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FULL-WAVEFORM INVERSION

Practicalities and Progress

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Outline

- Overview of full-waveform inversion
- Towed-streamer field example
- OBC field example, pre-processing, validation
- Other parameters
- Method
- Pitfalls and practicalities
- Quality assurance
- New directions
- Q & A

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Full Waveform Inversion

- Method for generating high-resolution high-fidelity models of physical properties in the subsurface
- Seeks a model which can predict the entire recorded wavefield, wiggle-for-wiggle
- Has become practical for 3D field datasets within the last few years
  - software advances
  - hardware advances

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Full Waveform Inversion

- Generates high-resolution model of physical properties
- In principle any property that affects seismic data is possible:
  - p-wave attenuation
  - p-wave anisotropy
  - s-wave velocity
  - density
  - elastic anisotropy
  - anelastic anisotropy
- Commercially → p-wave velocity

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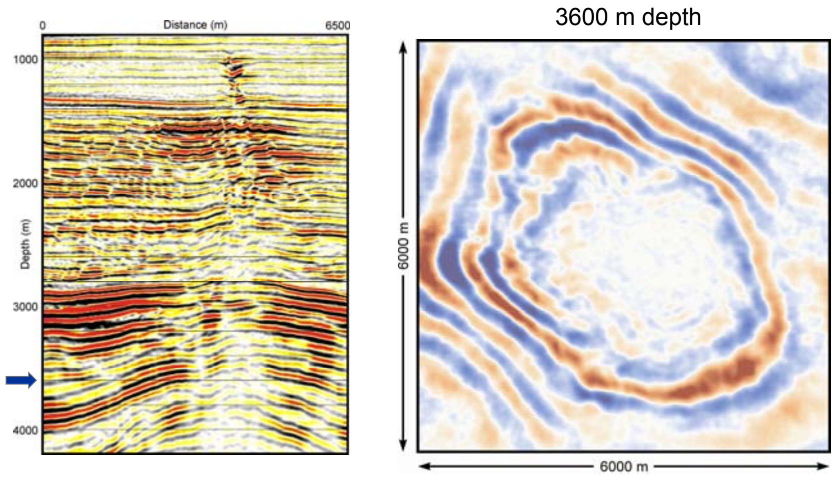
RTM with tomography model



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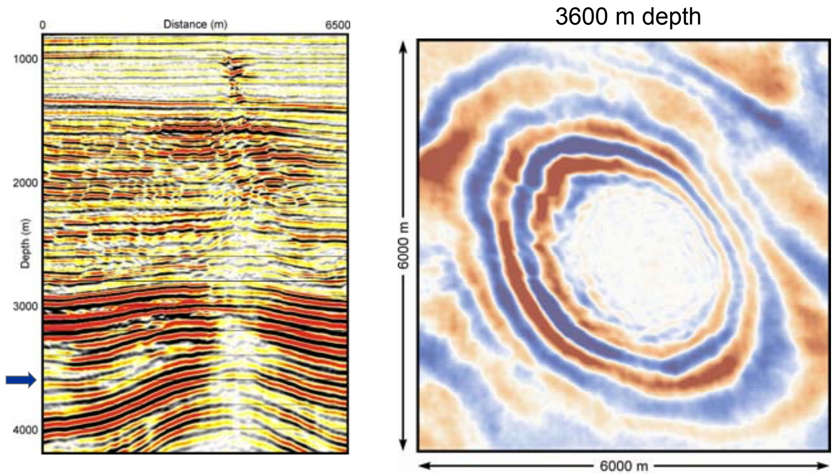
RTM with FWI model



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Full Waveform Inversion

Most of what you know about conventional imaging will not apply to FWI workflows

- uses low frequencies
- uses transmitted arrivals
- iterative inversion from starting model
- details can be critical → does not fail elegantly

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Travel-time tomography

- travel times
- ray theory
- cheap
- robust
- low resolution

  ~ Fresnel zone

  ~ $\sqrt{\lambda d}$

  ~ 700 m

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Full Waveform Inversion

- raw wavefield
- wave theory
- expensive
- still developing
- high resolution

  ~ half wavelength

  ~ λ / 2

  ~ 140 m

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Reverse Time Migration

- uses primary reflections only
- does not deal with multiples
- does not deal with transmitted arrivals
- semi-quantitative imaging
- needs a velocity model
- details may not be critical

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Full Waveform Inversion

- uses the entire unprocessed wavefield
- inverts the multiples
- inverts the transmitted arrivals
- fully-quantitative inversion
- builds the velocity model
- details can be vital

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Practicalities

- FWI is not yet robust
- Requires an accurate starting model
  - local minima
  - cycle skipping
- Careful QC is essential
- Synthetic testing desirable
- Different implementations and practitioners will affect outcomes

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Applications

- Shallow
  - drilling hazards
  - land statics → dynamic corrections
- Intermediate
  - depth migration through heterogeneous overburden
  - delineation of salt flanks
- Deep
  - applied directly at the reservoir

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Cost

- Full 3D acoustic FWI
  - commercialised and affordable
  - with TTI anisotropy
- Lower in cost/hardware than RTM
  - many iterations
  - but reduced bandwidth
  - compute scales as at least n^4

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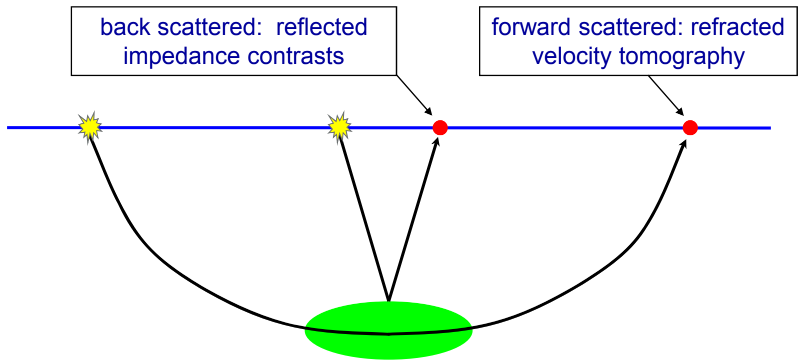
Two types of Imaging



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Migration and Tomography

FWI uses both reflected and transmitted data:

- tomography from forward-scattered waves
- depth migration of back-scattered waves

Refractions → macro-velocity model

Reflections → impedance contrasts

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Refraction *vs* Reflection FWI

There are currently two ways to formulate FWI:

- Use all incident angles to build a velocity model at all length scales
  - needs wide-angle, refracted, long-offset data
- Use near-normal-incident reflections to build a band-limited impedance model
  - reflection FWI needs a simple structure, clean data, and a superb starting model

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Acquisition for FWI

- Long offsets
  - 3 to 6 times target depth necessary
- Low frequencies
  - 2 to 3 Hz desirable
- Many azimuths desirable
  - narrow azimuth possible
- Dense acquisition not necessary

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Common FWI workflow

1. Conventional acquisition, processing, model building & depth imaging
2. Use FWI to improve velocity model in top ~ 2 km of heterogeneous overburden
3. Re-migrate using RTM with the shallow FWI velocity model

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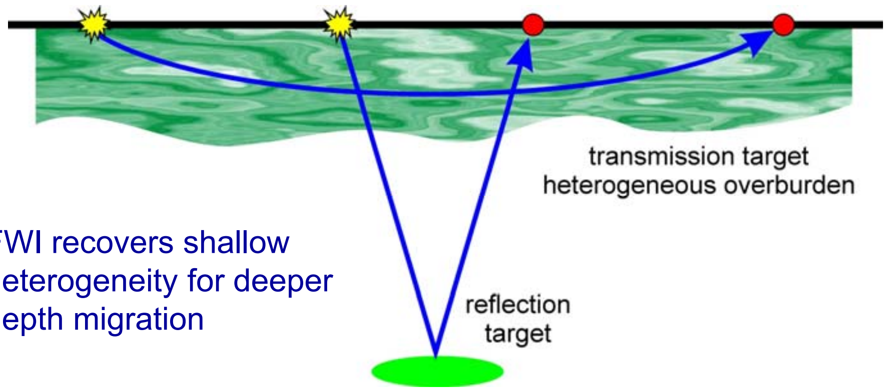
Heterogeneous overburden



FWI recovers shallow heterogeneity for deeper depth migration

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Field example

Samson Dome, Barents Sea

Morgan et al, 2013. *Next-generation seismic experiments.* **Geophysical Journal International, 195,** 1657–1678.

Data courtesy of BG-Group and PL 534 partners

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Samson Dome, Barents Sea

- Complex geological setting:
  - Faulted dome + erosional unconformity overlain by Quaternary
- FWI area ~ 1000 km^2
- Acquisition parameters:
  - 10 streamers, 6km cable, 100m cable separation, 12.5m flip-flop, no low-cut in recording system, shot depth 5m, receiver depth 7m
- Pre FWI processing:
  - Swell noise attenuation, linear radon de-noise, bandpass 2-7 Hz

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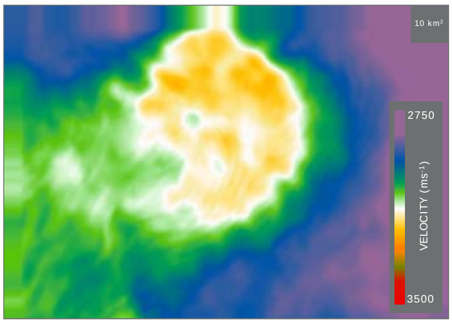
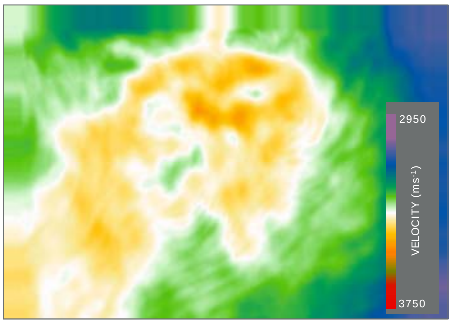
Starting velocity model





1100 m depth

1350 m depth

faulted dome

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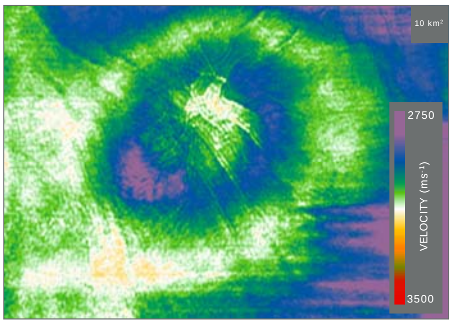
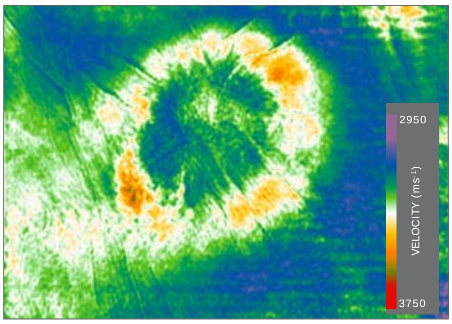
FWI velocity model





