Phase-residual based **quality control** methods and techniques for mitigating **cycle skips**

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Why?

Full-waveform inversion (FWI) is powerful

...dangerous

...expensive

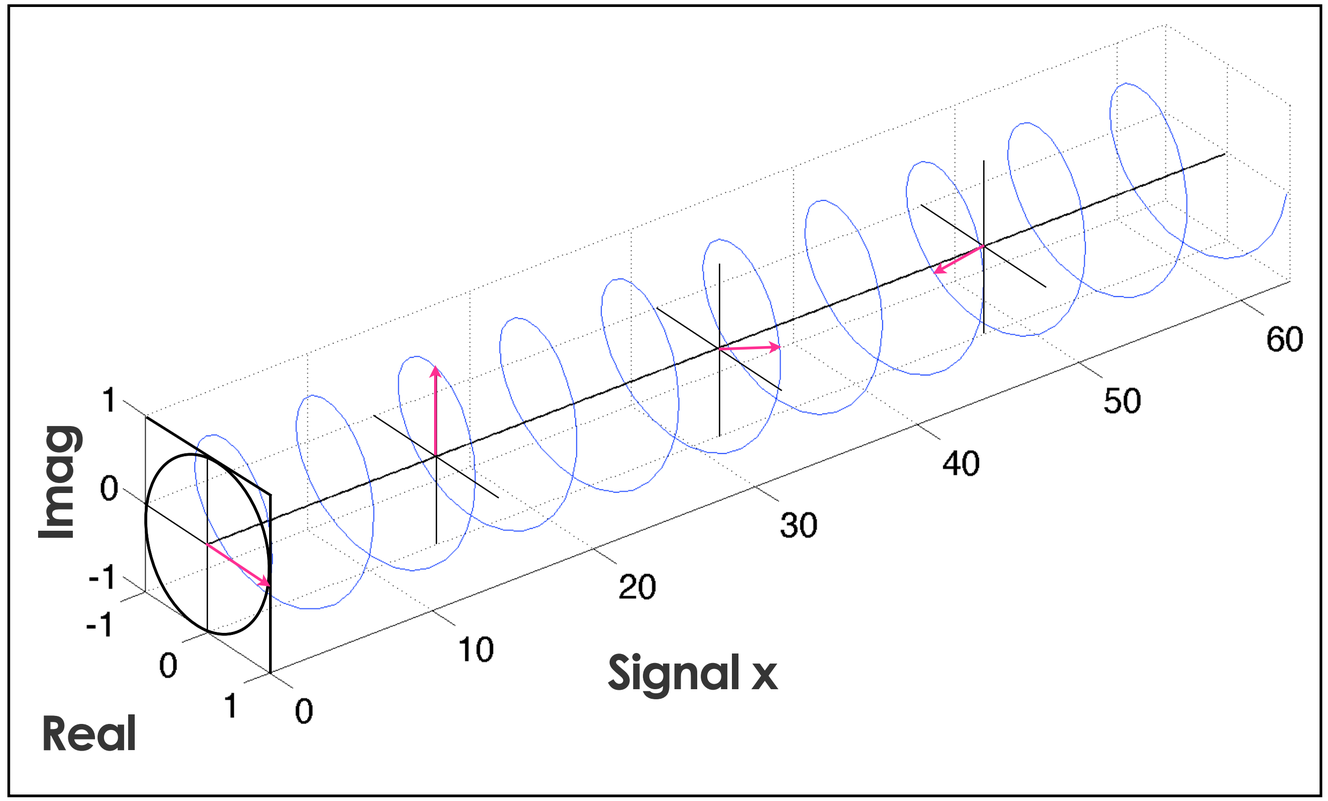
...unreliable

If you don't know what you're doing.

Phase-based quality control

Waveform phase is the frequency-domain analogue to traveltime – mainly sensitive to velocity

What is phase?



$$e^{i\omega t} = \cos(\omega t) + i\sin(\omega t)$$

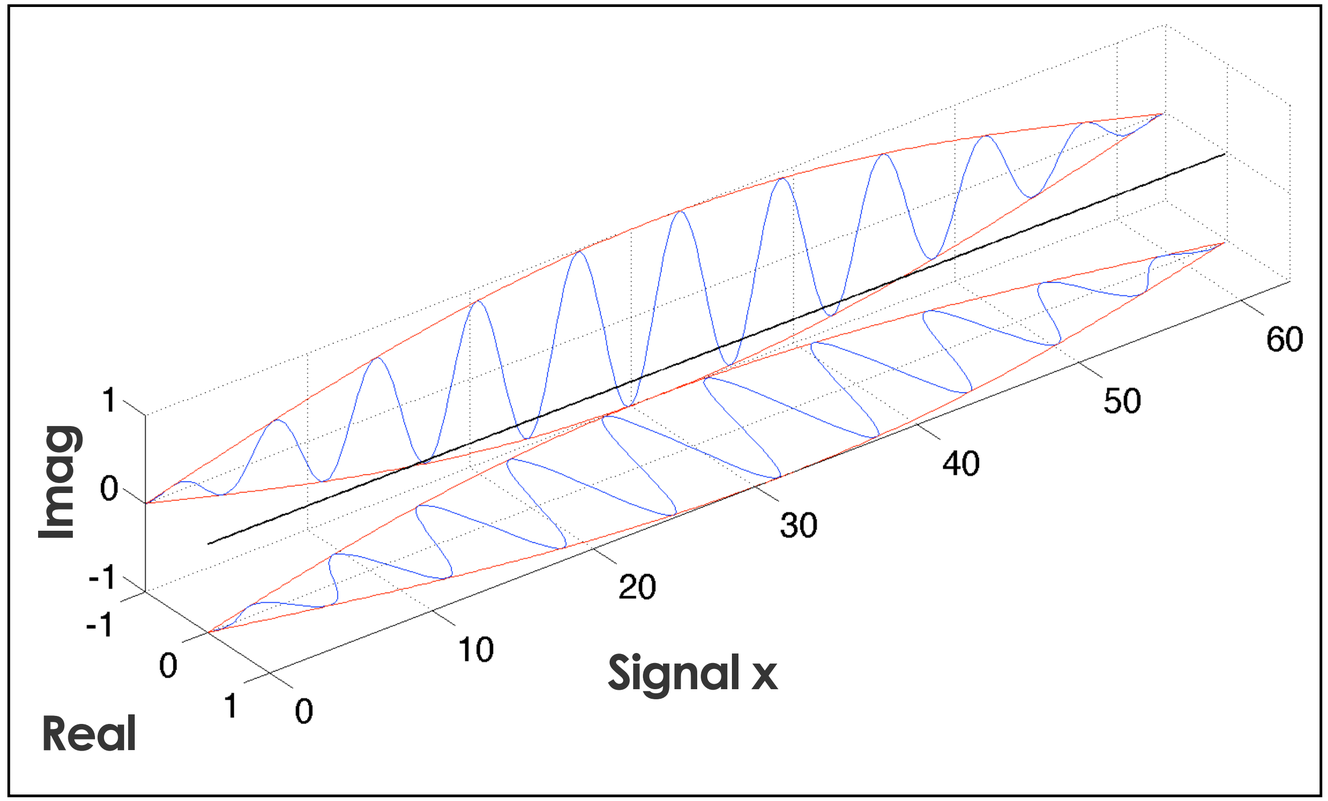
Parts of a complex signal

Phase

...angle part of a complex signal
...one number per trace, per freq.
...mainly affected by velocity

Patterns exist if examined spatially along the array.

What is amplitude?



$$Ae^{i\omega t} = A\cos(\omega t) + iA\sin(\omega t)$$

Parts of a complex signal

Amplitude

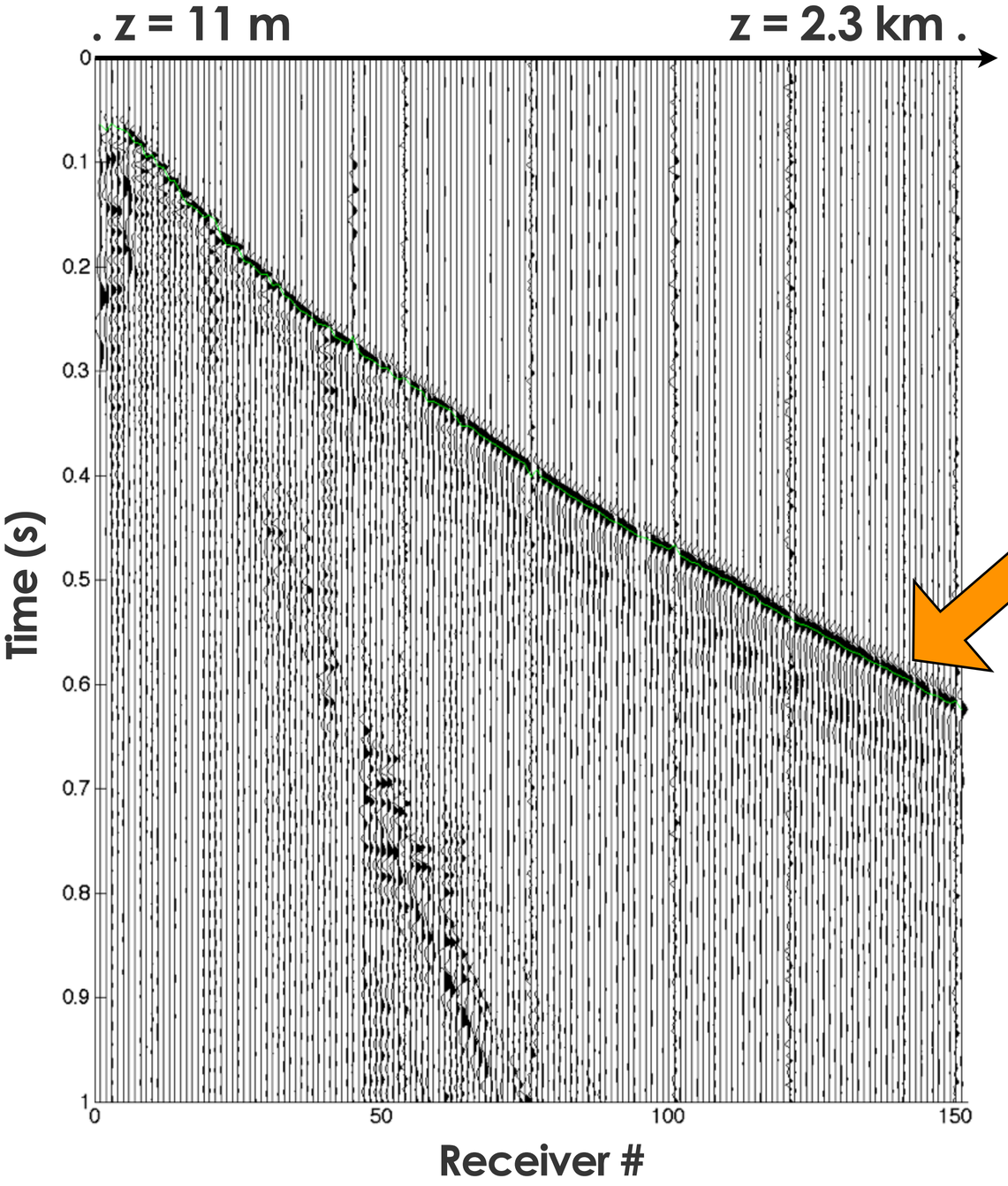
...is affected mainly by:

- proximity to source
- focussing effects
- signal attenuation

...can be decoupled from phase

1D Example

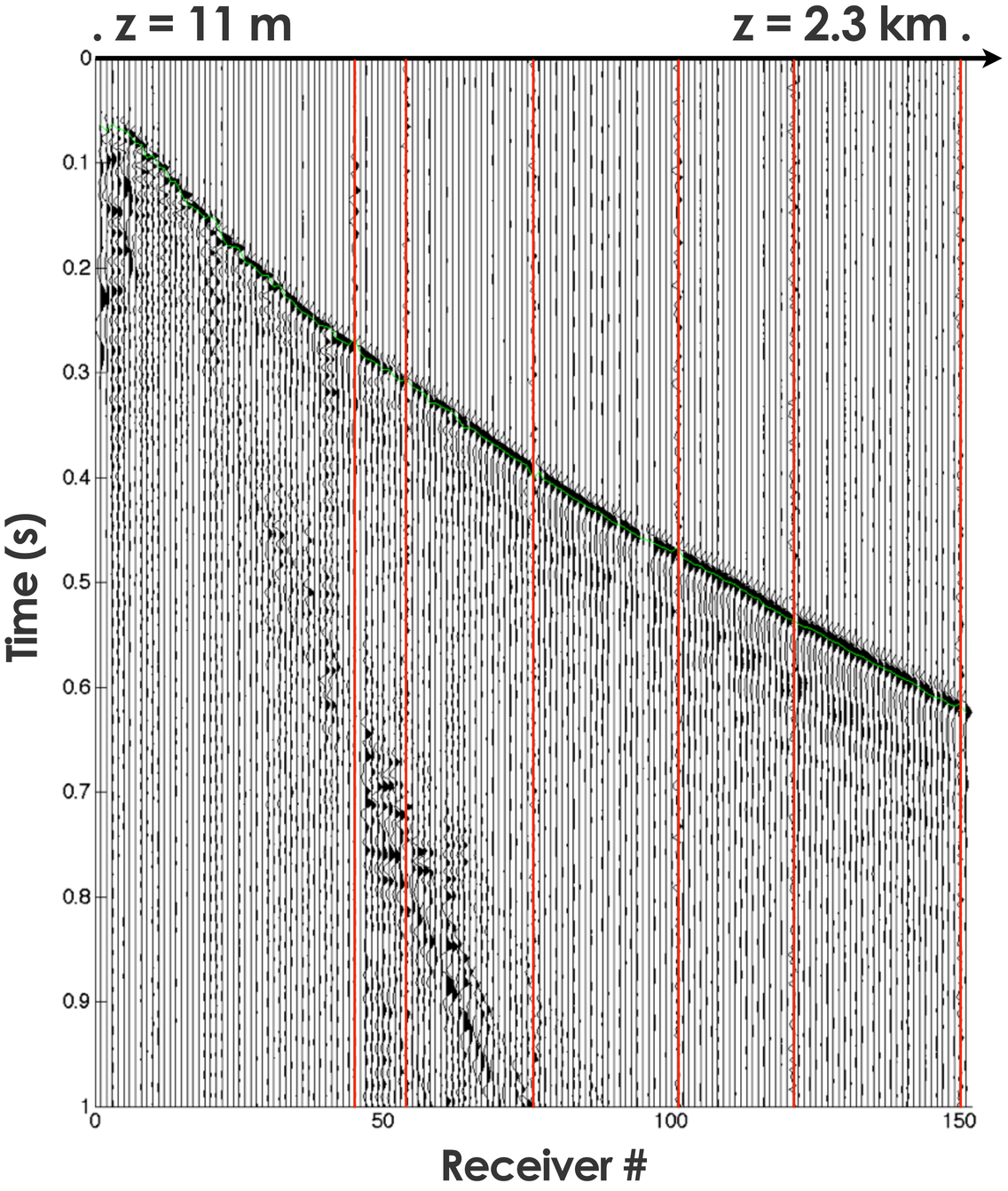
VSP Dataset from the Permian Basin, TX, USA

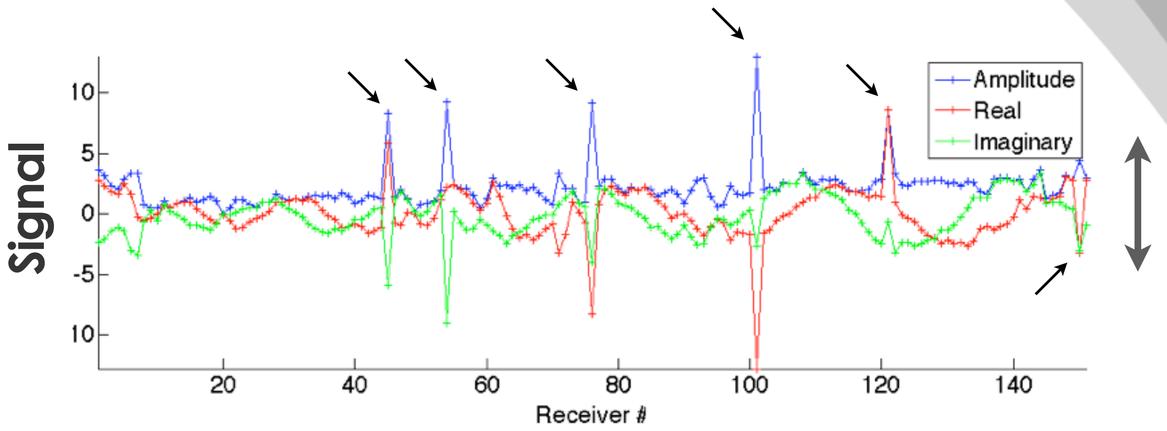


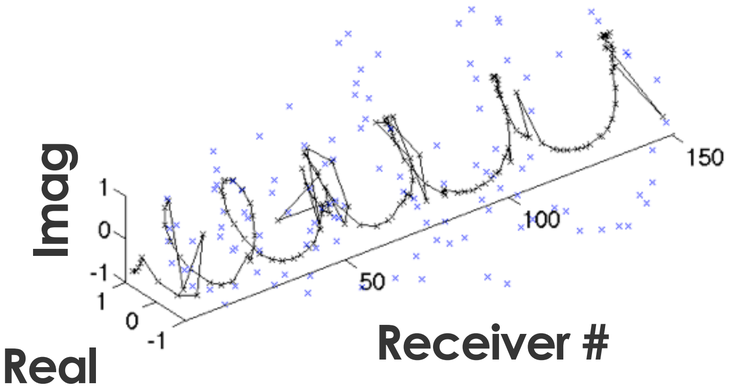
Checkshot from VSP survey

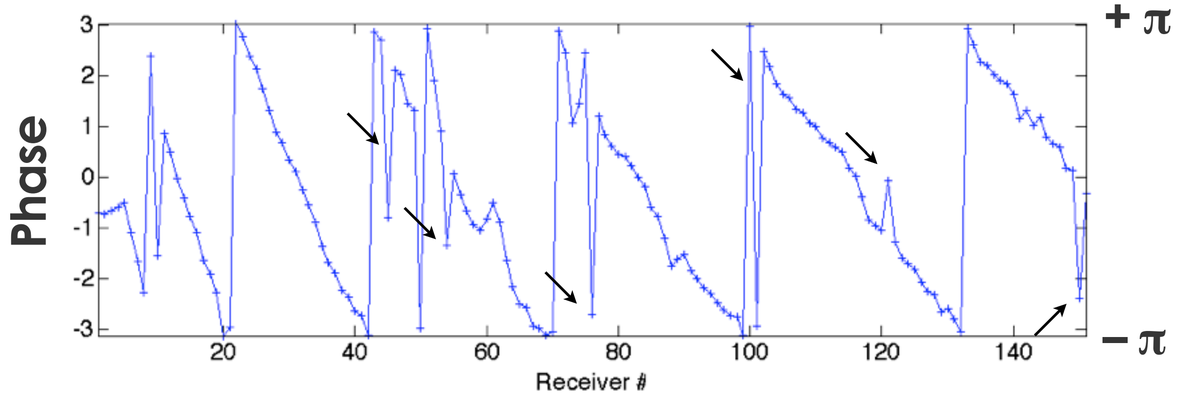
Receiver 001 at ~ 11 m depth
Receiver 151 at ~ 2.3 km depth

