Early-arrival waveform inversion for

Xukai Shen

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Outline

1. Motivation
2. Theory
3. Synthetic Examples
4. Conclusions

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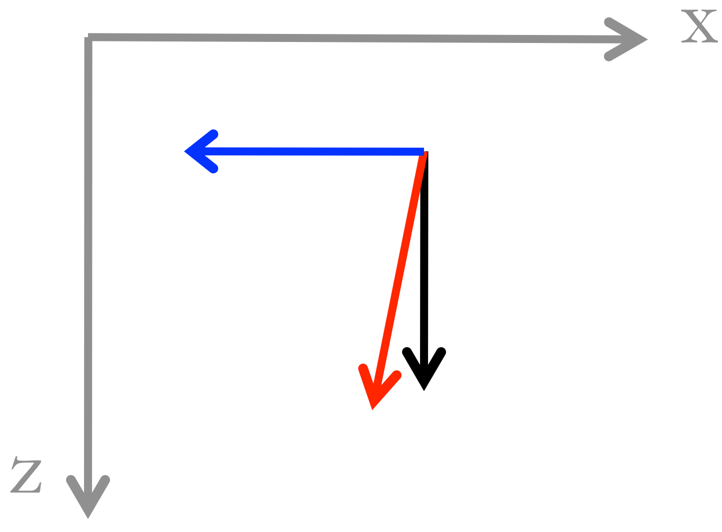
Introducing anisotropic parameters

Velocity vector diagram



v Vertical velocity

ε Anisotropic parameter

δ Anisotropic parameter

Introducing anisotropic parameters

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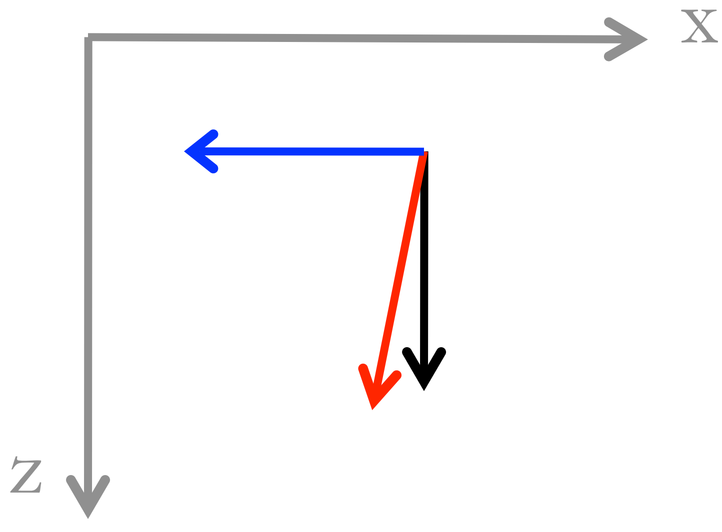

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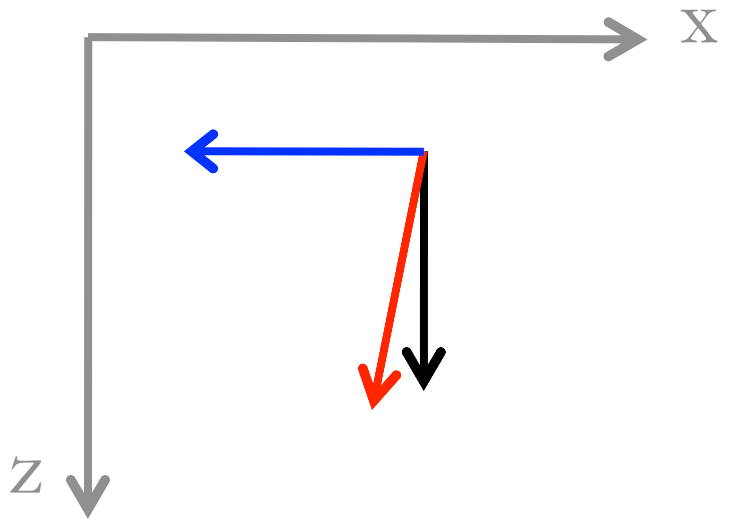

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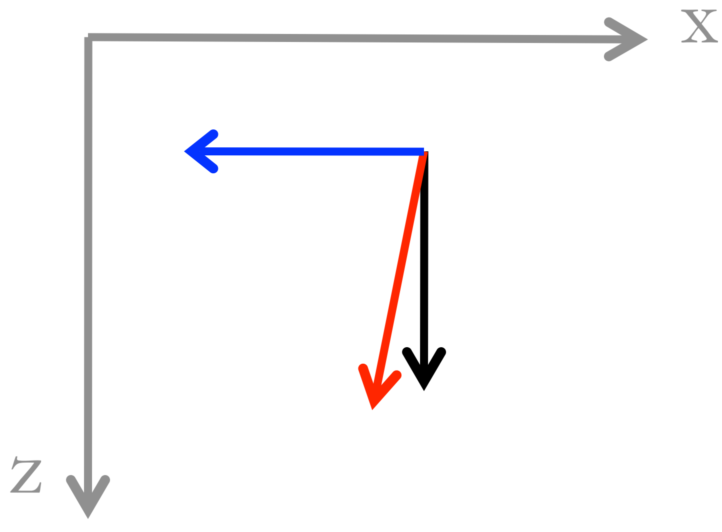

v **Vertical velocity**

ε Anisotropic parameter

δ **Anisotropic parameter**

Early Arrival Full Waveform Inversion (EAFWI)

$$\min f(\mathbf{v})$$

where

$$f(\mathbf{v}) = \sum_{s,r,t} \left\| \mathbf{d}_{\mathbf{ea,obs}} - \mathbf{d}_{\mathbf{ea,mod}}(\mathbf{v}) \right\|^2$$

$\mathbf{v}$	Near surface velocity
$\mathbf{d}_{\mathbf{ea,obs}}$	Observed early arrivals
$\mathbf{d}_{\mathbf{ea,mod}}$	Forward modeled early arrivals

EAFWI

How does isotropic inversion of anisotropic data look like?

$$\min f(\mathbf{v})$$

where

$$f(\mathbf{v}) = \sum_{s,r,t} \left\| \mathbf{d}_{\mathbf{ea,obs}} - \mathbf{d}_{\mathbf{ea,mod}}(\mathbf{v}) \right\|^2$$

$\mathbf{v}$	Near surface velocity
$\mathbf{d}_{\mathbf{ea,obs}}$	Observed early arrivals
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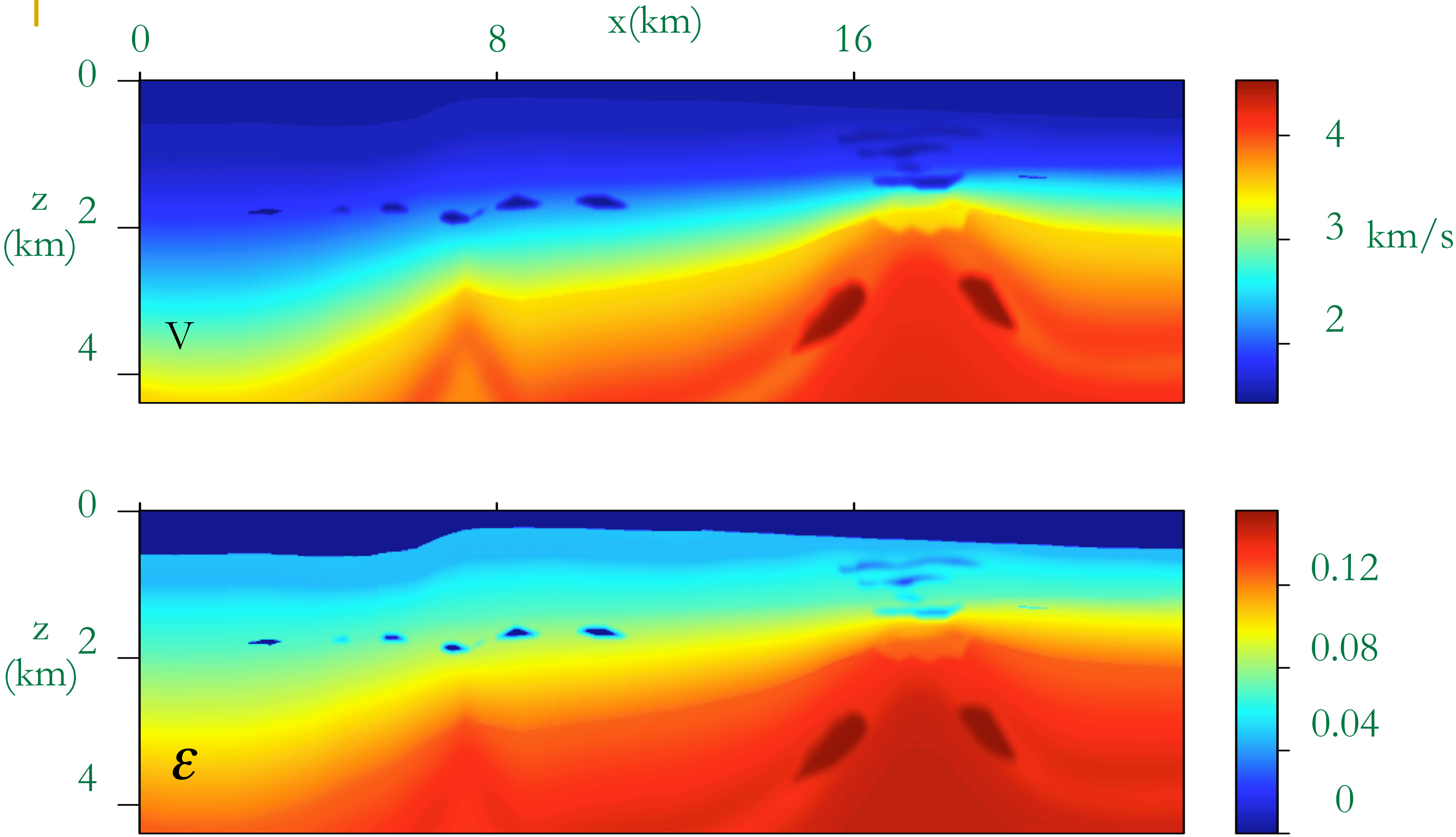
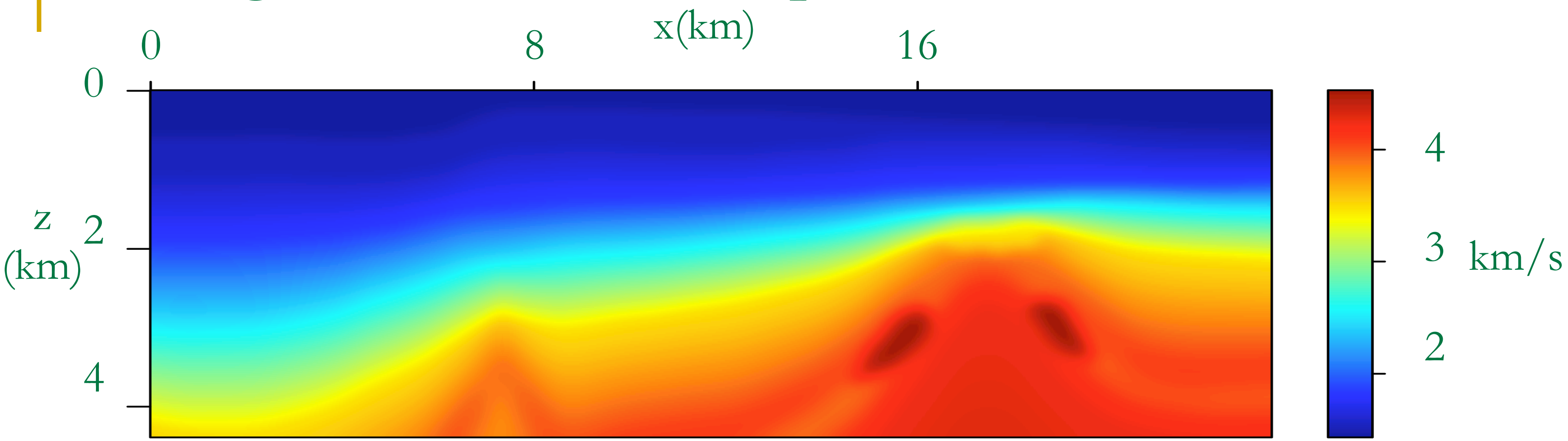
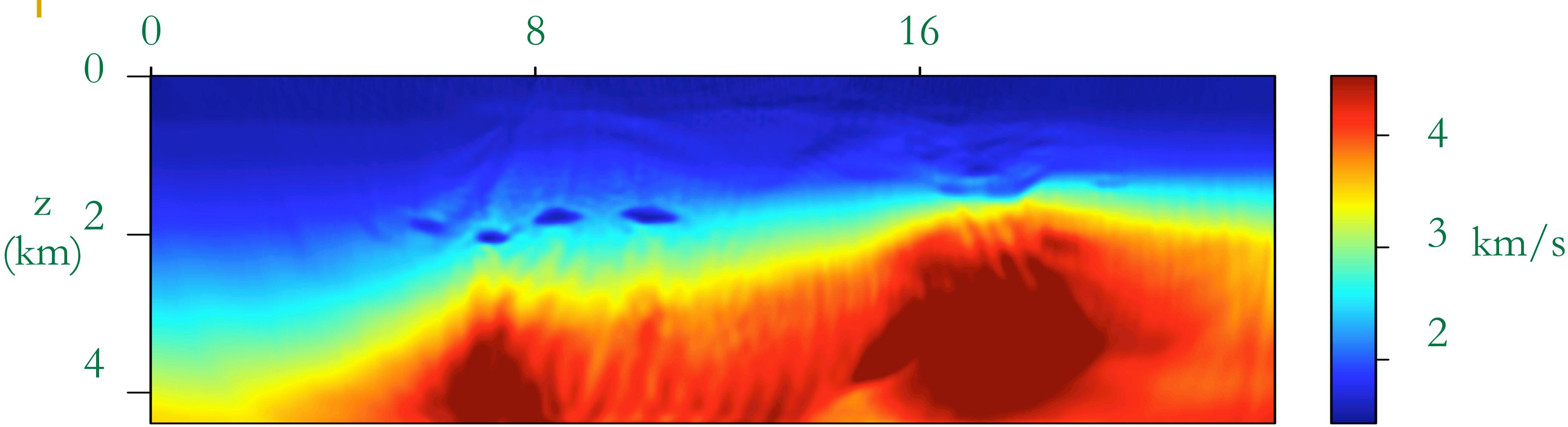
True anisotropic model



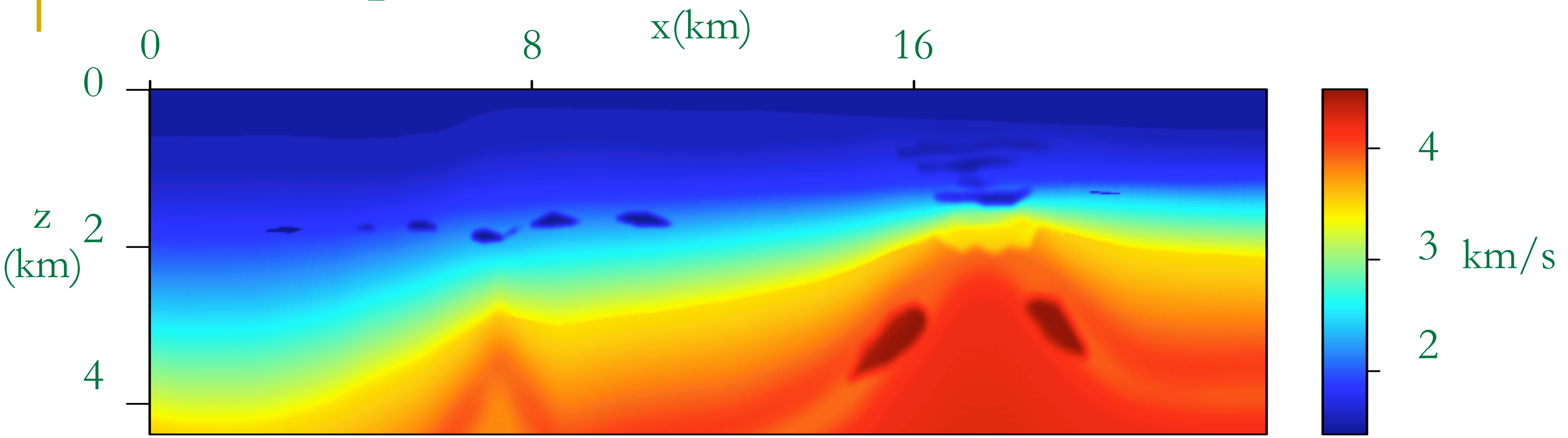
Starting velocity for isotropic inversion



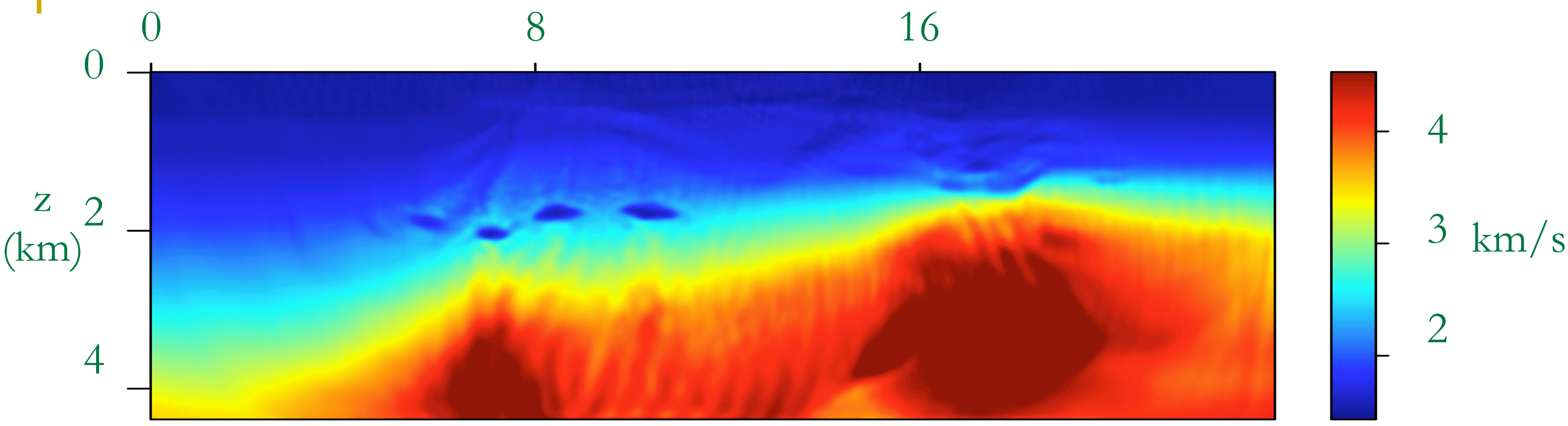
Final velocity from isotropic inversion



True isotropic velocity



Final velocity from isotropic inversion



How does isotropic inversion of anisotropic data look like?