1100 m depth

1350 m depth

faulted dome

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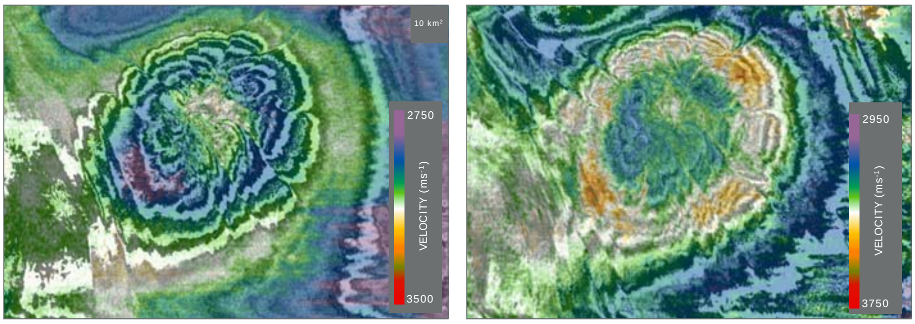
FWI velocity model with seismic overlay



1100 m depth

1350 m depth

faulted dome

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Surface streamer FWI

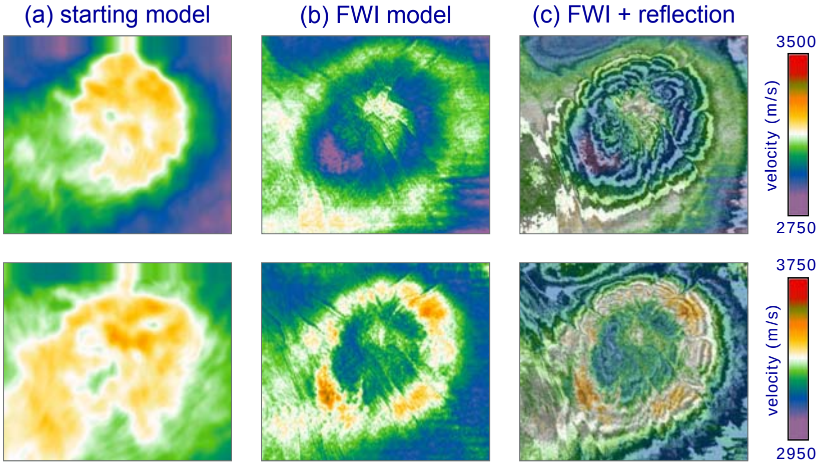
(a) starting model

(b) FWI model

(c) FWI + reflection

1100 m depth

1350 m depth



30 km

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Field example

Tommeliten

Warner et al (2013) *Anisotropic 3D full-waveform inversion*. **Geophysics, 78**, No 2, R59-R80.

Data courtesy of ConocoPhillips and PL 044 partnership

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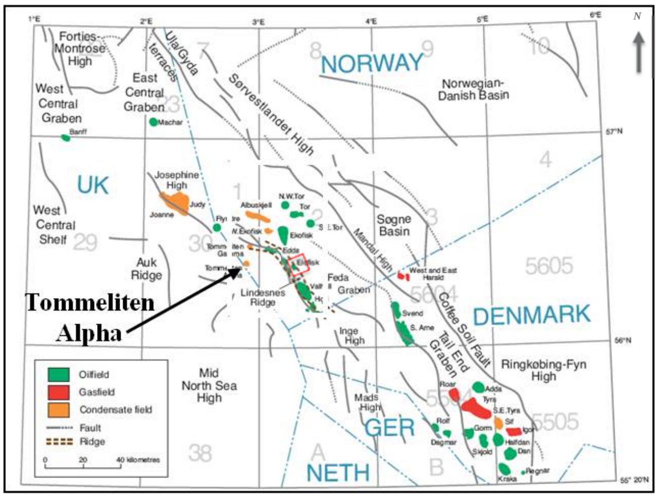
Tommeliten



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Tommeliten

- 4-component OBC
- invert pressure data
- Vp model above reservoir
- shallow gas
- low velocities
- high attenuation
- significant anisotropy

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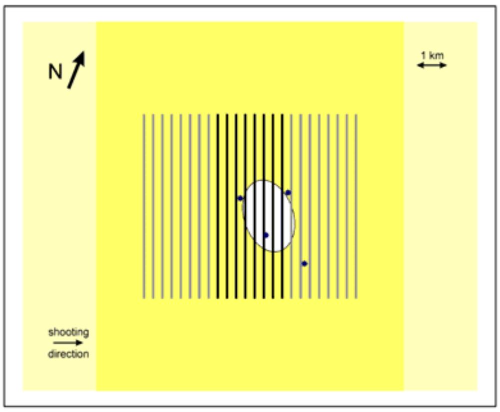
3D OBC field data



acquisition geometry

- 4C OBC
- 3 swaths of 8 cables
- 75 m water depth

- 6 km cables
- 25 m receiver spacing
- 300 m cable spacing
- 6000 receivers

- 25 m shot interval
- 75 m shot-line spacing
- 100,000 shots

- full azimuth to 7000 m
- max offset 11,000 m
- 180 sq km

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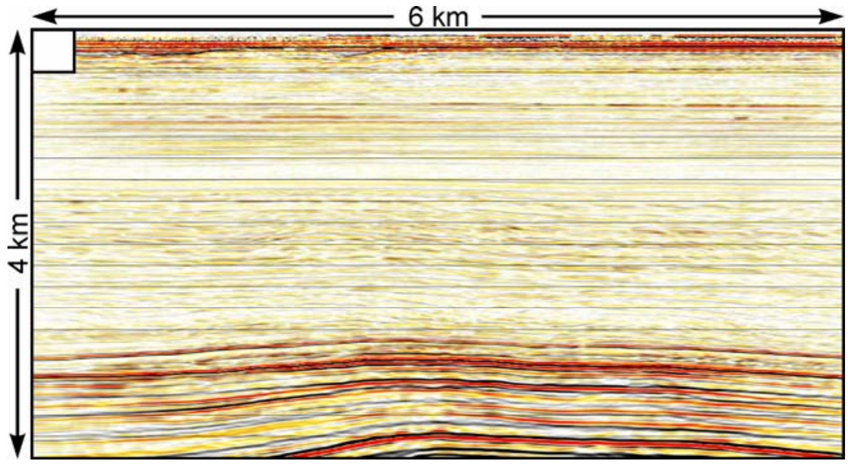
PP PSDM



PZ-summed – deghosted and demultipled

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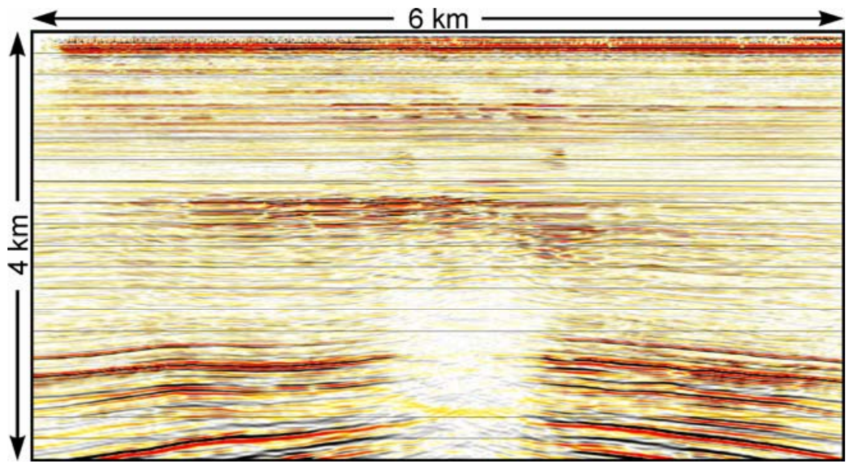
PP PSDM



PZ-summed – deghosted and demultipled

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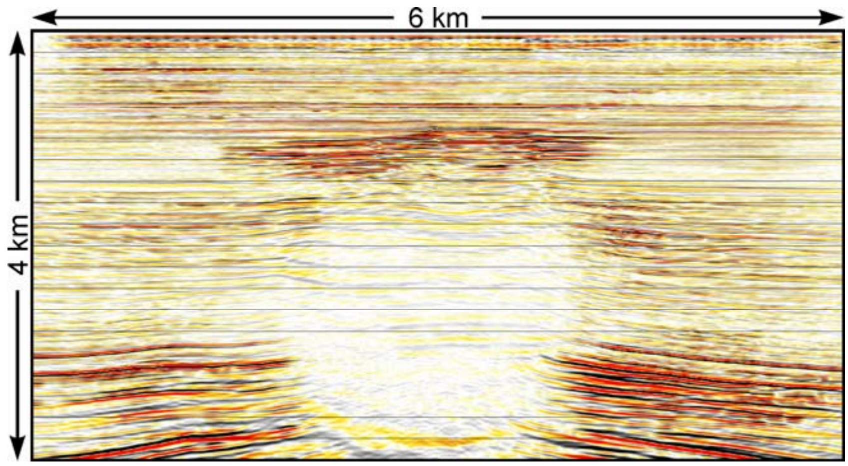
PP PSDM



PZ-summed – deghosted and demultipled

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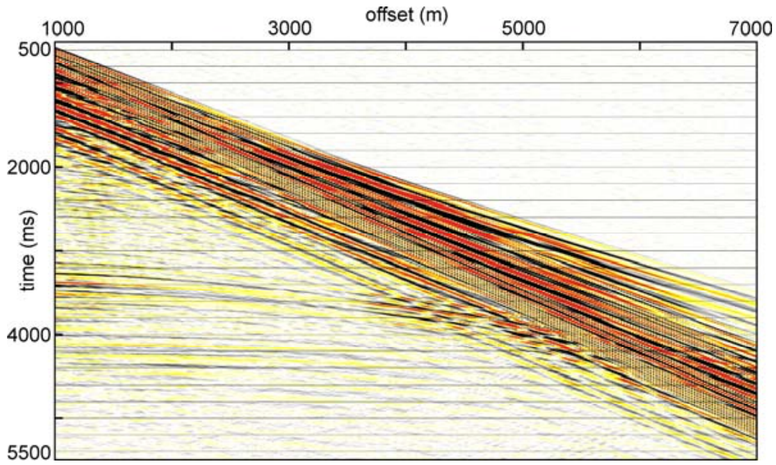
Raw shot record



hydrophone only – include all ghosts and multiples

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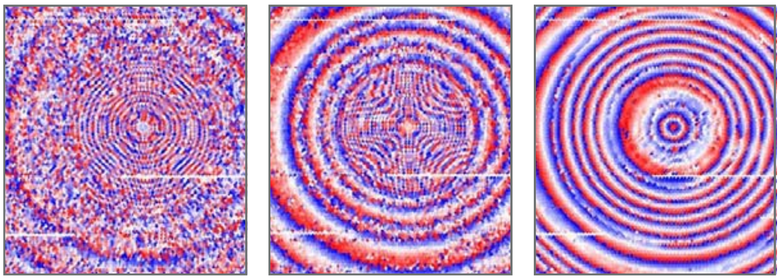
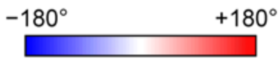
Picking the starting frequency

single-frequency phase



2.4Hz 3.0Hz 3.6Hz



common receiver gather

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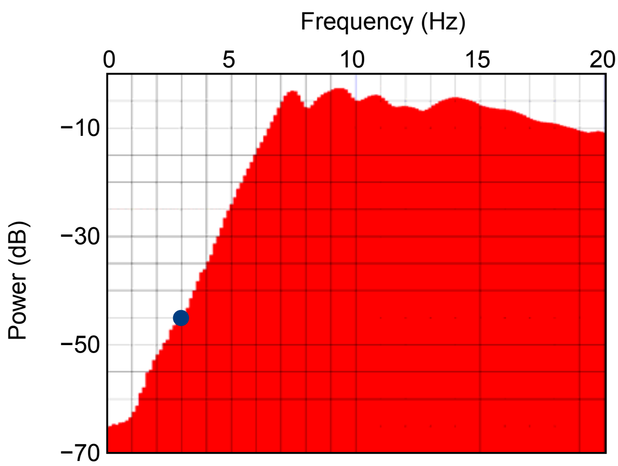
Picking the starting frequency



start at
3 Hz
−45 dB

raw data – amplitude spectrum

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Pre-processing

- No deghost
- No demultiple
- No debubble
- No wavelet shaping
- No low-cut filter
- No deconvolution
- No PZ sum
- No AGC
- No divergence correction

