Staggered-grid reverse-time migration imaging with/without multiples

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December 3, 2010, Banff

22nd Annual CREWES Sponsors Meeting

UNIVERSITY OF CALGARY

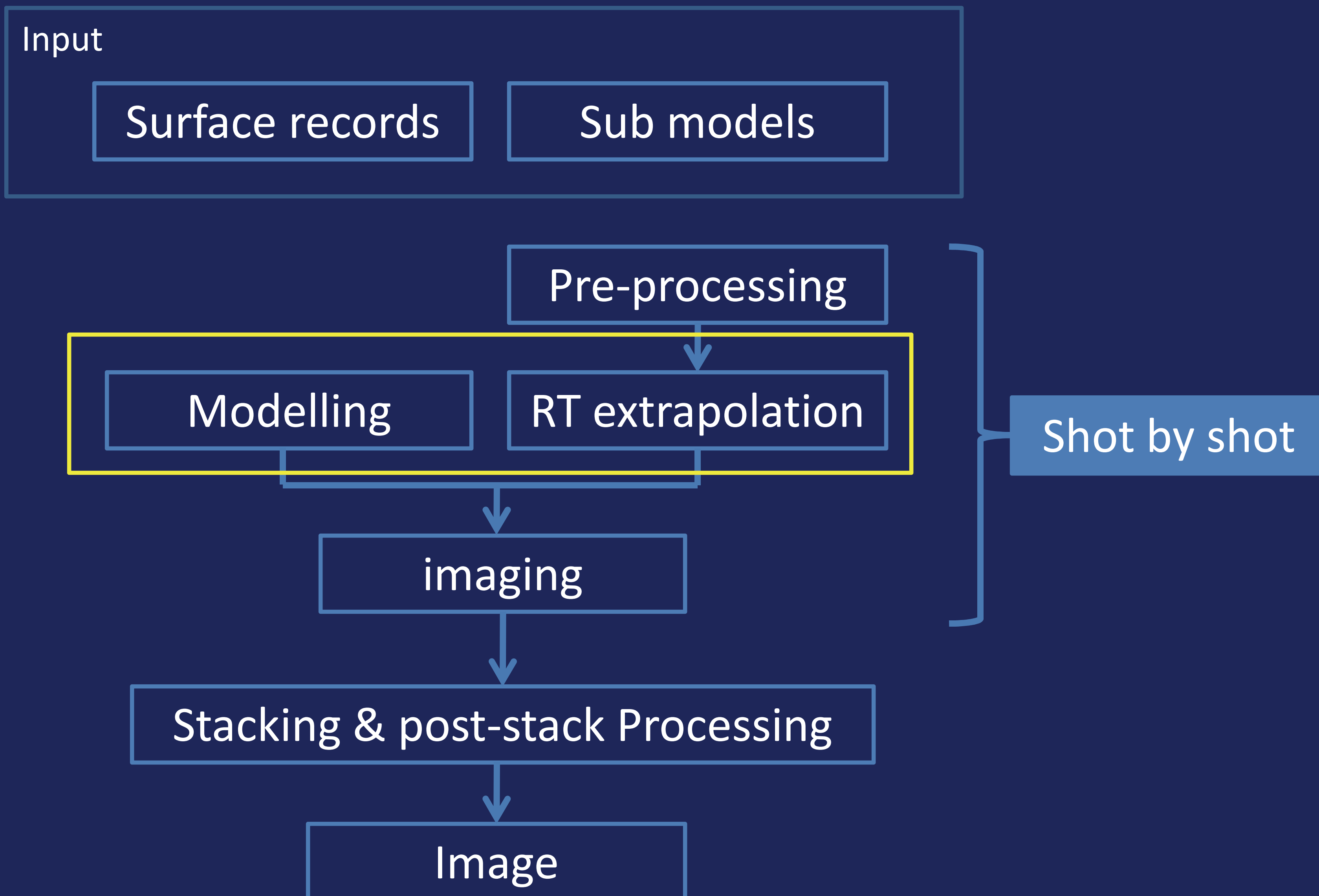
GeoScience

CREWES

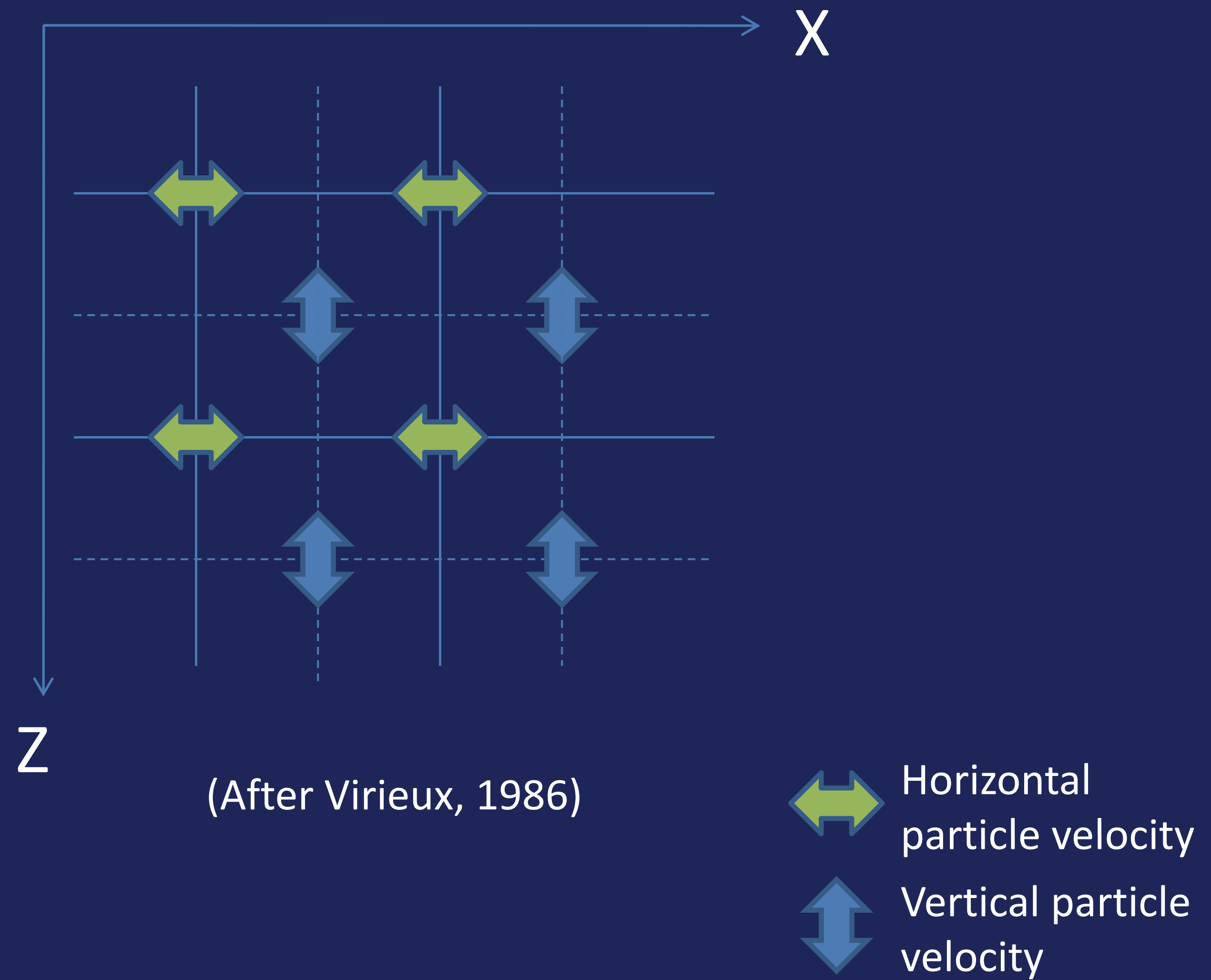
Outline

- **Staggered-grid schemes are accurate**
  - **Liquids [literature review]**
  - **Rigid boundary: math and numerical modelling**
- **Combined boundary conditions**
- **Two imaging conditions**
  - **Cross-correlation: with all multiples**
  - **First Arrival: with fewer multiples**

