Constraining Yellowstone magmatic processes beneath the eastern Snake River Plain from Rayleigh wave ambient noise

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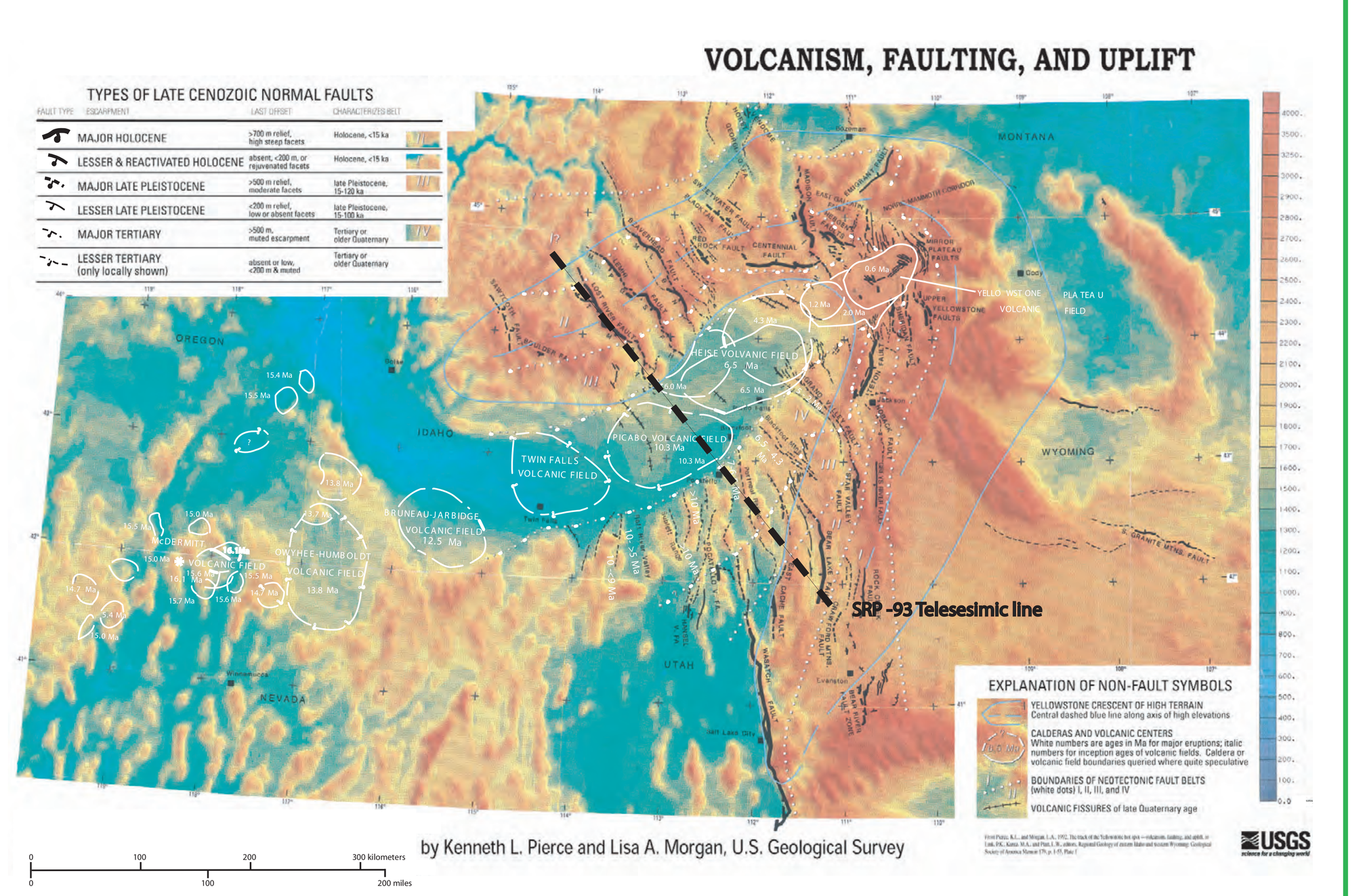
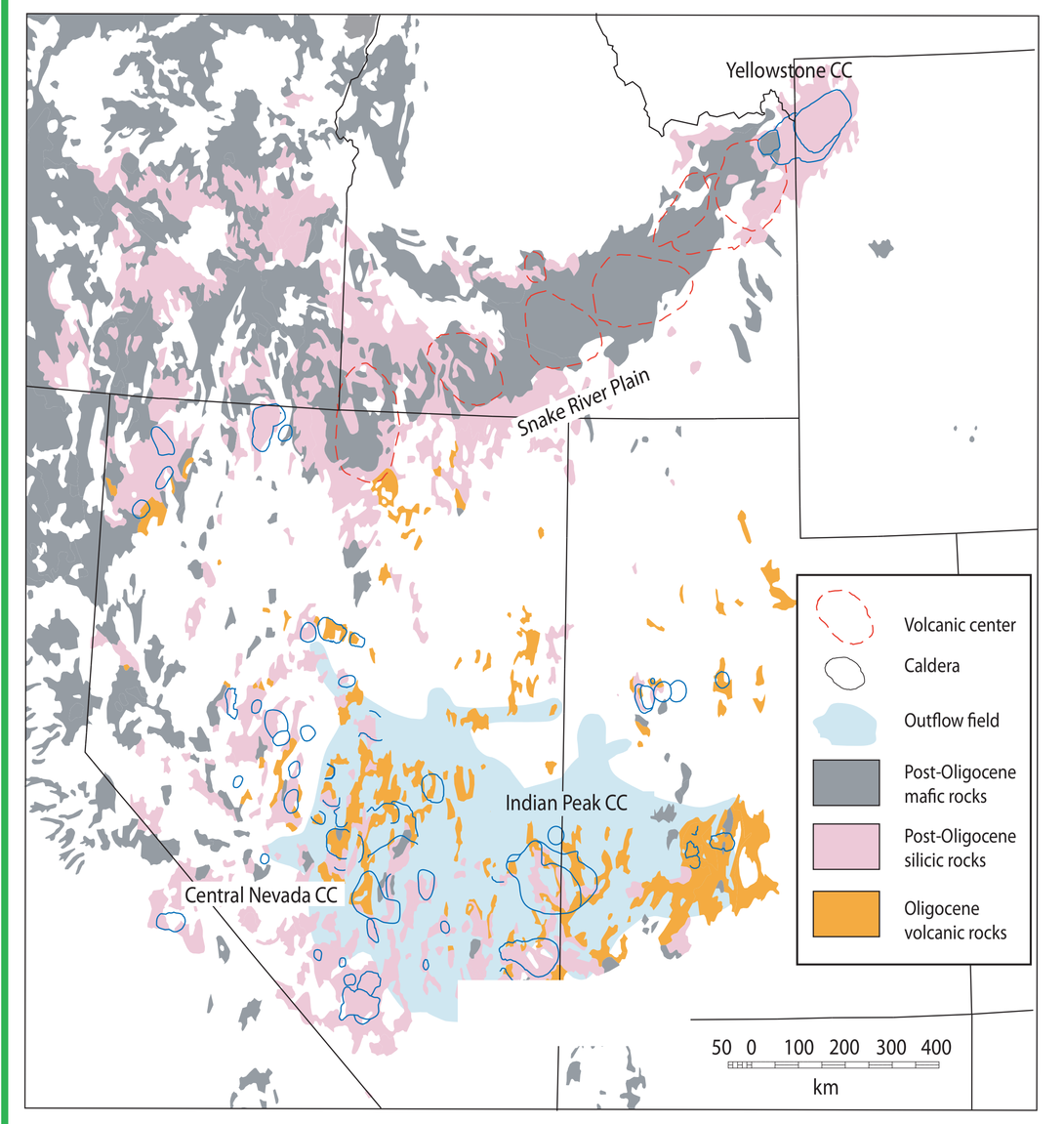
Space-time history of magmatic input and lower crustal flow along the Yellowstone hotspot track: Petrologic, GPS site velocity, and seismic constraints



by Kenneth L. Pierce and Lisa A. Morgan, U.S. Geological Survey

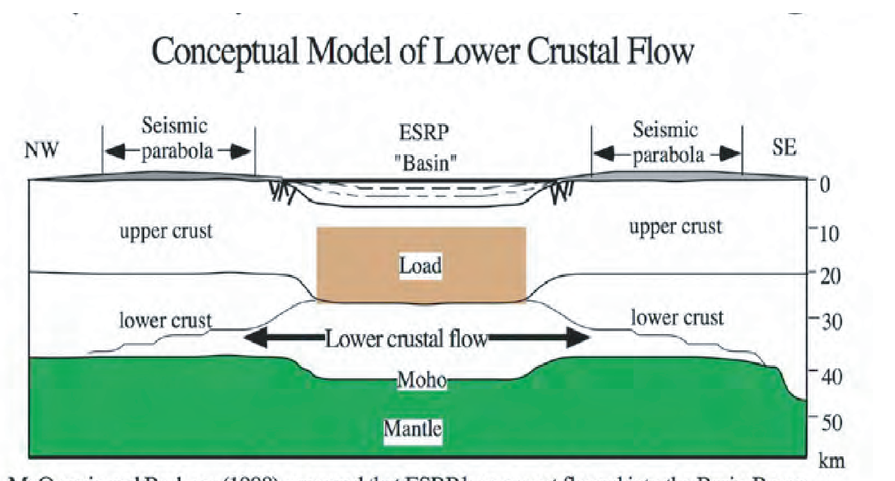


Above and Below figure from Christiansen and McCurry (in review)

The above figure shows the distribution of volcanics rocks. Remarkable is the difference in petrologic characteristics and eruption temperature between the Oligocene volcanic flareup and the Post-Miocene Yellowstone hotspot volcanic track.