Vertical stretch of true velocity model !

Multi-parameter Waveform Inversion strategy:

Serial inversion (Gholami et al., 2011)

Joint inversion (Plessix and Rynja, 2010; Plessix and Cao, 2011)

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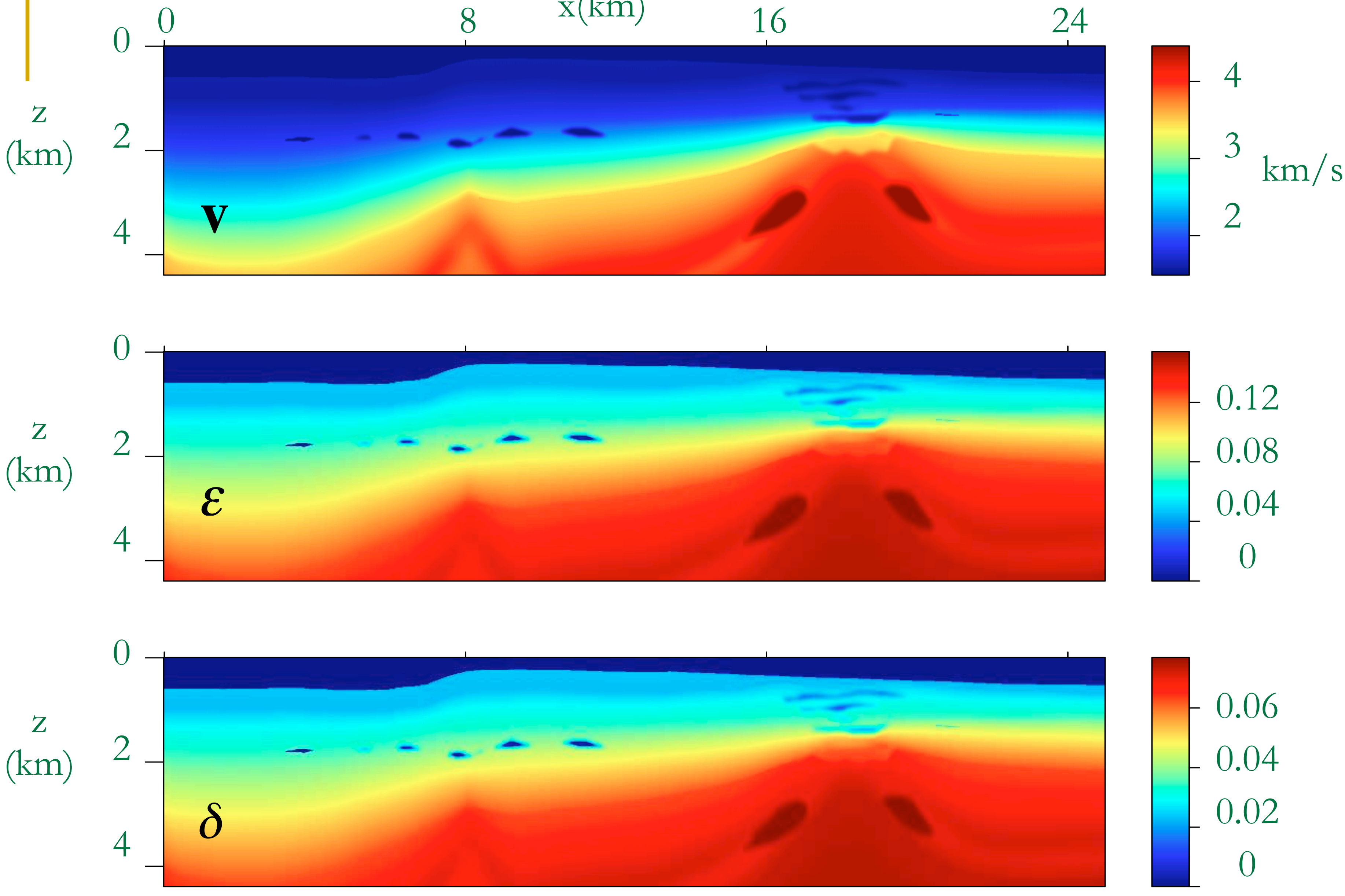
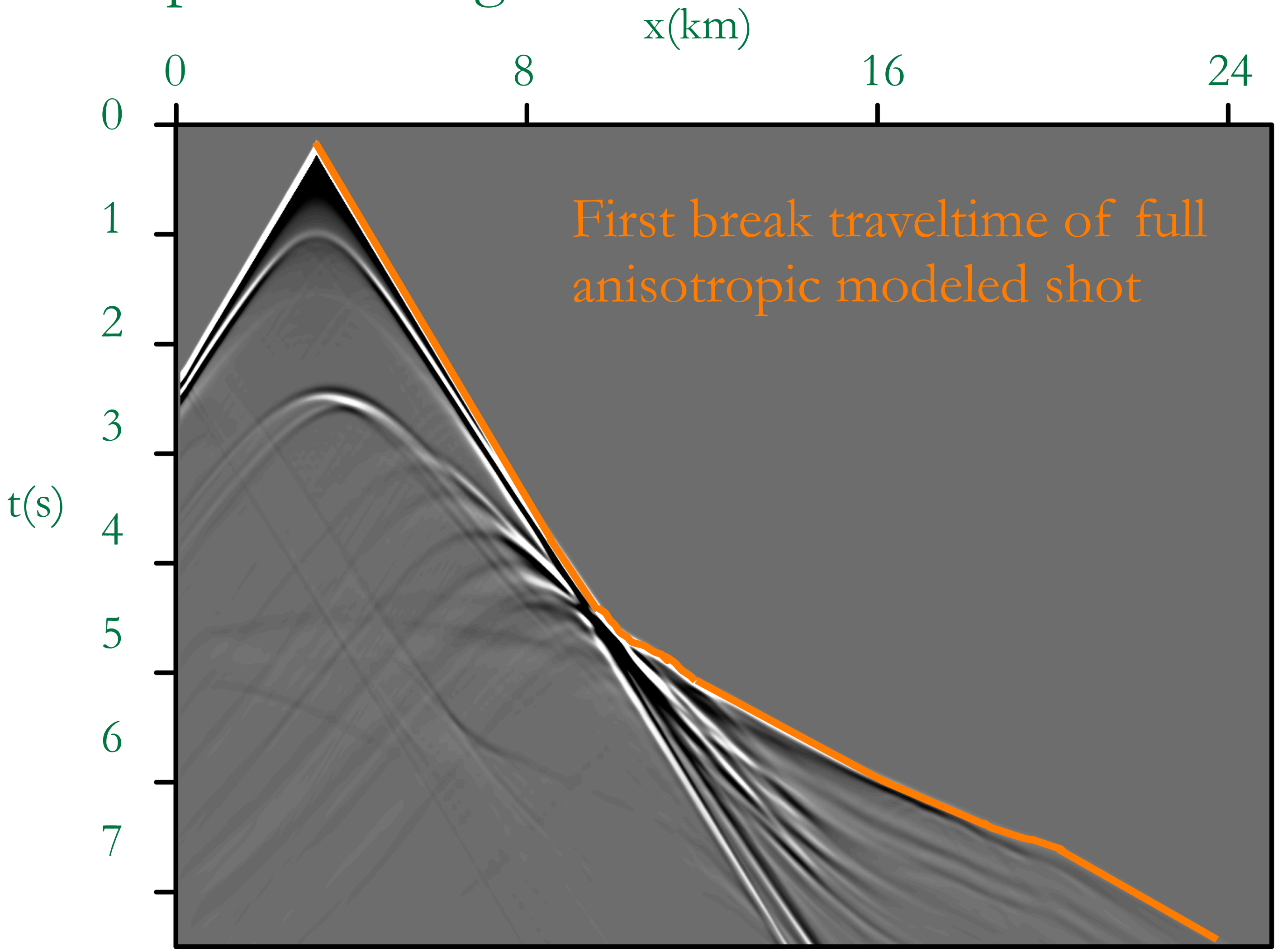
Data sensitivity to model perturbation

$$\mathbf{d}_{\mathbf{ea,mod}}(\mathbf{v},\varepsilon,\delta)$$

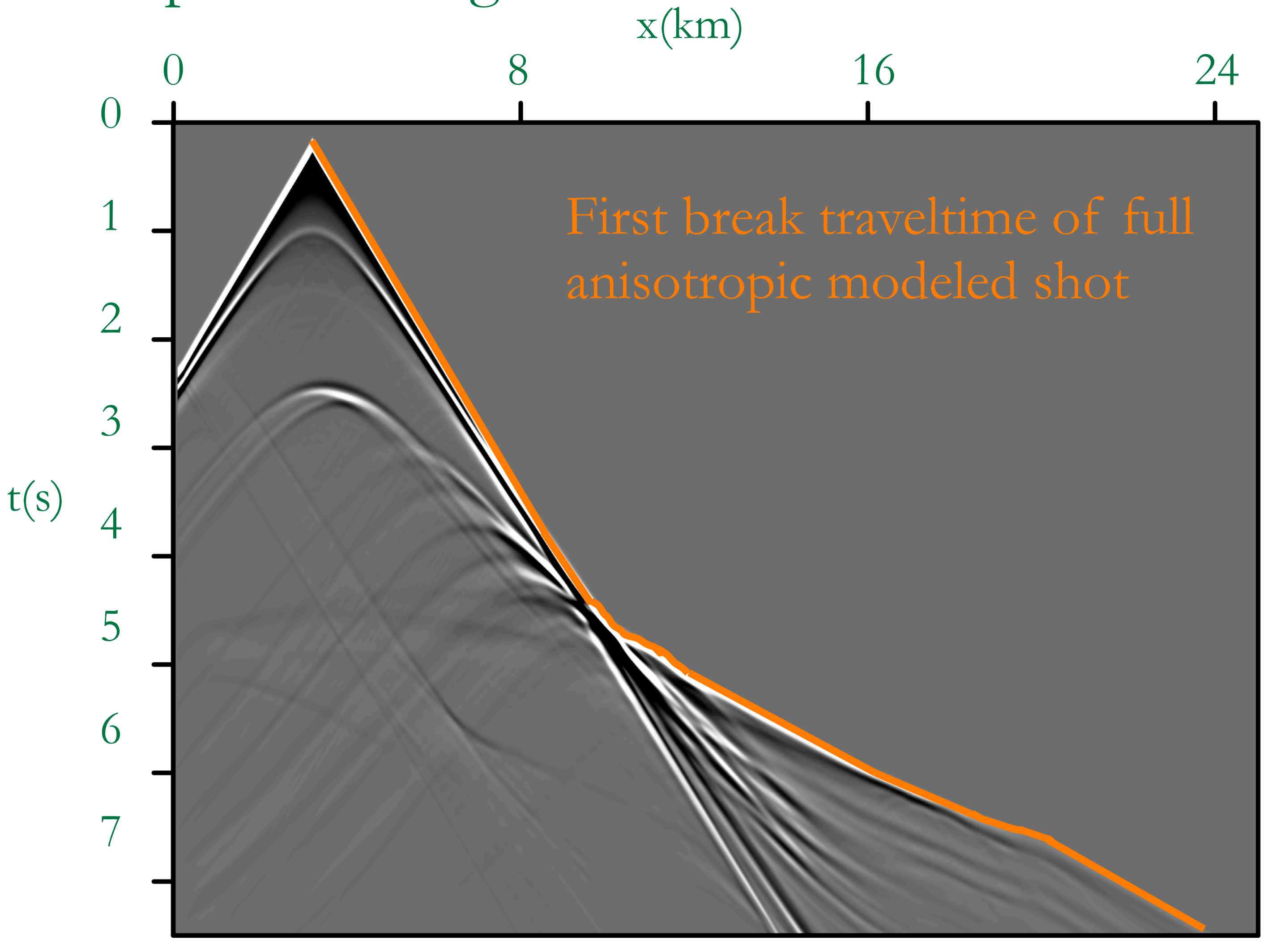
$\mathbf{v}$	Vertical near surface velocity
ε	Anisotropic parameter
δ	Anisotropic parameter
$\mathbf{d}_{\mathbf{ea,mod}}$	Modeled early arrivals


