Microseismic event localization using both wavefields and their spatial gradients

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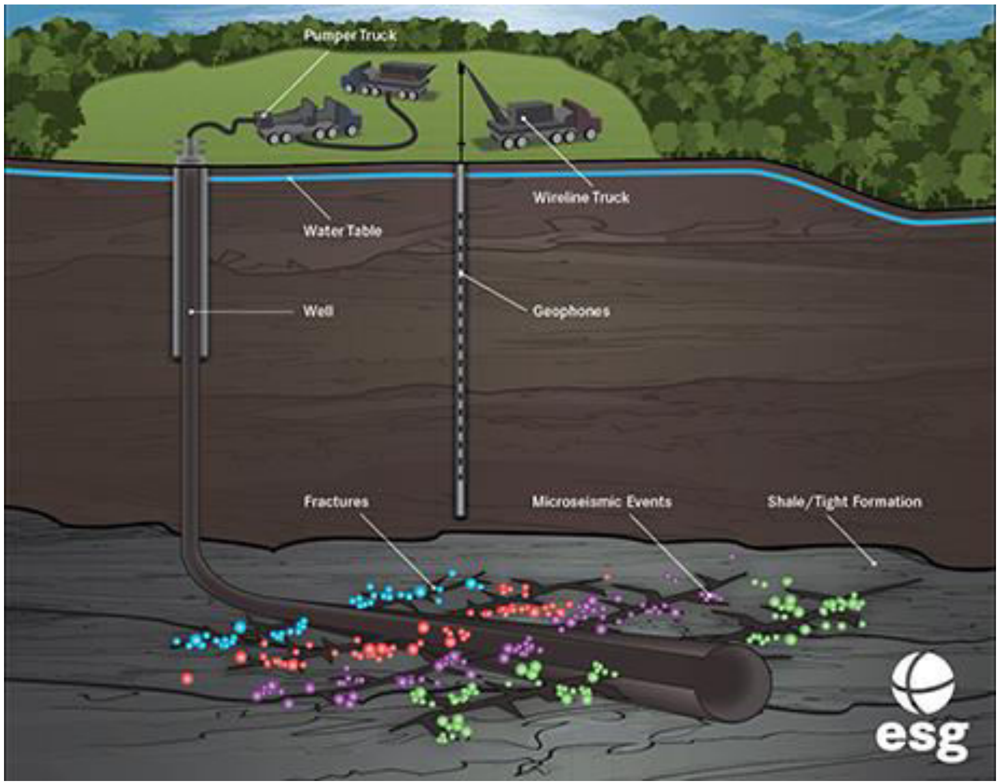
Microseismic monitoring



Microseismicity :

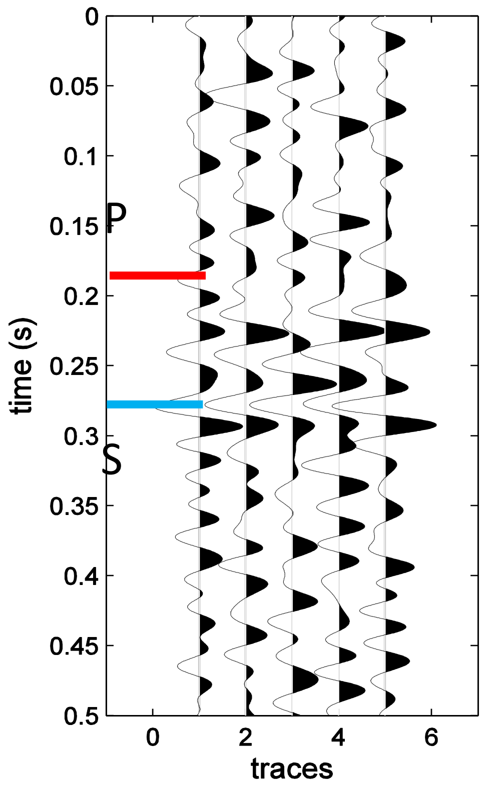
1. Human-activity related
   (mining, oil/gas production)

2. Very small magnitude
   (smaller than 0)

3. Indication of fracture development
   (accurate determination of
   microseismic event locations)

Color coding: hydraulic fracture stages

Microseismic event localization



Example of surface array microseismic record

Ray-based method :

1. P- and S-wave first arrival picking
2. Polarization analysis for all the pickings (incident direction)
3. Travel time inversion based methods

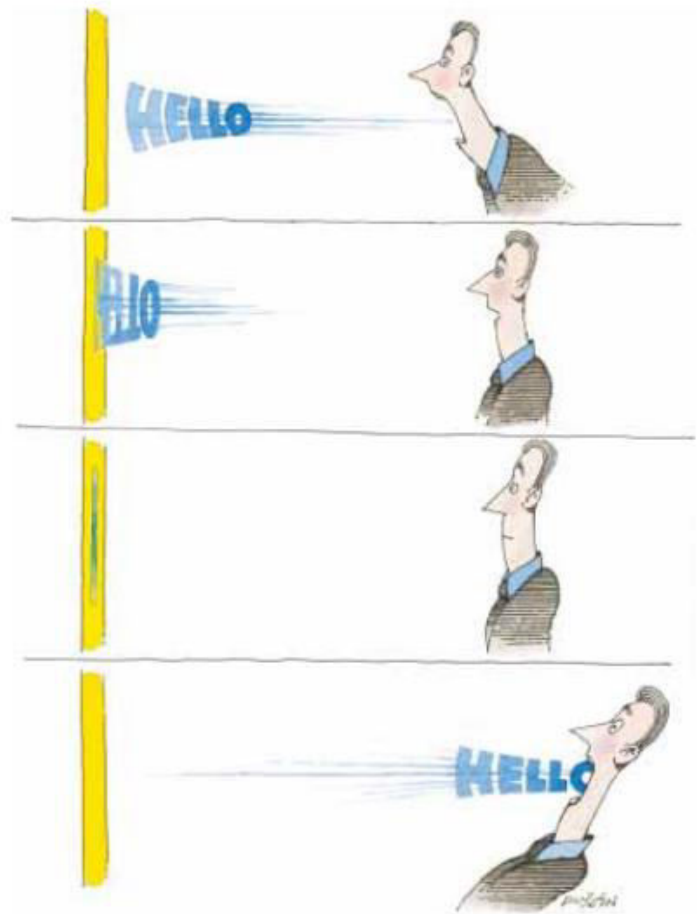
Advantages:

1. Fast algorithms
2. Less computation requirement

Drawbacks:

1. Picking errors from miss-picking and inaccurate picking
2. Manual picking can be very time-consuming (especially for surface array)
3. High frequency approximation is seriously affected by medium velocity errors

