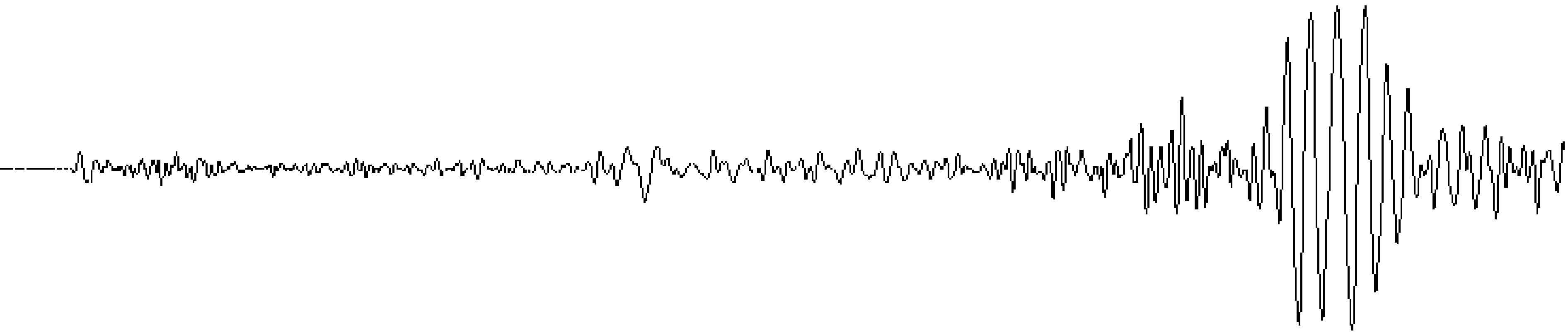

Crustal and Upper Mantle Structures of the Red Sea and Arabian Shield

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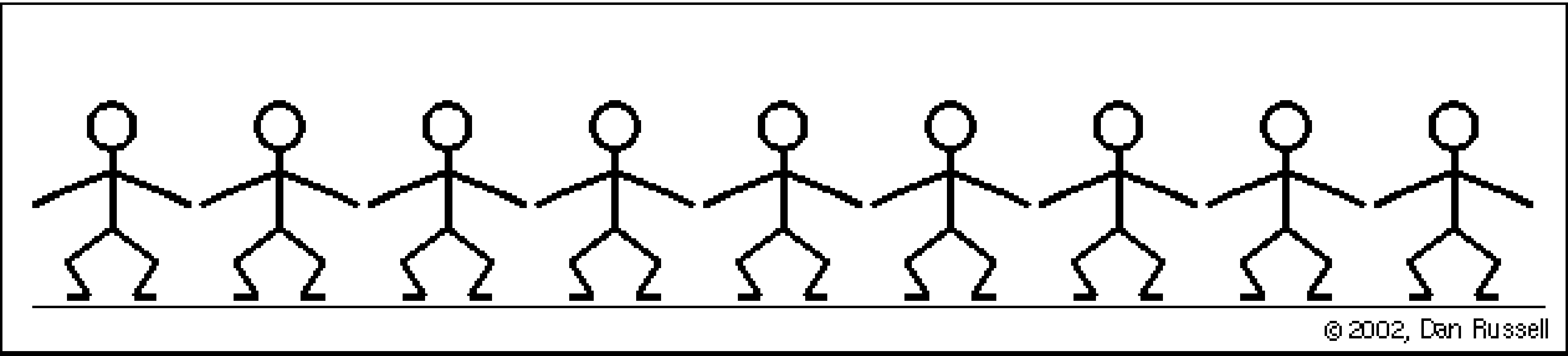


SEISMOLOGICAL BACKGROUND

1992 : Spectral Analysis of P & S

1995 : First GSN / RAYN station in the Middle East

1996 : First Broadband Experiment

2000 : EQ. Location & Magnitude Calibration

2003 : Crustal Structures Studies

2006 : Upper Mantle Structure Studies

2008 : First Seismic Array in the Arabian Region

2010 : Geothermal & Volcanic Evolution

2012 : Ground Motion Simulations

2014 : Mantle Upwelling & LAB

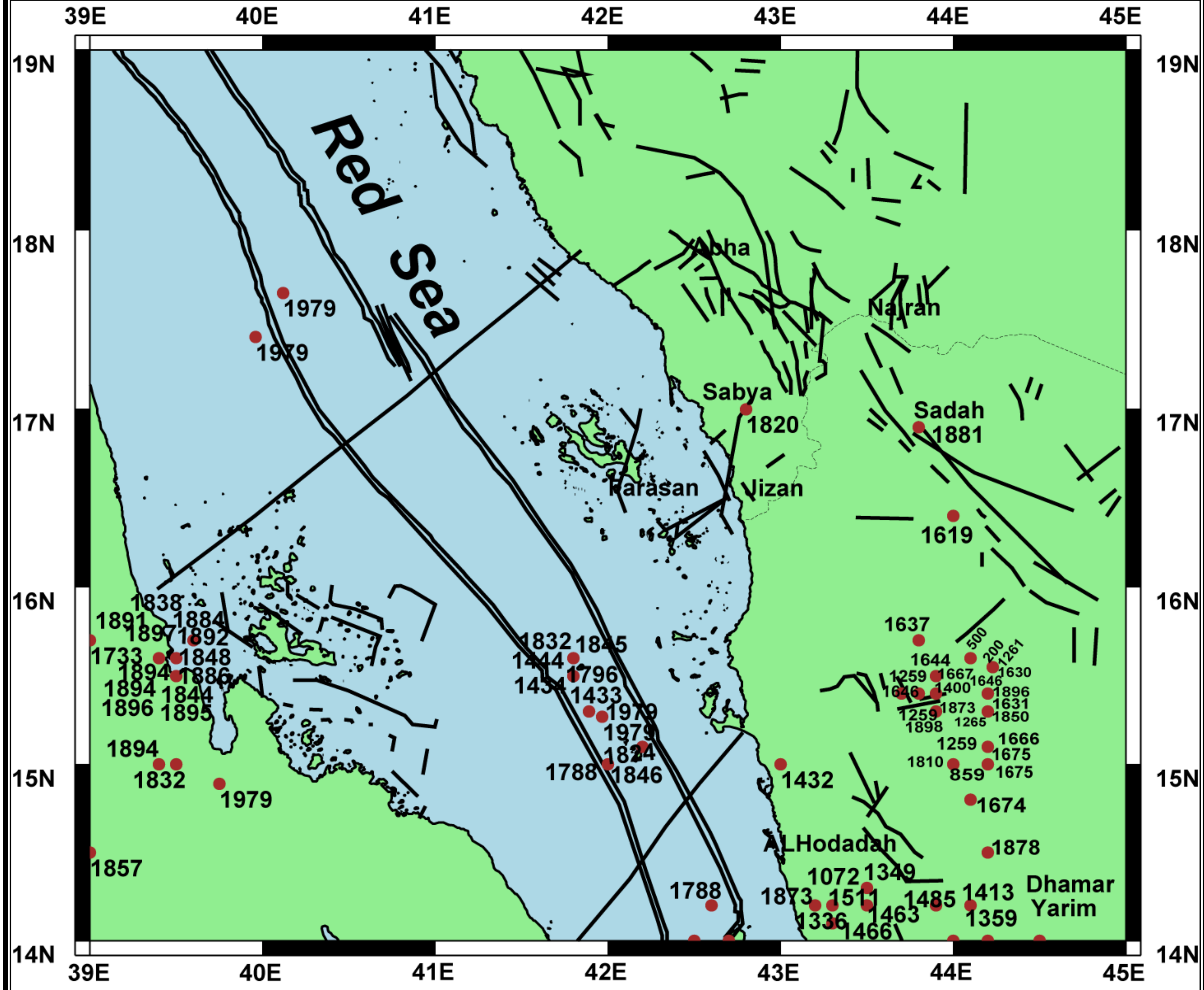
Tectonic questions worthy of investigation

- 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?

METHODS

- Teleseismic P- and S-wave travel time tomography;
- Teleseismic receiver functions for crustal structure;
- Teleseismic receiver functions for upper mantle
- Teleseismic shear-wave splitting;
- Teleseismic surface waveform modeling.
- Rayleigh Wave Tomography



39E
40E
41E
42E
43E
44E
45E
19N
18N
17N
16N
15N
14N
Red Sea
Abha
Najran
Sabya
1820
Sadah
1881
Farasan
Jizan
1619
1979
1979
1838
1891
1884
1897
1892
1733
1848
1894
1886
1894
1844
1896
1895
1894
1832
1979
1857
1832
1845
1444
1796
1454
1433
1979
1979
1824
1788
1846
1432
1637
1644
1630
1896
1631
1850
1666
1675
1675
1810
859
1674
1878
ALHodadah
1072
1349
1873
1511
1485
1413
1336
1463
1359
1466
1788
Dhamar
Yarim

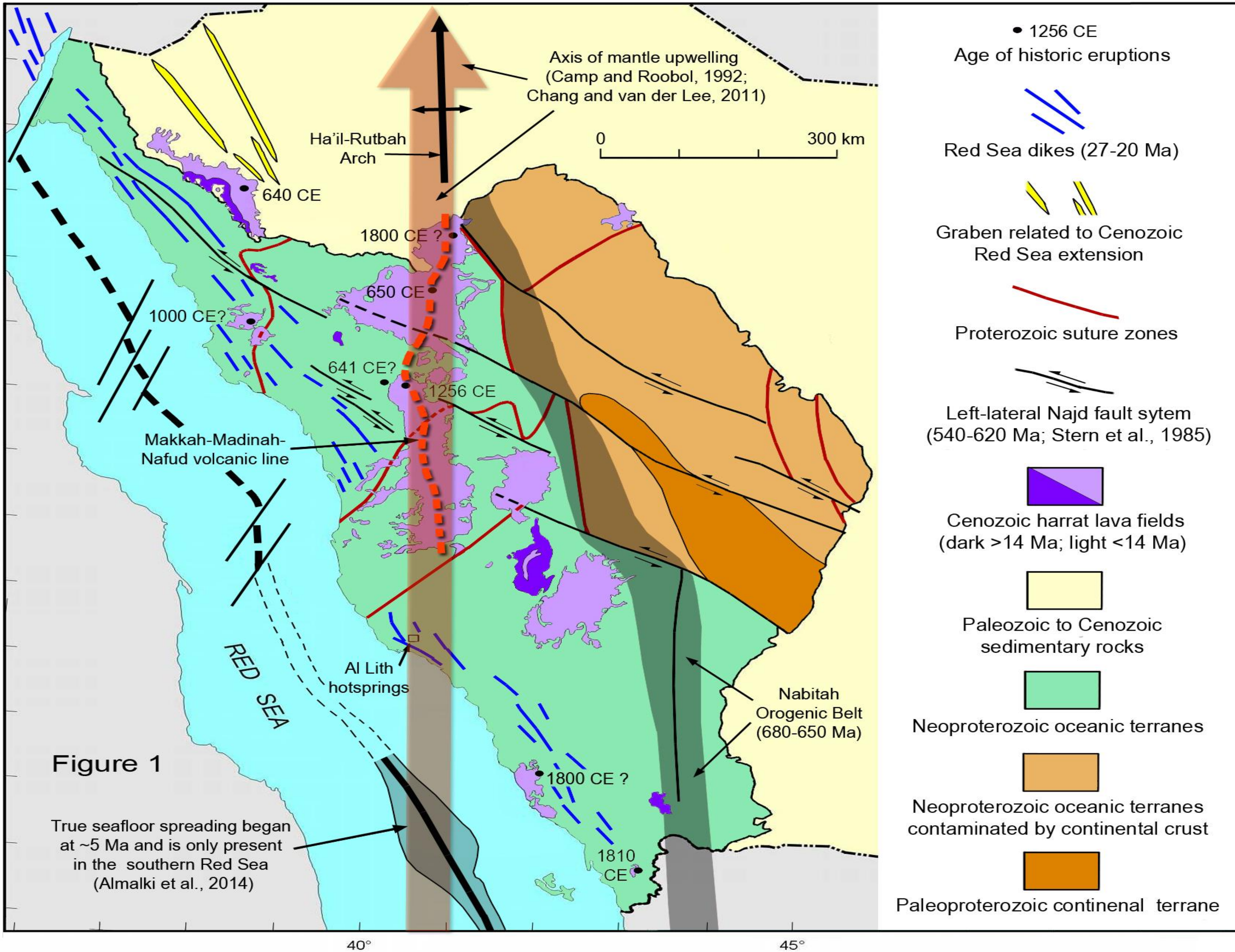

1256 CE
Age of historic eruptions
Red Sea dikes (27-20 Ma)
Graben related to Cenozoic Red Sea extension
Proterozoic suture zones
Left-lateral Najd fault sytem (540-620 Ma; Stern et al., 1985)
Cenozoic harrat lava fields (dark >14 Ma; light <14 Ma)
Paleozoic to Cenozoic sedimentary rocks
Neoproterozoic oceanic terranes
Neoproterozoic oceanic terranes contaminated by continental crust
Paleoproterozoic continenal terrane
Axis of mantle upwelling (Camp and Roobol, 1992; Chang and van der Lee, 2011)
Ha'il-Rutbah Arch
0
300 km
640 CE
1800 CE ?
650 CE
1000 CE?
641 CE?
1256 CE
Makkah-Madinah-Nafud volcanic line
Al Lith hotsprings
RED SEA
Nabitah Orogenic Belt (680-650 Ma)
1800 CE ?
1810 CE
True seafloor spreading began at ~5 Ma and is only present in the southern Red Sea (Almalki et al., 2014)
25°
20°
40°
45°