x(km)
0
8
16
24
z
(km)
0
2
4
v
4
3
2
km/s
ε
0.12
0.08
0.04
0
δ
0.06
0.04
0.02
0

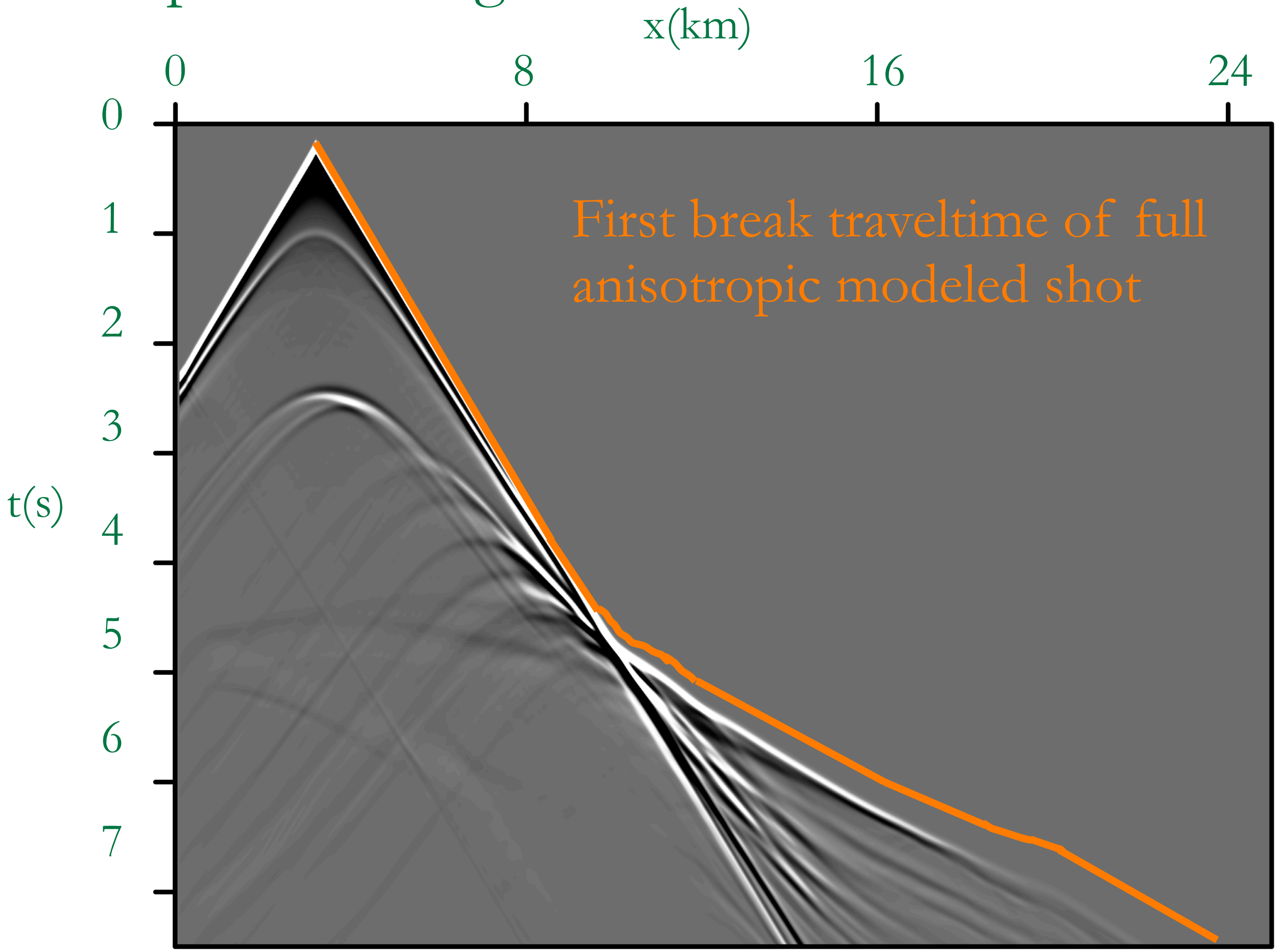
Anisotropic modeling with

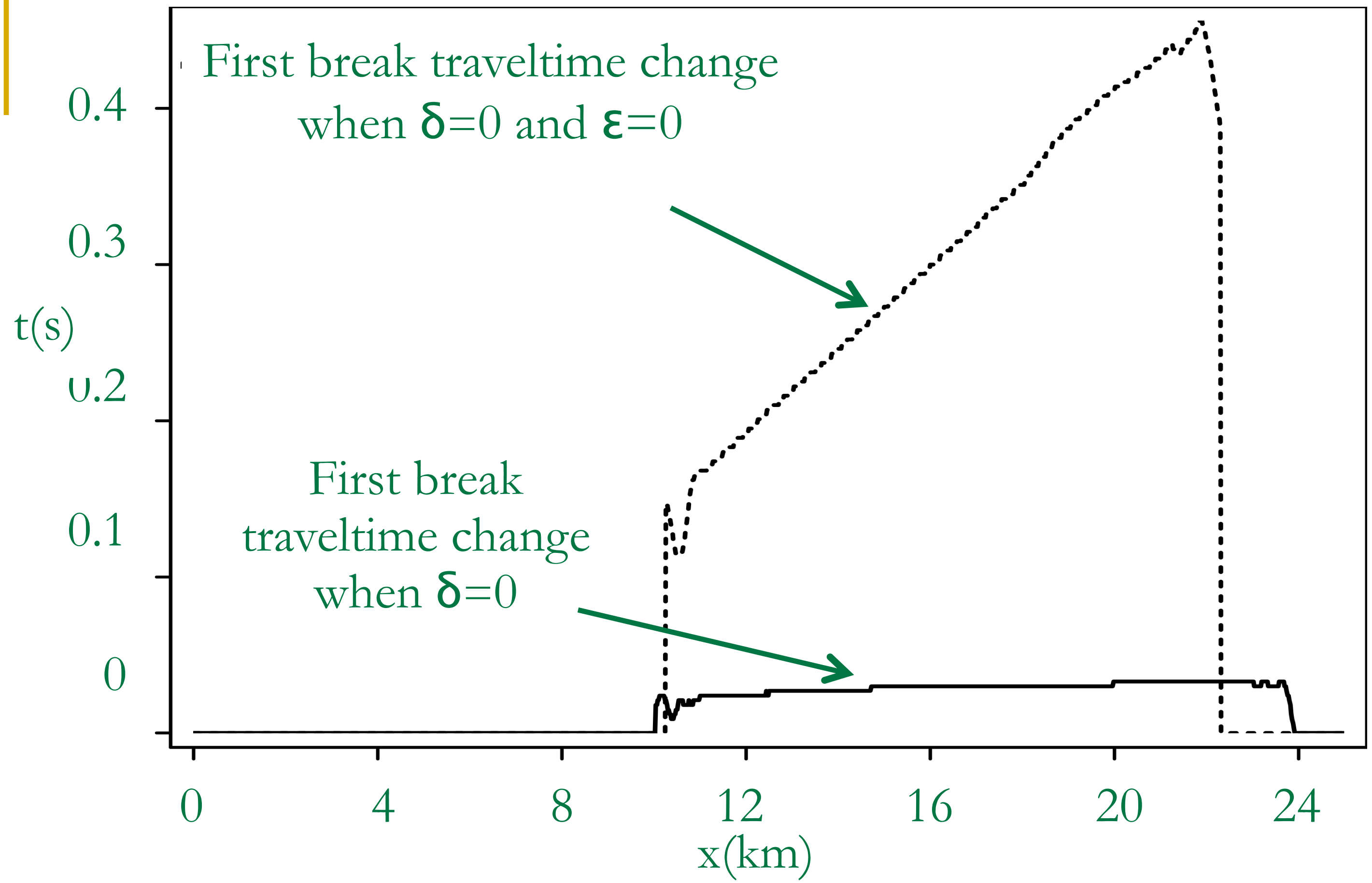


Anisotropic modeling with δ=0

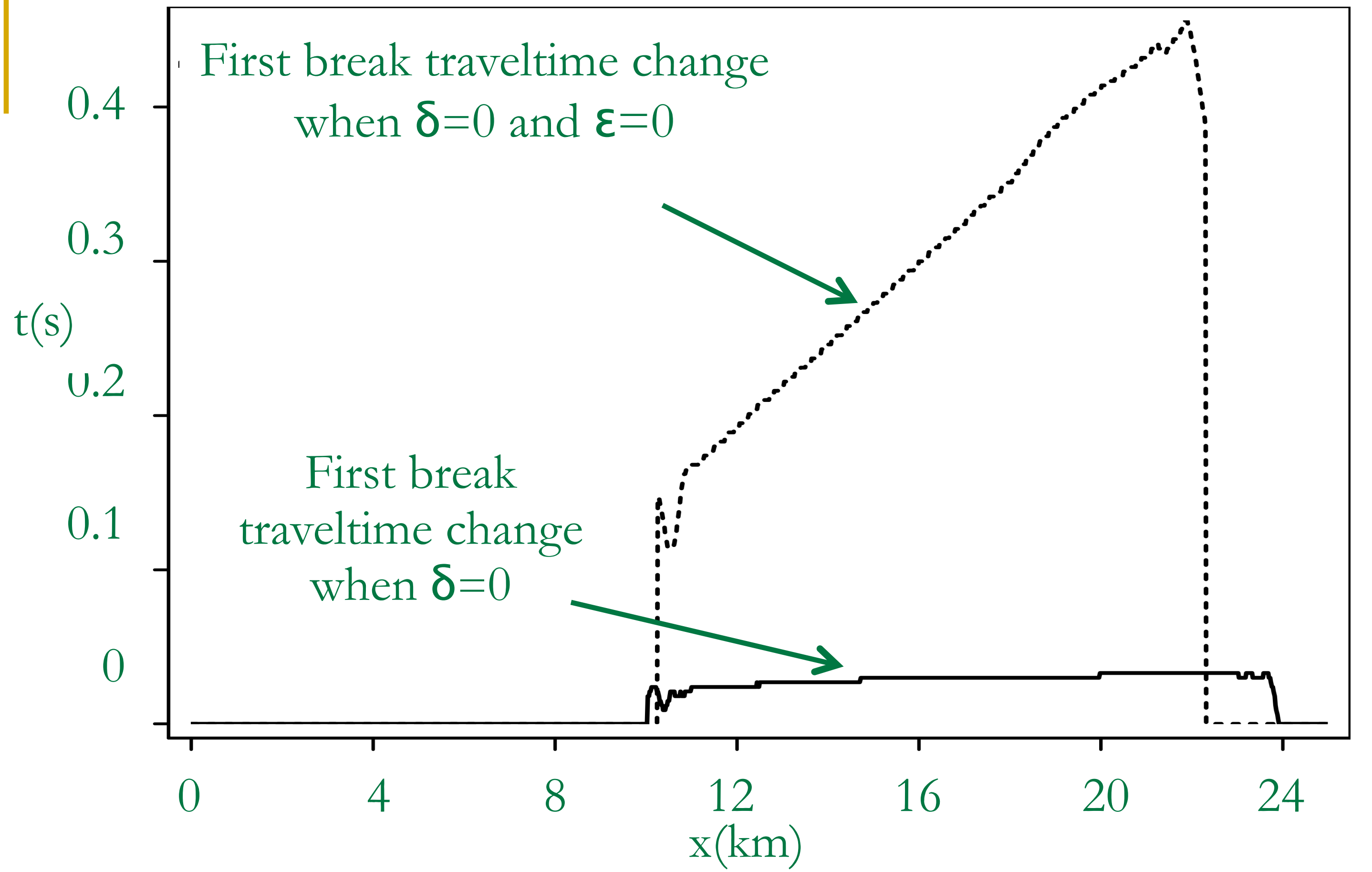


Anisotropic modeling with δ=0 and ε=0





First break traveltime change when δ=0 and ε=0
First break traveltime change when δ=0
t(s)
0.4
0.3
0.2
0.1
0
0
4
8
12
16
20
24
x(km)



Early-arrivals are more sensitive to **v** and **ε**

Inversion strategy

Joint inversion of **v** and **ε**, fixing **δ**

Inversion strategy

Joint inversion of **v** and **ε**, fixing **δ**

Acoustic anisotropic wave equation

$$\frac{\partial^2 p}{\partial t^2} = v^2(1+2\varepsilon)\frac{\partial^2 p}{\partial x^2} + v^2(1+2\delta)\frac{\partial^2 r}{\partial z^2}$$

$$\frac{\partial^2 r}{\partial t^2} = v^2(1+2\delta)\frac{\partial^2 p}{\partial x^2} + v^2\frac{\partial^2 r}{\partial z^2}$$

v	Vertical near surface velocity
ε	Anisotropic parameter
δ	Anisotropic parameter
p	Horizontal pressure wavefield
r	Vertical pressure wavefield

Parameterization choices

Straightforward

$$m_1 = v^{-2}$$

$$m_2 = 1 + 2\varepsilon$$

Velocity

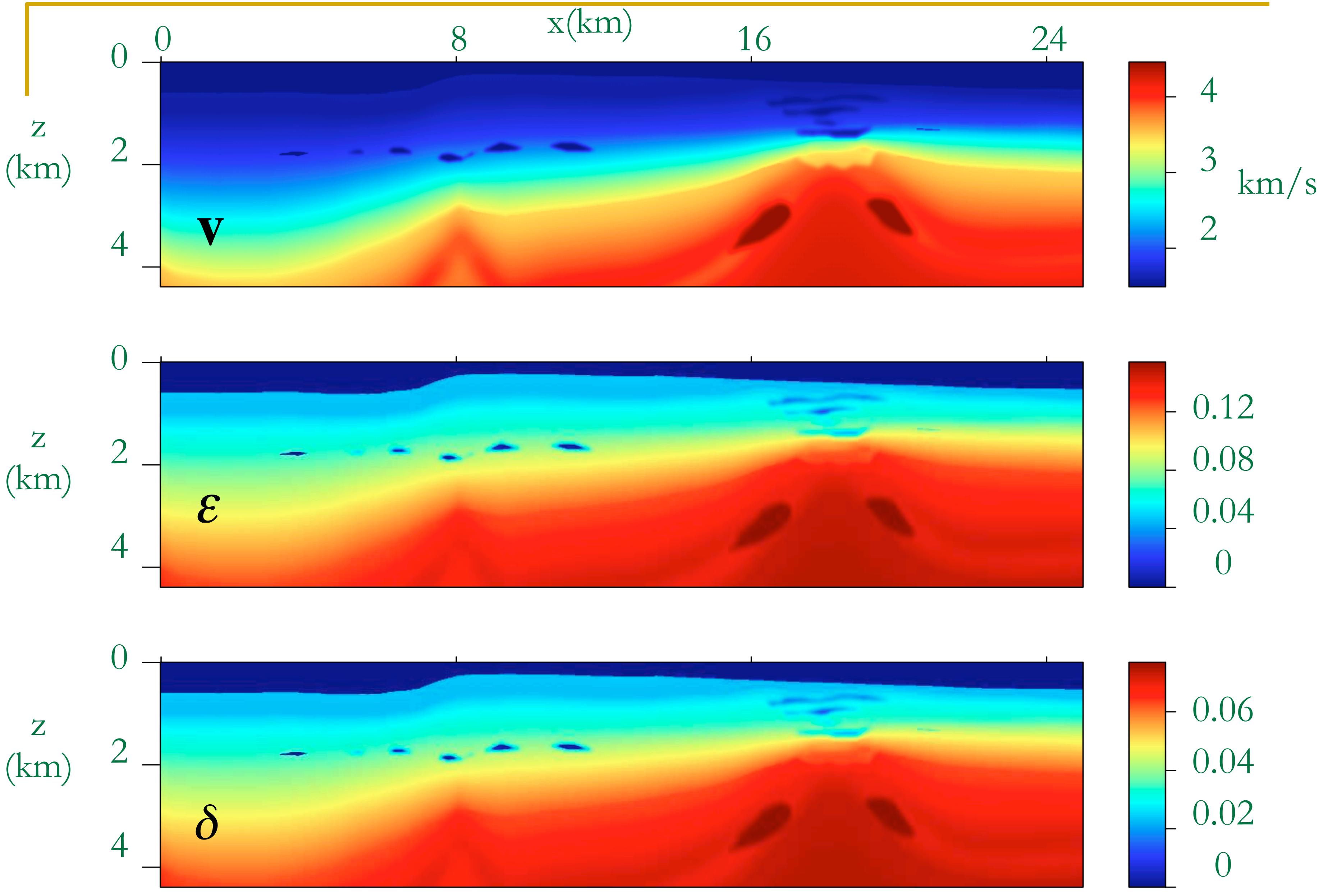
$$m_1 = v^2$$

$$m_2 = {v_h}^2 = v^2(1 + 2\varepsilon)$$

Logarithm slowness

$$m_1 = \log(v^{-2})$$

$$m_2 = 1 + 2\varepsilon$$


x(km)
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16
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z
(km)
0
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v
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4
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2
ε
0.12
0.08
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δ
0.06
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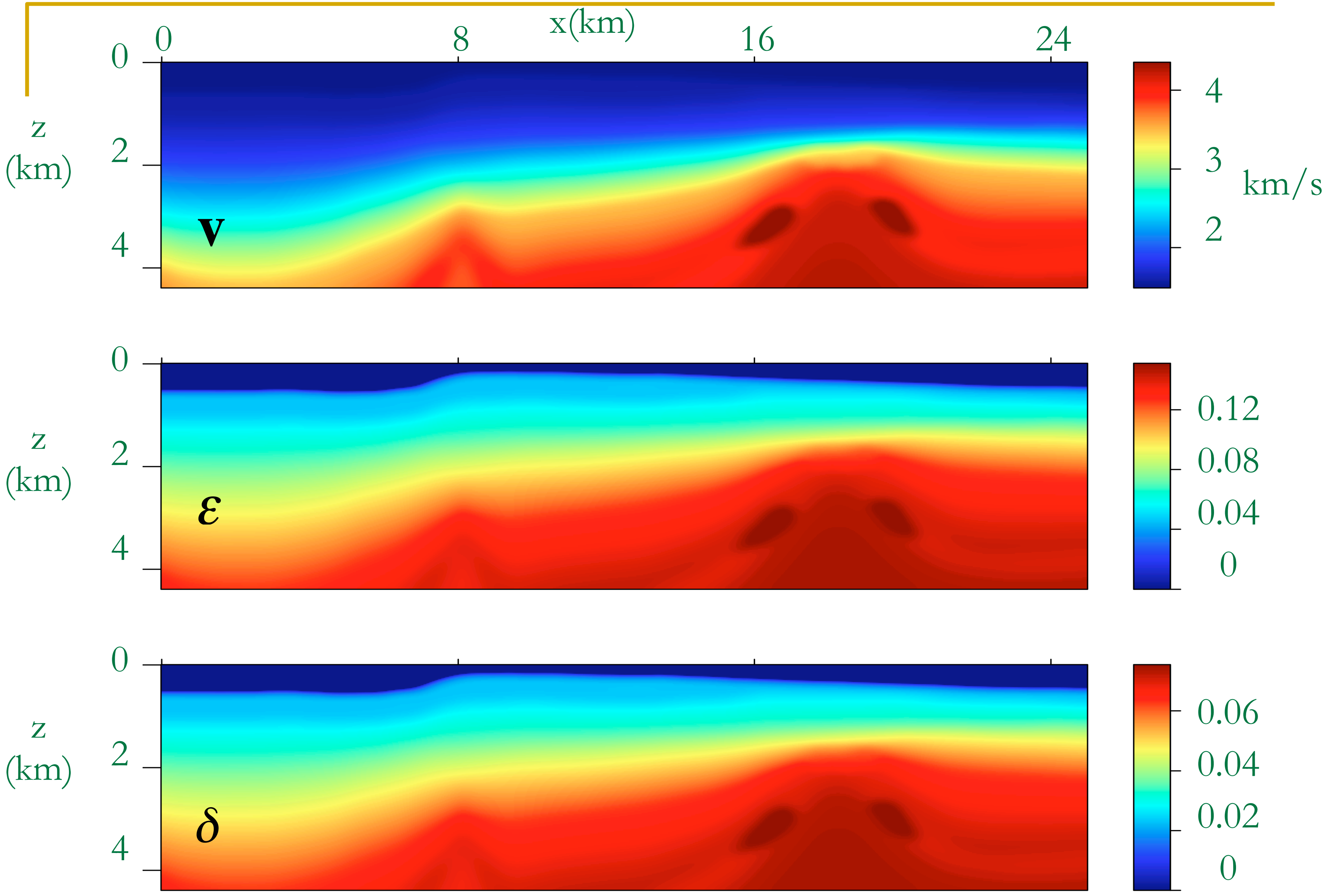
0.02
0


x(km)
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8
16
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0
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4
v
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2
km/s
ε
0.12
0.08
0.04
0
δ
0.06
0.04
0.02
0

