Reverse time migration using several-order surface-related multiples

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Motivation

- Multiples are sensitive to small velocity changes about the medium because they travel longer distance
- That makes them specially useful for time-lapse studies
- Multiples illuminate regions than primaries
- Smaller reflection angles provide higher vertical resolution

Illumination of primary and multiple

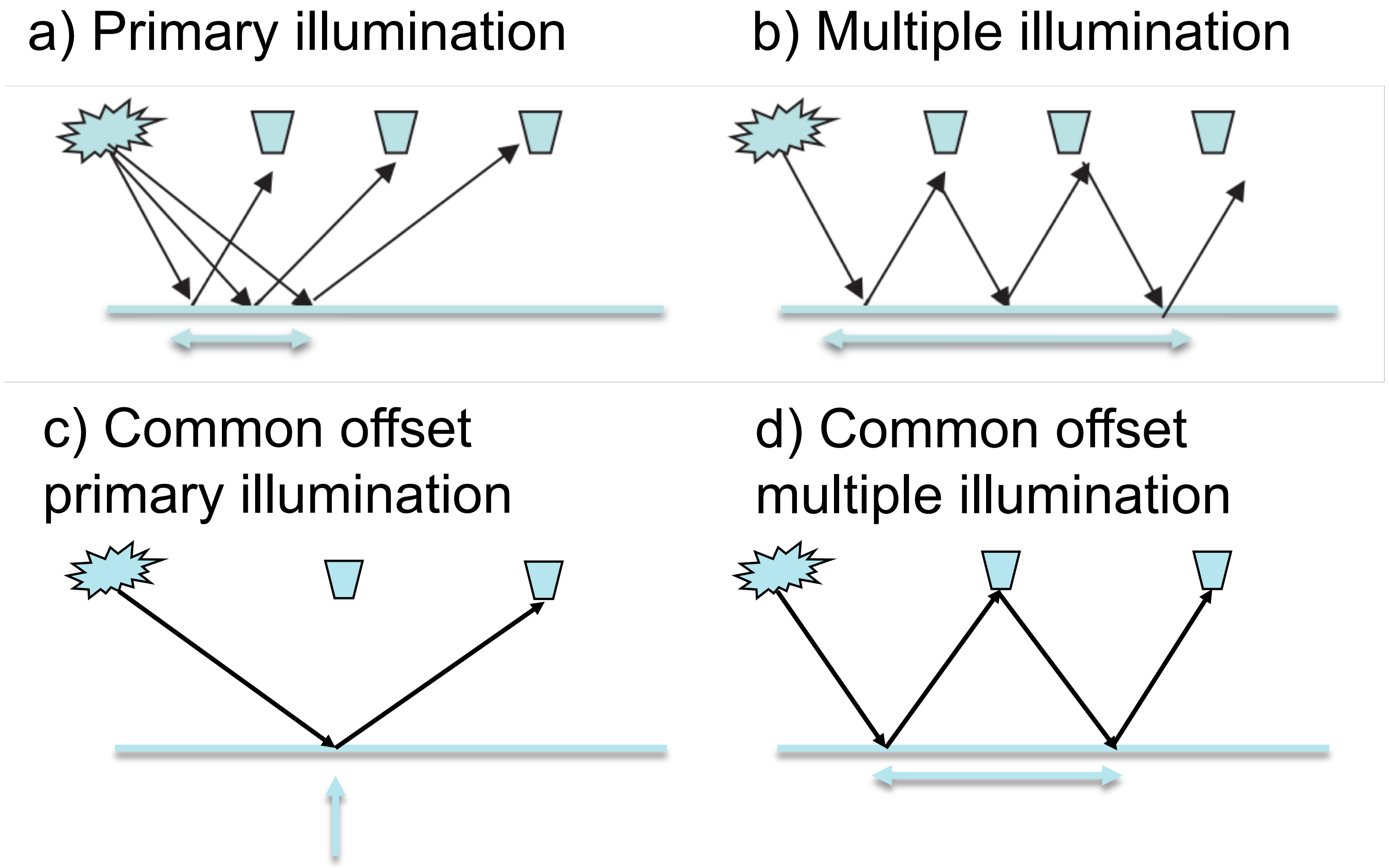
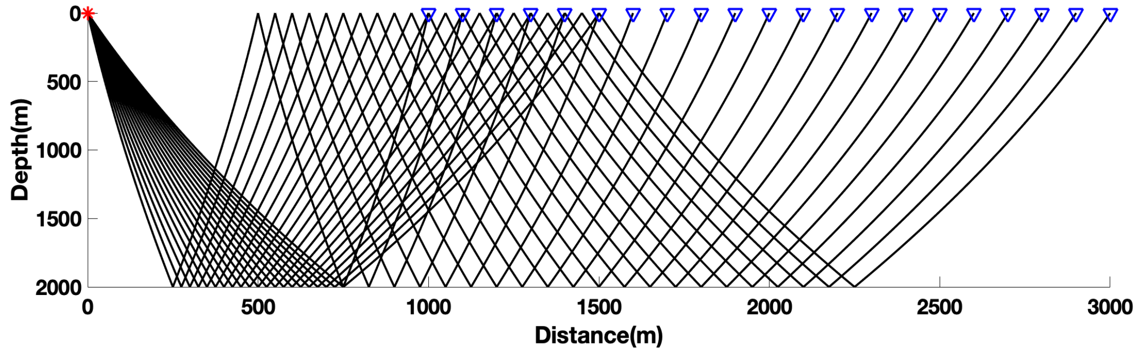
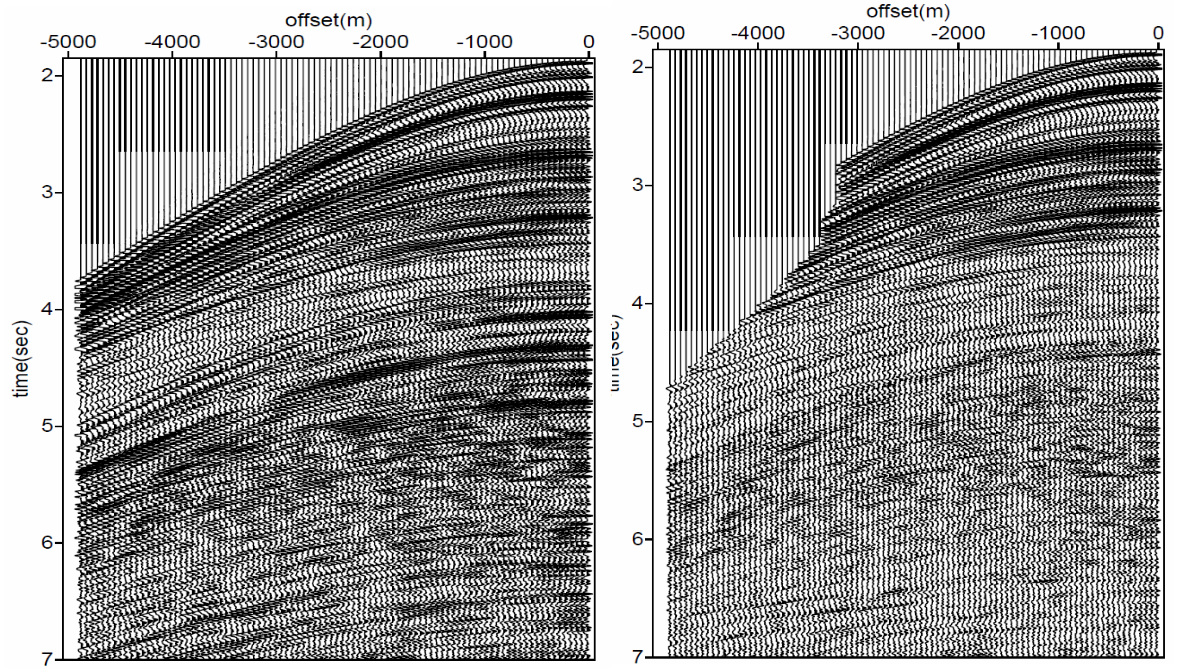


Fig 1 a) primary illumination b) multiple illumination
c) Common offset primary illumination d) common offset multiple illumination
(adapted from Zhang and Schuster (2014))

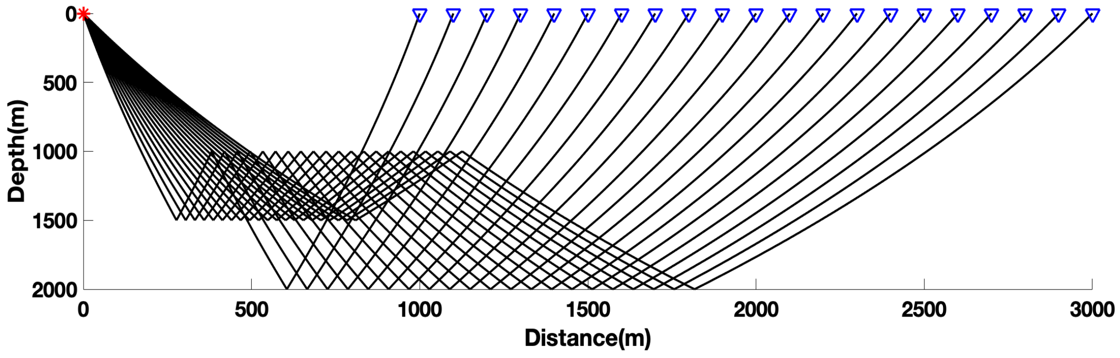
Surface multiple and internal multiple

First-order surface multiple





First-order internal multiple



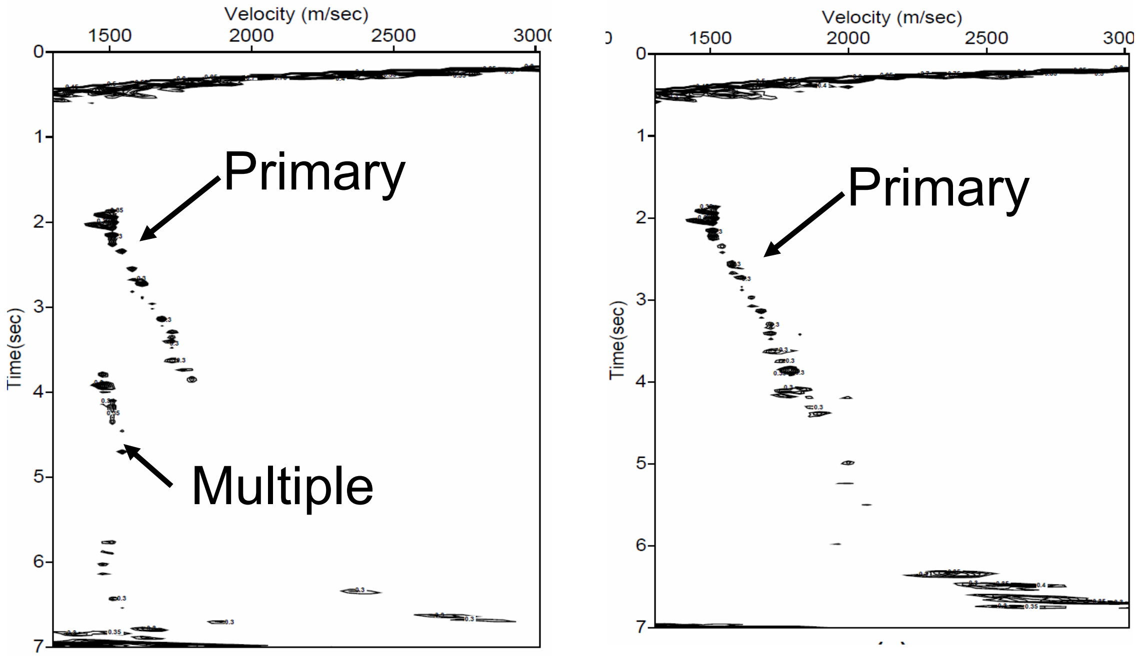


Fig 2. Multiples are often the most energetic part of the data (Trad).

Resolution increase when imaging with multiples (Verschuur, TLE 2015)

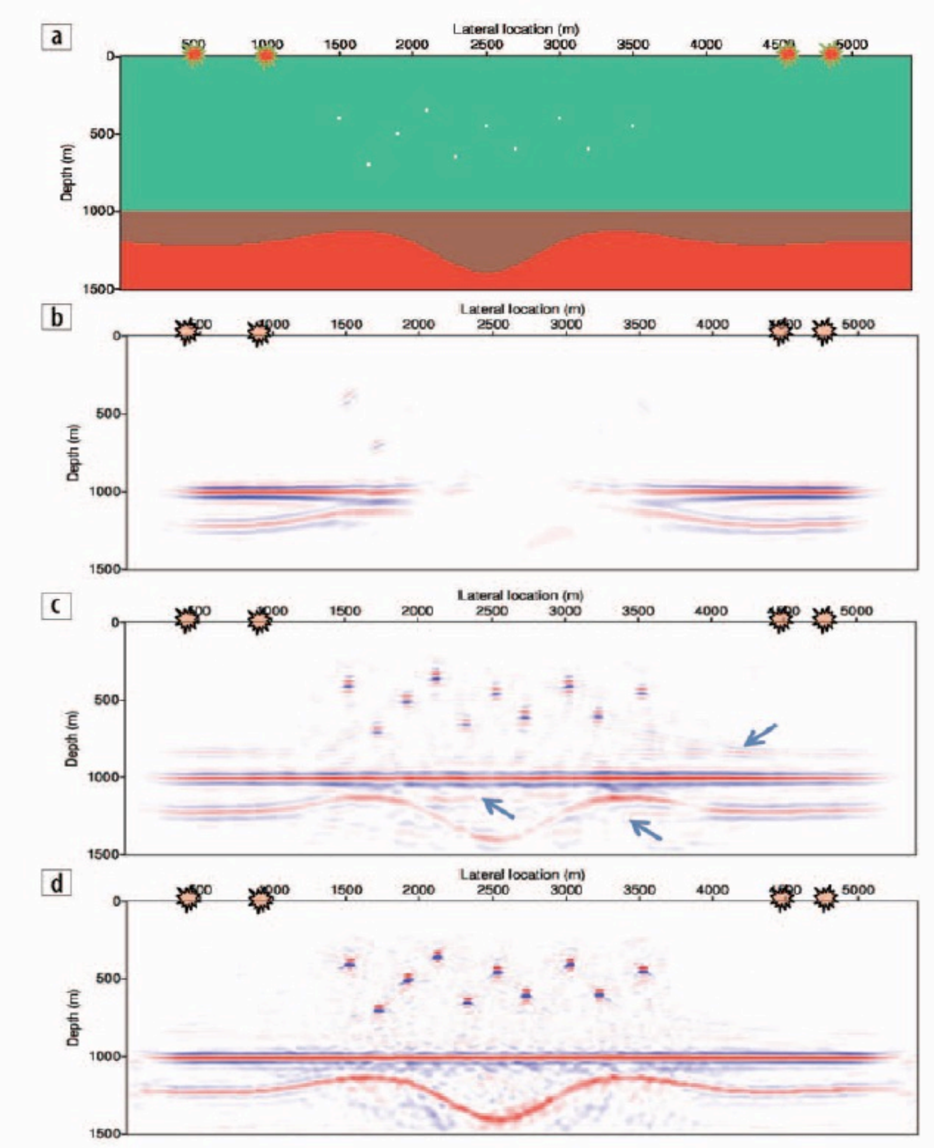


Figure 4. Extreme test for imaging with multiples: (a) In the subsurface model, only four shots are generated, and receivers are located along the complete profile. (b) Image of the primaries. (c) Image of the surface multiples. Note the vast increase in illumination in the multiple image. Also note the cross talk generated in the multiple image (see arrows). (d) Closed-loop image of the surface multiples. Note the improvement for the multiple image compared with part (c).