Usually essential to return to raw field data

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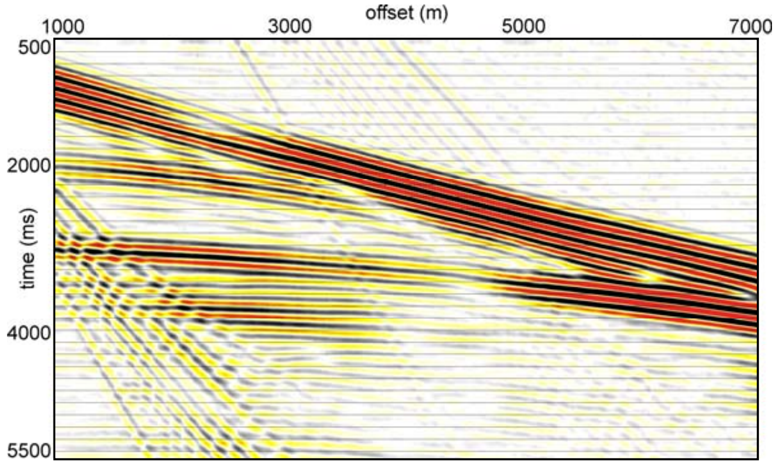
Scholte waves at lowest frequencies



hydrophone

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Pre-processing

- Mute ahead of first breaks
- Mute Scholte waves
- Truncate to 5500 ms
- Cut frequencies above 8 Hz
- Delete three quarters of receivers
- Delete two thirds of sources
- Delete offsets < 100 m
- Delete geophones, retain hydrophones only
- Apply source-receiver reciprocity

Most of this is to reduce compute time, and to avoid adding noise into the inversion

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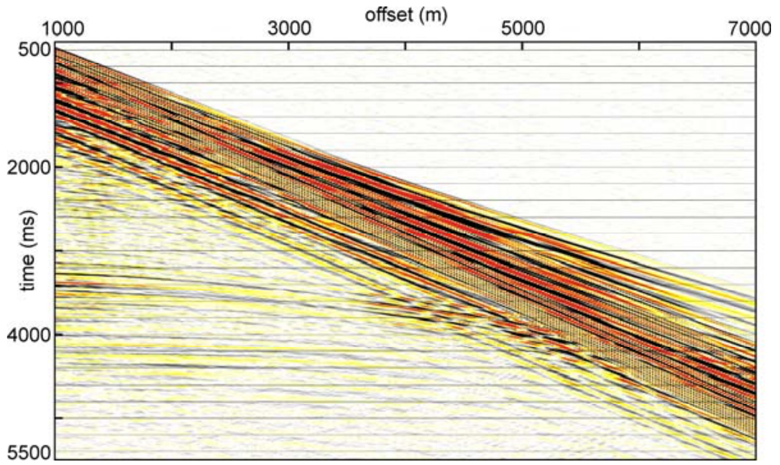
Raw shot record



hydrophone

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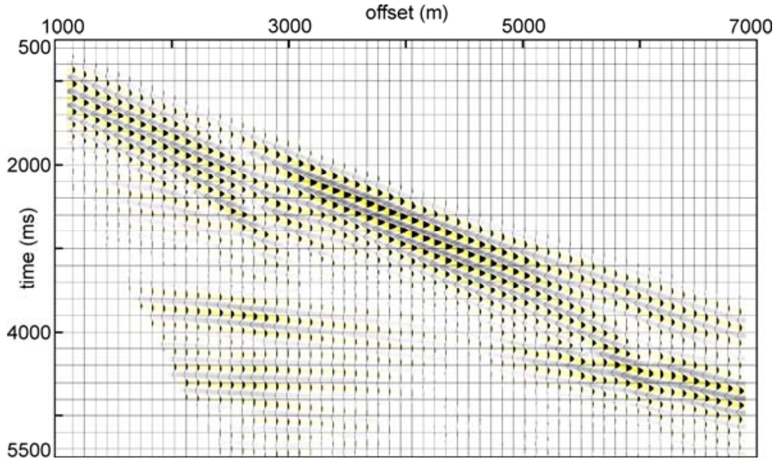
Pre-processed for acoustic FWI



hydrophone

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Pre-processing

Surface streamer data:

- remove swell noise
- low-frequency de-noise
- shape amplitude spectrum to boost lowest frequencies

Land data:

- compensate geophone roll-off at low frequency
- remove shear-waves, converted waves, surface waves
- remove local noise sources
- surface consistent wavelet
- interpolate additional sources
- convert geophones to hydrophones

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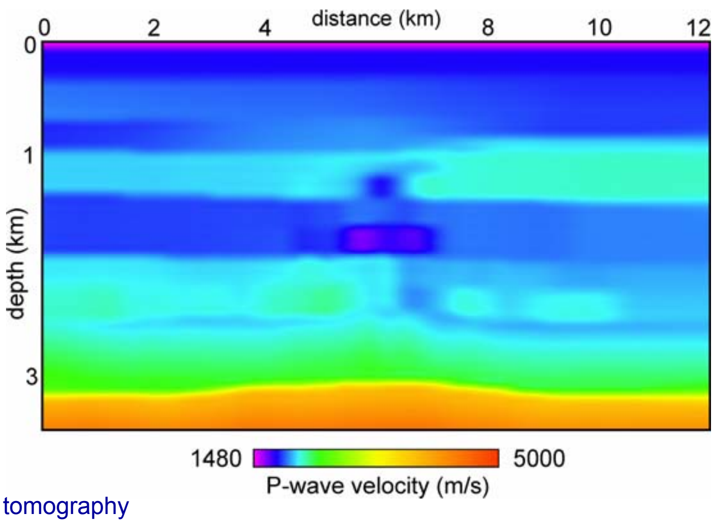
Starting model



reflection tomography

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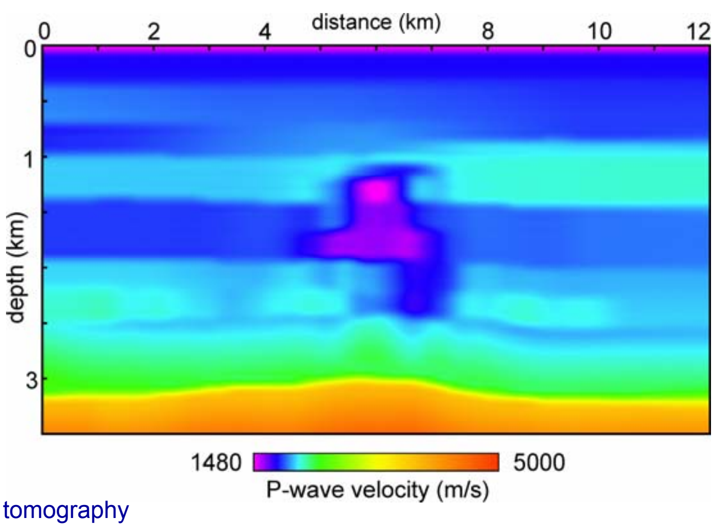
Starting model



reflection tomography

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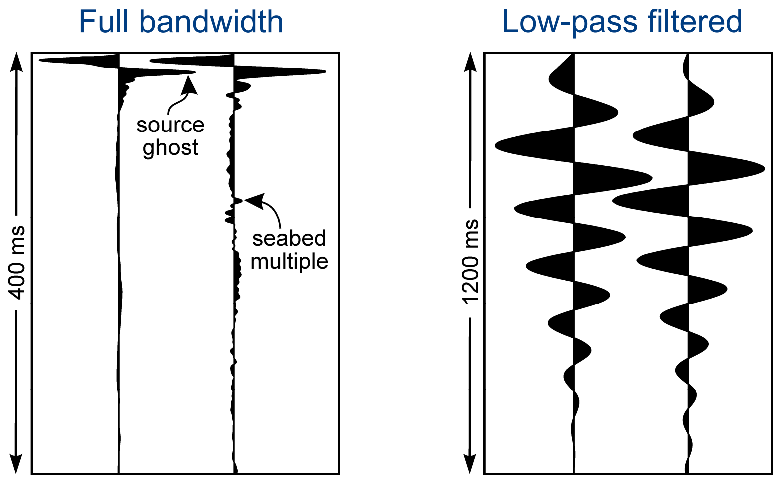
Source wavelet



Contractor’s wavelet *vs* Near-source OBH

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Wavelet

- Low-frequency wavelet
- Same zero-time as pre-processed data
- Same filters as pre-processed data
- Wavelet with no source ghost
- Can be non-causal

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Inversion parameters

- Time domain, acoustic 3D, VTI anisotropy
- Hydrophones only → include ghosts and multiples

- Apply reciprocity
- 6000 → 1440 sources
- 80 sources per iteration

- Six frequency bands from 3.0 → 6.5 Hz
- 18 iterations per frequency
- Each source used once per frequency

