

Selected figures from

**Seismological constraints
on subduction zone
processes**

**MARGINS workshop on the
modeling of subduction zone dynamics
and thermal structure
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University of Michigan**

Karen Fischer
Brown University

Collaborators:

Jen Rilling and Marc Parmentier

Brown University

Chad Hall, Caltech

Matt Fouch, Arizona State

Doug Wiens and Gideon Smith

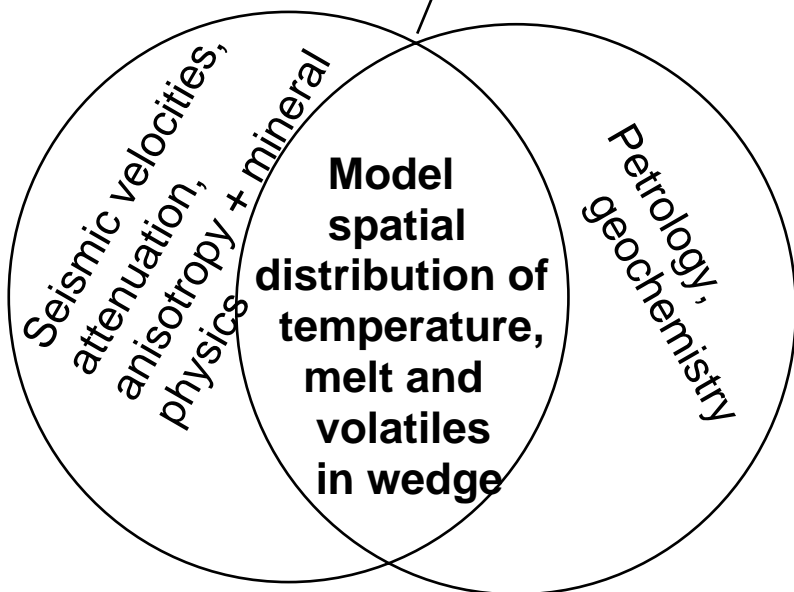
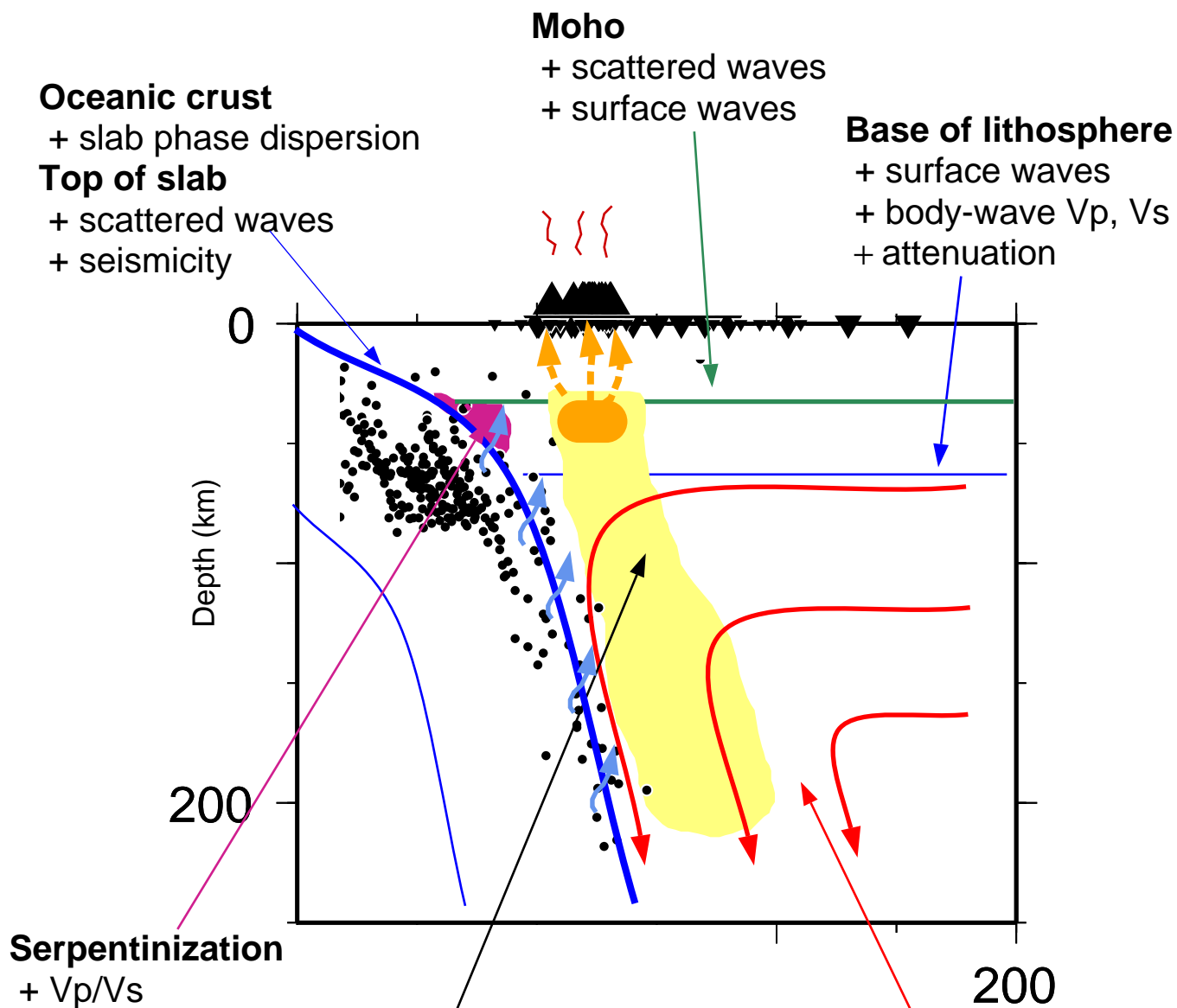
Washington University, St. Louis

