Travel Time & Full Waveform Tomographic Inversion

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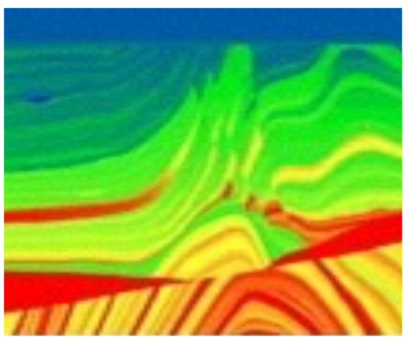
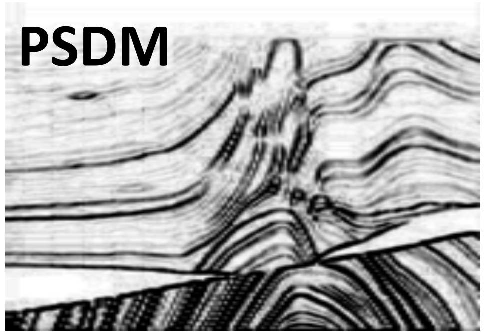
Work Funded (largely) by REPSOL

Why using Full Waveform Inversion to explore the subsurface structure?

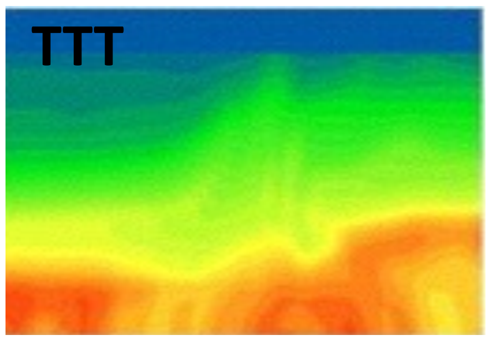
Target

Image &
Properties

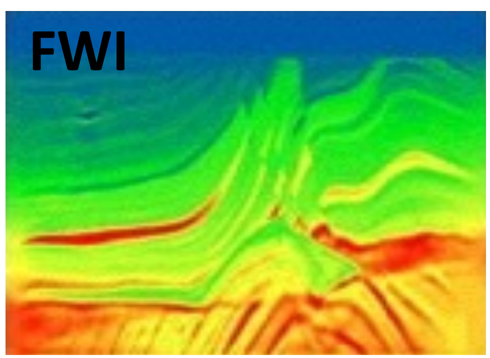




- **Depth migration** of MCS data
- Excellent definition of boundaries and geometry (e.g. RTM)
- Limitations to determine physical properties **> need velocity model building (TTT)**



- **Travel Time Tomography** (Inversion) using arrival time of refracted + reflected phases.
- Ray theory > Resolution ~$(\lambda d)^{1/2} \approx 10^3$ m
- Moderately non-linear > robust; moderate computational cost; limited resolution.



- **Full waveform inversion** (phases and amplitudes) > Advantages TTT & PSDM.
- Wave equation > Resolution ~$\lambda/2 \approx 10^1$-10^2 m (similar to MCS+PSDM).
- Strong non-linearity > Initial model, low freq, noise, source, computational cost.

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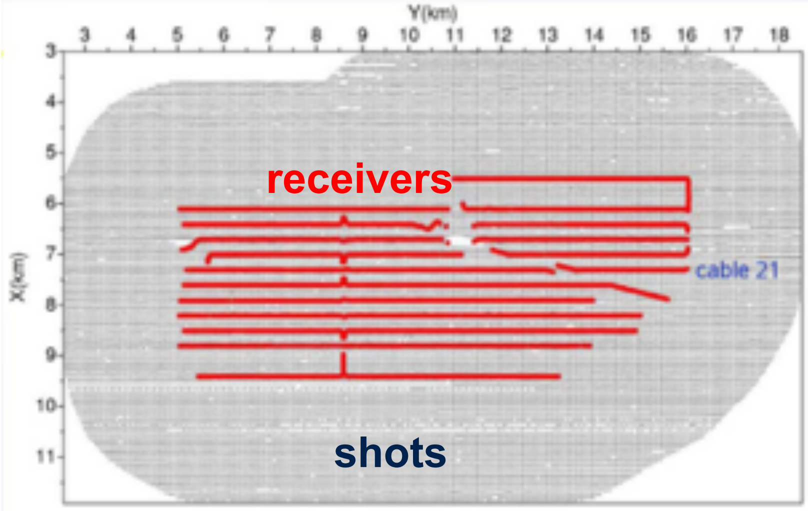
Is FWI worth implementing?



