Full Waveform inversion

Beyond ray theory,
Towards full waveform

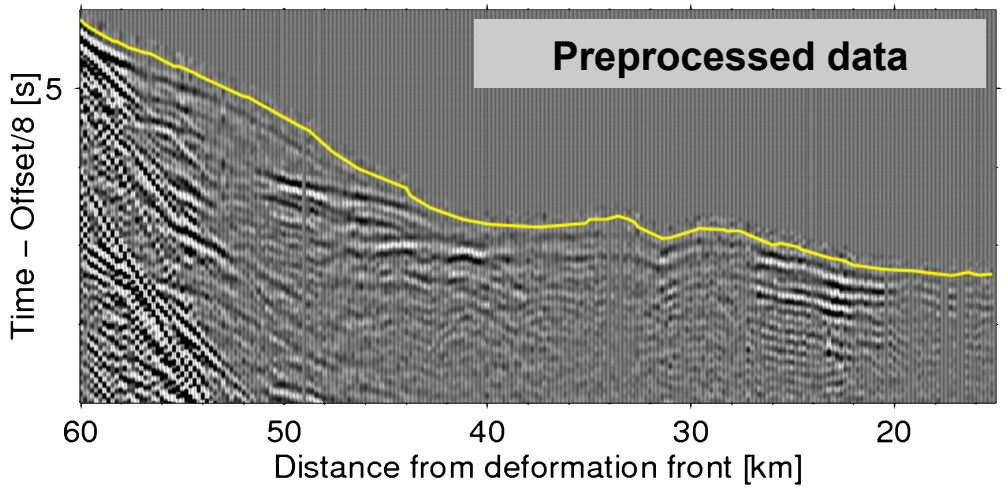
Rie Kamei

Western University

Acknowledgement

- Heiner Igel, Greta Kueppers, Celine Hadziioannou
- Andreas Fichtner
- Phillip Knaute, Andrea Colombi, Lubica Valentova, Andrew Valentine, Alan Schiemenz
- R. Gerhard Pratt, Andrew Brenders, Michael Afanasiev, Brendan Smithyman
- Takeshi Tsuji
- Vincent Etienne

Power of Waveform Inversion: Active seismic experiments from Nankai subduction zone



Kamei, R., Pratt, R. G., Tsuji, T. et al.. (2012). EPSL

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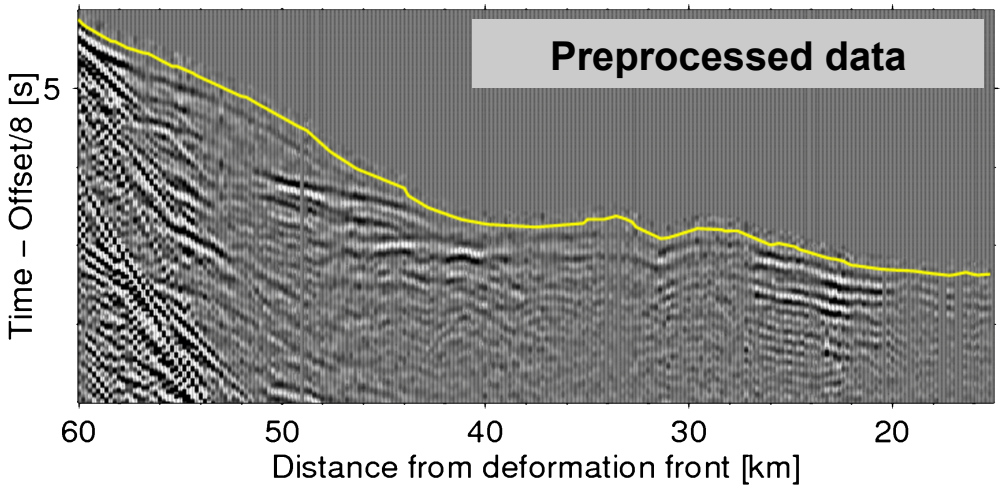
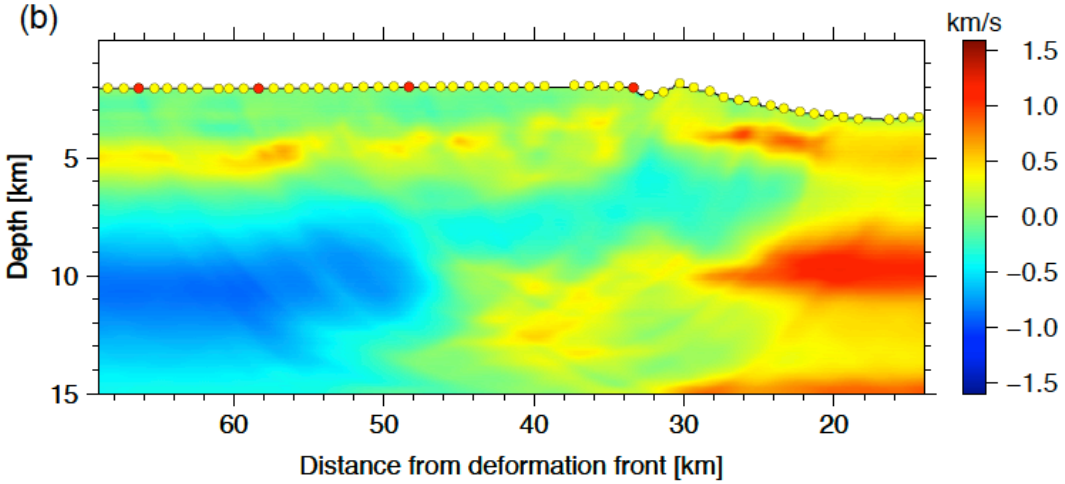


Kamei, R., Pratt, R. G., Tsuji, T. et al.. (2012). EPSL

Traveltime Tomography



Nakanishi, A., Kodaira, S., Miura, S., Ito, A., Sato, T., Park, J.-O., Kido, Y., et al. (2008). JGR

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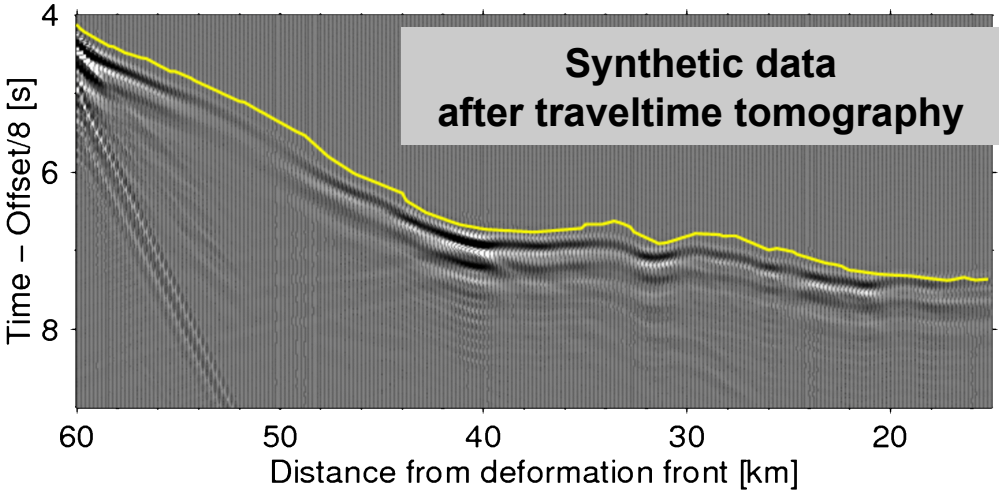

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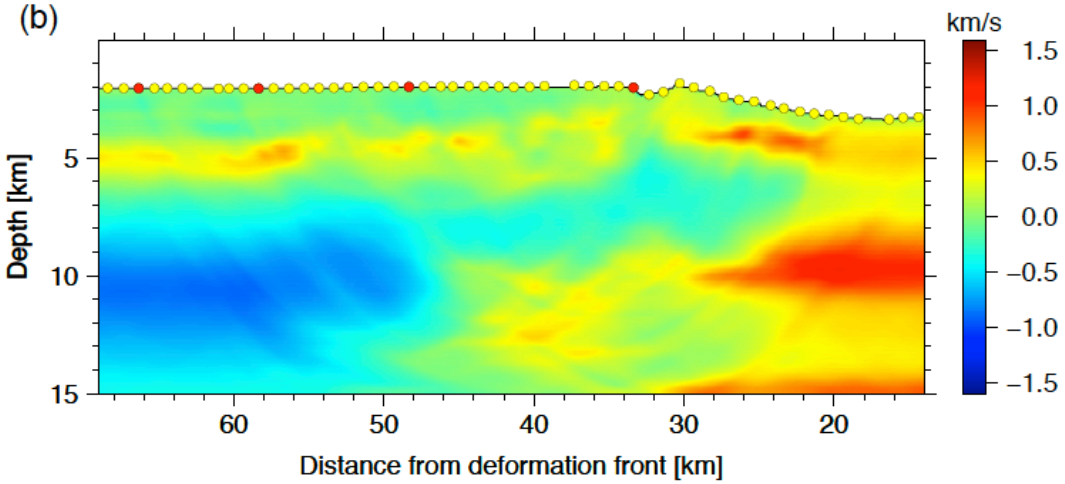

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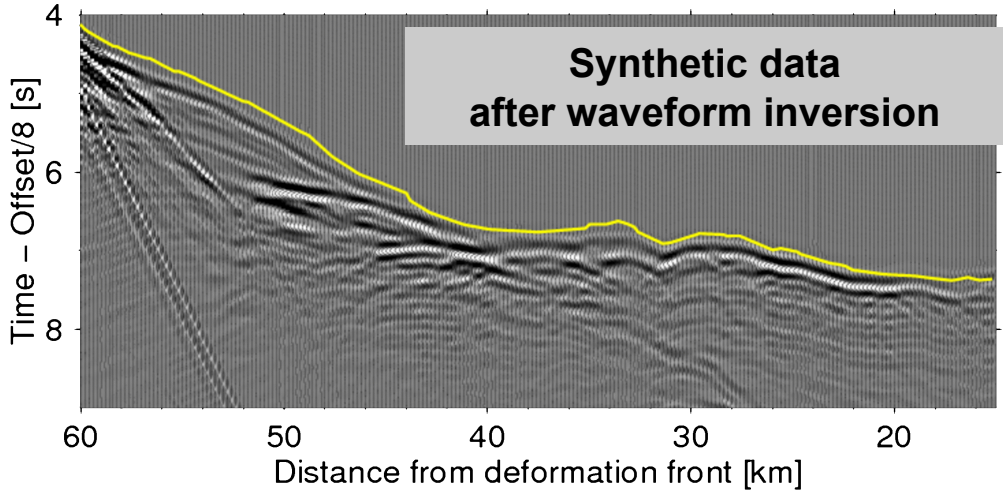

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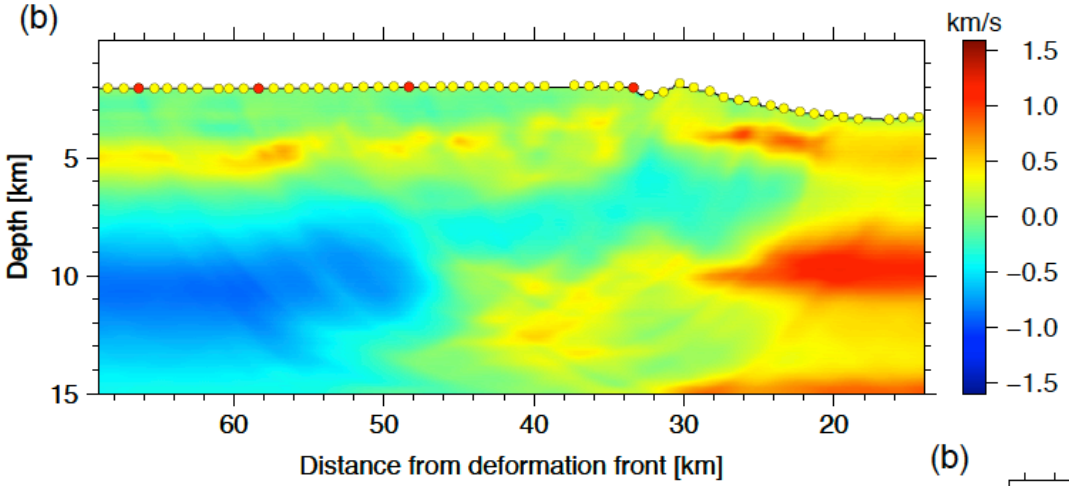

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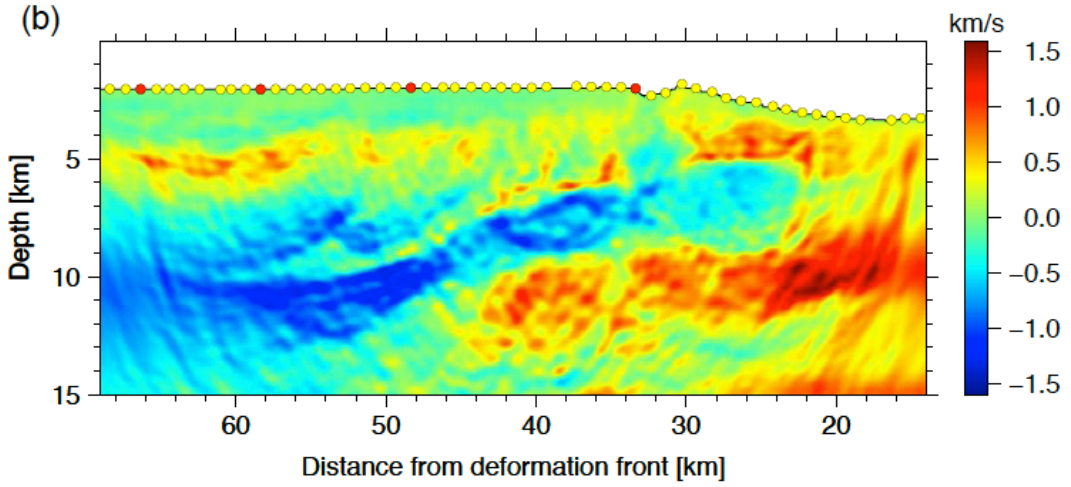

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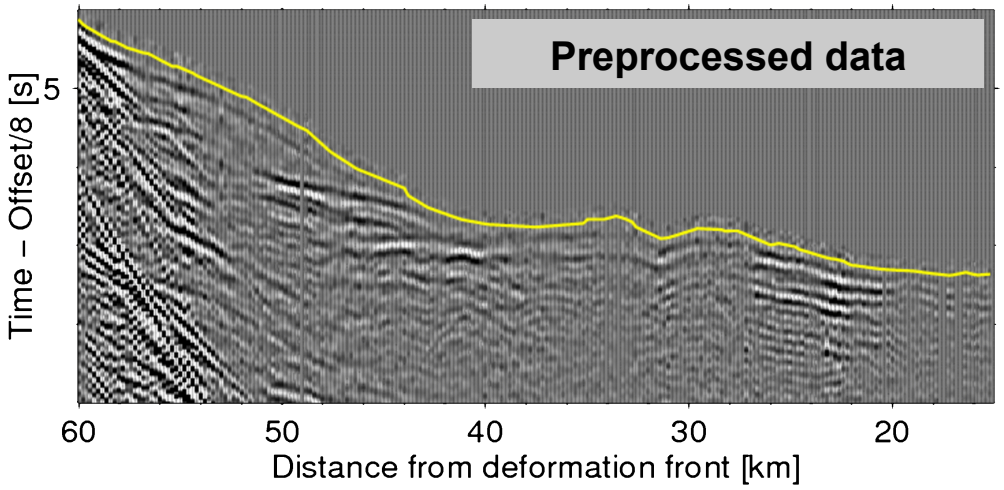

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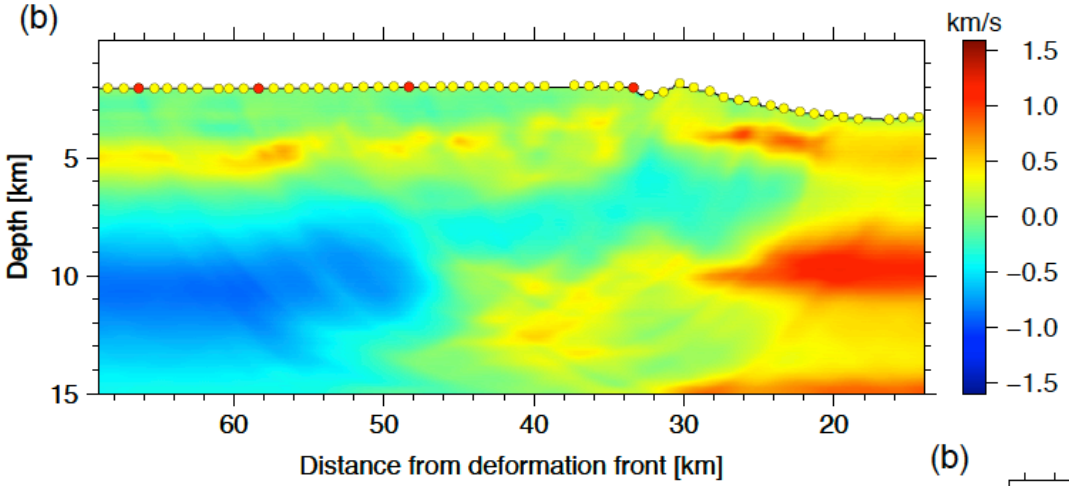

