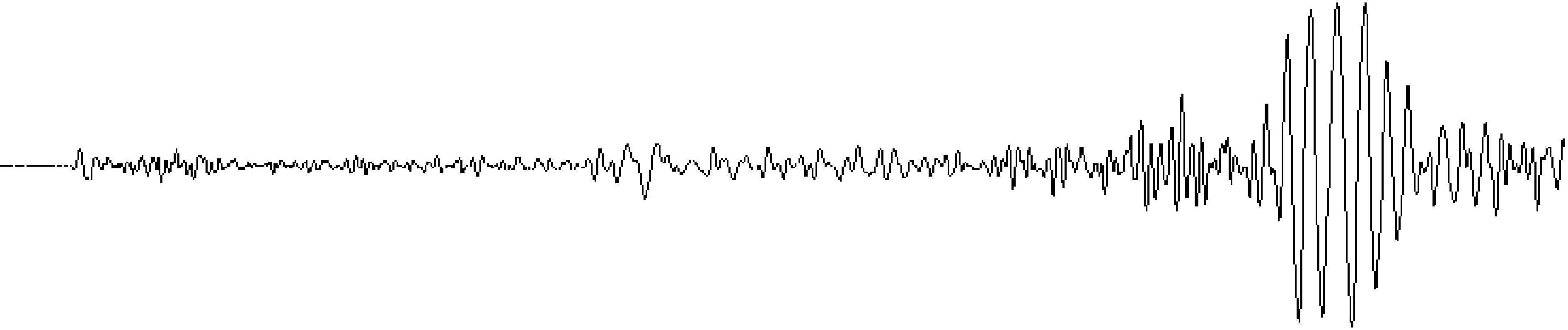

Crustal and Upper Mantle Structures of the Red Sea and Arabian Shield

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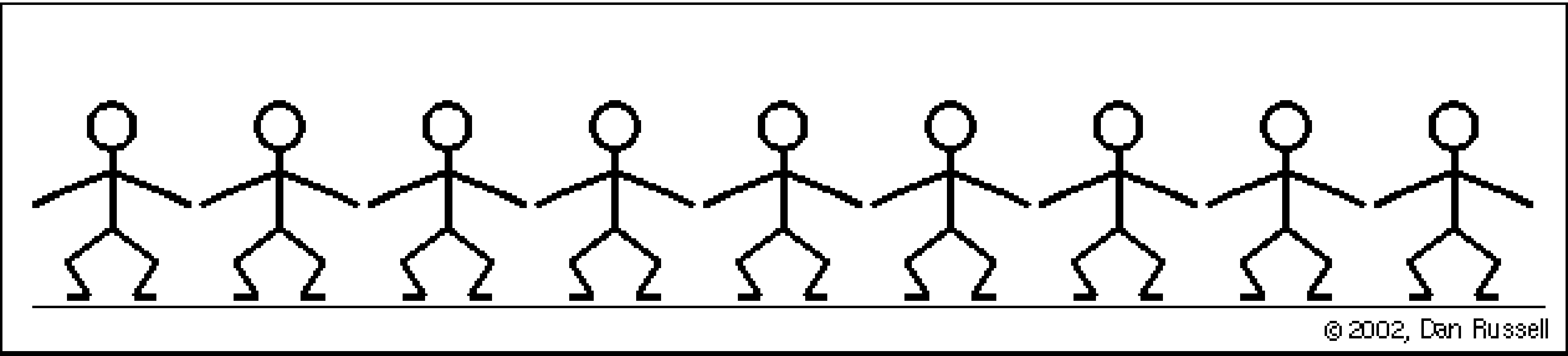


ARABIAN PLATE BOUNDARIES

1. ACTIVE SEA-FLOOR SPREADIG: Along the axial troughs of the Red Sea and Gulf of Aden.
2. DEAD SEA FAULT SYSTEM: Predominantly left lateral transform fault which defines the NW boundary of the Arabian plate.
3. TAURUS-ZAGROS THRUST BELT: As result of continental collision associated with the NE boundary between the Arabian plate and the Persian and Turkish plates.
4. MAKRAN BELT: In the Gulf of OMAN. The Arabian plate is subducting beneath the Makran region of Pakistan and Iran, Thus marking the Eastern plate boundary.
5. THE OWEN FRACTURE ZONE: Relativity active transform fault forms the SE boundary of the plate.

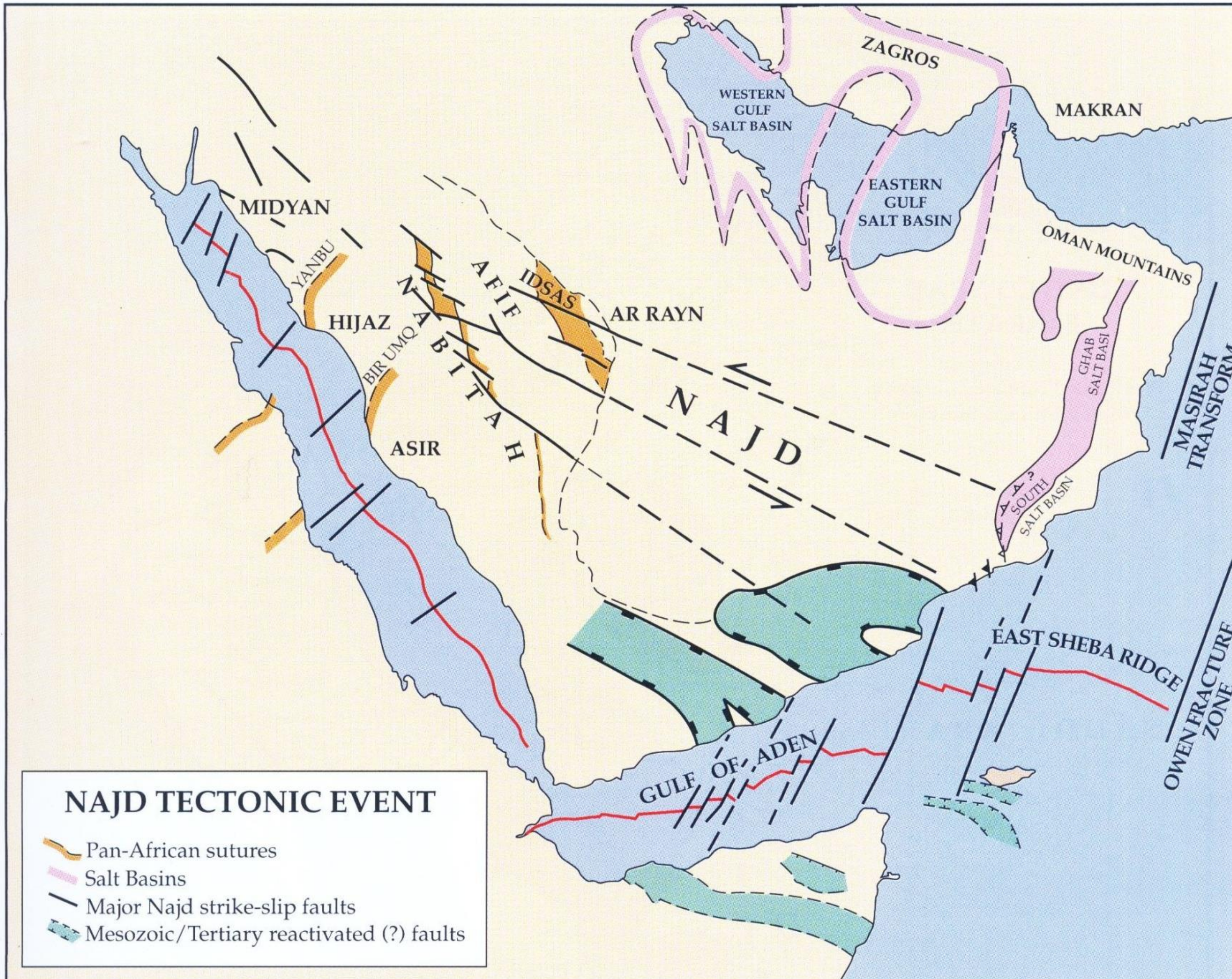


Figure 1: The Arabian Peninsula, with Precambrian terranes in the Arabian Shield area of western Saudi Arabia and the Infra-Cambrian sinistral Najd tectonic event (600-530 Ma) (Brown and Jackson, 1960; Moore, 1979) with its Mesozoic and Tertiary reactivations (Bott et al., 1992; Richardson et al., 1995). Microplate boundaries based on Stoesser and Camp (1985).

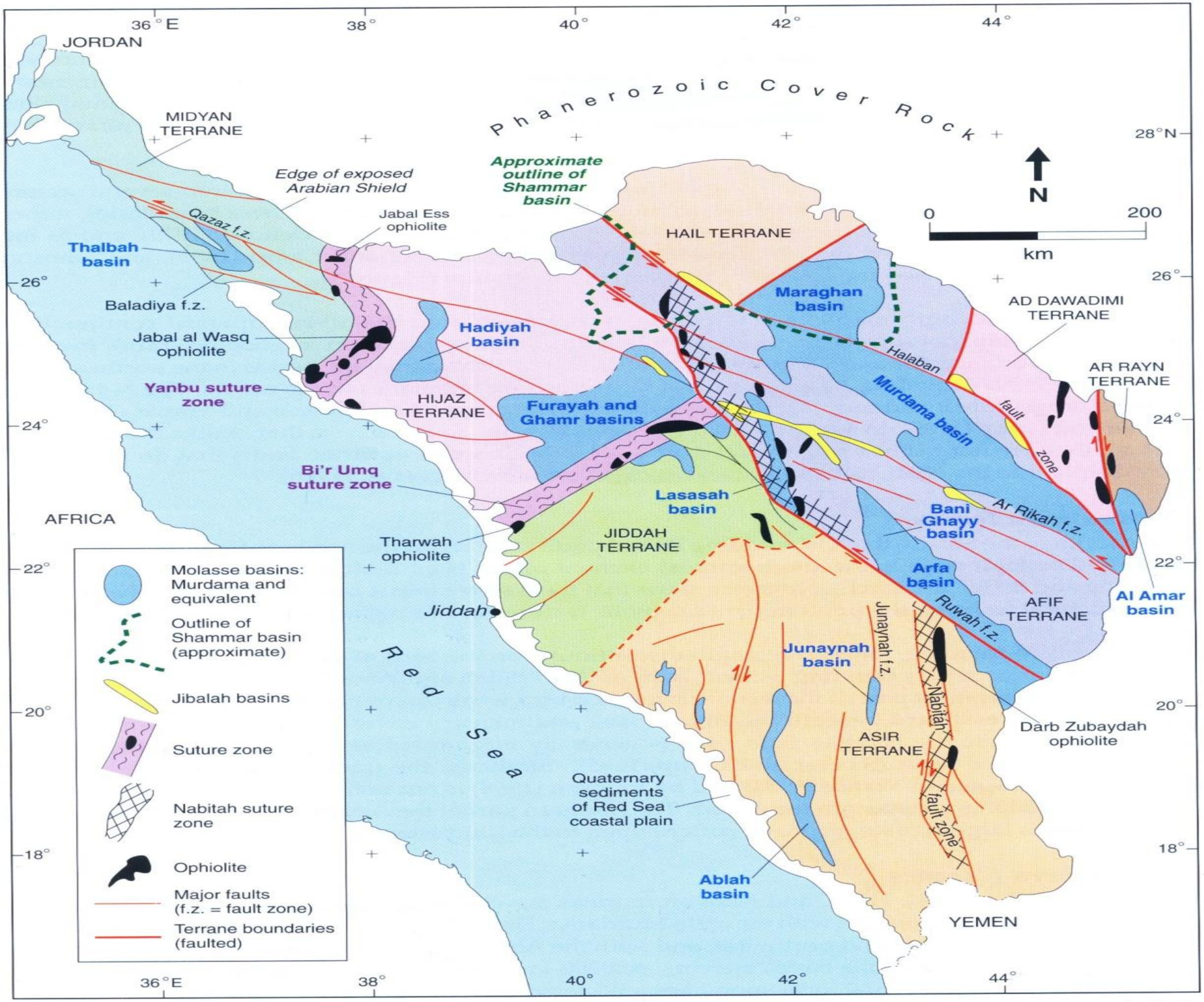
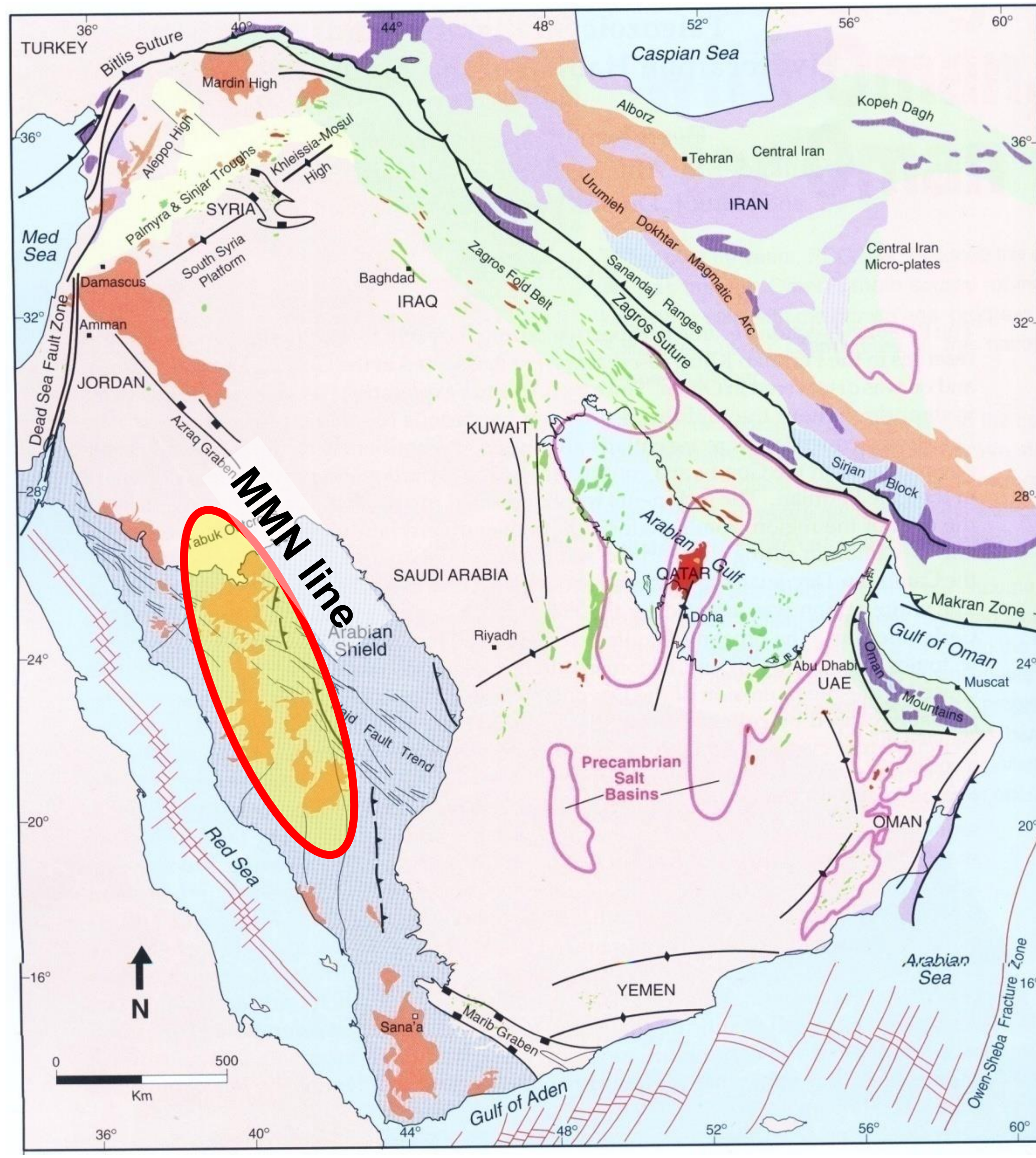


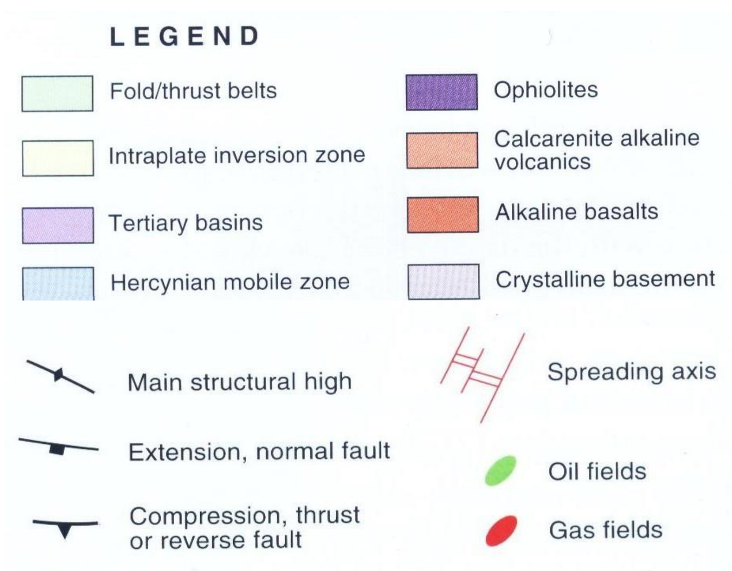
Figure 3: Simplified geologic sketch map of the Arabian Shield showing the terranes and their boundaries, and the main Pan-African structural features and sedimentary basins. Major fault zones, such as Ruwah, Ar Rikah, Halaban, and Qazaz, belong to the Najd fault system.