Acquisition with OBC
Maximum offset: 13 km

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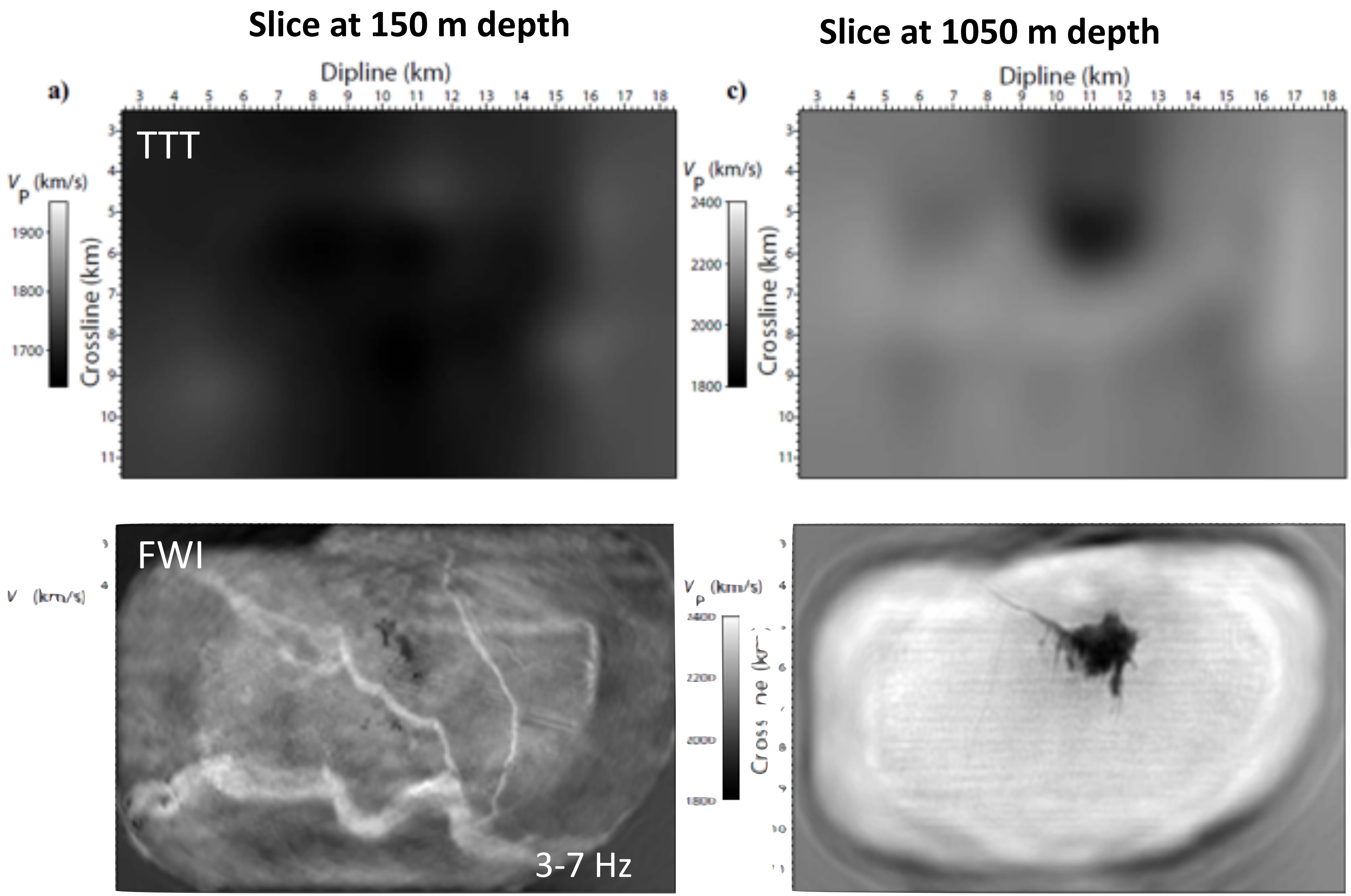
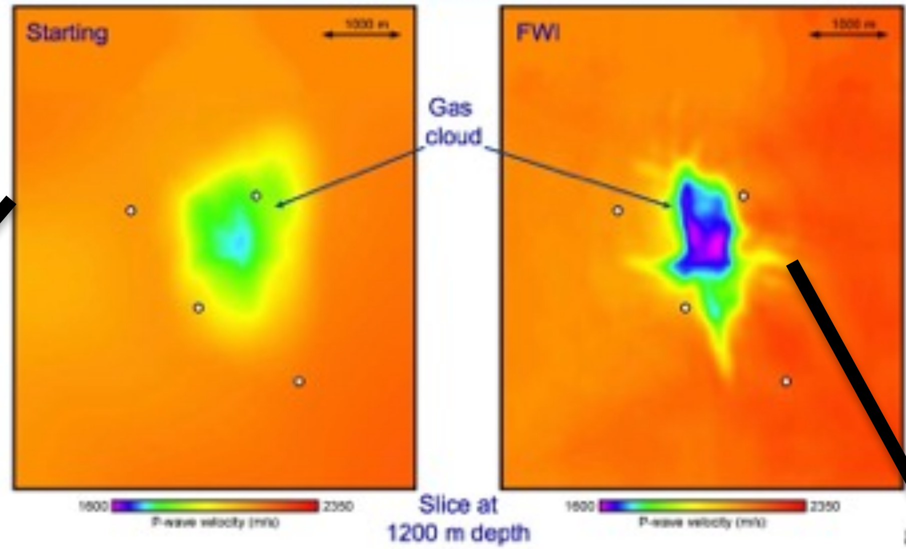
Is FWI worth implementing?



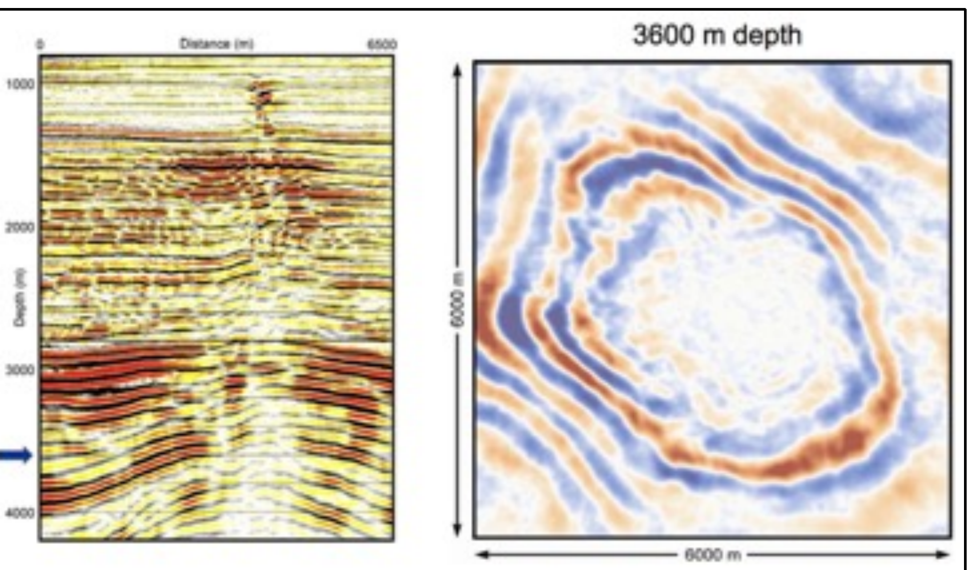
Sirgue et al., BP (2010)

Is FWI worth implementing?

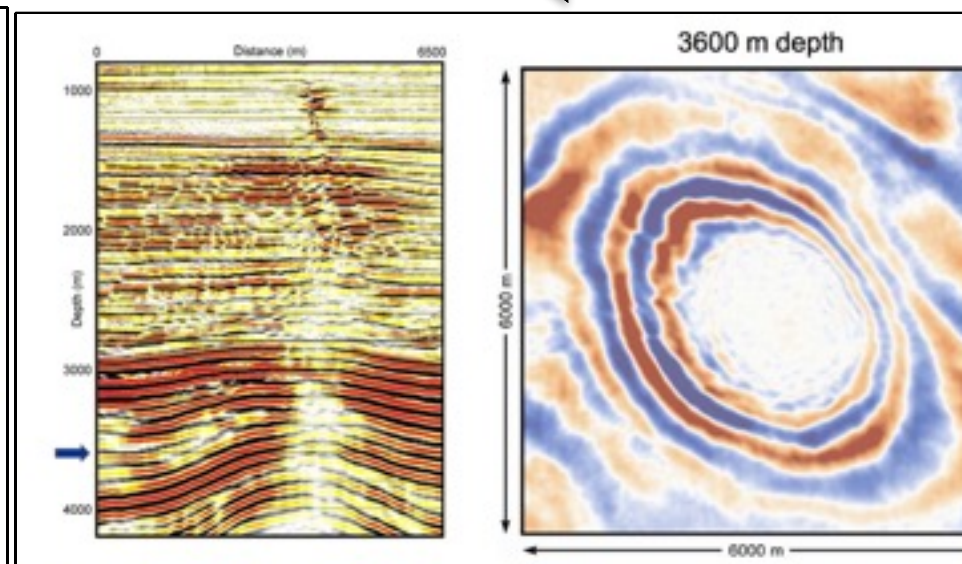
Tommeliten - North Sea
OBC - 6km
11 km offset



