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Wide-angle Seismology

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Wide-angle Seismology

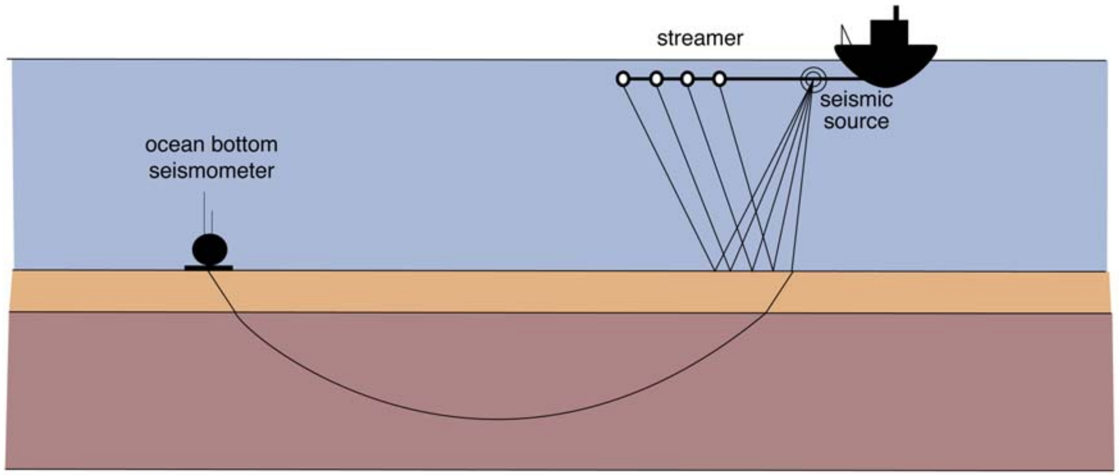
Donna Shillington, Lamont-Doherty Earth Observatory
18 August 2009 - Trieste, Italy

- What is it and why do we need it?
- Seismic wave-propagation
- Apparent velocity and reduction velocity
- Survey design and data analysis
- Characteristics that control wide-angle velocity
- Velocity structure of continental crust
- Velocity structure of oceanic crust

Seismic reflection vs wide-angle reflection/refraction

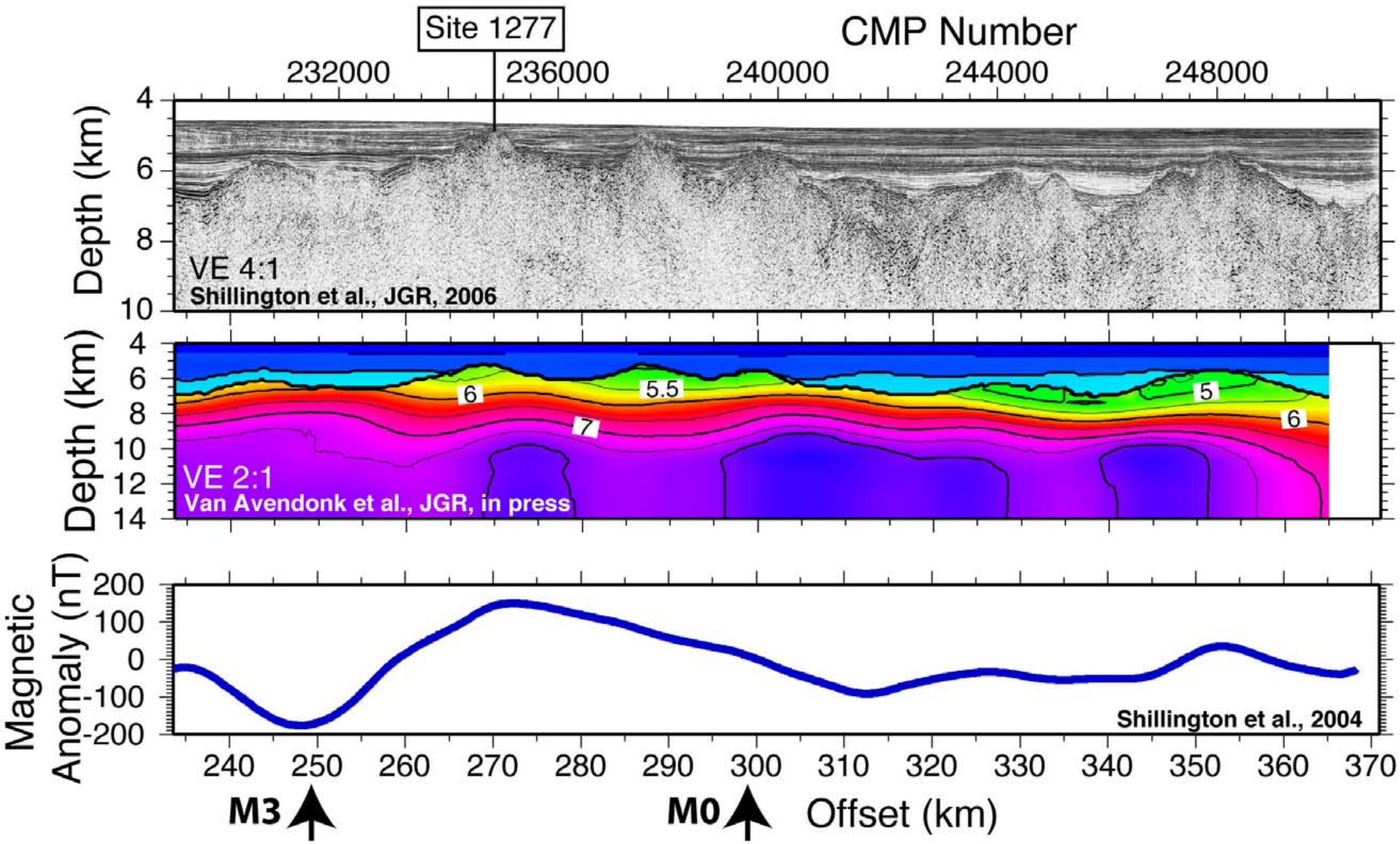
- Short ranges => near-normal incidence
- Produce “image” of impedance contrasts
- Detailed structures
- Traditionally led by developments in industry

- Long ranges => large angles of incidence
- Produce “model” of velocity structure
- Major variations only
- Traditionally led by developments in academia



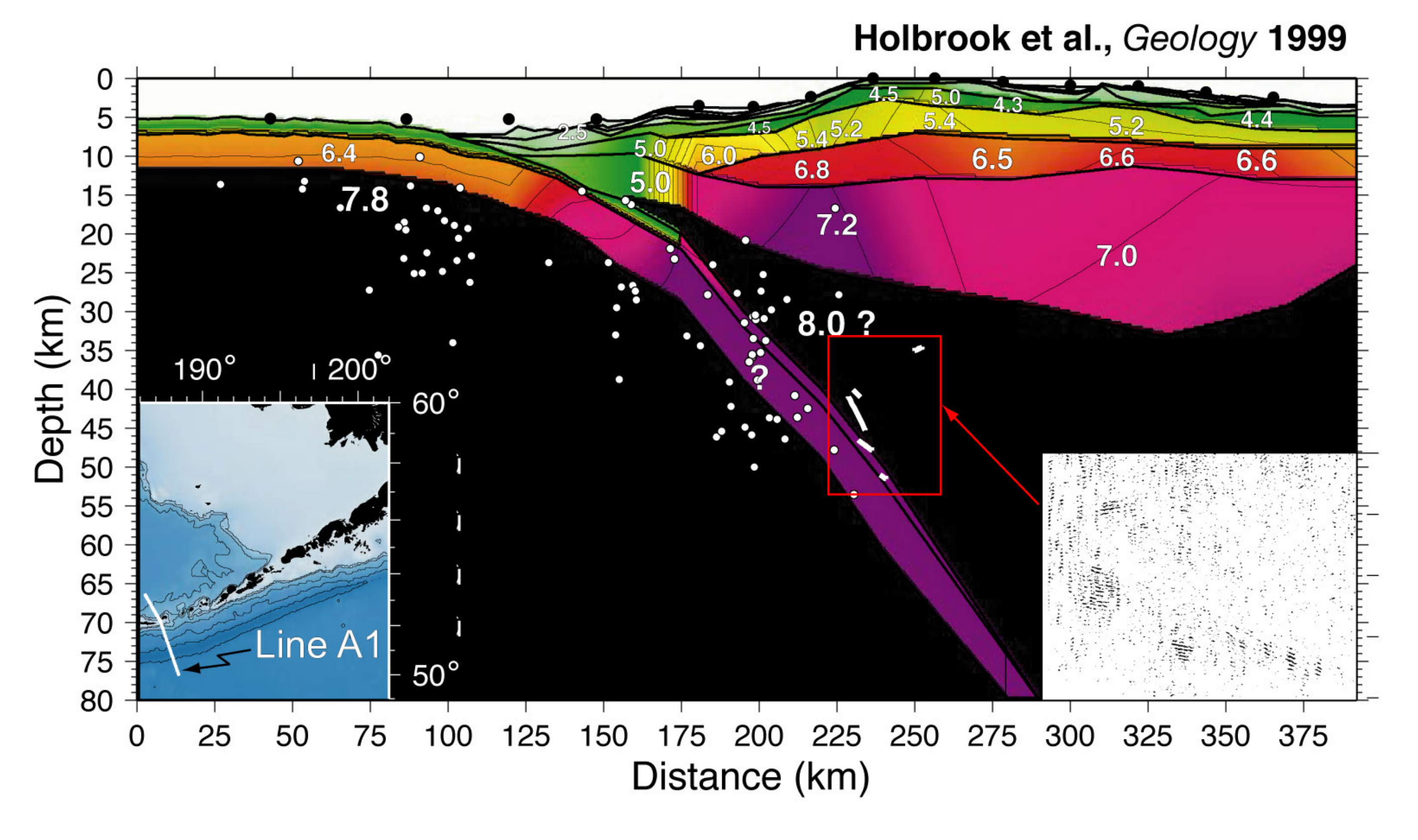
Seismic reflection vs wide-angle reflection/refraction:

an example from the Newfoundland rifted margin



What can wide-angle seismology tell us?

