SAND2023-02036C

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# Evaluating the efficacy of inverting local-scale, high frequency seismograms for effective source mechanisms using various source assumptions

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17–23 April 2023 // SSA Annual Meeting, San Juan, Puerto Rico

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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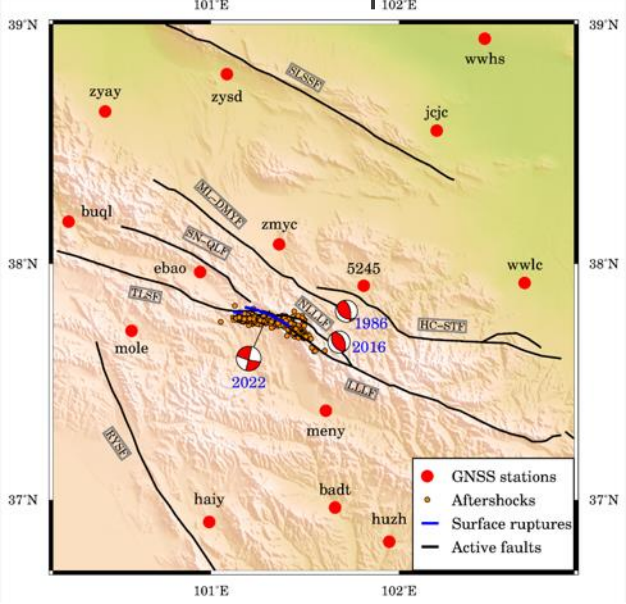
# Source Mechanism

Specifically, a seismic source mechanism

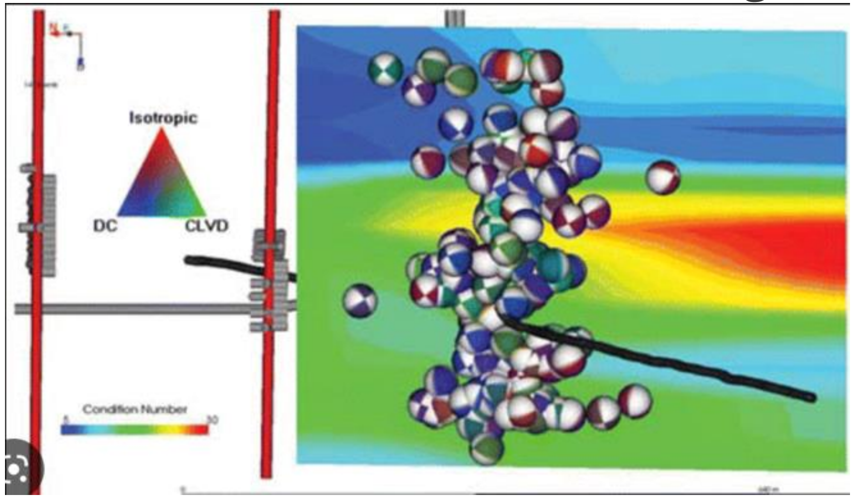
- Often represented as a “beachball”, a point on a source-mechanism plot (Hudson, fundamental Lune), or a 3x3 tensor
- Useful for …

tectonic interpretation



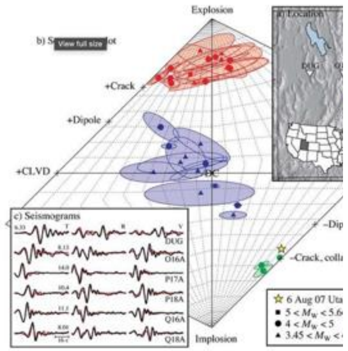

Li et al., 2022, doi.org/10.3390/rs14215378

well field fracture monitoring

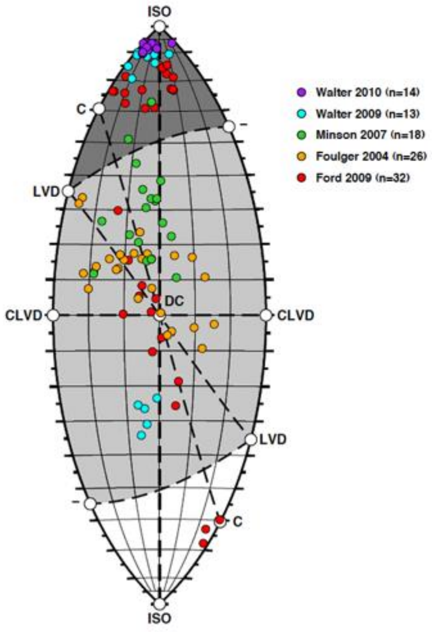



Baig and Urbanic, 2010, doi.org/10.1190/1.3353729

explosion/earthquake discrimination




Ford et. al, 2009 GJR 114, B01306




Tape et al., 2017

# Forward model: Seismic Moment Tensors

- Linearized inversion assumes
  - knowledge of the time and location of the source
  - source is "small" ($\lambda \gg$ source area)
  - data is a sum of M convolutions of M sources with the Earth:

$$M_{ij} = h(t)\begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$$

because of symmetry…

$$\rightarrow \; M_j = [M_1, M_2, M_3, M_4, M_5, M_6]^T$$

$$u_i(\mathbf{x}', t') = \sum_{j=1}^{M} \int_{-T}^{T} G_{ij}(\mathbf{x}, t\colon \mathbf{x}', t - t') M_j(\mathbf{x}_j, t)\, dt$$

