# An Introduction to Surface Wave Analysis

## ADVANCED STUDIES COURSE IN JOINT INVERSION OF RECEIVER FUNCTIONS AND SURFACE WAVE DISPERSION

Kuwait City, KUWAIT
21 January, 2013

**Michael E. Pasyanos**
***Lawrence Livermore National Laboratory***

LLNL-PRES-609981
Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94551
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

# Outline

Section 1 – Background on Surface Waves

- Basics, Applications, Results, Mideast

Section 2 – Surface Wave Analysis

– Measurement, Tomography, Inversion

Section 3 – Model and Access Tool

Section 4 - Using Surface Waves to Build a Global Model

- LITHO1.0 model

# Section 1 – Background on Surface Waves

The Basics of Surface Waves

- Surface Waves vs. Body Waves
- Group Velocity vs. Phase Velocity
- Rayleigh Waves vs. Love Waves
- Higher Mode Surface Waves
- Historical Background
- Variations due to crustal thickness, sediments thickness, etc.
- Sensitivity Kernels

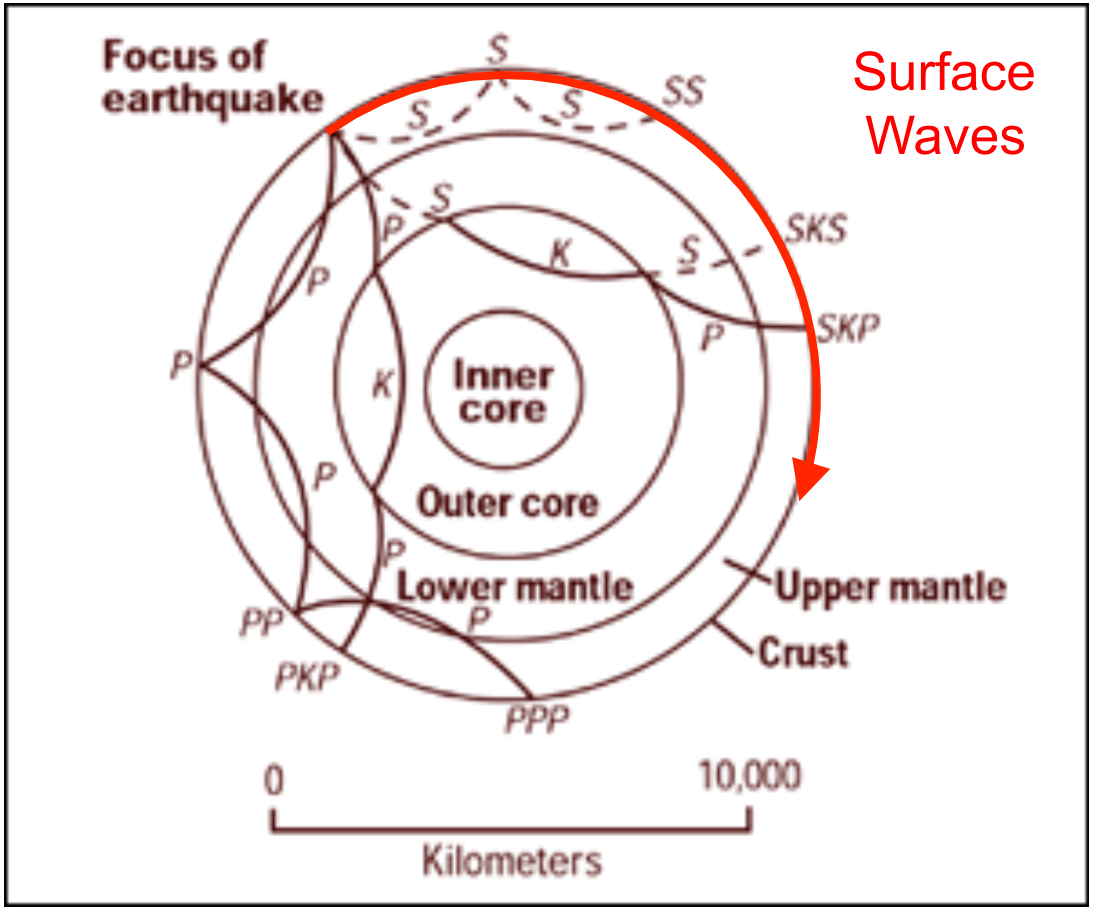
Applications

Results

Examples from the Middle East

# Surface Waves

*Surface waves* refer to seismic waves that travel along the earth's surface, as opposed to *body waves*, which travel through the earth's interior



# Group Velocity vs. Phase Velocity

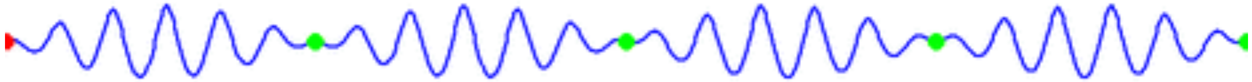
Surface waves are *dispersive*, which gives the characteristic that their velocities are a function of frequency (period) and that their group velocities are generally not equal to their phase velocities.

Group Velocity ($U = d\omega/dk$) is the velocity in which the wave energy moves

Phase Velocity ($C = \omega/k$) is the velocity that a peak or trough moves

red dot = phase velocity

green dot = group velocity

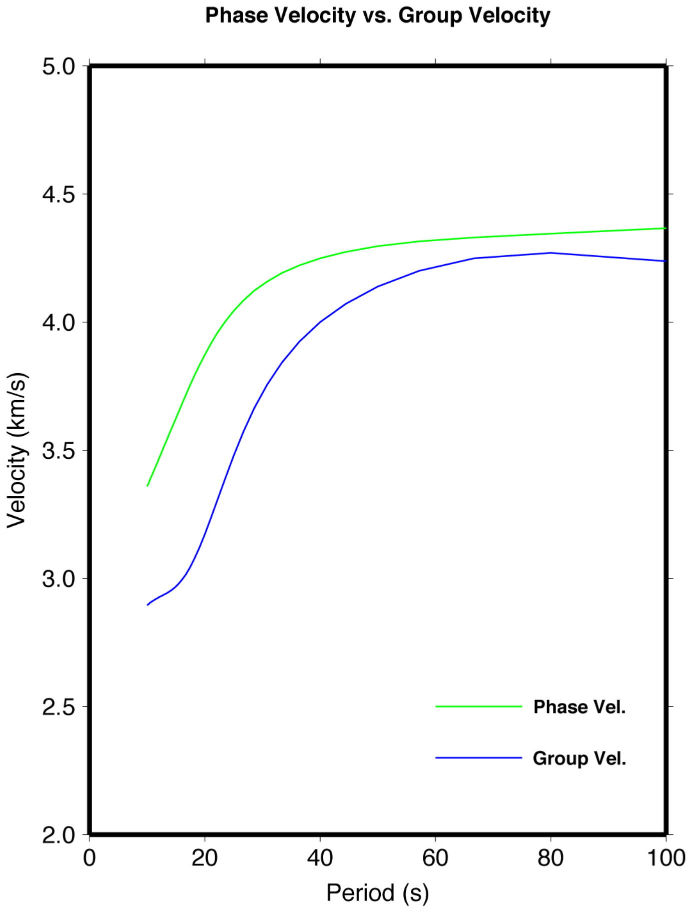


# Group Velocity vs. Phase Velocity

For typical earth profiles, the phase velocity is generally faster than the group velocity.

While the group velocity can increase or decrease with increasing period, phase velocities are monotonically increasing.

If the group velocities are constant over a wide period range, then they can produce a high-amplitude body-wave looking pulse that is called an *Airy phase*



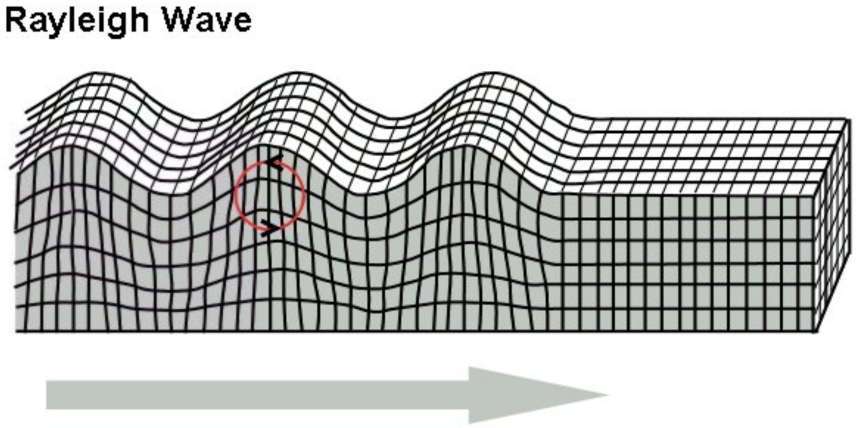
# Rayleigh Waves

Designated LR = “Long-period Rayleigh”

Also referred to as “ground roll” in refraction/reflection surveys and other applications

They are sensitive to P-SV

Produce retrograde motion on Z (vertical) and R (radial) components

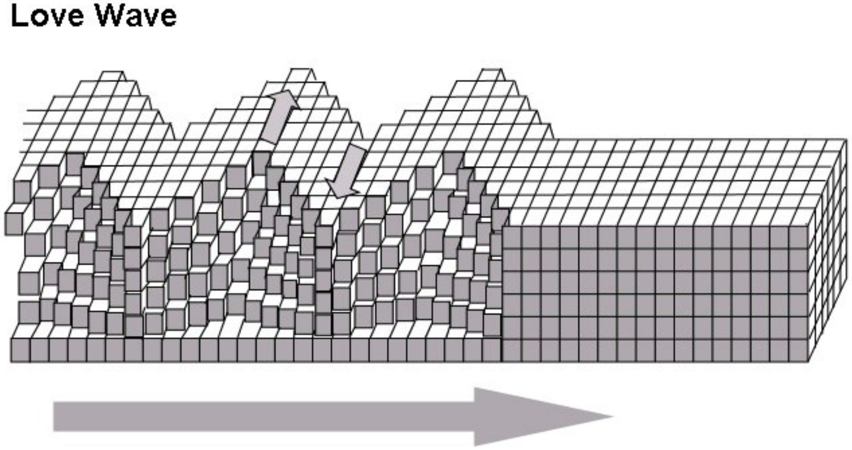


# Love Waves

Designated LQ = “Long-period Querwellen” (German for transverse waves)

Sensitive to SH (horizontally propagating shear waves)

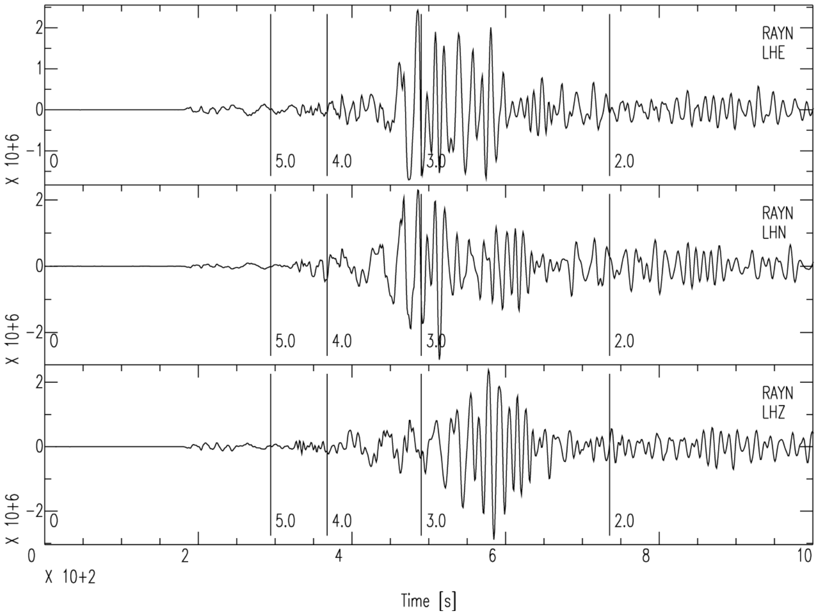
Shear motion on T (transverse) component

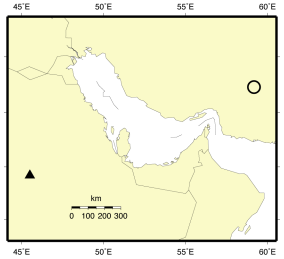


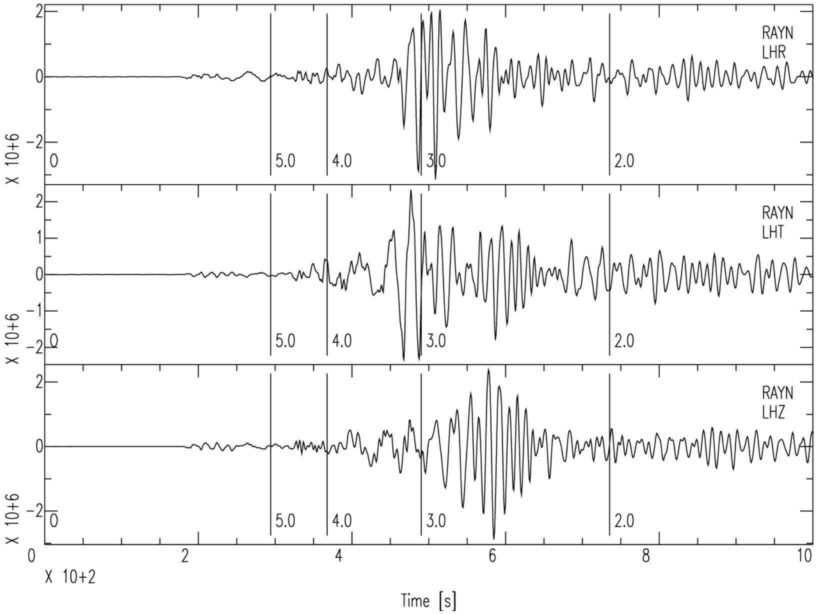
# Rayleigh Waves vs. Love Waves

Unrotated – LHE,LHN,LHZ

Rotated – LHR,LHT,LHZ



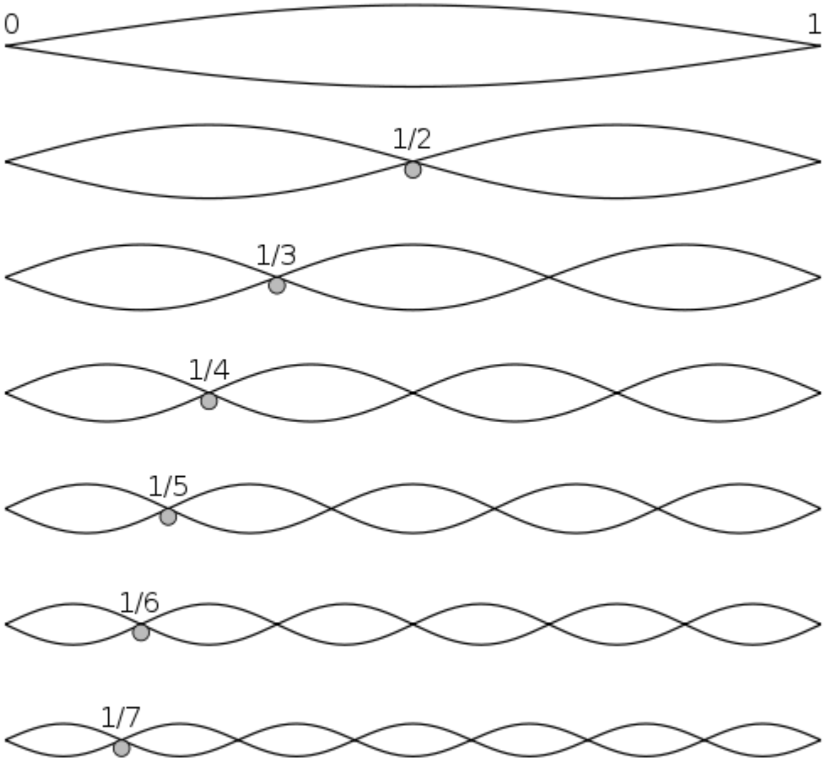




# Higher Mode Surface Waves

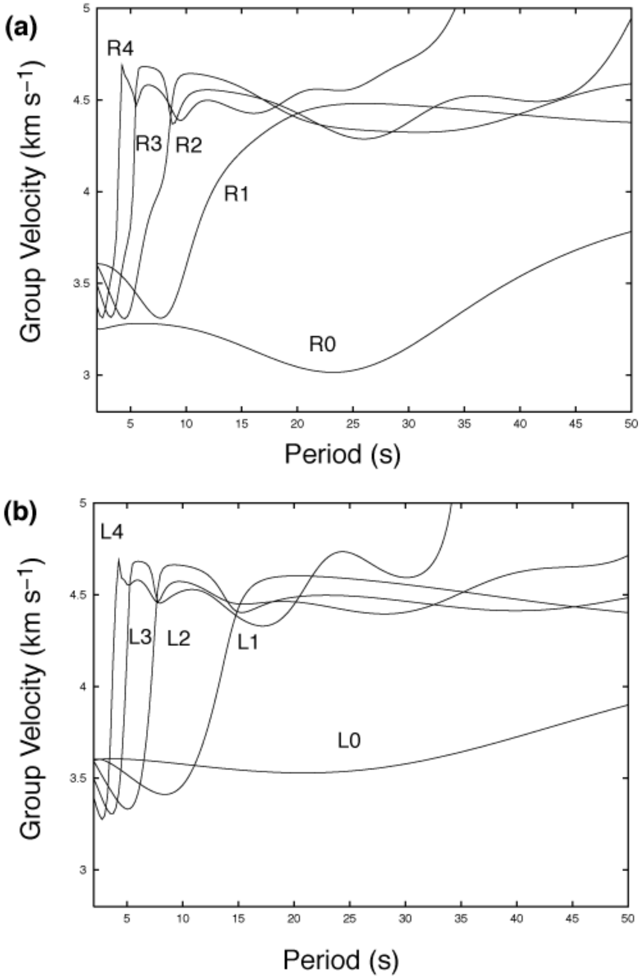
So far, we have been talking about *fundamental mode* surface waves.

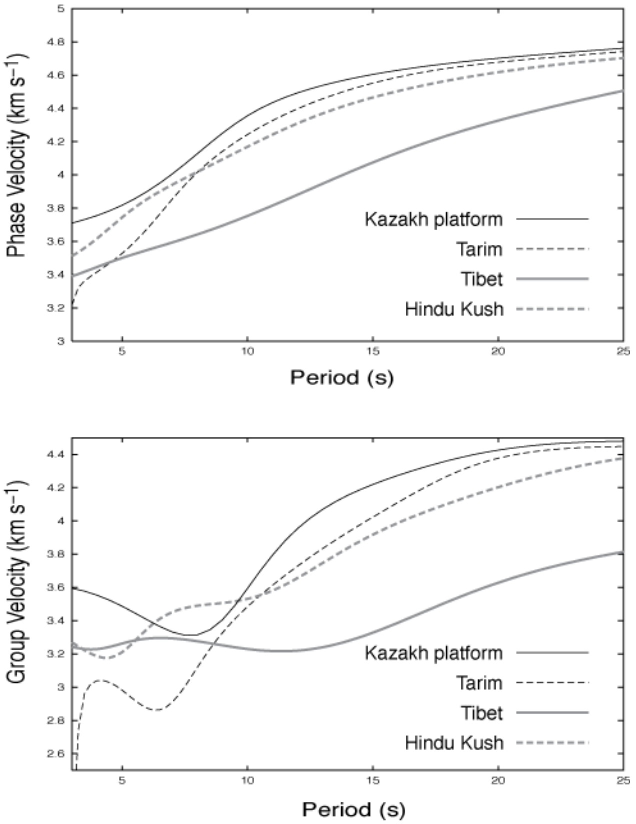
There exists an infinite number of *higher mode* solutions



