3D time-lapse RTM of data from the Snowflake 2018-2022 experiments

Xiaohui Cai, Kris Innanen, Ziguang Su, Don Lawton

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FACULTY OF SCIENCE
Department of Earth, Energy, and Environment
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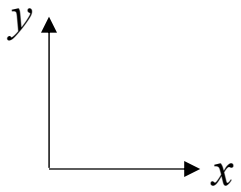
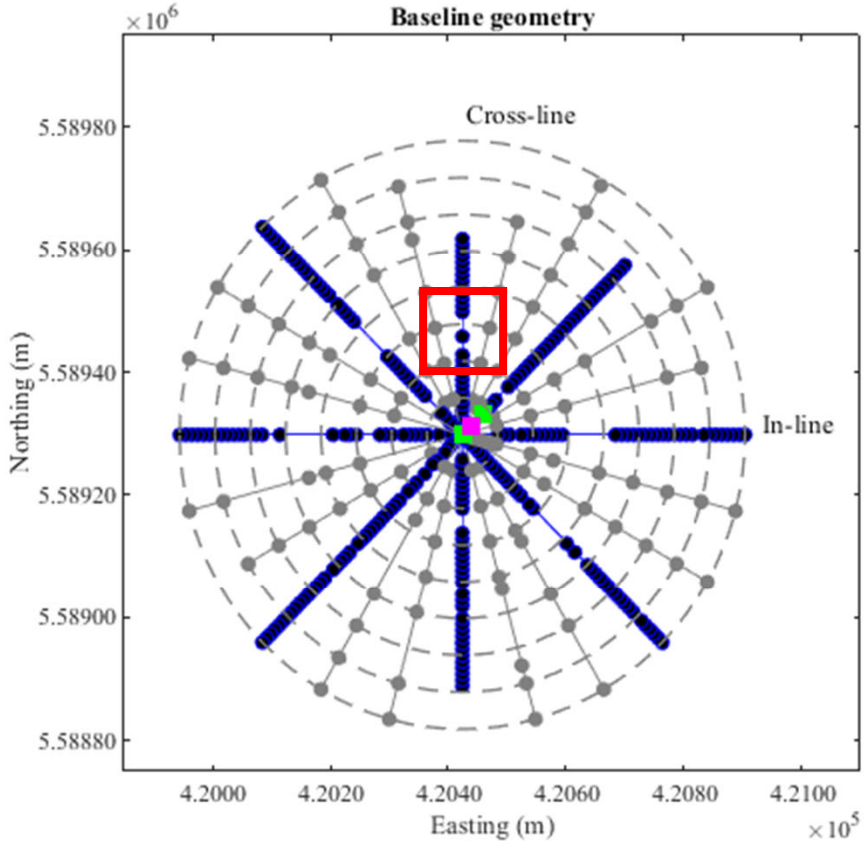
Snowflake experiments——Geometry



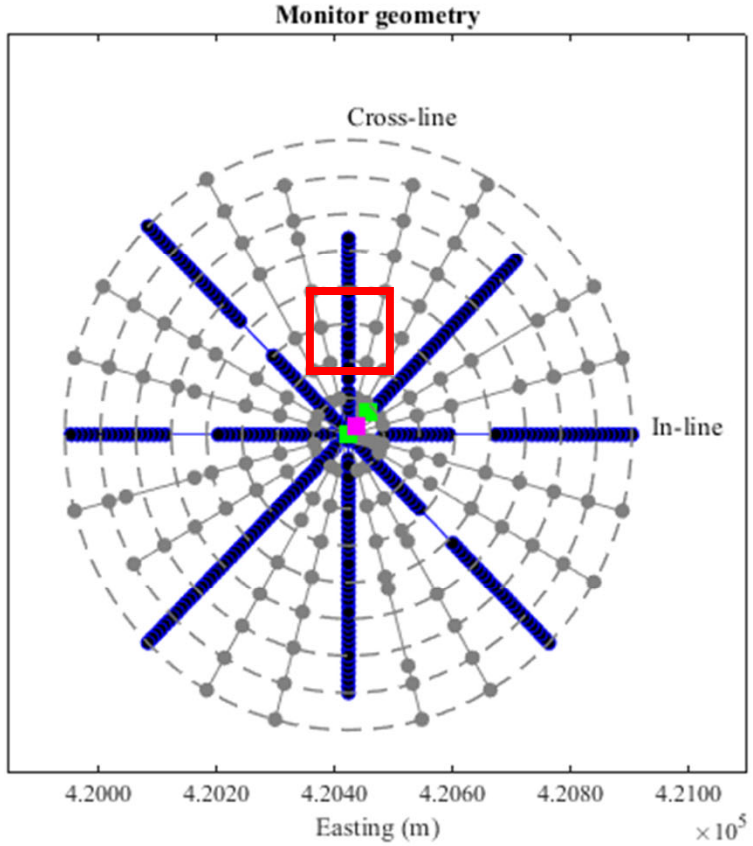
Injection depth:
290 m-305 m

DAS space interval:
0.667 in 2018
1 m in 2022.