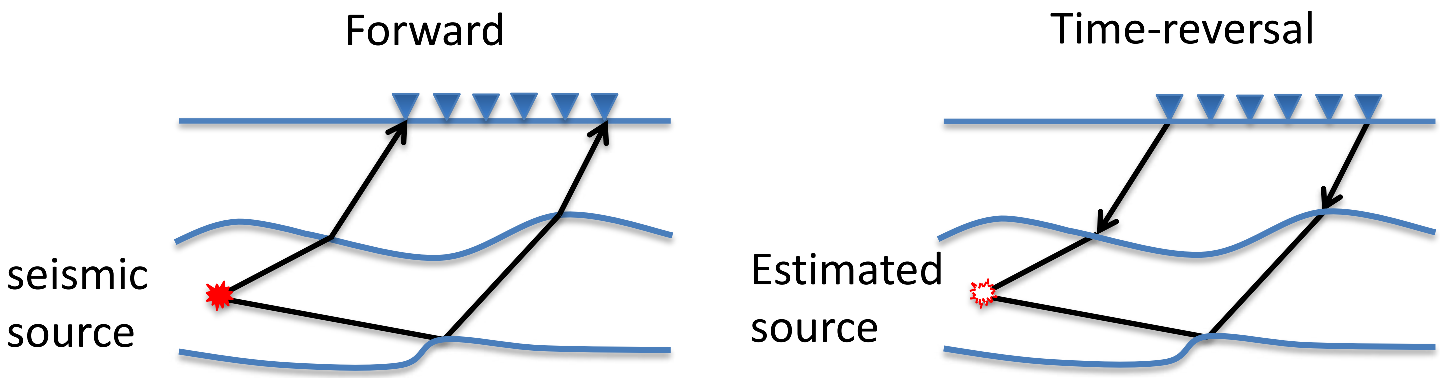
Microseismic event localization



What will happen if you shout to the wall

Fink, 1999

Microseismic event localization



Reverse-time-extrapolation (RTE) based method :

1. Injecting full 3C elastic recordings into the estimated medium
2. Focusing criterion (where and when)

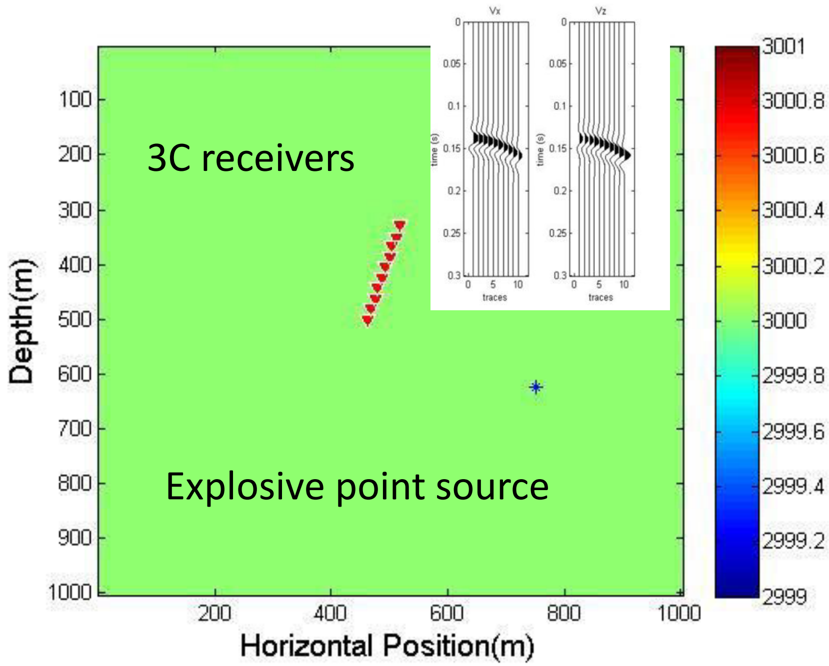
Advantages:

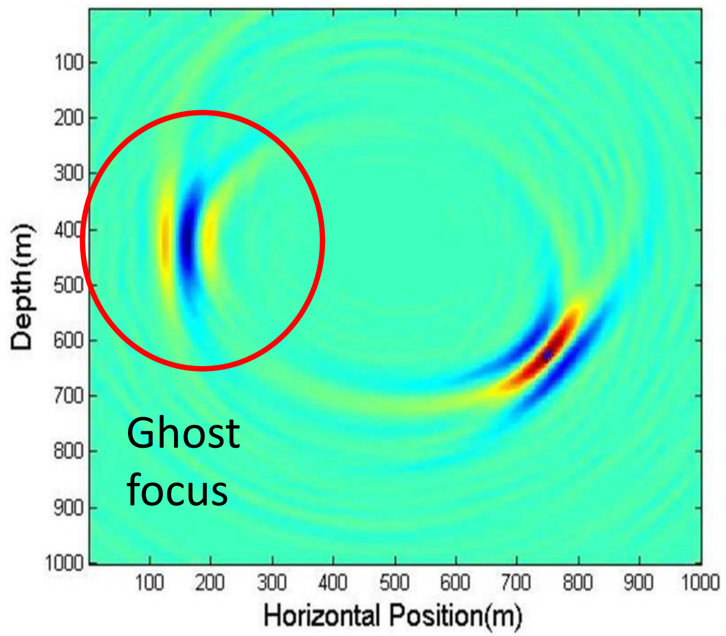
1. No picking needed
2. Stacking increases image signal-to-noise ratio
3. Simple algorithm

Limitations:

1. Relatively accurate velocity
2. Computationally intensive (Parallel computing)
3. May introduce artifacts for vertical borehole recordings for traditional RTE based method