Large-scale geologic framework

Major features are the Arabian Shield and Arabian Platform

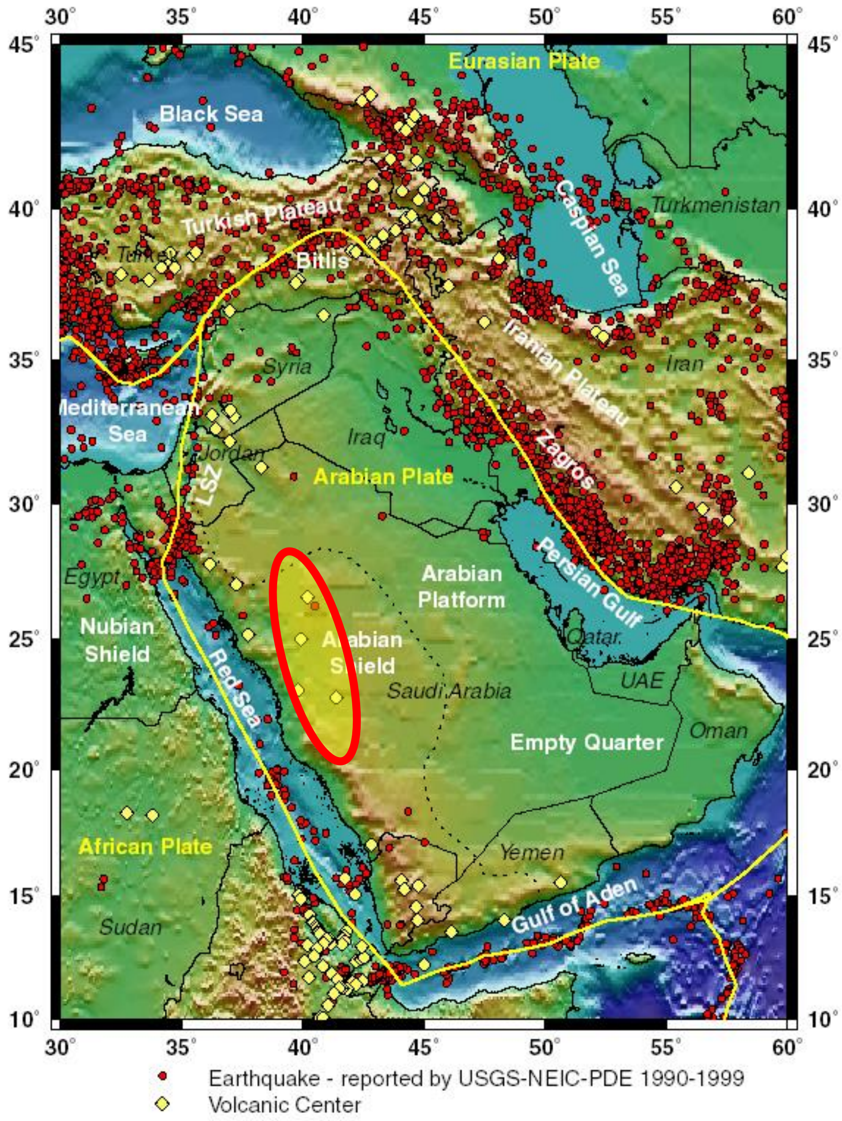
Sediments thicken from the Shield-Platform boundary toward the Zagros thrust





Earthquakes define plate boundaries, Shield is penetrated by volcanics

Volcanic centers penetrate the Arabian Shield along the Makkah-Medina-Nafud (MMN) line



Lithospheric Structures of the Arabian Peninsula

THE PROBLEM

1. The Saudi Seismic Networks are locating earthquakes using automatic selection and global average velocity models.

2. Previous seismic studies indicate structural differences between the Arabian shield and platform that lead to more questions about the source of weak body-wave amplitudes.

OBJECTIVES

O B J E C T I V E S

Determination of Crustal and Lithospheric Mantle Structure under the Arabian Shield and Red Sea by applying an improved method for inverting receiver functions and shear wave group velocity (SWGV) measurements.

METHODS

- Teleseismic P- and S-wave travel time tomography;
- Teleseismic receiver functions for crustal structure;
- Teleseismic receiver functions for upper mantle discontinuity structure;
- Teleseismic shear-wave splitting;
- Regional and far-regional surface waveform modeling.

- **Together these analyses result in a unified model of the structure and physical state of the lithosphere beneath the Arabian Shield and Red Sea.**
- **The dense station spacing and excellent quality of data allow for very detailed resolution of structure.**

Tectonic questions worthy of investigation

- What is the crustal structure across the Arabian Peninsula?

- How is the lithospheric structure impacting by Red Sea spreading?
  - Is there a lithospheric signature of active or passive spreading?
- How are the Harrats connected with deeper structure in the upper mantle?

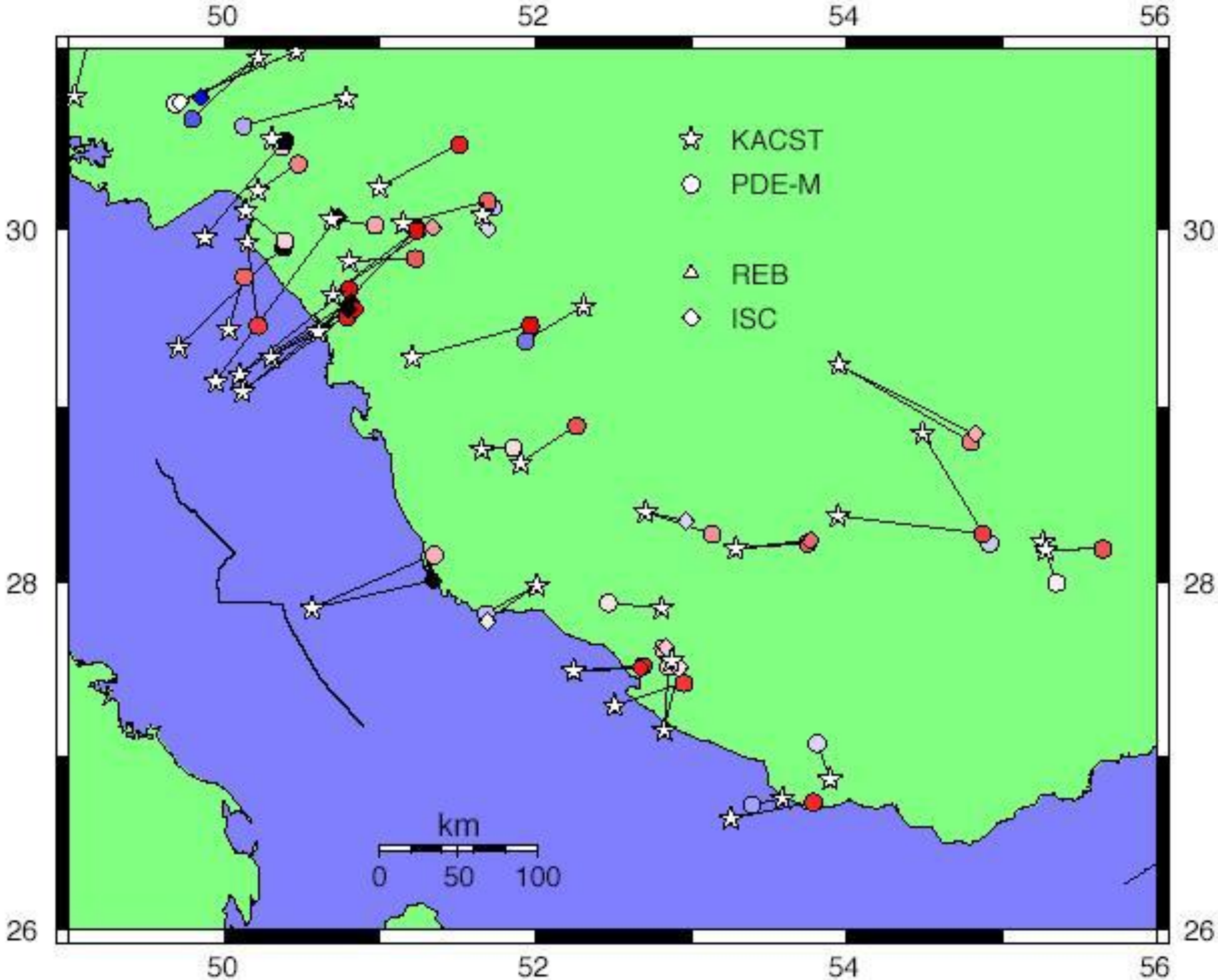


Figure 13. Comparison of SANDSN (stars) and global network locations (other symbols) for the Zagros Mountains region. The color of the symbols for global network locations are scaled by the origin time difference.

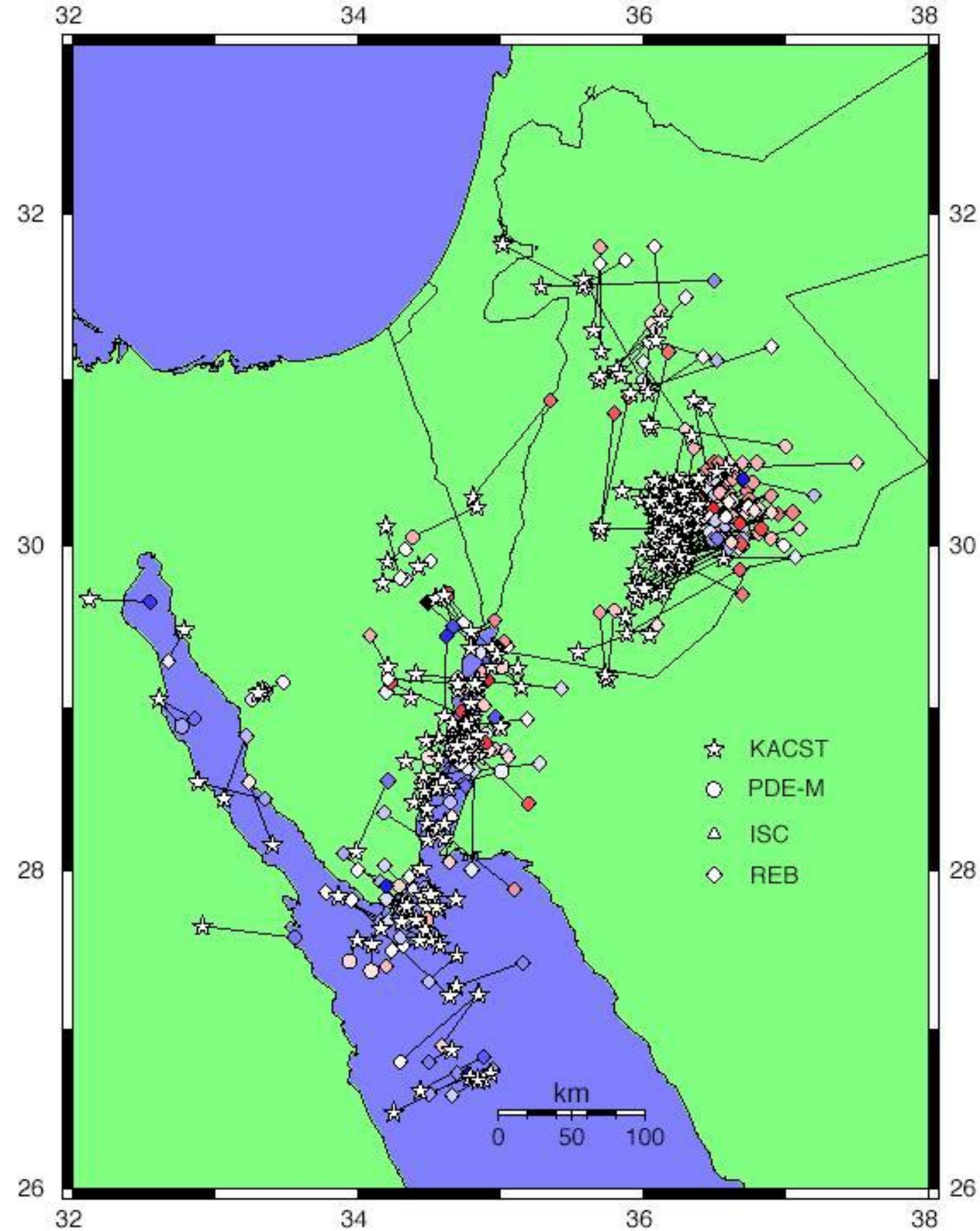
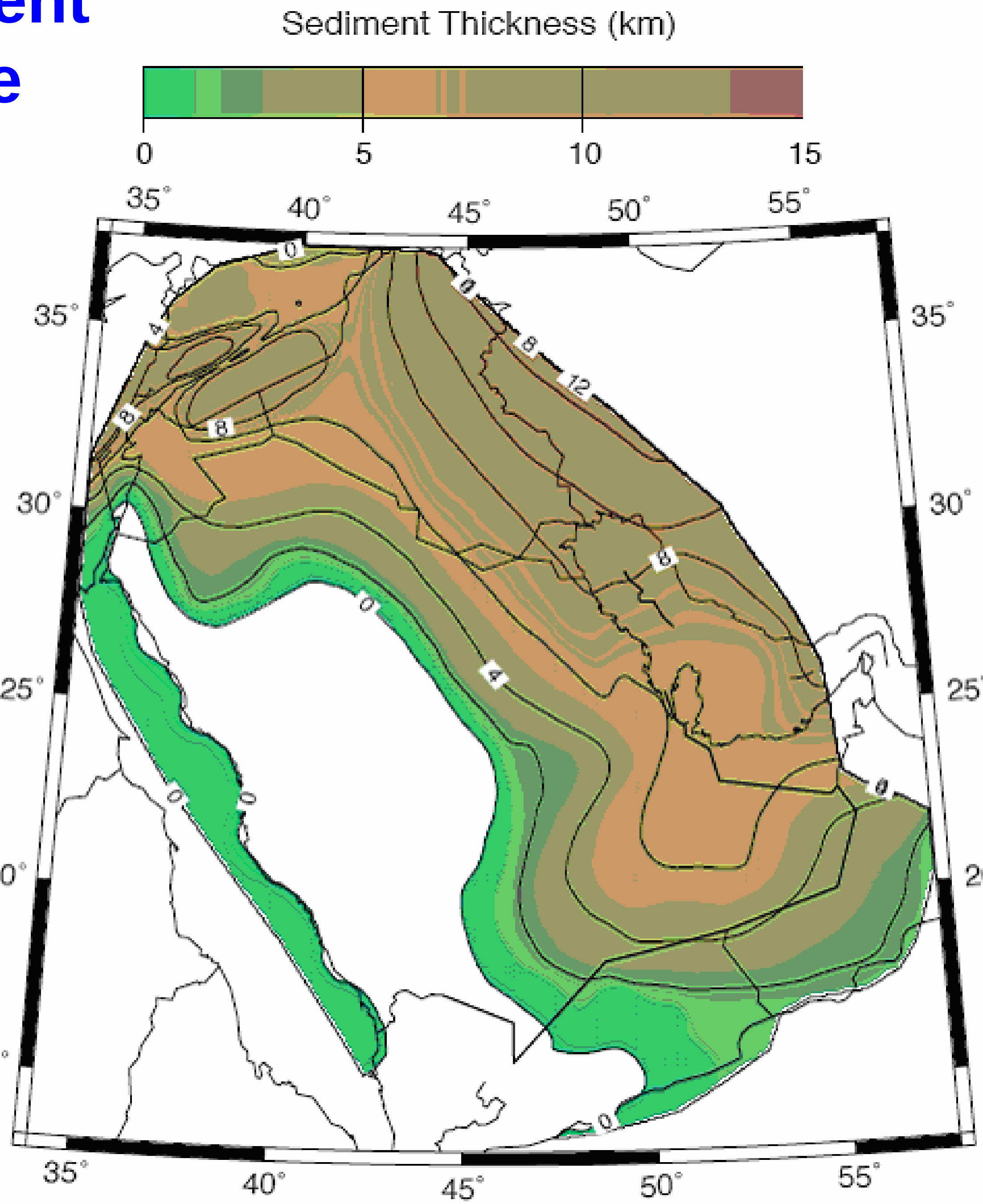
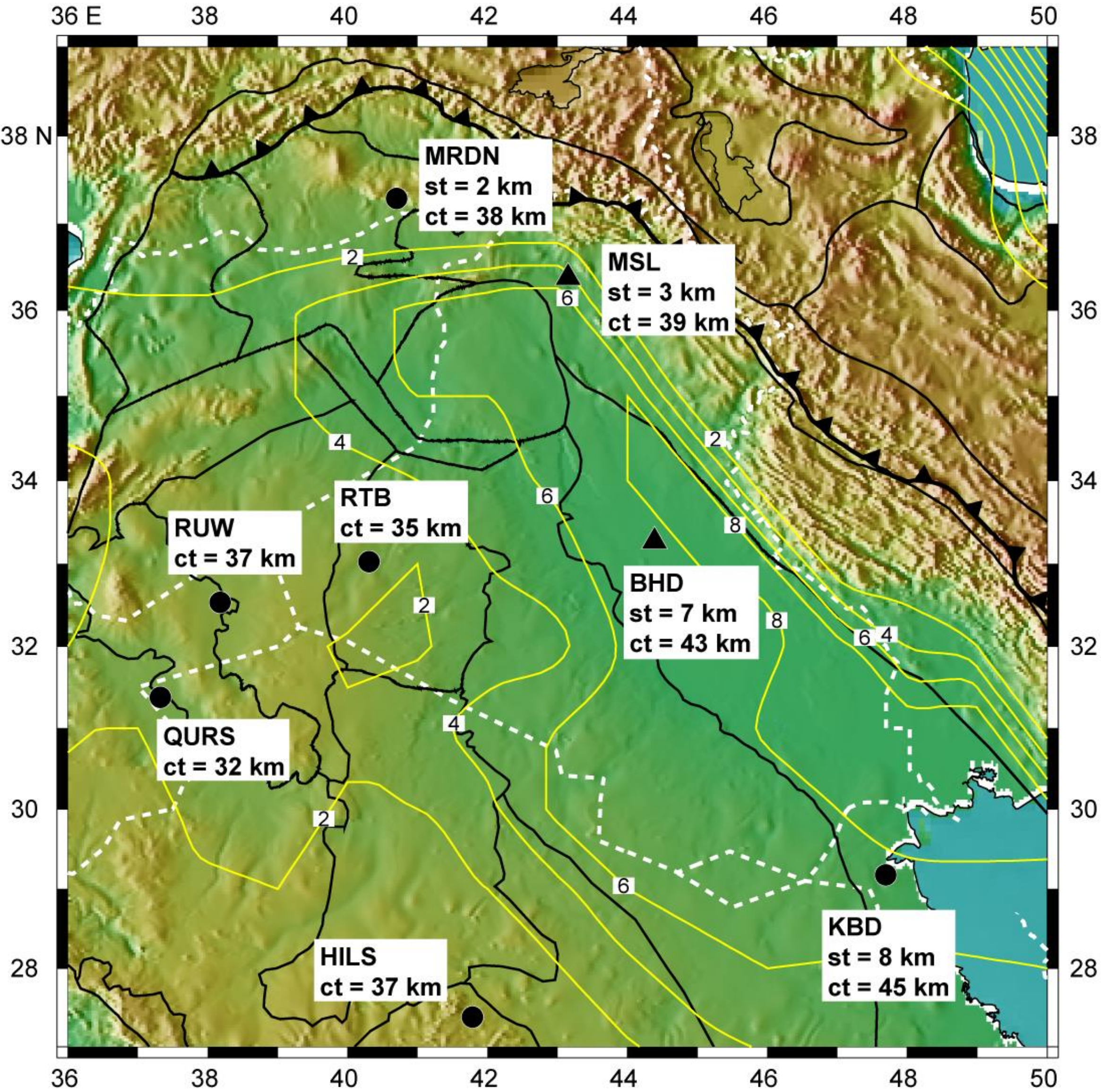


Figure 11. Comparison of SANDSN (stars) and global network locations (other symbols) for the Dead Sea/Gulf of Aqaba region. The color of the symbols for global network locations are scaled by the origin time difference.