Image from primaries

Image from multiples

Image from multiples with inversion

Background

Liu et al. (2011a, 2011b)

- Reverse time migration of all-order multiples (RTMM)

Zhang and Schuster (2014)

- Least-squares reverse time migration of multiples

Verschuur and Berkhout (2015)

- A closed-loop approach to migrate internal multiple and surface multiple

Liu et al. (2016)

- Least-squares reverse time migration using the first-order multiple reflections

Background

Berkhout and Verschuur (2016)

- Full-wavefield migration using multiple scattering to enhance the illumination and resolution

Lu et al. (2018)

- Least-squares full-wavefield migration

Davydenko and Verschuur (2018)

- Application of full-wavefield migration of internal multiples

In this project

- Apply first- and second-order multiple into the least-squares reverse time migration

In these experiments

- We use 2D acoustic, constant density, wave equation

- Absorbing boundary condition is applied for three boundaries except for the top boundary to generate surface multiples

- Amplitudes only apply theoretical divergence, some extra factors such as transmission are not considered in this case

$$\frac{\partial^2 p(x,z,t)}{\partial x^2} + \frac{\partial^2 p(x,z,t)}{\partial z^2} - \frac{1}{v^2}\frac{\partial^2 p(x,z,t)}{\partial t^2} = f(x,z,t)$$

Reverse time migration of first-order free-surface multiple

The primaries are used as the time histories of virtual sources at the hydrophones

↓

The first-order surface-related multiples are the observed data

↓

Imaging condition

Reverse time migration of first-order free-surface multiple

The primaries are used as the time histories of virtual sources at the hydrophones

↓

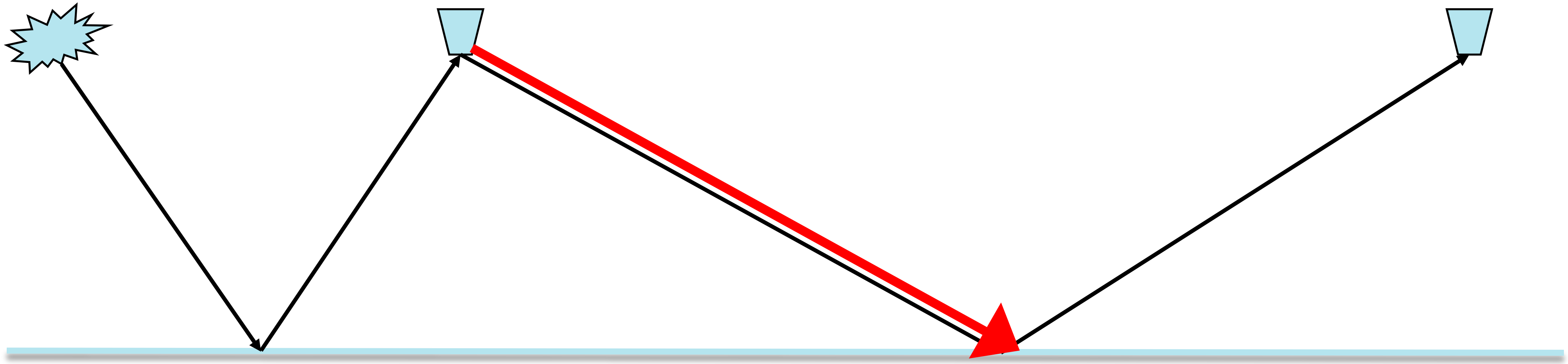
The first-order surface-related multiples are the observed data

↓

Imaging condition

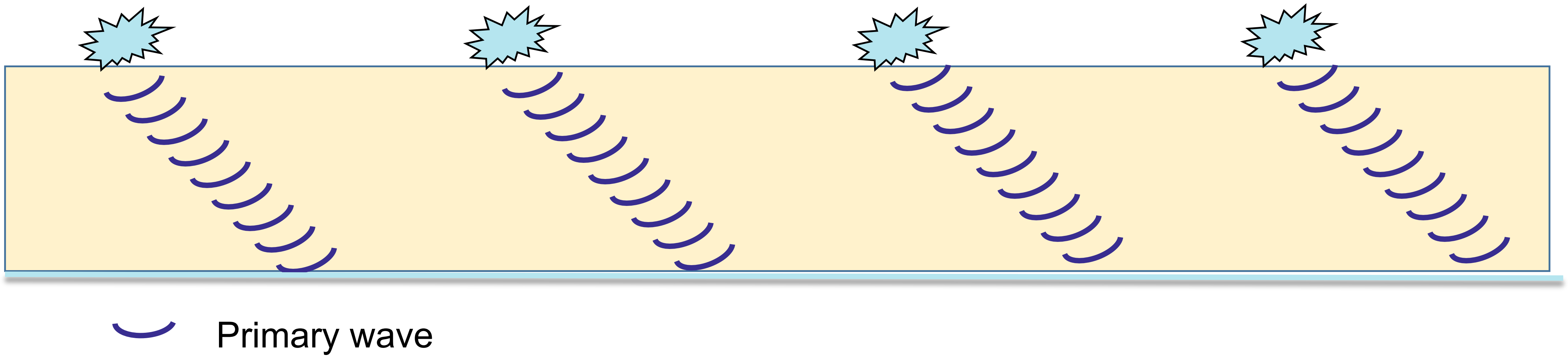
Reverse time migration of first-order free-surface multiple

- The primaries are used as the downgoing wavefields at each receiver



Simultaneous shots

- Inject the primary as simultaneous sources to reverse time migration
- All shots generate a simultaneous source wavefield that propagates downward



Reverse time migration of first-order free-surface multiple

The primaries are used as the time histories of virtual sources at the hydrophones

↓

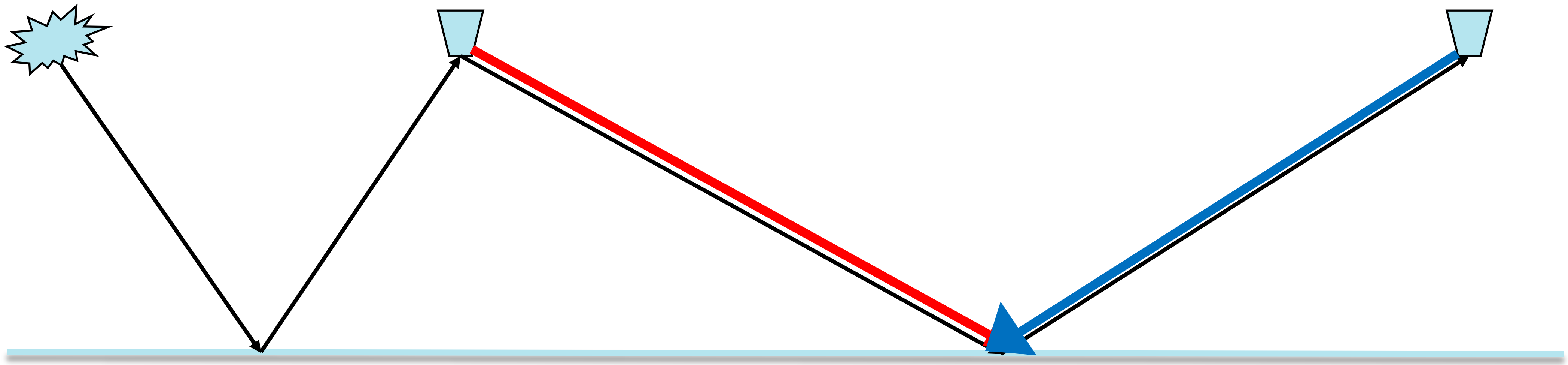
The first-order surface-related multiples are the observed data

↓

Imaging condition

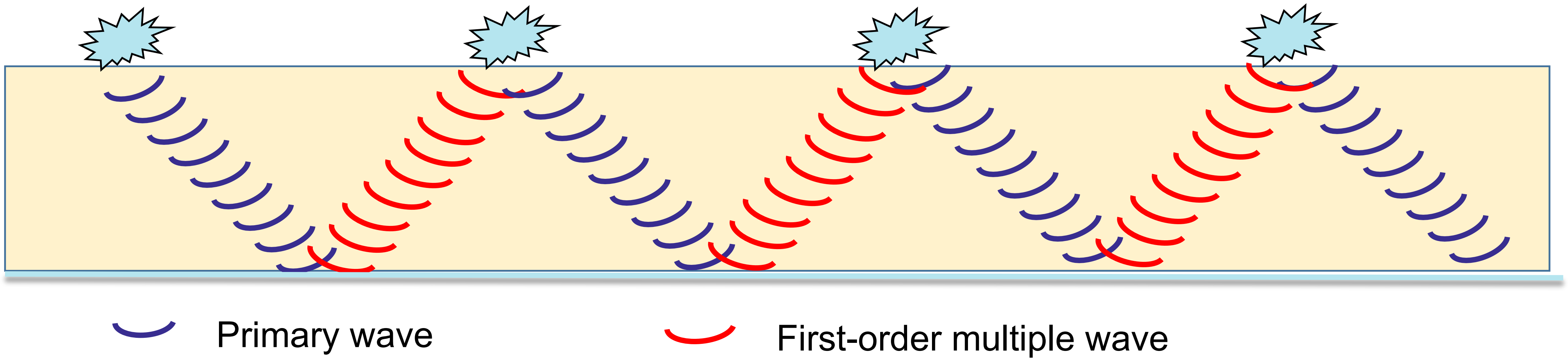
Reverse time migration of first-order free-surface multiple

- The primaries are used as the downgoing wavefields at each receiver
- The first-order surface-related multiples are the back-propagated wavefields



Simultaneous shots and back-propagated surface multiple

- Inject the primary as simultaneous sources to reverse time migration
- All shots generate a simultaneous source wavefield that propagates downward
- Surface multiples are back propagated to generate receiver wavefield



Reverse time migration of first-order free-surface multiple

The primaries are used as the time histories of virtual sources at the hydrophones

↓

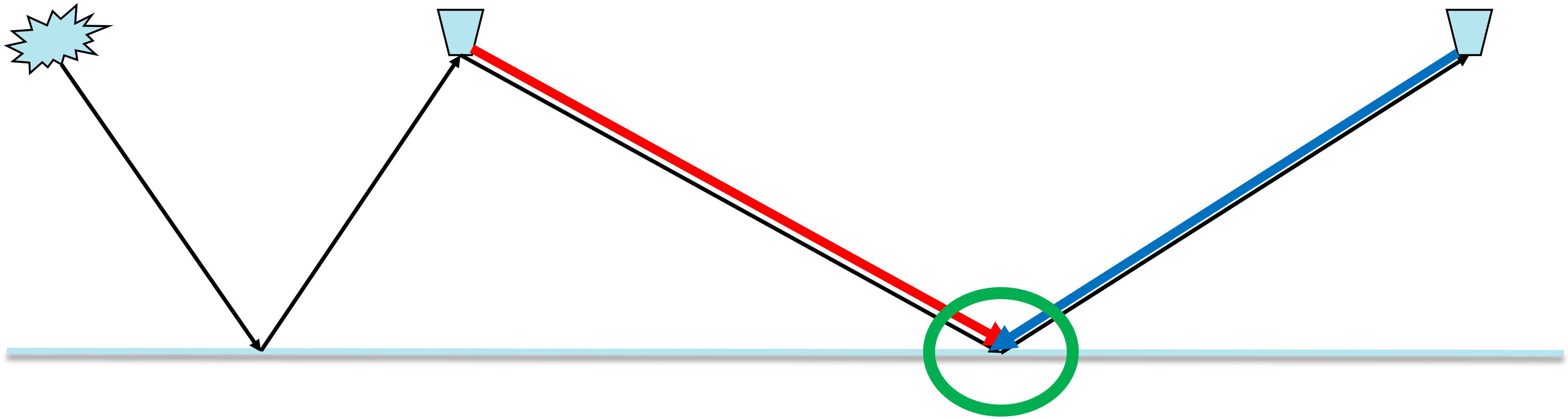
The first-order surface-related multiples are the observed data

↓

Imaging condition

Reverse time migration of first-order free-surface multiple

- The primaries are used as the downgoing wavefields at each receiver
- The first-order surface-related multiples are the back-propagated wavefields



- Correlate the primary downgoing wavefields with the back-projected surface-related multiples to give the migration image

$$Image(x,y,z) = \sum_{t=0}^{t_{max}} \{P_F(x,y,z,t) + M_F(x,y,z,t)\} * M_B(x,y,z,t)$$

(Liu et al., 2016)

Imaging condition

- RTM of multiples gives an artifact-free image when the downgoing (*N−1*)th-order multiple correlates with the back-propagated *N*th-order multiple of the input data.