$M$ source terms

convolution

← mathematical model

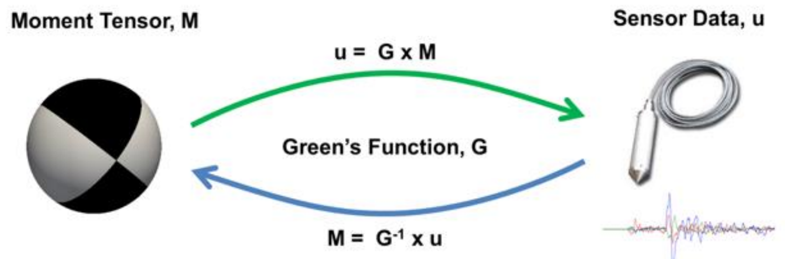
seismic data at station $i$

The $j$-th Green's function from source location to station $i$. This is a function of the Earth model!!

The $j$-th source term located at $\mathbf{x}_j$ (the epicenter)

$$\mathbf{u} = \mathbf{G}\mathbf{M}$$

← set up as a system of linear equations and solve for M




Tierney, 2019

# How are inversions usually done?

$$u_i(t) = \sum_{j=1}^{6} \widehat{G_{ij}}(t) m_j$$

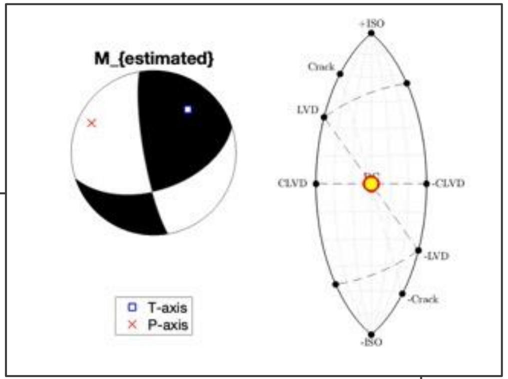
pseudo-Green's functions scaled by $m_j$

$$\mathbf{u} = \mathbf{G}\mathbf{m}$$

solve for $\mathrm{m}$

six scalar values

$$m_j = \begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \\ m_6 \end{bmatrix} \rightarrow M_{ij} \rightarrow \begin{bmatrix} m_{xx} & m_{xy} & m_{xz} \\ & m_{yy} & m_{yz} \\ & & m_{zz} \end{bmatrix}$$




"absorb" source function into the forward model by convolving it with the Green's function

$$\widehat{G_{ij}}(t) = \int_{-T}^{T} G_{ij}(t) s(t-\tau)\, d\tau$$

- $s(t)$ is the source function; assumed, *a-priori*
- **for teleseismic data, s(t) is usually modeled as a delta function**
- $s(t)$ is the 'source time function', but we usually use $ds(t)/dt$, which we refer to as the moment rate function

## Assumptions

- linear
- single point source
- source function identical for all components of the MT
- low frequency wavefield insensitive to Earth heterogeneities
- **the source function is known** ← this is kind of a big deal