Example - Homogeneous acoustic model with noiseless data





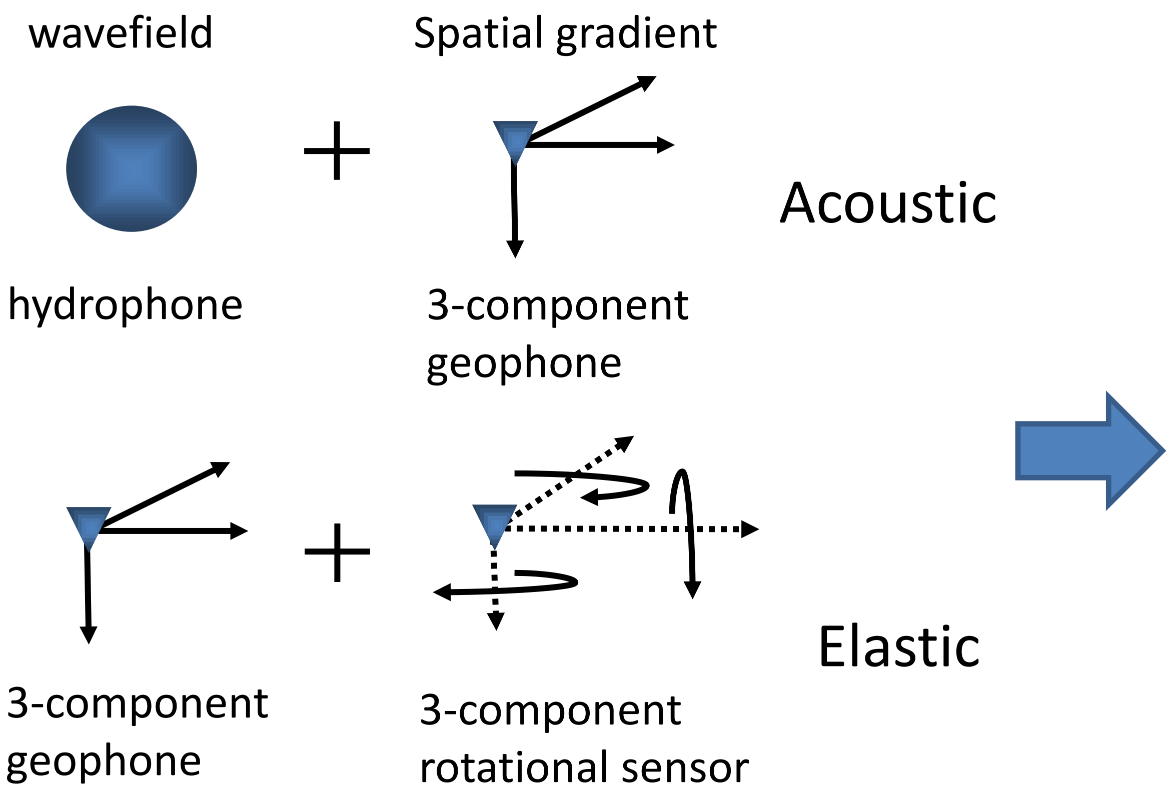
We want to

1. Keep advantages of RET based methods
2. Remove ghost focus

How?

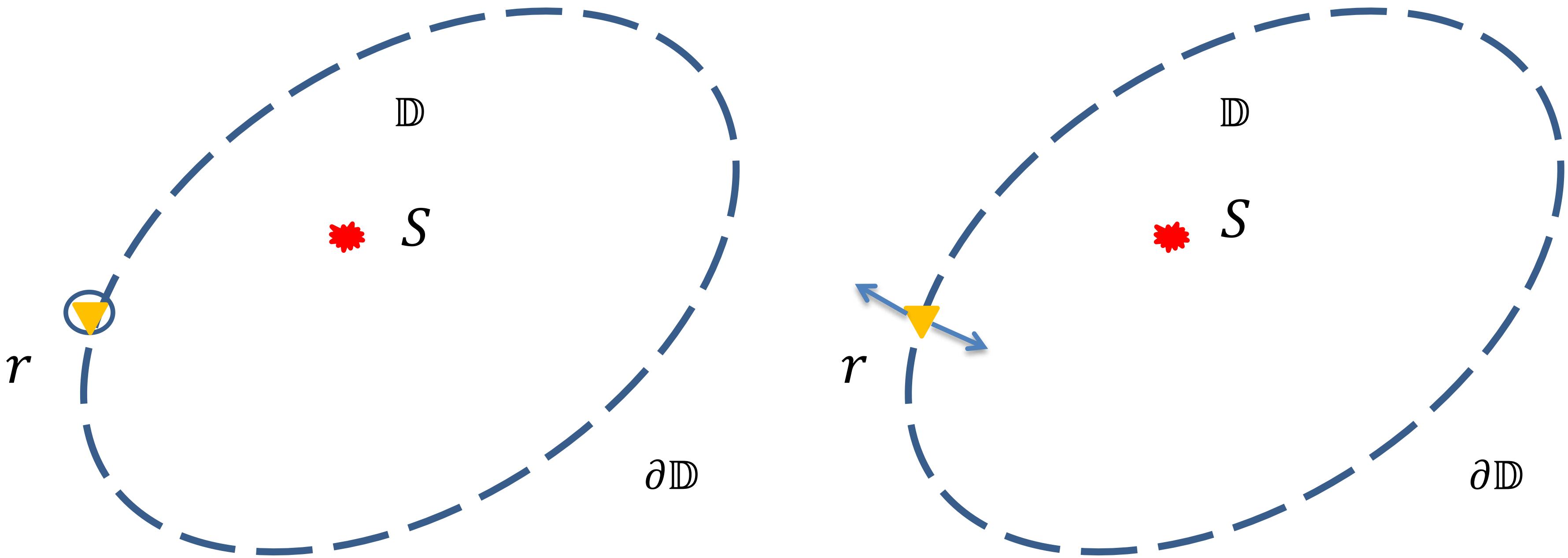
By combining both wavefields and their spatial gradients

How?