- Otherwise, there will be crosstalk in the migration image.

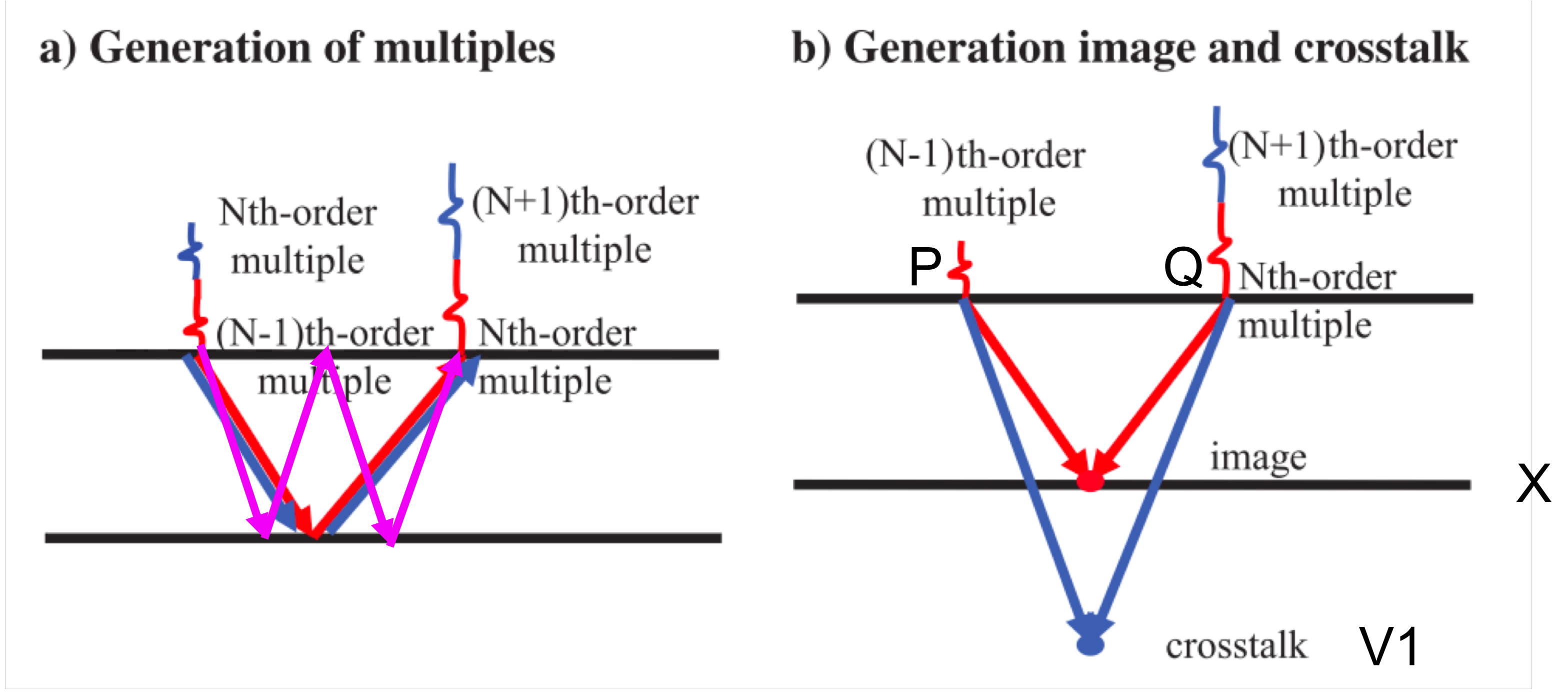


Fig 4. a) Generation of multiples b) Generation image and crosstalk (Zhang and Schuster, 2014)

Table 1: Imaging condition for RTM of surface-related multiple

Forward-propagated source	Back-propagated data			
	Primary	First-order multiple	Second-order multiple	Higher-order multiples
Impulsive wavelet	Image	Artifact	Artifact	Artifact
Primary	Artifact	Image	Artifact	Artifact
First-order multiple	Artifact	Artifact	Image	Artifact

Generation of multiples

- Mute from the finite-difference synthetic shot record
- Time-distance equation and convolution
- Future: use multiple separation based on SRME, Radon or scattering

Use filter to separate primary and multiple

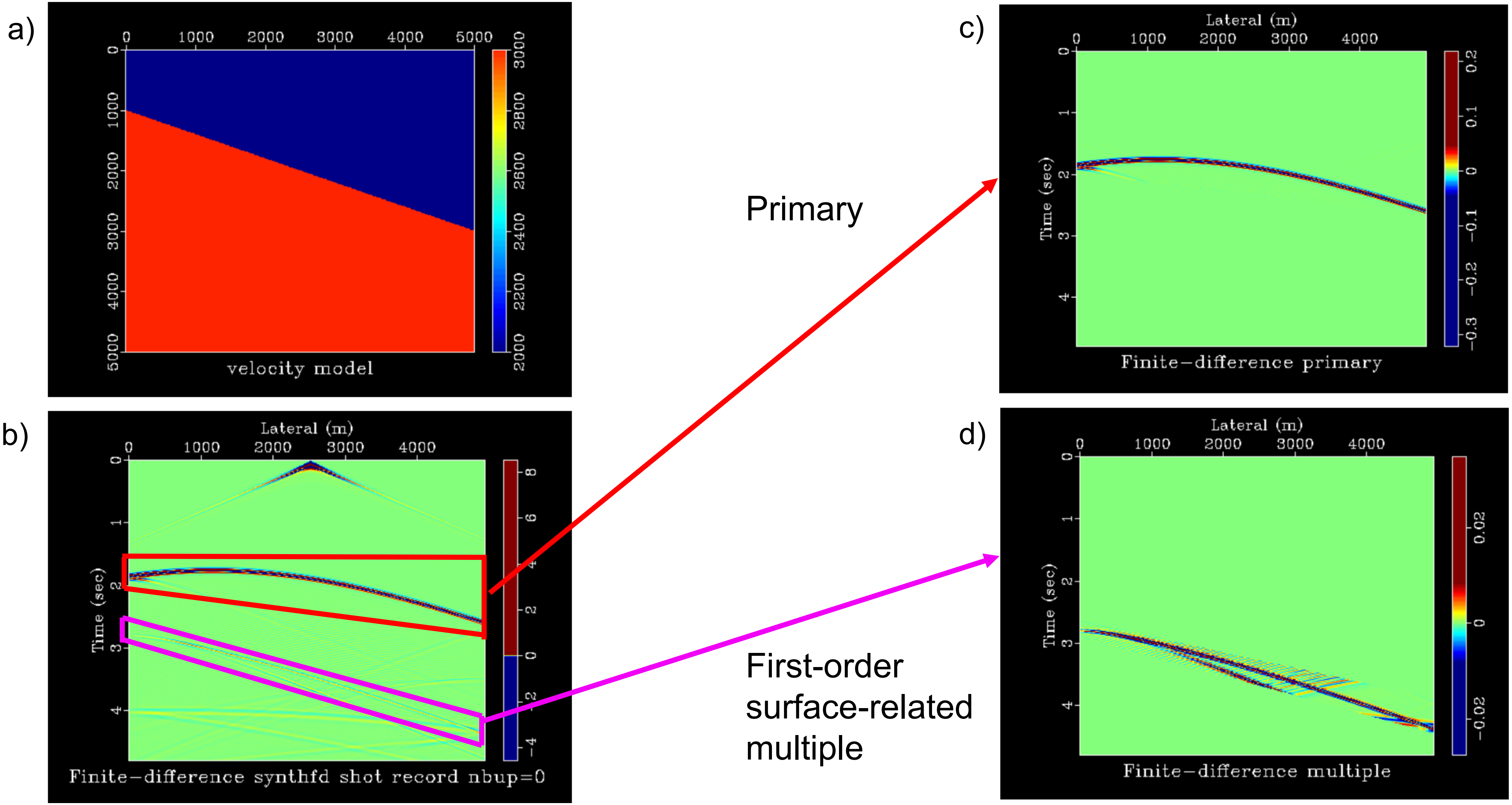


Fig 5. a) dipping event b) shot record c) primary d) first-order multiple

Traveltime for horizontal event

$$t^2 = \frac{h^2}{v^2} + (n+1)^2 {t_0}^2$$

- v is the upper layer velocity
- h is the offset
- n is the order of the multiple
- t_0 is the two-way zero-offset traveltime

a)
b)

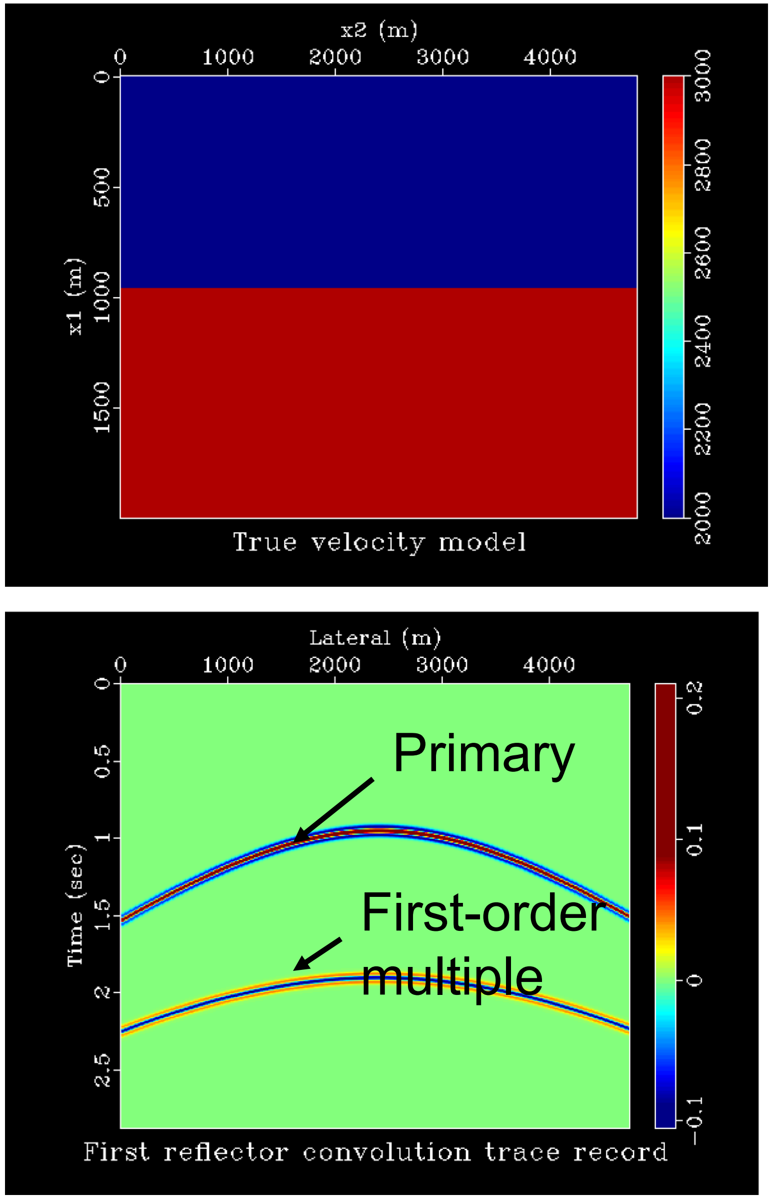


Fig 6. a) horizontal event b) shot record

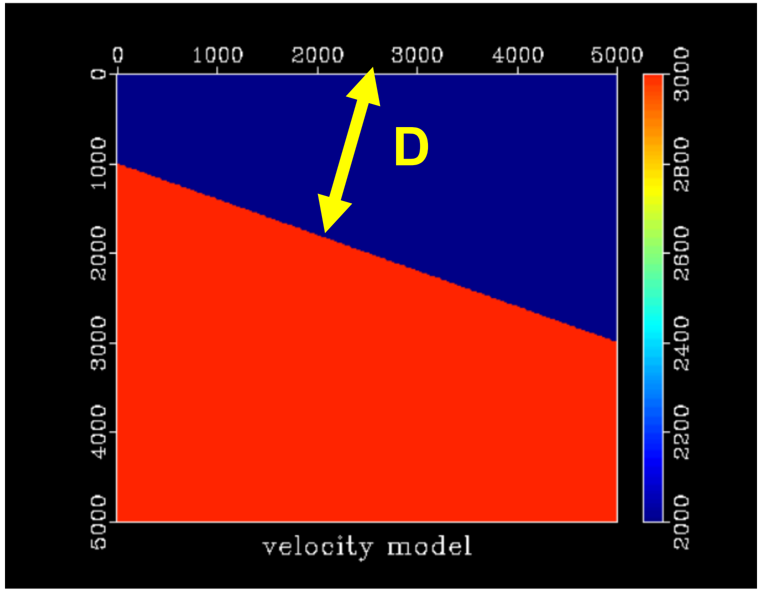
Traveltime for dipping event

$$t_n^2 = \frac{h^2 cos^2[(n+1)\phi]}{v^2} + \frac{4D^2 sin^2[(n+1)\phi]}{v^2 sin^2\phi}$$

(Levin and Shah, 1977)

- v is the upper layer velocity
- h is the offset
- n is the order of the multiple
- D is the distance between the common-depth-point and the dipping reflector
- ϕ is the dipping angle

a)



b)

