DAS modeling for hydraulic fracture and caprock monitoring

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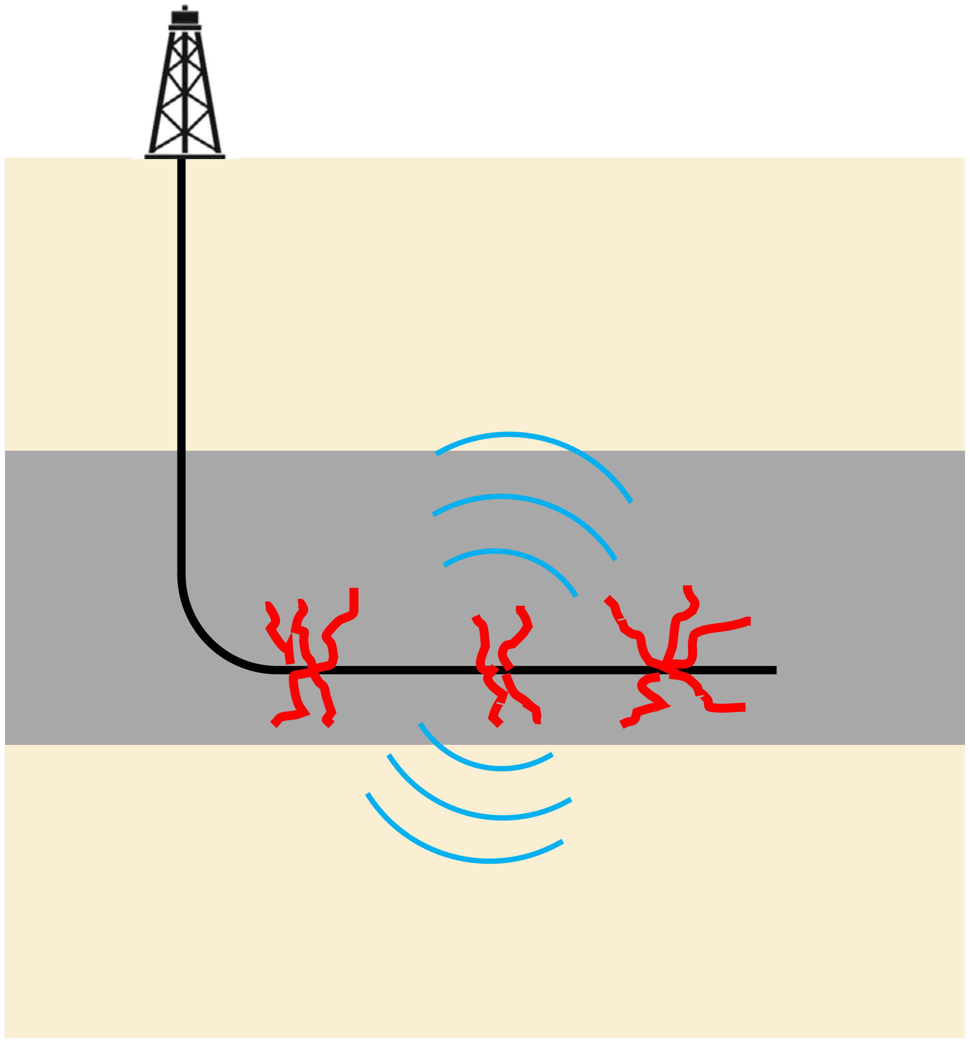
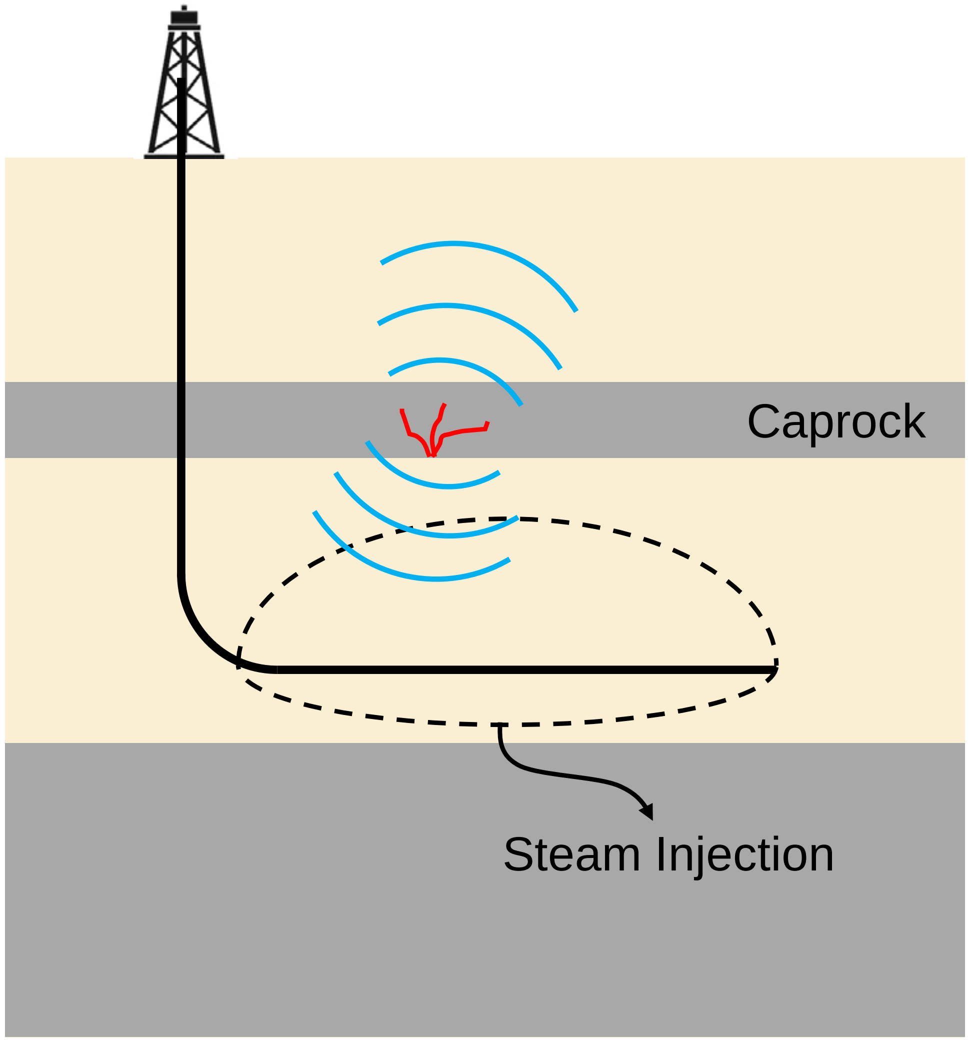
Motivations