- Amplitude equalisation
- Conjugate gradients
- Approximate diagonal Hessian

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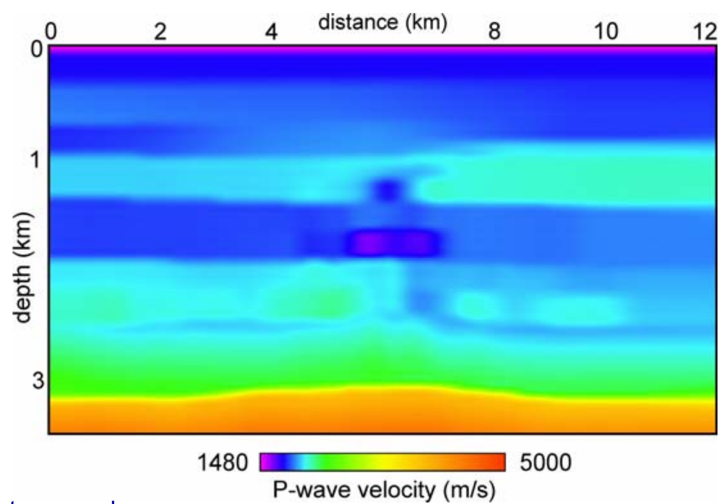
Starting model



reflection tomography

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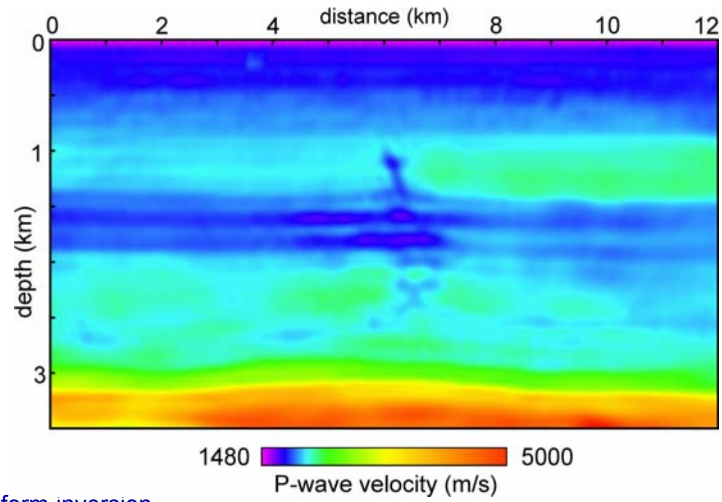
FWI model



full-waveform inversion

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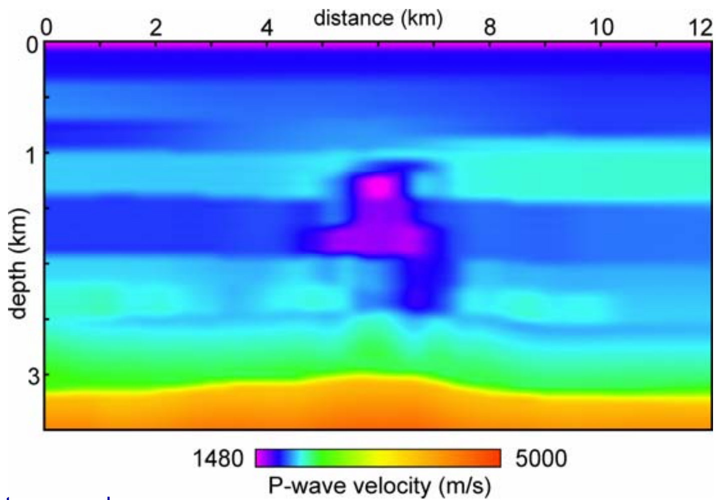
Starting model



reflection tomography

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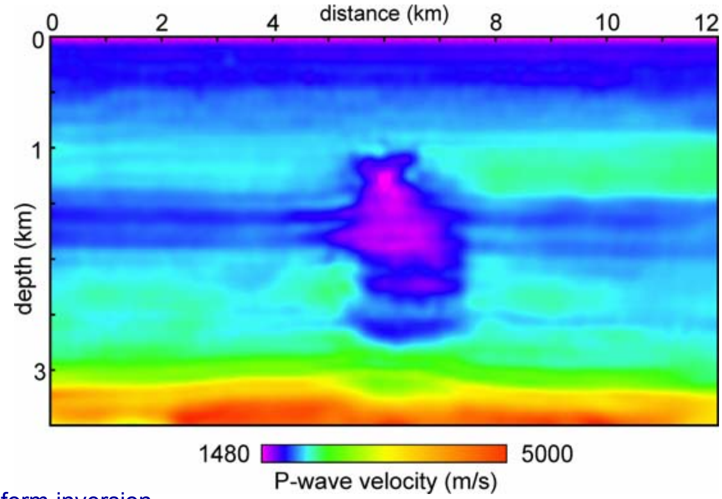
FWI model



full-waveform inversion

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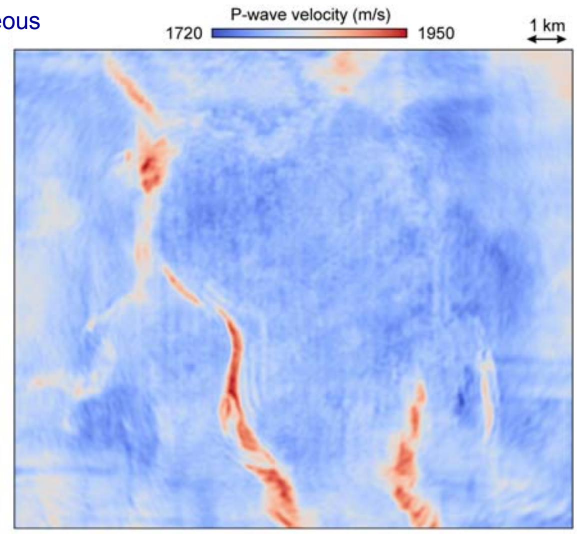
FWI results

from homogeneous start model



250 m depth

horizontal depth slice

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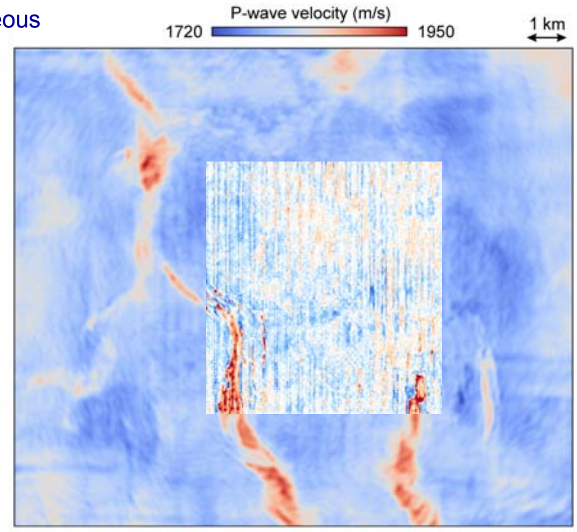
FWI results + original PSDM

from homogeneous
start model



250 m depth

horizontal
depth slice

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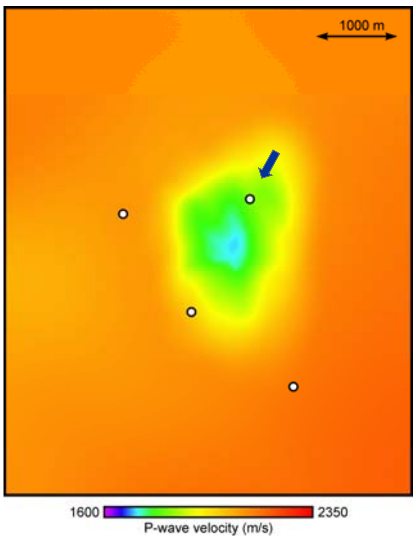
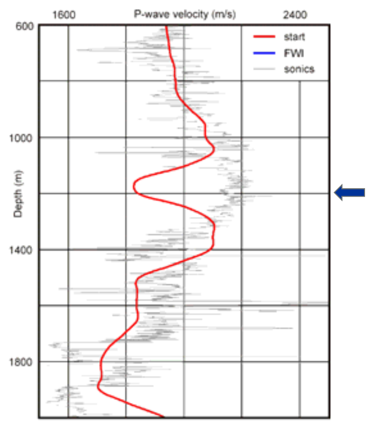
Starting model

1200 m
depth





well log

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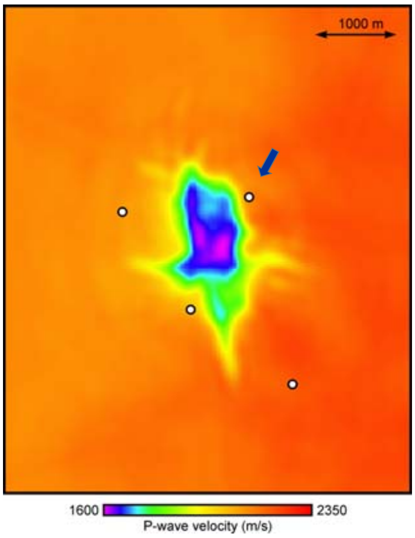
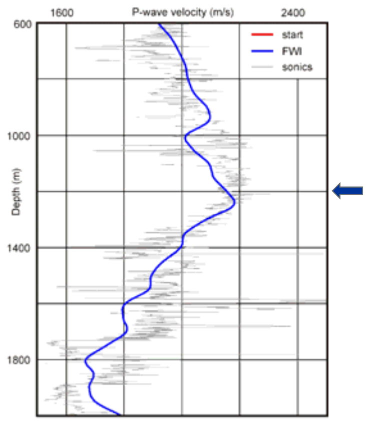
FWI model

1200 m depth





well log

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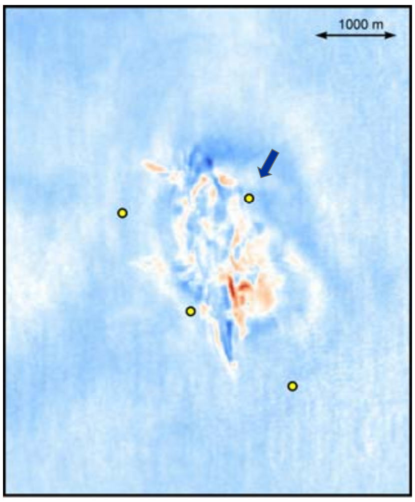
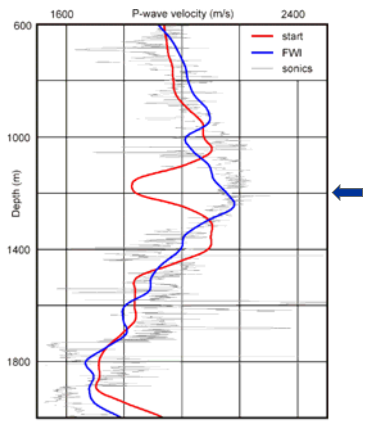
PSDM

1200 m depth





well log

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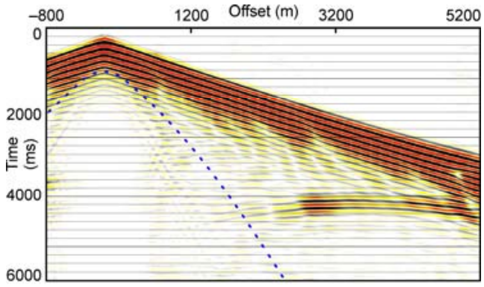
Field data

Field data



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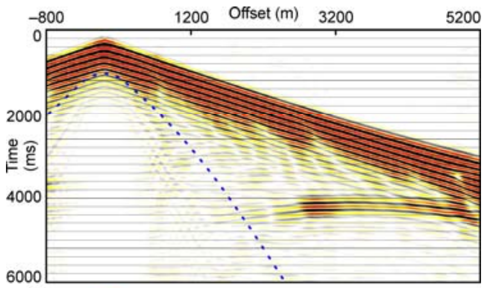
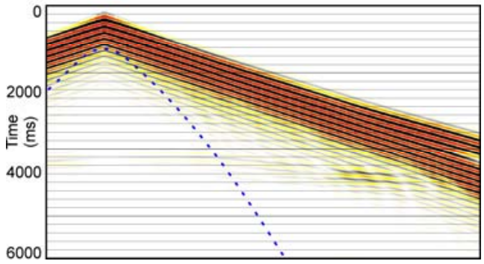
Start model