TTT-RTM



FWI-RTM



Warner et al., 2013, Geophysics

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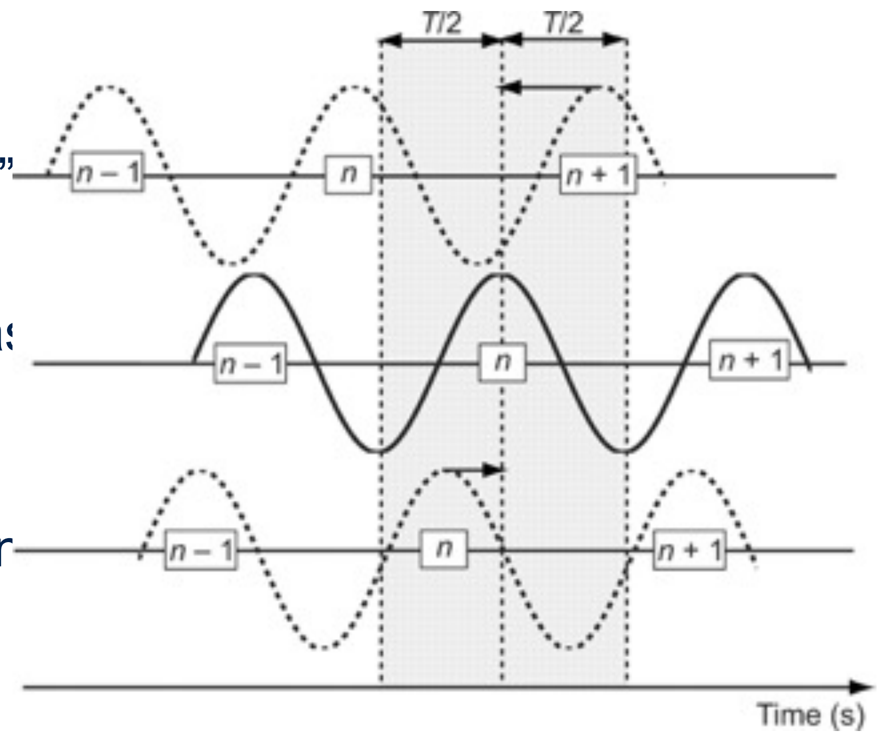
Non-linearity in FWI

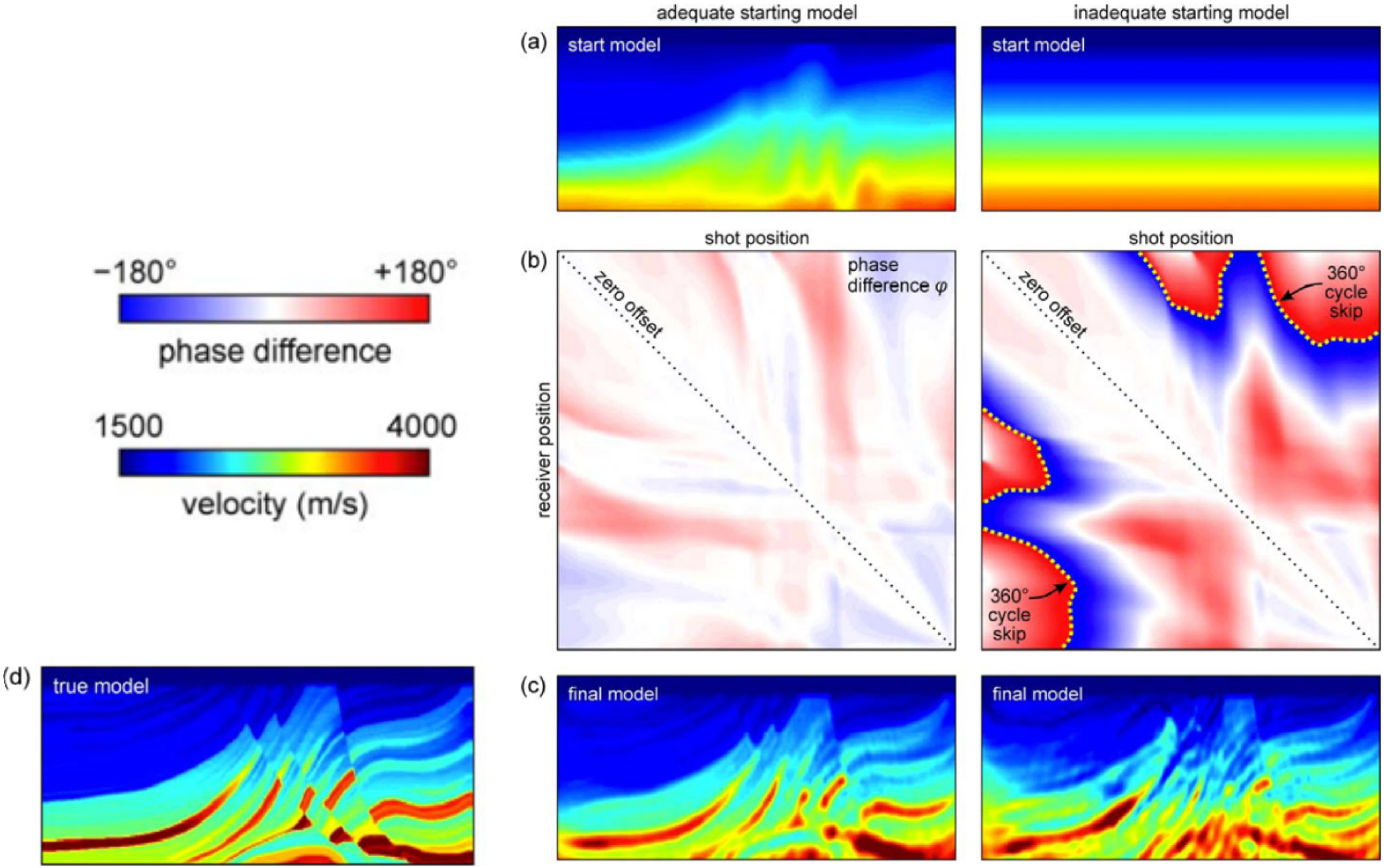
- Assuming that we can reproduce the physics of wavefield propagation with the required accuracy, the key remaining problem is “**non-linearity**”
- Minimization of **objective function** using J-based (CG…) or “approximate H” based approaches (L-BFGS…)
- Most schemes use/**assume L2-norm** as objective function (see SEG 2013 abstracts)
- L2-norm is highly nonlinear (comparison point by point of the trace) > subject to “**cycle skipping**”

L2-norm: $\|\mathbf{u}(t) - \mathbf{d}(t)\|^2$



Operto & Virieux (2009)

