Seismic Imaging of the SW South China Sea Deep Crustal Structure Shows Evidence for a Ductile Lower Crust during Rifting*

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Framework for Study

The South China Sea (SCS) is the largest marginal basin of SE Asia. Yet its mechanism of formation is still debated. While the NE part of the SCS northern margin exhibits ~400 km of extended continental crust, its SW part shows nearly 800 km of extended continental crust, which makes it one of the widest rifted margin in the world. In June 2011, Chinese and French scientists conducted a joint geophysical experiment across the SW sub-basin of the SCS. A 1000-km-long wide-angle refraction profile has been acquired along the conjugate margins using a total of 50 Ocean Bottom Seismometers (OBS). A coincident multichannel seismic (MCS) line was also shot using a 6-km-long streamer and a 6600 cu.in. Airgun array (page 4 for location). 41,100 first refraction and 6622 PmP reflection arrival travel times have been picked from the refraction dataset. A travel time tomography inversion was first performed to obtain a 2-D velocity model of the crustal and upper mantle structures (page 20). Ray coverage is sufficient to image the entire crustal thickness down to the upper mantle. The Moho depth is displayed in white in areas where the PmP Moho reflections are observed.

Interpretation

Based on this new tomographic model, northern and southern margins are found genetically linked since they share common structural characteristics: an average 12-km-thick crust and crustal scale lateral velocity variations. Ongoing processing of the MCS line shows that these lateral variations correlate well with seismic reflection observations of the crustal structures. Small-scale normal faults (grabens and horsts, with a spacing of ~15-30 km) are commonly associated with an apparent tilt of the iso-velocity contours affecting the upper crust. The upper-middle crust shows clear high lateral velocity variations defining low velocity bodies (LVB), bounded by large-scale normal faults (also referred as "Through-going crustal faulting"). Major sedimentary basins are located above the LVBs, interpreted as hanging-wall blocks. The

Moho interface remains rather flat (less than 4°) over the extended domain, suggesting that large normal faults root in a ductile lower crust, where sub-horizontal reflectors are observed in the seismic reflection profile. Along the northern margin, the wavelength of the LVBs decreases from 90 to 45 km as the total crust thins toward the Continent-Ocean Transition (COT). On both refraction and reflection seismic profiles, extension across the conjugate margins of the SW SCS is distributed on small-scale and large-scale normal faulting with a spacing of ~15-30 km and ~45-90 km, respectively. These two wavelengths of extensional deformation may directly relate to the presence of competent layers, here, the upper-middle crust and the shallow upper mantle, separated by a ductile lower crust.

Selected References

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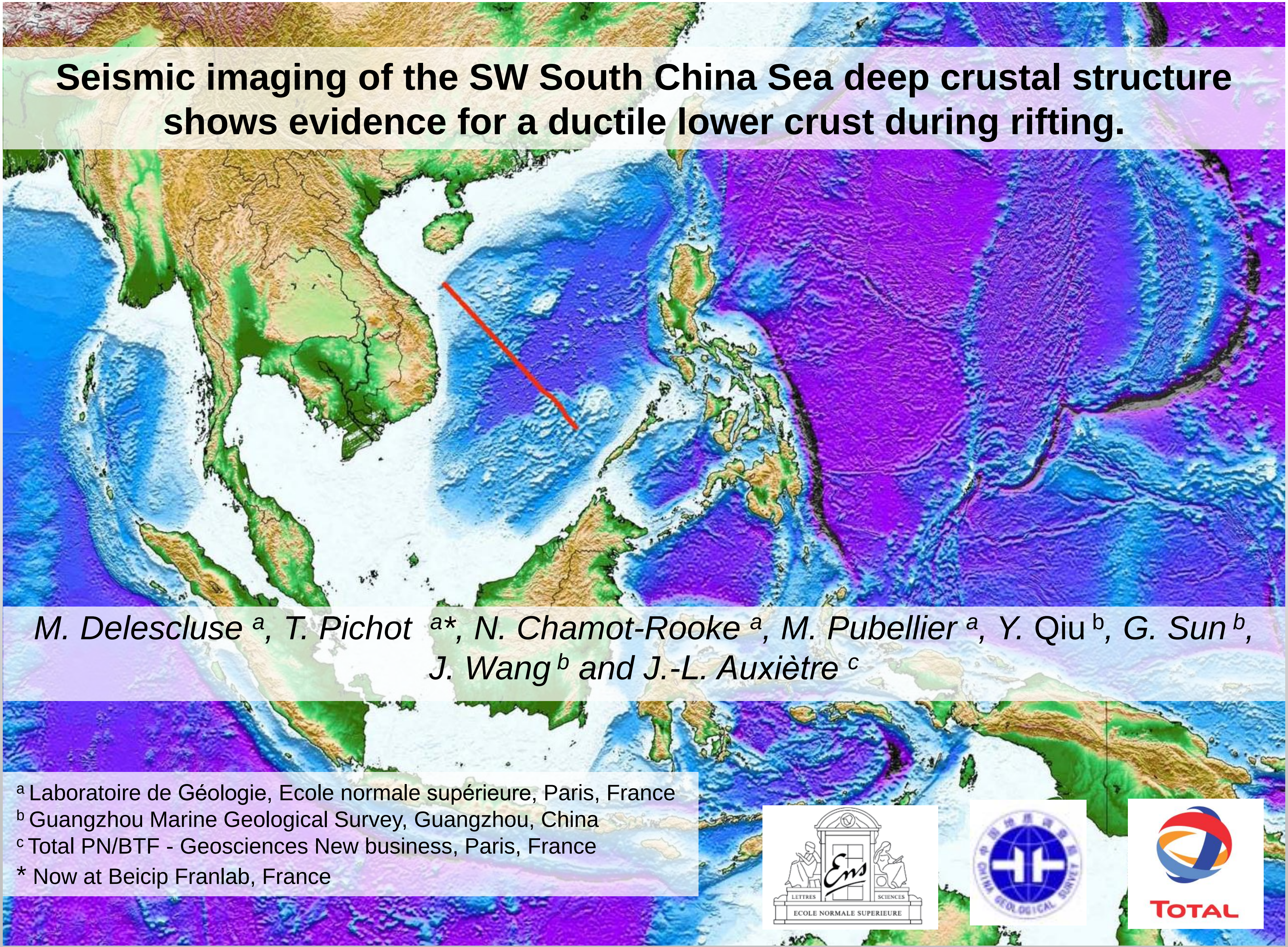

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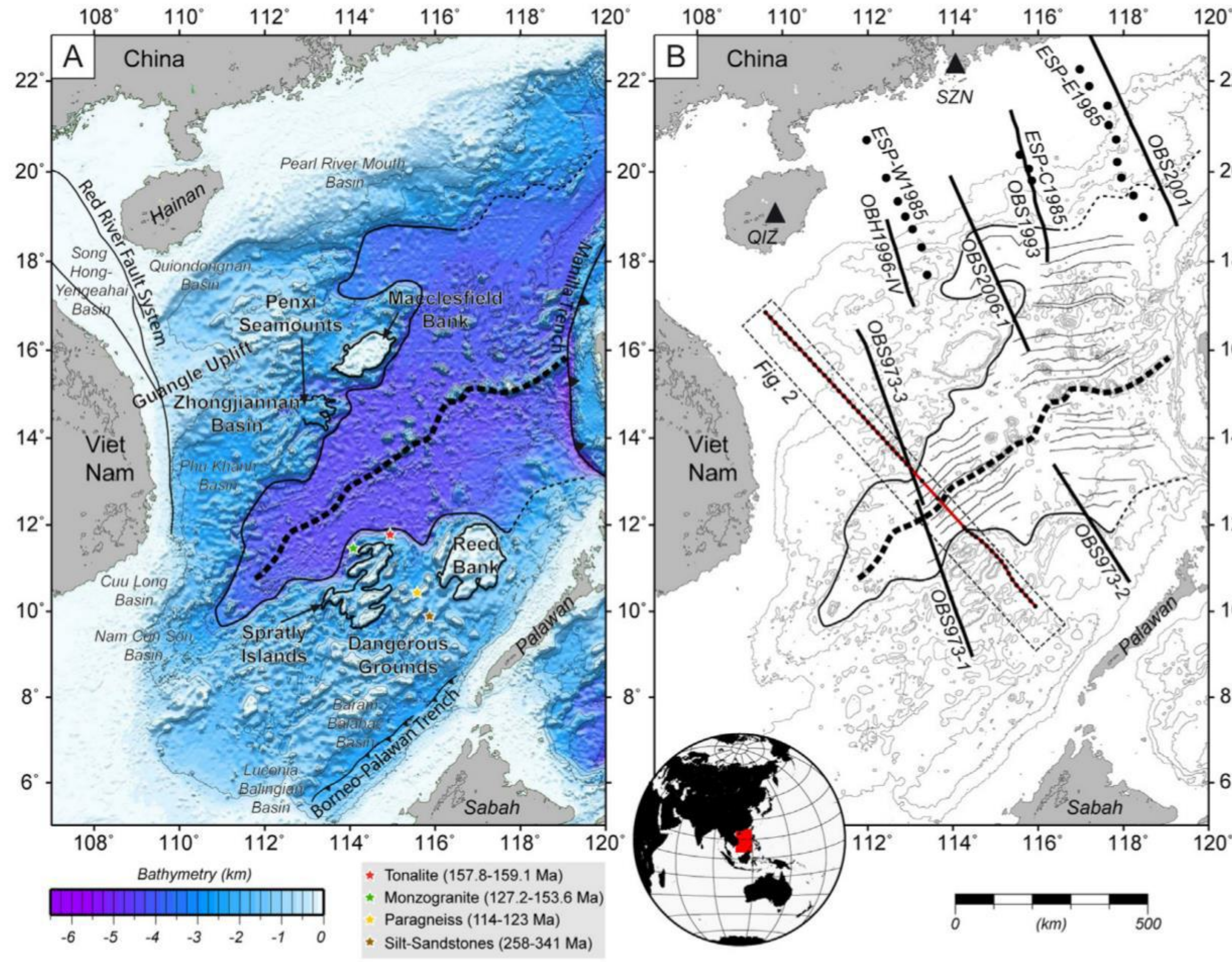
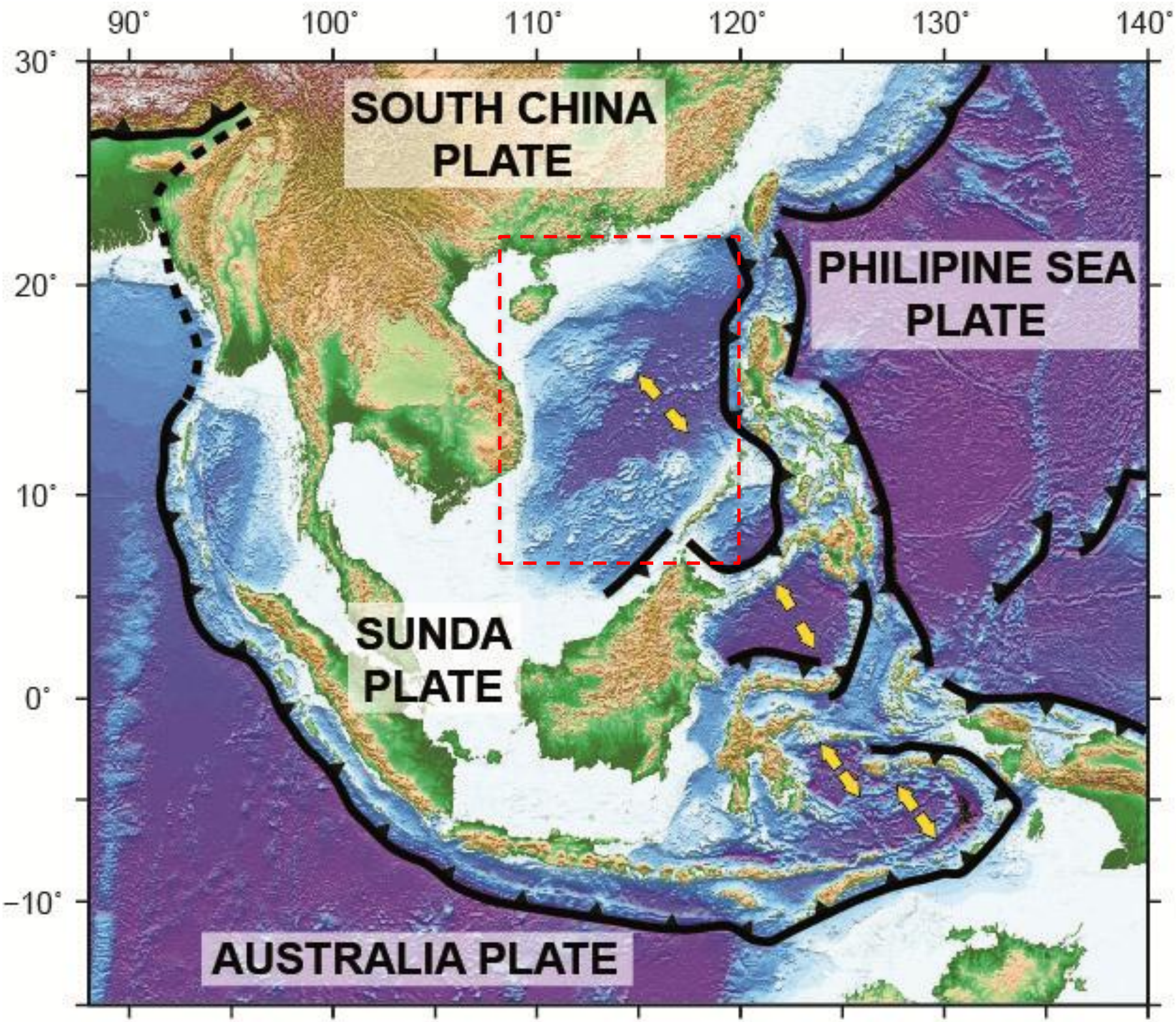


A
China
Hainan
Red River Fault System
Song Hong-Yengeahai Basin
Quiondongnan Basin
Pearl River Mouth Basin
Guangle Uplift
Penxi Seamounts
Macclesfield Bank
Zhongjiannan Basin
Manila Trench
Viet Nam
Phu Khanh Basin
Reed Bank
Cuu Long Basin
Nam Con Son Basin
Spratly Islands
Dangerous Grounds
Palawan
Baram Balabac Basin
Borneo-Palawan Trench
Luconia Balingian Basin
Sabah
Bathymetry (km)
-6 -5 -4 -3 -2 -1 0
Tonalite (157.8-159.1 Ma)
Monzogranite (127.2-153.6 Ma)
Paragneiss (114-123 Ma)
Silt-Sandstones (258-341 Ma)
B
China
SZN
QIZ
ESP-E1985
ESP-W1985
ESP-C1985
OBS2001
OBS1993
OBH1996-IV
OBS2006-1
OBS973-3
OBS973-1
OBS973-2
Fig. 2
Viet Nam
Palawan
Sabah
0 (km) 500
108° 110° 112° 114° 116° 118° 120°
6° 8° 10° 12° 14° 16° 18° 20° 22°

Geodynamical framework of SE Asia:



- Mesozoic-Cenozoic:

- Rollback of the Pacific Plate
- Formation of marginal basins

↓

Including, the **South China Sea**

The South China Sea:

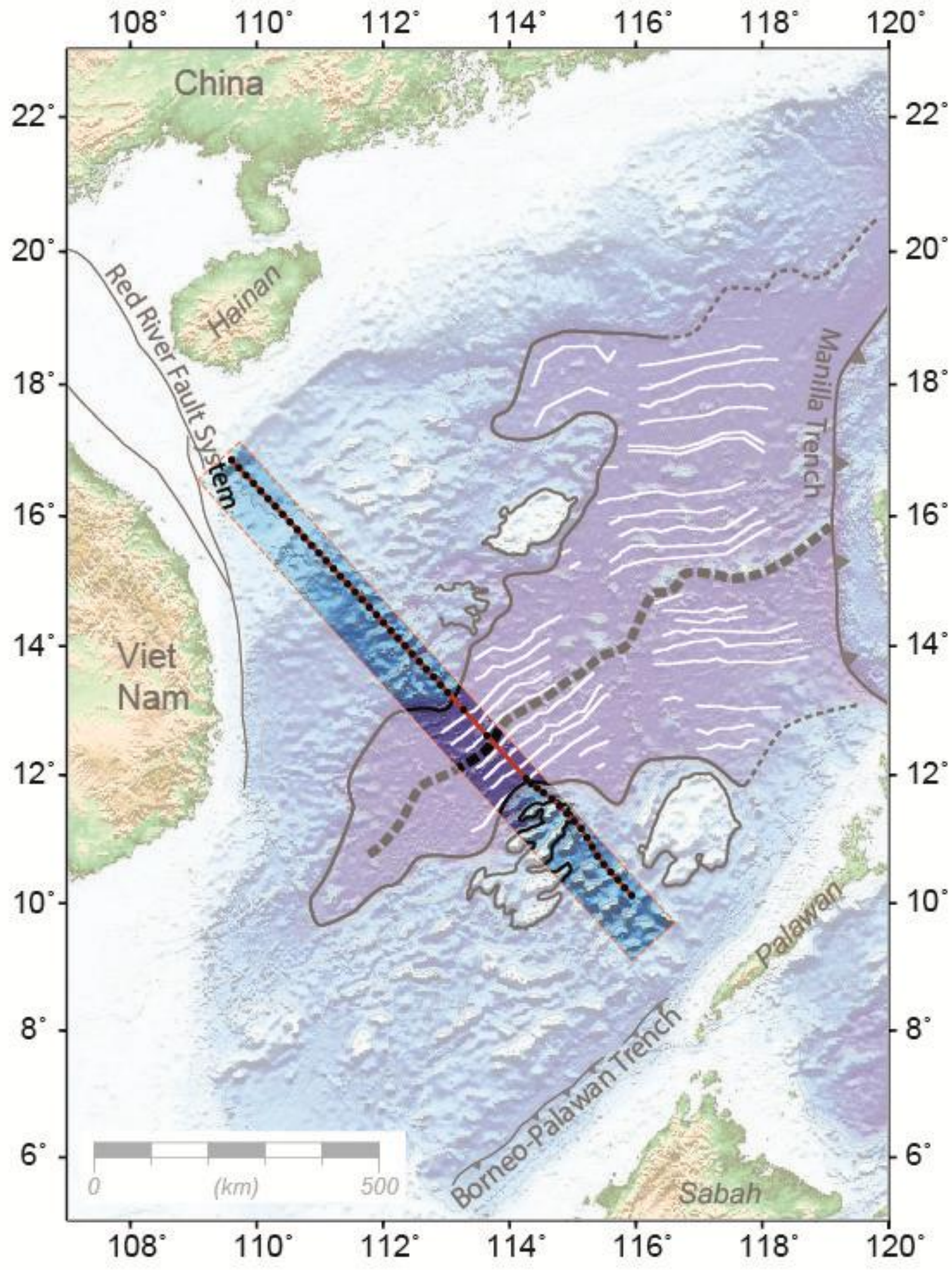
- Oceanic spreading started at 33Ma
- Propagated to the SW

- SW sub-basin: longest extended continental crust of SCS

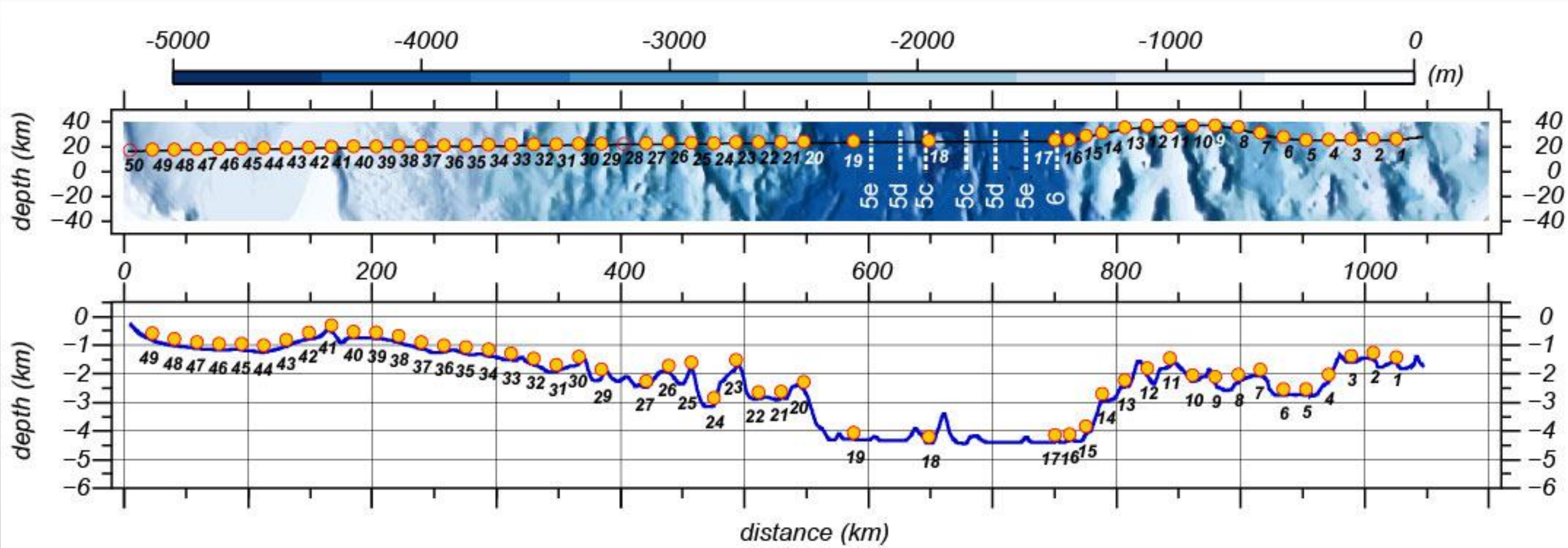
What is the crustal structure of such widely extended conjugate margins?

➡ 1000 km-long wide-angle refraction seismic profile

➡ runs across conjugate margins and ocean basin



Seismic experiment:



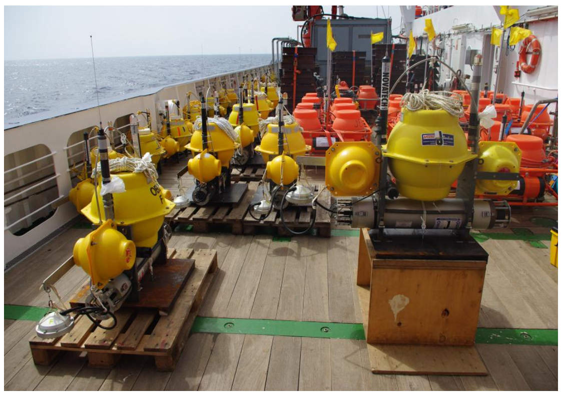
(Pichot et al., 2014, MPG)

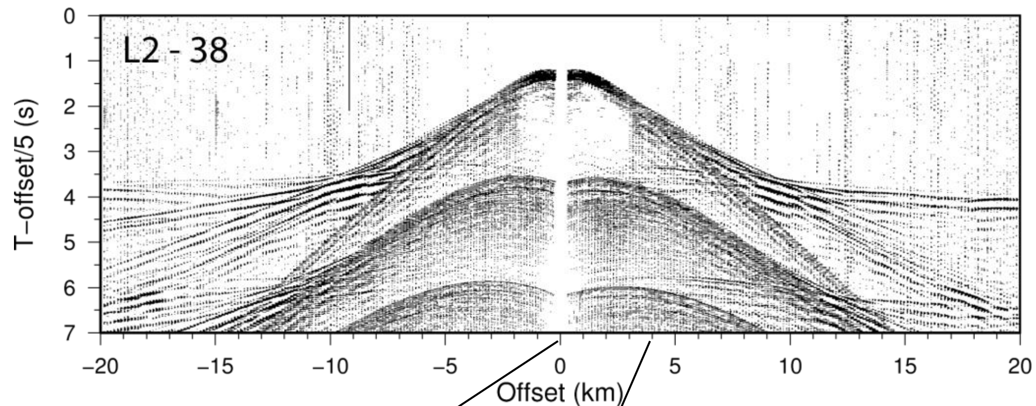
- Summary:

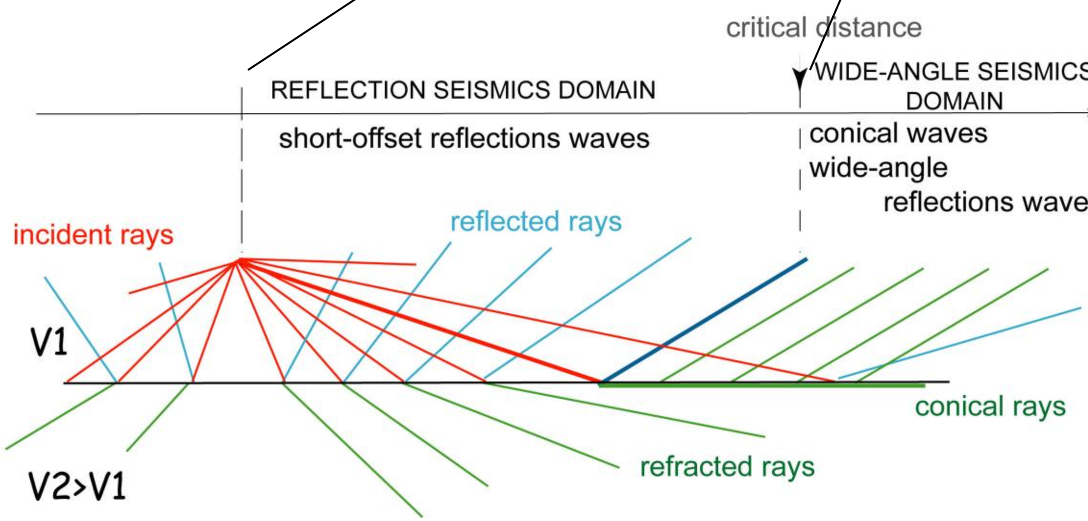
  - 50 Ocean Bottom Seismometers (OBS)
  - Spacing along continental crust = 18 km
  - Spacing along oceanic crust = variable
  - OBS-28 & OBS-50 = No data
  - MCS profile acquired two years later