- How does thickness of the crust vary across a region?
- How much magmatism occurred?
- How does composition/temperature of the crust/upper mantle vary across a region?



Velocity model created from wide-angle seismic data collected across the Aleutian Island Arc.

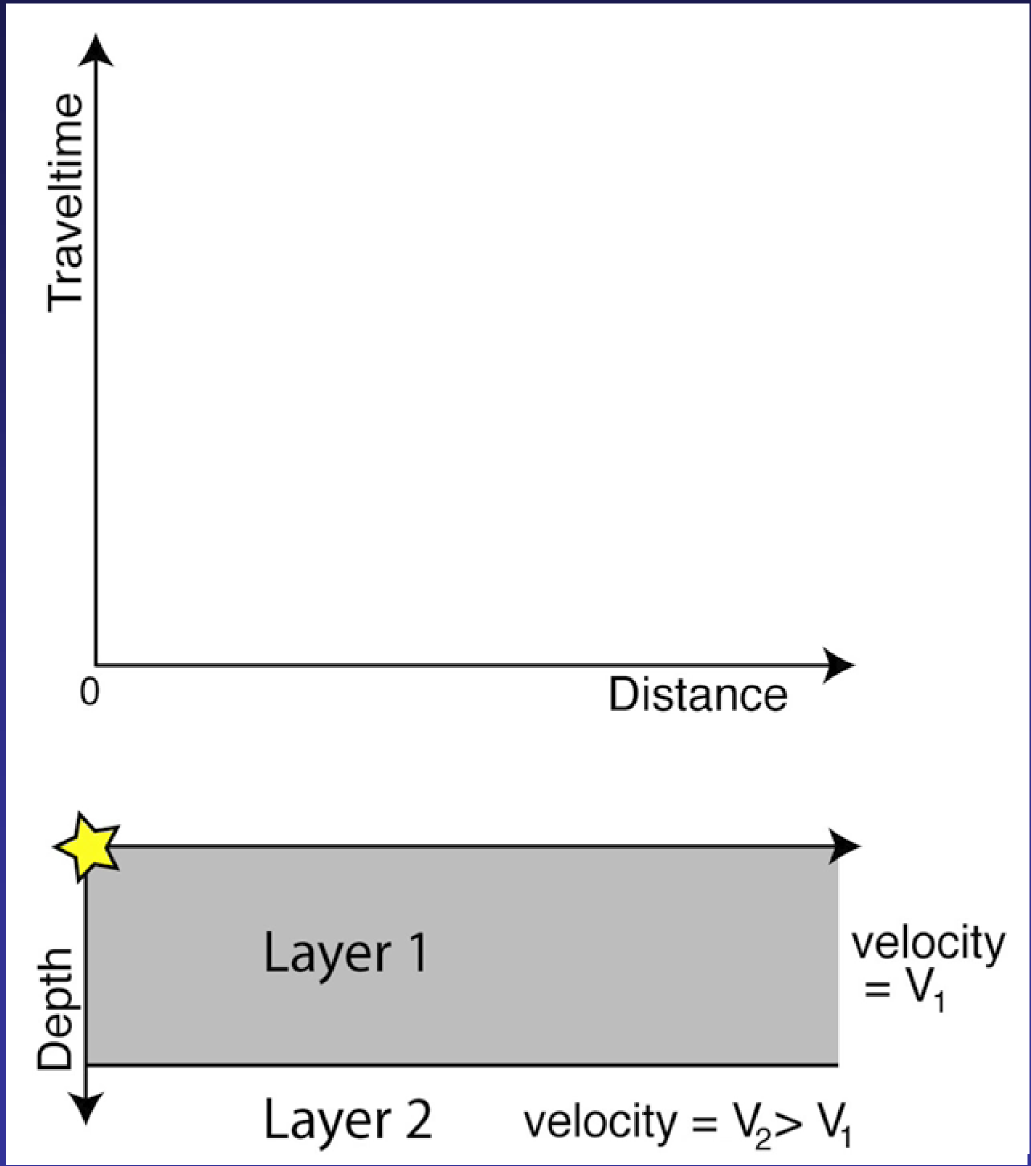
The authors were able to make estimates of arc composition and volume from this model.

Refracted and reflected phases for simple 2-layer, constant velocity structure

- Simple two-layer structure: amplitudes increase towards the **critical point**, then decrease.

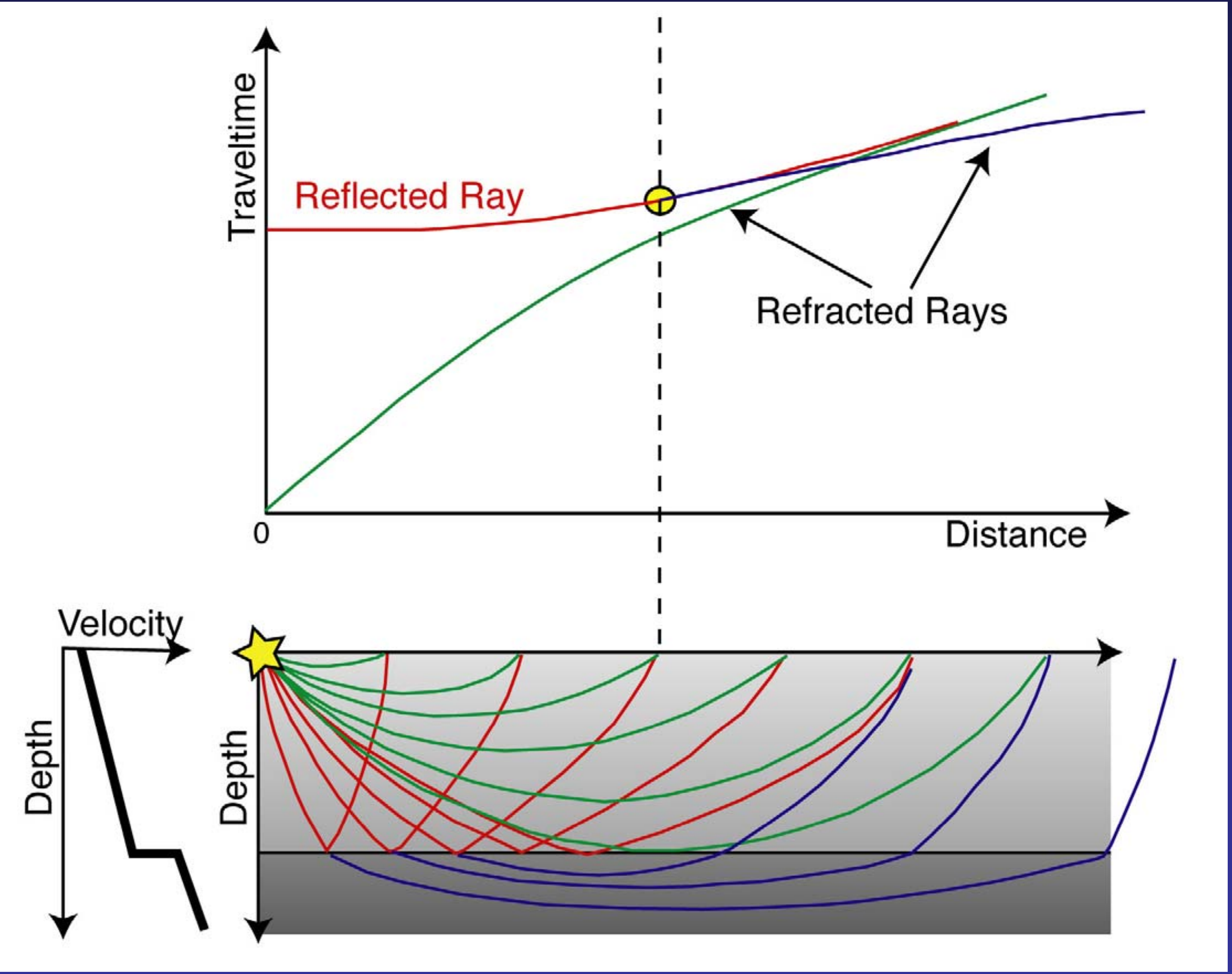
- Wide-angle seismology primarily concerned with **postcritical** signals

- Apparent velocity of the reflected ray gradually converges towards apparent velocity of layer through which its travelling.