The acoustic/elastic representation theorem

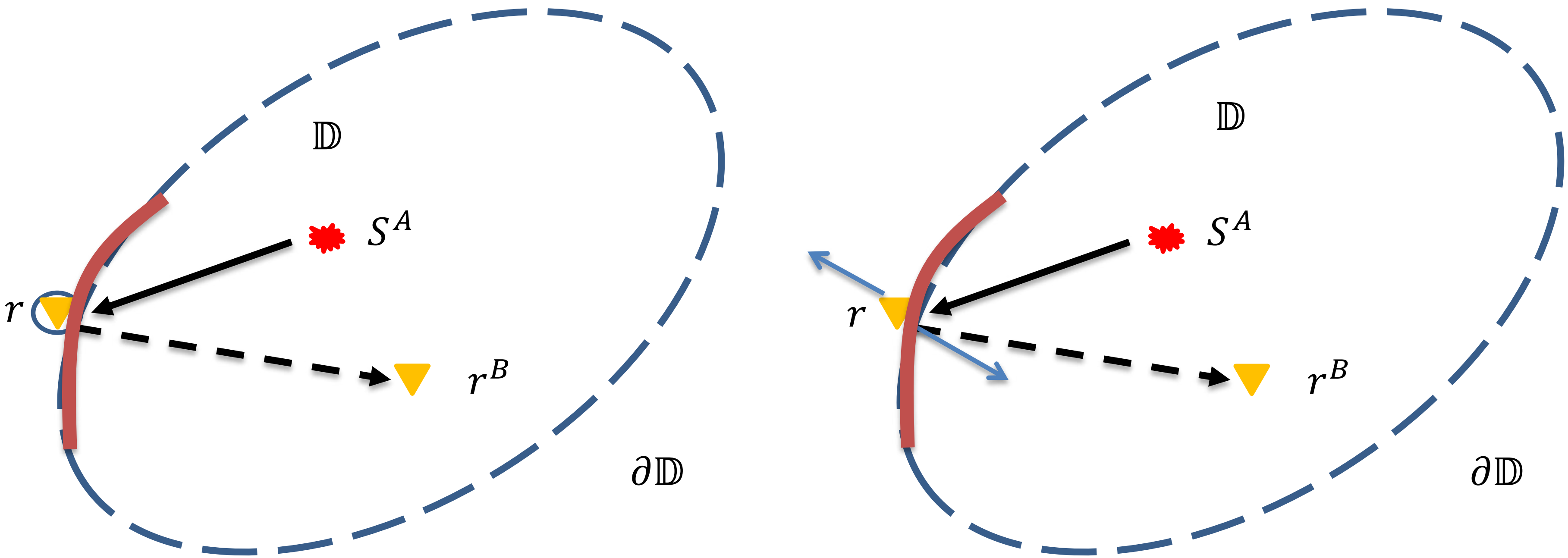
The body force equivalence of seismic source



Wavefield + Spatial gradient of the wavefield

(Aki and Richards, 2002, chapter 3, eq. 3.3)

2D acoustic reverse time extrapolation



Pressure wavefield back-propagation image

+

3C particle velocity/displacement back-propagation image

2D acoustic reverse time extrapolation

Back-propagated pressure wavefield

Acoustic Sink

$$\hat{P}^*(\boldsymbol{r}^B,\boldsymbol{r}^A) + \oint_{\mathbb{D}} \hat{s}^*(\omega)\hat{G}(\boldsymbol{r},\boldsymbol{r}^B)\hat{\delta}(\boldsymbol{r}-\boldsymbol{r}^A)dS$$

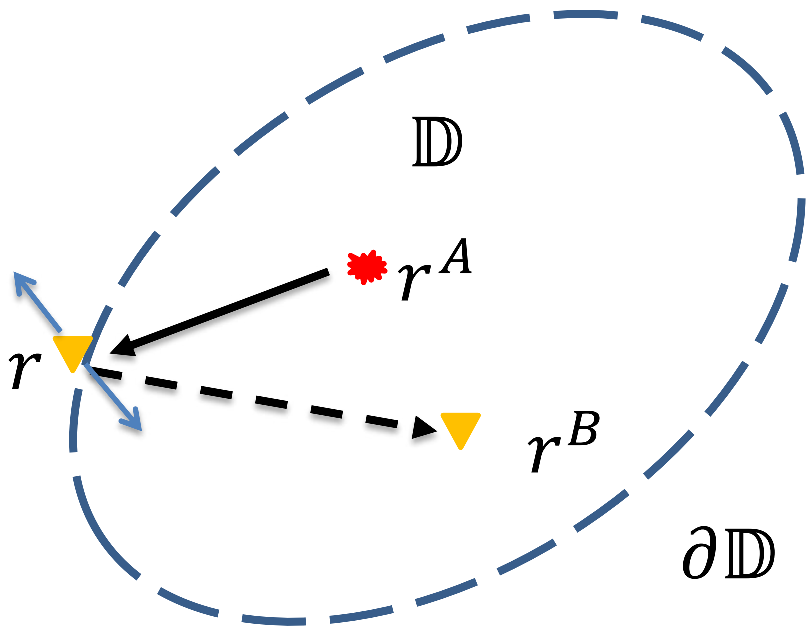
$$= -\int_{\partial\mathbb{D}} \boldsymbol{n}\cdot\left(\hat{G}(\boldsymbol{r},\boldsymbol{r}^B)\frac{1}{\boldsymbol{i}\omega\rho}\nabla\hat{P}^*(\boldsymbol{r},\boldsymbol{r}^A)\right.$$

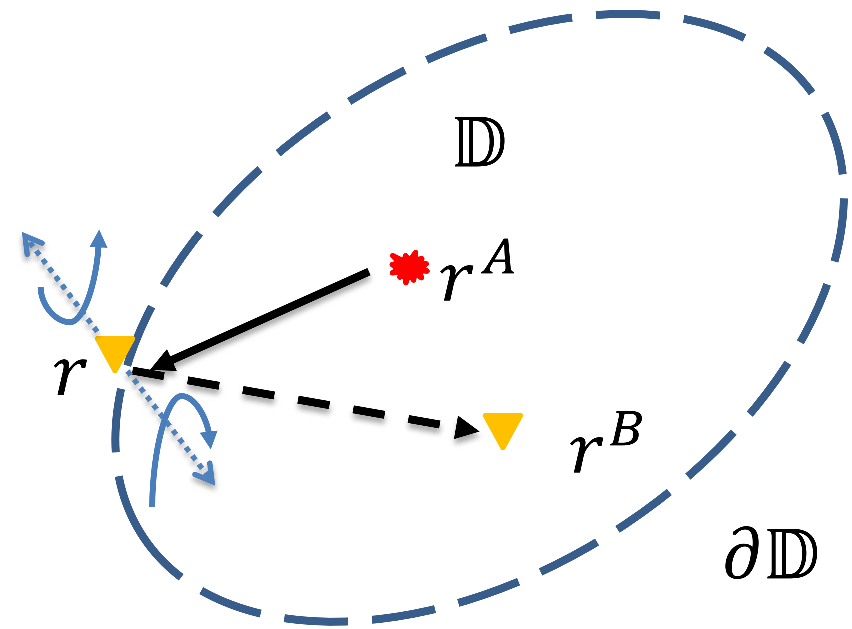
$$\left. - \hat{P}^*(\boldsymbol{r}\quad,\boldsymbol{r}^A)\frac{1}{\boldsymbol{i}\omega\rho}\nabla\hat{G}(\boldsymbol{r},\boldsymbol{r}^B)\right)dl,$$

Measured pressure field

Measured particle displacement/velocity

2D elastic reverse time extrapolation





3C particle velocity/displacement back-propagation image

+

3C rotational wavefield back-propagation image

2D elastic reverse time extrapolation

Reconstructed backpropagation translational wavefield

Sink

$$\hat{u}_n^*(\boldsymbol{r}^B, \boldsymbol{r}^A) - \int \hat{f}_i^A \hat{G}_{in} dV$$

$$= \oint (\lambda + 3\mu) n_j (\epsilon_{ikj} \hat{\Omega}_k^{A*} \hat{G}_{in} - \epsilon_{ikj} \hat{\Omega}_{kn}^G \hat{u}_i^{A*}) dS.$$