Figure 1

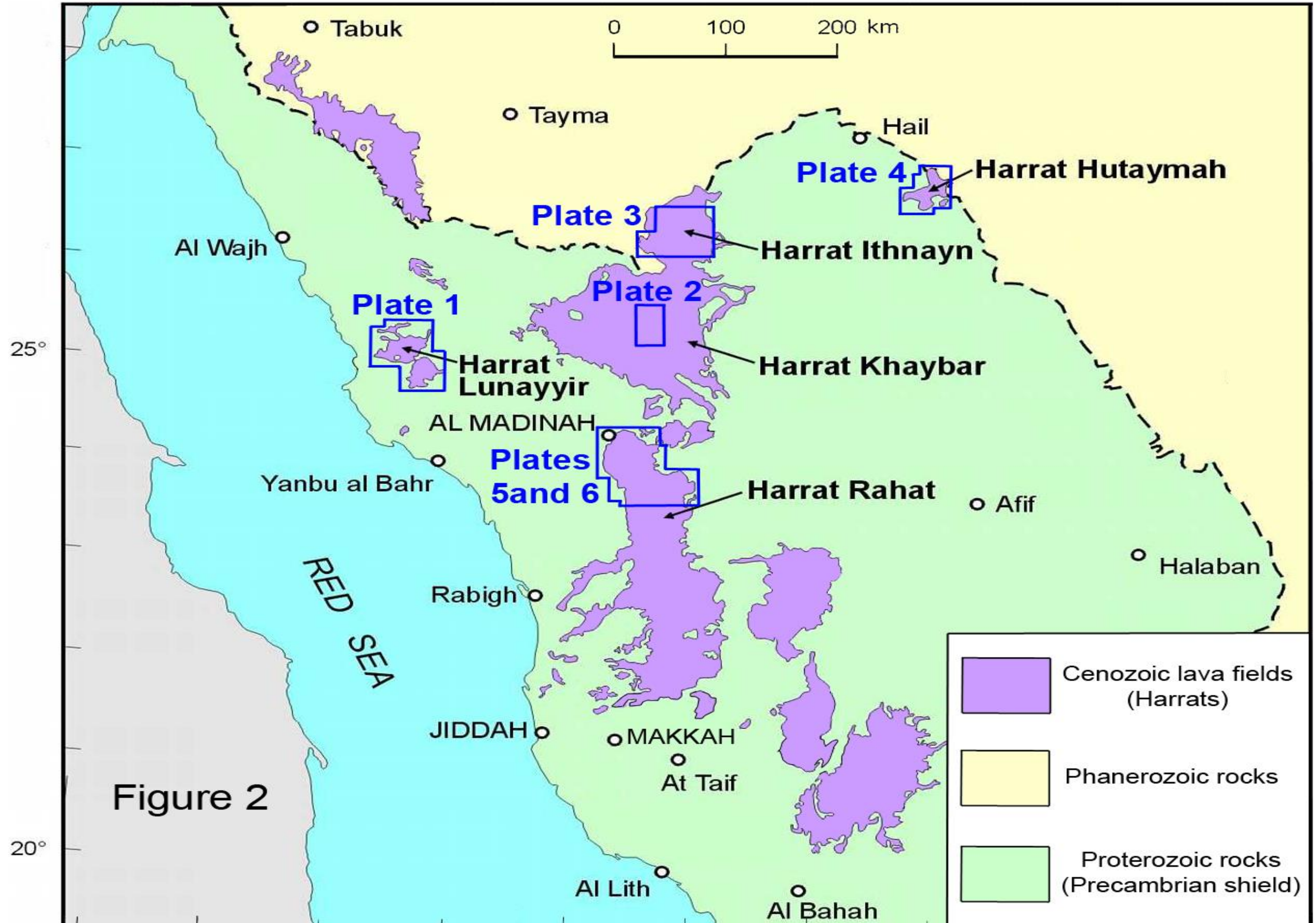
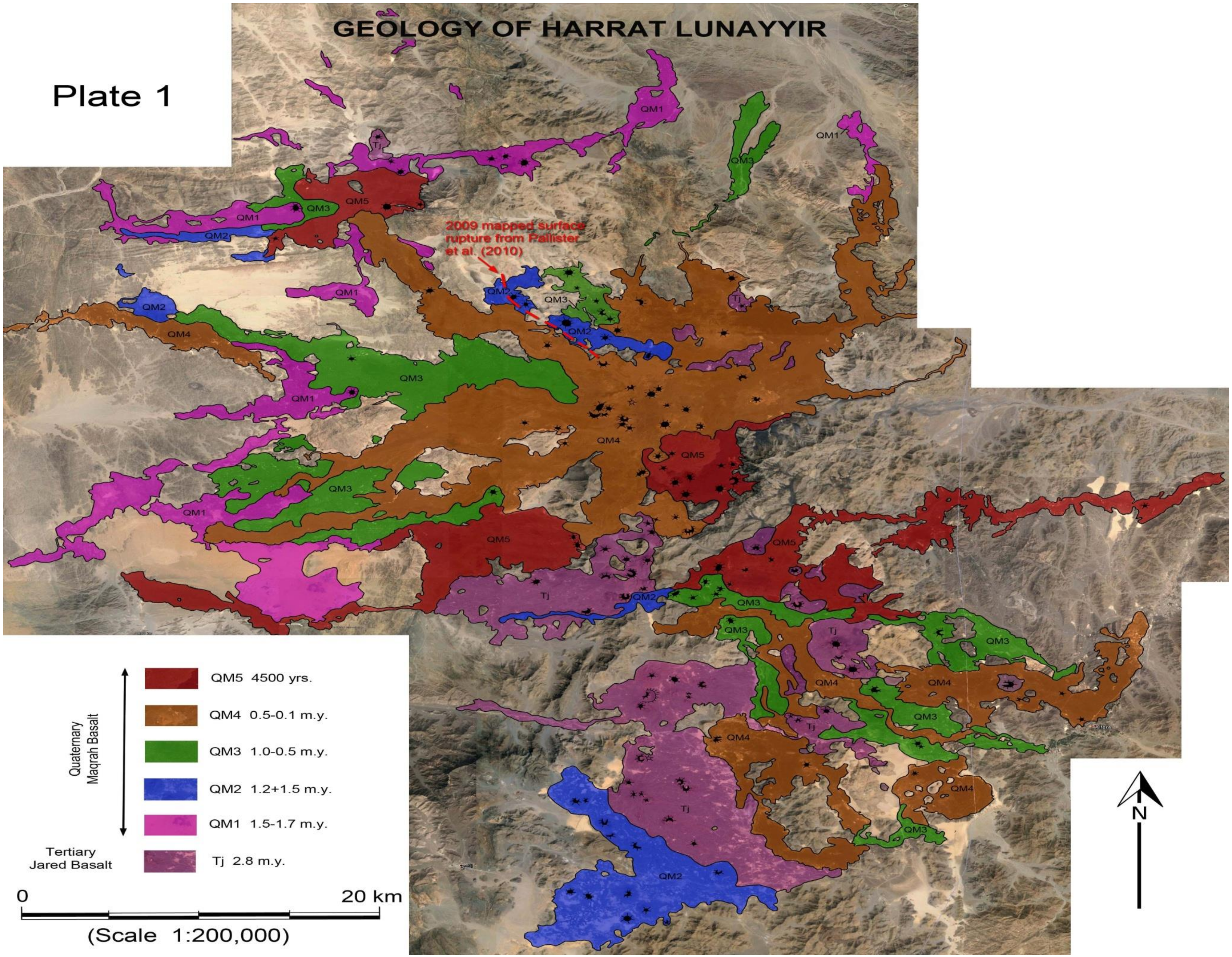
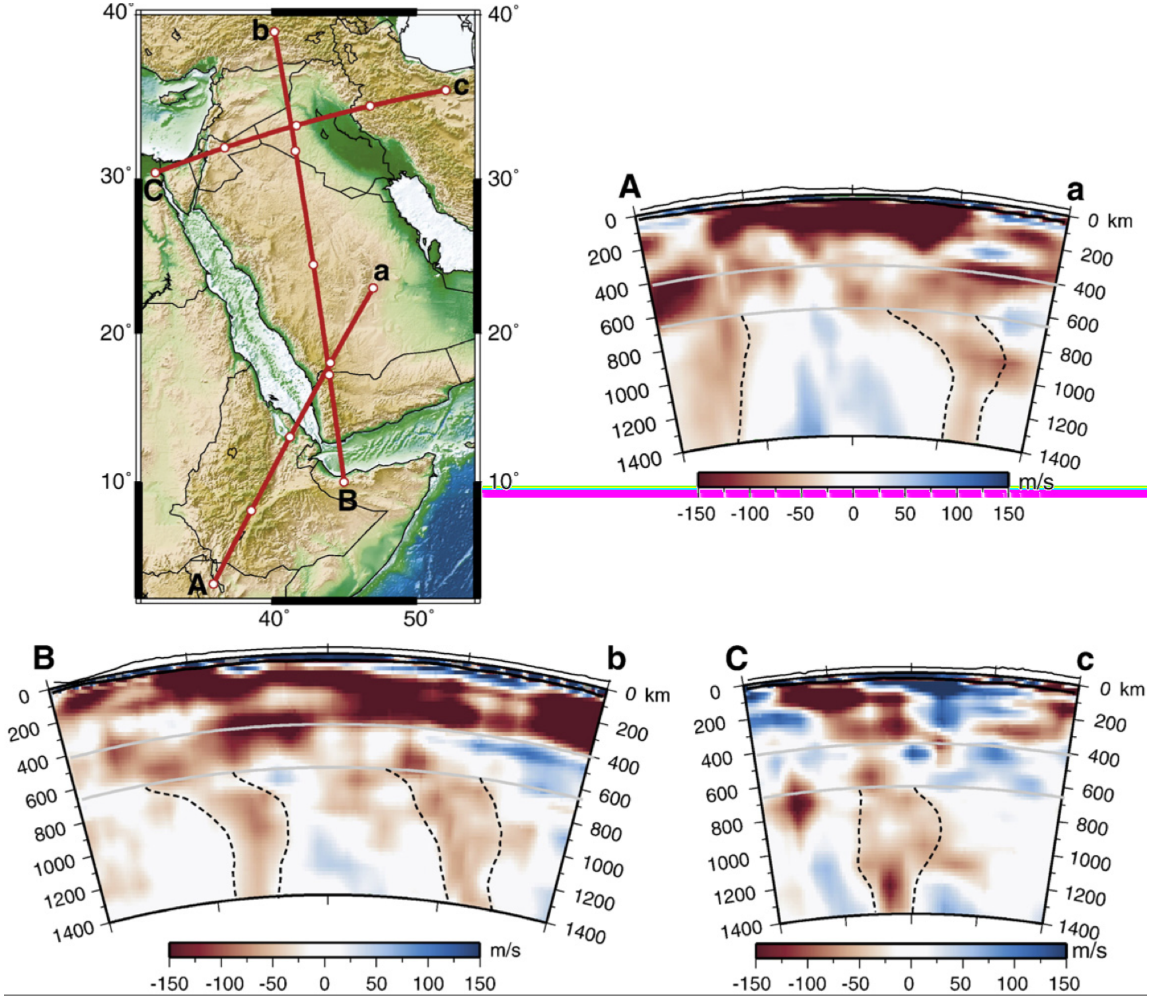

Tabuk
0
100
200 km
Tayma
Hail
Plate 4
Harrat Hutaymah
Plate 3
Harrat Ithnayn
Al Wajh
Plate 2
Plate 1
25°
Harrat
Lunayyir
Harrat Khaybar
AL MADINAH
Plates
5and 6
Harrat Rahat
Yanbu al Bahr
Afif
Halaban
RED SEA
Rabigh
Cenozoic lava fields
(Harrats)
JIDDAH
MAKKAH
At Taif
Phanerozoic rocks
20°
Al Lith
Al Bahah
Proterozoic rocks
(Precambrian shield)
40°
45°
Figure 2

Plate 1


GEOLOGY OF HARRAT LUNAYYIR
2009 mapped surface rupture from Pallister et al. (2010)
QM1
QM2
QM3
QM4
QM5
Tj
Quaternary Maqrah Basalt
QM5 4500 yrs.
QM4 0.5-0.1 m.y.
QM3 1.0-0.5 m.y.
QM2 1.2+1.5 m.y.
QM1 1.5-1.7 m.y.
Tertiary Jared Basalt
Tj 2.8 m.y.
0
20 km
(Scale 1:200,000)
N

Tomographic cross sections

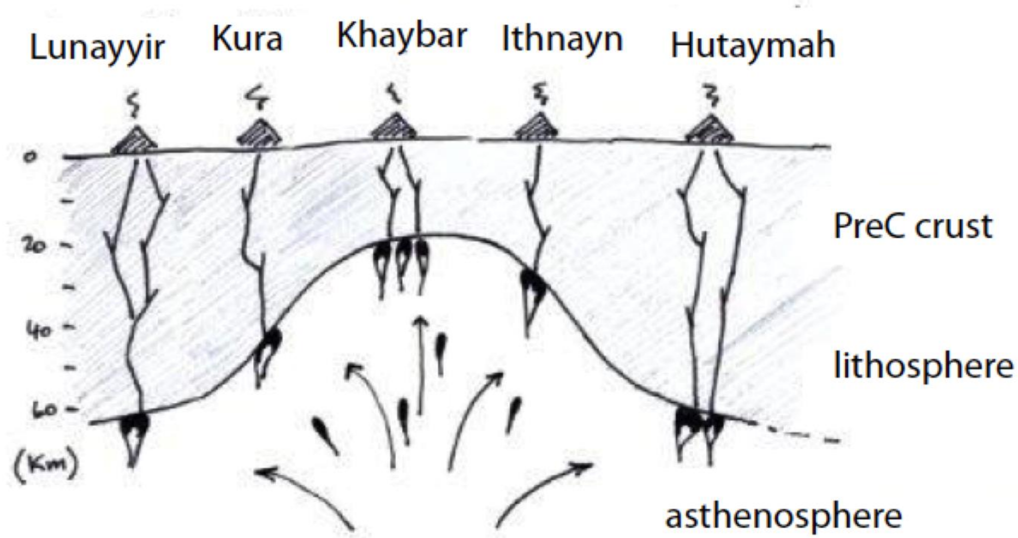
- deep thermal anomalies
- plumes or conduits?
- active or passive?