2018

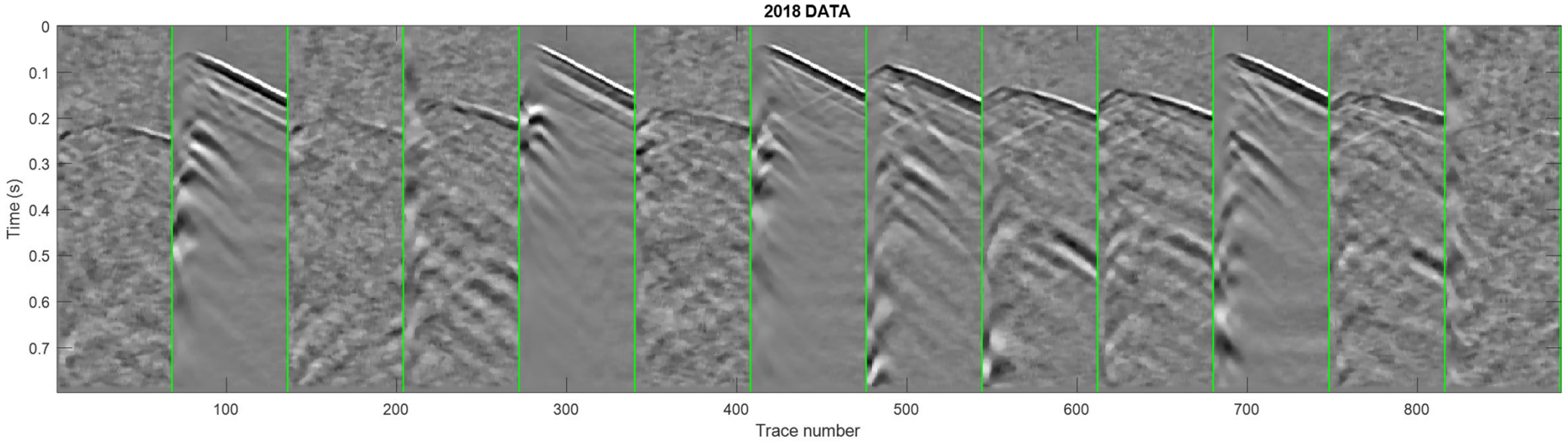


2022

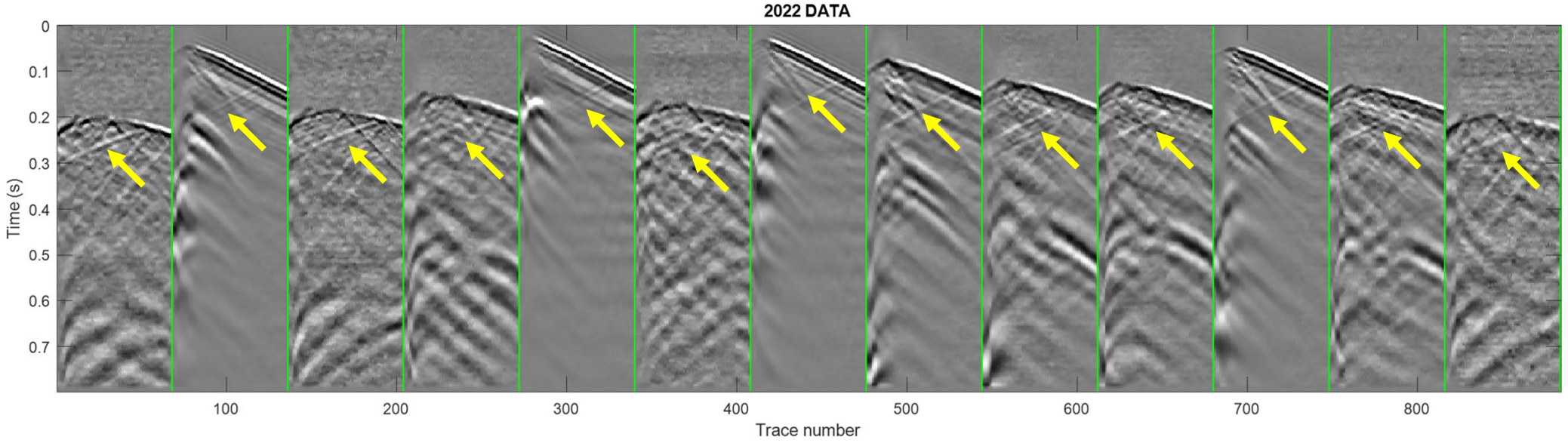


Snowflake experiments——Shot gathers

2018

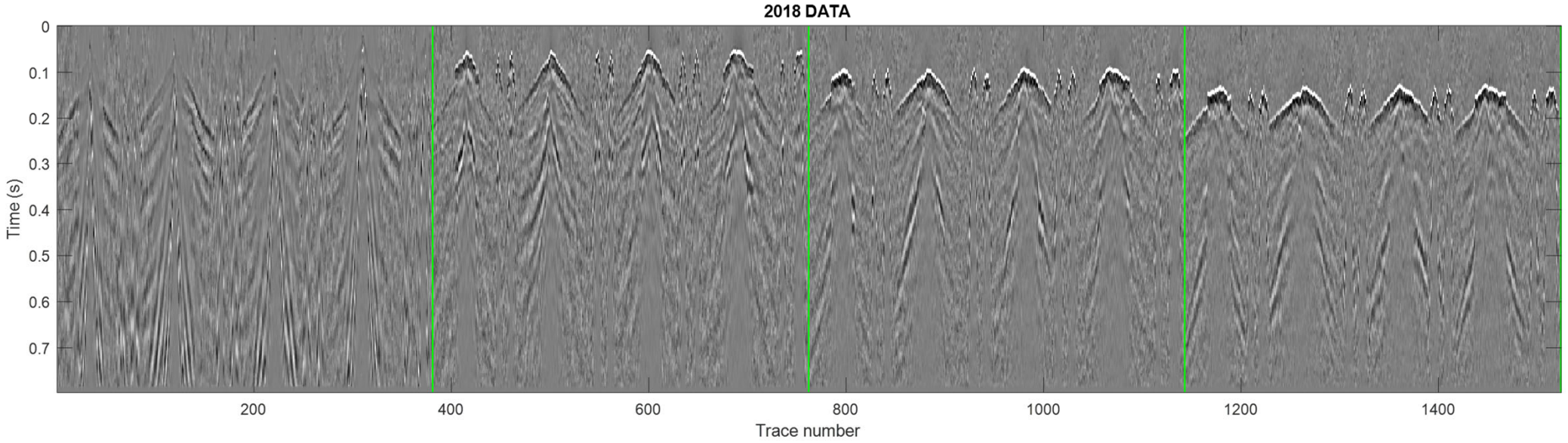


2022

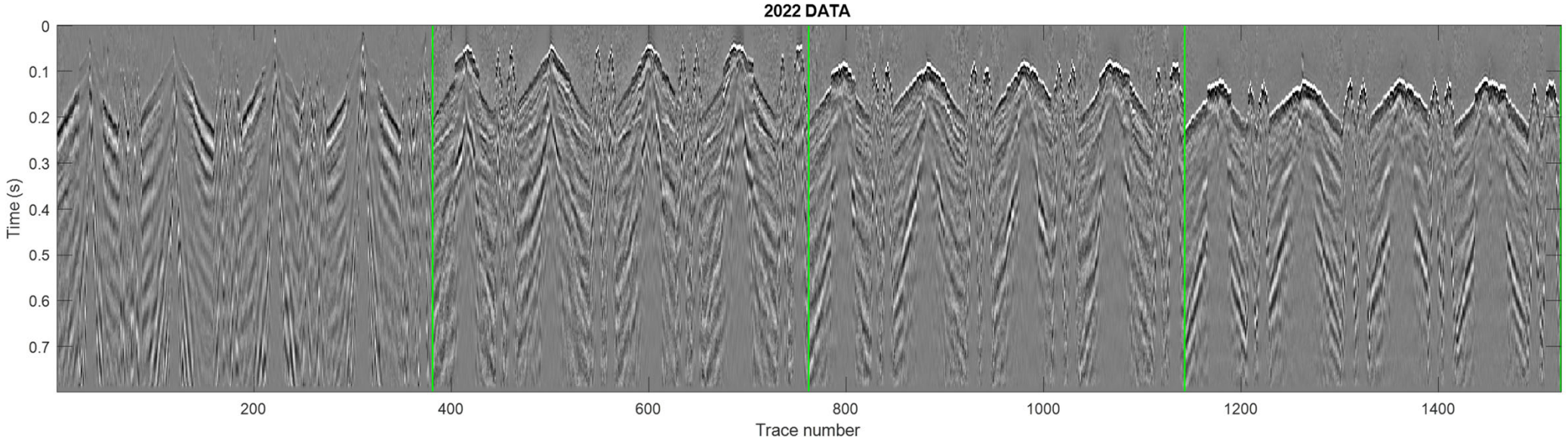


Snowflake experiments——Reciprocity gathers

2018



2022



3D Reverse-Time Migration Strategy

- 3D finite-difference modeling based on optimal least-squares (Cai et al., 2015)
- 3D hybrid absorbing boundary condition (Liu and Sen., 2010)
- Crosscorrelation imaging conditions (Chattopadhyay and McMechan, 2008)
- Azimuth-dependent RTM

Parallel Computing Strategy

- Effective boundary and checkpointing strategy (Clapp, 2008)
- GPU and POSIX thread (Cai et al., 2018)

Method——3D finite-difference method based on optimal least-squares (LS)

3D acoustic wave equation:

$$\frac{1}{v^2}\frac{\partial^2 p}{\partial t^2}=\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2}$$

Conventional finite-difference coefficients

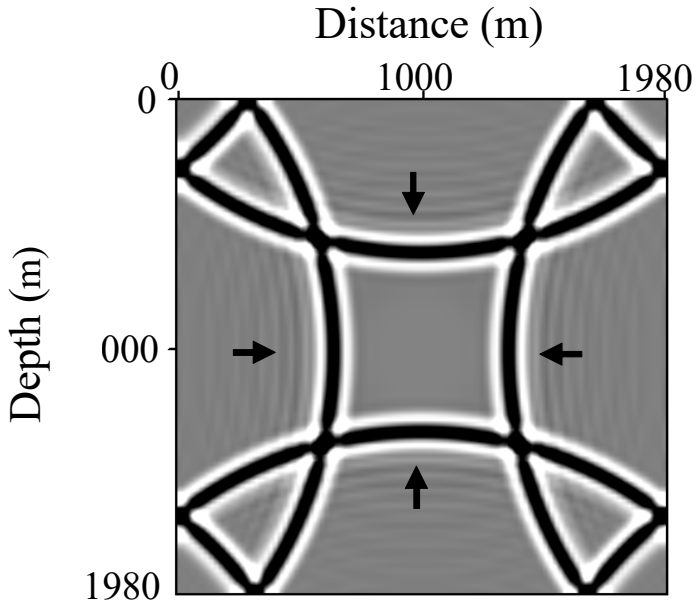
$$a_m=\frac{(-1)^{m+1}}{m^2}\prod_{1\le n\le M,n\ne m}\left|\frac{n^2}{n^2-m^2}\right|,m=1,2,...M$$

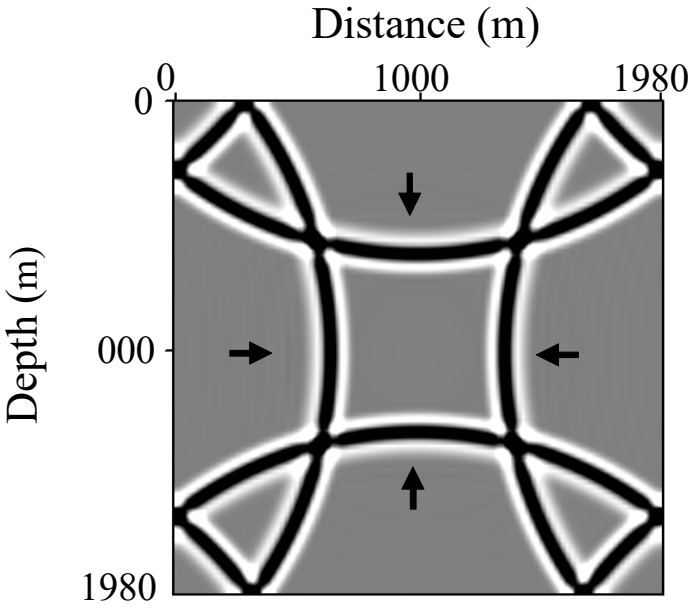
Finite-difference coefficients based on optimal LS

$$\sum_{m=1}^{M}\left(\int_0^b\int_0^\pi\int_0^{2\pi}\varphi_m(\beta,\theta,\phi)\varphi_n(\beta,\theta,\phi)d\beta d\theta d\phi\right)a_m=\int_0^b\int_0^\pi\int_0^{2\pi}\varphi_n(\beta,\theta,\phi)d\beta d\theta d\phi$$

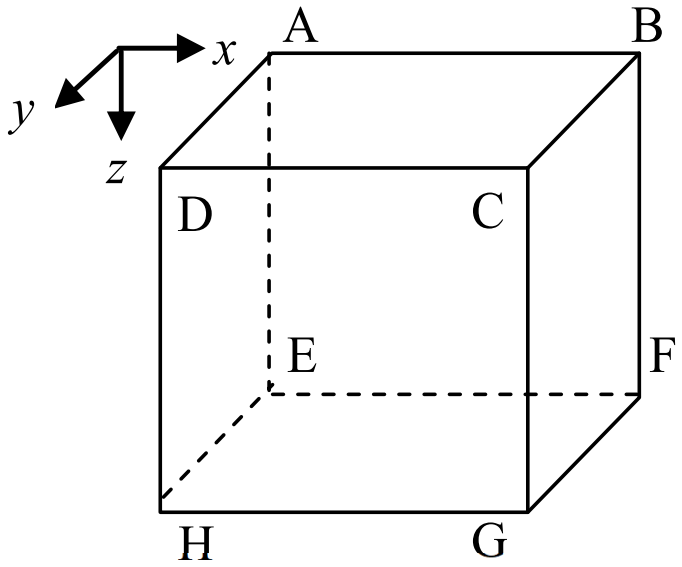
$$\varphi_m(\beta,\theta,\phi)=\frac{\cos(mk_xh)+\cos(mk_yh)+\cos(mk_zh)-3}{r^{-2}(\cos(w\tau)-1)},$$

(Cai et al., 2015)





Method——3D hybrid absorbing boundary condition (ABC)



x=0 slice

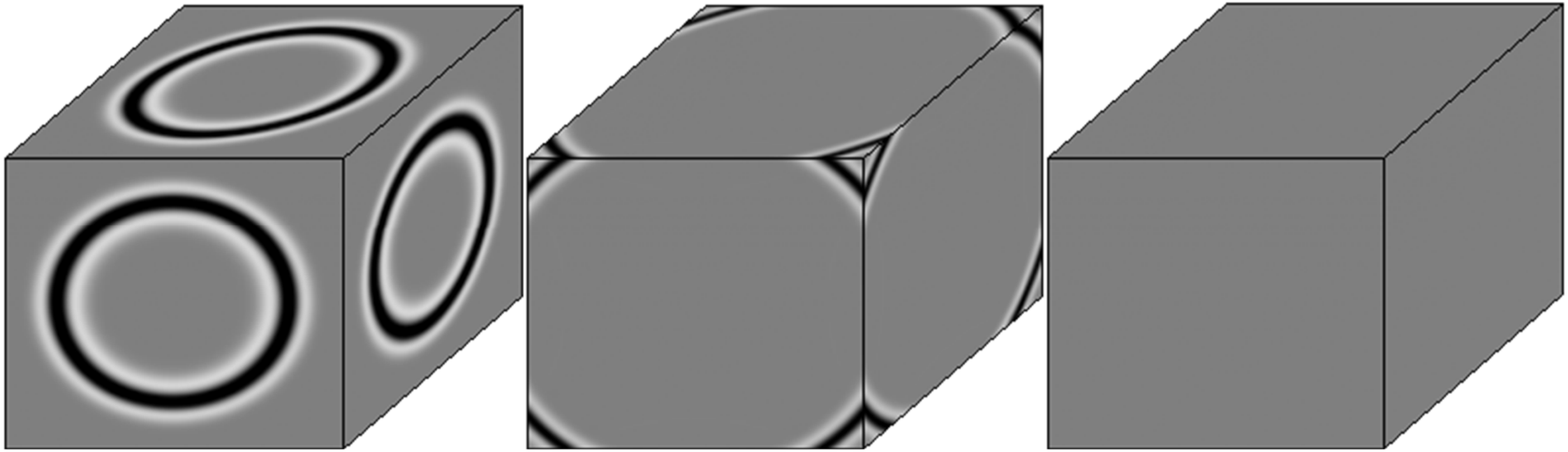
$$\frac{1}{v}\frac{\partial^2 p}{\partial t^2}-\frac{\partial^2 p}{\partial x \partial t}-\frac{v}{2}\left(\frac{\partial^2 p}{\partial y^2}+\frac{\partial^2 p}{\partial z^2}\right)=0$$