# Higher Modes

Higher mode exist, but are more difficult to measure

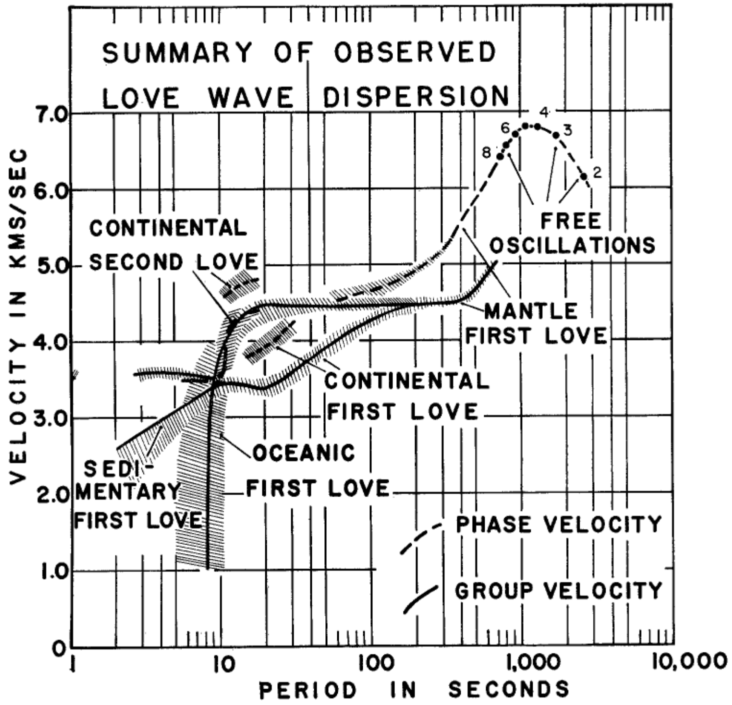


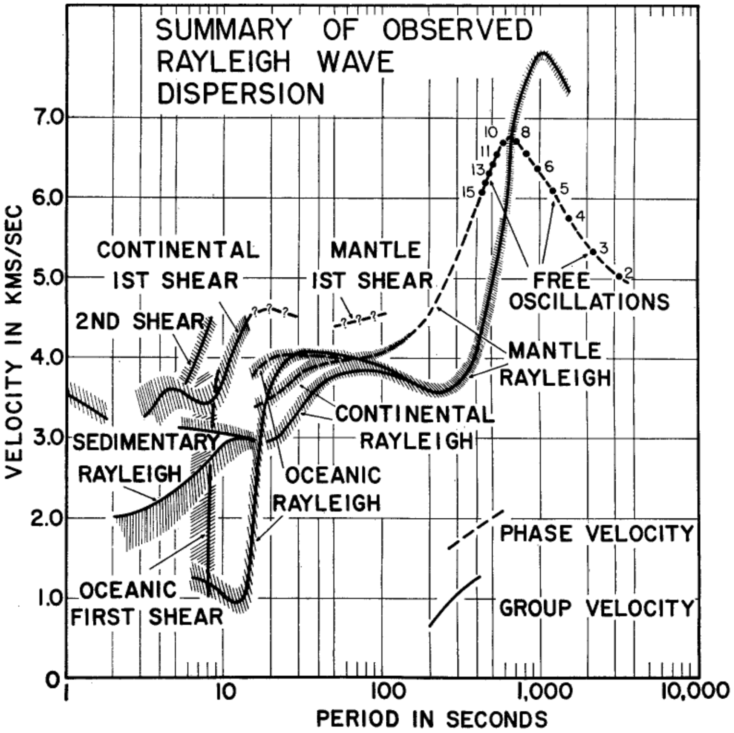


From Levshin et al. (2005)

# Some Historical Results

Surface wave studies have been around for a long time in seismology



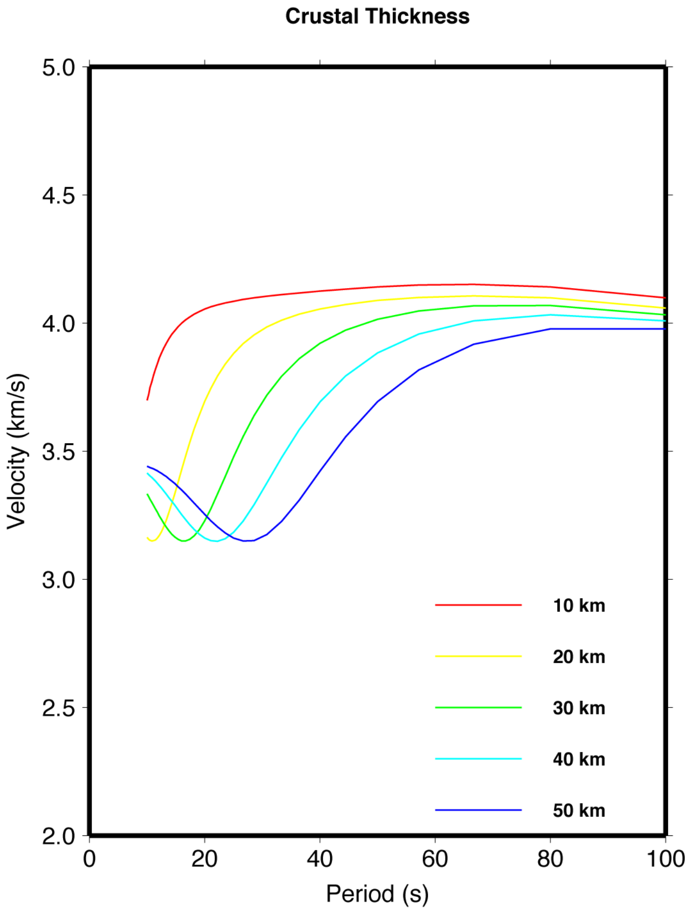


From Oliver (1962)

# Dispersion Variations: Crustal Thickness

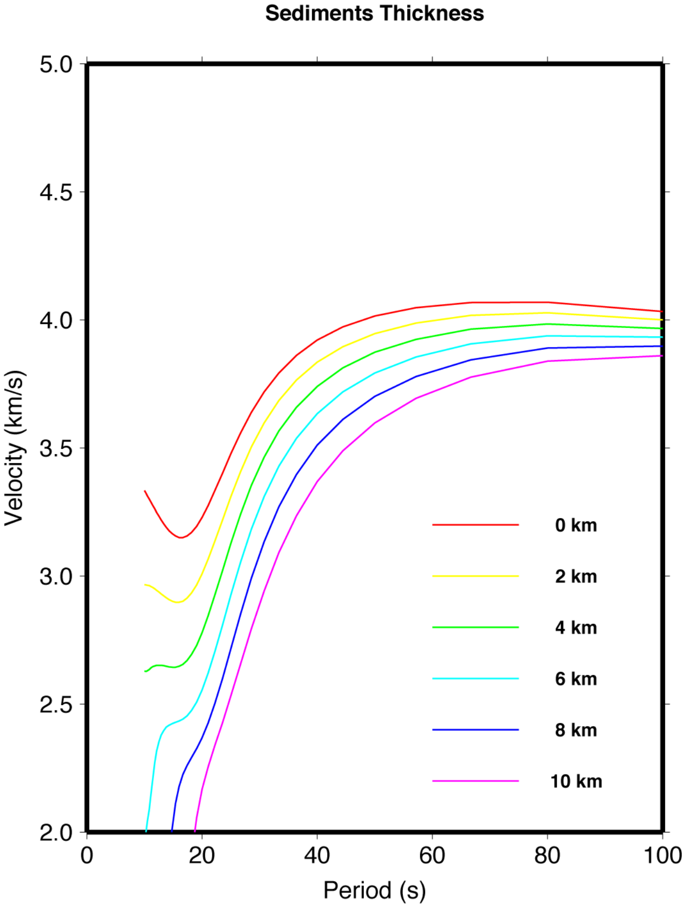
Oceanic crust typically has crustal thicknesses of < 10 km

Continental crust has crustal thickness that ranges between 15 and 80 km, but typically around 35 km



# Dispersion Variations: Sediments Thickness

Sediment thicknesses range from 0 km to over 20 km.



# Sensitivity kernels

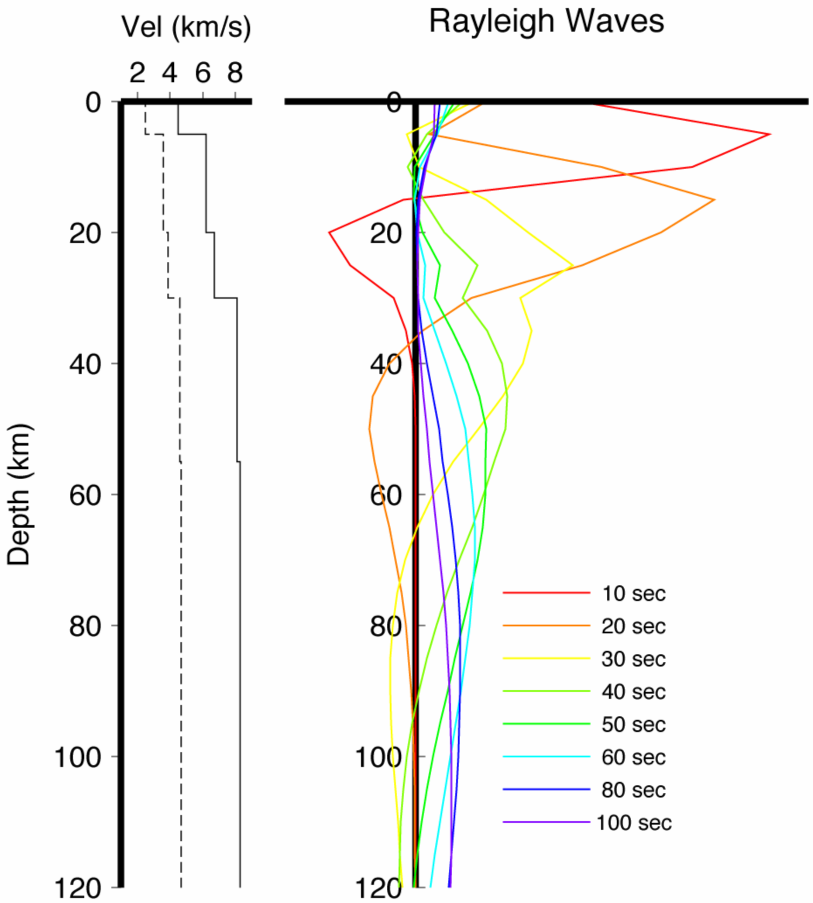
Sensitivity kernels show the relationship between dispersion velocities and earth structure.

They are calculated by taking the partial derivative of the dispersion velocities with respect to other parameters, such as shear-wave velocity. For instance, $\delta U/\delta\beta$ is often shown here.

With increasing period, surface waves become sensitive to deeper velocity structures.

They are themselves dependent on the velocity structure, so it is non-linear.

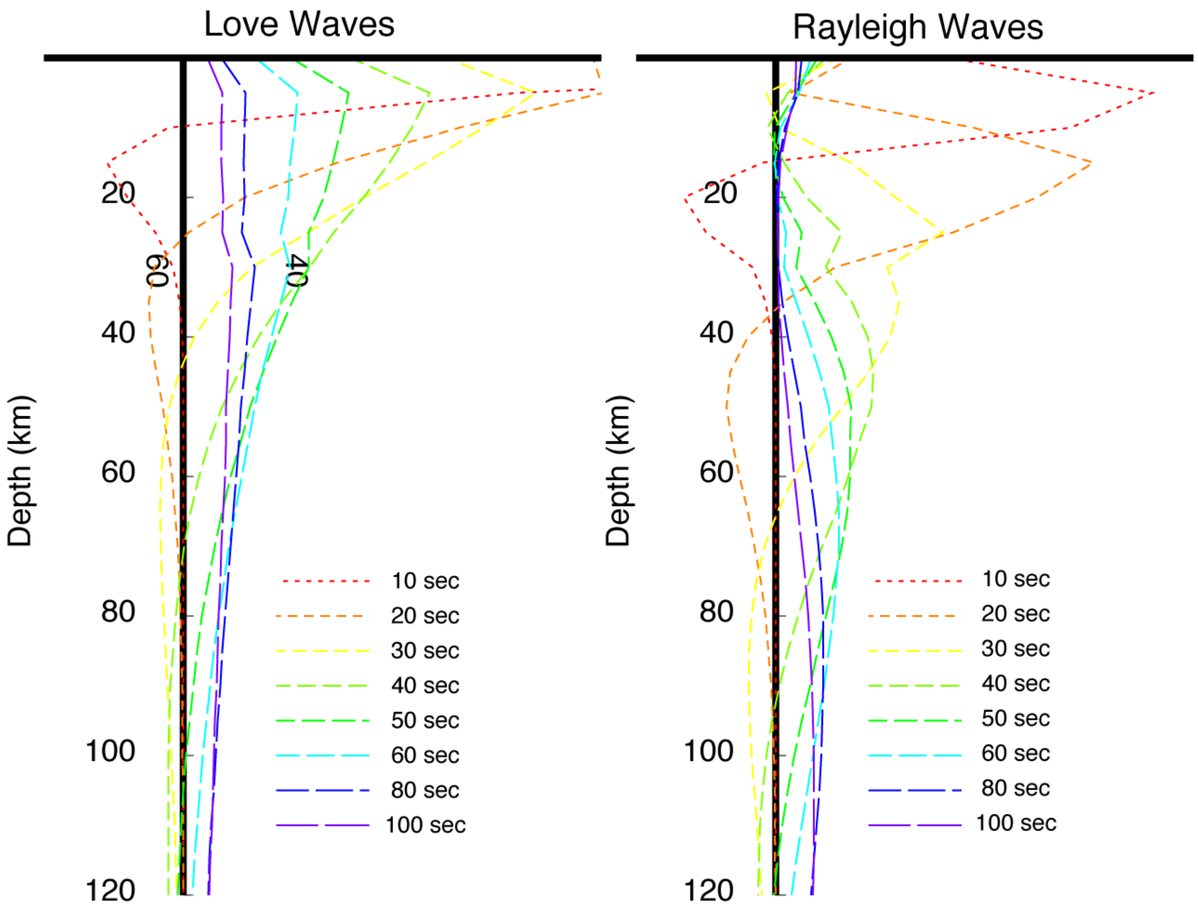
Sensitivity kernels are used to invert the dispersion curves for layered velocity structure.



# Sensitivity kernels

Rayleigh waves and Love waves have different sensitivity kernels

The longer the period, the deeper the structure sampled



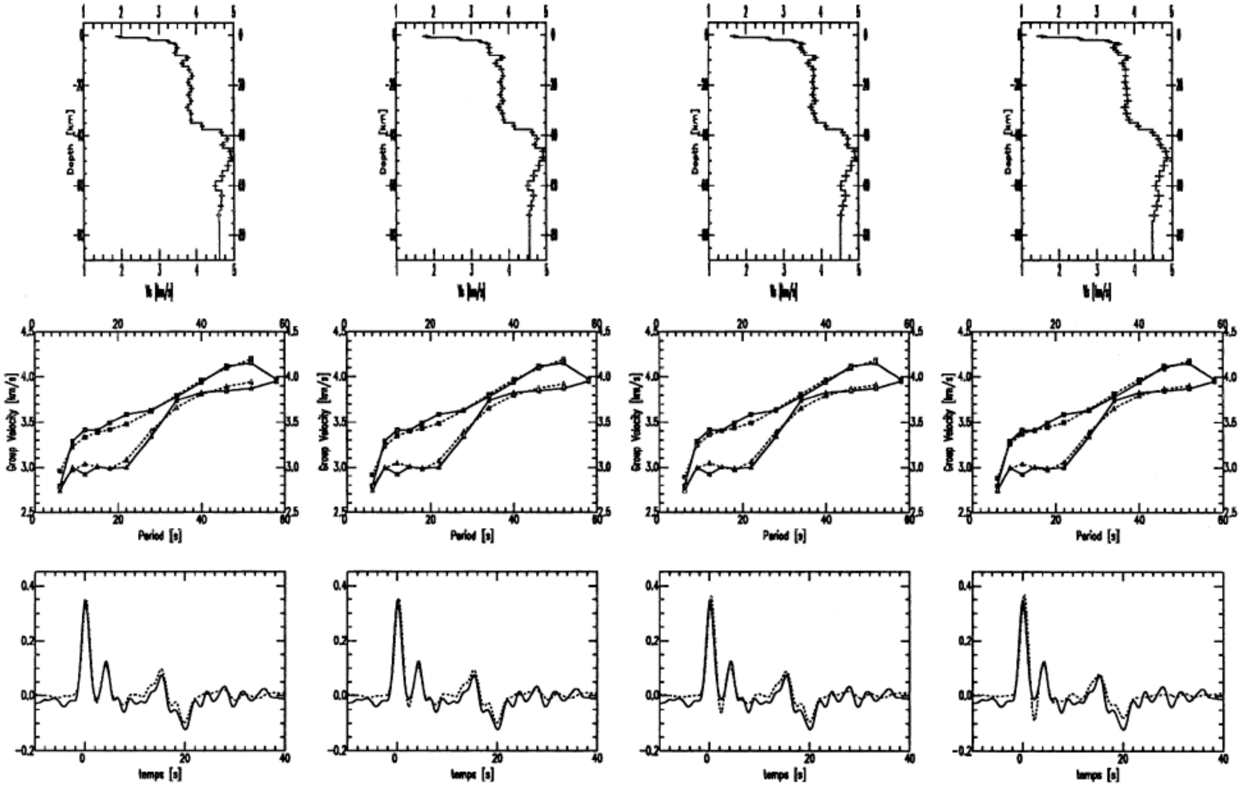
# Applications

Joint inversion of surface waves and receiver functions (Julia et al., 2000)

$$E_{y|z} = \frac{p}{N_y} \sum_{i=1}^{N_y} \left( \frac{y_i - \sum_{j=1}^{M} Y_{ij}\, x_j}{\sigma_{y_i}} \right)^2 + \frac{1-p}{N_z} \sum_{i=1}^{N_z} \left( \frac{z_i - \sum_{j=1}^{M} Z_{ij}\, x_j}{\sigma_{z_i}} \right)^2$$

$p = 0.2$ $p = 0.4$ $p = 0.6$ $p = 0.8$

mostly
receiver
function

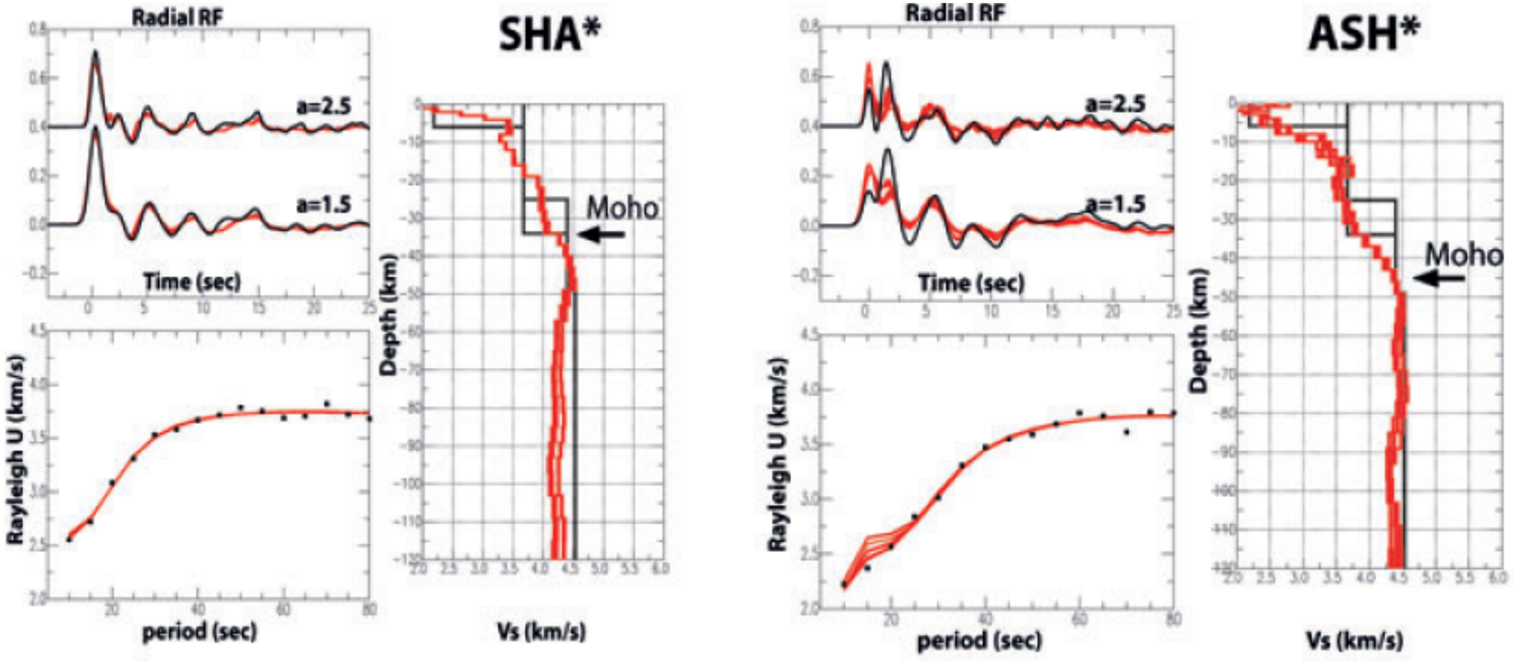


mostly
surface
waves

# Applications

Example of joint inversion results in Oman (Al-Hashmi et al., 2011)

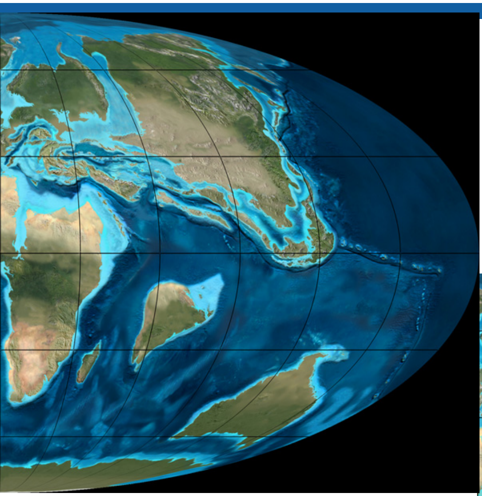
- red lines show results from different starting models, influence parameters (p=0.3,0.5,0.7), and layering smoothness to show range



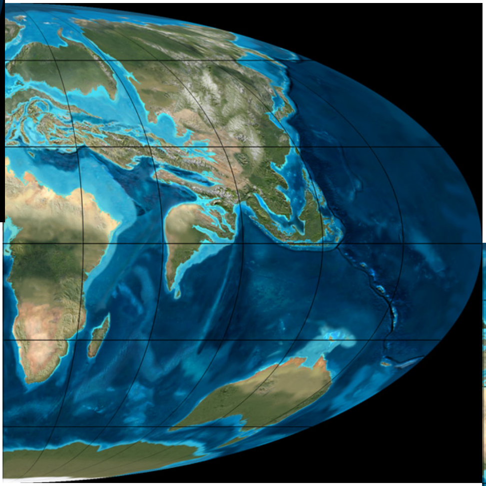
Al-Hashmi, S., R. Gök, K. Al-Toubi, Y. Al-Shijbi, I. El-Hussain, and A.J. Rodgers (2011). Seismic velocity structure at the southeastern margin of the Arabian Peninsula, Geophys. J. Int., DOI: 10.1111/j.1365-246X.2011.05067.x