Map of the sediment thickness of the Arabian Plate



Crustal Structure in the Northern Arabian Platform

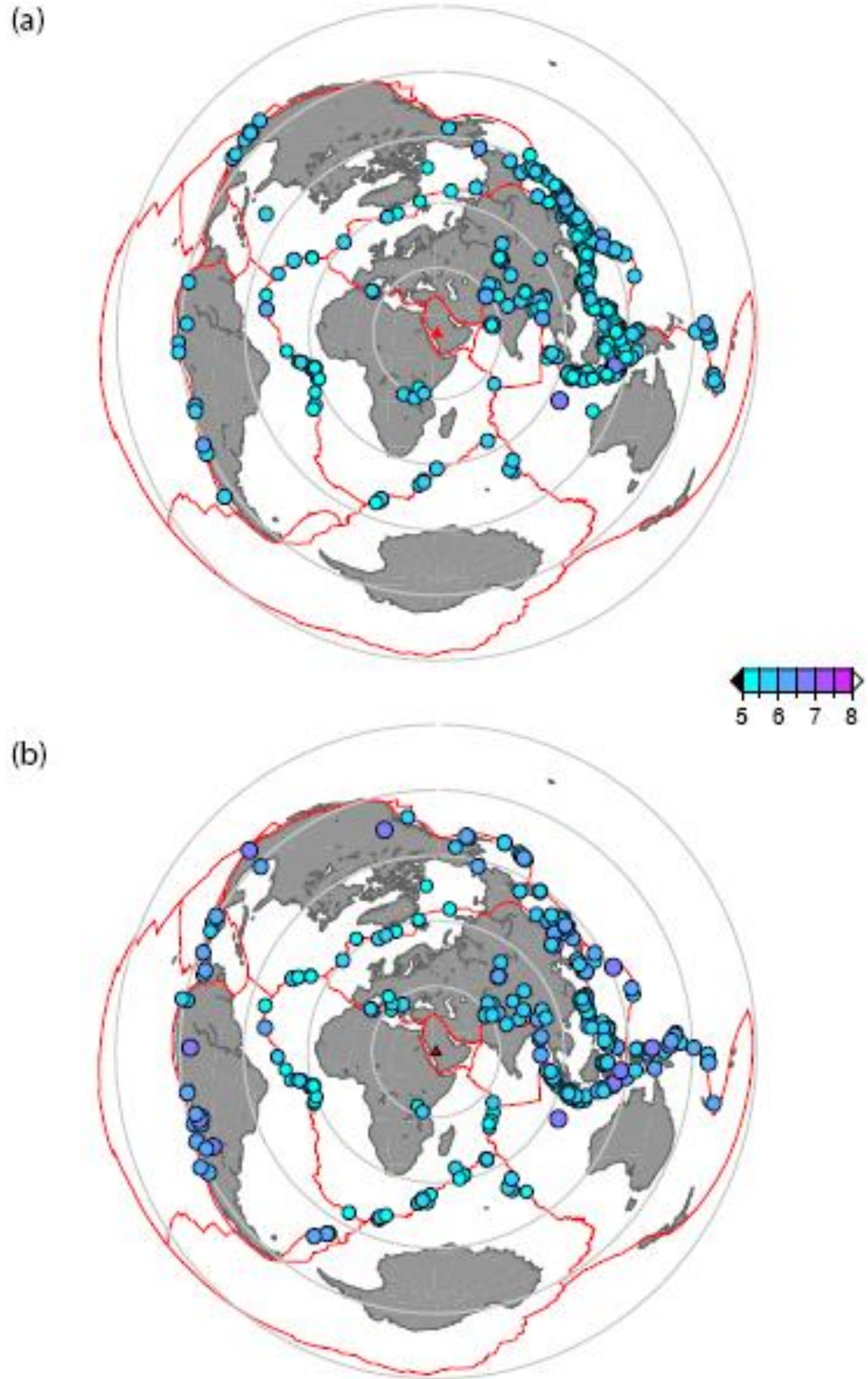


st = sediment thickness
ct = crustal thickness

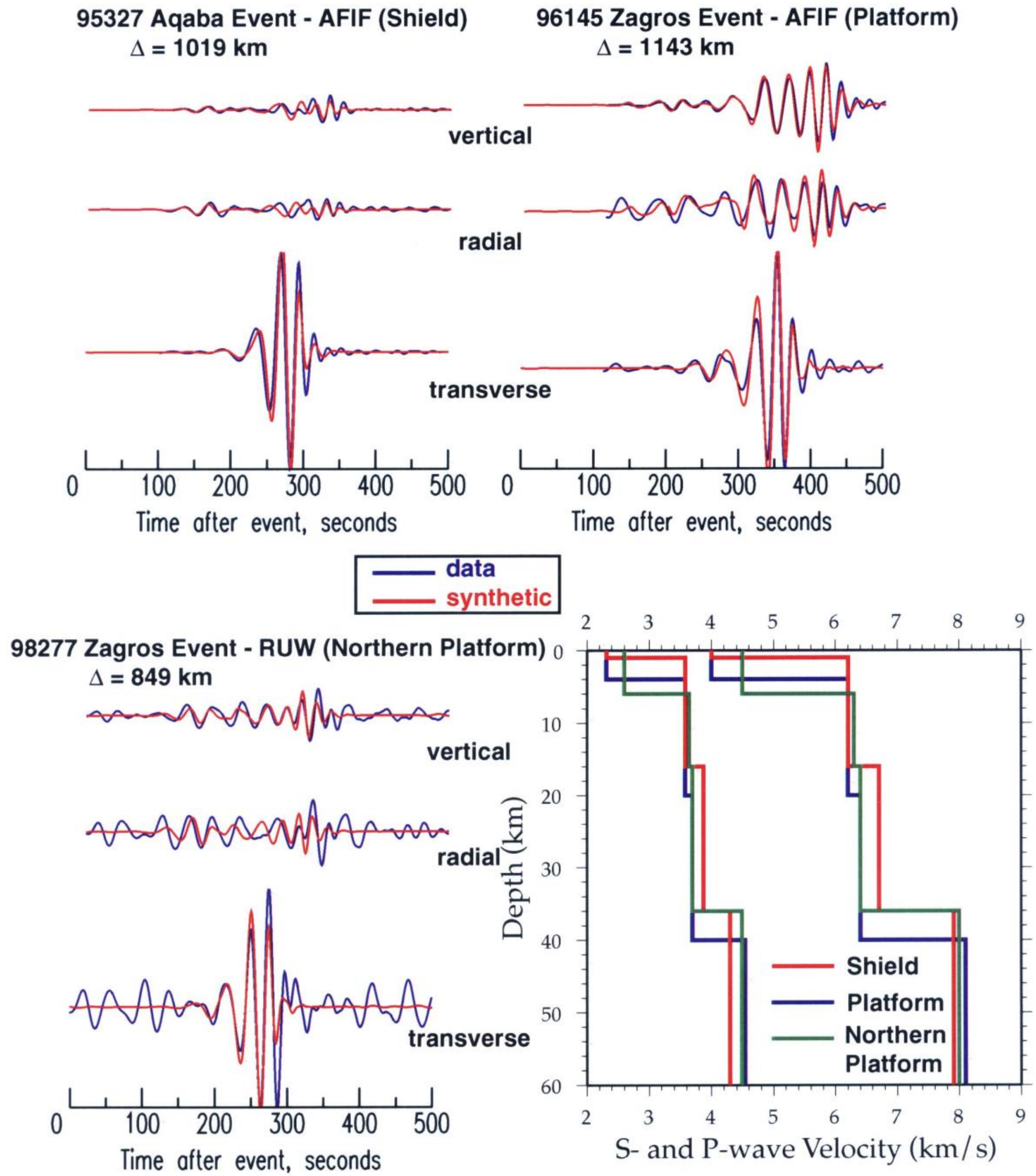
Crystalline crustal thickness (ct-st) is relatively constant in the northern Arabian Platform at about 36-37 km.

This suggests the proto-Platform had relatively uniform crustal structure before sediments were deposited.

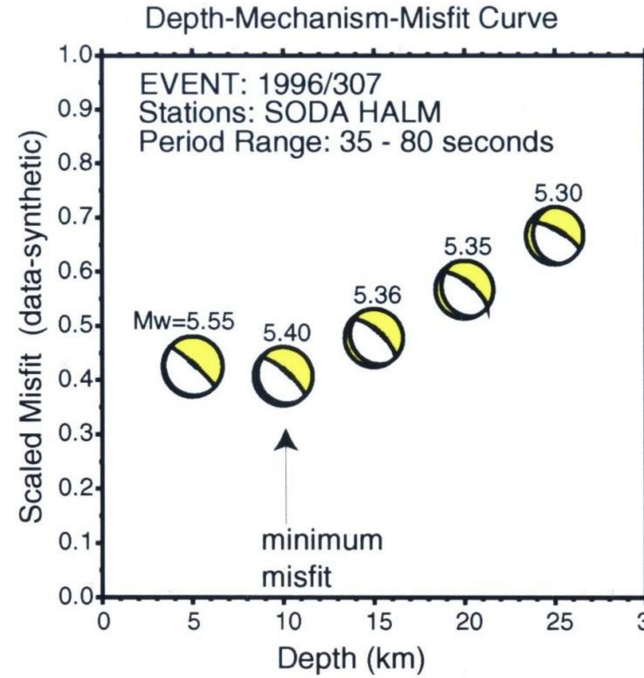
The distribution of earthquakes for (a) P wave (3416 rays from 401 events) and (b) S wave (1602 rays from 201 events). The colors scale indicates magnitude of each event, the red solid lines show plate boundaries, and each circle represents 30 degree distance interval from the center of KACST seismic array.



Waveform Modeling for Structure of the Arabian Peninsula

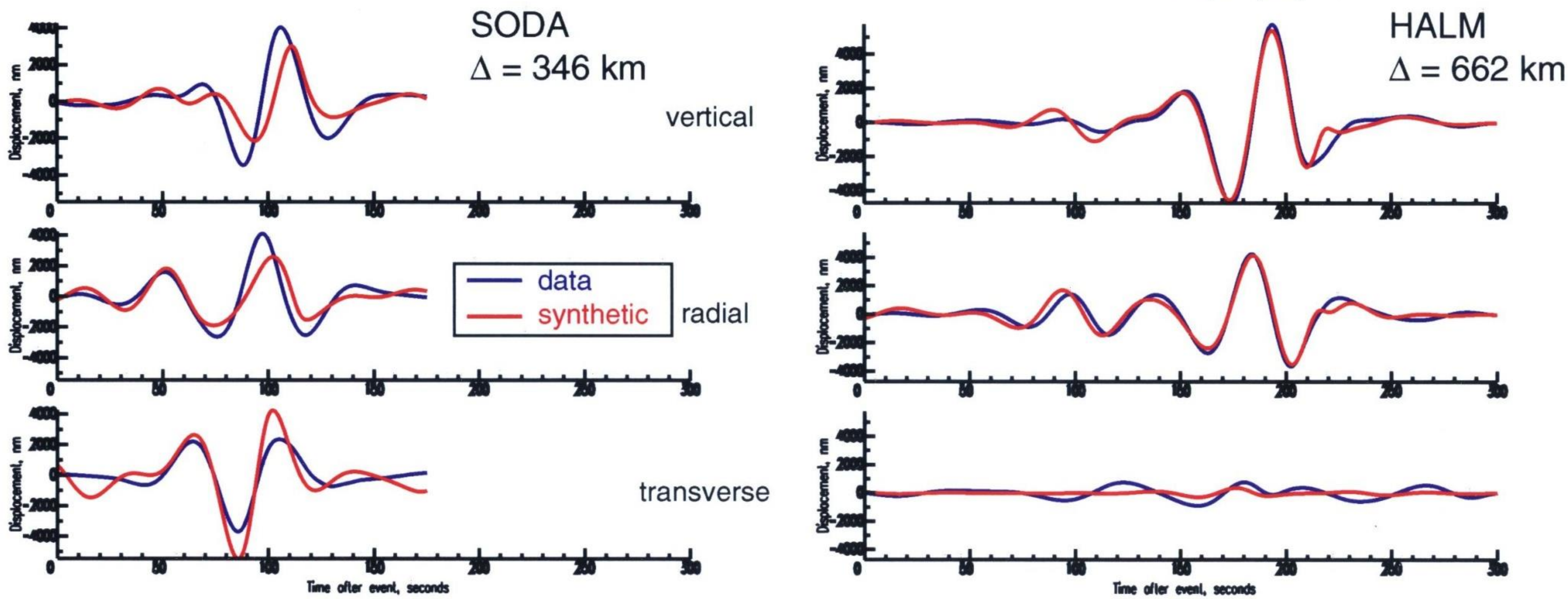


Waveform modeling to estimate earthquake moment, depth and best double-couple focal mechanism for the Red Sea event (1996/307)

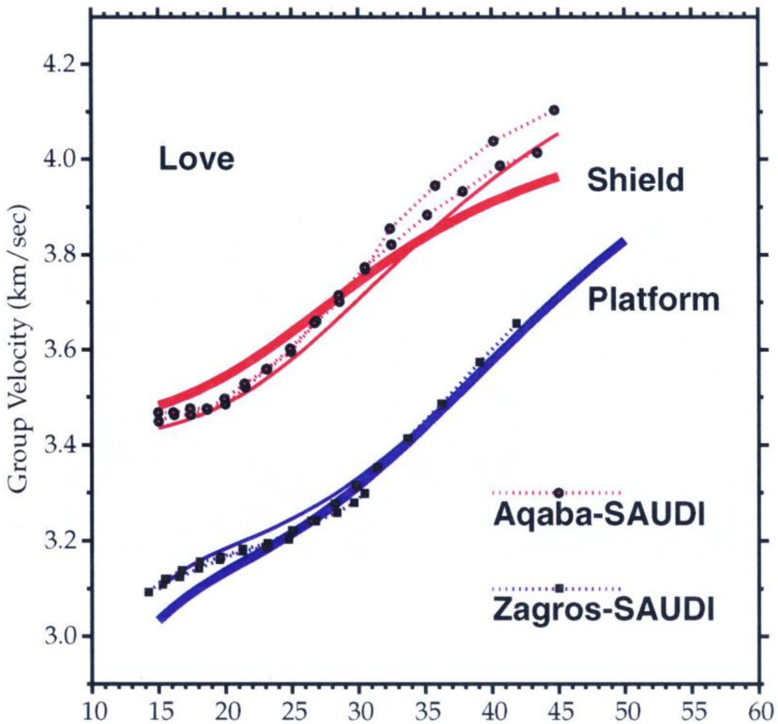


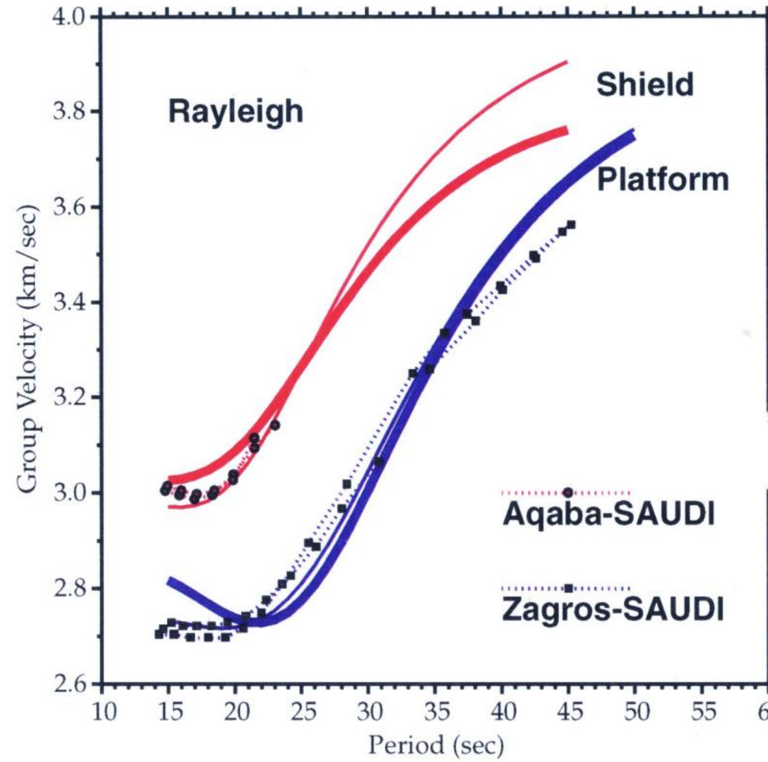
Event Parameters

strike (deg)	dip (deg)	rake (deg)	depth (km)	moment (dyne-cm)	Mw
150	16	-72	10	1.41e24	5.4 (LLNL solution)
153	20	-68	15	0.99e24	5.3 (Harvard CMT)



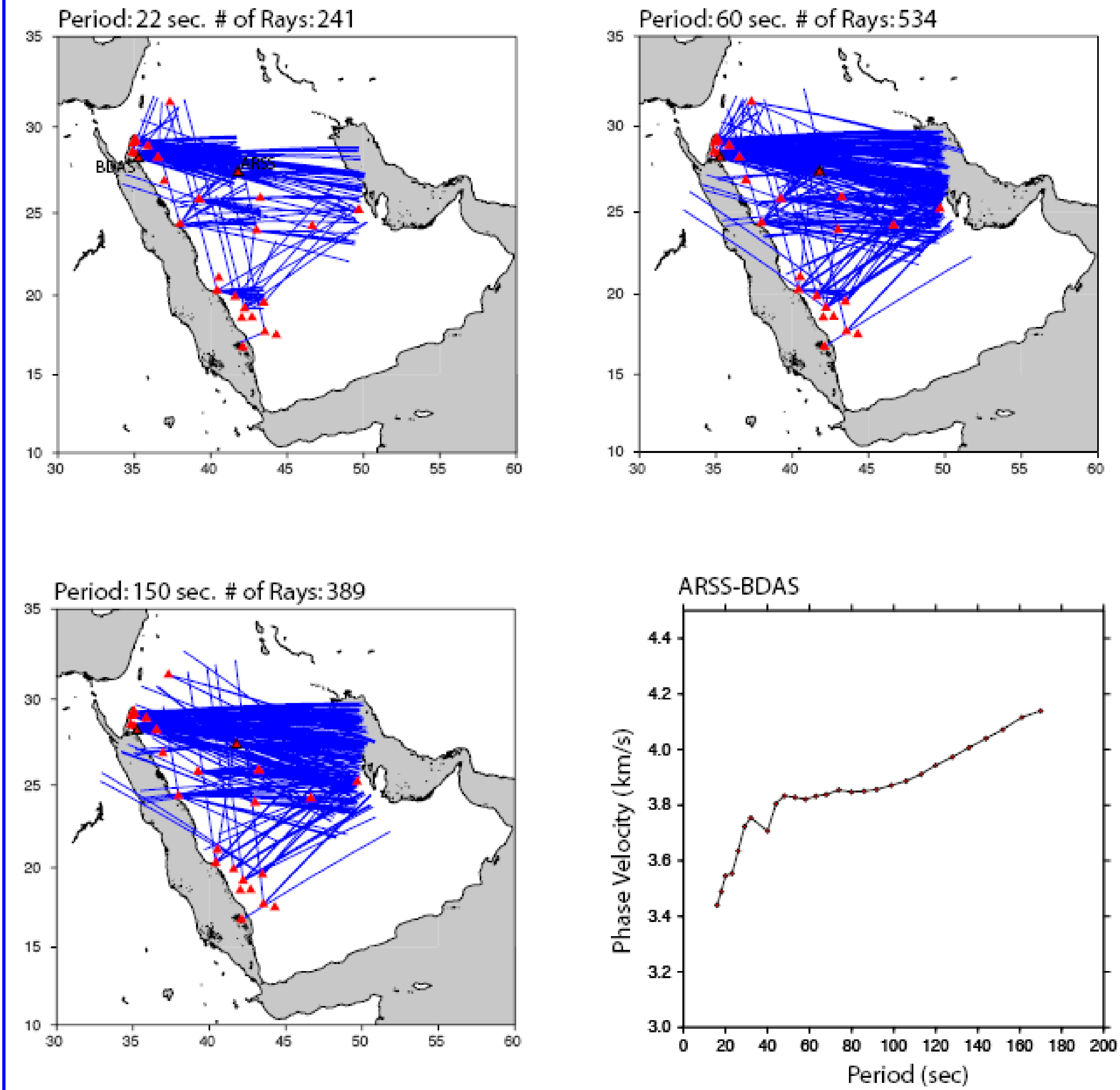
Surface Wave Group Velocities Reveal Significant Differences Between the Lithospheric Velocities of the Arabian Shield and Platform