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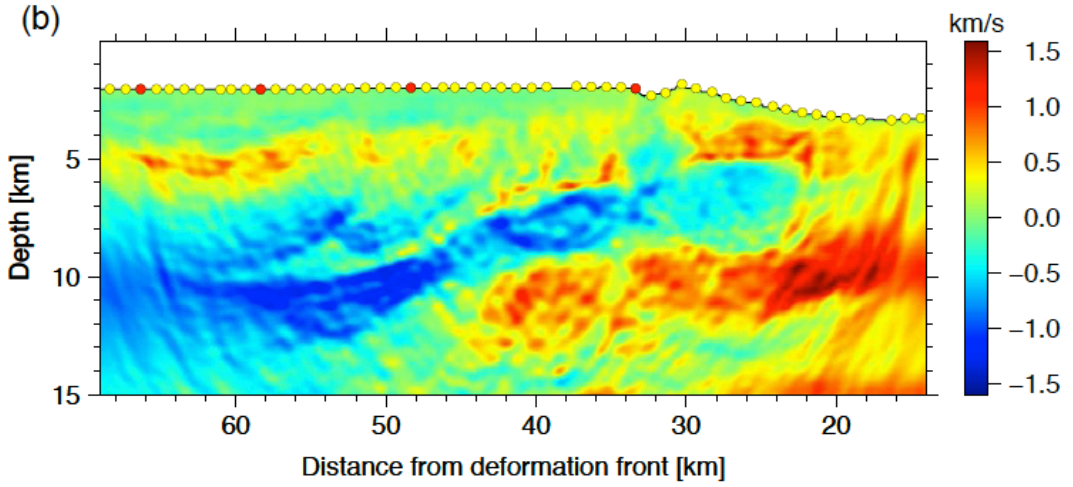


Kamei, R., Pratt, R. G., Tsuji, T. et al.. (2012). EPSL

Outline

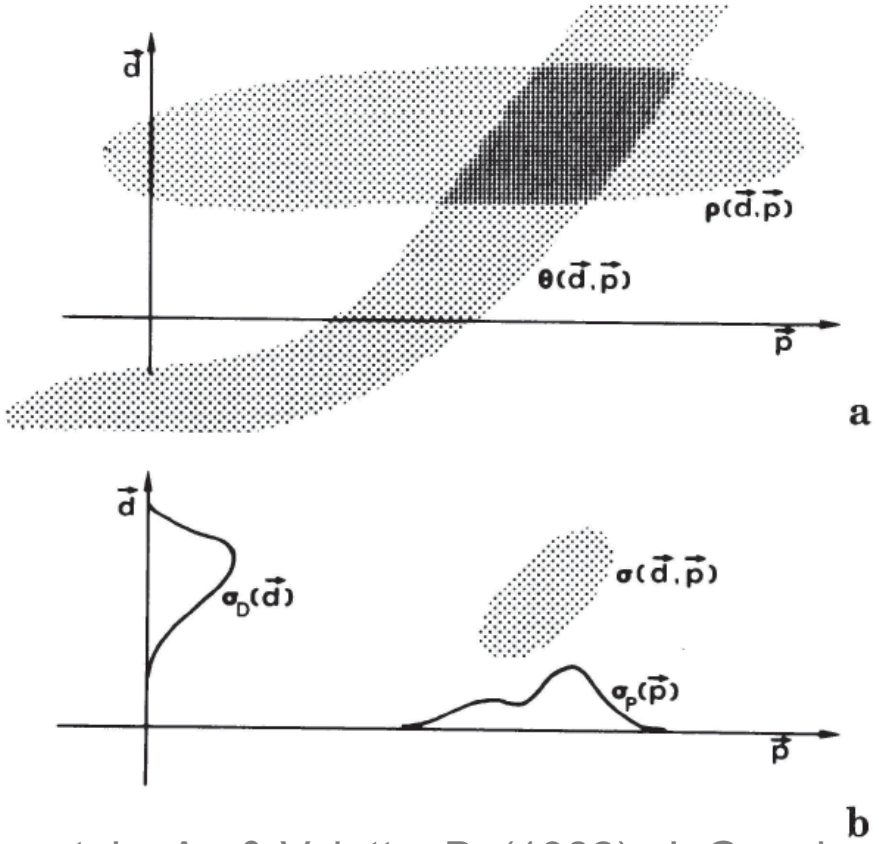
- Waveform inversion
  - Problem statement
  - Workflow
- Examples: A tour through scales

Goal of full waveform inversion

Using **full waveforms = P + S + surface waves**
and **accurate waveform modeling code,**
describe **probability distribution** of elastic parameters

(ideally full 21 parameters)

which accounts for
- waveform misfit
- modelization errors
- measurement errors
- priori knowledge about model



Tarantola, A., & Valette, B. (1982). J. Geophys.

Practical goal of (full) waveform inversion

Using **most significant component of waveforms**
and **feasible numerical waveform modelling code,**
obtain **one model + uncertaintity** of most robust, non-unique parameters by **non-linear local optimization**:

min waveform misfit + regularization term

which incorporate
- measurement errors
- priori model knowledge

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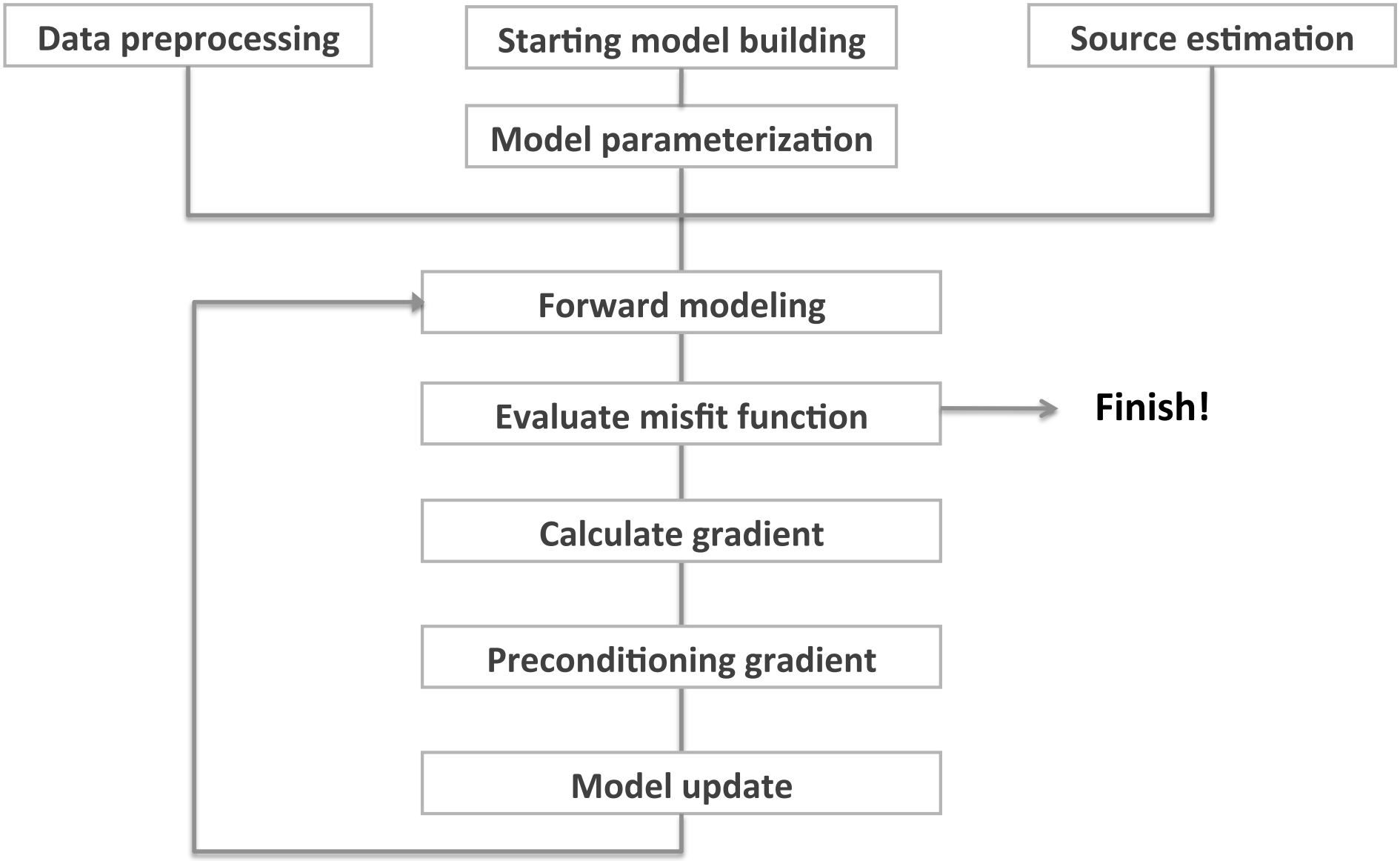
Workflow


Data preprocessing
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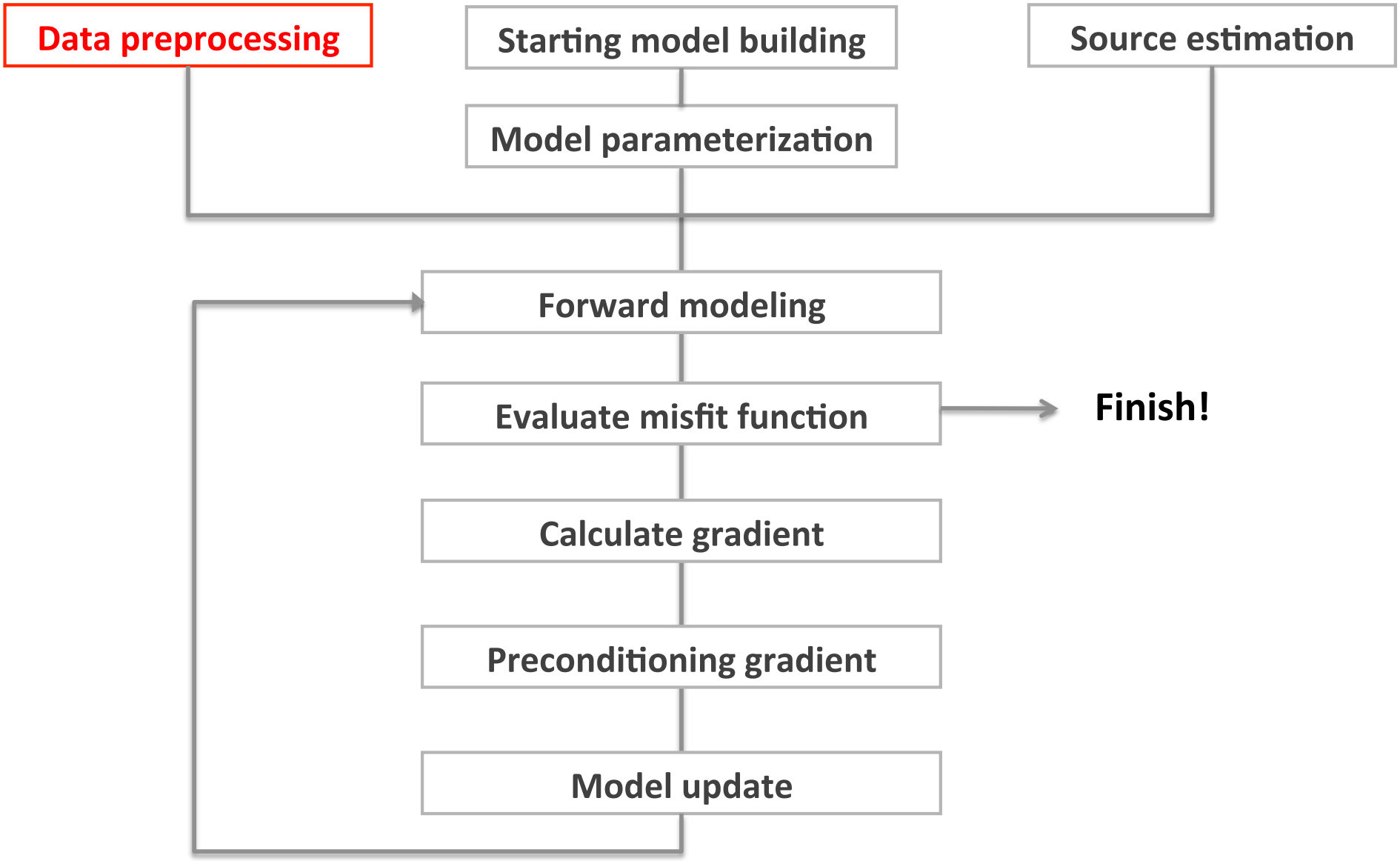
Model parameterization
Forward modeling
Evaluate misfit function
Finish!
Calculate gradient
Preconditioning gradient
Model update

Workflow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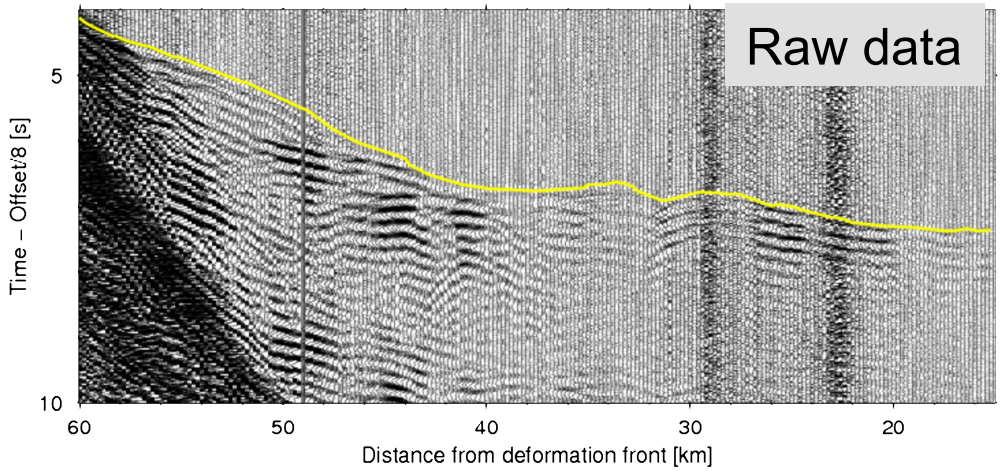
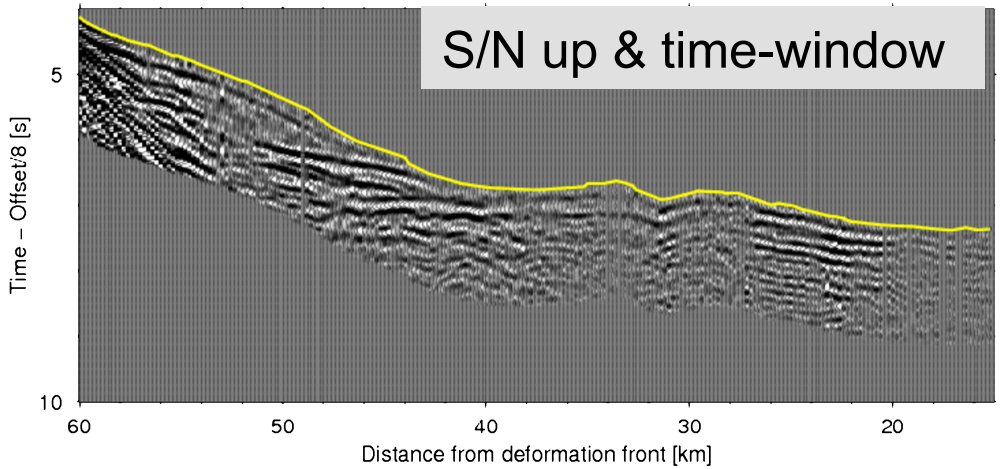
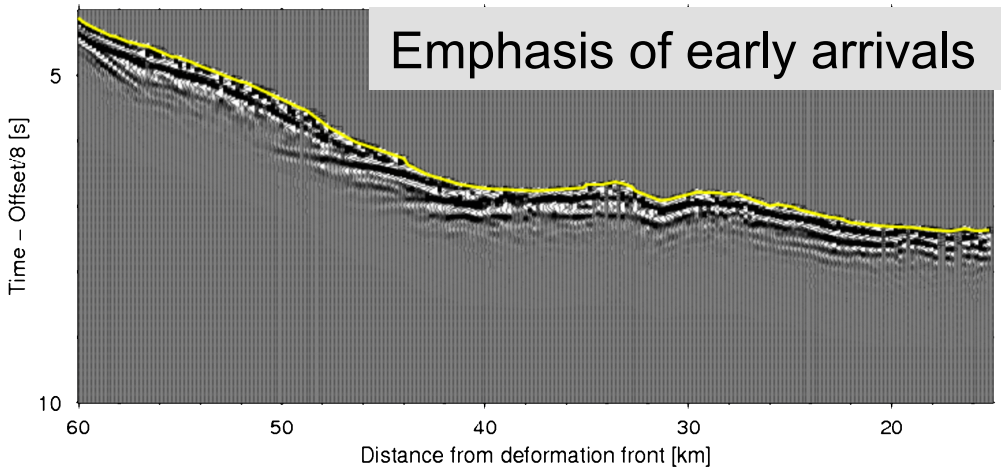
Preprocessing