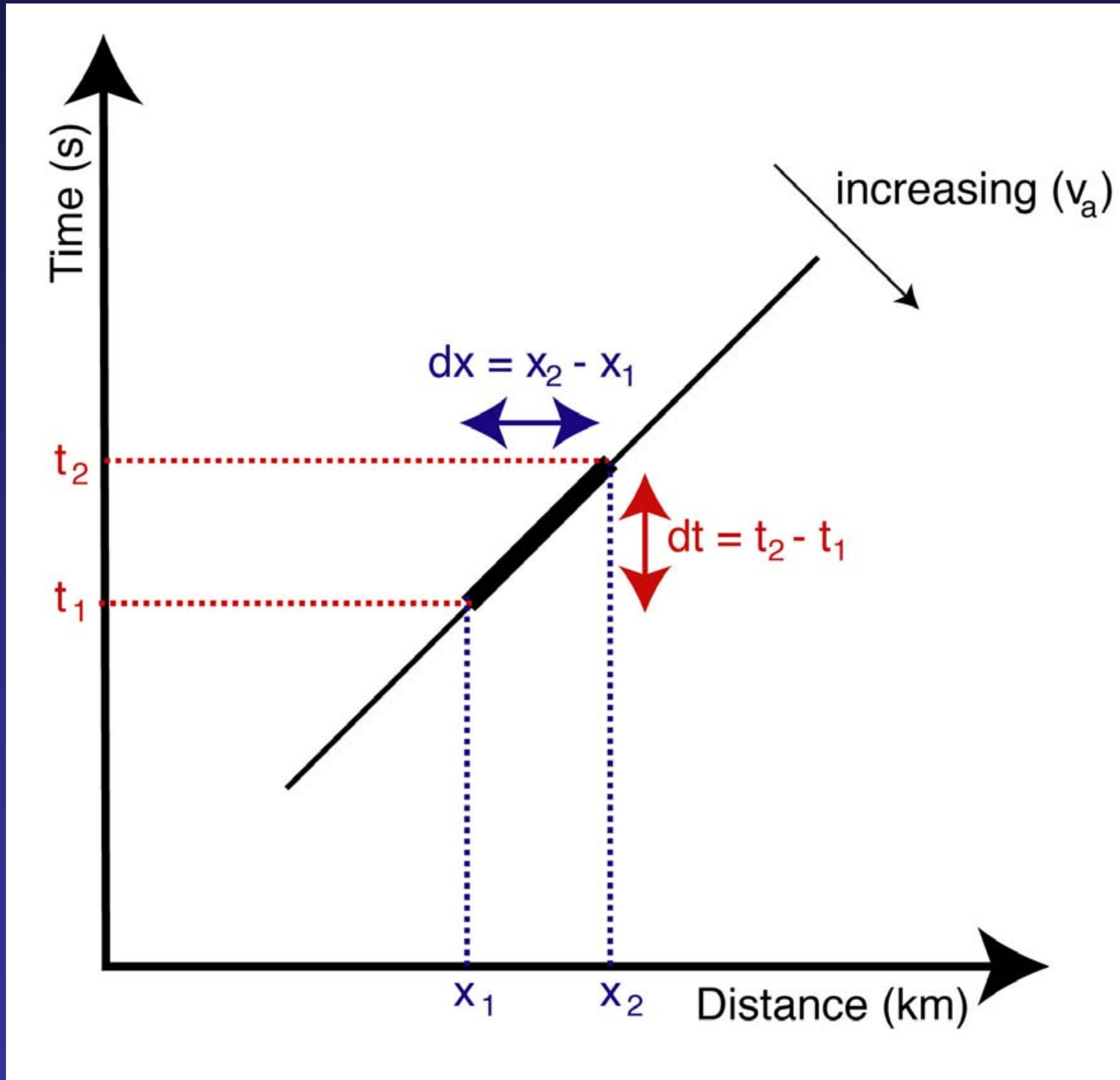
movie

More realistic structure: velocity increases with depth in each layer and travel-time branches are curved

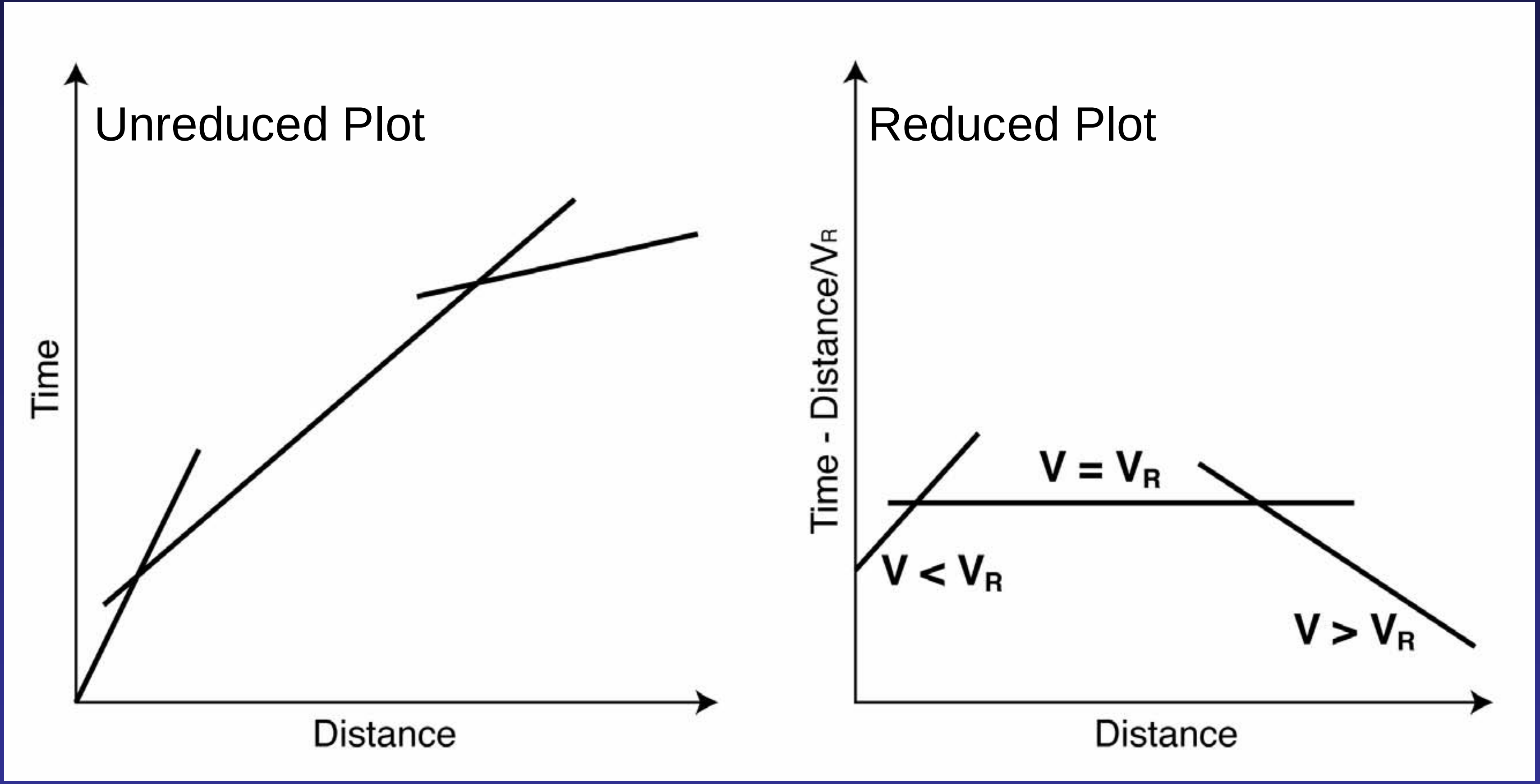


Apparent velocity: a first look at velocity characteristics of the subsurface

- apparent velocity, $v_a = dx/dt$
- can be used to make a first estimate of velocity of different layers
- **CAUTION**: this velocity is also affected by dipping layers, etc…



Reduction Velocity



- reduced time = time - (distance / reduction velocity)
- On the reduced plot, phases that appear horizontal have an apparent velocity equal to the reduction velocity

Acquisition: sources and receivers

Land

- Sources are normally explosives
- Receivers may be geophones or 3-component seismometers

Marine

- Sources are usually airgun arrays
- Receivers are ocean bottom hydrophones or seismometers (OBH/OBS), sonobuoys or towed hydrophone streamers