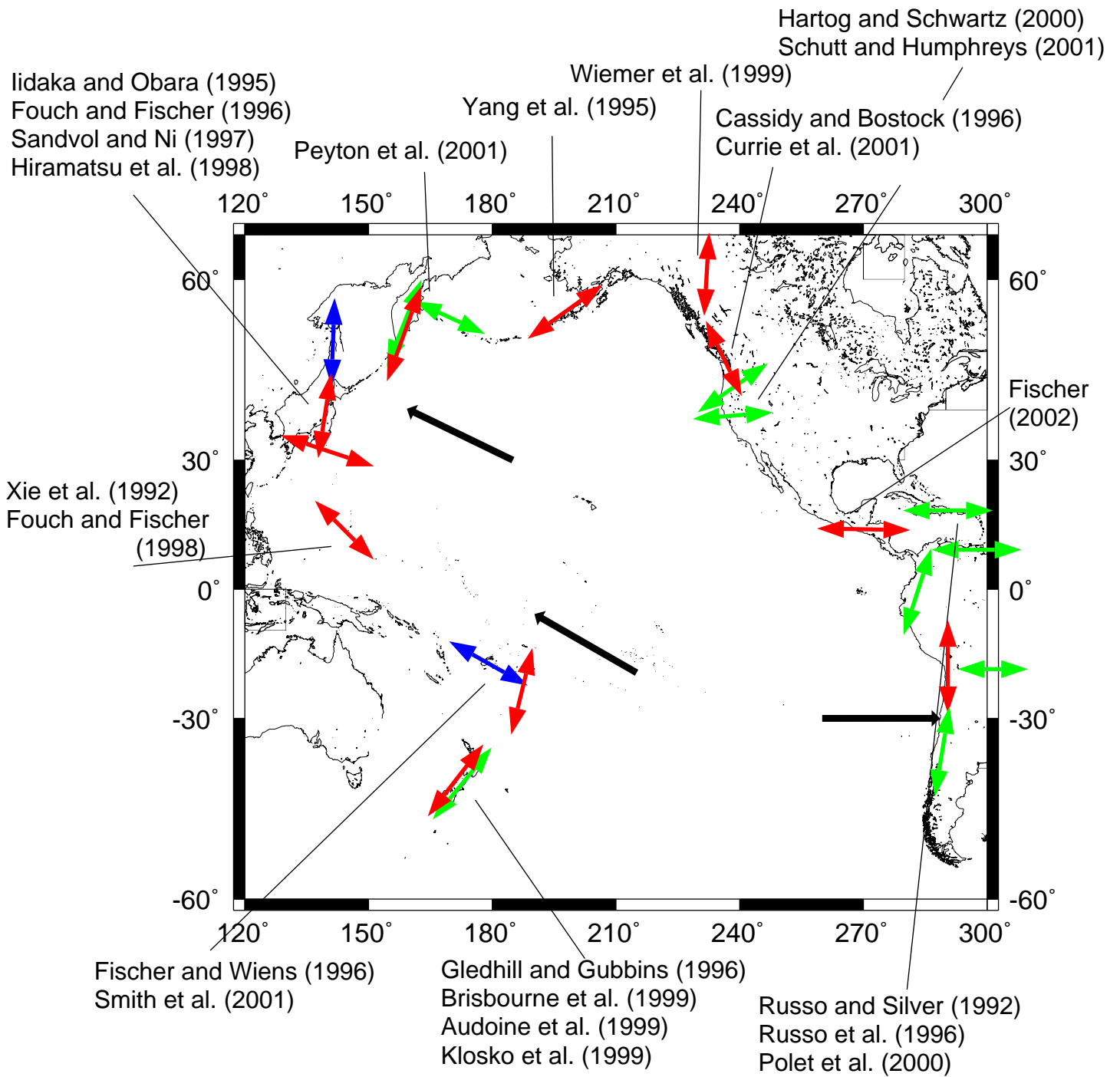
Abstract

Seismology offers numerous constraints for models of subduction zone thermal structure, flow and melting processes. For example, isoviscous flow models typically produce sub-arc mantle wedge temperatures lower than those suggested by petrologically defined geotherms, possible sediment melting, and heat flow data, but models with temperature-dependent viscosity have been shown to be capable of matching these observations. However, increasing the temperature-dependence of viscosity will also thicken the back-arc lithosphere, and seismic estimates of this thickness can place an upper bound on the temperature-dependence.