Chang and van der Lee, 2011

Lithosphere-Asthenosphere boundary

- topography controls melting; increasing with time??
- topography guides upper mantle flow



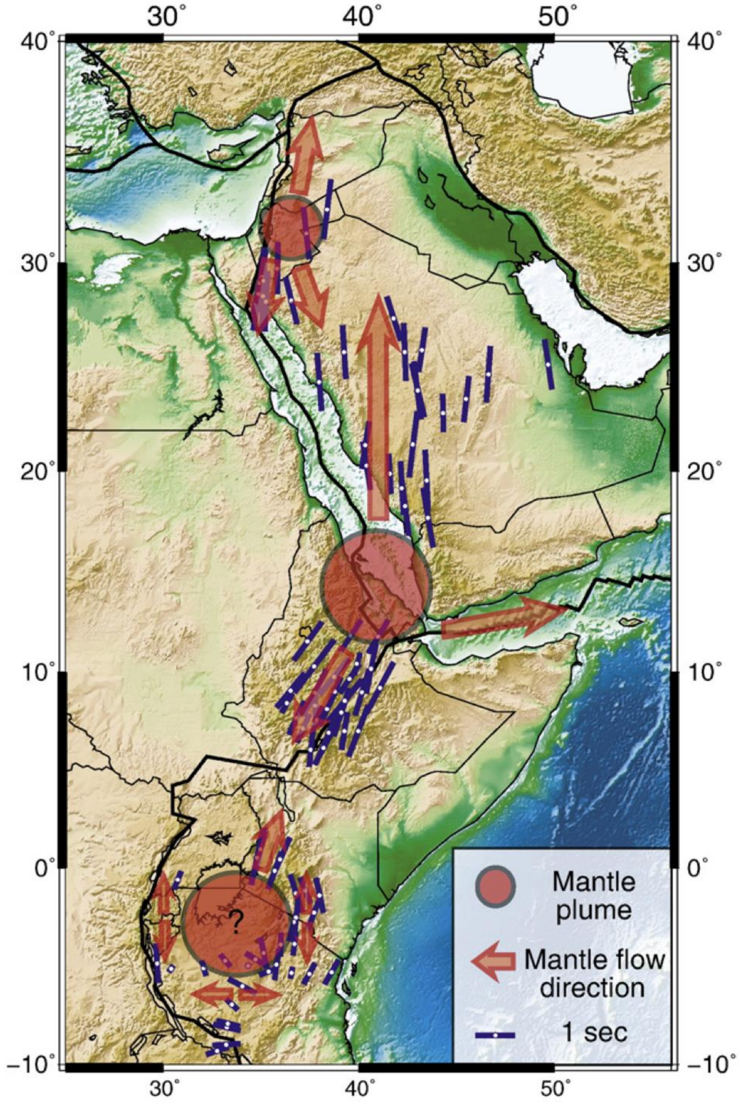
What might this mean?

• upper mantle anisotropy – flow direction?

• how many mantle plumes?

• Afar and plate breakup

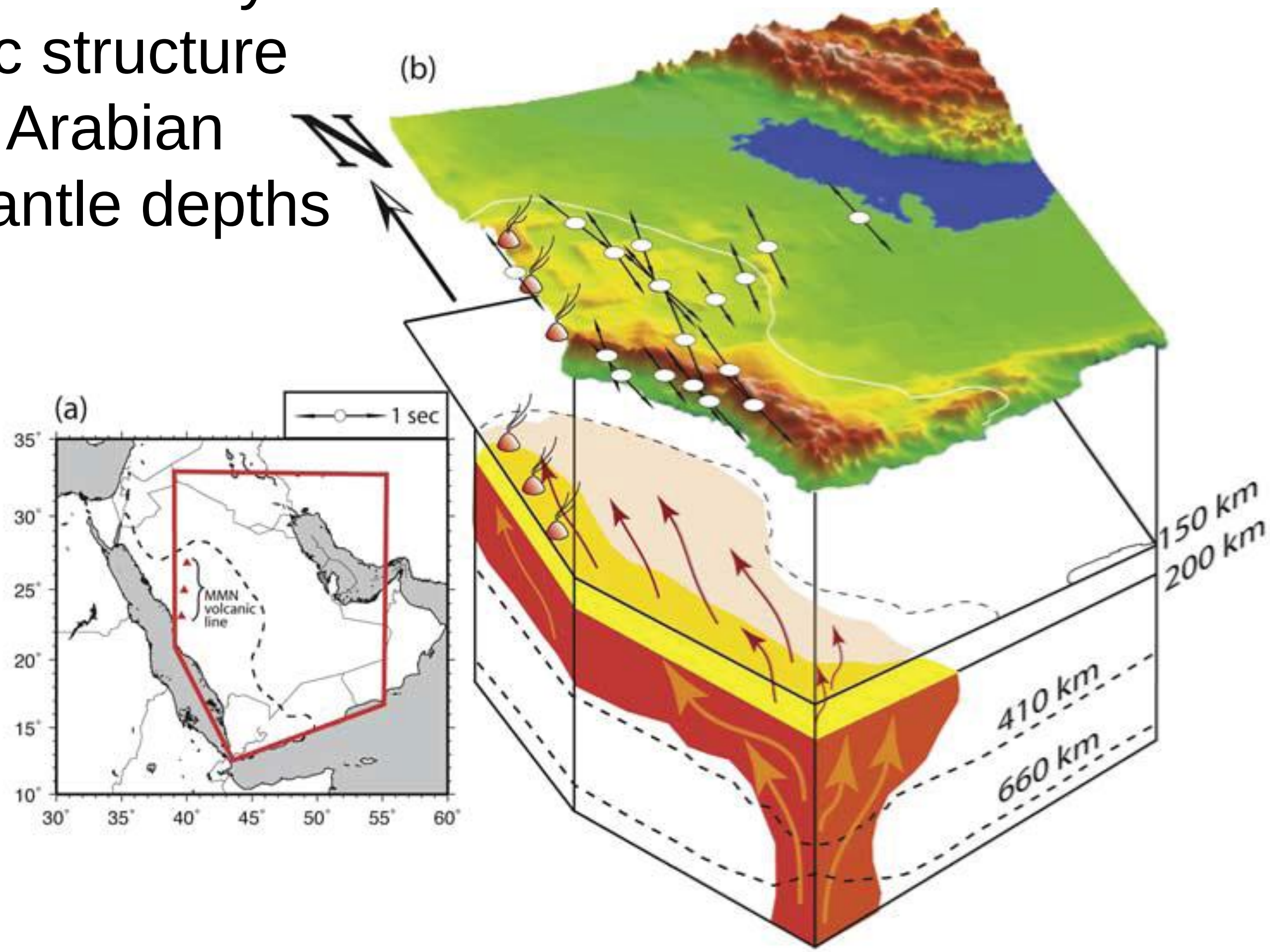
• N-S “channel” beneath western Arabian shield – flexure or thermal erosion?



Relationship between Afar Hot Spot upwelling, Rea Sea and Arabia

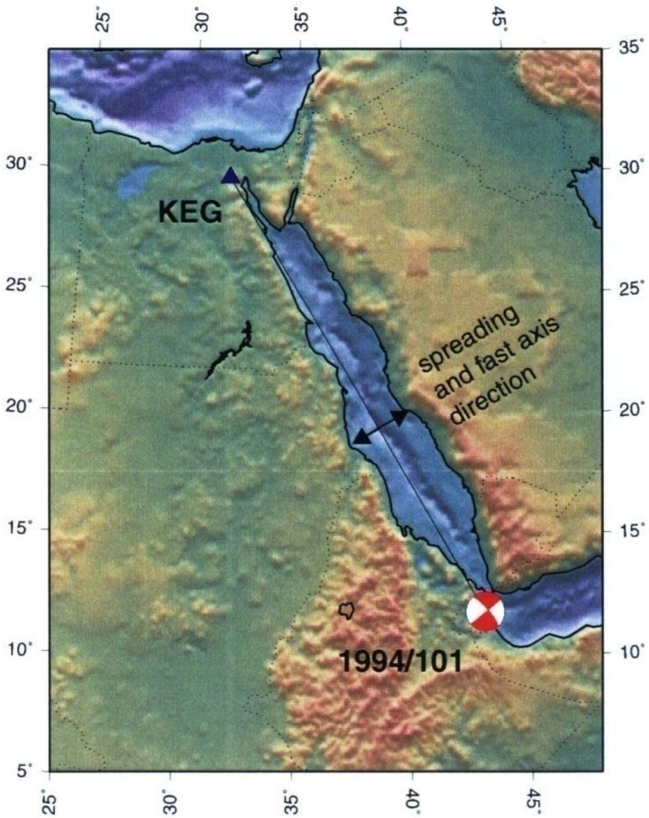
Upwelling penetrates transition zone beneath Afar, is channeled by southern Red Sea lithospheric structure and spreads across Arabian Shield at shallow mantle depths

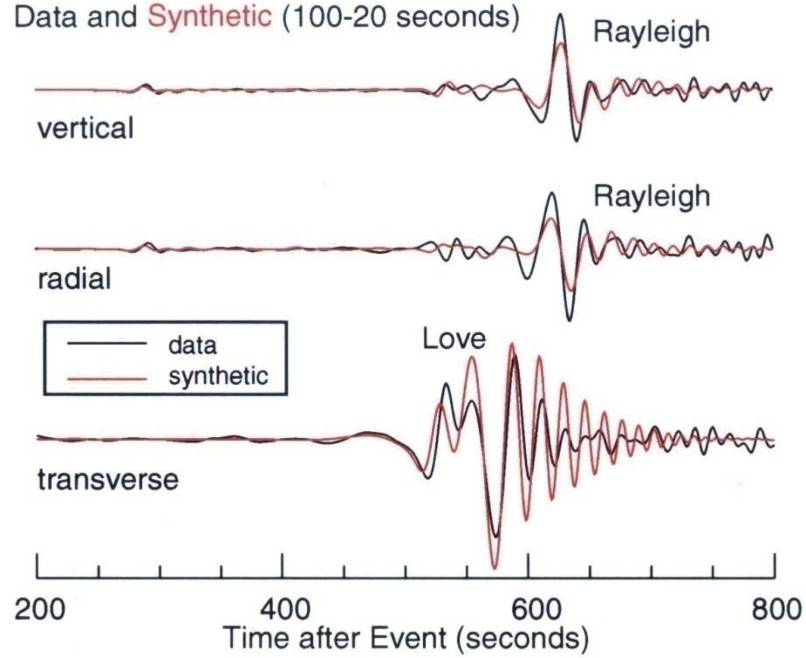
Northerly flow is consistent with shear wave splitting

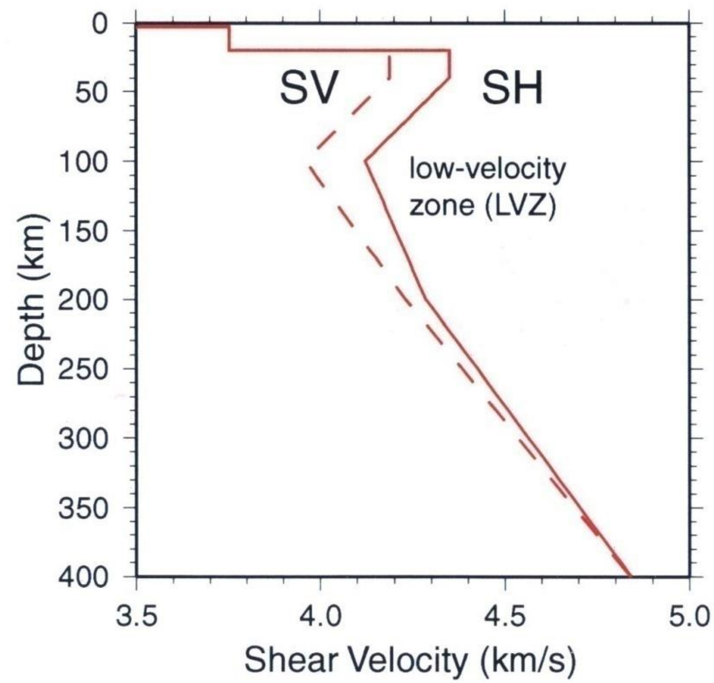


Red Sea Paths Require Anisotropy

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.