# Recent Tectonic History of Middle East Region

- closure of the Tethys Ocean
- assembly of terranes in southern Eurasia prior to the collision of Africa and India
- orogeny and plateau building along Tethys collision zone
- continuing subduction in the Mediterranean and in the Makran

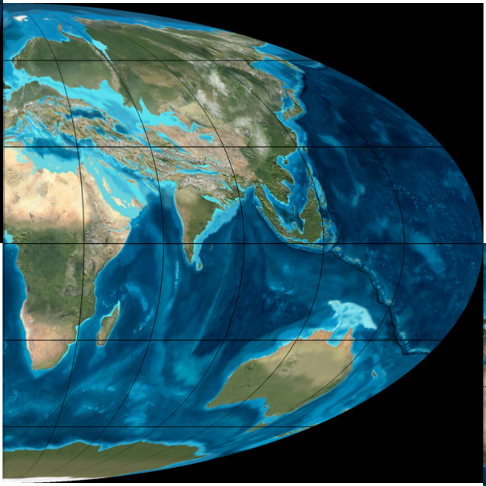


65 Ma

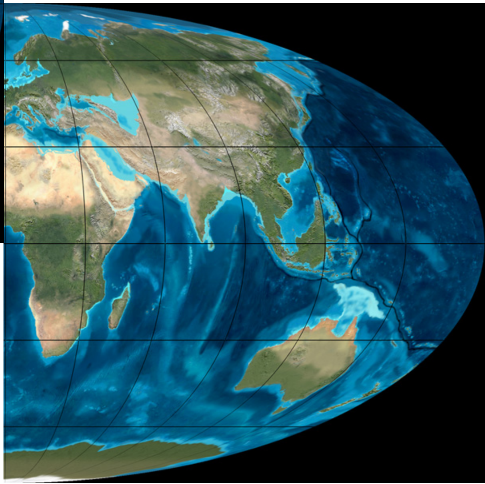


50 Ma

35 Ma



20 Ma

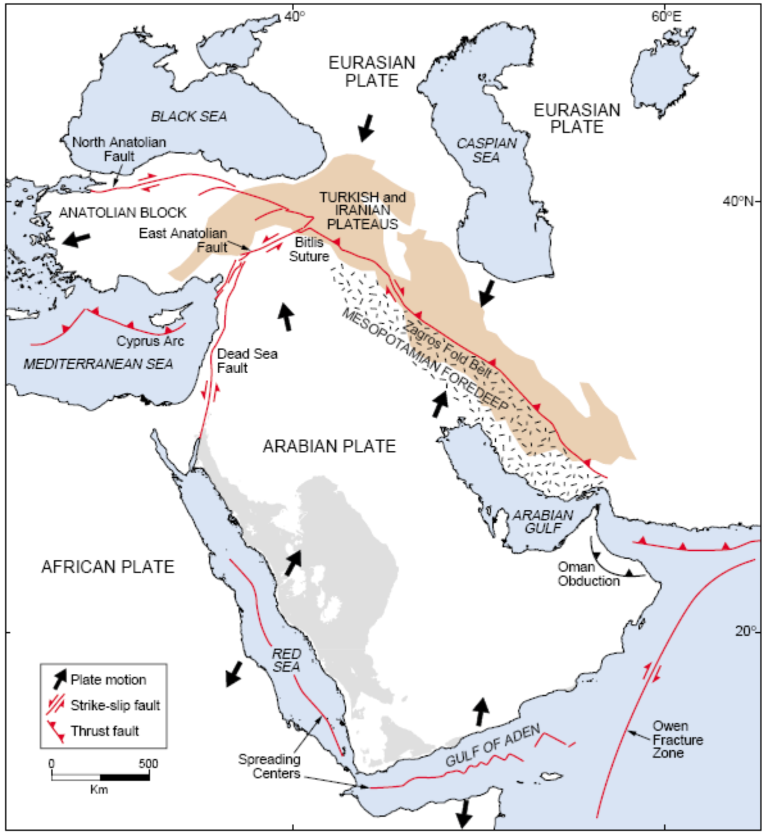


Figures courtesy of Ron Blakey, Northern Arizona University

# Quick tectonic overview

- Convergence between Arabian and Eurasia Plates producing the continued uplift of the Zagros Mts. and Turkish and Iranian Plateaus
- Rifting along axes of Afar Triple Junction creating Red Sea, Gulf of Aden, and East African Rift Zone
- Remnant oceanic crust in Black and Caspian Seas
- Subduction of oceanic crust in the Mediterranean Sea and along the Makran
- Large strike-slip faults along the Dead Sea Fault, East Anatolian Fault, and North Anatolian Fault
- Very deep sedimentary basins along the Persian/Arabian Gulf, Mesopotamian Foredeep, eastern Mediterranean and Caspian Sea.
- Precambrian Arabian-Nubian Shield

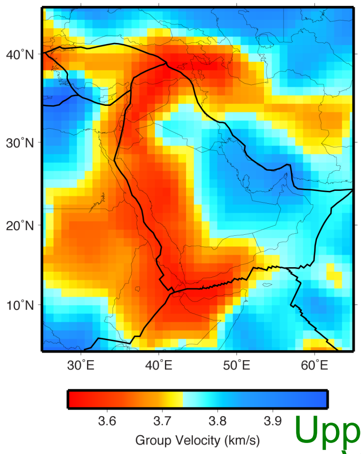
Simplified tectonic map from Seber et al. (2000)



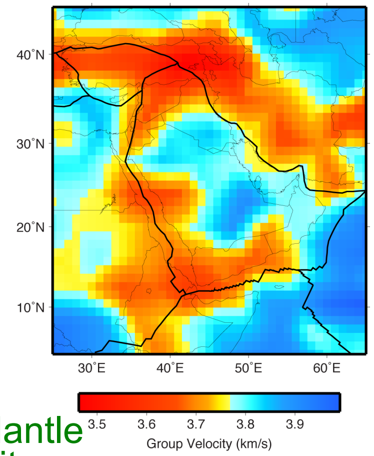
# Surface Wave Results for the Middle East

Model from Ma et al. (2012) in preparation

Data Rayleigh Wave Group Velocity 10.00 mHz

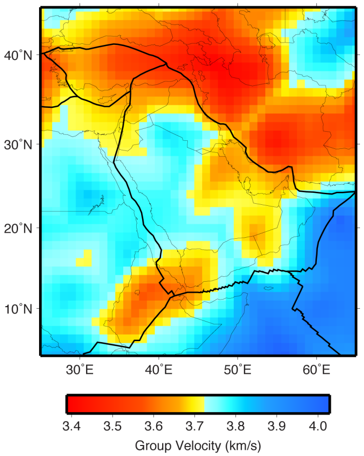


Data Rayleigh Wave Group Velocity 15.00 mHz

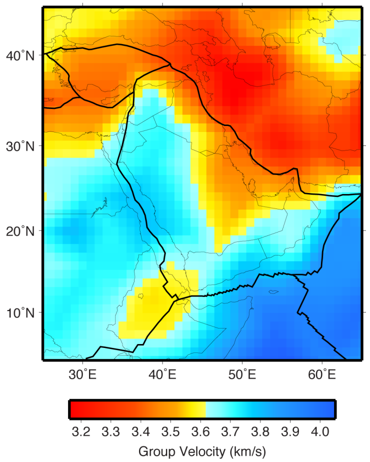


Upper Mantle
Velocity

Data Rayleigh Wave Group Velocity 20.00 mHz

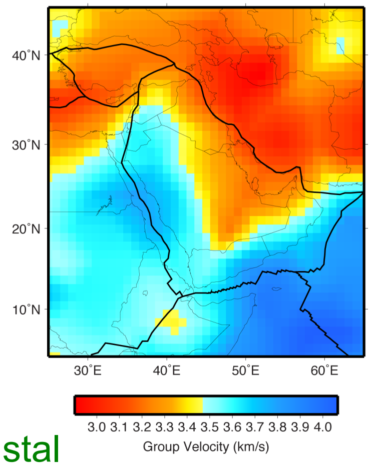


Data Rayleigh Wave Group Velocity 25.00 mHz

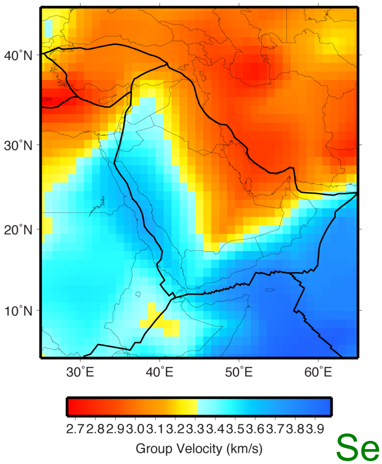


Crustal
Thickness

Data Rayleigh Wave Group Velocity 30.00 mHz

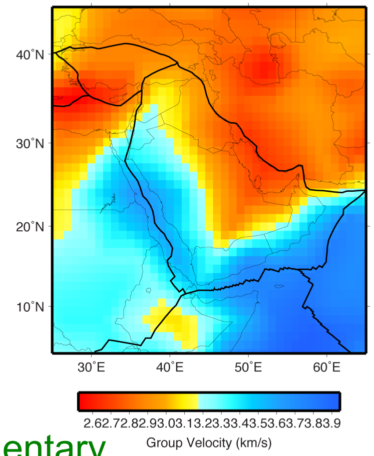


Data Rayleigh Wave Group Velocity 35.00 mHz



Sedimentary
Thickness

Data Rayleigh Wave Group Velocity 40.00 mHz



## Summary

- Surface waves are a well-known and well-understood way of studying the earth
- Surface waves are effective at sampling aseismic regions.
- The differing sensitivities of Love and Rayleigh wave phases, and for different periods, allows us to sample the depth profile of the earth.
- We will use them in conjunction with receiver functions to develop more robust models.

# Section 2 - Surface Wave Analysis – Measurement and Tomography

Surface Wave Measurements (Dispersion along Paths)

- Event Based, Ambient Noise, Clustering

Seismic Tomography (Lateral Dispersion)

- System of equations, Damping

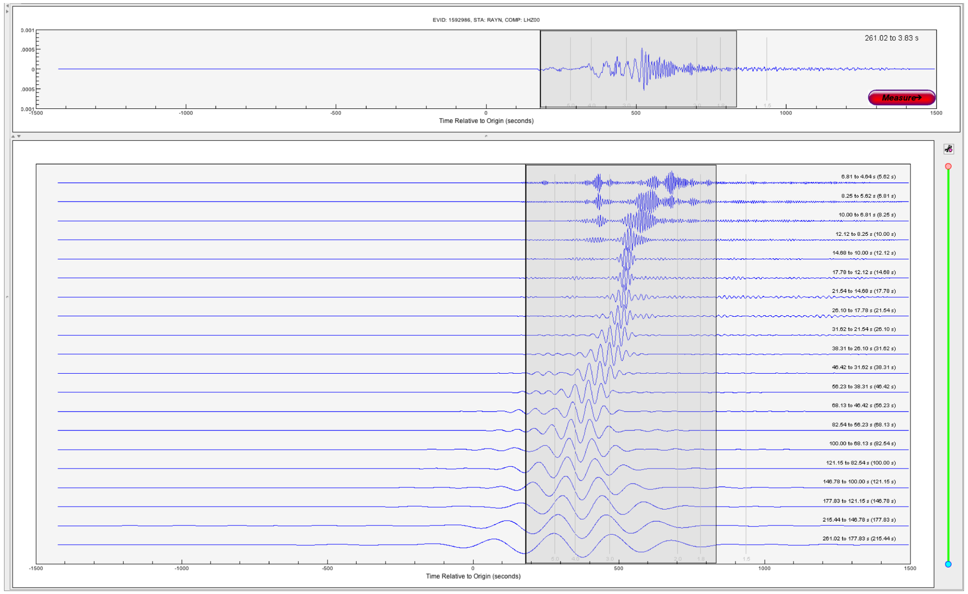
Layered Velocity Inversion (Dispersion to Velocity)

- Inversion vs. Grid Search

# Multiple-Filter Analysis

Multiple-Filter Analysis – a narrow-band Gaussian filter is applied over many different periods (e.g. Dziewonski, et al., 1969; Herrmann, 1973)

FTAN (Frequency-Time Analysis) – Levshin et al., 1972



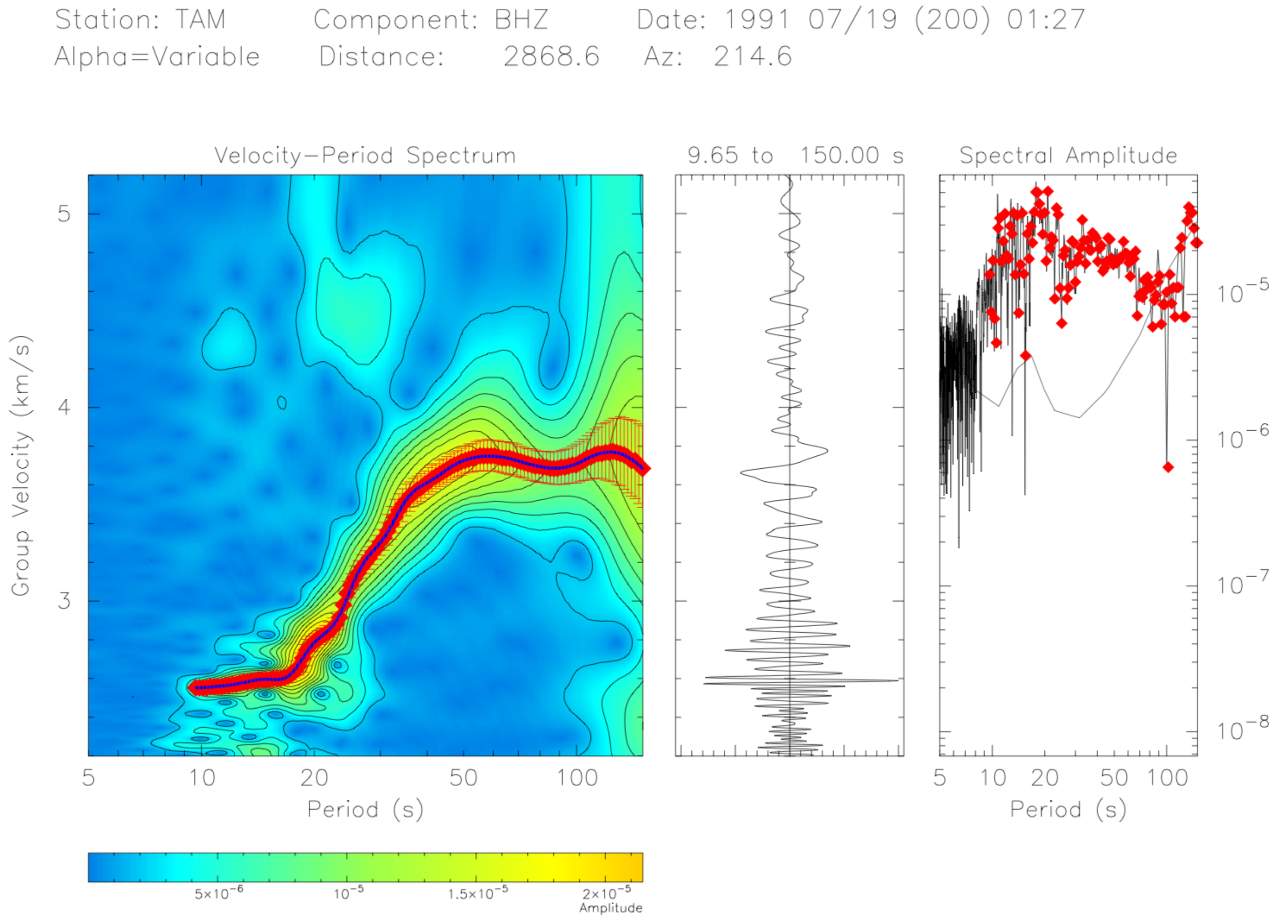
Dziewonski, A., S. Bloch, and M. Landisman (1969). A technique for the analysis of transient seismic signals, Bull. Seism. Soc. Amer., 59, 427-444.

Herrmann, R.B. (1973). Some aspects of bandpass filtering of surface waves, Bull. Seism. Soc. Amer., 63, 663-671.

Levshin, A.L., V.F. Pisarenk, G.A. Pogrebin (1972), Frequency-time analysis of oscillations, Annales de Geophysique, 28, 211

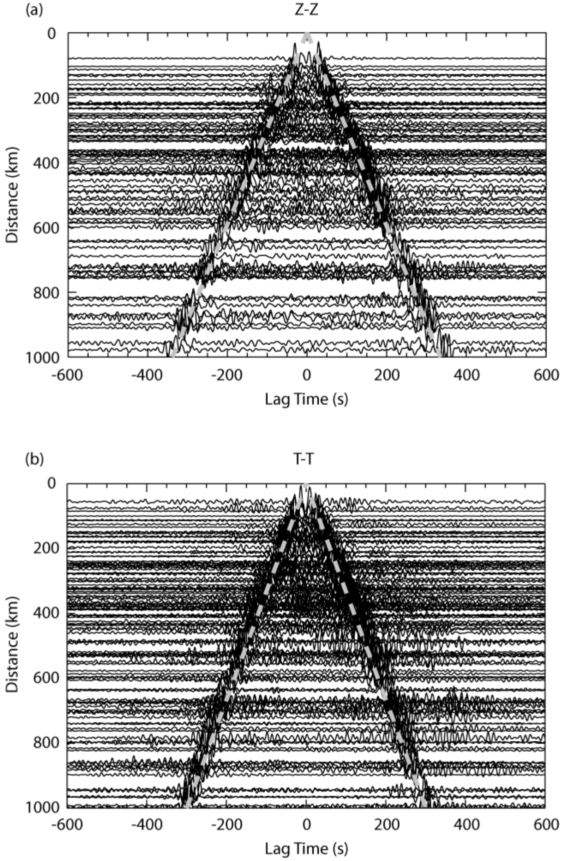
# Multiple-Filter Analysis

PGSWMFA = PGplot Surface Wave Multiple Filter Analysis
uses PGPLOT plotting package



# Ambient Noise Analysis

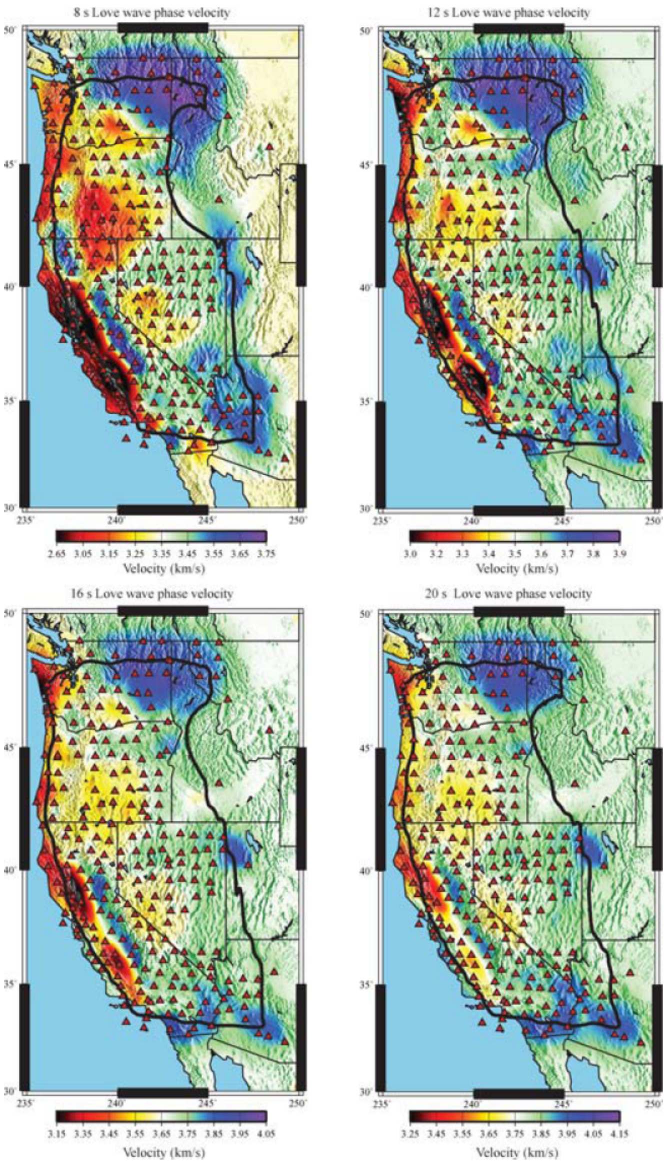
Algorithms developed by the University of Colorado group (and detailed in Bensen et al., 2007)



Bensen, G.D., M.H. Ritzwoller, M.P. Barmin, A.L. Levshin, F. Lin, M.P. Moschetti, N.M. Shapiro, and Y. Yang (2007), Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, Geophys. J. Int., (169), 1239–1260.