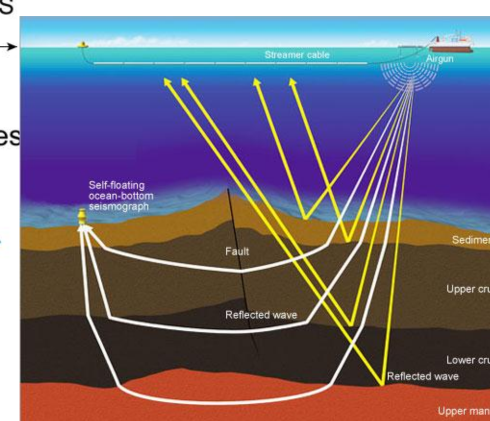
Data observation

OBS Data







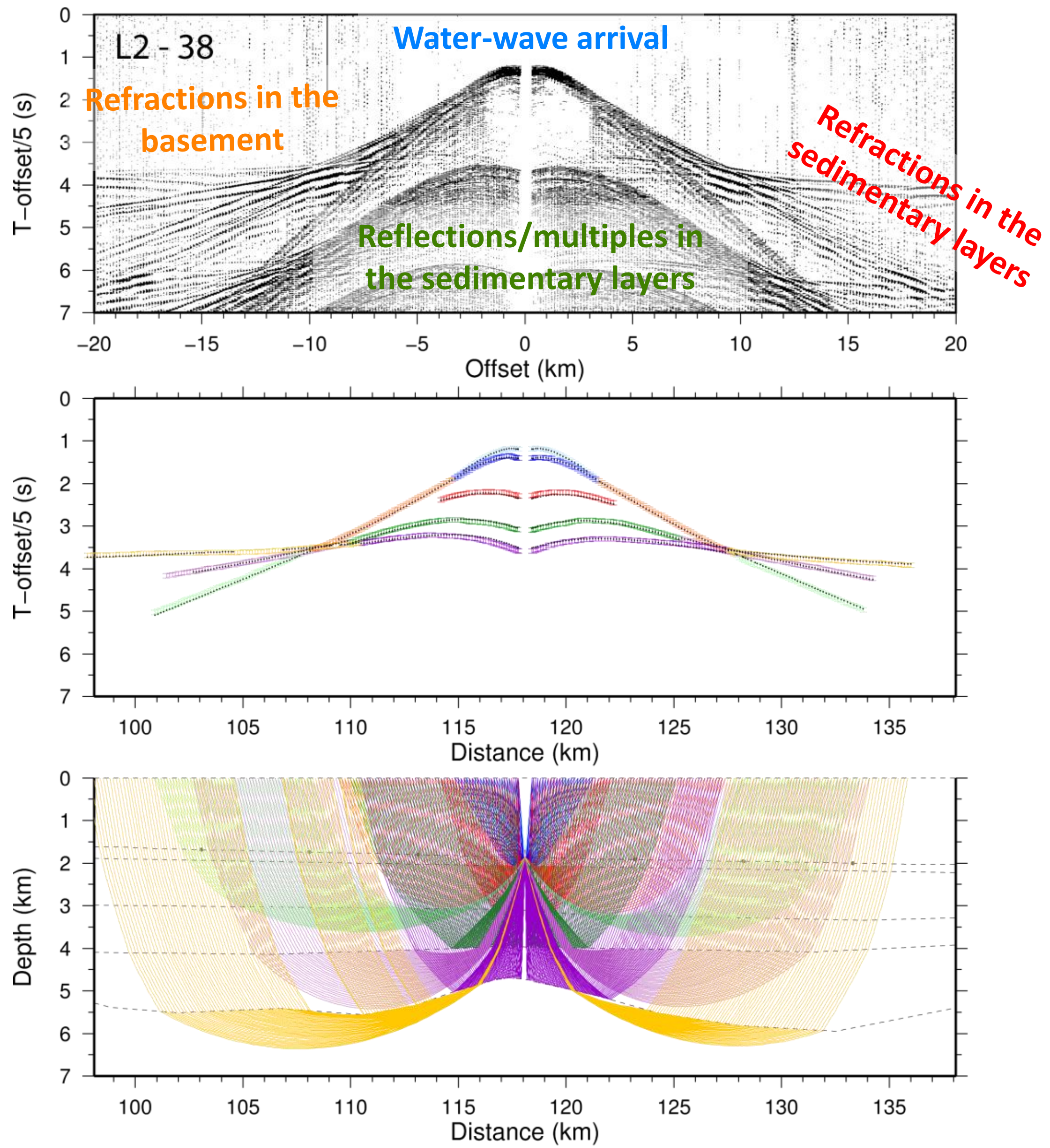


Seismic phases

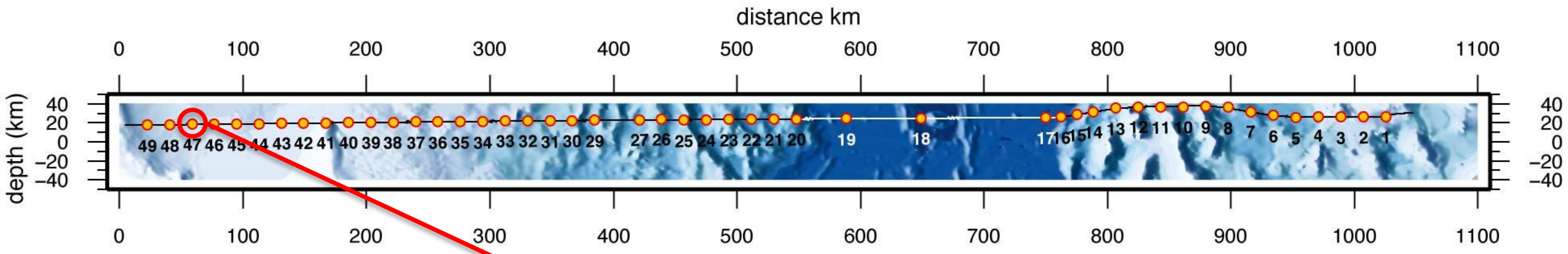
OBS Data

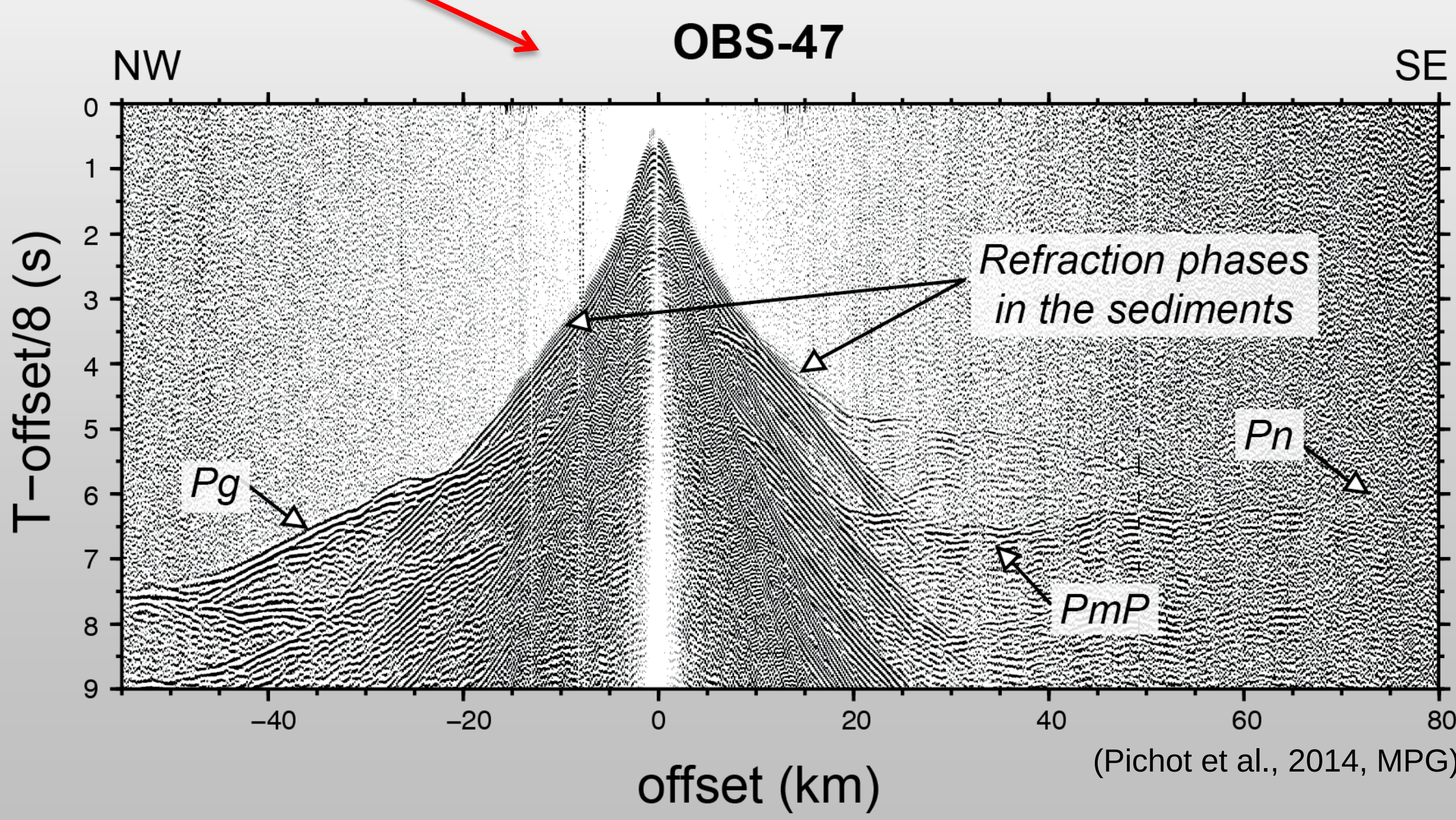
Arrival time picks

Ray tracing



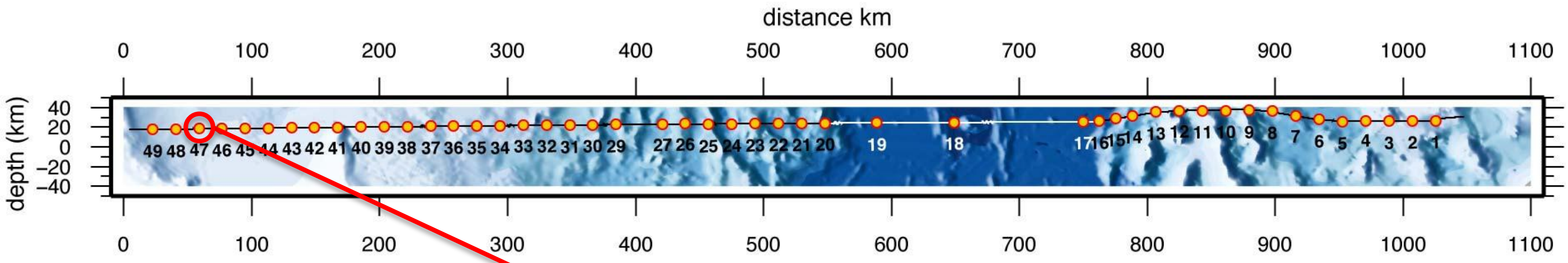
Seismic phases identification:

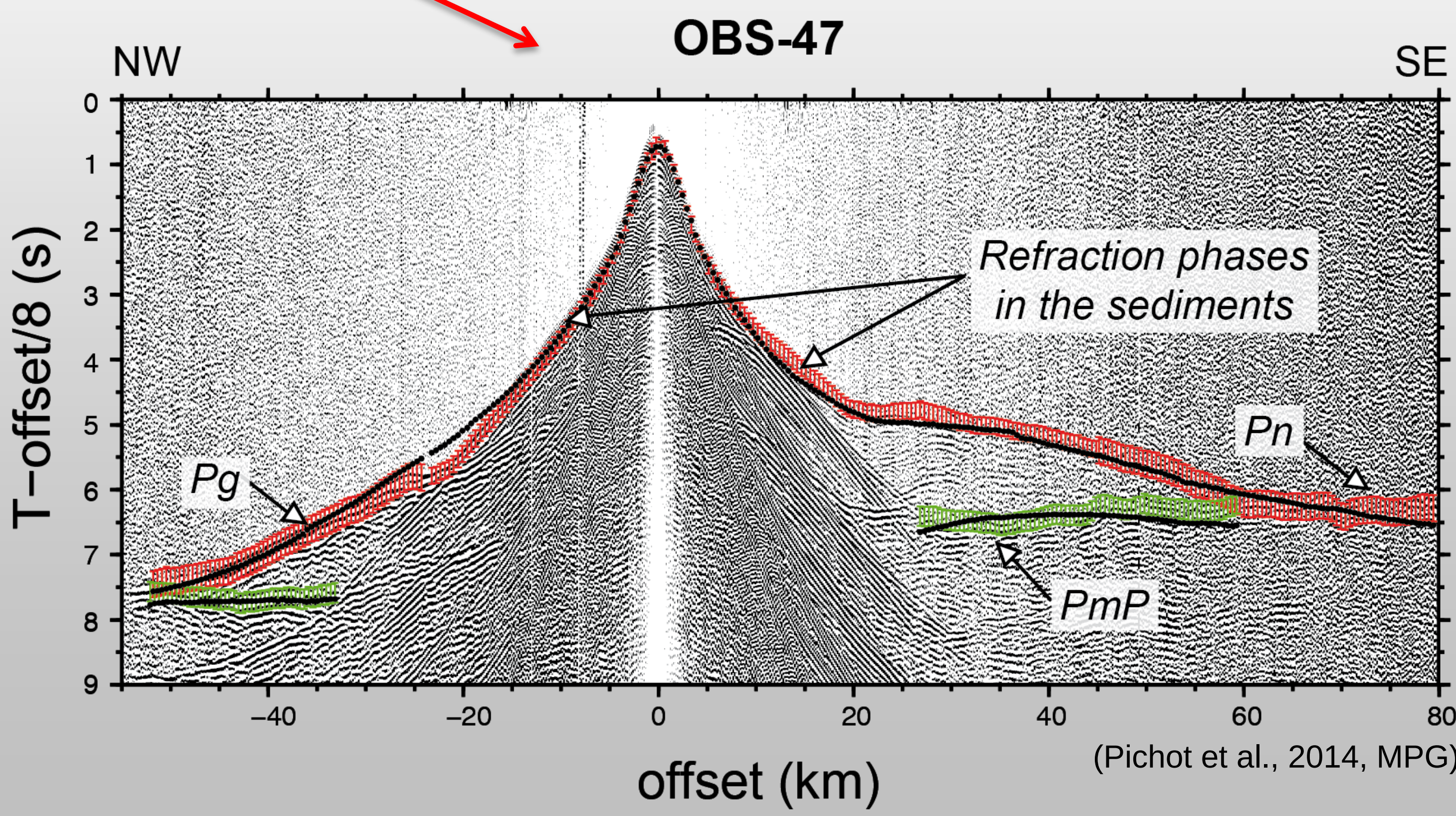




(Pichot et al., 2014, MPG)

Seismic phases identification:





(Pichot et al., 2014, MPG)

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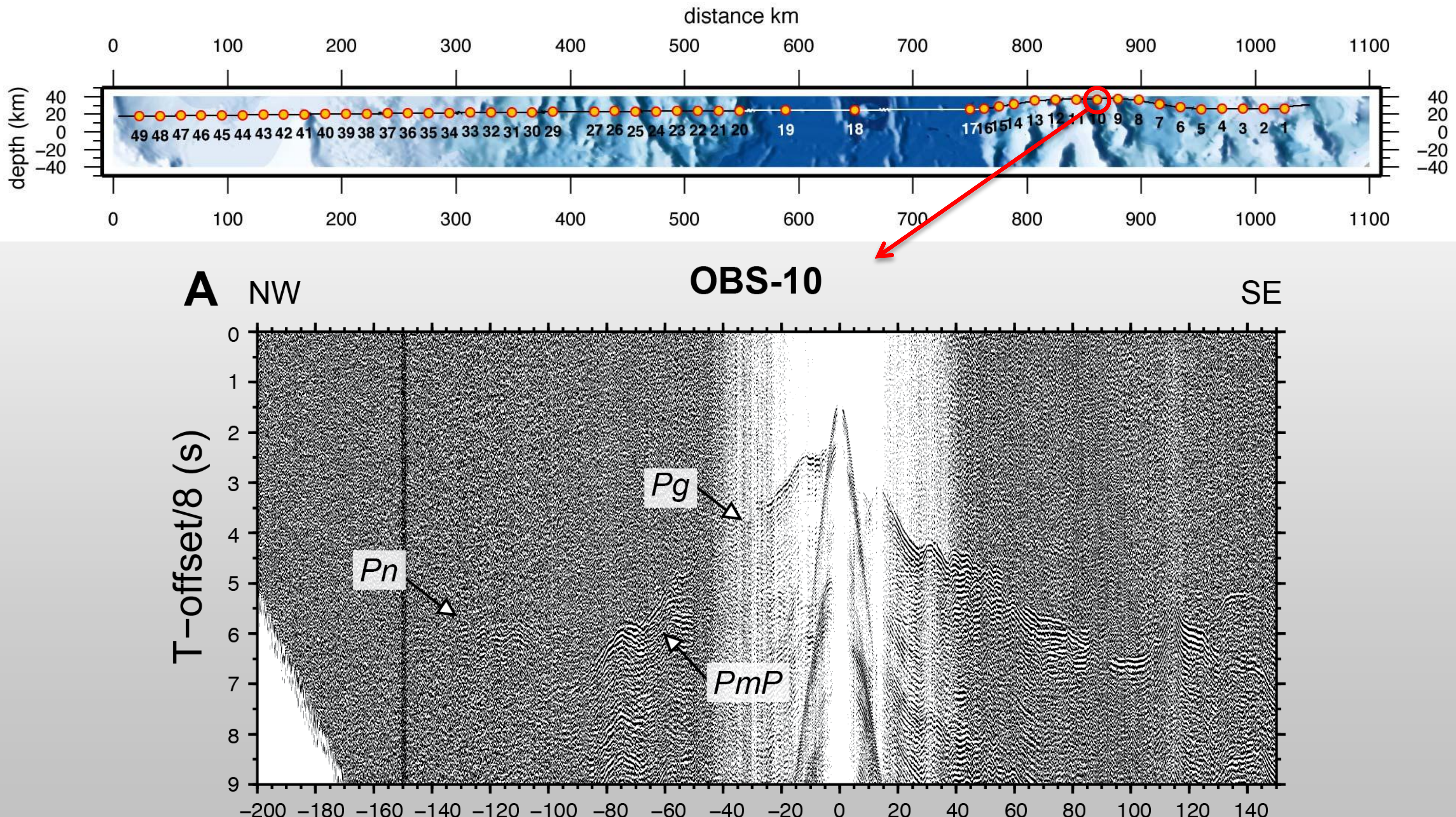

(Pichot et al., 2014, MPG)

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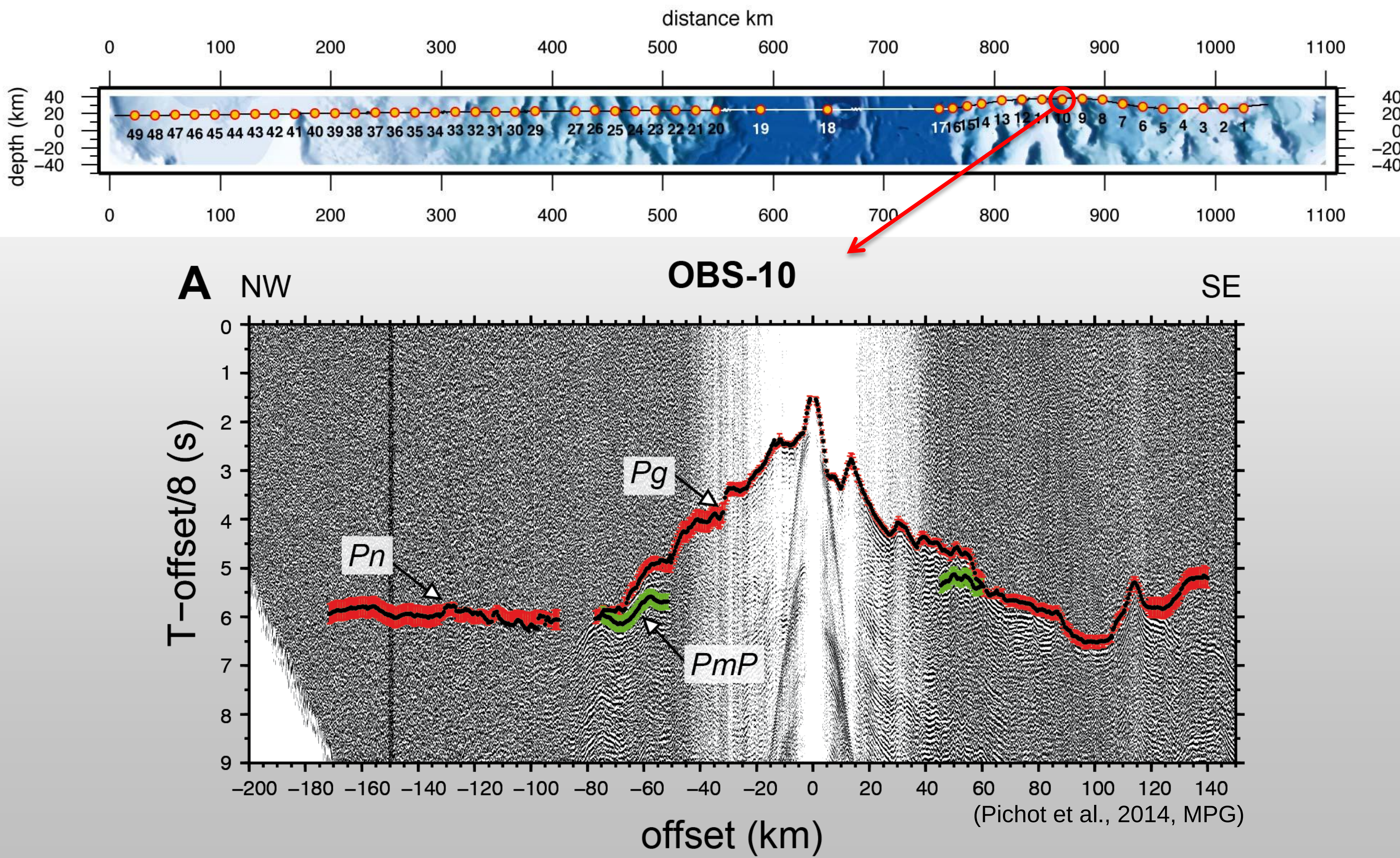