Pre-stack RTM



Staggered-grid for elastic modelling



(After Virieux, 1986)

Staggered-grid schemes are more accurate - liquids

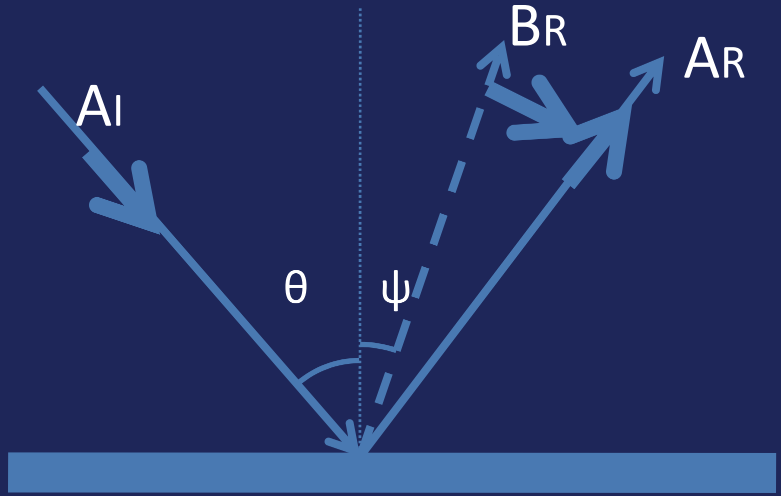
- **Virieux, 1986:**
  - **"This (dispersion analysis) suggests, as is confirmed later, that our numerical scheme behaves correctly inside liquids, and at liquid-solid interfaces. "**
- **Levander, 1988**
- **Stephen, 1988**

Staggered-grid schemes are accurate – rigid boundary

- **From Zoeppritz equations and rigid boundary conditions (no displacements):**

$$A_R = \frac{\cos(\theta+\psi)}{\cos(\theta-\psi)} A_I$$

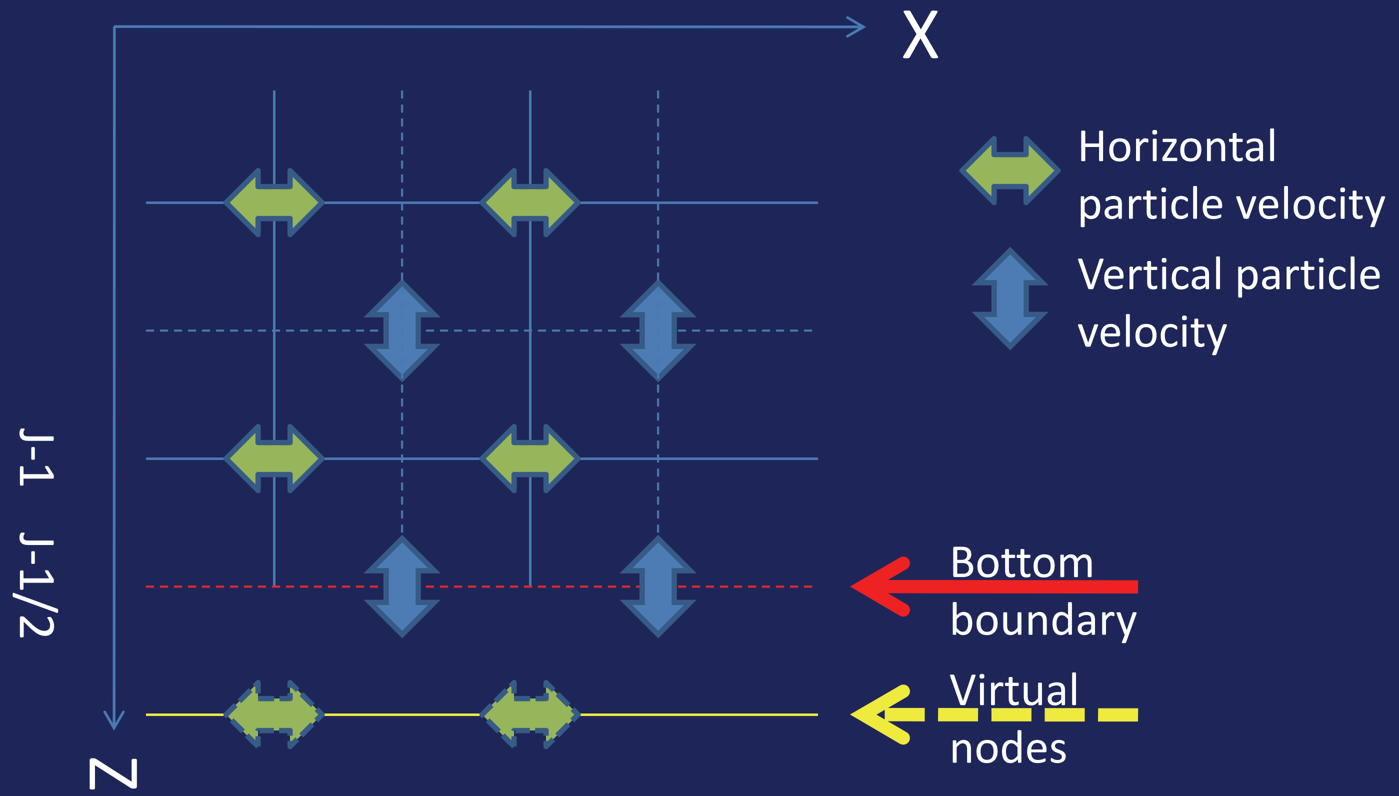
$$B_R = -\frac{\sin(2\theta)}{\cos(\theta-\psi)} A_I$$



A: P-wave
B: SV-wave
Θ: incident angle
Ψ: SV reflected angle
Bold-face arrow: displacement direction

- **Θ+Ψ=90° → A_R=0: no PP.**
- **From Θ+Ψ=90° and Snell's law →Θ=arctan(Vp/Vs).**
- **Different polarities of PP show up.**

Rigid boundary conditions for staggered-grid scheme



- **Numerical implementation: on bottom boundary (line J-1/2):**
  - **Vertical particle velocity = 0**
  - **Horizontal particle velocity = 0, by using virtual nodes at Jth line**