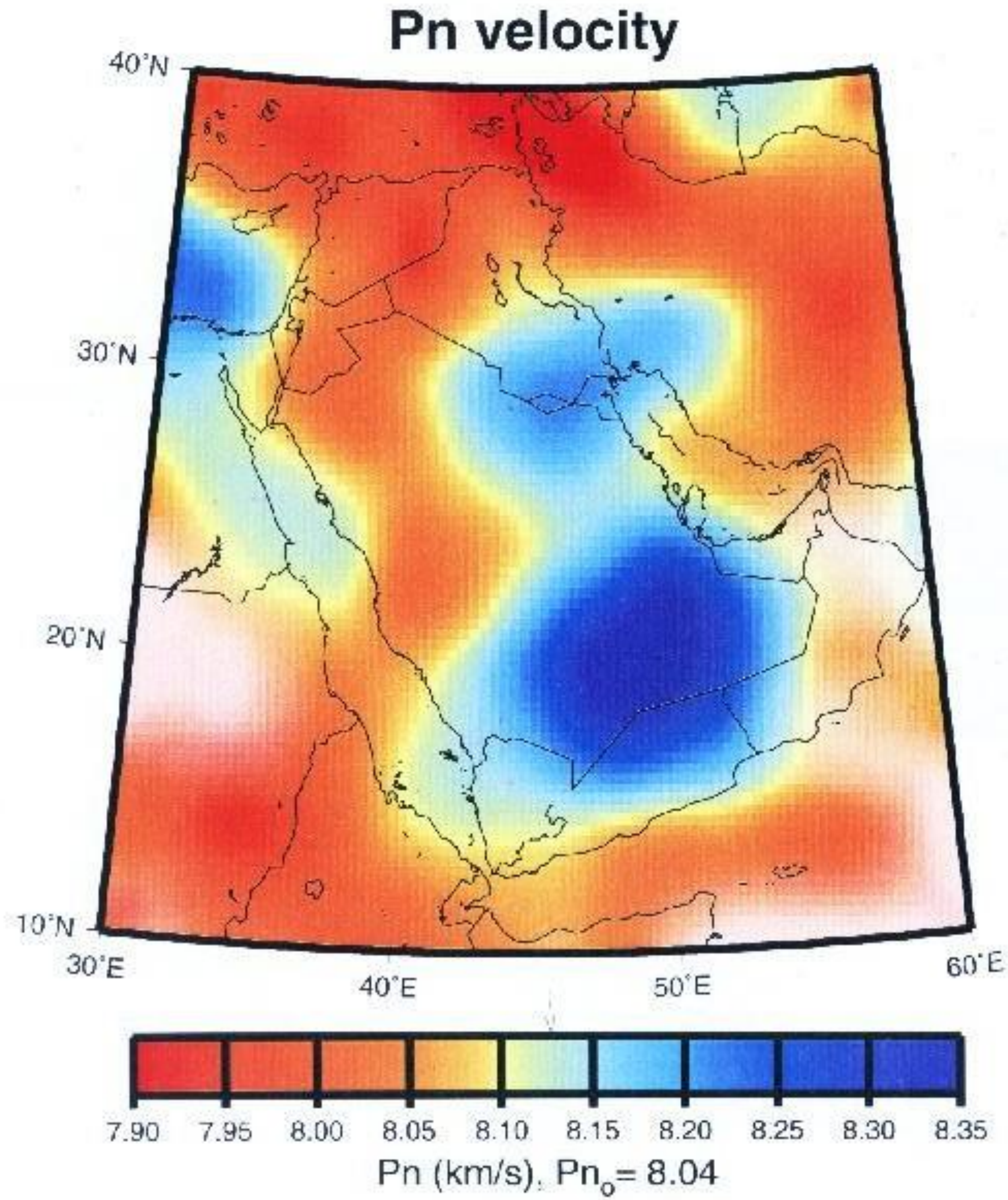


We modeled the group velocities to obtain starting models for waveform modeling.

The observed waveforms are more sensitive to lithospheric velocity structure than the surface wave group velocities.



Rayleigh wave dispersion curves for three period bands centered at 22 s, 60 s and 150 s. The fourth panel shows the Rayleigh wave dispersion curve for the inter-station path between KACST station ARSS and BDAS in Ethiopia.



Pn velocity
40°N
30°N
20°N
10°N
30°E
40°E
50°E
60°E
7.90
7.95
8.00
8.05
8.10
8.15
8.20
8.25
8.30
8.35
Pn (km/s), Pn_o= 8.04

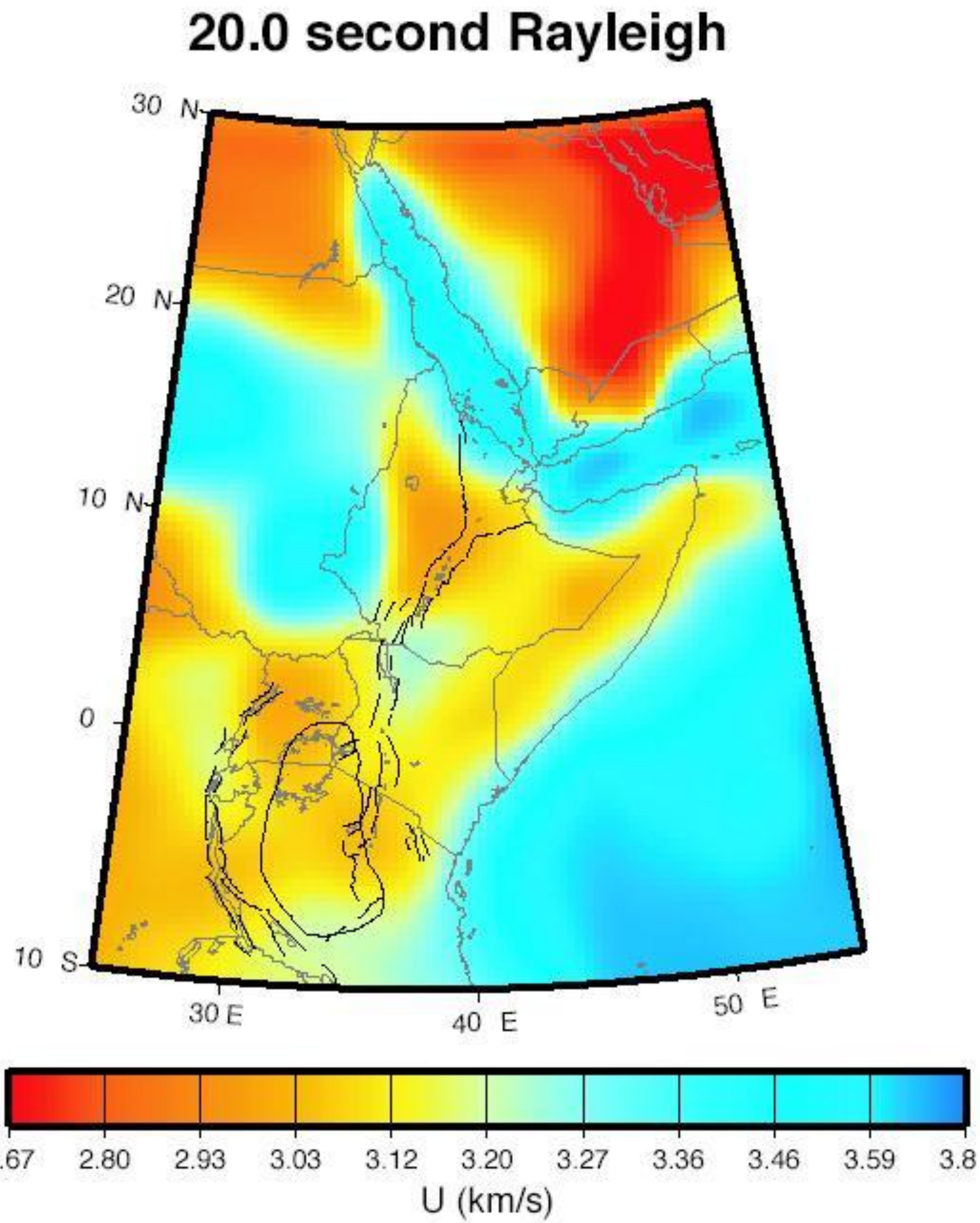
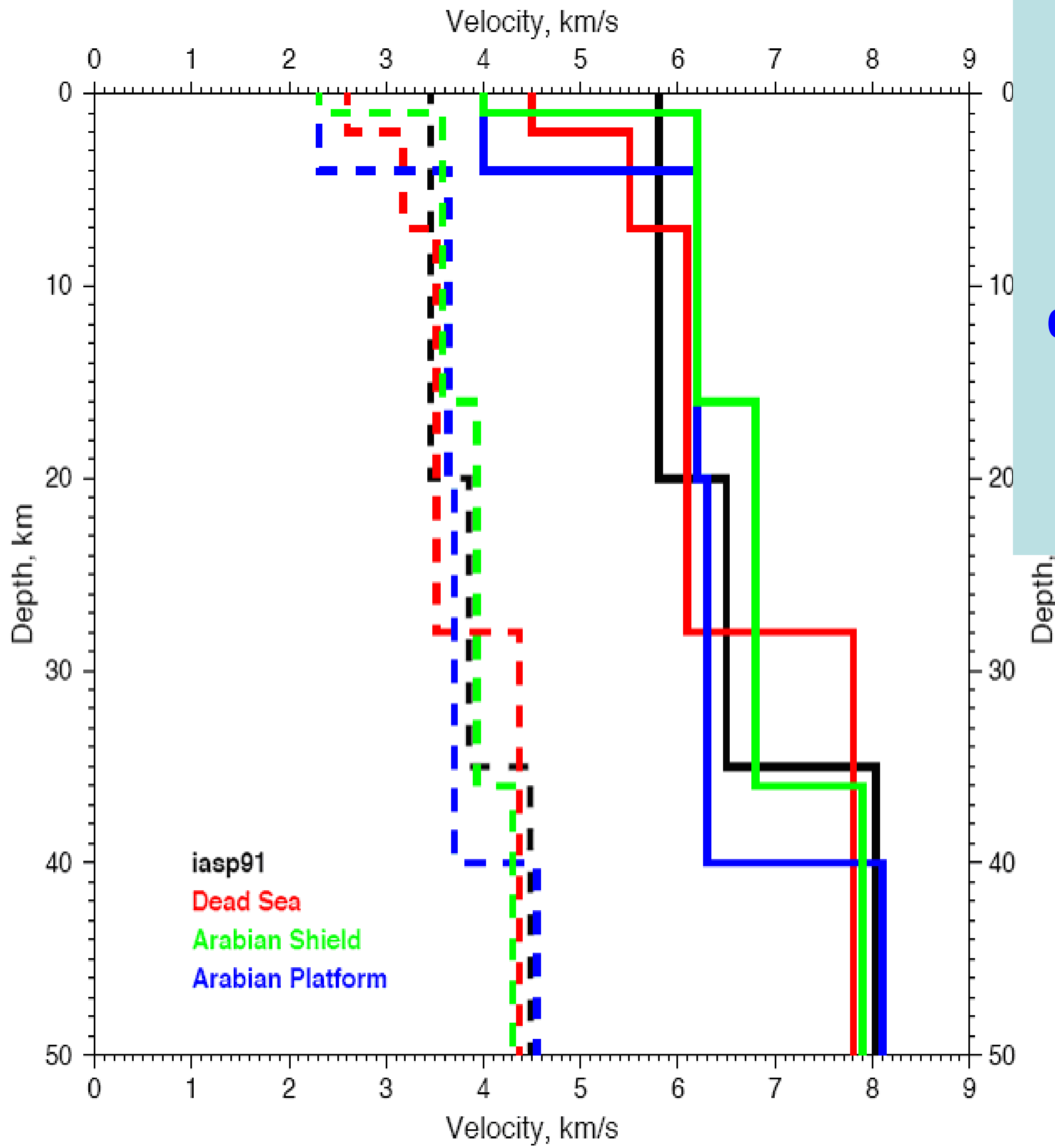


Figure 23. Rayleigh wave group velocities at 20 seconds for the Arabian Peninsula, African Rift and surrounding regions.



Seismic P- and S-wave velocity models, solid and dashed respectively, for the Arabian Peninsula from various sources.

Seismic Velocity Model for the Gulf of Aqabah/Dead Sea Region

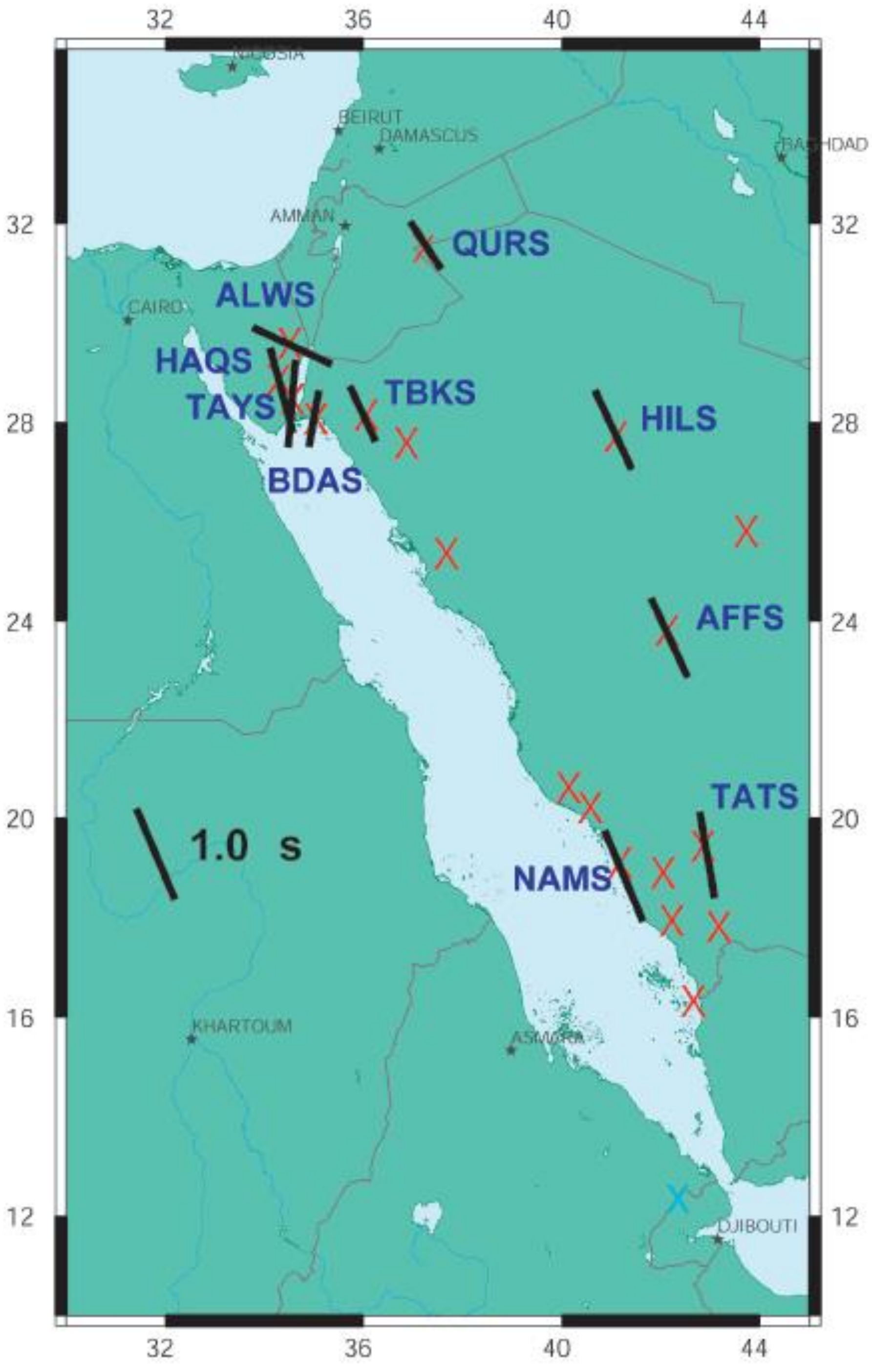
Depth (km)	Thickness (km)	V_P (km/s)	V_S (km/s)
0	2	4.5	2.6
2	5	5.5	3.18
7	10	6.1	3.52
17	11	6.2	3.6
28	∞	7.8	4.37

Seismic Velocity Model for the Arabian Shield Region

Depth (km)	Thickness (km)	V_P (km/s)	V_S (km/s)
0	1	4	2.31
1	15	6.2	3.58
16	20	6.8	3.93
36	∞	7.9	4.3