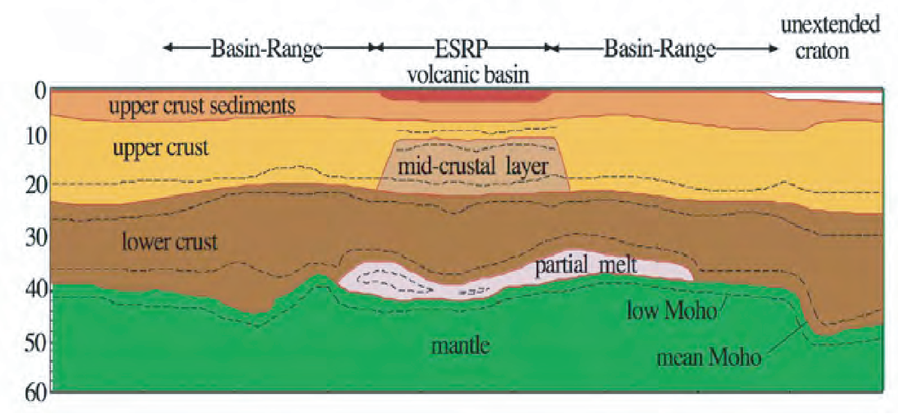
The below figure suggests the difference between the Oliogocene flare-up (wet melting above Farallon subduction) and the Yellowstone hotspot track (hot plume) is fundamental.

Conceptual Model of Lower Crustal Flow



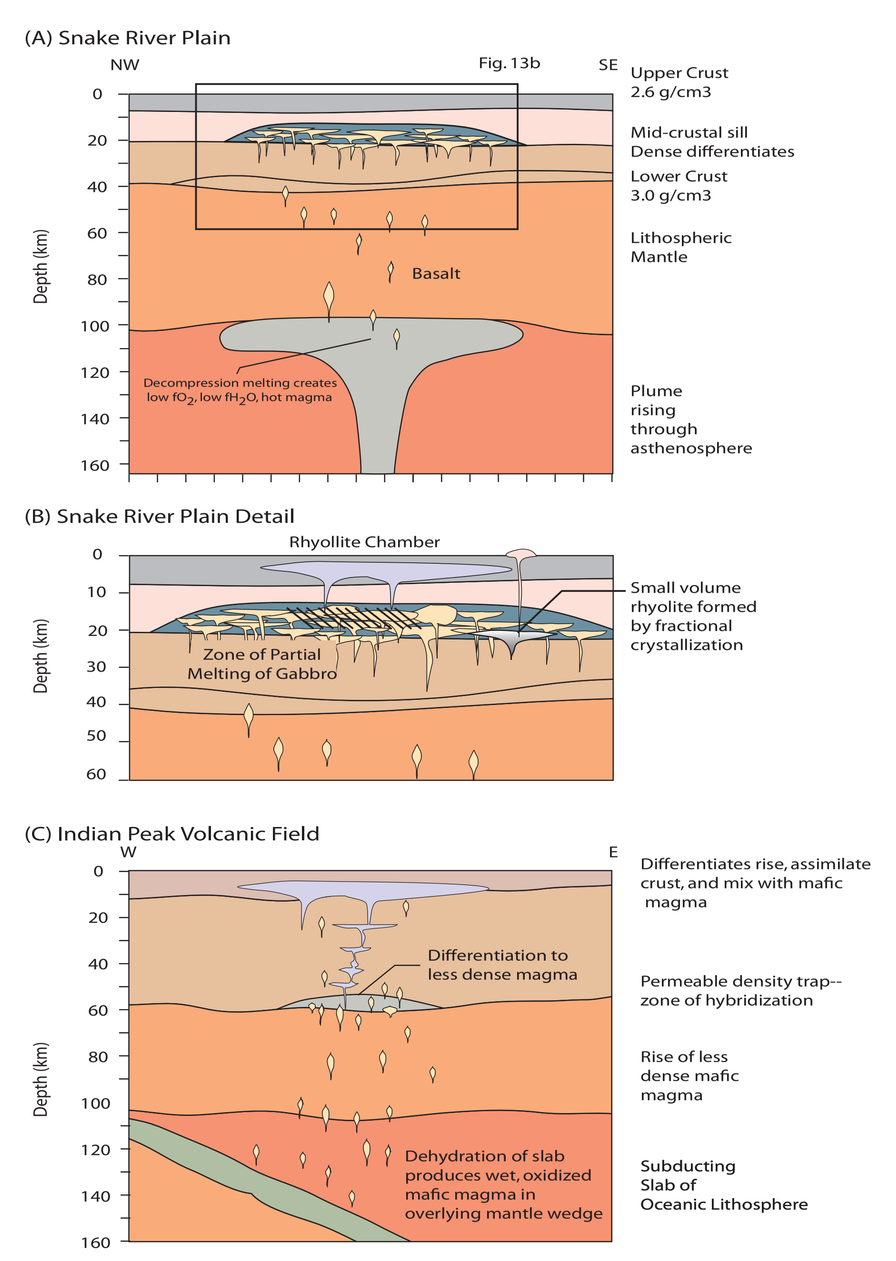
McQuarrie and Rodgers (1998) proposed that ESRP lower crust flowed into the Basin-Range to accommodate isostatic subsidence of the dense mid-crustal load and overlying volcanic basin. Evidence includes the 6 km subsidence of the volcanic basin compared to ~2 km depression of ESRP Moho, and flexural modeling of the ESRP basin which requires isostatic compensation in the lower crust.

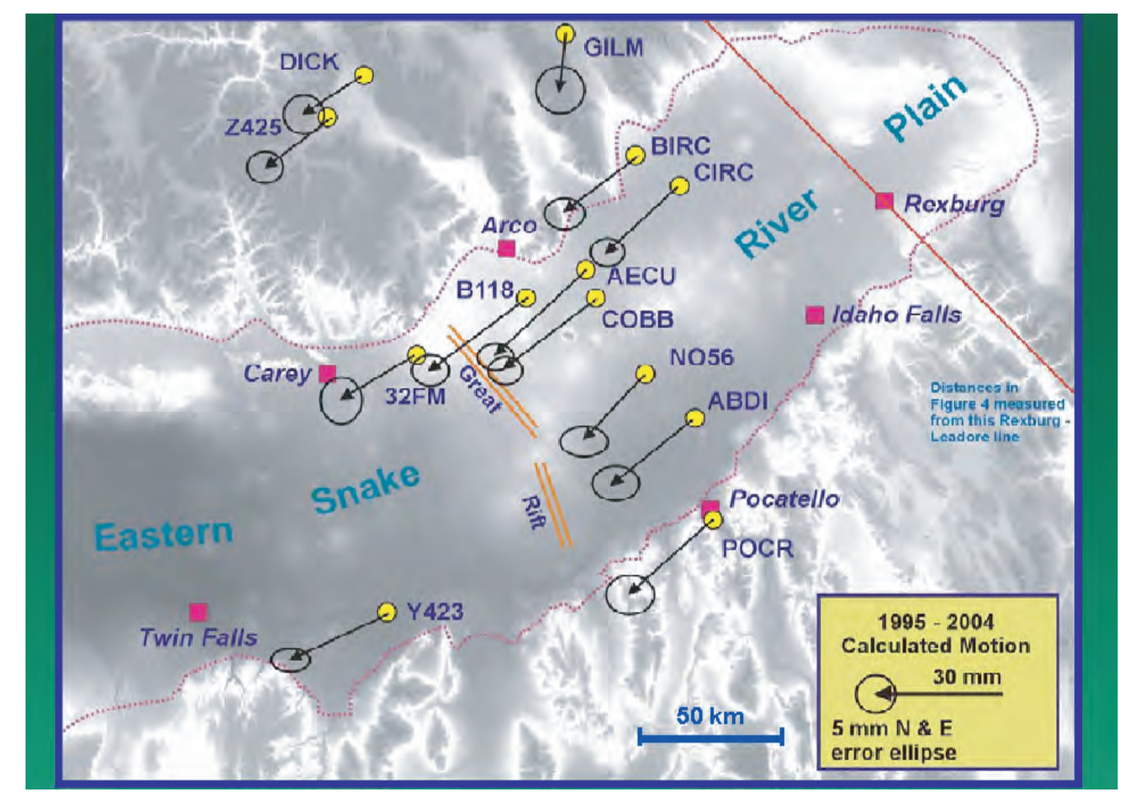
Estimate of Excess Mass in Adjacent Basin-Range Province



Magmatic addition to ESRP crust may densify the mid-crust and create a load that drives crustal outflow from the eastern Snake RIver Plain.