# Ambient Noise Analysis

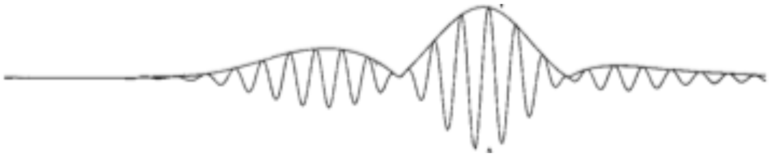
Has the potential to produce very high resolution models where station coverage is dense



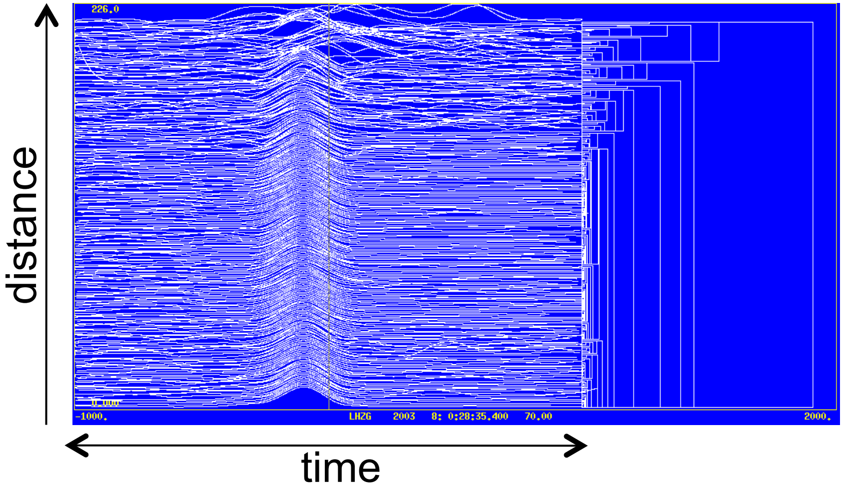
Lin, F.-C., M.P. Moschetti, and M.H. Ritzwoller (2008). Surface wave tomography of the western United States from ambient seismic noise: Rayleigh and Love wave phase velocity maps, Geophys. J. Int. doi: 10.1111/j.1365-246X.2008.03720.x

# Surface wave model developed using cluster analysis

We have developed a new, very large global surface wave dataset build using a new, efficient measurement technique that employs cluster analysis



envelope functions for Rayleigh 20mHz

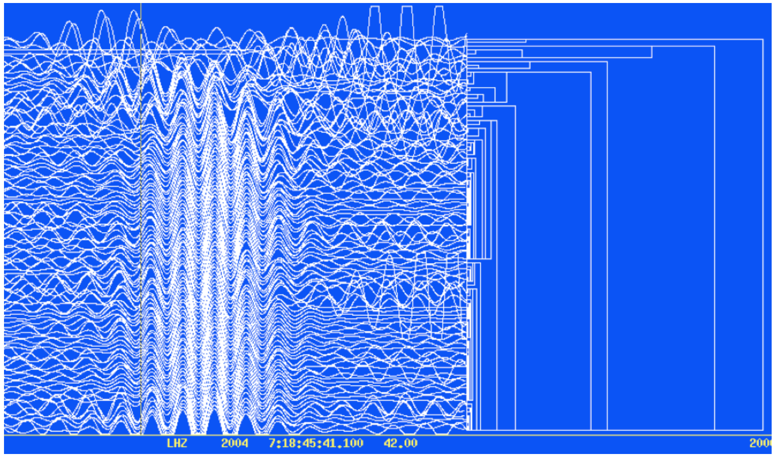


grouped by similarity

cluster trees

Measurement algorithm

- "Undisperse" using a 1-D phase velocity curve
- Correct for source phase and amplitude
- Correct for predicted phase shift from 3D structure using a nominal phase velocity map



Rayleigh 10mHz

Ma et al. (2012) in preparation

# Consistency between group and phase velocity maps is achieved through cubic splines

Relationship between group velocity U and phase velocity c

$$\frac{1}{U} = \frac{1}{c} + \omega \frac{d}{d\omega}\frac{1}{c}$$

$$\frac{1}{U} = \sum B_i(\omega) a_i$$

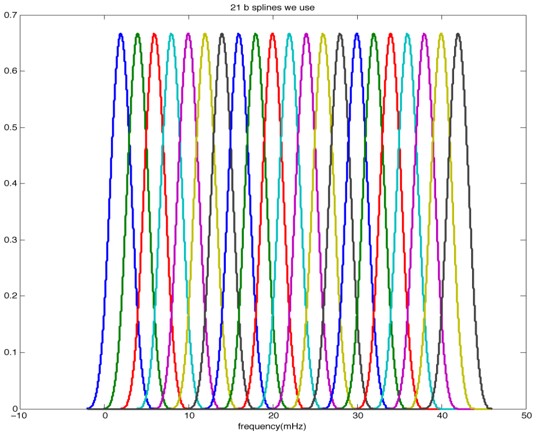
$$\frac{\omega}{c} = \sum [\int_{\omega_0}^{\omega} B(\omega') d\omega'] a_i + a_0$$

or

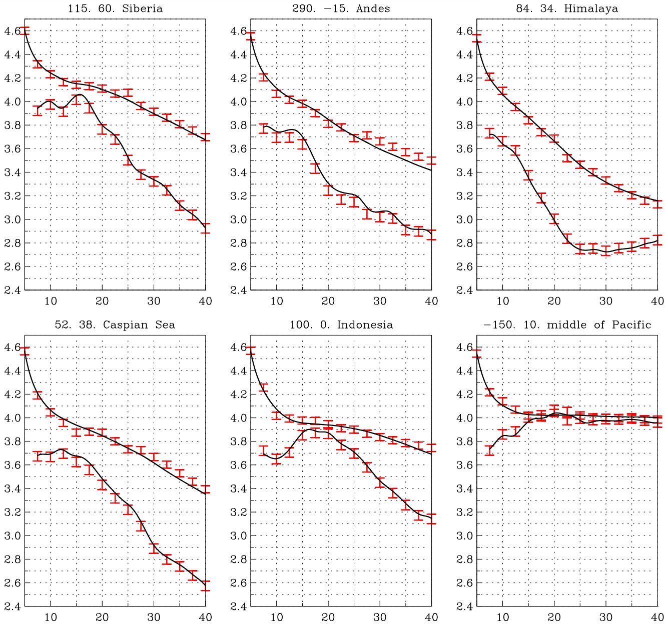
$$\frac{1}{c} = \sum B_i(\omega) a_i$$

$$\frac{1}{U} = \sum [\omega B_i'(\omega) + B_i(\omega)] a_i$$

where $B_i(\omega)$ are b spline functions, $B_i'(\omega)$ are the derivatives and $a_i$ are the coefficients



Ma et al. (2012) in preparation



# Phase Velocity Measurements

Single station (event-station)

- Need to know the source phase $\phi_0$, $2\pi$ indeterminacy

Mechanism and depth needed to determine source phase $\phi_0$.

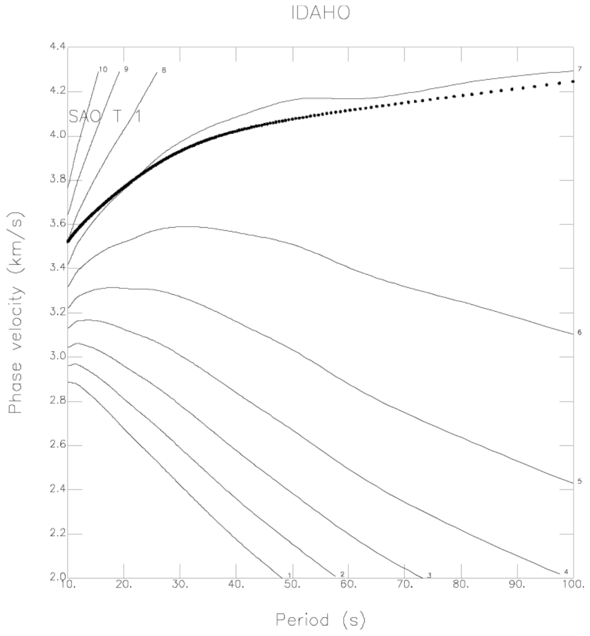
Unwrapping the phase by working from long periods.

AMPLITUDE PHASE

$$u(x,t) = \frac{1}{\pi}\int_0^\infty \hat{u}(\omega,x) \times \cos\left(\omega t - \frac{\omega}{c(\omega)}x + \phi_0(\omega)\right) d\omega$$

$$\phi(\omega) = \phi_0(\omega) - \frac{\omega x_1}{c(\omega)} + 2\pi N + \omega t$$

$$\psi_1(\omega) = \omega t_1 + \phi_o(\omega) - \frac{\omega x_1}{c(\omega)} + 2\pi N$$



# Phase Velocity Measurements

Two-station method (event-event)

- Source phase $\phi_0$ cancels
- Still have 2π indeterminacy

$$\psi_1(\omega) - \psi_2(\omega) = \omega(t_1 - t_2) - \frac{\omega}{c(\omega)}(x_1 - x_2) + 2\pi M$$

$$c(\omega) = \frac{x_1 - x_2}{(t_1 - t_2) + T[M - (1/2\pi)(\psi_1(\omega) - \psi_2(\omega))]}$$

Two-plane method (Forsyth, 1998)

- uses the sum of two plane waves, each with initially unknown amplitude, initial phase, and propagation direction to represent the nonplanar incoming wavefield, i.e., a total of six parameters to describe the incoming wavefield.

$$U(\omega) = A_1(\omega)\exp(-i\phi_1) + A_2(\omega)\exp(-i\phi_2)$$

$$\phi_1 = \phi_1^0 + \omega[r\cos(\psi - \theta_1) - x]/c(\omega) + \omega(\tau - \tau_0)$$

$$\phi_2 = \phi_2^0 + \omega[r\cos(\psi - \theta_2) - x]/c(\omega) + \omega(\tau - \tau_0)$$

# Seismic Tomography

Tomography is an imaging method widely used in seismology for the derivation of bulk earth properties such as velocity and attenuation from measured properties along paths.

It is analogous to tomography methods used in medical imaging, such as CT scans, but generally with much poorer coverage of the study region.

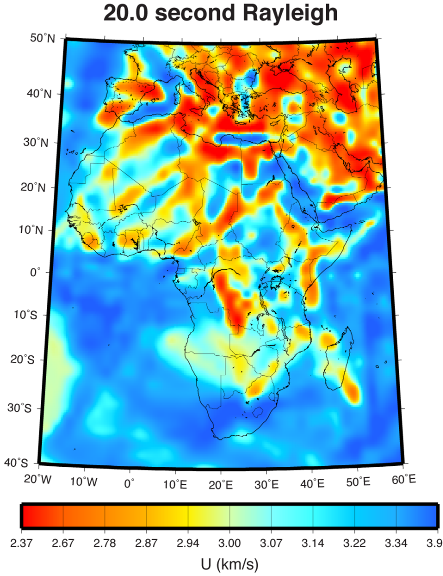
$$\mathbf{t} = \mathbf{A}\,\mathbf{x}$$

We use it to invert dispersion measurements for spatially varying dispersion values.

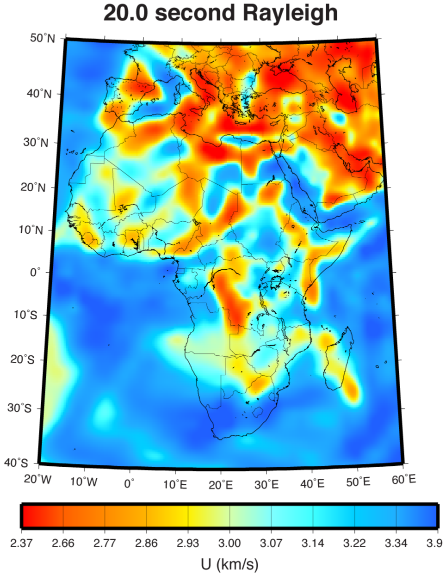
There are many methods to solve the inversion.  We will be using a program that uses the conjugate gradient method.

# Seismic Tomography – Importance of Damping

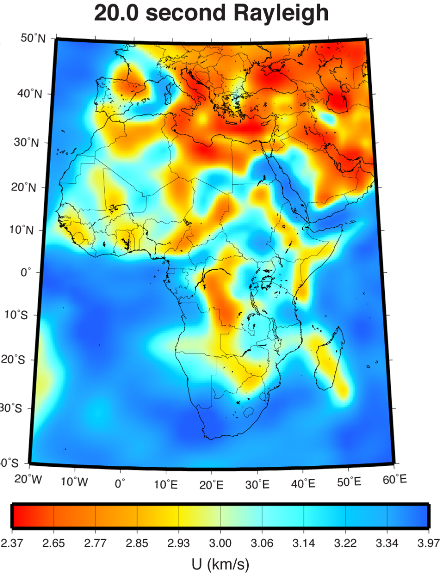
λ=0.5


20.0 second Rayleigh

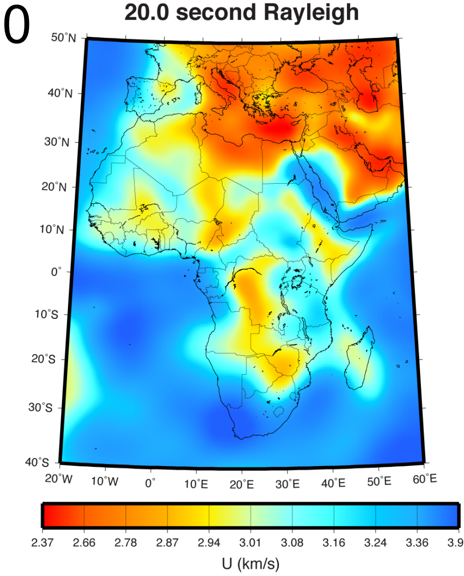
λ=1.0


20.0 second Rayleigh

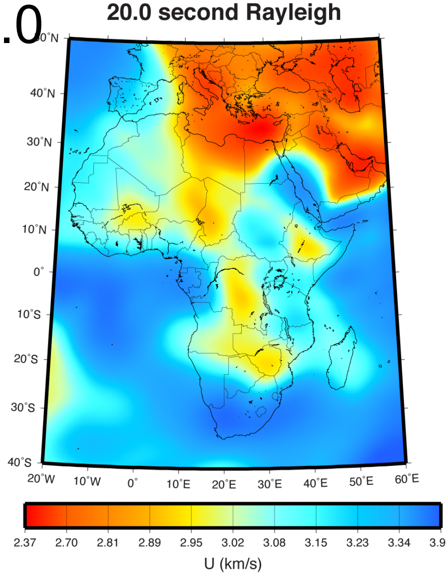
λ=2.0


20.0 second Rayleigh

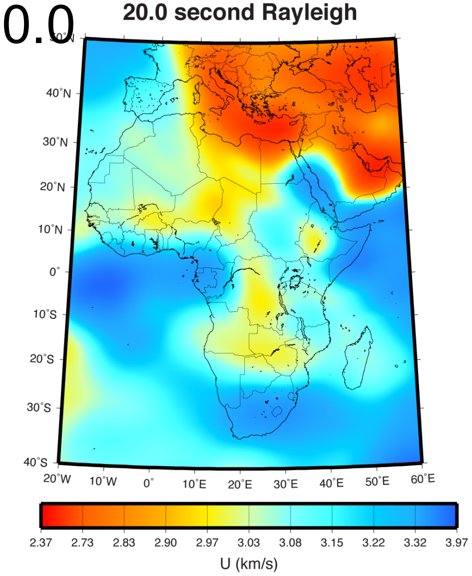
λ=5.0


20.0 second Rayleigh

λ=10.0


20.0 second Rayleigh

λ=20.0


20.0 second Rayleigh

# Layered Velocity Inversion

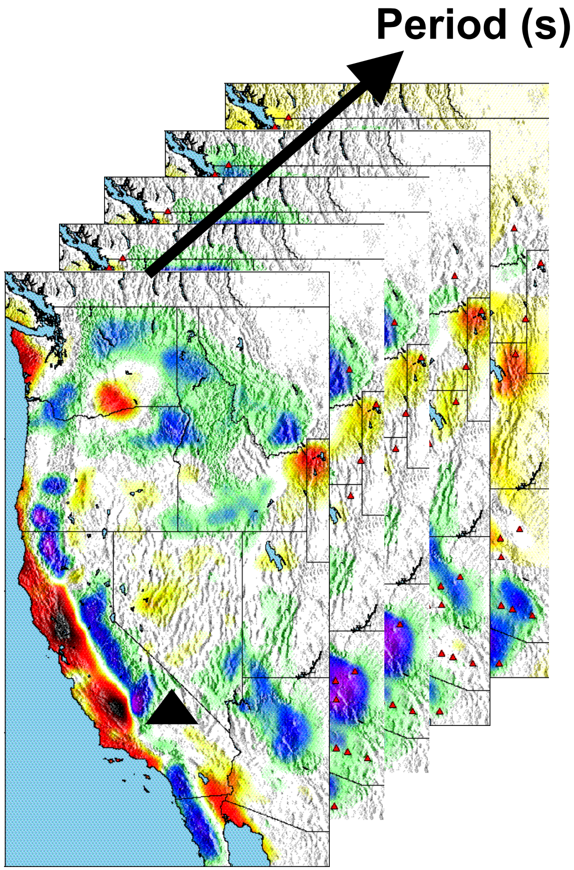
Inverting group velocities and phase velocities for layered earth structure is both:

- Non-unique (many possible models can fit the same dispersion data)
- Non-linear (the sensitivity kernels used to invert for the earth structure itself depend on the earth structure)

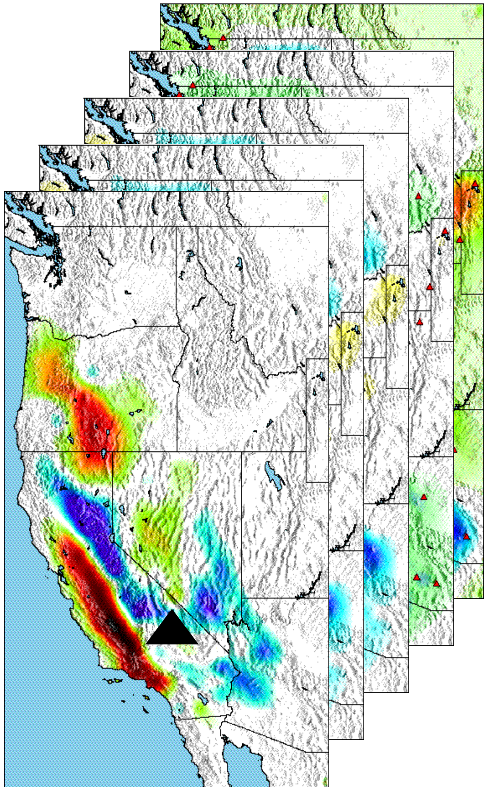
I usually employ a grid-search method to estimate the layered velocity structure.

One advantage is that one doesn't actually perform an inversion, just a series of forward calculations.  This allows us to explore the model space.

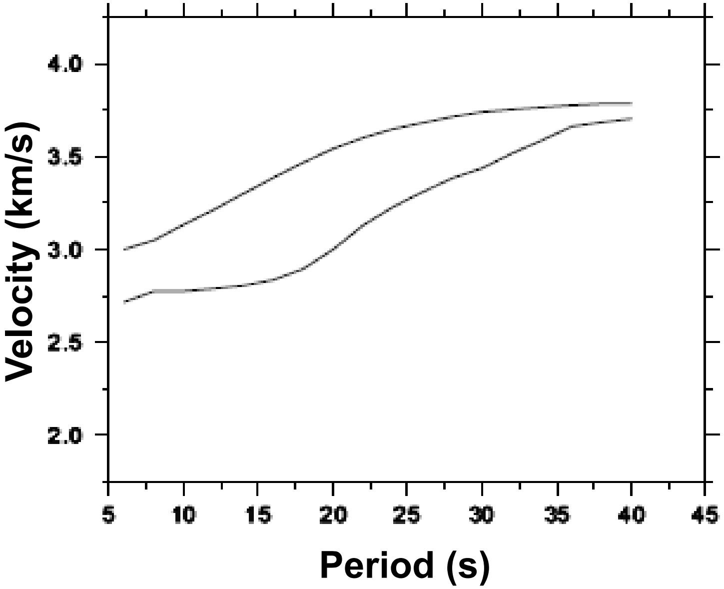
# Getting from dispersion maps and dispersion curves to layered velocity structure



Group velocity maps



Phase velocity maps



# Sensitivity kernels

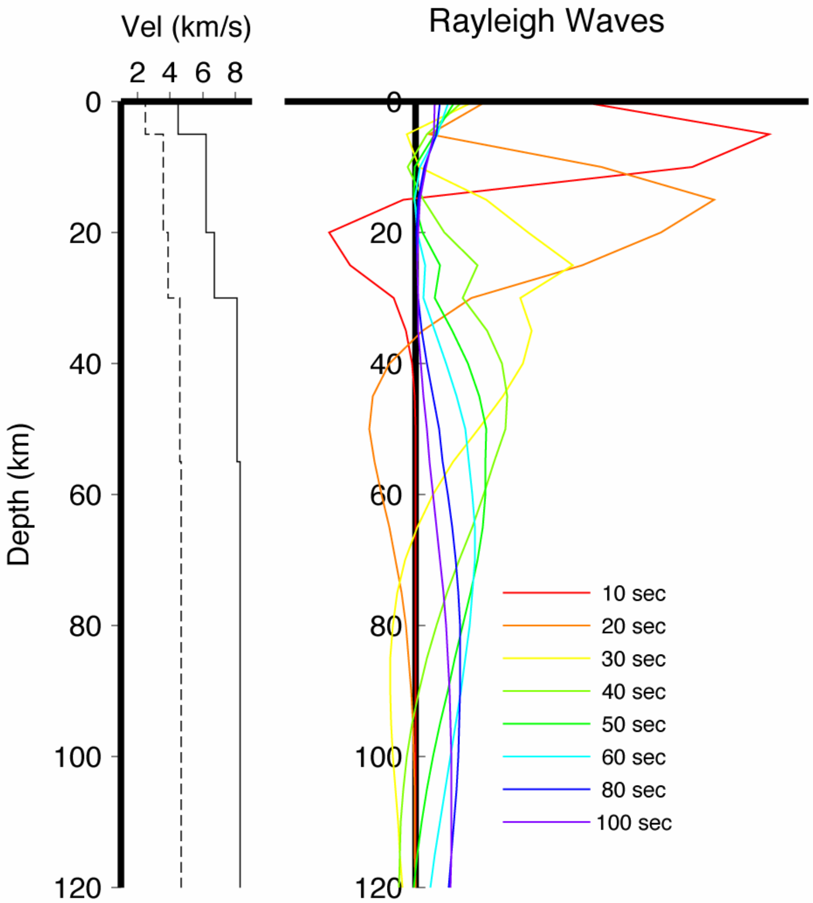
Sensitivity kernels show the relationship between dispersion velocities and earth structure.