Relative sensitivity kernel evaluation

$$k_{m_i} = \Delta m_i / m_i$$

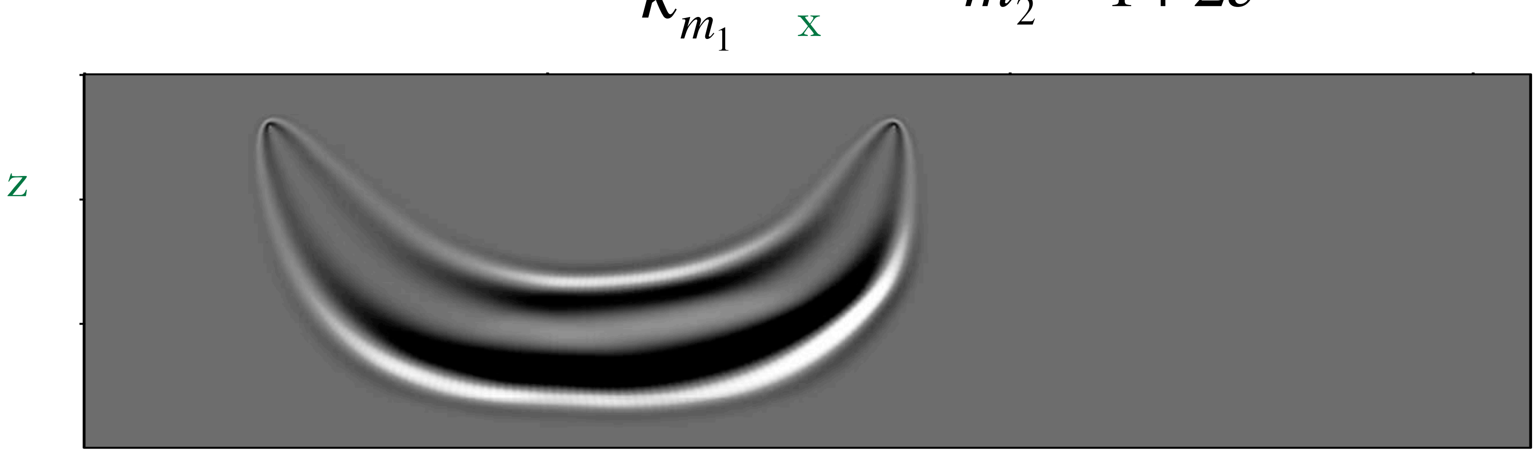
Δm_i Gradient of model component *i*

Straightforward parameterization

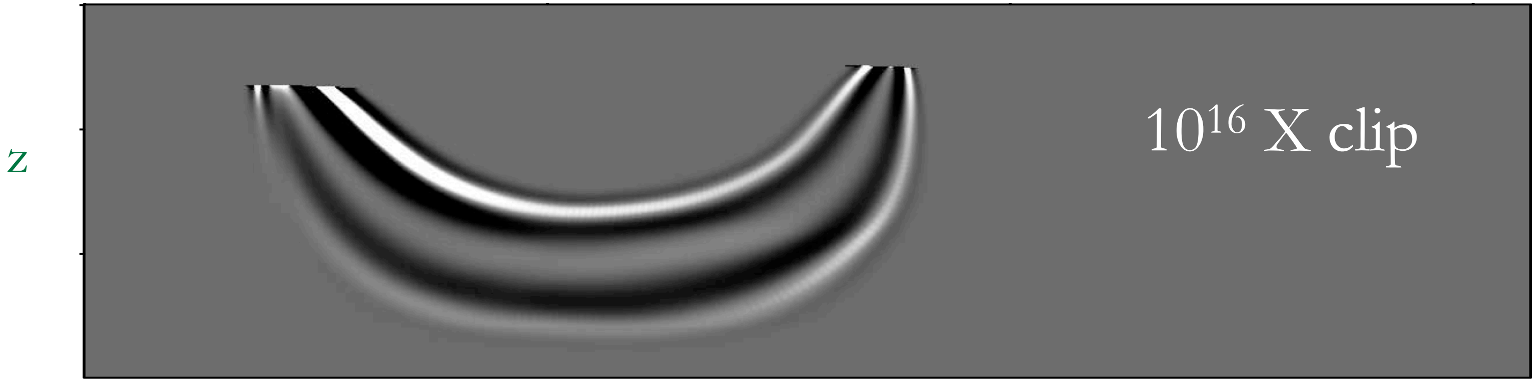
$$m_1 = v^{-2}$$

$$m_2 = 1 + 2\varepsilon$$

k_{m_1}



k_{m_2}



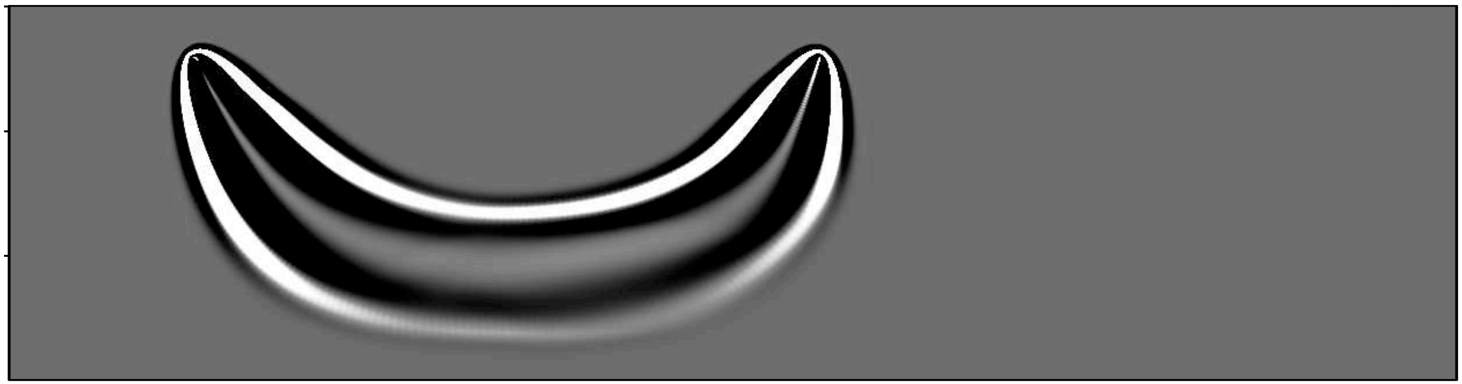
Velocity parameterization

$$m_1 = v^2$$

$$m_2 = v_h^{\ 2} = v^2(1+2\varepsilon)$$

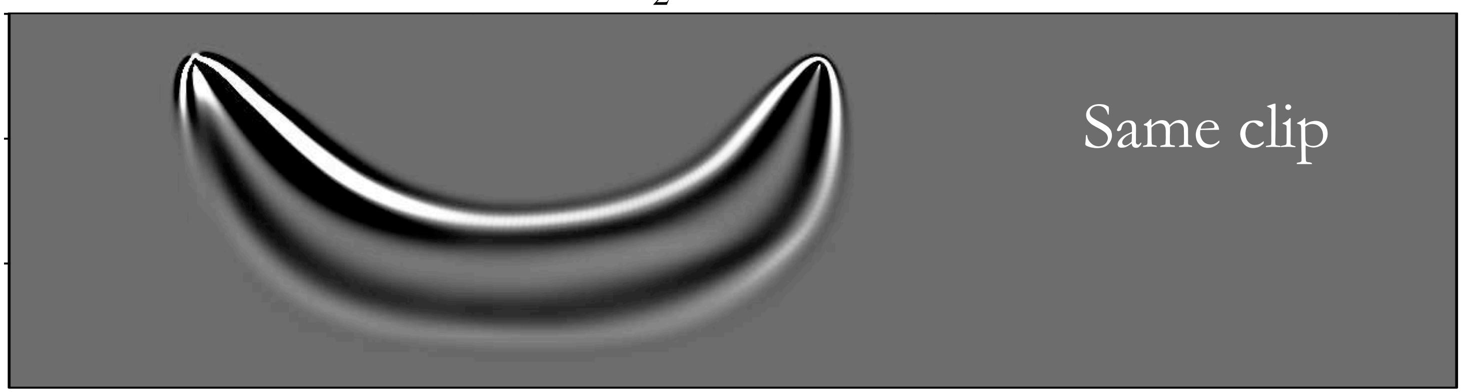
k_{m_1} x

z



k_{m_2}

z

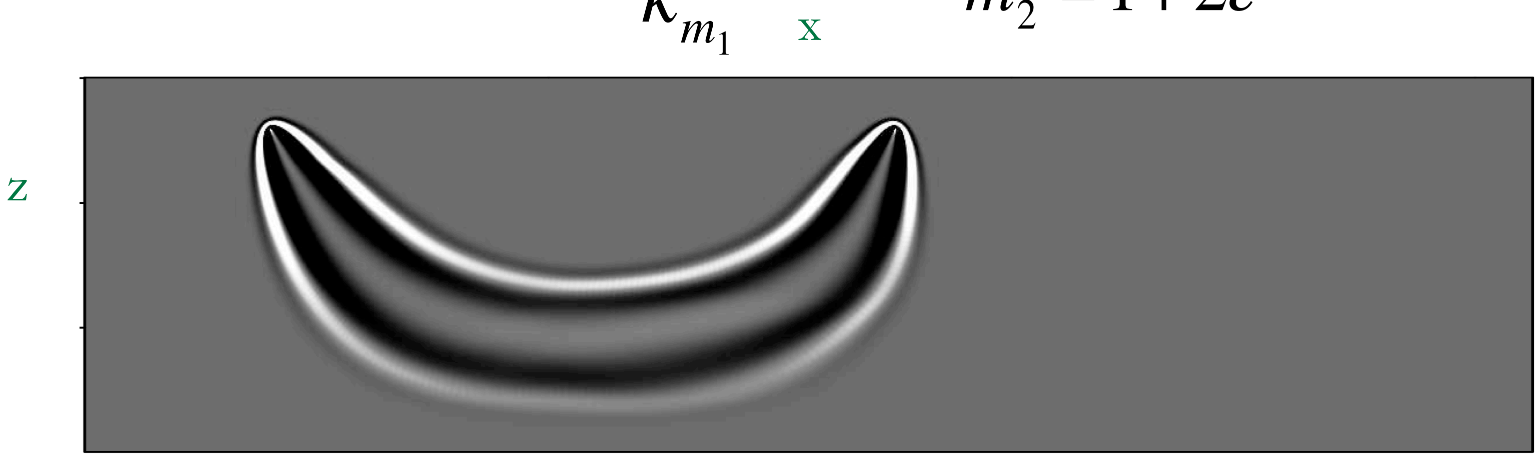


Logarithm slowness parameterization

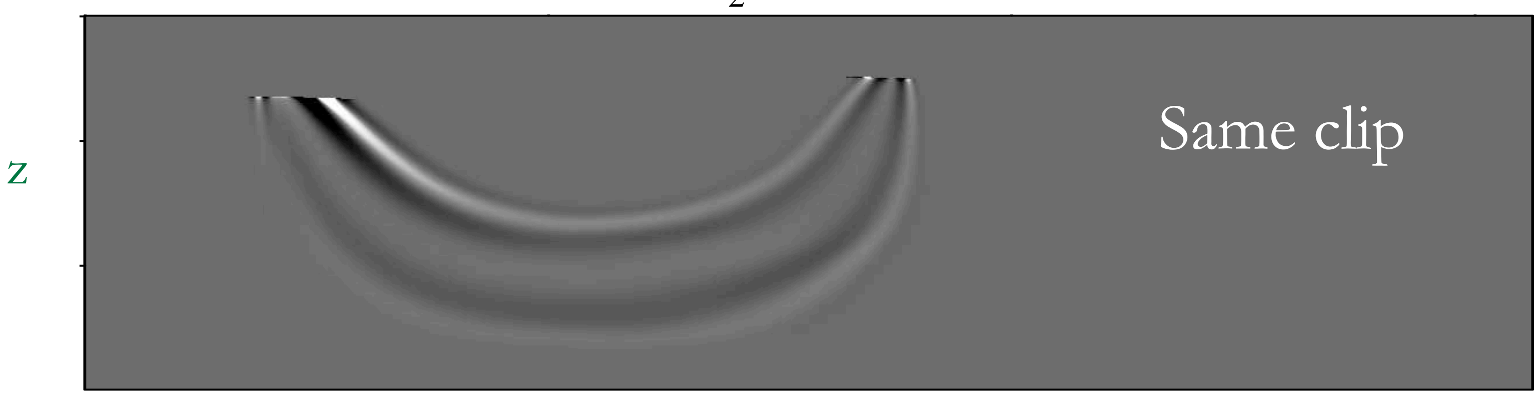
$$m_1 = \log(v^{-2})$$

$$m_2 = 1 + 2\varepsilon$$

k_{m_1}



k_{m_2}



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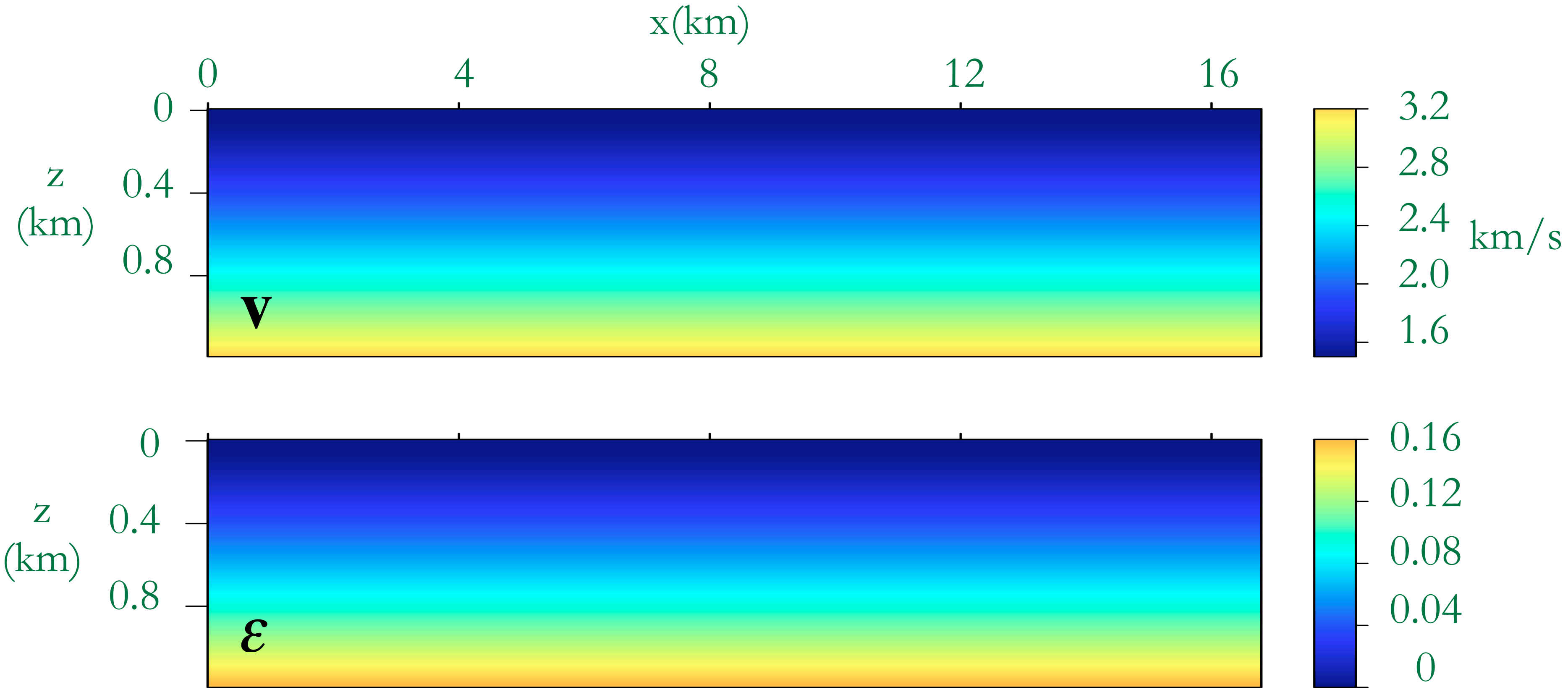
Background model