x=0, y=0 edge

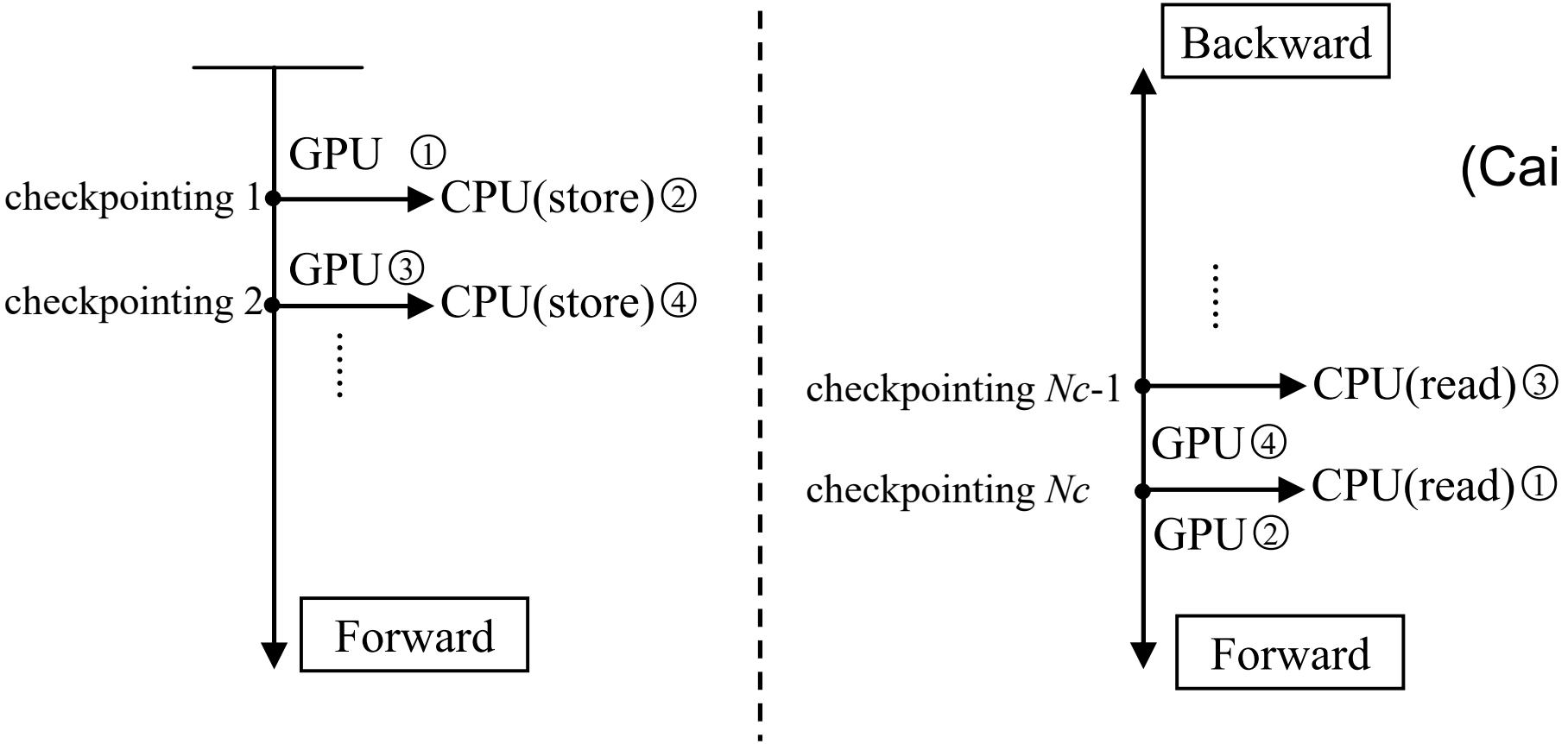
$$-\frac{\partial p}{\partial x}-\frac{\partial p}{\partial y}+\frac{\sqrt{2}}{v}\frac{\partial p}{\partial t}=0$$

x=0, y=0, z=0 corner

$$-\frac{\partial p}{\partial x}-\frac{\partial p}{\partial y}-\frac{\partial p}{\partial z}+\frac{1+\sqrt{2}}{v}\frac{\partial p}{\partial t}=0$$



(Liu and Sen., 2010)



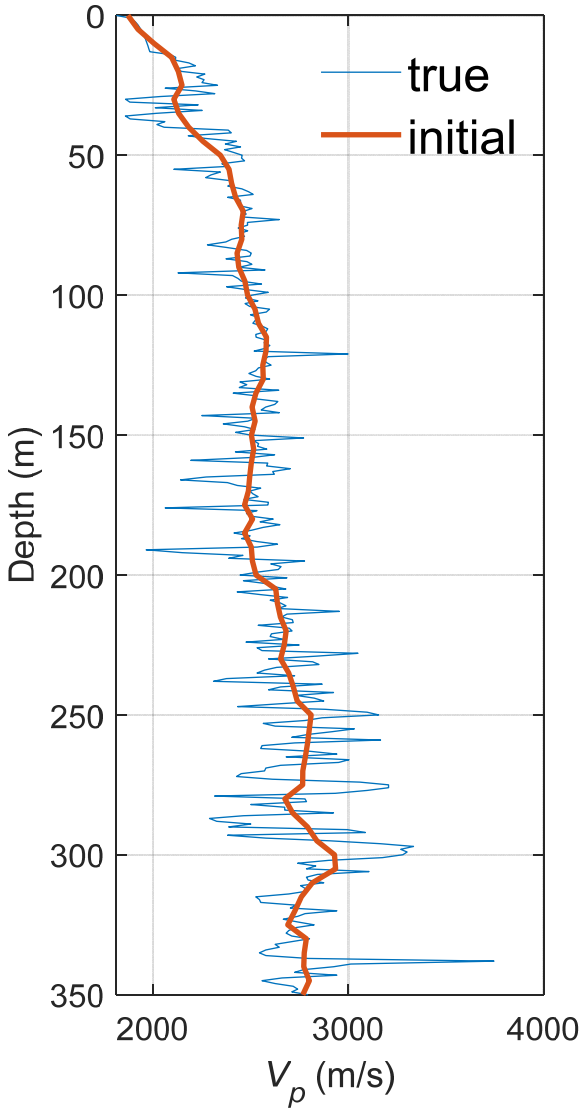
(Cai et al., 2018)

Imaging condition:

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

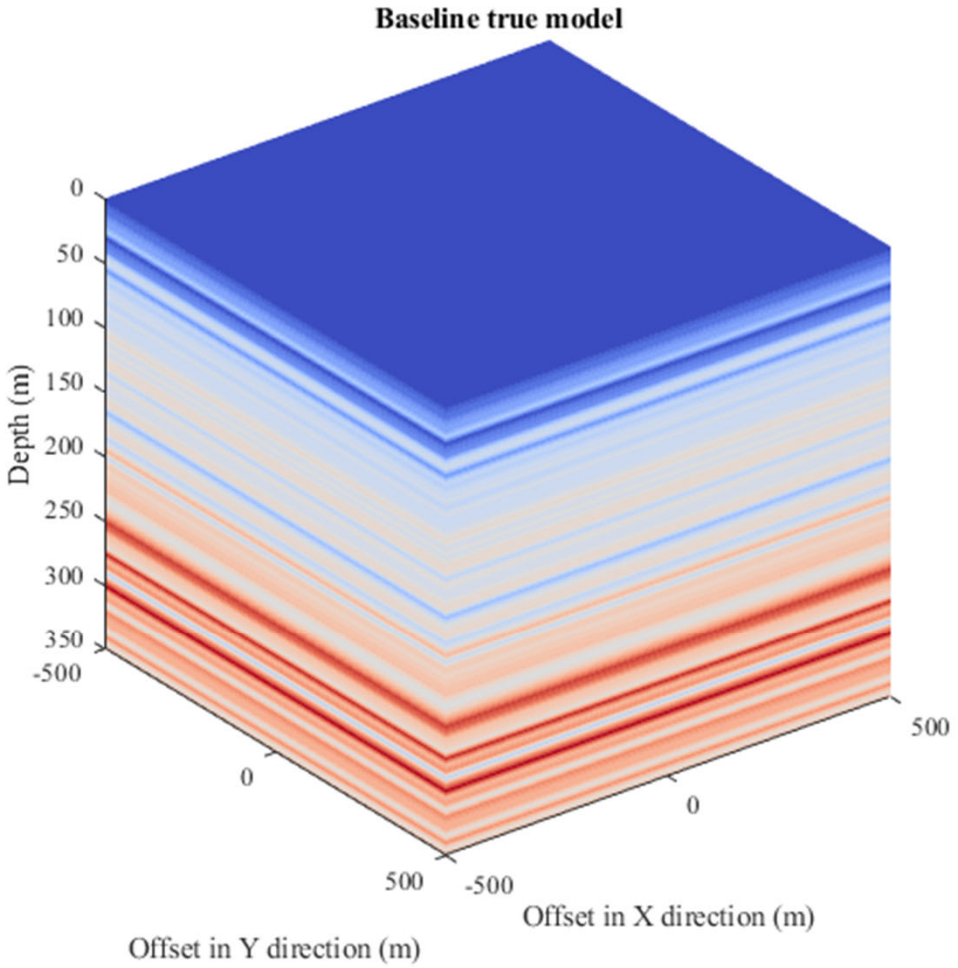
(Chattopadhyay and McMechan, 2008)