They are calculated by taking the partial derivative of the dispersion velocities with respect to other parameters, such as shear-wave velocity. For instance, δU/δβ is often shown here.

With increasing period, surface waves become sensitive to deeper velocity structures.

They are themselves dependent on the velocity structure, so it is non-linear.

We will be using them later when we invert our dispersion curves for layered velocity structure.



# Inversion vs. grid search

The inverse problem can be conceptually formulated as follows:

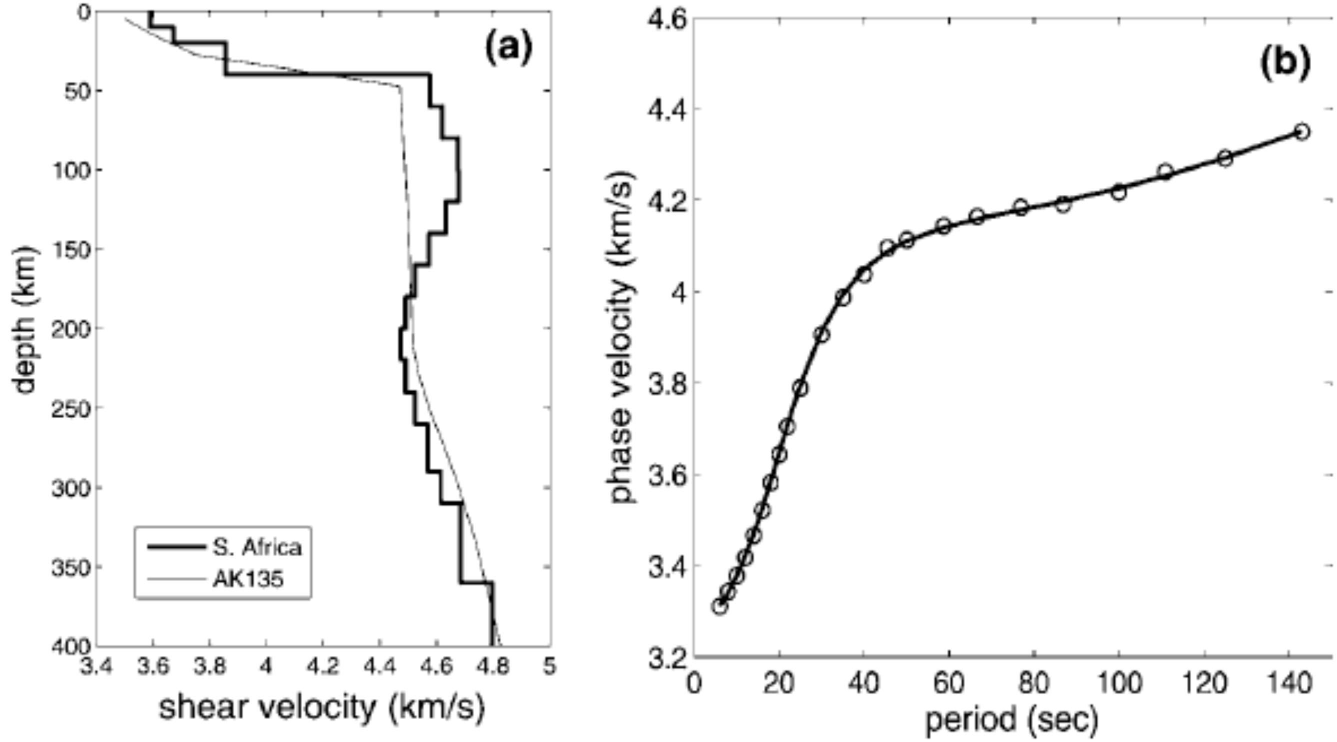
Data → Model parameters

The inverse problem is considered the "inverse" to the forward problem which relates the model parameters to the observed data:

Model parameters → Data

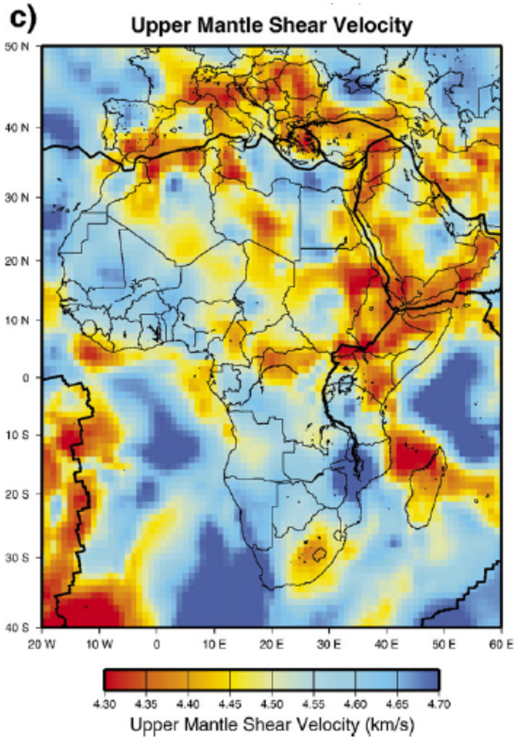
A grid search performs an inversion by calculating the forward problem multiple times and comparing the predicted data to the observed data.

# Example of inverting surface wave dispersion maps for 1-D shear-velocity profile

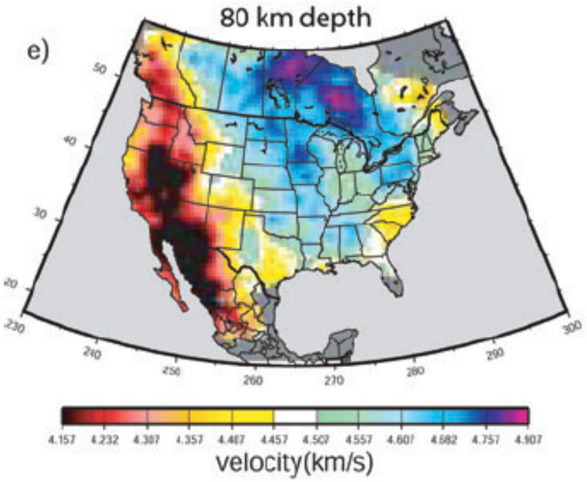


# Results can be combined to produce 3-D structural models

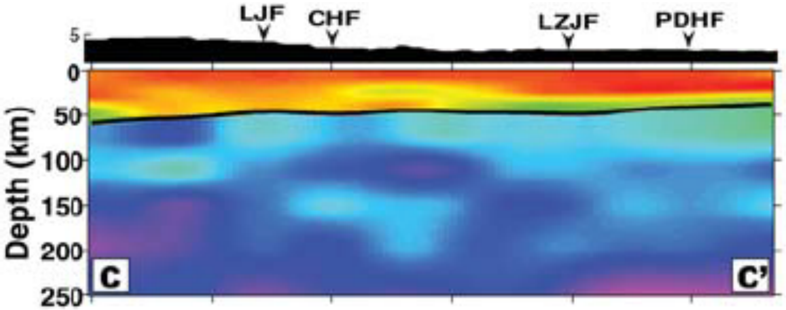
## Examples of structure derived from surface waves



Pasyanos and Nyblade, 2007



Bensen et al, 2009



Yao et al, 2008

# Inversion vs. Grid-Search

Inversion

Issues:
- Invert for layer thickness
- Invert for layer velocity
- Starting model
- Non-linear inversion
- Layer smoothing

Grid Search

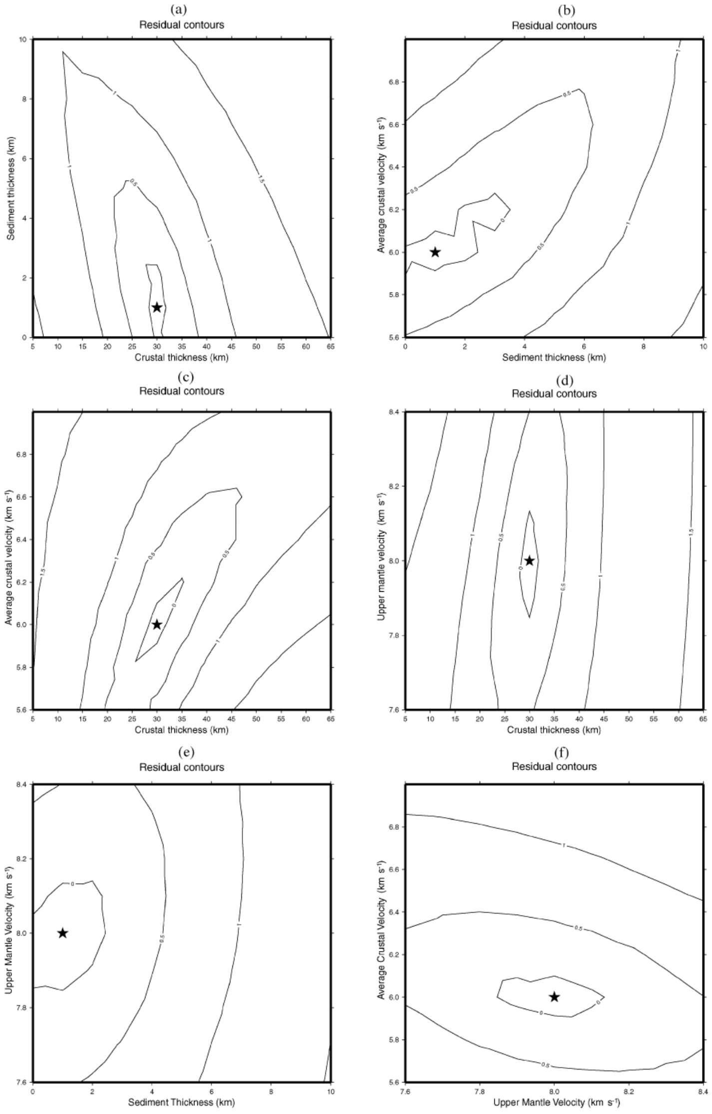
Issues:
- Fewer inversion parameters
- Usually slower
- Unique dispersion curve for each trial model
- Can be used to map out model space

Programs

Computer Programs in Seismology (Bob Herrmann, SLU) is a nice package of software to enable inversion of dispersion measurements (and a lot more)

MINOS (Woodhouse, Masters) is a comprehensive package that computes surface wave dispersion by summing normal modes

# Tradeoffs among various parameters



Pasyanos, M.E. and W.R. Walter (2002). Crust and upper-mantle structure of North Africa, Europe and the Middle East from inversion of surface waves, Geophys. J. Int. 149, 463-481.

Adding other types of data (for example, receiver functions) can help reduce these tradeoffs

# Inversion Parameters

Possible inversion parameters
- Sediment thickness
- Crustal thickness
- Crustal velocity
- Crustal Vp/Vs
- Upper mantle velocity
- Upper mantle Vp/Vs
- Upper mantle anisotropy
- Lithospheric thickness

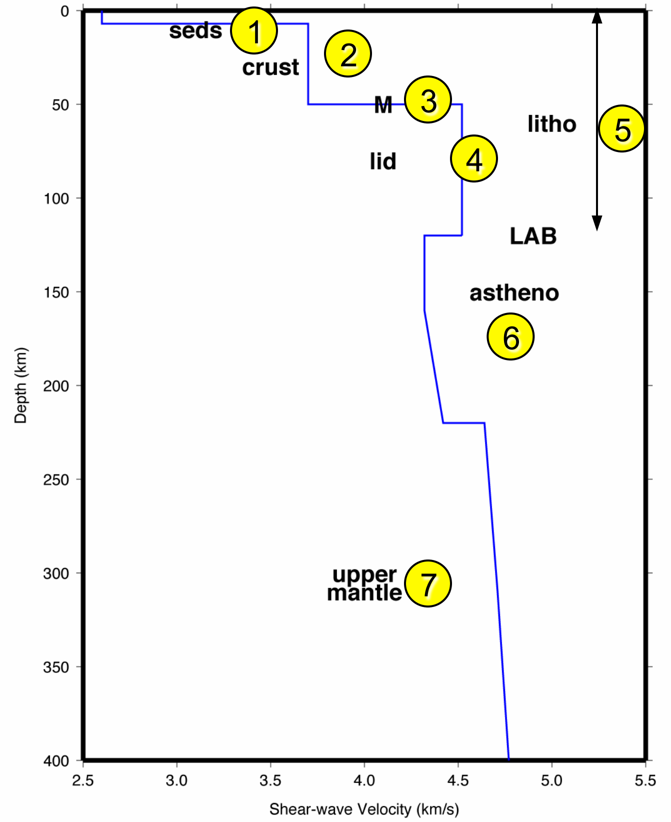
# One approach employed in Pasyanos and Nyblade (2007) and Pasyanos (2010)

Grid search

- fix sediments from Laske sediment profile ①
- solve for $v_p/v_s$, ② crustal thickness, ③ $p_n/s_n$, ④ lithospheric thickness ⑤
- asthenosphere ⑥ has lower Vp and higher Poisson’s ratio ($\sigma$=0.29)
- upper mantle ⑦ is transitioned into ak135 model (Kennett et al., 1995)

NOT solving for

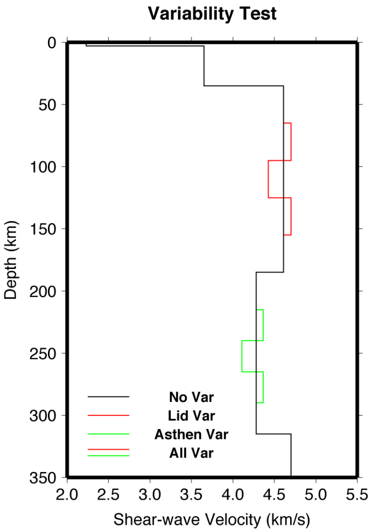
- detailed variations in velocity or Poisson’s ratio in crust or lid

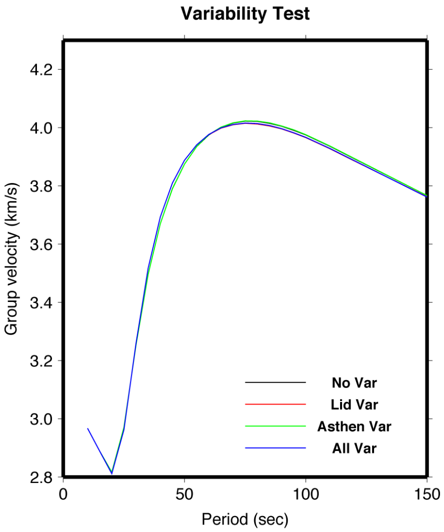


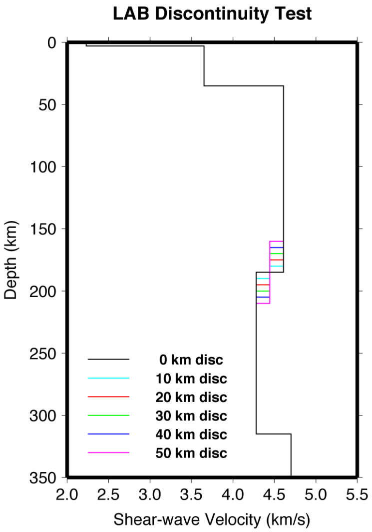
Pasyanos, M.E. and A.A. Nyblade (2007), A top to bottom lithospheric study of Africa and Arabia, Tectonophysics, 444, 27-44, doi:10.1016/j.tecto.2007.07.008.

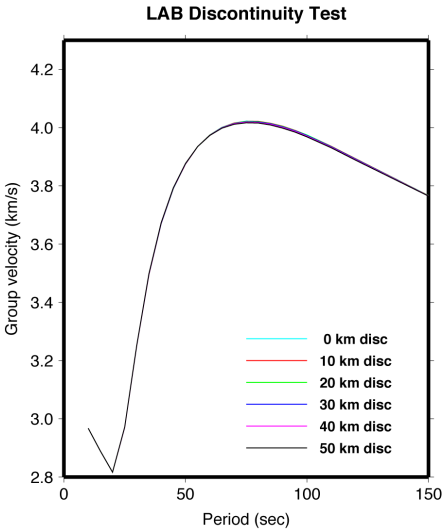
Pasyanos, M.E. (2010). Lithospheric thickness modeled from long-period surface wave dispersion, Tectonophys., 481, 38-50.

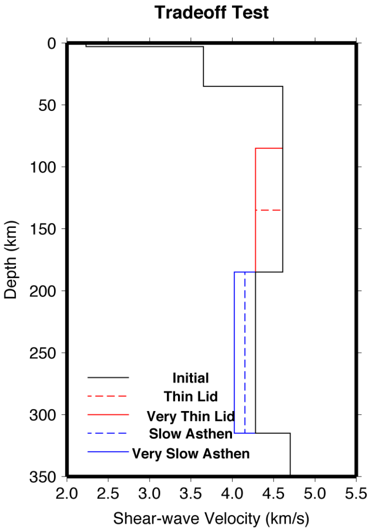
# Inversion Tests

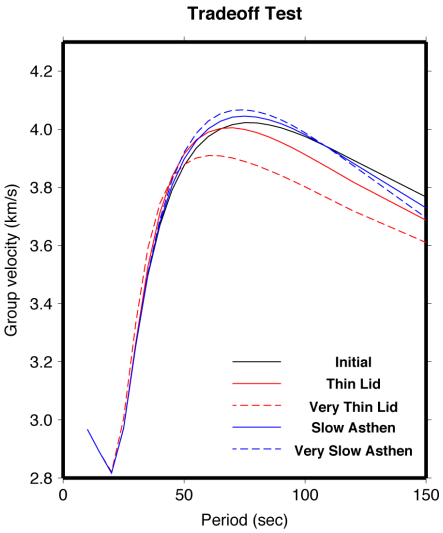

Variability Test

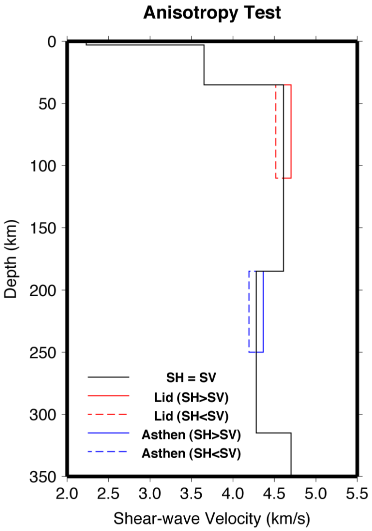

Variability Test

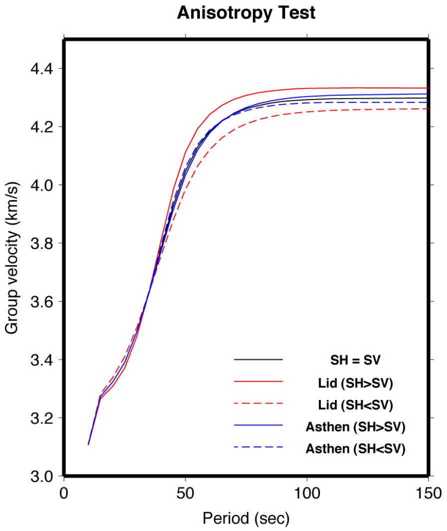

LAB Discontinuity Test


LAB Discontinuity Test


Tradeoff Test


Tradeoff Test


Anisotropy Test


Anisotropy Test

from Pasyanos et al. (2010)

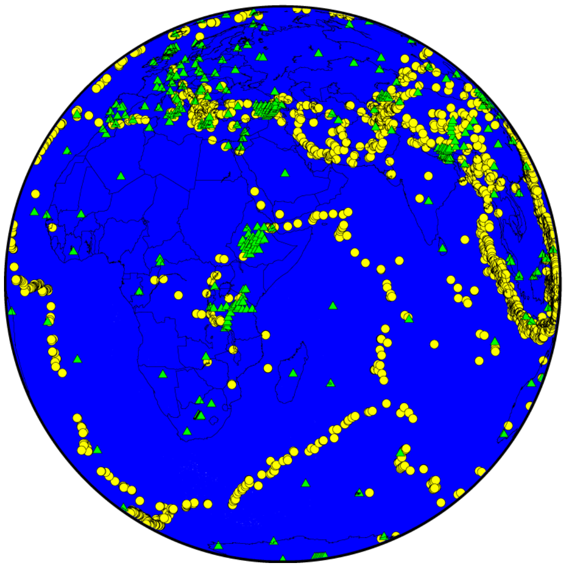
## Summary

- The analysis of seismic surface waves are a well-established method of estimating earth structure.
- There are several ways of measuring seismic dispersion
- Seismic tomography can be used to invert those values for lateral variations in dispersion
- Another inversion must be used to determine what velocity structure  is consistent with the observed dispersion
- Profiles over broad regions can be combined to produce 3-D structural models.