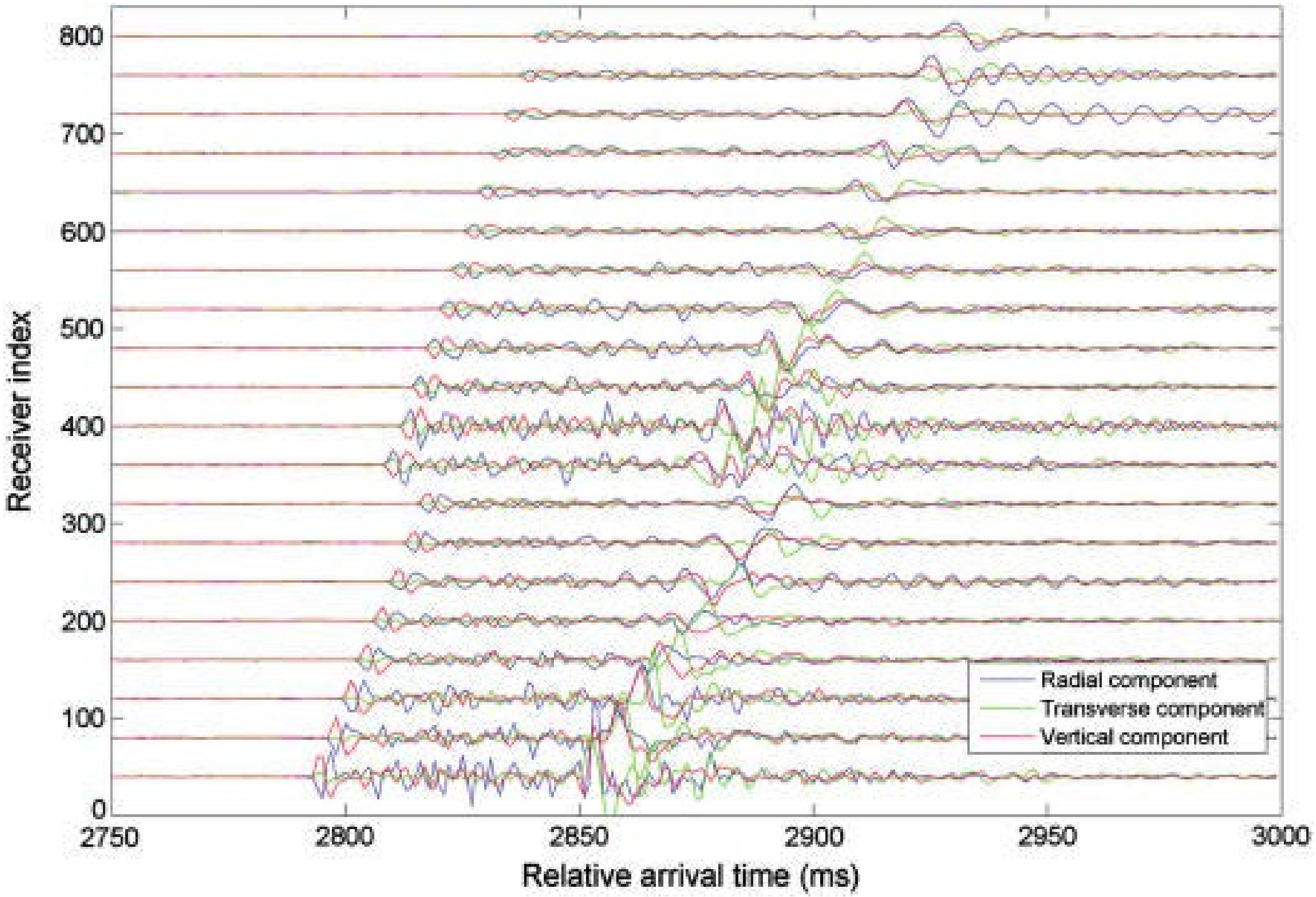


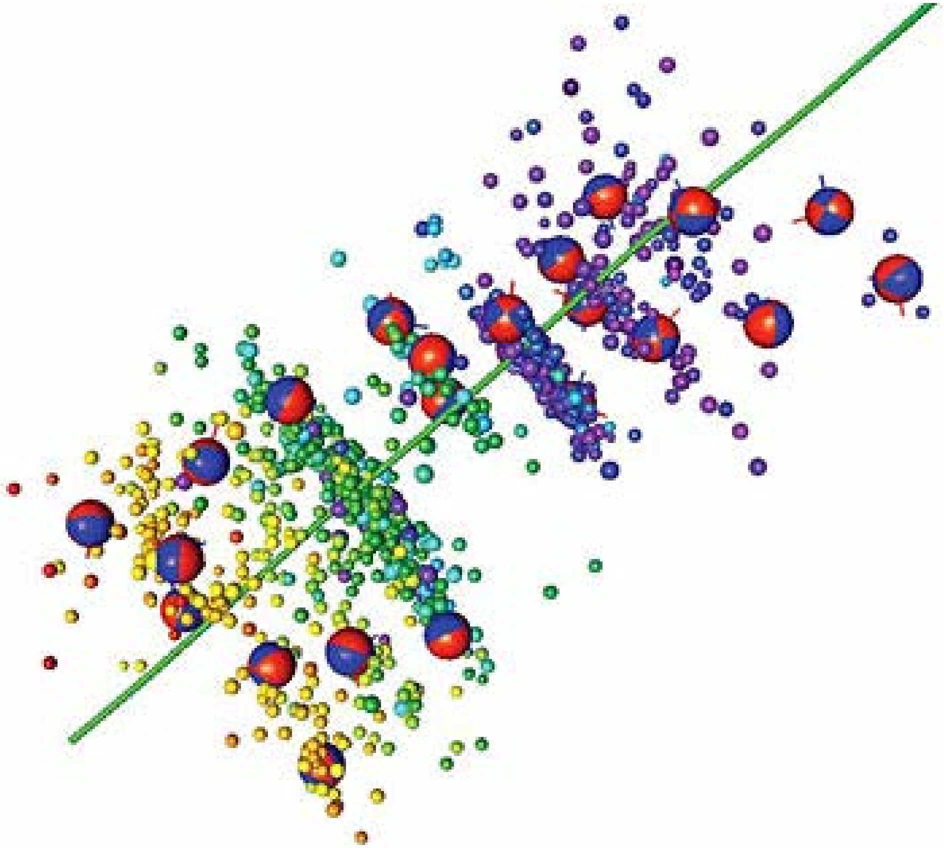
Hydraulic Fracturing



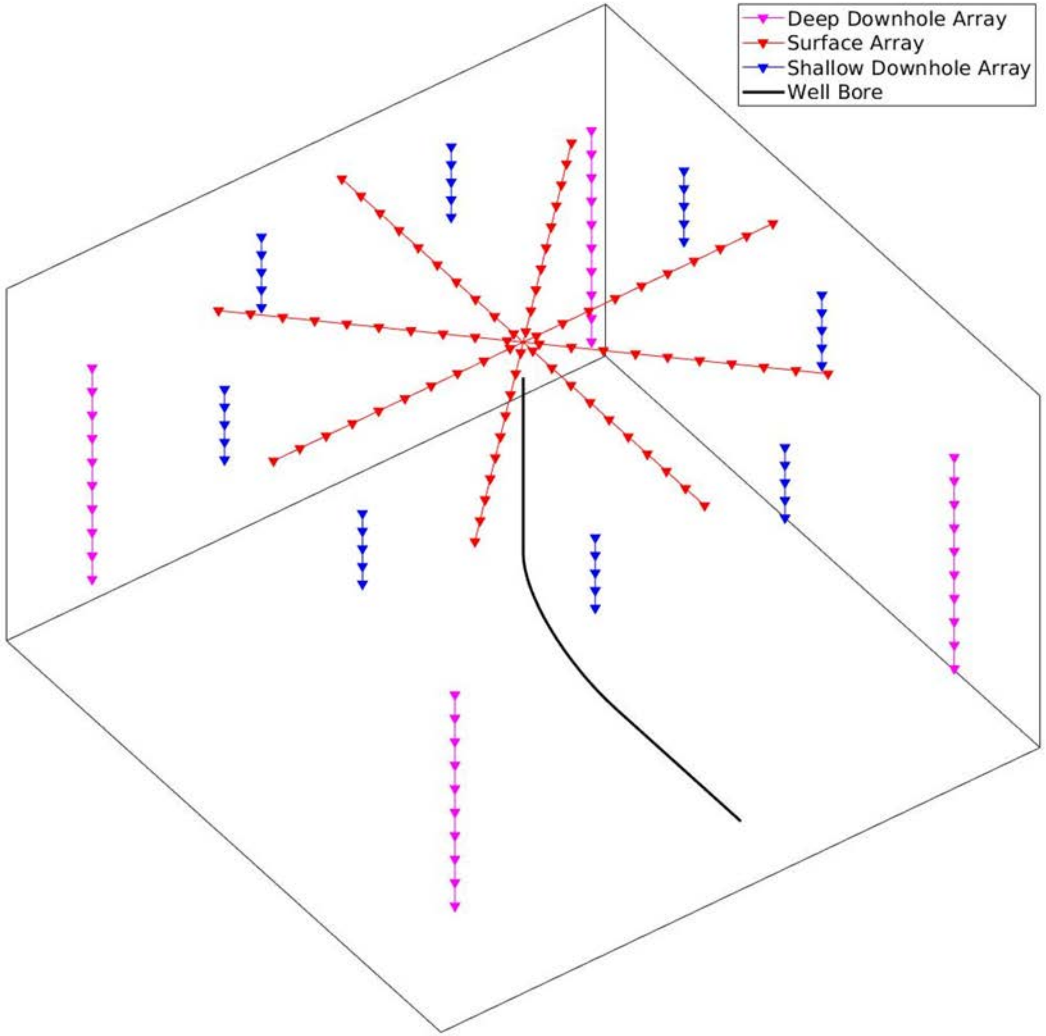
Cyclic steam stimulation

Microseismic data





Microseismic Monitoring Array Types: Geophones



Conventionally, microseismic data has been recorded with networks of 1C and 3C geophones in three main array types:

1. Surface Arrays
2. Shallow Downhole Arrays
3. Deep Downhole arrays

Desirable geometries have the properties:

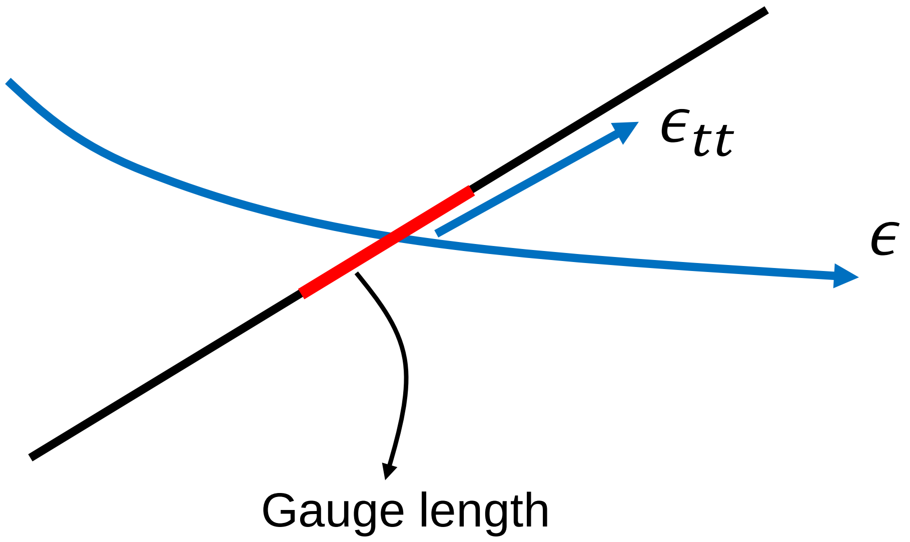
- Close proximity to treatment well
- Sample sufficiently large aperture
- Ideally cover a range of depth intervals
- Cost-effective

Distributed Acoustic Sensing

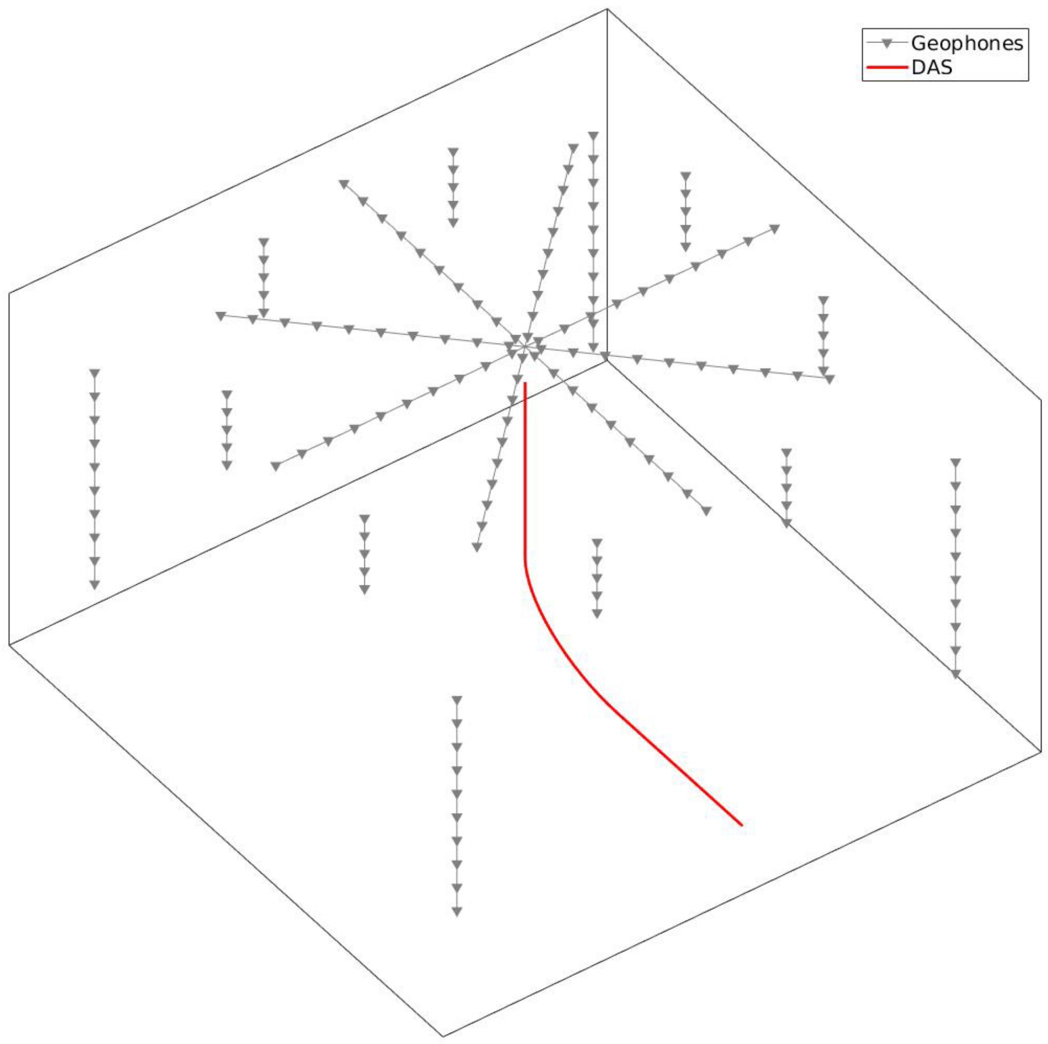
- DAS uses an optical fibre to make measurements of seismic strain

- Fibres are only sensitive to strain along the tangent of the fibre

- Measurements are spatially averaged over the gauge length to improve SNR



Microseismic Monitoring Array Types: DAS



Advantages

- Non-invasive: can be placed in frack well or nearby monitoring well, allowing for dual purpose wells.
- Dense spatial sampling ~ 3ft sample interval.
- Large aperture recording with 1000’s of receivers.
- Ultra low frequency (near-DC) strain measurements.

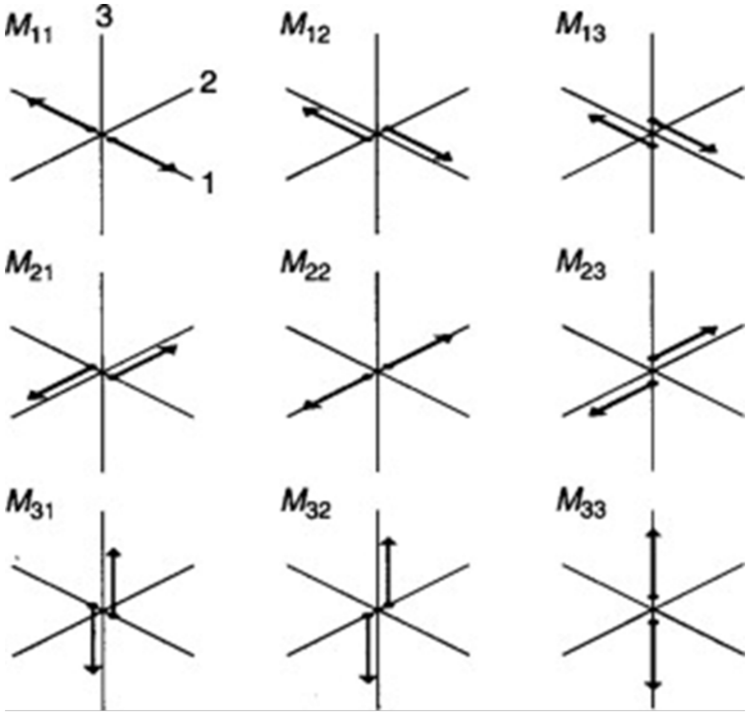
Disadvantages

- Low signal-to-noise ratio, and generally lower sensitivity.
- Single component recording.
- Expensive to deploy