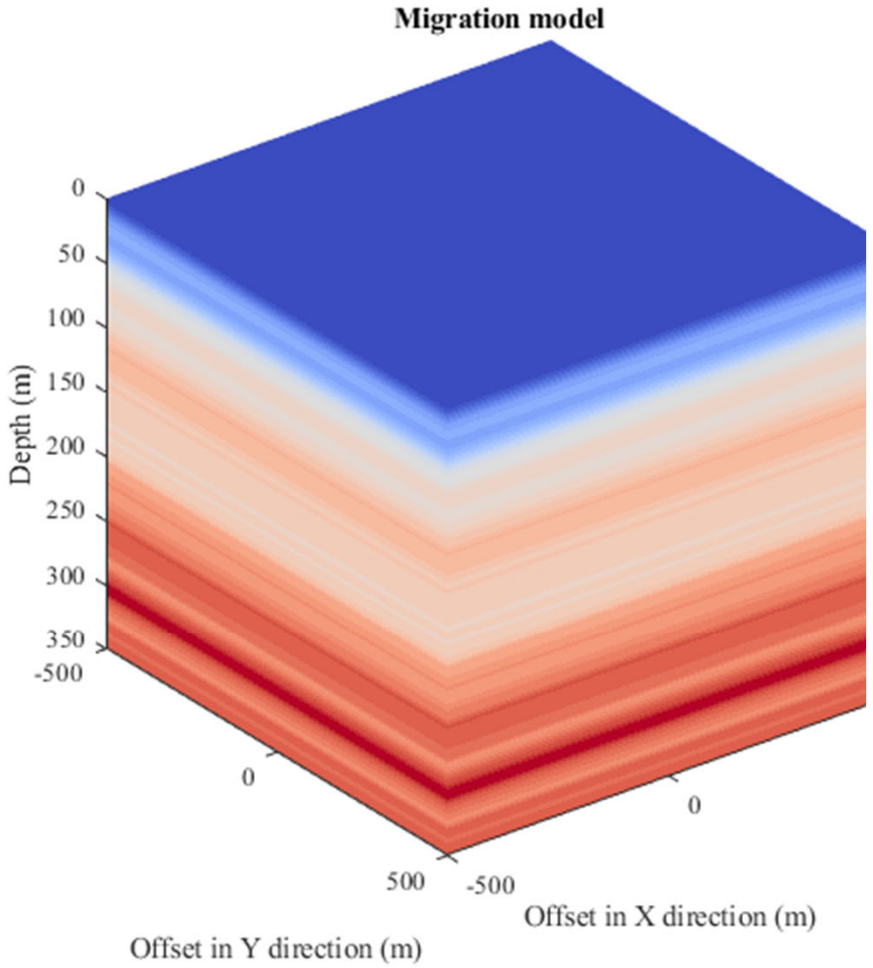
Synthetic Test——Snowflake model example



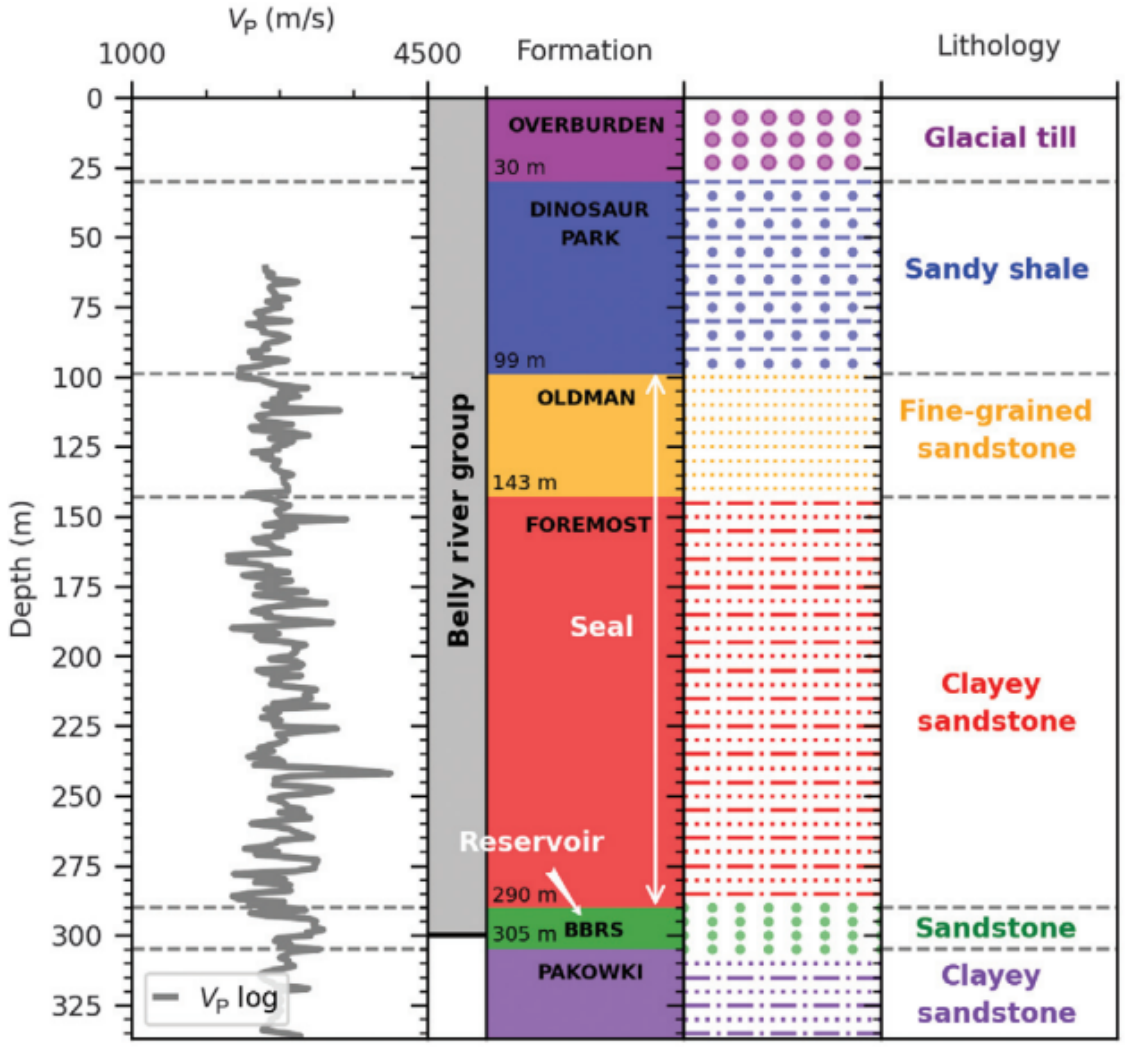
Size: 201*201*71

Space interval: 5 m * 5 m *5 m

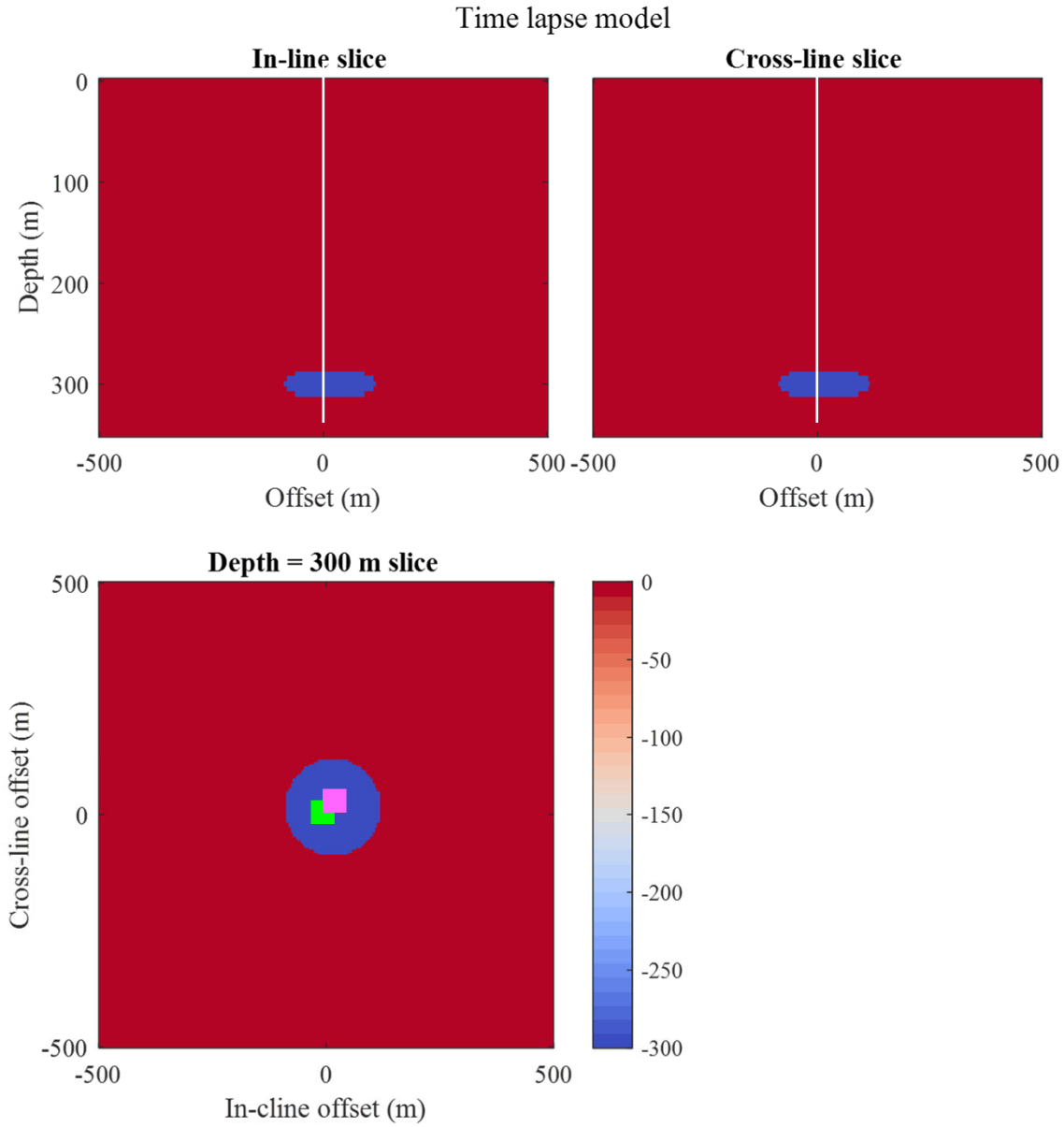




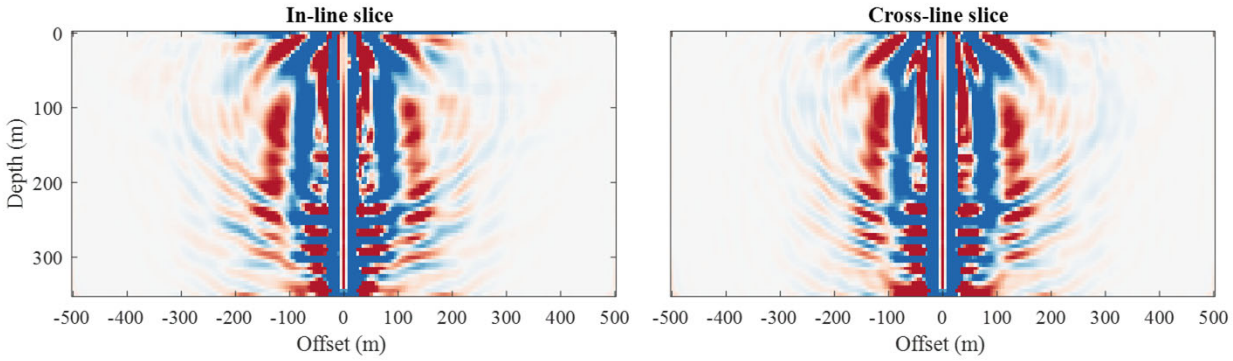
Synthetic Test ——Snowflake model example