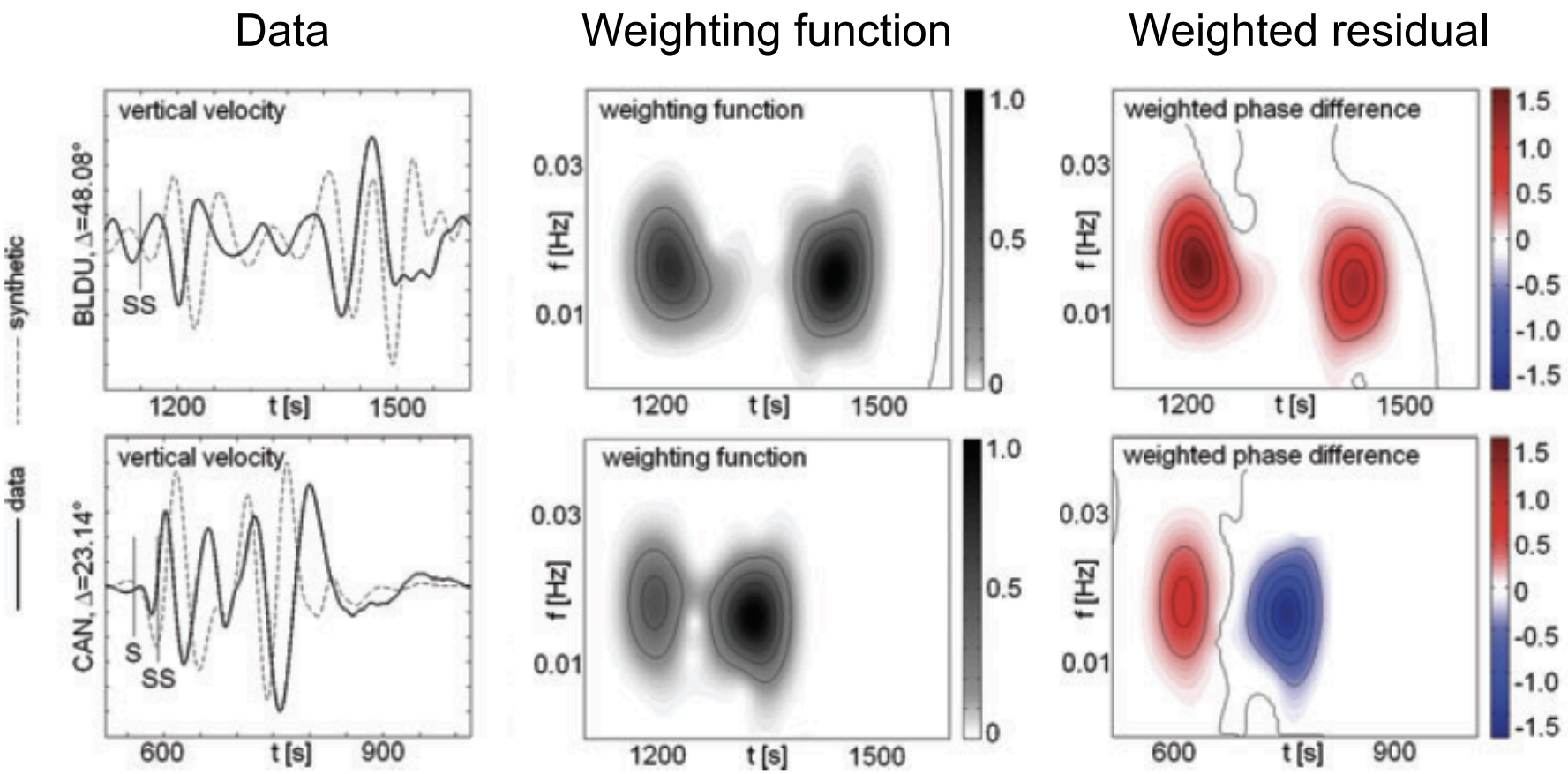






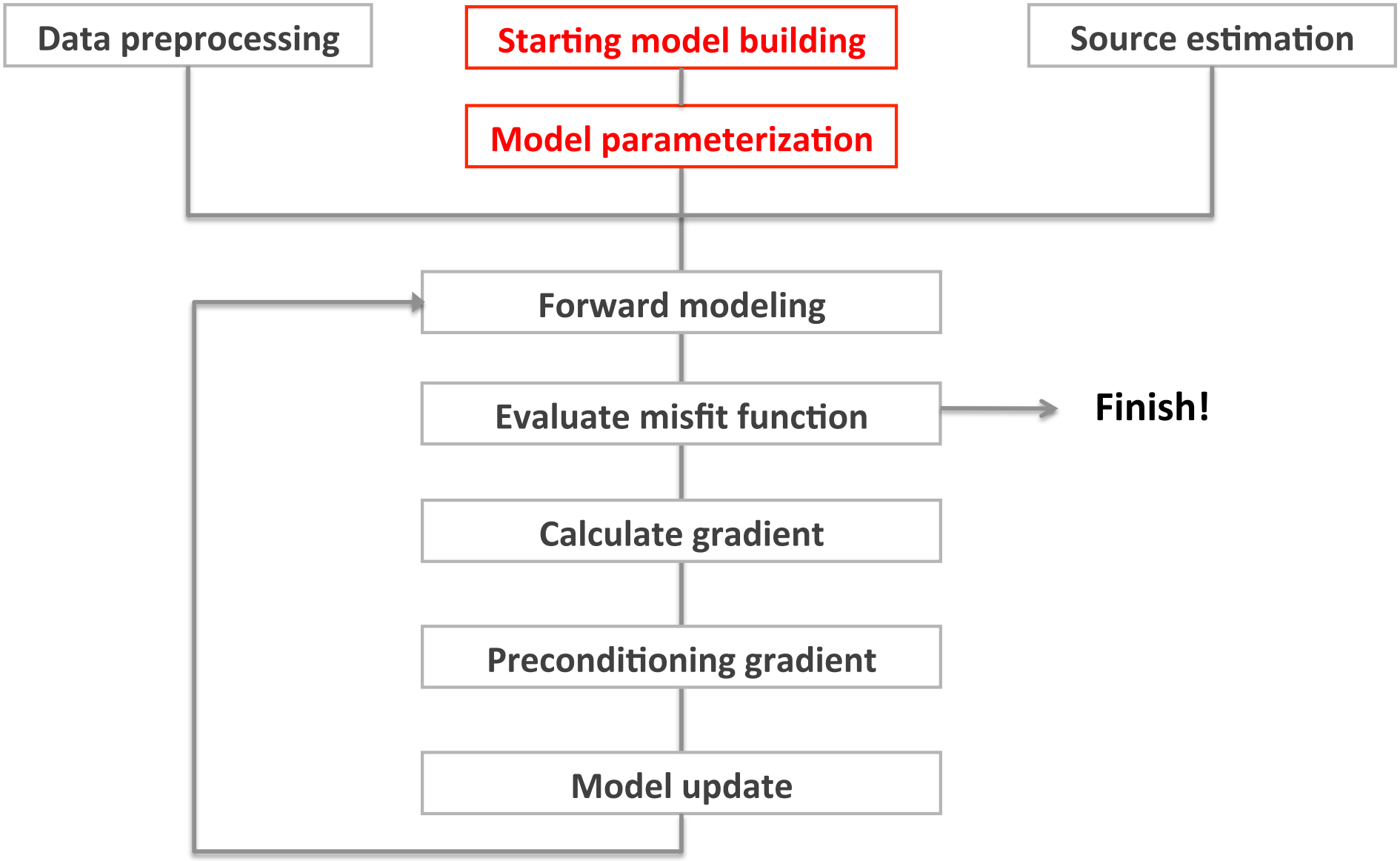
Kamei, R., Pratt, R. G., Tsuji, T., (2012), EPSL

Preprocessing



Modified from Fichtner, A., Kennett, B. L. N., Igel, H., & Bunge, H.-P. (2009). GJI

Workflow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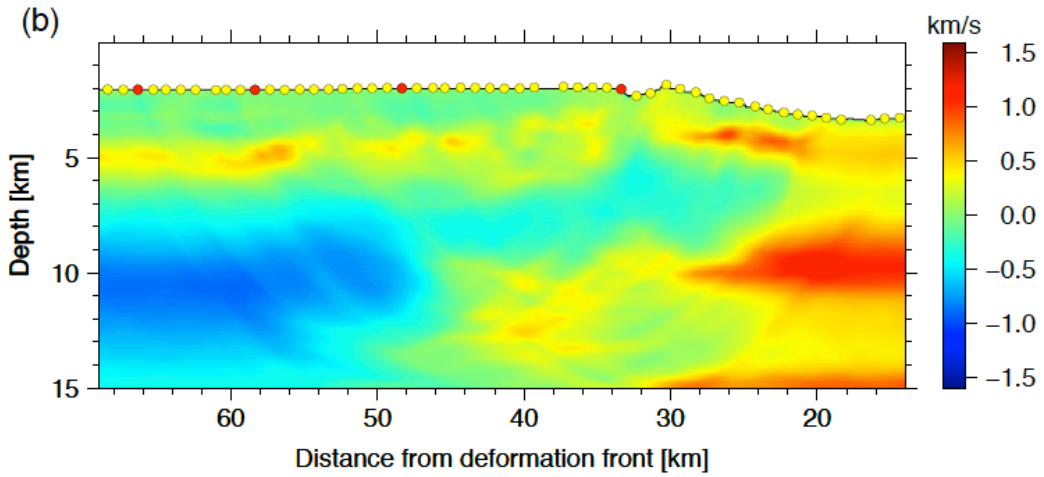
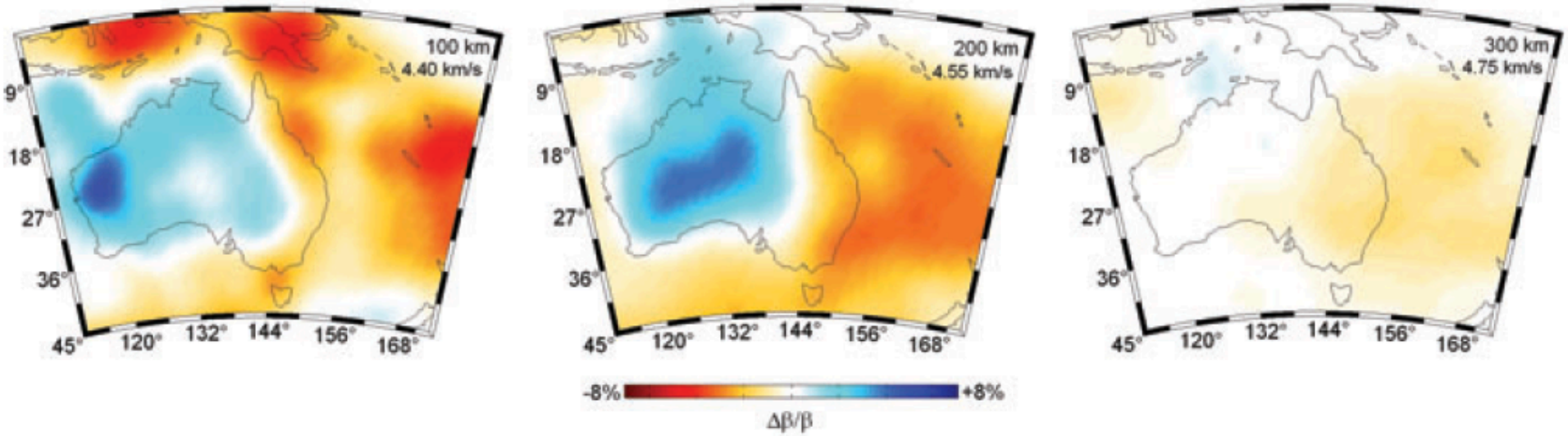
Starting model