Hybrid onshore/offshore experiments also possible

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Wide-angle survey design

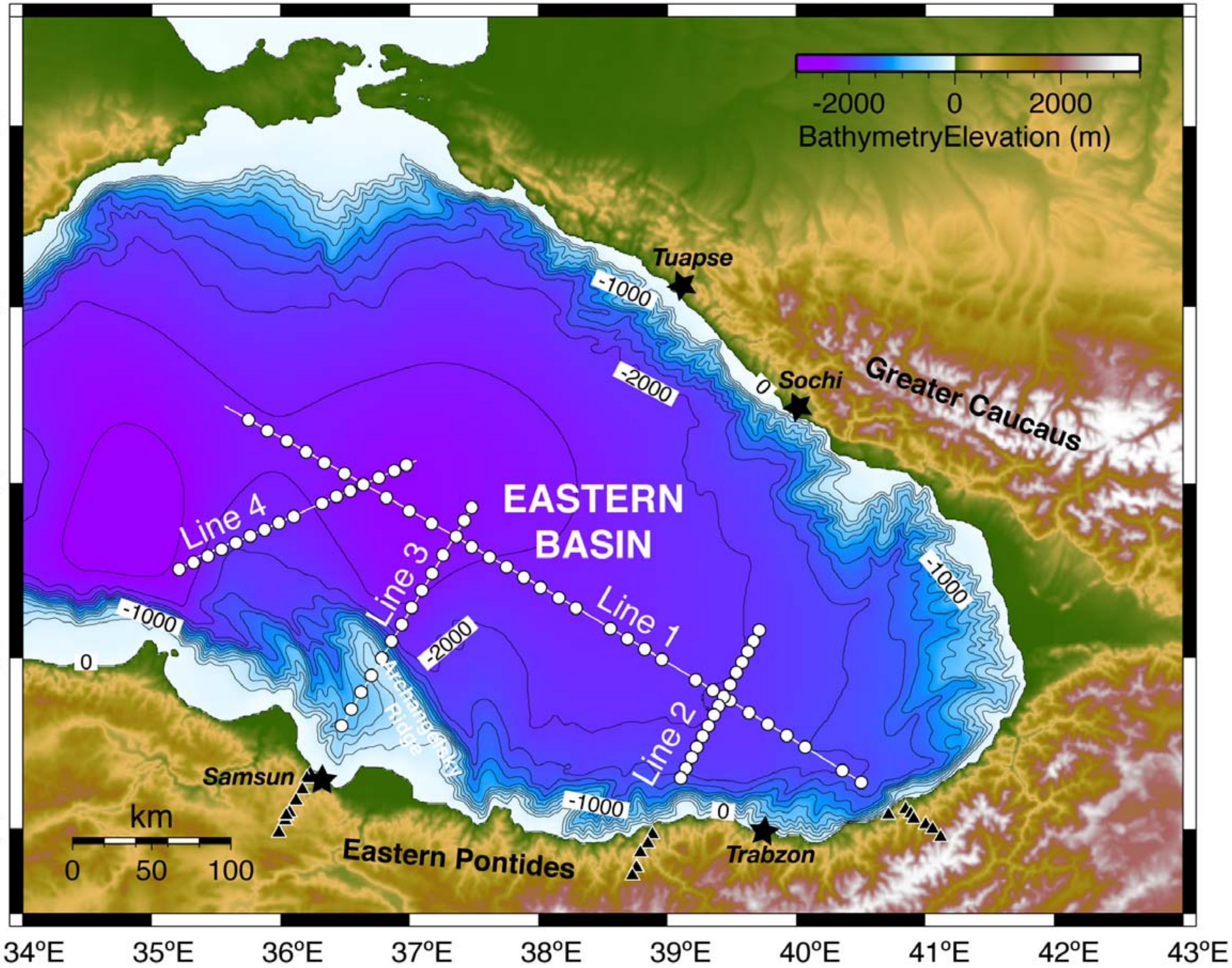
Geometrical considerations:

- 2d profiles perpendicular to strike (e.g., across continental margin, basin or mountain belt)
- 3d for 3d structures (e.g. volcano)

Practical considerations:

- Source-receiver range required ~ 5 x depth of penetration => 10s km on oceanic crust, 100s km in the continents
- Land => few sources (normally explosives), many receivers (seismometers in concrete-lined pits for good coupling)
- Marine => many sources, few receivers (normally OBH/OBS)

Example of onshore-offshore seismic refraction experiment in the eastern Black Sea



Minshull et al., 2005
Shillington et al., 2009

Wide-angle data analysis

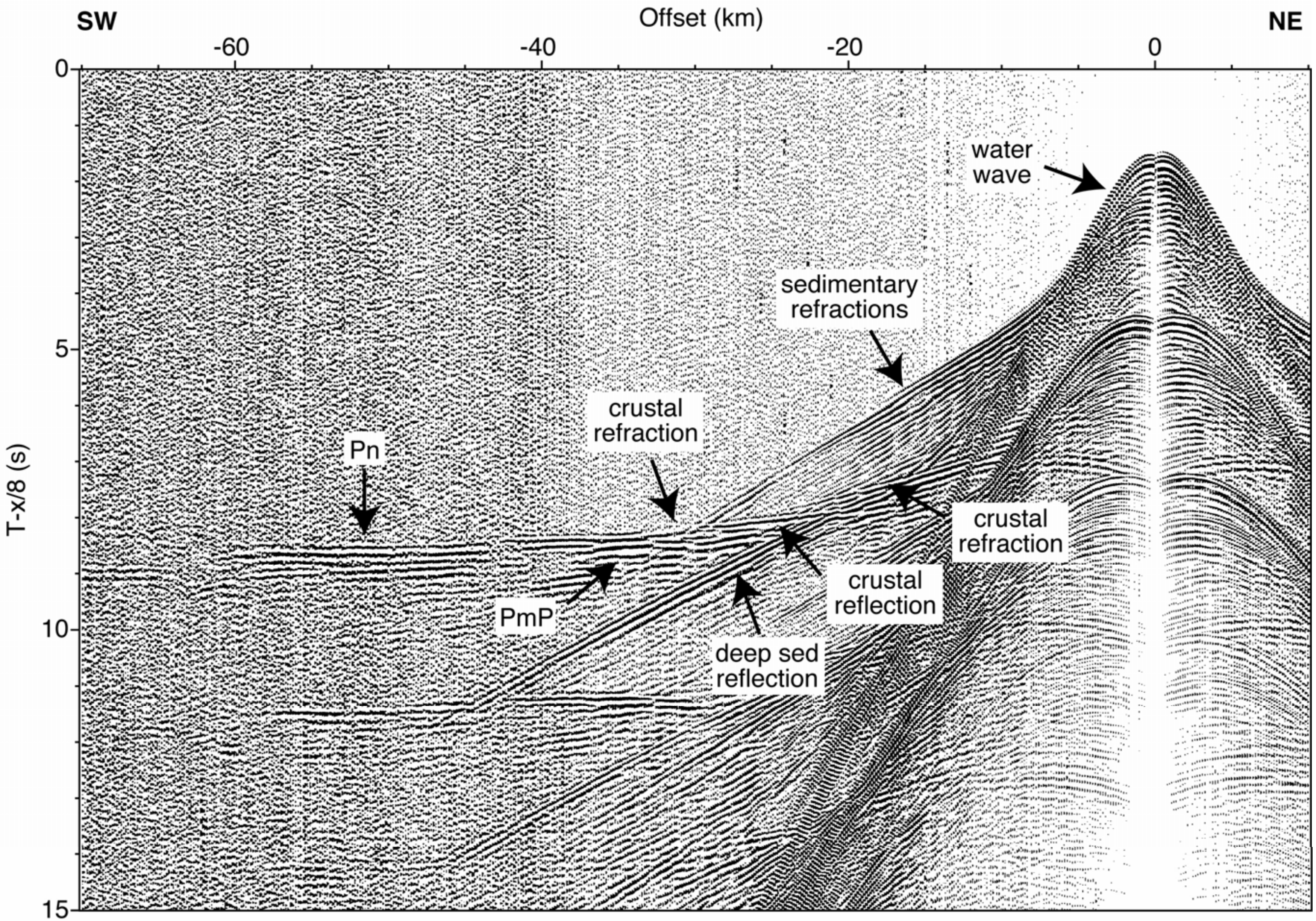
First Steps

- 1d graphical fit (e.g., apparent velocities!)
- 1d modelling of traveltimes
- 2d modelling/inversion of traveltimes
- Put in known structure - e.g. seabed from echosounder, basement from reflection data, sediment velocities from mcs data