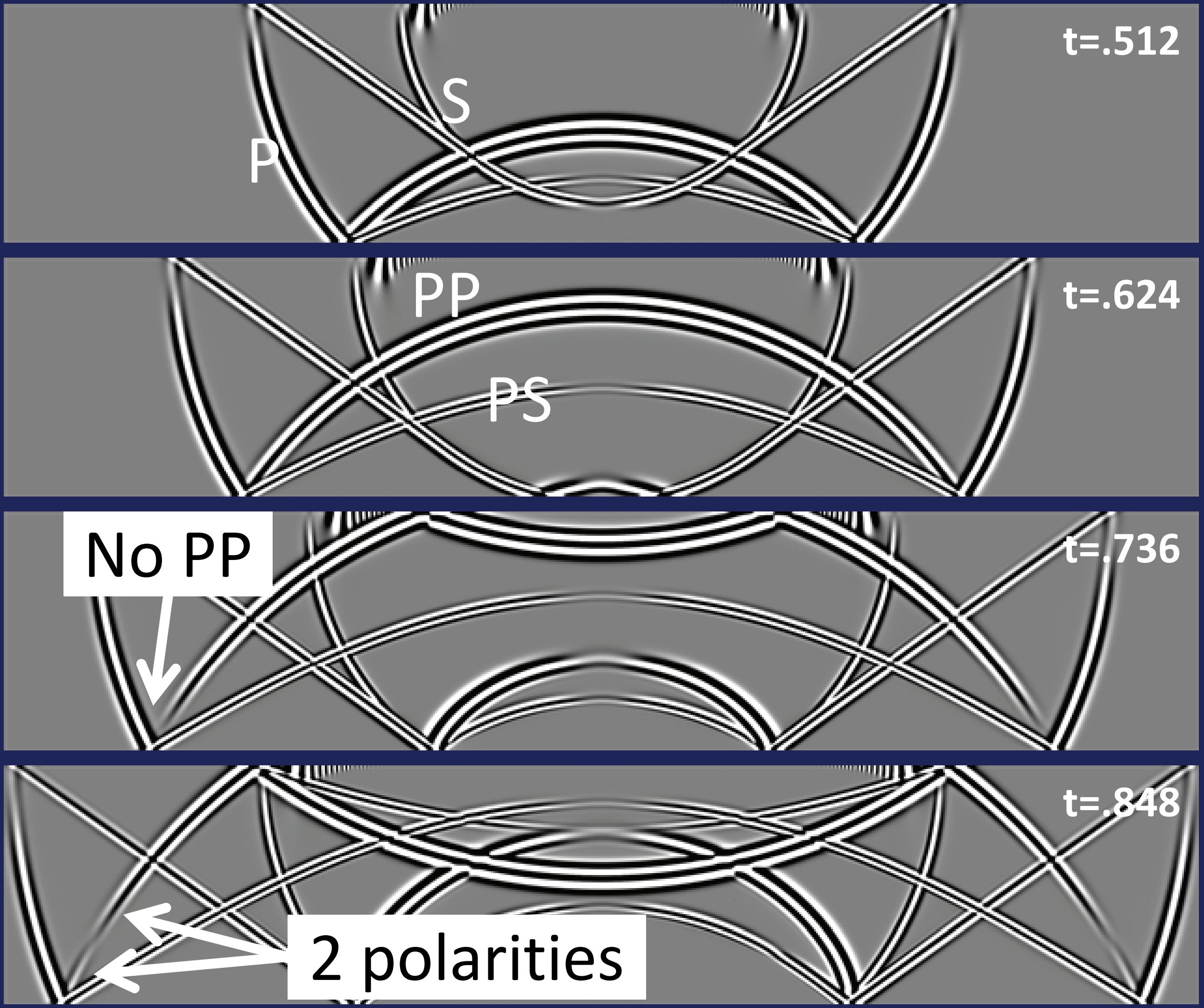
Staggered-grid schemes are accurate – rigid boundary

Medium

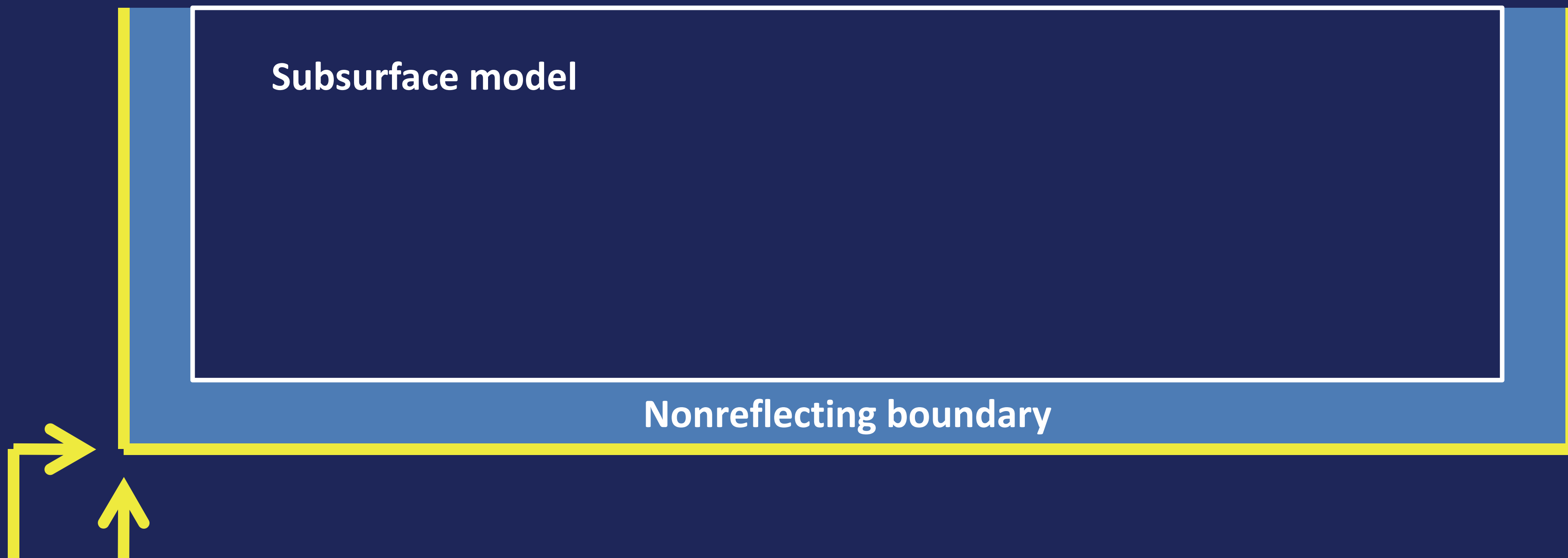
- **Vp=3,000**
- **Vs=1,732**

→ If Θ=60°, no PP wave.

Modelling MATCHES Mathematics



Computational boundary conditions in practise: nonreflecting + absorbing



Absorbing boundary conditions

(Ref: CREWES report 2009, SEG abstract 2010)

Rigid

Absorbing

Nonreflecting

Nonreflecting
+ Absorbing

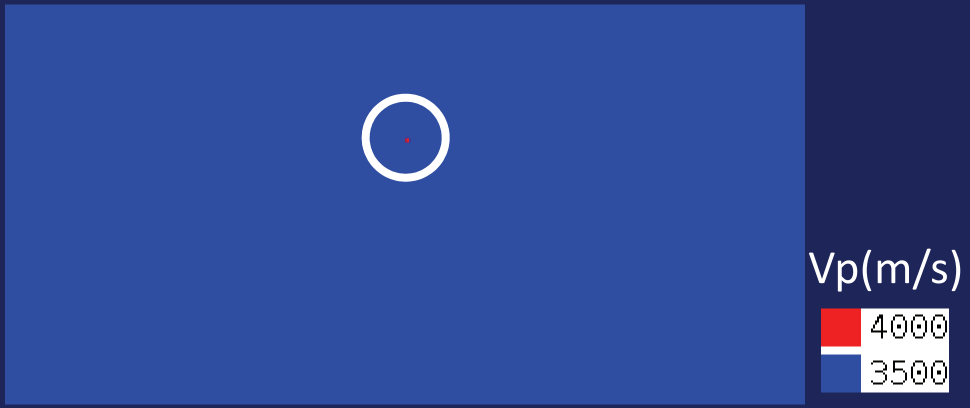
Source-normalized cross-correlation imaging condition