# Section 3 – Model and Access Tool

We have provided a tool to retrieve dispersion information from the global surface wave model of Ma et al. (2012).

# Surface Wave Model - Coverage



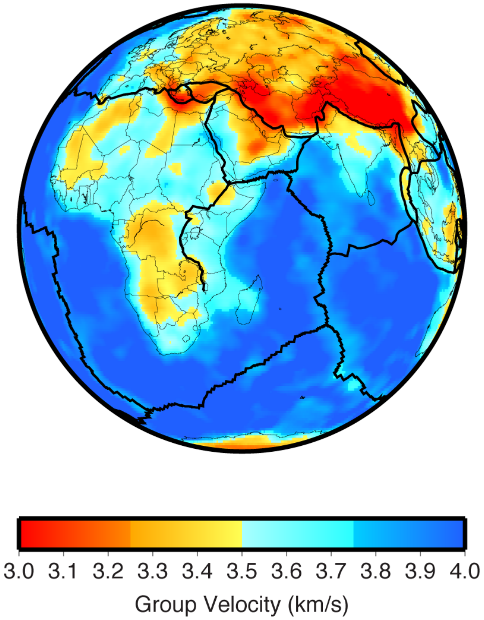
Surface Wave Paths

## Paths at each frequency

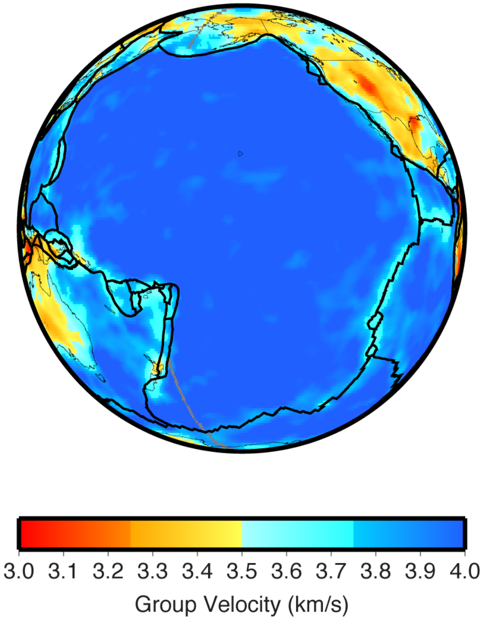
| Frequency (mHz) | | 5 | 7.5 | 10 | 12.5 | 15 | 17.5 | 20 | 22.5 | 25 | 27.5 | 30 | 32.5 | 35 | 37.5 | 40 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rayleigh | Phase | 305k | 502k | 582k | 609k | 603k | 595k | 400k | 525k | 414k | 489k | 320k | 403k | 282k | () | () |
| | Group | | 316k | 353k | 331k | 299k | 316k | 334k | 322k | 199k | 210k | 203k | 214k | 109k | 110k | 113k |
| Love | Phase | | 140k | 198k | 246k | 175k | 222k | 145k | 219k | 152k | 194k | 108k | | | | |
| | Group | | | 189k | 182k | 166k | 180k | 171k | 176k | 166k | 77k | 76k | | | | |

# Surface Wave Model - Results

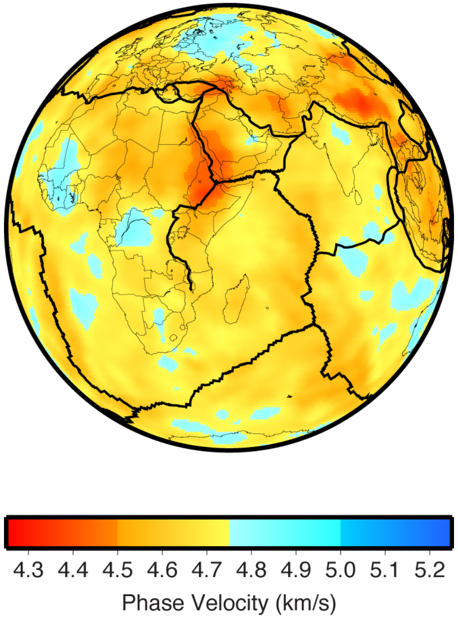
**Rayleigh Wave Group Velocity 30.0 mHz**



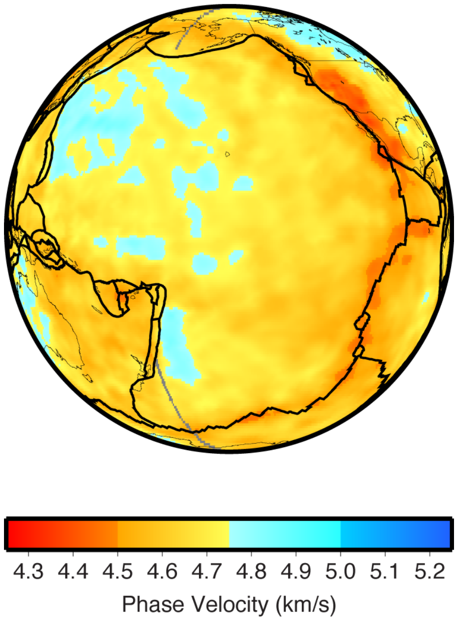
**Rayleigh Wave Group Velocity 30.0 mHz**



**Love Wave Phase Velocity 10.0 mHz**



**Love Wave Phase Velocity 10.0 mHz**



# Examples

```
get_dispersion 23.522499 45.503201

Getting dispersion values from surface wave model
 lat =    23.5224990000000       lon =    45.5032010000000
 avg nblk=           1
 nfreq =          15          10
 RAYLEIGH
 Freq (mHz)  Period (s)  Group Vel (km/s)  Phase Vel (km/s)
    5.0000  200.0000  -99.0000    0.0400    4.5560    0.0300
    7.5000  133.3333    3.6787    0.0400    4.1909    0.0300
   10.0000  100.0000    3.7663    0.0400    4.0654    0.0300
   12.5000   80.0000    3.7896    0.0400    4.0049    0.0300
   15.0000   66.6667    3.8010    0.0400    3.9687    0.0300
   17.5000   57.1429    3.7885    0.0400    3.9434    0.0300
   20.0000   50.0000    3.6876    0.0400    3.9173    0.0300
   22.5000   44.4444    3.6096    0.0400    3.8846    0.0300
   25.0000   40.0000    3.5748    0.0400    3.8535    0.0300
   27.5000   36.3636    3.4627    0.0400    3.8212    0.0300
   30.0000   33.3333    3.3749    0.0400    3.7834    0.0300
   32.5000   30.7692    3.3130    0.0400    3.7456    0.0300
   35.0000   28.5714    3.2361    0.0400    3.7075    0.0300
   37.5000   26.6667    3.1533    0.0400    3.6684    0.0300
   40.0000   25.0000    3.0424    0.0400    3.6269    0.0300
 LOVE
 Freq (mHz)  Period (s)  Group Vel (km/s)  Phase Vel (km/s)
    7.5000  133.3333  -99.0000    0.0600    4.6965    0.0400
   10.0000  100.0000    4.2473    0.0600    4.5931    0.0400
   12.5000   80.0000    4.0981    0.0600    4.5036    0.0400
   15.0000   66.6667    4.0472    0.0600    4.4231    0.0400
   17.5000   57.1429    3.9942    0.0600    4.3620    0.0400
   20.0000   50.0000    3.9145    0.0600    4.3057    0.0400
   22.5000   44.4444    3.8609    0.0600    4.2554    0.0400
   25.0000   40.0000    3.7287    0.0600    4.2044    0.0400
   27.5000   36.3636    3.6923    0.0600    4.1535    0.0400
   30.0000   33.3333    3.7505    0.0600    4.1119    0.0400
```

```
get_dispersion 29.17556 47.69333

Getting dispersion values from surface wave model
 lat =    29.1755600000000       lon =    47.6933300000000
 avg nblk=           1
 nfreq =          15          10
 RAYLEIGH
 Freq (mHz)  Period (s)  Group Vel (km/s)  Phase Vel (km/s)
    5.0000  200.0000  -99.0000    0.0400    4.5539    0.0300
    7.5000  133.3333    3.8017    0.0400    4.2537    0.0300
   10.0000  100.0000    3.9035    0.0400    4.1443    0.0300
   12.5000   80.0000    3.9397    0.0400    4.1014    0.0300
   15.0000   66.6667    3.8425    0.0400    4.0644    0.0300
   17.5000   57.1429    3.7577    0.0400    4.0246    0.0300
   20.0000   50.0000    3.7232    0.0400    3.9861    0.0300
   22.5000   44.4444    3.6562    0.0400    3.9517    0.0300
   25.0000   40.0000    3.5130    0.0400    3.9121    0.0300
   27.5000   36.3636    3.3422    0.0400    3.8624    0.0300
   30.0000   33.3333    3.1968    0.0400    3.8045    0.0300
   32.5000   30.7692    3.0621    0.0400    3.7428    0.0300
   35.0000   28.5714    2.8974    0.0400    3.6751    0.0300
   37.5000   26.6667    2.7815    0.0400    3.6040    0.0300
   40.0000   25.0000    2.6532    0.0400    3.5327    0.0300
 LOVE
 Freq (mHz)  Period (s)  Group Vel (km/s)  Phase Vel (km/s)
    7.5000  133.3333  -99.0000    0.0600    4.7466    0.0400
   10.0000  100.0000    4.4932    0.0600    4.6999    0.0400
   12.5000   80.0000    4.2743    0.0600    4.6317    0.0400
   15.0000   66.6667    4.0344    0.0600    4.5447    0.0400
   17.5000   57.1429    3.8634    0.0600    4.4478    0.0400
   20.0000   50.0000    3.7098    0.0600    4.3528    0.0400
   22.5000   44.4444    3.5095    0.0600    4.2558    0.0400
   25.0000   40.0000    3.4041    0.0600    4.1586    0.0400
   27.5000   36.3636    3.2392    0.0600    4.0659    0.0400
   30.0000   33.3333    3.1273    0.0600    3.9727    0.0400
```

# Tools

get_dispersion is a tool which retrieves the surface wave dispersion at any given location

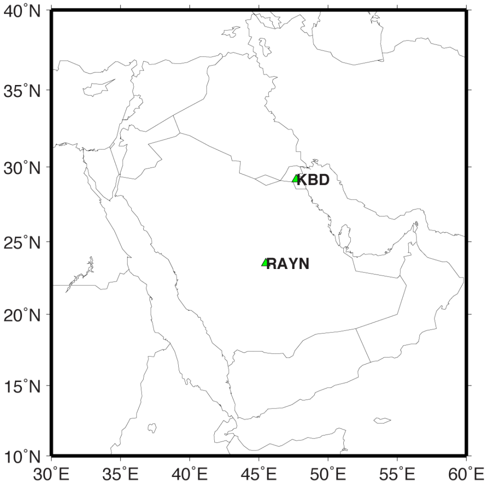
Surface wave data is from the model of Ma, Masters, Laske (UCSD Scripps) and Pasyanos (LLNL)

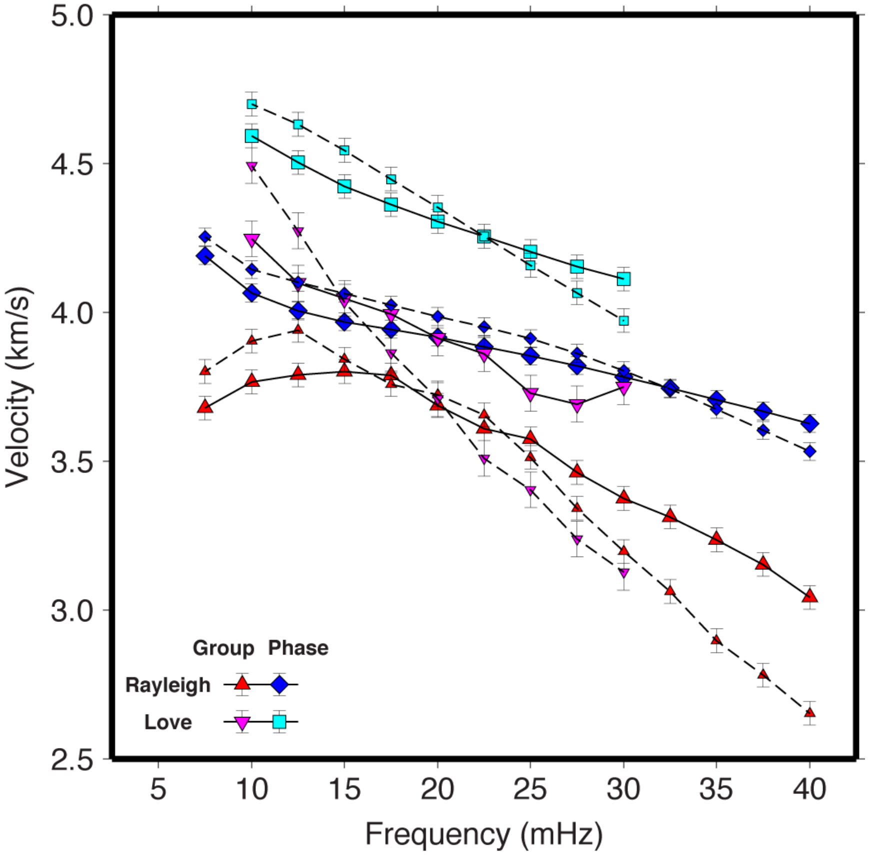
Rayleigh/Love
group/phase
5 - 40mHz (200 – 25 sec period)

```
get_dispersion [lat] [lon]
get_dispersion 23.522499 45.503201
```

# Tools

Comparing between dispersion at KBD and RAYN.





Phase velocities somewhat similar, but group velocities, which sample shallower structure (especially at high frequencies) are very different.

# Section 4 – Using Surface Waves to Build a Global Model

We present an example from a current research project:

“LITHO1.0 – An updated crust and lithospheric model
of the Earth developed using multiple data constraints”
Michael E. Pasyanos (LLNL)
Guy Masters, Gabi Laske and Zhitu Ma (IGPP, UC San Diego)

This section is a modified version of a talk that we gave at the Fall 2012 AGU Meeting in San Francisco

# Introduction

Crustal models like CRUST5.1 (Mooney et al., 1998) and successor models like CRUST2.0 (Bassin et al., 2000) have been well-utilized in the seismological and geophysical communities (e.g. CRUST5.1 has 474 citations in Web of Science 11/2012)

Useful to varied sections of the communities

- global tomography in order to remove the crustal “noise” to see the mantle “signal”
- smaller scale crustal studies as starting model or comparison model

Downsides

- Poor predictor of travel times
- Resolution poor for many applications
- Model is of questionable quality in many poorly-covered regions

We are creating a 1 degree model of the crust and upper mantle that is consistent with

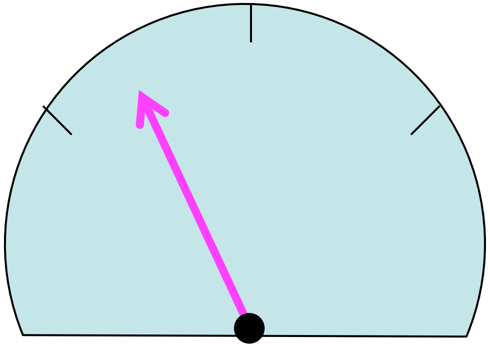
- Our extensive knowledge on sedimentary basins
- Improved information on crustal thickness
- Upper mantle velocities from regional travel times (e.g. Pn, Sn)
- High-resolution surface wave models across a broad frequency band

**Our goal is to develop a higher-resolution model that extends deeper into the mantle to include the lithospheric lid. This is the LITHO1.0 model**

# Method

Our philosophy is to test a large series of models which are perturbations of a starting model which is consistent with other information about crust and upper mantle structure (e.g. tectonic regions, crustal thickness from receiver functions and other information, upper mantle velocities from travel time models, thermo-tectonic information, etc.)

There is a balance between honoring prior information and allowing enough variation to fit the surface wave data



**Starting model**

- Honors prior information
- Model may be poor
- Doesn’t allow sufficient variations
- Often doesn’t fit surface wave data

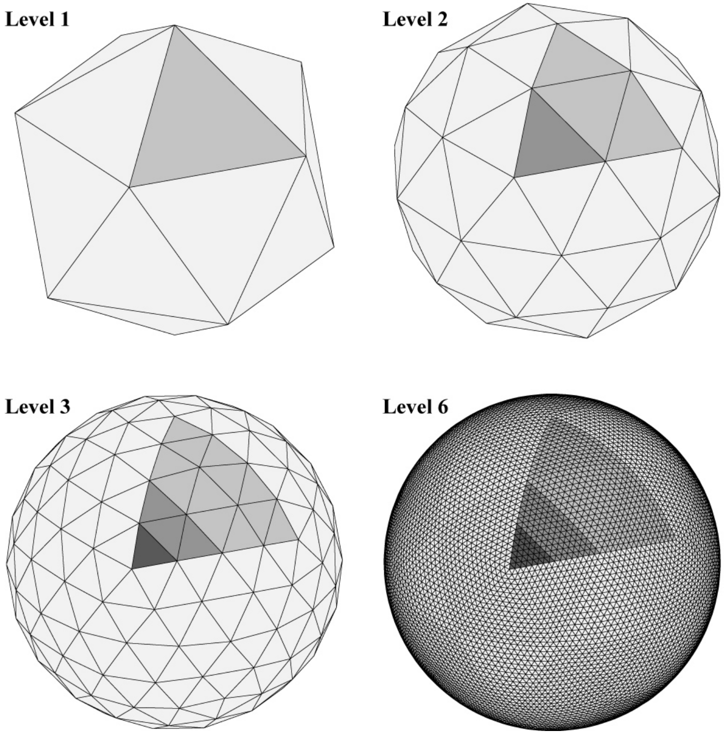
**Surface Waves**

- Provides varied models
- More sensitive to bulk properties, rather than discontinuities
- Doesn’t honor prior information
- Important for global tomography models

# Parameterization

Lateral Parameterization is achieved through tessellated nodes

Depth parameterization through the thickness and associated parameters of layers



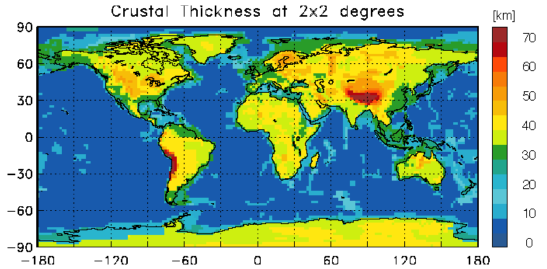
Level 1 = 12 nodes at ~60° resolution
Level 2 = 42 nodes at ~30° resolution
Level 3 = 162 nodes at ~15° resolution
Level 4 = 642 nodes at ~8° resolution
Level 5 = 2562 nodes at ~4° resolution
Level 6 = 10,242 nodes at ~2° resolution
Level 7 = 40,962 nodes at ~1° resolution

| Layer | Layer Name | Associated Parameters |
|---|---|---|
| W | Water/Ice | thick, vp, vs, density, Qp, Qs |
| S1 | Sediment Layer 1 | thick, vp, vs, density, Qp, Qs |
| S2 | Sediment Layer 2 | thick, vp, vs, density, Qp, Qs |
| S3 | Sediment Layer 3 | thick, vp, vs, density, Qp, Qs |
| C1 | Upper Crust | thick, vp, vs, density, Qp, Qs |
| C2 | Middle Crust | thick, vp, vs, density, Qp, Qs |
| C3 | Lower Crust | thick, vp, vs, density, Qp, Qs |
| M1 | Lithospheric Lid | thick, vp, vs, density, Qp, Qs |
| M2 | Asthenosphere | thick, vp, vs, density, Qp, Qs |
| M3 | Upper Mantle | thick, vp, vs, density, Qp, Qs |

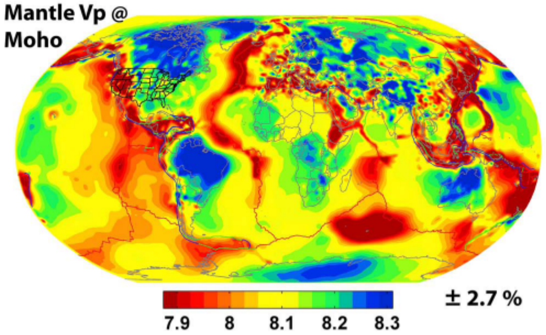
# Building the starting model

CRUST1.0 prototype

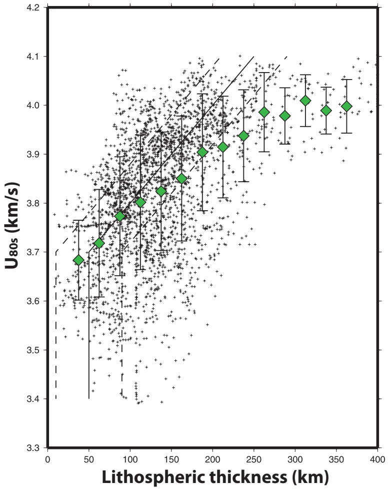
- Modified CRUST2.0 crustal model at higher resolution
- Full three-layer sediment model (Laske and Masters, 1997)
- Updated crustal thickness map



Upper mantle velocities from LLNL-G3Dv3 derived from regional and teleseismic travel times (Simmons et al., 2012)



Lithospheric thickness from the regression of long period dispersion and lithospheric thickness estimates from heat flow (continents) and lithospheric cooling (oceans) (Pasyanos, 2005)

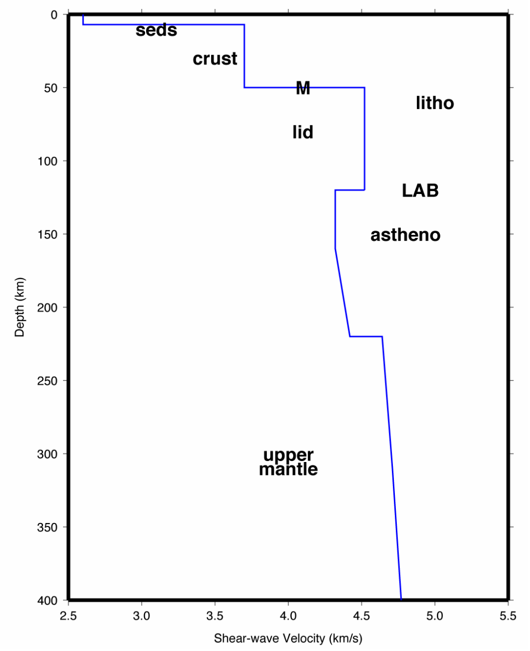


Transitioned into ak135 model (Kennett et al., 1995) at depth

# Varying the starting model

After creating an initial model, we perturb a number of model parameters (crustal velocities, mantle velocities, crustal thickness, lid thickness) to create a suite of about 10,000 models.