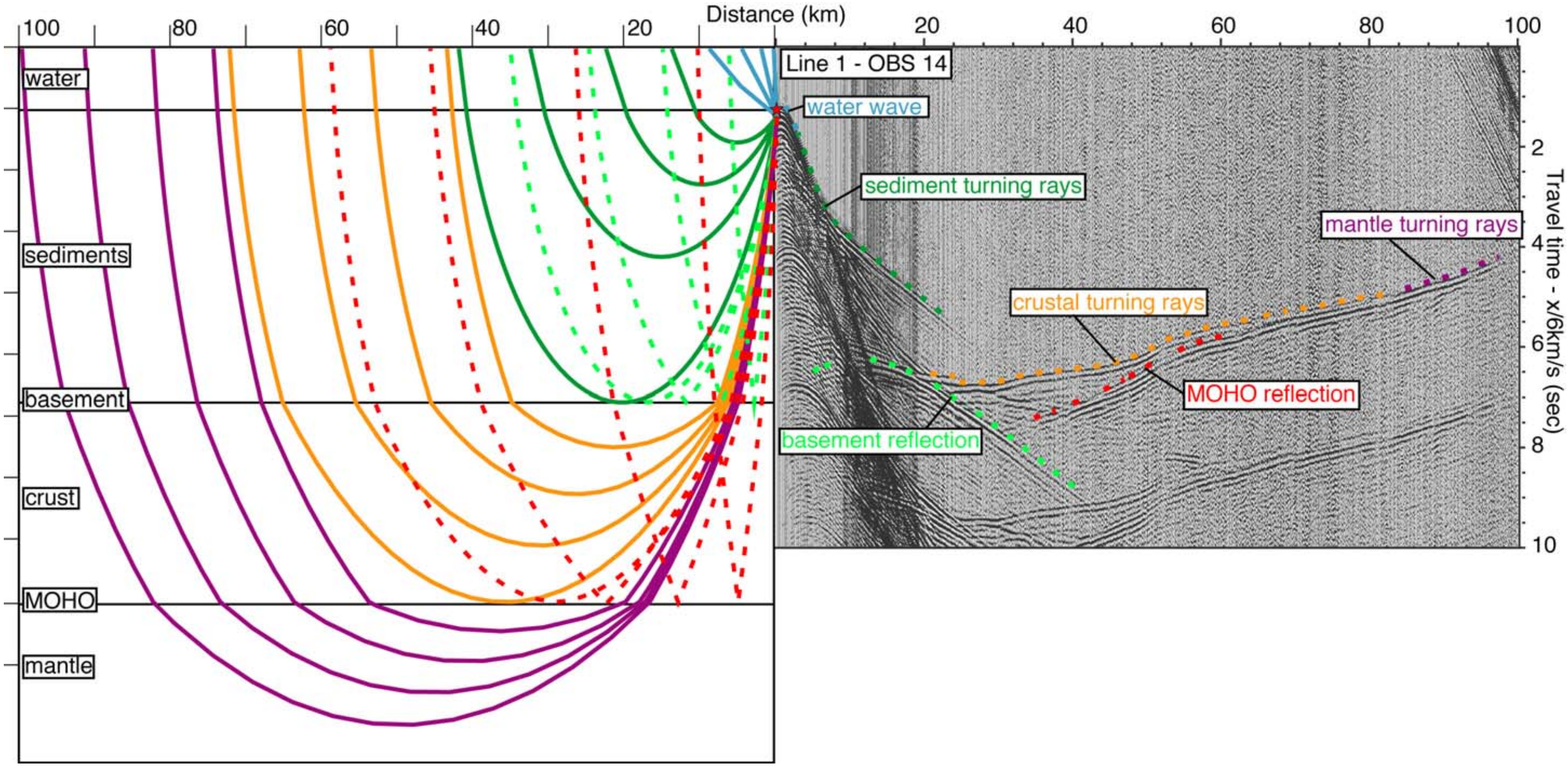
More advanced analysis

- 1d modelling/inversion of amplitudes (“reflectivity”)
- Adjustment of 2d model to match amplitudes (ray theory/finite difference)
- 2d waveform inversion (early days with this!)
- 3d tomographic inversion

Example of record from ocean bottom seismometer

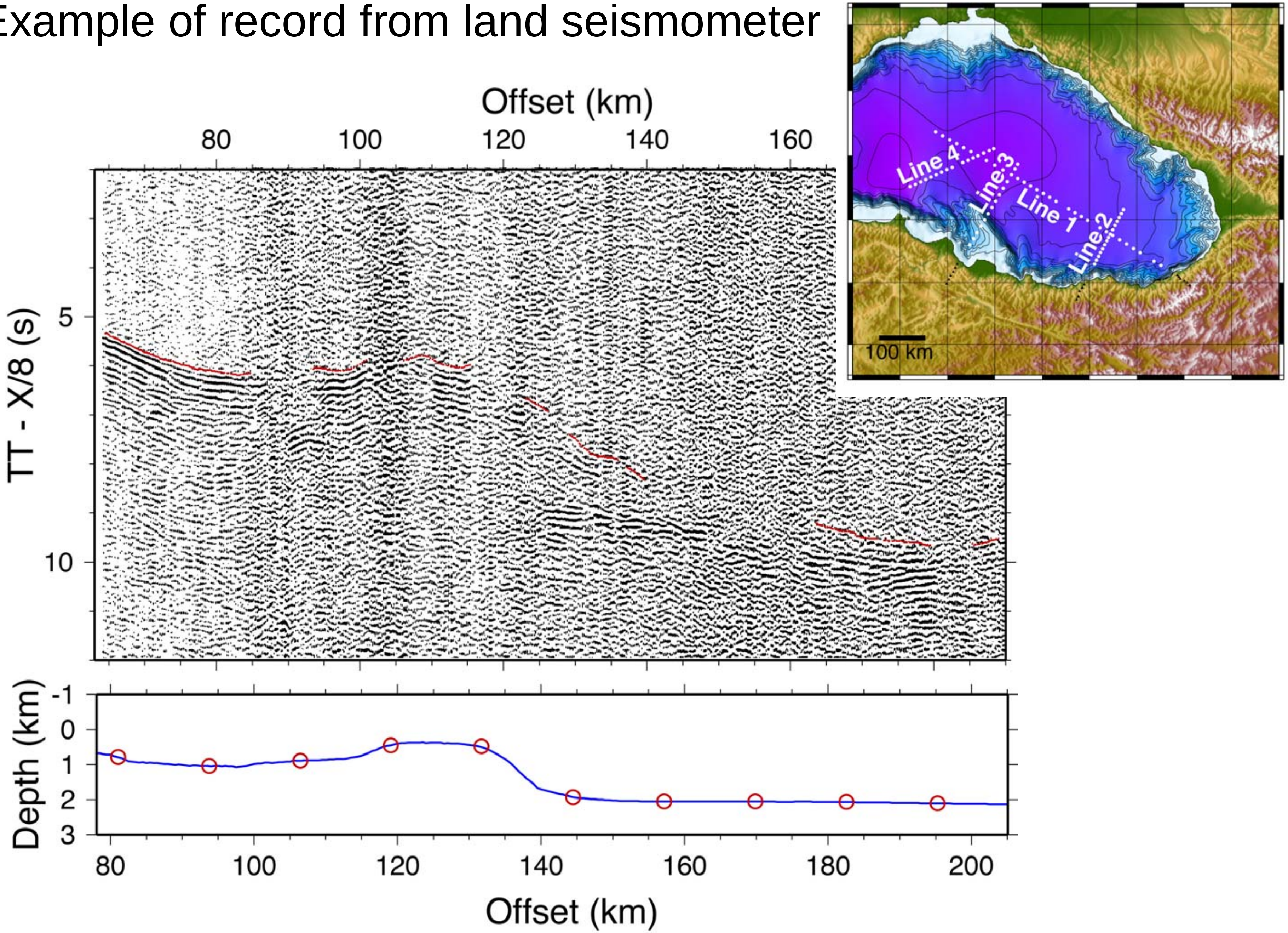


Line 3, OBS 2



Distance (km)
100
80
60
40
20
20
40
60
80
100
Line 1 - OBS 14
water
water wave
sediment turning rays
sediments
mantle turning rays
crustal turning rays
basement
MOHO reflection
basement reflection
crust
MOHO
mantle
Travel time - x/6km/s (sec)
2
4
6
8
10

Example of record from land seismometer



Different methods for creating 2D P-wave velocity model used in this study

1. Forward modeling and ray-tracing

   (Rayinvr, Zelt and Smith, 1992)

