WOODS HOLE OCEANOGRAPHIC INSTITUTION

Toward "full-wavelength imaging" of oceanic crust using full waveform inversion of active-source seismic data

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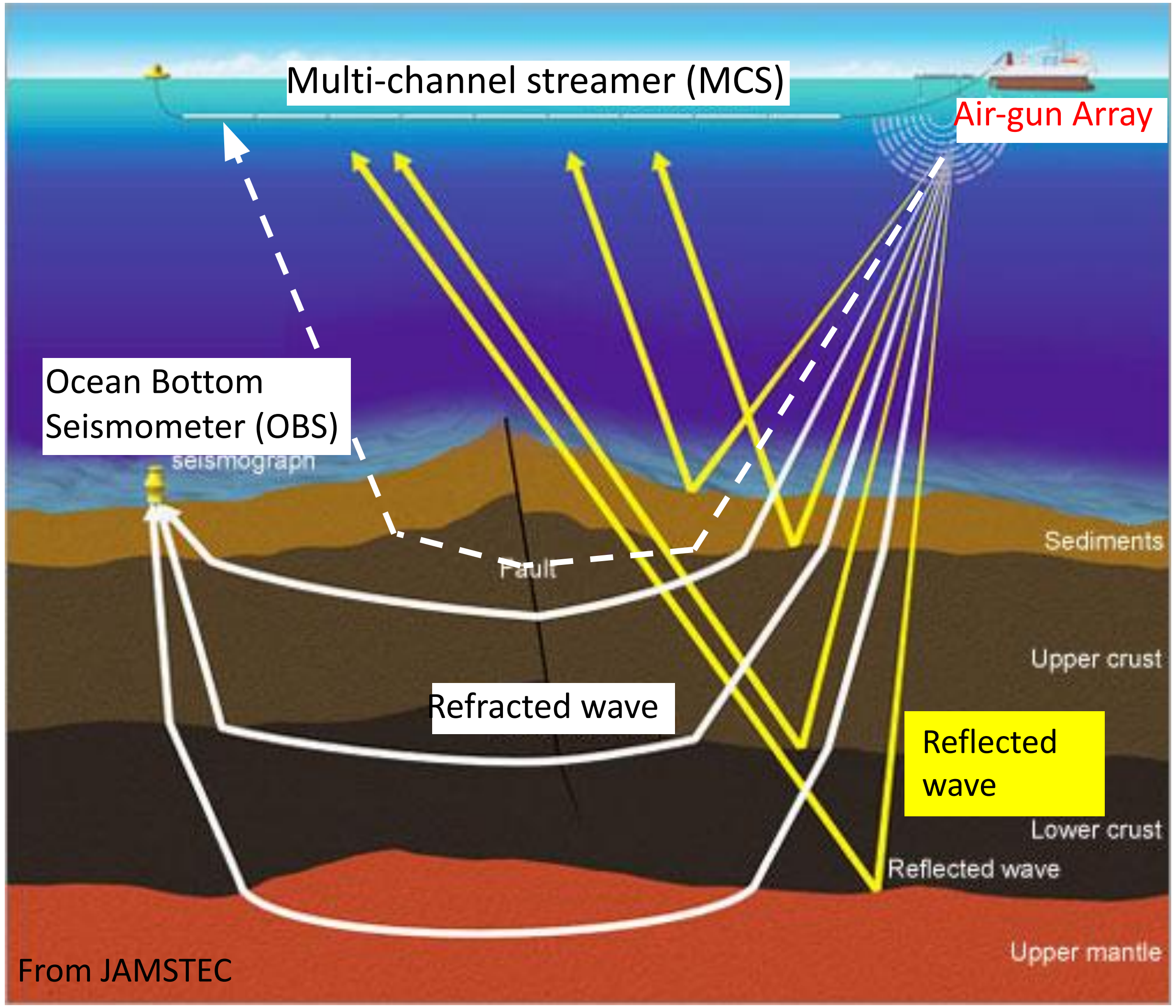
in collaboration with Drs. J. Pablo Canales (WHOI), Satish Singh (IPGP), Mladen Nedimović (Dalhousie Univ.) and others

MSROC Early Career Workshop

San Francisco, December 9, 2023

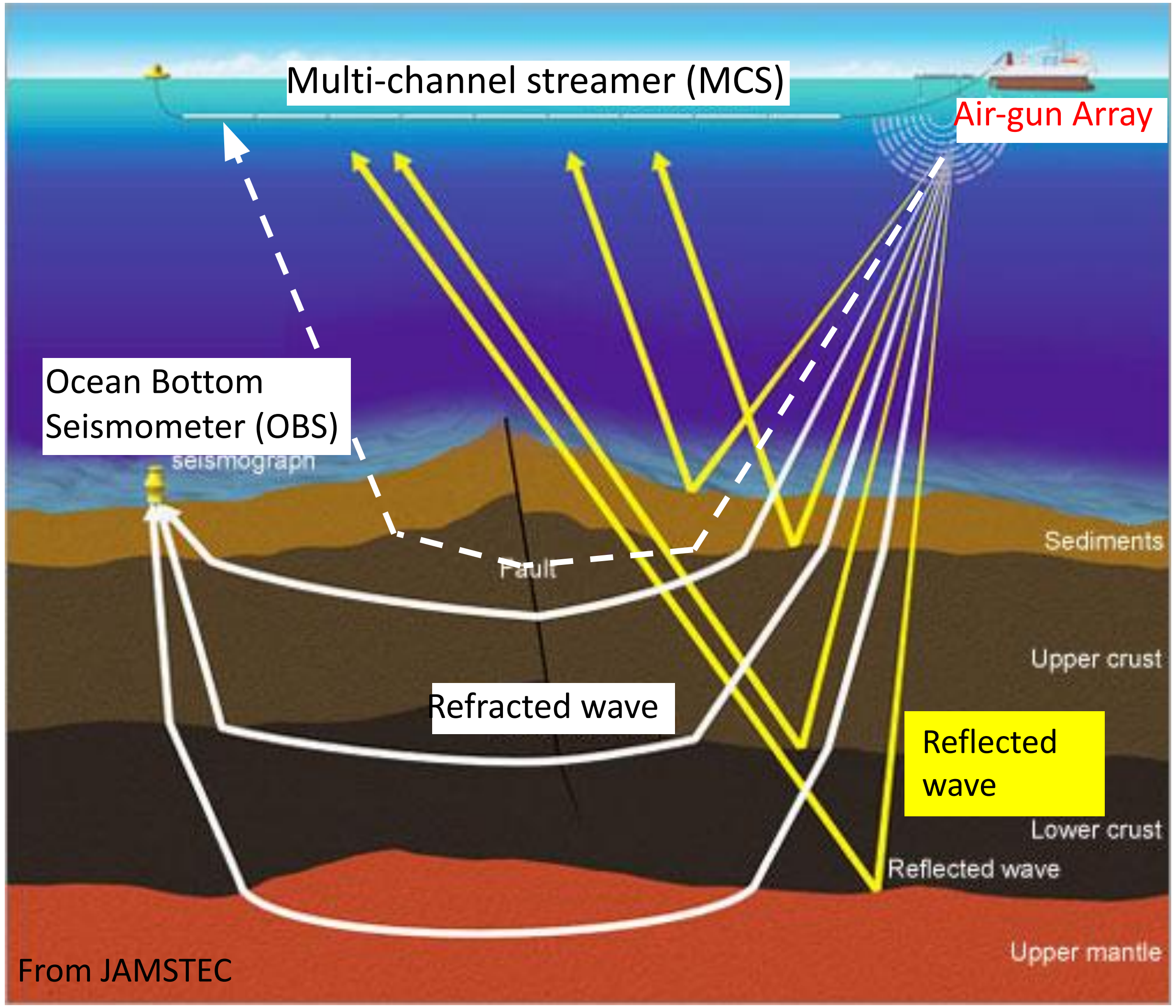
Active-source marine seismic survey - instruments



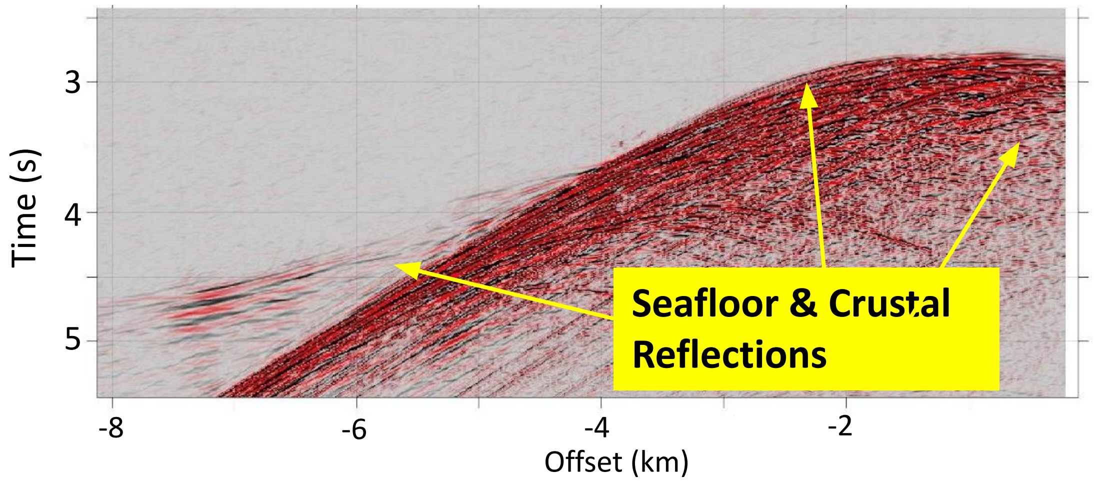
High-resolution imaging of oceanic crust demands active-source survey with two types of receivers:

- Multi-channel streamer (MCS):
  - ✔ High density (receiver spacing of 10-20m)
  - X Floating on sea surface
  - X Limited offset (maximum offset 3-15 km)
- Ocean bottom seismometer (OBS):
  - ✔ Record on seafloor
  - ✔ Large offset (tens to hundreds km)
  - X Low density (typical instrument spacing 3-20 km)

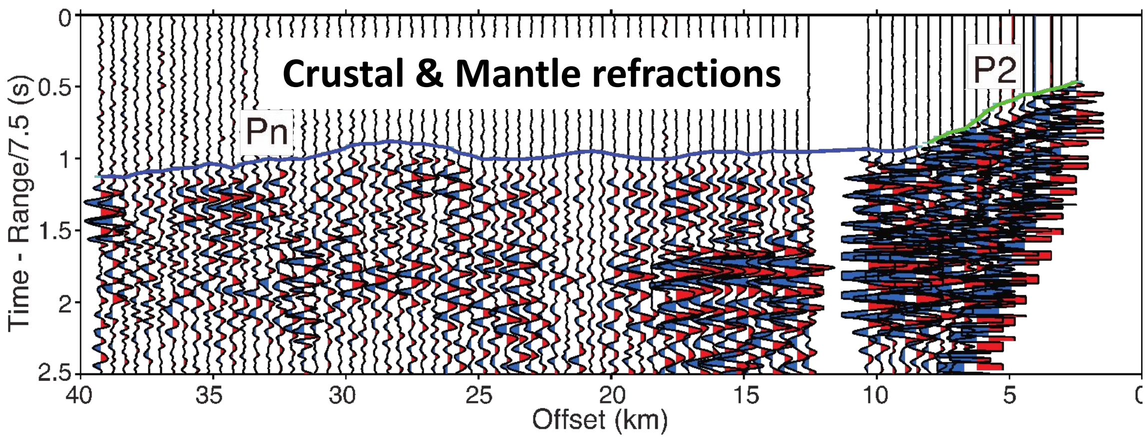
Active-source marine seismic survey – data example