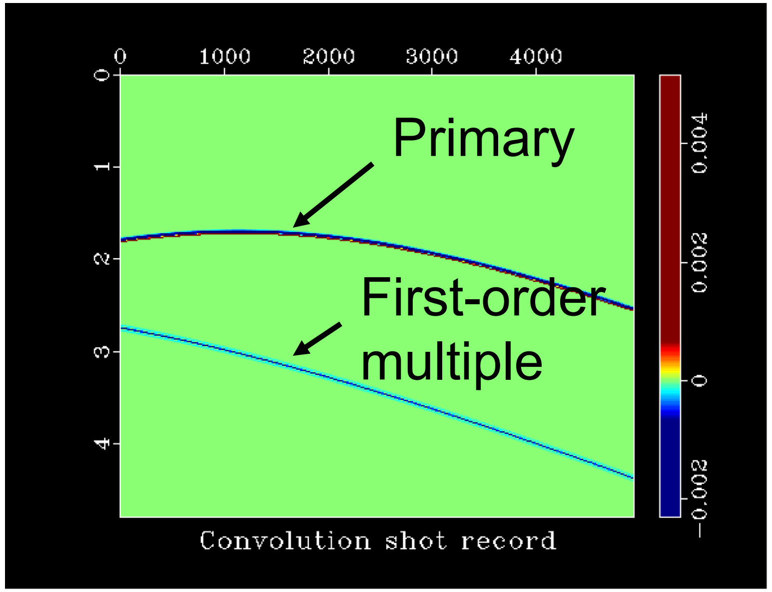


Fig 7. a) dipping event b) shot record

Convolution for generating the first-order multiple

- The amplitude of synthetic shot record should be the convolution of Ricker wavelet and reflectivity coefficient

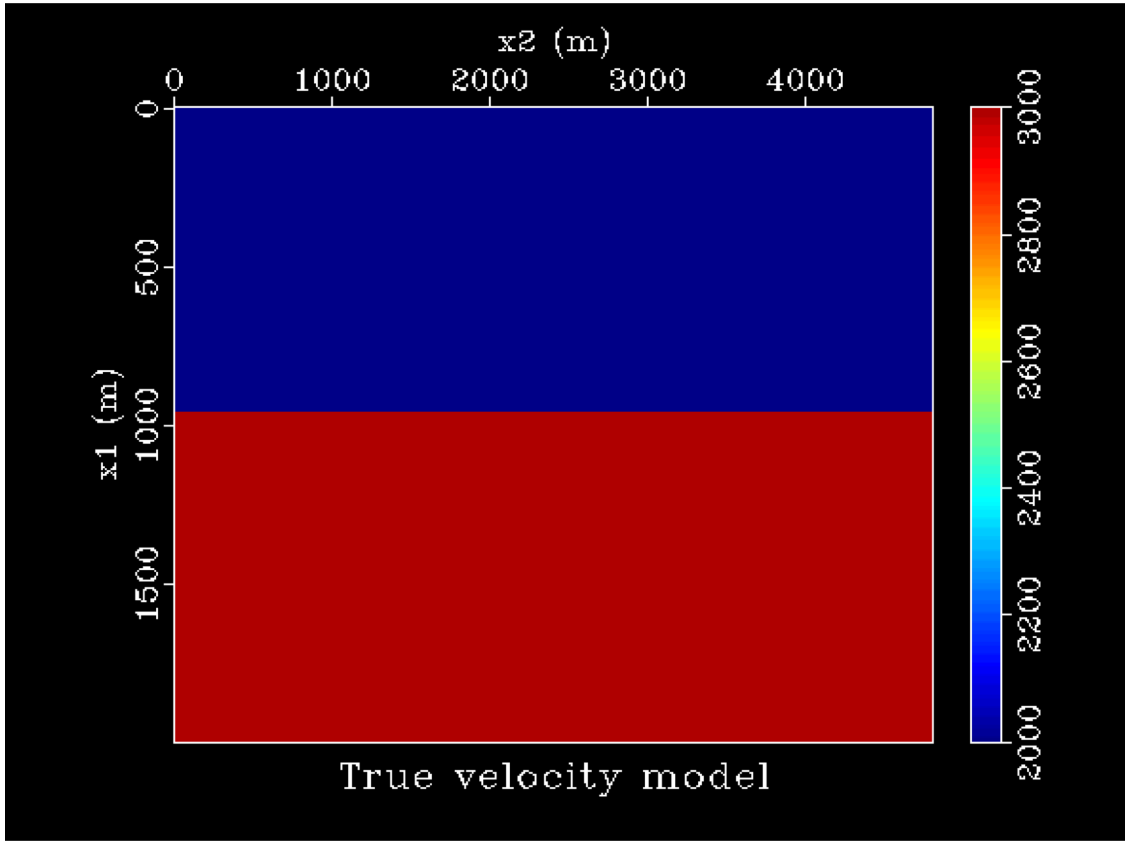
$$s(t) = w(t) * r(t)$$

(Kanasewich, 1981)

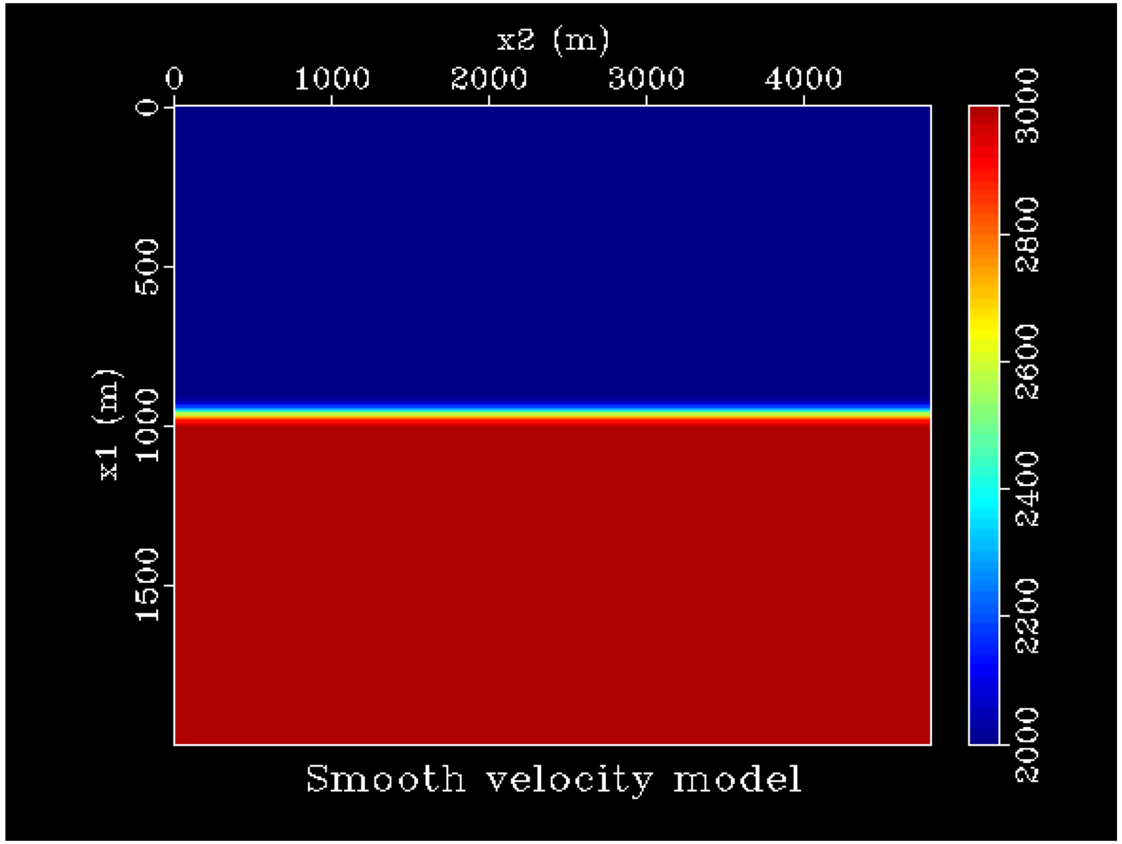
$$r_i = \frac{\rho_{i+1}v_{i+1} - \rho_i v_i}{\rho_{i+1}v_{i+1} + \rho_i v_i}$$