McCurry and Rodger (northern Earthscope workshop 2005)





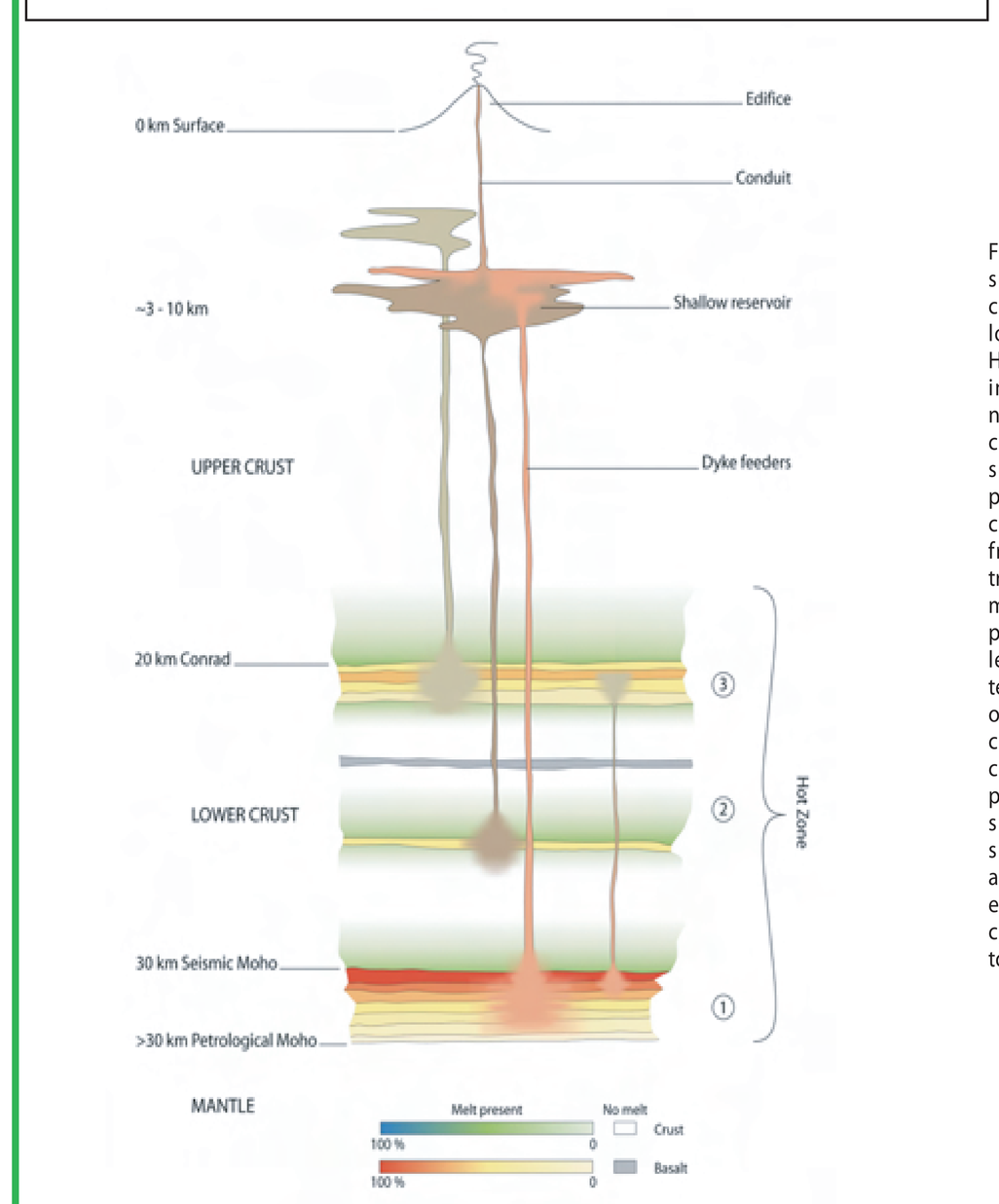
Eastern Snake River Plain crustal velocities from GPS: Chadwick and Rodgers (2005)

The velocities range is 2.7 - 3.5 mm/yr .

The overall conclusion is that the eastern Snake River Plain and its surrounding margins are moving uniformly. This means that no crustal thickness variation between the ESRP and its margin have been created by differential extension.

Quantitative model for generation of high-silica rocks (Annen et al., 2006)

Repeated injection of basalt gradually heat the lower and mid-crust enough that the basalt can be remelted to make higher silica rocks. The exact amount of remelting and fractional crystallization to create the suite of obseved geochemical and petrologic signals is debated. What is well constrained is that little melting and assimilation of the ESRP achrean crust has occuring based on Nd and Sr isotopes.

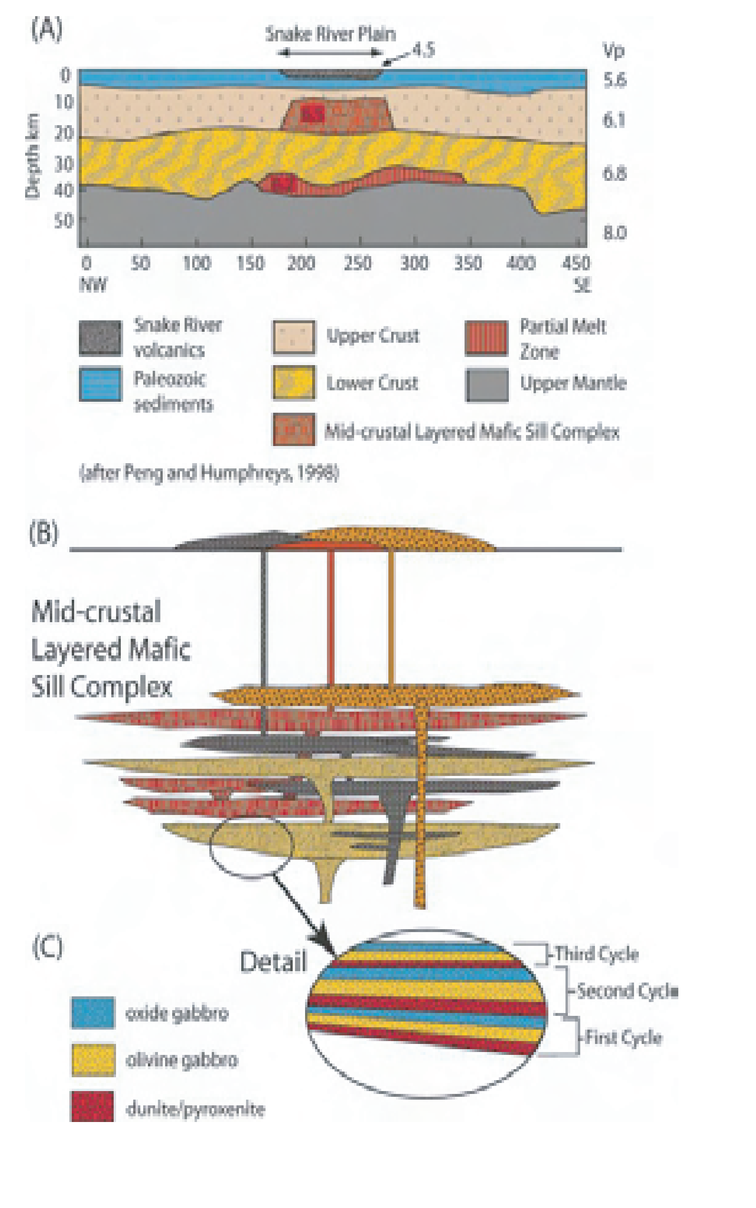


Basalt injection, remelting and fractionation to create eastern Snake River Plain Quaternary basalt flows and Rhyolite domes (From Shervais et al., 2006).

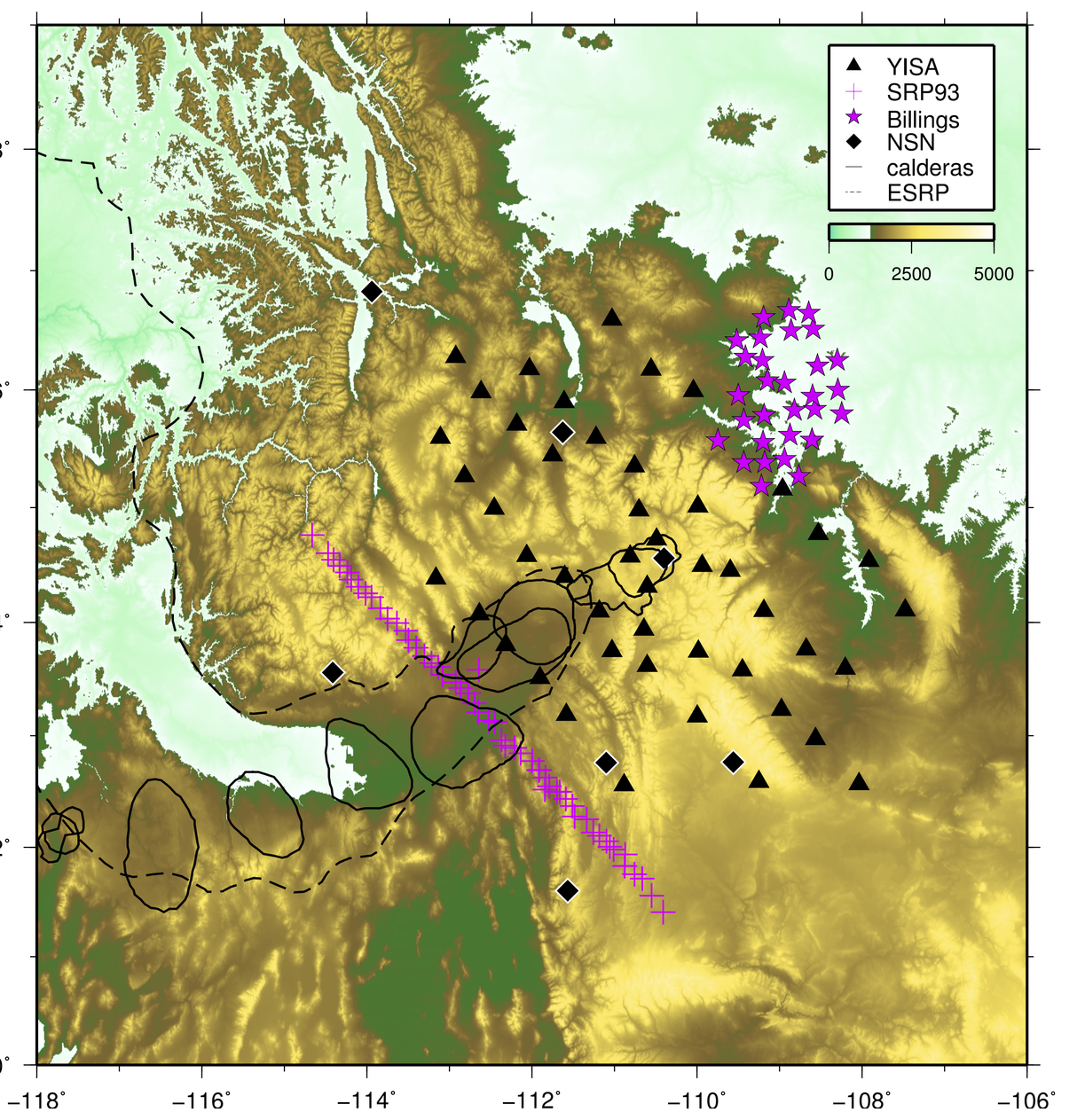
Velocity model from Peng and Humphreys (1996).