Acquisition geometry

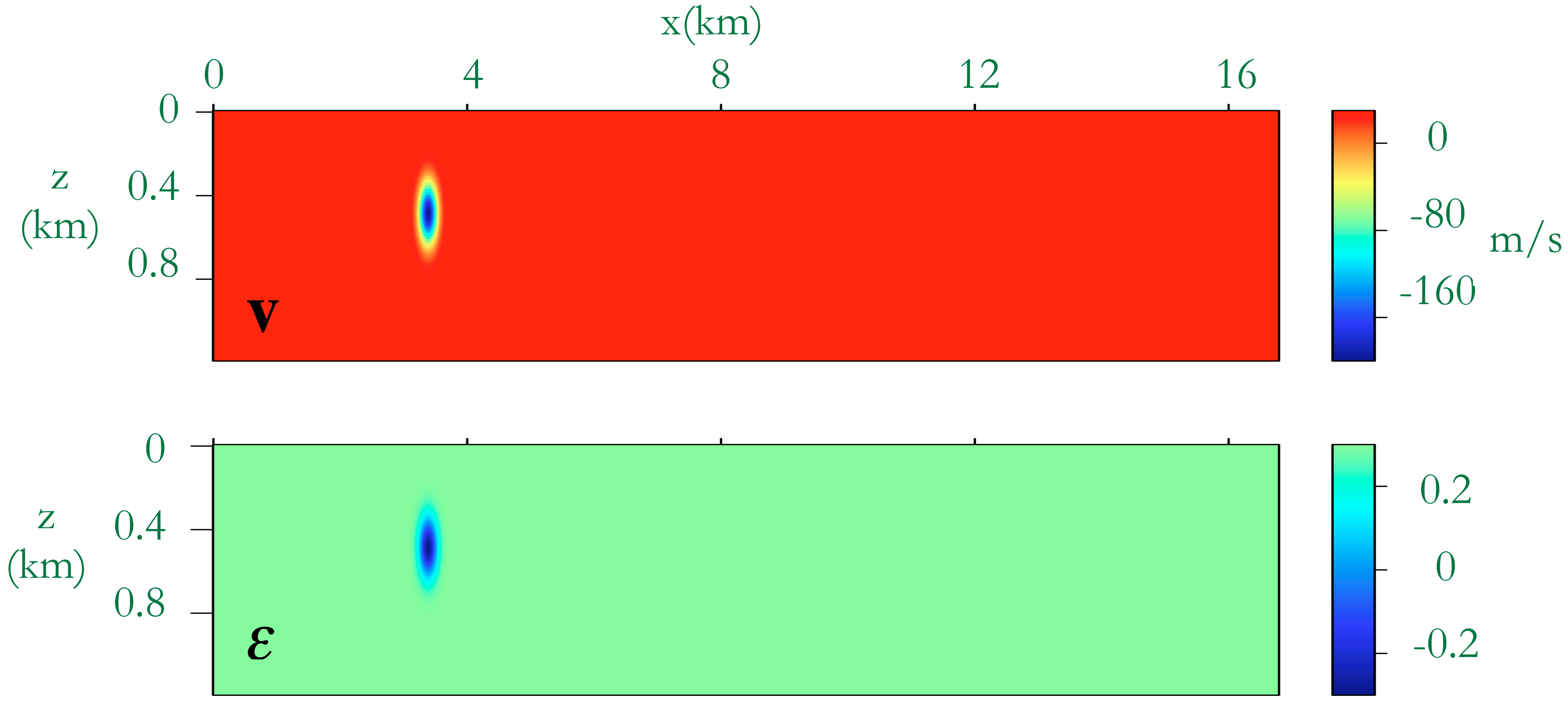
1120 *80 grid points, 15 m spacing

64 shots, 225 meter spacing

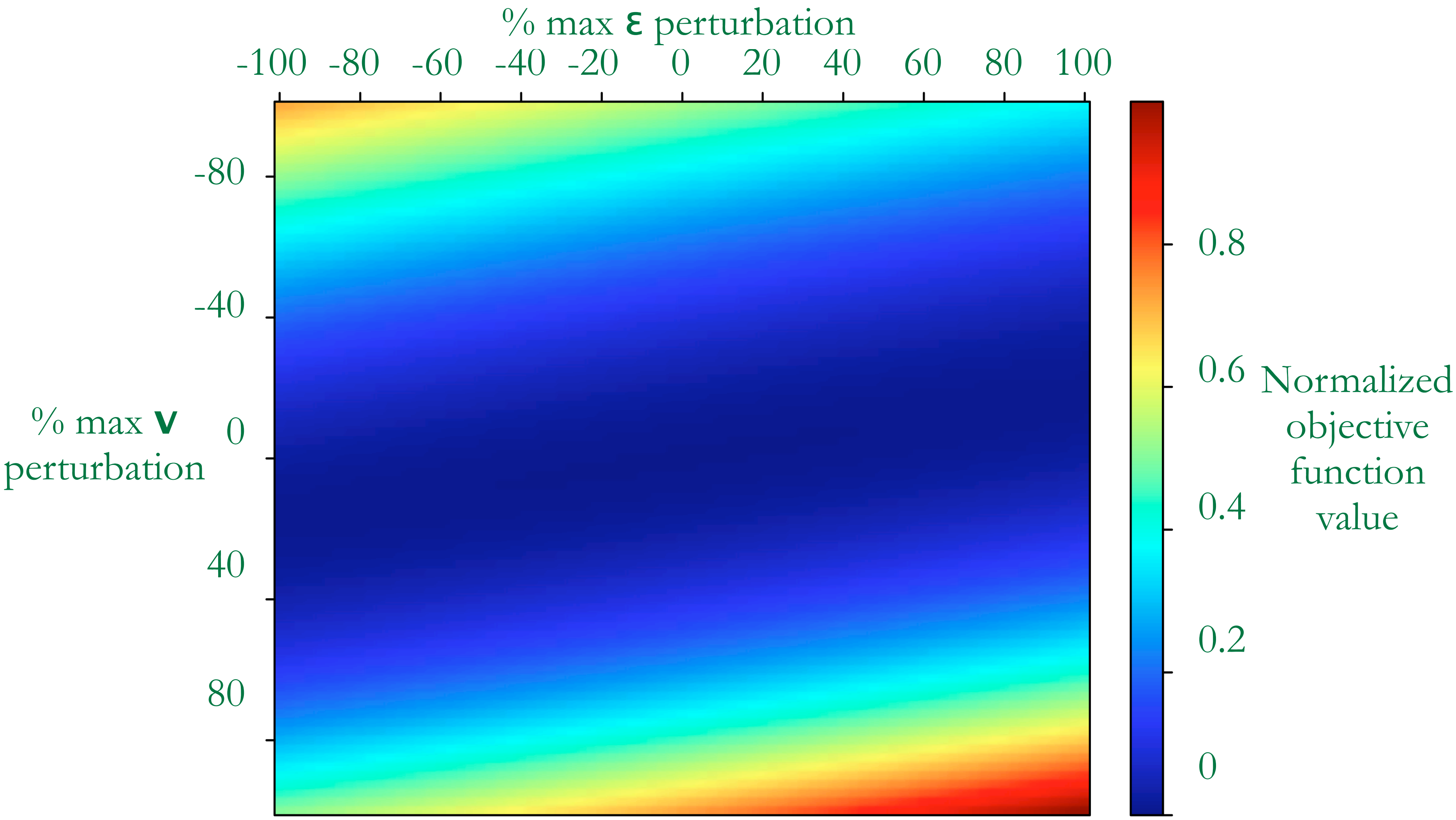
7Hz peak frequency source

Receivers everywhere on the surface

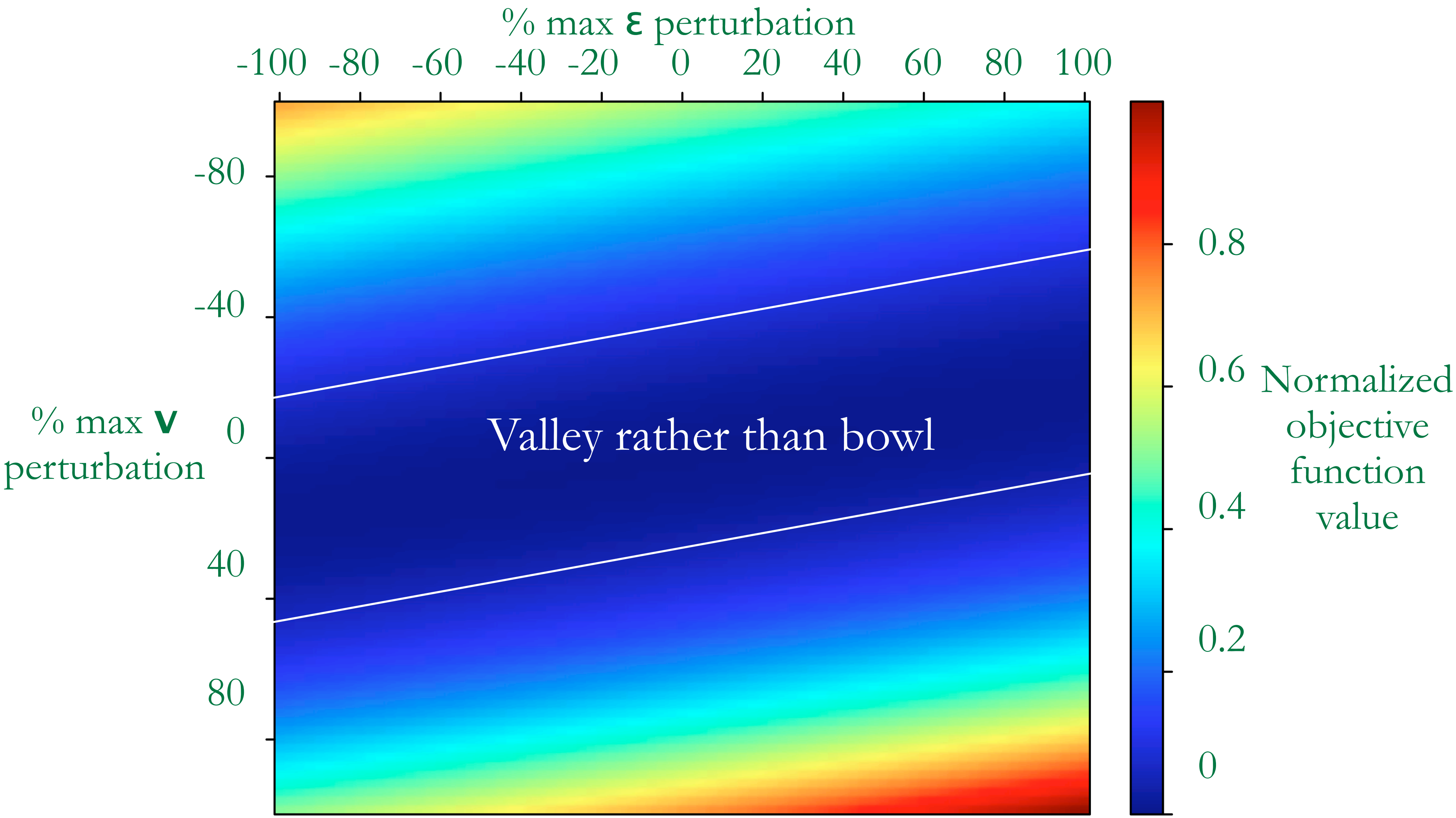
Maximum perturbation



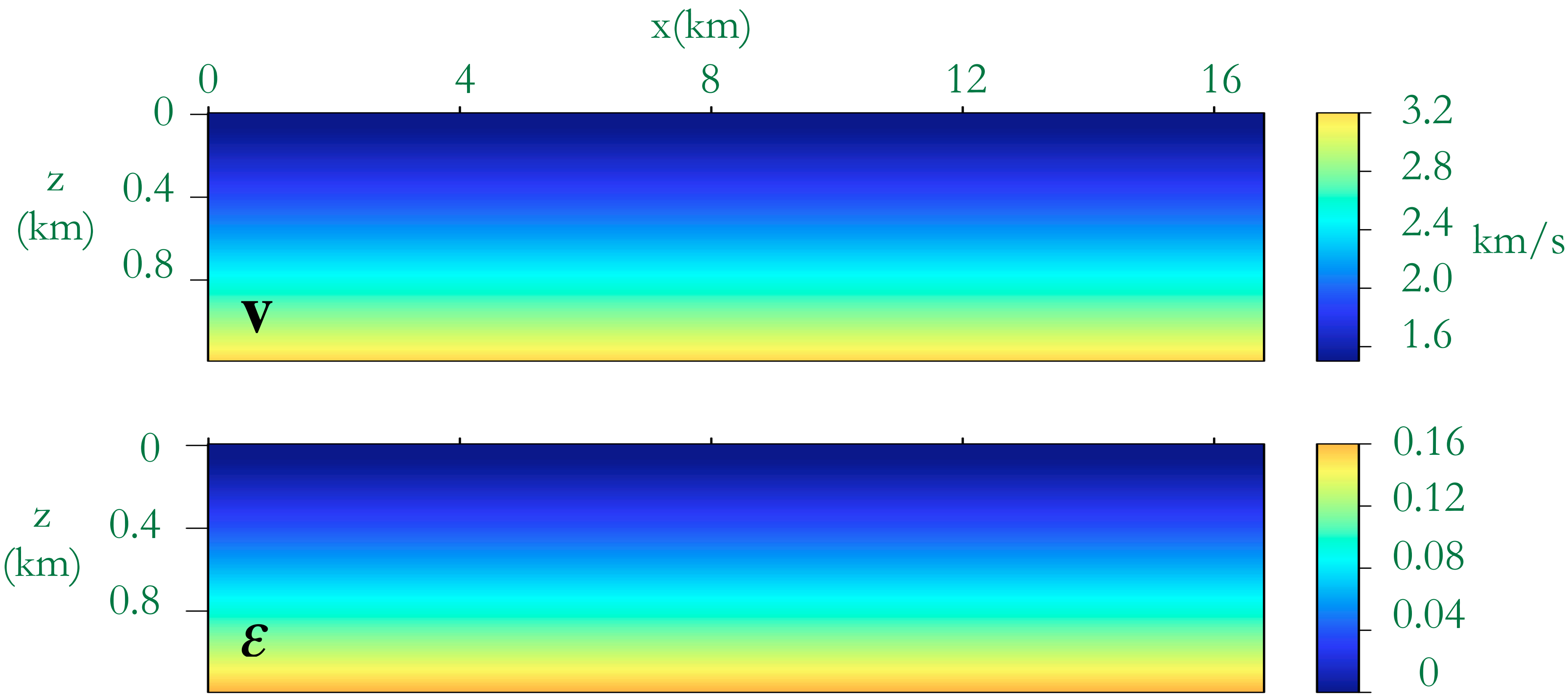
Objective function evaluation



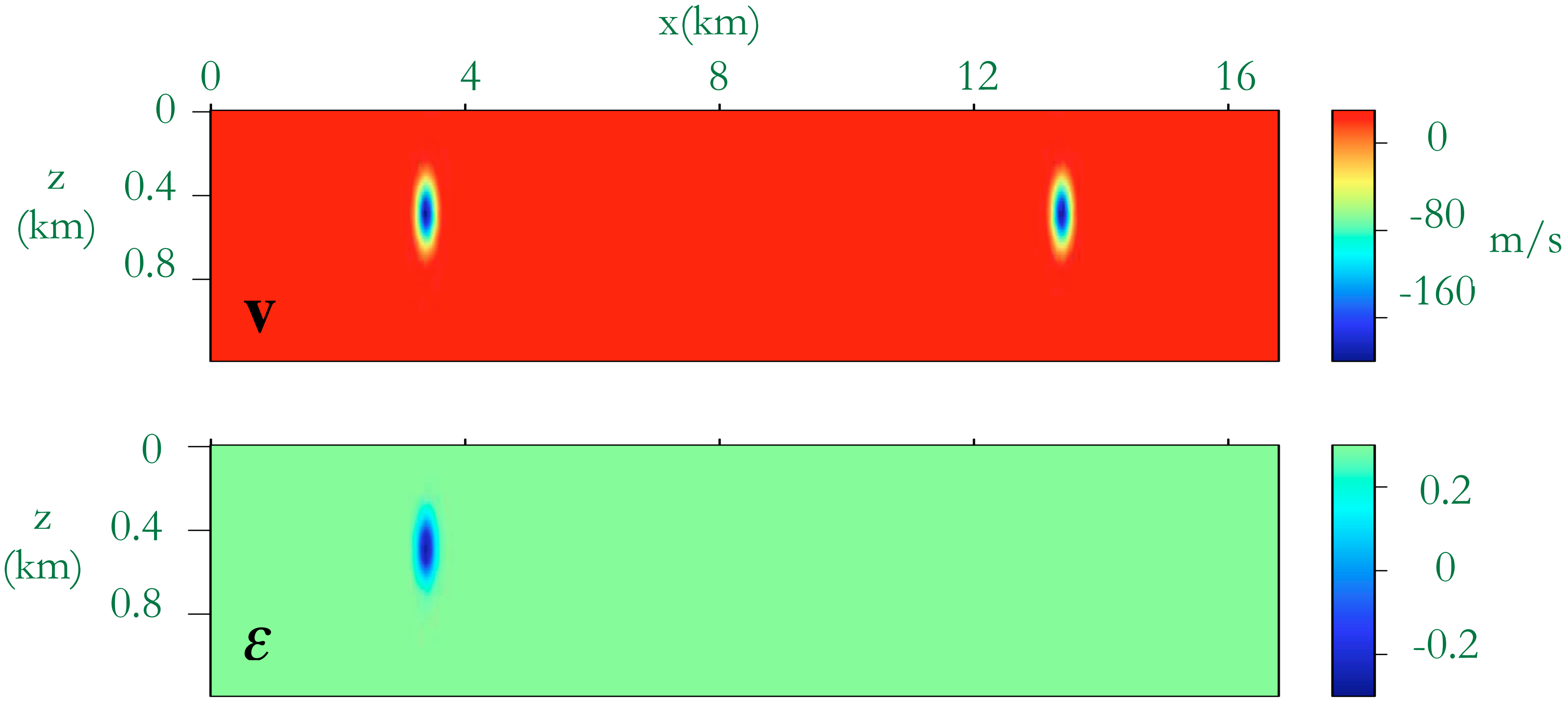
Ambiguity between **v** and **ε**