Numerical example 1 – Horizontal layer

True velocity model

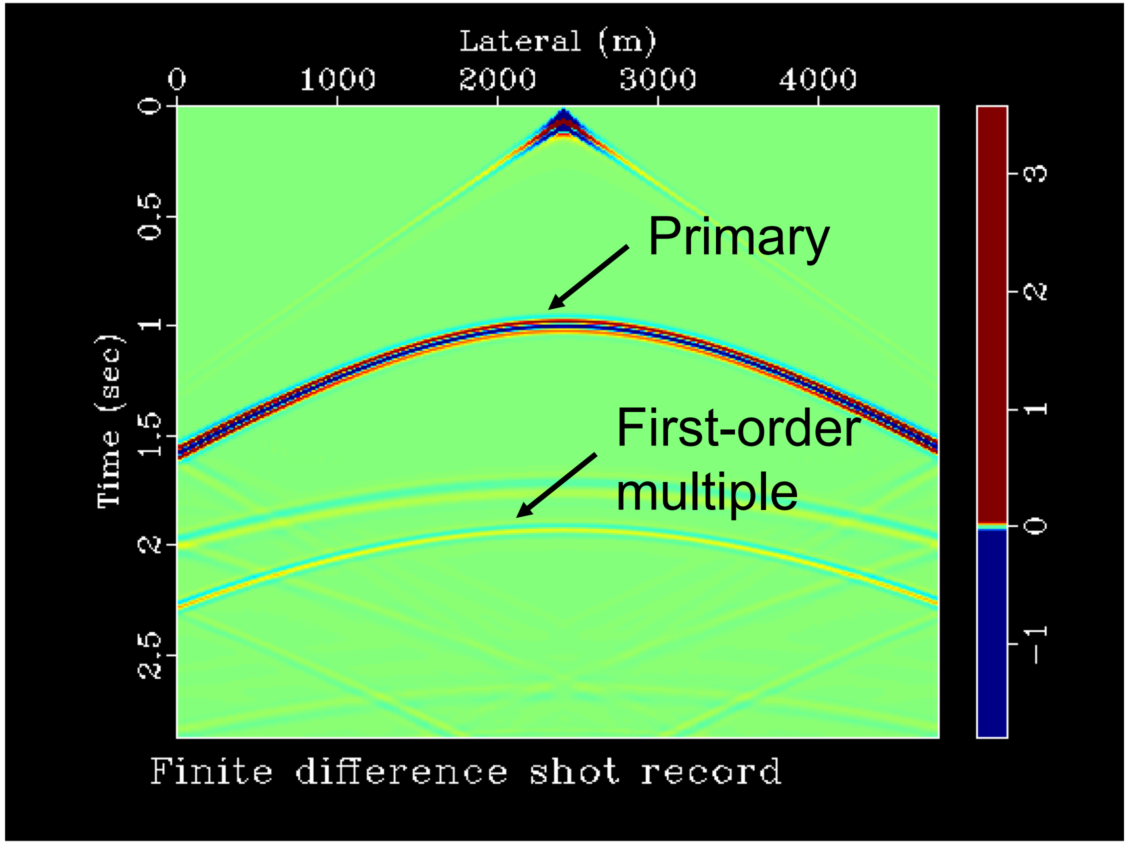


Smoothed velocity model

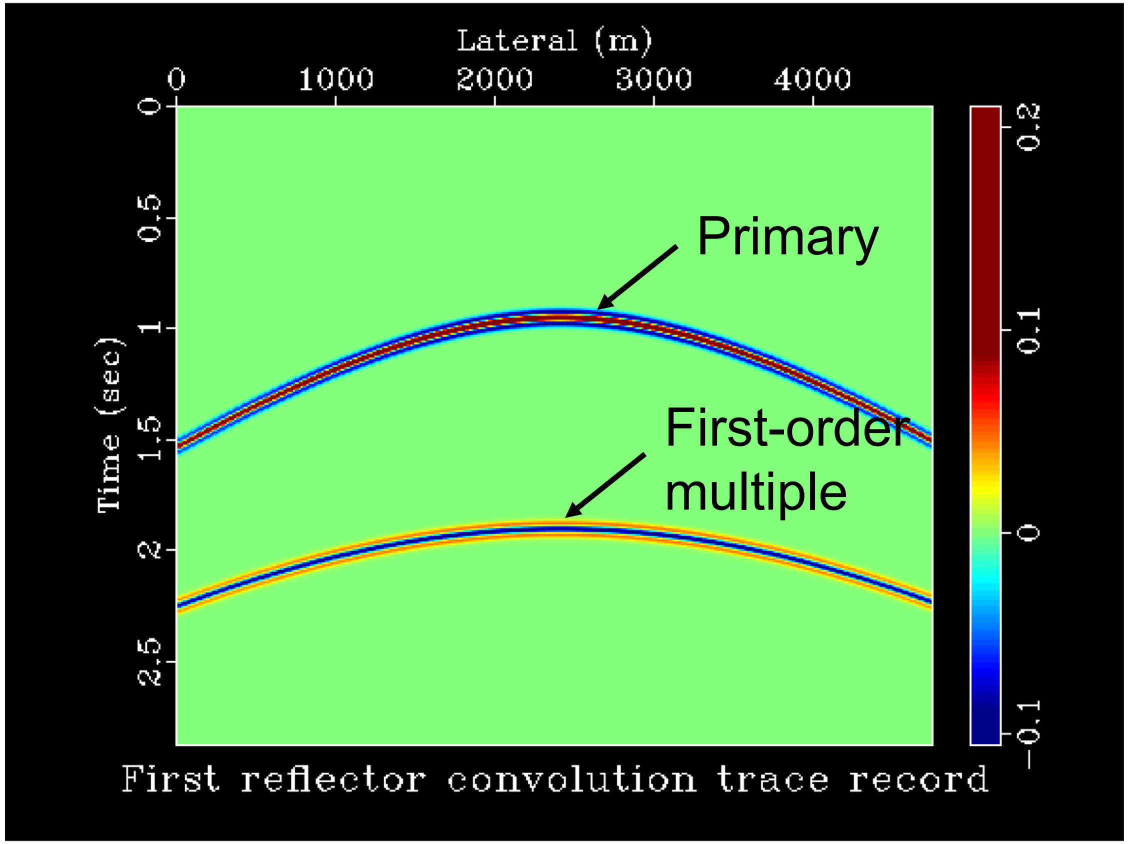


Synthetic shot record by finite difference and convolution

Finite-difference shot record

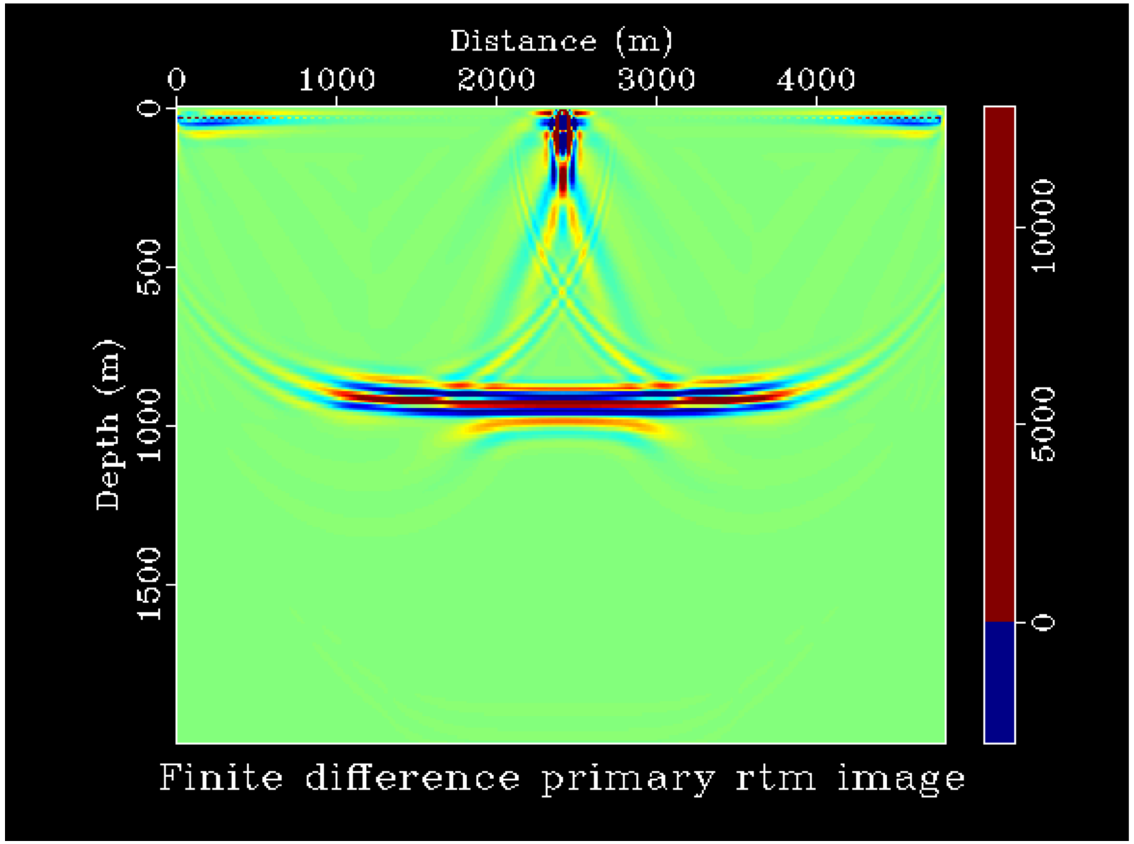


Convolution shot record

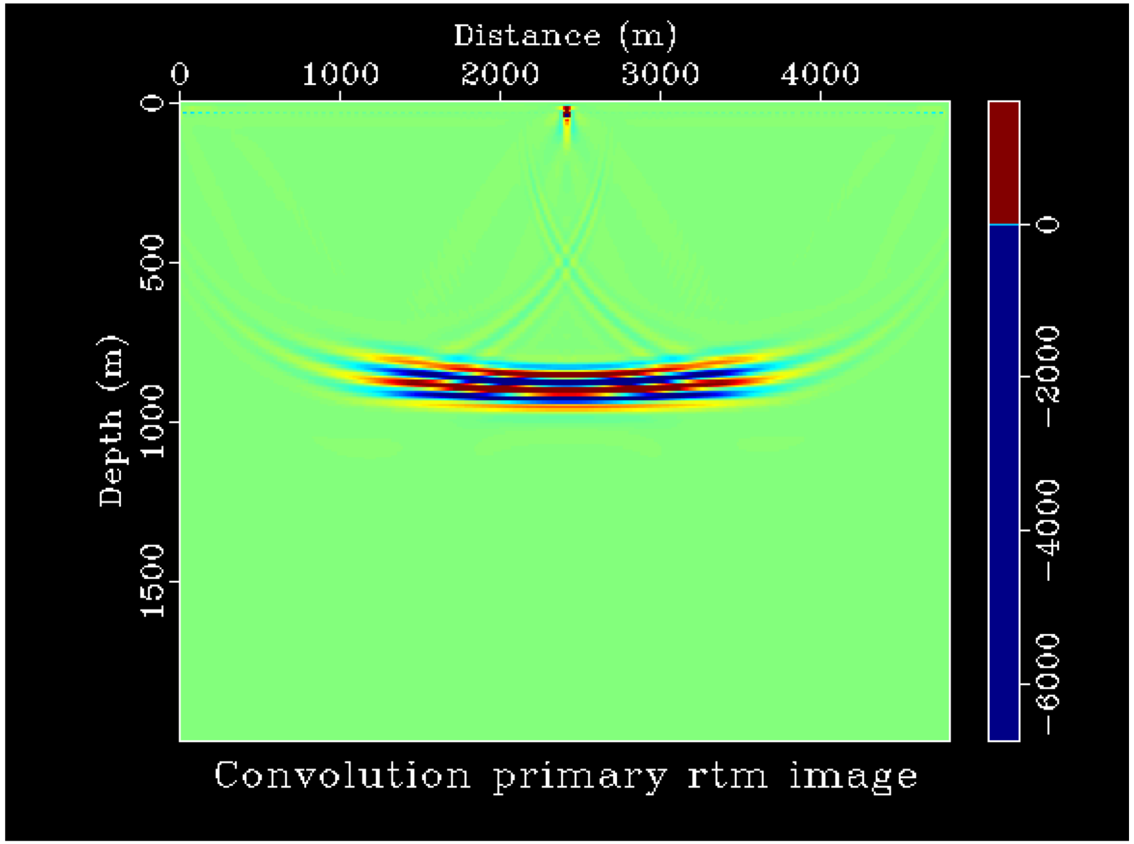


RTM of primary wave

Finite-difference primary rtm image

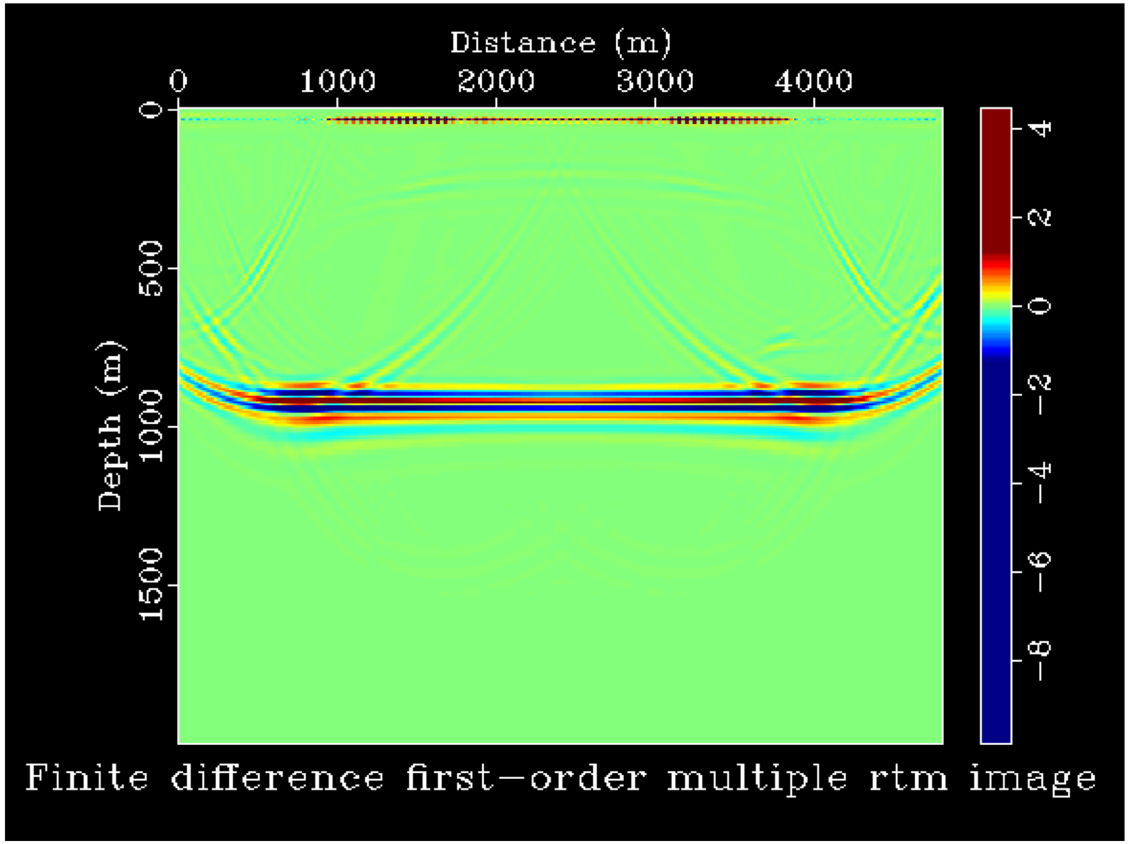


Convolution primary rtm image

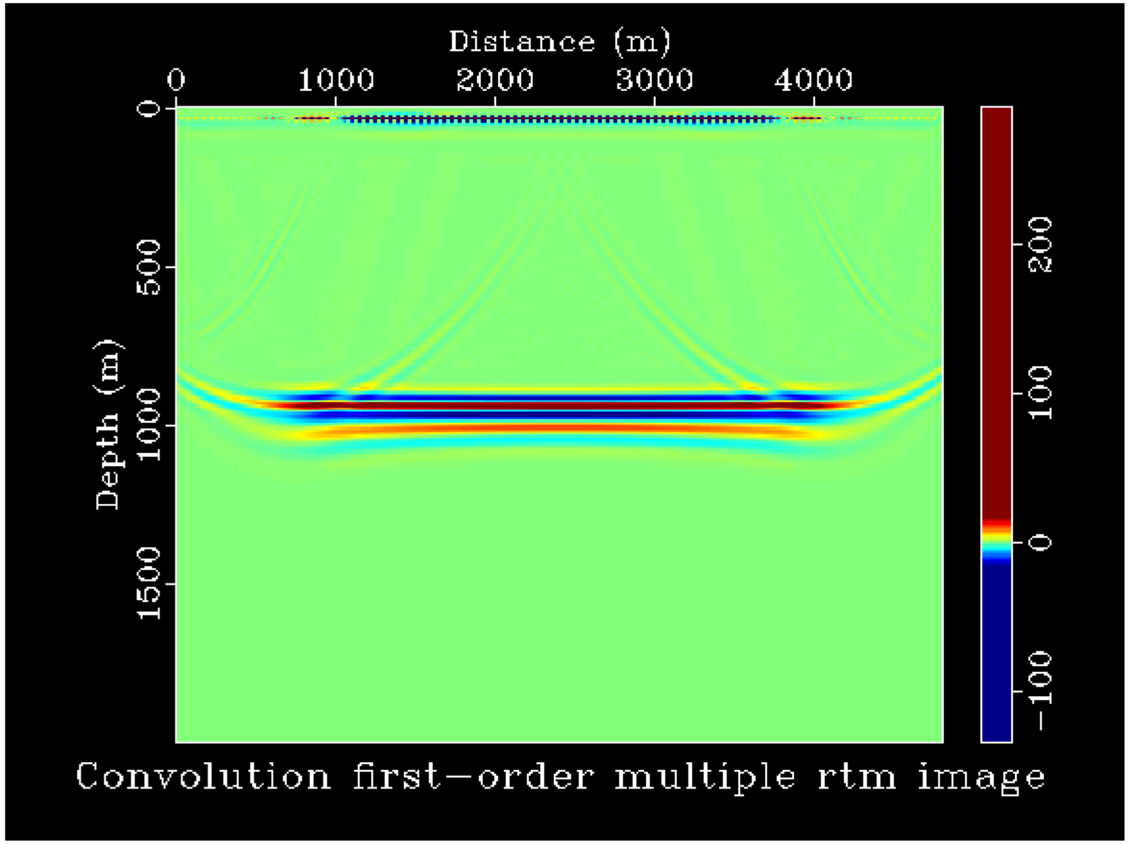


RTM of first-order surface-related multiple

Finite-difference first order multiple rtm image

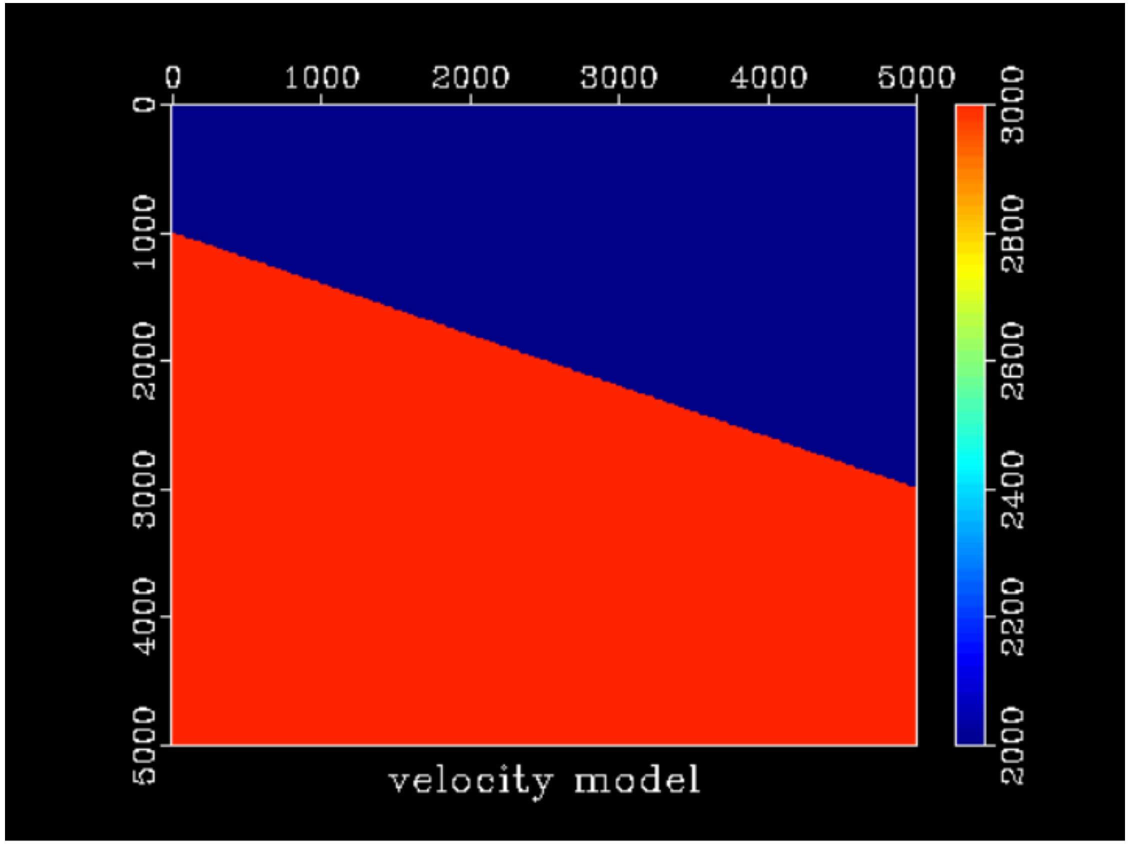


Convolution first-order multiple rtm image

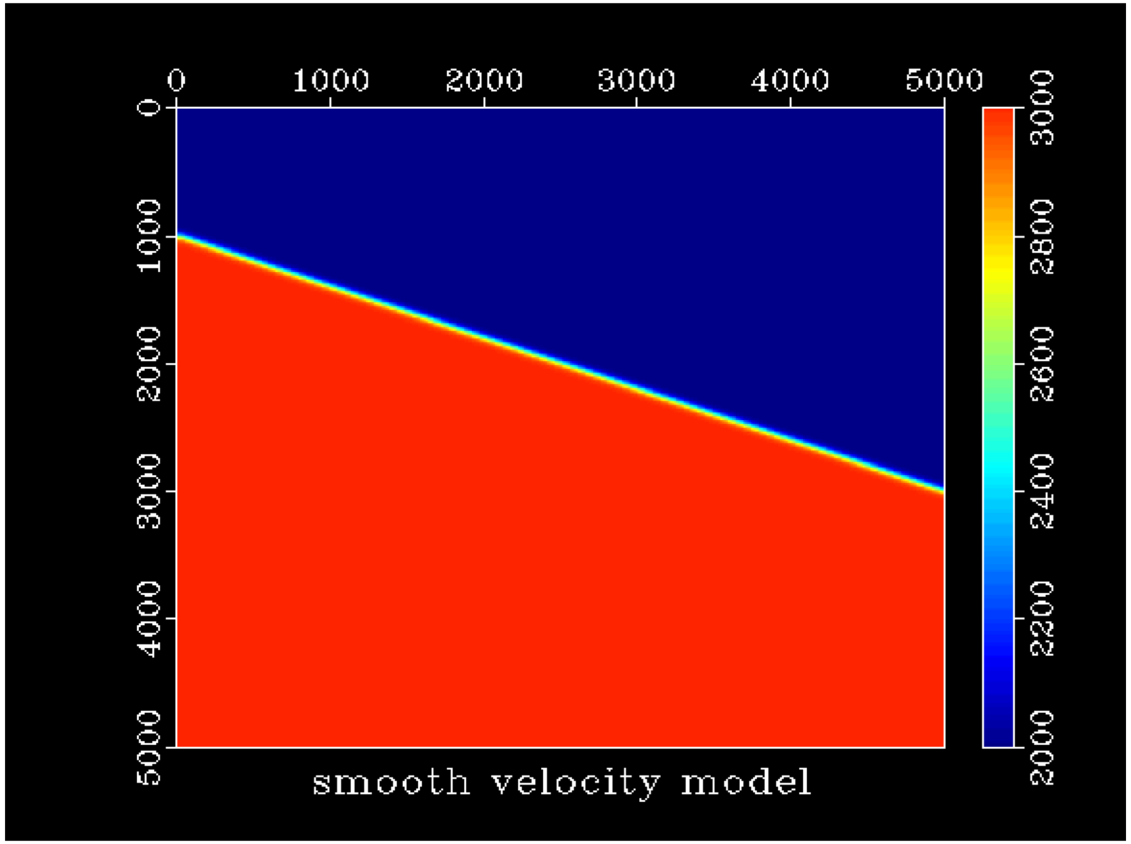


Numerical example 2 – Dipping layer

True velocity model

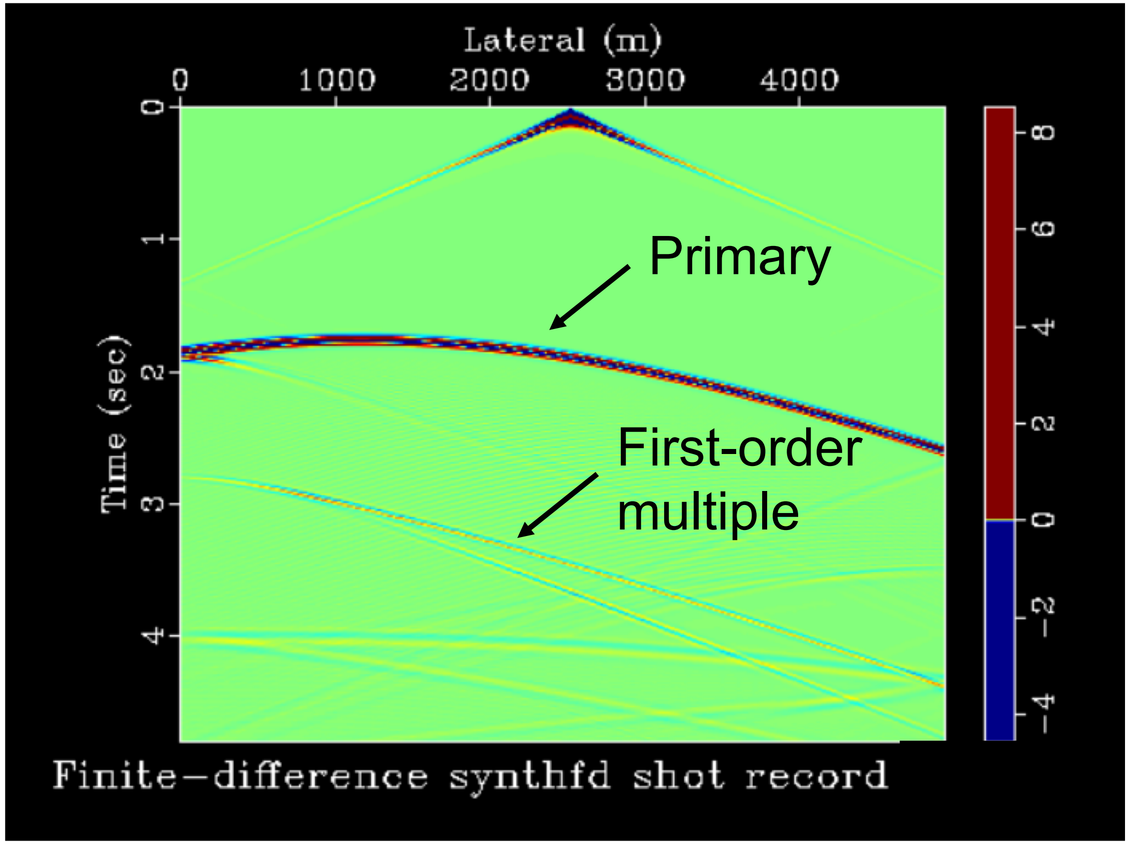


Smoothed velocity model