A MCS common-shot gather



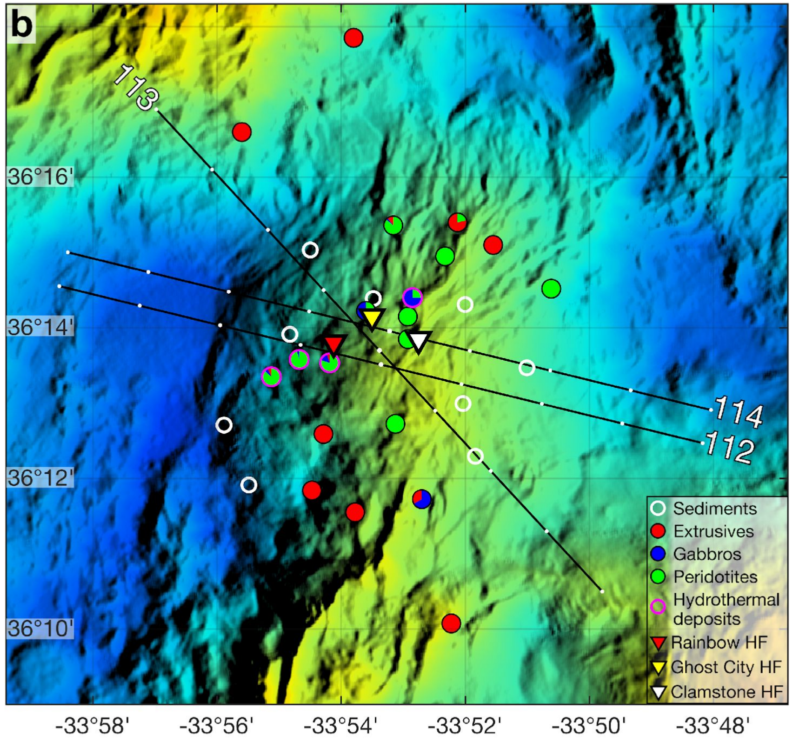
An OBS gather with reduced time (Dunn et al., 2017)



Active-source marine seismic survey – conventional processing

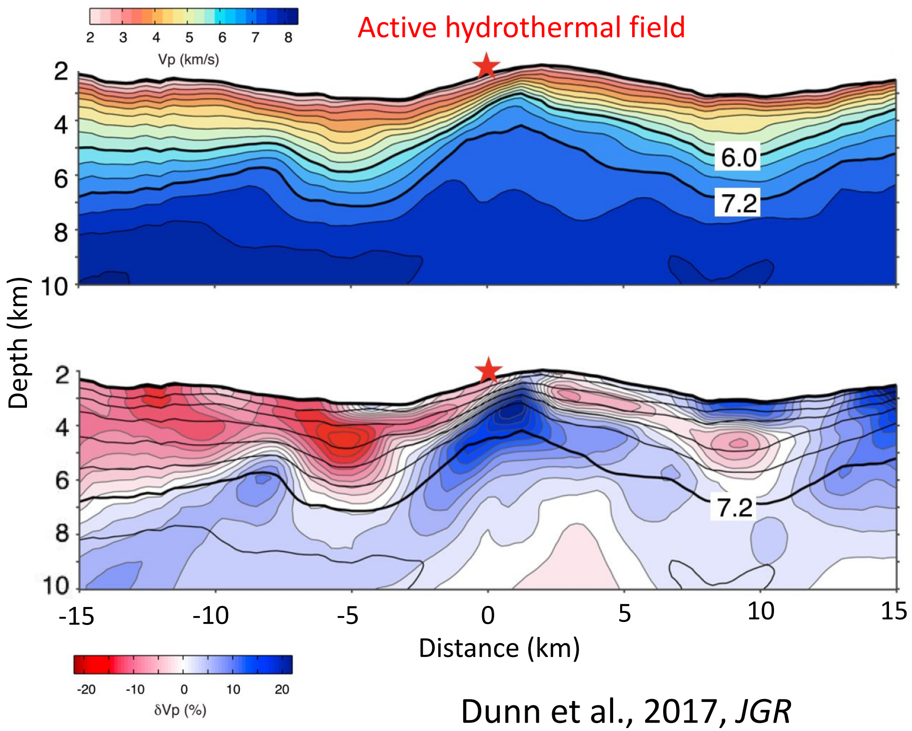
- Traveltime tomography using OBS data constrains the crustal and upper mantle structures with spatial resolution up to 2 km.
- Reflection images of the MCS data reveal sharp reflectors (Canales et al., 2017, *Geology*).

Seismic experiment layout



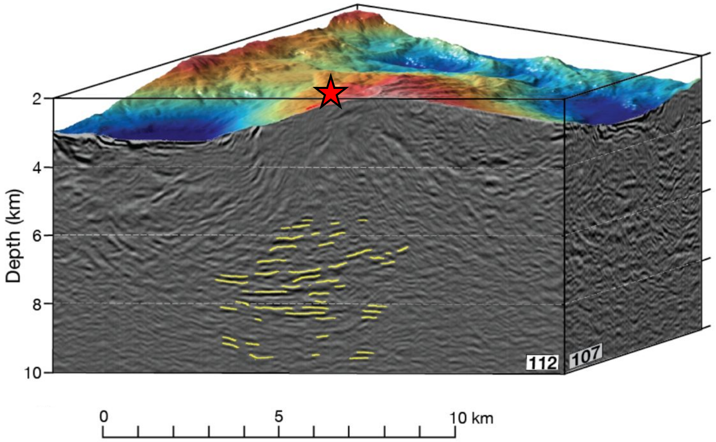
Jian, Canales, Nedimović and Dunn, *in review*

OBS Tomography result



Dunn et al., 2017, *JGR*

MCS reflection image



Canales et al., 2017, *Geology*

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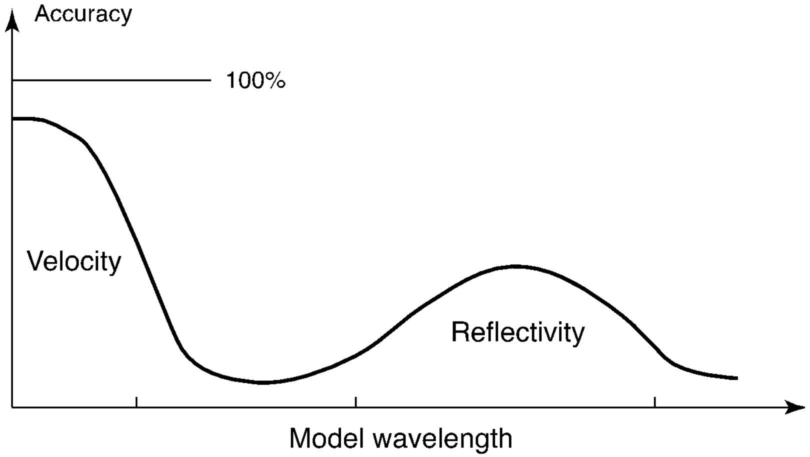
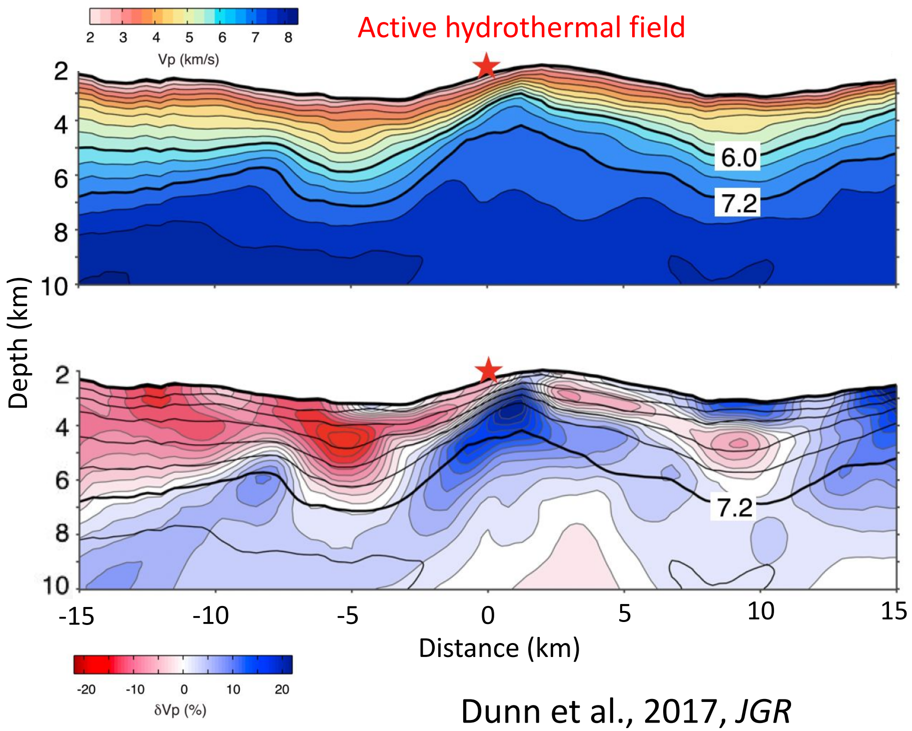
The resolution gap



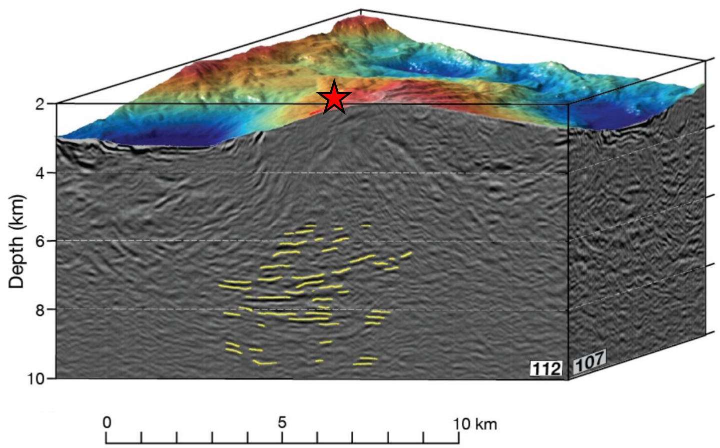
After Claerbout (1984)