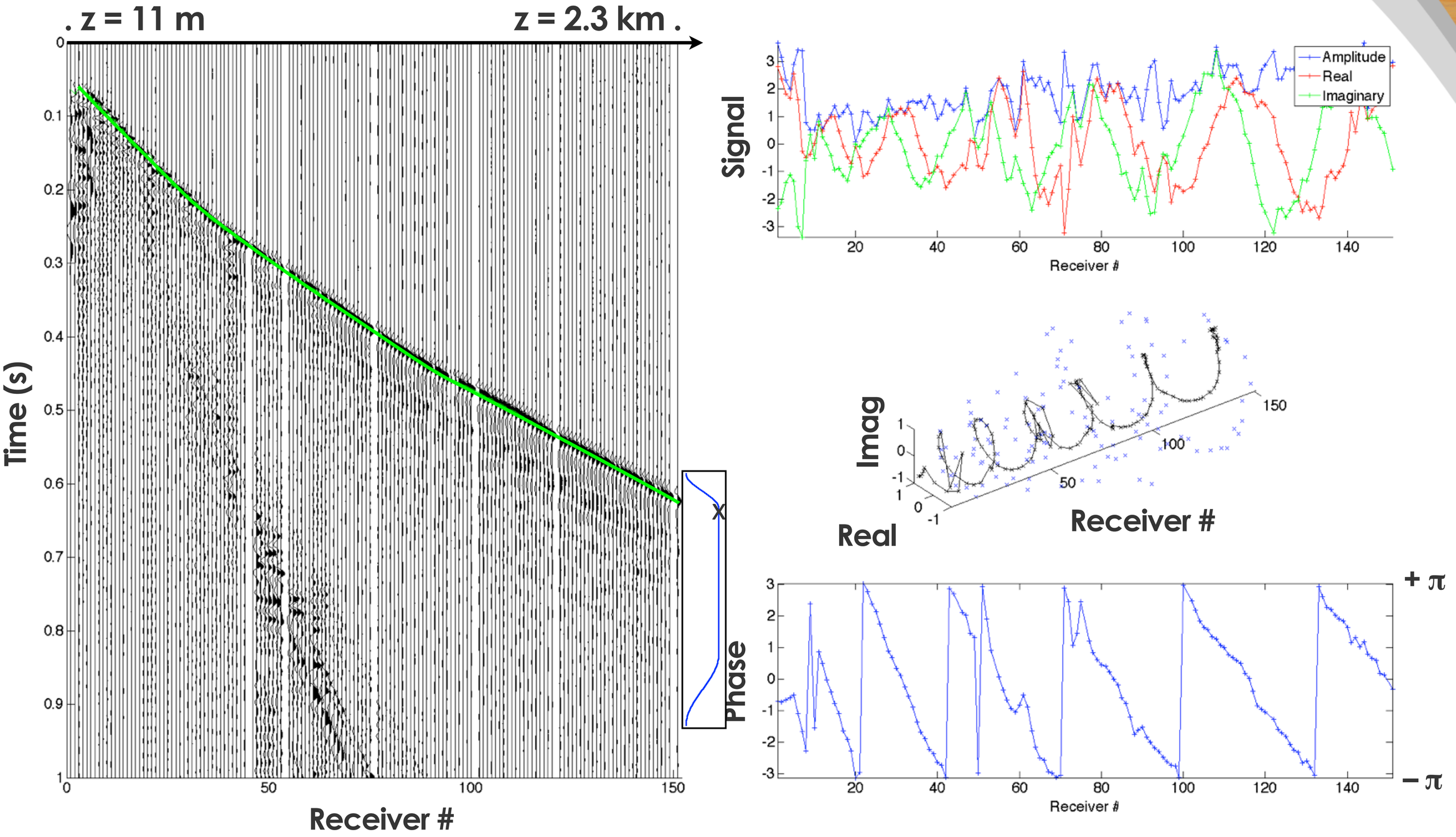
Main event of interest for FWI is
the direct / refracted arrival

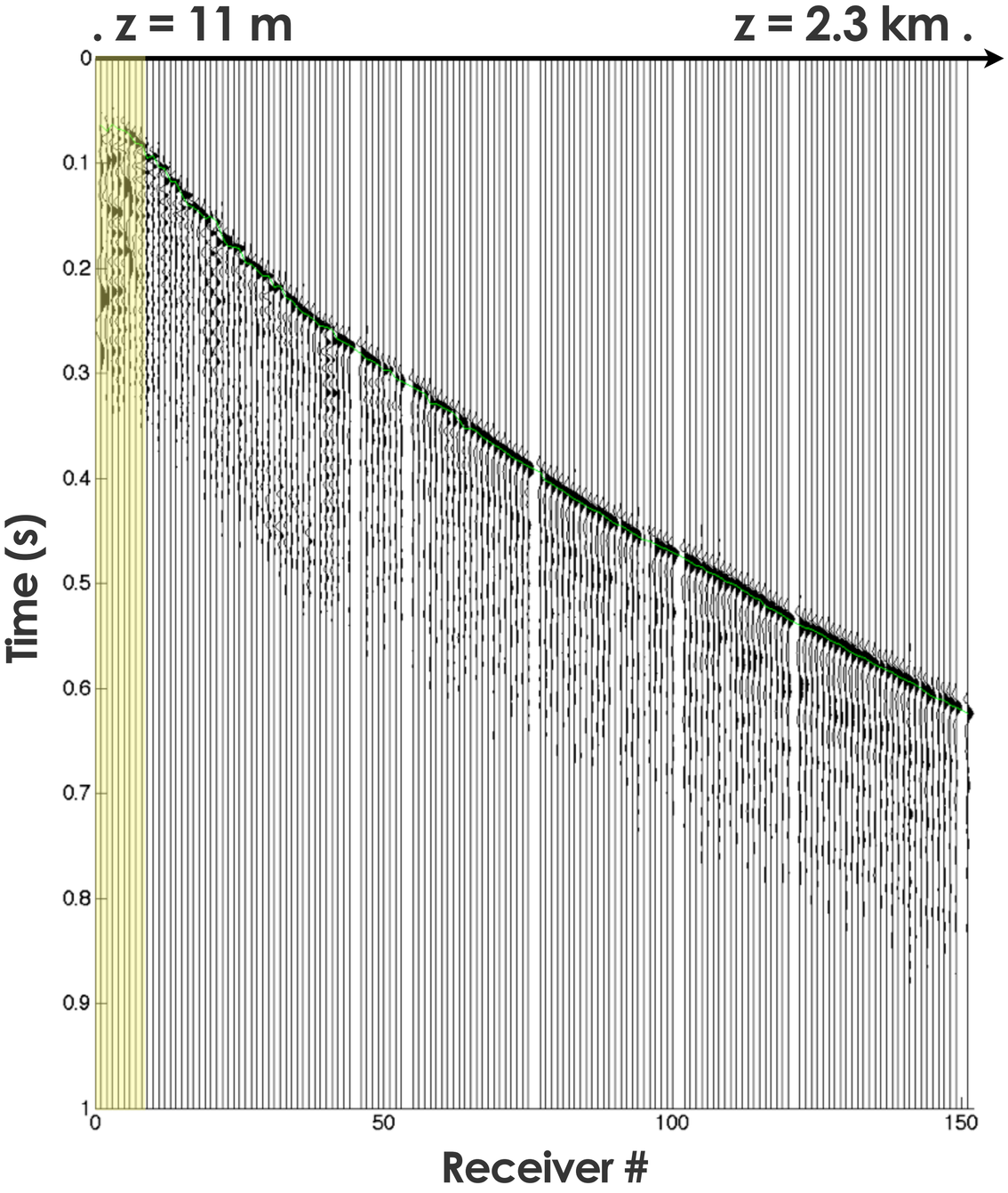

. z = 11 m
z = 2.3 km .
Time (s)
Receiver #

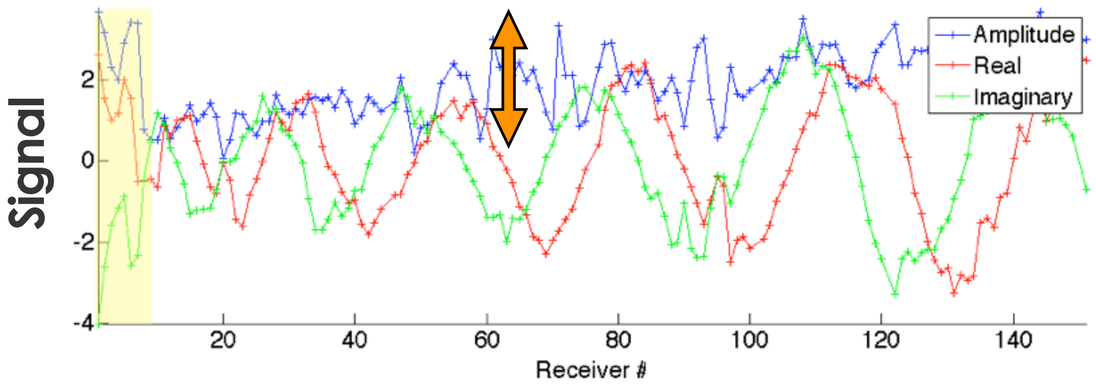

Signal
Amplitude
Real
Imaginary
Receiver #


Imag
Real
Receiver #

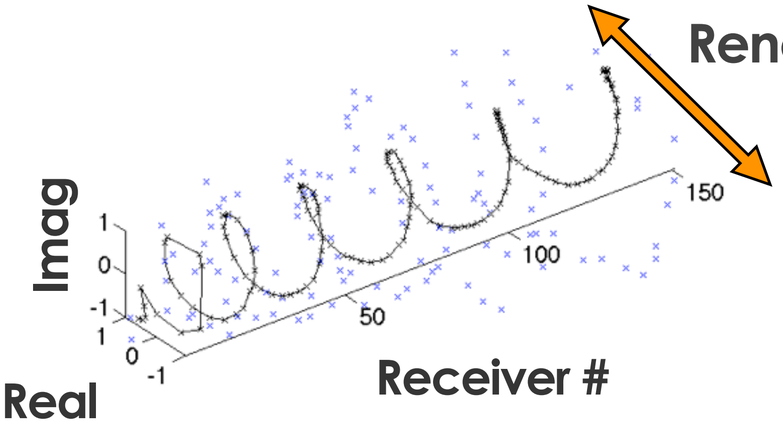

Phase
+ π
– π
Receiver #

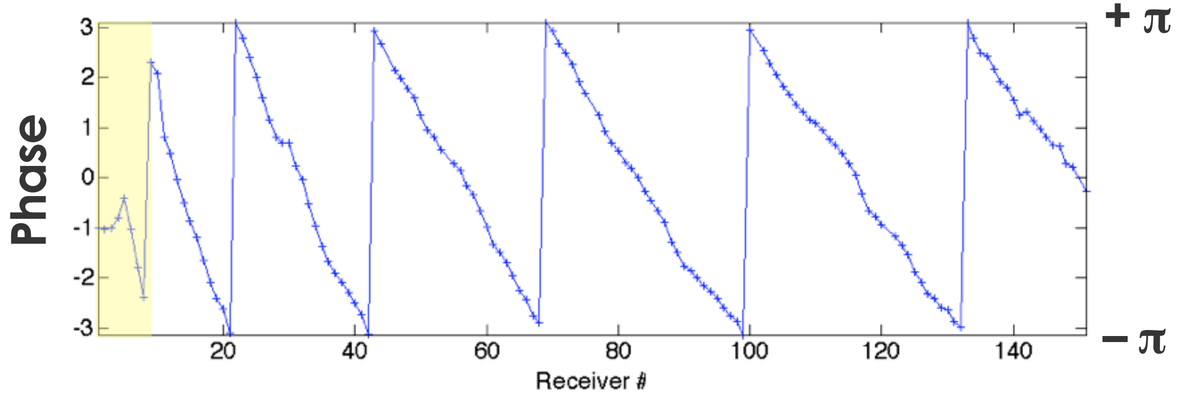

. z = 11 m
z = 2.3 km .
Time (s)
Receiver #
Signal
Amplitude
Real
Imaginary
Receiver #
Imag
Real
Receiver #
Phase
+ π
– π
Receiver #