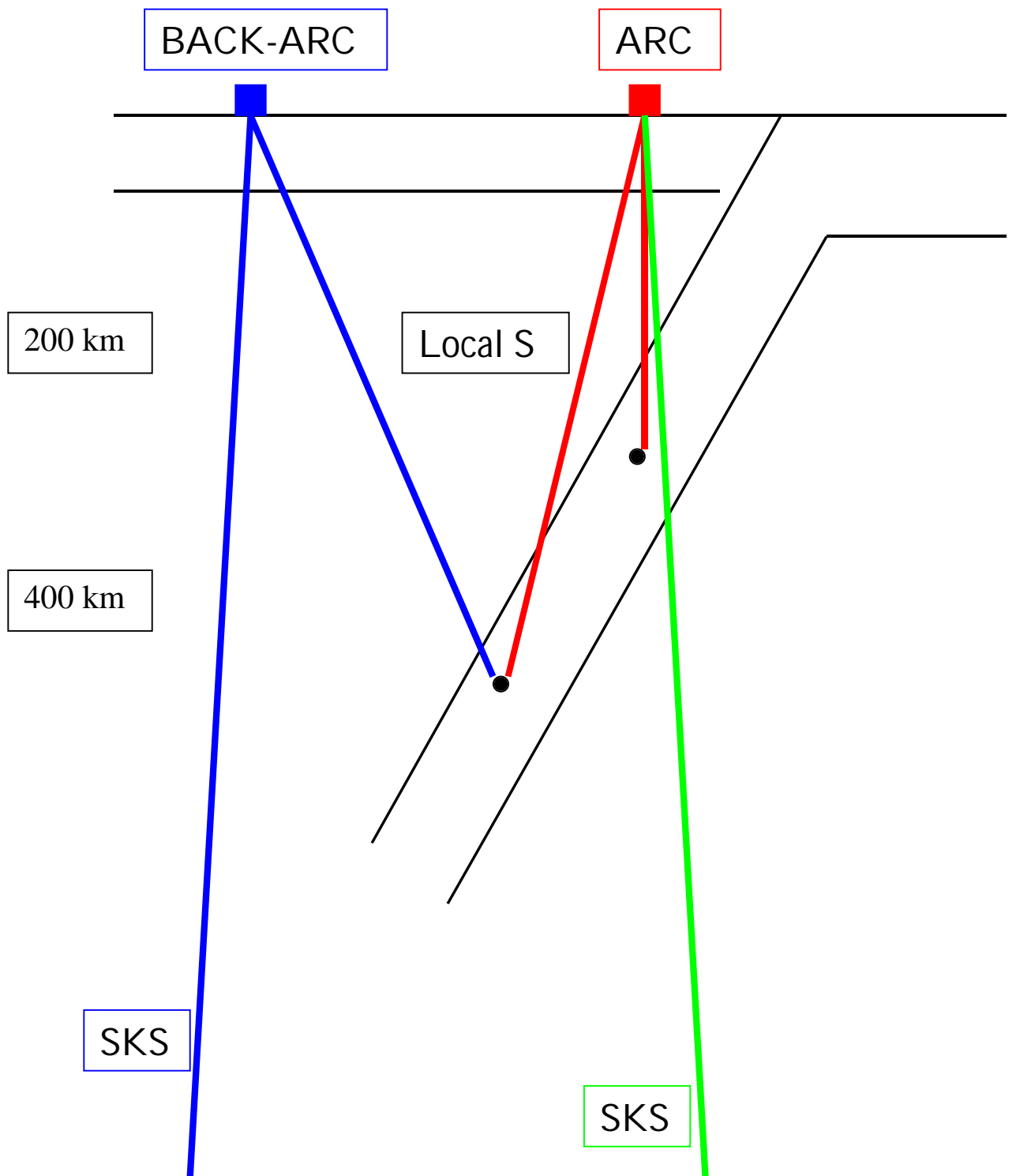
The pattern of mantle flow in subduction zones exerts strong control on subduction zone thermal structure and on the source of the mantle wedge rocks that eventually melt to form the volcanic arc. Seismic anisotropy can help to map the geometry of wedge flow. At back-arc stations, the fast directions of anisotropy inferred from shear-wave splitting show strong variations between subduction zones. In the Tonga back-arc, fast directions are roughly parallel to the azimuth of subducting plate motion, while in the southern Kurils, fast directions lie parallel to a back-arc strike-slip shear zone. In both cases, the observed anisotropy may be modeled by lattice preferred orientation of olivine in simple flow models driven by coupling to observed three-dimensional plate motions, assuming that olivine a-axes align with flow direction or maximum finite extension.

At stations located within arcs, the implications of observed shear-wave splitting are more ambiguous. In most arcs, including Tonga, shear-wave splitting observations from local earthquakes reveal anisotropy with a fast direction parallel to the arc, but fast directions in the Izu and Mariana arcs are exceptions to this rule and lie roughly normal to the arc. Correlations of splitting times with path lengths in the mantle wedge and full waveform modeling of shear-wave propagation in anisotropic subduction zone models demonstrate that the observed splitting is dominated by anisotropy in the mantle wedge beneath many arcs. Assuming that olivine a-axes align parallel to flow (i.e. the typical dry olivine fabric or the wet and low stress fabric seen by Mehl et al. (2002) in the Talkeetna arc) the observed splitting may be explained by an arc-parallel component of flow beneath most arcs, and predominantly arc-normal flow (e.g. typical corner flow) in Izu and the Marianas. On the other hand, recent laboratory studies indicate that different olivine lattice-preferred orientation patterns develop given high water and stress (Jung and Karato, 2000) or melt compaction (Holtzman et al, 2001) conditions, and oriented zones of melt may produce their own competing anisotropic signatures. However, unless the distributions of water and melt vary strongly between arcs without producing an obvious signature in arc volcanics, such effects cannot alone explain the global pattern of observed arc fast directions, suggesting that three-dimensional variations in wedge flow do occur.