Kamei, R., Pratt, R. G., Tsuji, T., (2012), EPSL



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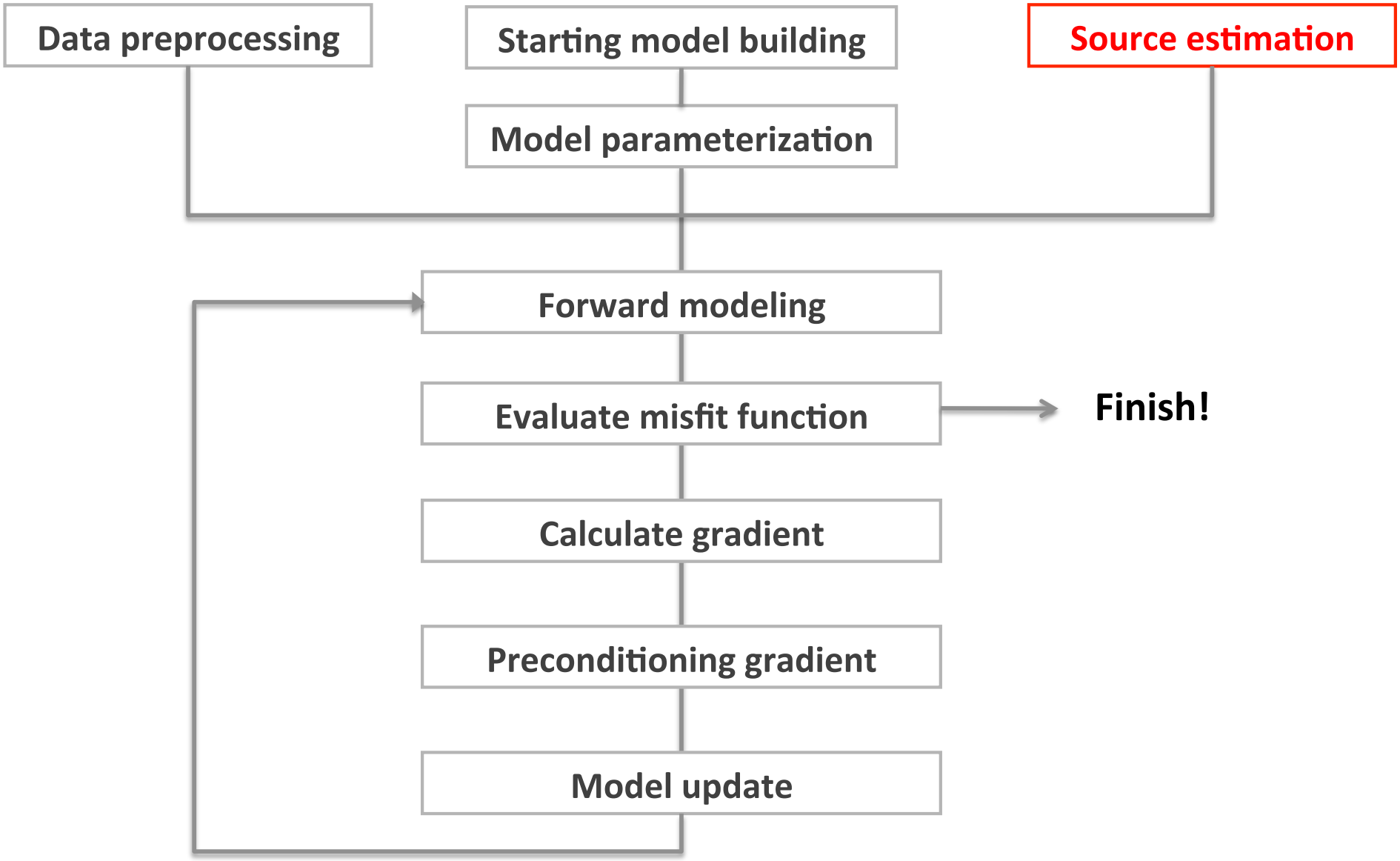
Workflow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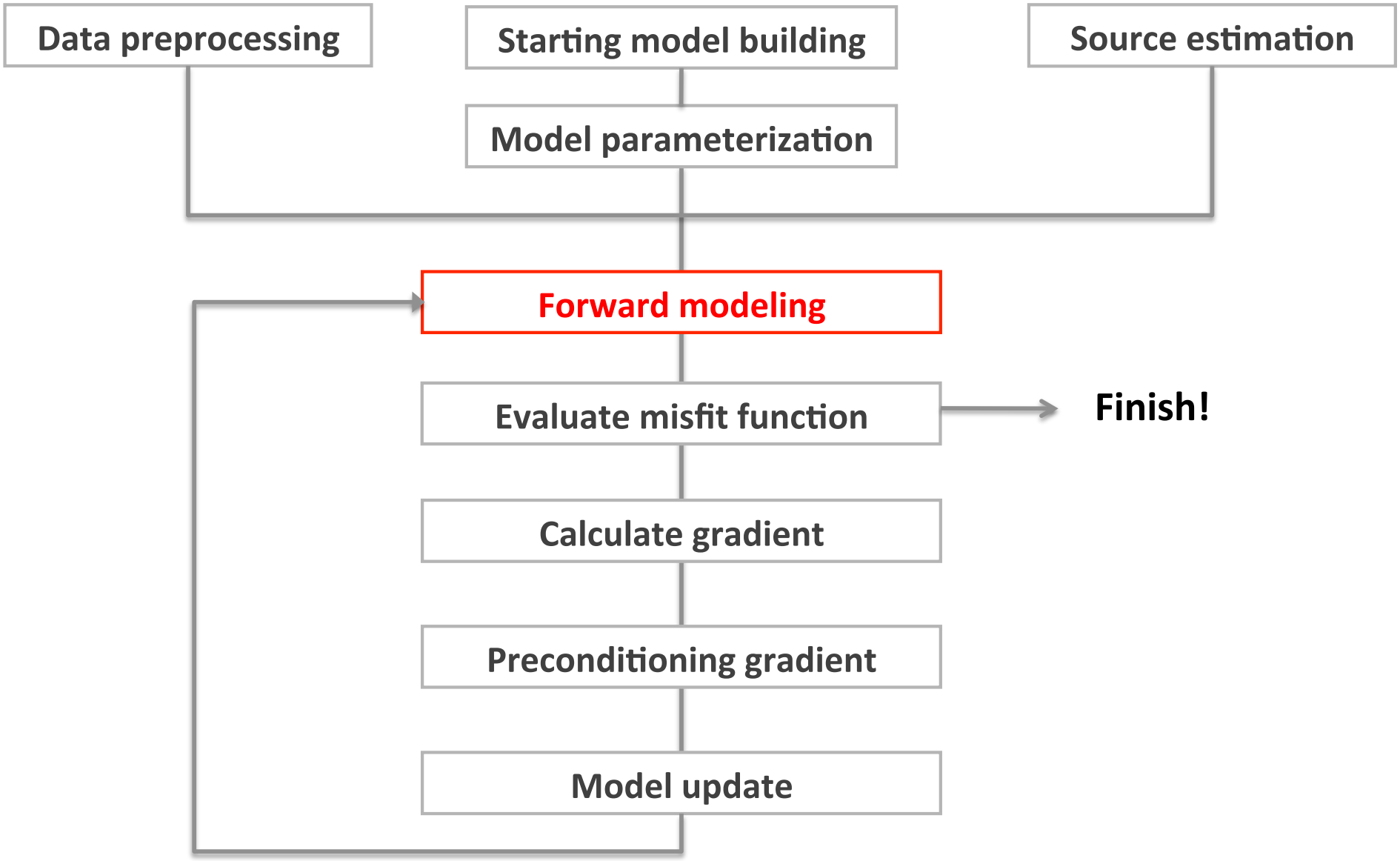
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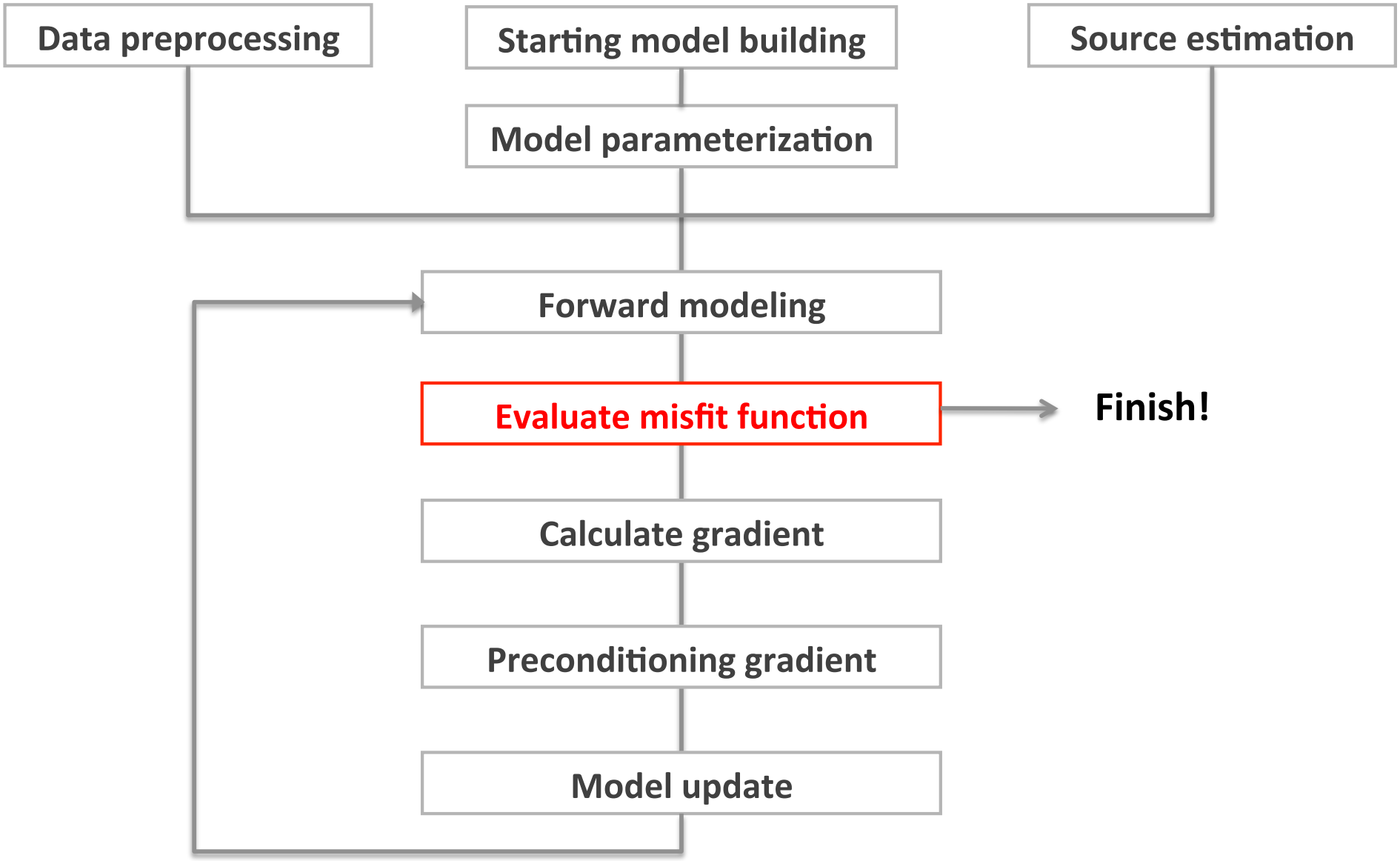
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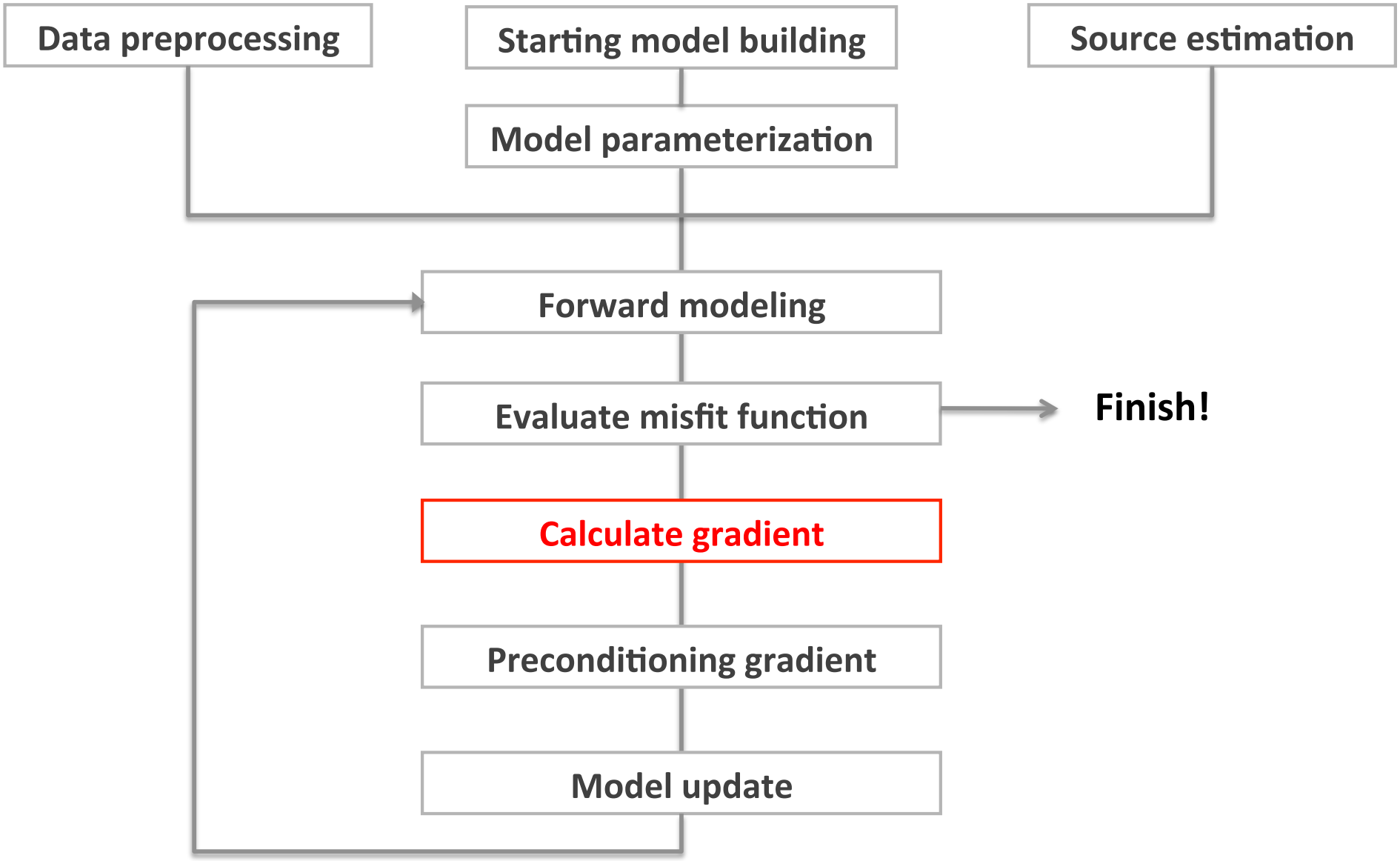
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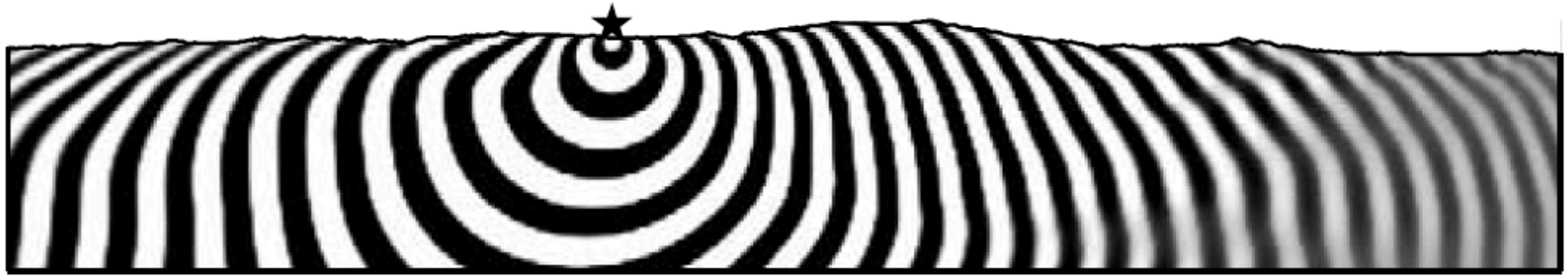
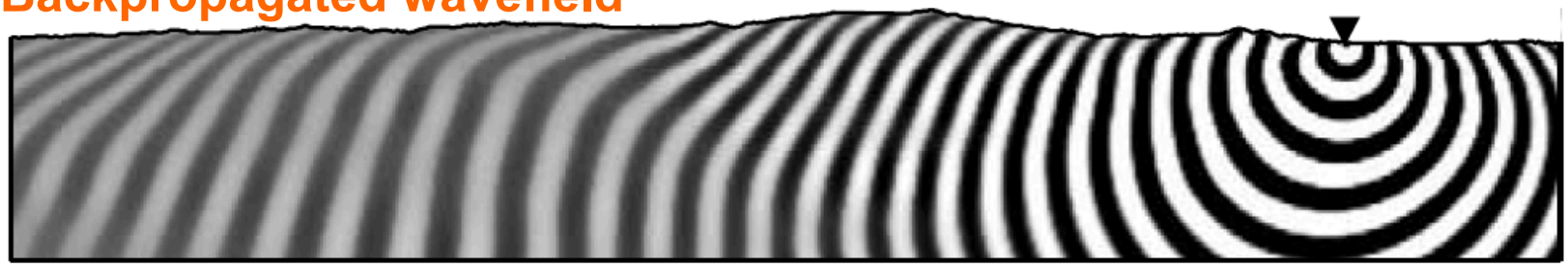
Gradient by adjoint method