Yuan and Dueker (Poster) finds evidence for the top of high-velocity mid-crustal sill, but no evidence for the crustal low velocity zone.

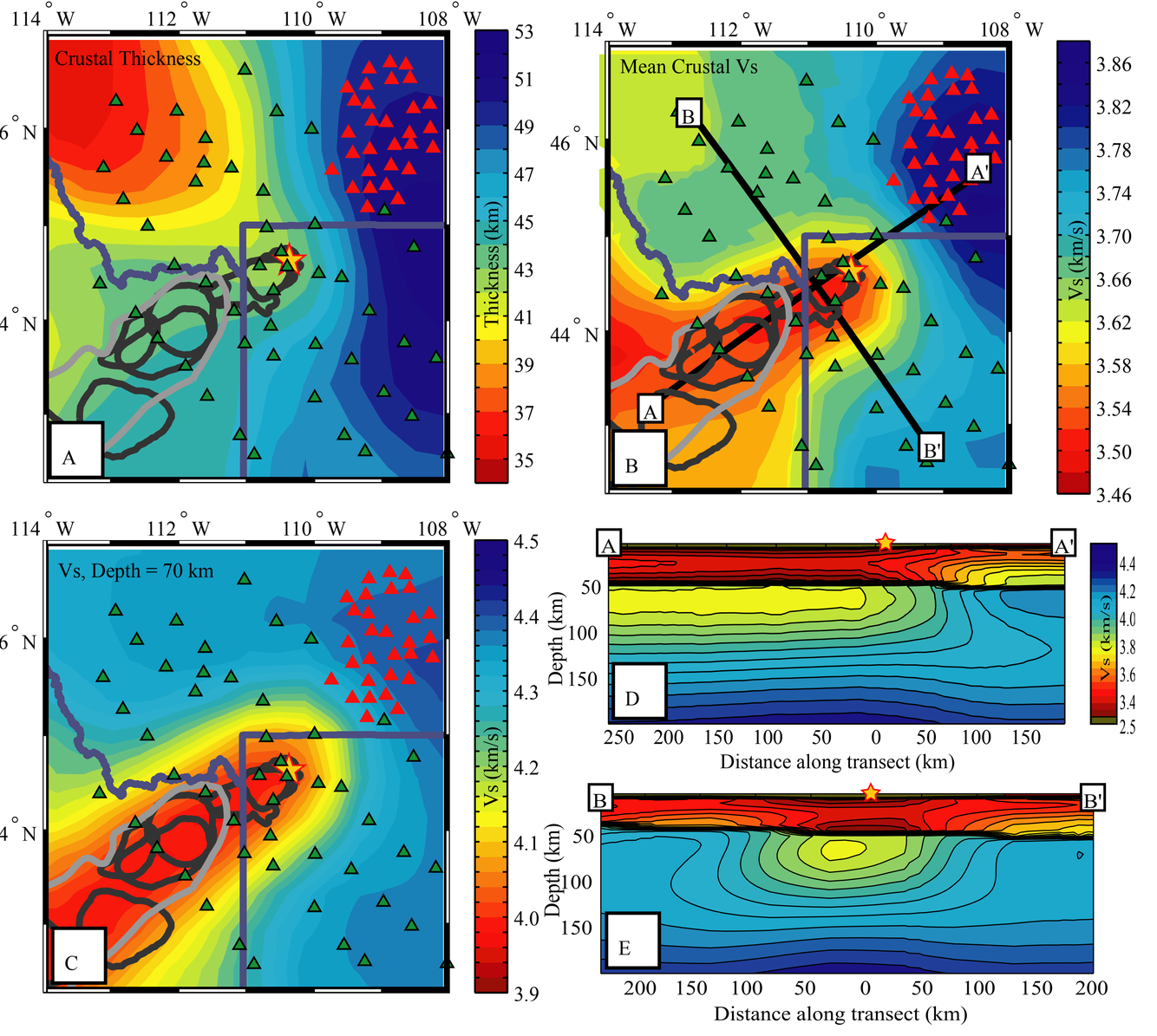
Figure 4. Model cross sections of crust with sill complex. A: Seismic velocity model of Peng and Humphreys (1998), showing location and thickness of inferred mafic sill complex. B: Detailed schematic with our interpretation of mafic sill complex as interpreted from compositional trends in lavas; separate magma batches may pond at more than one level in crust and may interact with partial melts or residual melts in partly congealed Fe-Ti basalt cumulates prior to replenishment. C: Inset showing detail ofl ayered sill with multiple fractionation cycles forming layered intrusion; repeated cycles form in response to magma replenishment.



A. Recent Seismic Results



Yellowstone Array (YISA) = June 2000 – May 2001
47 stations –> 1081 possible station pairs
Billings Array (BILL) = Oct 1999 – Aug 2000



Ballistic Rayleigh–wave image. (a) Crustal thickness. (b) Mean crustal shear velocity. (c) Shear velocity at 80 km depth. (d–e) cross sections indicated in (b). Schutt and Dueker (in review).

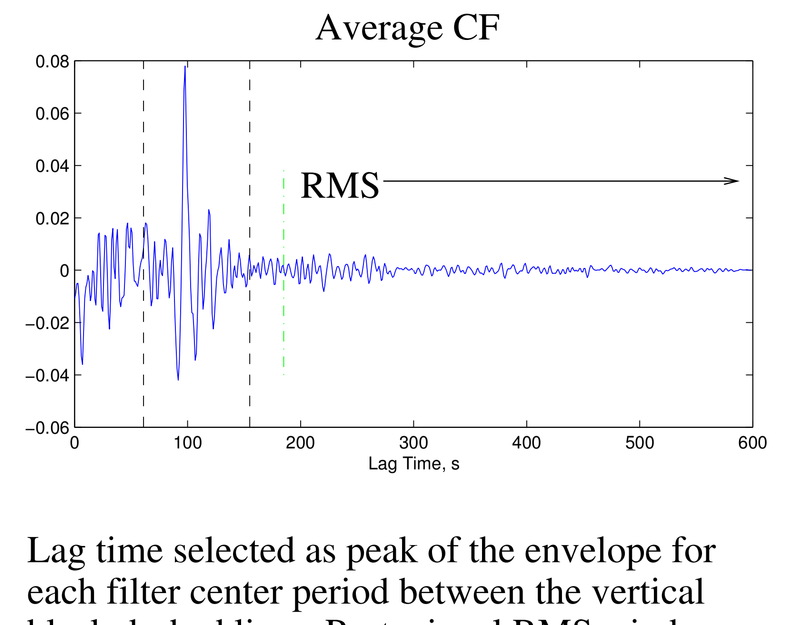
B. Determining Group Velocity from Ambient Noise

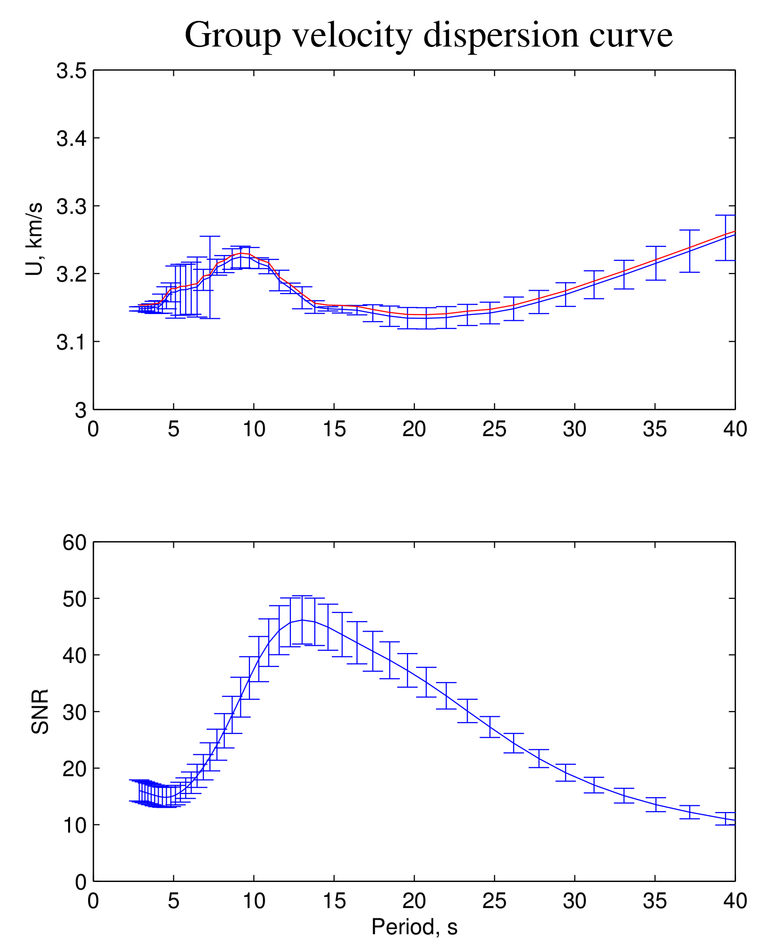
1. Compute cross correlation function (CF)
2. Filter CF with Gaussian from 5 to 50 sec every 5 sec.
3. Take average of CF for positive and negative lag times
4. Calculate envelope of average CF
5. Pick peak of envelope to get lag time

Bootstrap with replacement method used to obtain robust measurement of group velocity arrival time at each filter period for each station pair.