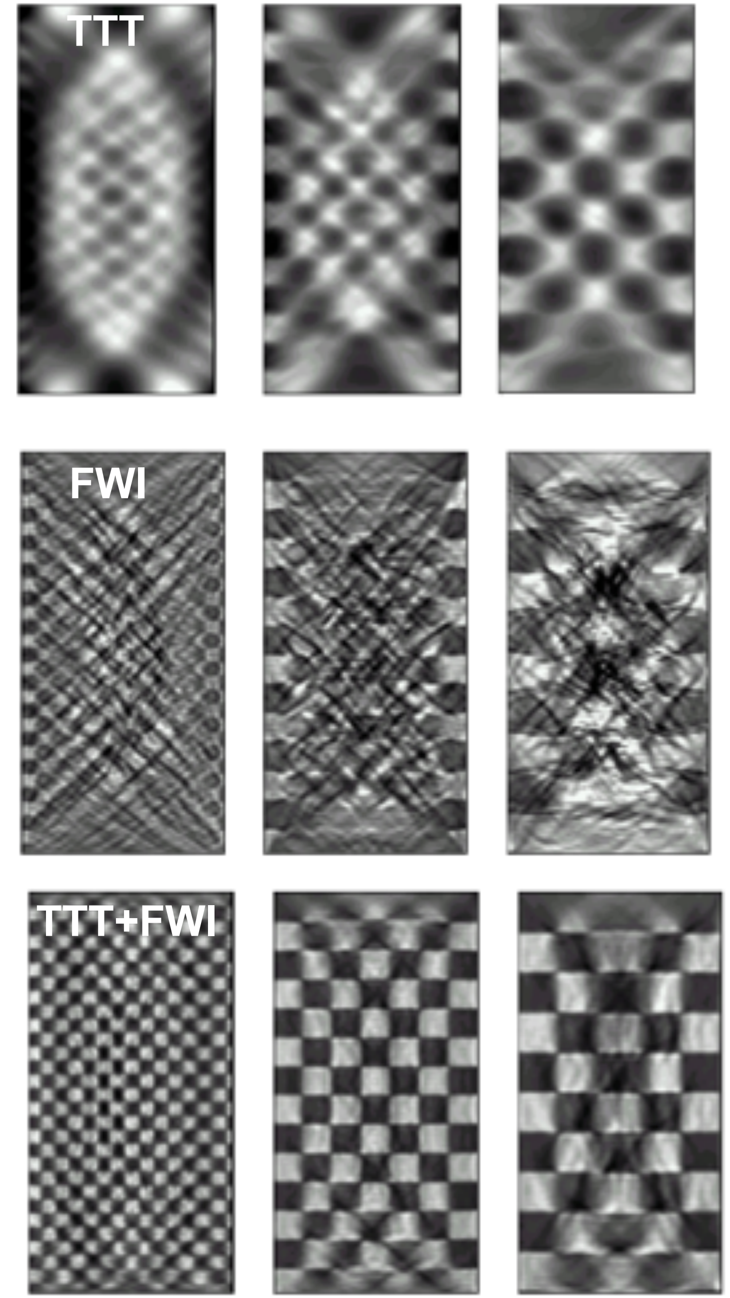
Non-linearity in FWI: cycle skipping



Shah et al., IC (2013)

Strategies to overcome cycle skipping

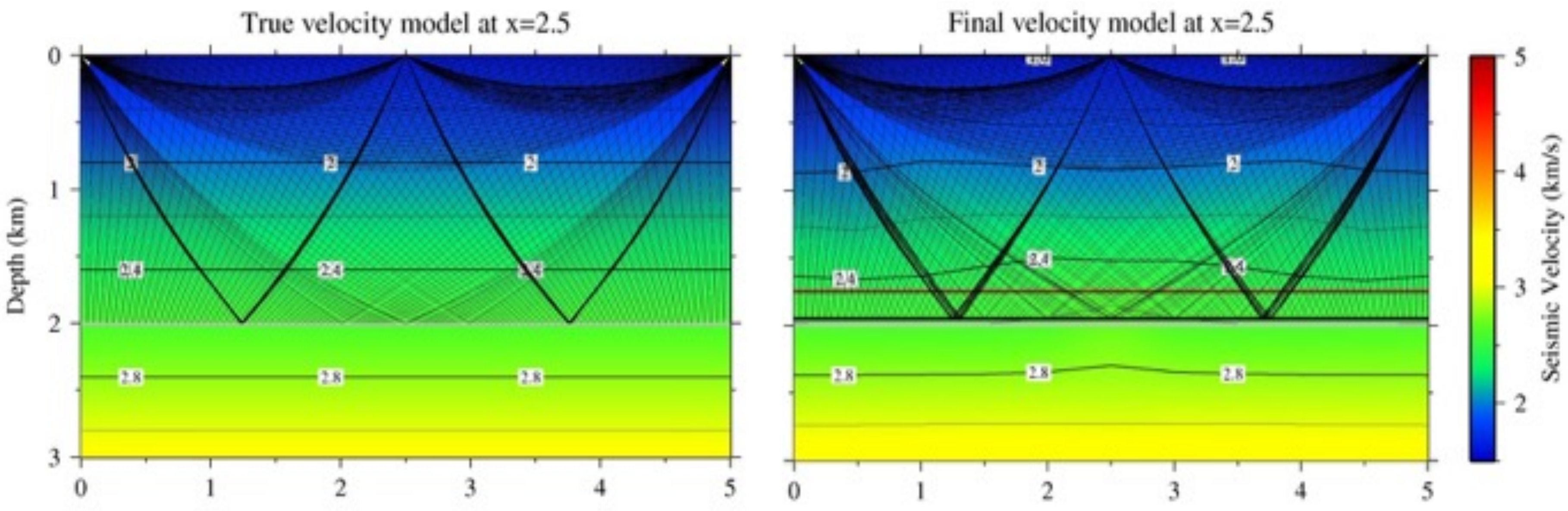
First apply TTT and then use the result as initial model for FWI (e.g. Pratt et al., 2002)



Pratt et al. (2002)

Joint 3D refraction/reflection travel-time tomography (tomo3D)

Parallelized Code is available for download



Meléndez et al., (GJI 2015)