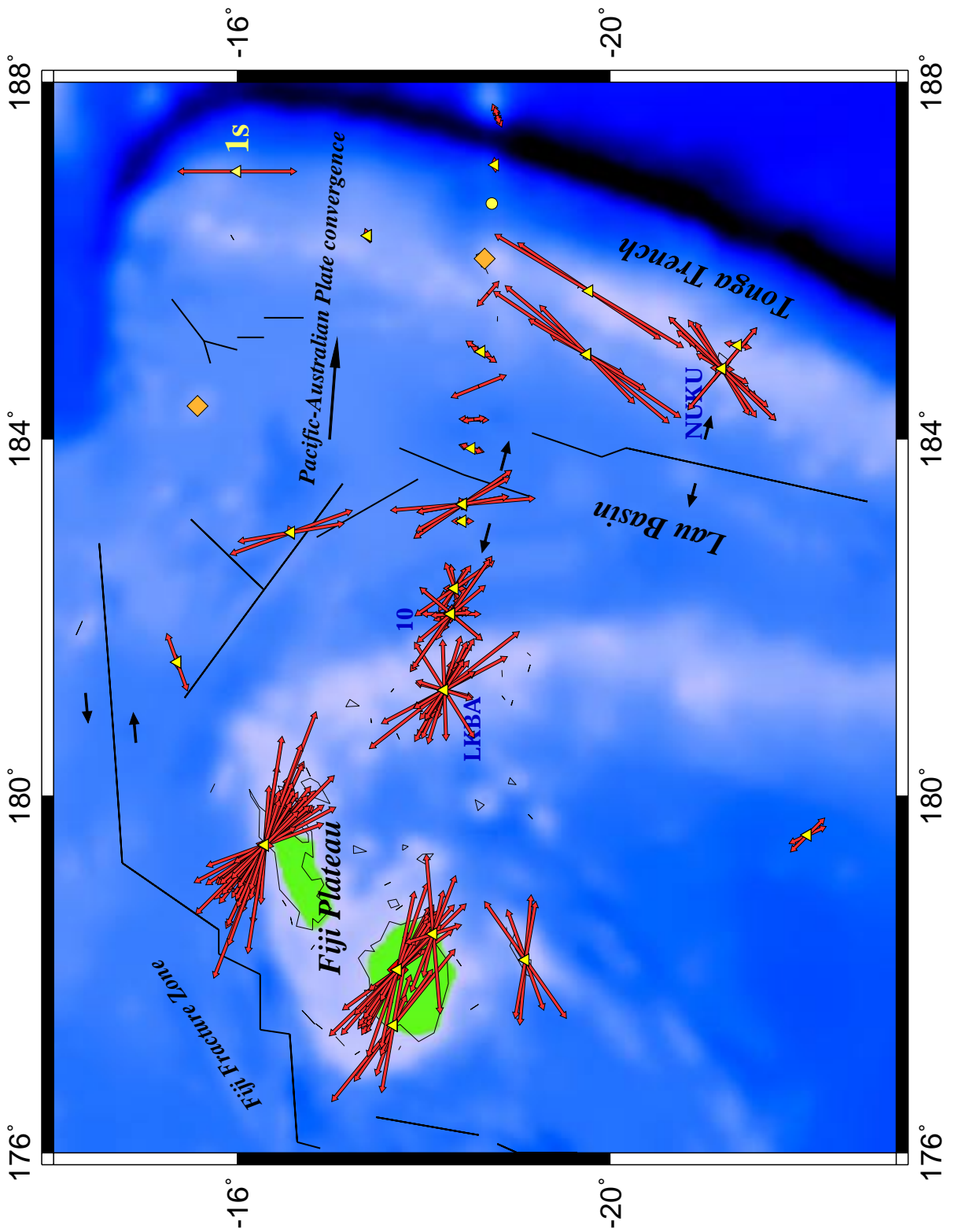




Summary map of recent subduction zone anisotropy studies.

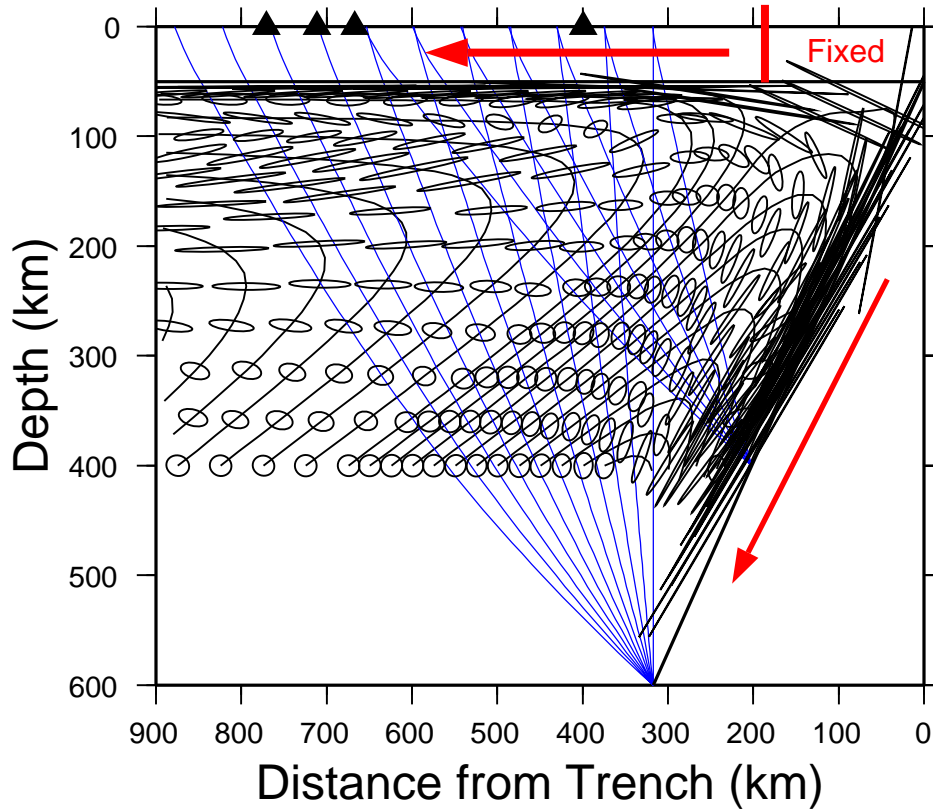


Schematic of shear-wave paths to illustrate color-coding of fast directions in shear-wave splitting summary map.