Background model & Starting model for inversion



True perturbation



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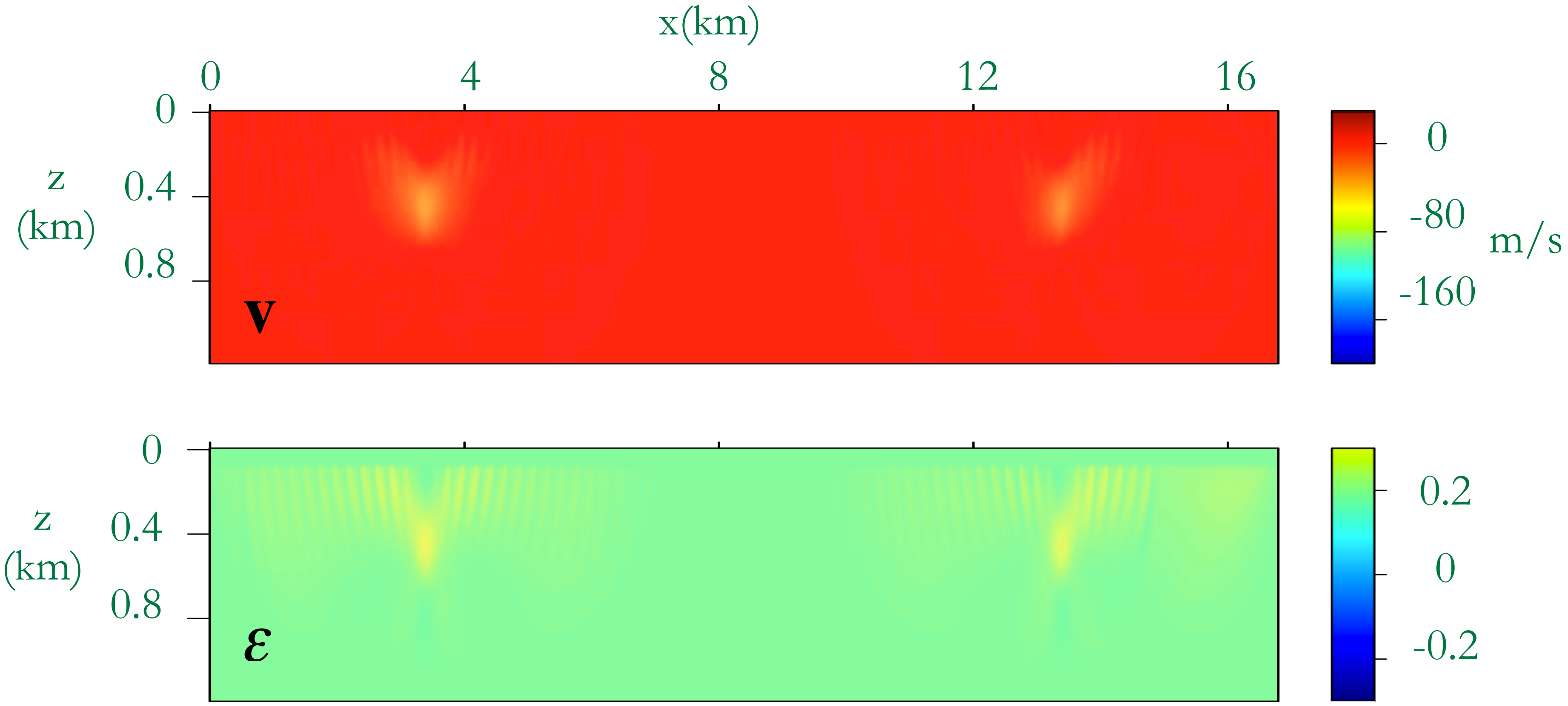
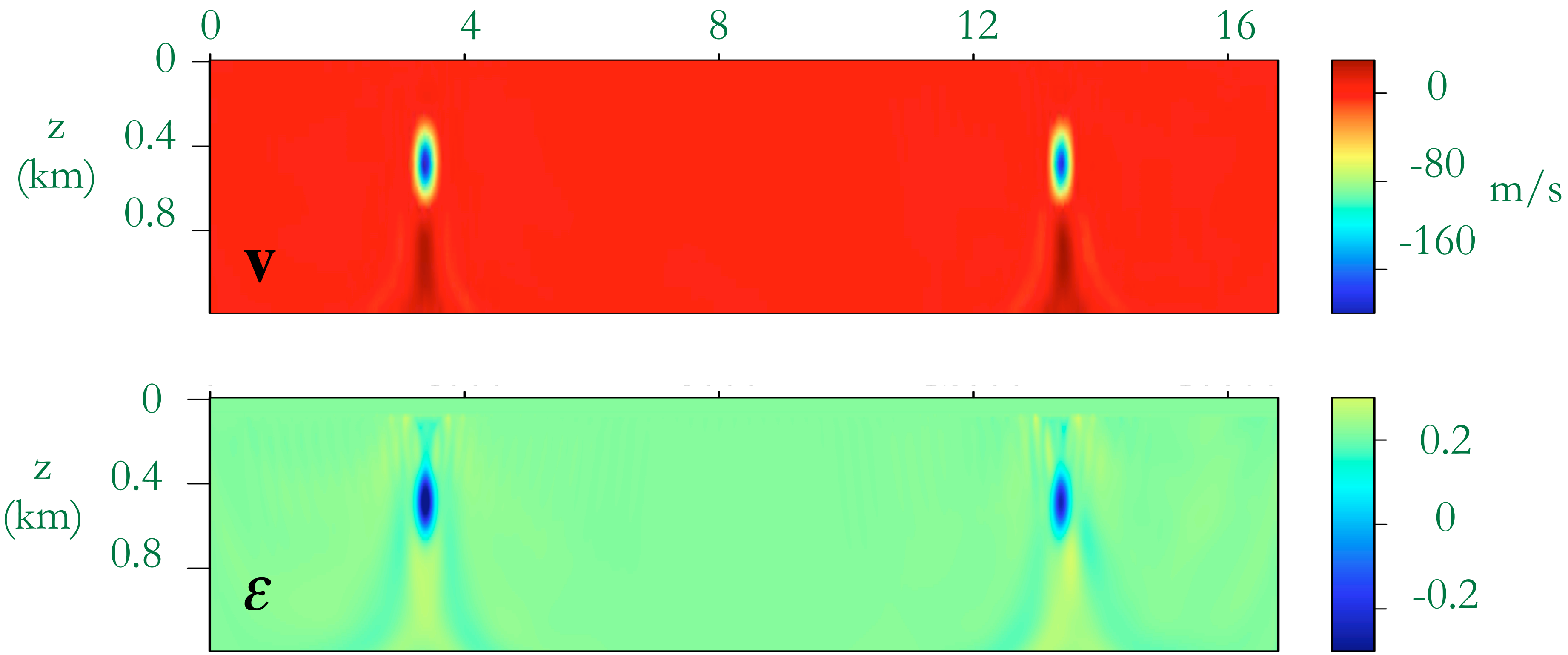
Receivers everywhere on the surface

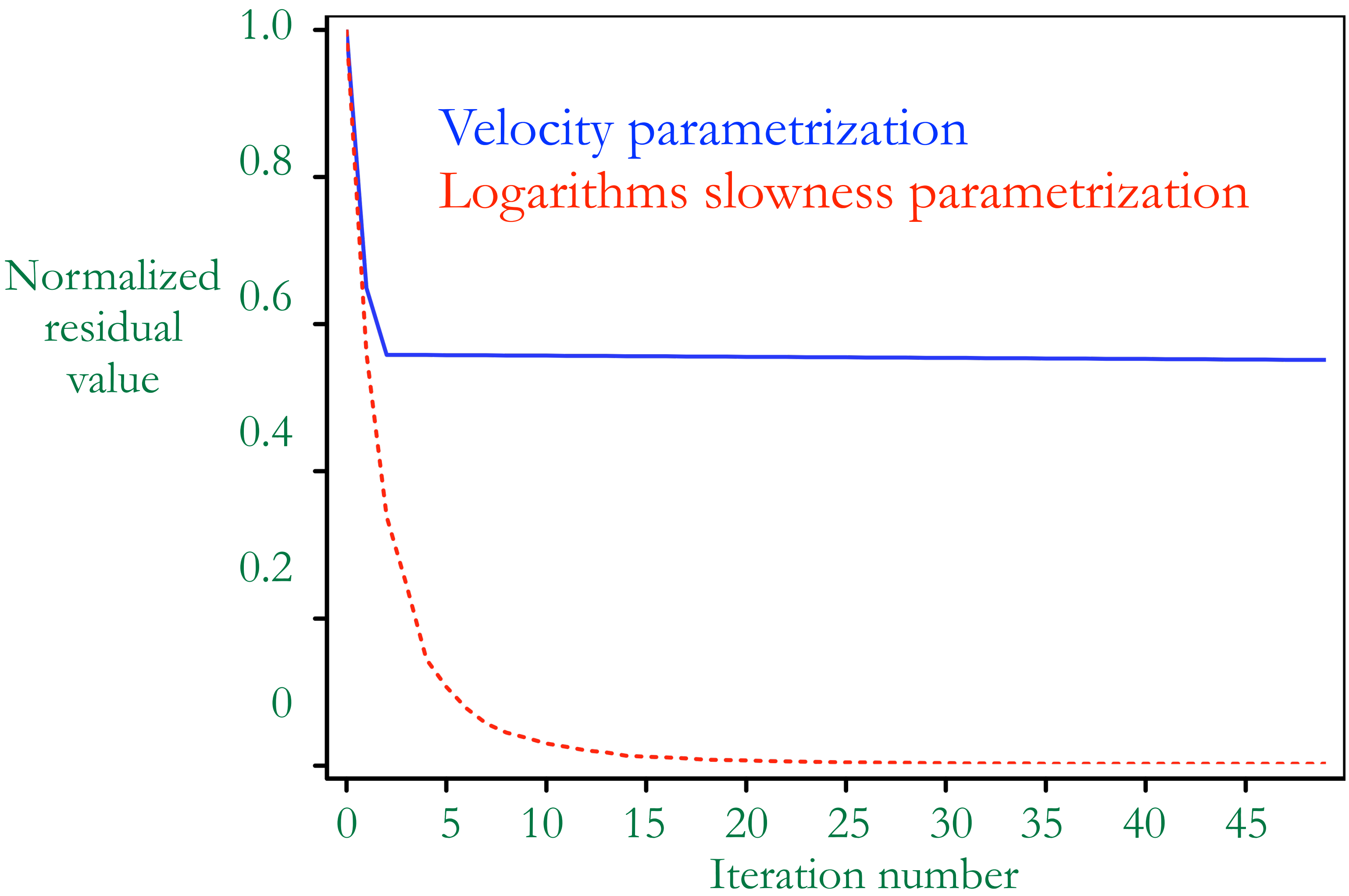
Estimated perturbation, velocity parametrization



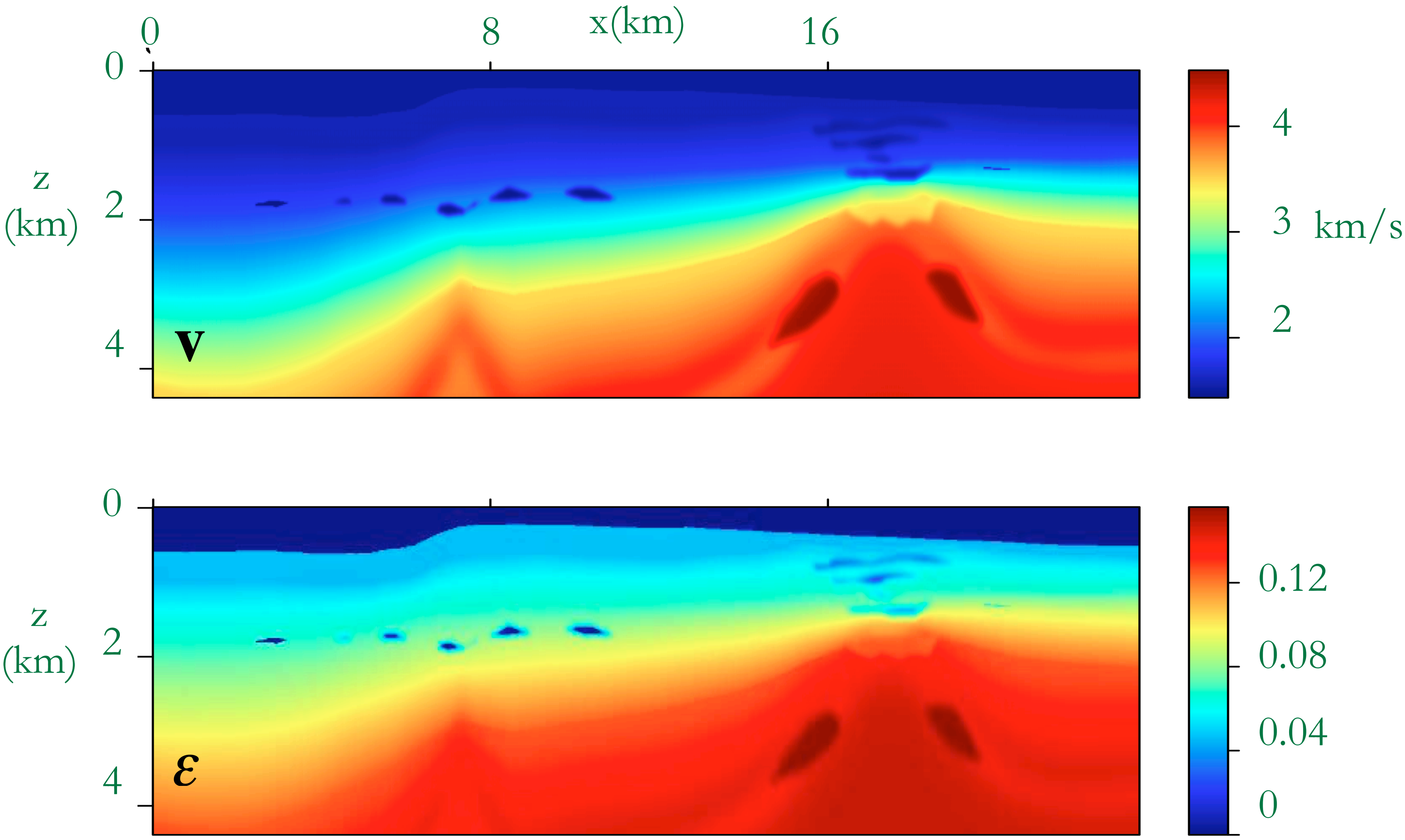
Estimated perturbation, logarithm slowness parametrization