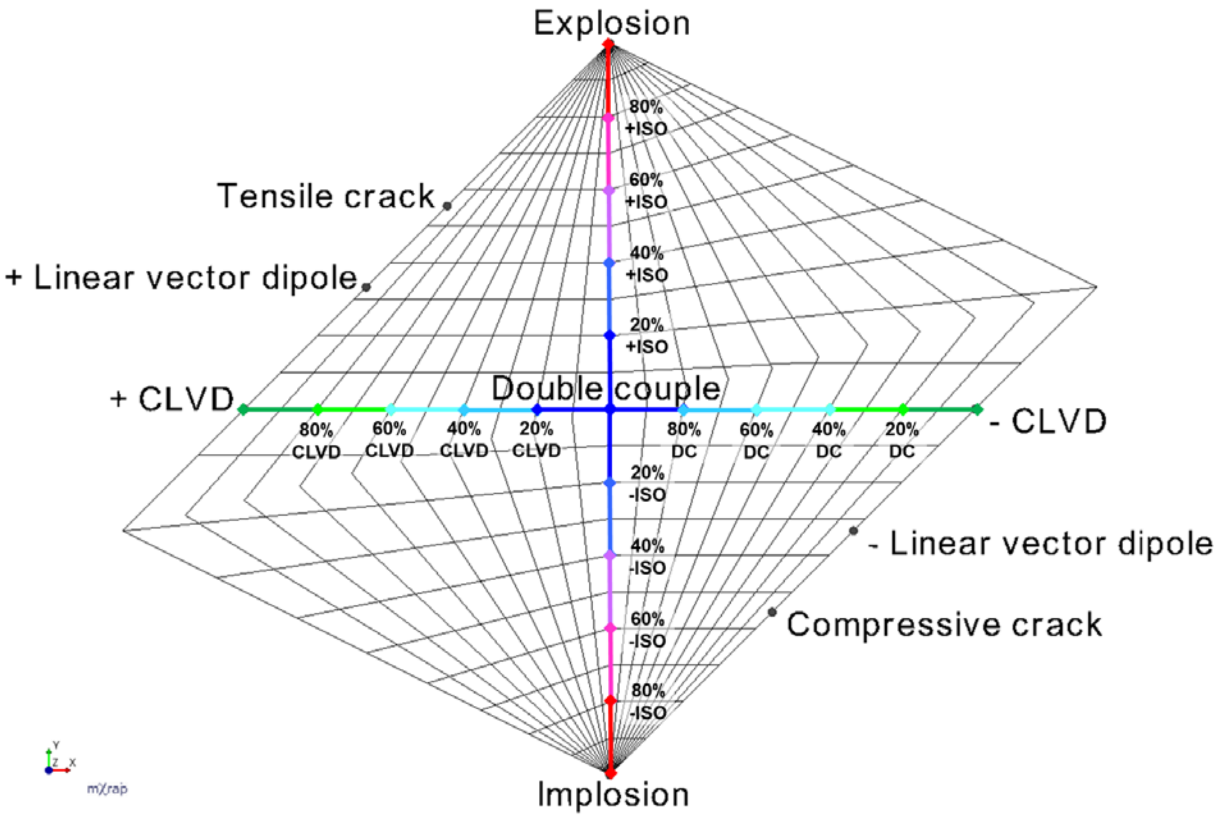
Moment Tensor Sources

Moment tensors provide a mathematical representation of the slip on a fault (fracture) during an earthquake (hydraulic fracture).

$$\mathrm{M} = \mathrm{M}_{\mathrm{ISO}} + \mathrm{M}_{\mathrm{DC}} + \mathrm{M}_{\mathrm{CLVD}}$$



$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}$$



Modeling displacement from moment tensor sources

$$u_i = u_i^{NF} + u_i^{IF} + u_i^{FF}$$

Near-field

Far-field

Intermediate-field

$$u_i^{FF} = u_i^{P} + u_i^{S} = \frac{c_P}{\alpha^3 r}\psi_p(M)\dot{s}\left(t - \frac{r}{\alpha}\right) + \frac{c_S}{\beta^3 r}\psi_s(M)\dot{s}\left(t - \frac{r}{\beta}\right)$$

Decay with 1/r

Radiation pattern

First derivative of wavelet

Modeling strain from moment tensor sources

$$\epsilon_{ij}^{FF} = \epsilon_{ij}^{P} + \epsilon_{ij}^{S} = \frac{1}{2}\underbrace{\left(\frac{\partial u_i^P}{\partial x_j} + \frac{\partial u_j^P}{\partial x_i}\right)}_{\text{P-wave strain}} + \frac{1}{2}\underbrace{\left(\frac{\partial u_i^S}{\partial x_j} + \frac{\partial u_j^S}{\partial x_i}\right)}_{\text{S-wave strain}}$$

Comparison of displacement and strain terms

Analytic displacement:

$$u_i^{FF} = u_i^P + u_i^S = \frac{c_P^u}{\alpha^3 r}\psi_p(M)\dot{s}\left(t - \frac{r}{\alpha}\right) + \frac{c_S^u}{\beta^3 r}\psi_s(M)\dot{s}\left(t - \frac{r}{\beta}\right)$$

Analytic strain:

$$\epsilon_{ij}^{FF} = \epsilon_{ij}^P + \epsilon_{ij}^S = \frac{c_P^\epsilon}{\alpha^4 r}\psi_p'(M)\ddot{s}\left(t - \frac{r}{\alpha}\right) + \frac{c_S^\epsilon}{\beta^4 r}\psi_s'(M)\ddot{s}\left(t - \frac{r}{\beta}\right)$$

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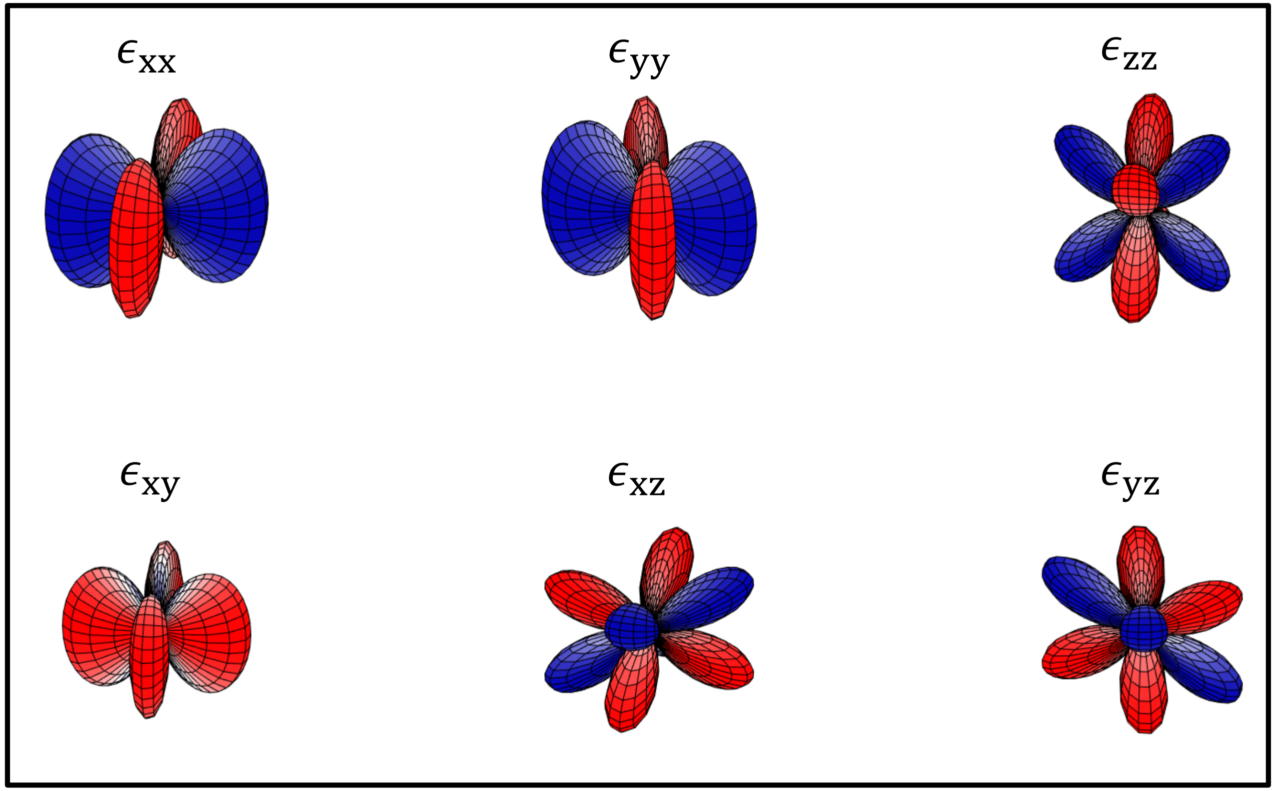
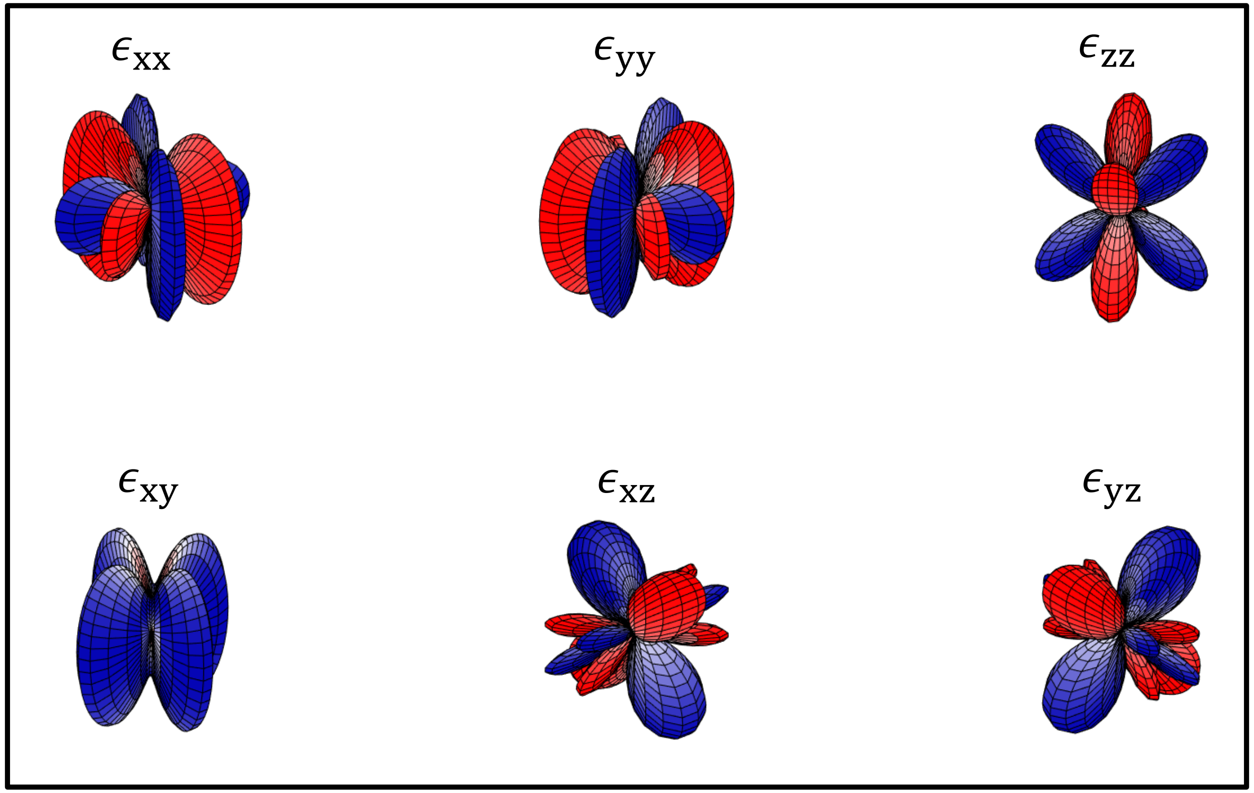
Radiation patterns