Imaging principle (Claerbout, 1971):

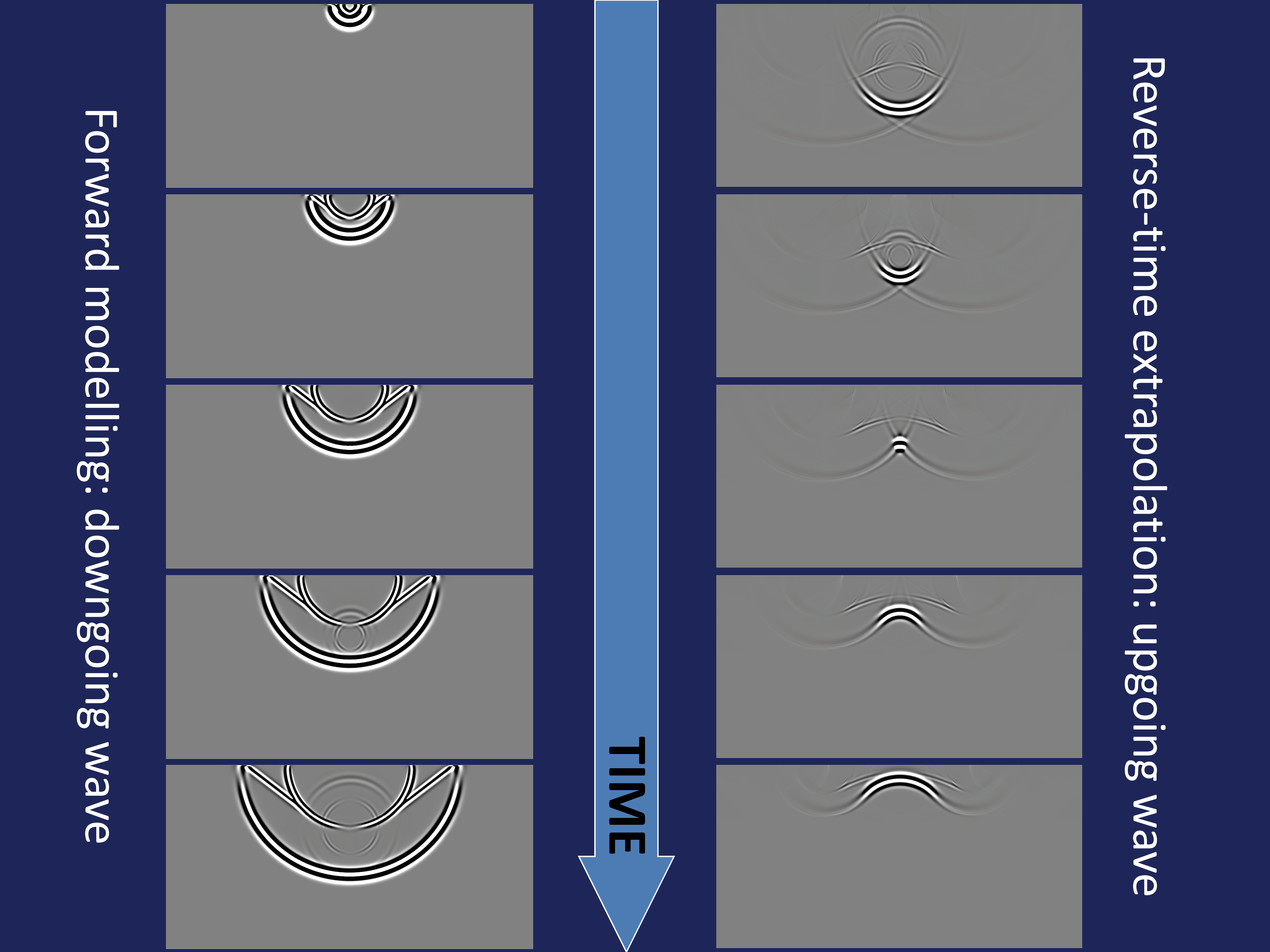
Reflectors exist at points where a downgoing wave is time coincident with an upgoing wave.

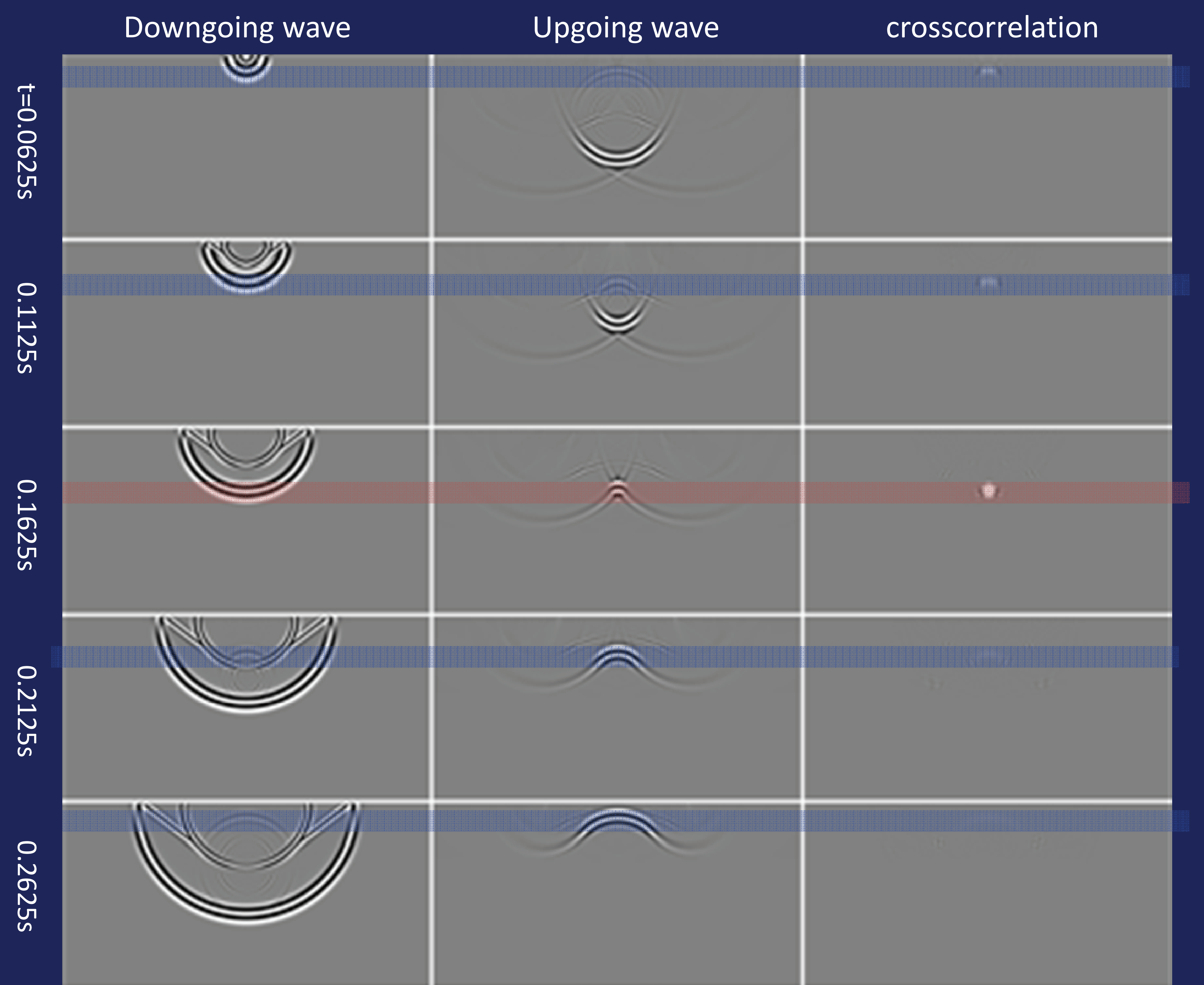
$$\text{Image}(x,z) = \frac{\sum_{time} S(x,z,t)R(x,z,t)}{\sum_{time} S^2(x,z,t)}$$