OBS Tomography result



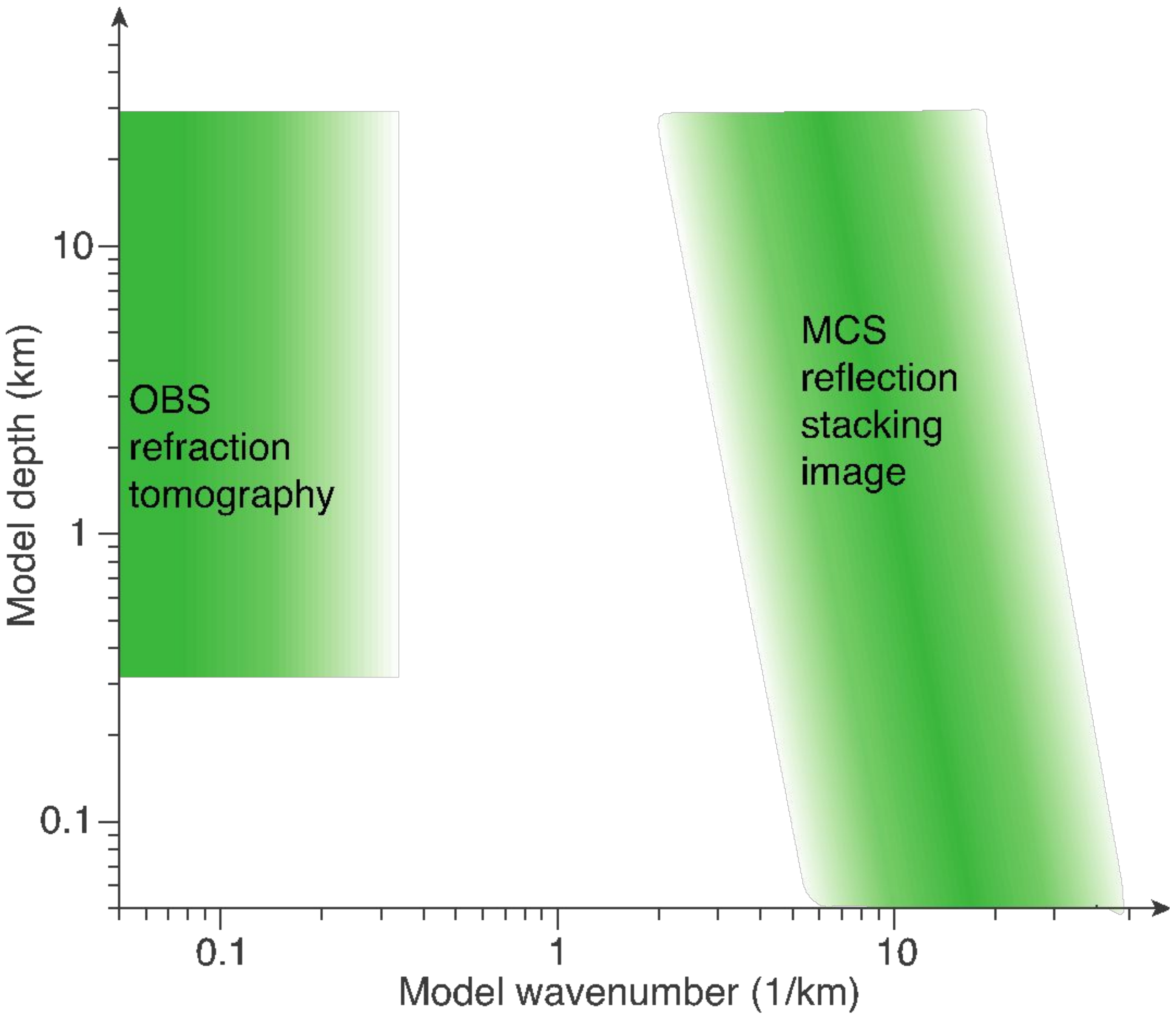
Dunn et al., 2017, *JGR*

MCS reflection image



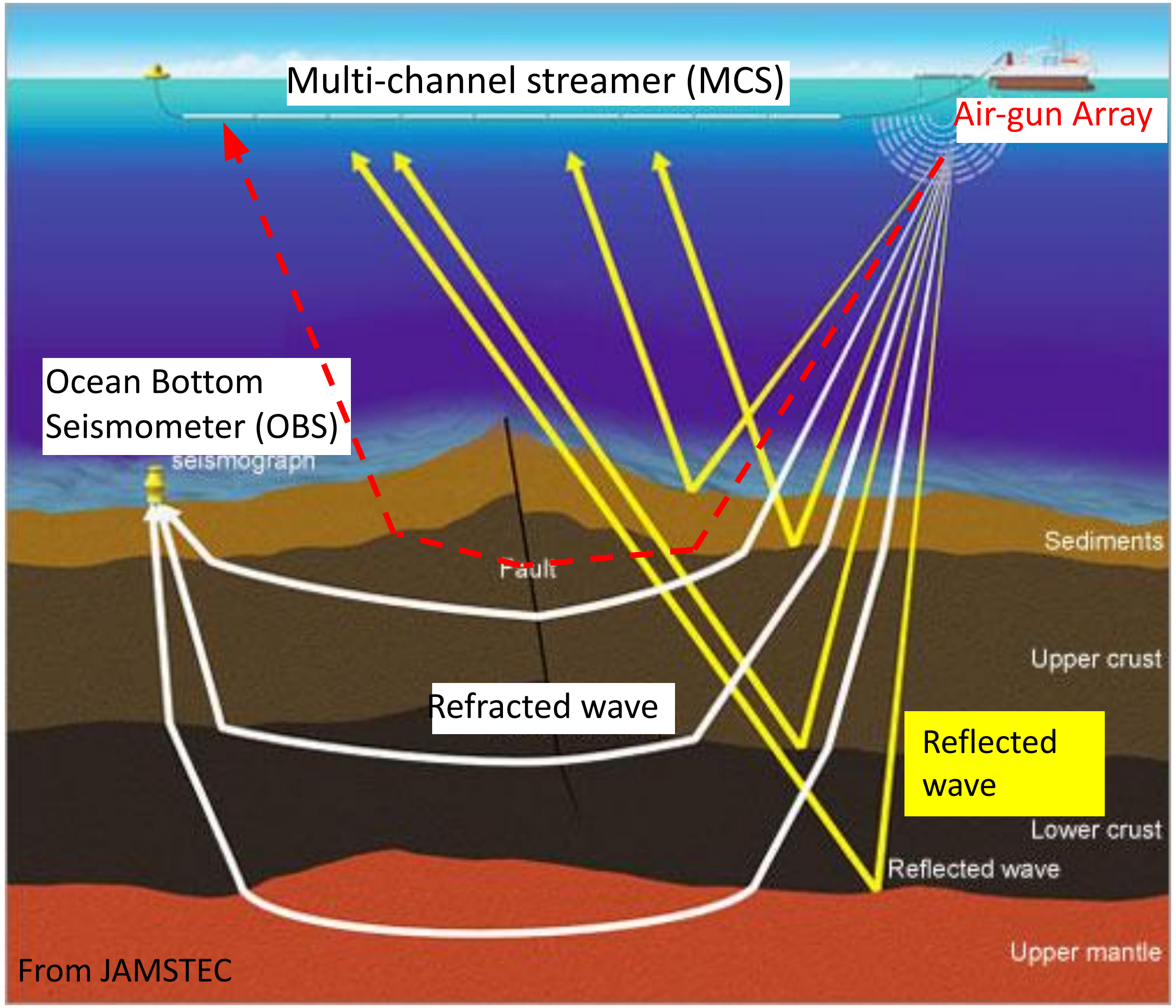
Canales et al., 2017, *Geology*

Towards “full-wavelength imaging” of oceanic crust

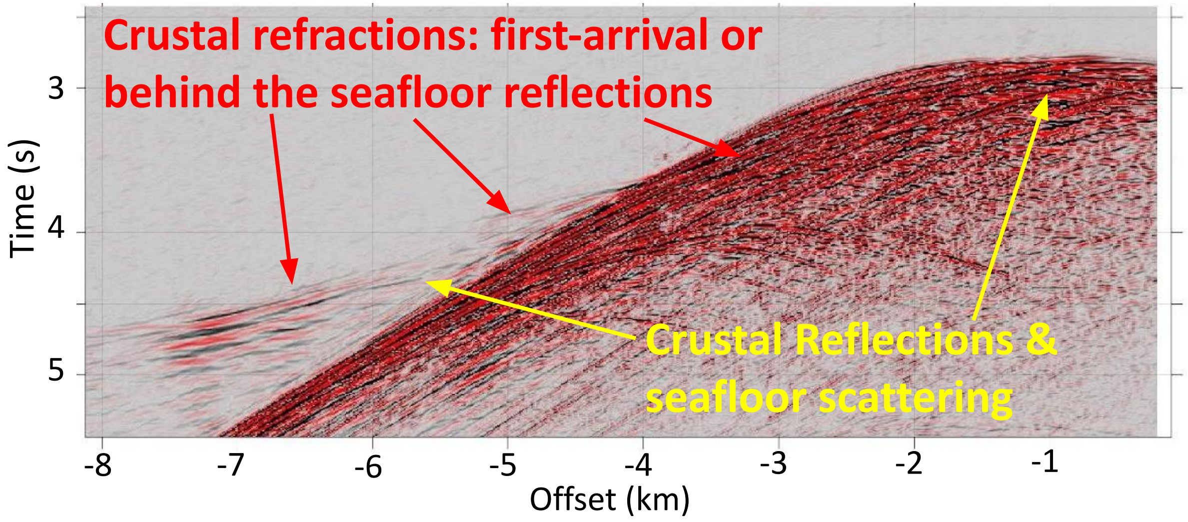


- Conventional marine seismic data analysis leads to Huge resolution gap that impedes the understanding of important features and processes, such as:
  - Hydrothermal pathway
  - Fault distribution
  - Magma transport
  - Fluid drainage from subducting plate
  - And more …

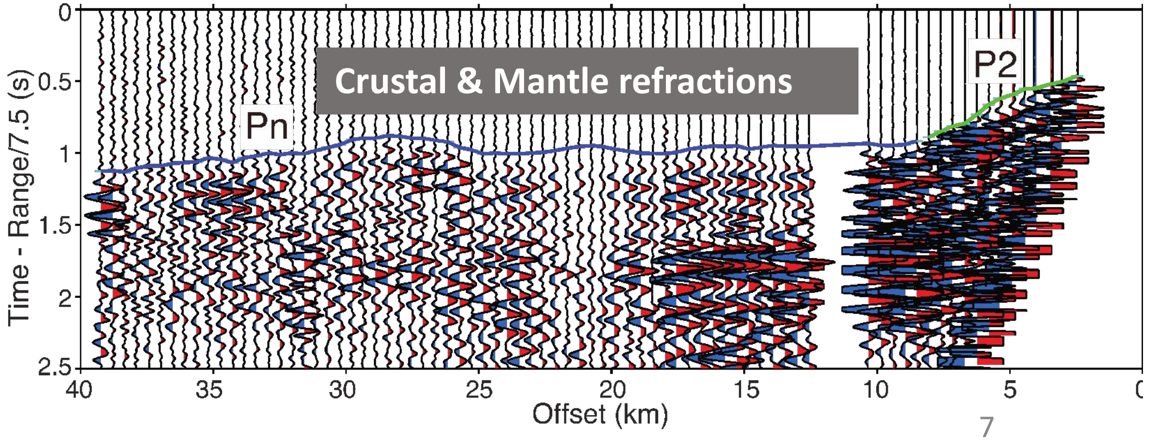
Active-source marine seismic survey – example data & result



A MCS common-shot gather



An OBS gather with reduced time (Dunn et al., 2017)

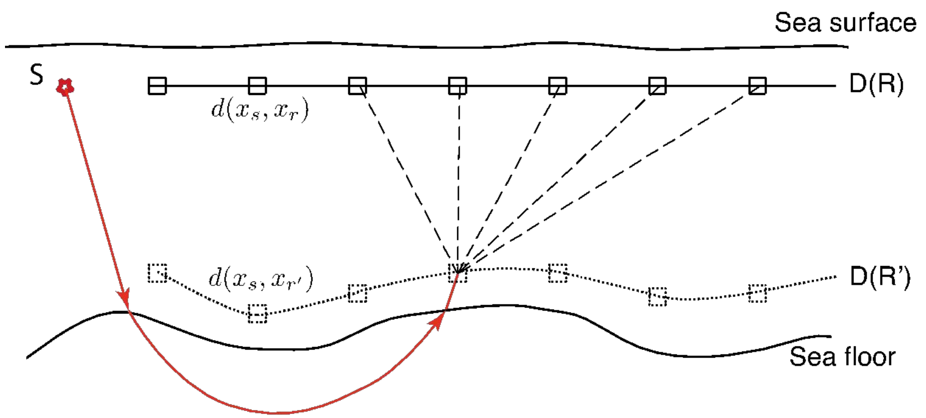


Downward Extrapolation & Travel Time Tomography of MCS data

Downward extrapolation (Arnulf et al., 2011, *GRL*, Harding et al., 2016, *G-cubed*) acts as:

- Migration operator: bring near-offset refraction ahead seafloor reflection.
- Coherency filter: enhance SNR, accelerate travel time picking efficiency by > 10 times.

Benefit: more high-quality crustal arrivals can be used in travel time and waveform inversion.