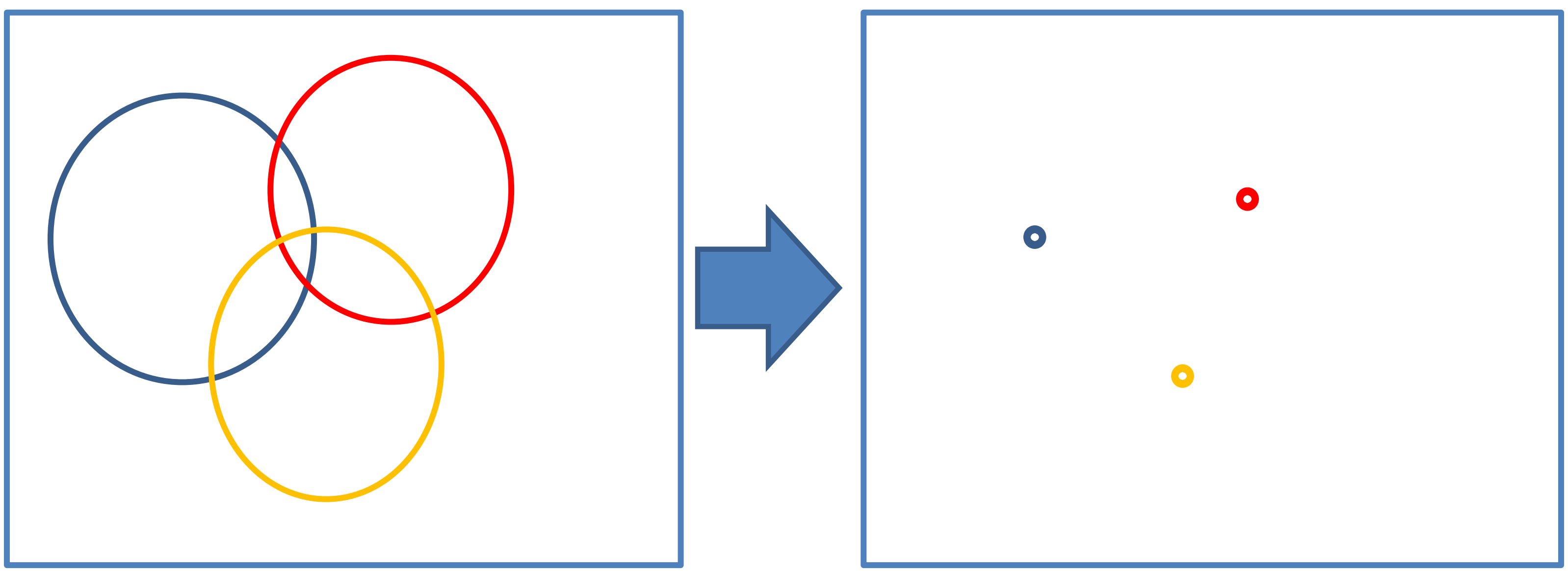
Measured Rotational motion with translational Green's function

Measured translational motion with rotational Green's function

The first time we involve rotational signal in reverse-time extrapolation

Focusing criterion (2D)

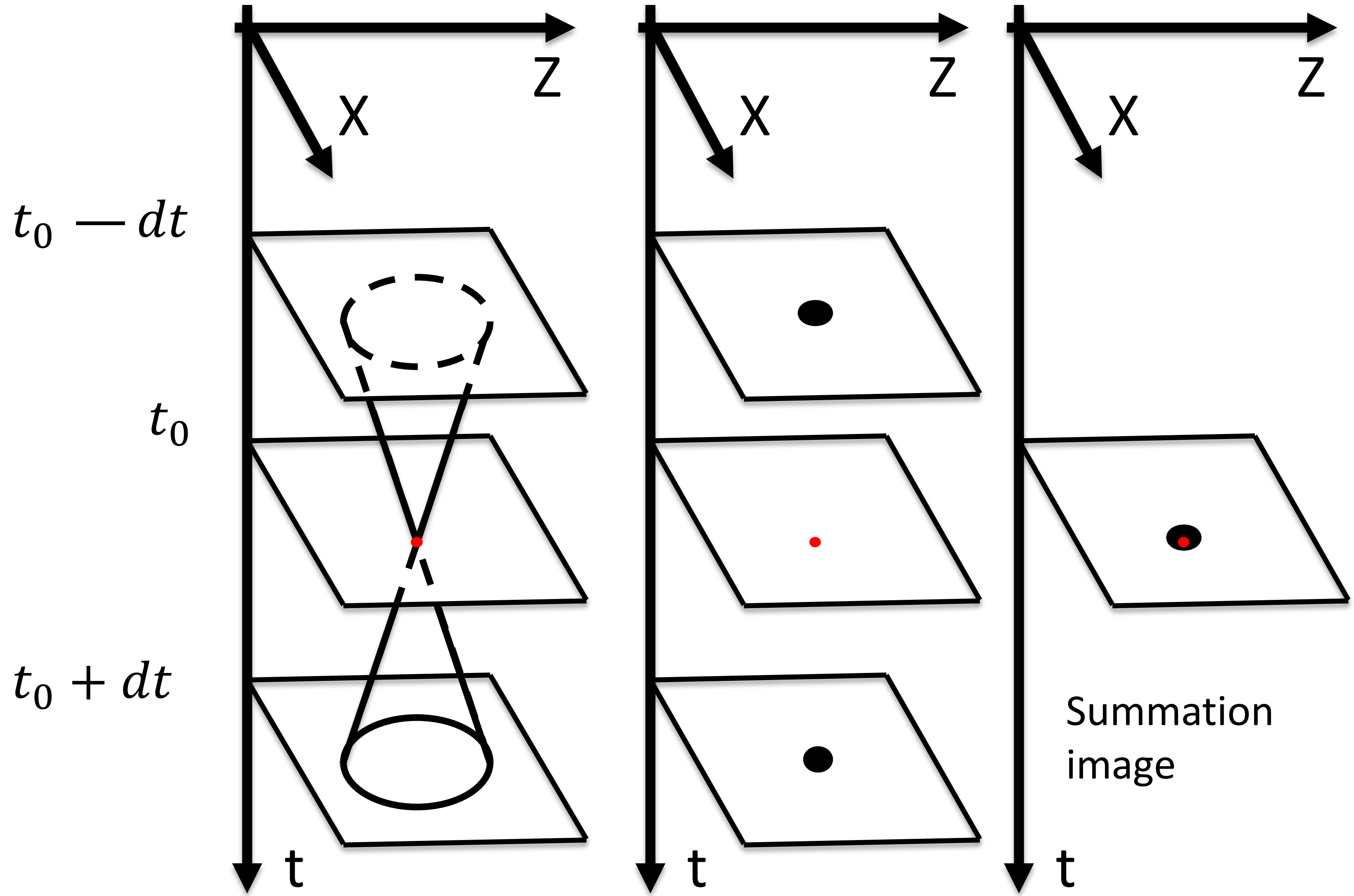
The Hough transform （HT）
- Shape detection (Circle)
- Value Accumulation