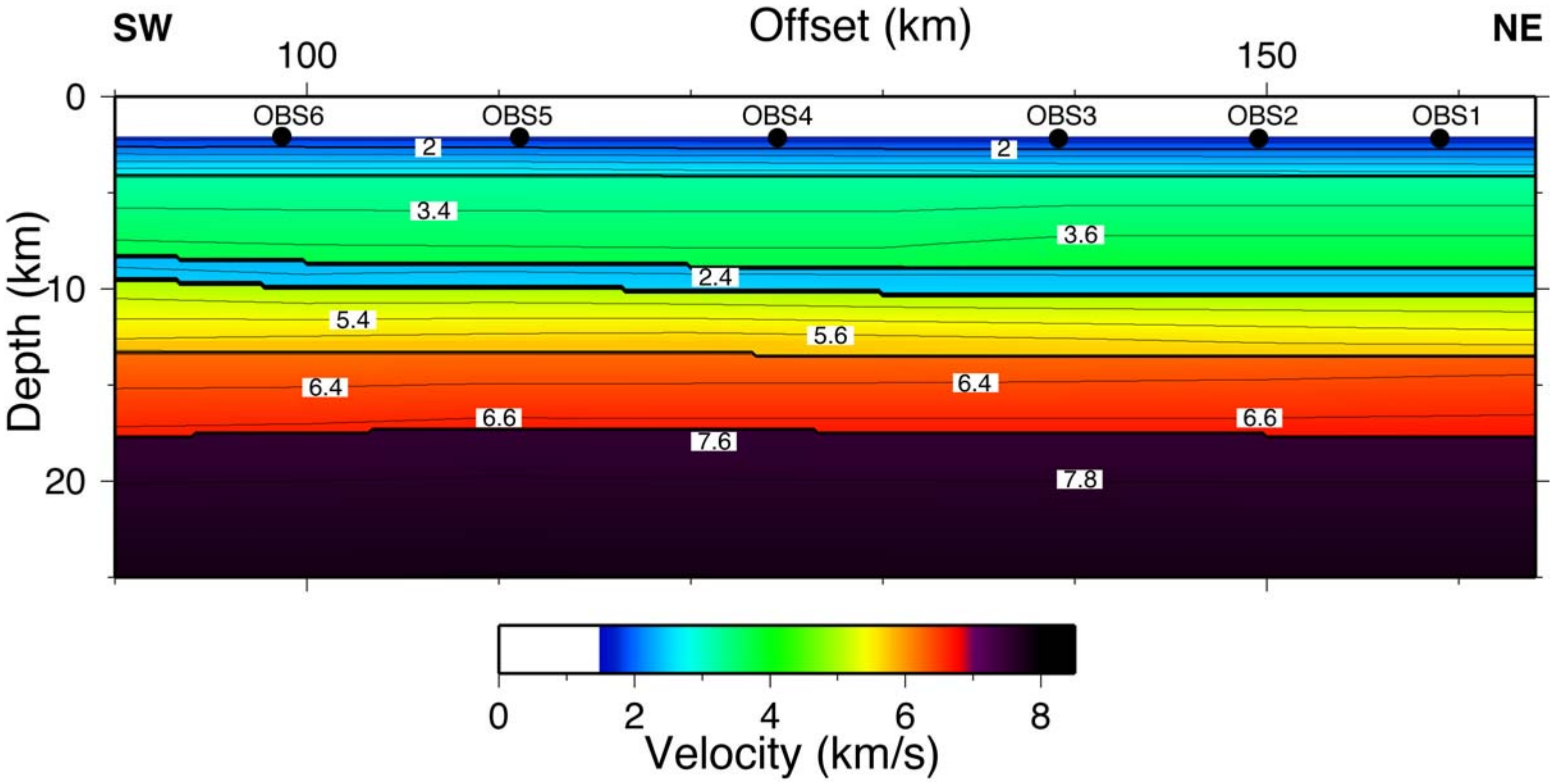
2. First arrival tomography

   (FAST, Zelt and Barton, 1998)

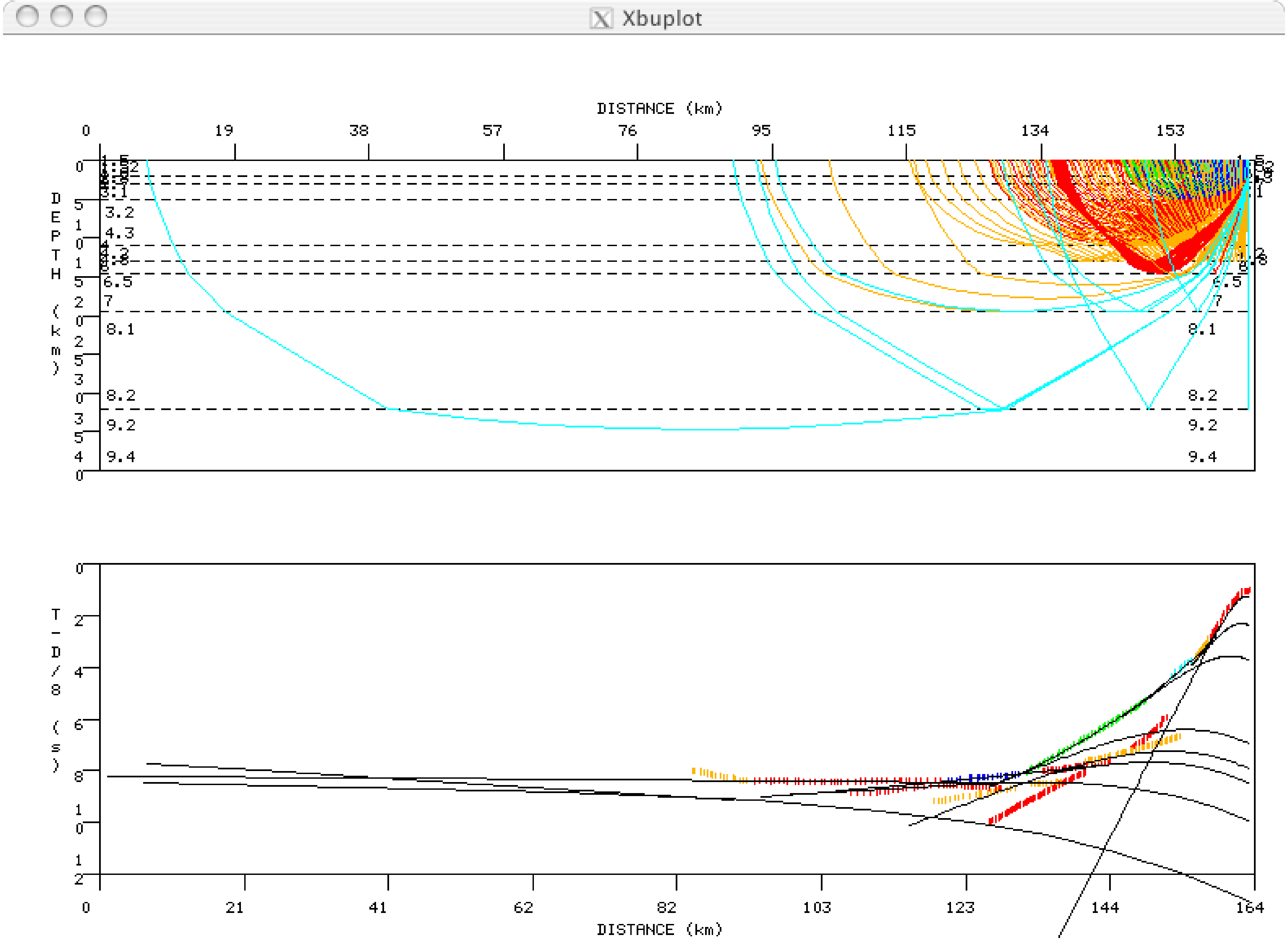
3. Reflection/refraction tomography

   (JIVE, Hobro et al., 2003)

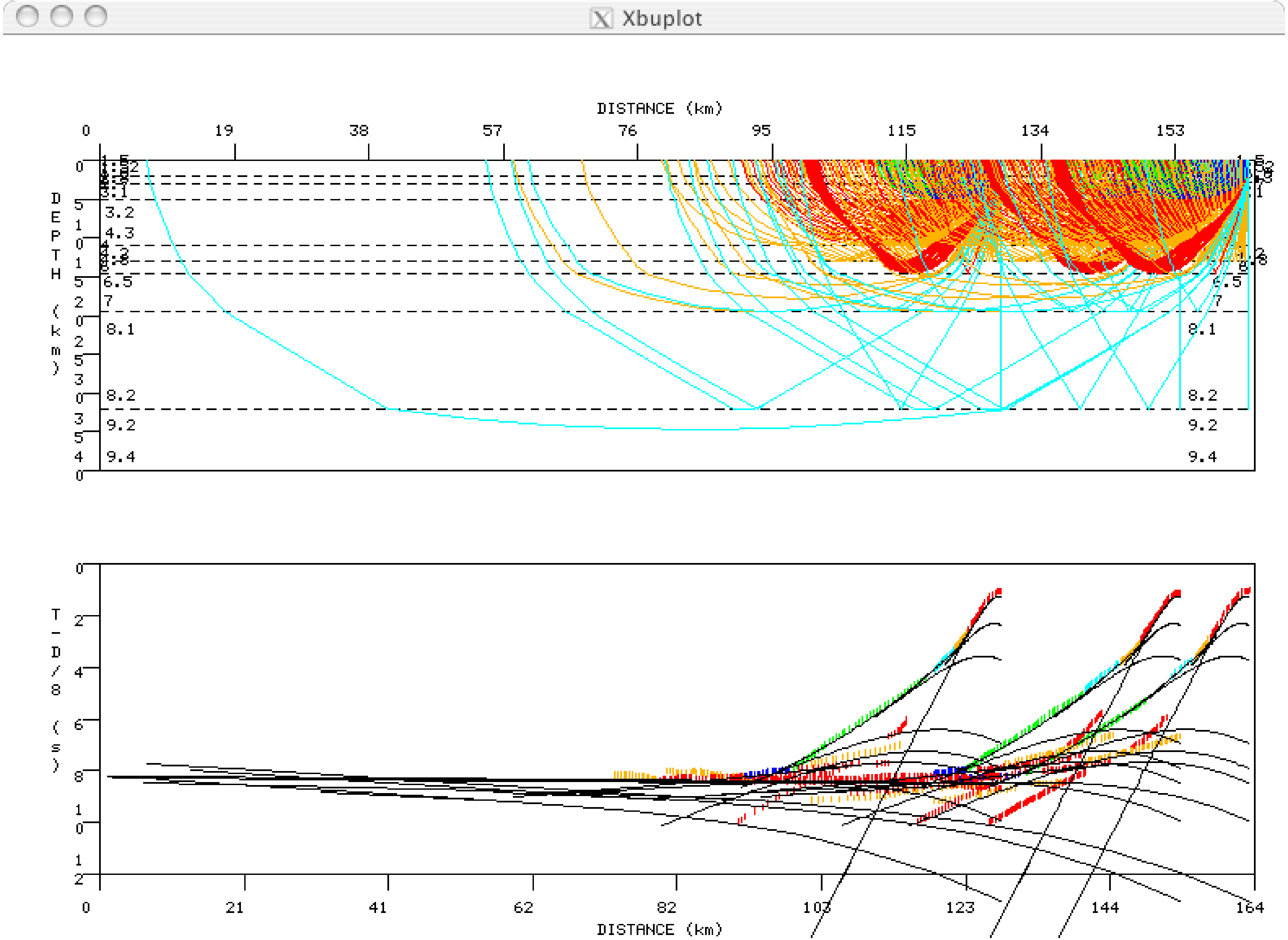
Results from initial velocity modeling using forward modeling (RAYINVR)