Forward wavefield



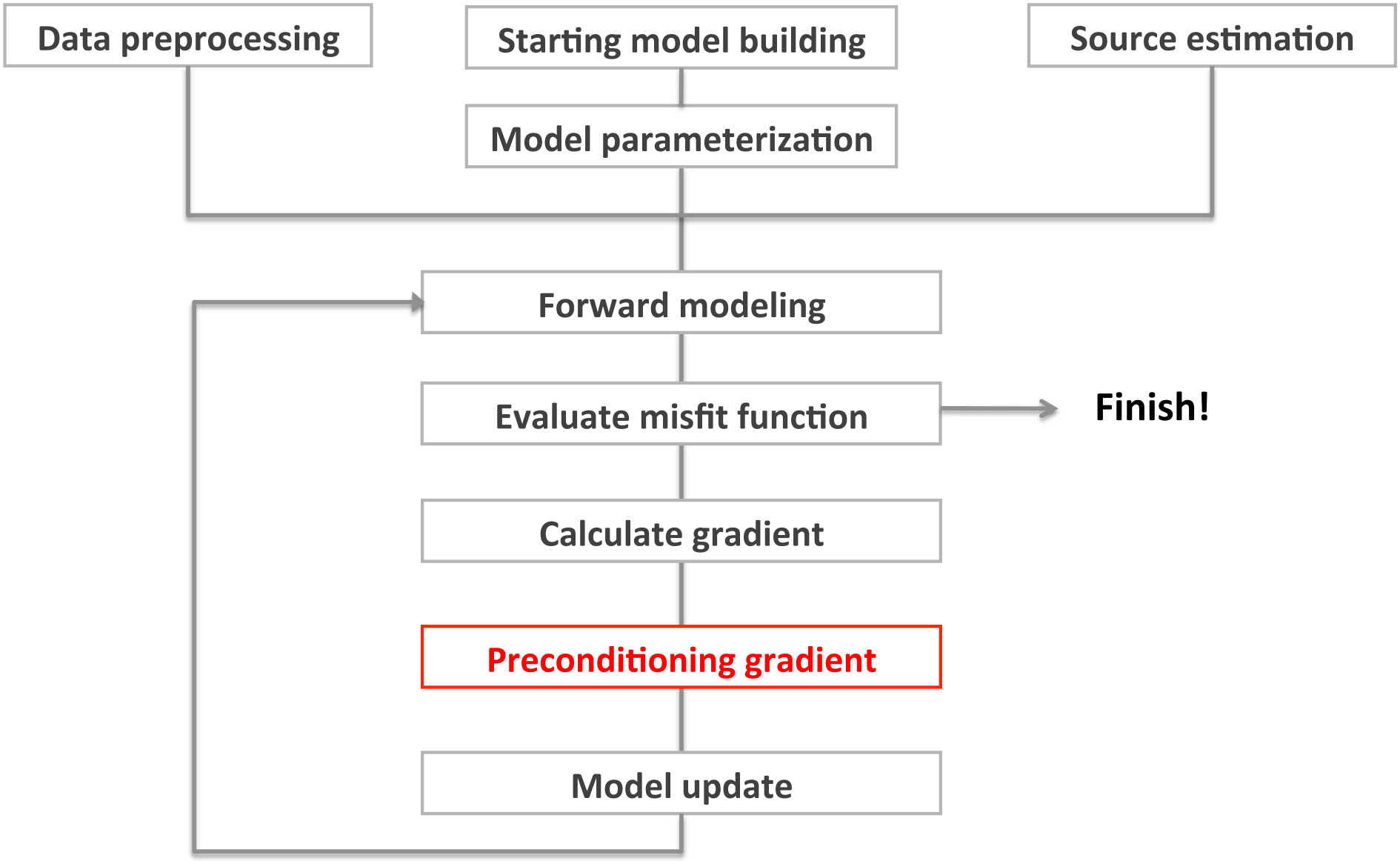
Backpropagated wavefield



Gradient from a source-receiver pair

Bleibinhaus, F., Hole, J. A., Ryberg, T., & Fuis, G. S. (2007). JGR

Workflow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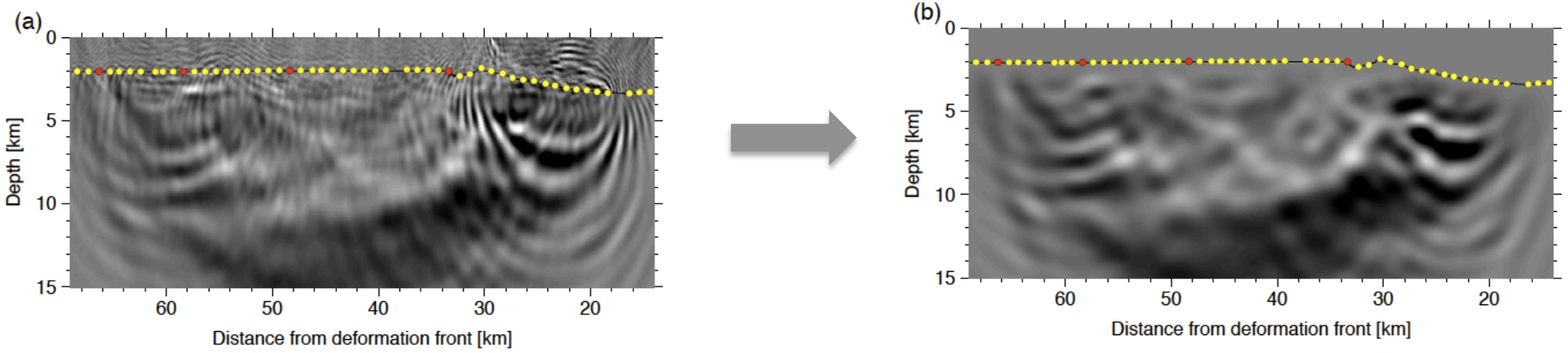
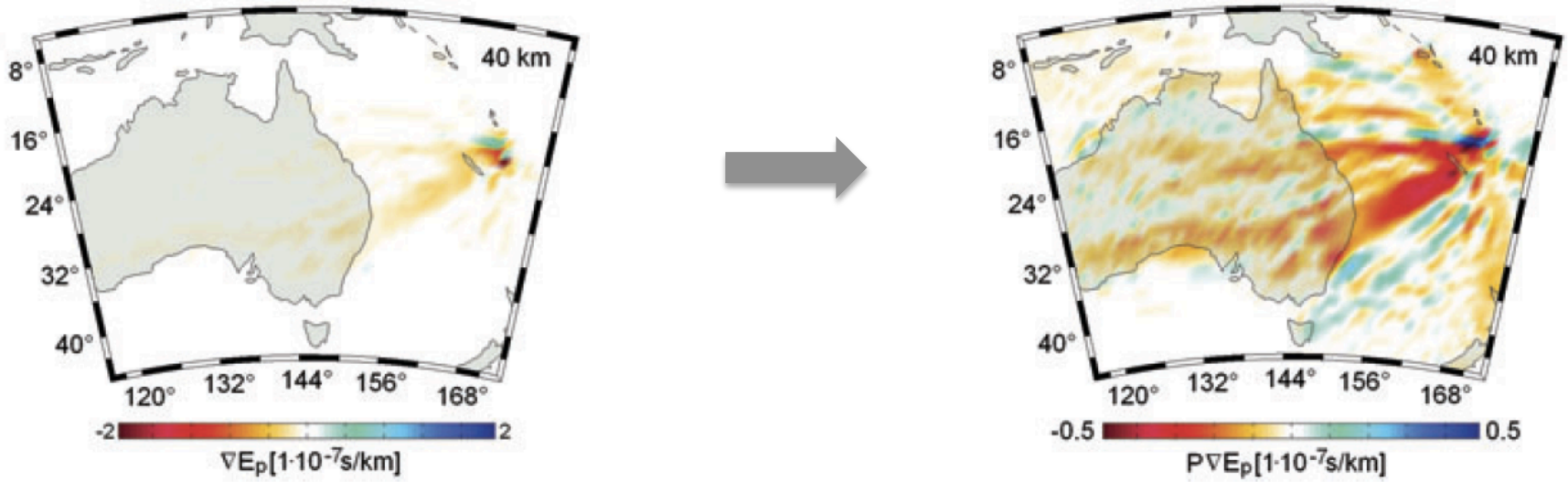
Raw gradient

Preconditioned gradient



Kamei, R., Pratt, R. G., Tsuji, T., (2012), EPSL



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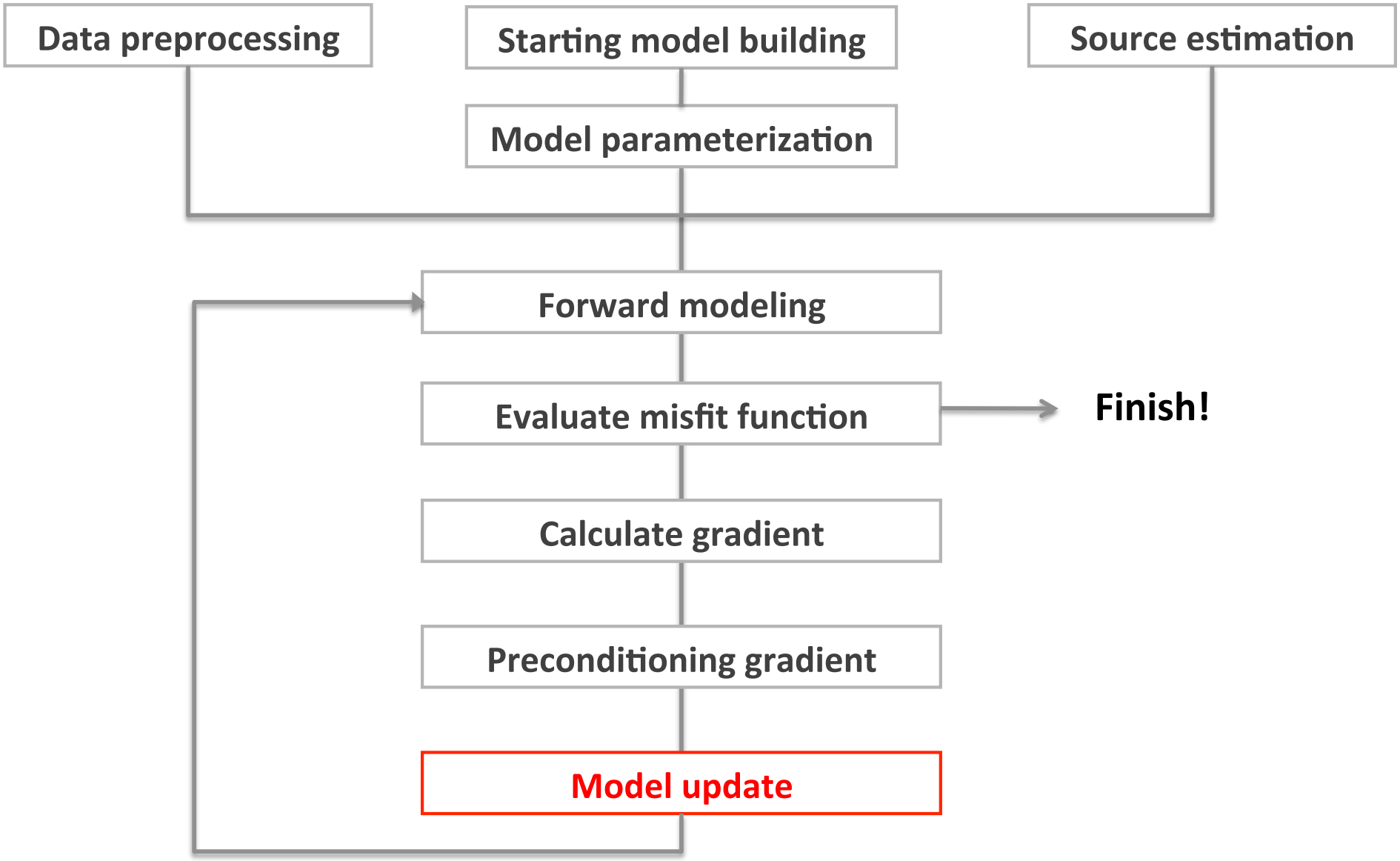
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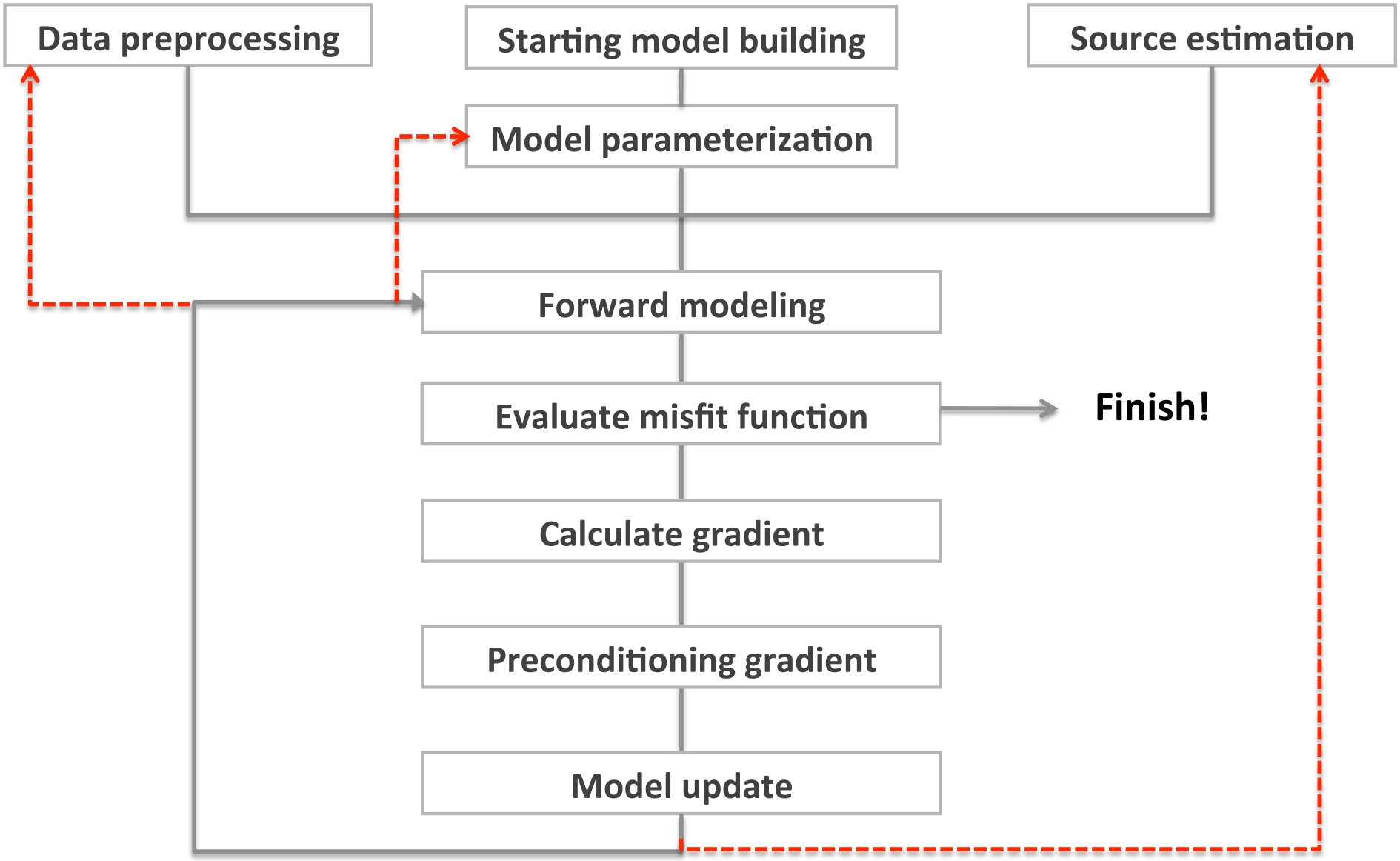
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Examples

1. Upper mantle structure *(Fichtner et al., 2009, GJI)*
2. Crustal structure *(Tape et al., 2010, GJI)*
3. Crustal structure *(Kamei et al., 2012, EPSL)*
4. 3D oil/gas exploration *(Sirgue et al., 2010, Fast Break)*
5. Cross-well gas hydrate exploration *(Pratt et al., 2004, GSC Bulletin)*

Examples

Passive sources

1. Upper mantle structure *(Fichtner et al., 2009, GJI)*
2. Crustal structure *(Tape et al., 2010, GJI)*
3. Crustal structure *(Kamei et al., 2012, EPSL)*
4. 3D oil/gas exploration *(Sirgue et al., 2010, Fast Break)*
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Examples

Active sources

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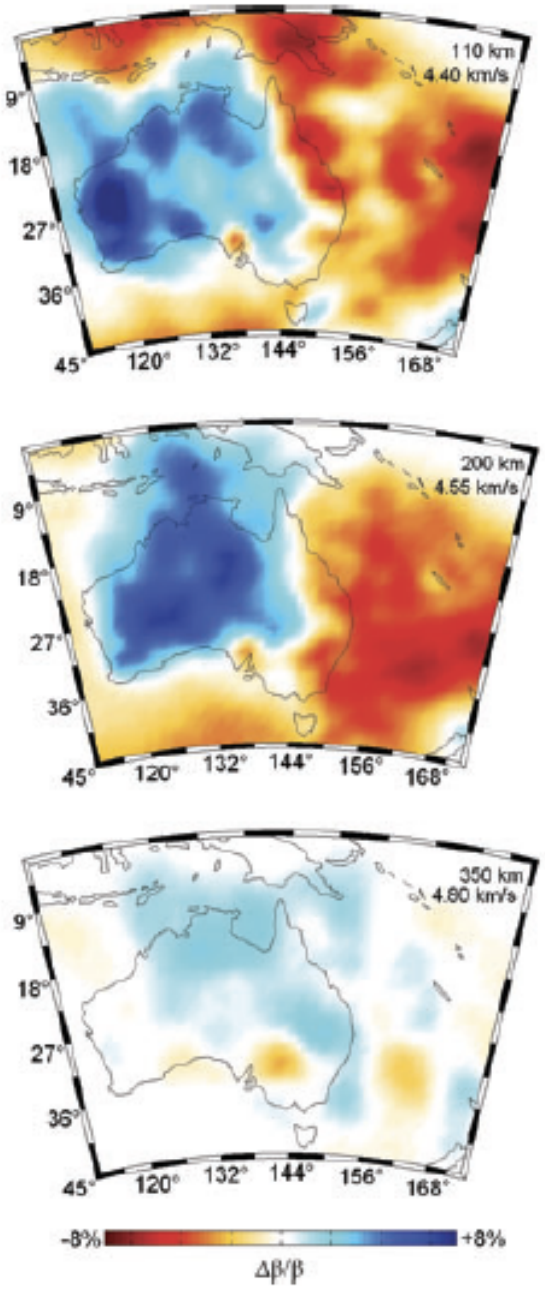
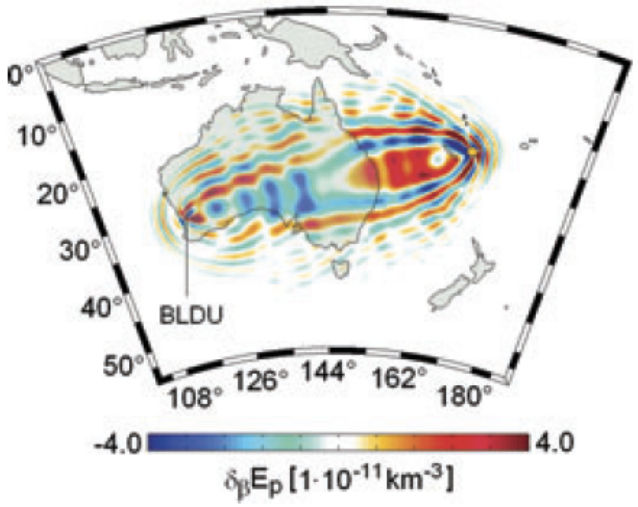
Ex 1: Upper mantle structure beneath Australia