(Ref: Claerbout, 1971; Whitmore and Lines, 1986; Kaelin and Guitton, 2006; Chattopadhyay and McMechan, 2008**)**

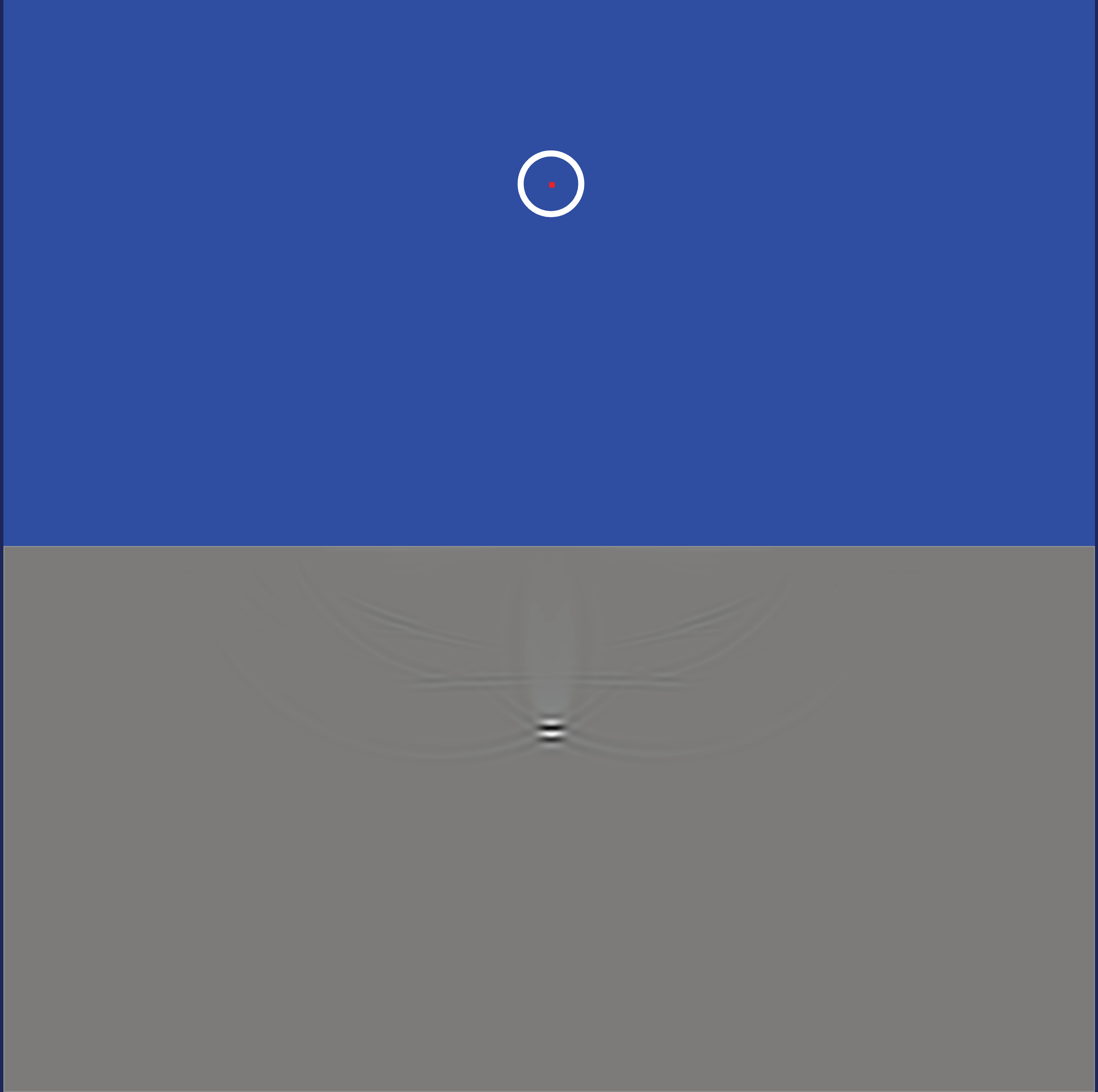


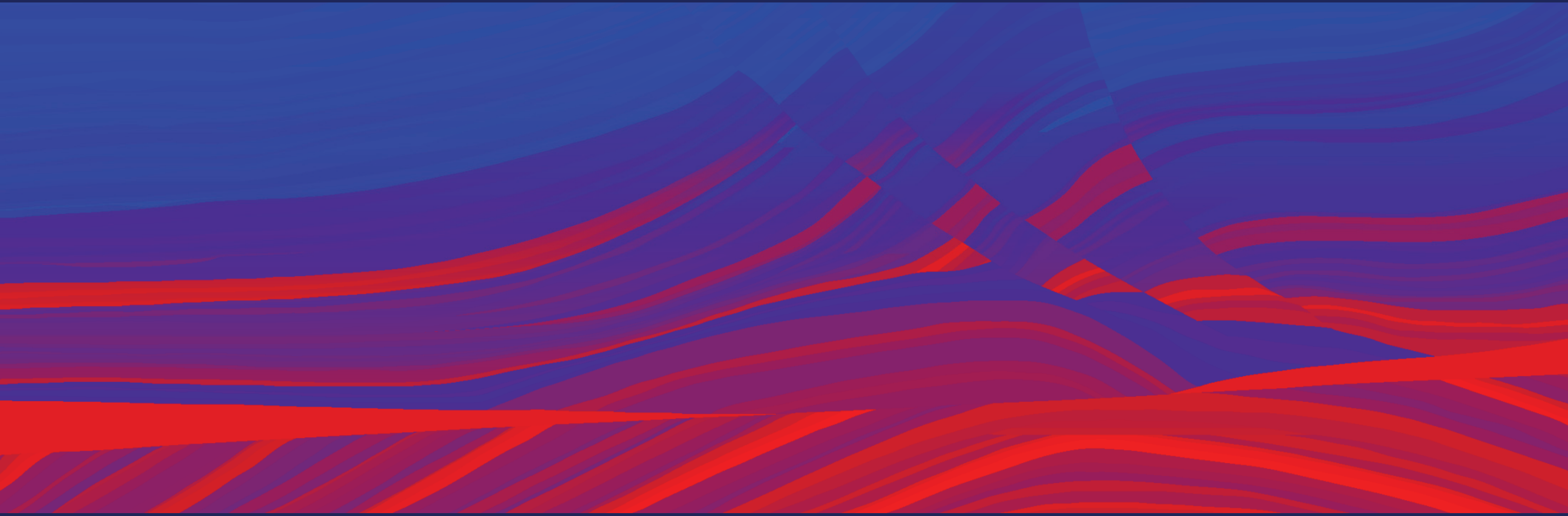
2772m X 1386m

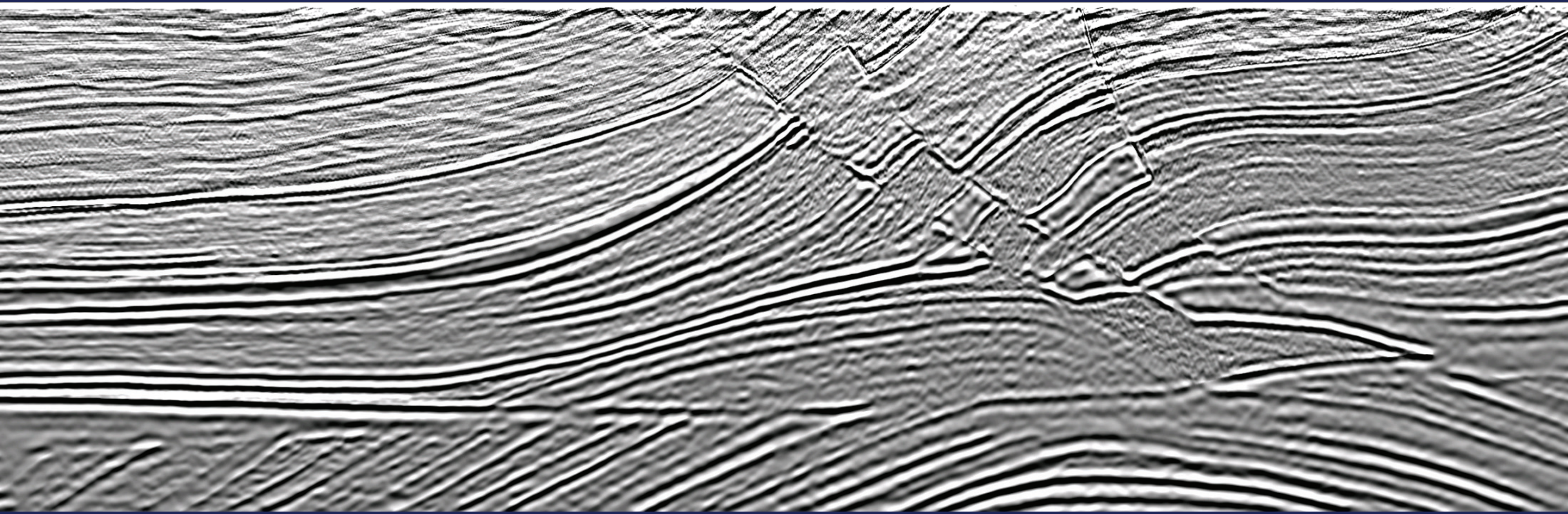

Forward modelling: downgoing wave
TIME
Reverse-time extrapolation: upgoing wave


Downgoing wave
Upgoing wave
crosscorrelation
t=0.0625s
0.1125s
0.1625s
0.2125s
0.2625s

Imaging result







Computational costs

- **Snapshots need to be stored → Disk space requirement**
  - **Solution: doing modelling twice instead of once**
- **Long computational time**
  - **Solution: parallel computing**
- **Disk I/O: bottle neck of speed**

(Ref: CREWES report 2009, CSEG abstract 2010)

First arrival imaging condition

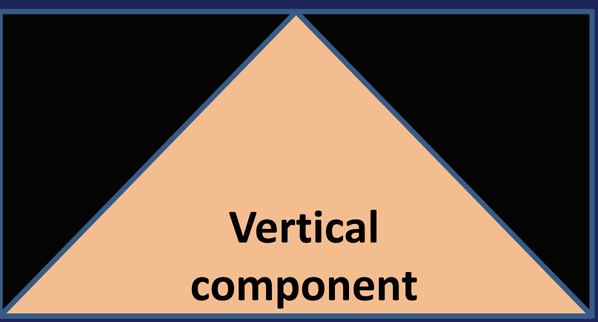
$$\mathrm{Image(x,z)} = \frac{R(x, z, \mathit{firstArrivalTime})}{S(x, z, \mathit{firstArrivalTime})}$$

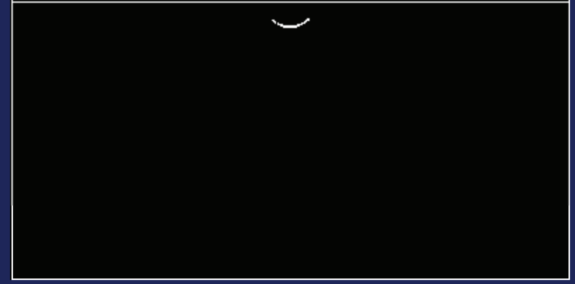
Extracting first arrival from downgoing wave