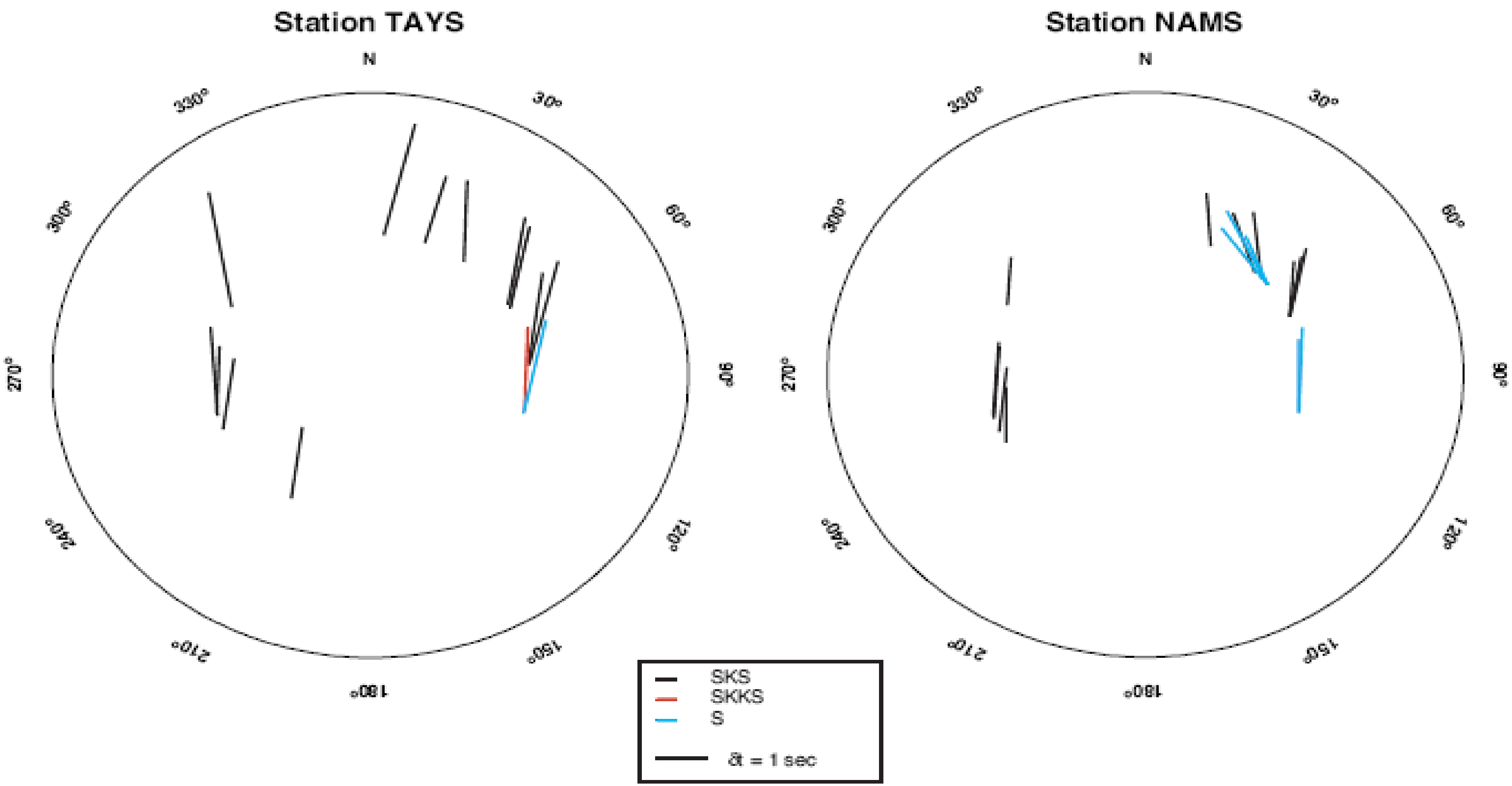
Seismic Velocity Model for the Arabian Platform Region

Depth (Km)	Thickness (km)	V_P (km/s)	V_S (km/s)
0	4	4	2.31
4	16	6.2	3.64
20	20	6.4	3.7
40	∞	8.1	4.55



SKS splitting parameters for several KACST stations. Red crosses indicate station locations with too few SKS splitting parameters to determine a meaningful average. The direction of the black bar indicates the average direction of fast polarization and its length is scaled by the delay time between the fast and slow waves. Most stations east of the Red Sea Rift show consistent northwesterly fast directions with some complications arising in the vicinity of the Dead Sea.

Hemispherical plots for two KACST stations: Gulf of Aqabah station TAYS and Arabian Shield station NAMS. Each line displays the splitting parameters for one event, where the line is oriented in the fast polarization direction (φ) and is scaled to the delay time (δt). Black lines correspond to SKS phases, red lines correspond to SKKS phases, and blue lines correspond to S phases.

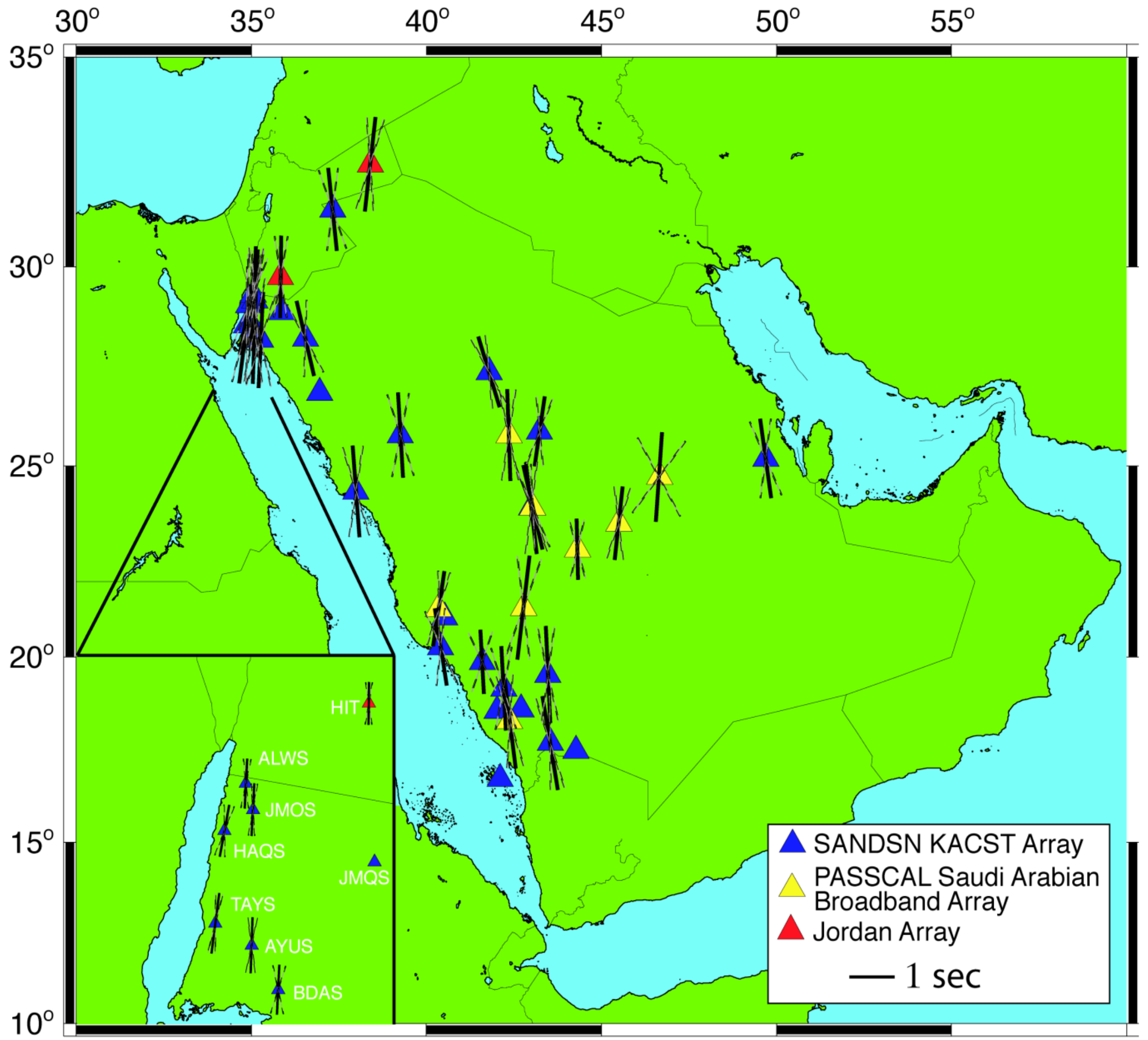


Shear-Wave Splitting Results

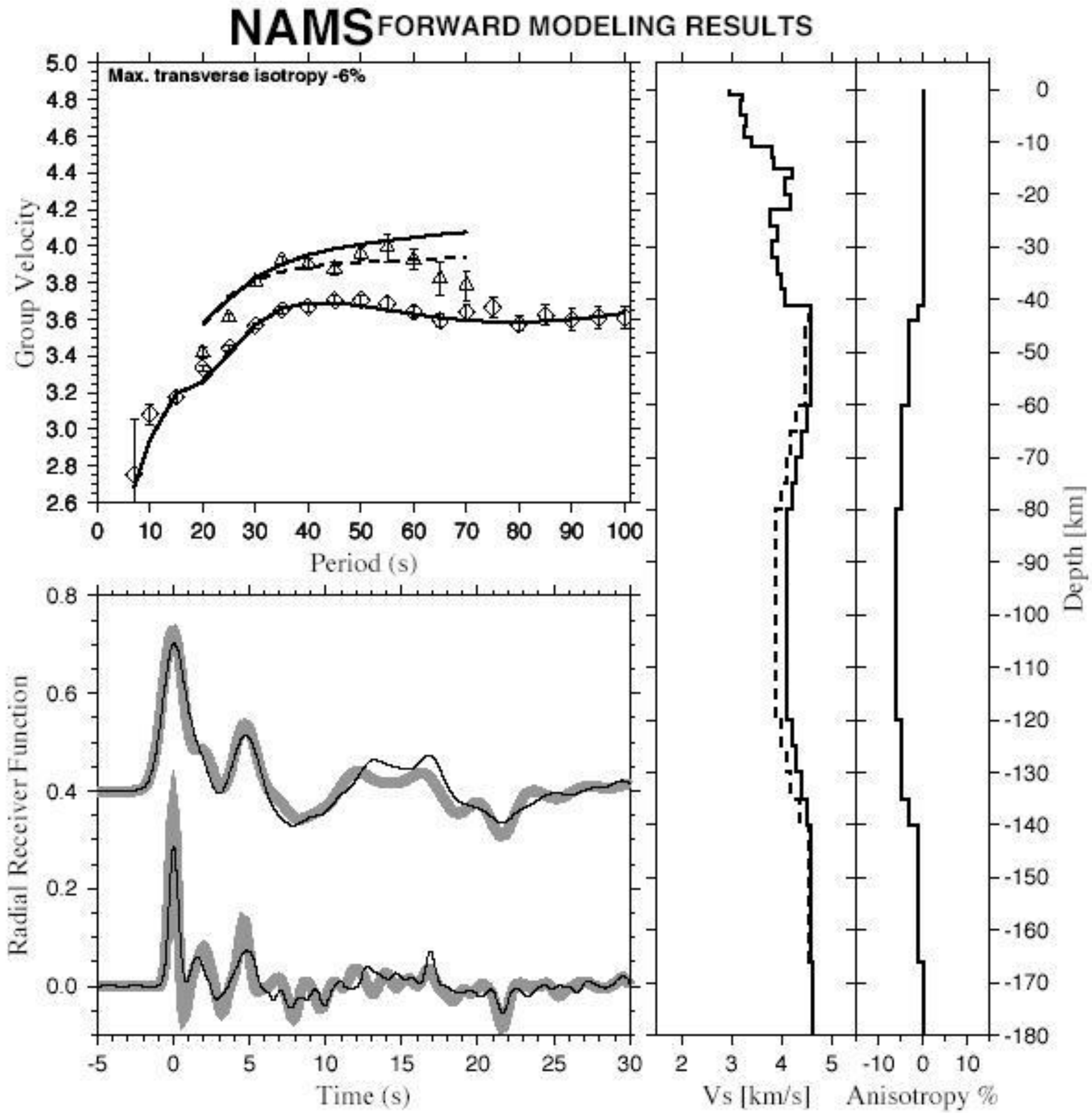
Average splitting is remarkably uniform

Generally north-south fast direction, ~ 1.4 sec

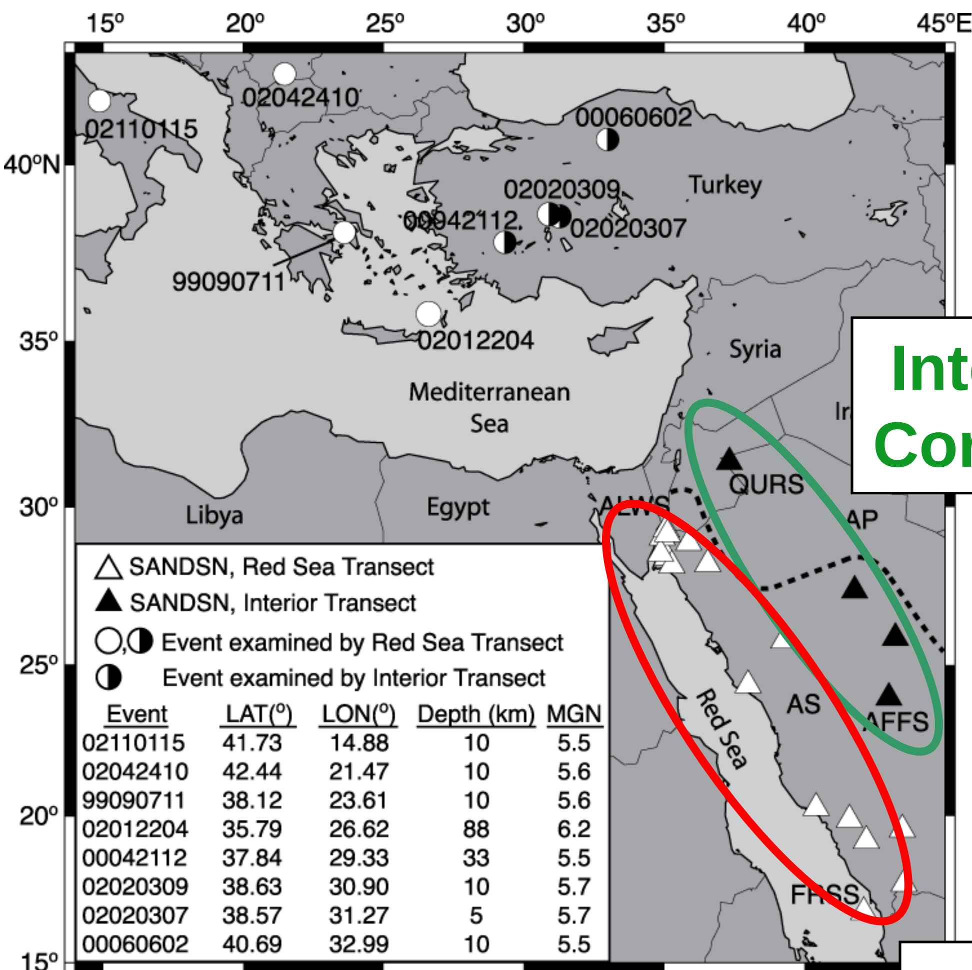
Consistent with Wolfe et al. (1997) for PASSCAL array



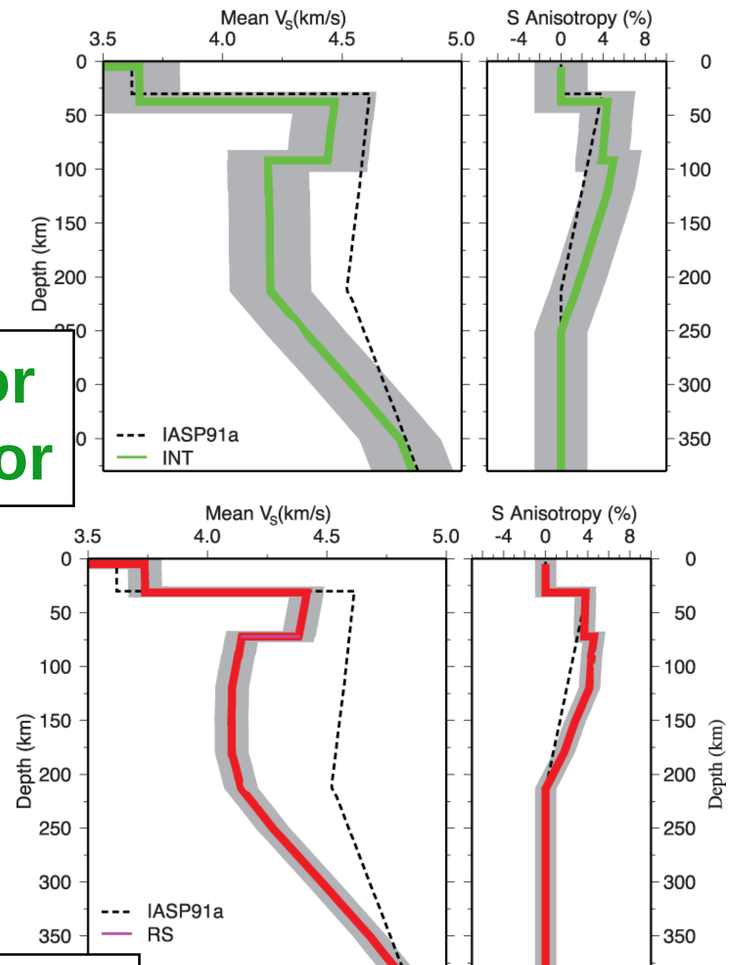
Forward modeling of velocity and anisotropy structure in the upper mantle from Love and Rayleigh wave group dispersion for NAMS station. The model shows the final fit to the data. A broad transverse isotropy coinciding with the low velocity zone in the mantle is required with Vsv exceeding Vsh by 6%.