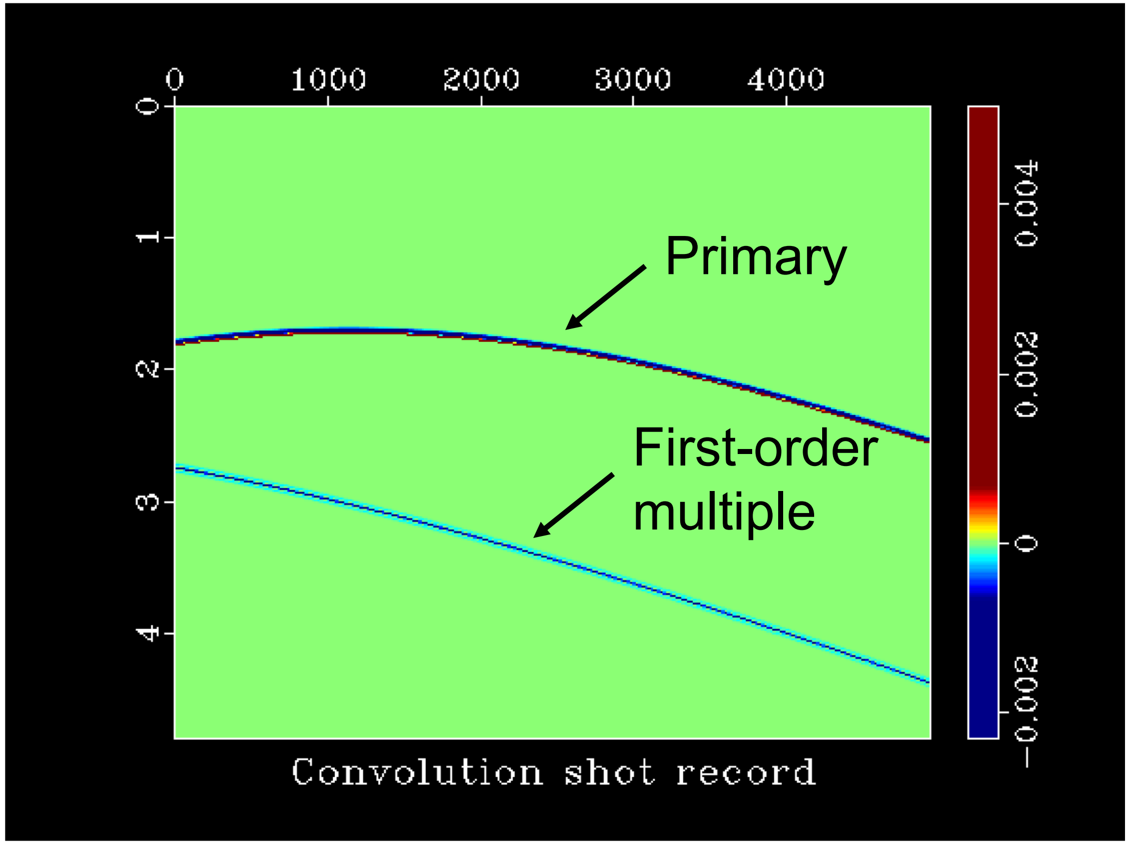


Synthetic shot record by finite-difference and convolution

Finite-difference shot record

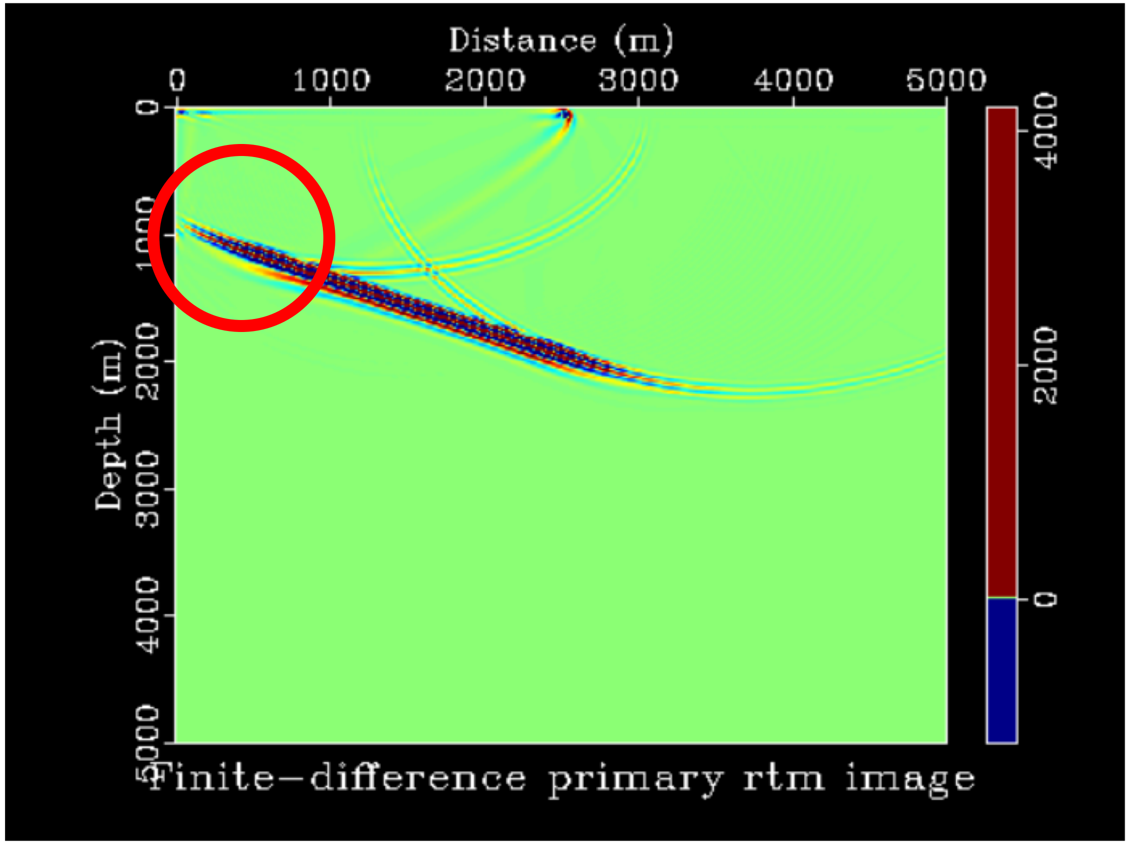


Convolution shot record

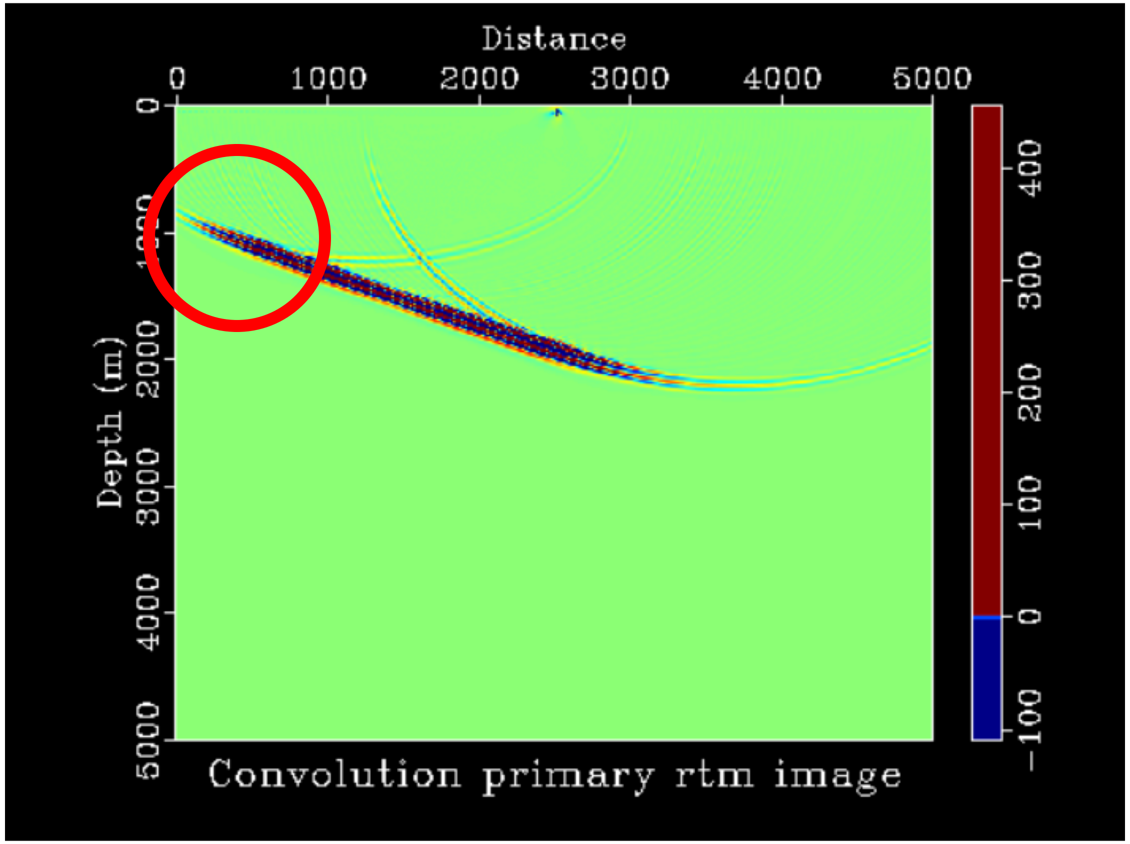


RTM image of primary wave

Finite-difference primary rtm image

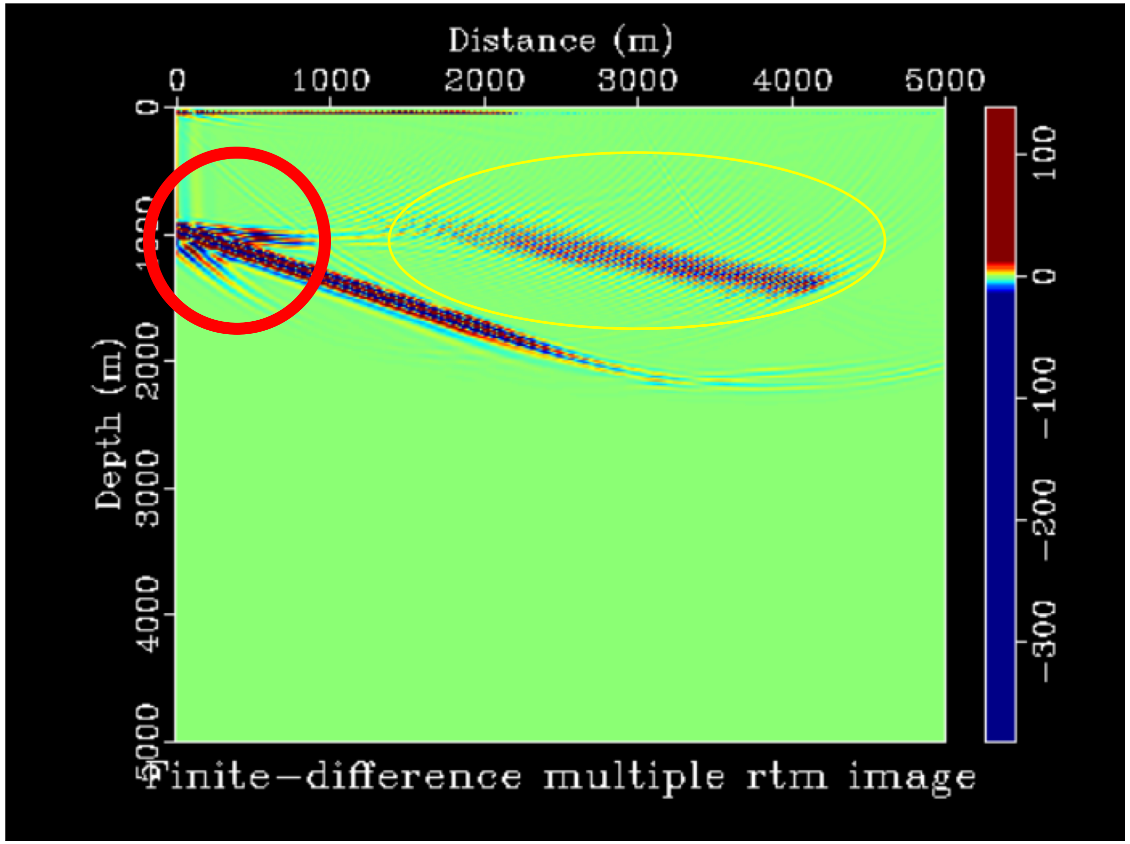


Convolution primary rtm image

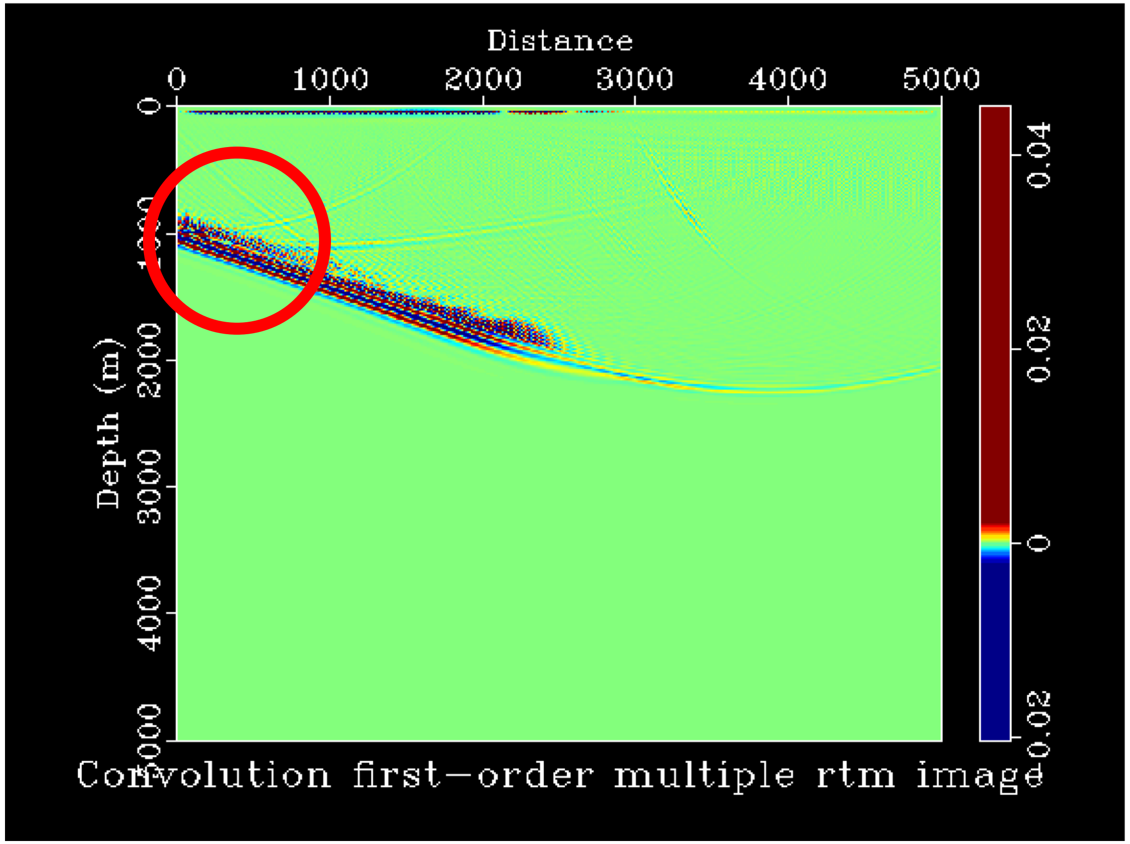


RTM of first-order surface-related multiple

Finite-difference first order multiple rtm image

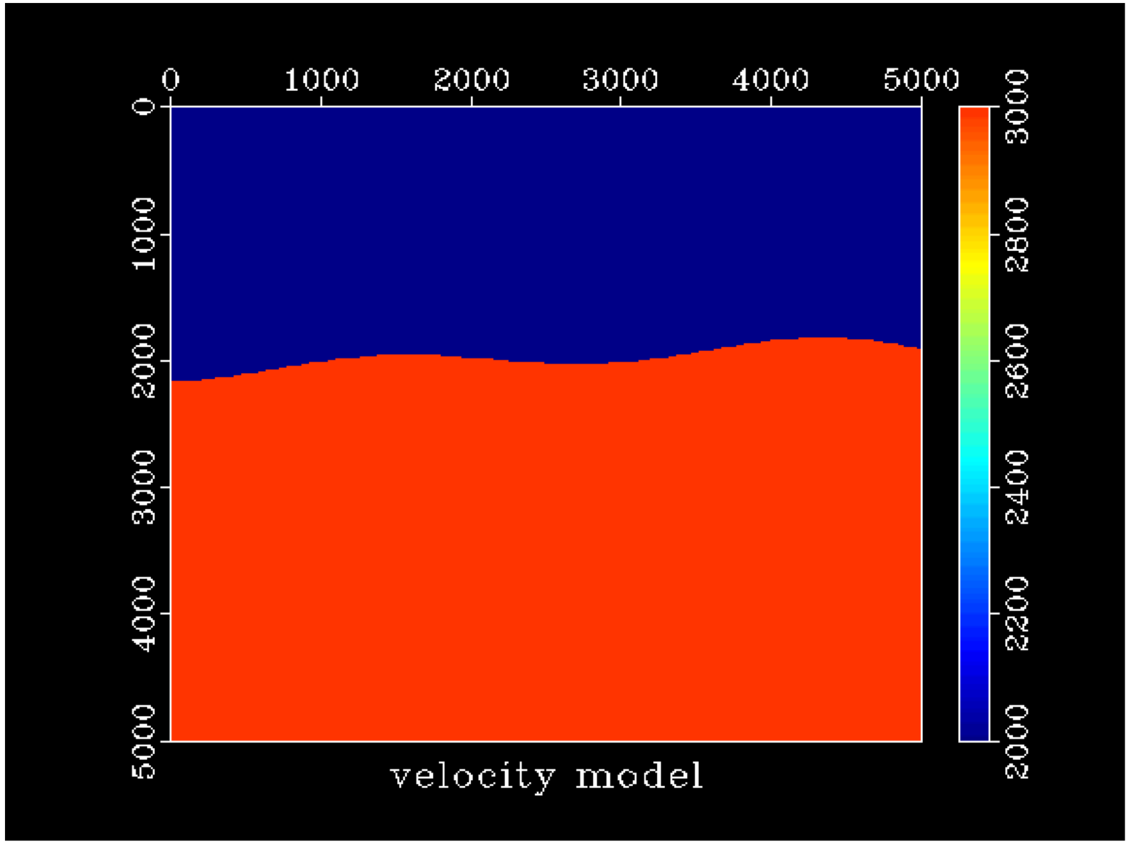


Convolution first-order multiple rtm image

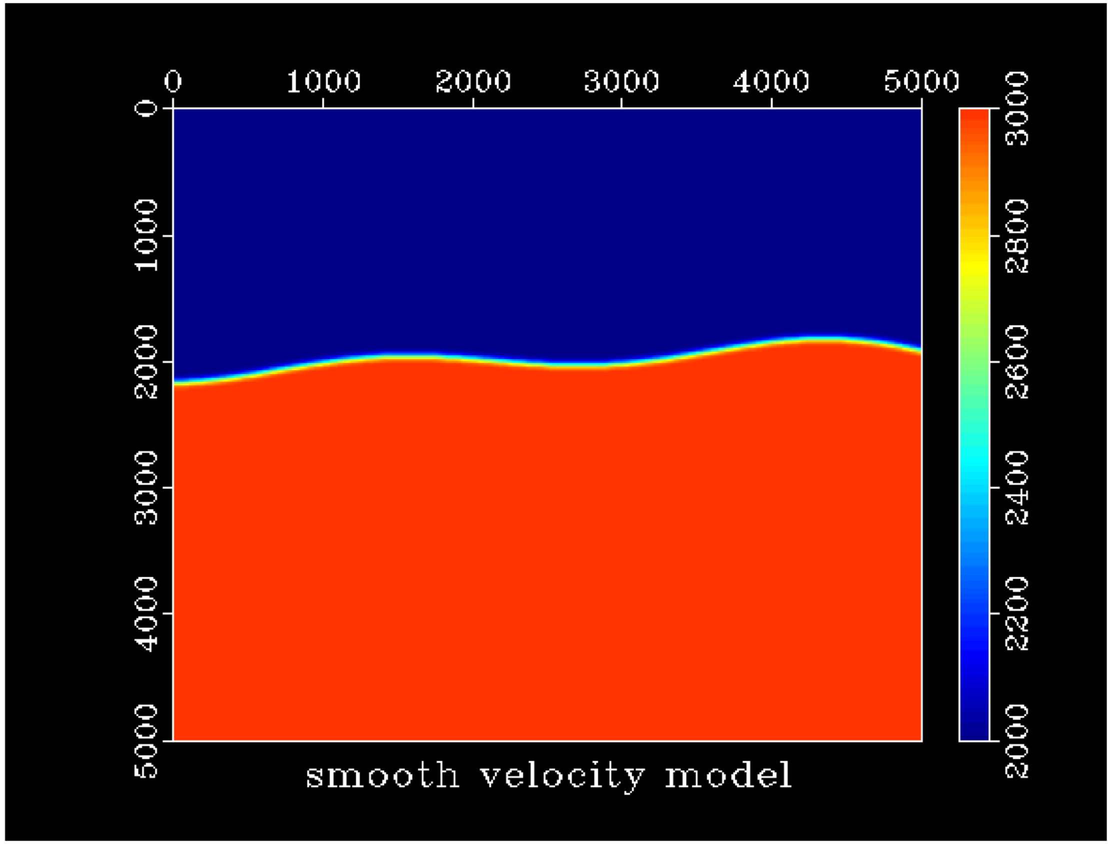


Numerical example 3 – Curve layer

True velocity model

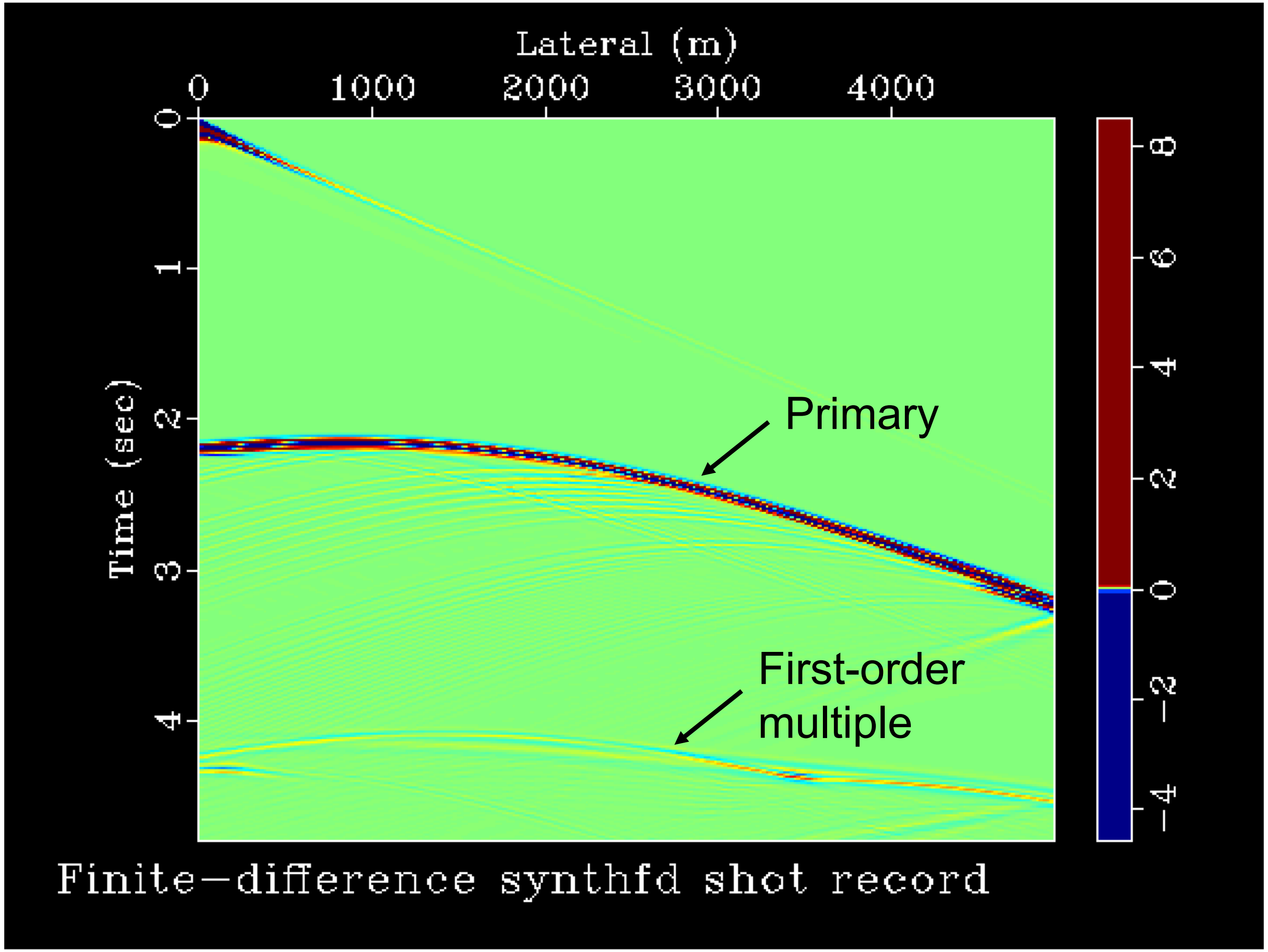


Smoothed velocity model



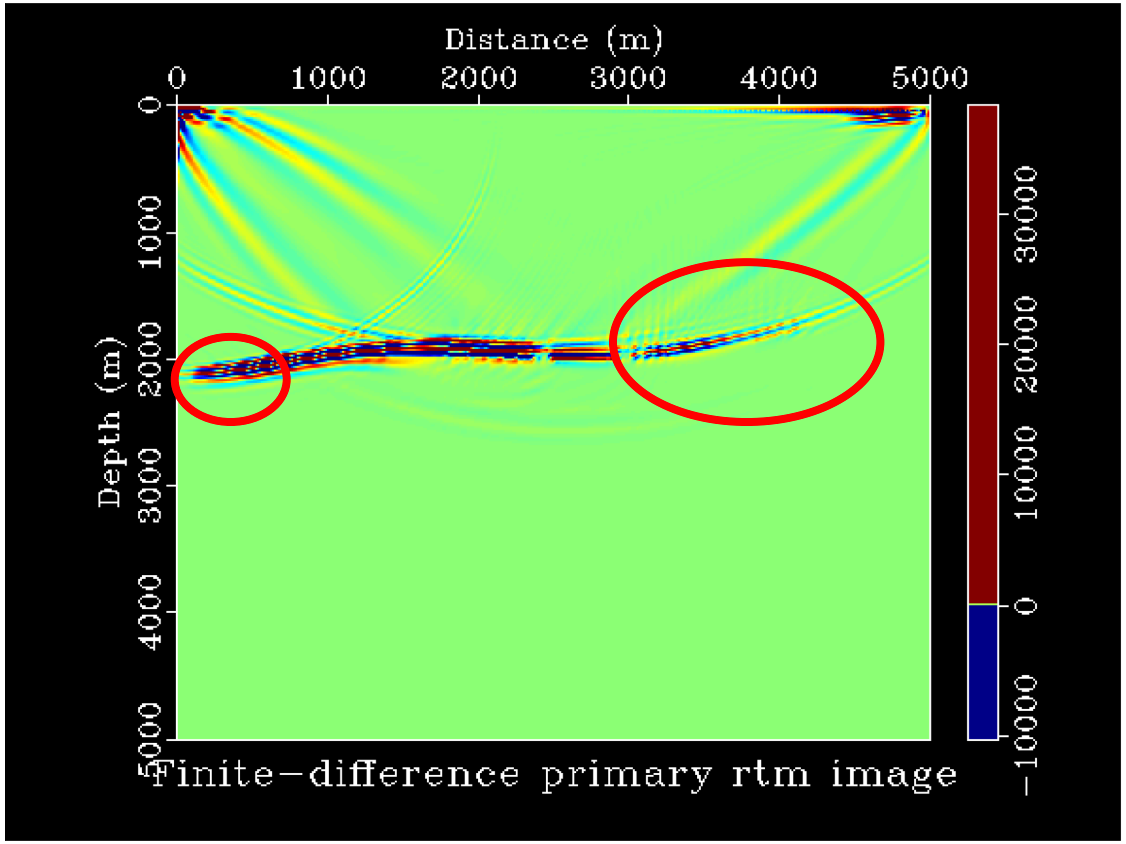
Synthetic shot record by finite-difference

Finite-difference shot record

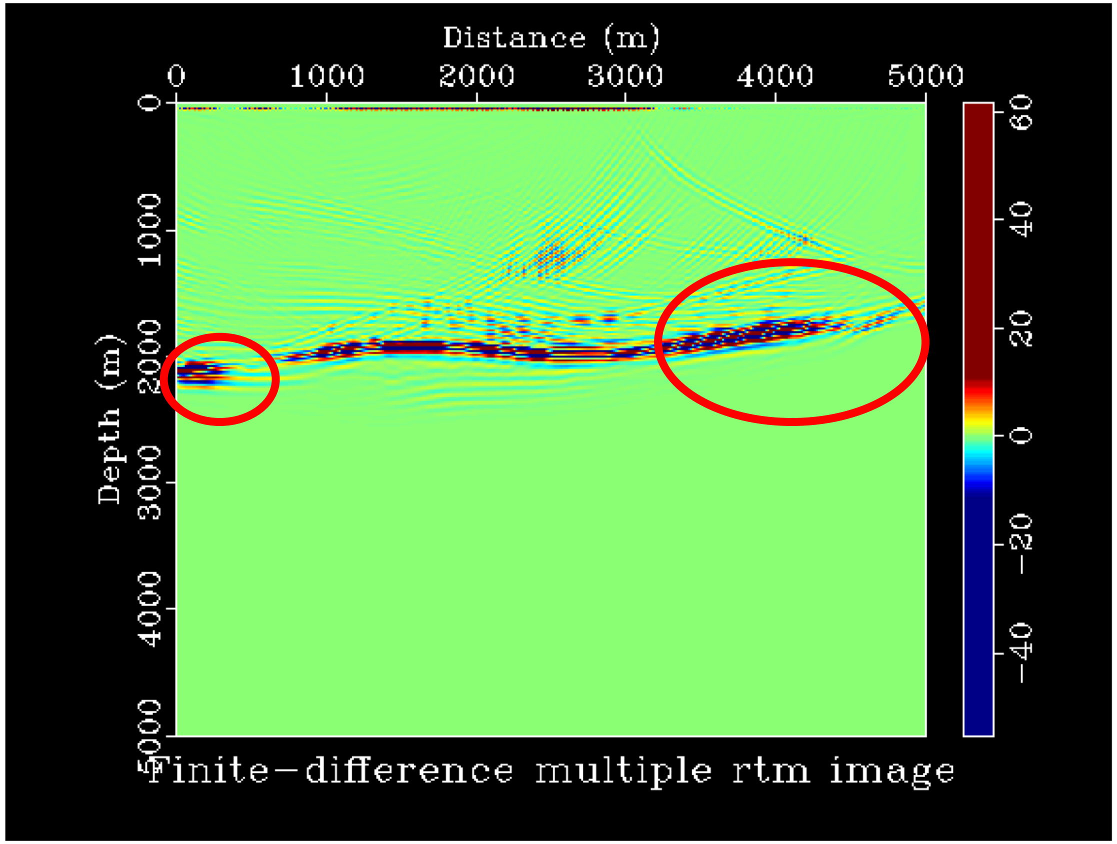