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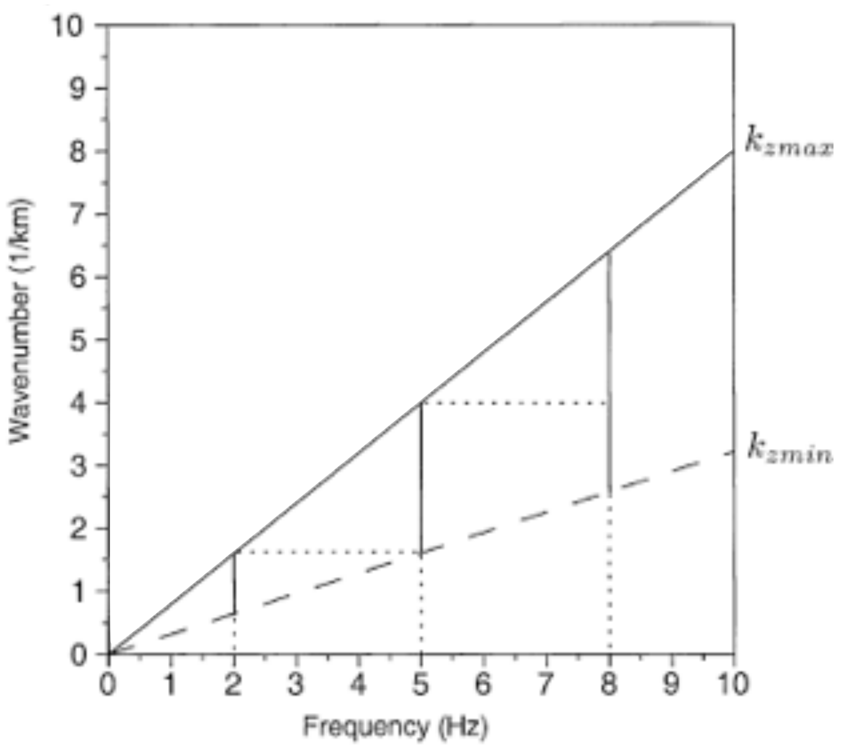
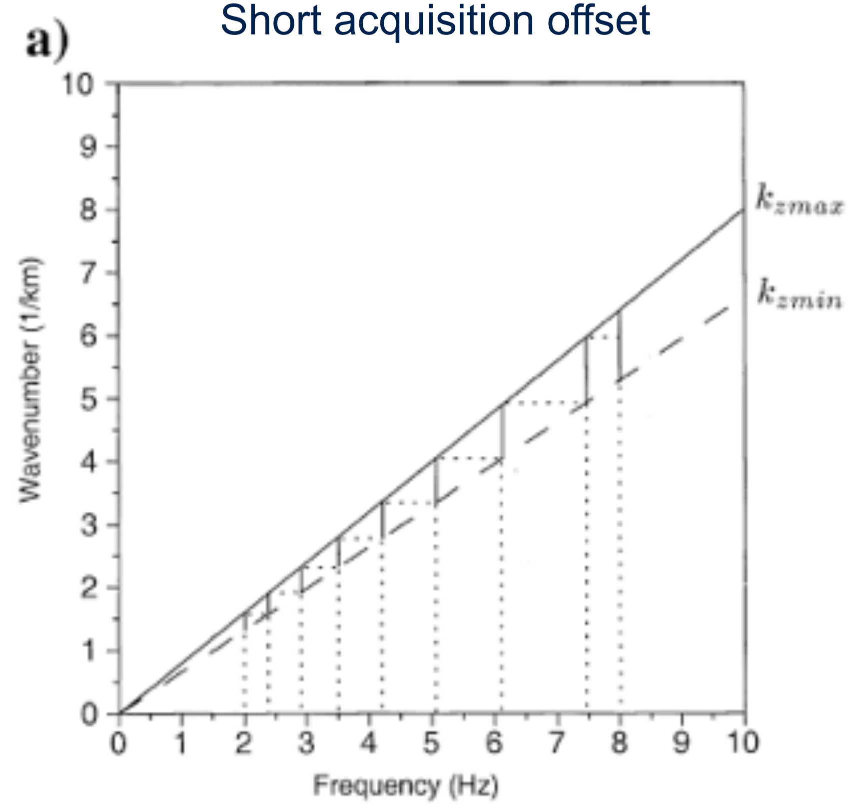
Strategies to overcome cycle skipping

1) Multi-scaling: Add data sequentially, proceeding from low to high frequencies (Bunks et al., 1995)

Long acquisition offset



Short acquisition offset



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Sirgue & Pratt (2003)

Industry 2D Example: 2 ship 2 streamer with a total 18 km offset

Application on Gulf of Mexico Data

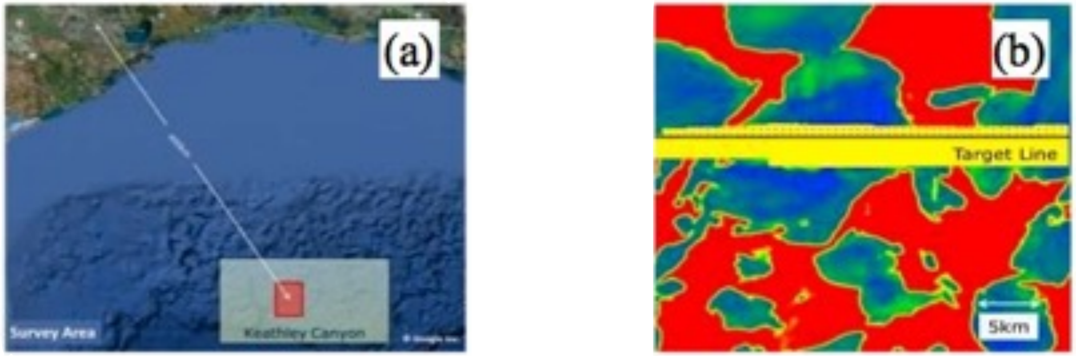

Figure 3: *(a) Survey location in Gulf of Mexico; (b) Shot/receiver map around the target line.*