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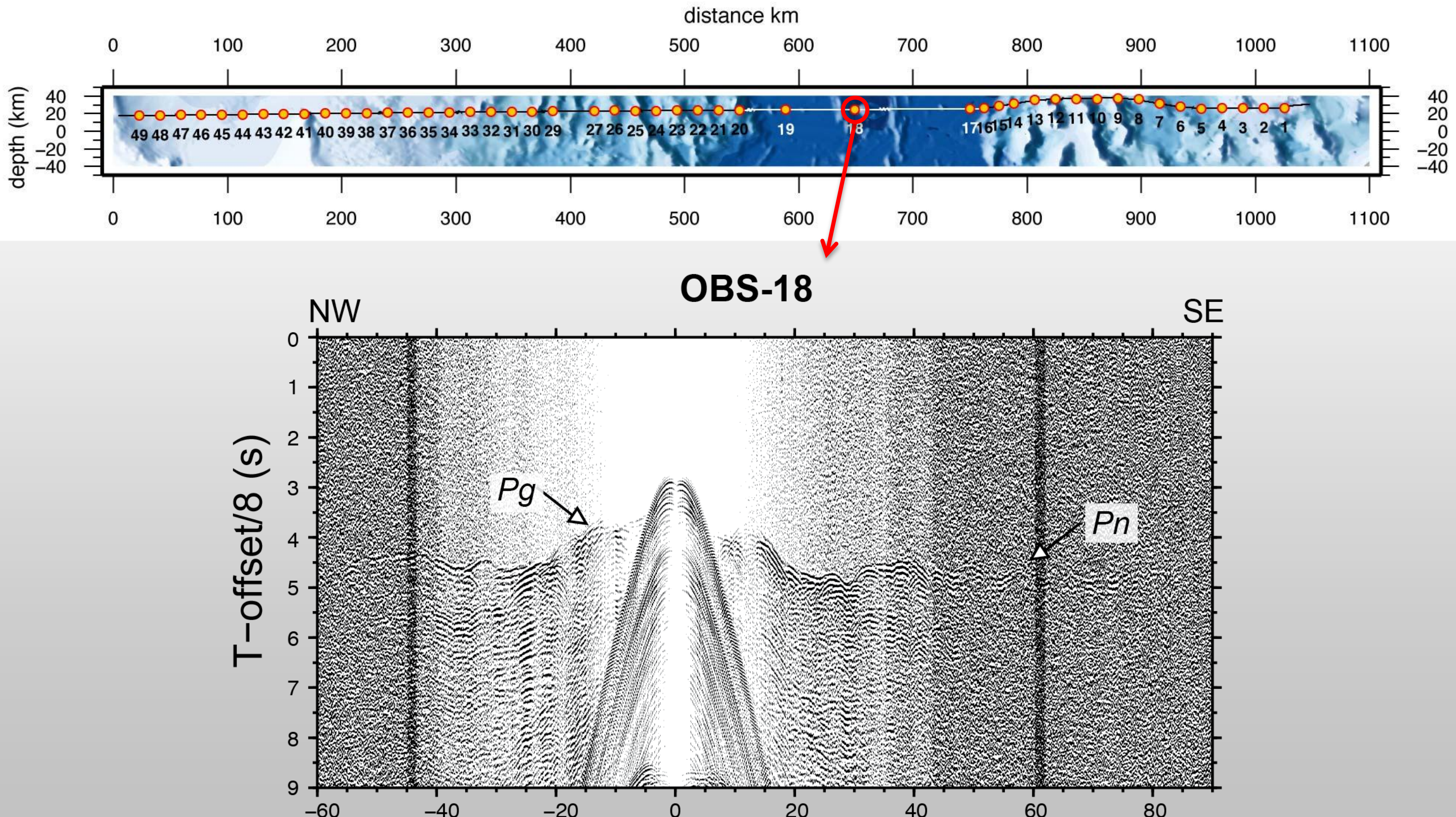

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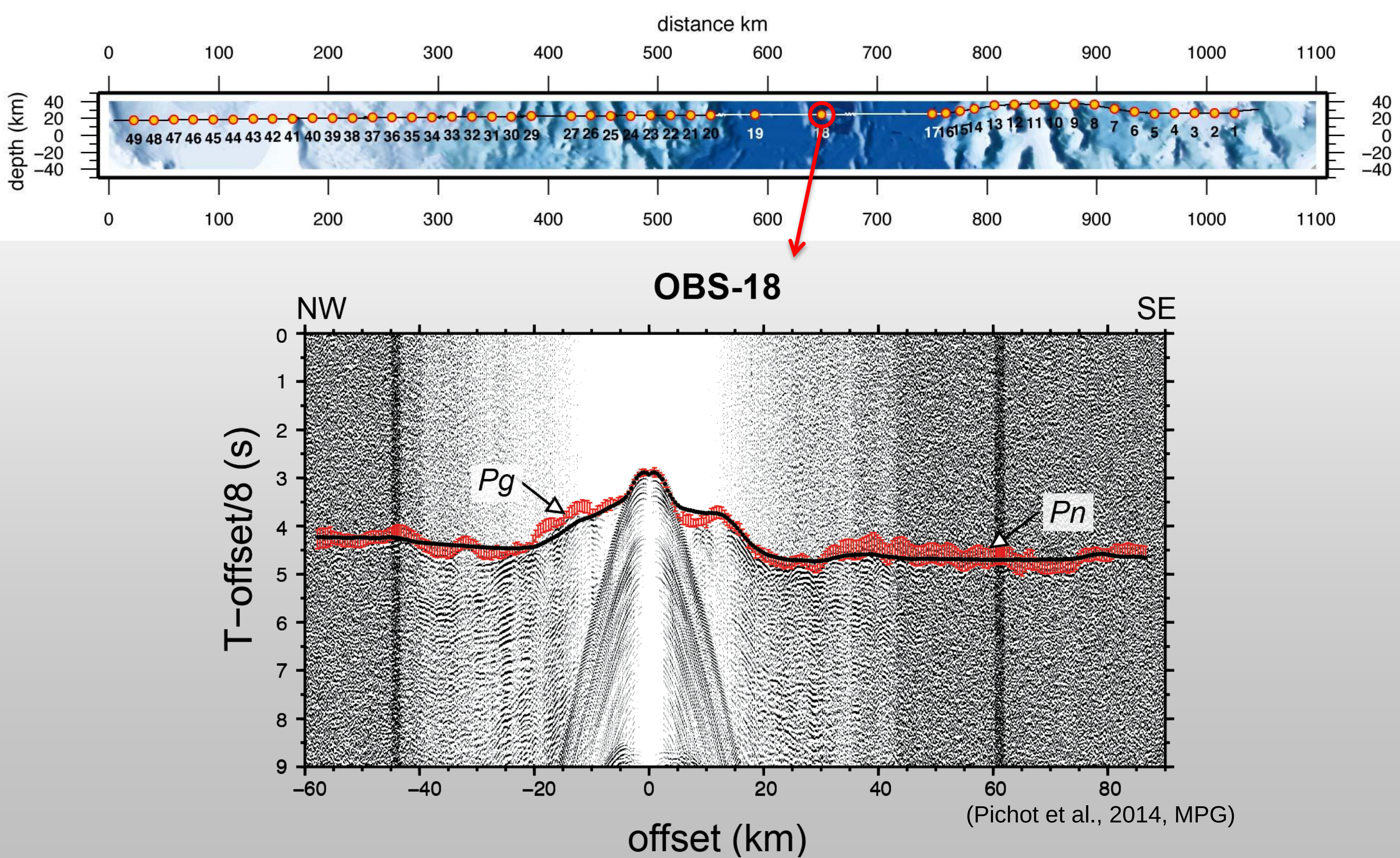
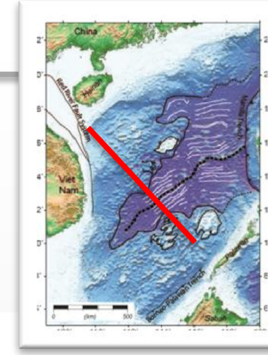
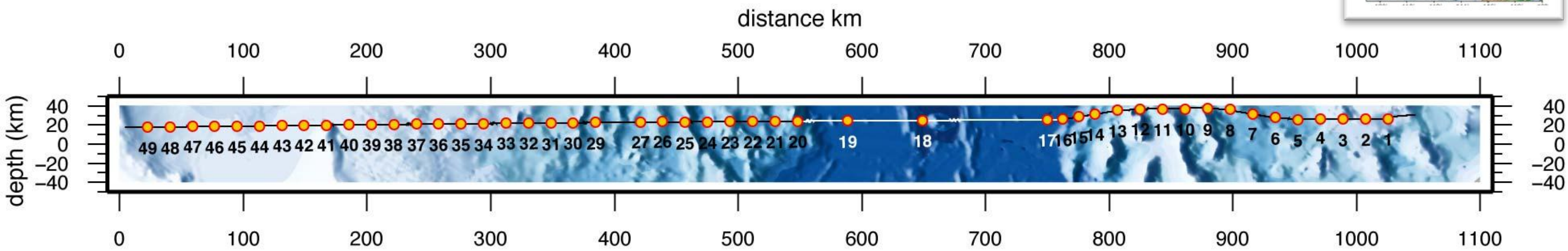


(Pichot et al., 2014, MPG)



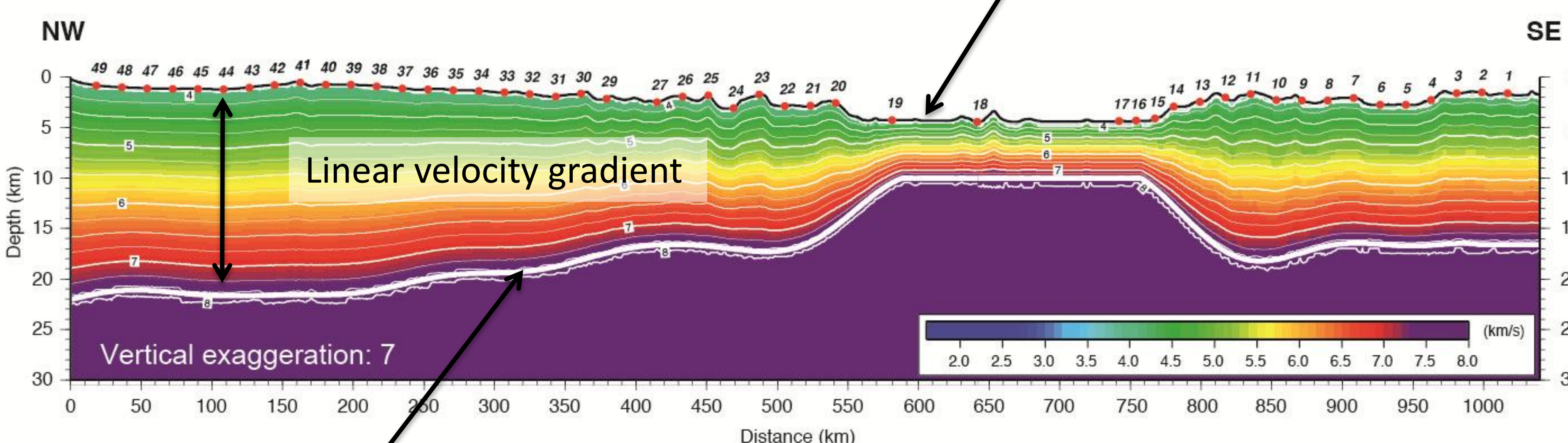
Modeling: joint reflection and refraction seismic travel time inversion
(TOMO2D, Korenaga et al. 2000)

INITIAL VELOCITY MODEL:



Input parameters:

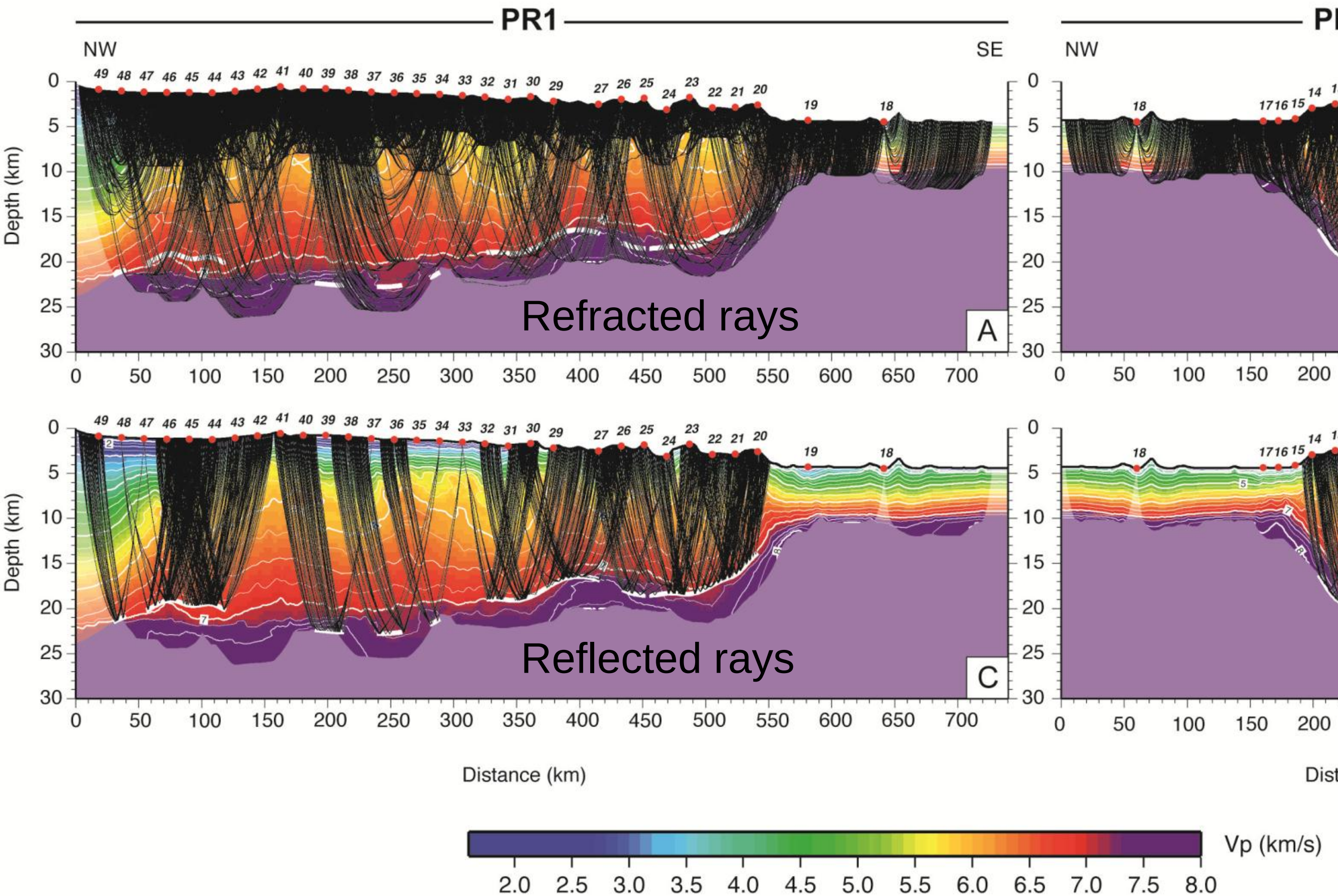
Seafloor bathymetry

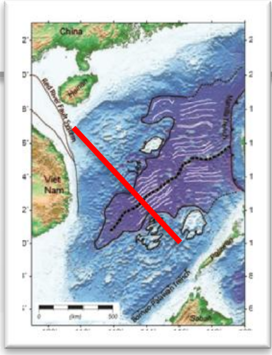


Moho depth
(defined by Bouguer gravity inversion)

(Pichot et al., 2014, MPG)

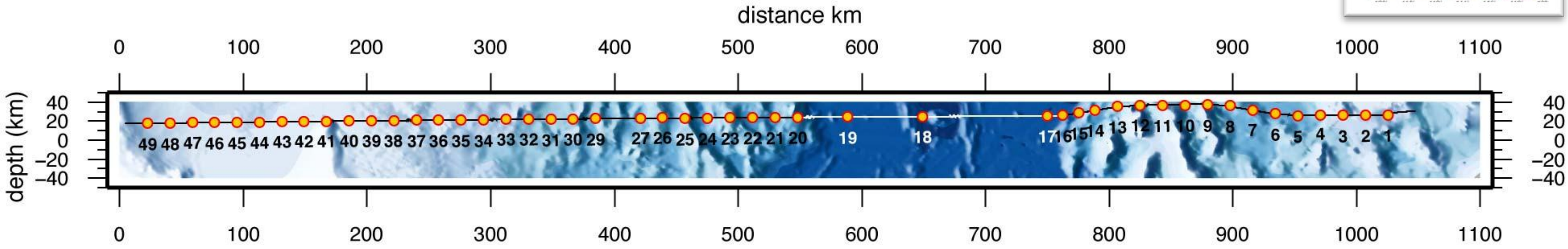
Modeling: joint reflection and refraction seismic travel time inversion