Original image

The Hough image

Focusing criterion (2D)



Focusing criterion (2D)

Maxima on each summation image

Spatial Coordinates (X,Z) Summation Magnitude Corresponding Time Minimum distance to receivers

Distance Threshold $\mathbb{T}_D$

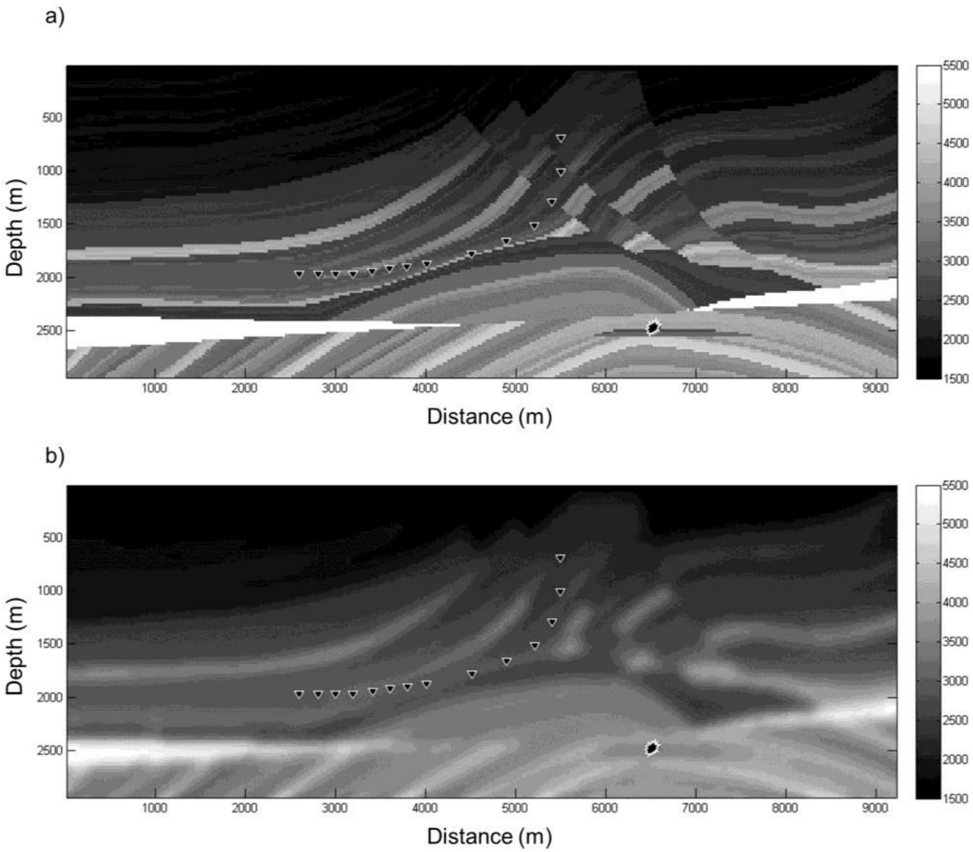
Magnitude Threshold $\mathbb{T}_M$

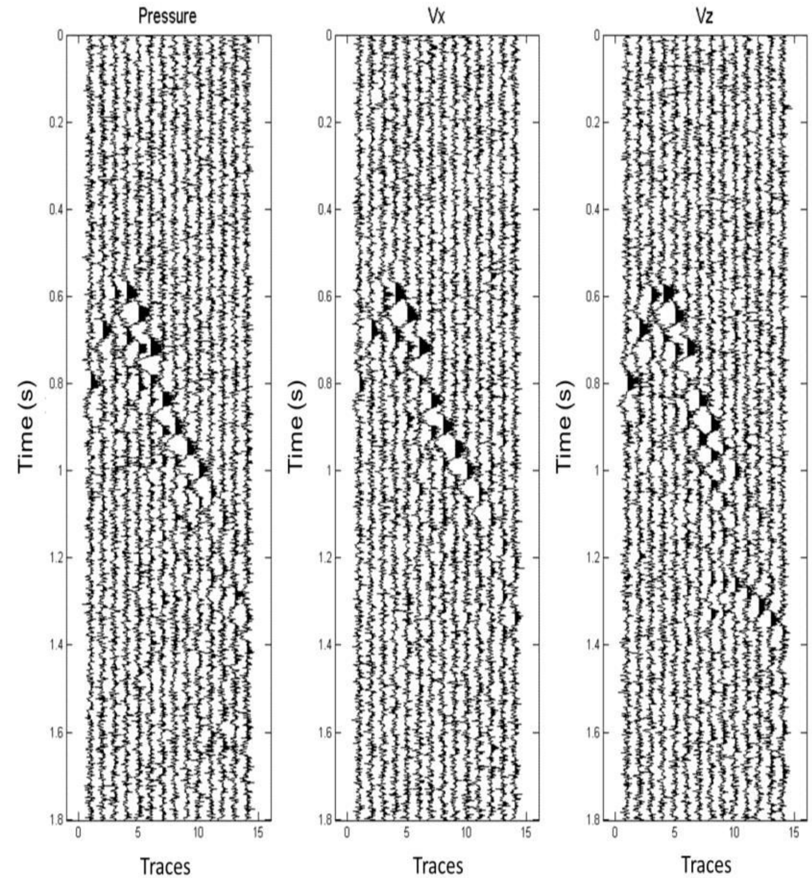
→

Estimated microseismic event

Event location origin Time

Example - Acoustic

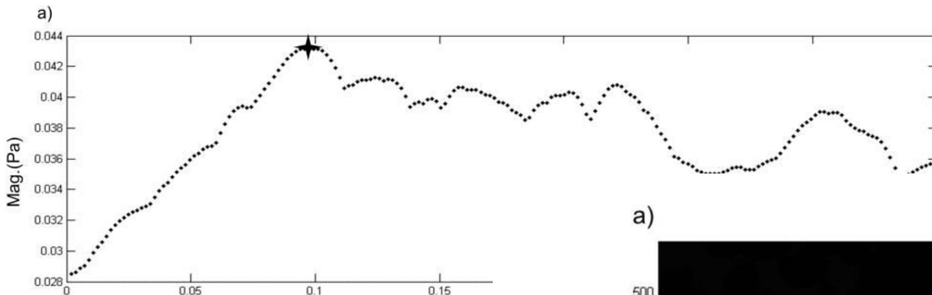




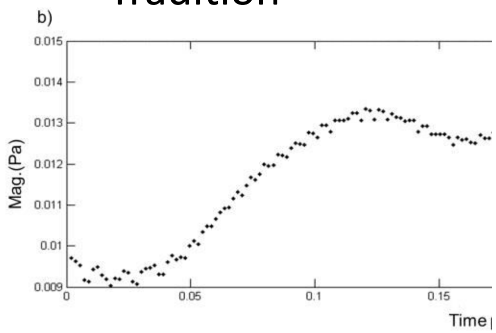
Deviated borehole with an explosive source