P-strain



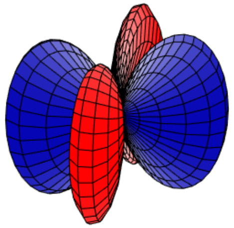
S-strain



Radiation patterns

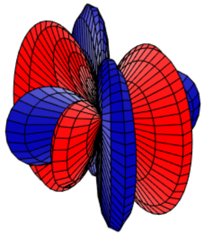
P-strain

ϵ_{xx}

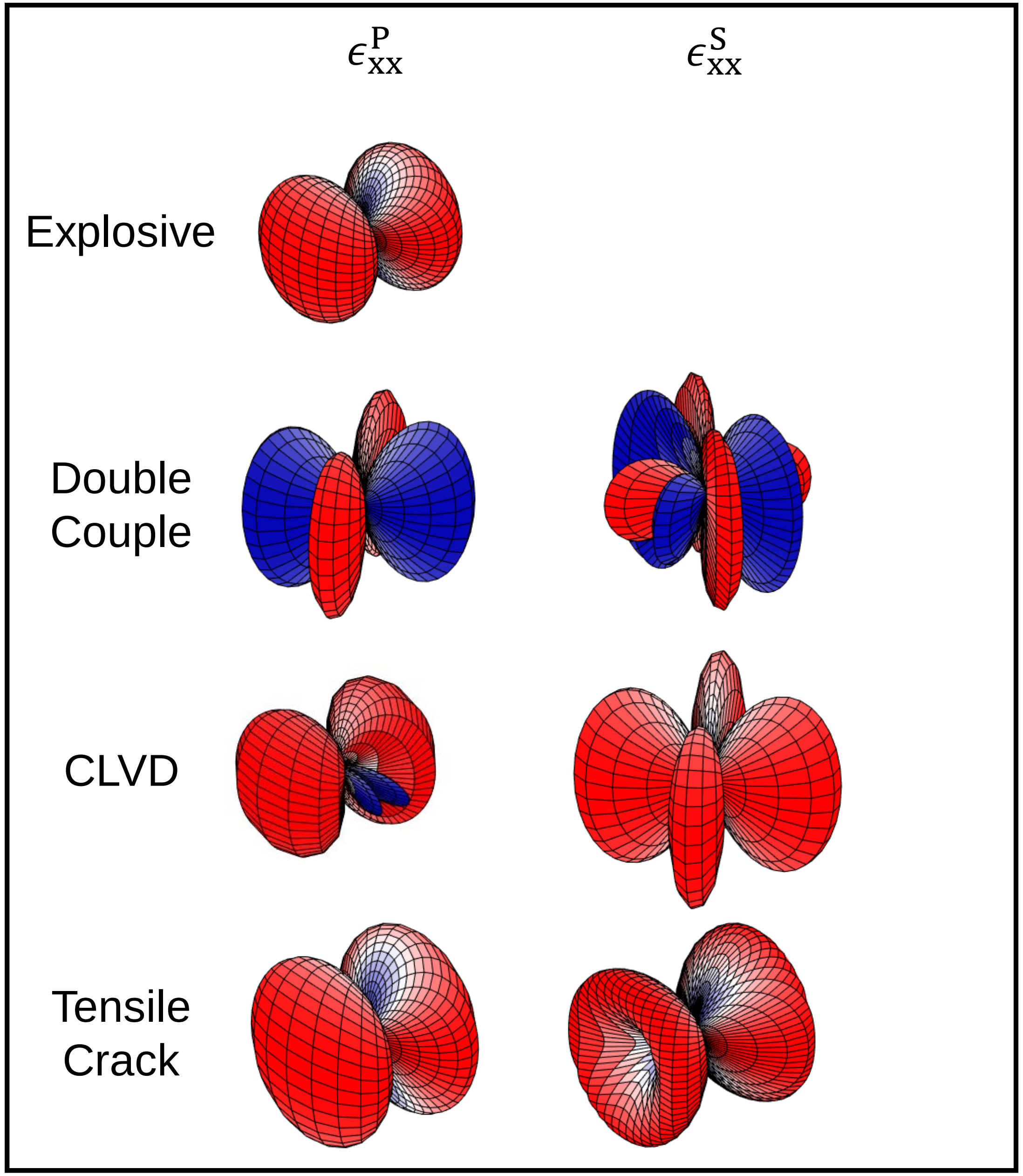


S-strain

ϵ_{xx}

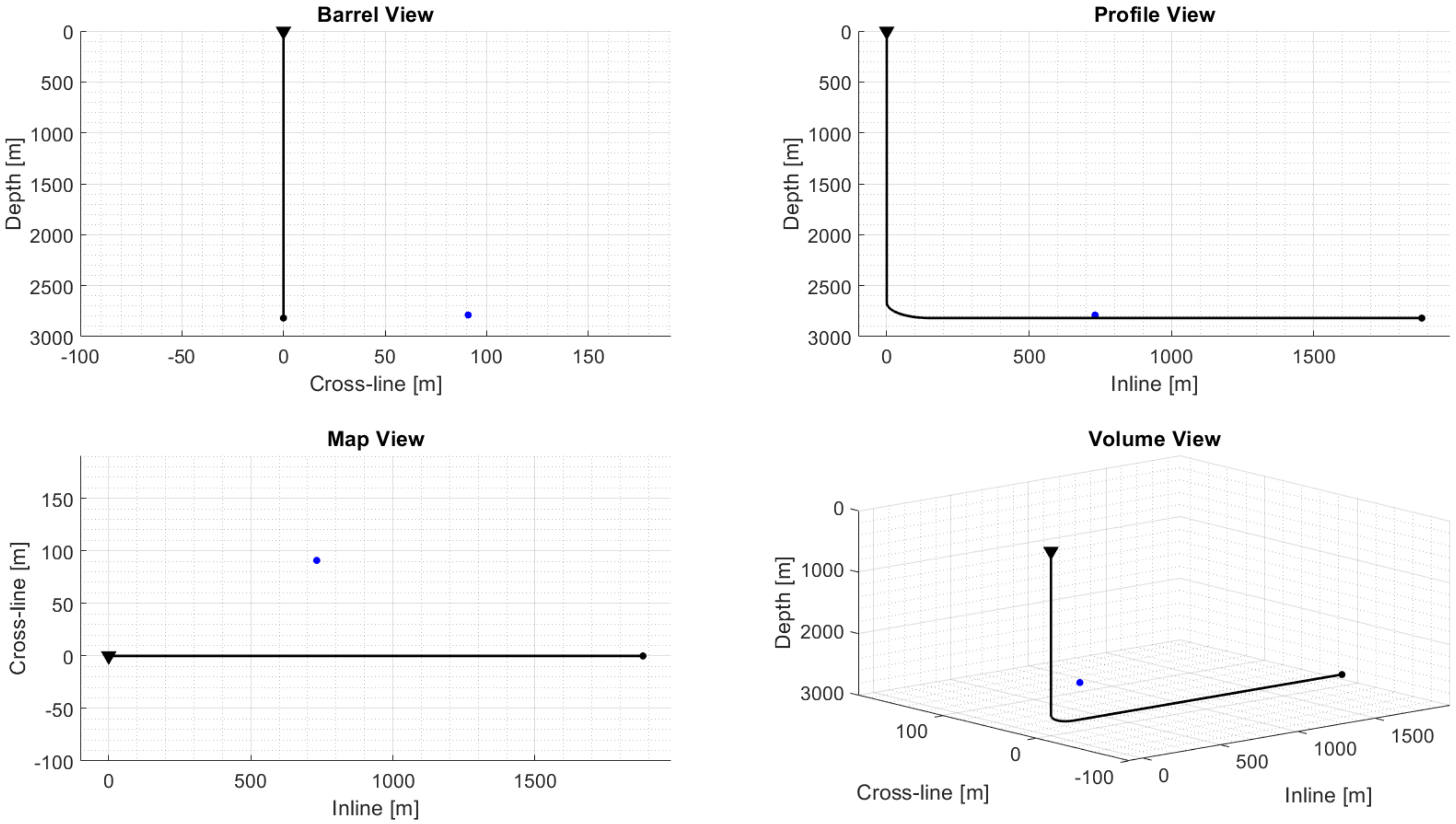