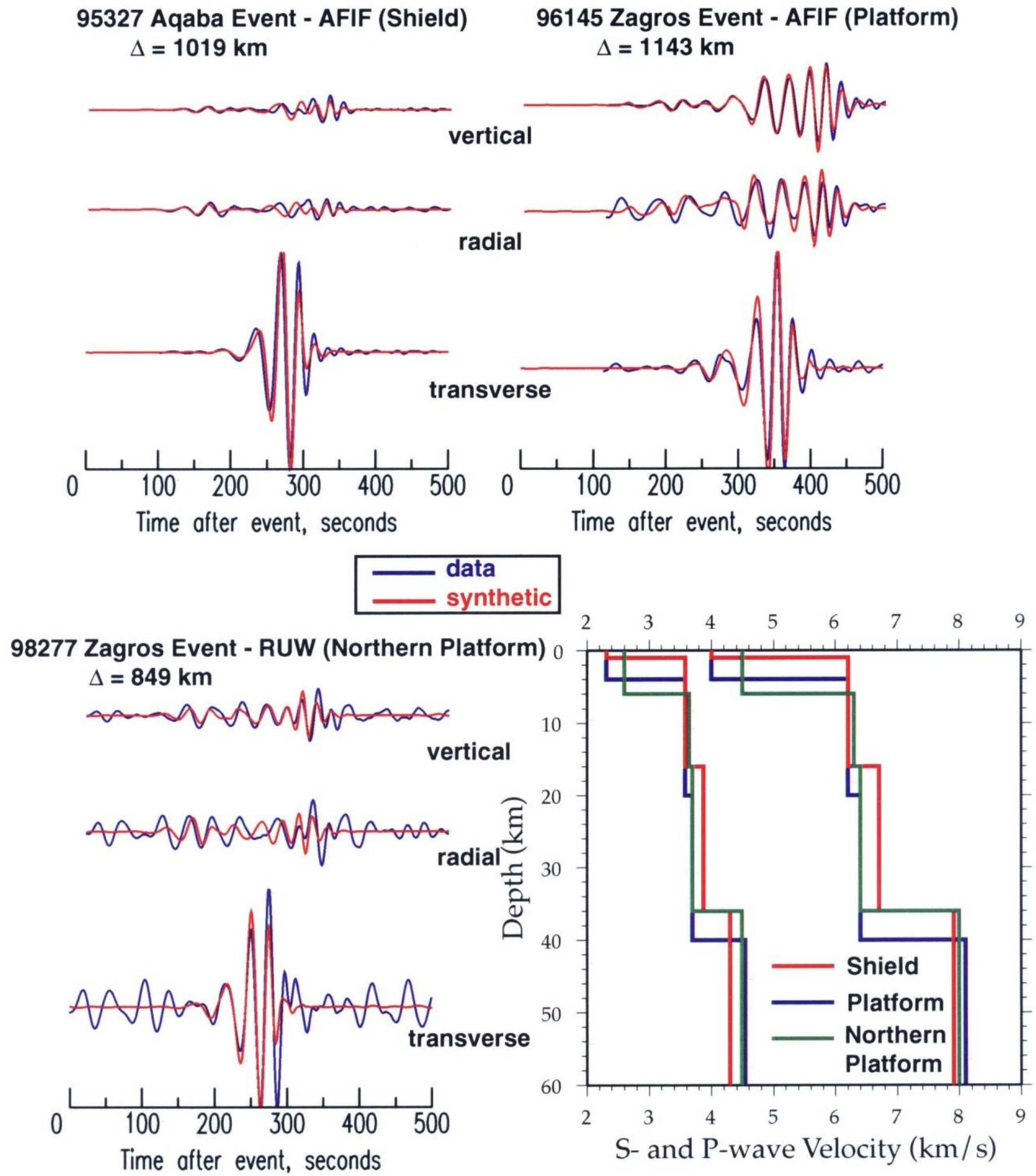


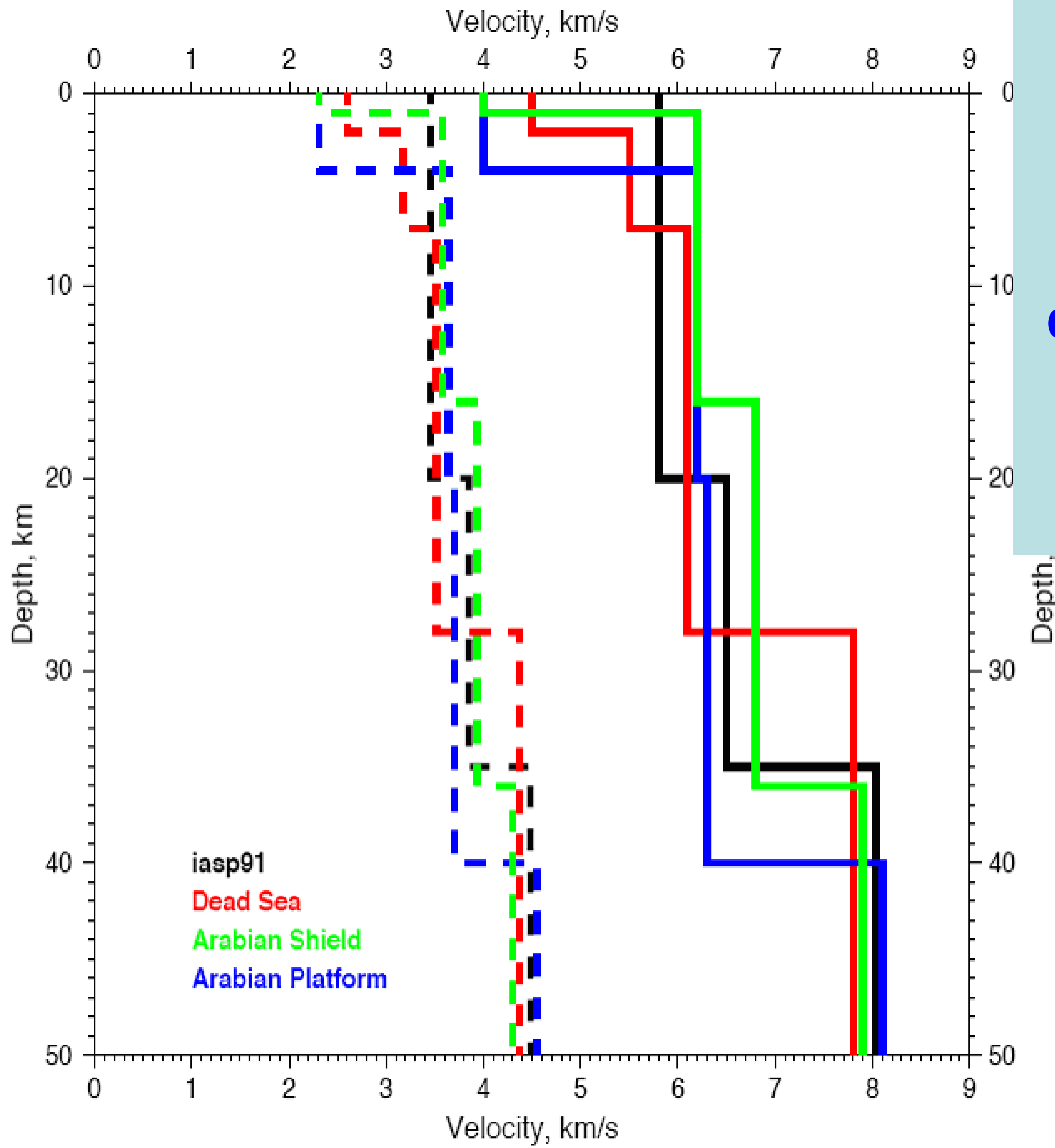




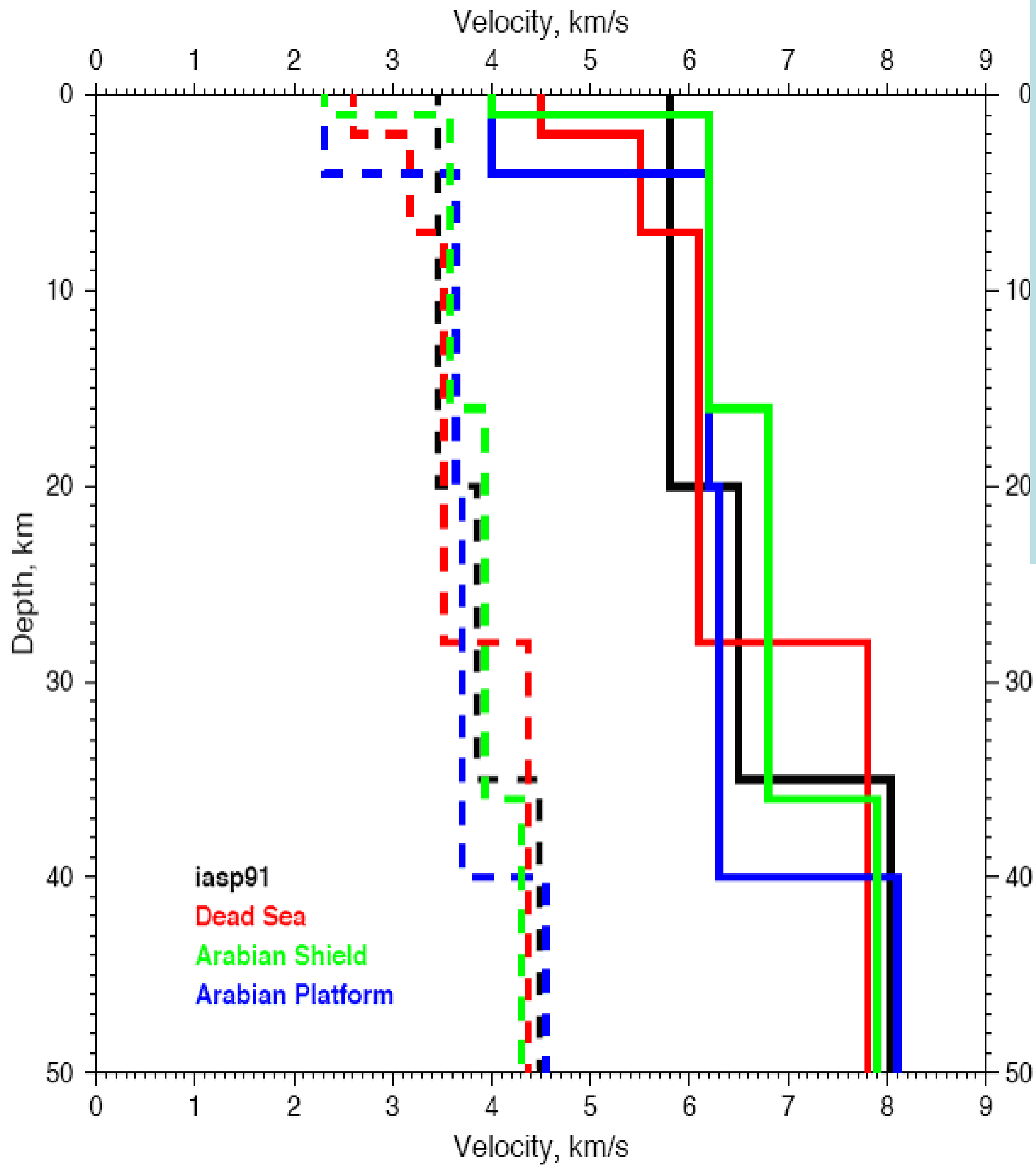
Courtesy of Sara Russell, UC Santa Cruz

Waveform Modeling for Structure of the Arabian Peninsula





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



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	4.50	2.60
2	5	5.50	3.18
7	10	6.10	3.52
17	11	6.20	3.60
28	∞	7.80	4.37