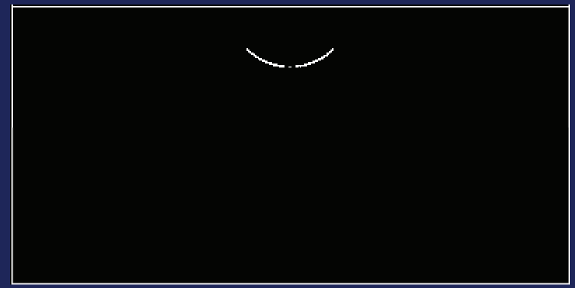
– Maximum amplitude criterion

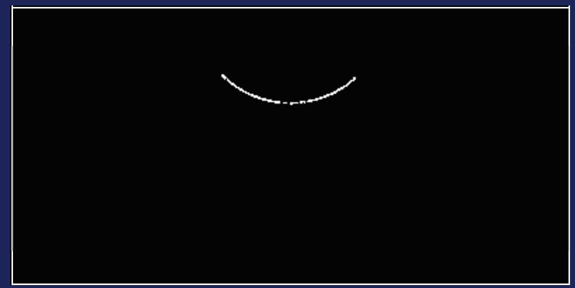
– Minimum time criterion

First Arrival




t=0.0625s


t=0.1125s