Radiation patterns

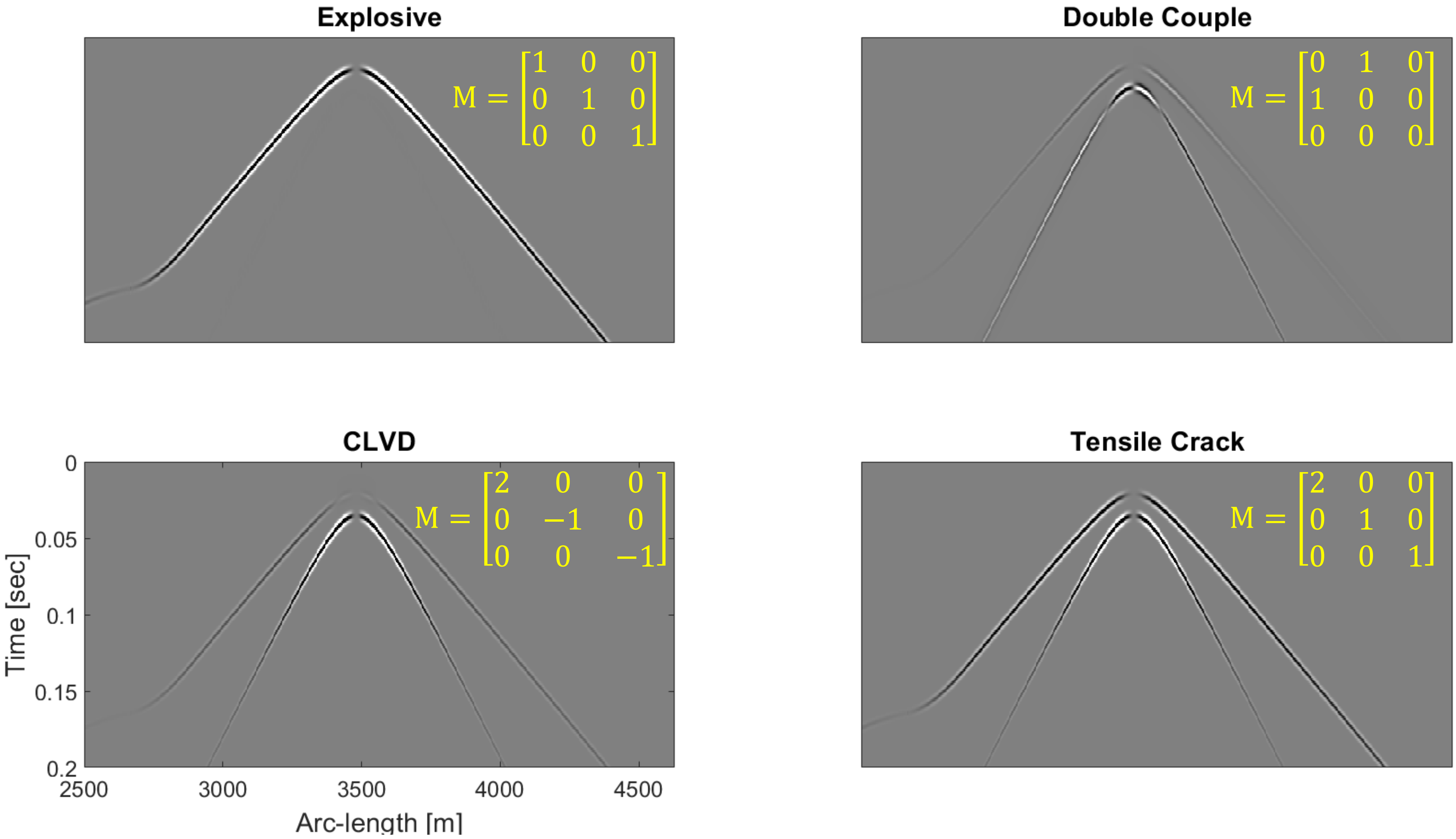


- Distinct differences in strain radiation patterns offer insight into source mechanics
- Shaping fibre can improve the sensitivity to the radiation patterns from more strain components