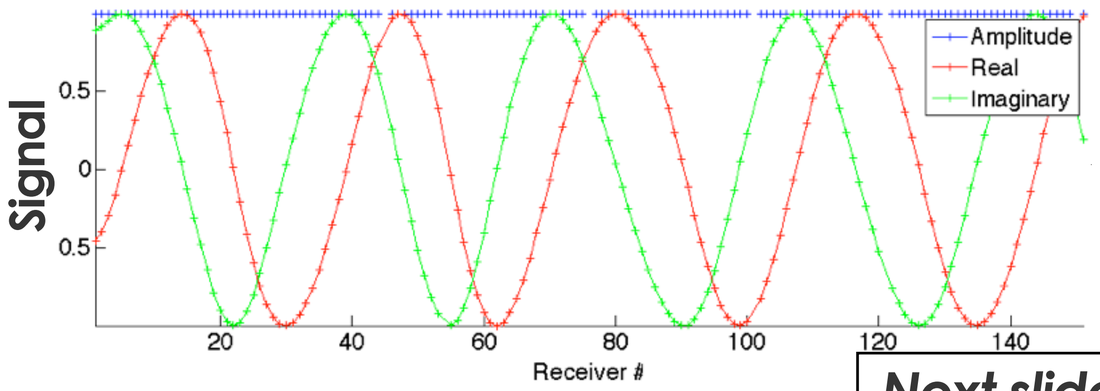


Renormalize data

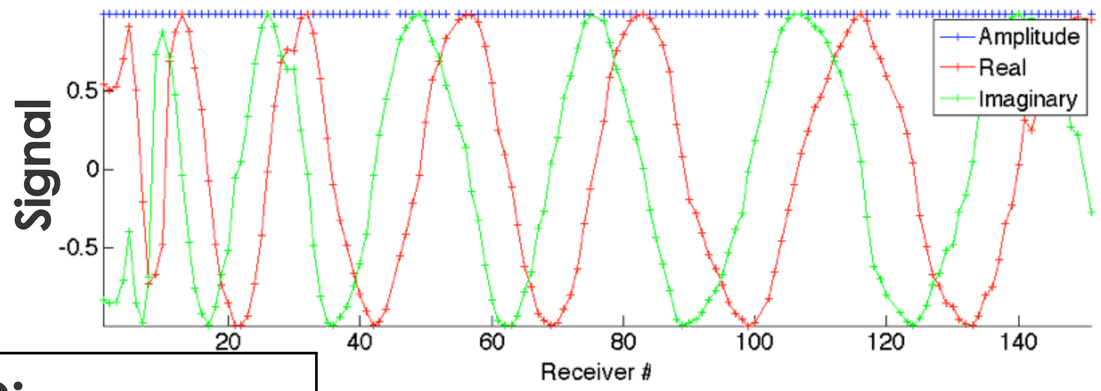




Synthetic Data

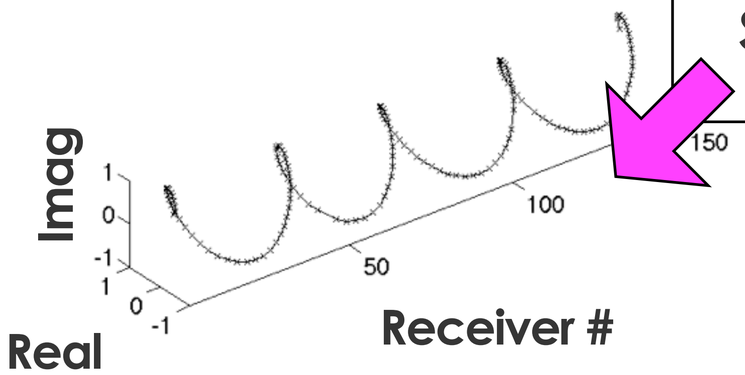


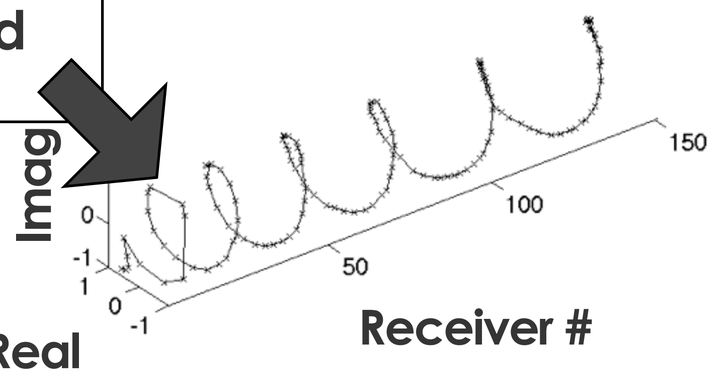
Field Data

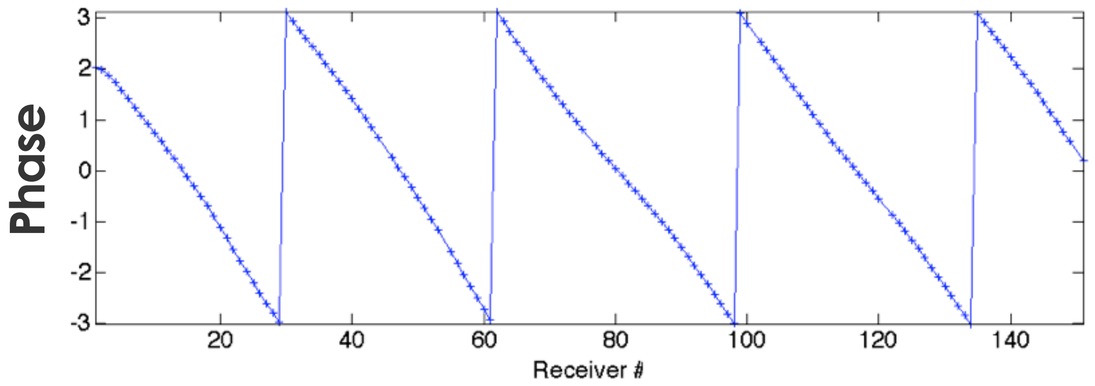


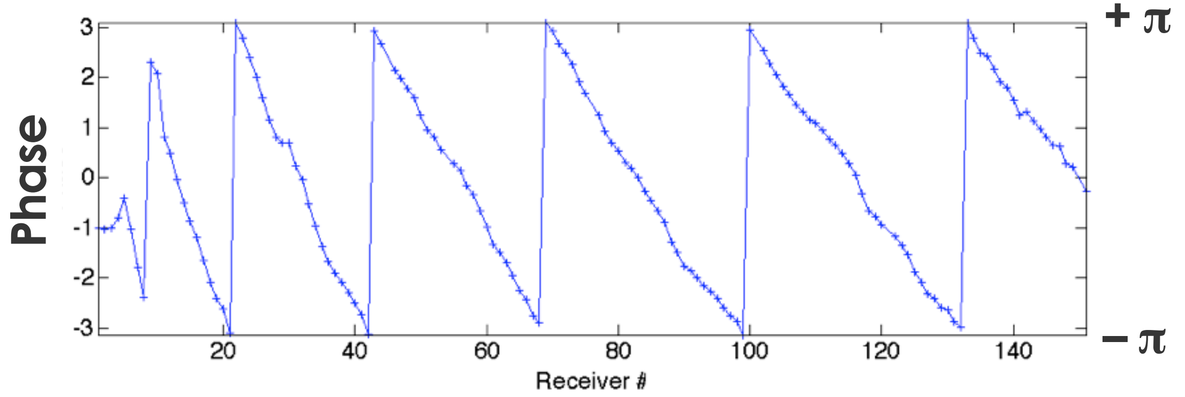
Next slide:

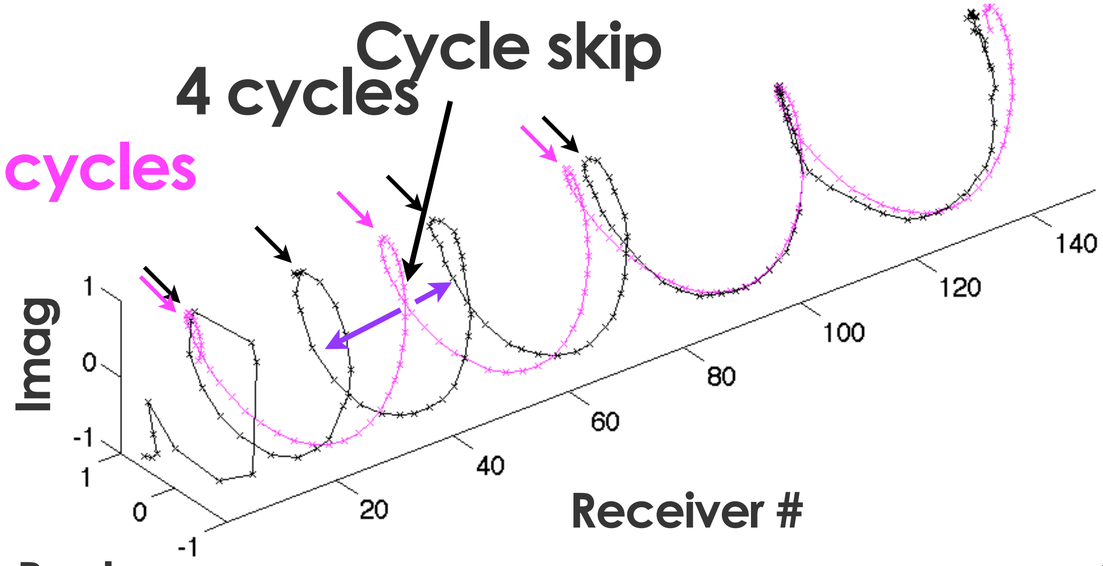
Synthetic **Field**







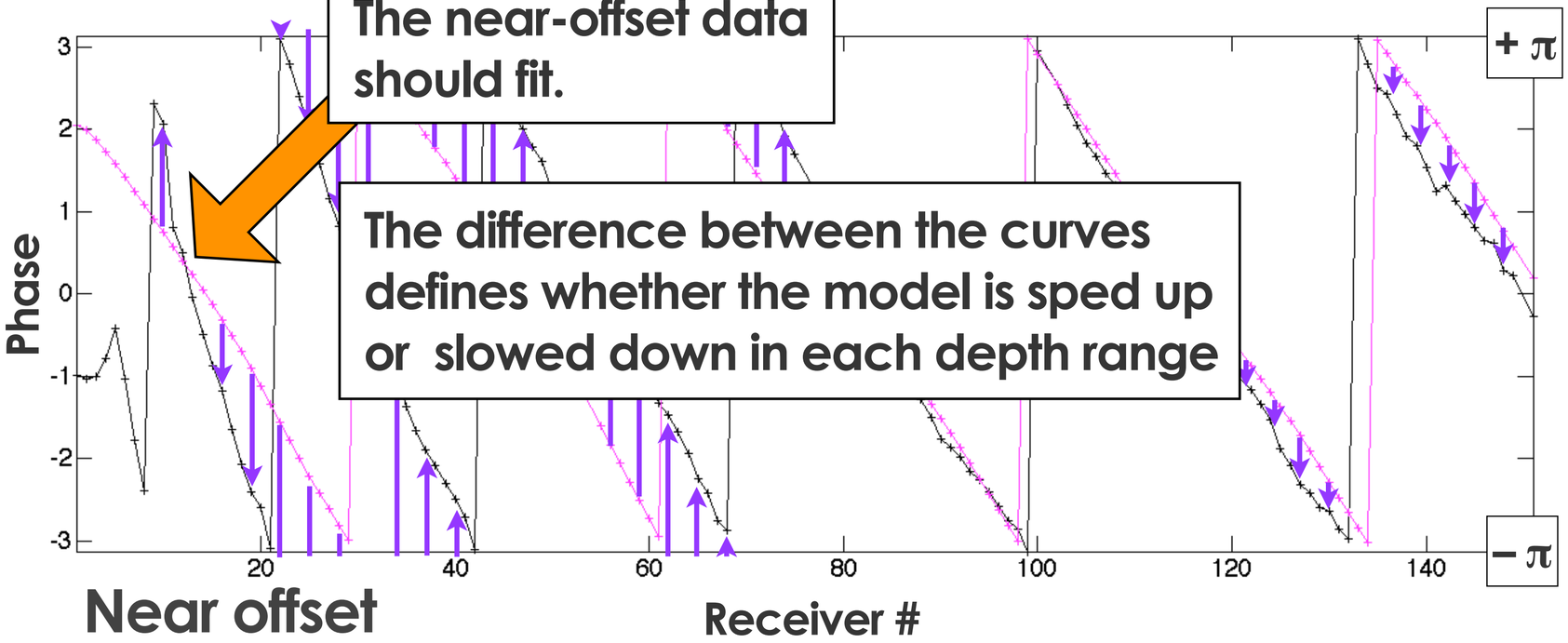


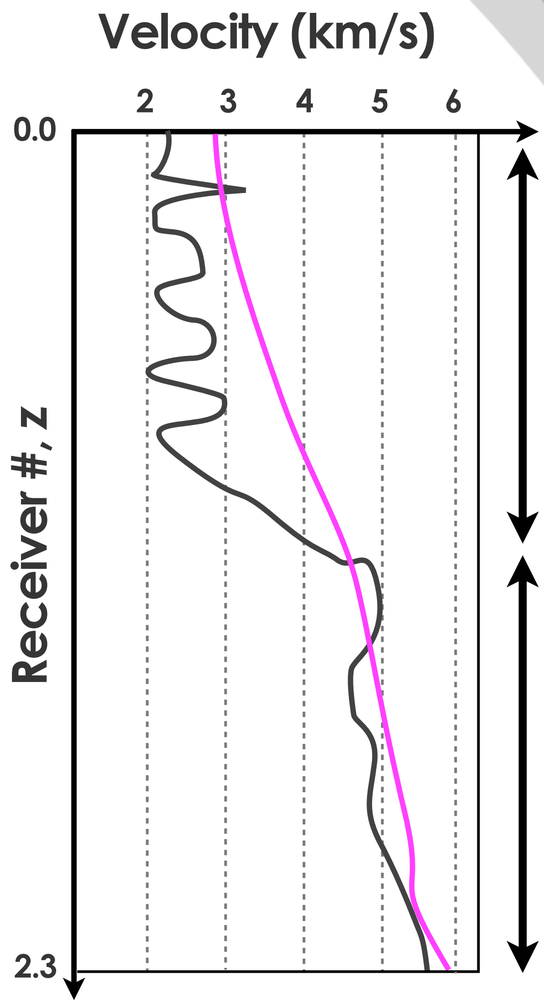


Conceptually:

Baseline assumption
The near-offset data should fit.

The difference between the curves defines whether the model is sped up or slowed down in each depth range





