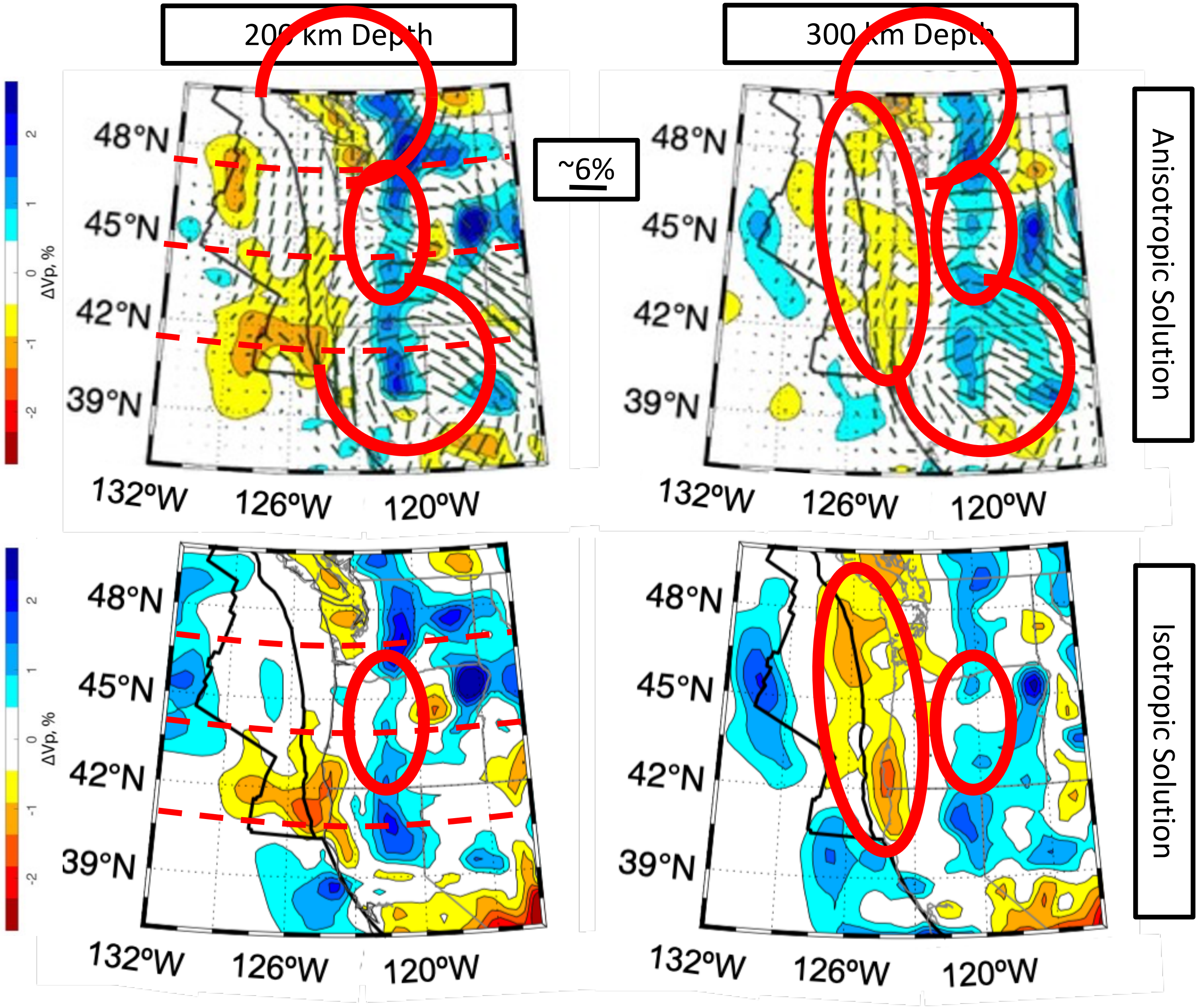
Application to the Western US



Bodmer et al., 2020

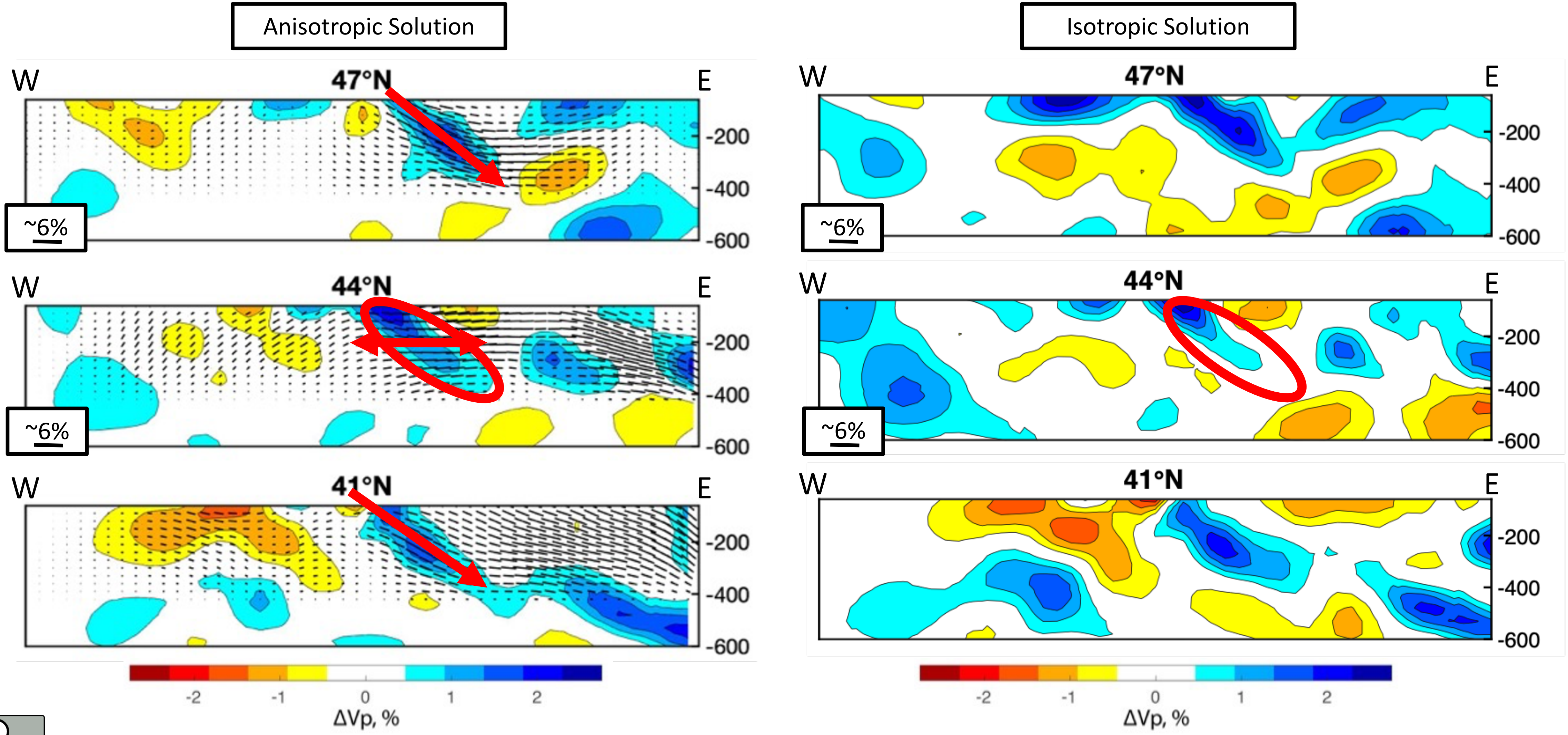
- Lots of data combined with onshore and offshore station coverage
- Extensive database of SKS splits against which anisotropic models can be validated
- Open questions regarding dynamics of Juan de Fuca plate with surrounding mantle
  - Role of slab hole in facilitating large-scale toroidal flow (Long, 2016)
  - Sub-slab low-velocity anomalies (Hawley et al., 2016; Bodmer et al., 2018)