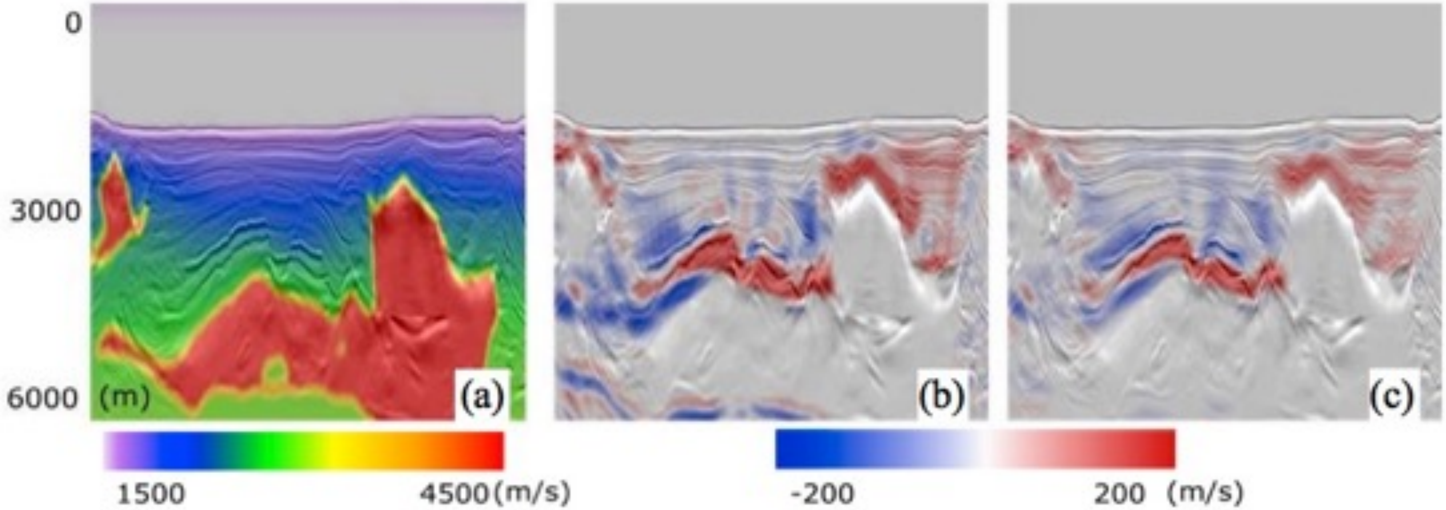

Figure 4*: (a) Initial model; (b) Velocity perturbation from conventional FWI without data selection; (c) Velocity perturbation from FWI with data selection.*

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Bi & Lin CGG (76th EAGE Conference & Exhibition 2014)

Academia 3D Example: Whole Mantle Tomography

LETTER

doi:10.1038/nature14876

Broad plumes rooted at the base of the Earth's mantle beneath major hotspots

Scott W. French[1]† & Barbara Romanowicz[1,2,3]

September 2015

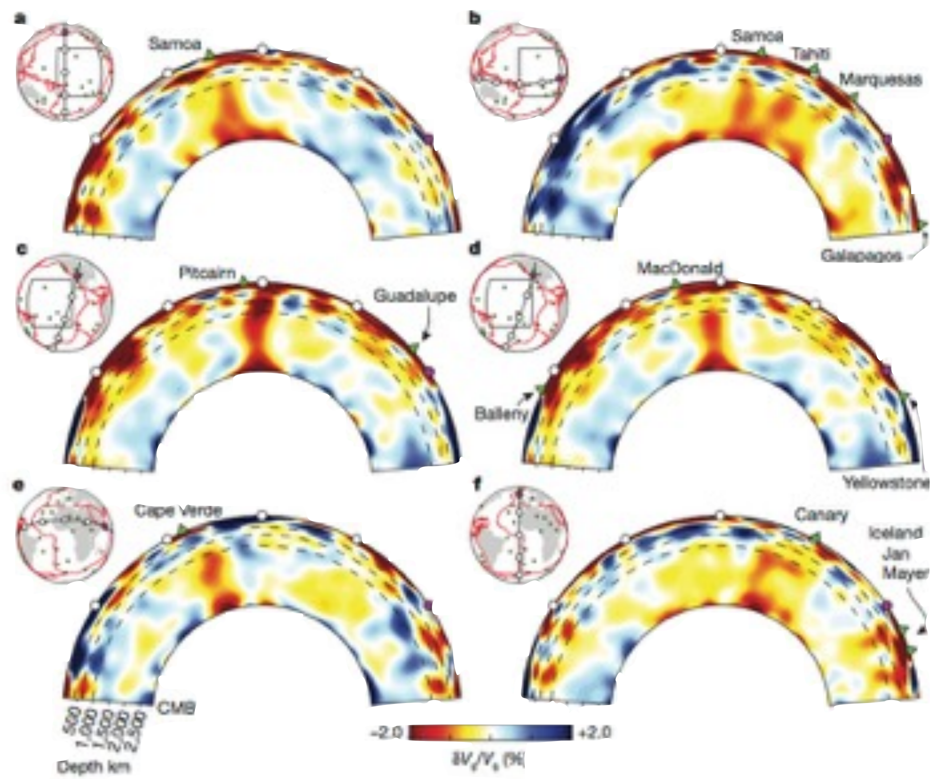

Figure 1 | Whole-mantle depth cross-sections of relative shear-velocity variations in model SEMUCB-WM1[4], in the vicinity of major hotspots. The sections are shown in the inset maps, with the direction of the projection indicated by the position of the purple dot in both map and cross-section views (black boxes correspond to the three-dimensional rendering regions in Fig. 2). Green dots and triangles mark the locations of hotspots[27]. The reference model is the corresponding global one-dimensional average shear-wave velocity (V_s) profile of SEMUCB-WM1. The colour scale has been chosen to emphasize lower-mantle structures, resulting in substantial saturation in the upper mantle. Broken lines indicate depths of 410 km, 660 km and 1,000 km. Focused, quasi-vertical, broad plumes extend continuously from patches of strongly reduced V_s at the base of the mantle to depths of at least 1,000 km in the vicinity of: **a**, Samoa; **b**, Tahiti, the Marquesas, the Galapagos and Samoa; **c**, Pitcairn; **d**, MacDonald; **e**, Cape Verde; and **f**, the Canary Islands. These plumes stand out from other low-velocity features in these cross-sections, which span nearly half of Earth. **d**, Note the absence of a noticeable anomaly in the lower mantle immediately beneath the Yellowstone hotspot. However, a faint low-velocity conduit appears to the southwest (offshore of North America), anchored by a low-velocity patch in the D″ mantle region. It is beyond the resolution of our study to verify whether this feature is related to the Yellowstone or the Guadalupe (**c**) hotspot.