→ works pretty good for low frequency teleseismic and/or global scale data

→ Because at low frequencies the source function is virtually a delta function

# Blue Canyon Dome

- 1 kg TNT-equivalent HE source
- 24 m, in a water-filled borehole


SNL, PNNL, EMRTC

SNL, PNNL, EMRTC

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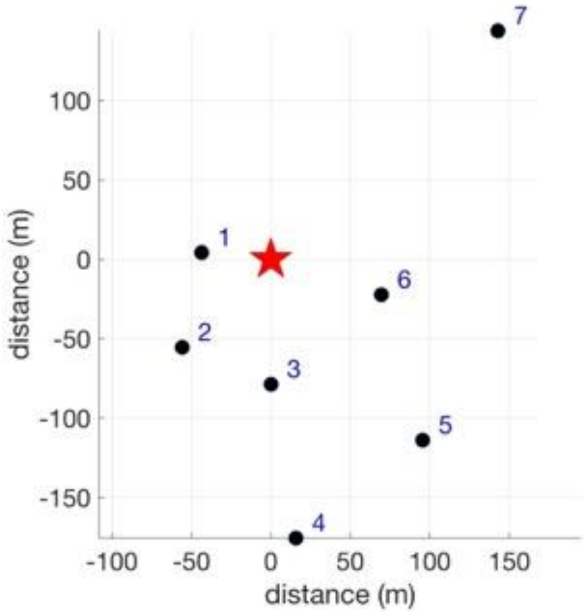
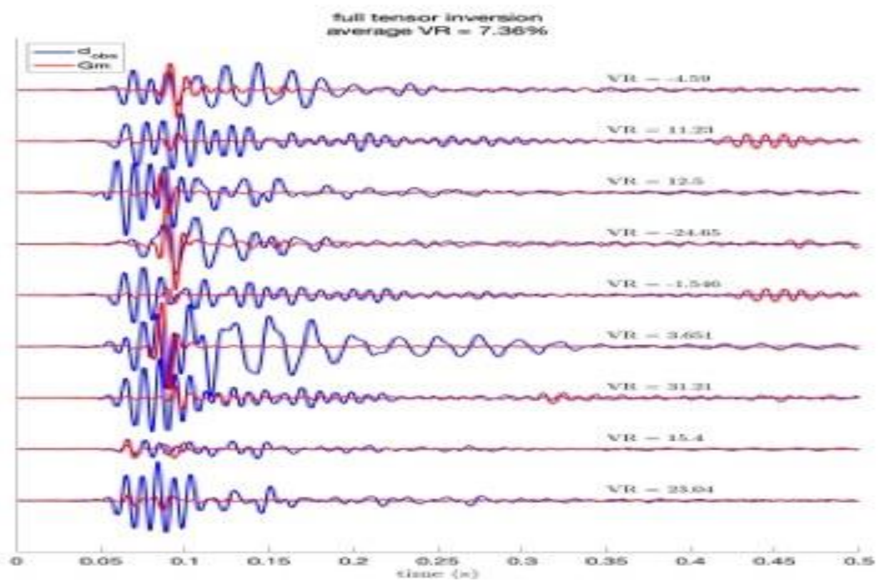
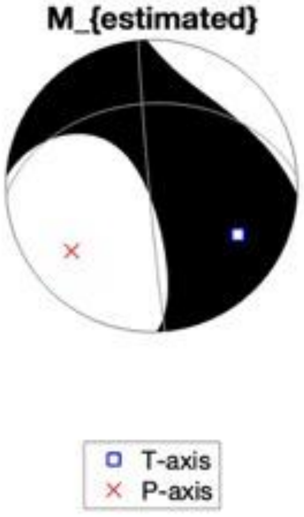
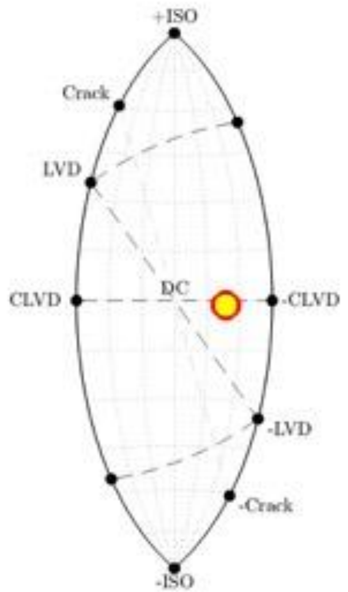
# Invert near-source, high frequency explosion seismograms

- Inverted for MT ($30 \leq f \leq 130$ Hz)
- Results are terrible




Questions:

- Why are the results so bad?
- Is this even the correct approach to invert this type of data?

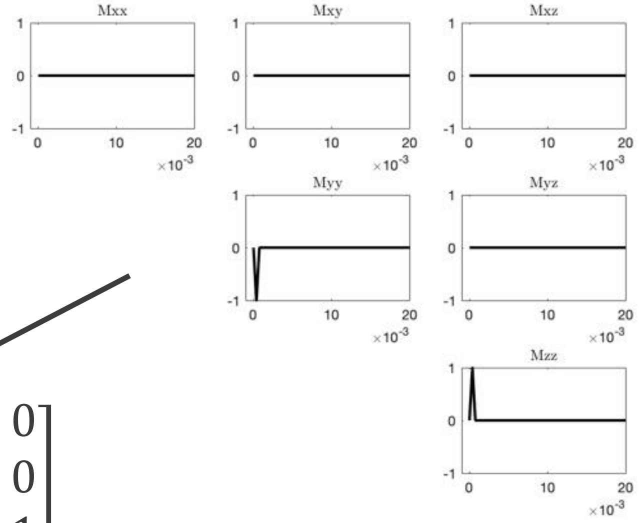
# For this type of data the source function can be multi-mechanism and have a resolvable time history

## this is how it's normally done

teleseismic scale data

- 0.01 > f > 0.1
- moment rate function can be approximated as a delta function at time=0
- moment rate function is assumed to be identical for each component of the tensor
- source mechanism has no time dependance!