1D Anisotropic Models from Rayleigh and Love Phase Velocities



Interior Corridor

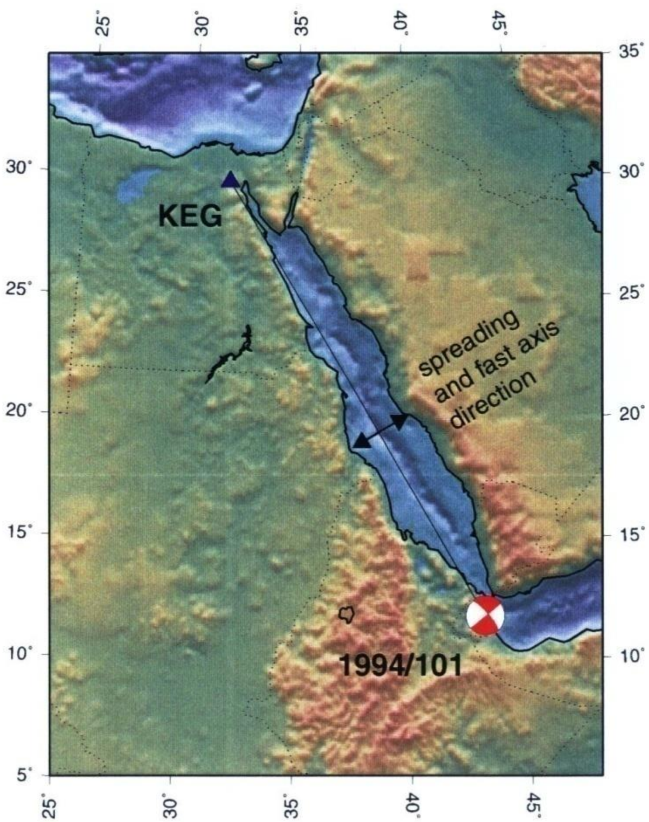


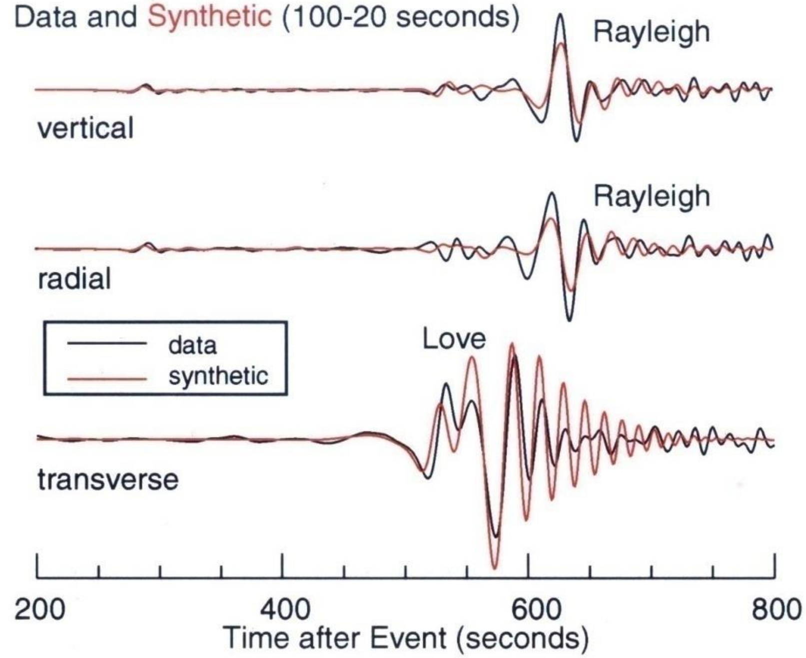
Red Sea Corridor

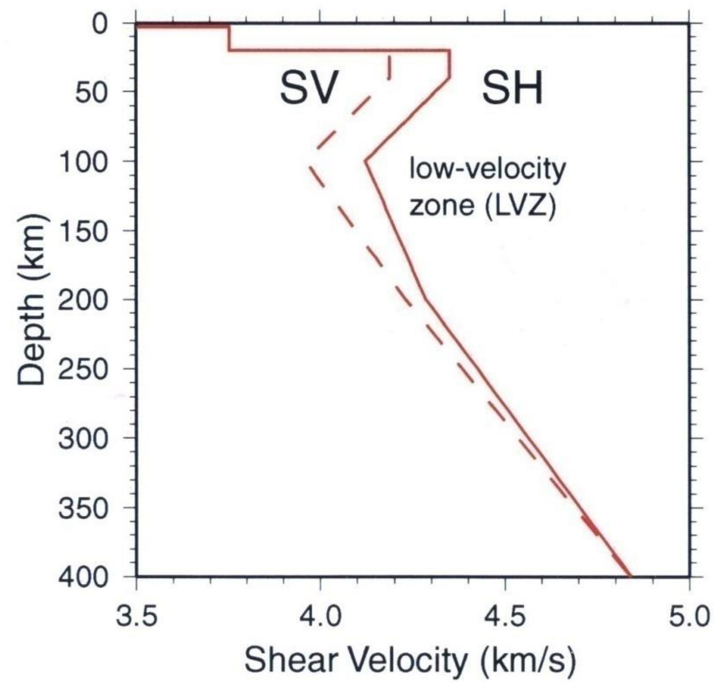
Note low velocities!

Red Sea Paths Require Anisotropy

Waveforms for the April 11, 1994 Afar earthquake recorded at station KEG (Kottamya, Egypt, $\Delta = 20.8^{\circ}$) reveal anisotropy in the upper mantle. SH and SV cannot be fit with the same isotropic model. These data are fit (upper right) with an anisotropic model (lower right) with SH about 4% faster than SV. This is consistent with the fast axis of anisotropy aligned with the spreading direction.







Courtesy of Sara Russell, UC Santa Cruz

P- and S-wave travel time tomography resolution tests

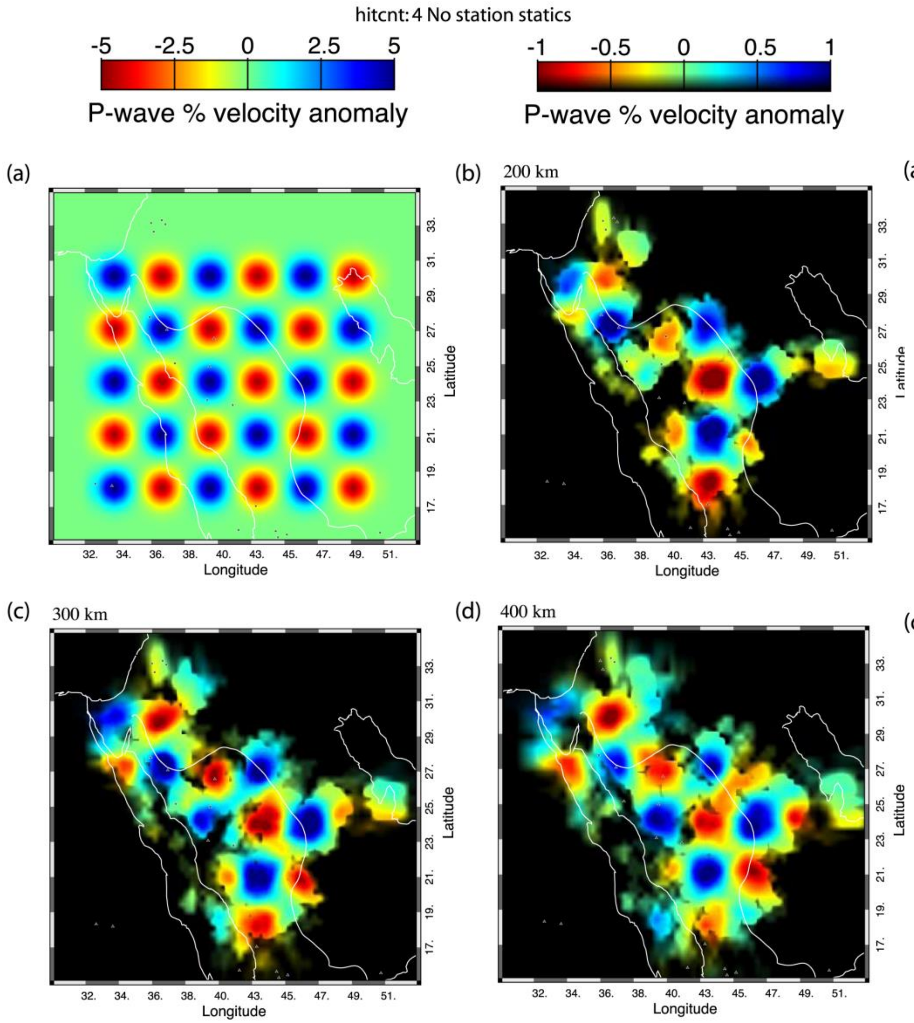


Figure 7.

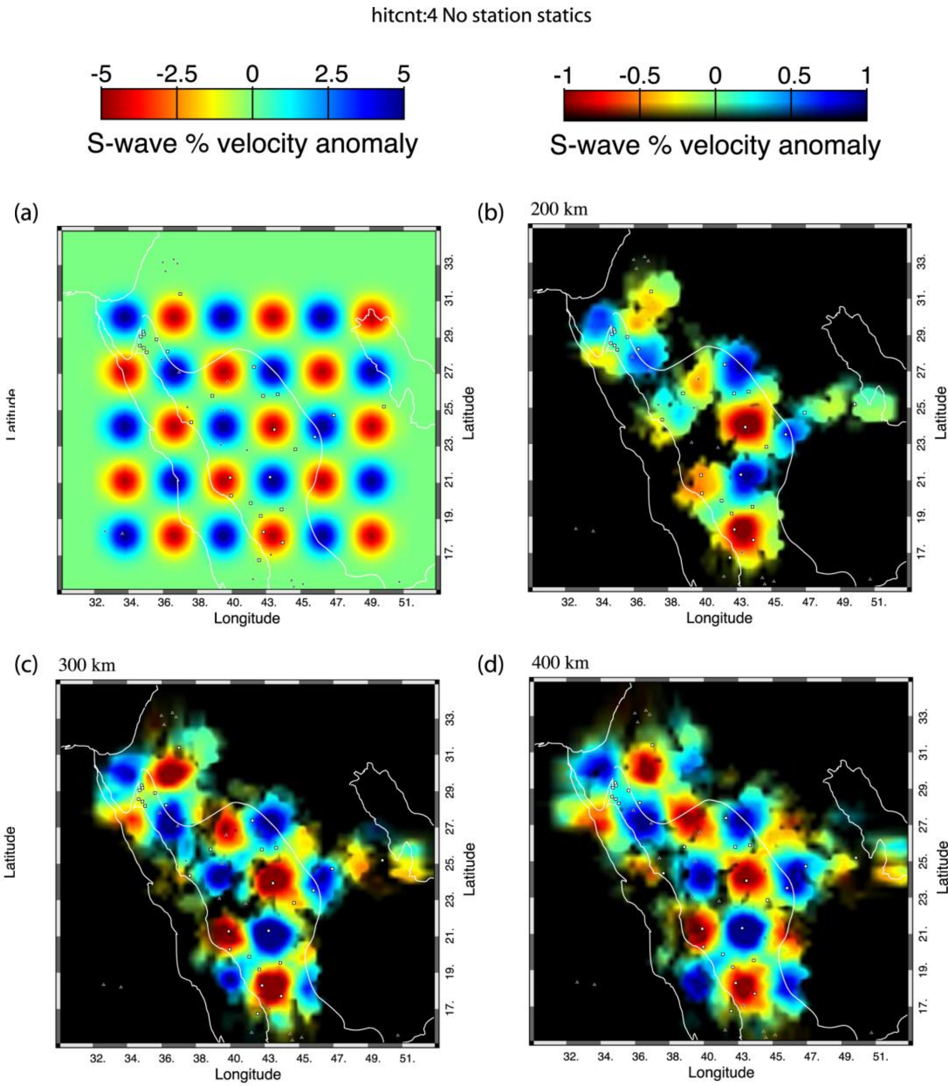
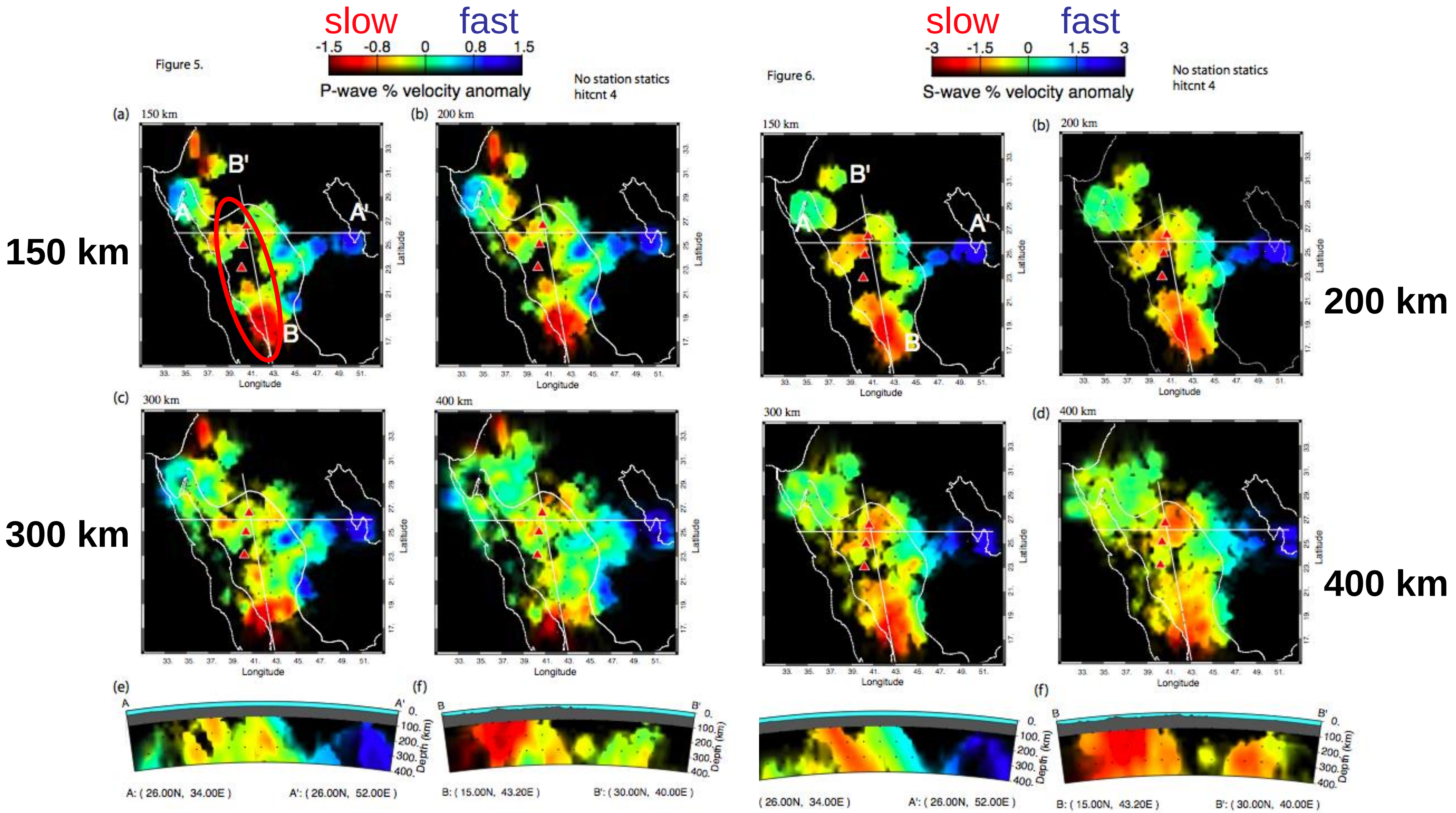


Figure 8

Upper mantle tomography results from P- and S-wave travel time



Low velocities underlie the southern Red Sea and Harrats (▲)