t=0.1625s


t=0.2125s

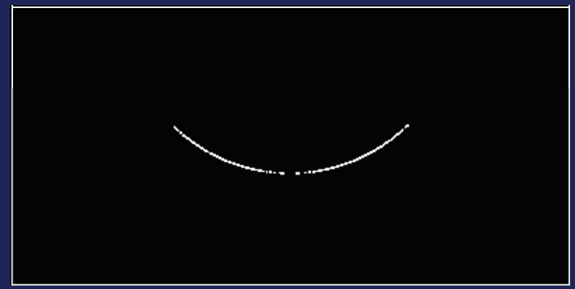
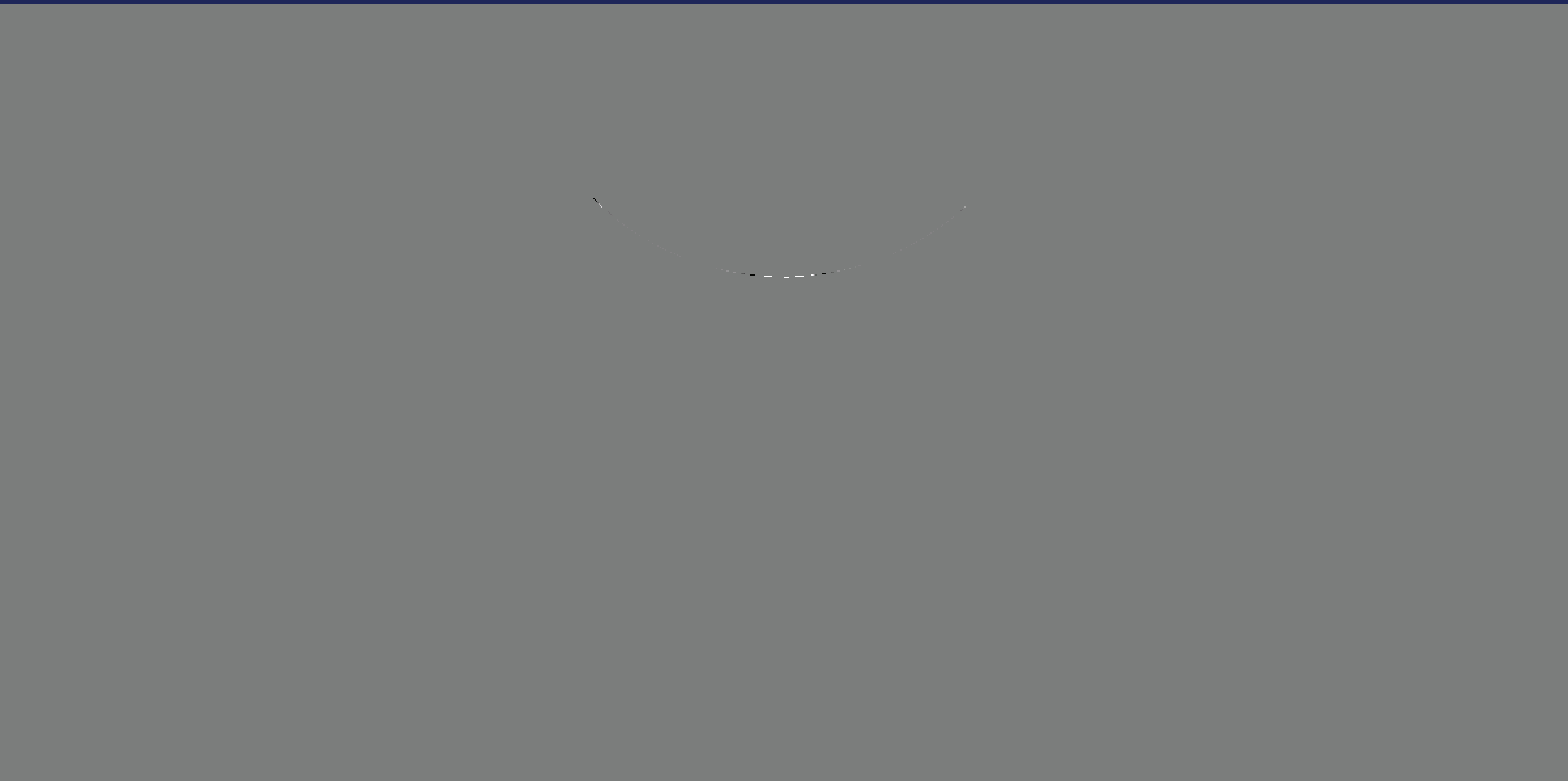
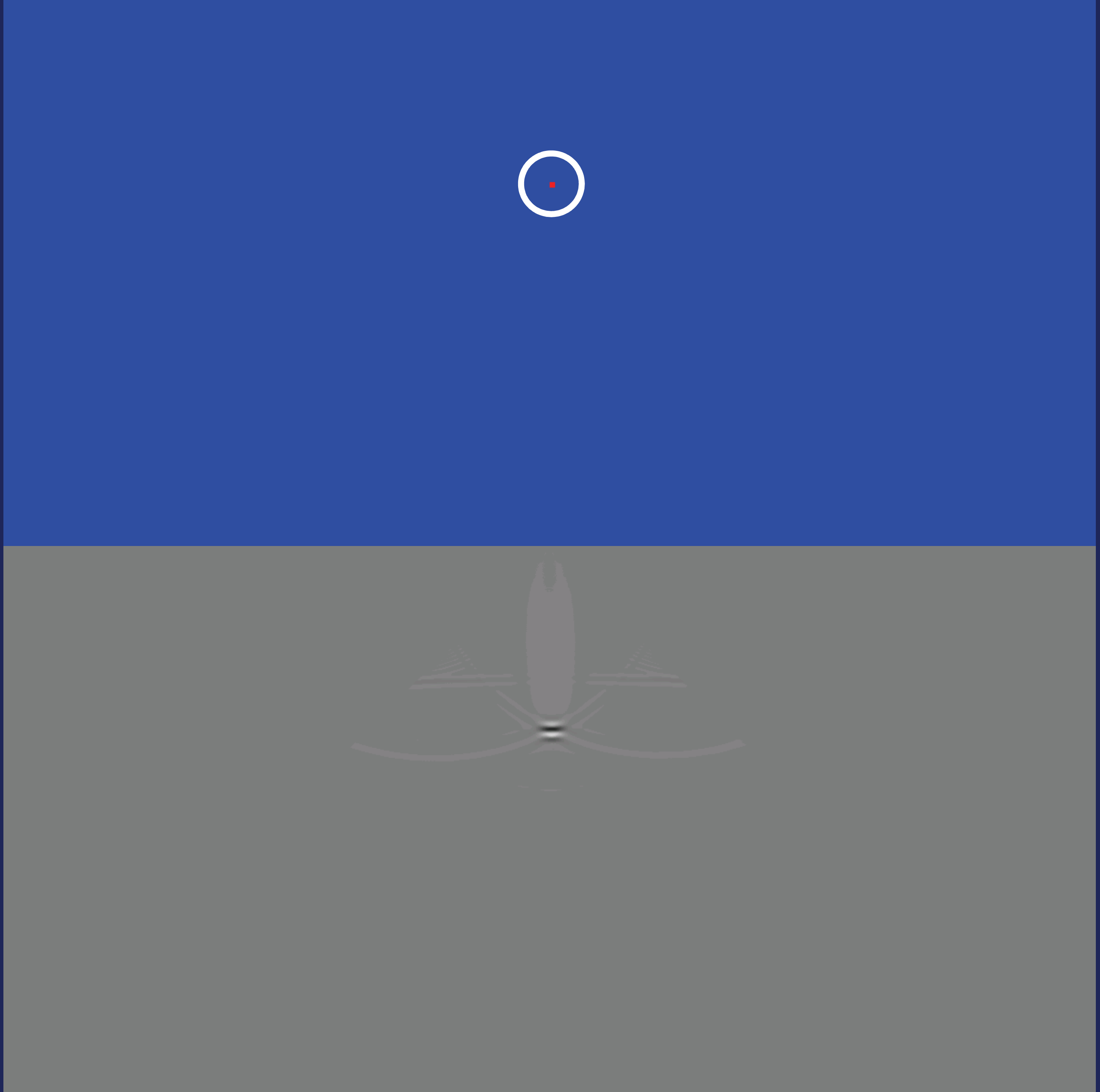
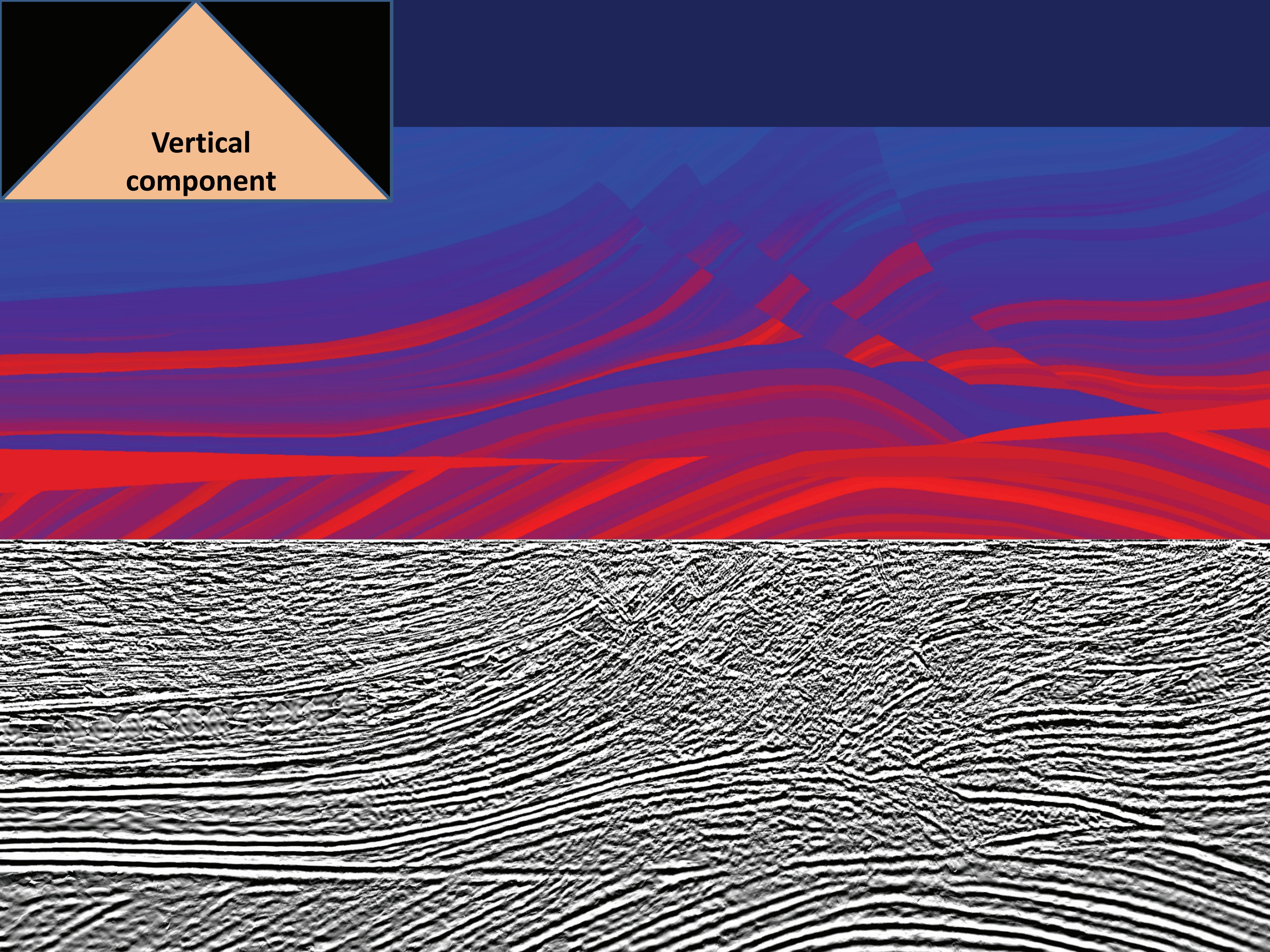