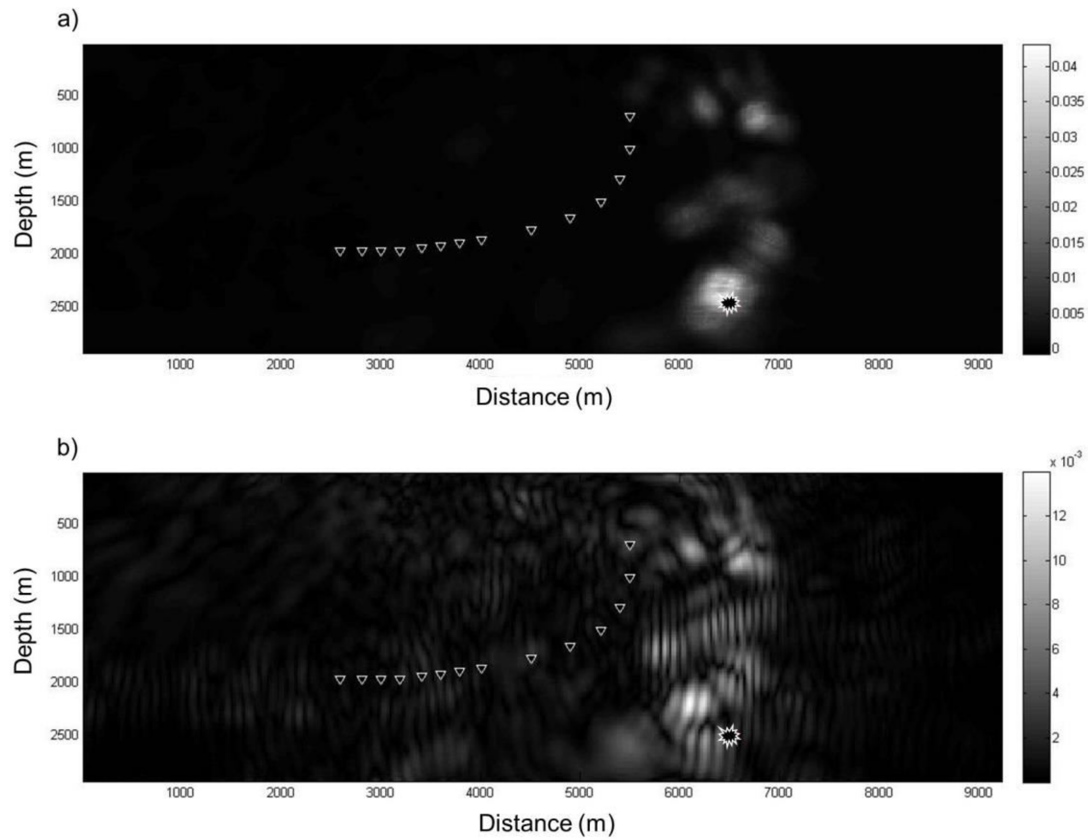
Example - Acoustic

Representation theorem

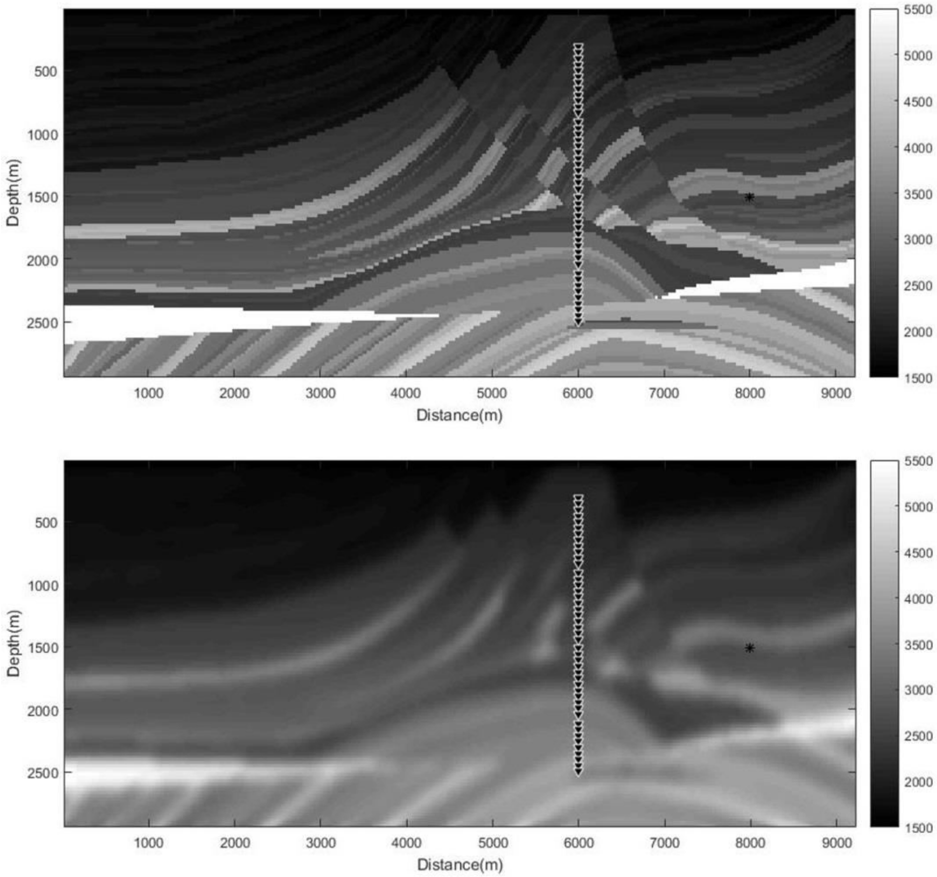


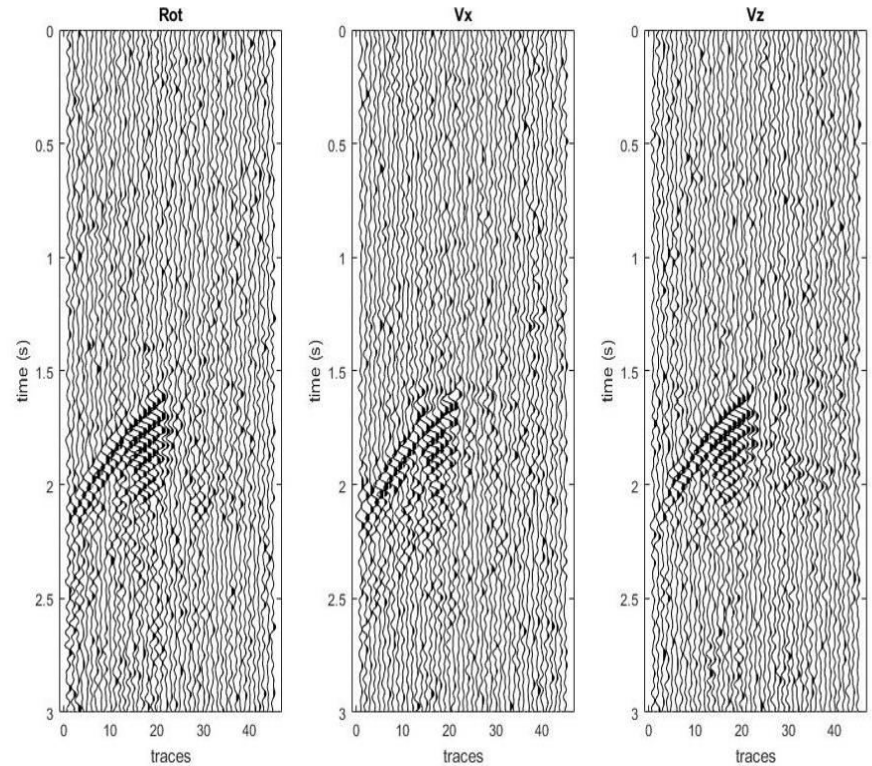
Tradition





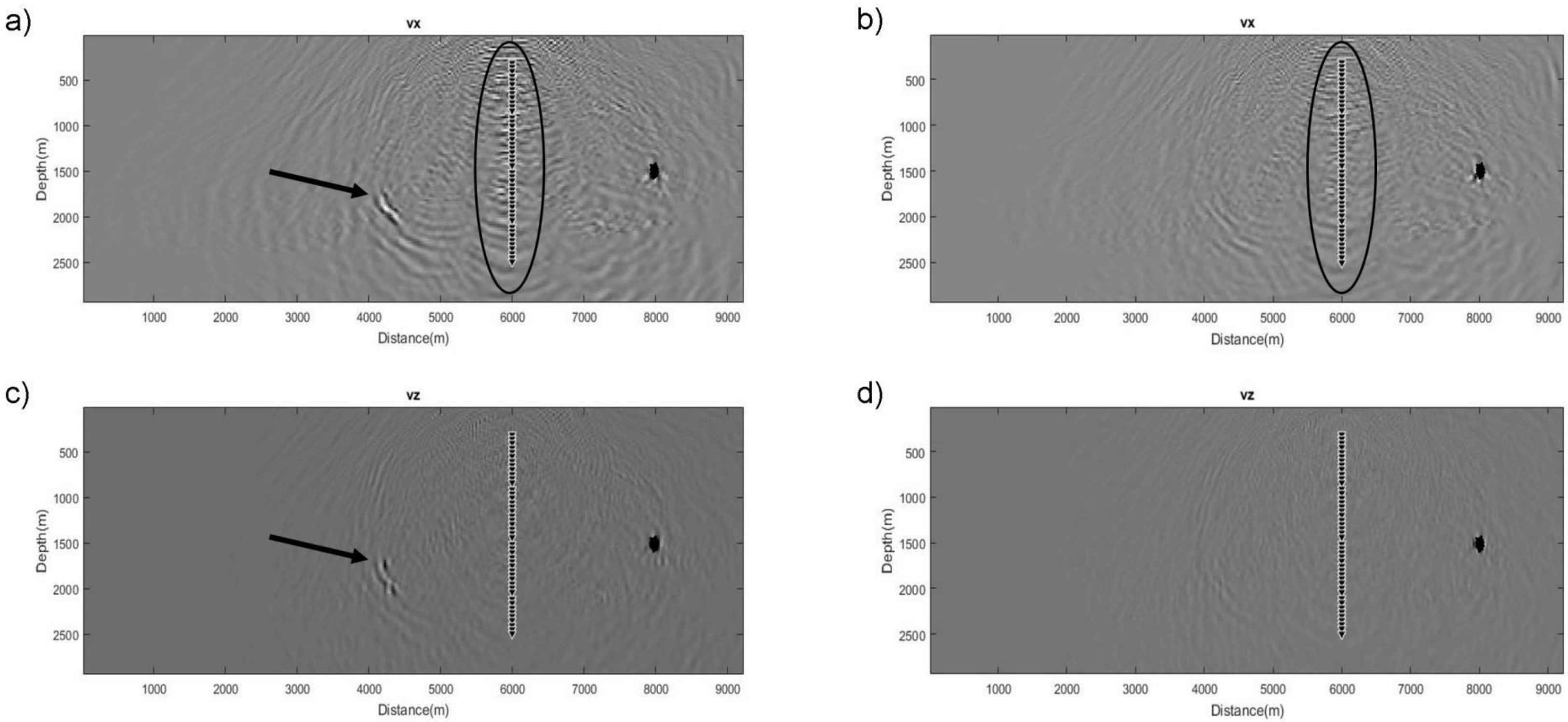
Example - Elastic





Vertical borehole with a double couple source

Example - Elastic



Conclusion

- Reverse time extrapolation doesn’t require P- and S-wave first arrival picking
- The acoustic focusing criterion can conveniently determine microseismic event location and time
- Acoustic case: hydrophone + three-component receivers = > better locations
- Elastic case: three-component translational + three component rotational sensors = > better locations
- Flexible combination of wavefields to improve source image
- Surface receivers are more suitable for this method

Acknowledgements

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Thank You!