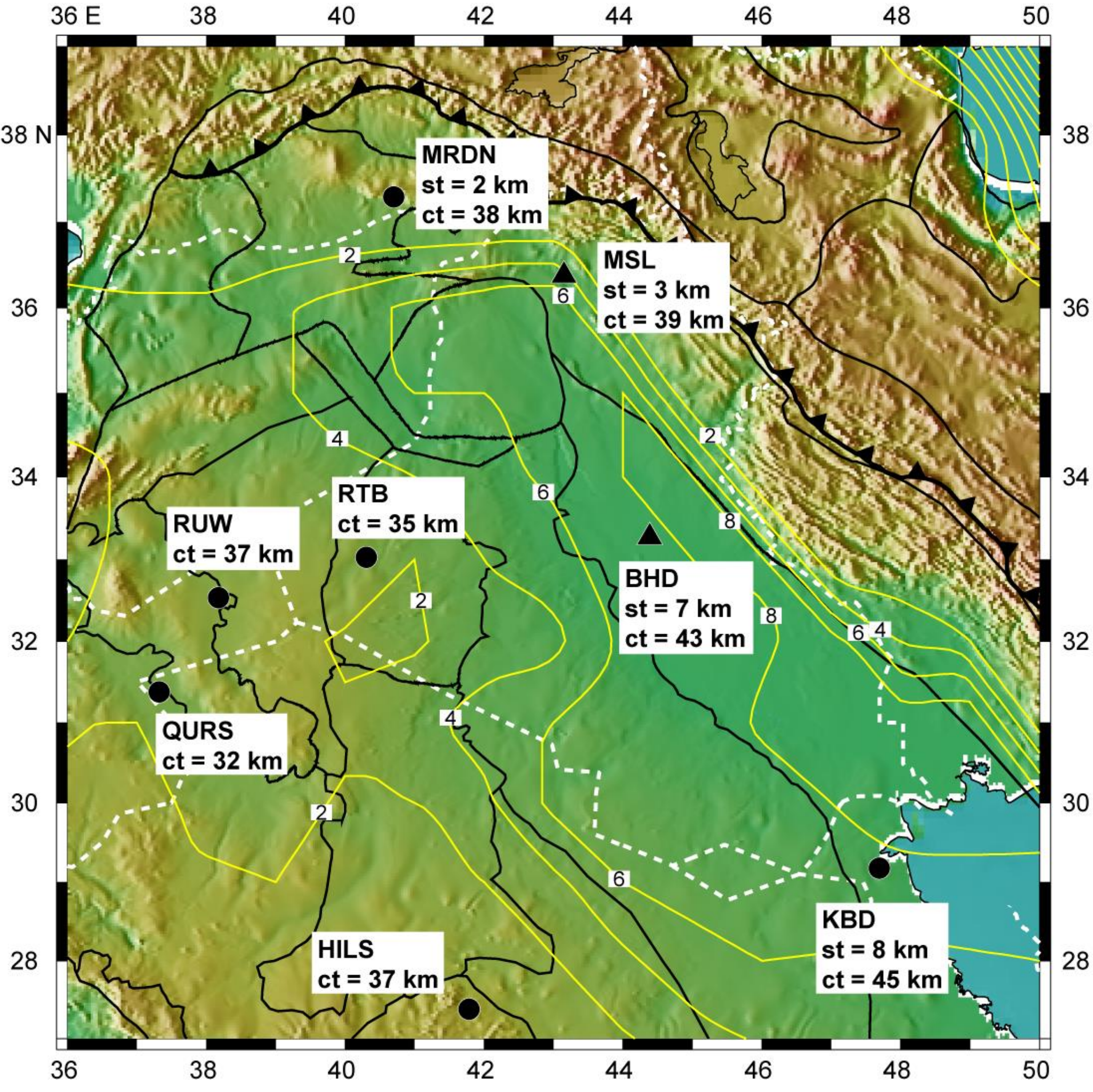
Seismic Velocity Model for the Arabian Shield Region

Depth (km)	Thickness (km)	V_P (km/s)	V_S (km/s)
0	1	4.0	2.31
1	15	6.20	3.58
16	20	6.80	3.93
36	∞	7.90	4.30

Seismic Velocity Model for the Arabian Platform Region

Depth (Km)	Thickness (km)	V_P (km/s)	V_S (km/s)
0	4	4.00	2.31
4	16	6.20	3.64
20	20	6.4	3.70
40	∞	8.10	4.55

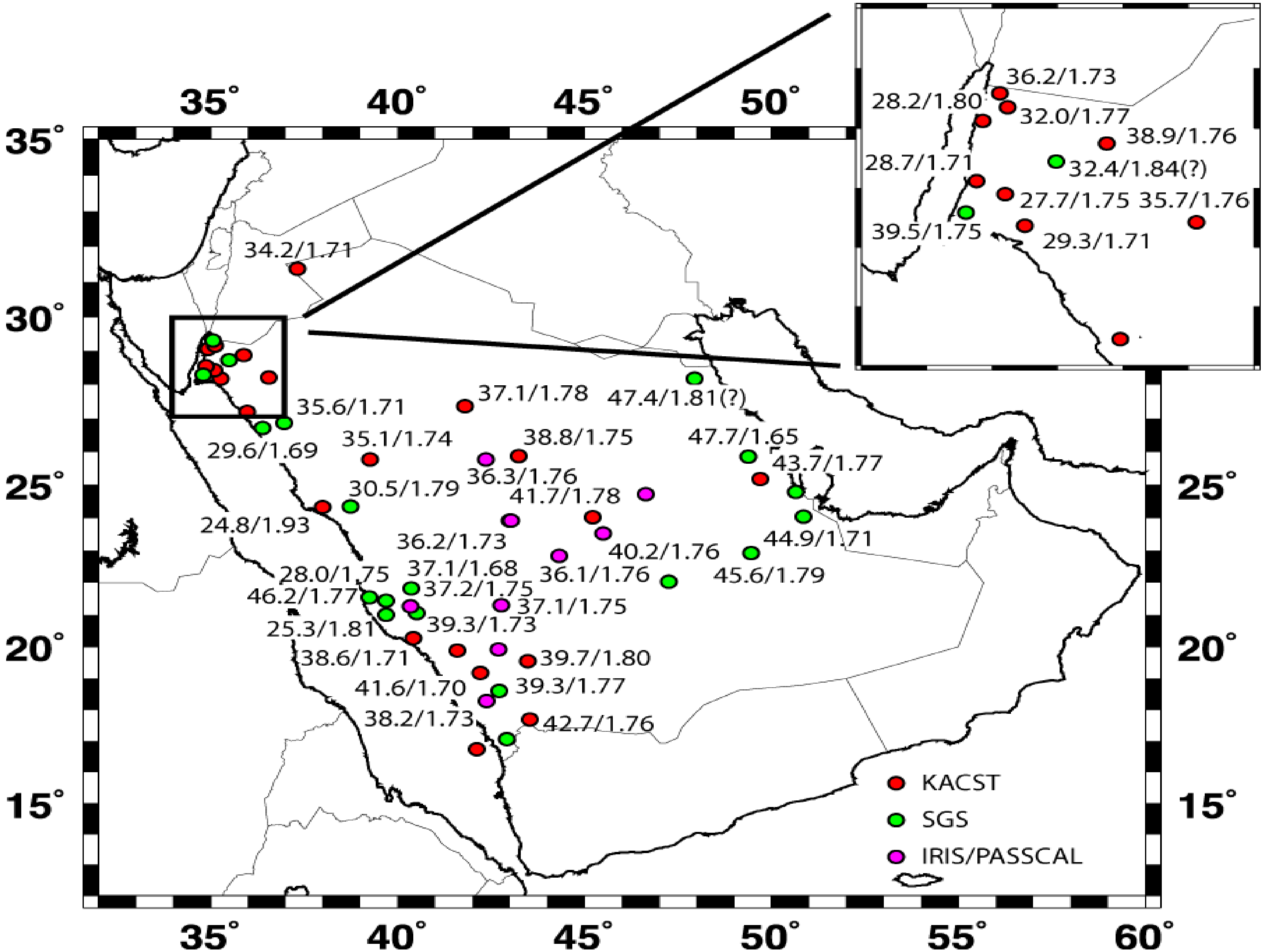
Crustal Structure in the Northern Arabian Platform



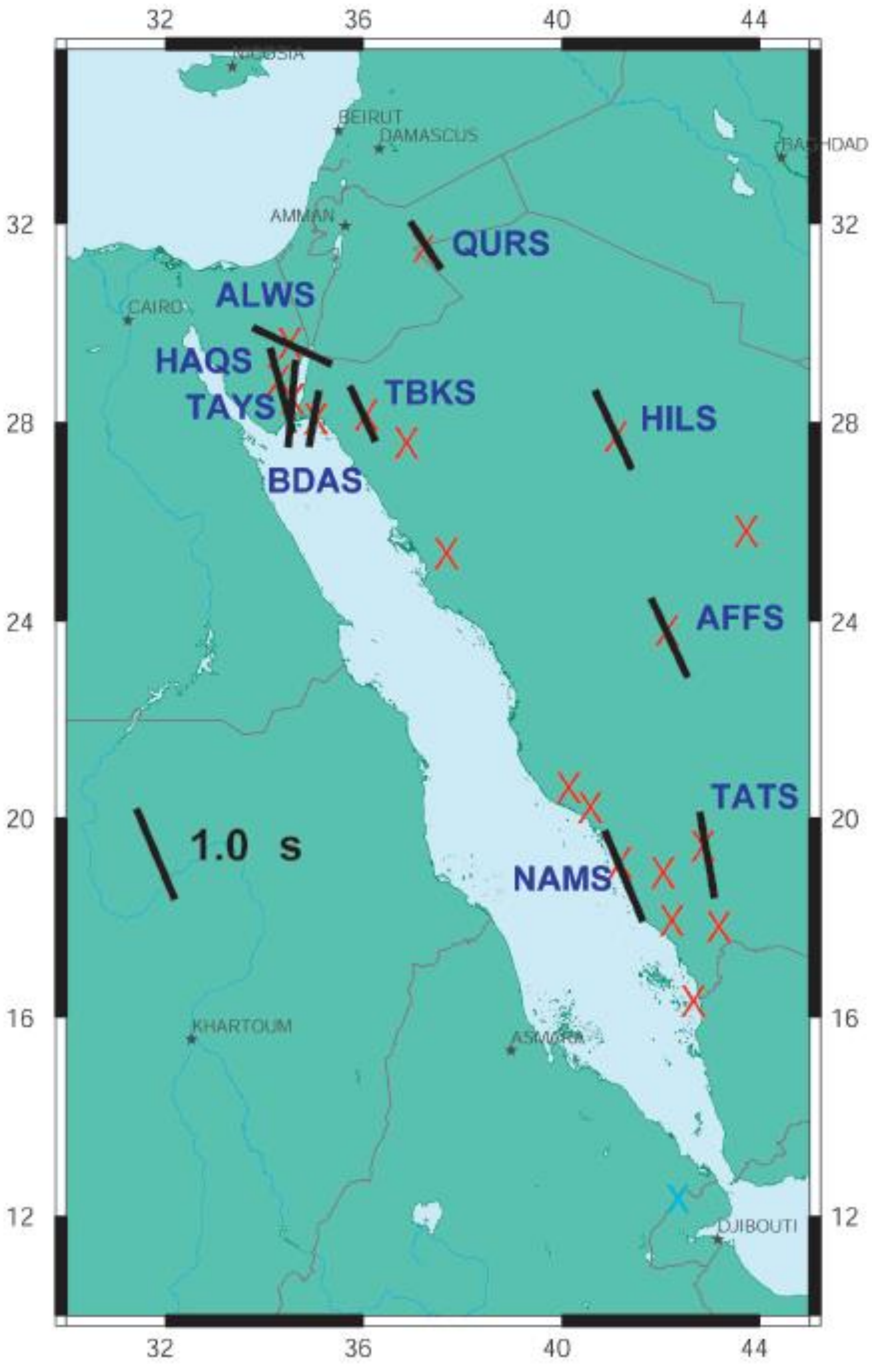
st = sediment thickness
ct = crustal thickness

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.