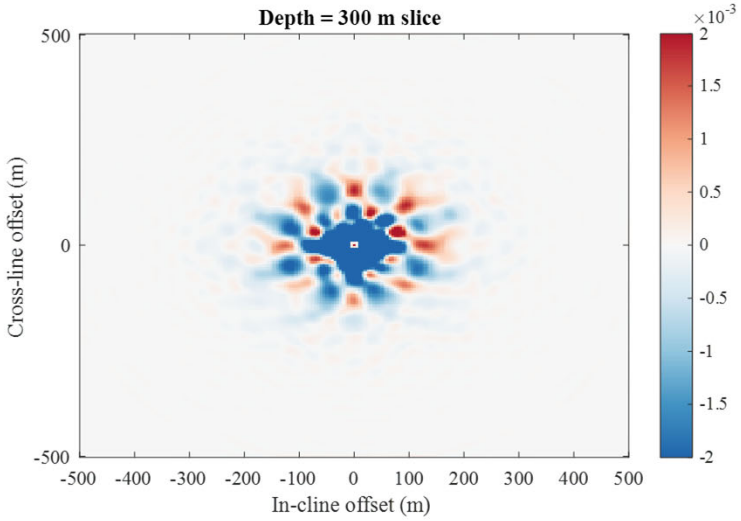


(Pan et al, 2023)

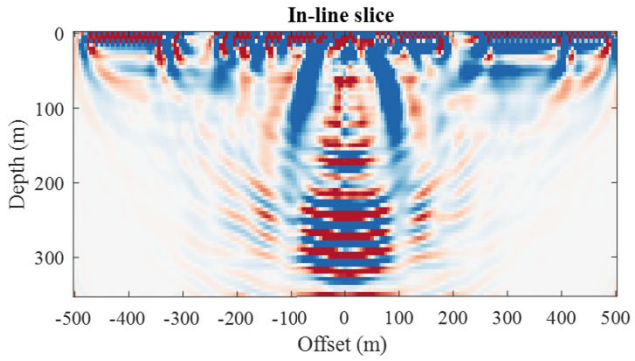


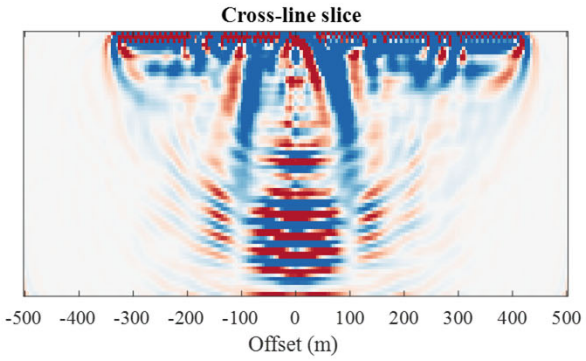
Synthetic Test——Baseline data RTM result