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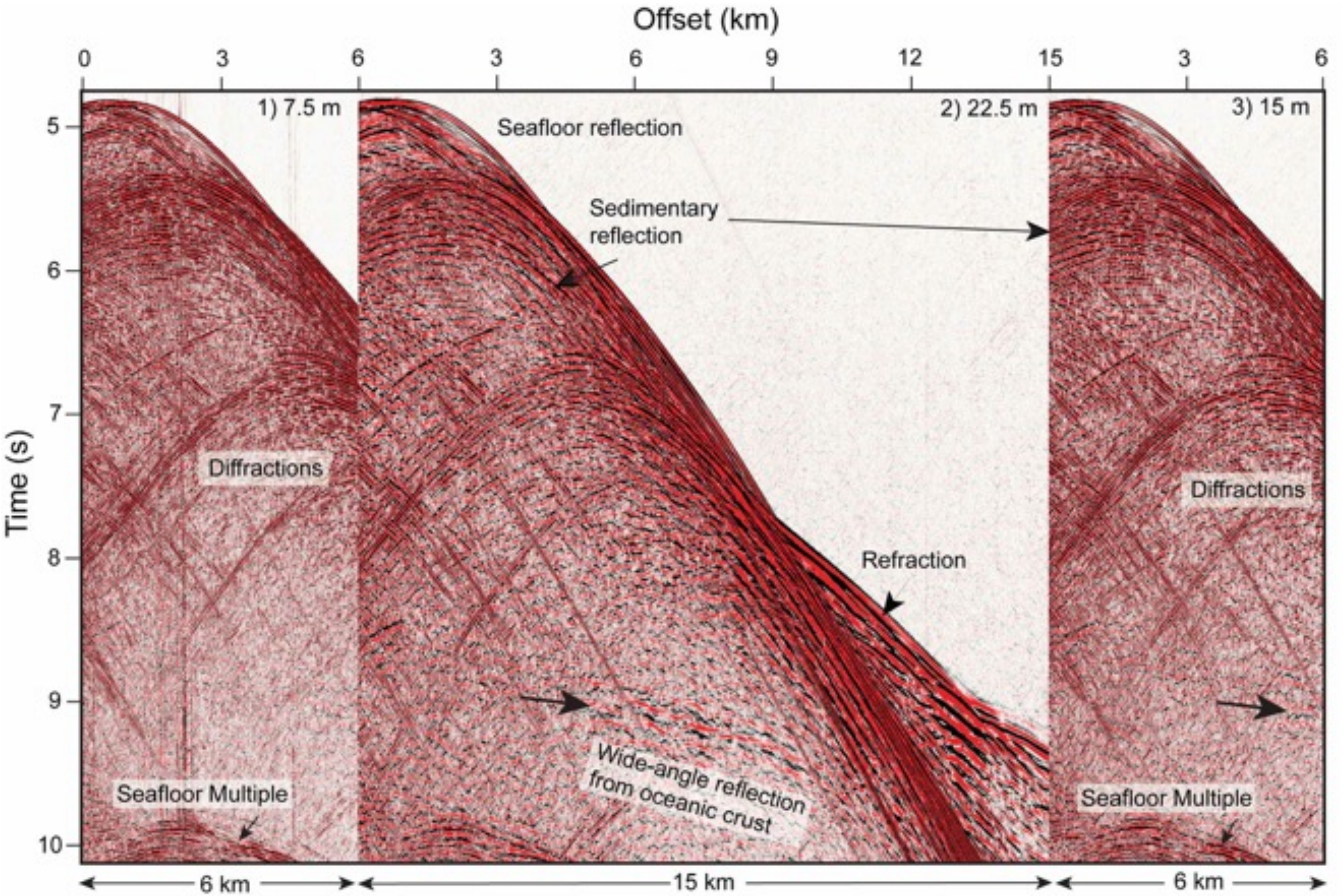
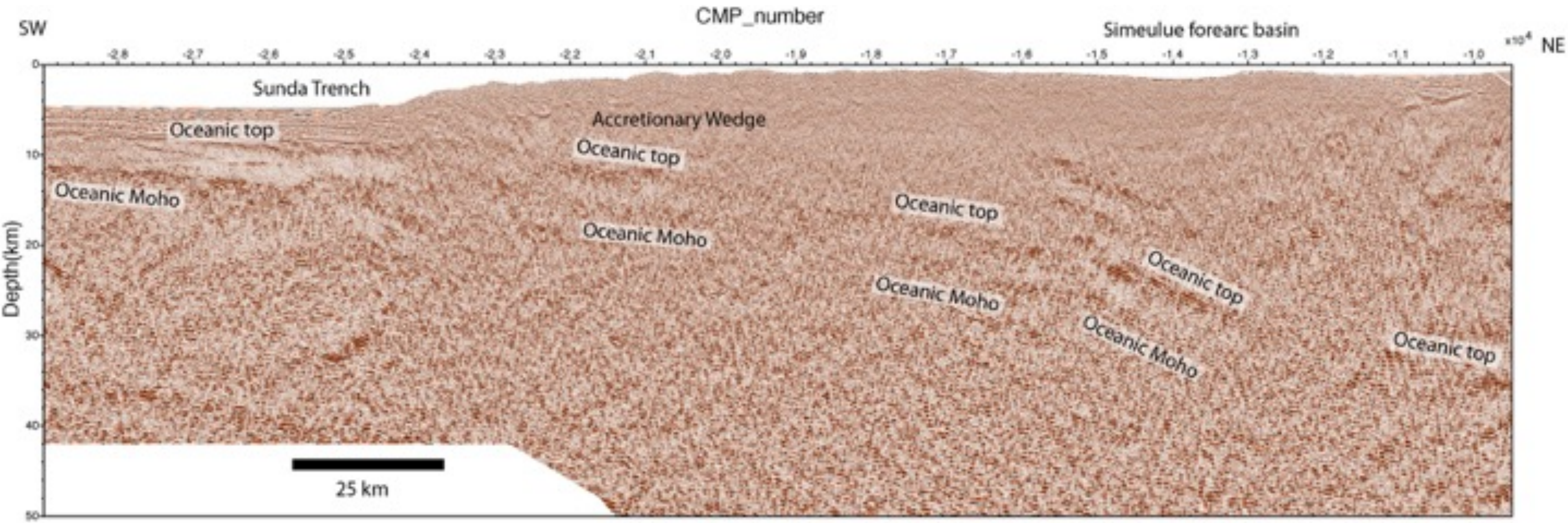
Long-offset streamers



Singh (EOS, 2012)

Long-offset streamers



Singh et al., (2013)

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What seismic information is needed for FWI?