35°
40°
45°
50°
55°
60°
30°
25°
20°
15°
34.2/1.71
35.6/1.71
29.6/1.69
37.1/1.78
47.4/1.81(?)
35.1/1.74
38.8/1.75
47.7/1.65
43.7/1.77
36.3/1.76
30.5/1.79
41.7/1.78
24.8/1.93
44.9/1.71
36.2/1.73
40.2/1.76
28.0/1.75
37.1/1.68
36.1/1.76
45.6/1.79
46.2/1.77
37.2/1.75
37.1/1.75
25.3/1.81
39.3/1.73
38.6/1.71
39.7/1.80
41.6/1.70
39.3/1.77
38.2/1.73
42.7/1.76
36.2/1.73
28.2/1.80
32.0/1.77
38.9/1.76
28.7/1.71
32.4/1.84(?)
27.7/1.75
35.7/1.76
39.5/1.75
29.3/1.71
KACST
SGS
IRIS/PASSCAL



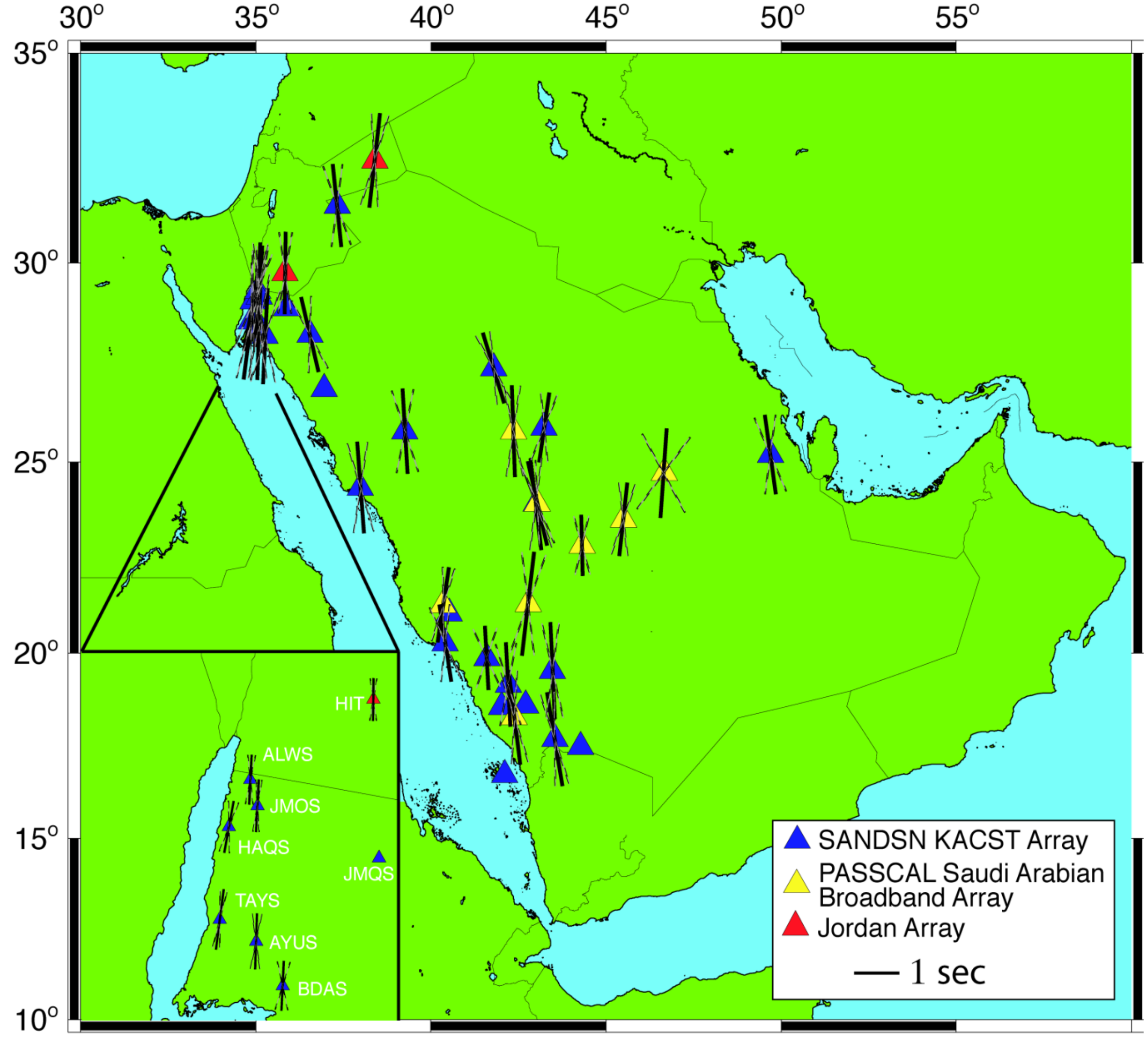
SKS splitting parameters for several KACST stations. Red crosses indicate station locations with too few SKS splitting parameters to determine a meaningful average. The direction of the black bar indicates the average direction of fast polarization and its length is scaled by the delay time between the 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.

Shear-Wave Splitting Results

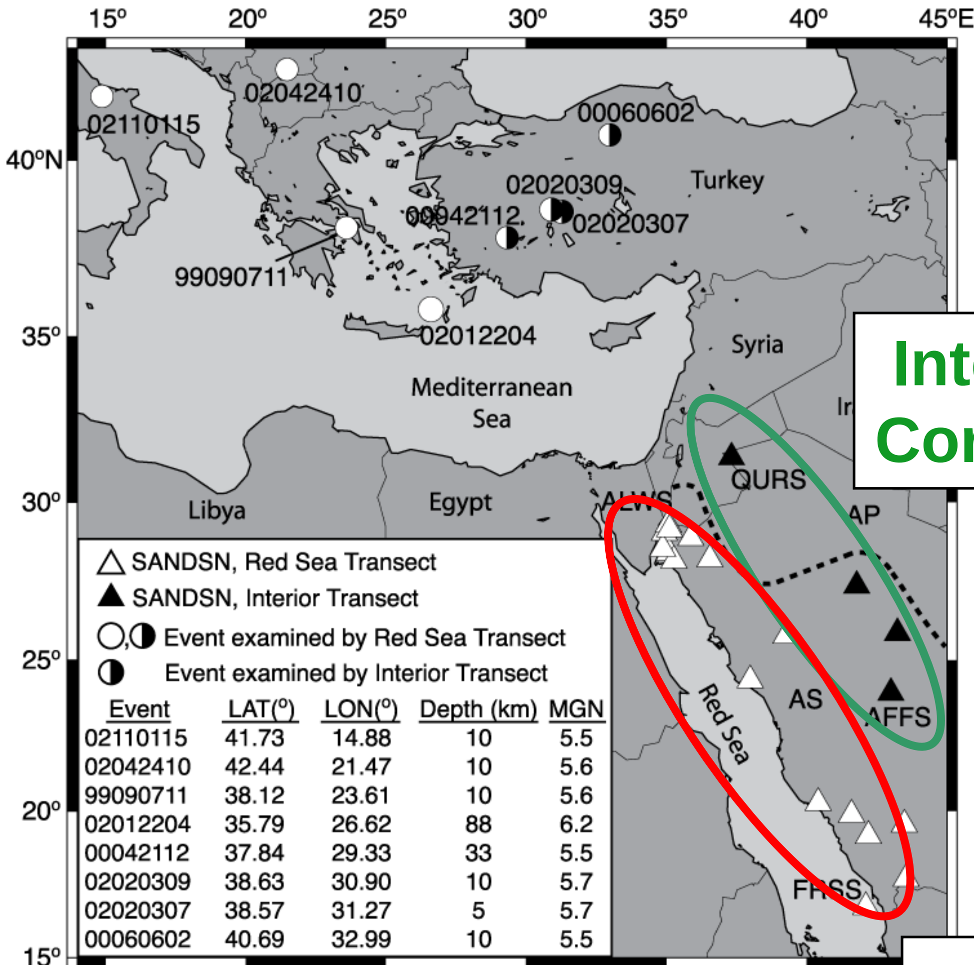
Average splitting is remarkably uniform

Generally north-south fast direction, ~ 1.4 sec

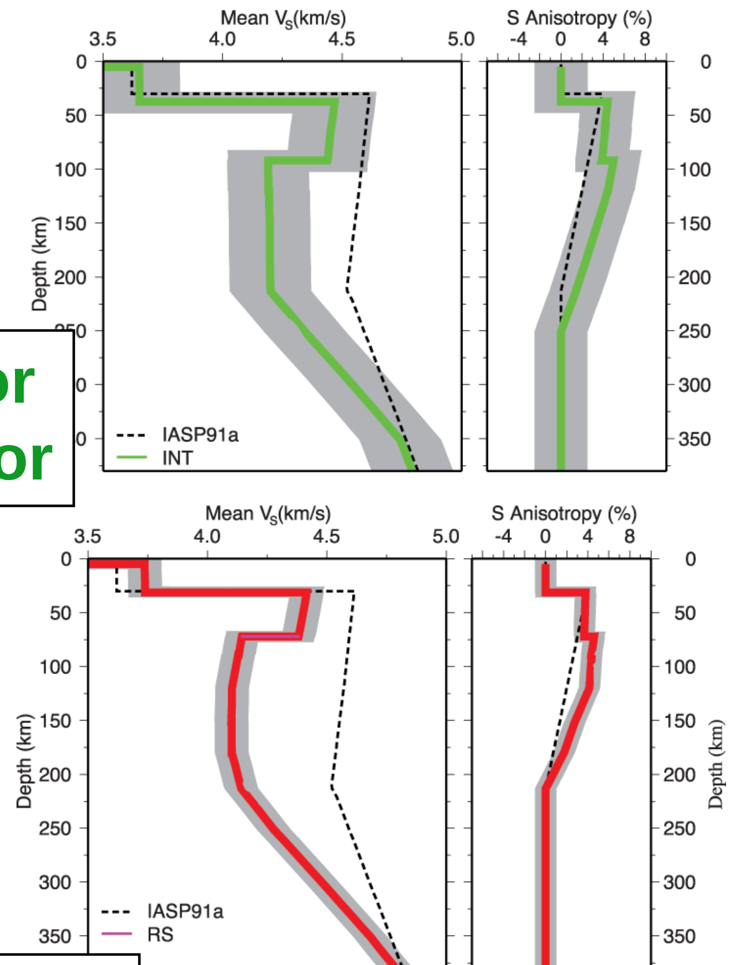
Consistent with Wolfe et al. (1997) for PASSCAL array



1D Anisotropic Models from Rayleigh and Love Phase Velocities



Event	LAT(°)	LON(°)	Depth (km)	MGN
02110115	41.73	14.88	10	5.5
02042410	42.44	21.47	10	5.6
99090711	38.12	23.61	10	5.6
02012204	35.79	26.62	88	6.2
00042112	37.84	29.33	33	5.5
02020309	38.63	30.90	10	5.7
02020307	38.57	31.27	5	5.7
00060602	40.69	32.99	10	5.5