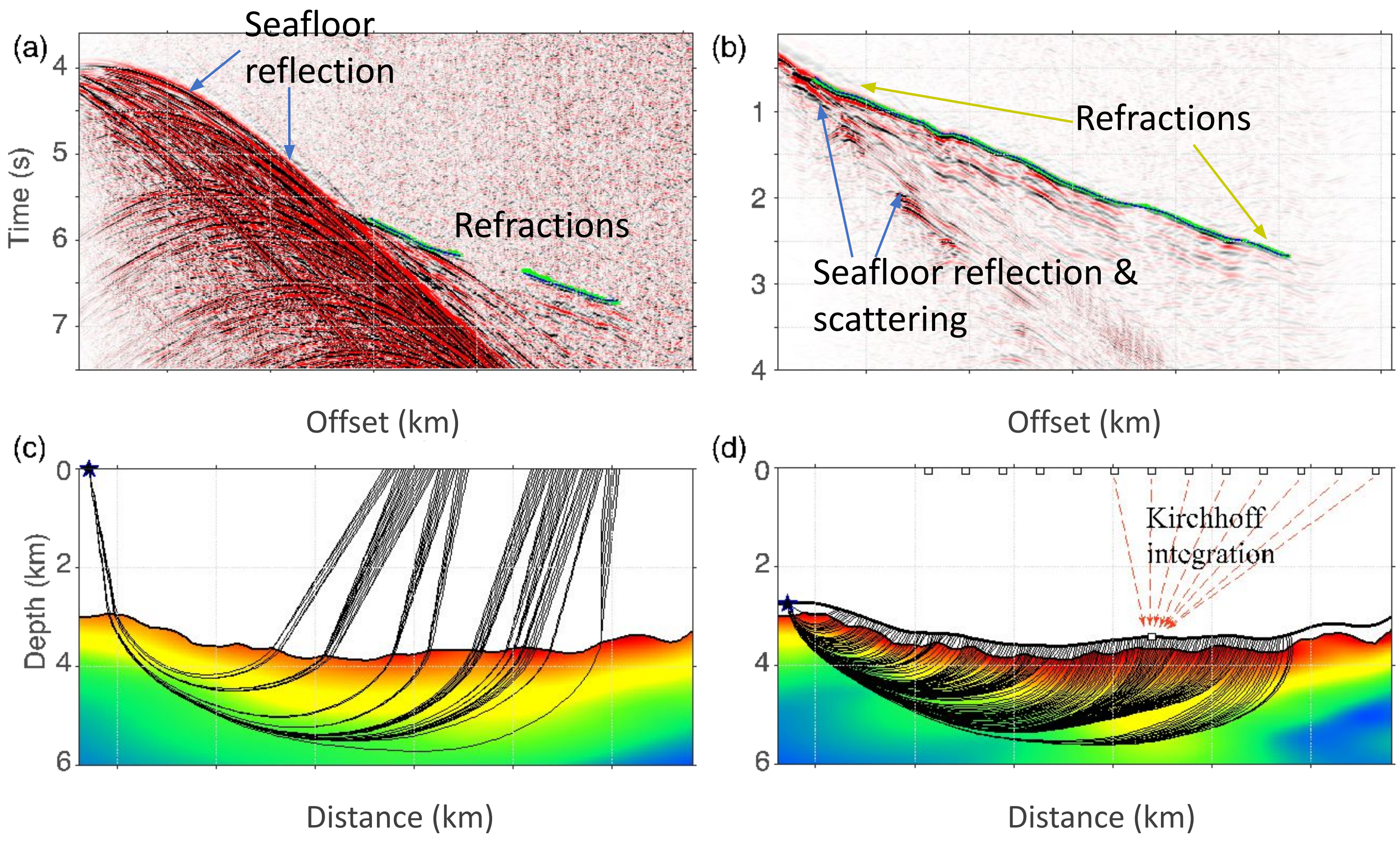


Upward propogation (Huygens' principle)

$$d(x_s, x_r) = \int_{D(R')} d(x_s, x_{r'}) \otimes G(x_r, x_{r'})$$

Downward Continuation

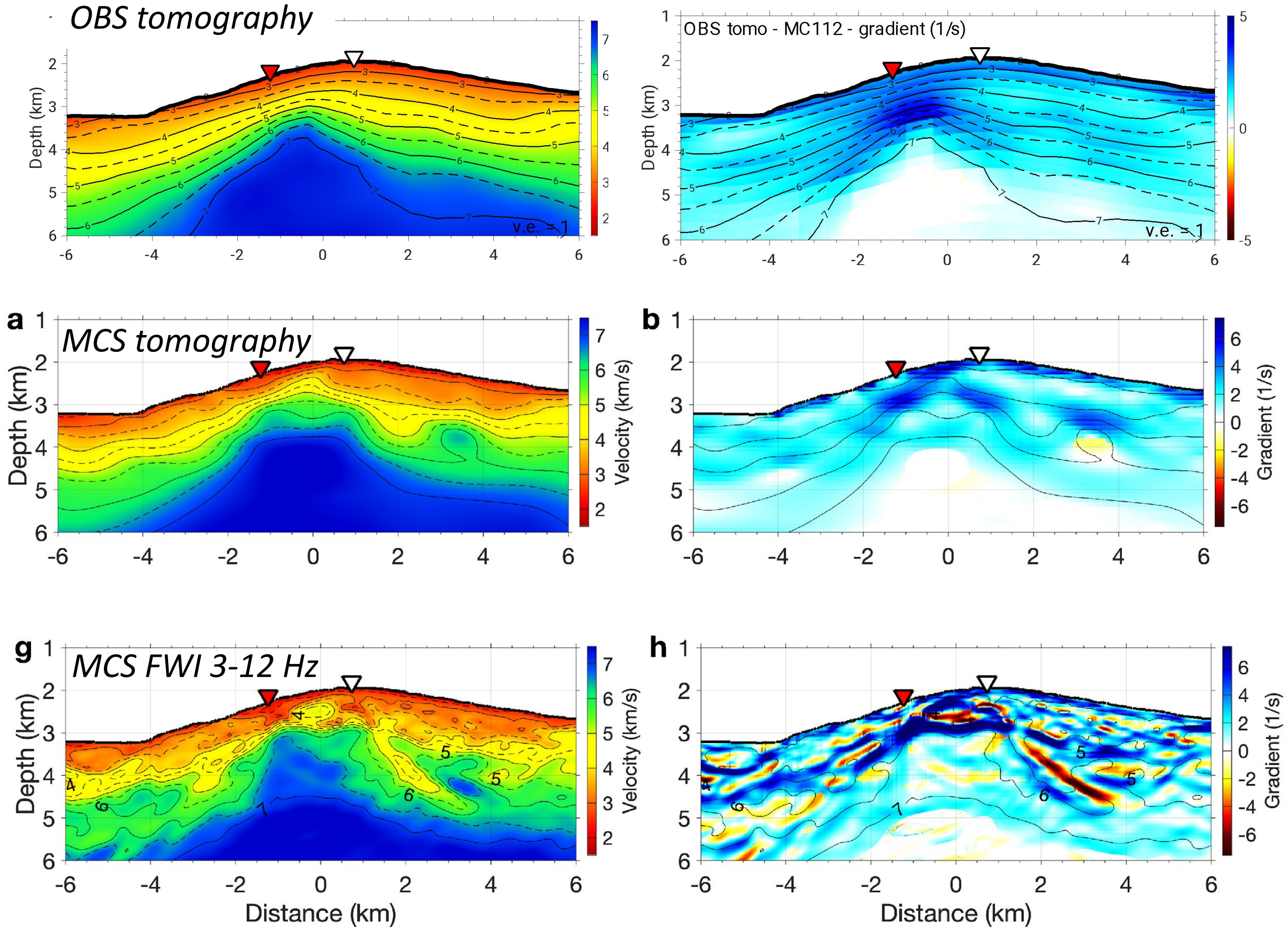
$$d(x_s, x_{r'}) = \int_{D(R)} d(x_s, x_r) \otimes G^*(x_{r'}, x_r)$$