P- and S-wave travel time tomography anomaly tests

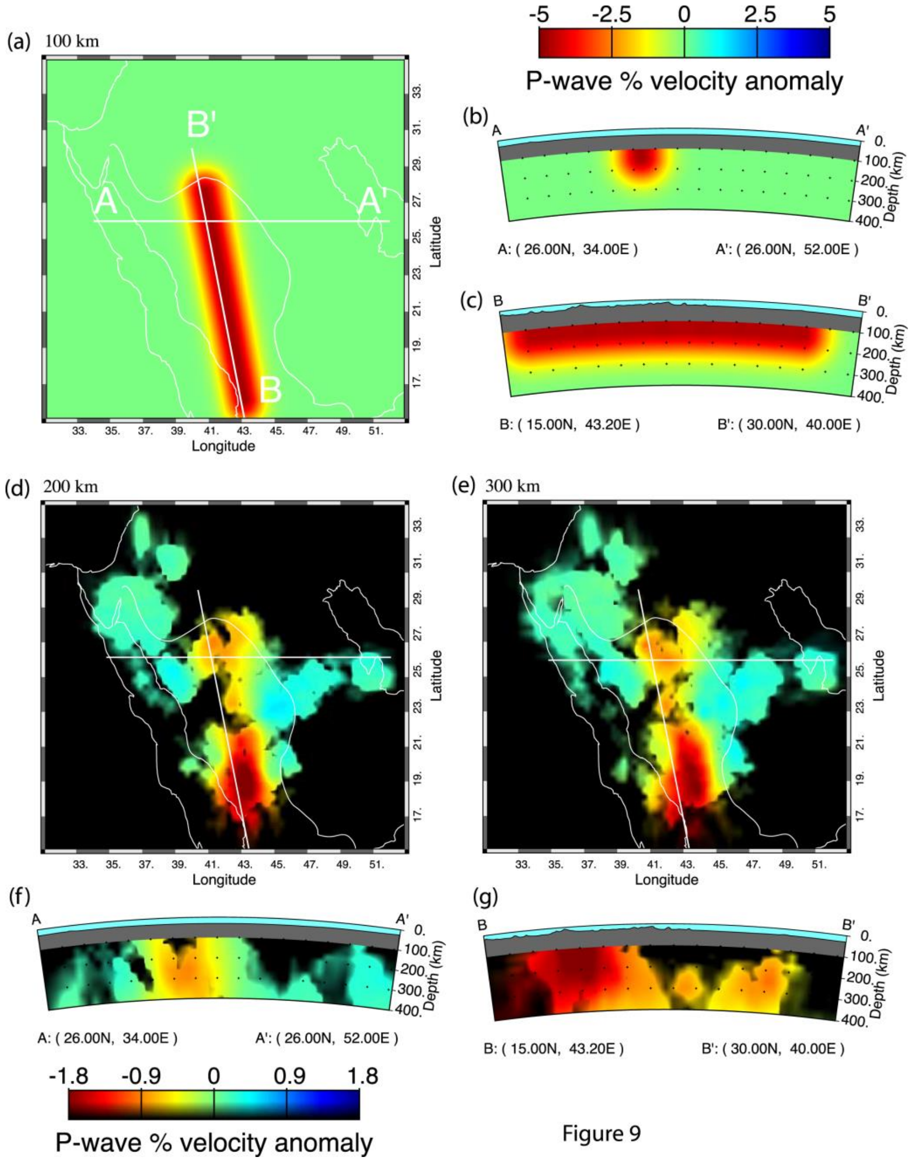


Figure 9

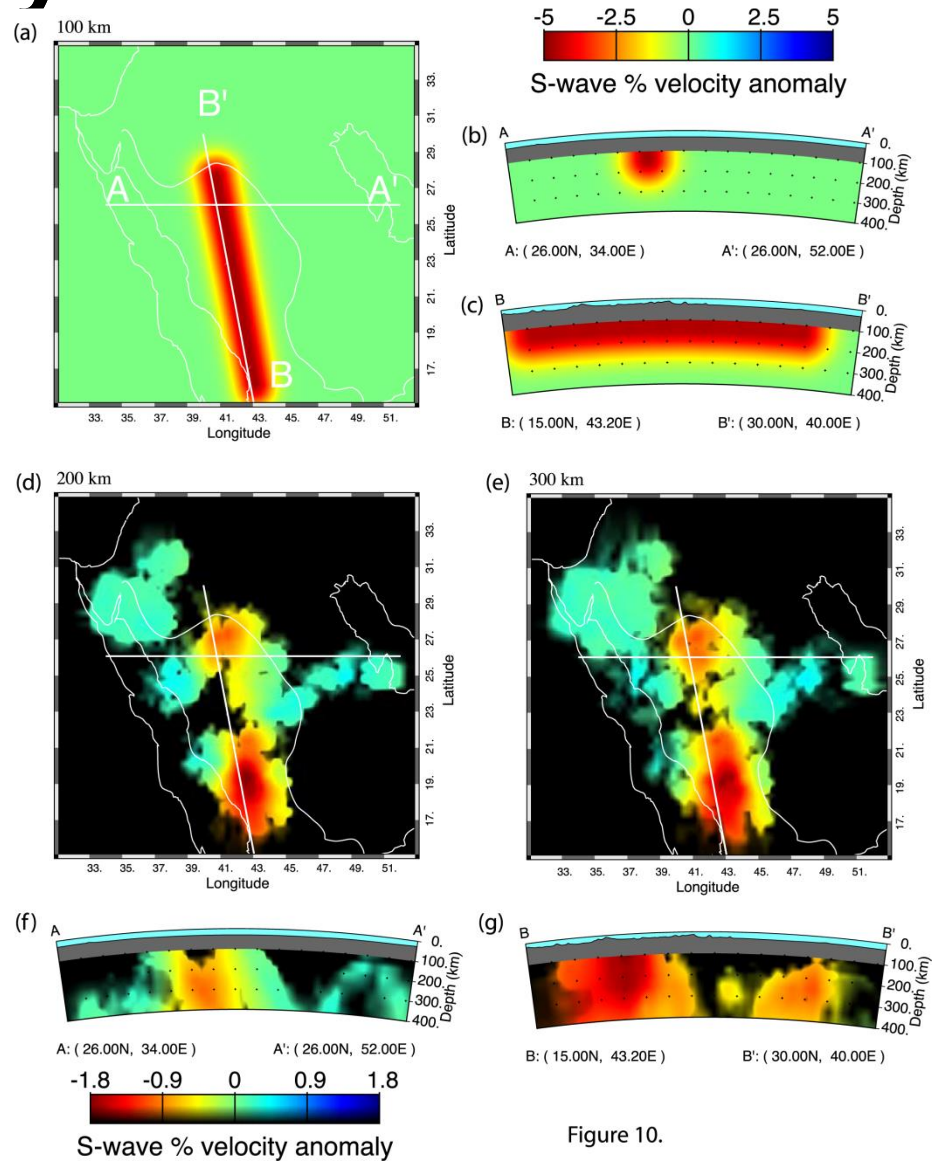
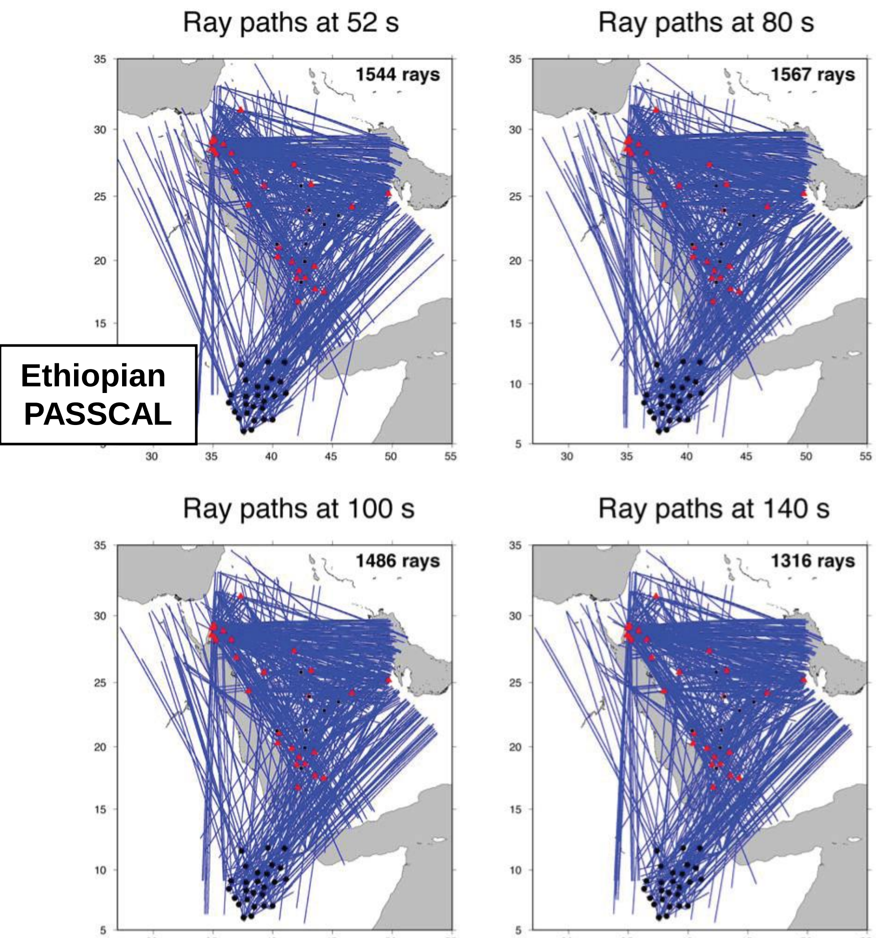
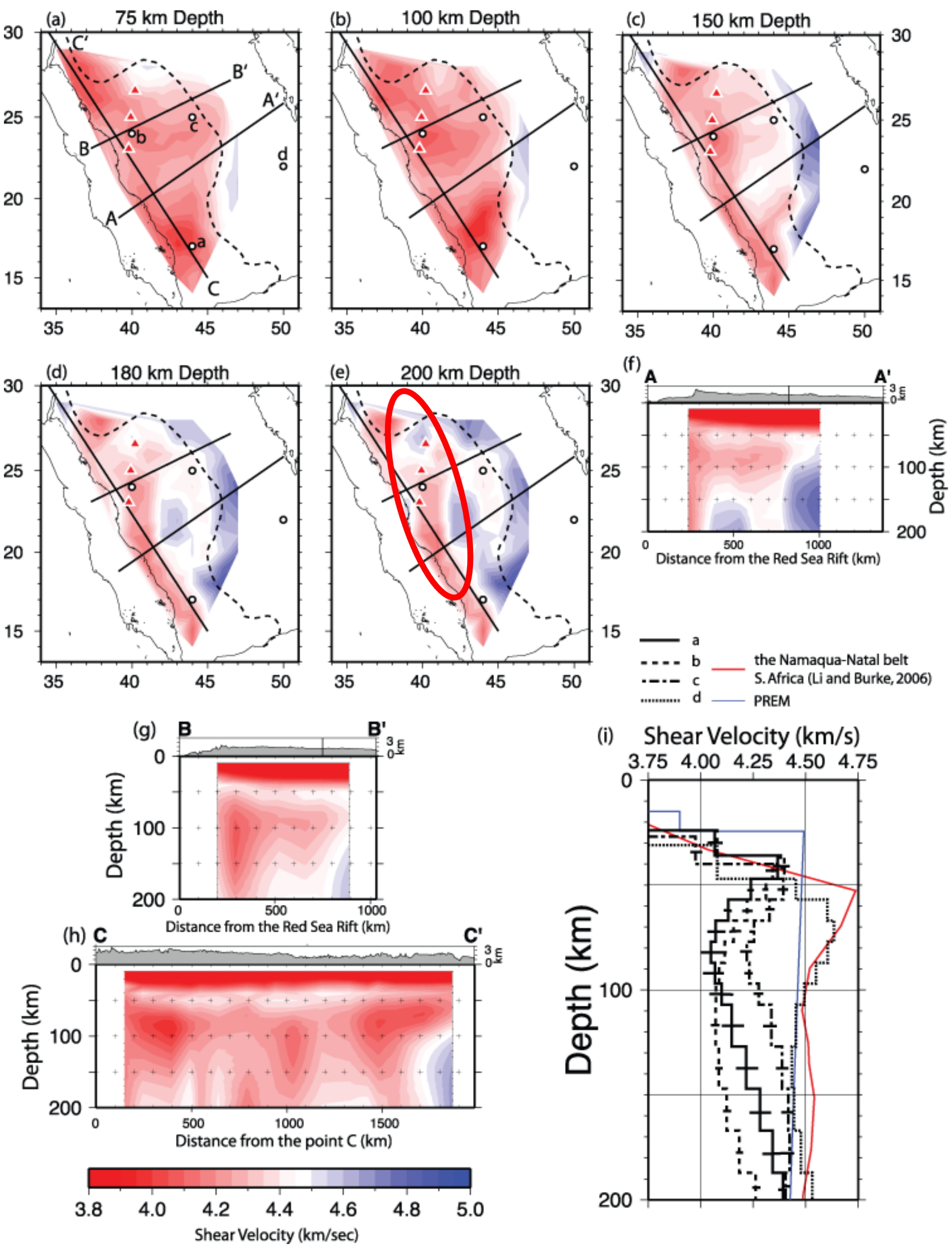


Figure 10.

Rayleigh Wave Tomography

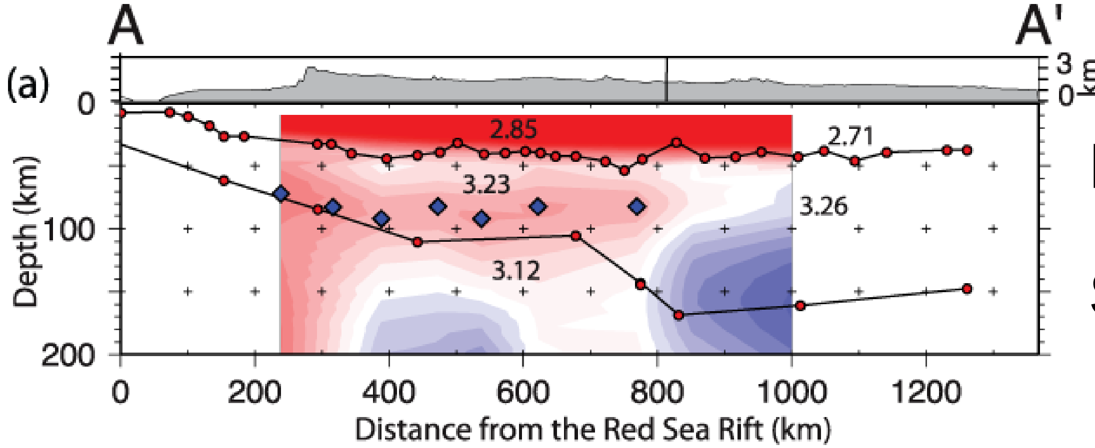
Modified array approach of Lawrence et al. (2008)