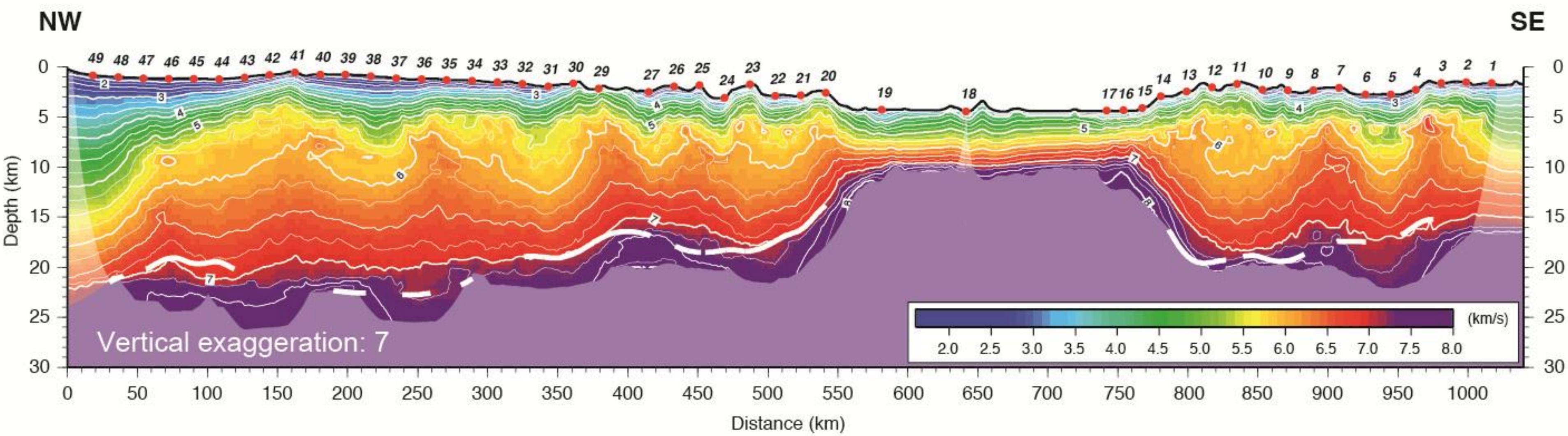




Modeling: joint reflection and refraction seismic travel time inversion

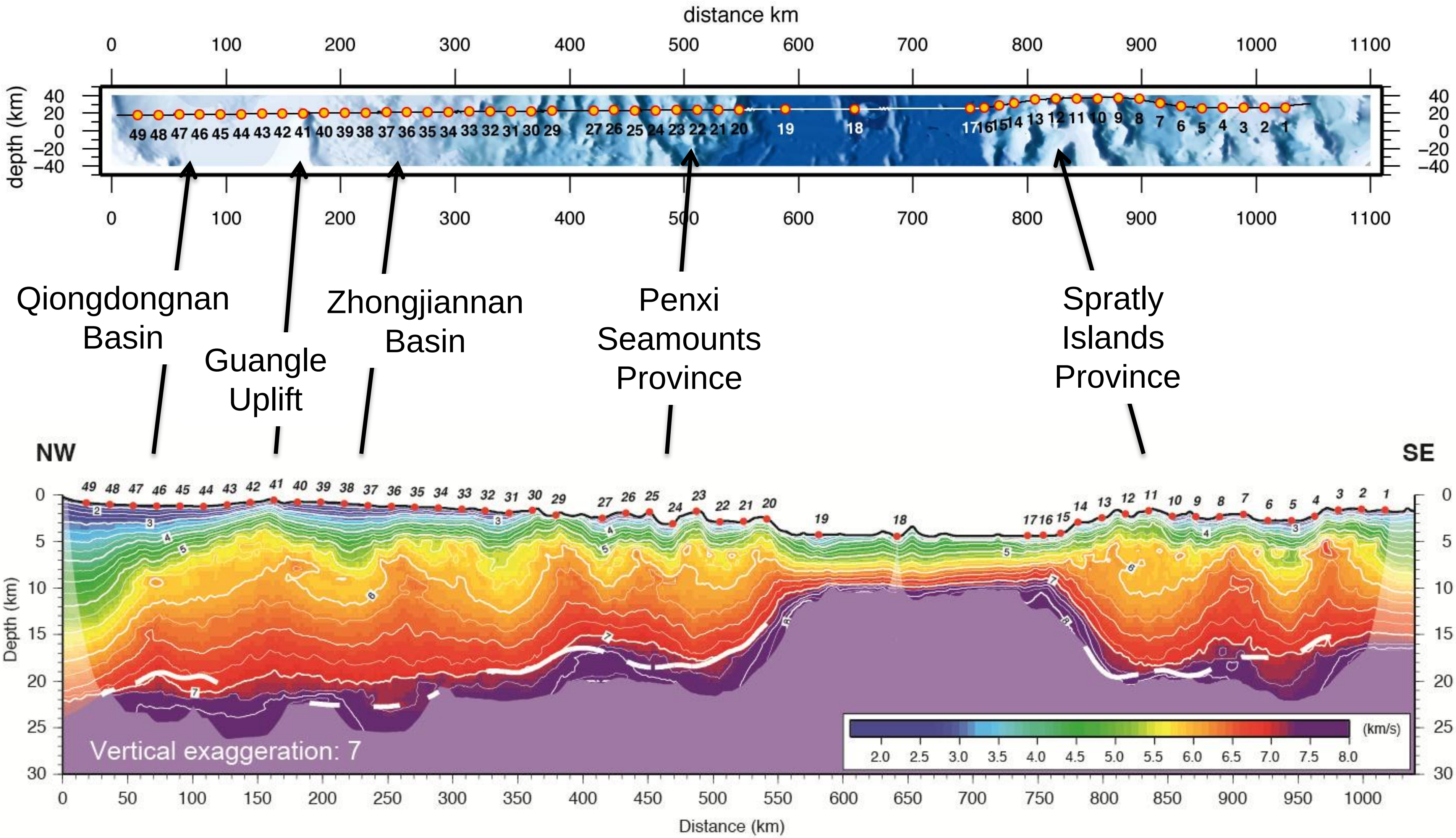
FINAL VELOCITY MODEL:



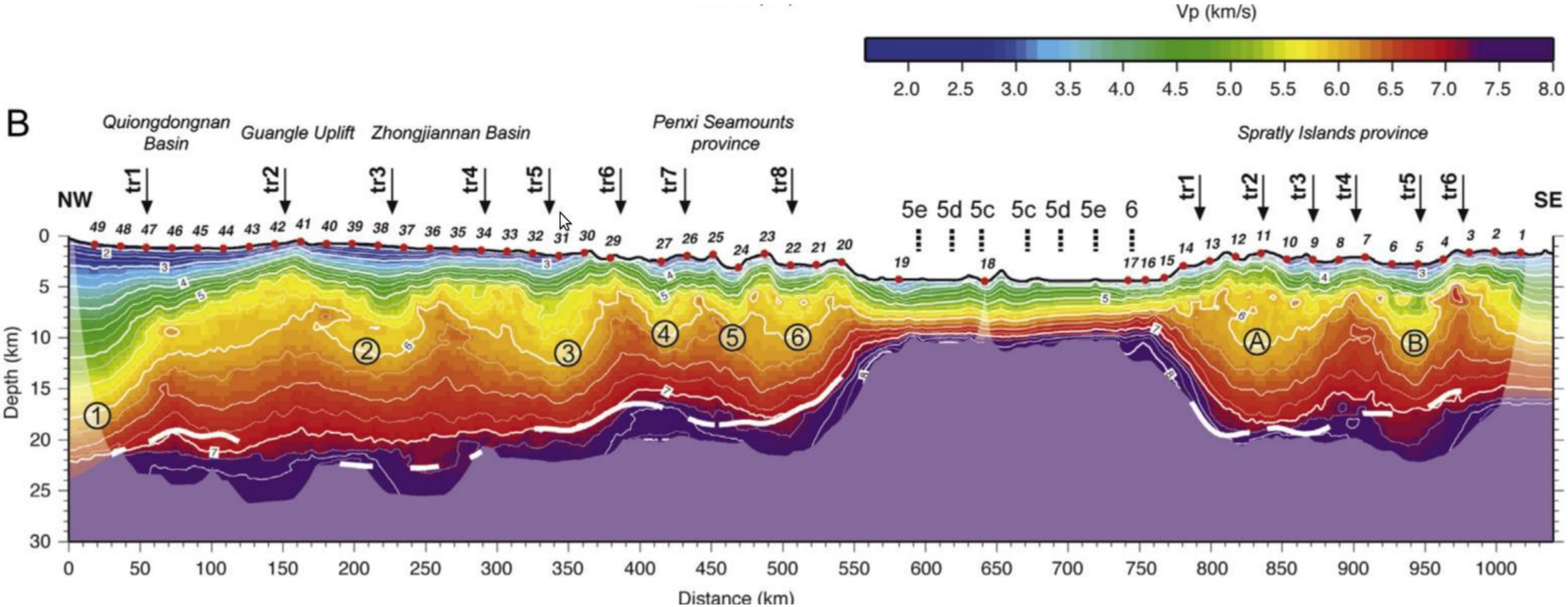


(Pichot et al., 2014, MPG)

FINAL VELOCITY MODEL: • Subsurface structures

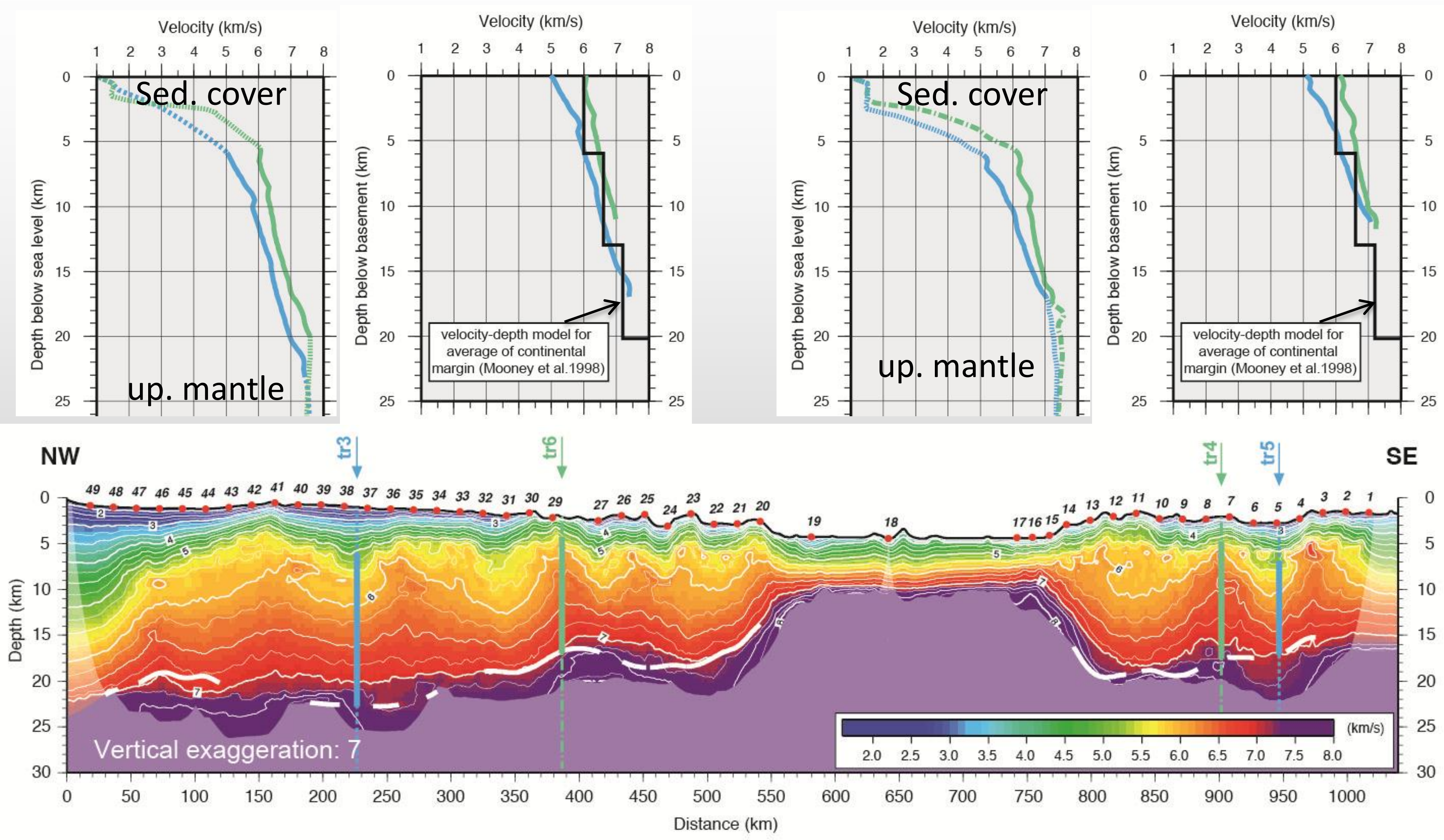


• Well imaged basins and basement highs

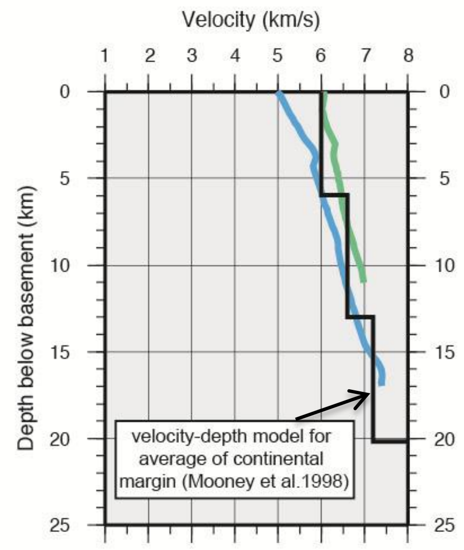


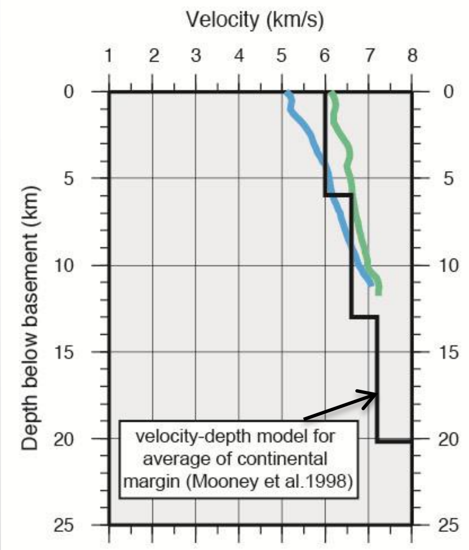
Vp (km/s)
2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0
B
Quiongdongnan Basin
Guangle Uplift
Zhongjiannan Basin
Penxi Seamounts province
Spratly Islands province
NW
SE
tr1 tr2 tr3 tr4 tr5 tr6 tr7 tr8
5e 5d 5c 5c 5d 5e 6
tr1 tr2 tr3 tr4 tr5 tr6
Depth (km)
Distance (km)