Field data



Start model data



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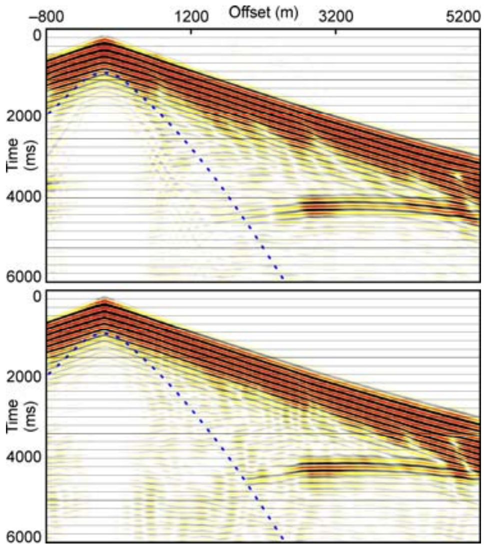
FWI model

Field data

FWI model data



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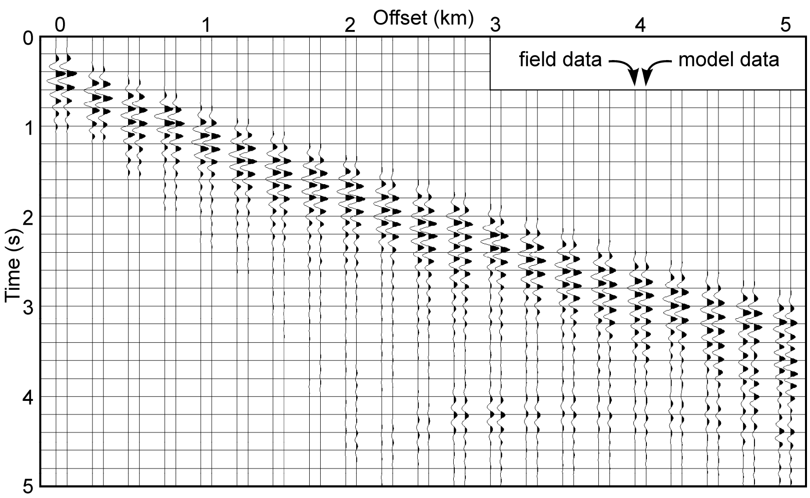
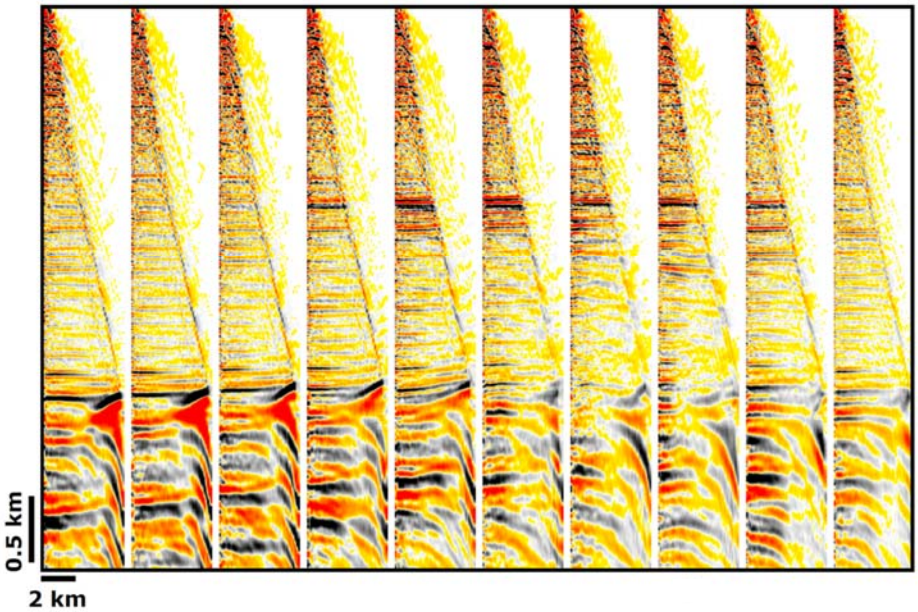
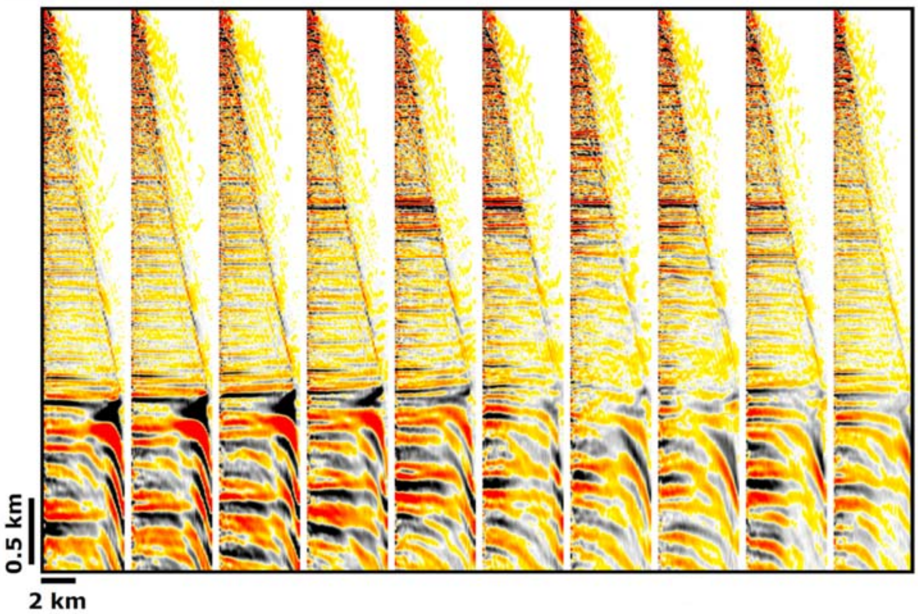
Match to Synthetics



VTI Kirchhoff CIG's using starting velocity model



VTI Kirchhoff CIG's using FWI velocity model



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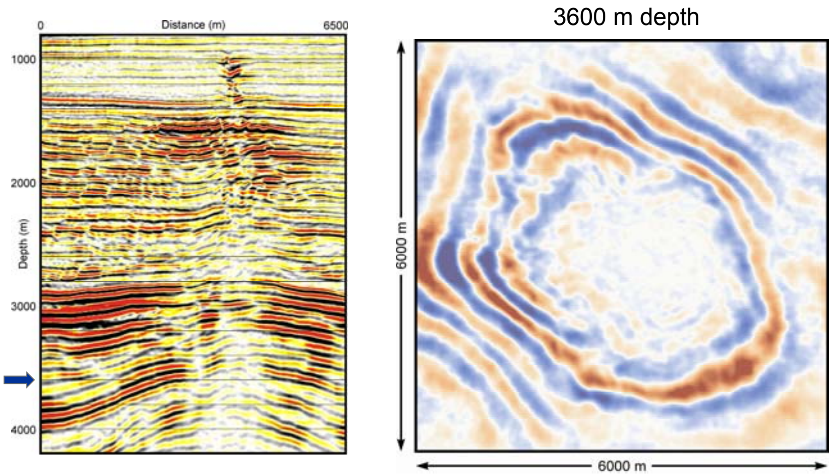
RTM with PSDM model



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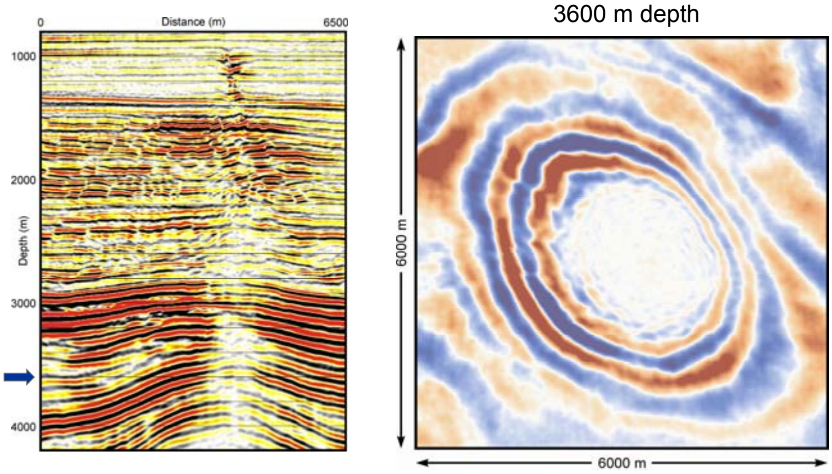
RTM with FWI model



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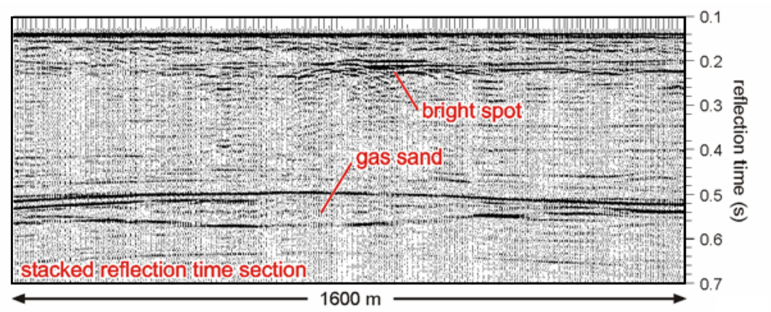
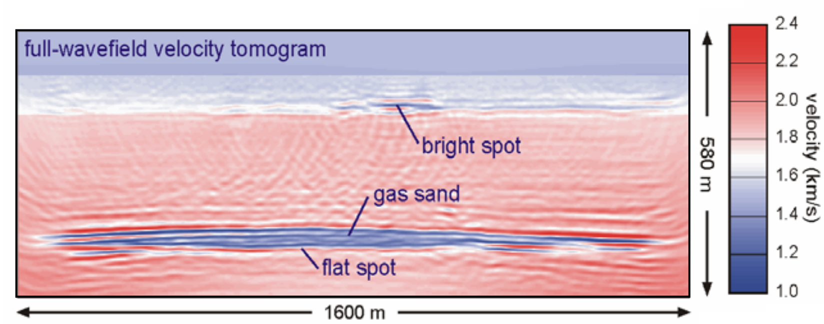
Other parameters

Field data – site survey



Hicks & Pratt (2001) Geophysics, v66, p598.

Acoustic wavefield tomography



Hicks & Pratt (2001) Geophysics, v66, p598.