LAB from SRF's and shear velocities form Rayleigh wave tomography

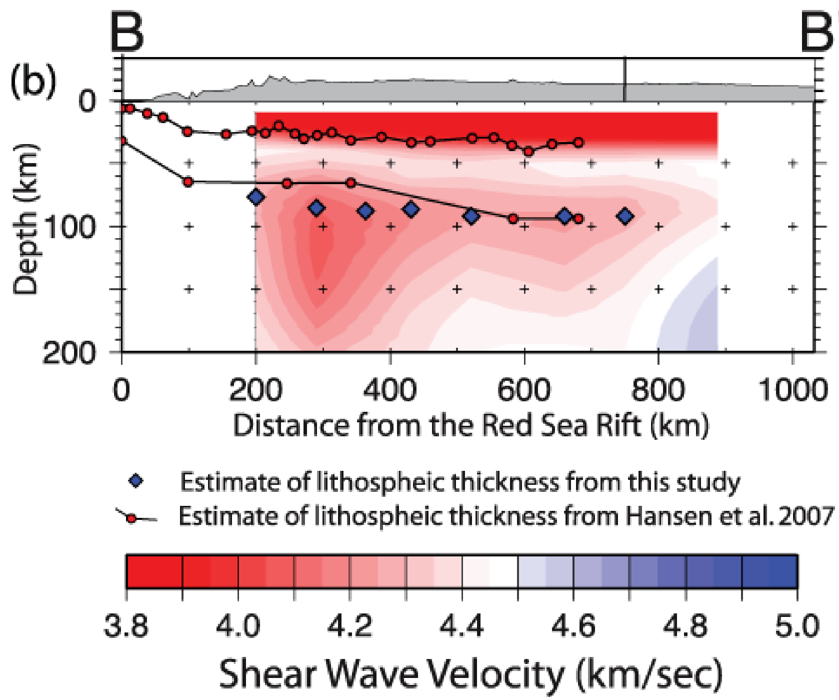
Southern



Moho Depth

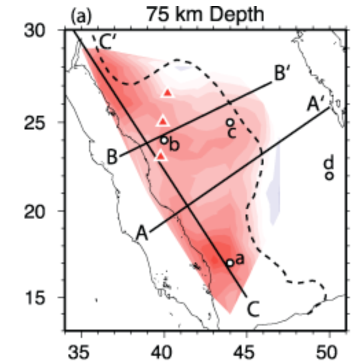
SRF LAB Depth

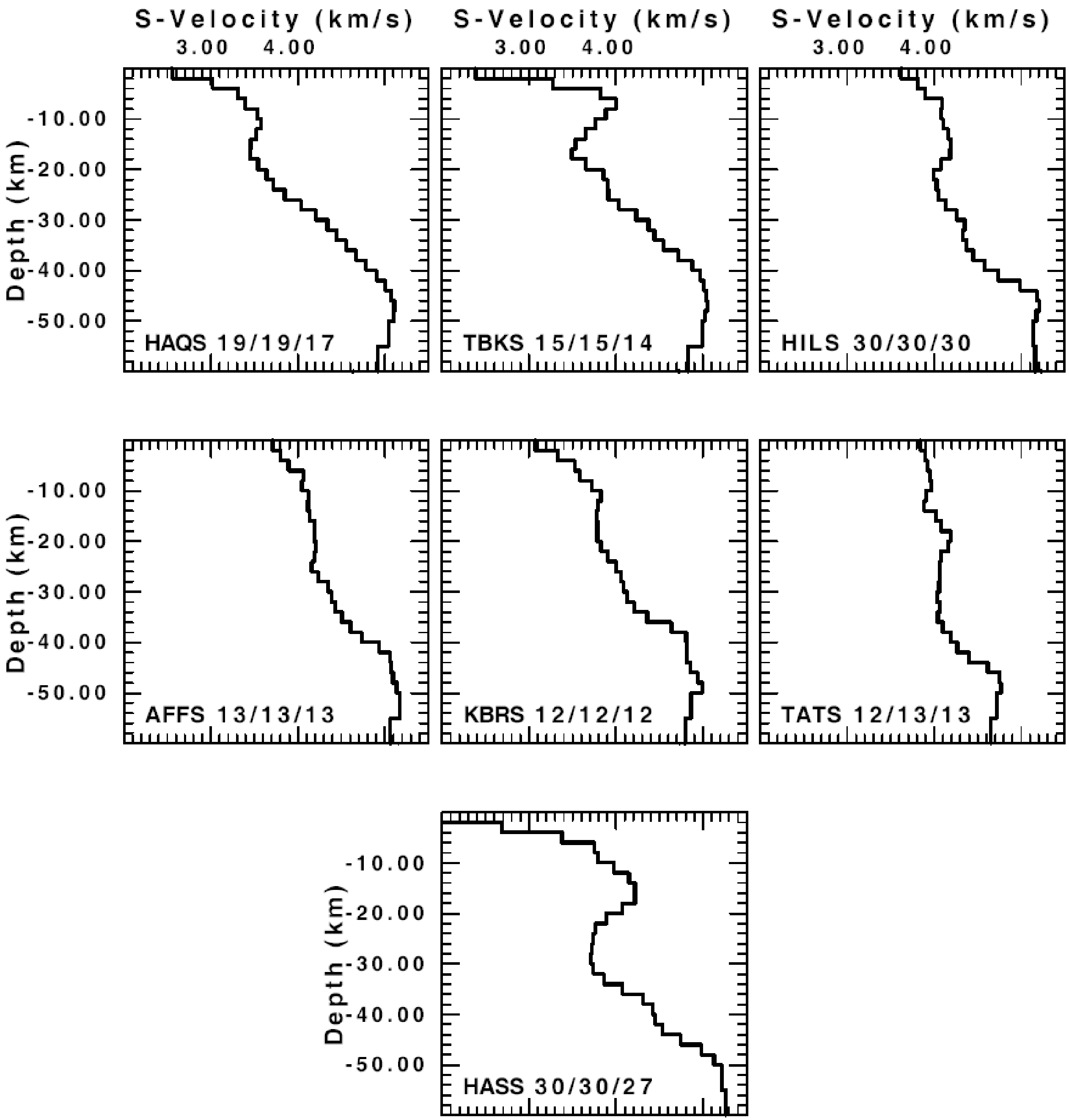
Northern



Moho Depth

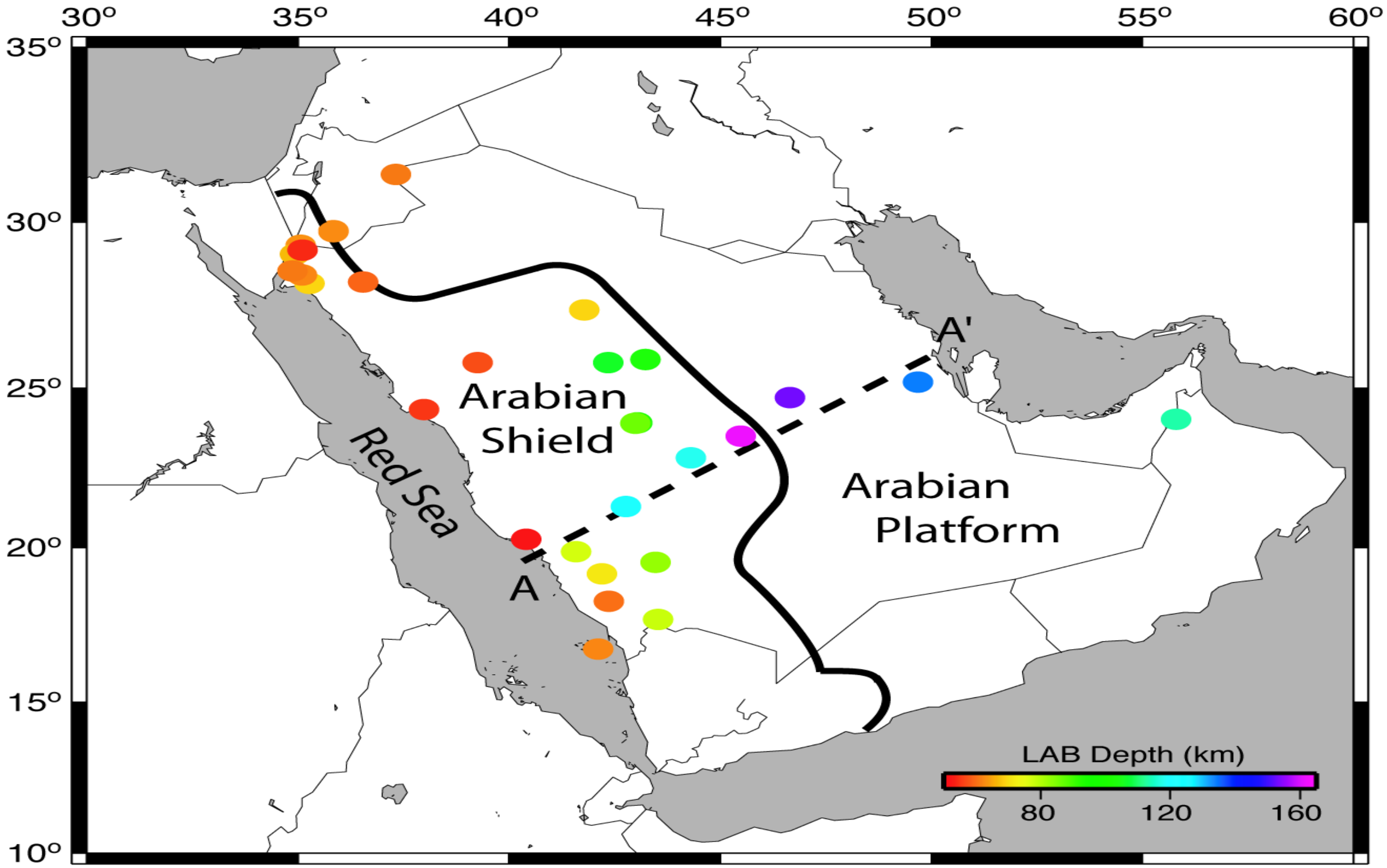
SRF LAB Depth





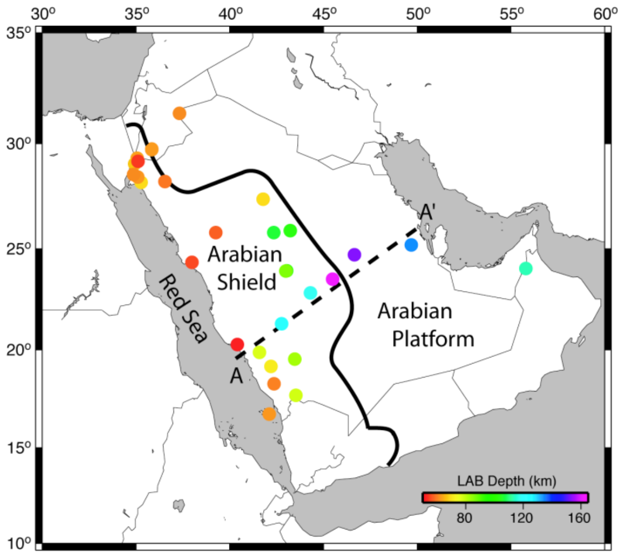
The final shear velocity model inverted from receiver function. The model compares stations used on this study. This figure shows the total receiver function used for the inversion.

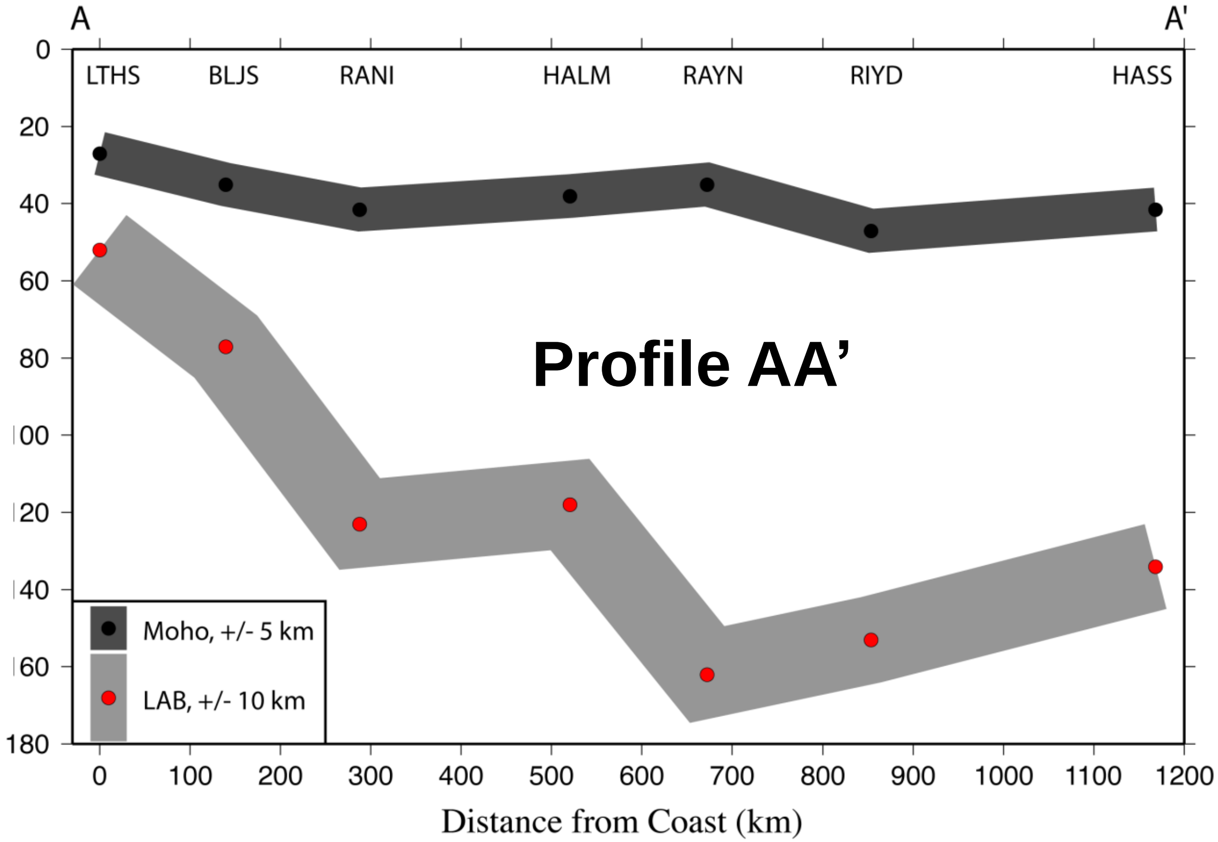
S-wave RF's constrain LAB (lithosphere-asthenosphere boundary) depth



Shallow (40-60 km) LAB along Red Sea coast and Gulf of Aqaba
Thickens (80-120 km) toward interior of Shield
Step (20-40 km) across the Shield-Platform boundary

Modeling SRF’s provides Moho and LAB depth and uncertainties





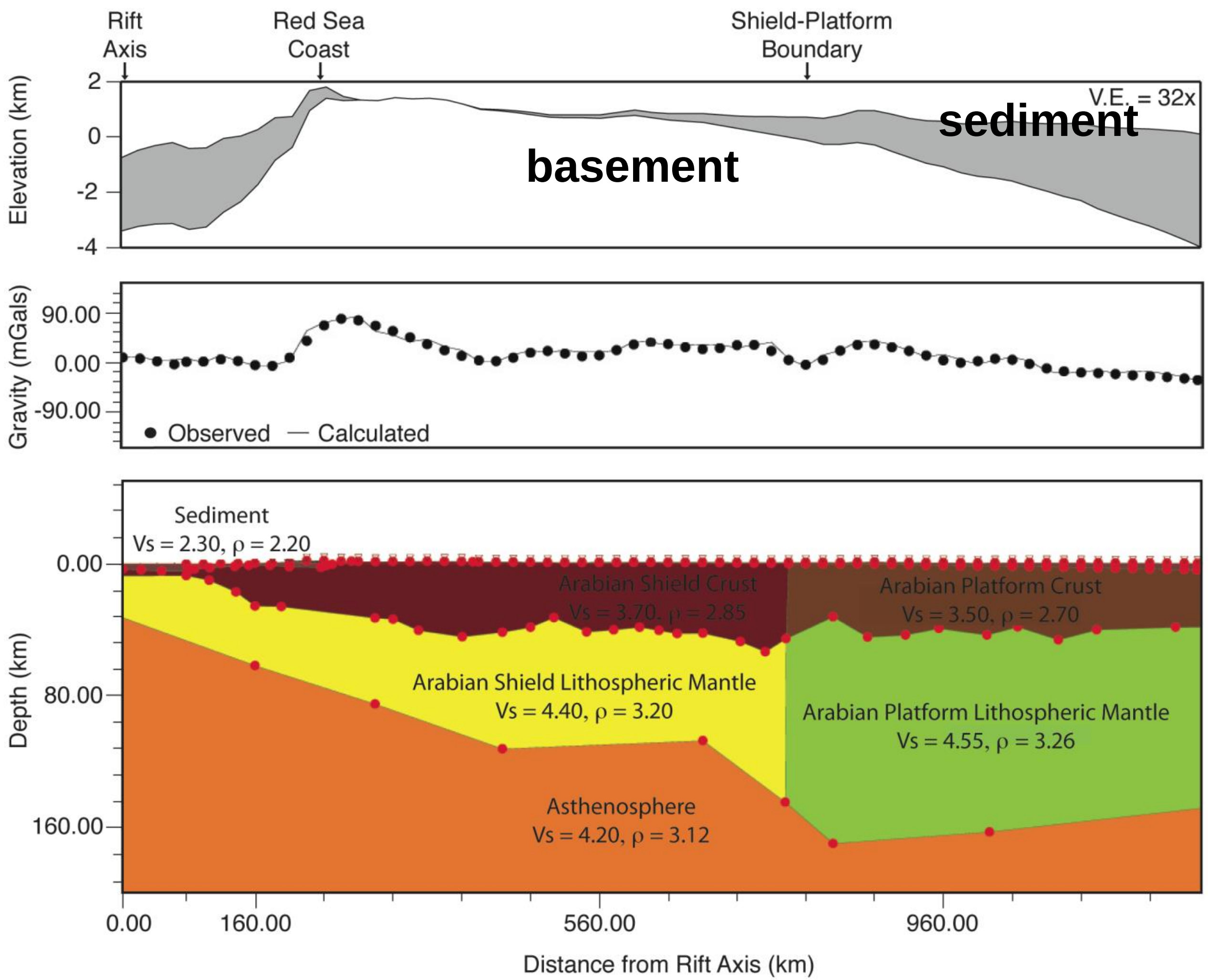
Uncertainties in estimated Moho and LAB depths were inferred from modeling observed SRF’s and finding the range of model parameters that provide an adequate fit.

Inferred lithospheric cross-section predicts gravity

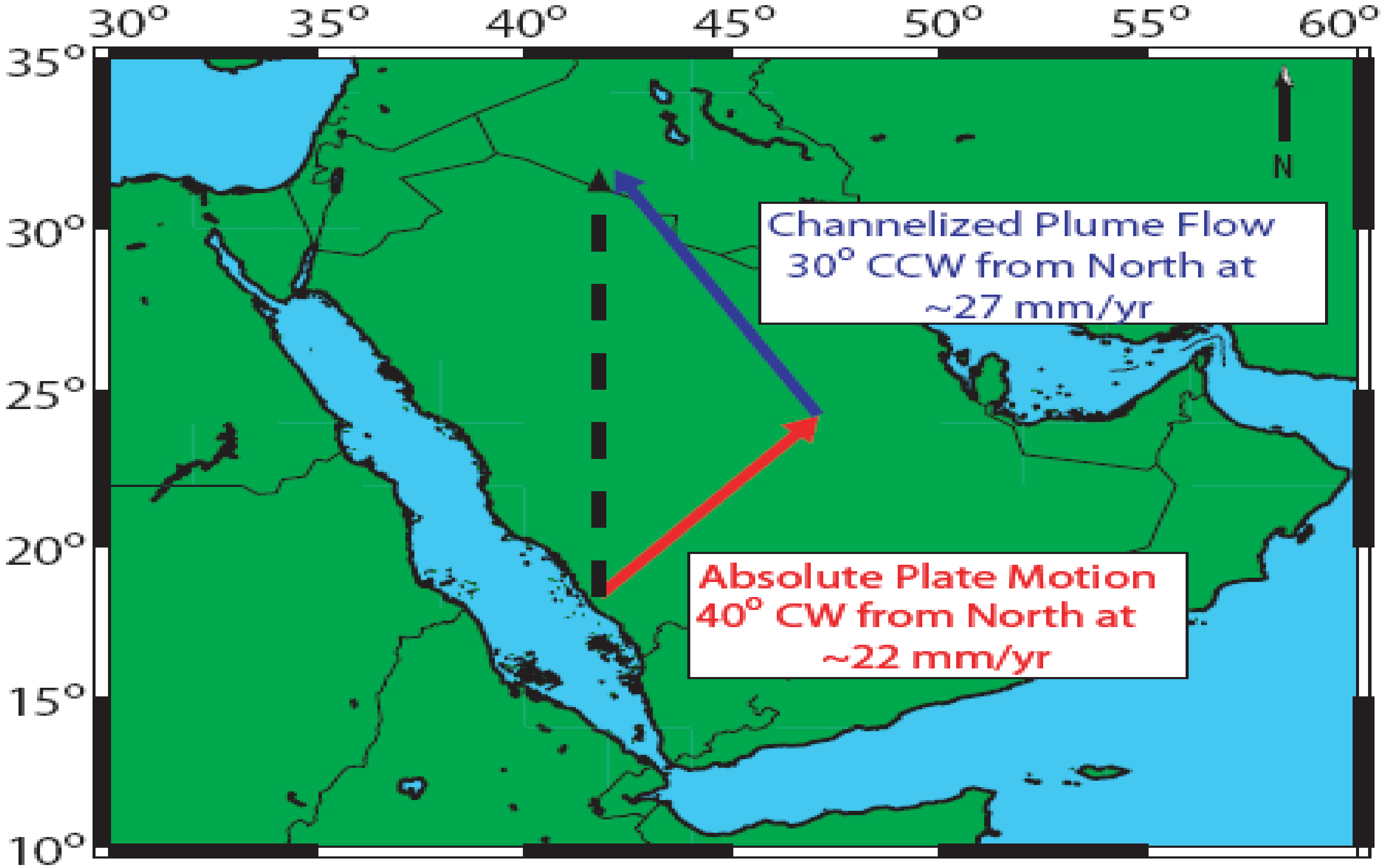
Topography, sediment and basement

Observed (dots) and predicted (line) gravity anomaly

Lithospheric cross-section with shear velocities and densities



Observed gravity data taken from GRACE satellite



Vector examination of plate motion (red arrow) coupled with channelized upwelling flow (blue arrow) beneath Saudi Arabia. If we estimate that absolute plate motion is oriented N40E at a rate of 22 mm/yr and that channelized hotspot flow is oriented approximately N30W, then the rate of hotspot flow needed to obtain a north-south resultant (black dashed arrow) is ~27 mm/yr.

Summary of upper mantle structure of the Arabian Peninsula

- Arabian shield is characterized with
  - Thinned mantle lithosphere, with thinnest lithosphere under the Red Sea (depth ~ 60 km) and thickest lithosphere (depth ~ 120 km) beneath the central Shield
  - Low seismic velocities (-3% for S-waves) in 200-400 km depth range
  - Uniform shear-wave splitting
- Red Sea margin has very low shear velocities (~ 4.0 km/s) in the shallow upper mantle (100-250 km)
- Arabian Platform is characterized by
  - Thick mantle lithosphere (depth ~ 140 km)
  - High seismic velocities (+3% for S-waves) in 200-400 km depth range

Interpretation of upper mantle structure

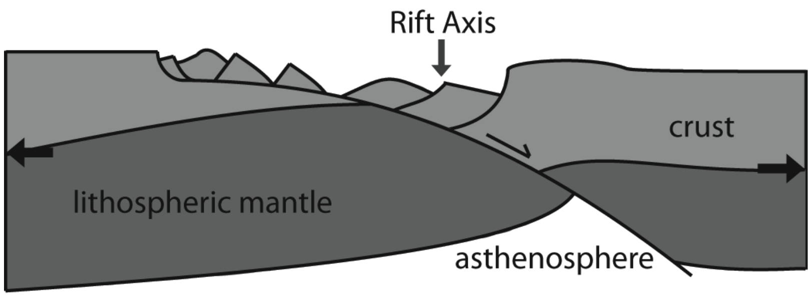
- Lower velocities, probably related to higher than average temperatures are observed beneath the Arabian Shield
  - Especially in the southern Asir Province adjacent to the Red Sea
  - Low velocities could be due to temperature variations of up to 330K
  - Low velocities likely caused Cenozoic uplift and Harrat volcanism
- Higher velocities, probably related to lower than average temperatures are observed beneath the Arabian Platform
  - Resolution is poor in the Arabian Platform due to many fewer seismic stations, but inferred velocities more normal for stable continent
- Low velocity anomaly is present beneath the Arabian Shield
  - Depth range 200-400 km is resolved
  - Rayleigh wave tomography complements body-wave travel time tomography, with improved resolution in shallow (< 200 km) mantle

Further interpretations

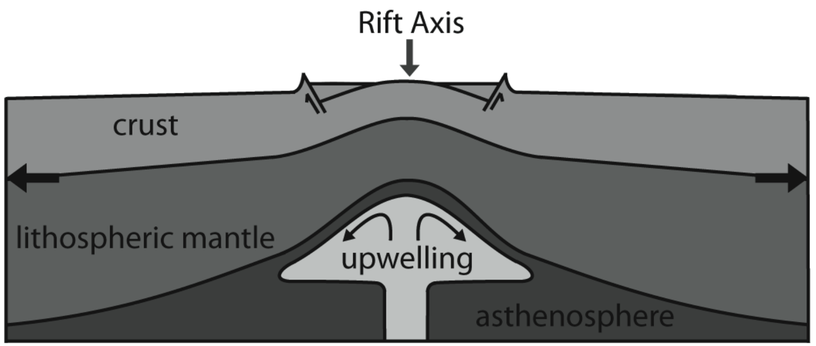
- Red Sea rifting and current spreading caused mantle lithosphere to thin from the central Red Sea to the Arabian Shield
  - Current morphology consistent with active rifting
- Low velocities beneath the Arabian Shield are likely due to a single massive upwelling
  - This likely connects with the low velocity anomaly extended from the core-mantle boundary to the East African Rift and Afar hot spot

Lithospheric structure supports active rifting mechanism (currently)

Passive Rifting



Active Rifting



We observe lithospheric thickening that is symmetric about rift axis, consistent with active mechanism.

Geologic evidence indicates that rifting was initiated by passive mechanism.

We conclude Red Sea rifting has two-stages: initiated passively, then maintained actively.

Relationship between Afar Hot Spot upwelling, Rea Sea and Arabia

Upwelling penetrates transition zone beneath Afar, is channeled by southern Red Sea lithospheric structure and spreads across Arabian Shield at shallow mantle depths

Northerly flow is consistent with shear wave splitting