- approximate crustal thickness = 8 km
- approximate sedimentary thickness = 10-11 km
- normalized chi-squared = 1.2, Residual RMS = 0.03 s



Xbuplot
DISTANCE (km)
0
19
38
57
76
95
115
134
153
DEPTH (km)
3.1
3.2
4.3
6.5
7
8.1
8.2
9.2
9.4
T-D/8 (s)
0
21
41
62
82
103
123
144
164
DISTANCE (km)


Xbuplot
DISTANCE (km)
0 19 38 57 76 95 115 134 153
DEPTH (km)
3.2
4.3
6.5
7
8.1
8.2
9.2
9.4
T-D/8 (s)
0 21 41 62 82 103 123 144 164
DISTANCE (km)

What do seismic velocities mean?

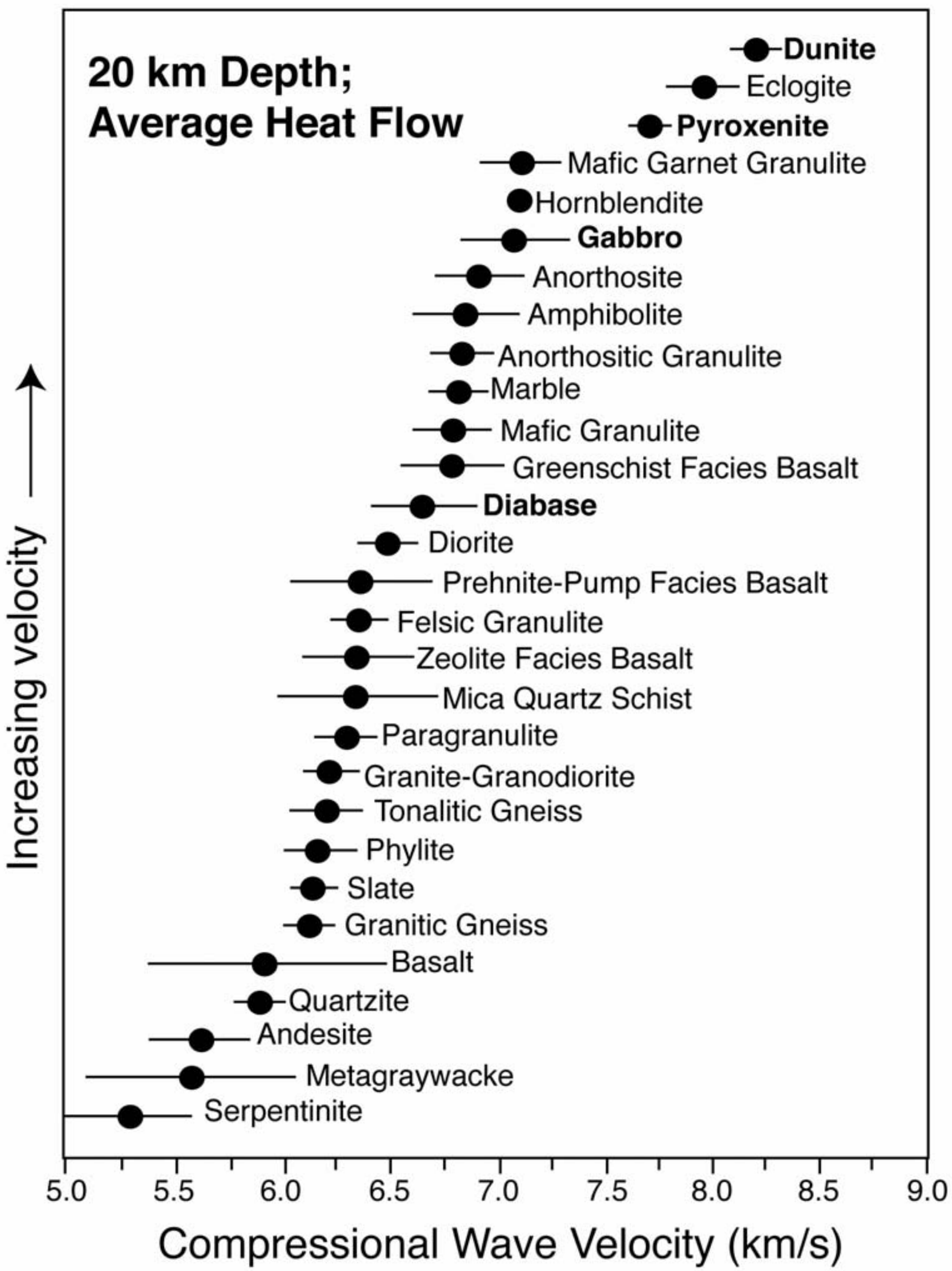
- **Porosity**
  (depths < 10 km)

- **Temperature**
  (~0.4-0.56 m/s/ºC)

- **Pressure**
  (~0.2 x 10^{-3} km/s/MPa)

- **Composition**
  - Vp decreases with SiO_2
  - Vp increases with MgO
  - Other primary relationships?

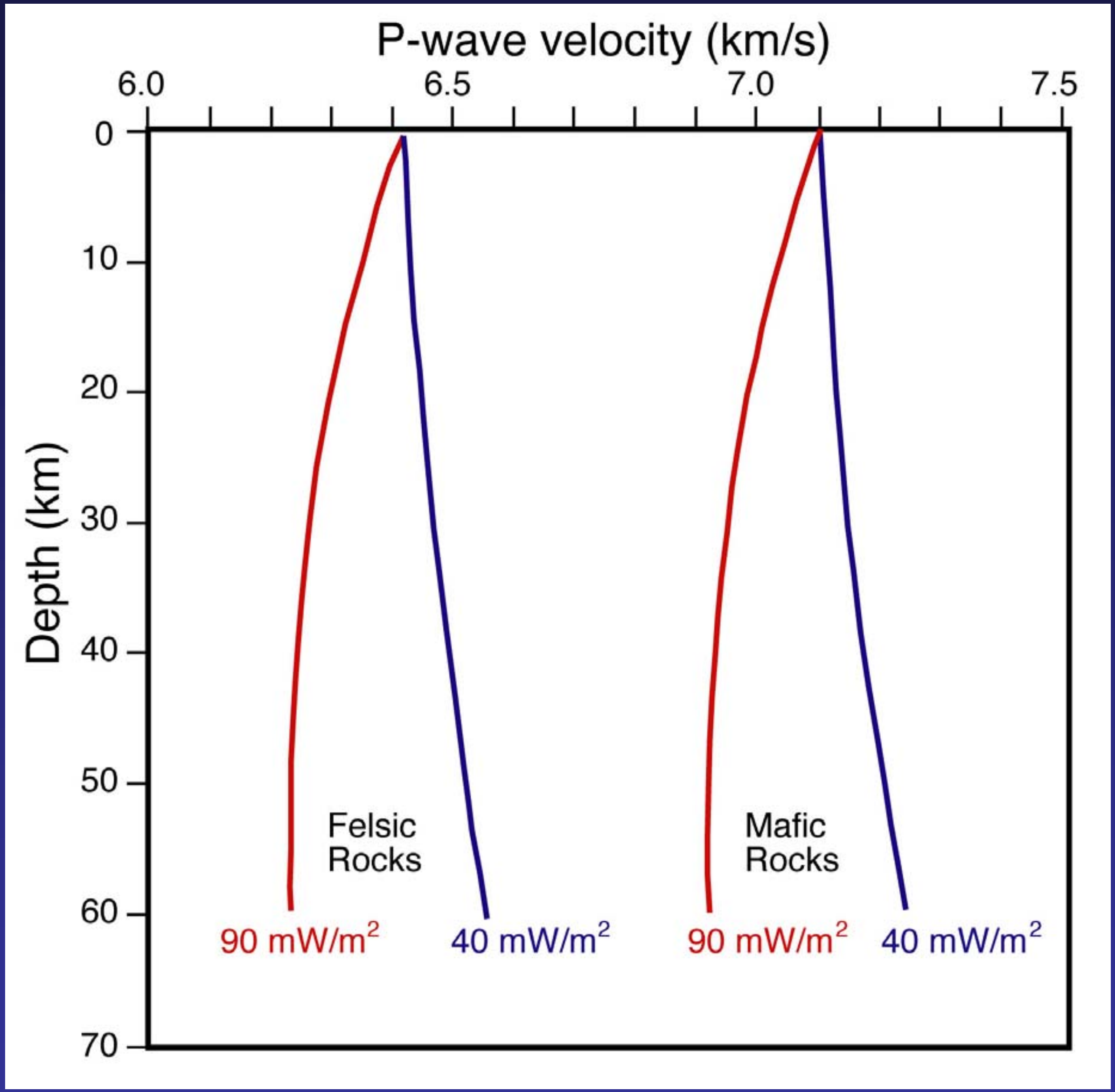
Carlson & Gangi, 1985; Korenaga et al., 2002