example: pure double couple



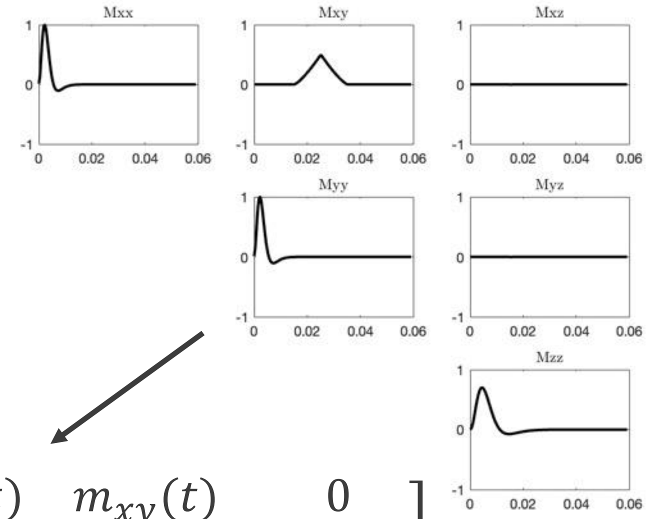

$$M_{ij} = \begin{bmatrix} 0 & 0 & 0 \\ & -1 & 0 \\ & & 1 \end{bmatrix}$$

## maybe we should be doing it this way

local, high frequency explosion data

- f>>1Hz
- moment rate function is a waveform: time dependence!
- moment rate function is not identical for all components

example: non-isotropic explosion followed by a shearing fracture (double couple)

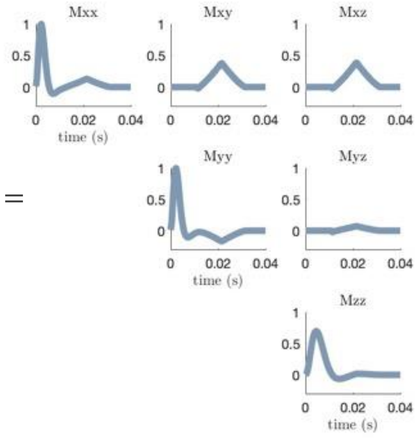



$$M_{ij} = \begin{bmatrix} m_{yy}(t) & m_{xy}(t) & 0 \\ & m_{yy}(t) & 0 \\ & & m_{zz}(t) \end{bmatrix}$$

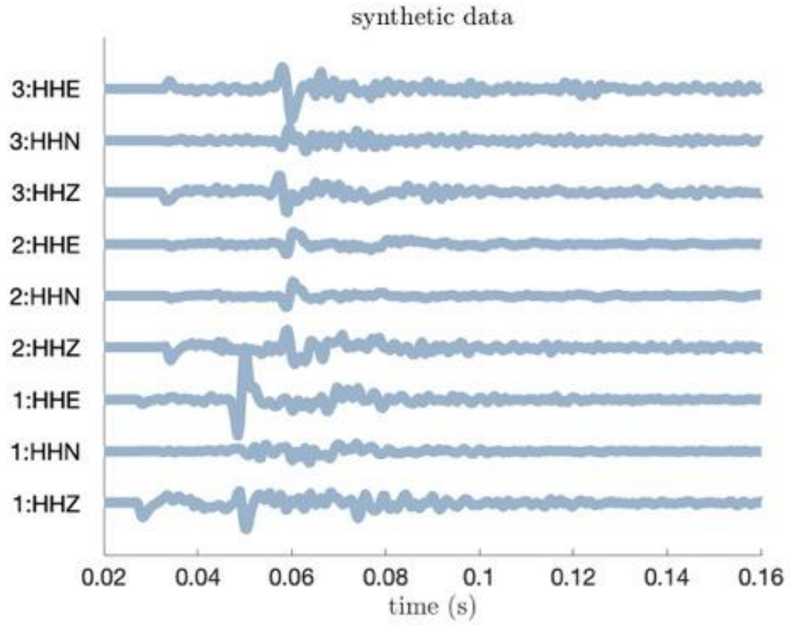
# Synthetic example 1: invert data with delta function source assumption

## actual source functions

$$M_{ij} = \begin{bmatrix} M_{xx}(t) & M_{xy}(t) & M_{xz}(t) \\ & M_{yy}(t) & M_{yz}(t) \\ & & M_{zz}(t) \end{bmatrix} =$$

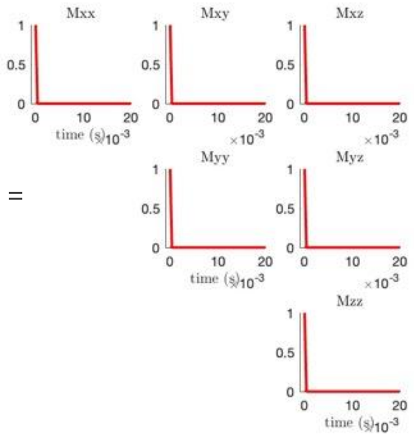



gives this data



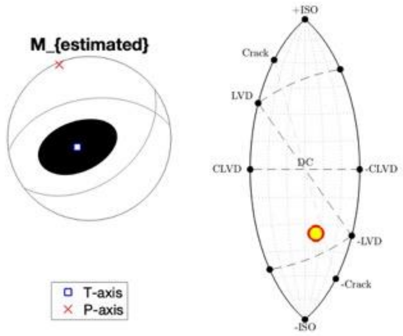

## assumed source functions for inversion

$$M_{ij} = \delta(t) \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ & M_{yy} & M_{yz} \\ & & M_{zz} \end{bmatrix} =$$