110 km

200 km

350 km





Target:
Upper-mantle structure

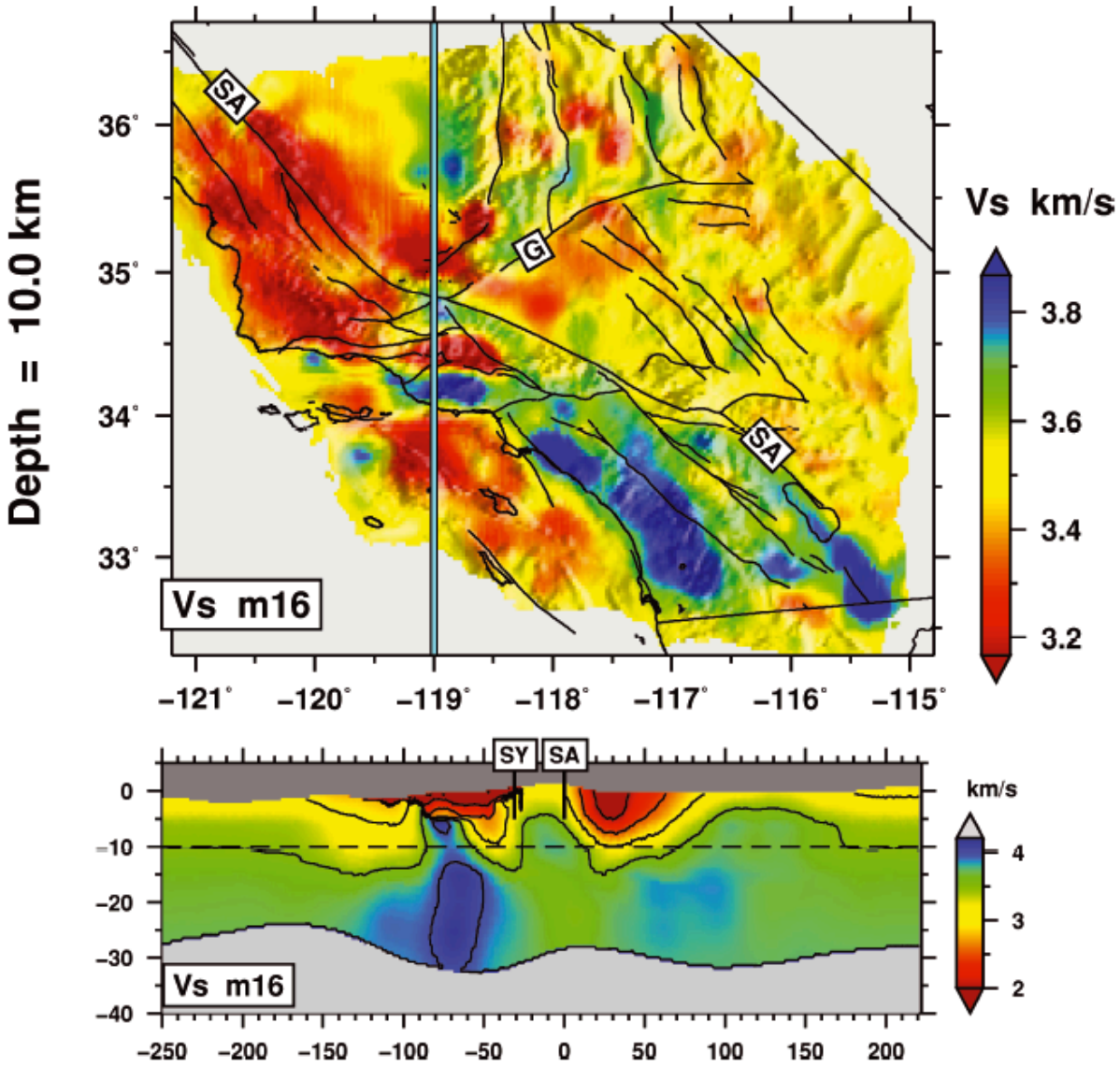
Frequency: 1/250 – 1/30 Hz
Wavelength: 135 – 1125 km
Distance: < 800 km
Scale: 5 – 37 λ

event: 57
traces: ~1000
iteration: 10

3D viscoelastic

Fichtner, A., Kennett, B. L. N., Igel, H., & Bunge, H.-P. (2009). GJI

Ex 2: Crustal imaging: Southern California



Tape, C., Liu, Q., Maggi, A., & Tromp, J. (2010). GJI

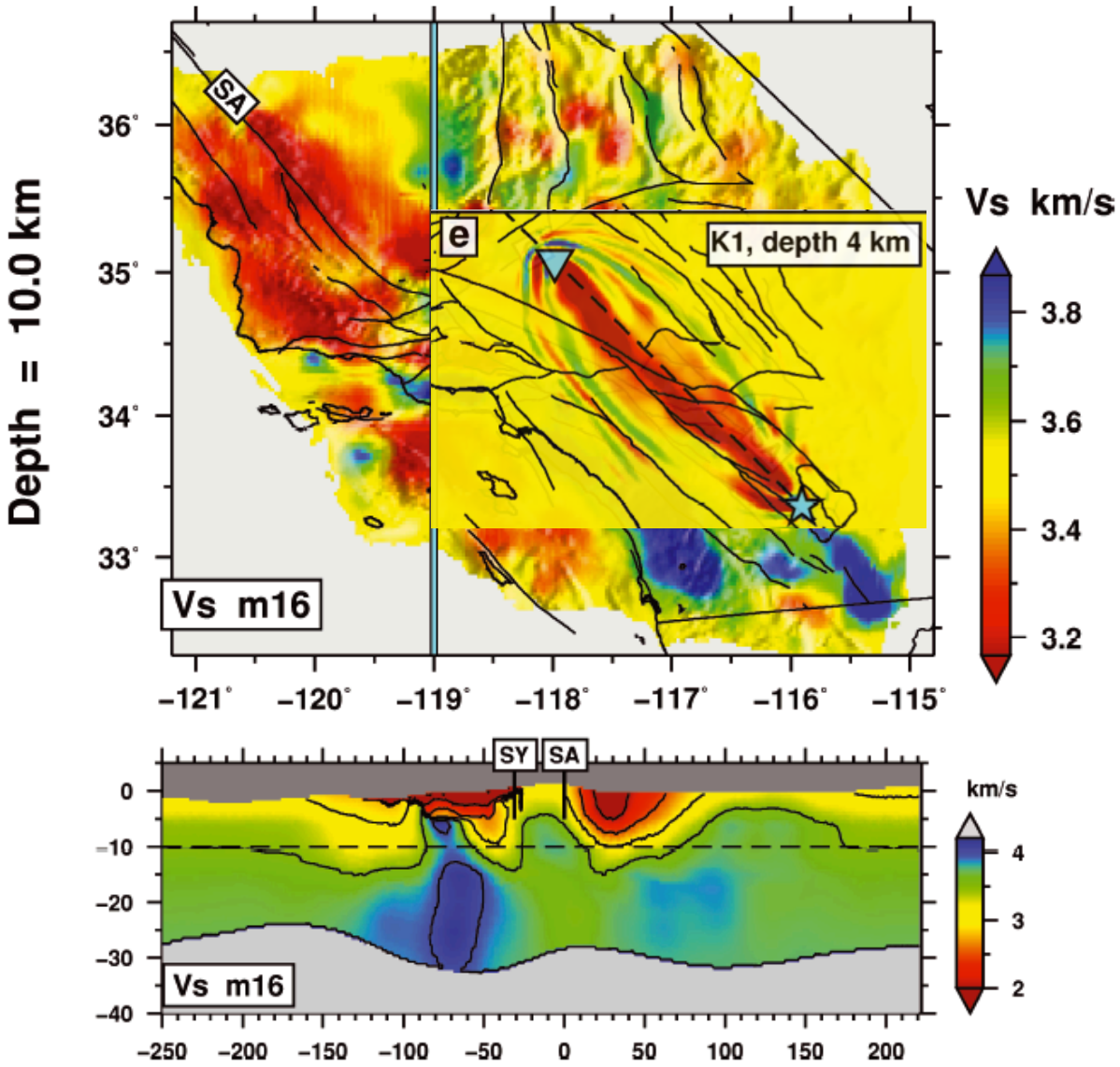
Target:
Basin
Composition across Fault

Frequency: 1/30 – 1/2 Hz
Wavelength: 8 – 120 km
Offset: < 800 km
Scale: 7– 35 λ

event: 143
receiver: 203
traces: 52,000

iteration: 16
3D viscoelastic

Ex 2: Crustal imaging: Southern California



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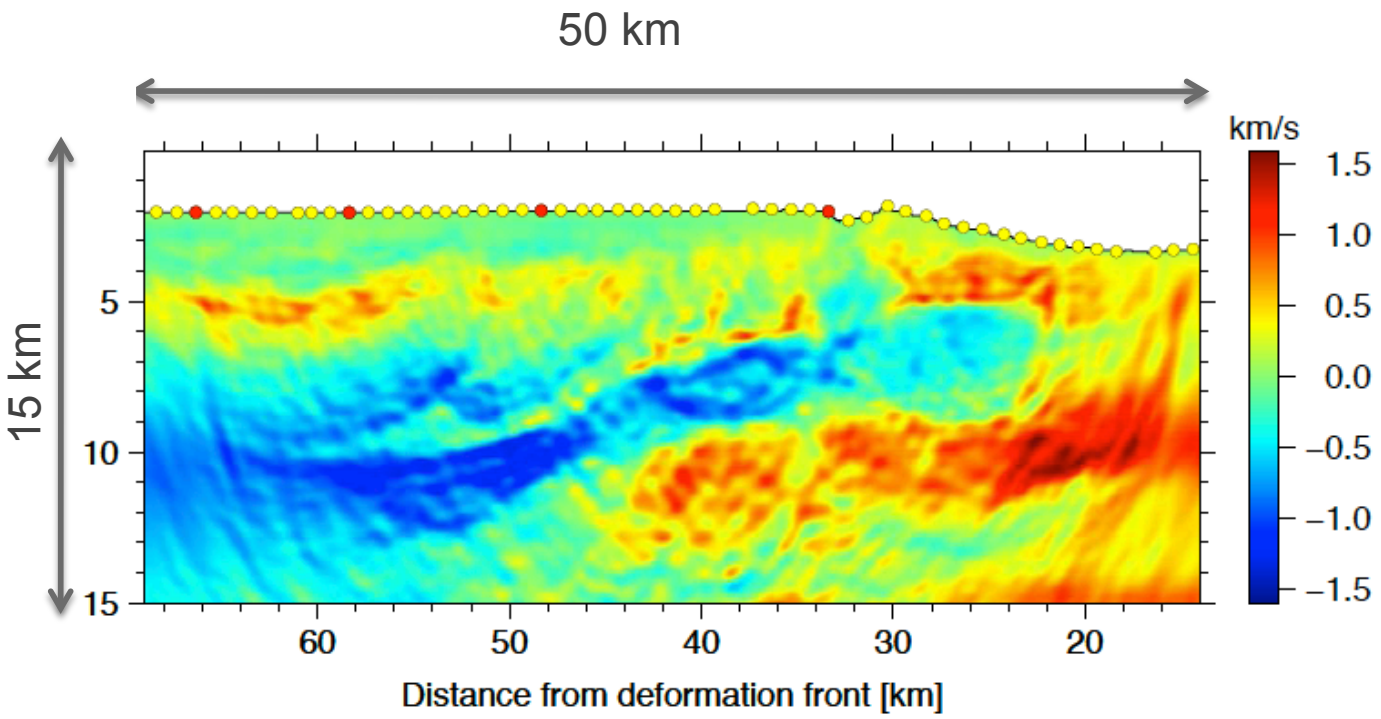
Ex 3: Crustal imaging in Nankai subduction zone



Target:
megasplay fault
low velocity zones

Frequency: 2.25 – 8.5 Hz
Wavelength: 0.47 – 1.6km
Offset: < 50 km
Scale: 31– 106 λ

source: 285
receiver: 54
traces: 15,400

iteration: 450

2D visco-acoustic

Kamei, R., Pratt, R. G., Tsuji, T. (2012) EPSL

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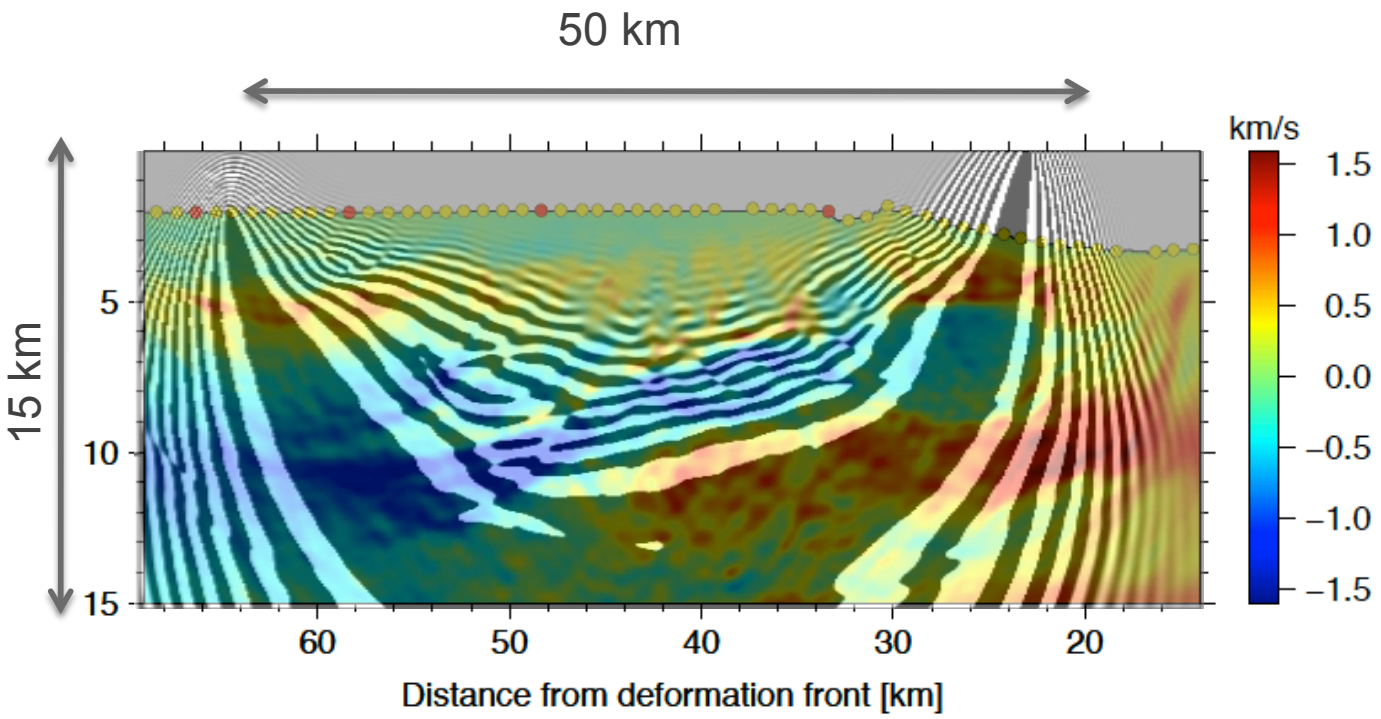

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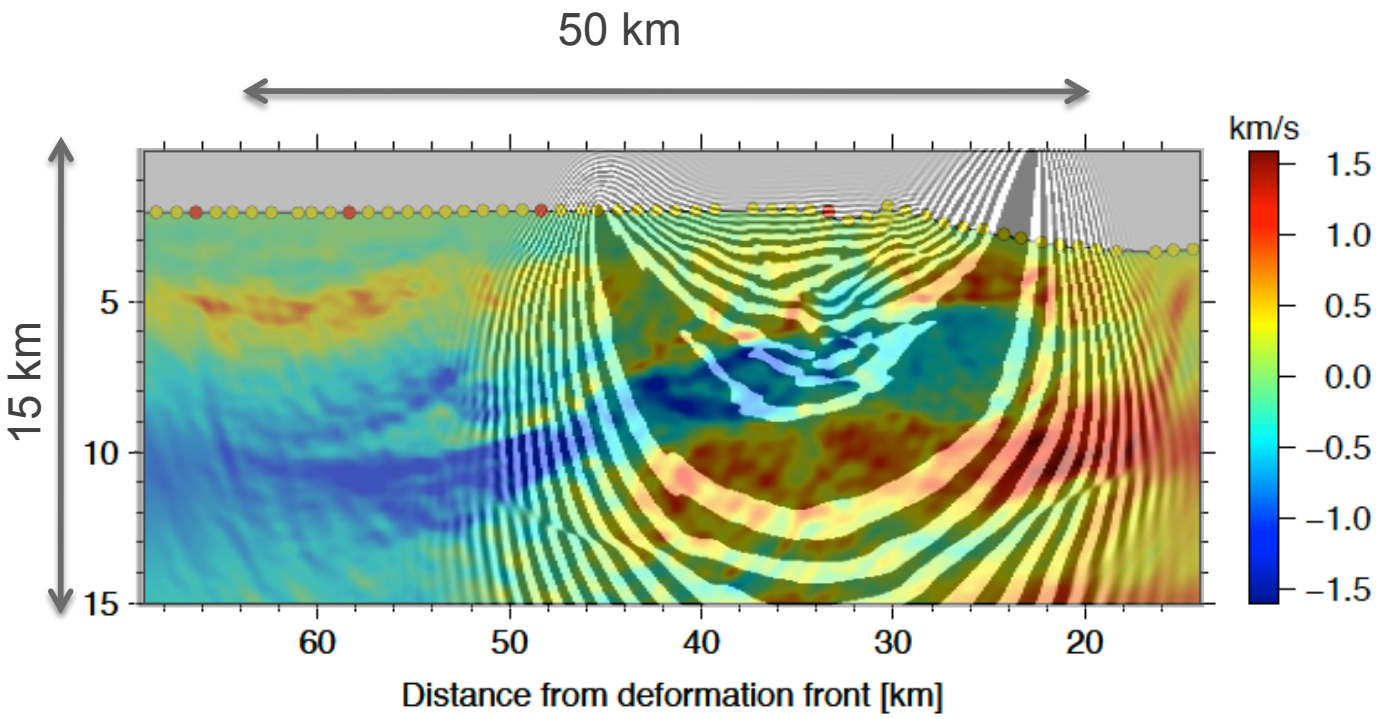