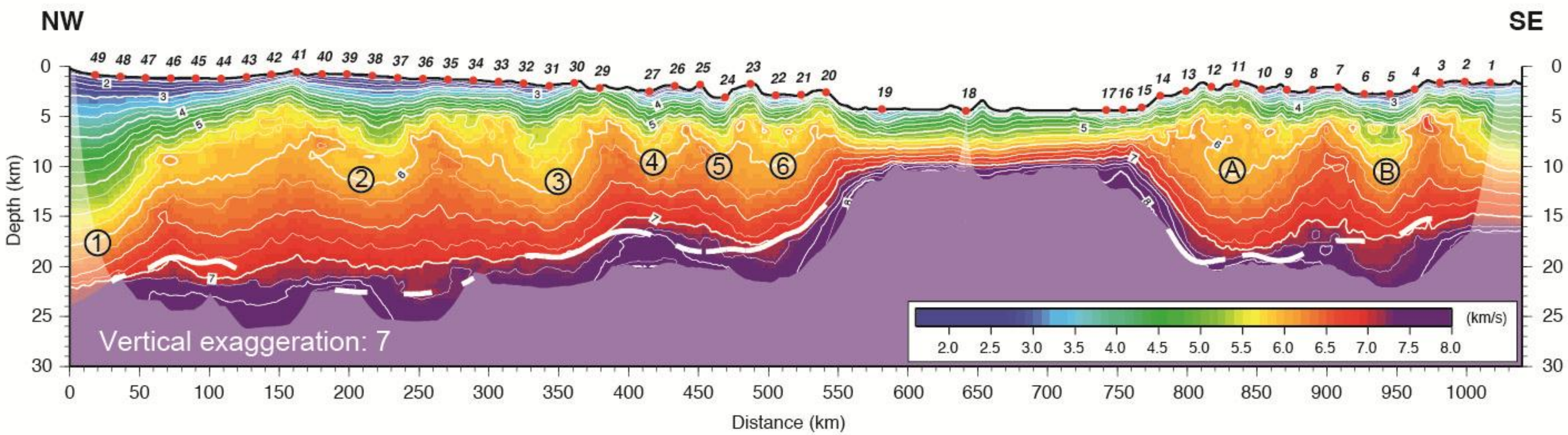
FINAL VELOCITY MODEL: • Strong lateral velocity variation in the upper and mid. crust



FINAL VELOCITY MODEL: • Strong lateral velocity variation in the upper and mid. crust



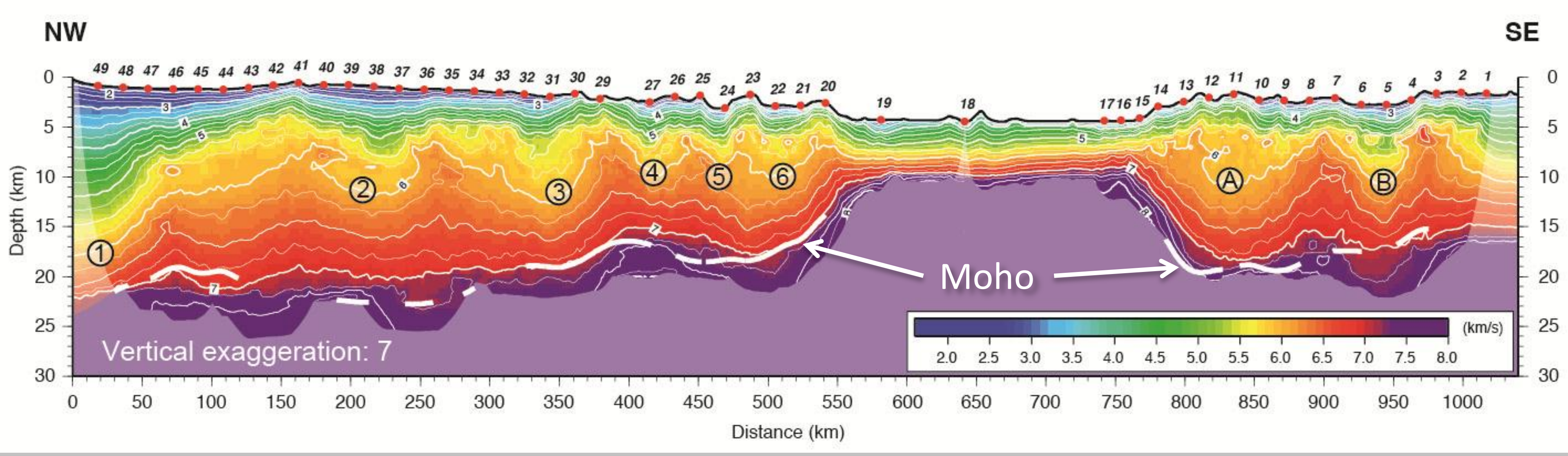




• Presence of Low Velocity Bodies (LVBs)

FINAL VELOCITY MODEL: • Base of the crust

➡ No strong velocity variations at the base of the crust

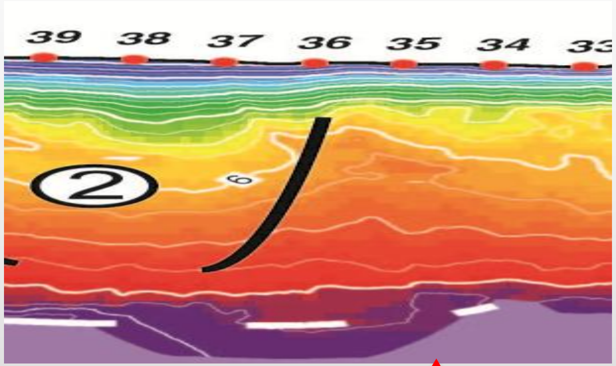


- Rather flat geometry at the lowermost crust and Moho interface

MECHANISM OF EXTENSION

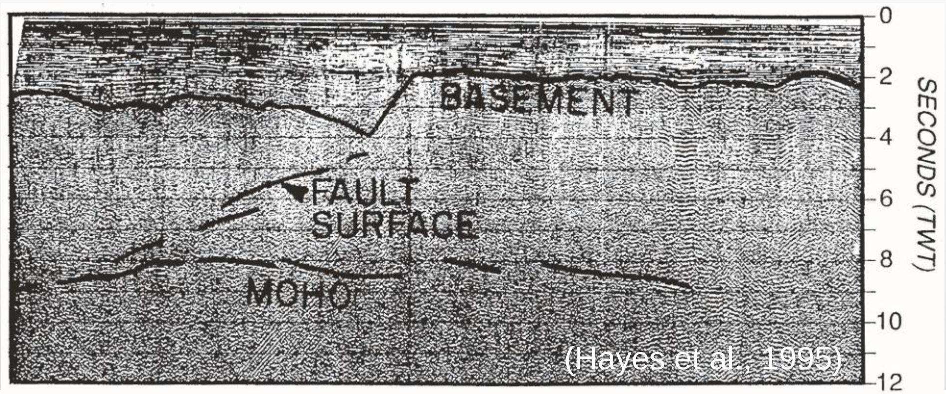
- Refraction data:

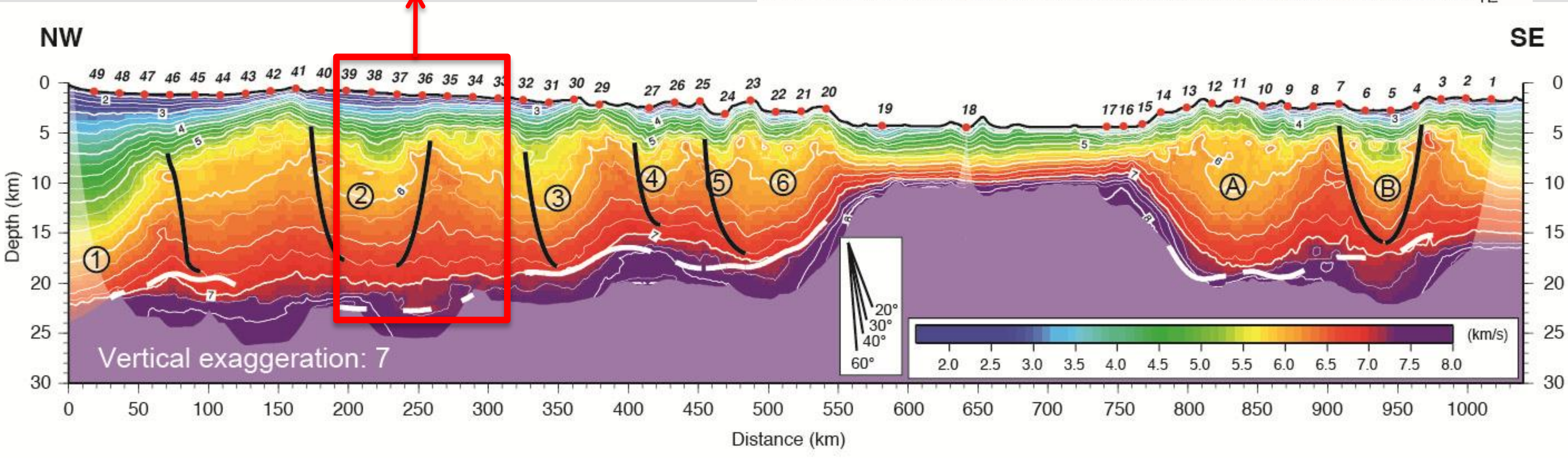
Abrupt velocity contrast through the upper-mid. crust



- Reflection data:

"Throughgoing crustal fault"



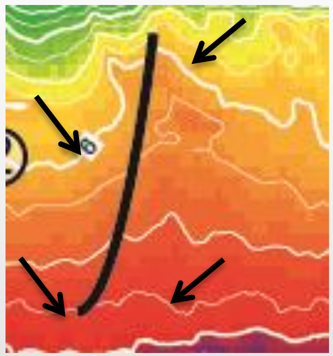


- Up. and Mid. crust = brittle deformation; Large-scale normal fault every 45-90 km

MECHANISM OF EXTENSION

1)

2)

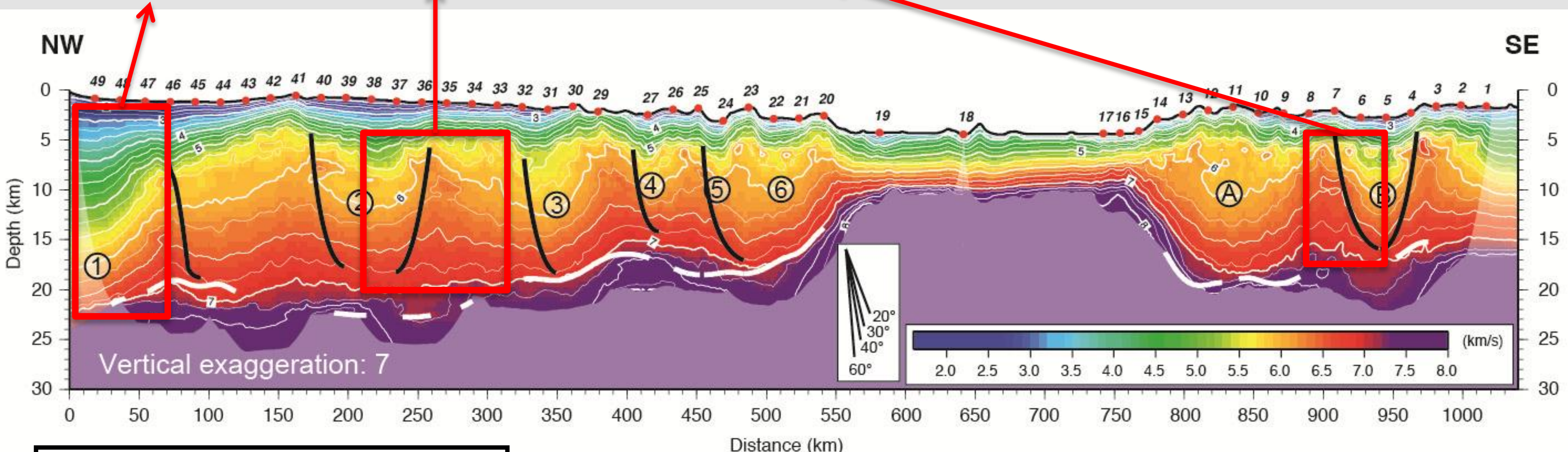


3)

1) • Thin lower crust where thick sediment pile exists

2) • No strong lateral velocity variation in the lowermost crust

3) • Accumulation of lower crust at the footwall of the fault

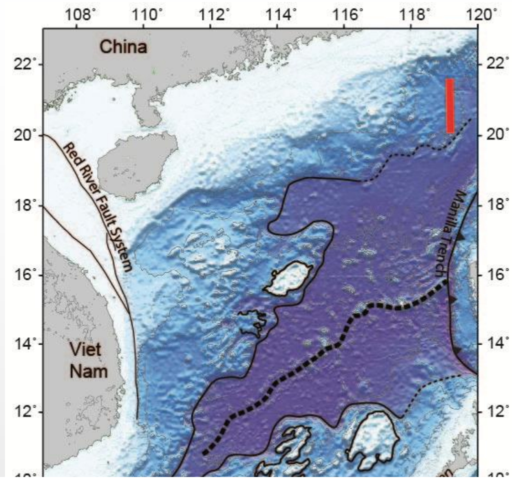


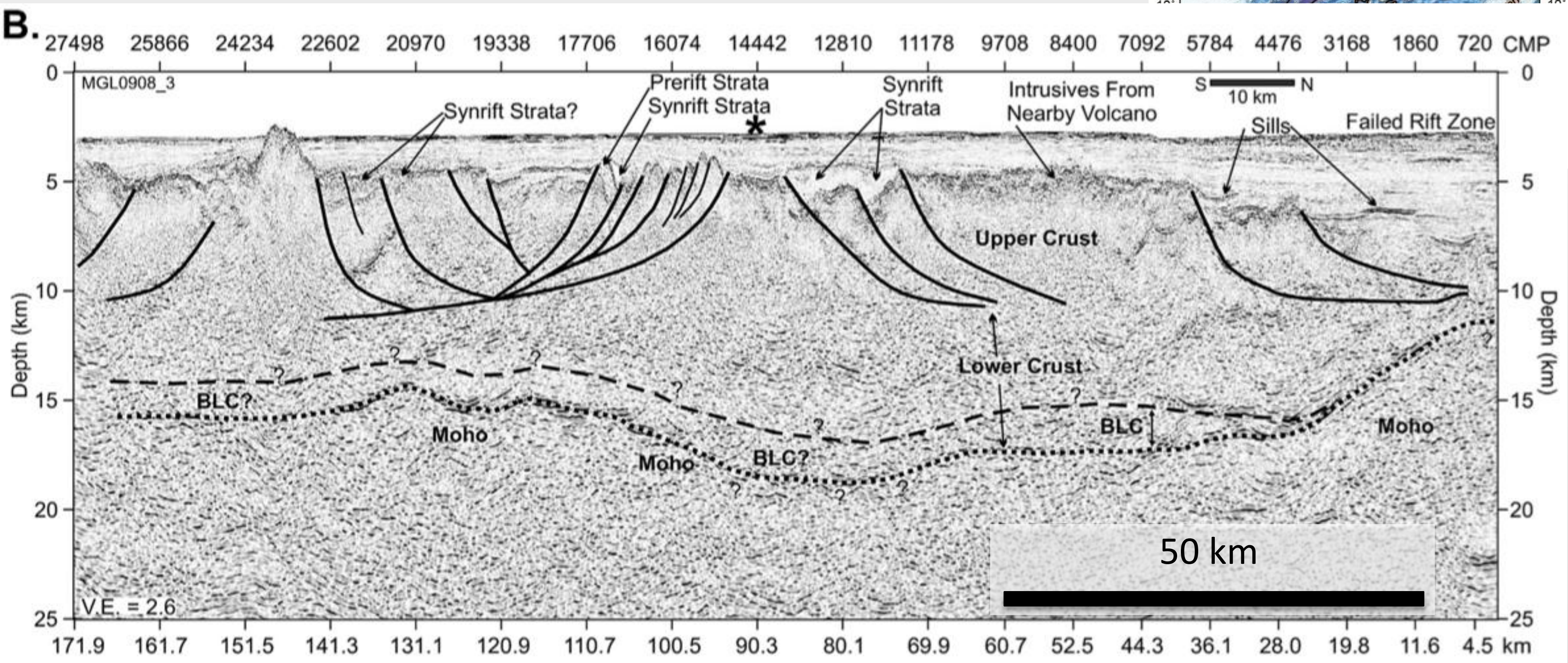
- Flat Moho
- Ductile lowermost crust

MECHANISM OF EXTENSION

- In agreement with reflection seismic data:

➡ rift-related normal faults root into a mid-lower-crustal detachment





(McIntosh et al., 2014, MPG)

MECHANISM OF EXTENSION

- In agreement with reflection seismic data:

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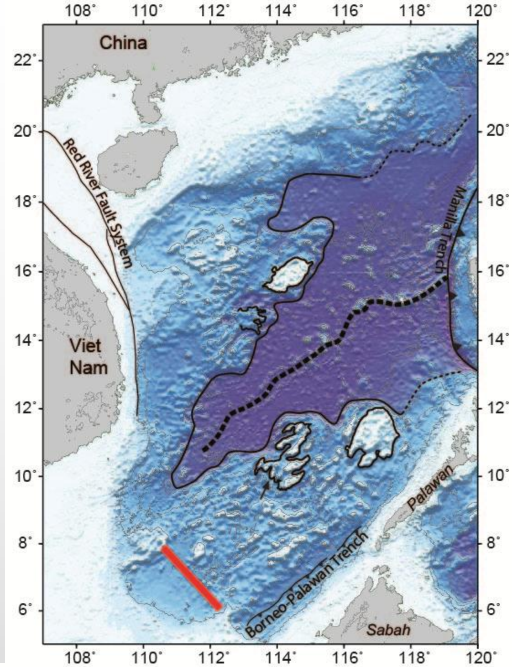
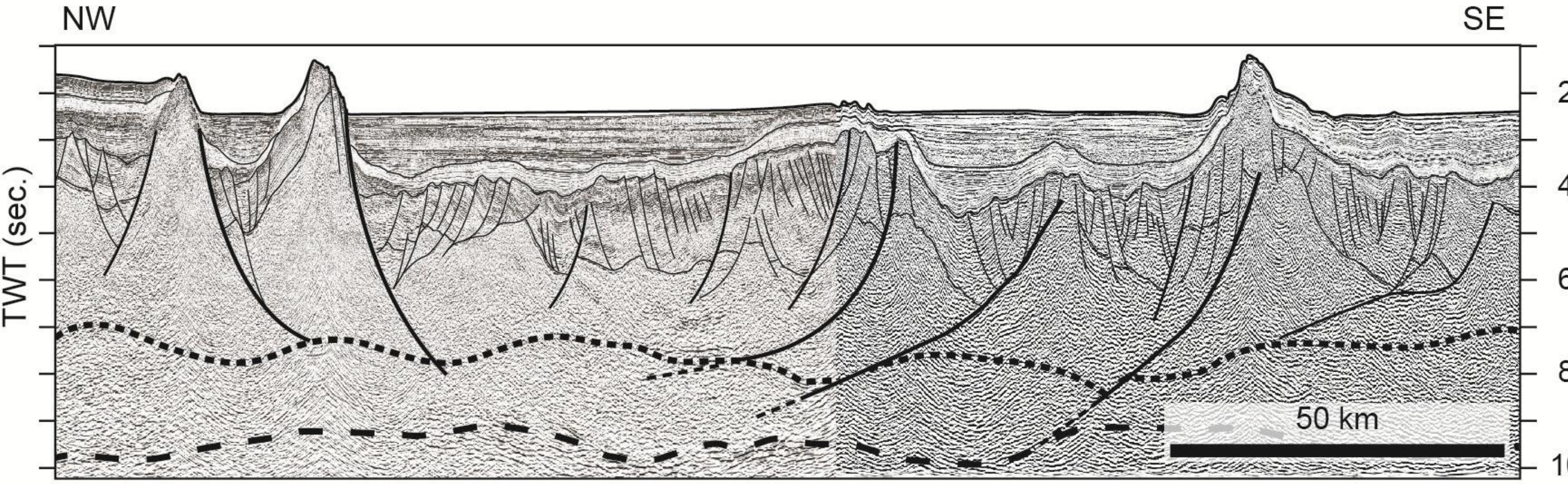


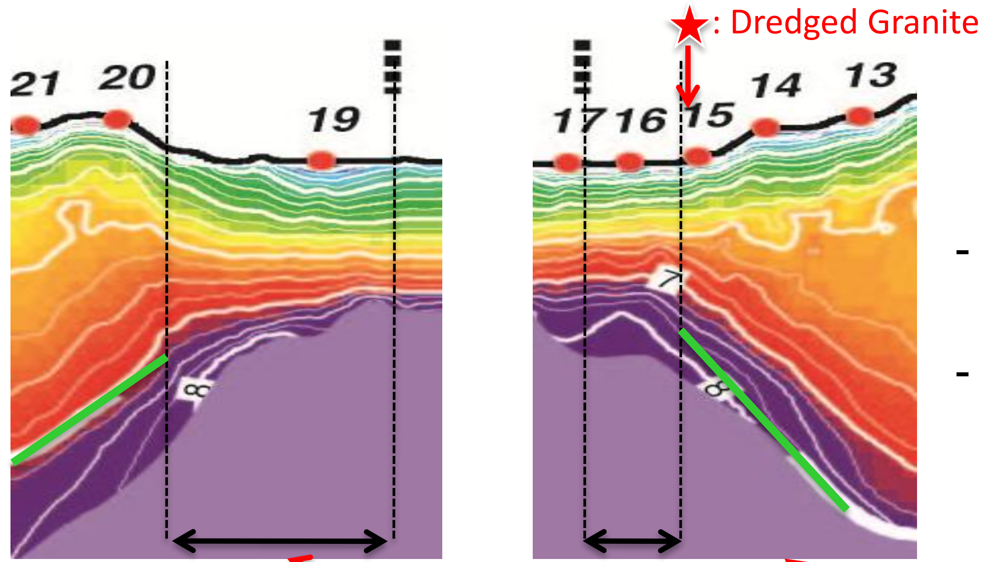


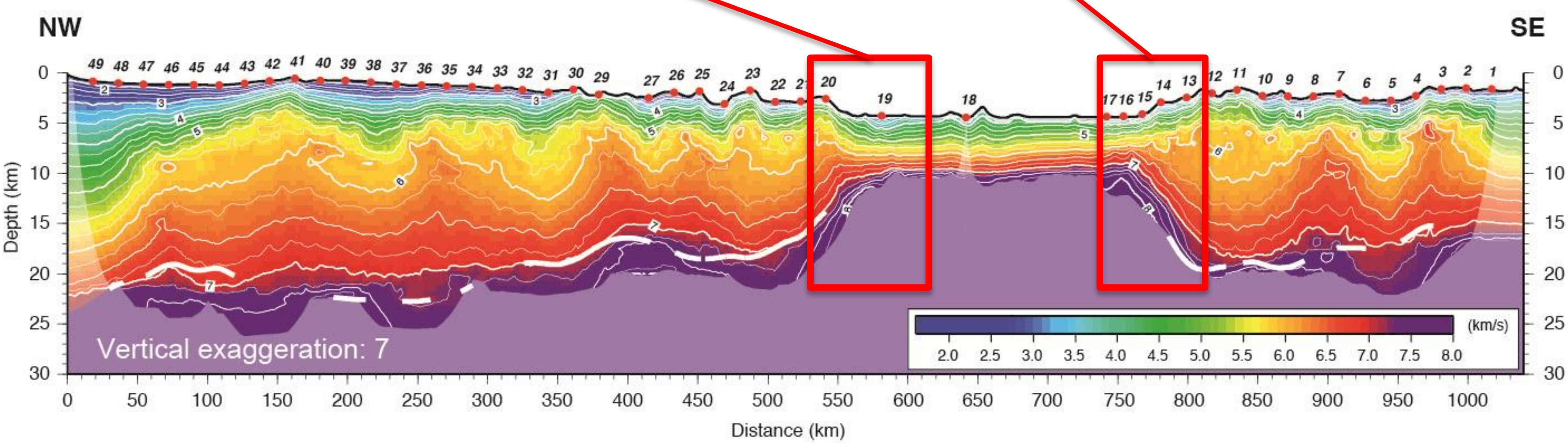
(modified from Savva, 2013, Ph.D.)

FINAL VELOCITY MODEL: • The Continent-Ocean Transition (COT)

- Northern COT:
  - no larger than 60 km
  - angle = 5°

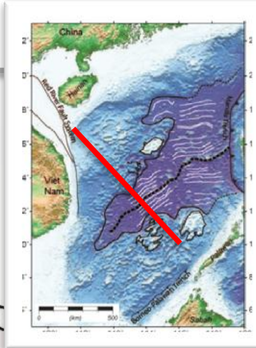
- Southern COT:
  - no larger than 30 km
  - angle = 8.5°

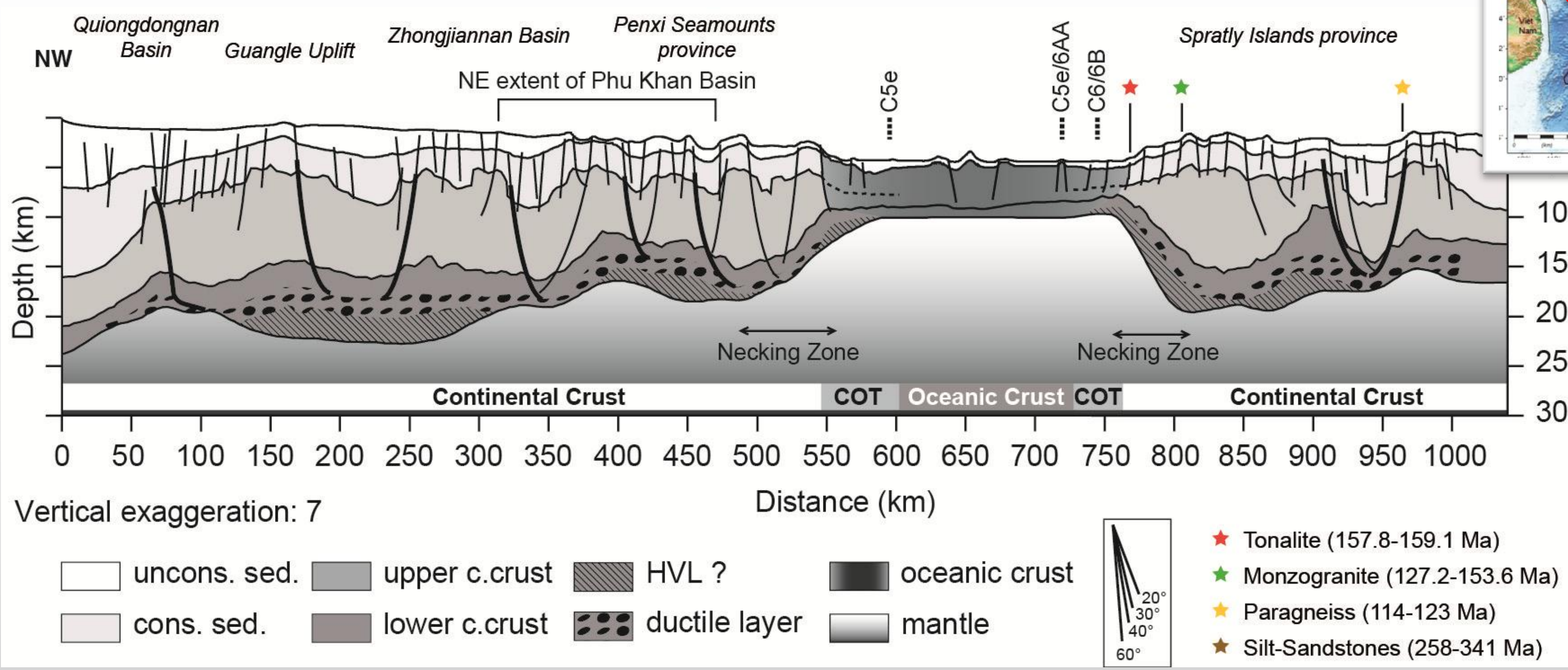




- Narrow COT, slightly asymmetric

The crustal structure of a very wide rifted continental margin:



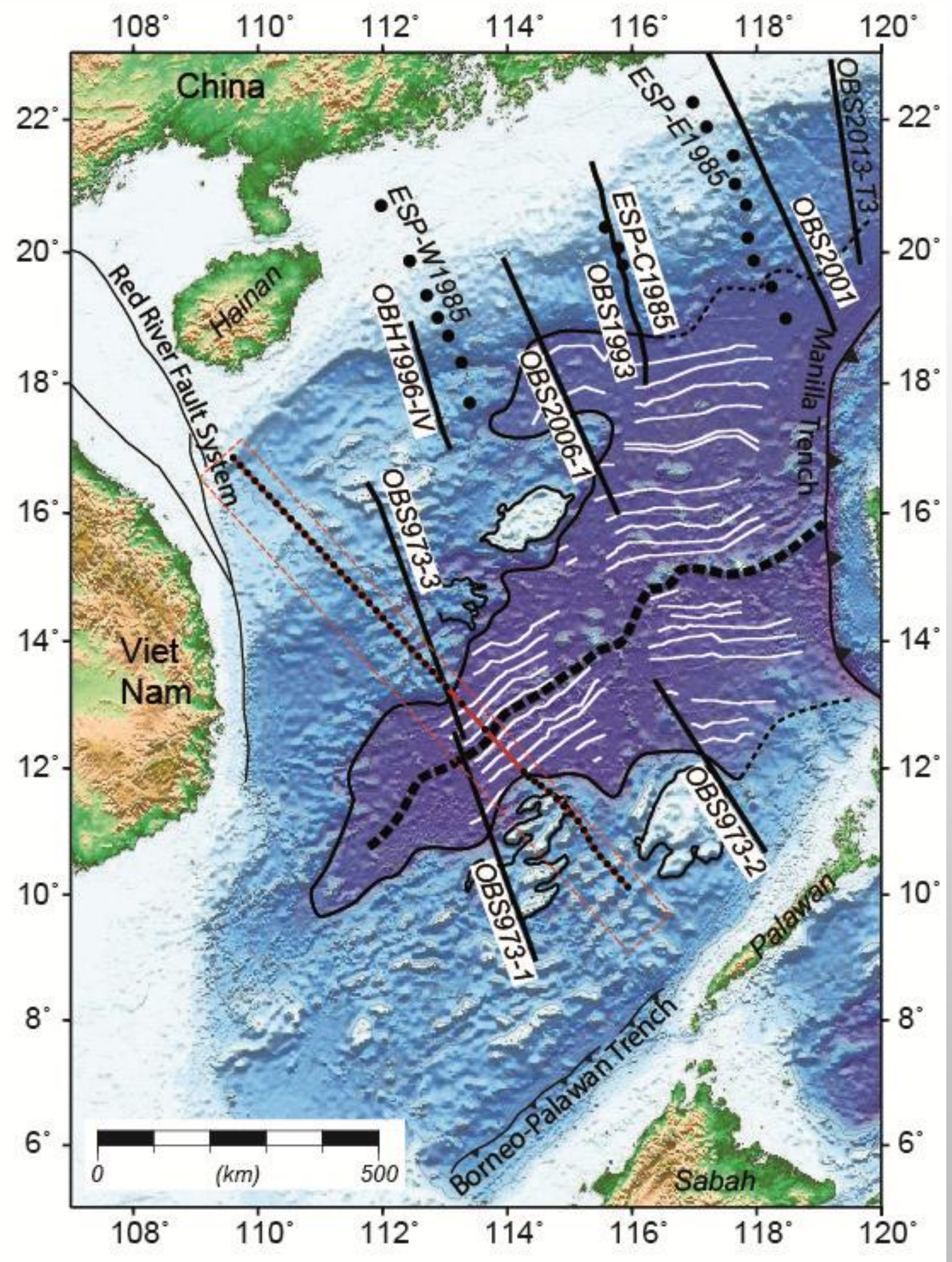


(Pichot et al., 2014, MPG)

- Conjugate margins share common structural characteristics
- Rather flat Moho
- Up. and mid. crust experienced brittle deformation
- Lowermost crust experienced ductile deformation
- Sedimentary basin located above Low Velocity Bodies

Appendix
Additional Slides

The South China Sea:

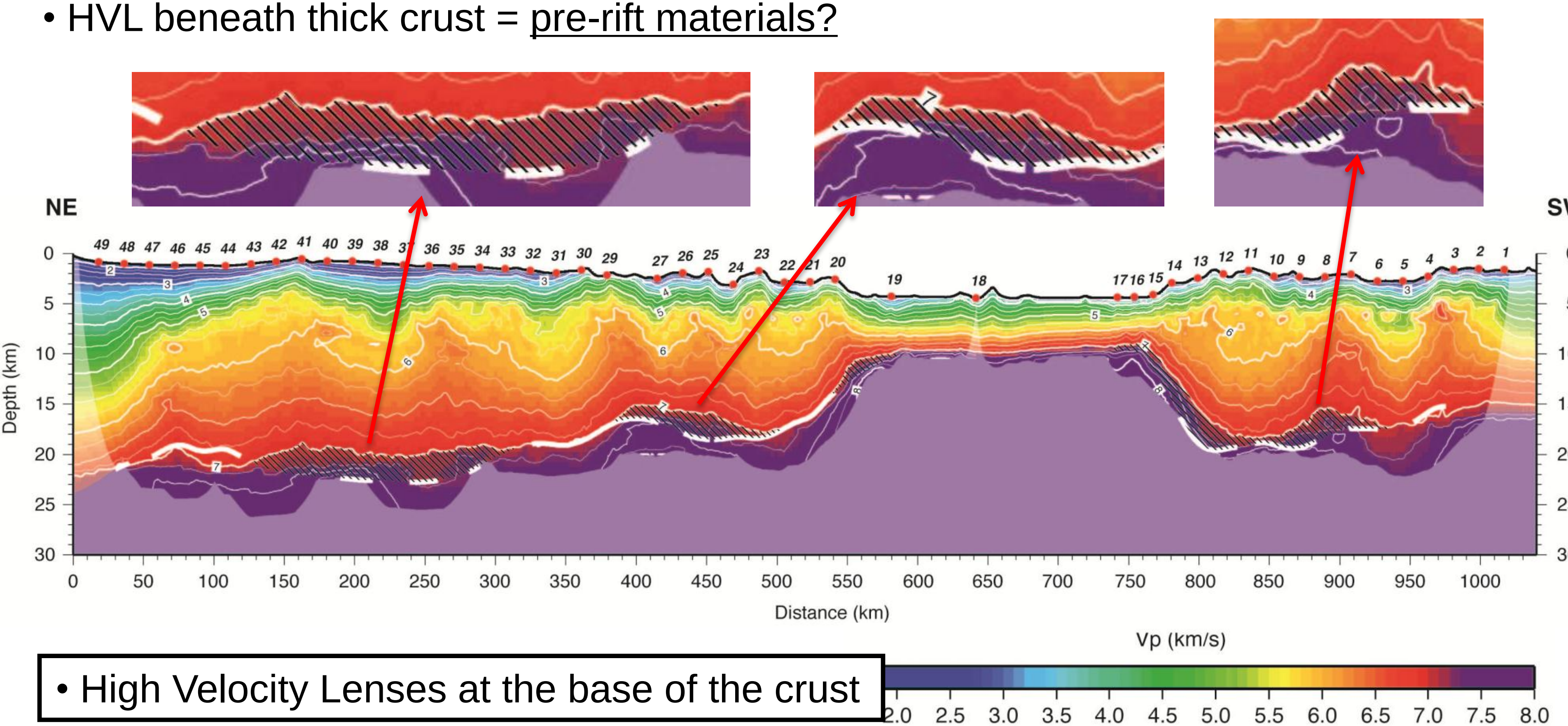


Final velocity model:

- 7.0 < Vp < 7.7 km/s

- Thin lenses (2-3 km thick) < 4-5 km commonly found for underplating material

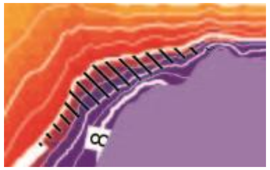
- HVL beneath thick crust = <u>pre-rift materials?</u>

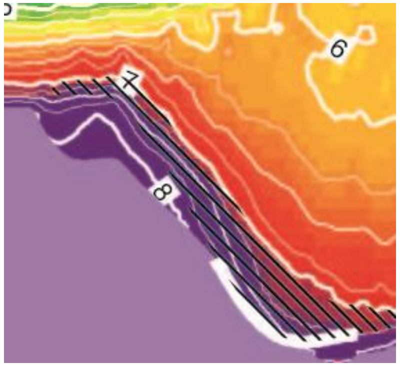


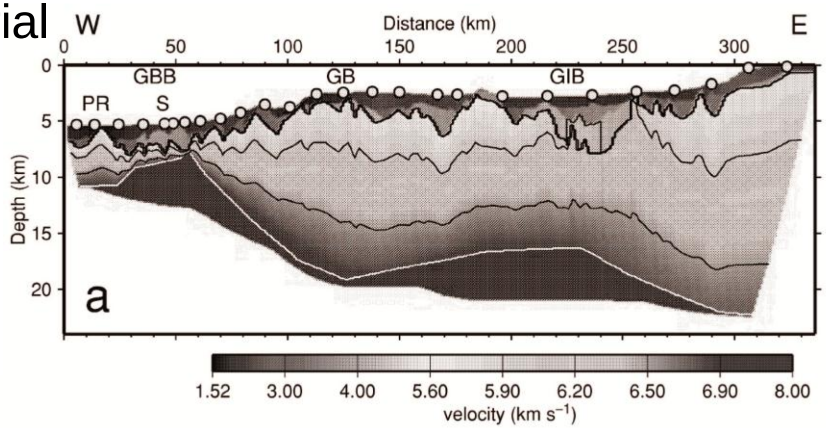
- High Velocity Lenses at the base of the crust

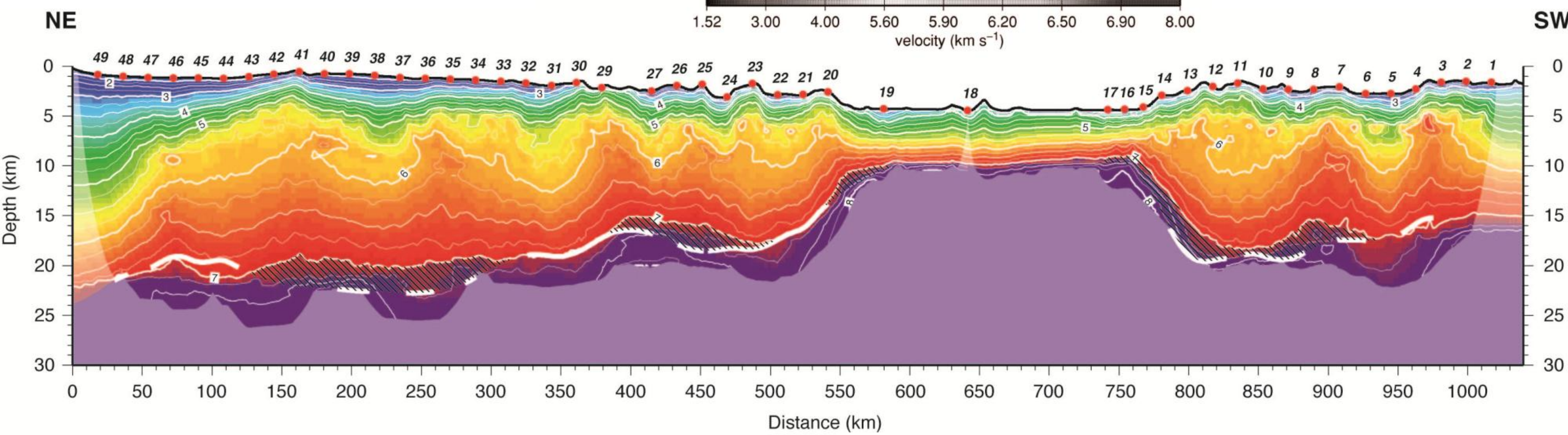
Final velocity model:

- 7.0 < Vp < 7.7 km/s
- Thin lenses (2-3 km thick) < 4-5 km commonly found for underplating material
- shape similar to <u>serpentinized upper mantle</u>

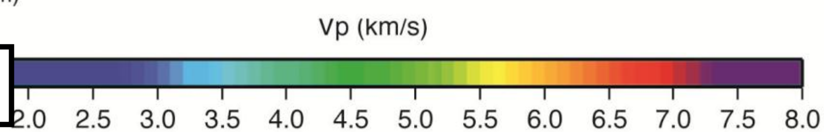




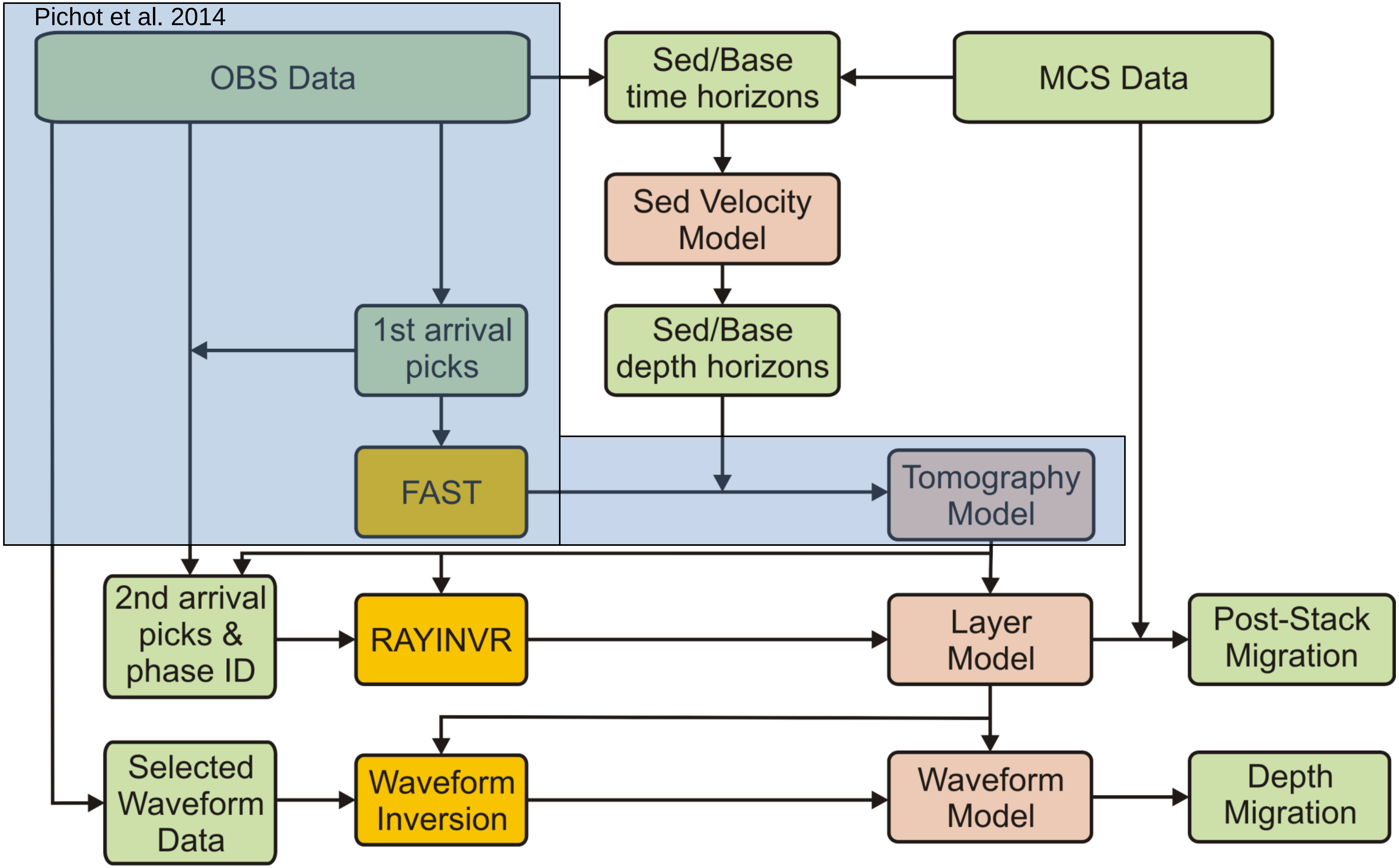




- High Velocity Lenses at the base of the crust



2-D Velocity Modeling



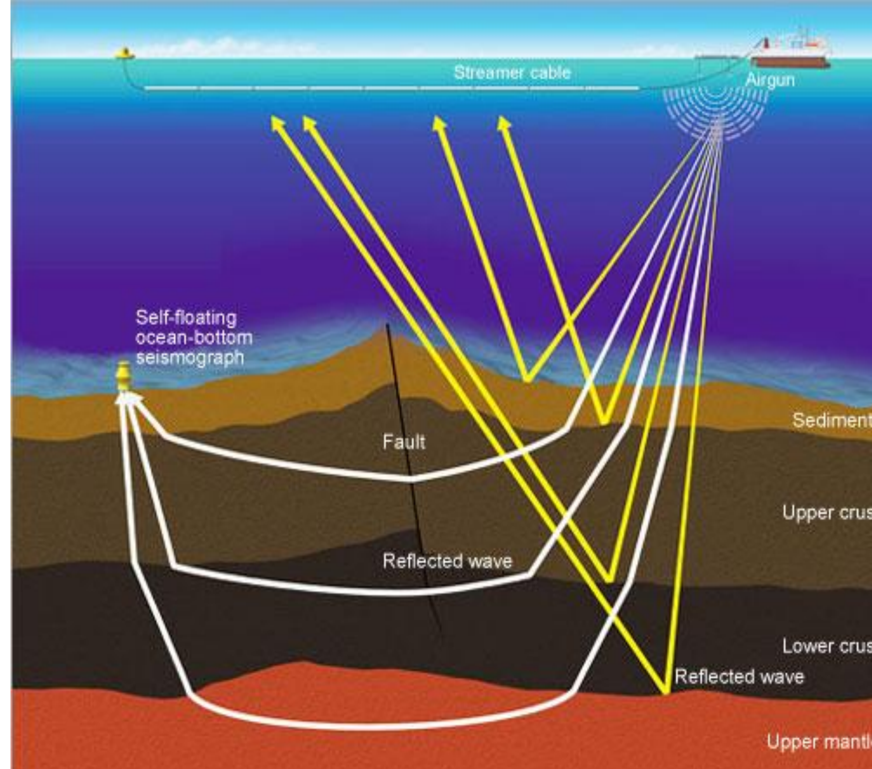
OBS = Ocean Bottom Seismometer

• Hydrophone (records pressure variations)

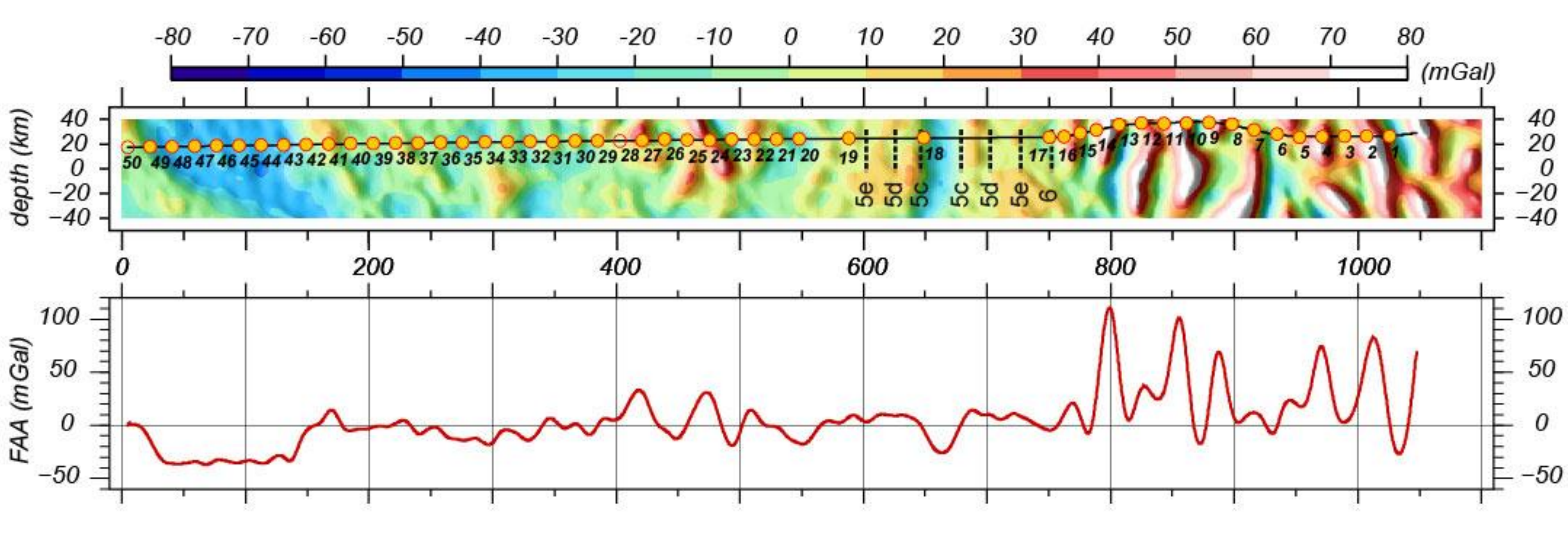
• Geophones (f>4.5Hz): records ground motion on three components

• Autonomous clock => clock drifts

• The obs moves away from its deployment position as it follows water currents during descent



Free air gravity signal:



- Northern margin tends to 0 mGal
- Southern margin shows short wavelength (~20 km)
- COT not well defined