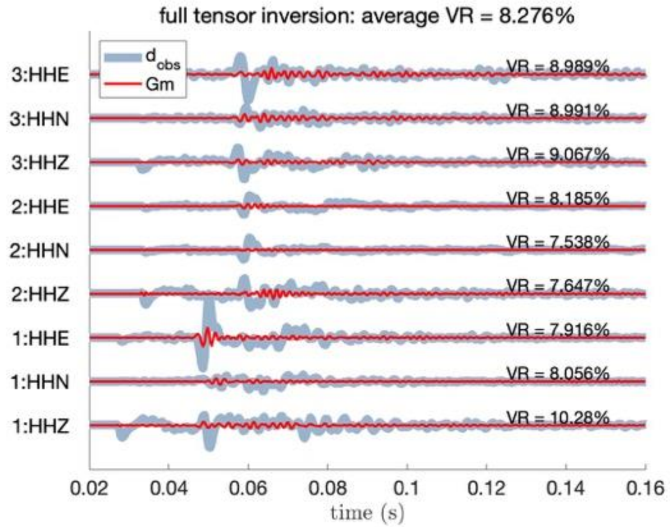



## estimated MT

$$M_{ij} = \begin{bmatrix} -.87 & .29 & -.11 \\ & -.29 & -.09 \\ & & .16 \end{bmatrix}$$




## fit to data = atrocious

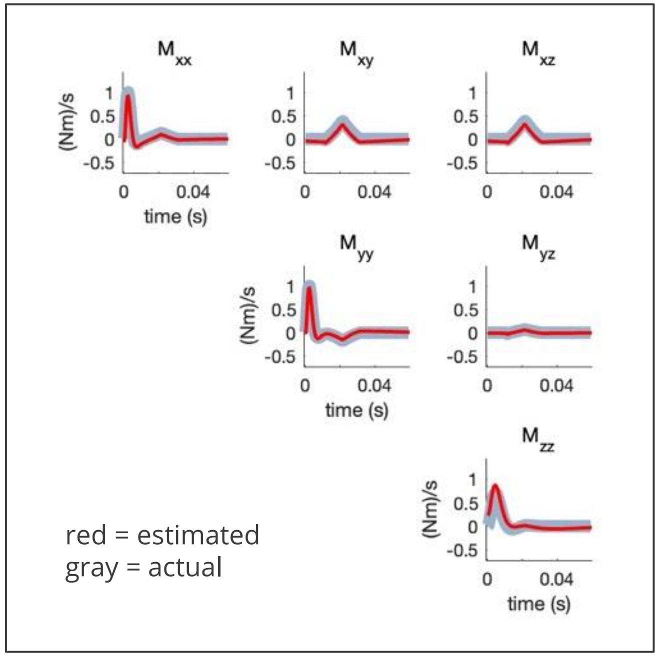


# Synthetic example 2: invert data with independent, time variable source assumption

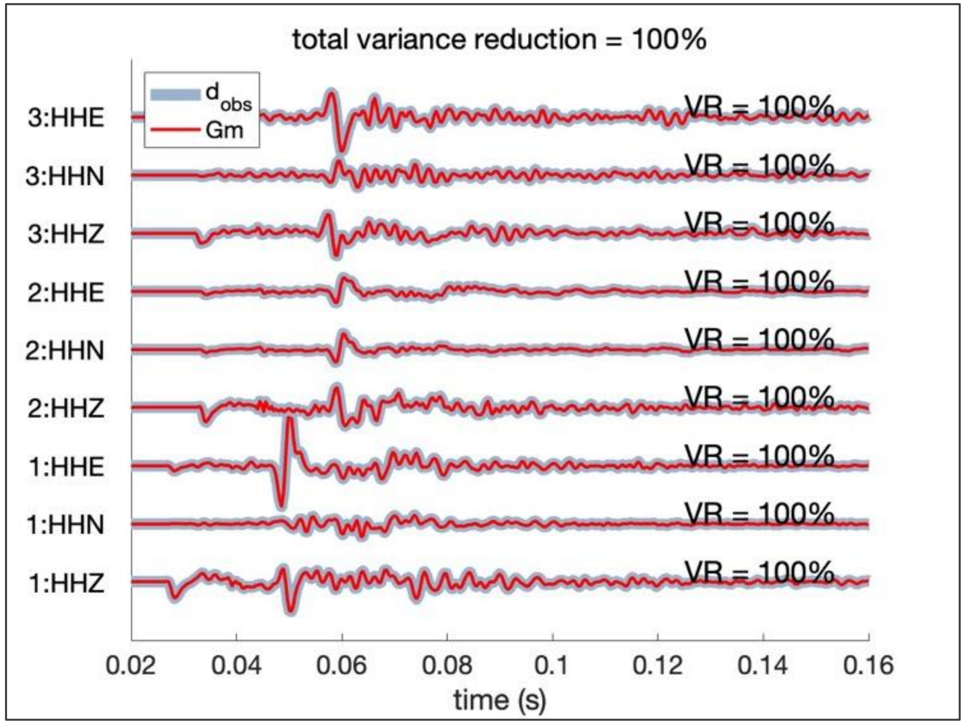
source assumption in inversion

$$M_{ij} = \begin{bmatrix} M_{xx}(t) & M_{xy}(t) & M_{xz}(t) \\ & M_{yy}(t) & M_{yz}(t) \\ & & M_{zz}(t) \end{bmatrix}$$