t=0.2625s

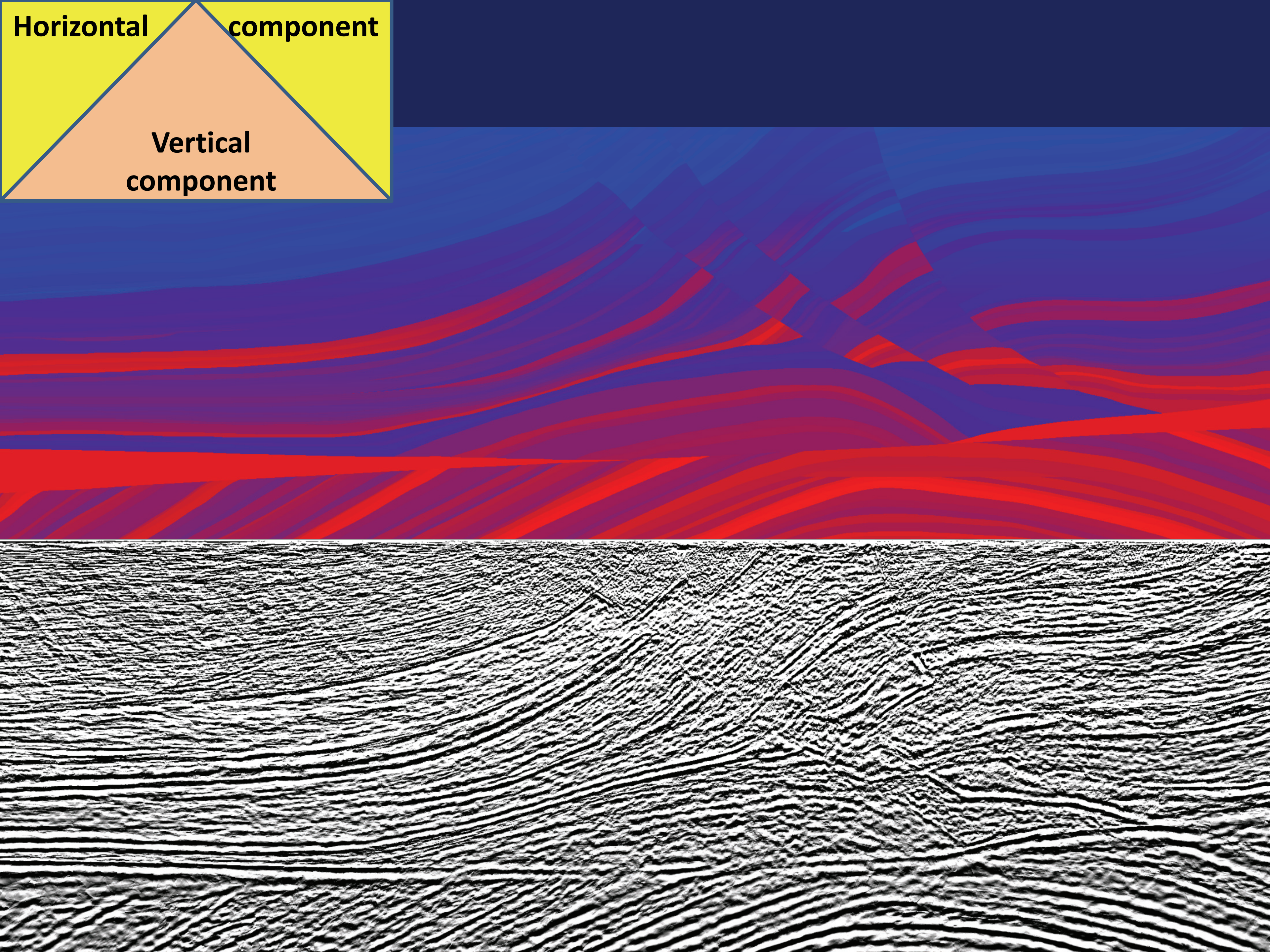
Image at time 0.1625s



Imaging result




Vertical
component


Horizontal
component
Vertical
component

Comparison

	Cross-correlation imaging	First Arrival imaging
Disk space requirement, disk I/O operations	Exists	Almost none
Computational time	2.5	1
Effect	Good	Need to improve

Conclusions

- **Staggered-grid schemes are accurate.**
- **Rigid boundary – math & modelling**
- **Combined boundary conditions**
- **Cross-correlation imaging conditions**
  - **All multiples**
  - **Higher costs, better results.**
- **The first arrival imaging condition**
  - **Fewer multiples**
  - **Less expensive, need to be improved.**
- **Horizontal component is useful for imaging.**

Acknowledgements

- **CREWES sponsors, U of Calgary**
- **Dr. E.S. Krebes**
- **CREWES staff & students**

Thank you!