Discretize region and invert group arrival times for group velocity map at each period.

EXAMPLE Station Y02 –> Y33 165 days, 309 km offset



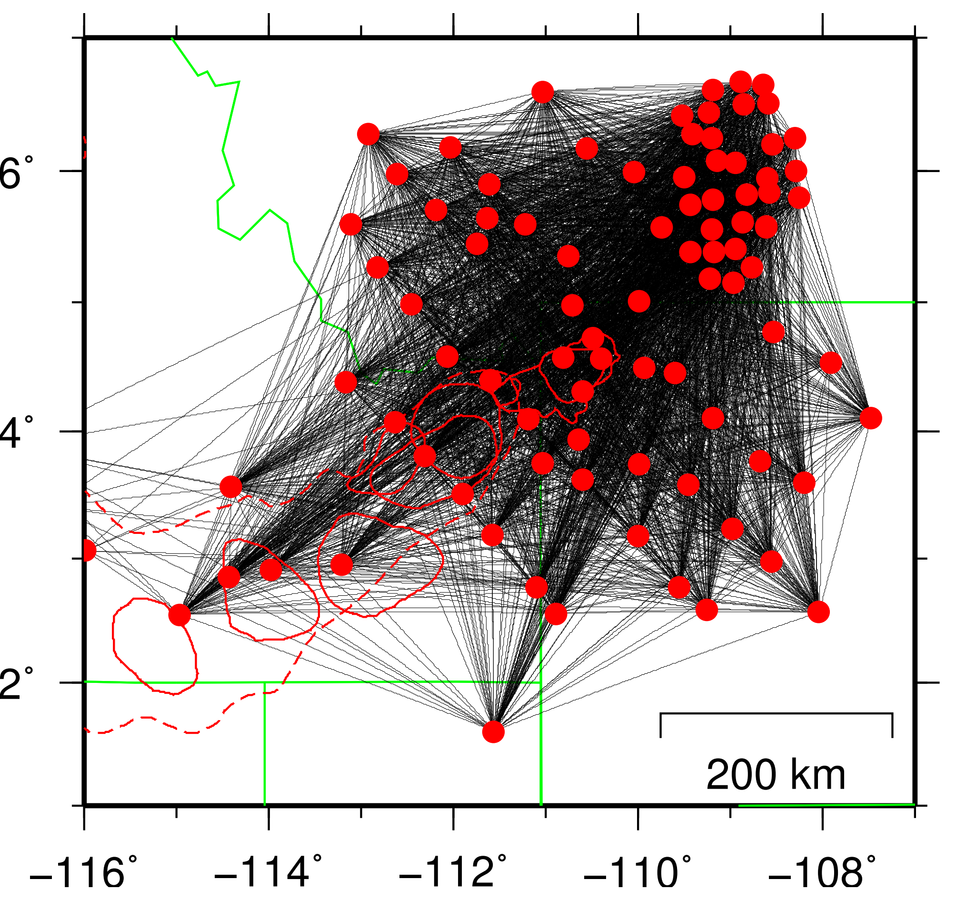


Lag time selected as peak of the envelope for each filter center period between the vertical black dashed lines. Post–signal RMS window selected after signal window as shown above.

SNR = Post–signal RMS / Peak signal amplitude

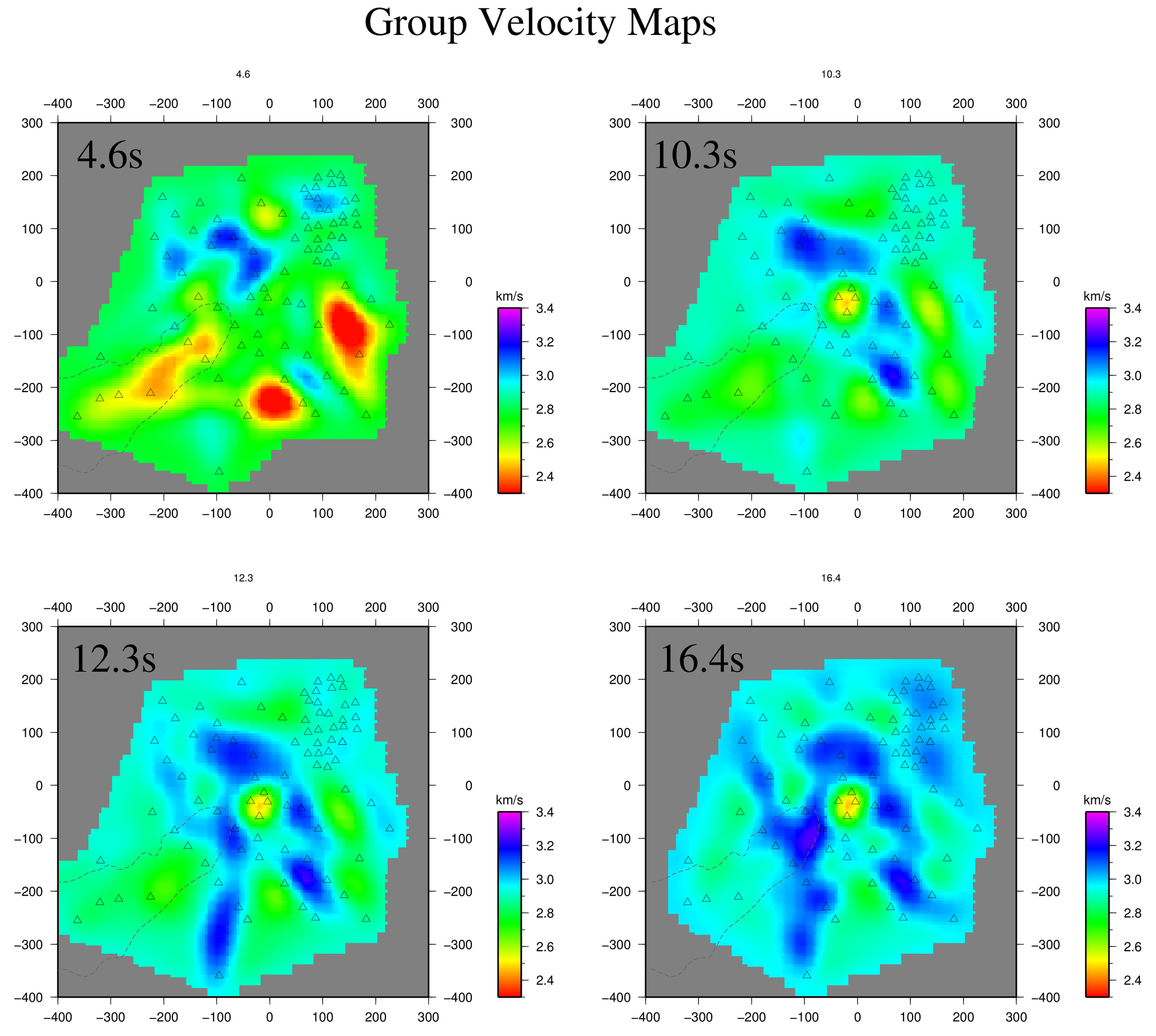
Error bars show one sigma standard deviation from 100 bootstraps.

Ray path for Y02–>Y33 shown as dashed line in block figure to right in Section C.



Ray path coverage for periods between 5 and 30 seconds with SNR > 10 and standard deviation of group velocity < 0.1 km/s. Block discretization of region shown to right, used to invert travel times for group velocity maps.