Western US: Clear Toroidal Flow Pattern and Reduced LVZs



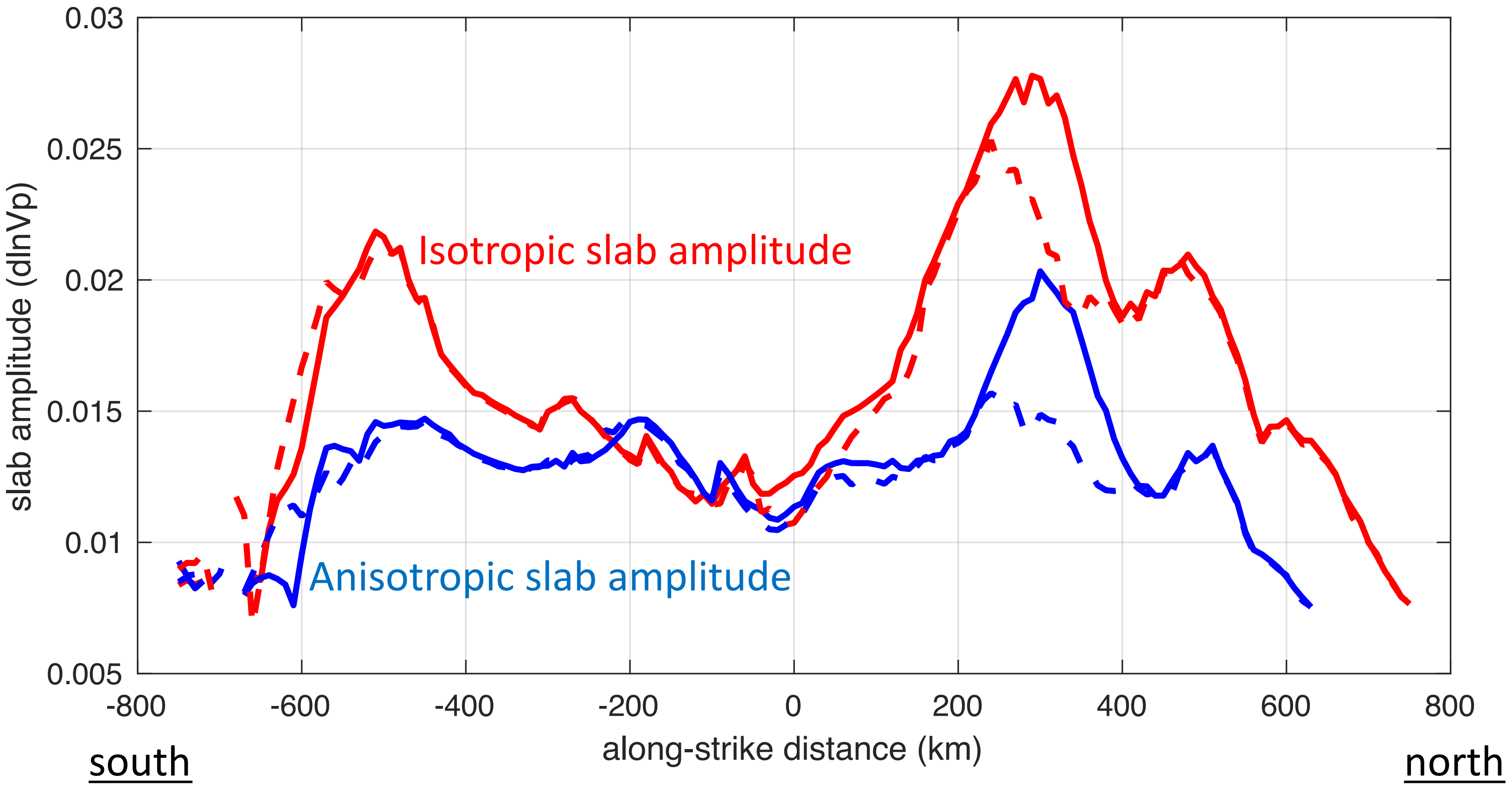
- P-wave delays image clear toroidal flow pattern in southern Cascadia and possibly similar pattern to the north
- No slab hole? Anisotropic model has more continuous slab
- Low-velocity zones reduced in anisotropic model

Western US: Slab-parallel Anisotropy Disrupted in Central Cascadia



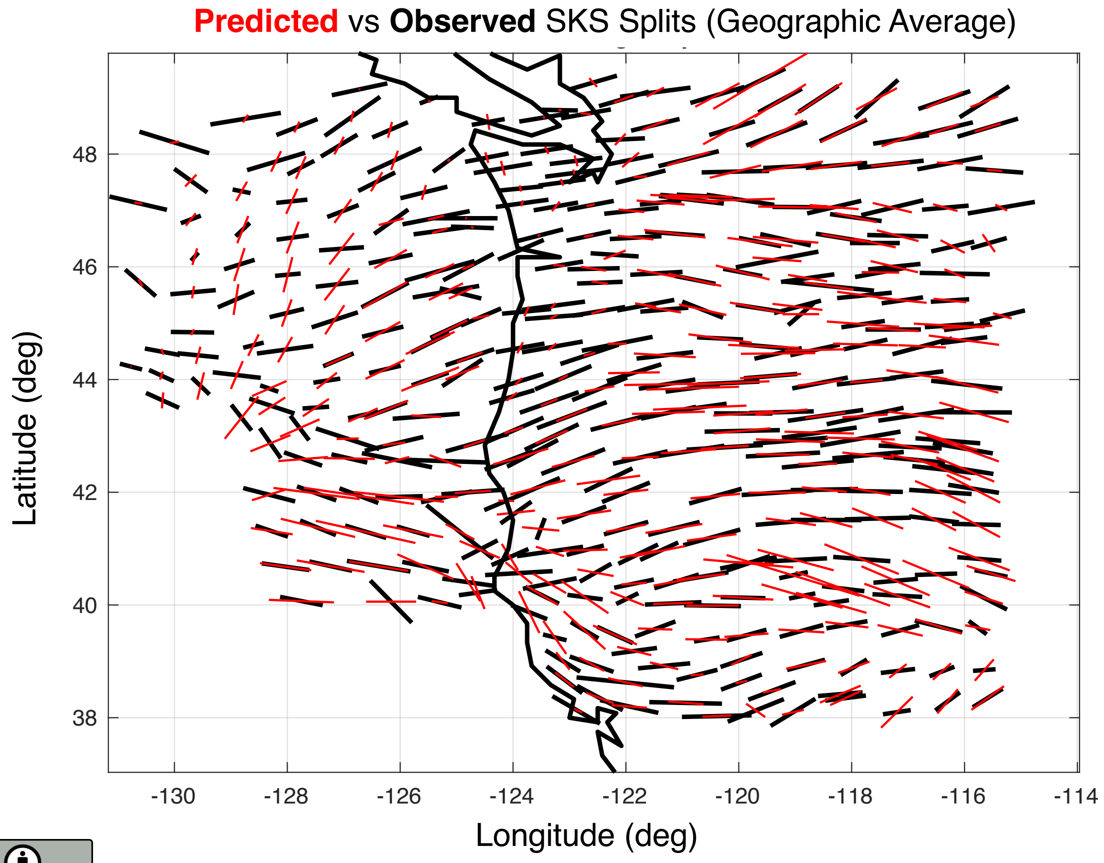
Western US: Average Slab Amplitude (Isotropic vs Anisotropic)