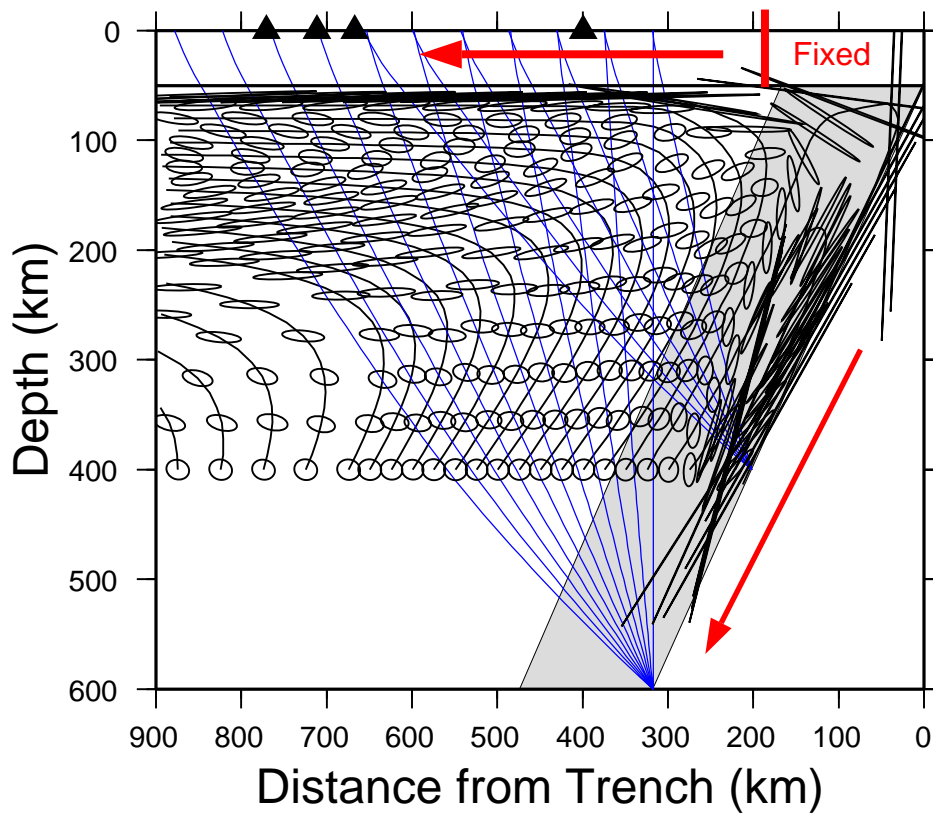


Smith et al. (2001)
 Shear-wave splitting in the Tonga subduction zone.