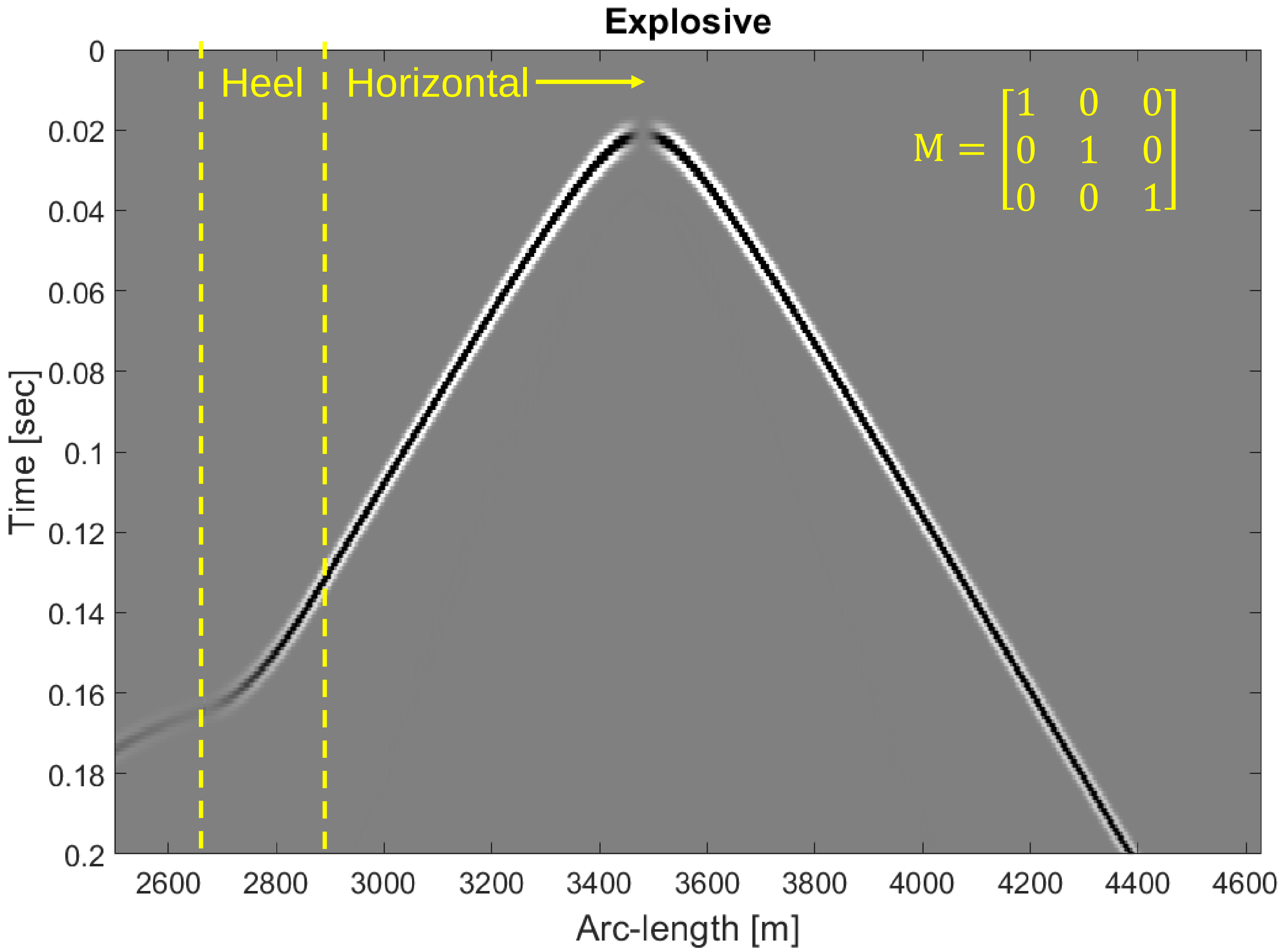
Experiment Geometry



Analytic strain from 4 source types

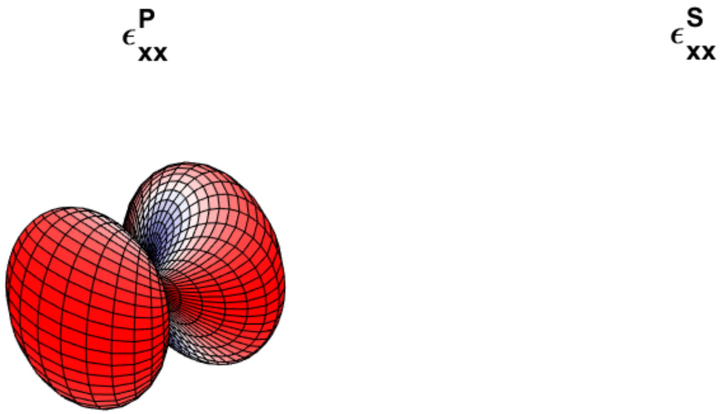


Explosive sources

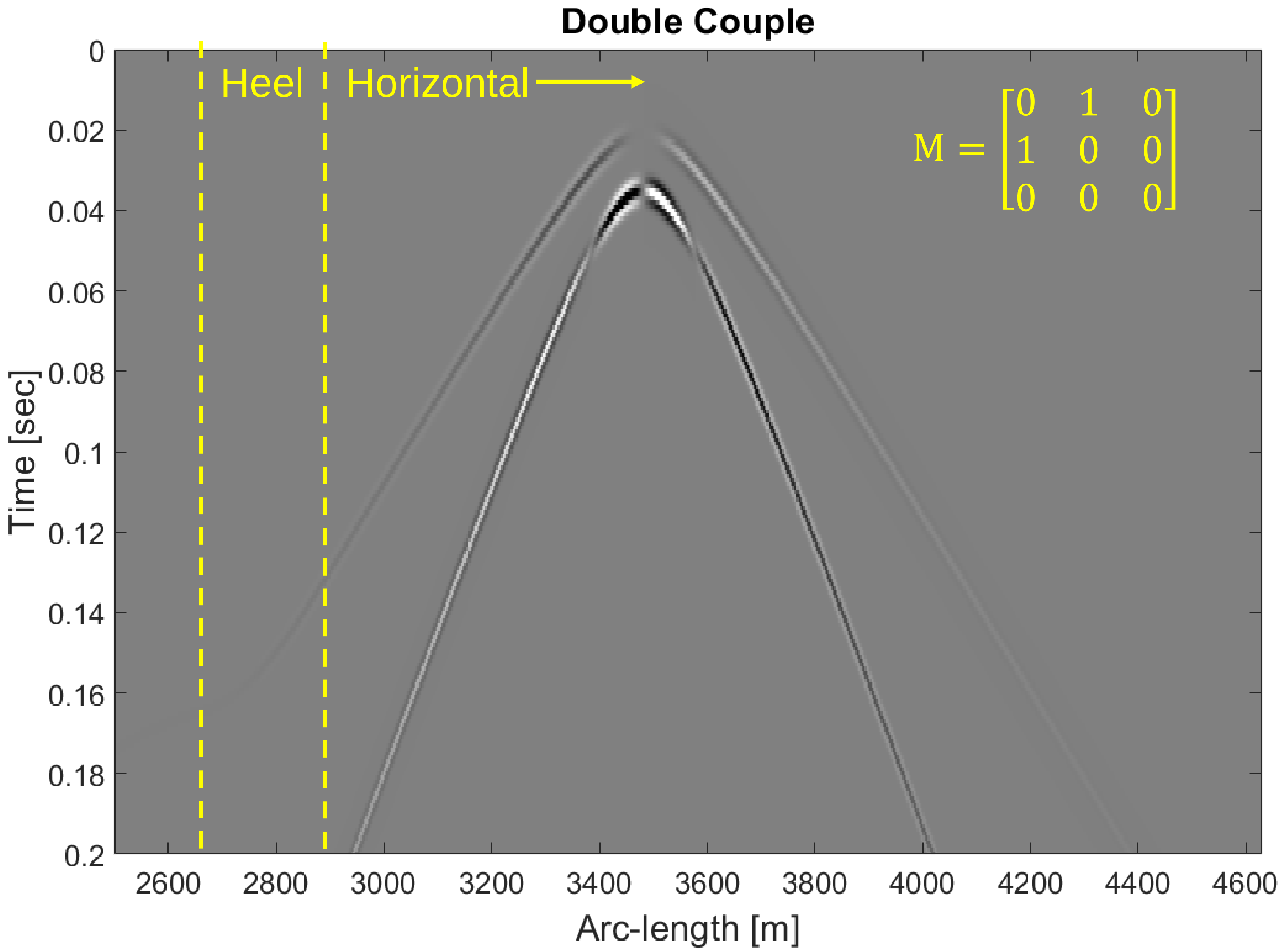


- Characterized by strong, symmetric P-wave and no S-wave

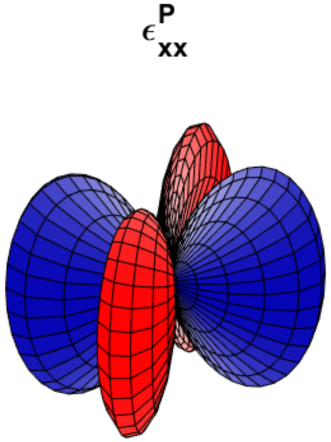
- Provides benchmark to test validity of this approach.