Group Velocity Maps



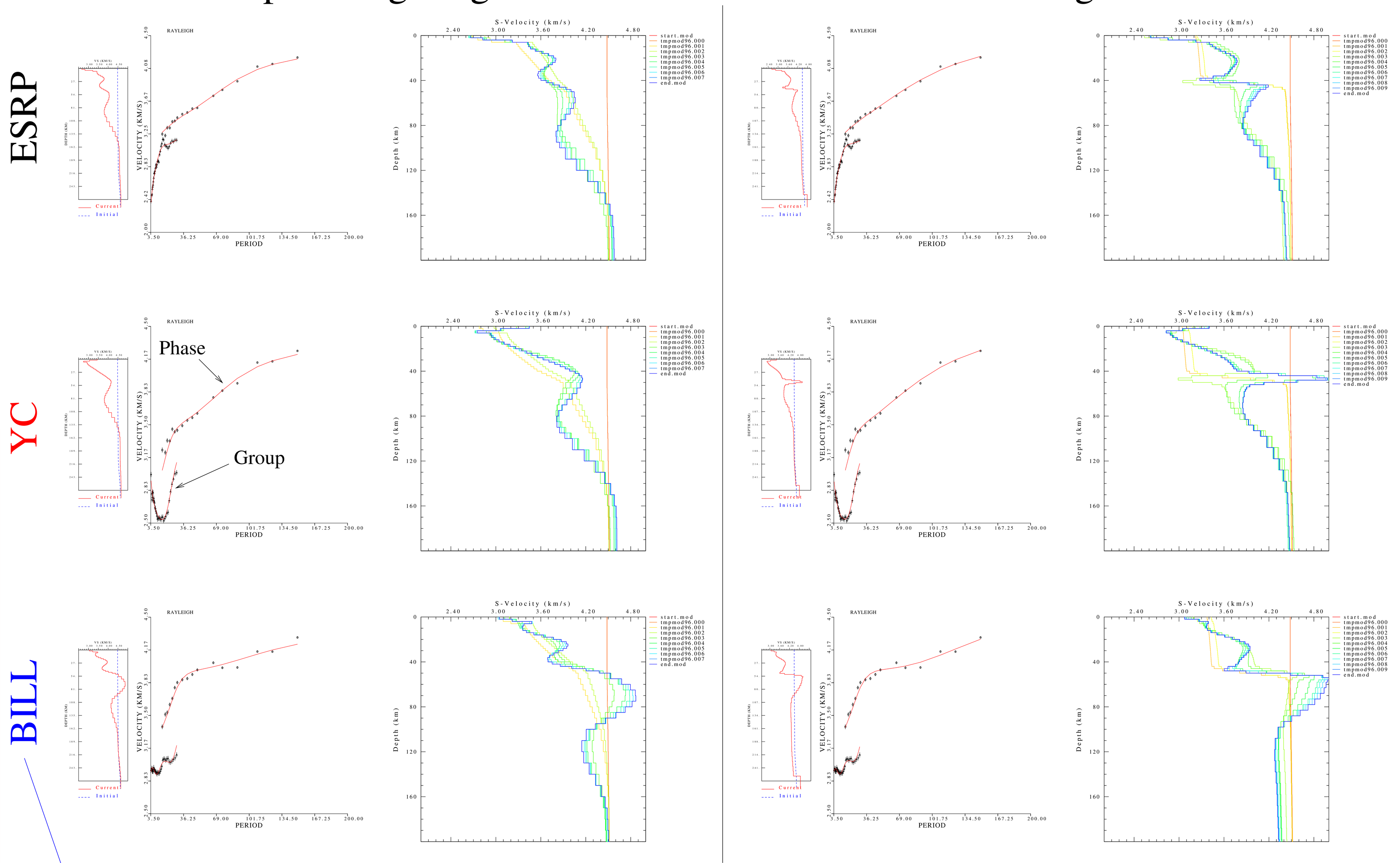
Maps to left show group velocity variations at periods indicated at top left corner. Higher periods sample greater depth.

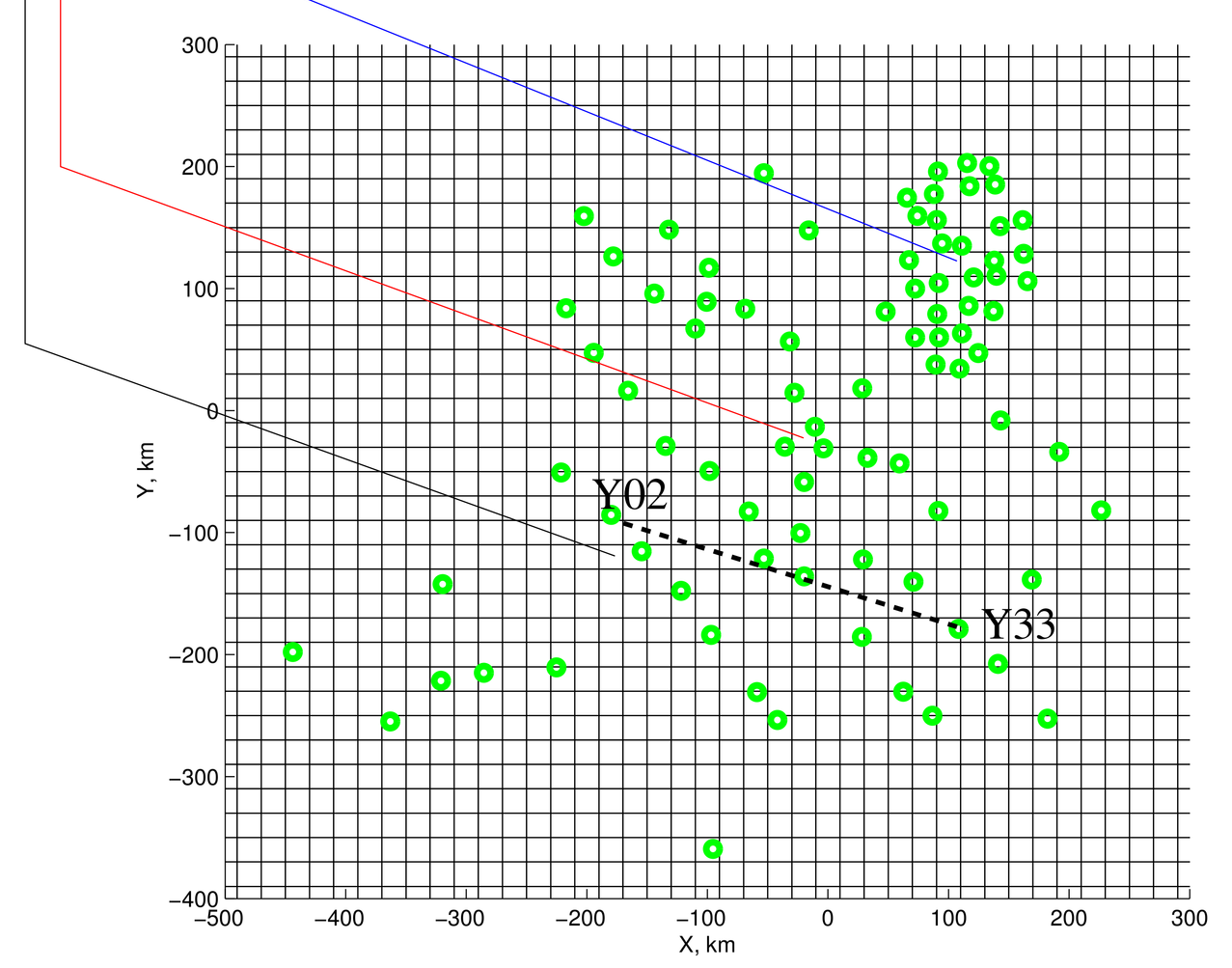
– At 4.6 s, low velocities are resolved beneath the Green River Basin, Wind River Basin, and eastern Snake River Plain.

– Low velocities are resolved beneath the Yellowstone Caldera between 10 and 16 s.

– Under eastern Snake River Plain, increase in group velocity 'downstream' from Yellowstone Caldera.