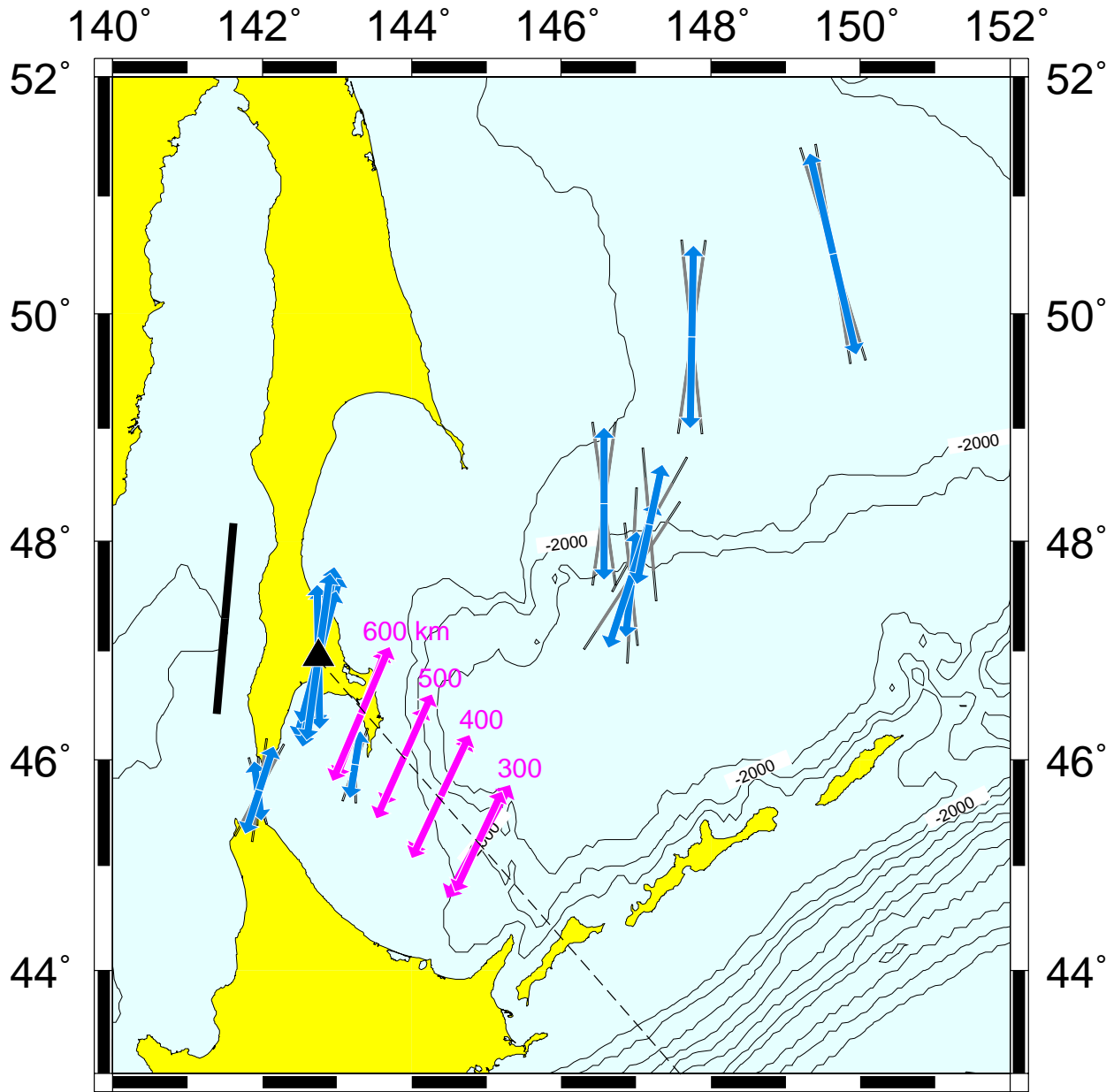
Uniform viscosity



LVZ at slab

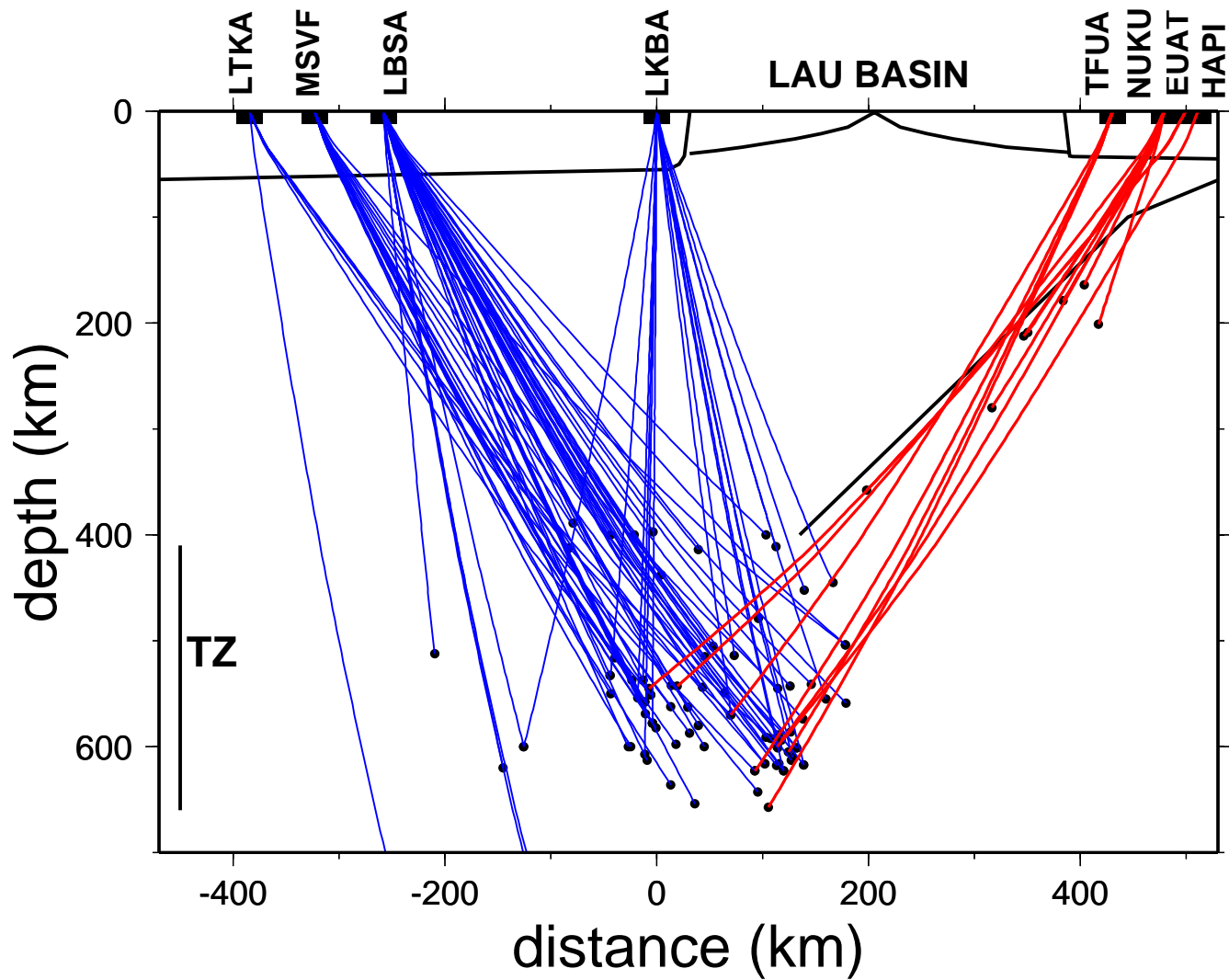


Model Predictions for Southern Kurils



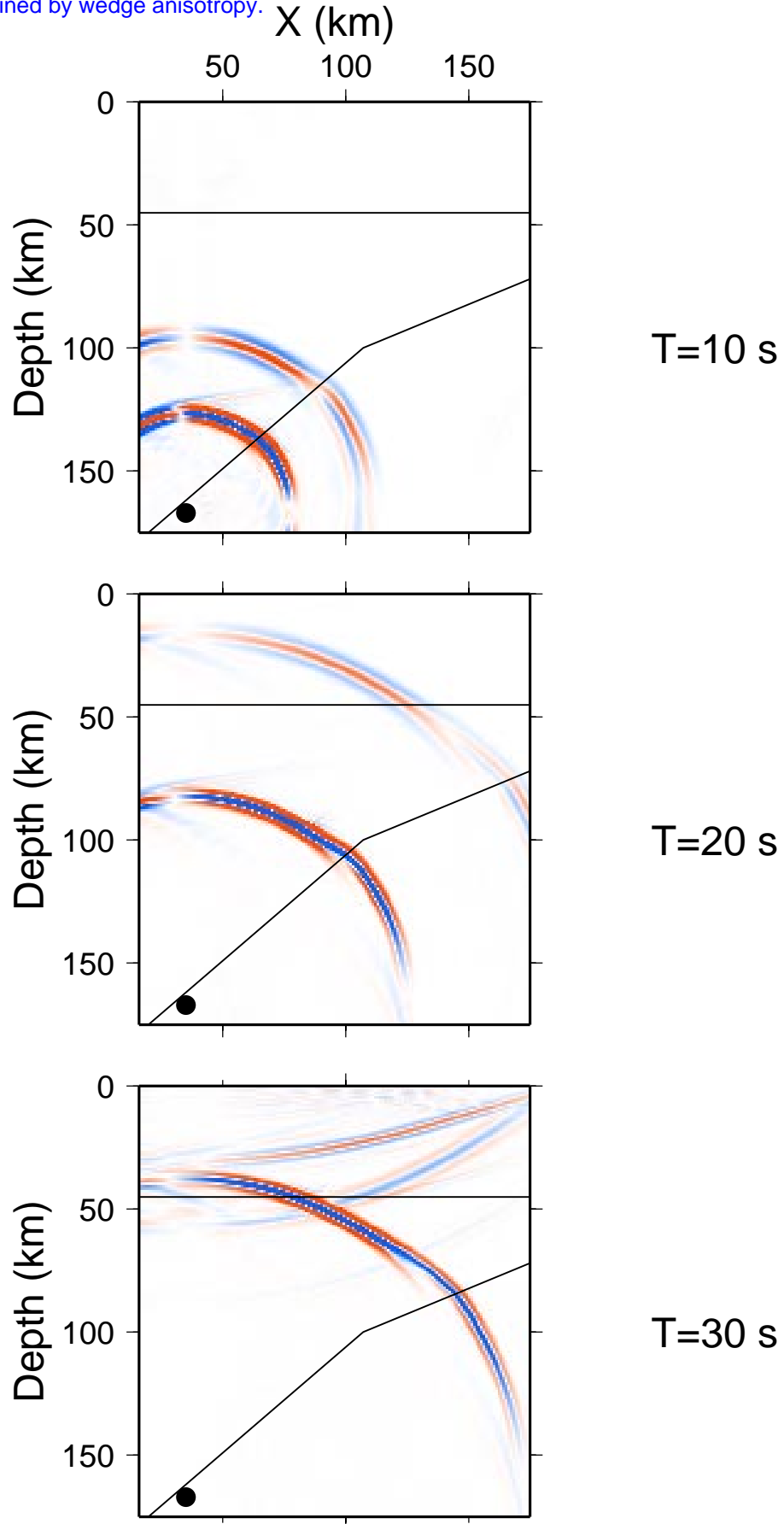
Observed Model
1.0 s

Hall (2000)
Shear-wave splitting predicted by wedge flow coupled to 3D plate motions (violet vectors) provides reasonable fit to splitting observed in southern Kuril back-arc (blue vectors).