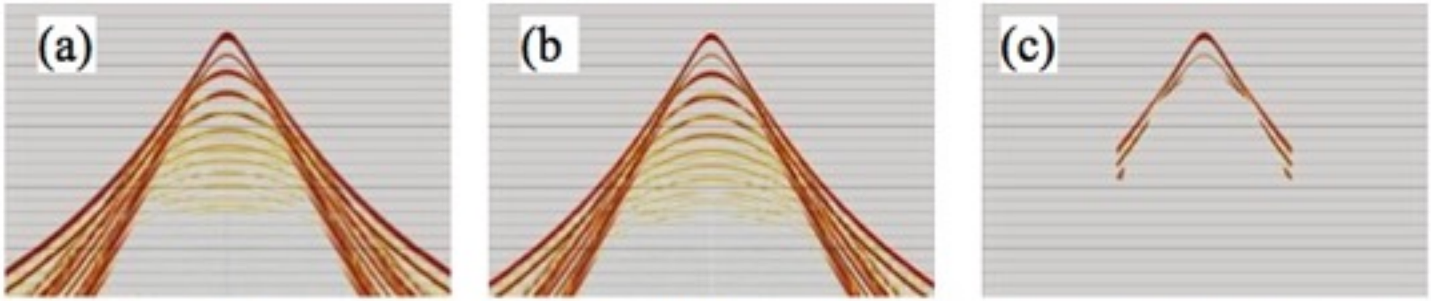

***Figure 1:** Illustration of data selection: (a) real data; (b) predicted synthetic data; (c) data selection for FWI.*

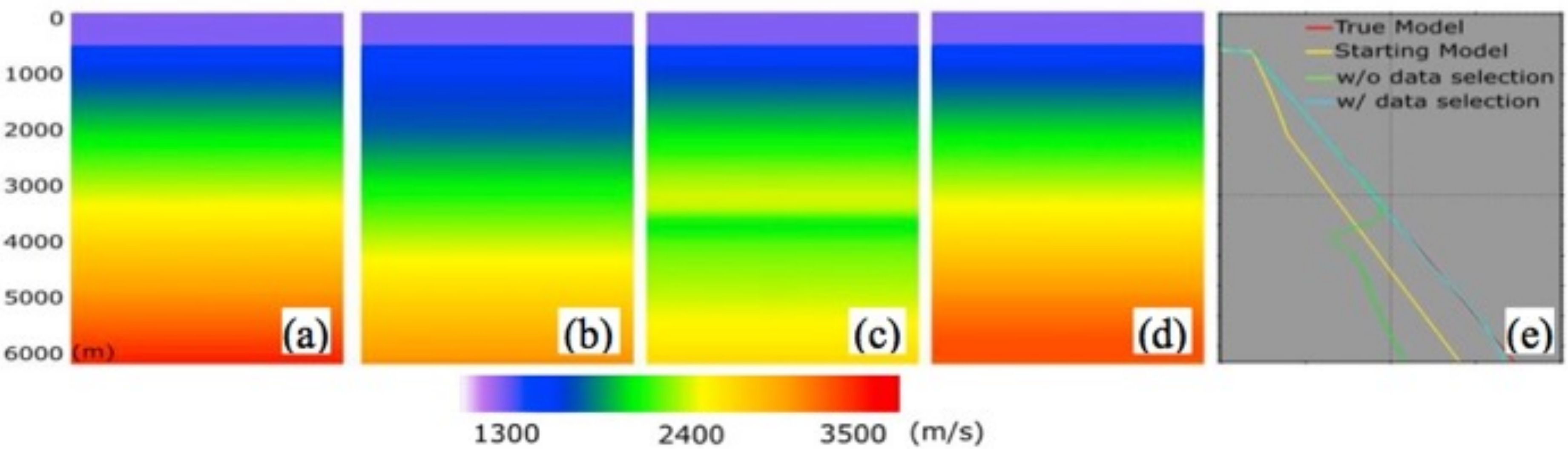

***Figure 2**: (a) True velocity model; (b) Initial model for FWI; (c) Conventional FWI result w/o data selection; (d) Data selection FWI result; (e) Velocity profile as a function of depth for models (a)-(d).*

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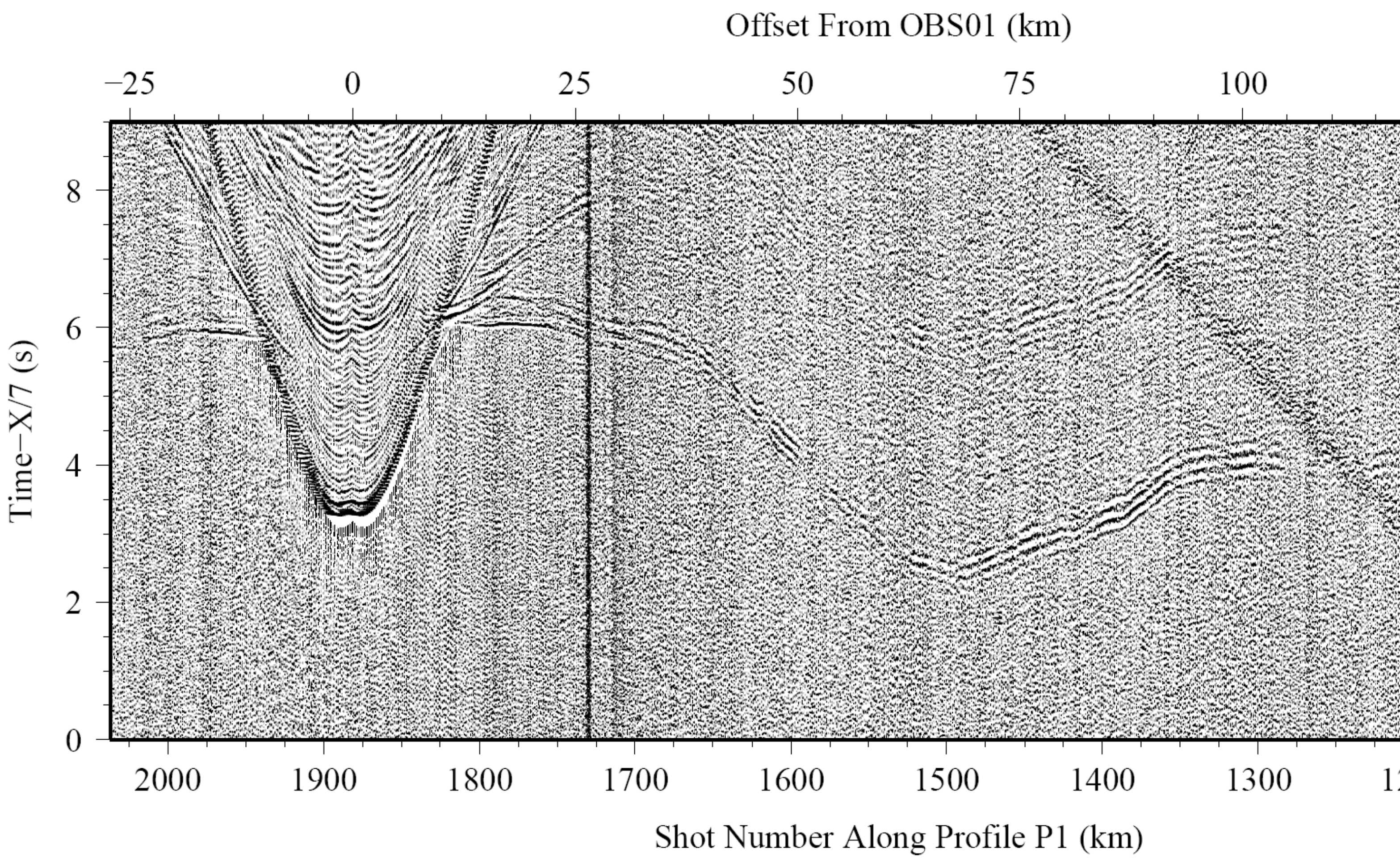
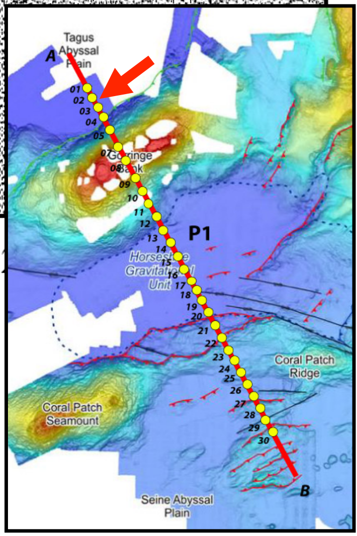
The longest offsets with diving waves





Sallares et al 2013

Conclusion

Our group view:

A (small?) revolution in seismic imaging is underway but requires the proper acquisition tools.