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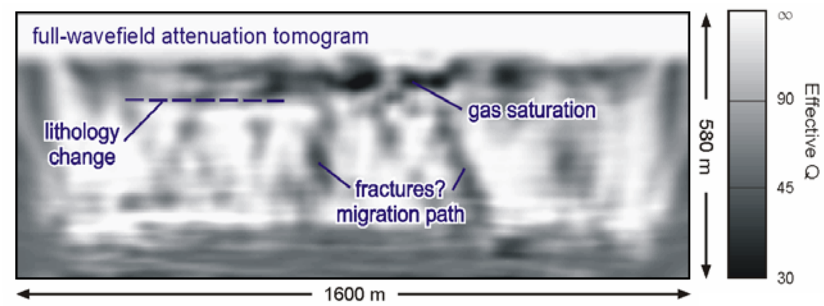
Attenuation tomography



Hicks & Pratt (2001) Geophysics, v66, p598.

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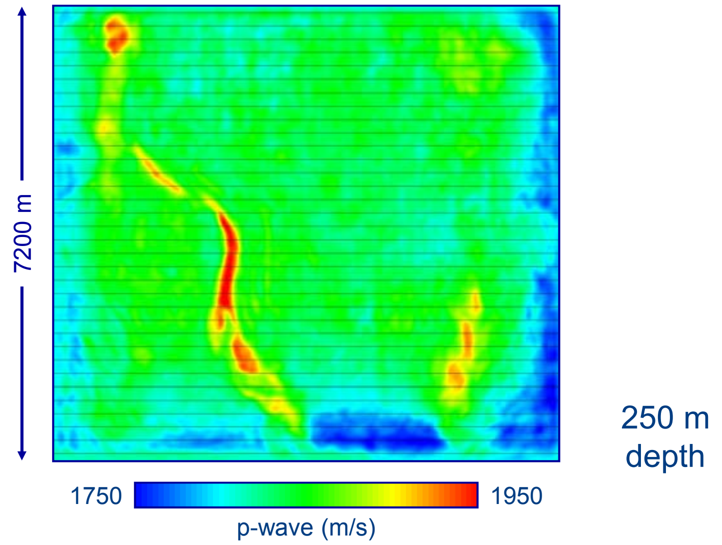
Elastic FWI: P-wave



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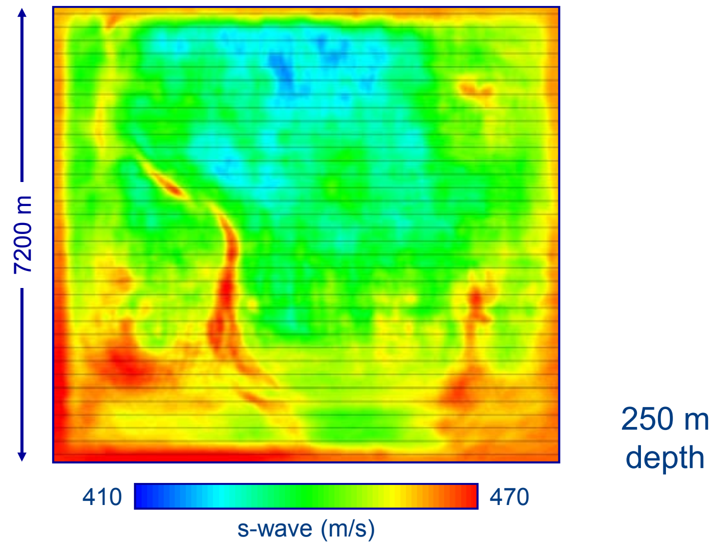
Elastic FWI: S-wave



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Difficulties with elastic FWI

- S-wave starting model
- Cross talk to p-wave velocity
- Cross talk to density & attenuation
- Elastic anisotropy – s-wave splitting
- Compute cost

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Elastic FWI

- Genuine elastic inversion is difficult…
  …but is possible on 3D hydrophone data
- For p-wave RTM…
  … not clear that elastic FWI is helpful
- For reservoir characterisation…
  … need elastic, anisotropy & attenuation

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Pitfalls & Practicalities

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Pitfalls

- local minima
- cycle skipping
- inadequate low frequencies
- inadequate starting model

Essential that starting model is not cycle skipped

- low frequencies
- high-quality start model
- rigorous QC

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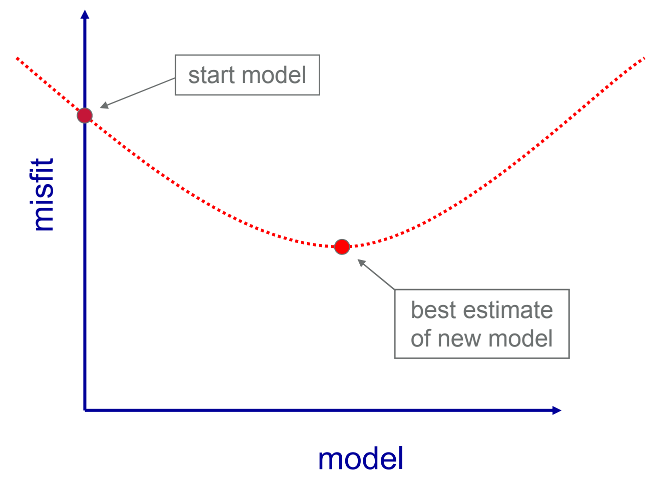
Local inversion



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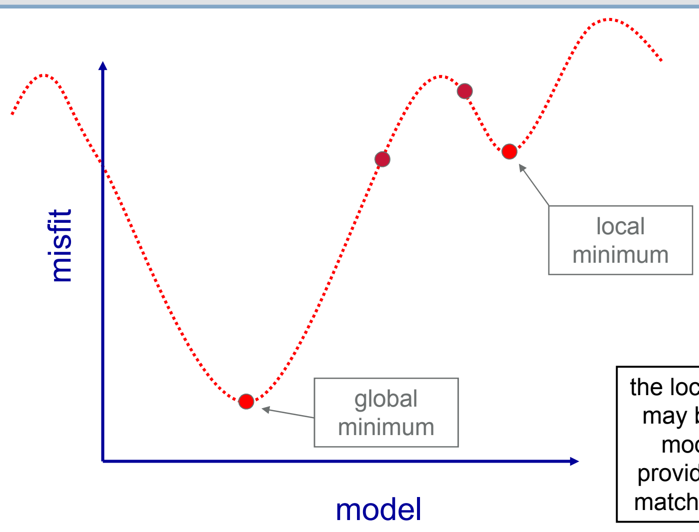
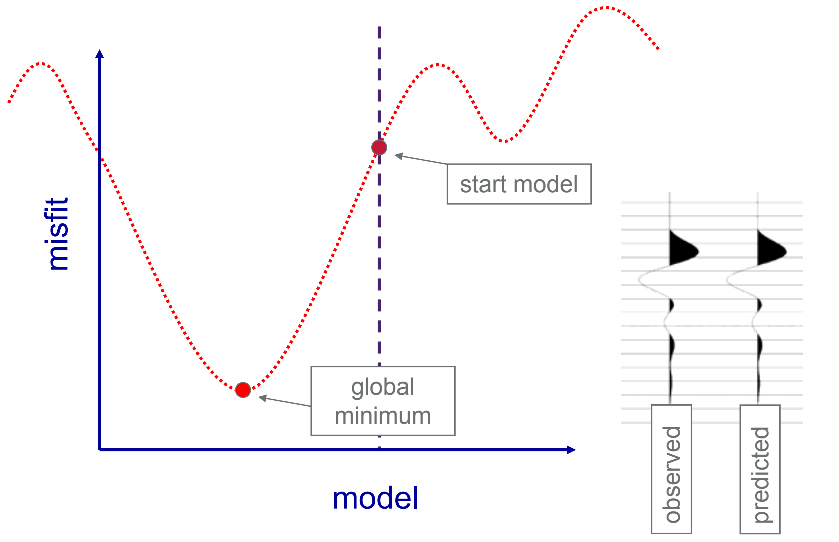
Local inversion

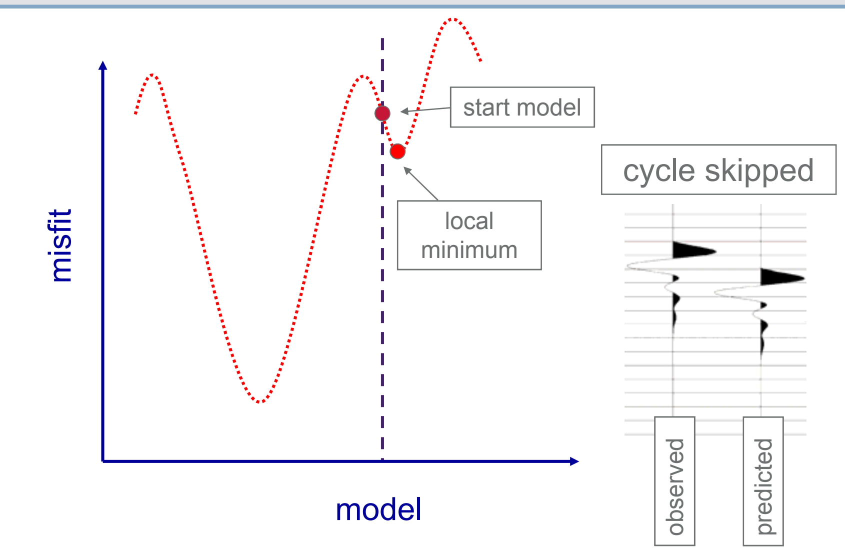


the local minimum may be a worse model, but it provides a better match to the data

Low frequency



High frequency



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Free surface strategy

- The free surface:
  - generates ghosts
  - generates free-surface multiples
  - suppresses direct arrival
- Must match field data and FWI modelling

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Free surface strategy

Marine: put free surface in model,
use deghosted source,
leave all multiples in data,
leave all ghosts in data,
get the seabed correct.

Land: put absorbing boundary in model,
remove free-surface multiples from data,
include ghosts and remnant multiples in the source wavelet,
deal with synthetic direct arrival.

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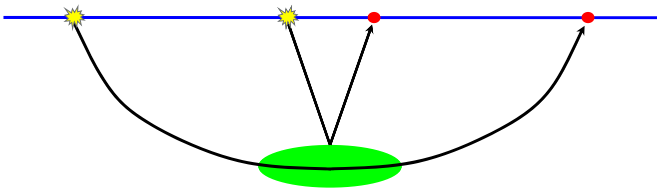
Insufficient offset



- Without long offsets:

  FWI → least-squares reverse-time migration

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FWI strategy

- low → high frequencies
- smooth → rough
- shallow → deep
- refractions → reflections
- phase → amplitude
- early → late arrivals
- primaries → multiples
- acoustic → elastic
- use variable sub-set of sources each iteration

QC often

Test with synthetics

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Workflow

- choose the right problem & acquire the right data
- determine start frequency
- build start model + anisotropy
- check adequacy of model, wavelet & field data
- pre-process & reduce data volume
- modelling & inversion strategy
- run FWI with QA
- check synthetic against field data
- check geometry, wells, image gathers,…
- run RTM on broadband reflection data

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Quality Assurance

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Quality assurance

- Is start model adequate?
- Is offset adequate?
- FWI result:
  - synthetics match field data
  - match improves
  - geometry matches reflectors
  - flattens gathers
  - matches wells
  - migrates reflections

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Cycle skipping in FWI

Cycle skipping is the main limitation on FWI

- drives requirement for low frequencies
- drives requirement for good start model
- limits applicability
- requires rigorous QC & QA
- can lead to (unsuspected) spurious results

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Quality assurance

- Given the data that we have, is the starting model good enough?
- Are we converging towards the global minimum?