Field Data
Synthetic Data

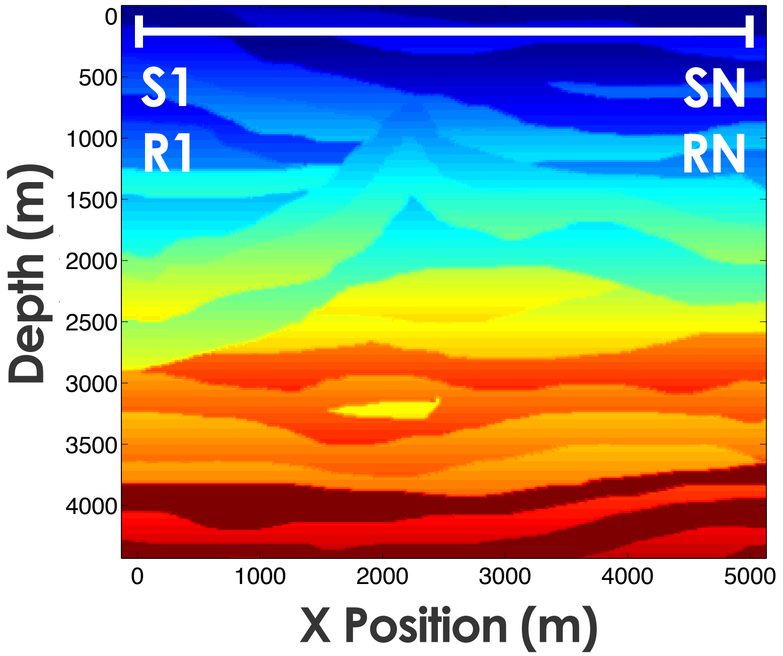
2D Example

Synthetic

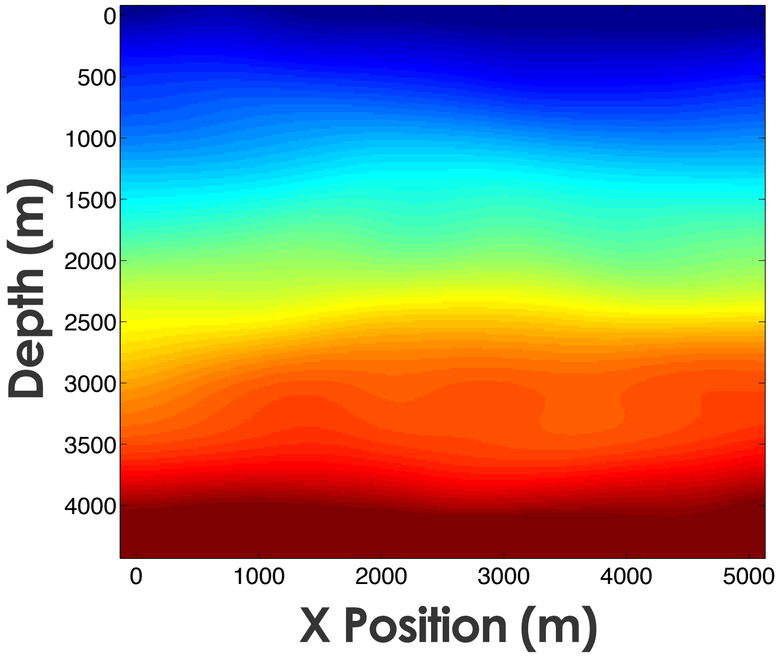
Demonstrating spatial features of note

Synthetic Example

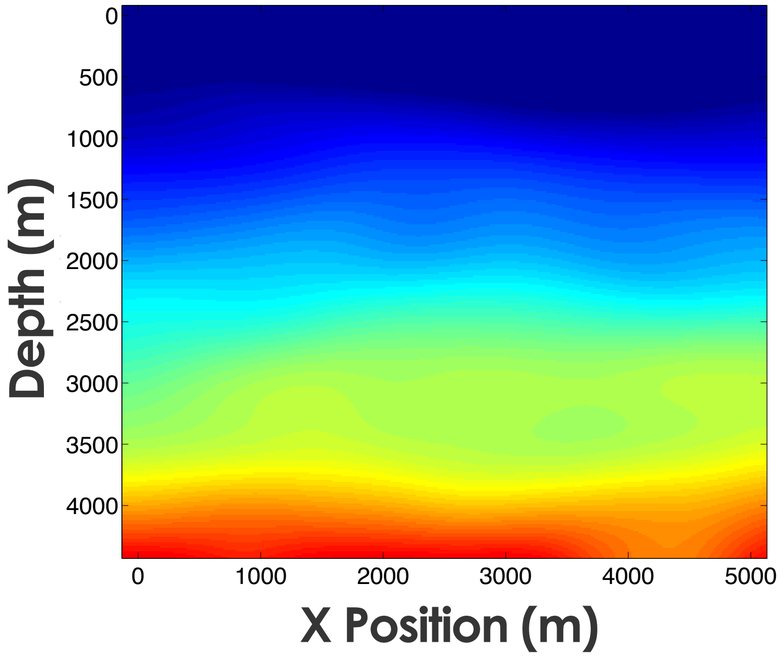
Original Model



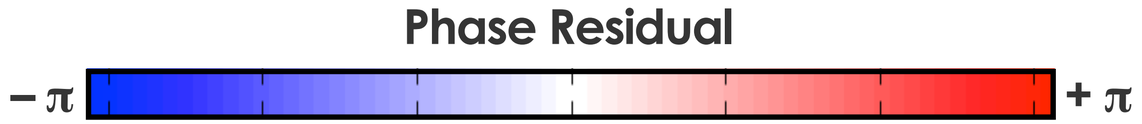
Smooth model, good 1D gradient



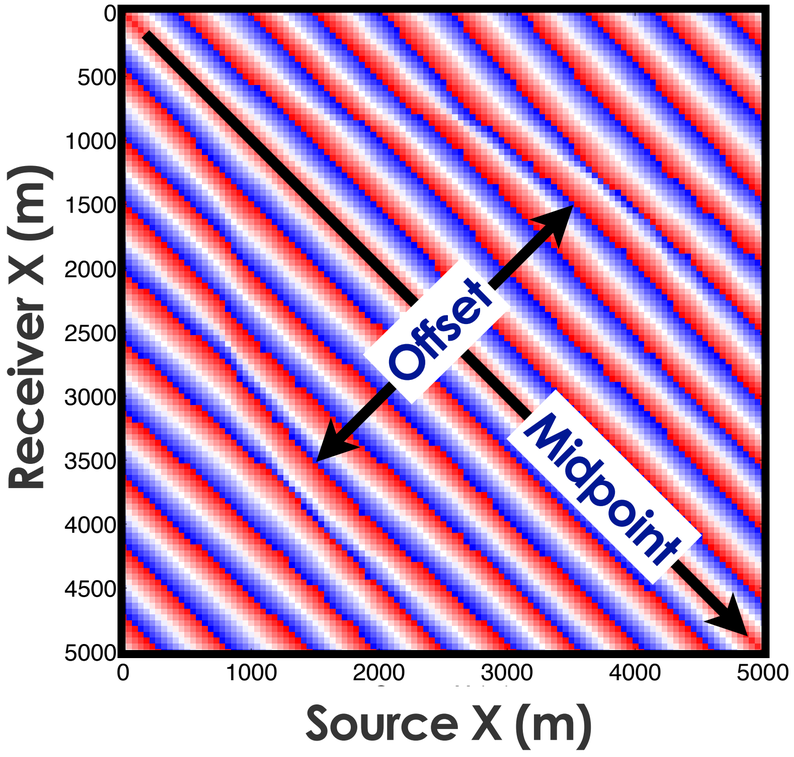
Smooth model, bad 1D gradient



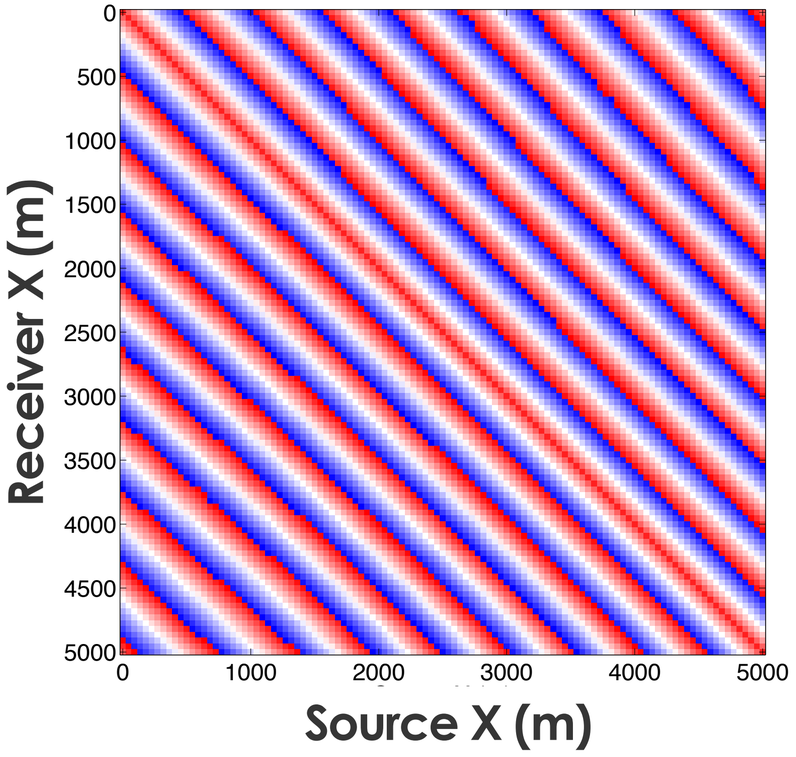
Synthetic Example



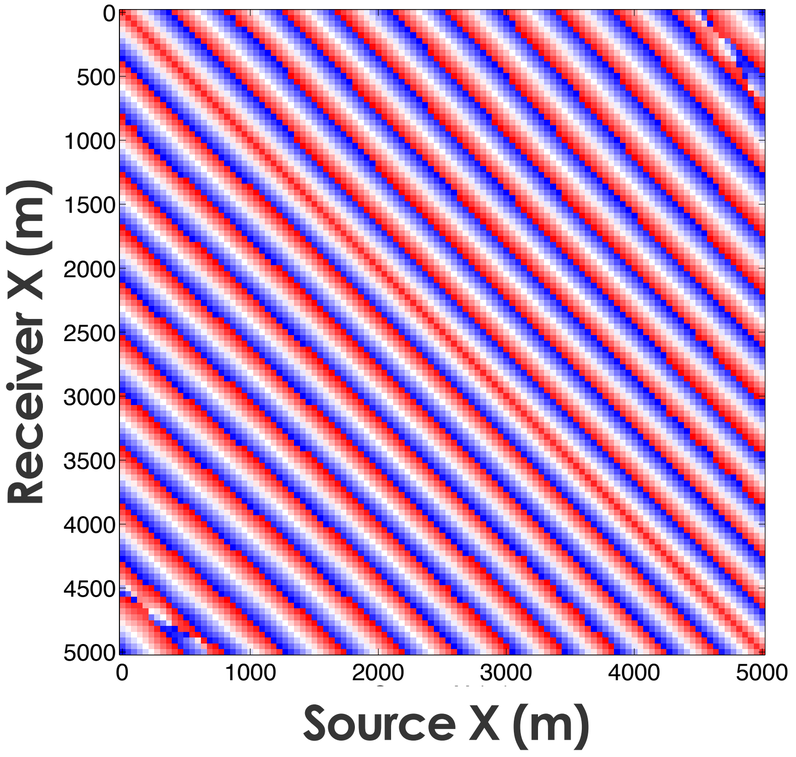
Original Model

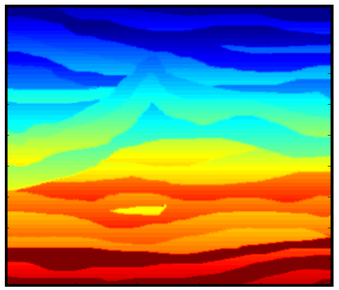


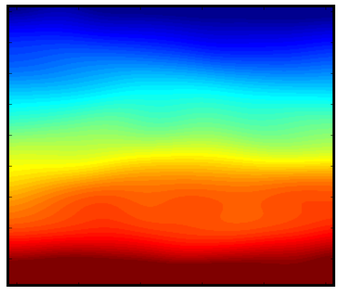
Smooth model, good 1D gradient

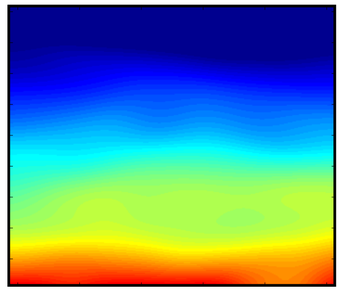


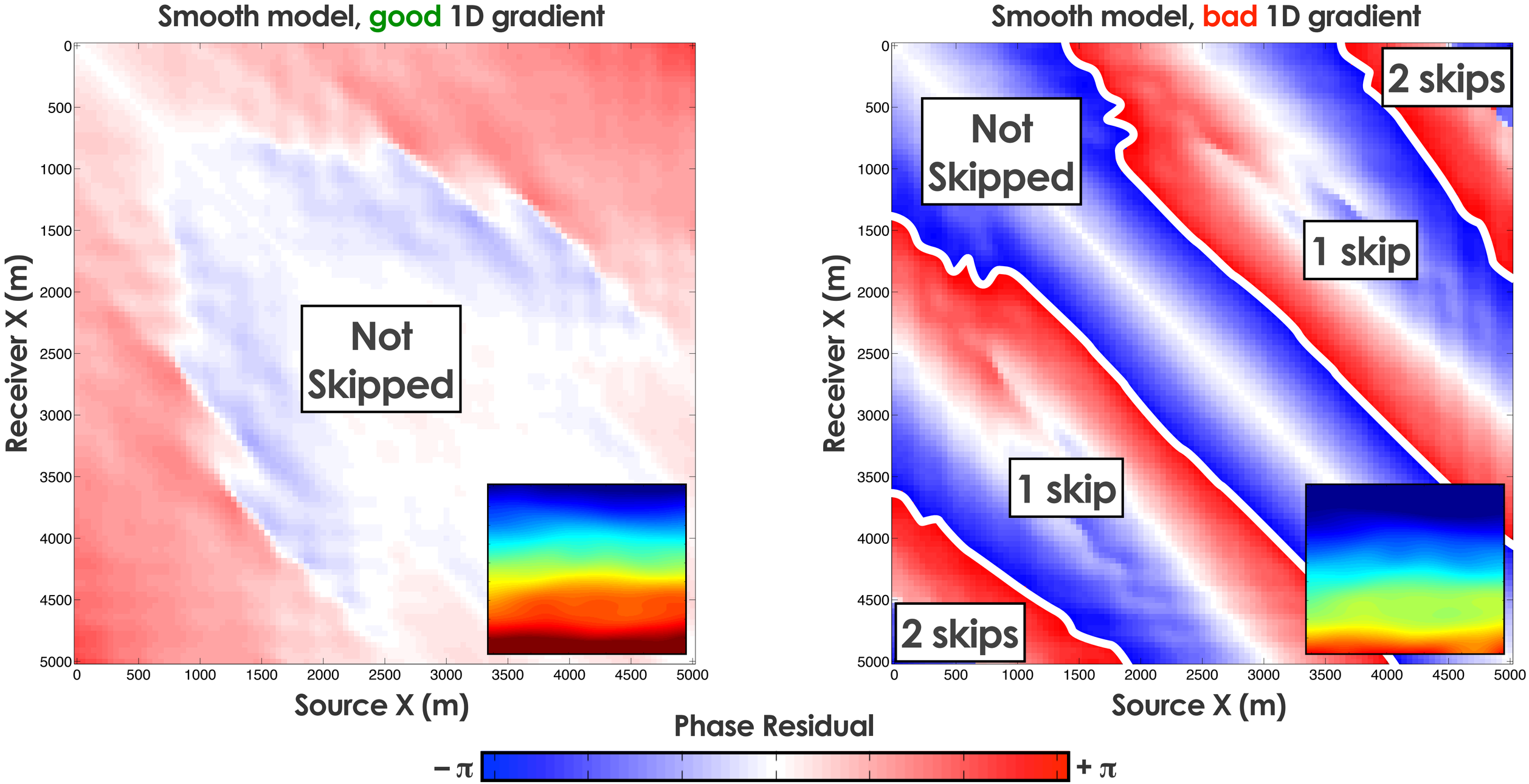
Smooth model, bad 1D gradient







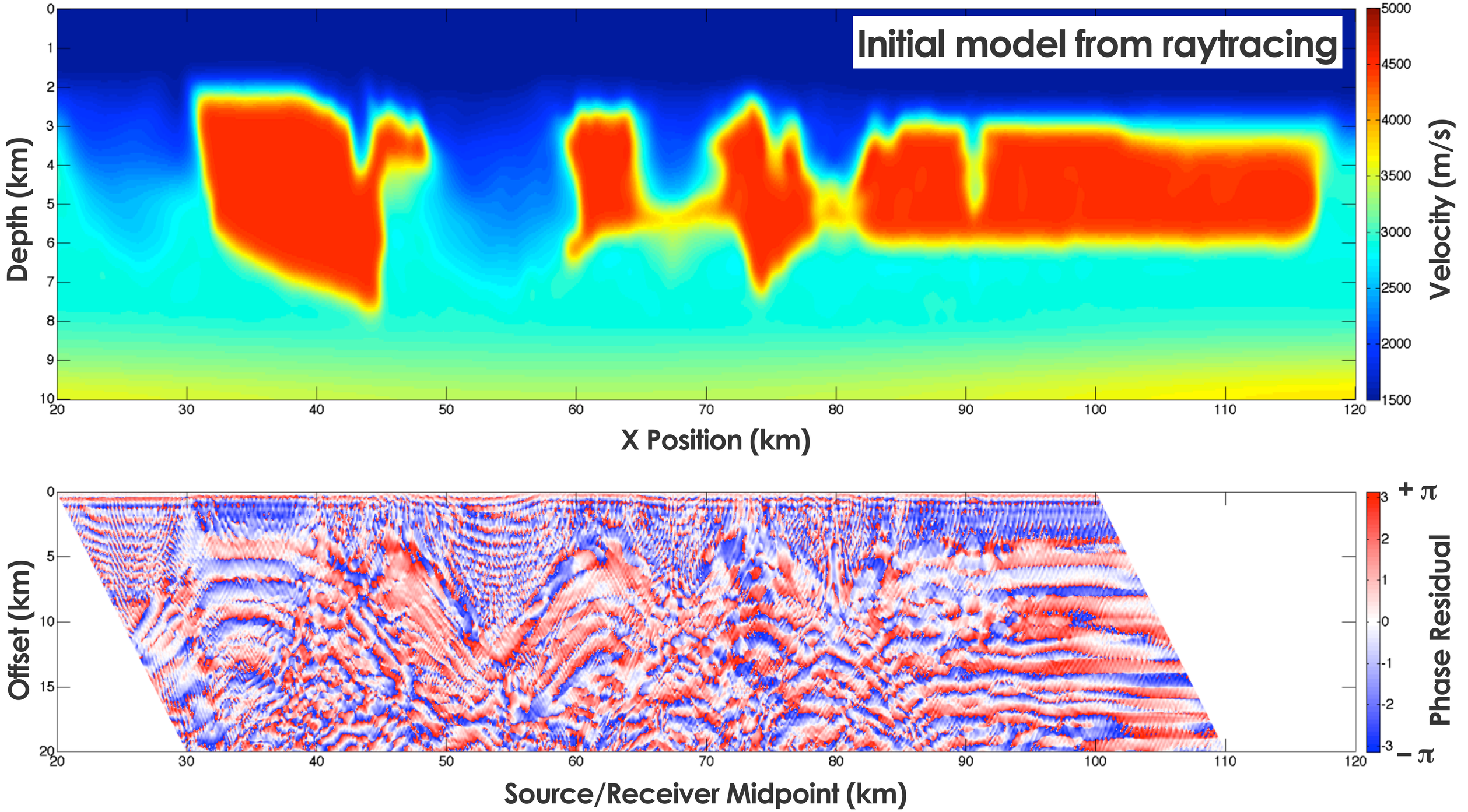


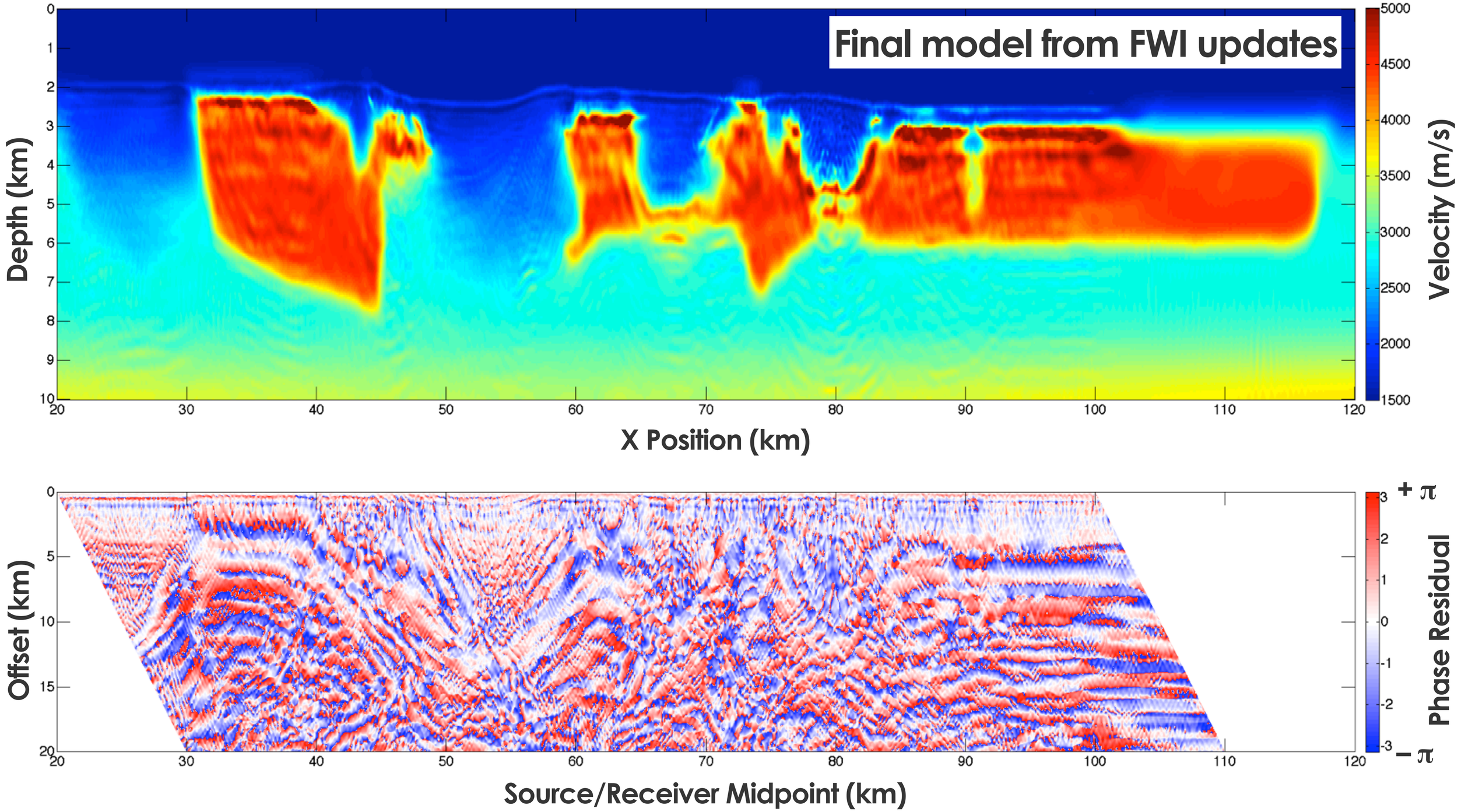

Smooth model, good 1D gradient
Smooth model, bad 1D gradient
Not Skipped
Not Skipped
1 skip
2 skips
1 skip
2 skips
Receiver X (m)
Source X (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Phase Residual
– π
+ π

2D Example

Chevron: Gulf of Mexico FWI Blind Test

with *Xiang Li*


Initial model from raytracing
Depth (km)
X Position (km)
Velocity (m/s)
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
110
120
5000
4500
4000
3500
3000
2500
2000
1500
Offset (km)
Source/Receiver Midpoint (km)
Phase Residual
+ π
– π
0
5
10
15
20
3
2
1
0
-1
-2
-3


Final model from FWI updates
Depth (km)
X Position (km)
Velocity (m/s)
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
110
120
5000
4500
4000
3500
3000
2500
2000
1500
Offset (km)
Source/Receiver Midpoint (km)
Phase Residual
+ π
– π
0
5
10
15
20
3
2
1
0
-1
-2
-3

Conclusions

- Full-waveform inversion (FWI) QC is complex
- FWI may not find the solution on its own
- Phase QC is useful for assessing data fit
- Automatic analysis of misfit in space + time may allow improved algorithms

If we can see it, so can a computer.

We should:

...assess cycle skips automatically

...use image analysis of phase misfit

...choose robust misfit function

...exclude bad data, possibly precondition

Acknowledgements

1D Example: Permian Basin VSP

Vecta Oil and Gas

2D Example: Chevron Gulf of Mexico Blind Test

Chevron and SEG

Work by N. Shah while @ *Imperial College*; go read it.