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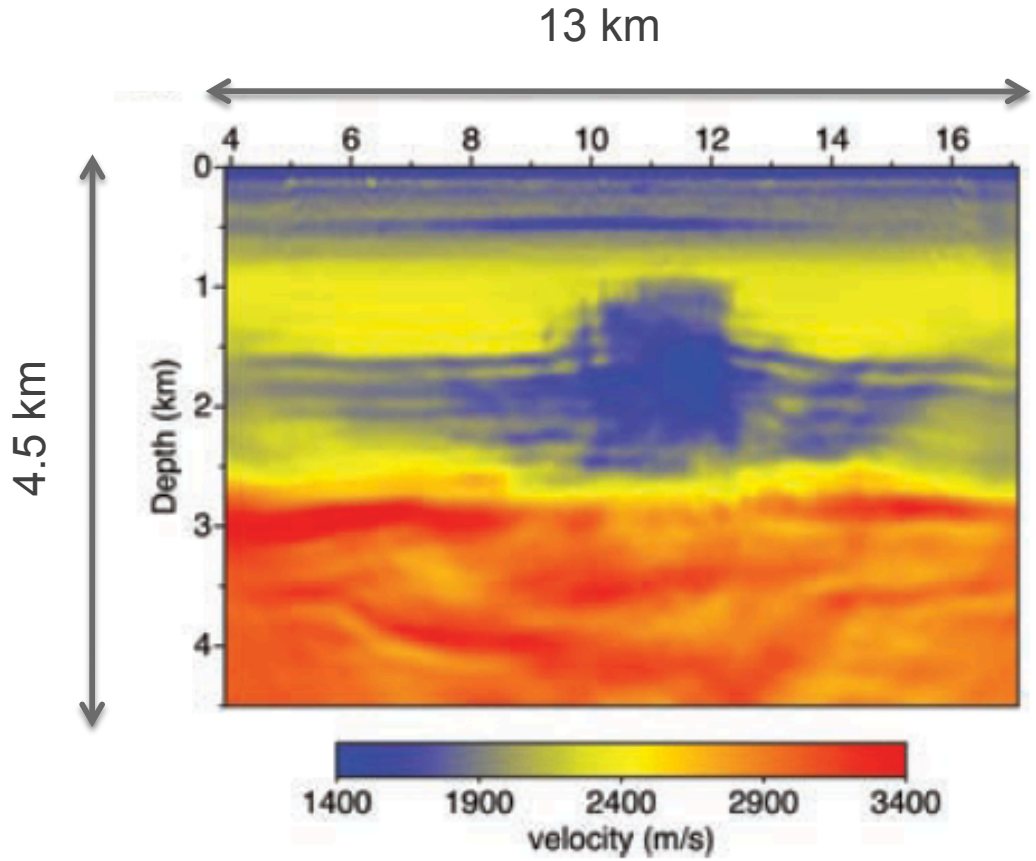
Kamei, R., Pratt, R. G., Tsuji, T. (2012) EPSL

Ex 4: 3D oil exploration in Valhall, North sea



Target:

Oil reservoir
Gas chimney

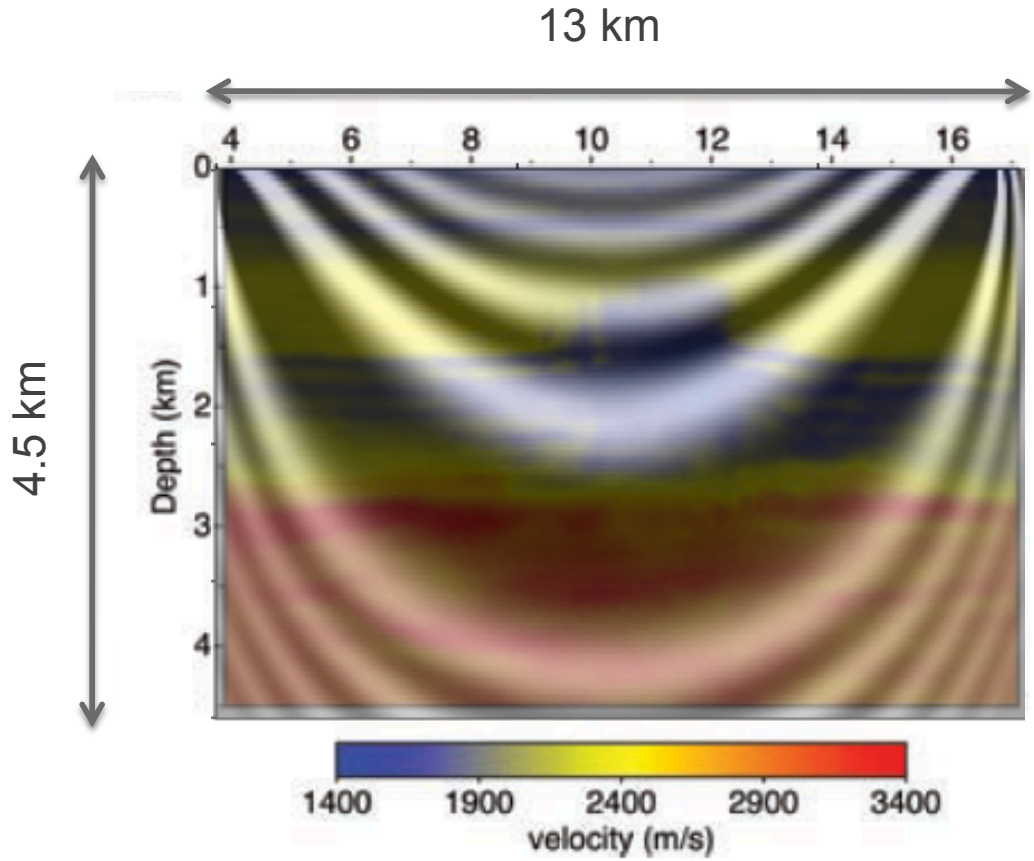
Frequency: 3.5 - 7 Hz
Wavelength: 0.36 – 0.72 km
Offset: < 13 km
Scale: 18 – 36 λ

source: 50,000
receiver: 2,300
traces: 120,000,000

3D acoustic

Sirgue, L., Barkved, O. I., Dellinger, J., Etgen, J., Albertin, U., & Kommedal, J. (2010). First Break
Etienne, V., Hu G., Operto, S. & Virieux, J. (2012) EGU

Ex 4: 3D oil exploration in Valhall, North sea



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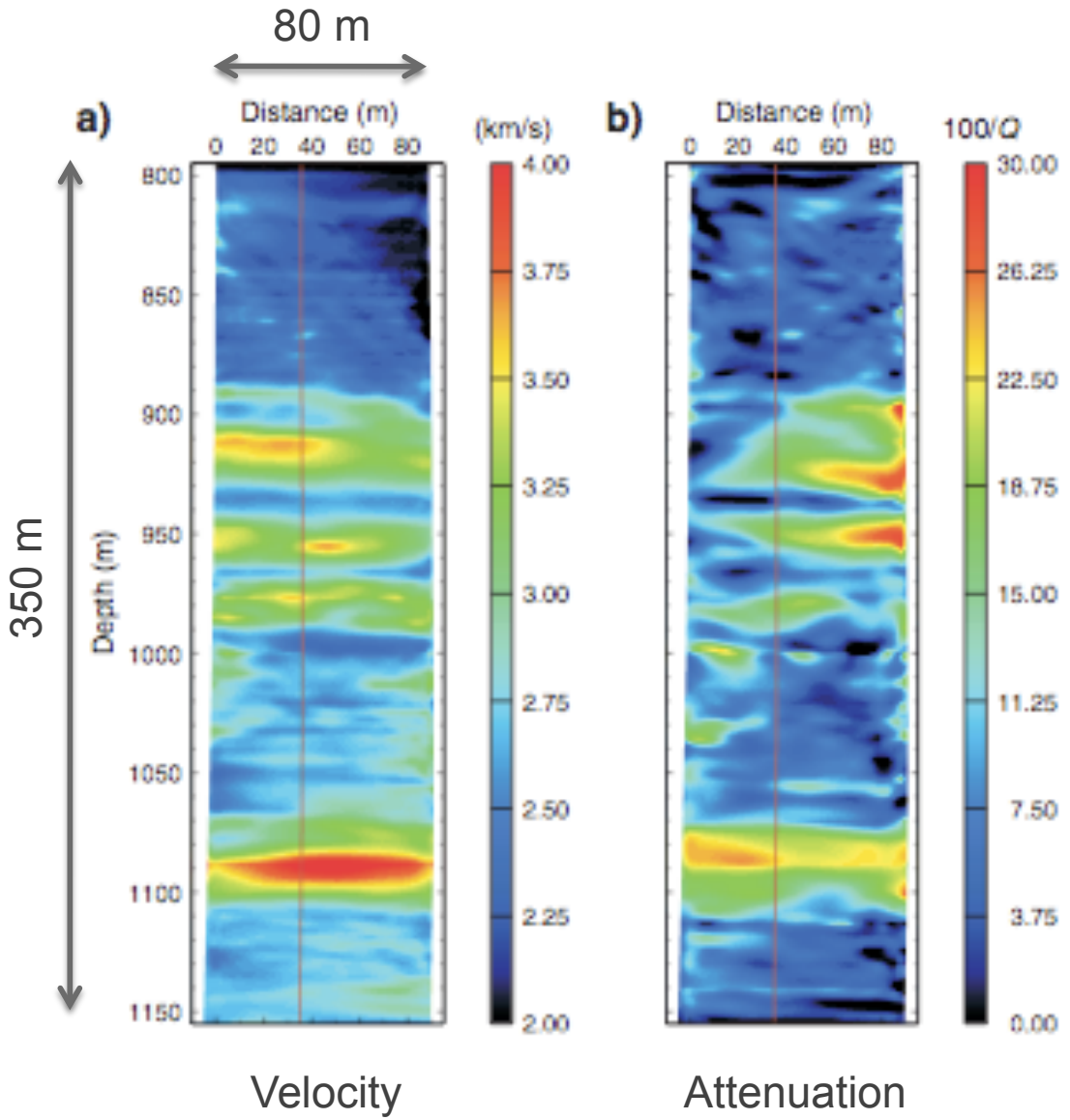
Ex 5: Gas hydrate production in Arctic Canada



Velocity

Attenuation

Target:
Hydrate zone
(high velocity, high Q^{-1})

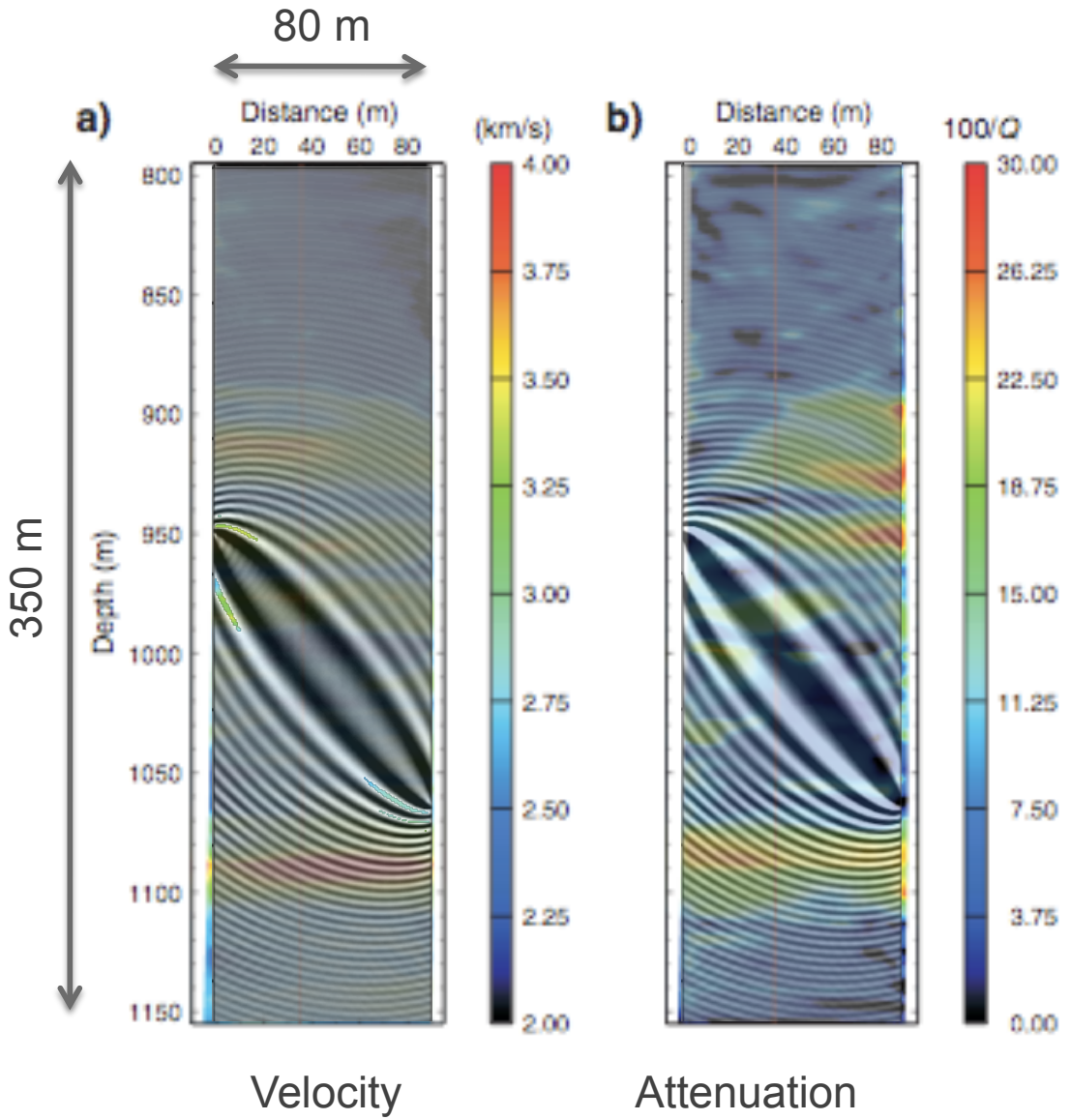
Frequency: 100 -1000 Hz
Wavelength: 3 – 30 m
Offset: < 128 m
Scale: 4 – 42 λ

source: 454
receiver: 480
traces: 150,000

2D Visco-acoustic
Elliptic anisotropy

Pratt, R. G., Hou, F., Bauer, K., & Weber, M. H. (2004). GSC Bulletin

Ex 5: Gas hydrate production in Arctic Canada



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Elliptic anisotropy

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	Active source	**Passive source**
Frequency	1-10^3 Hz	10^{-3} – 10^{-1} Hz
Model size	crosswell – crustal **1-100s of wavelengths**	local, regional, global **1-100s of wavelengths**
Iteration	2D: O(100), 3D: O(10)	O(10)
Survey geometry	**regular, dense**	**irregular, sparse**
Data	Pressure	3 components (Shear)
Data volume	**2D: O(1000)-O(100 000)** **3D: O(10^6)**	**O(1000)-O(10,000)**
Forward modelling	Acoustic, FDM	Elastic, SEM, FDM
Starting model	Previous work Traveltime/Reflection tomography	Previous work CRUST2.0
Inversion domain	Frequency domain Time domain	Time-frequency domain Time domain
Misfit function	L2 (L1) data misfit L2 logarithmic misfit L2 phase misfit	L2 phase misfit L2 cross-correlation misfit

	Active source	**Passive source**
Challenges	Non-linearity Non-uniqueness Computational cost (3D) Model appraisal Resolution analysis Multi parameter	
	data volume starting model topography	moment tensor irregular coverage crust, CMB

Thank you very much for your attention!