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Common QC tools in FWI

- data residuals decrease
- correlation with field data increases
- time-domain data match
- FWI model and PSDM image correlate
- flat gathers & improved RTM
- model is geologically plausible

All of these can fail to detect cycle skipping

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QC for cycle skipping

Generate phase residual plots at starting frequency:

- for start model
- after one iteration
- after final iteration
- for all offsets and azimuths
- for many sources/receivers

Phase residual is the phase difference between observed and predicted data (NOT the phase of the residual)

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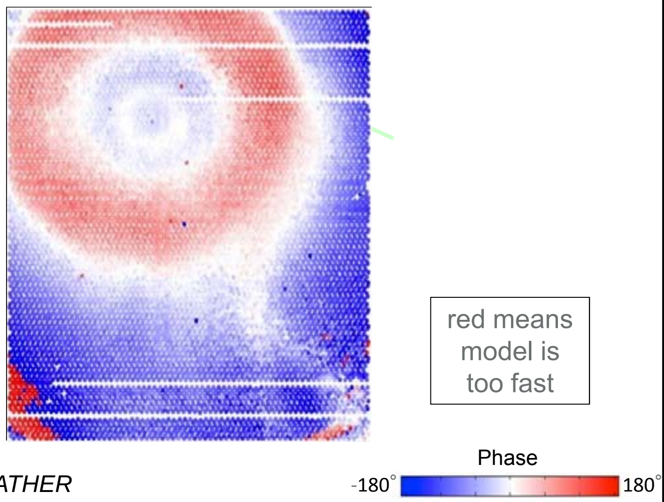
Phase residual in full-azimuth survey



COMMON RECEIVER GATHER

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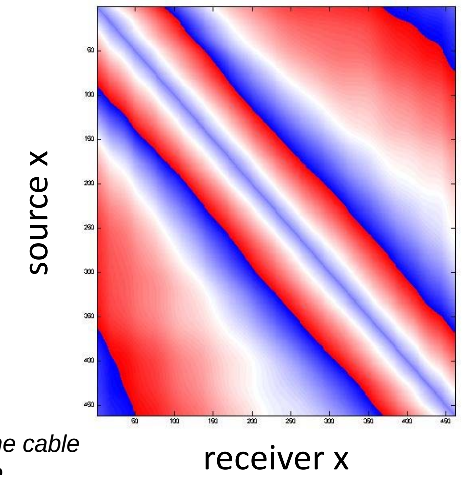
Phase residual in narrow-azimuth survey



stacking diagram for one cable and one sail line

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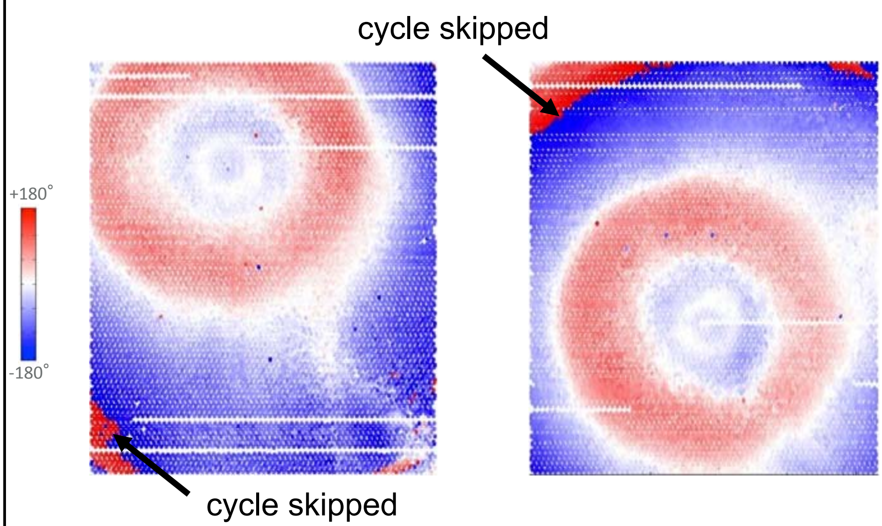
3Hz phase residual – shallow water OBC



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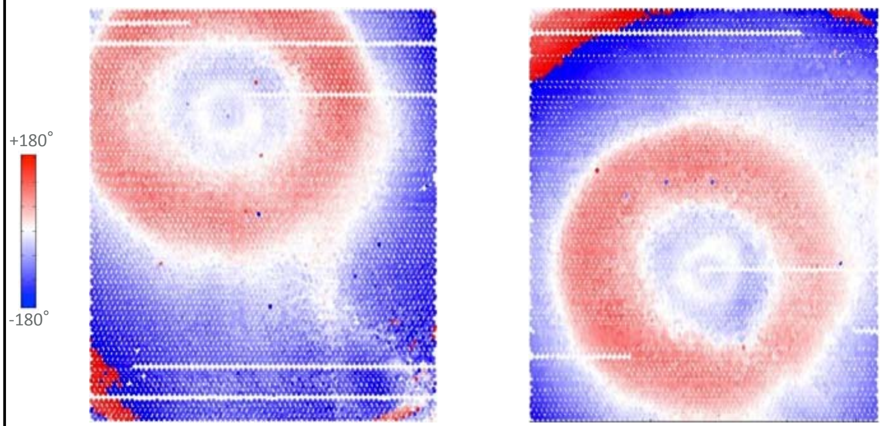
3Hz phase residual – start model



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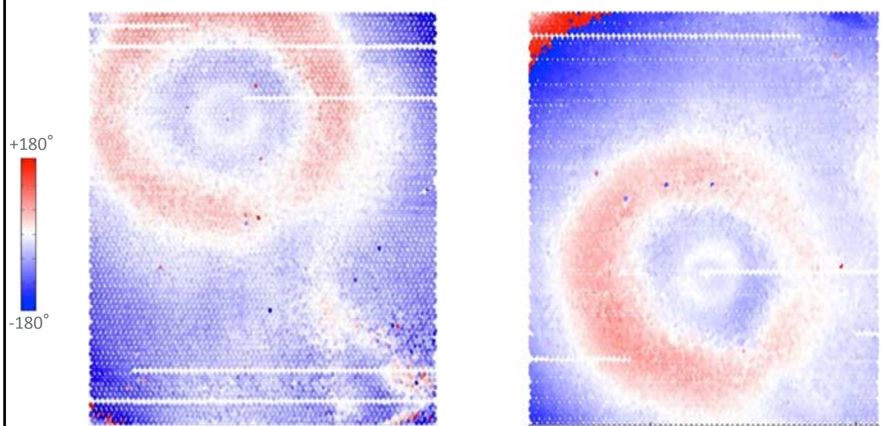
3Hz phase residual – after 1 iteration



CYCLE-SKIPPED REGION **SHRINKS**

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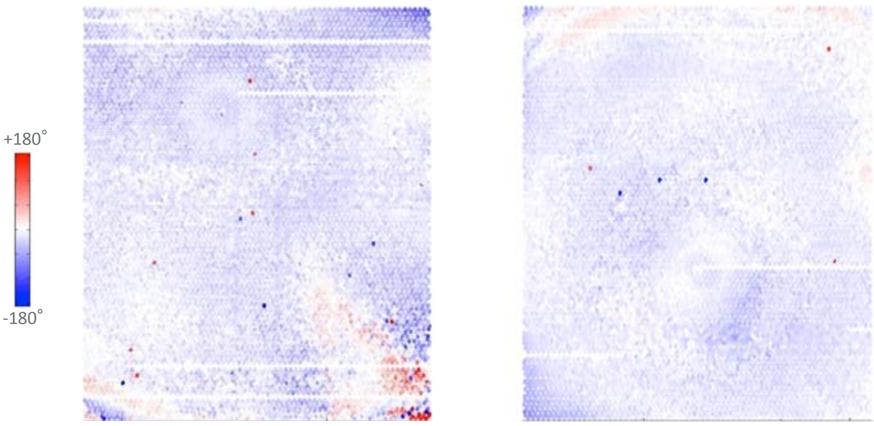
3Hz phase residual – after 18 iterations



CYCLE-SKIPPED REGION **VANISHED**

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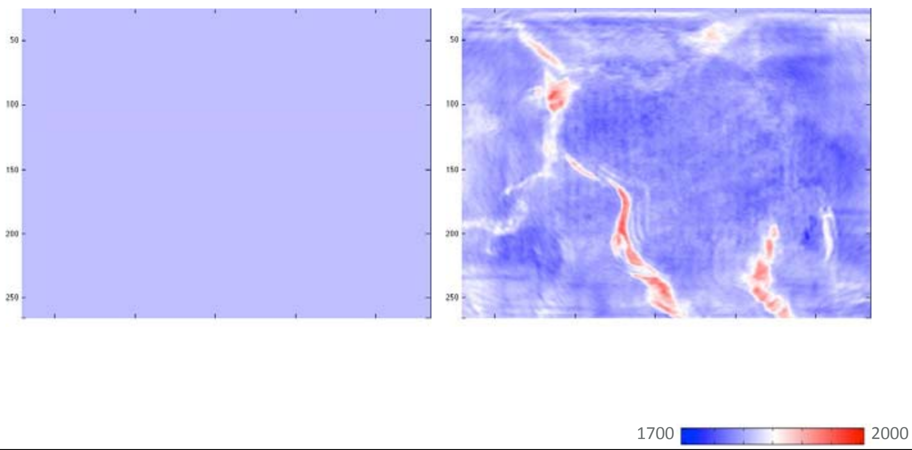
FWI result – 250 m

Start **After 108 iterations**



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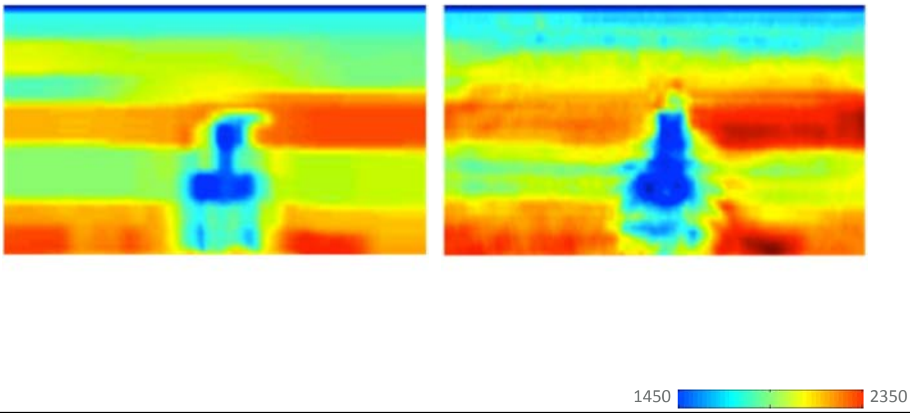
FWI result