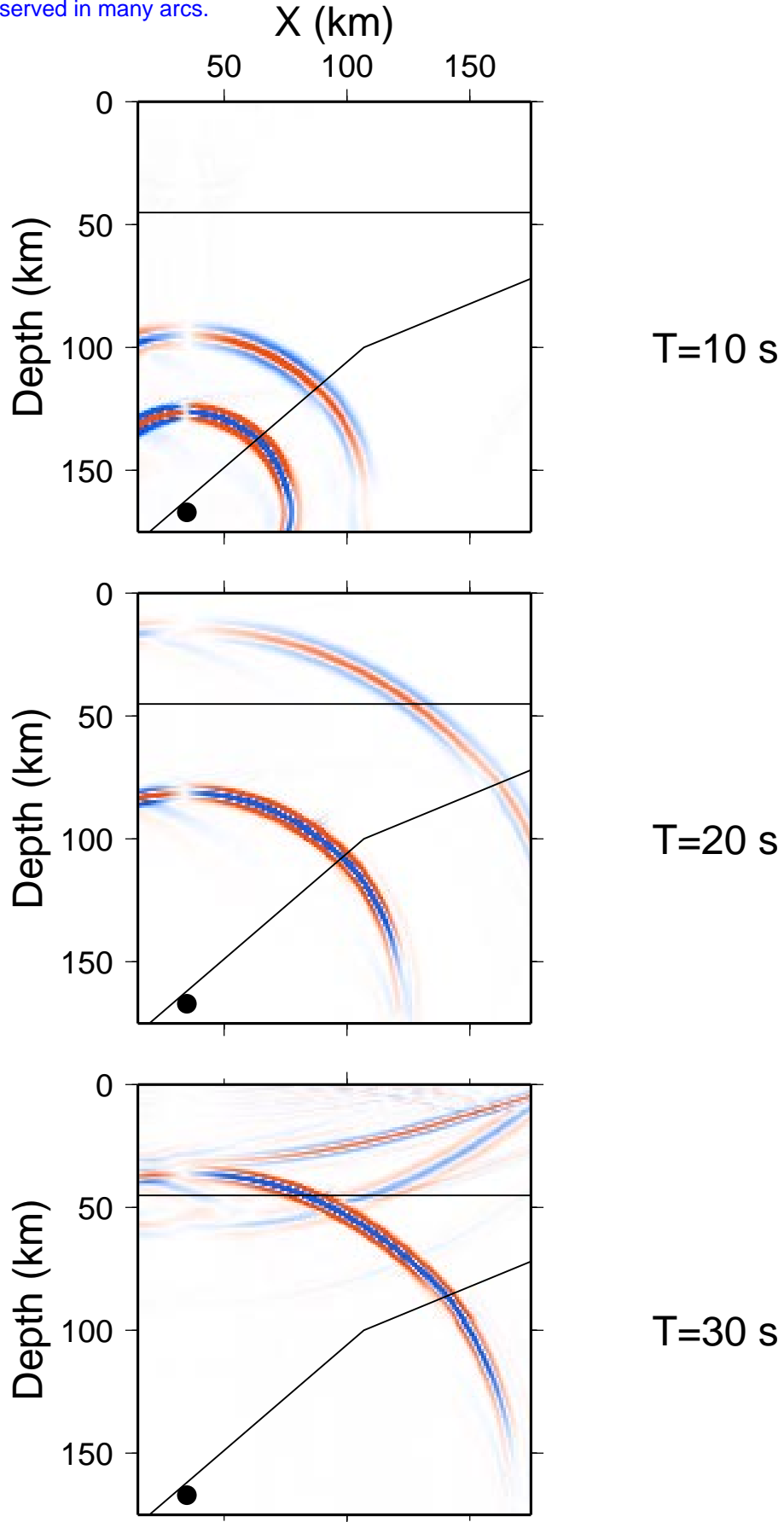
Ray paths to stations in the Tonga subduction zone. Paths to back-arc stations (blue) produce fast directions largely parallel to subducting plate motion; paths to arc stations (red) produce arc-parallel fast directions. The correlation of splitting times with wedge path length in this and other arcs indicates that the observed splitting is dominated by anisotropy in the wedge.

Full waveform (pseudospectral) calculation of seismic waves emanating from a subduction zone source (dot). Each panel shows a slice of 3D propagation through a 2D model, using the horizontal component of motion in the plane of the page. The S-wave is the later major phase seen in each panel. The wedge contains 3% anisotropy with a fast direction parallel to the arc. The upper plate and slab are isotropic and the slab is 5% fast. Analysis of synthetic shear-wave splitting recorded at surface stations shows that splitting observed in many arcs may be explained by wedge anisotropy.



Full waveform (pseudospectral) calculation of seismic waves emanating from a subduction zone source (dot). Each panel shows a slice of 3D propagation through a 2D model, using the horizontal component of motion in the plane of the page. The S-wave is the later major phase seen in each panel.

The slab contains 6% anisotropy with a fast direction parallel to the arc. The upper plate and wedge are isotropic and the slab is 5% fast. Analysis of synthetic shear-wave splitting recorded at surface stations shows that slab anisotropy cannot explain splitting observed in many arcs.



Hypotheses for sub-arc anisotropy:

- 1) Flow direction varies by region
Olivine a-axes parallel to flow
“dry” olivine fabric
“wet”, low strain rate fabric (Mehl et al., 2002)

Evidence:

- Geochemical data in Tonga (Turner and Hawkesworth, 1998)
- Arc-parallel shearing in Talkeetna arc (Mehl et al. 2002)

Could explain anisotropy in all arcs given 3D flow.

- 2) ~2D plate-driven flow plus variations in olivine LPO:
“wet”, high strain rate (Jung and Karato, 2000)
melt (Holtzman et al., 2001)

No apparent correlation of wedge water/melt content with arc fast-directions – but contributions from these effects cannot be ruled out.

3) ~2D plate-driven flow + melt anisotropy

Could match arc-parallel fast directions only.

Cannot explain splitting in Izu, Marianas.

Conclusions

- Seismic thickness of back-arc lithosphere provides upper bound on temperature dependence of viscosity
(Lower bound from petrological geotherm, sediment melting, heat flow...)
- **Back-arc anisotropy** (Tonga, S. Kurils) well-modeled by 3D wedge flow coupled to plate motions
- **Arcs:**
Most exhibit arc-parallel fast directions
Izu, Marianas fast directions arc-normal
Splitting dominated by mantle wedge anisotropy – confirmed by pseudospectral wavefield calculations
- Flow, volatiles, melt all affect LPO, but variation in arc fast directions explained most simply by **3D variations in flow**