SINBAD

NSERC CRSNG

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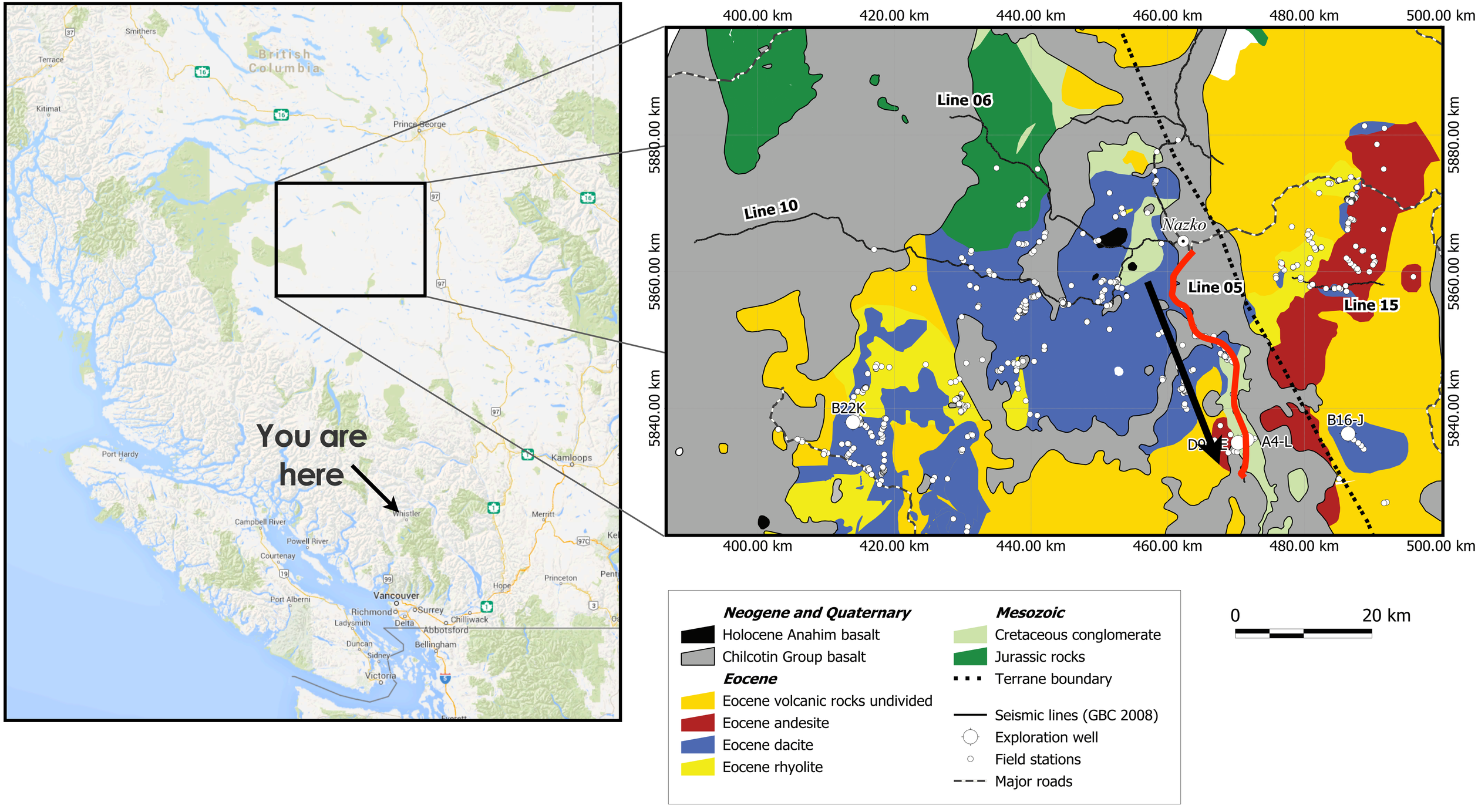
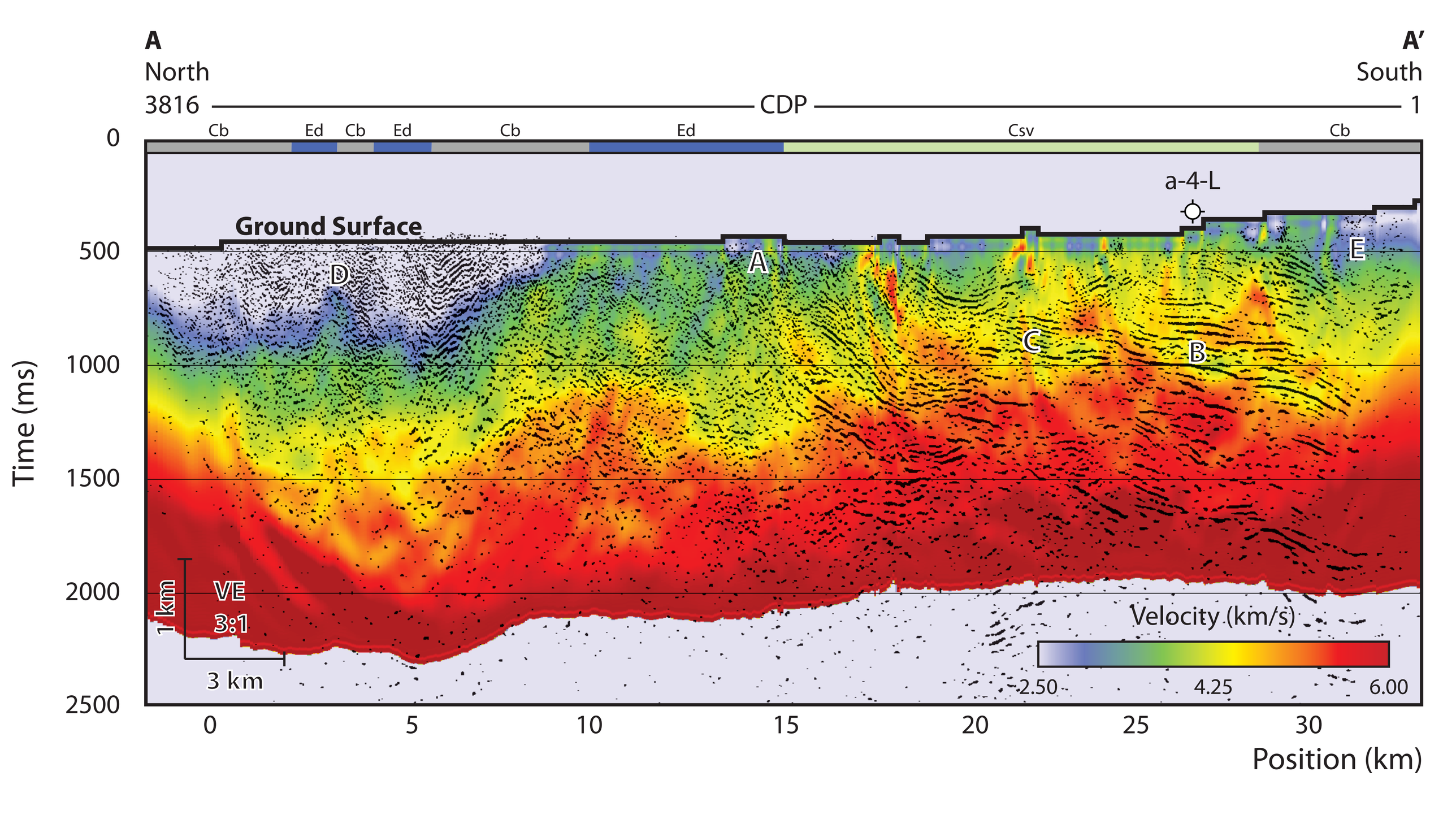
2D Example

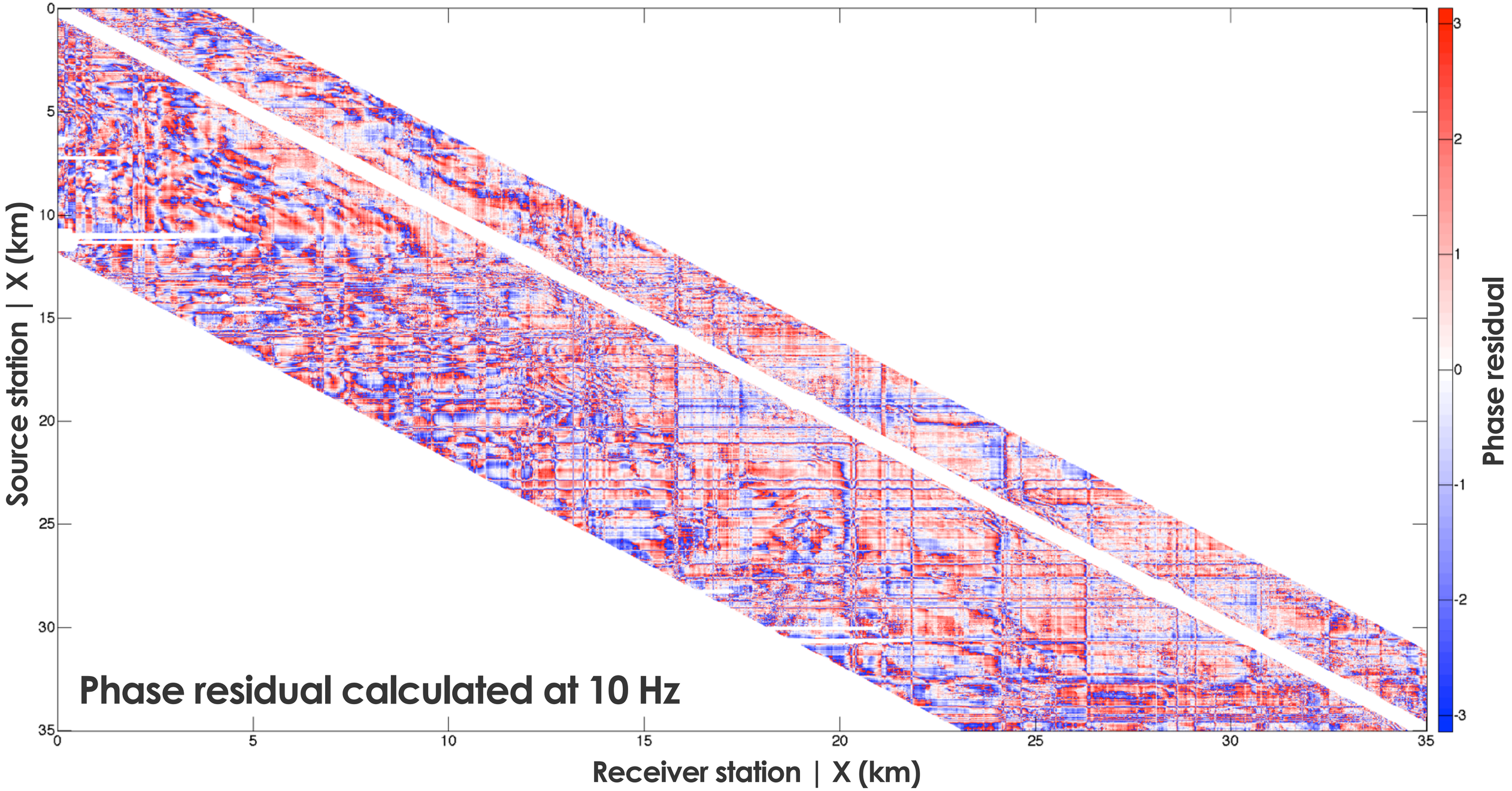
Nechako Basin, south-central BC, Canada

Smithyman and Clowes (2012; 2013)

Smithyman, Clowes and Bordet (in press)


You are here
British Columbia
Smithers
Terrace
Kitimat
Prince George
Kamloops
Whistler
Merritt
Campbell River
Powell River
Courtenay
Port Alberni
Port Hardy
Vancouver
Richmond
Surrey
Delta
Chilliwack
Abbotsford
Bellingham
Ladysmith
Duncan
Sidney
Victoria
Hope
Princeton
400.00 km
420.00 km
440.00 km
460.00 km
480.00 km
500.00 km
5880.00 km
5860.00 km
5840.00 km
Line 06
Line 10
Line 05
Line 15
Nazko
B22K
B16-J
A4-L
Neogene and Quaternary
Holocene Anahim basalt
Chilcotin Group basalt
Eocene
Eocene volcanic rocks undivided
Eocene andesite
Eocene dacite
Eocene rhyolite
Mesozoic
Cretaceous conglomerate
Jurassic rocks
Terrane boundary
Seismic lines (GBC 2008)
Exploration well
Field stations
Major roads
0
20 km


A
North
A'
South
3816
CDP
1
Cb
Ed
Cb
Ed
Cb
Ed
Csv
Cb
a-4-L
Ground Surface
A
B
C
D
E
0
500
1000
1500
2000
2500
Time (ms)
1 km
VE
3:1
3 km
Velocity (km/s)
2.50
4.25
6.00
0
5
10
15
20
25
30
Position (km)


Source station | X (km)
Receiver station | X (km)
Phase residual
Phase residual calculated at 10 Hz
0
5
10
15
20
25
30
35
3
2
1
0
-1
-2
-3