Start | **After 108 iterations**



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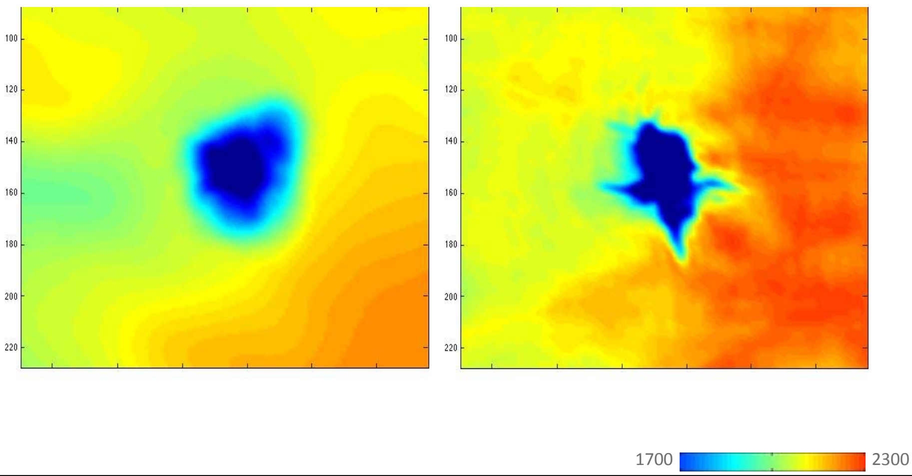
FWI result – 1200 m

Start | **After 108 iterations**



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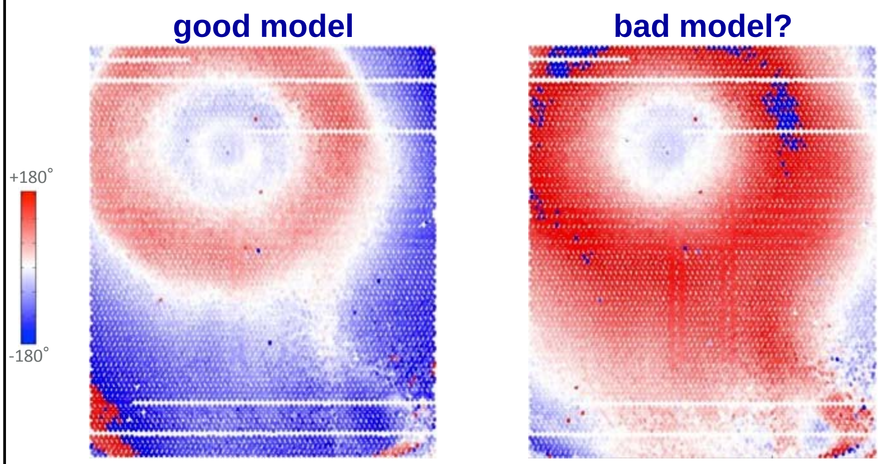
3Hz phase residual



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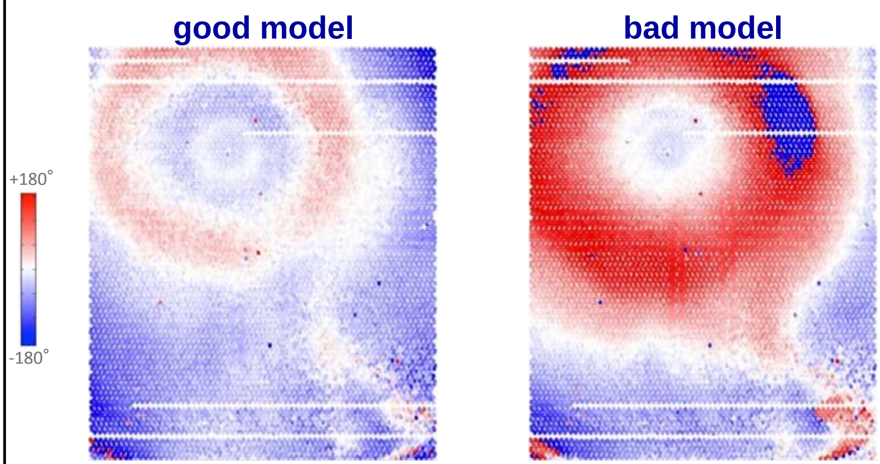
3Hz phase residual - after 1 iteration



CYCLE-SKIPPED REGION **SHRINKS** CYCLE-SKIPPED REGION **GROWS**

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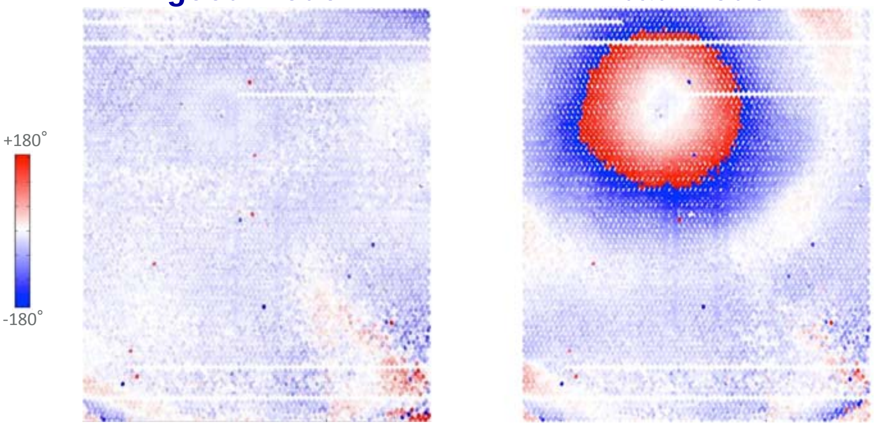
3Hz phase residual – after 18 iterations

good model | bad model



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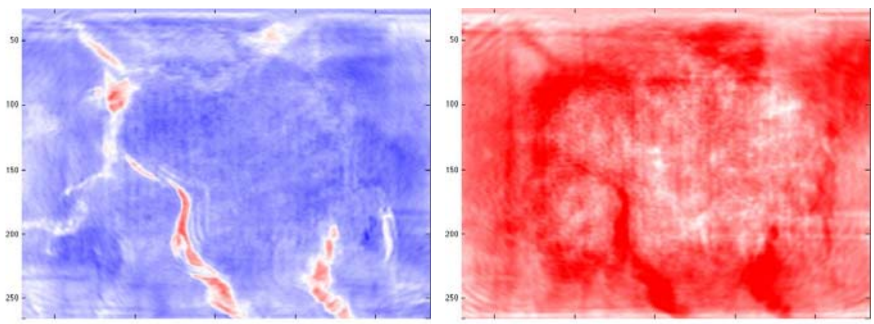
FWI result - after 108 iterations

good model | bad model



GLOBAL MINIMUM | LOCAL MINIMUM

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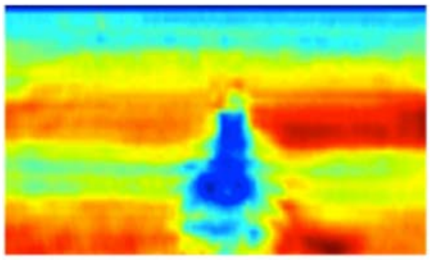
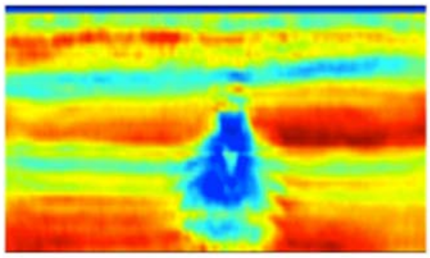
FWI result - after 108 iterations

good model **bad model**





GLOBAL MINIMUM LOCAL MINIMUM

1450 2350

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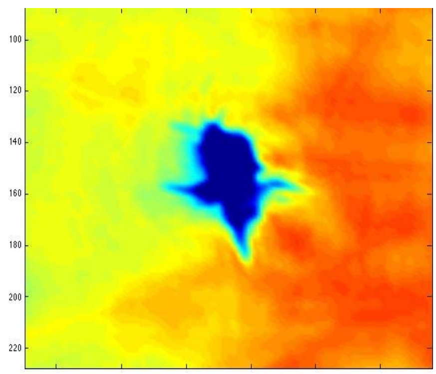
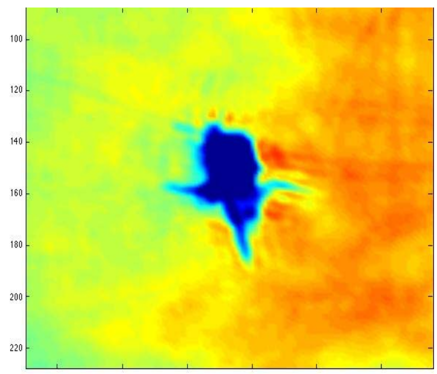
FWI result - after 108 iterations

good model **bad model**





GLOBAL MINIMUM LOCAL MINIMUM

1700 2300

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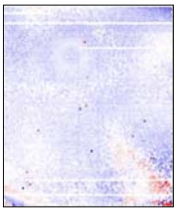
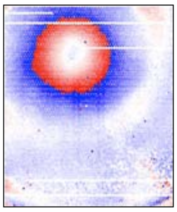
Conclusion

QA during FWI is essential & easy





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Implementation

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Implementation

- Efficient wave propagator
  - 3D, heterogeneous, two-way, wave equation
- Appropriate physics
  - acoustic, visco-acoustic, anisotropic, elastic
- Numerical method
  - finite differences, finite elements, spectral elements
- Domain
  - time, frequency, hybrid, Laplace, Fourier-Laplace

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Implementation – time domain

- CPU proportional to
  - model size $\sim n^3$
  - number of time steps $\sim n$
  - number of sources $\sim N$
- So CPU $\sim n^4 N$
  - maximise grid spacing
  - maximise time step
  - minimise number of sources
  - minimise local domain

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Implementation – time domain

- parallelised on multi-core clusters
- one source per node
- multiple cores per source
- feasible on GPUs

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Implementation – resources

- RAM and CPU for explicit-time and iterative-frequency are similar
- TTI anisotropy – RAM & CPU × 2
- Elastic – RAM & CPU × 10 to 1000 (depends upon Vp/Vs)

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Implementation – resources

- Run on clusters of multi-core workstations
- Parallelised using Posix threads or OpenMP
- Parallelised using MPI
- Forward modelling on single workstation
- Similar hardware to RTM

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Future directions

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Future directions

- apply to reservoir
- extend to all acquisition geometries and datasets
- overcome starting model limitations
- more robust & effective FWI
- beyond acoustic
  - elastic, anisotropic, fractures, fluids
- integrate with rock physics & CSEM
- statics → dynamics
- resolution & uncertainty analysis
- modified acquisition
- replace velocity model building, RTM, AVO & DHI

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Tarantola A (1984) *Inversion of seismic reflection data in the acoustic approximation.* **Geophysics, 49**, 1259-1266.

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