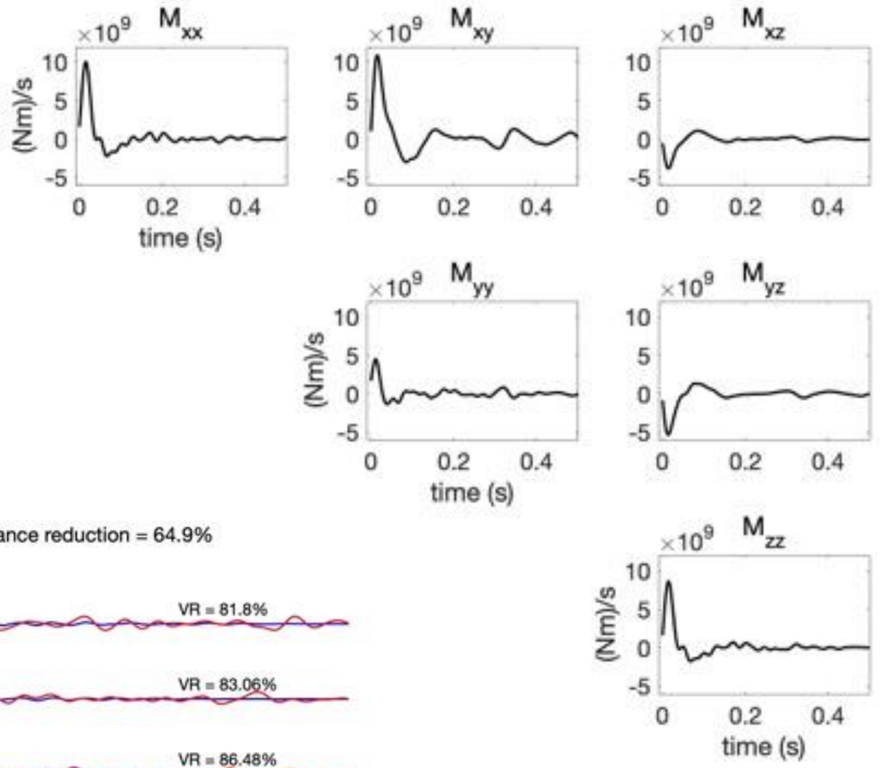
actual source terms (gray)
estimated source terms (red)