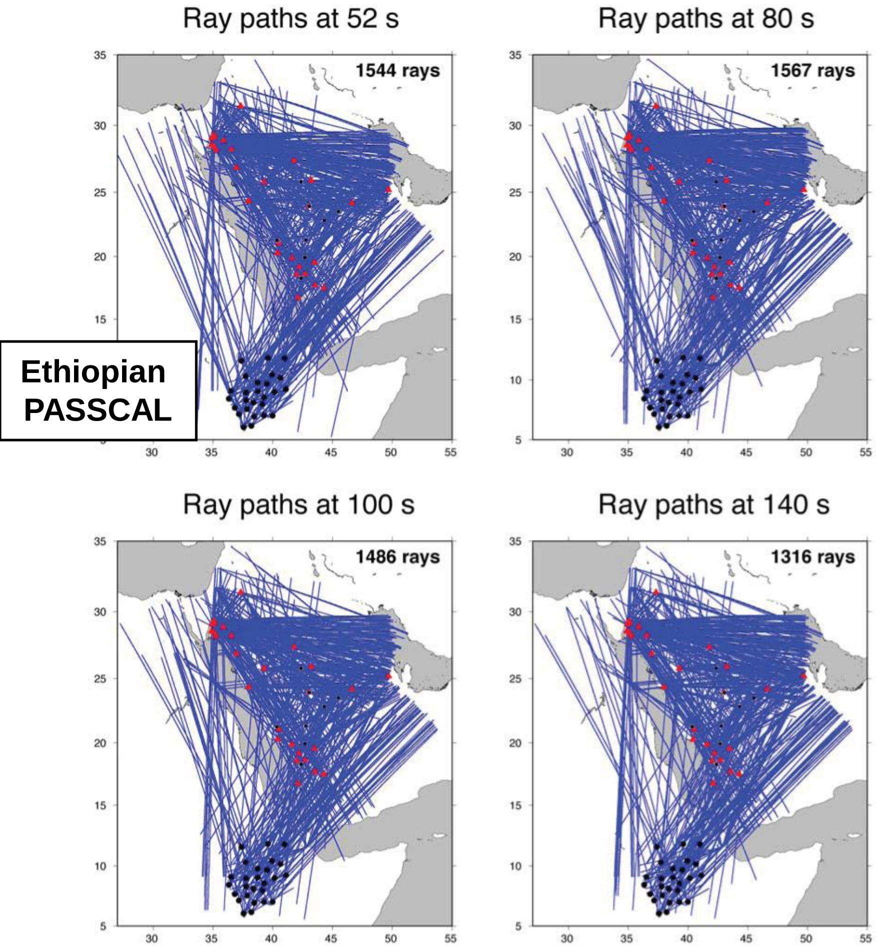
Interior Corridor

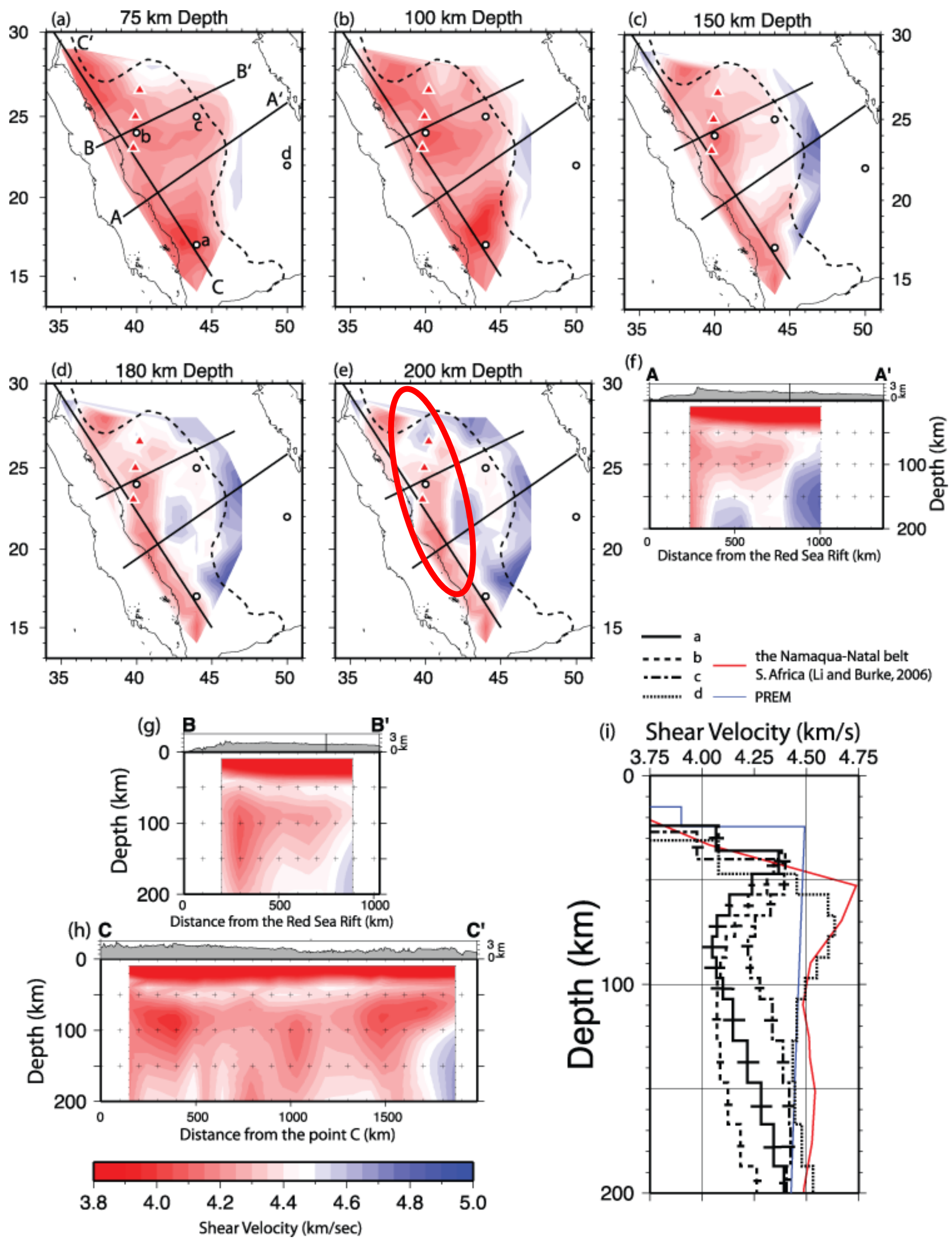
Red Sea Corridor

Note low velocities!

Rayleigh Wave Tomography

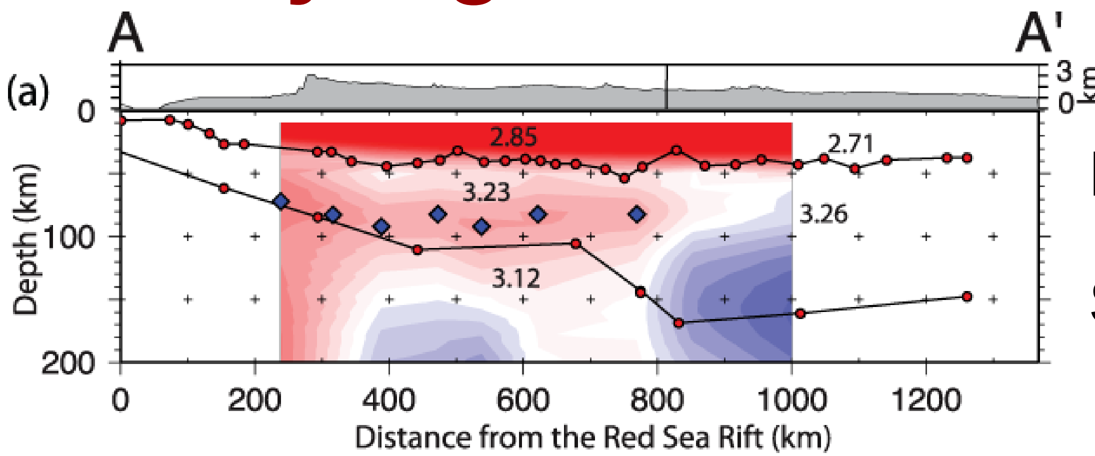
Modified array approach of Lawrence et al. (2008)