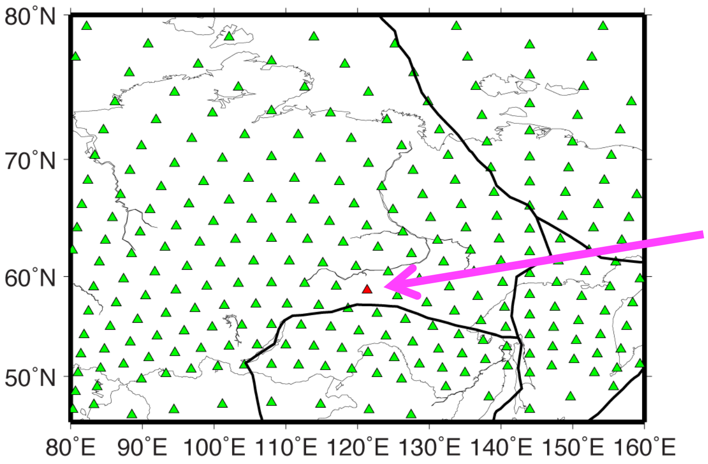
Water/ice/sediment structure – fixed
Crustal velocity stack – perturbed (±5%)
Crustal thickness – varied (±1.5 σ)
Upper mantle velocity – perturbed (±3%)
Lithospheric thickness – varied (±1.5 σ)
Transitioned into ak135 model
$v_p/v_s$ fixed in seds/crust from CRUST1.0
set for lid, astheno
fixed from ak135 in mantle



The dispersion values predicted by each model are then calculated using MINOS and compared to the observed dispersion from our high-resolution global surface wave model.

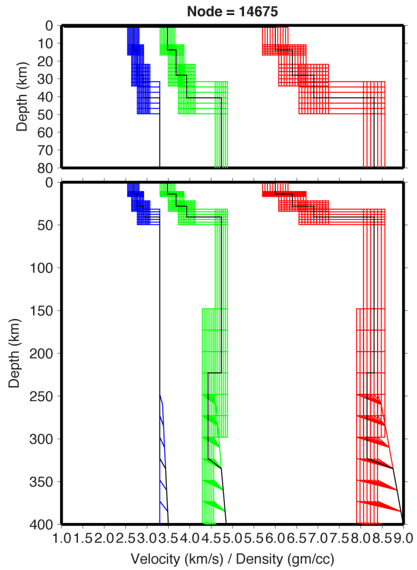
We select the model that fits the observed dispersion the best

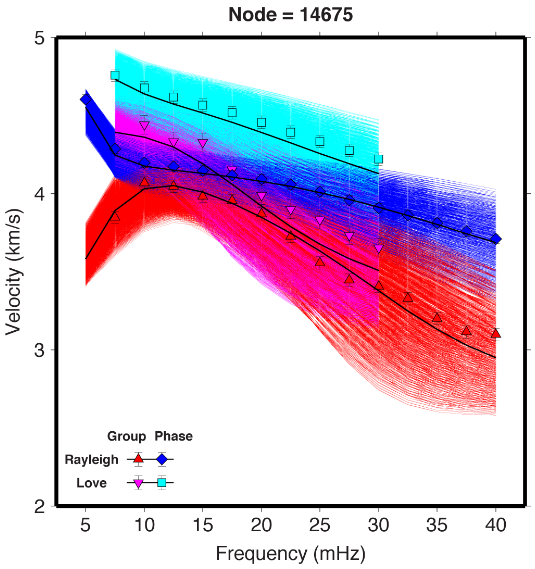
# Example – node 14675

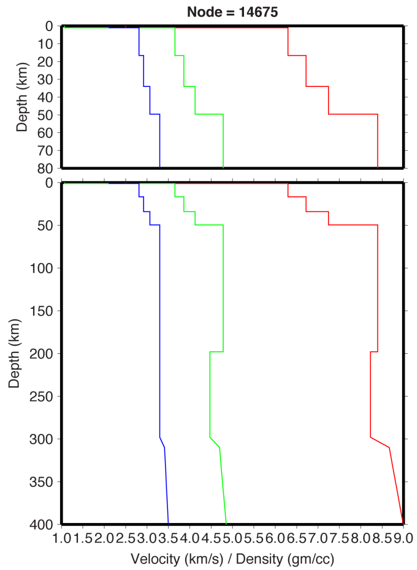


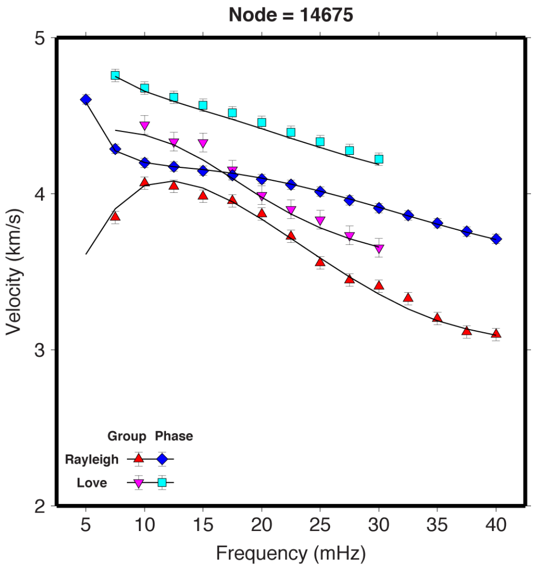
The range of models covers the parameter space in both depth space and dispersion space

For this node, we are able to fit the surface waves with a faster crust, a slightly faster mantle, a thicker crust, and a thinner lithospheric thickness



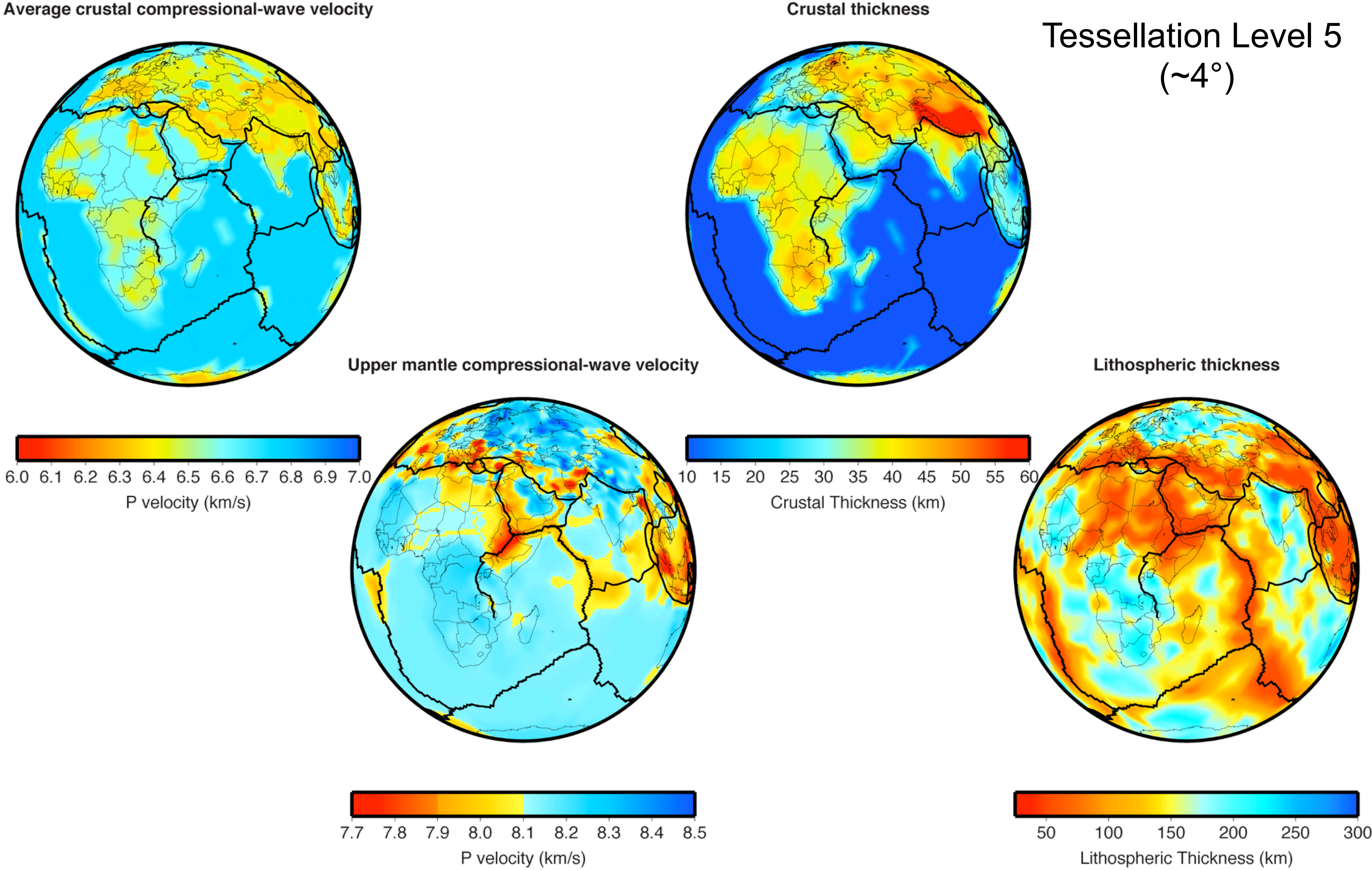






# We assemble the results to construct the full model – Global, low-resolution, starting model

Tessellation Level 5
(~4°)



Average crustal compressional-wave velocity

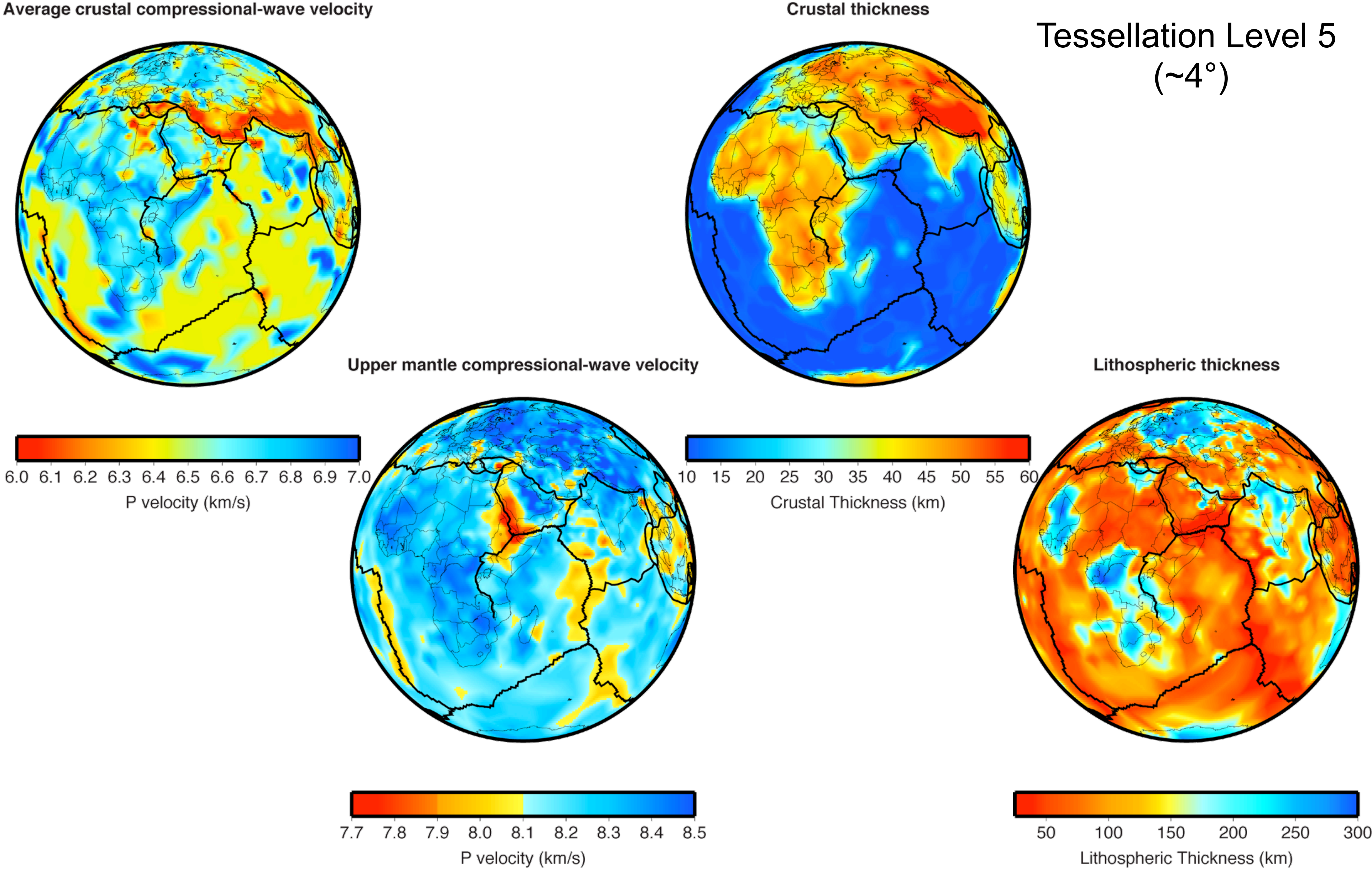
Crustal thickness

Upper mantle compressional-wave velocity

Lithospheric thickness

# We assemble the results to construct the full model – Global, low-resolution, inverted model

Tessellation Level 5
(~4°)



Average crustal compressional-wave velocity

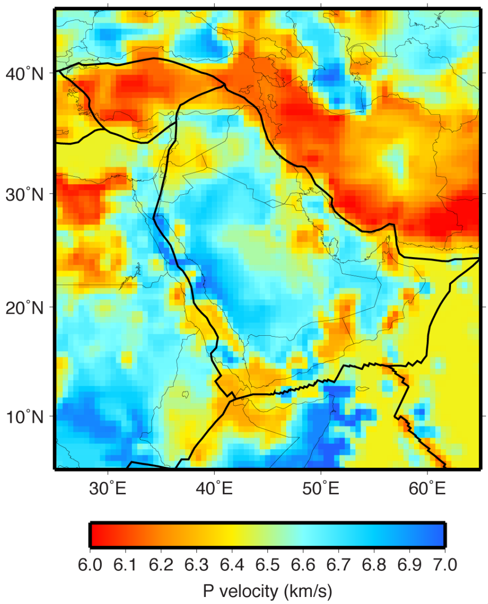
Crustal thickness

Upper mantle compressional-wave velocity

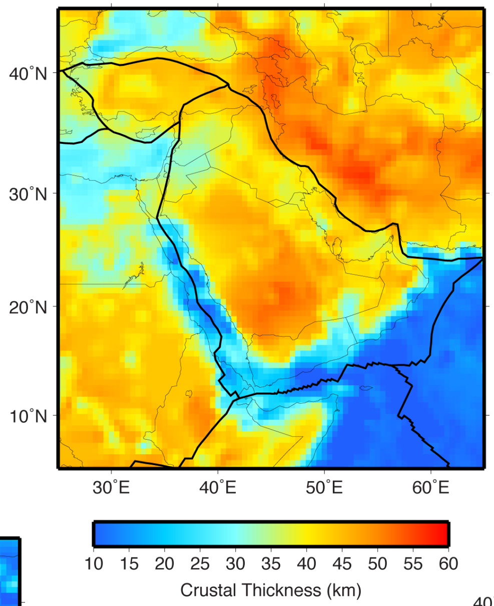
Lithospheric thickness

# High-resolution regional results for the Middle East

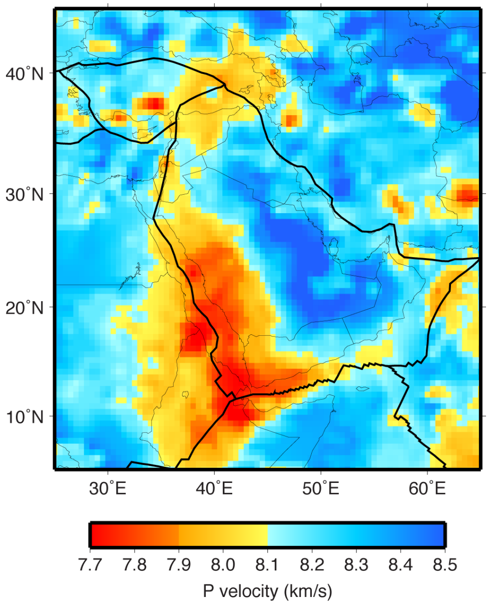
**Average crustal compressional-wave velocity**



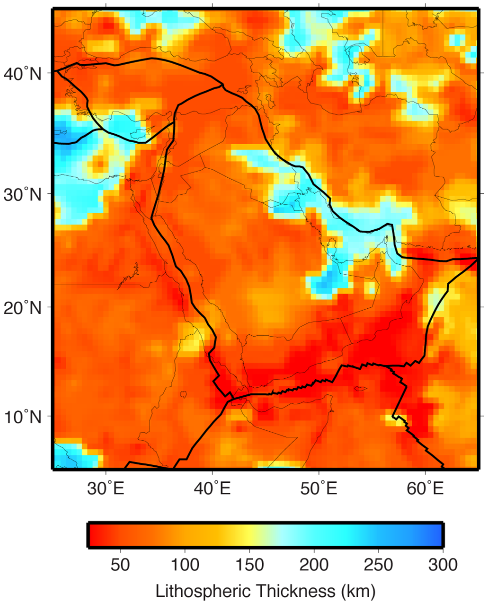
**Crustal thickness**



**Upper mantle compressional-wave velocity**



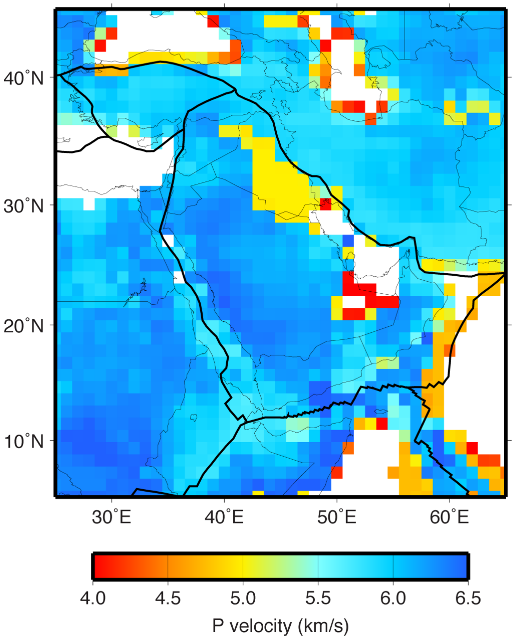
**Lithospheric thickness**



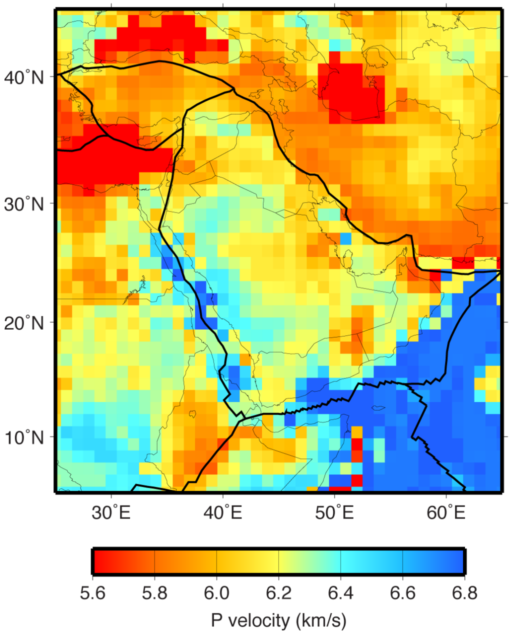
Tessellation Level 7
(~1°)