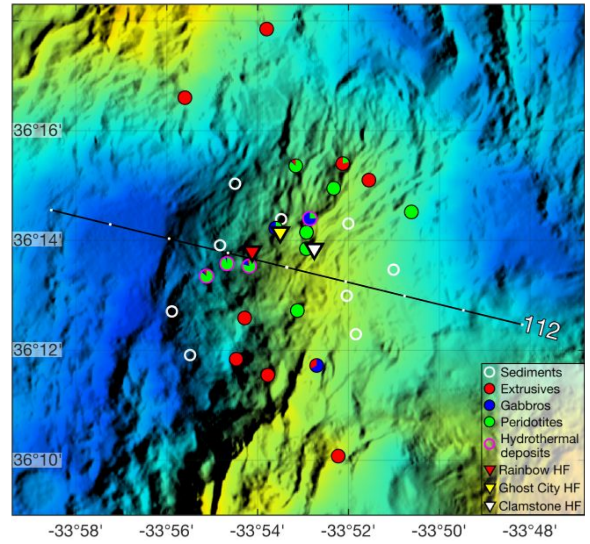


CASE I - Image hydrothermal pathways in Rainbow hydrothermal field

Velocity model – line 112

Velocity gradients – line 112



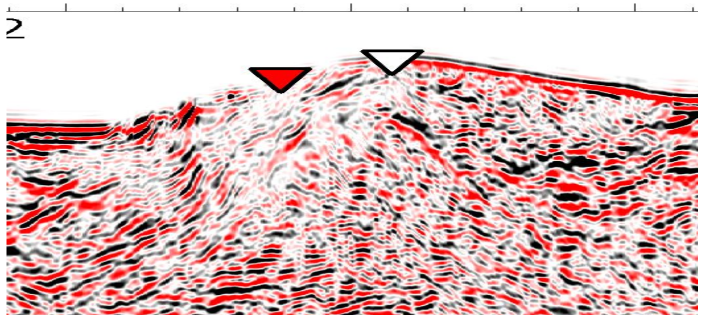


Hydrothermal vent fields

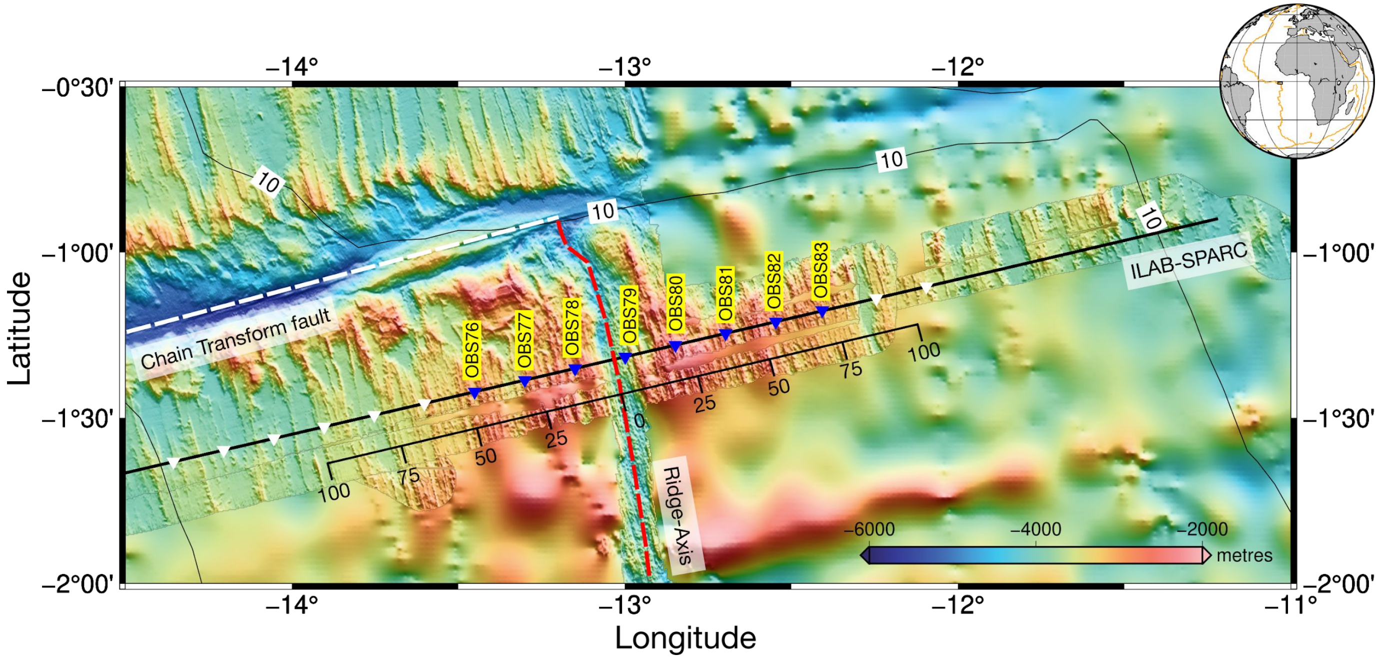
High-temperature active

Low-temperature fossil

PSDM image

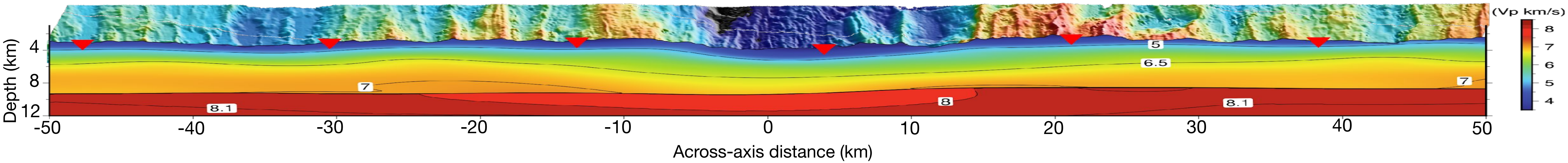


CASE II - Image faults across Equatorial Mid-Atlantic Ridge



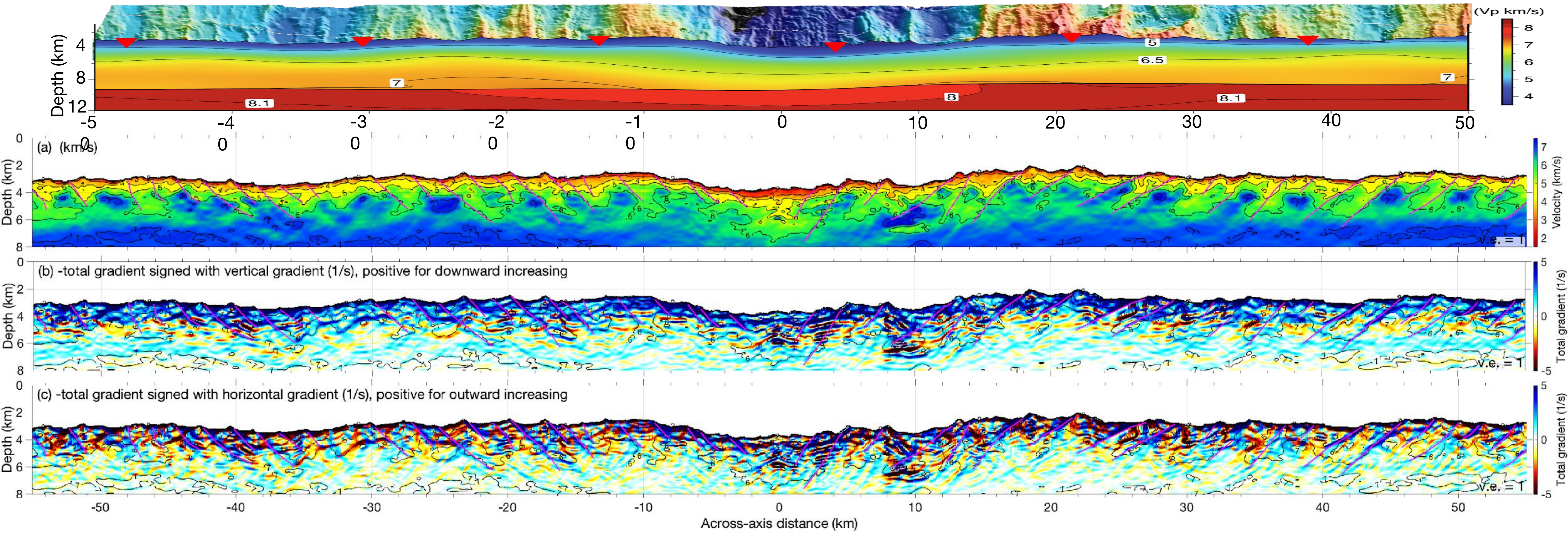
Ocean bottom seismometers

Multichannel seismic profile



Vaddineli, Jian and Singh, *in prep.*

CASE II - Image faults across Equatorial Mid-Atlantic Ridge



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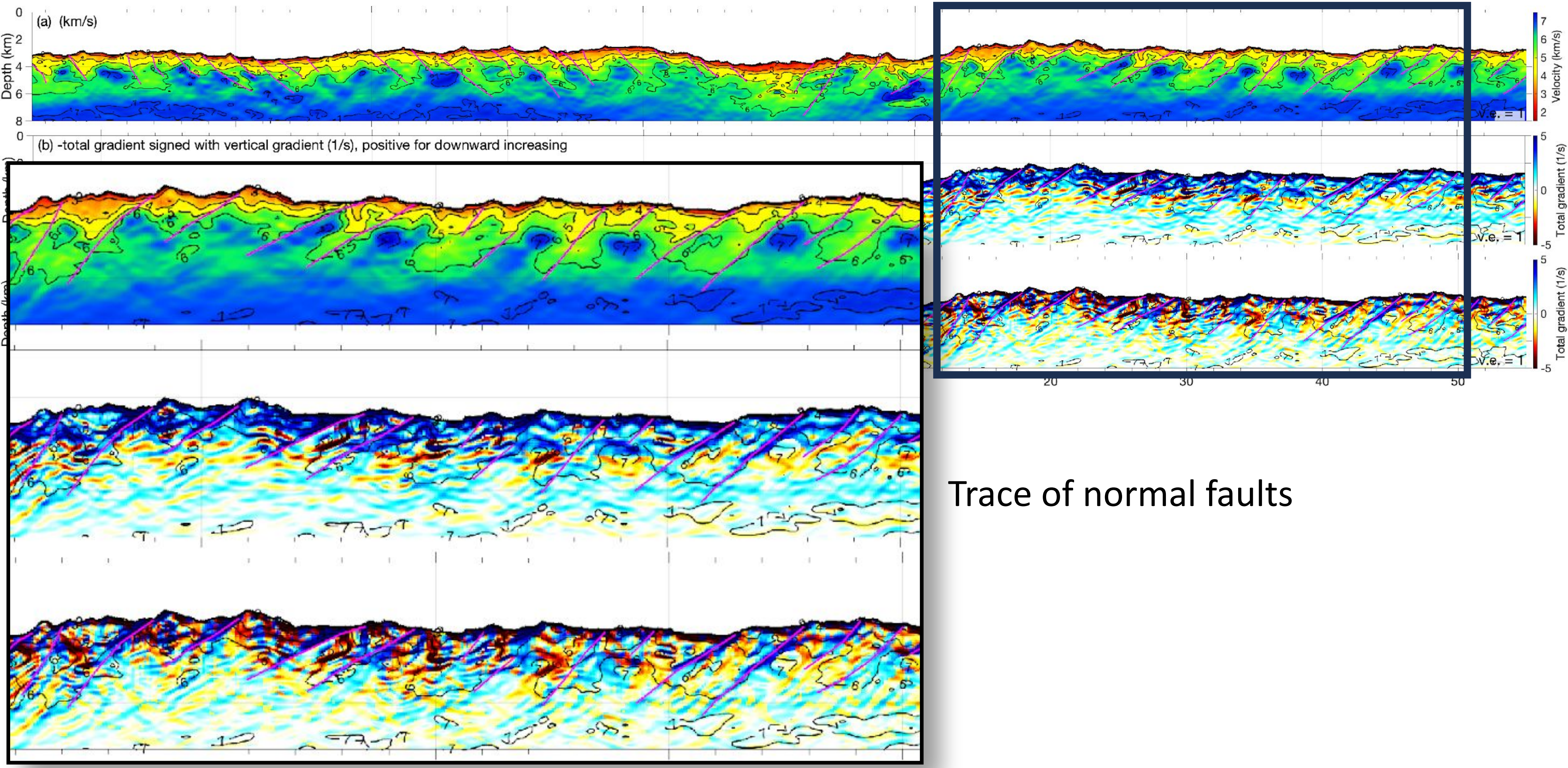
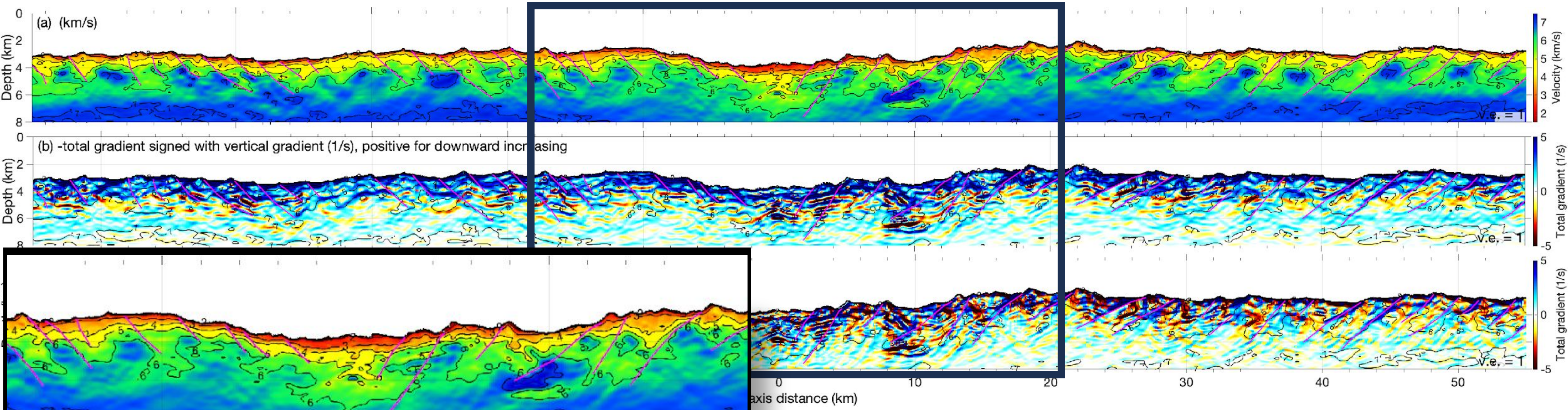
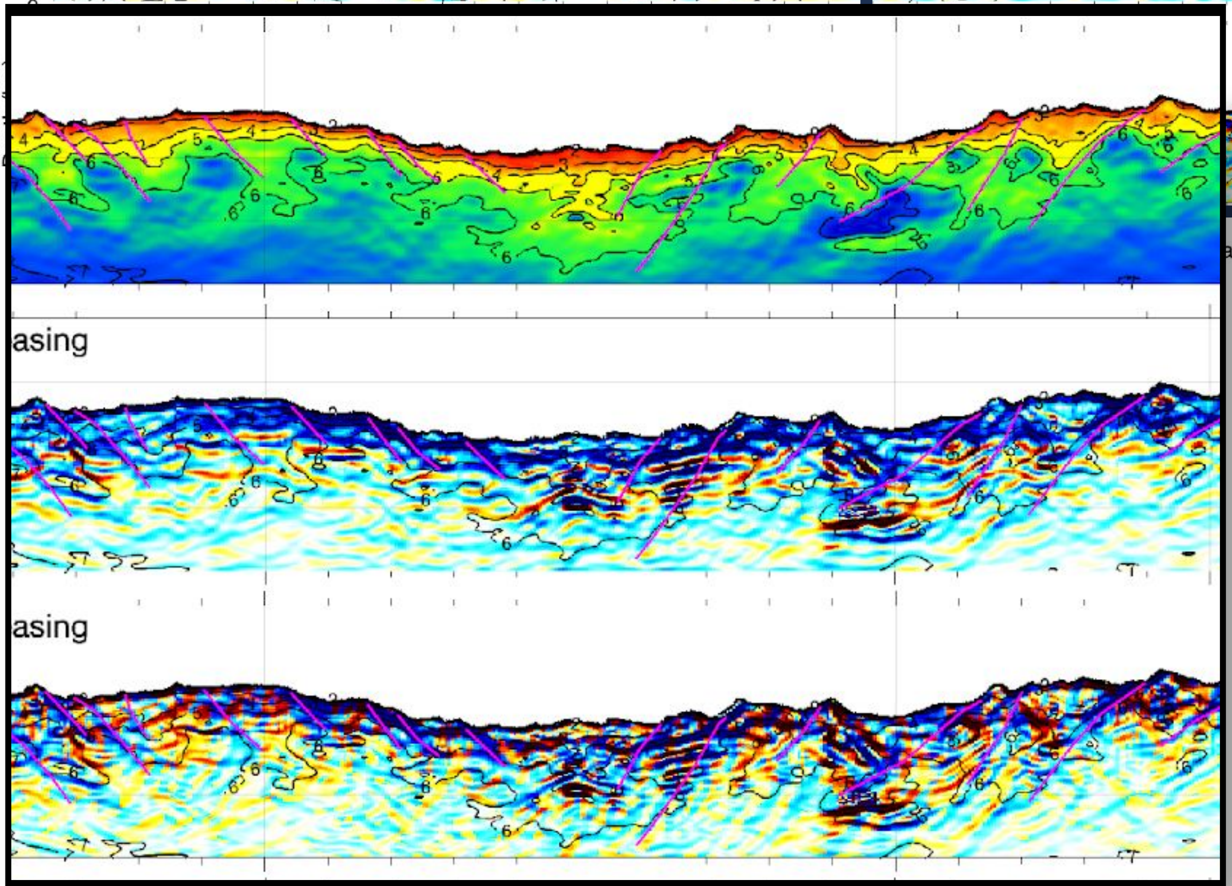