Christensen & Mooney (1995)

Effect of pressure and temperature on seismic velocity

- competing effects of increasing temperature and increasing pressure with depth
- velocity goes down with increasing temperature, but up with increasing pressure

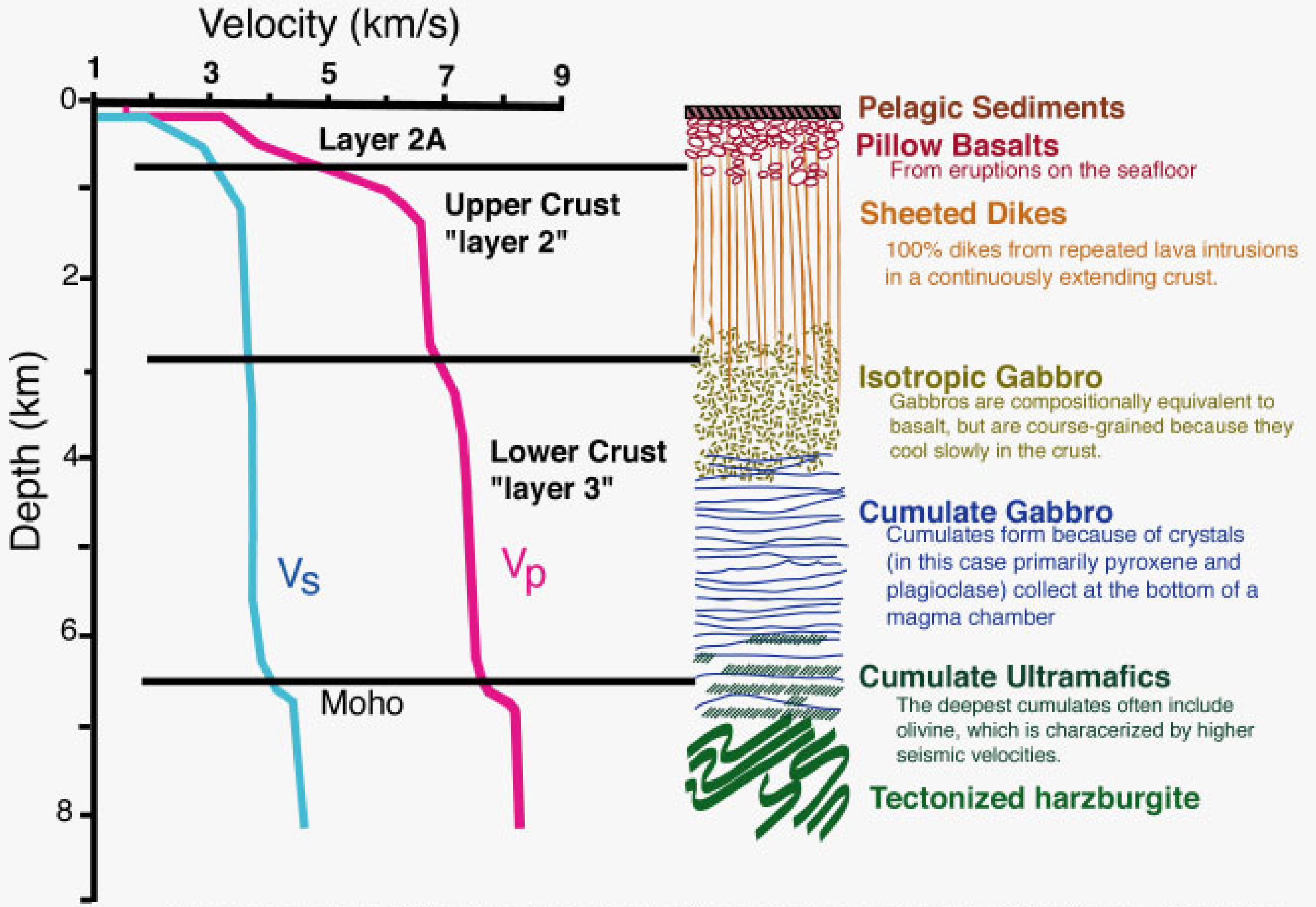


Modified from Rudnick and Fountain 1995

Oceanic Crust

- Thickness uniform globally (away from hotspot traces, fracture zones, and continental margins)
- Velocity controlled mainly by porosity/cracks
- Approximate correlation of Layer 2 with basalts/dykes and Layer 3 with gabbros, **but** not exact: in some places dykes have Layer 3 velocities and in others gabbros have Layer 2 velocities

Average velocity structure of oceanic crust

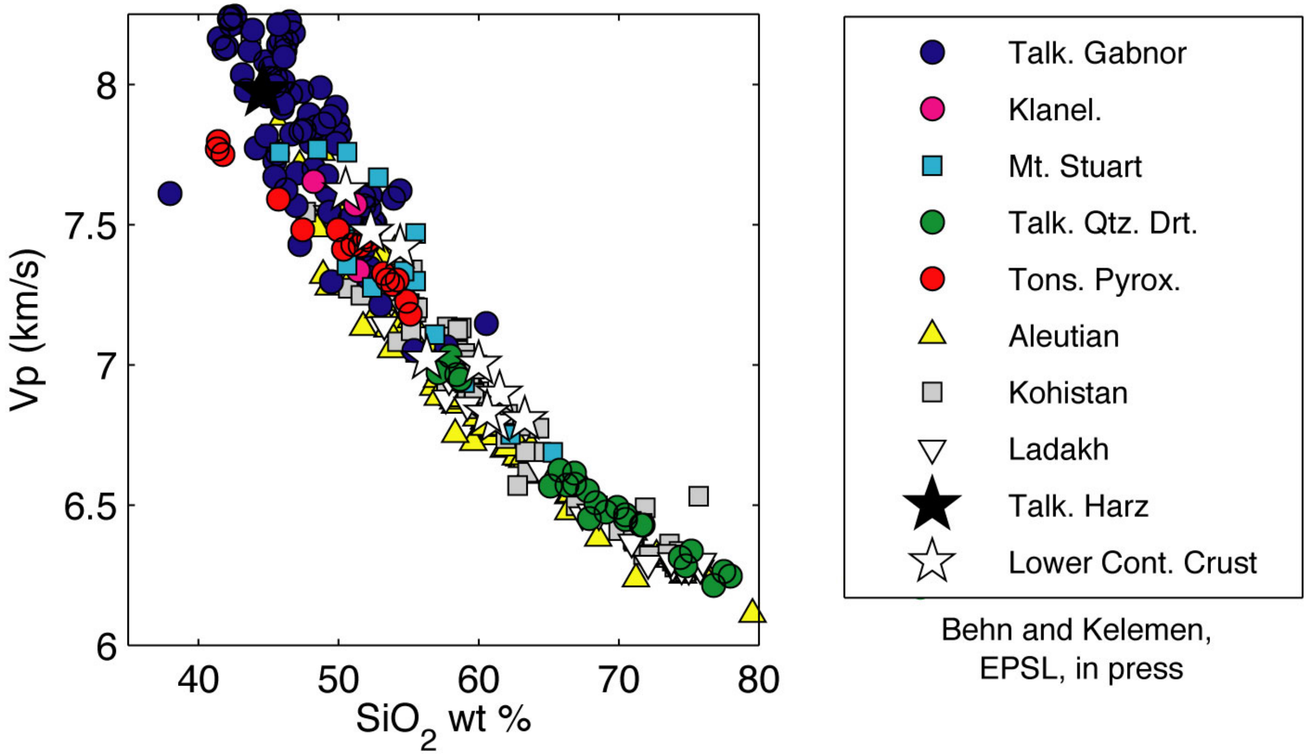


The ocean crust, combining the seismic structure (from seismic experiments) with the lithology of ophiolites.
Modfied from McClain (2002).

Continental Crust

- Thickness is related to crustal type (e.g., orogens thicker, extended crust thinner)
- Velocities typically increase from ~5.8 km/s at top to ~7.0 km/s at base. Average velocity of continental crust is 6.45 km/s
- Effect of pressure and temperature on velocity is small, so change with depth must be related to change of composition (more silica in upper crust, more magnesium in lower crust)

The BIG Caveat:
P-wave velocity is **NOT** a unique indicator of composition and/or temperature!!!!



Behn and Kelemen, EPSL, in press

Comparison between calculated velocity and composition of rock samples taken from exposed island arc sections