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

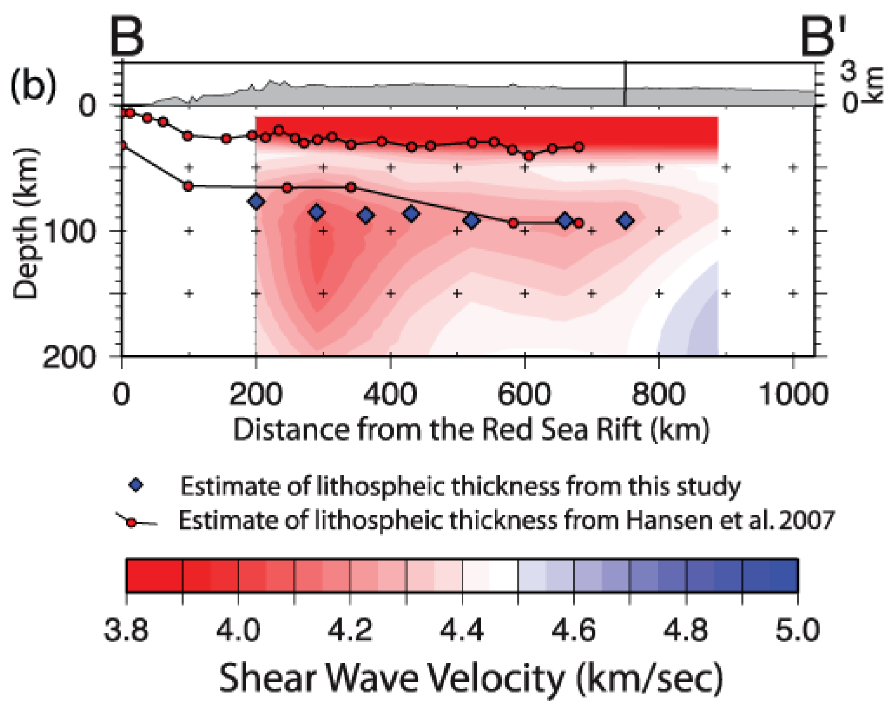
Southern



Moho Depth

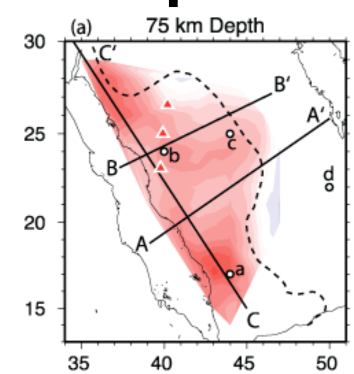
SRF LAB Depth

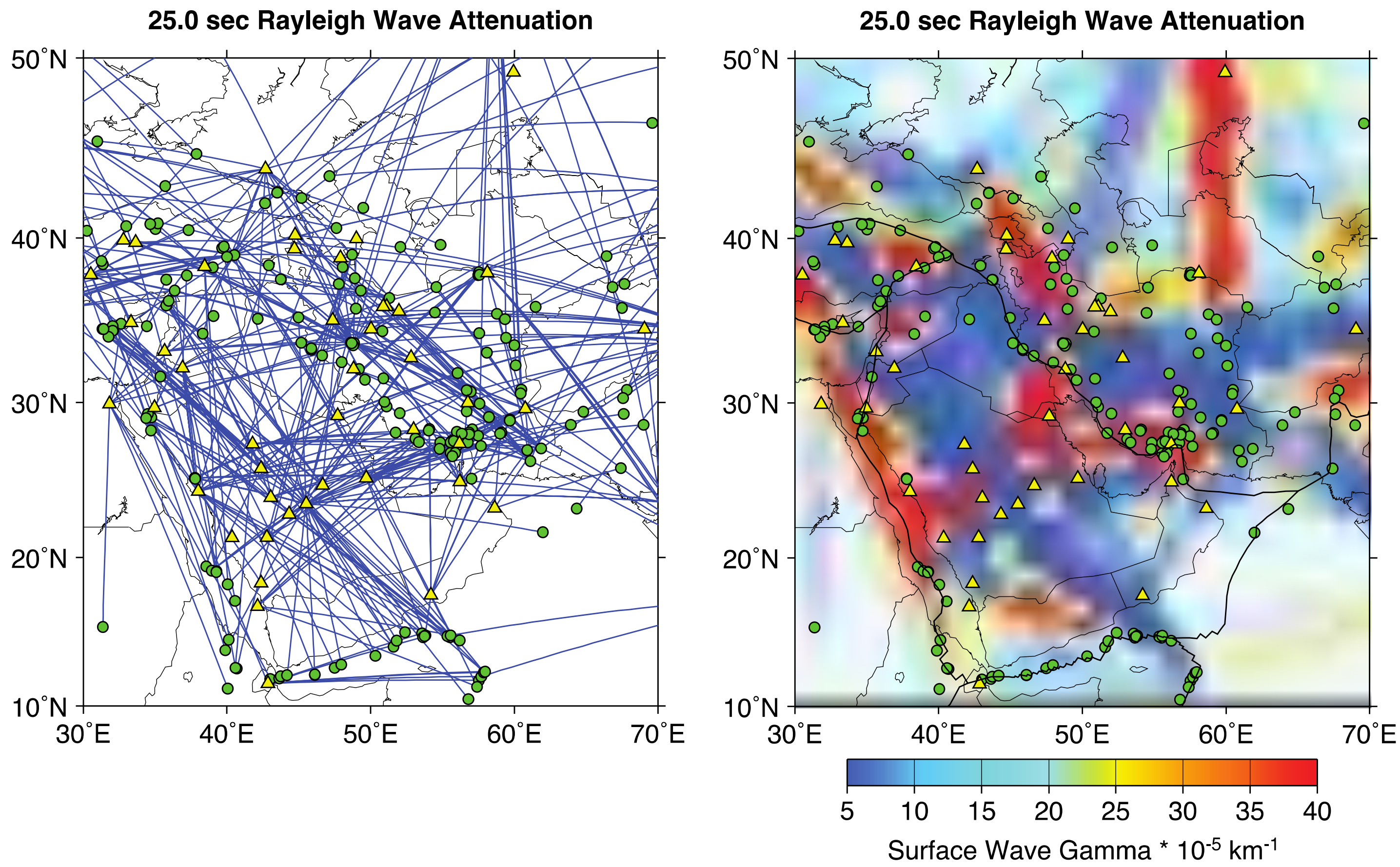
Northern



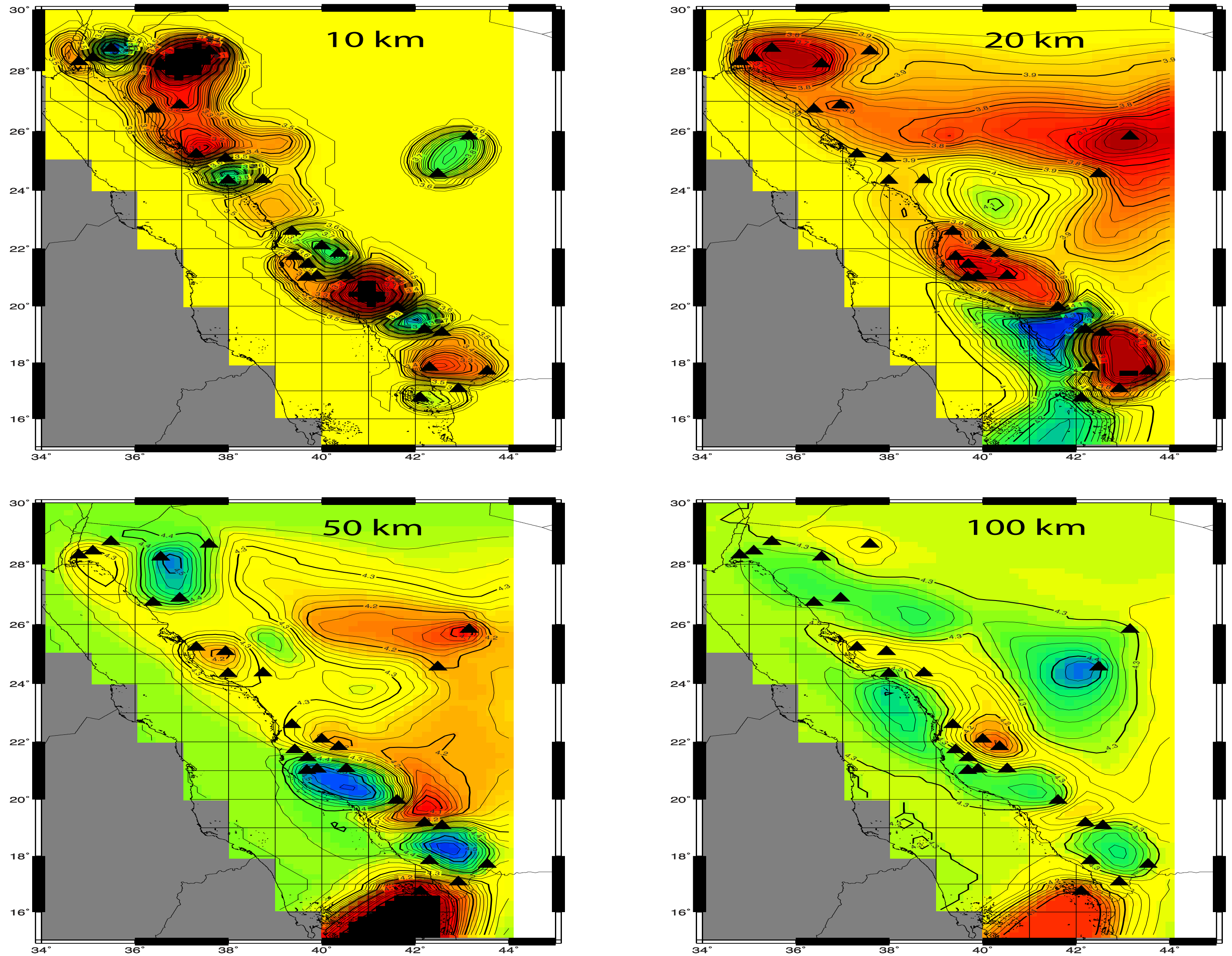
Moho Depth

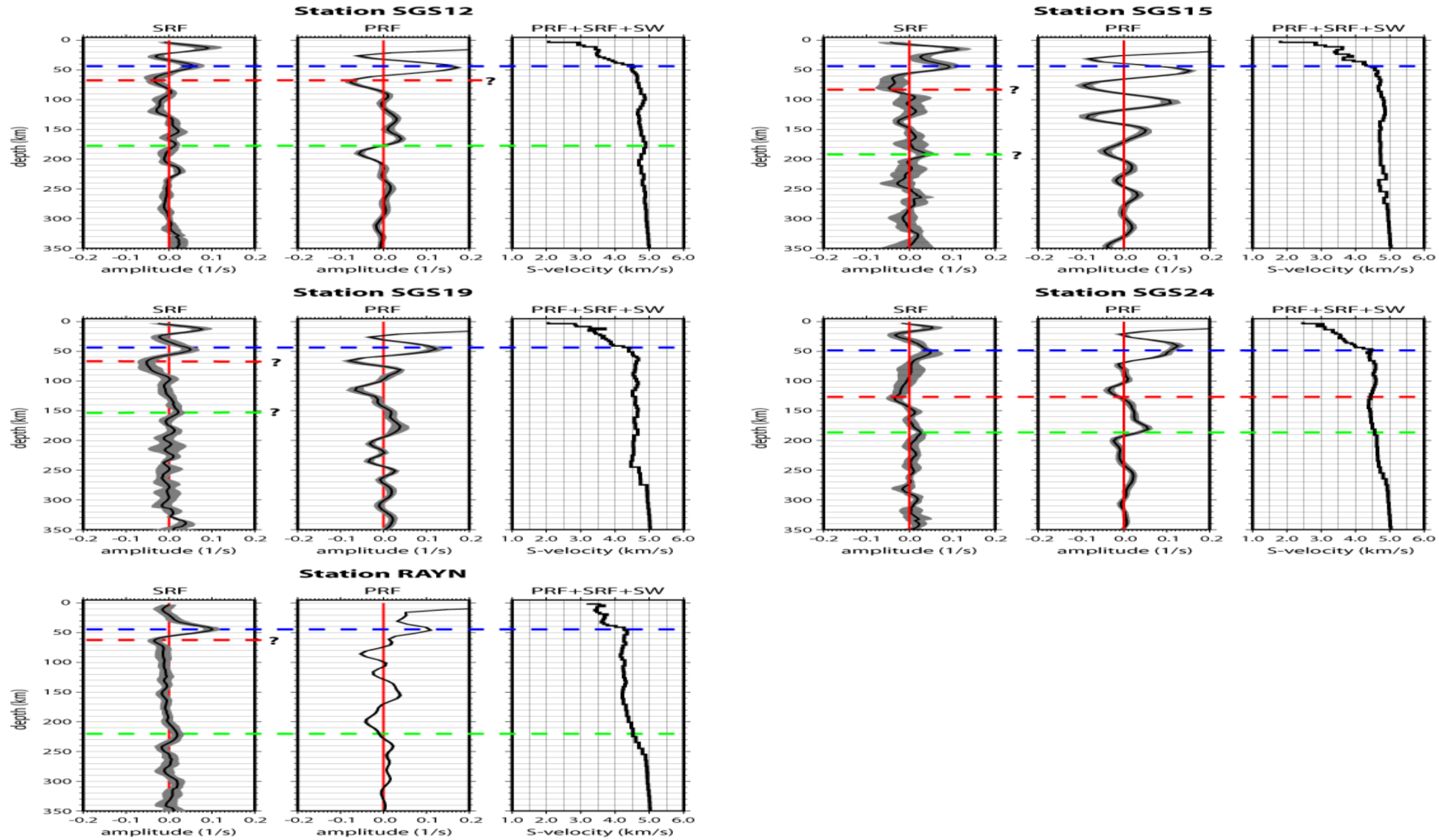
SRF LAB Depth



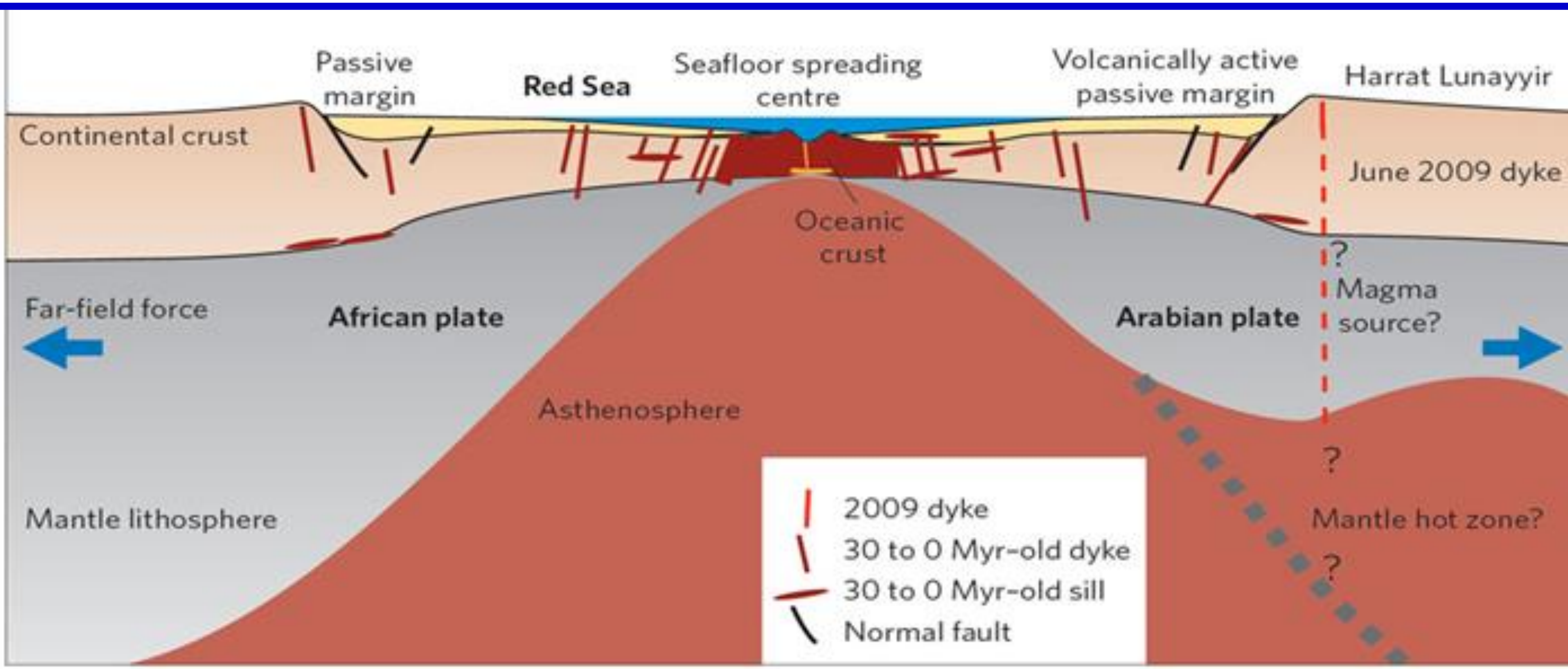


Surface Wave Attenuation: Path map (left) and initial result (right) for a surface wave inversion of the 25 second period Rayleigh wave. In these preliminary inversions, we show the attenuation parameter gamma where g=p/UTQ.


10 km
20 km
50 km
100 km
30°
28°
26°
24°
22°
20°
18°
16°
34°
36°
38°
40°
42°
44°



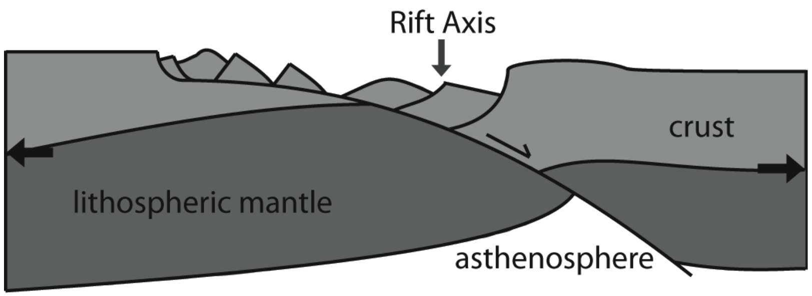
- Each panel displays the migrated SRF to the left, the migrated PRFs in the middle, and the joint inversion model (S-velocity) to the right. The grey bands indicate 2σ-confidence bounds for the stacks. The colored horizontal lines indicate the location of the Moho (blue), LAB (red), and bottom of the asthenosphere (green).



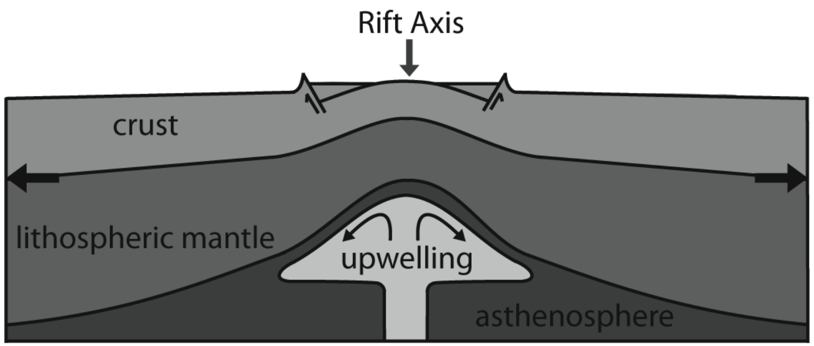
On either side of the spreading ridge, the continental lithosphere has been stretched and thinned, and hot mantle rises to fill the space created by the thinning. Active dyke intrusion and faulting are expected at or near the seafloor spreading ridge, whereas the flanking stretched continental lithosphere was thought to be inactive. Contrary to this assumption, Pallister *et al.*[1] document dyke intrusion in Harrat Lunayyir, about 200 km away from the active spreading centre, along the eastern passive margin of the rift.

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.

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
- 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

- 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

Simulation of Long-Period Ground Motions

- Long-period ground motions from distant earthquakes in the Zagros Mountains can be large enough to impact the eastern Gulf
  - Ground motions in Iran would be destructive
  - Large buildings, bridges and structures could expect to be impacted, although damage levels must be assessed by structural engineers
  - Reclaimed land could be subject to amplification and liquefaction

- Site response in large cities and industrial facilities needs to be investigated
  - Amplifications of 10 could be expected
- Simulations of ground motions can provide baseline for predictions from very large events
- Recommendations for future work:
  - Improved seismic velocity and density model with spatial resolution of 1-10 km
  - Must obtain geotechnical shear velocities
  - Need to include finite faulting for large earthquakes