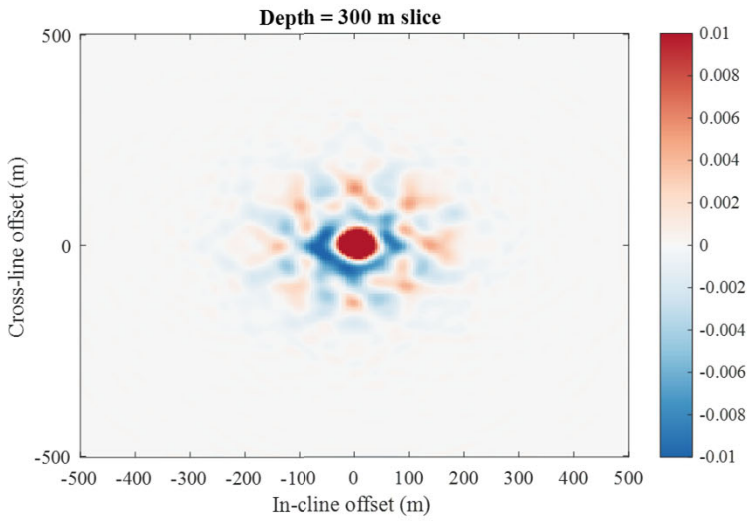




Shot gathers RTM





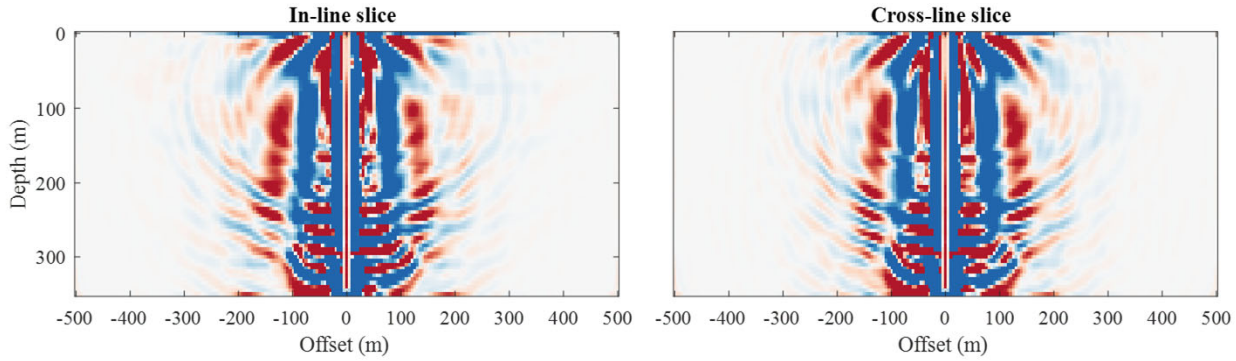


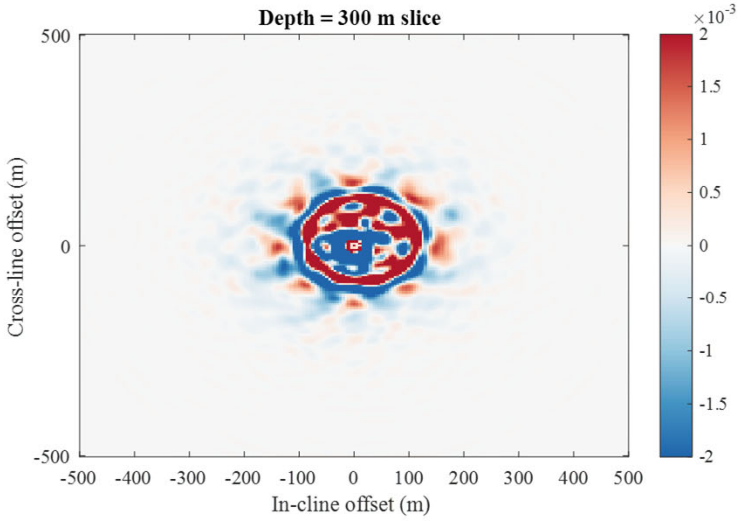
Reciprocity gathers RTM

3617 seconds

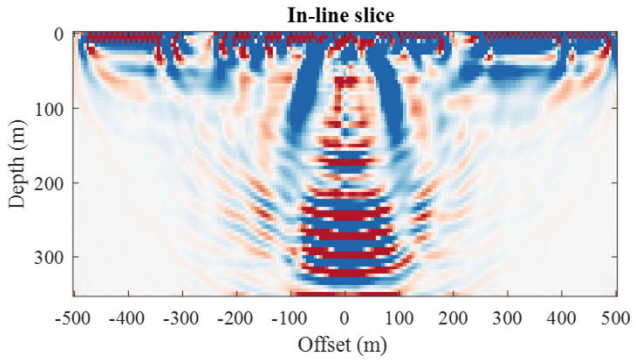
5896 seconds

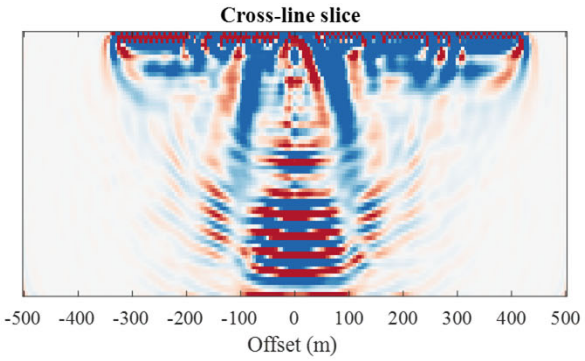
Synthetic Test——Monitor data RTM result

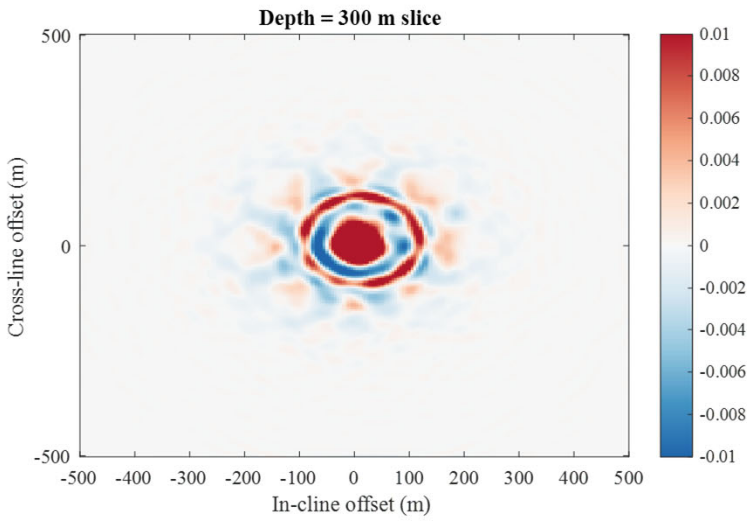




Shot gathers RTM





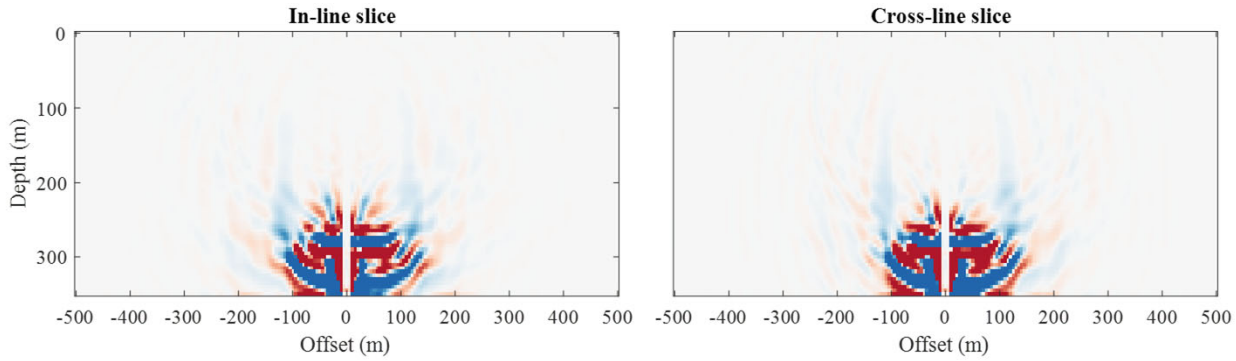


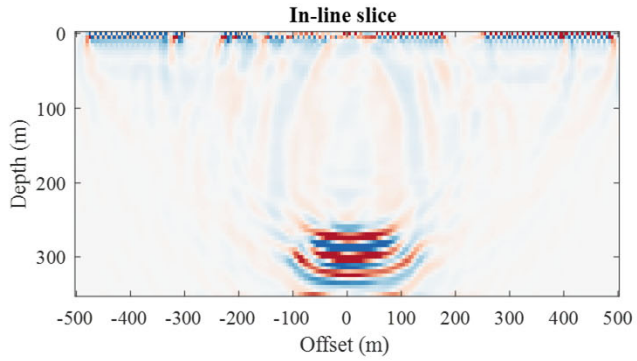
Reciprocity gathers RTM

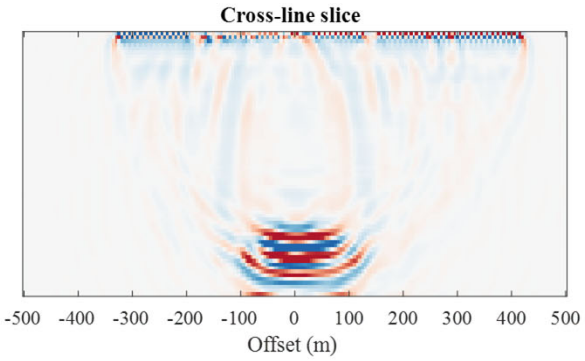
3536 seconds

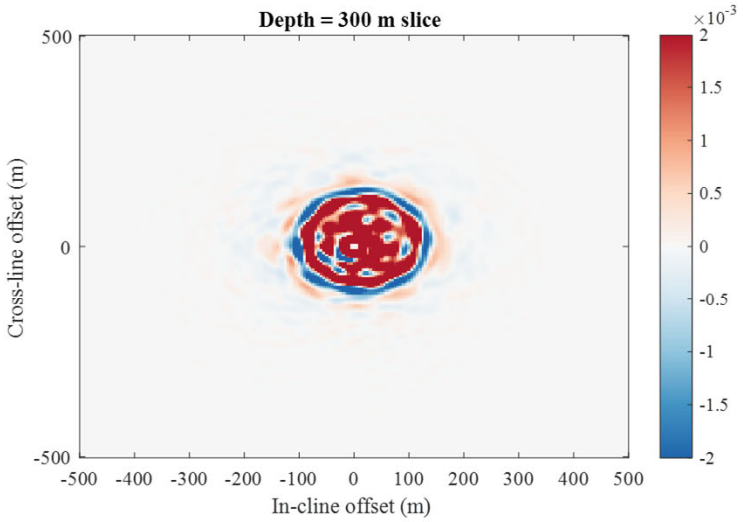
5910 seconds

Synthetic Test——Difference

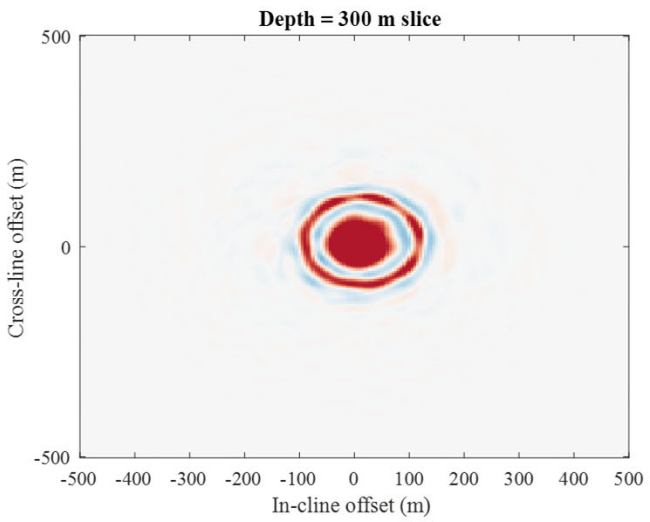