RTM of primary and first-order surface multiple

Finite-difference primary rtm image



Finite-difference multiple rtm image



Conclusion

Pros:

- There is no need to estimate the source wavelet
- RTM of first-order multiple has wider illumination
- A sparser distribution of sources or receivers can be applied to illuminate the subsurface

Cons:

- The initial velocity should be accurate
- The amplitude is not correct because of the amplitude attenuation and loss of high frequency
- RTM image of multiple is down-dip limited

Future work

- Pick out the multiples from the real data by surface-related multiple elimination (SRME) or Radon transform
- Least-squares migration scheme
- Consider the second-order surface multiple
- Apply complicated model
- Explore the method for proper imaging of internal multiples

Reference

[1]Berkhout, A. J. and D. J. Verschuur, 2016, Enriched seismic imaging by using multiple scattering: *The Leading Edge*, 35, no. 2, 128-133.

[2]Davydenko, M. and D. J. Verschuur, 2018, Including and using internal multiples in closed-loop imaging — Field data examples: *Geophysics*, 83, no. 4, 297-305.

[3]Kanasewich, E. R., 1973, Time sequence analysis in geophysics: University of Alberta Press.

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[5]Liu, Y., X. Liu and et al., 2016, Least-squares reverse time migration using controlled-order multiple reflections: *Geophysics*, 81, no. 5, 347-357.

[6]Lu, S., , F. Liu and et al., 2018, Least-squares full-wavefield migration: *The Leading Edge*, 37, no. 1, 46-51.

[7]Verschuur, D. J. et al., 2015, From removing to using multiples in closed-loop imaging: *The Leading Edge*, 34, no. 7, 744-759.

[8]Zhang, D. and G. T. Schuster, 2014, Least-squares reverse time migration of multiples: *Geophysics*, 79, no. 1, 11-21.

Questions?

Thank you