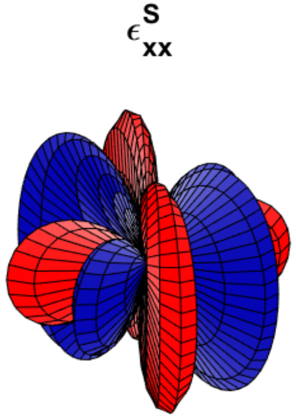


Double couple sources

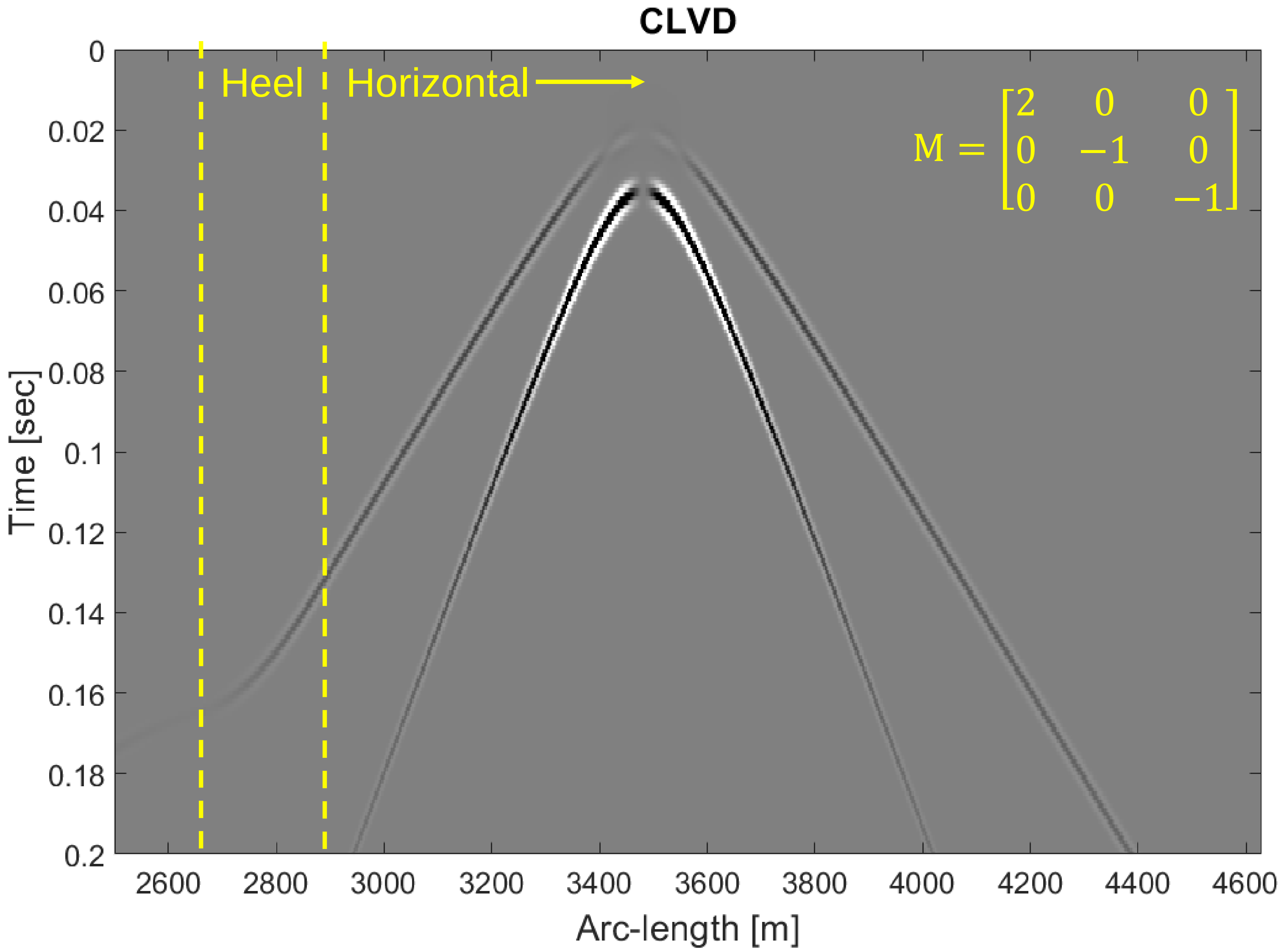


- Strong S/P wave amplitude ratio
- Polarity reversal in P-wave
- Distinct polarity pattern in S-wave

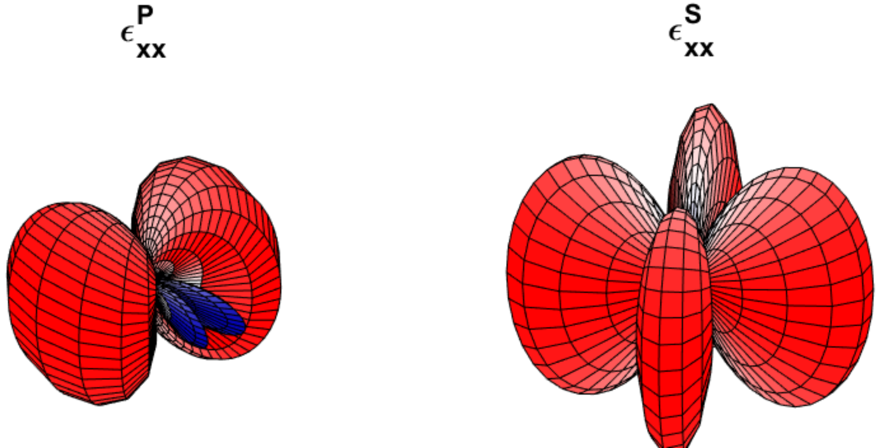




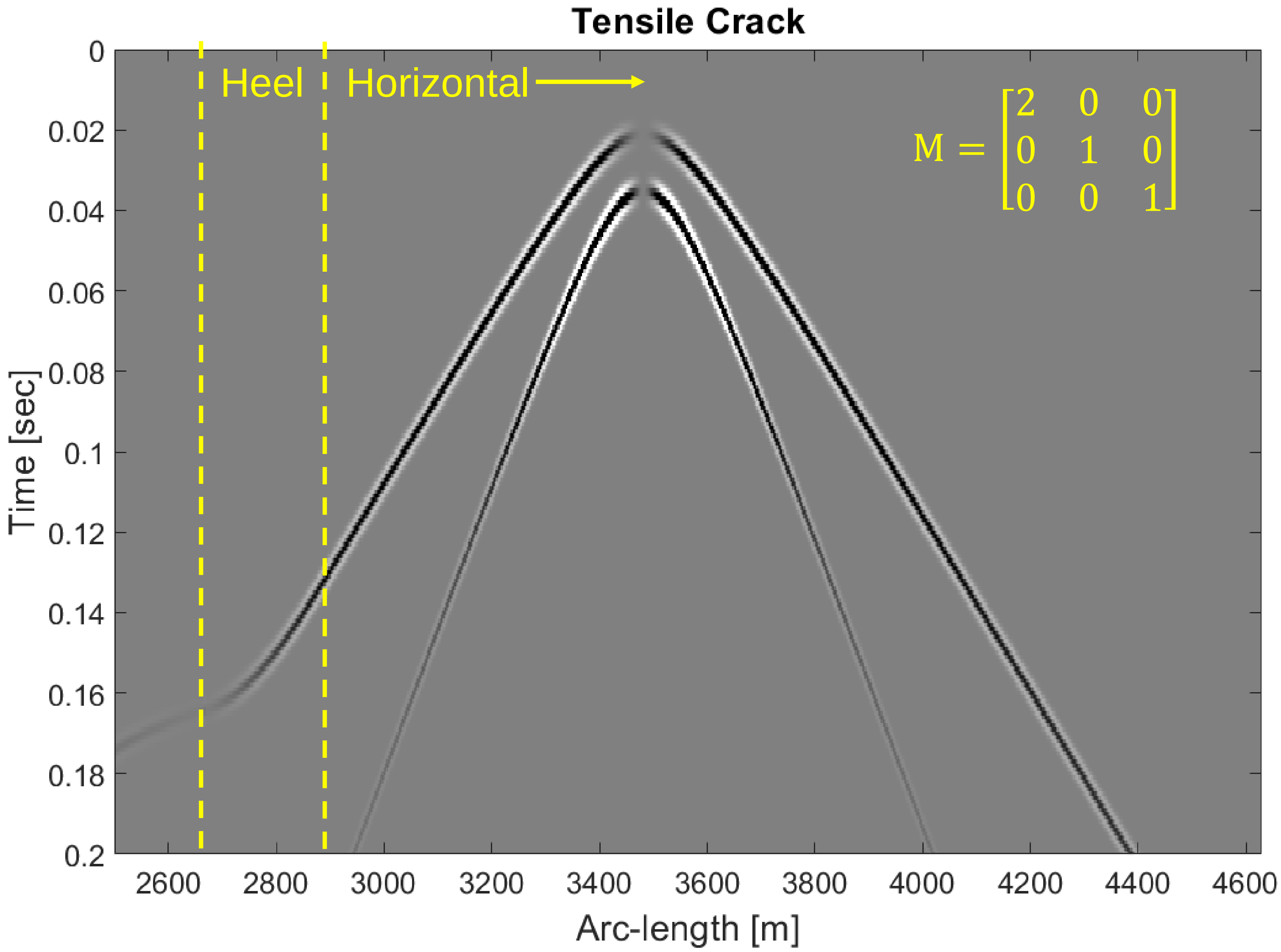
Compensated linear vector dipole sources



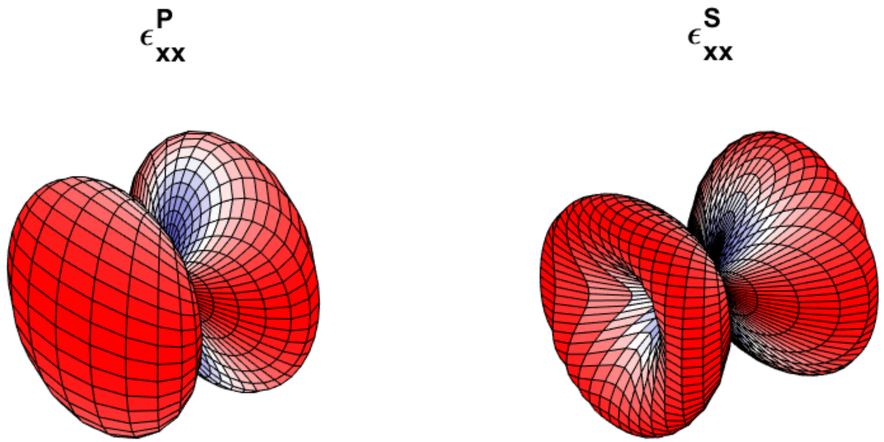
- Strong S/P wave amplitude ratio
- Near offset polarity reversal in P-wave
- Symmetric S-wave, same polarity as P-wave at long offset



Tensile crack sources



- Balanced S/P wave amplitude ratio
- Symmetric P-wave
- Symmetric S-wave with same polarity as P-wave



Conclusions and Future Work

- DAS provides a complementary dataset to geophones.
- Large sampling of solid angle, and close proximity to events makes DAS attractive.
- Developed a tool for the efficient appraisal of DAS and investigation of field data.
- Future work will look at using DAS data for moment tensor inversion.

Acknowledgements

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