fit to data = perfect



# Let's revisit the BCD data, invert with time-variable source assumption

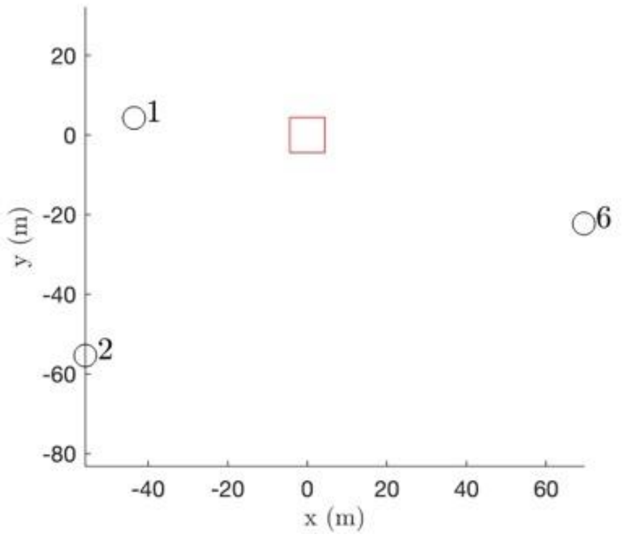


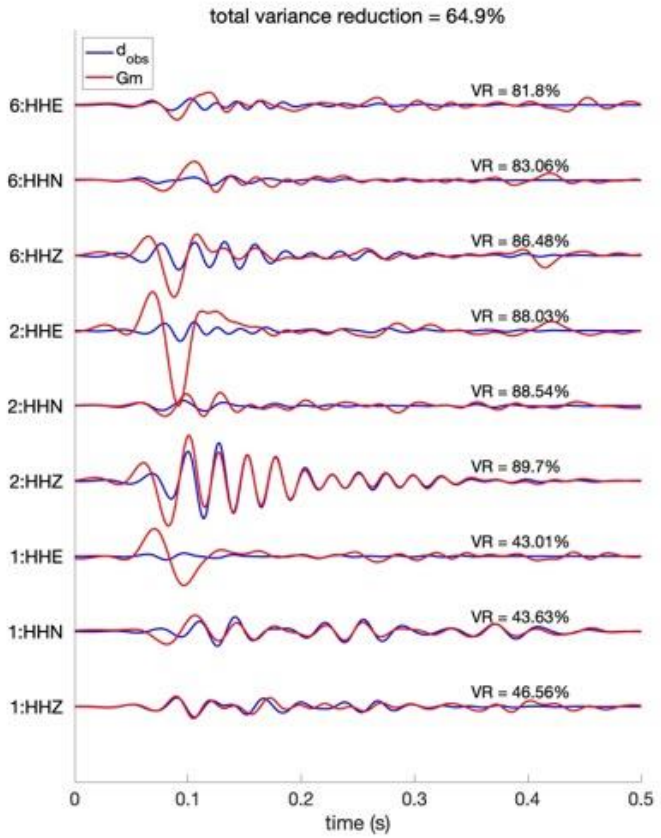

**Inversion specifics:**

- three 3C stations
- 30 < f < 130 Hz
- only minimal damping

**Results:**

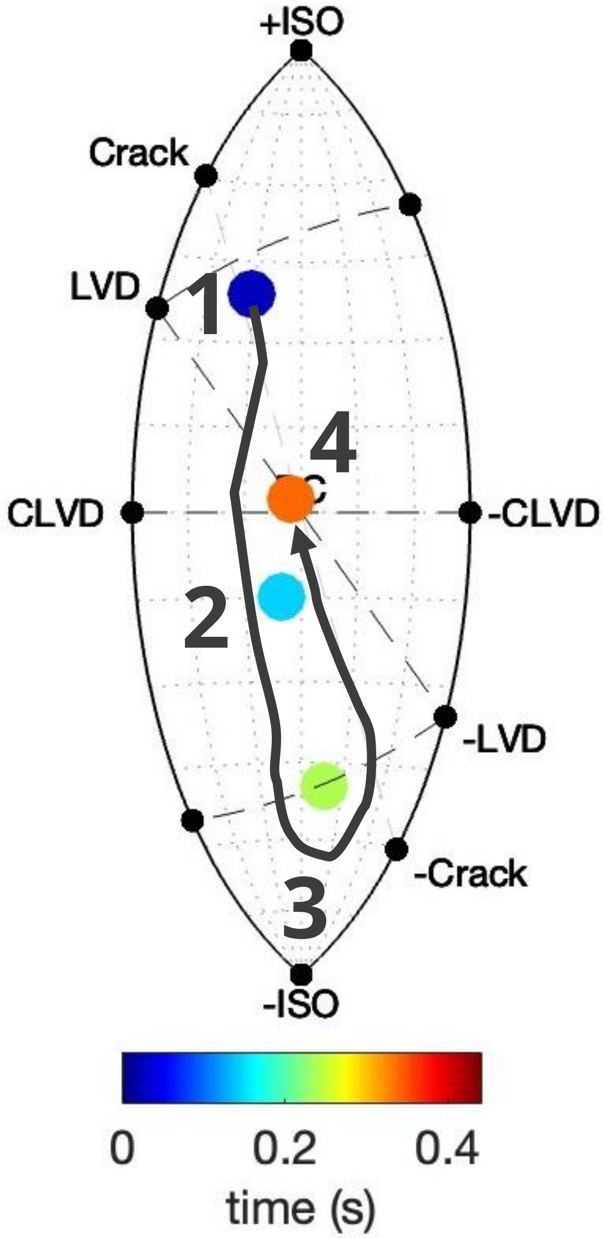
- initial P arrival not fit very well
- post-P fits very well
- strong isotropic component
- significant on-diagonal energy at t<0.1 s
- energy some off-diagonals at t~0.3s.