C. Invert dispersion curves for Shear Velocity Profiles



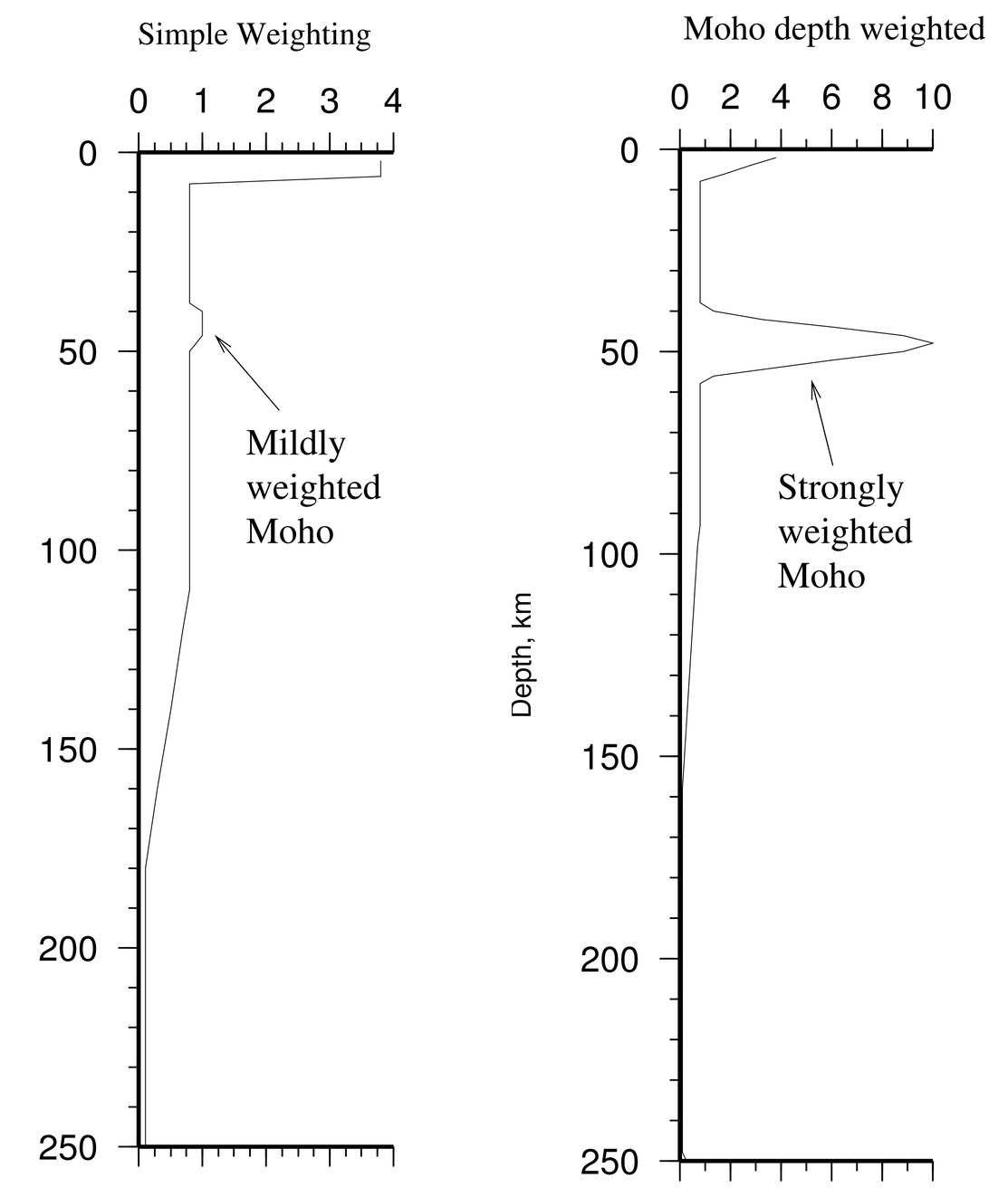


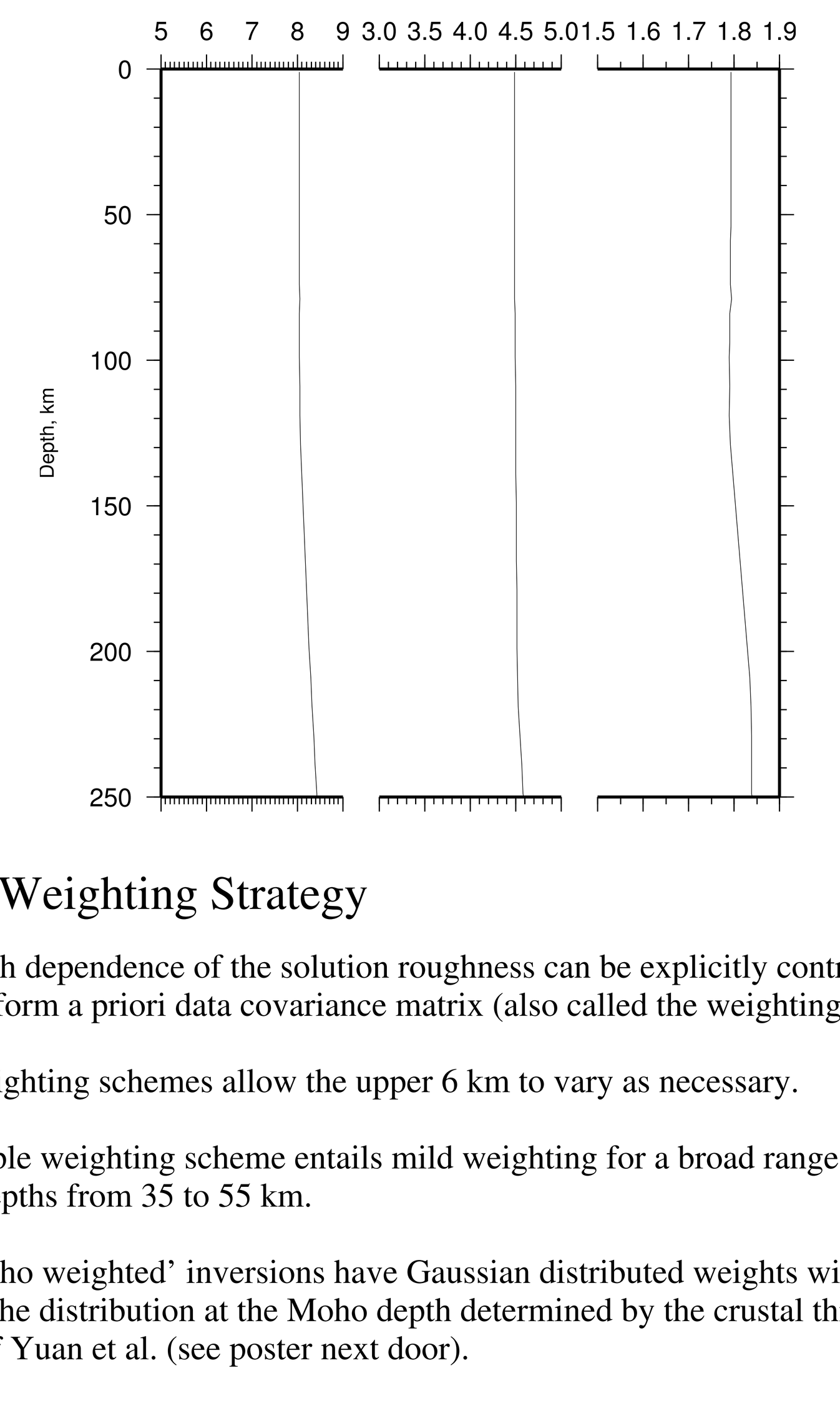
Block discretization used for group velocity tomography and subsequent discretization of phase velocity maps and Vs inversions.

Examples are shown above for Vs inversions from individual blocks in the major tectonic regions (ESRP, YC, BILL) for the two different weighting schemes (described below).

Group and phase velocity dispersion curves are inverted at each block in the grid shown at left using the surf96 routine from Computer Programs in Seismology (R.B. Herrmann, 2002). This method uses an iteratively weighted Levenberg–Marquardt generalized inversion scheme to solve for a one–dimensional velocity model. For each layer we use differential smoothing constraints and a fixed Vp/Vs ratio based upon the most non–prejudicial starting model (see below).

Example Moho Weighting functions





Moho Weighting Strategy

The depth dependence of the solution roughness can be explicitly controlled via a non–uniform a priori data covariance matrix (also called the weighting matrix).

Both weighting schemes allow the upper 6 km to vary as necessary.

The simple weighting scheme entails mild weighting for a broad range of Moho depths from 35 to 55 km.

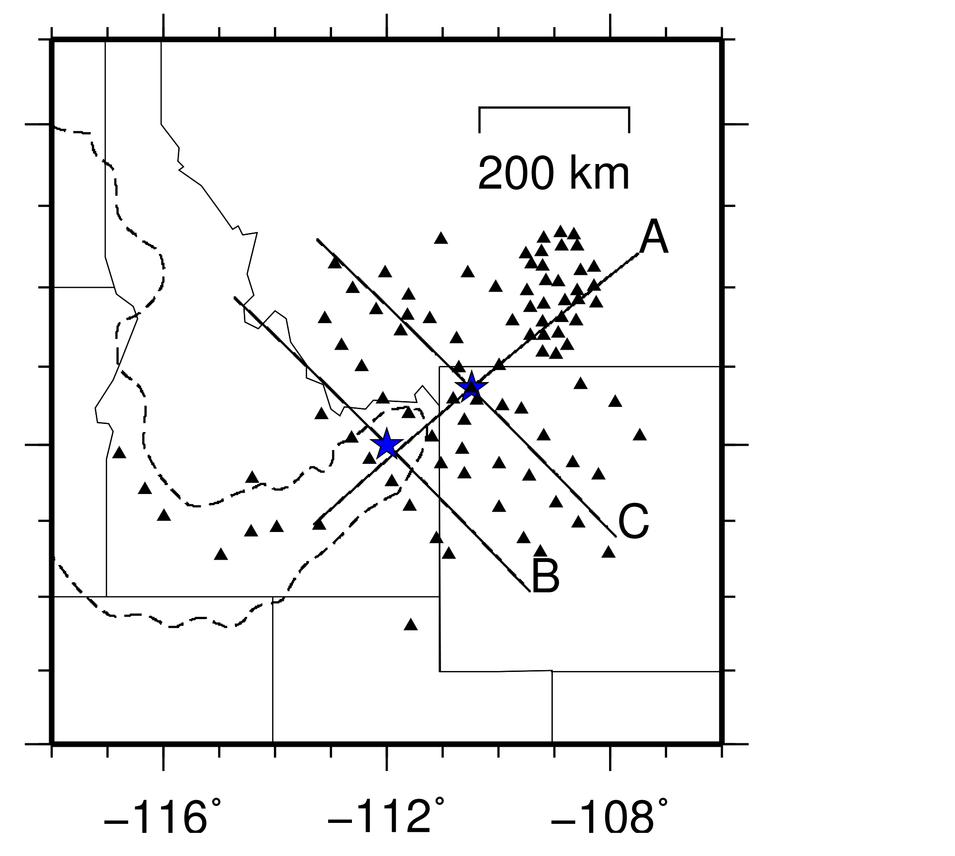
The 'Moho weighted' inversions have Gaussian distributed weights with the peak of the distribution at the Moho depth determined by the crustal thickness model of Yuan et al. (see poster next door).