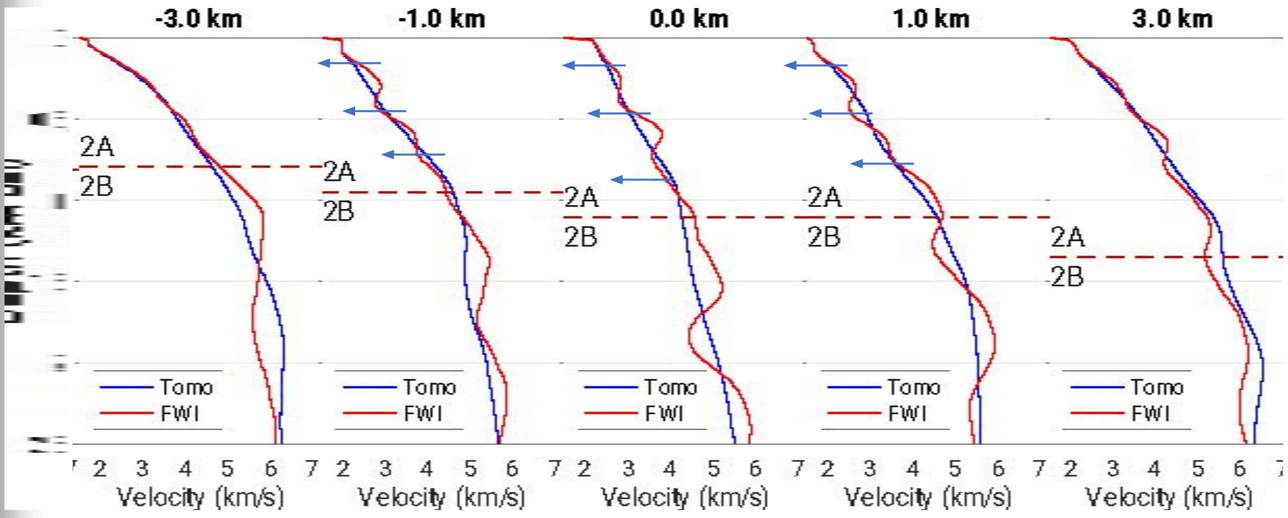
Trace of normal faults

CASE II - Image faults across Equatorial Mid-Atlantic Ridge

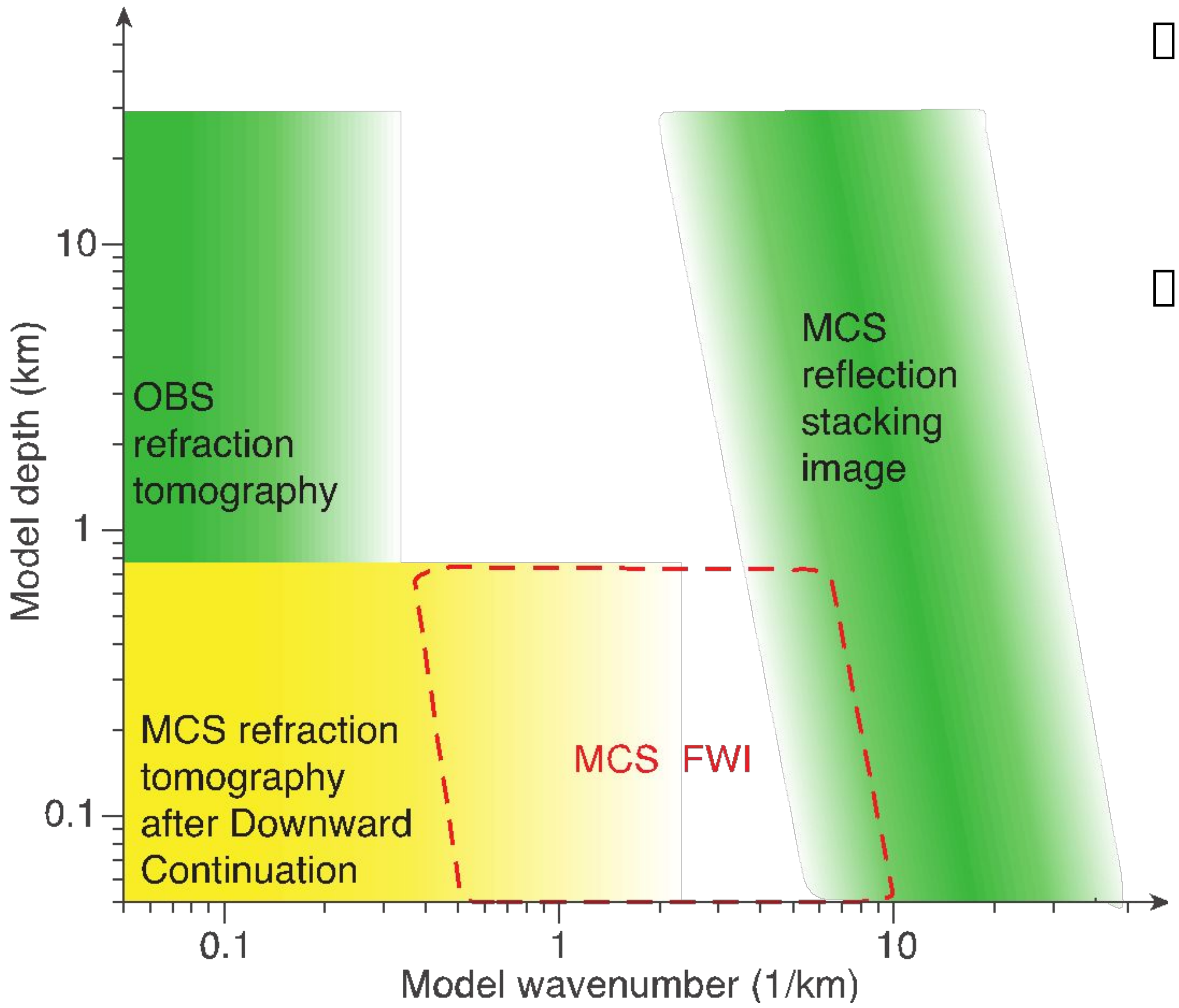




Multilayering of Layer 2A within the axial valley

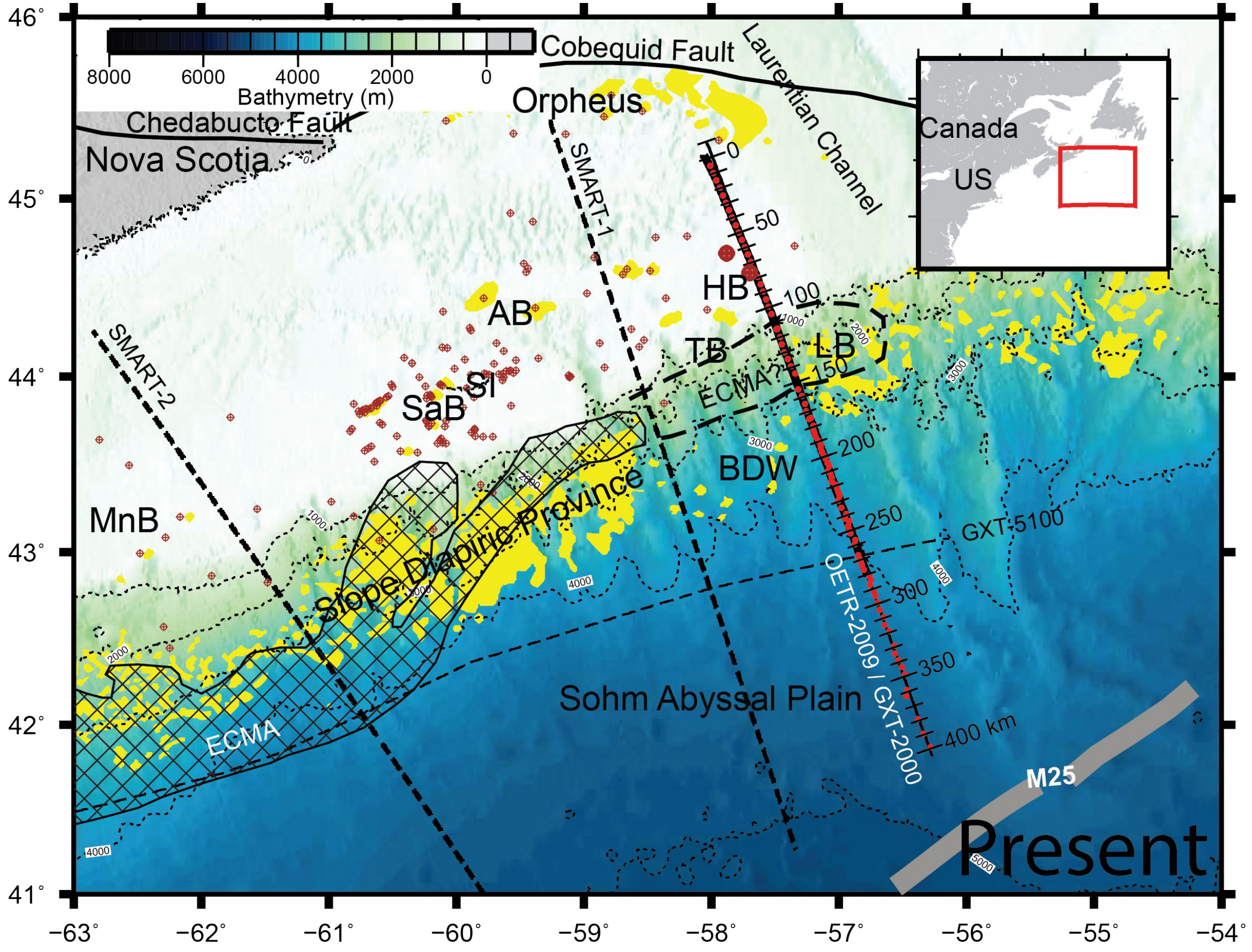


Towards “full-spectral imaging” of oceanic crust



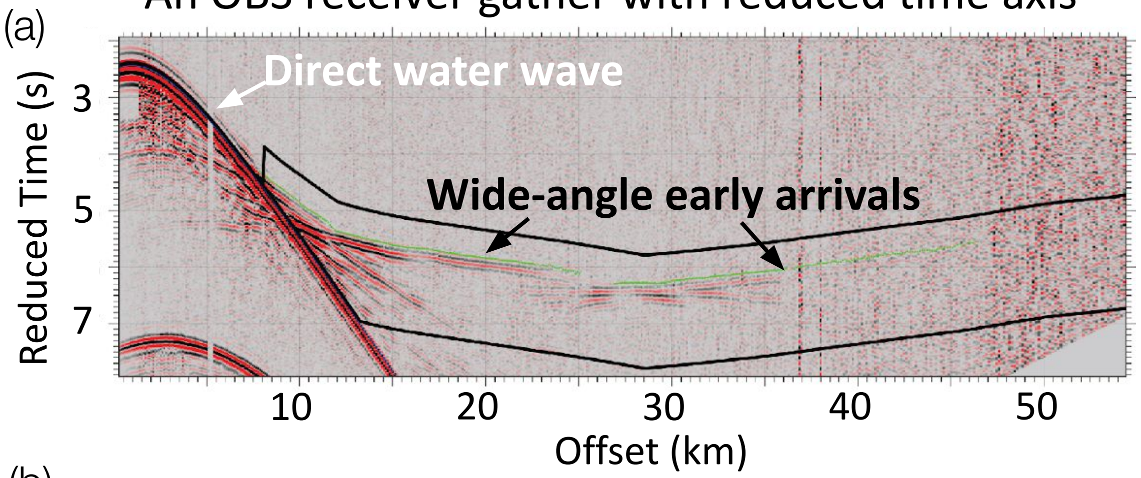
- Conventional marine seismic data analysis
  - OBS traveltime tomography
  - MCS reflection imaging
- MCS tomography and full waveform inversion after Downward extrapolation
  - Due to the high density of MCS data, the shallow crustal structure can be almost “perfectly” recovered using the multiscale inversion strategy
  - The larger depth where no coverage from MCS refraction data, however, still exhibits the resolution gap