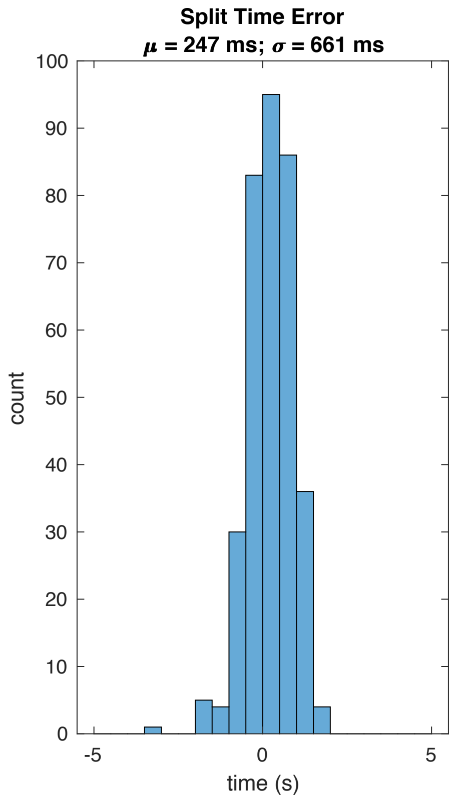
Anisotropic inversions do not exhibit strong along-strike slab amplitude variations as observed in prior isotropic imaging studies

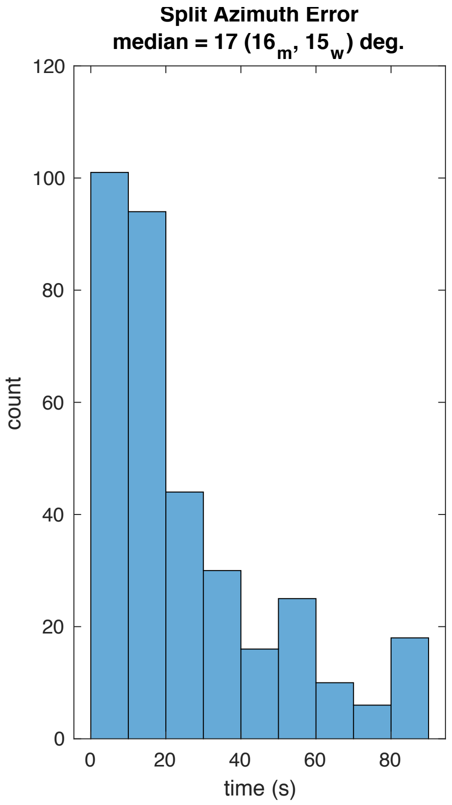


Western US: Anisotropic P-wave Model Predicts Independent Shear Wave Splitting Observations

SKS splits predicted through tomographic model agree remarkably well with observations!







Conclusions

- Neglecting anisotropy can result in significant teleseismic imaging artefacts
- Teleseismic P-wave delays can constrain 3D upper mantle anisotropic structure
- Accounting for fabric dip is key to removing anisotropic artefacts in isotropic structure
- Anisotropic P-wave imaging applied to the Western US (1) reveals clear toroidal flow pattern consistent with SKS splitting, (2) results in more coherent slab, and (3) reduces magnitude of mantle low-velocity zones