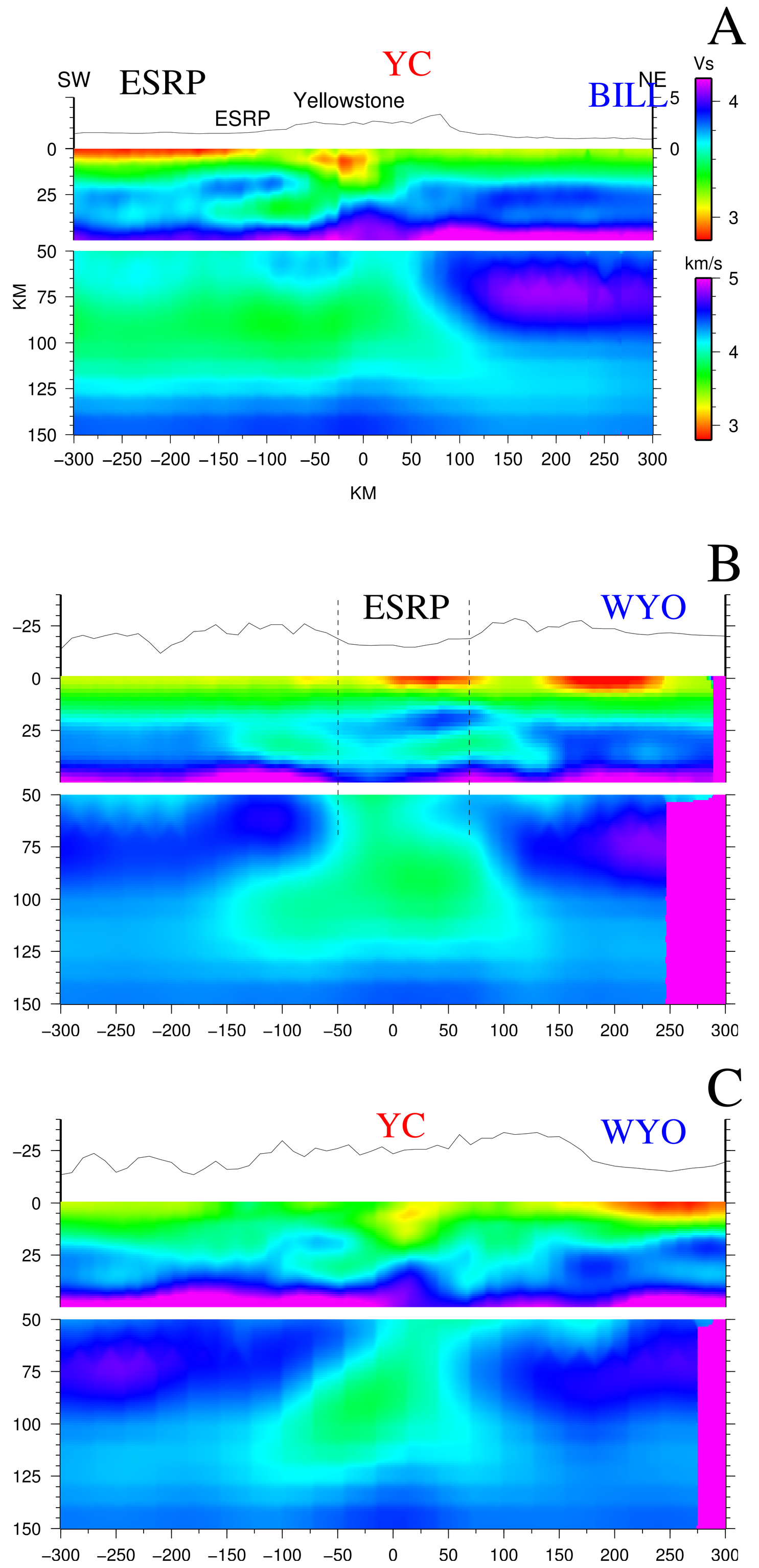
D. Results: Shear Velocity Variations

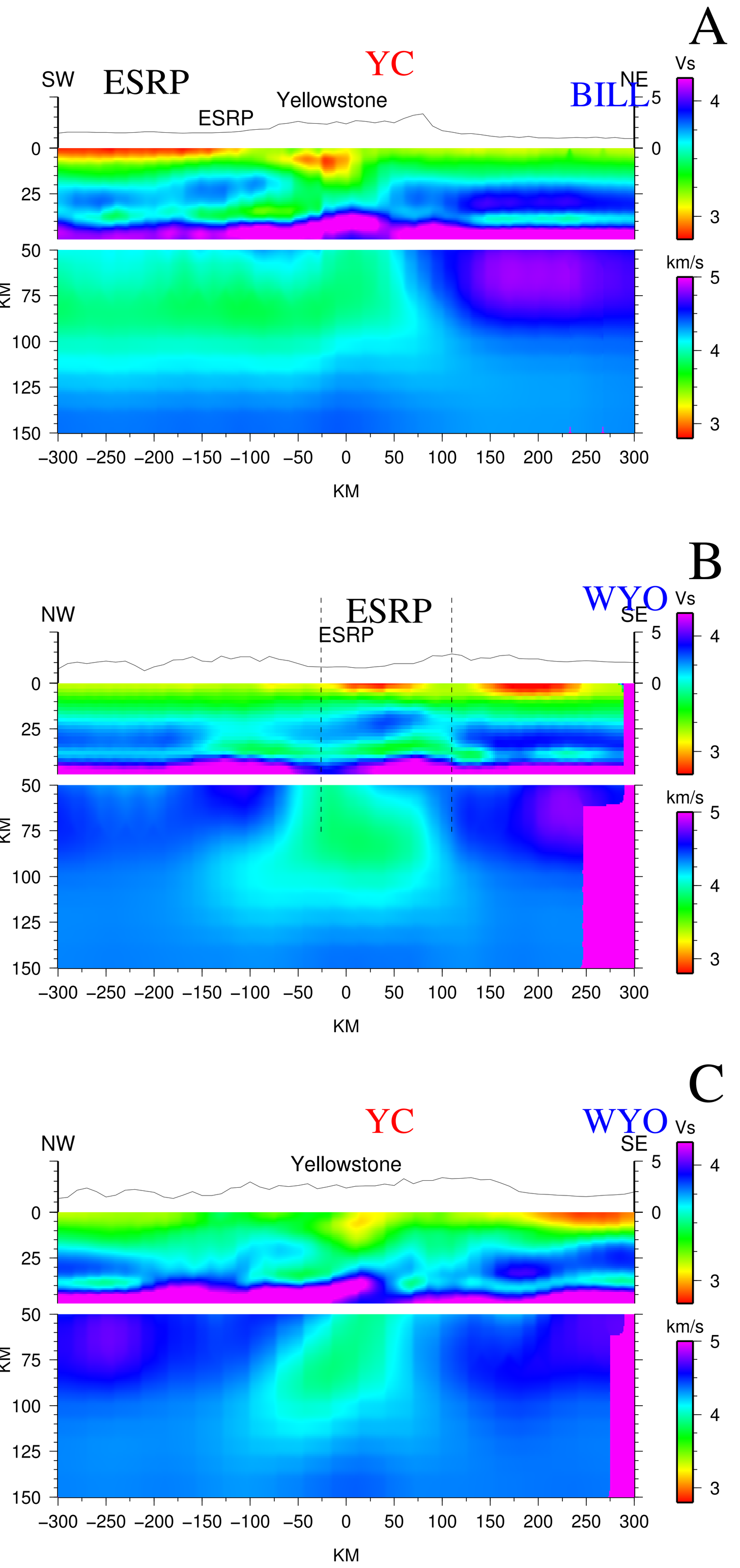
2–D slices through the 3–D shear velocity volume are shown below for orientations shown at right.
Refer to topography map in Section A for relation to structural features (and science panel to far left).

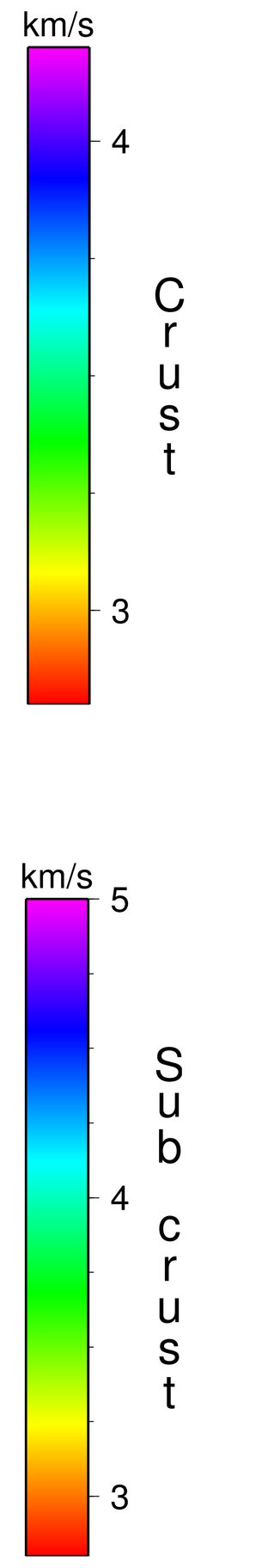
ESRP = eastern Snake River Plain
YC = Yellowstone Caldera
BILL = Billings Array (Wyoming Craton)

NOTE different color scales for crust and mantle.









E. Conclusions

1) Mantle at 80 km depth varies from 3.8 to 4.9 km/s (22% dVs/Vs).

2) Yellowstone Caldera Crustal Structure
- 2.8 to 3.1 km/s Vs in upper crust down to 12 km
- 5 km of crustal thickening (see Yuan et al. poster next door)
- Lower crust has normal velocity suggesting magma does not pond there.
- Vs model consistent with previous tomographic results.

3) eastern Snake River Plain
- High Vs mid crustal body resolved.
  - Begins at 2 Ma age Island Park Caldera.
  - At least 10 km thick
  - Dips to the southwest down ESRP, consistent with estimated structural subsidence (McQuarie and Rodgers, 1998)
- Lack of major crustal thickening beneath the ESRP suggesting wholesale lower crustal outflow.
- 3.3 km/s velocity lower crust resolved suggesting staging of late stage basalts here.
- ESRP down–warp, Volcanic Track, 'MCS', low Vs plume – all vertically correlated (cross–section B)
  - Low Vs lower crust extending beyond ESRP must be heat advected laterally by lower crustal flow.

Acknowledgements
Thanks to D. Schutt for ballistic wave phase velocity measurements, and H. Yuan for Moho depth maps.
Thanks to R.B. Herrmann for the software package Computer Programs in Seismology and support.