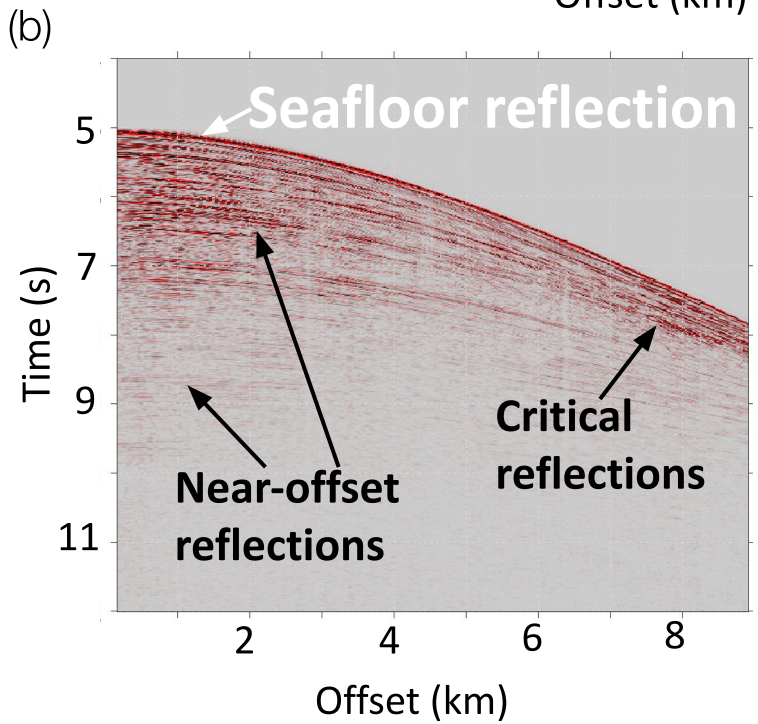
CASE III – Nova Scotian rifted margin



Jian, Nedimovic, Canales and Lau, 2021, *JGR*

An OBS receiver gather with reduced time axis





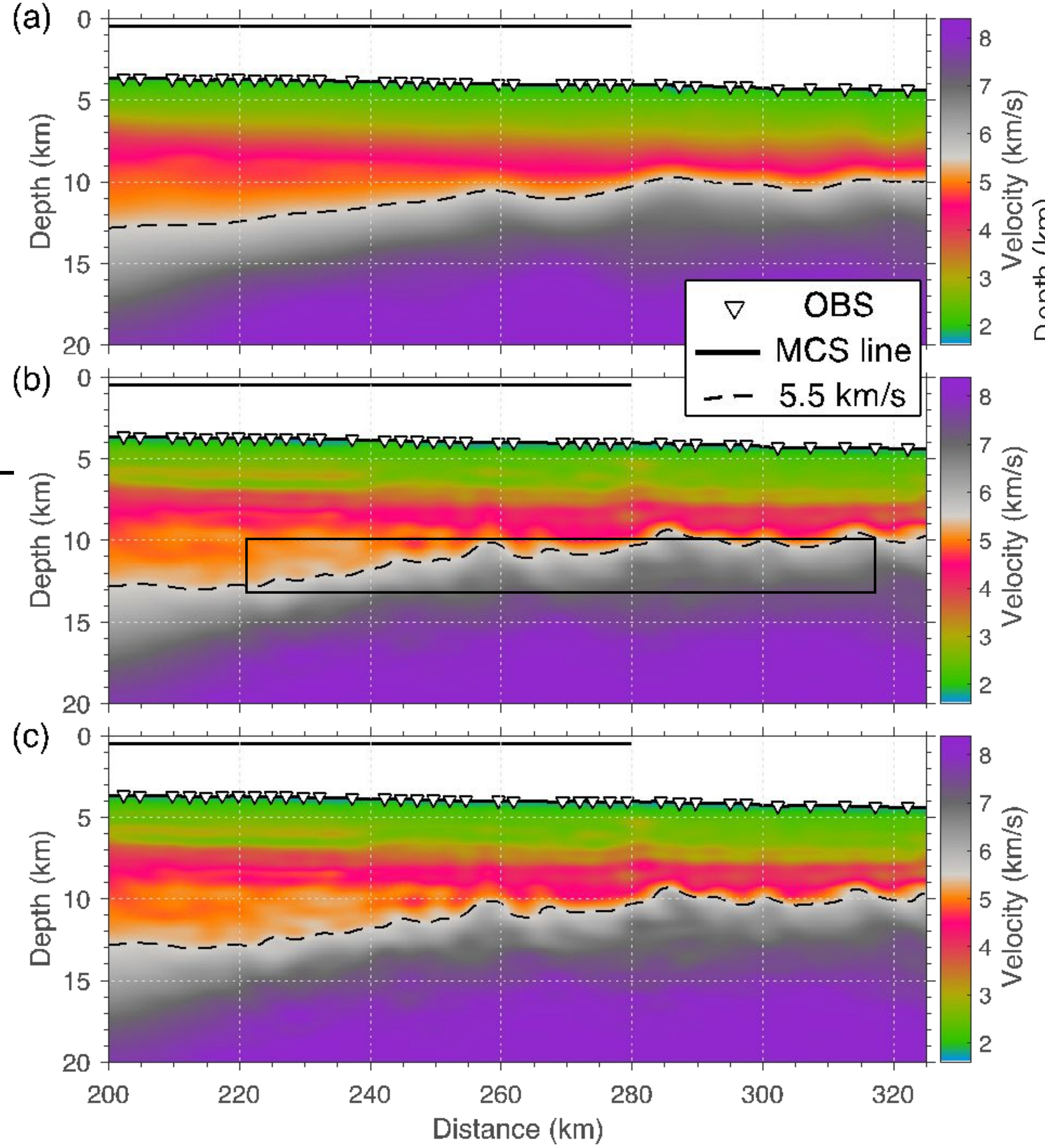
(b) A MCS shot gather.

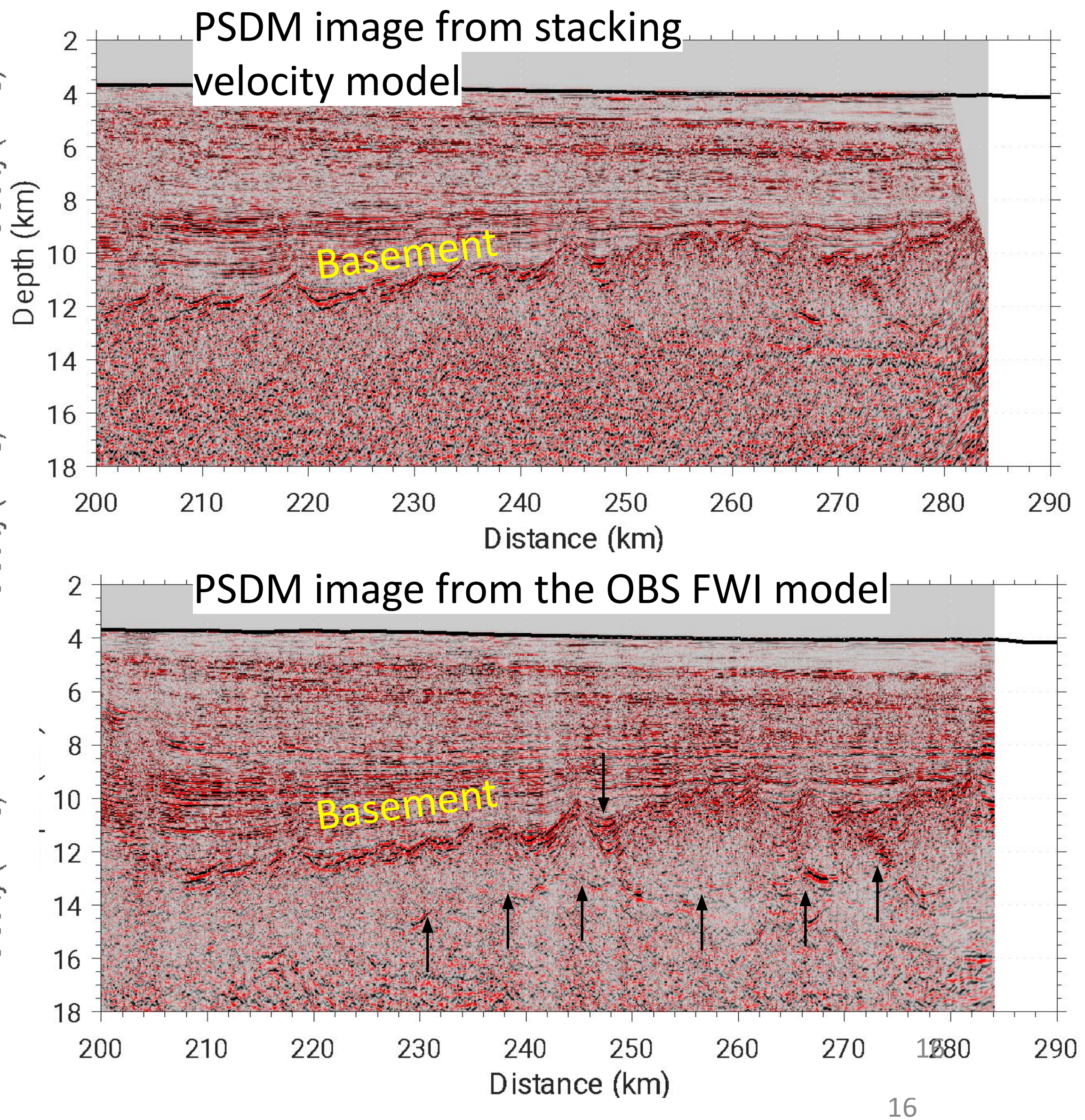
CASE III – Nova Scotian rifted margin: FWI of OBS wide-angle arrivals