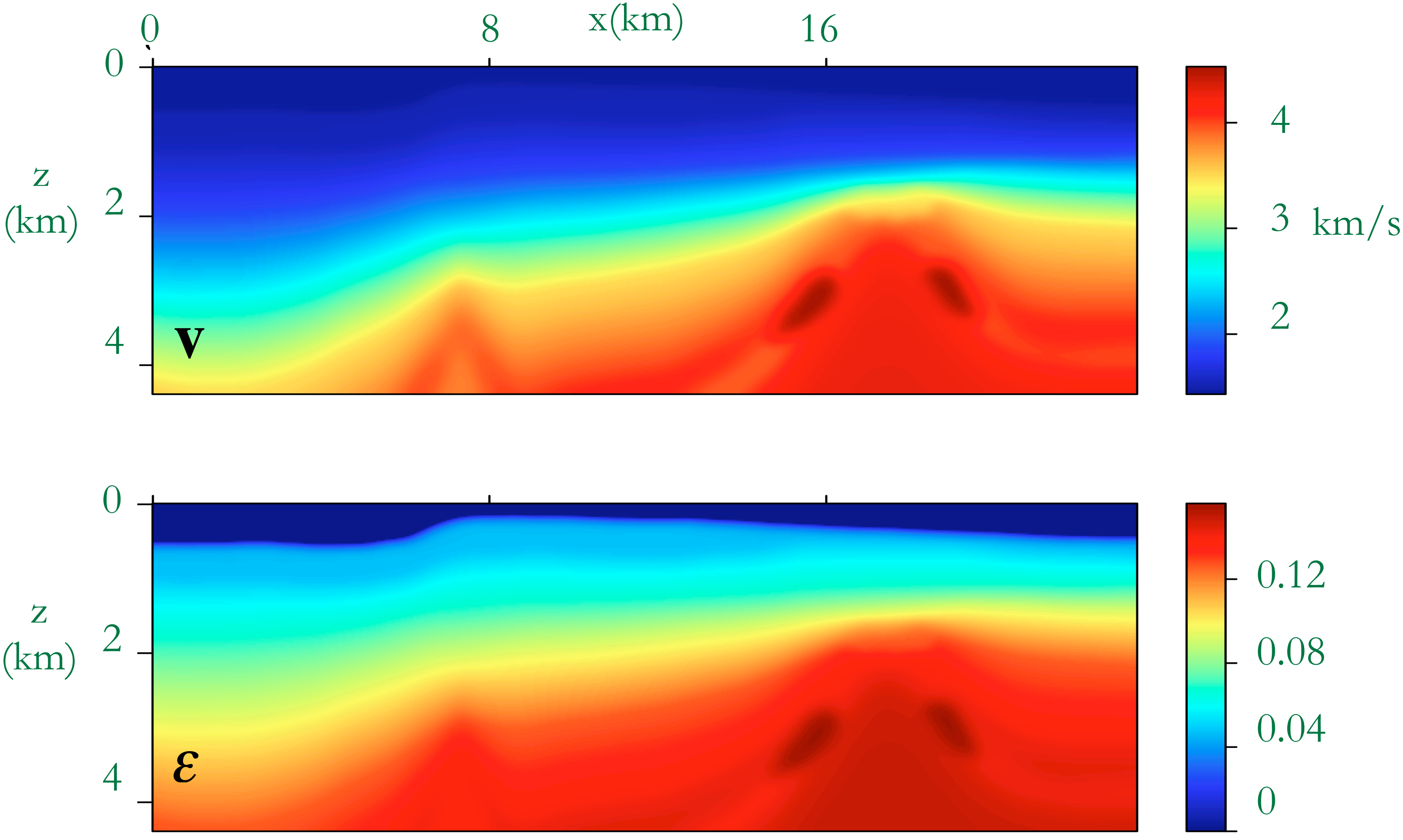
Residual comparison



True model



Initial model



Acquisition geometry

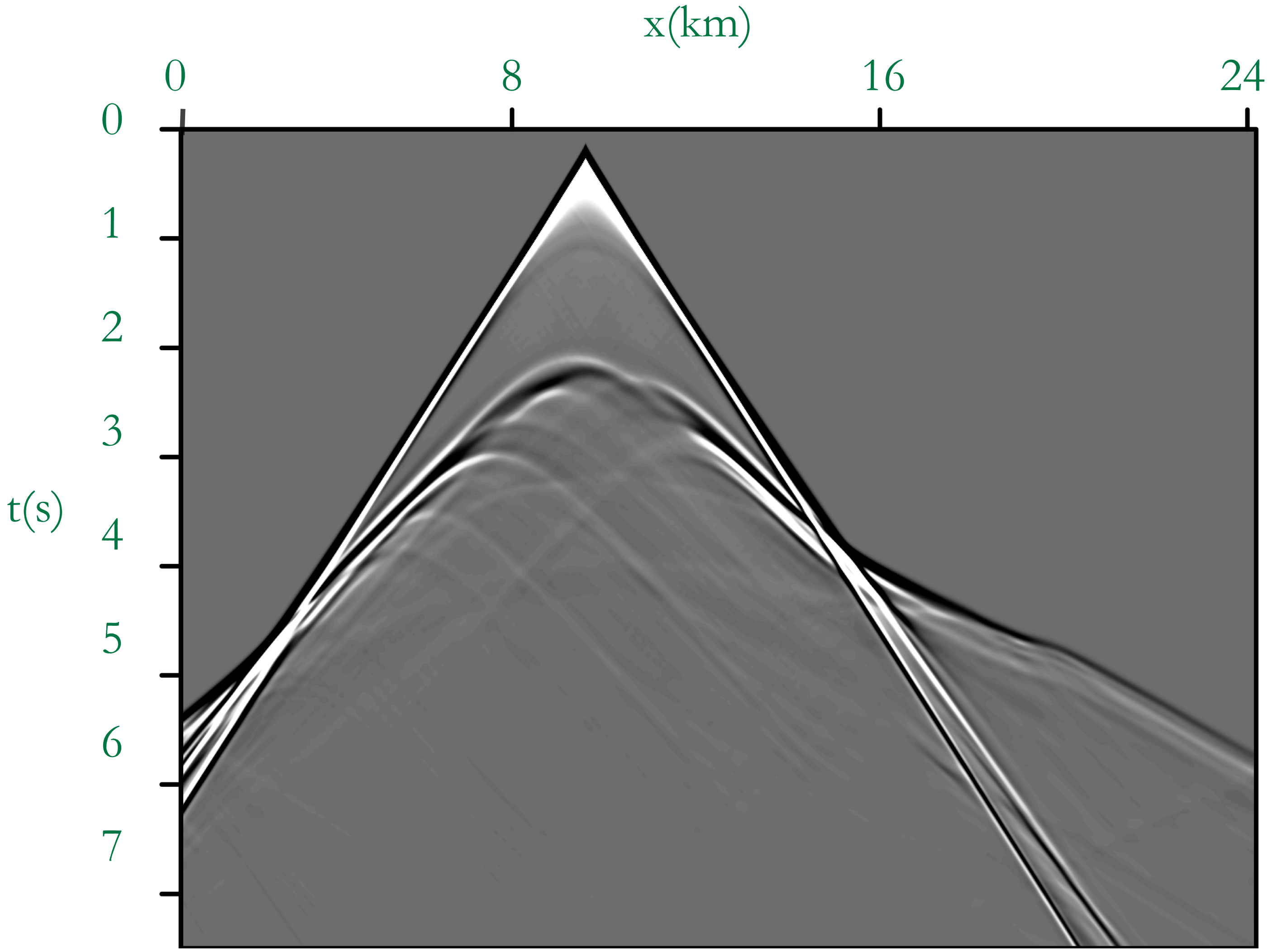
1170 *220 grid points, 20 m spacing

64 shots, 320 meter spacing

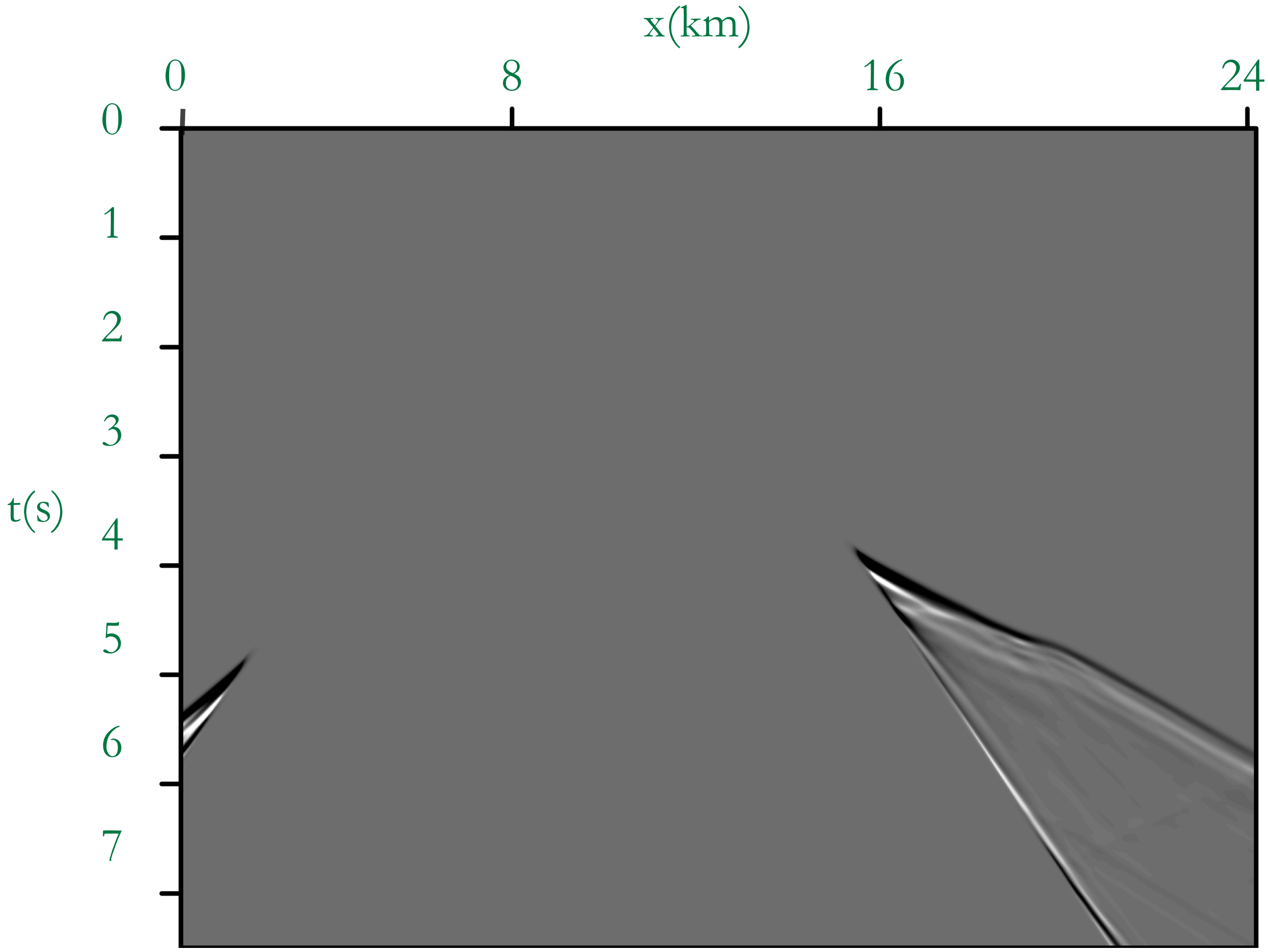
7Hz peak frequency source

Receivers everywhere on the surface

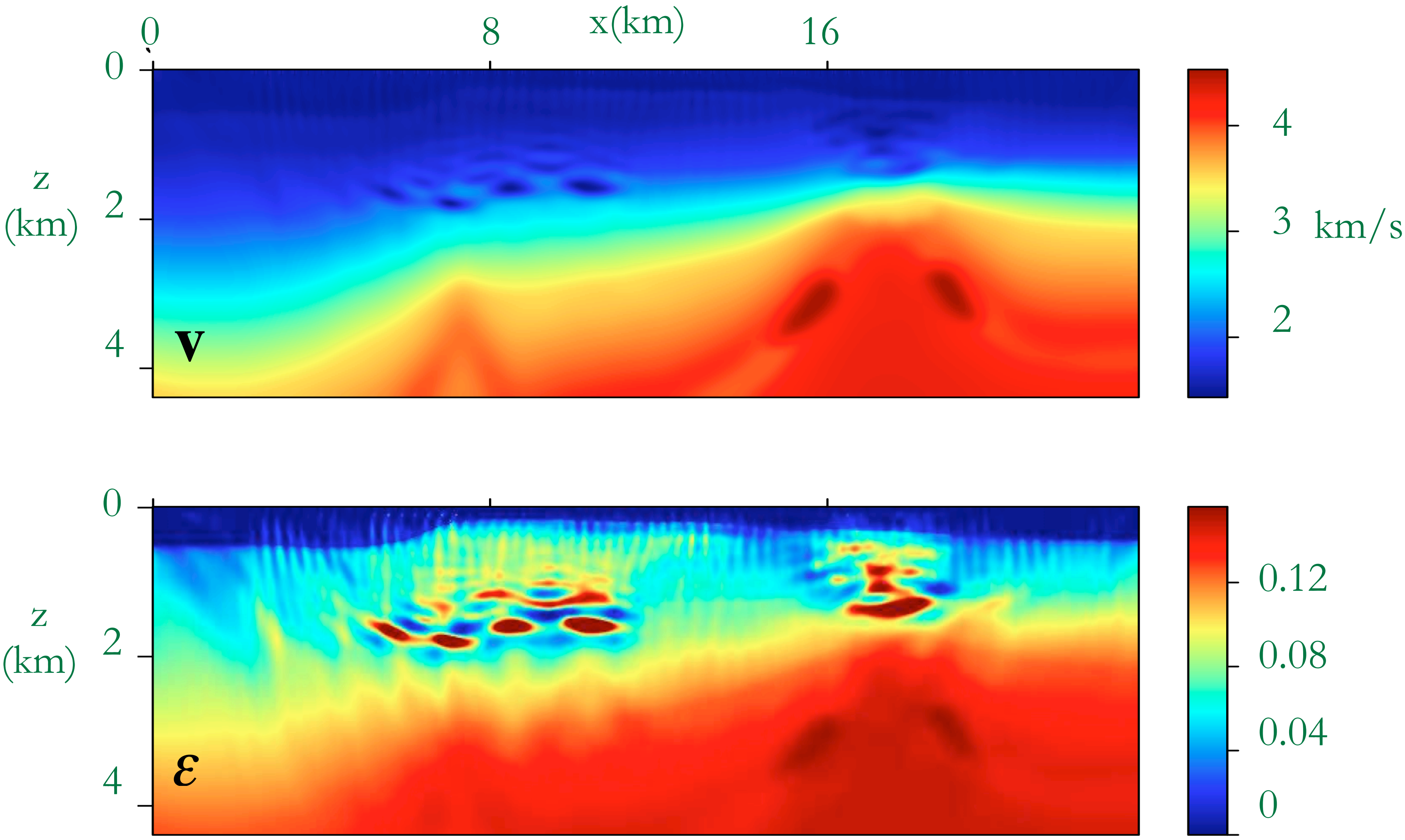
Shot



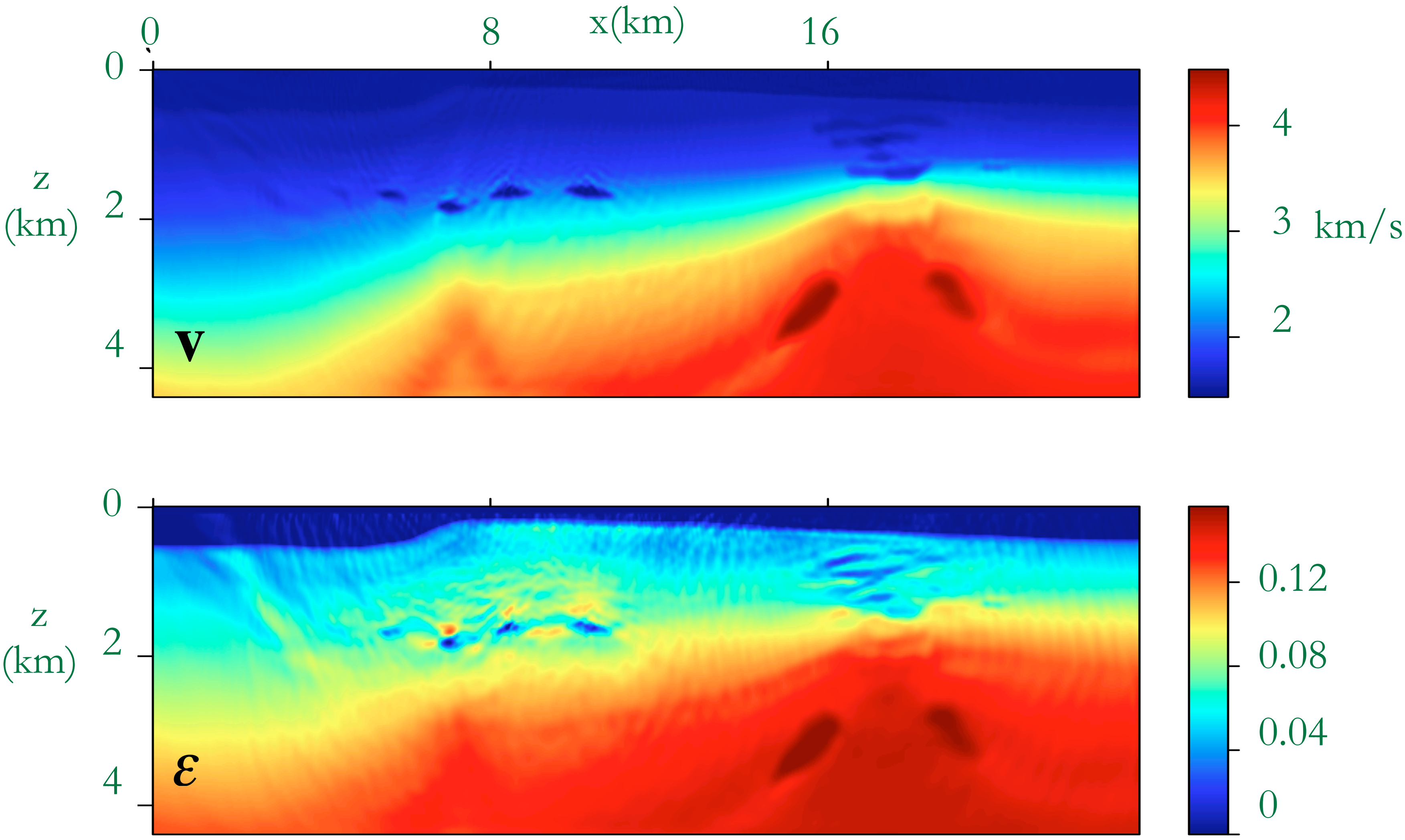
Masked shot



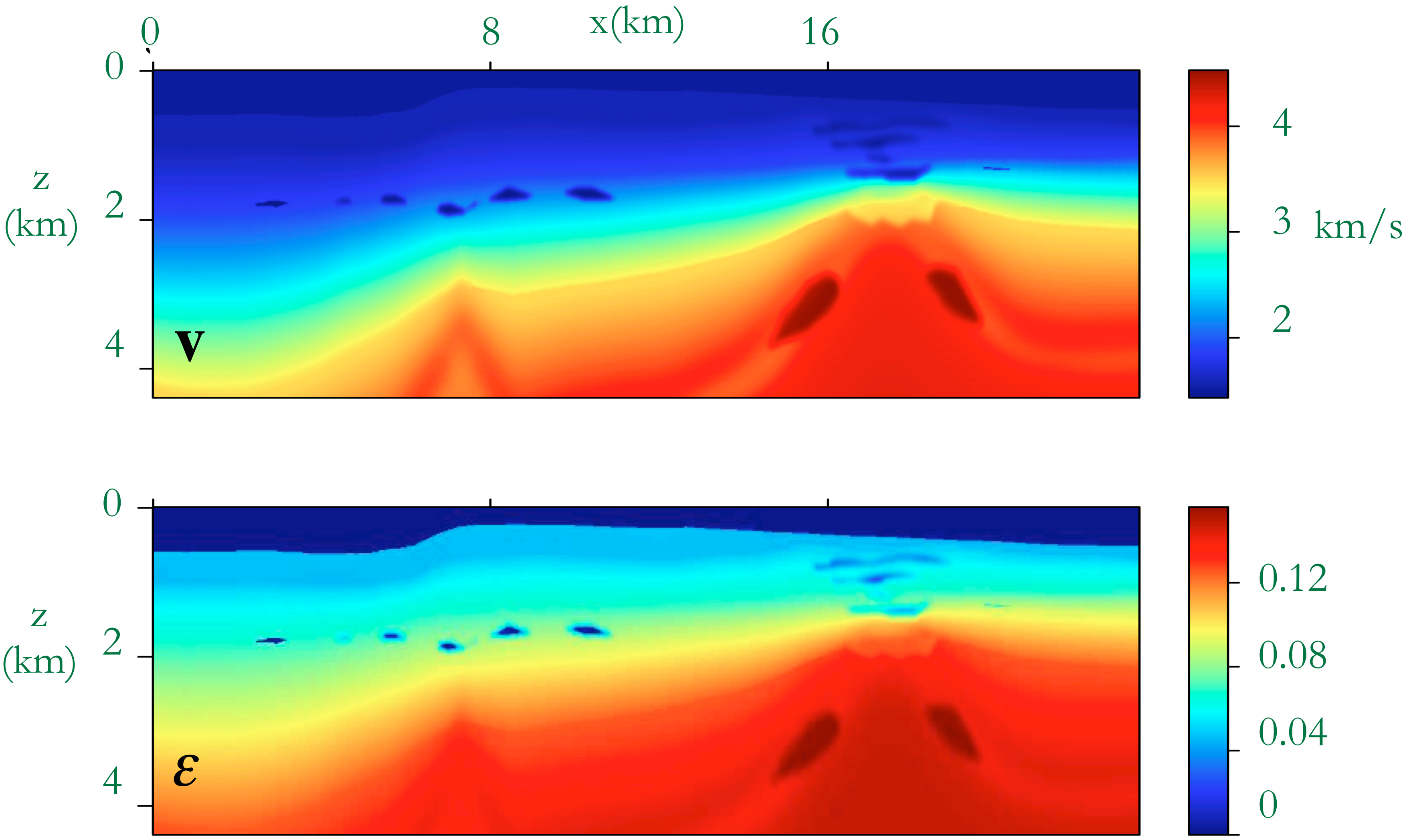
Estimated model, velocity parametrization



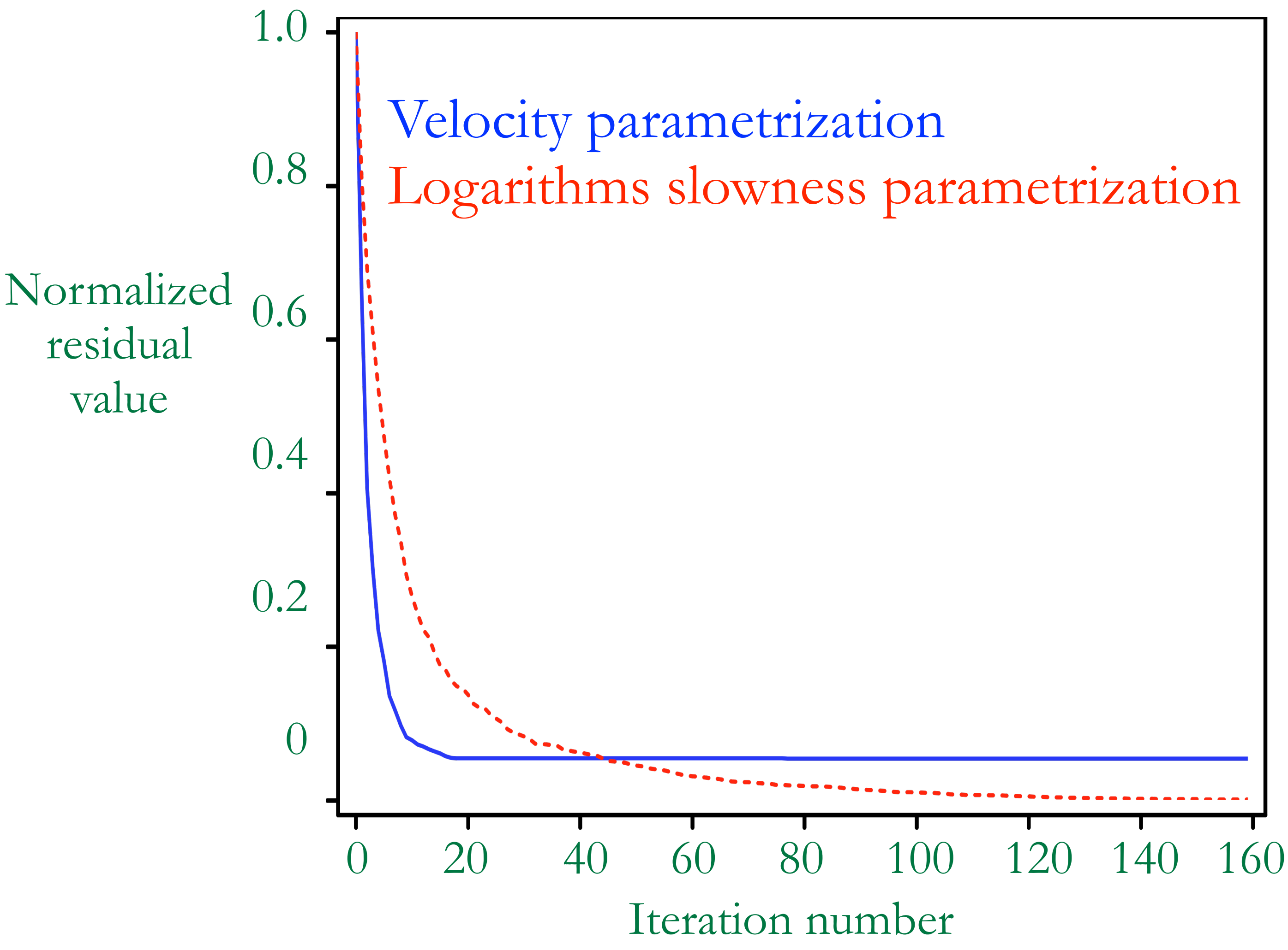
Estimated model, logarithm slowness parametrization



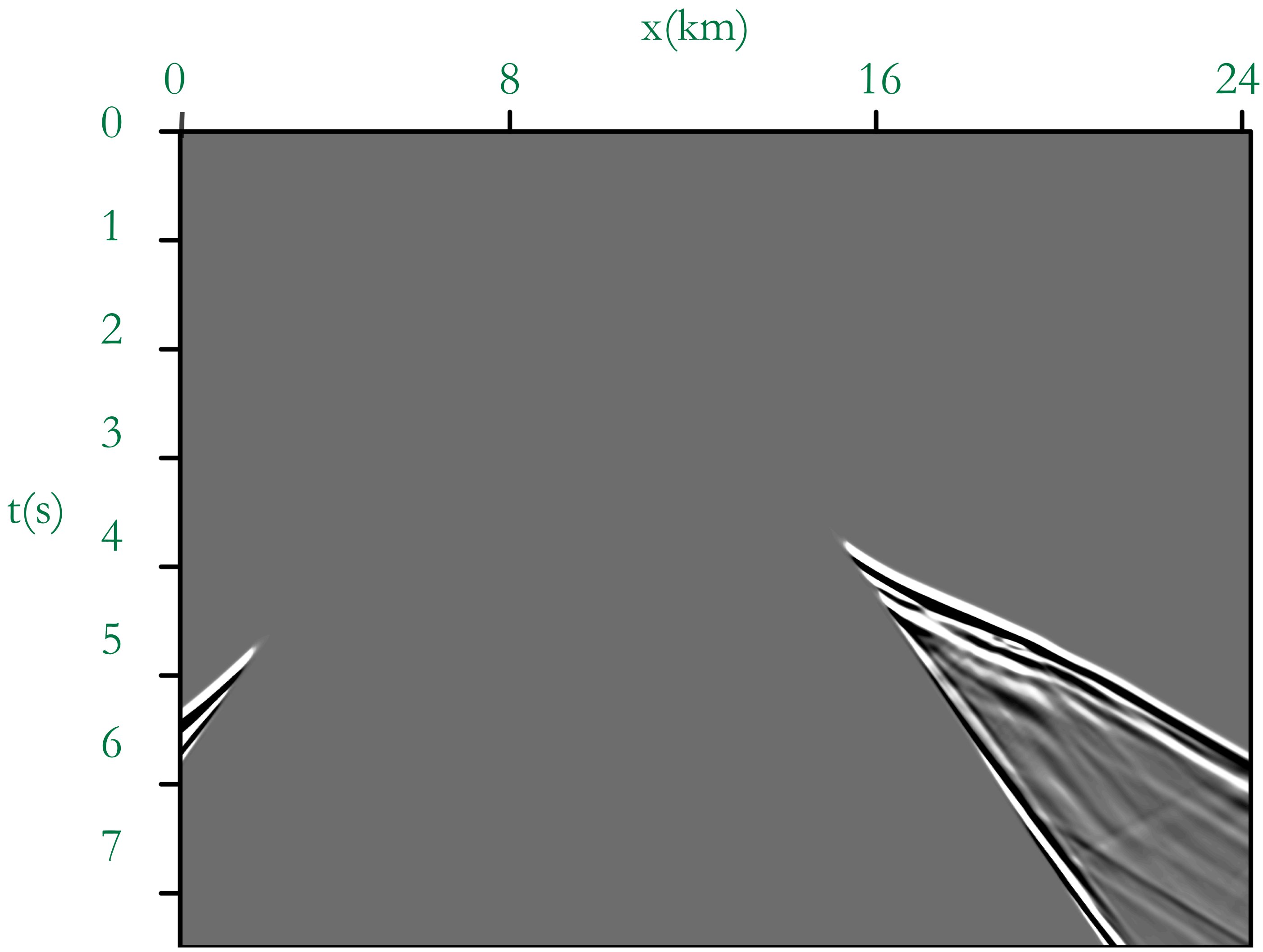
True model



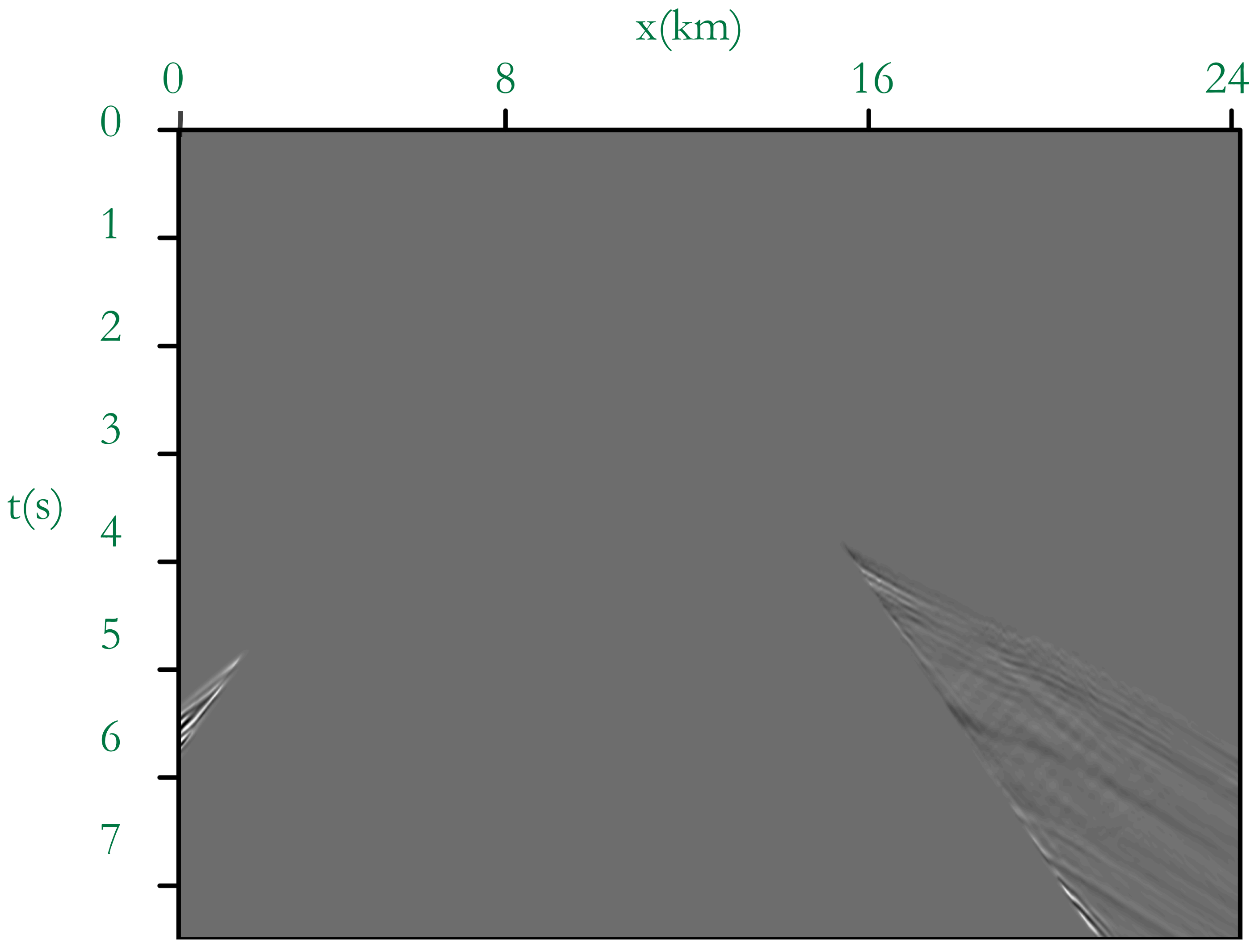
Residual comparison



Initial residual, logarithm slowness parametrization



Final residual, logarithm slowness parametrization



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Conclusions

- Including anisotropic parameter estimation as part of early-arrival waveform inversion is necessary for anisotropic data.

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- Logarithm parametrization works better than velocity parametrization.

Conclusions

- Including anisotropic parameter estimation as part of early-arrival waveform inversion is necessary for anisotropic data.
- Logarithm parametrization works better than velocity parametrization.
- Data ambiguity exist between velocity and anisotropy parameter. Solution needs to be investigated.

Acknowledgements

- SEP sponsors for the financial support of this research
- Elita for discussion about anisotropic parameter inversion
- SEP colleagues for suggestions about the synthetic examples

Thank you