# Depth slices through the model

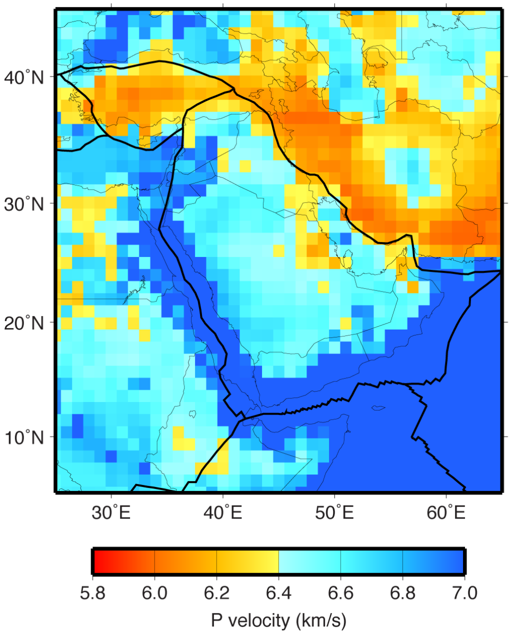
**5 km**



**10 km**

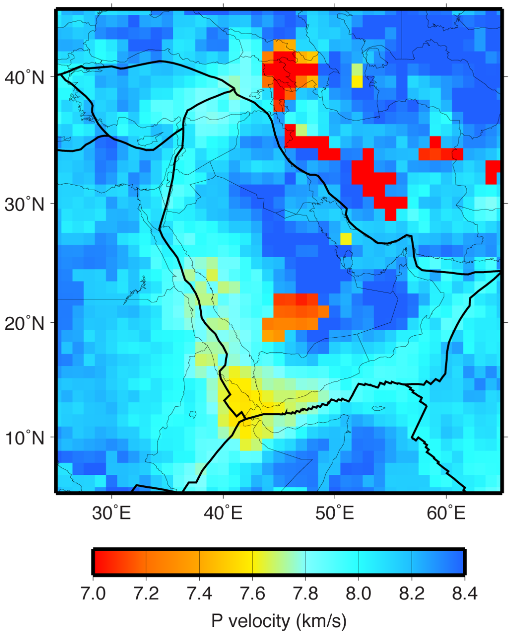


**25 km**

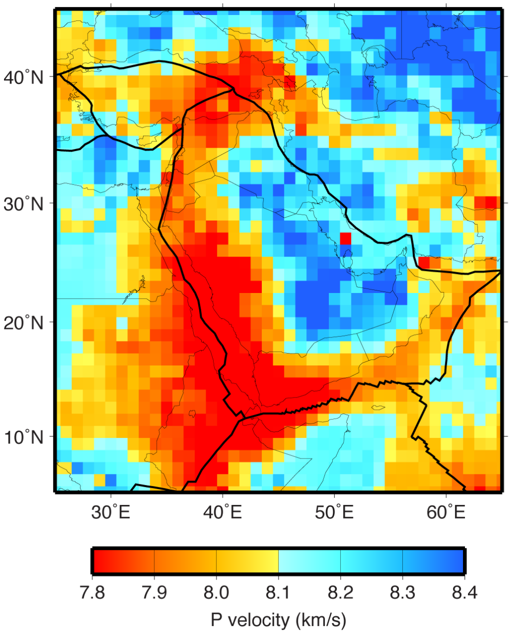


# Depth slices through the model

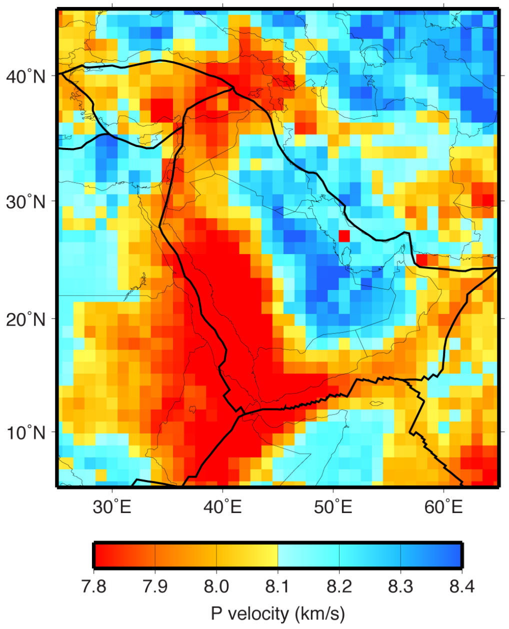
**50 km**



**75 km**

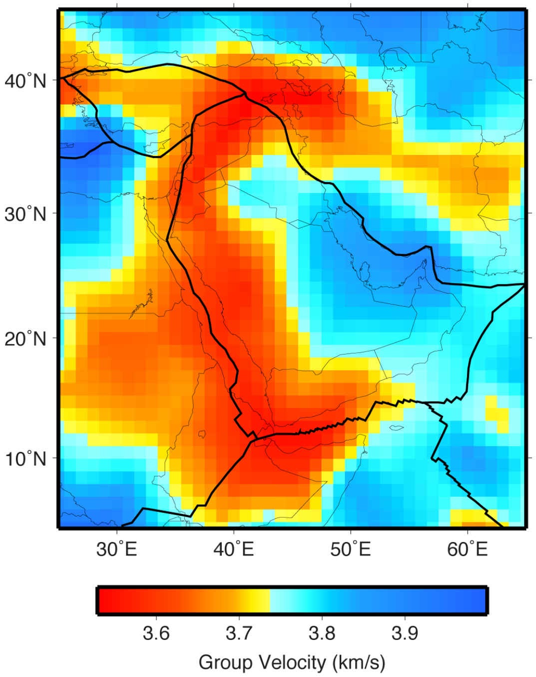


**100 km**

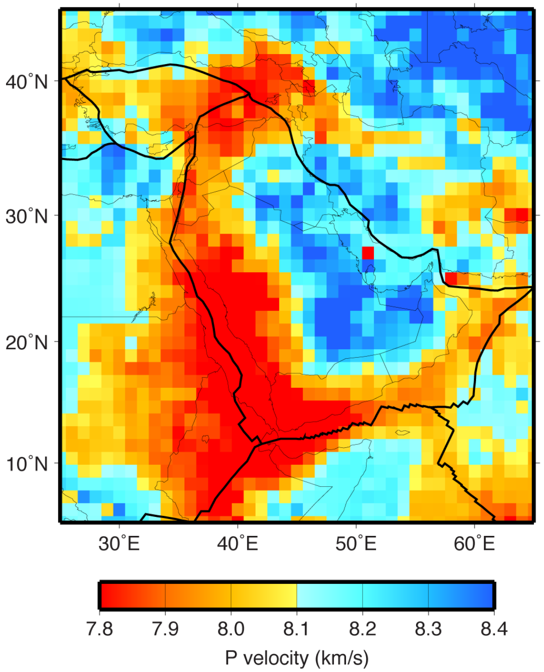


# Close relationship between surface wave model and LITHO1.0

## 100 s Rayleigh wave group vel



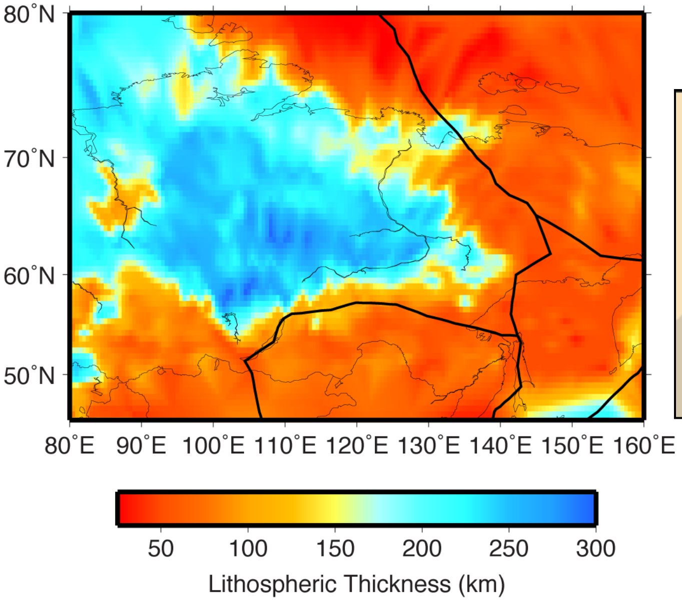
## 75 km depth slice

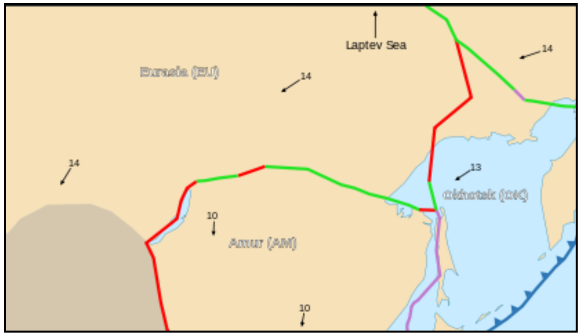


# High-resolution regional results for Siberia

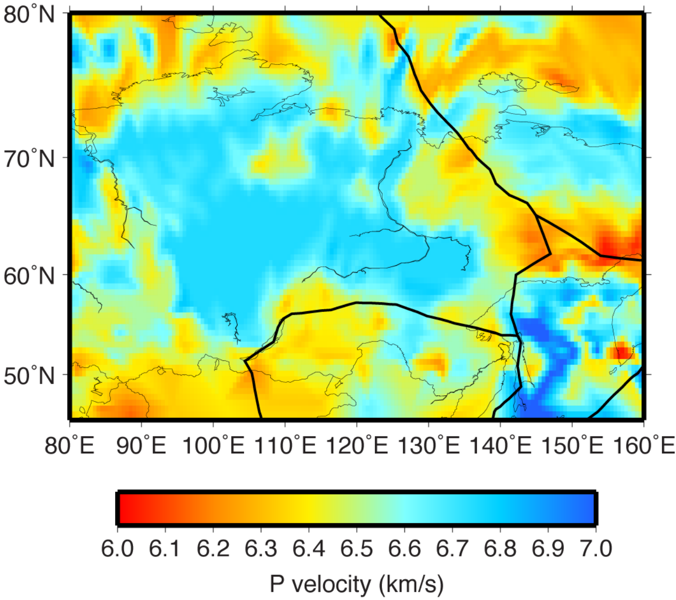
Tessellation Level 7
(~1°)

Lithospheric thickness



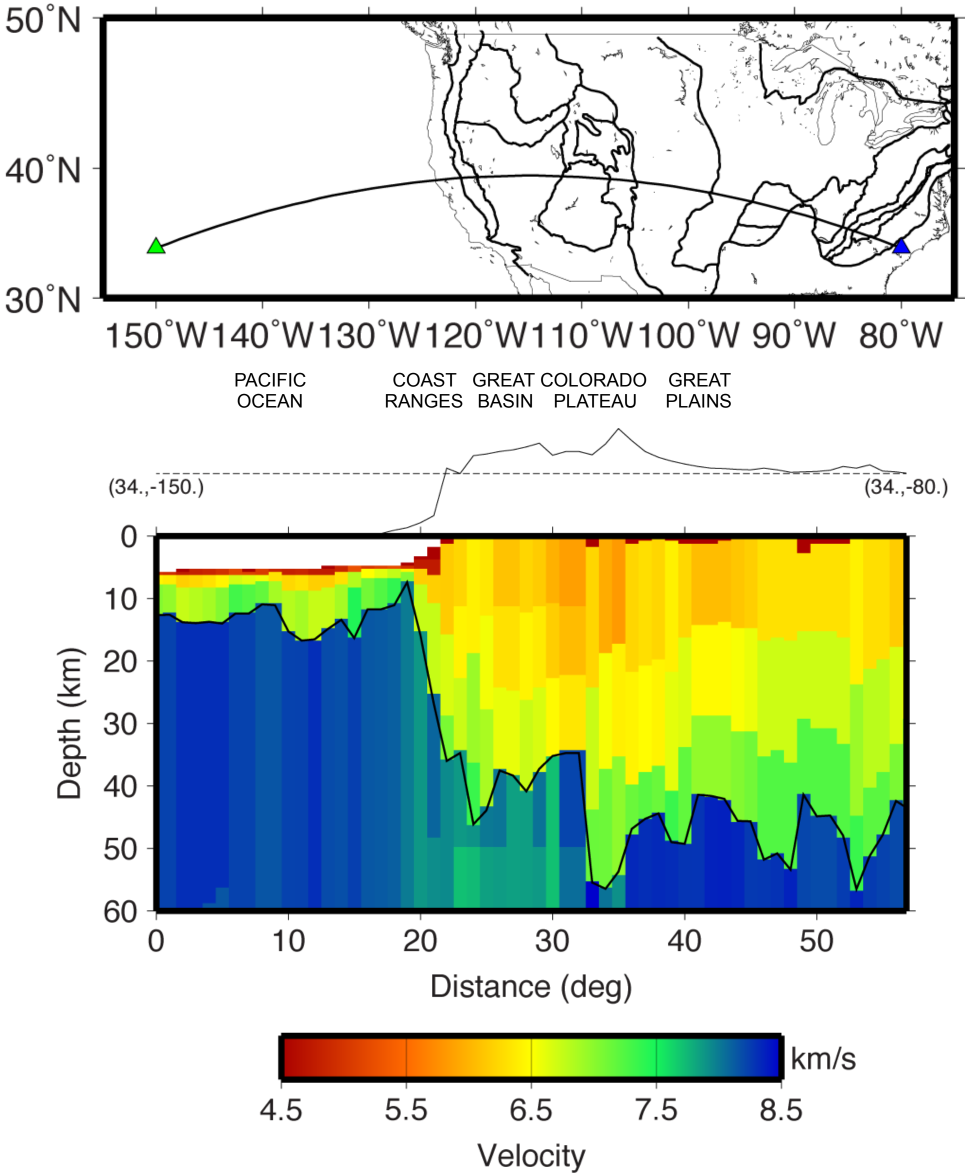


Average crustal compressional-wave velocity

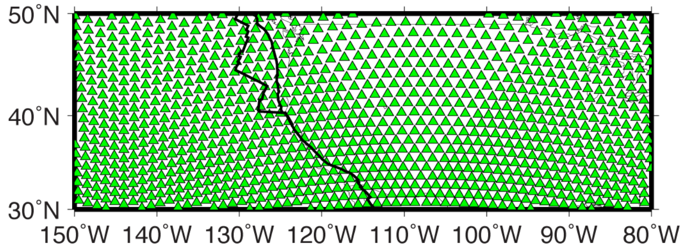


Constraints on lithospheric thickness can be used to provide information on the Siberian Shield and study the nature of this diffuse plate boundary between the Eurasia and North American Plates and the interaction with the Amur and Okhotsk Plates

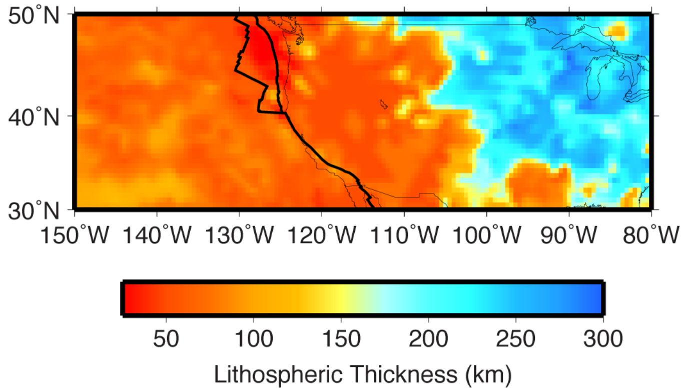
# High-resolution regional results for North America



**Nodes**

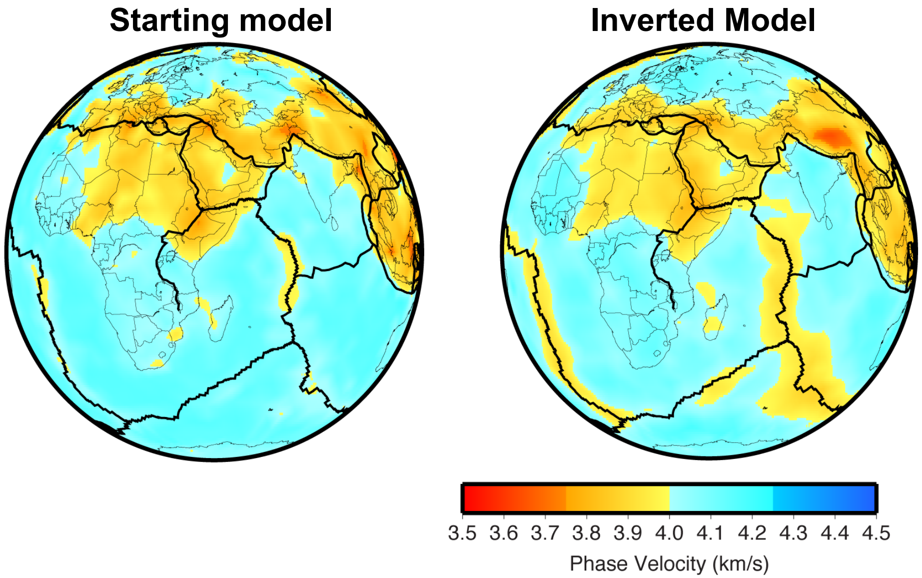


**Lithospheric thickness**



This is a fully 3D model with parameters at all points in the model

# The resulting model recovers the dispersion signal over a wide frequency range

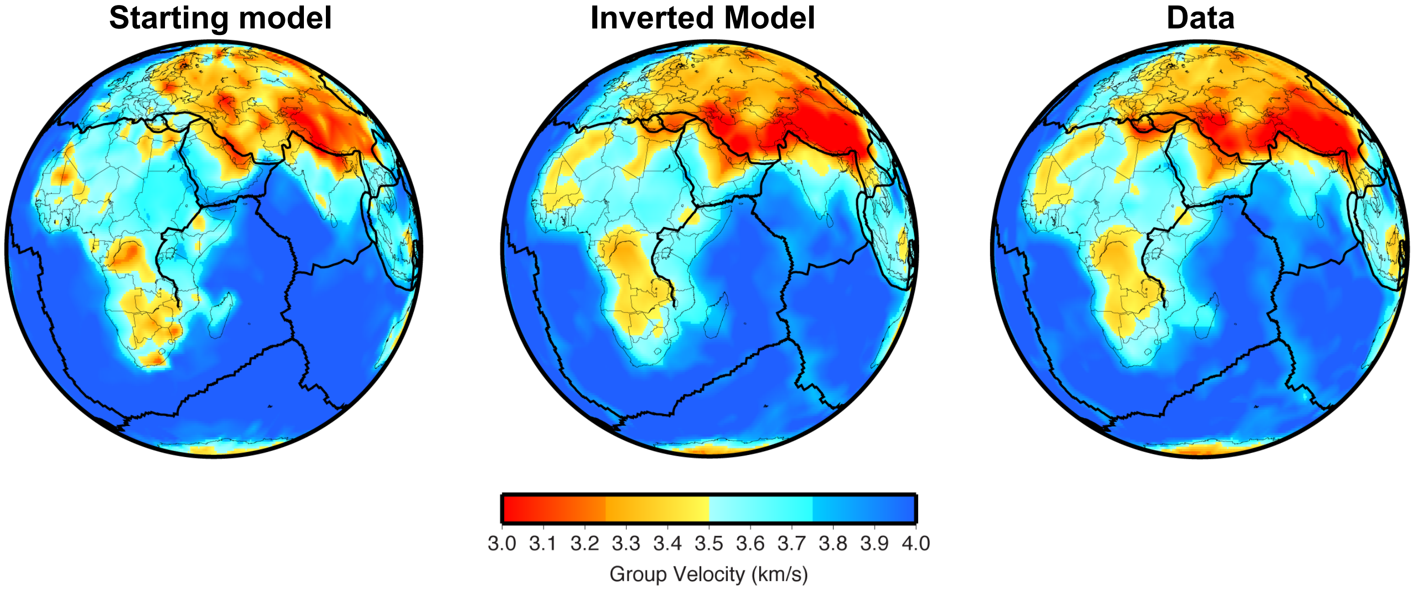


Starting model

Inverted Model

Data

**Rayleigh wave**
**Phase Velocity**
**20 mHz / 50 sec**



Starting model

Inverted Model

Data

**Rayleigh wave**
**Group Velocity**
**30 mHz / ~33 sec**

# LITHO1.0 - Summary and Future Work

The LITHO1.0 model appears to both fit the surface wave data and be consistent with other geophysical information and tectonic structure

We would like to validate this more rigorously with travel time, waveform, and other data

Finish the model

- We may still need to tweak the inversion to make crustal thickness changes smaller or convince ourselves that they are real
- We will incorporate anisotropy by allowing for a transversely isotropic mantle (in lid and asthenosphere)
- Make the runs at Tessellation Level 7 (~ 1°) globally

Make the model and interfaces available

- Create model in other formats (e.g. regular lat/lon grid, spherical harmonics?) from native tessellation format to be usable to the widest array of users
- Supply interfaces to provide depth profiles at arbitrary lat/lon locations and parameters (e.g. $V_P$, $V_S$, etc.) at arbitrary lat/lon/depth points.