Traveltime tomography

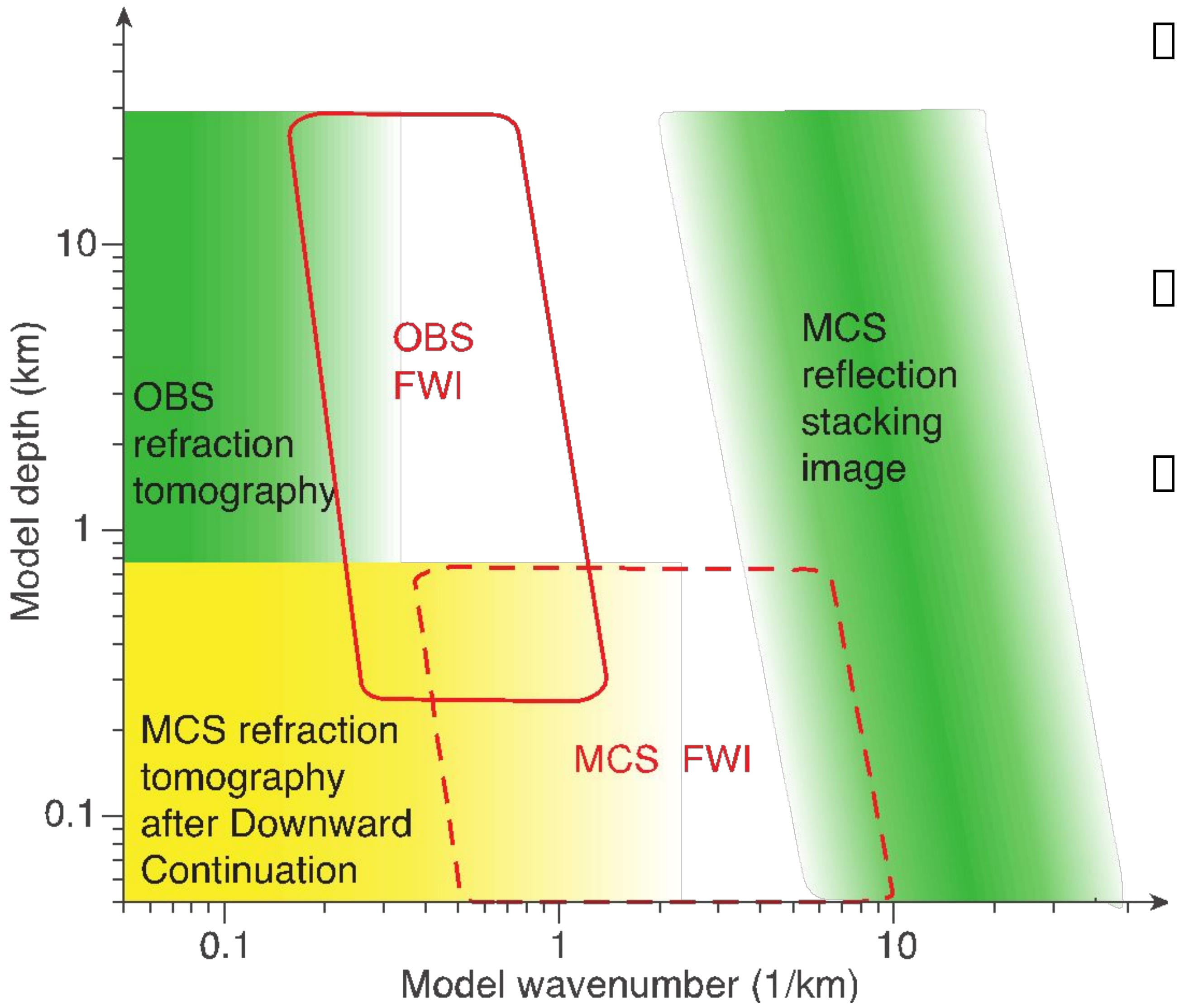
FWI of 3.5 – 6.5 Hz

FWI of 3.5 – 10 Hz





Towards "full-wavelength imaging" of oceanic crust

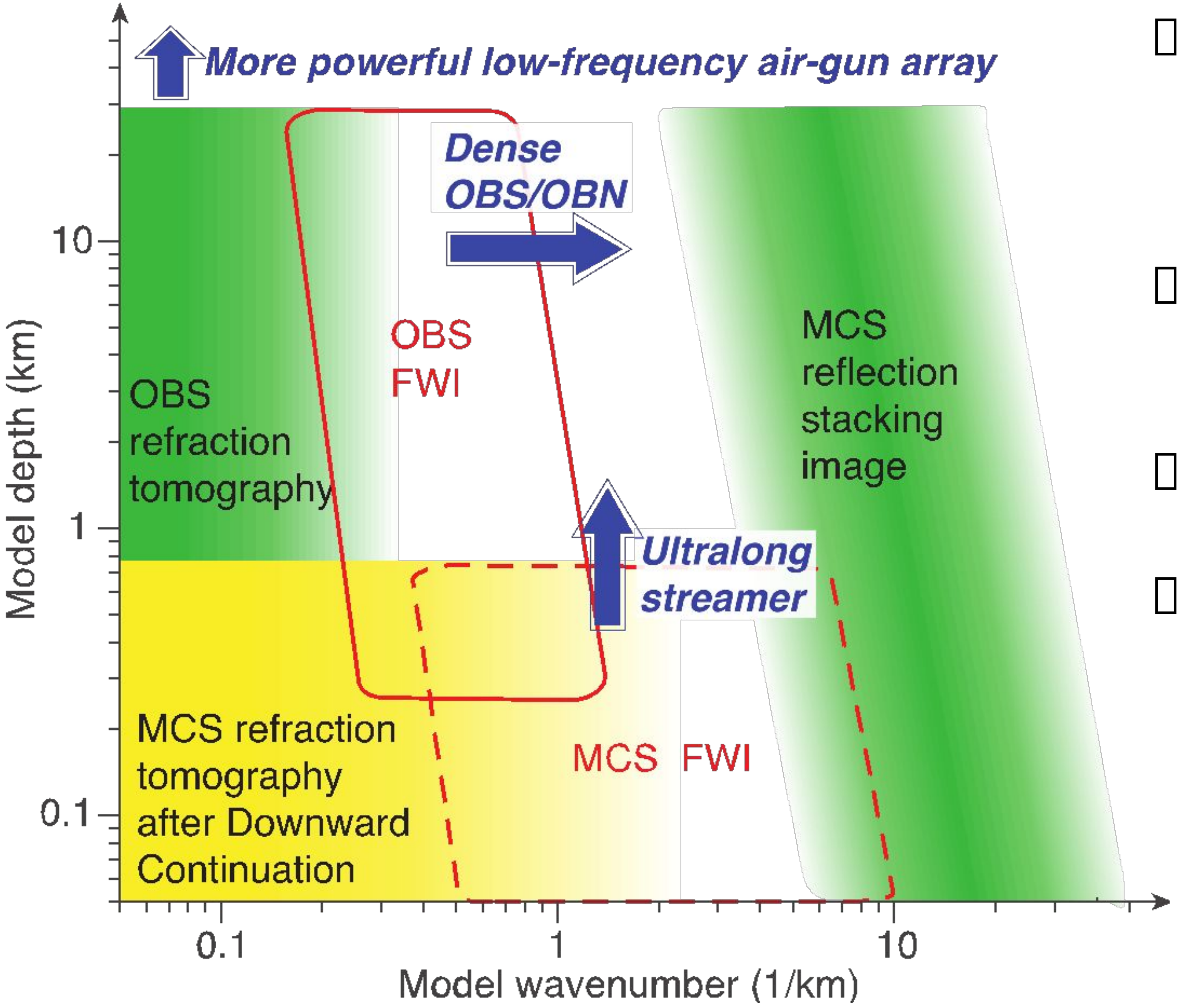


- Conventional marine seismic data analysis
  - OBS traveltime tomography
  - MCS reflection imaging

- MCS tomography and full waveform inversion after Downward extrapolation

- OBS full waveform inversion

Towards "full-wavelength imaging" of oceanic crust



- Conventional marine seismic data analysis
  - OBS traveltime tomography
  - MCS reflection imaging
- MCS tomography and full waveform inversion after Downward extrapolation
- OBS full waveform inversion
- New seismic data acquisitions shall consider:
  - Ultralong streamer (e.g. > 15 km)
  - Dense ocean bottom seismometer/node array
  - Plus waveform-based data analyzing techniques

Acknowledgement

- I am grateful for the crews, technicians and science parties of the cruises that acquired the seismic data used in this talk.
- I am also very thankful for the funding support from European Research Council (ERC), Ocean Frontier Institute (OFI) of Canada, and National Science Foundation (NSF)!

erc European Research Council
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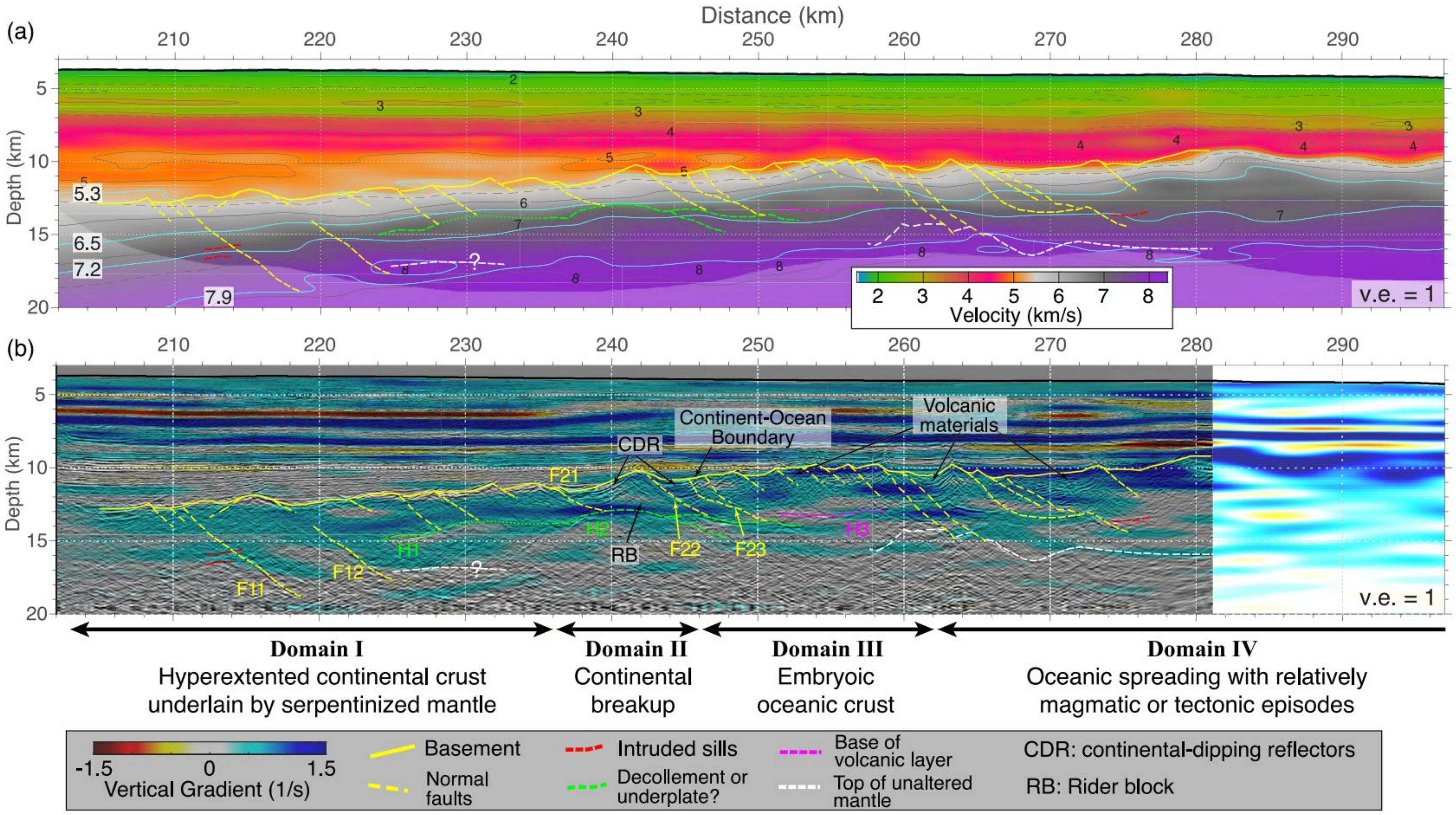
NSF National Science Foundation

CASE III – Nova Scotian rifted margin: Joint interpretation

The velocity gradient information in the FWI results assist in the interpretation of the improved reflection image.



Jian, Nedimovic, Canales and Lau, 2021, *JGR*