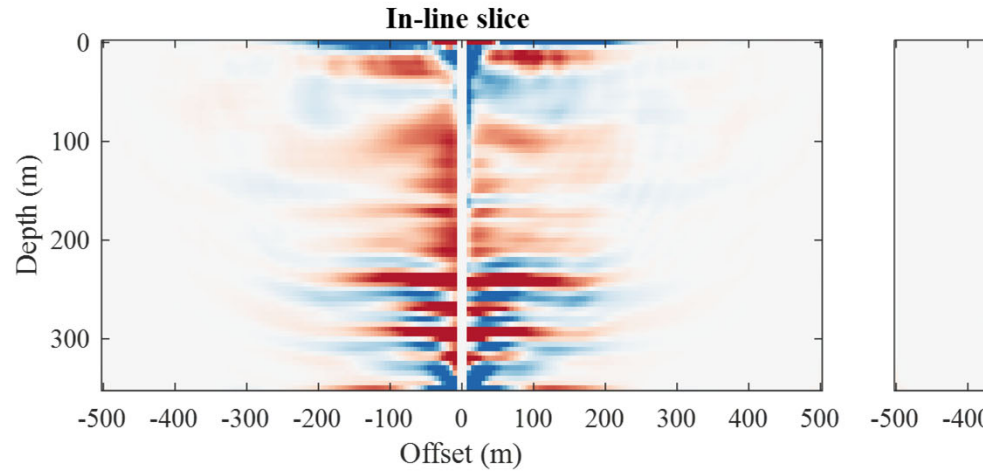


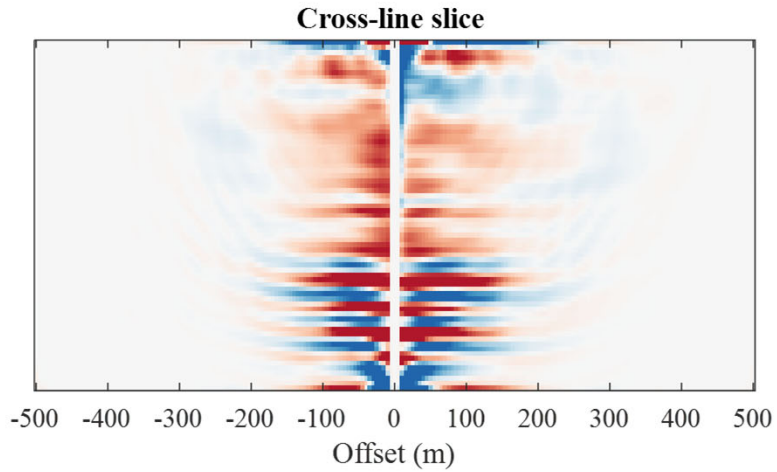
Shot gathers RTM

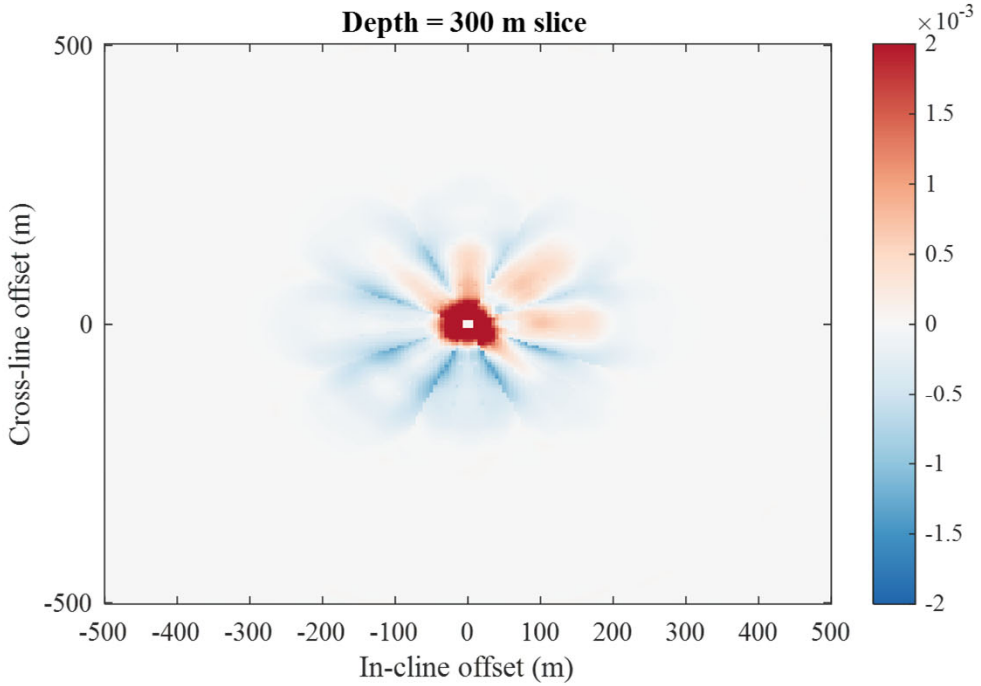


Reciprocity gathers RTM

Synthetic Test——3D azimuth-dependent RTM result

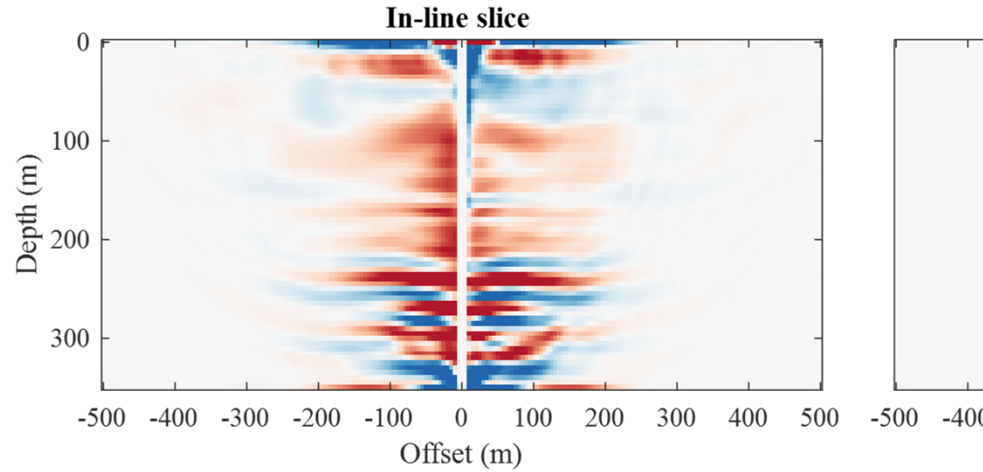


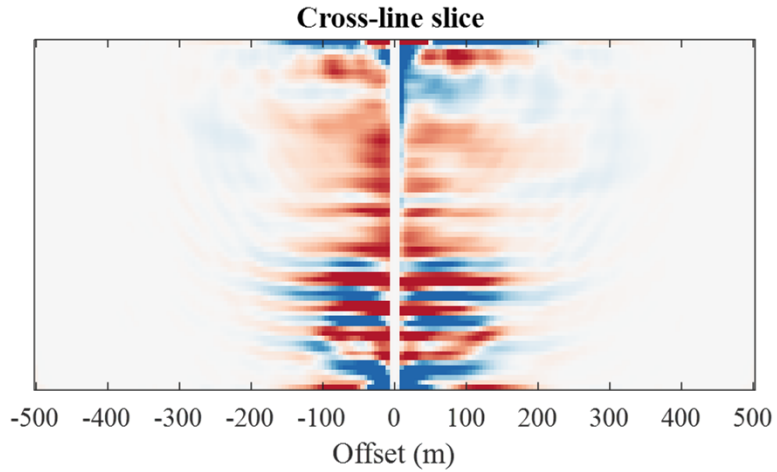


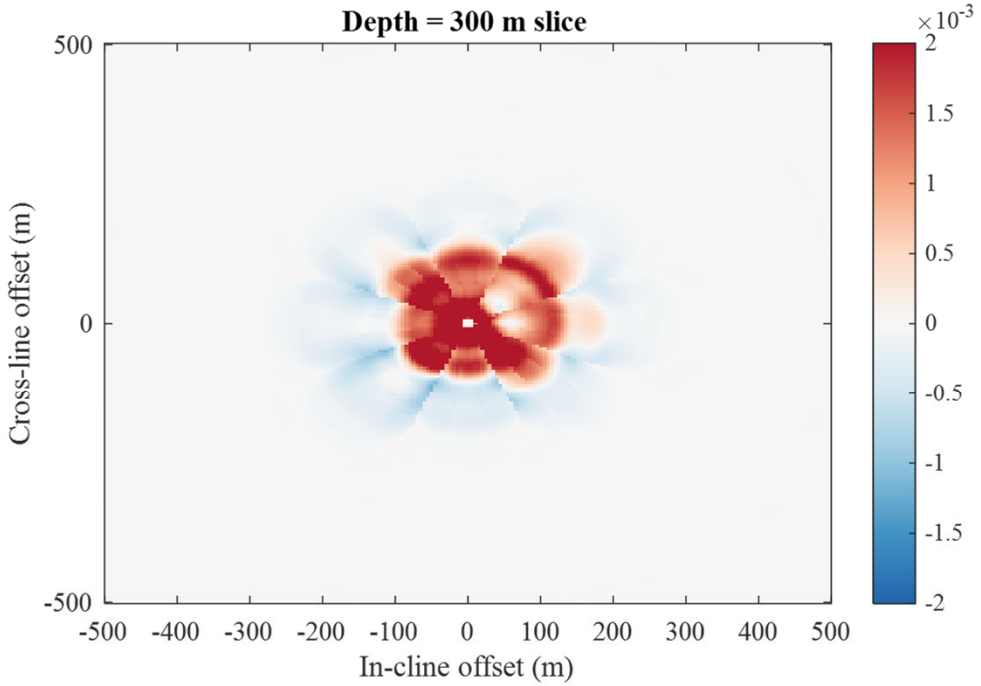


Baseline data

Synthetic Test——3D azimuth-dependent RTM result

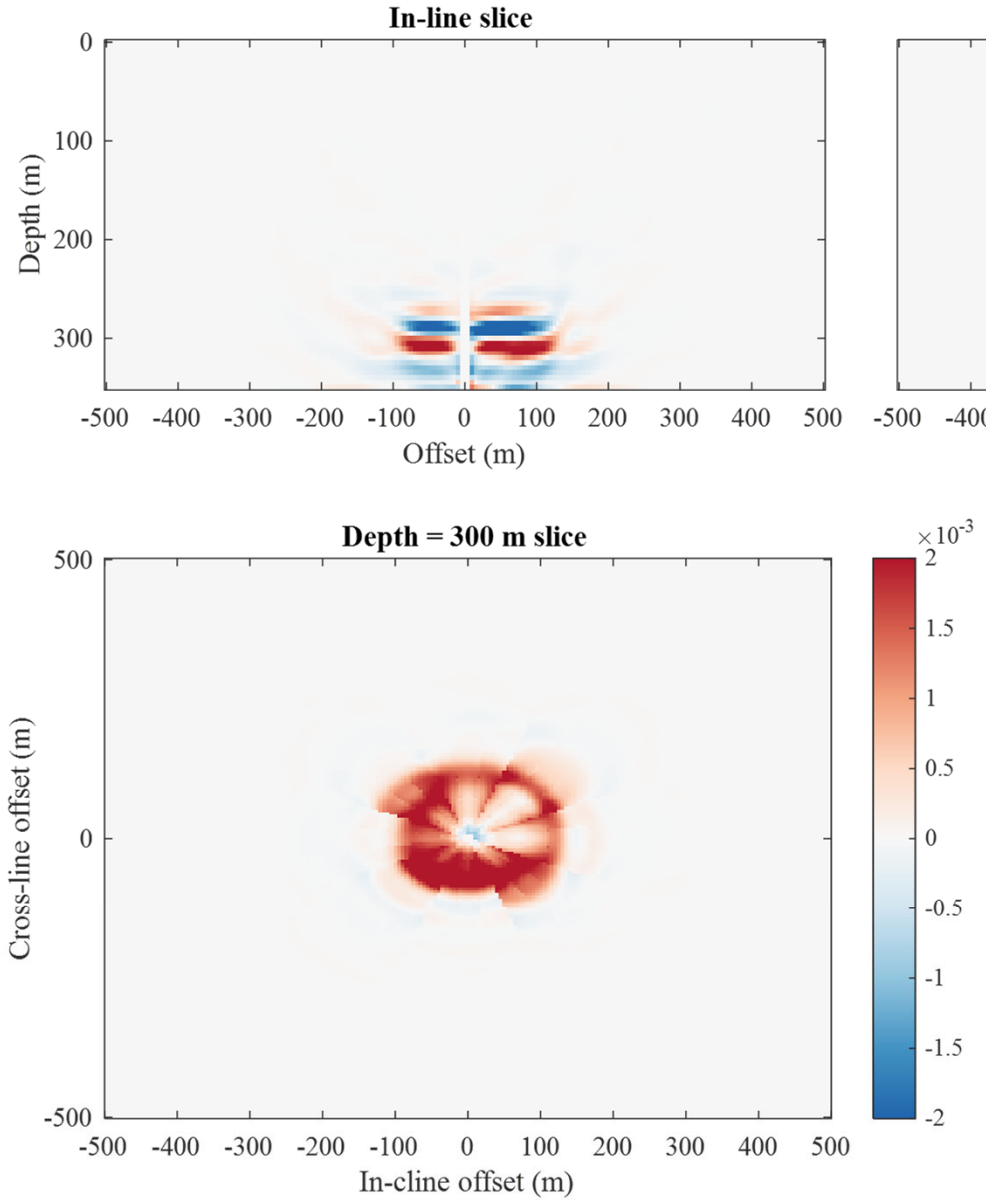






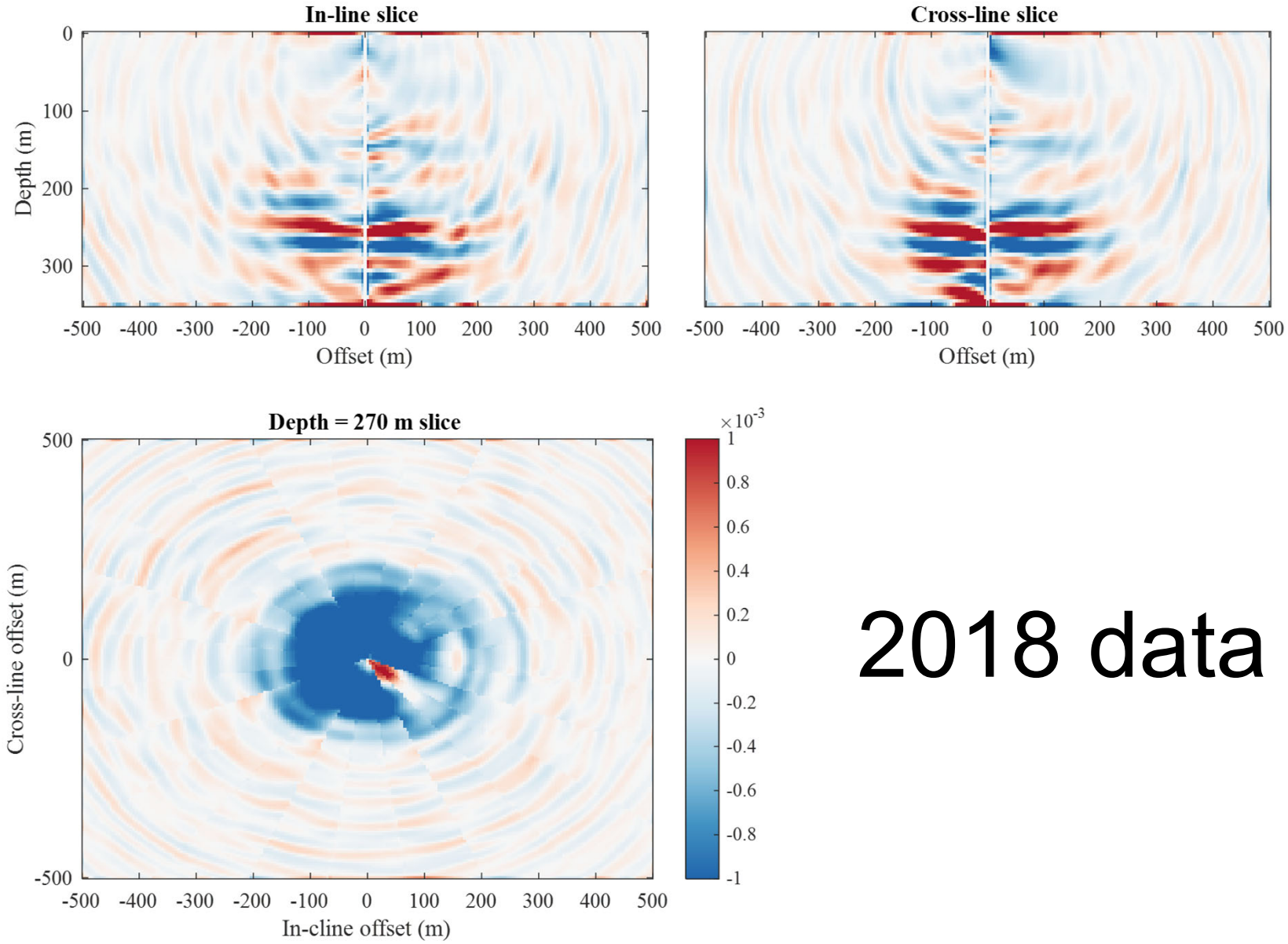
Monitor data

Synthetic Test——3D azimuth-dependent RTM result



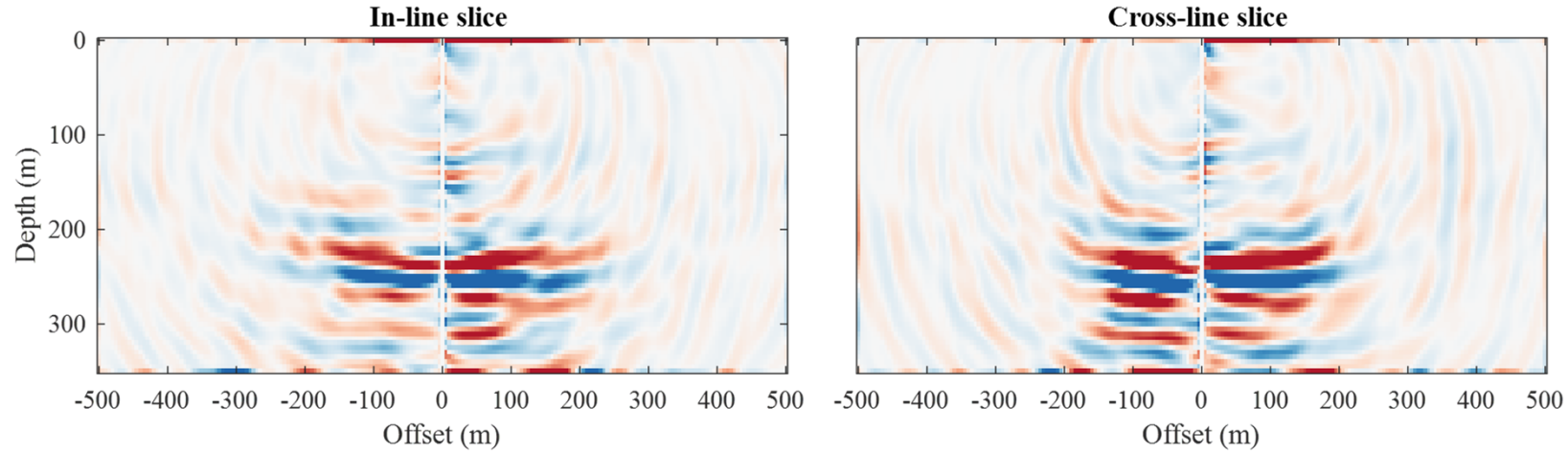
Difference

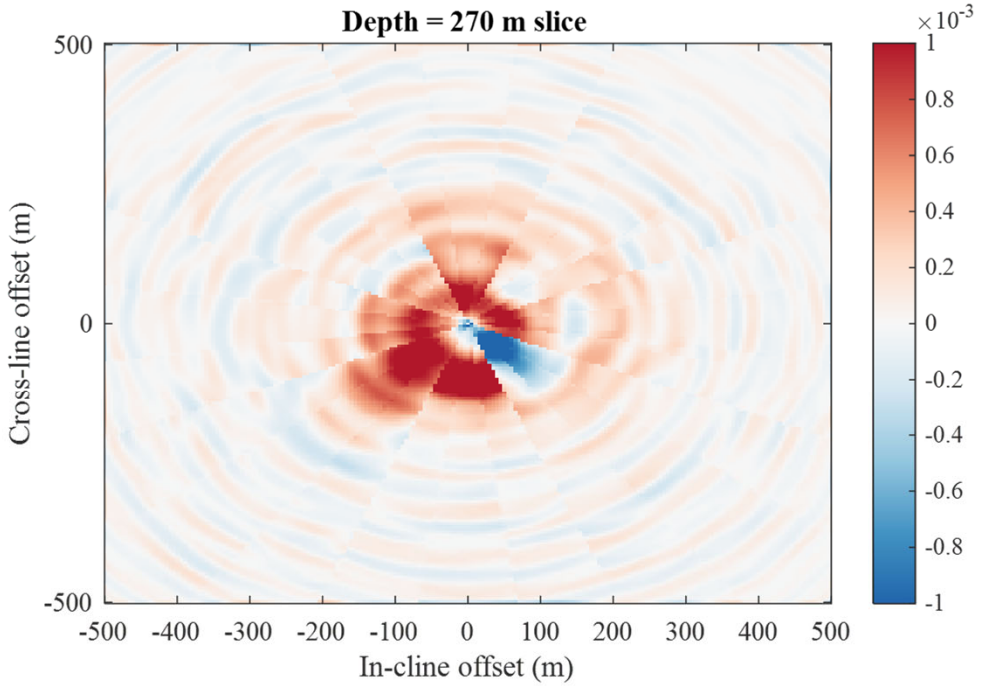
Field data——3D azimuth-dependent RTM result