Multiscale approach

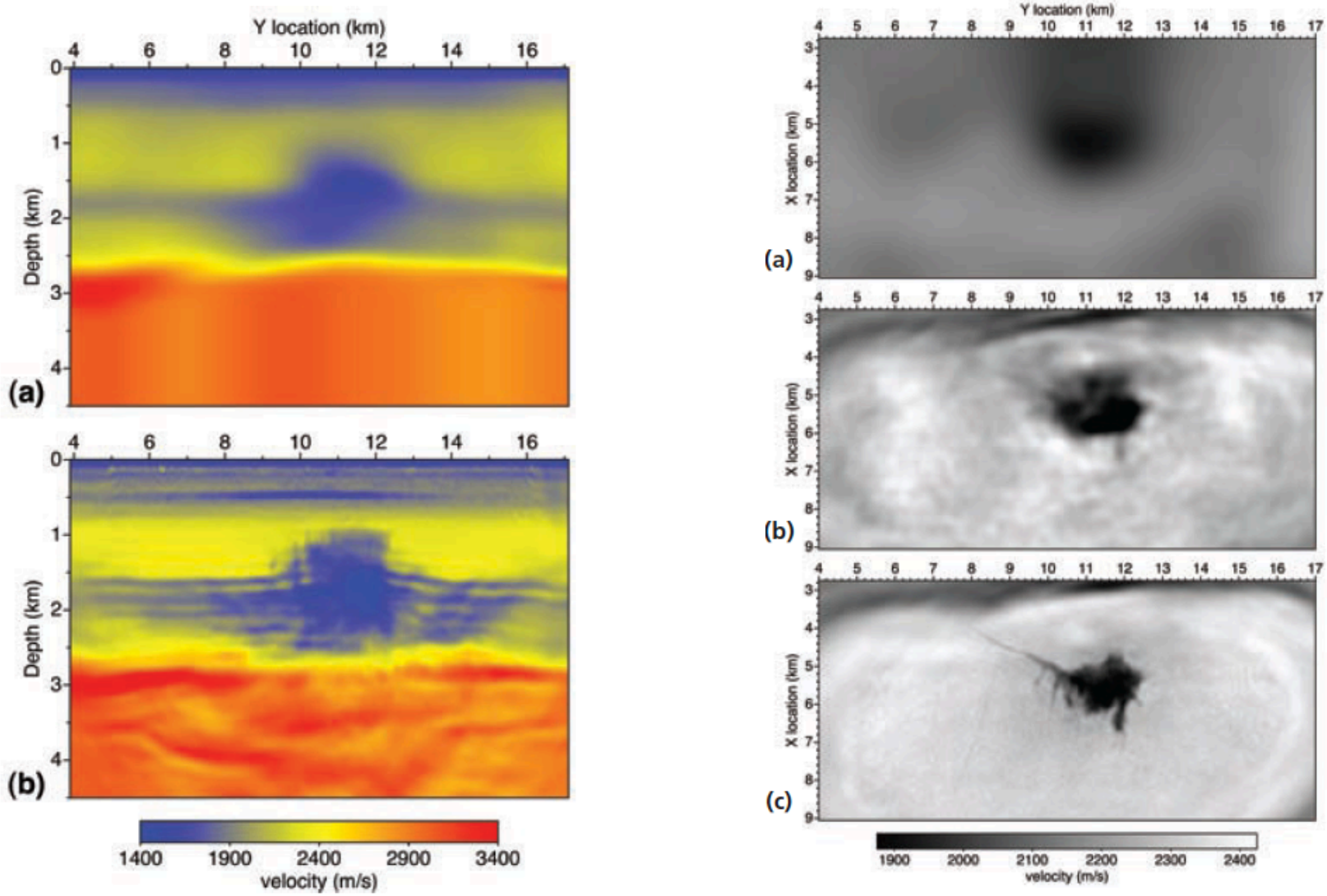
Large scale features

Small scale features

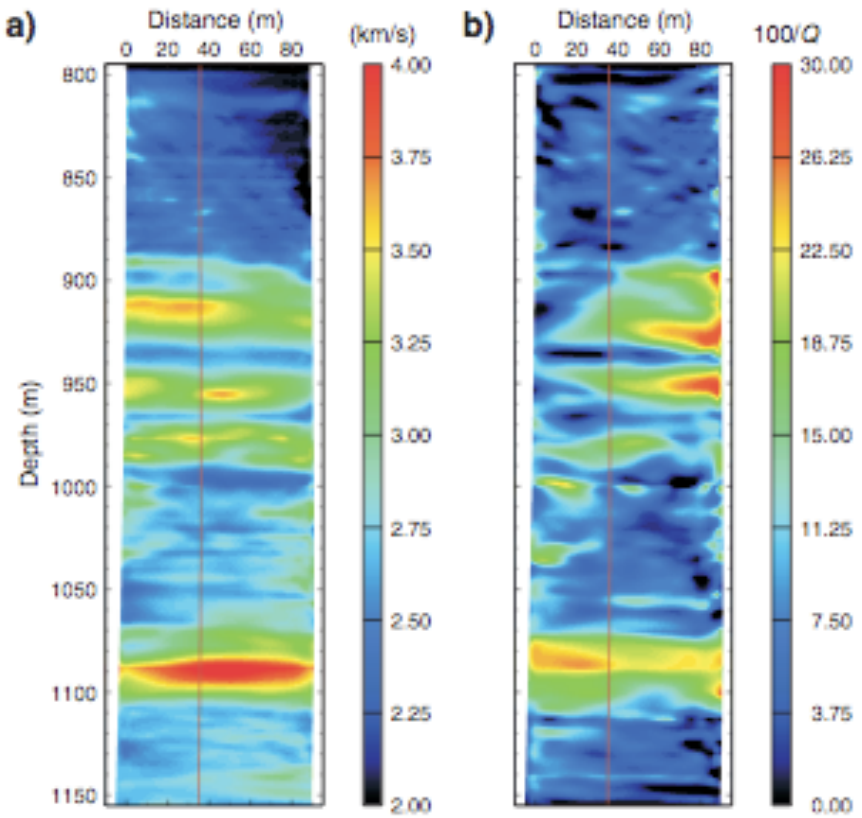
Low frequency component
Early arrivals

High frequency component
Later scattered arrivals

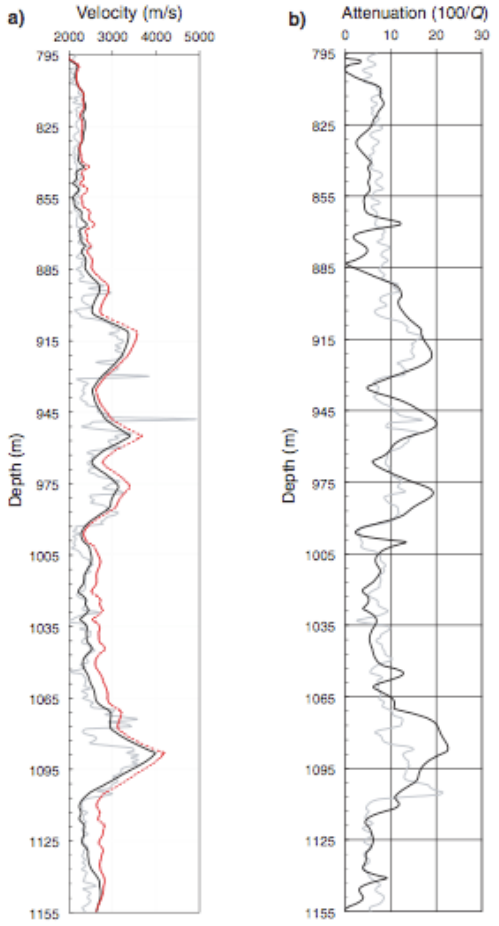
Ex 3: 3D Gas exploration in Valhall, North sea



Gas hydrate production monitoring in Arctic Canada



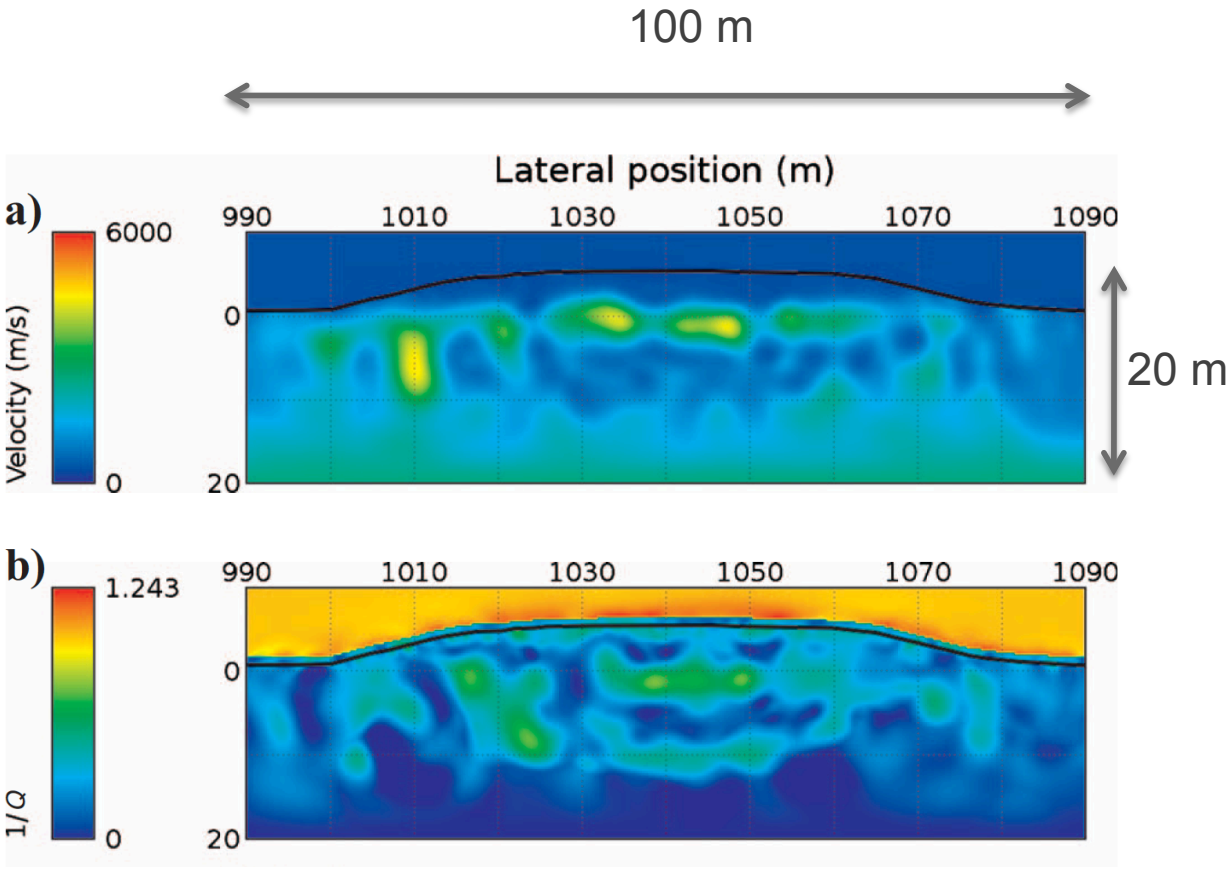
Velocity Attenuation



Velocity Attenuation

Pratt et al. (2004)

Ex 5: Object detection of near surface

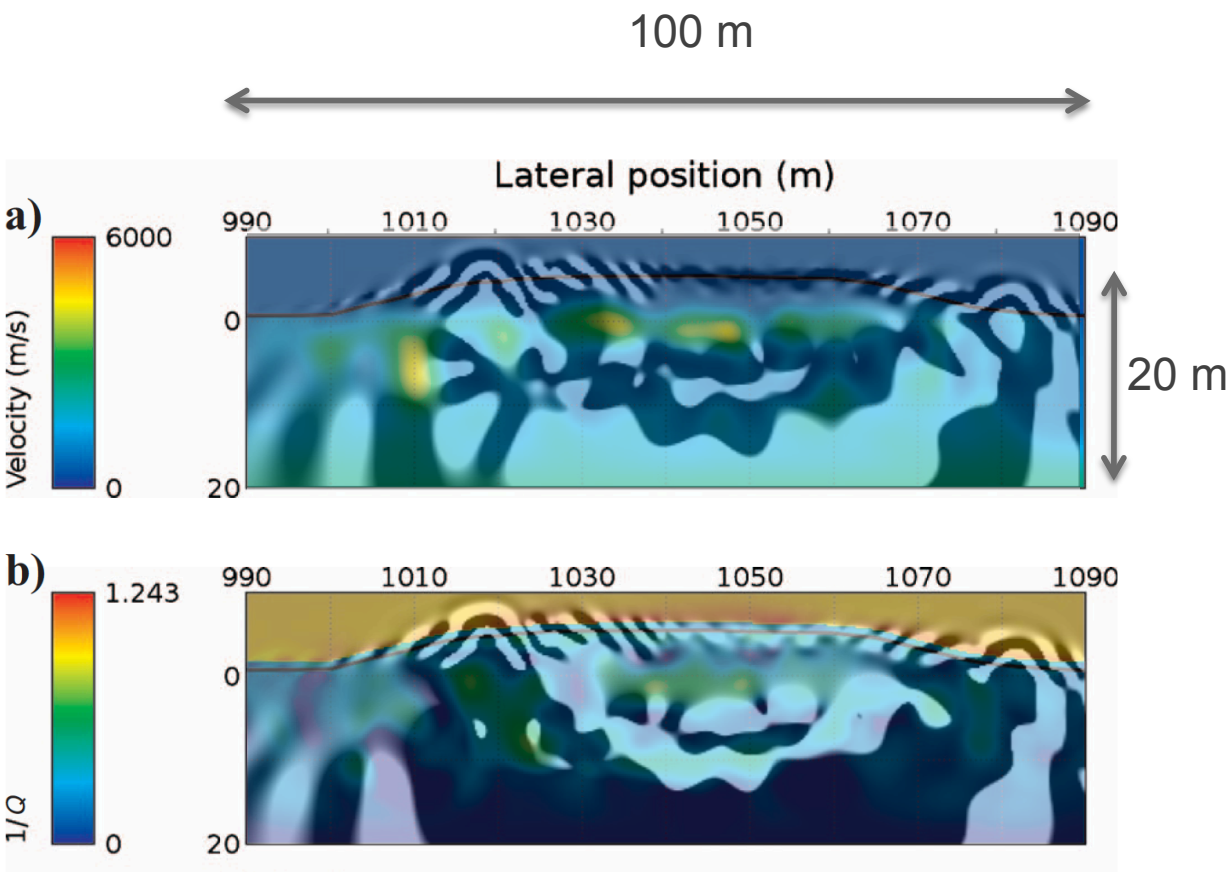


Frequency:	20 -150 Hz
Wavelength:	14 – 100 m
Offset:	< 80 m
Scale:	0.8 – 5.7 λ
# source:	70
# receiver:	48
# traces:	3360

Visco-acoustic

Smithyman et al. (2009)

Ex 5: Object detection of near surface



Smithyman et al. (2009) Geophysics

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Visco-acoustic

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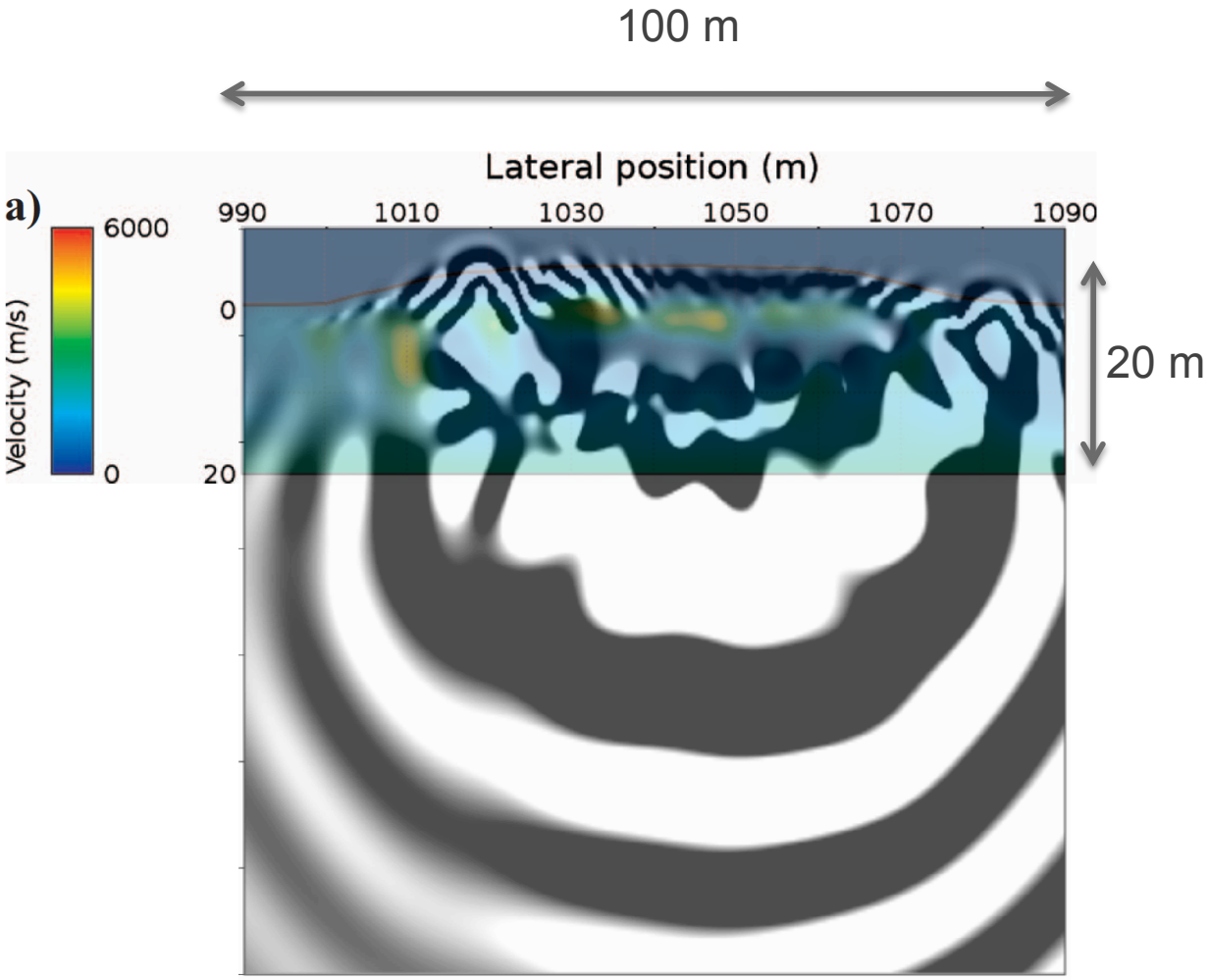

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