2018 data

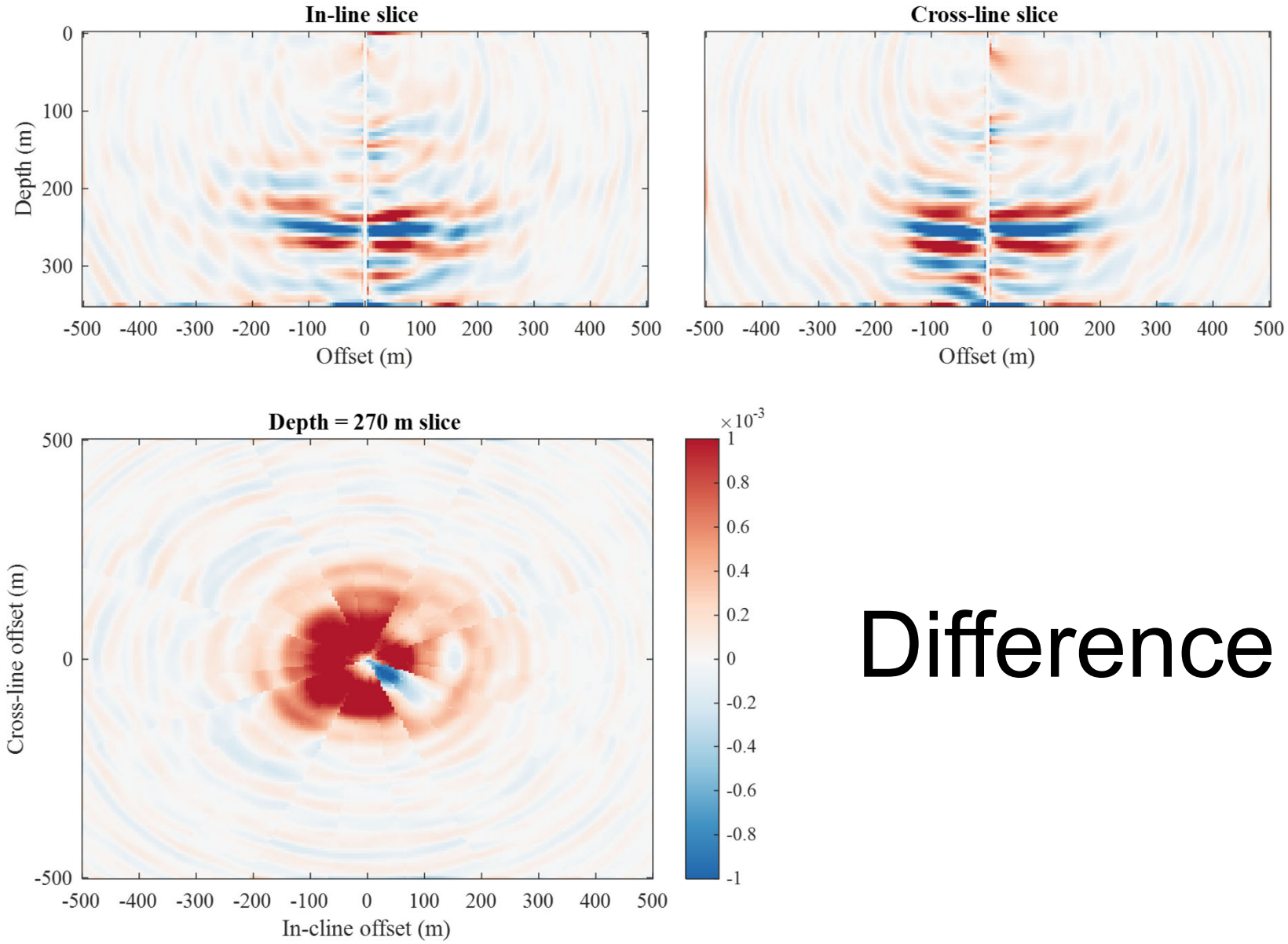
Field data——3D azimuth-dependent RTM result





2022 data

Field data——3D azimuth-dependent RTM result



Difference

Conclusions and Next steps

- Conclusions
  - Processing of the low signal-to-ratio DAS data is crucial
  - Azimuthal geometry makes the introduction of azimuth-dependent RTM essential.
  - The 3D time-lapse imaging serve as a source of inspiration for the low-cost CO2 monitoring: DAS, VSP
- Next steps
  - Reflection angle-dependent RTM
  - 3D Elastic LSRTM, FWI

Thanks

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University of Calgary Global Research Initiative

Carbon Management Canada