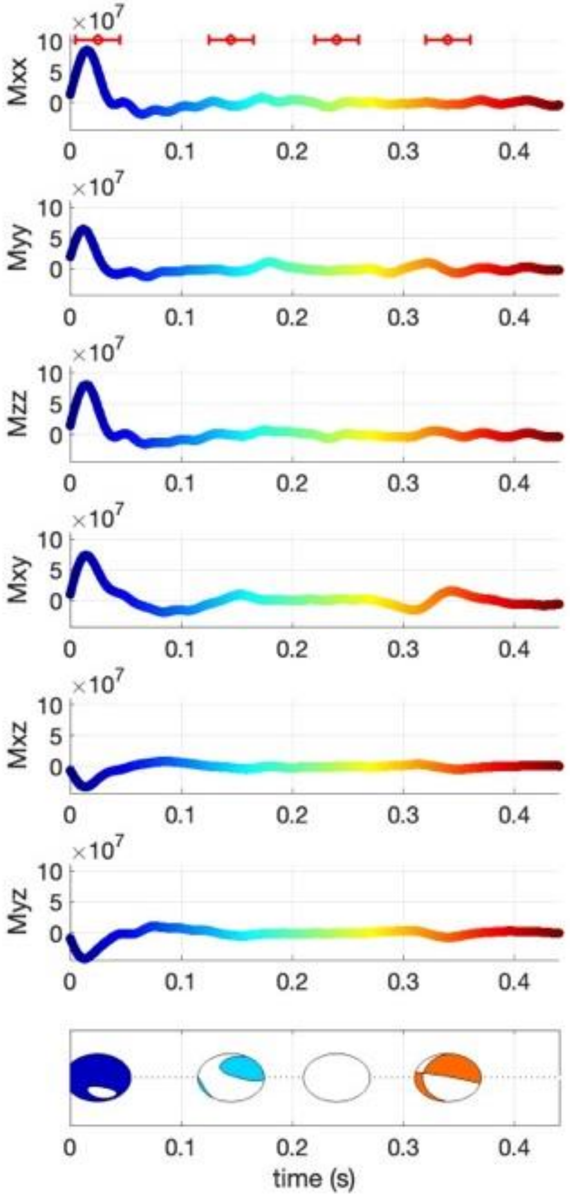


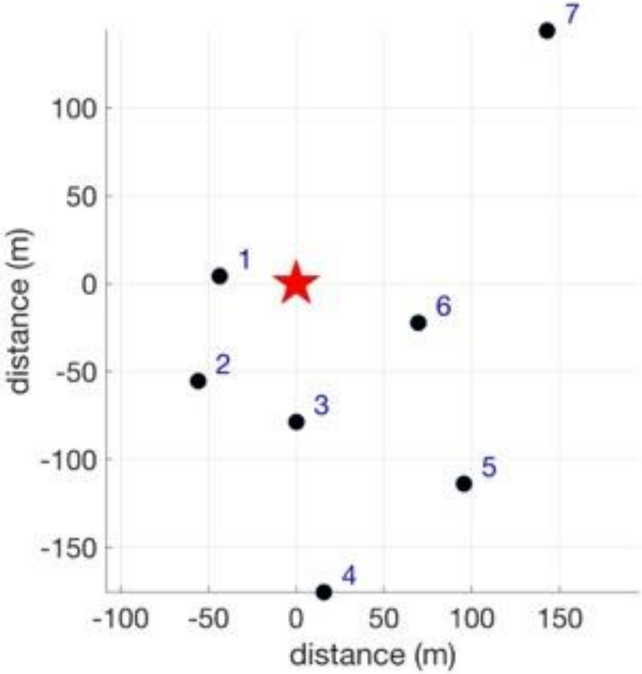




interpretation: initial explosion is 'pseudo isotropic', with double-couple energy arriving later! The source mechanism changes through time.

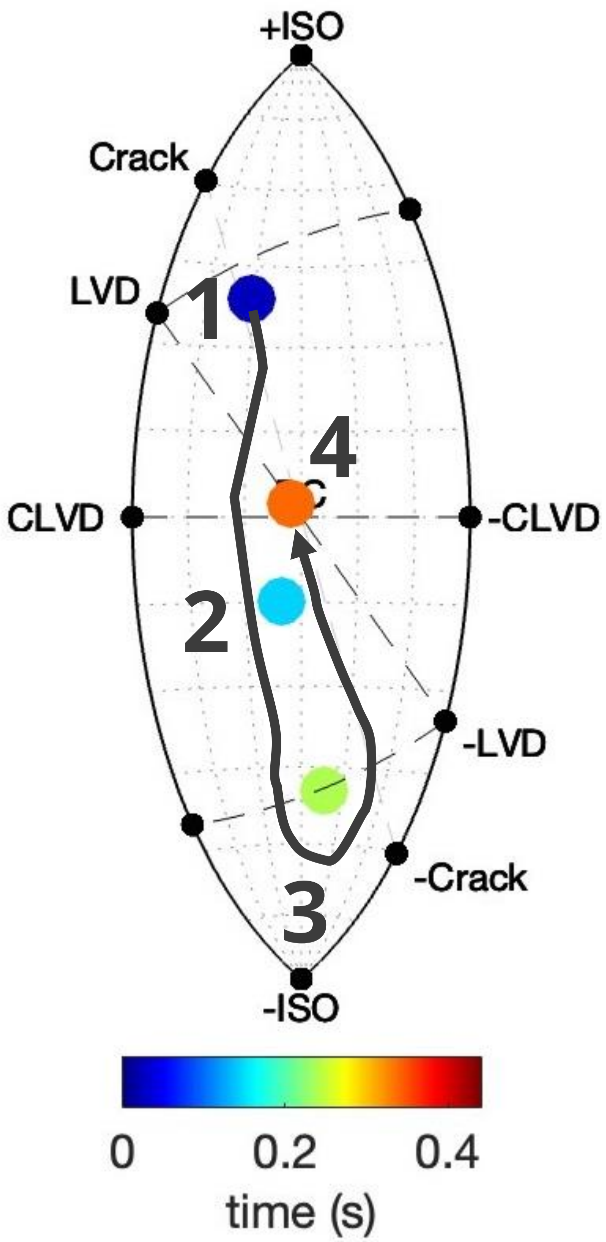
# Time-evolving source mechanism



# How do we interpret this?

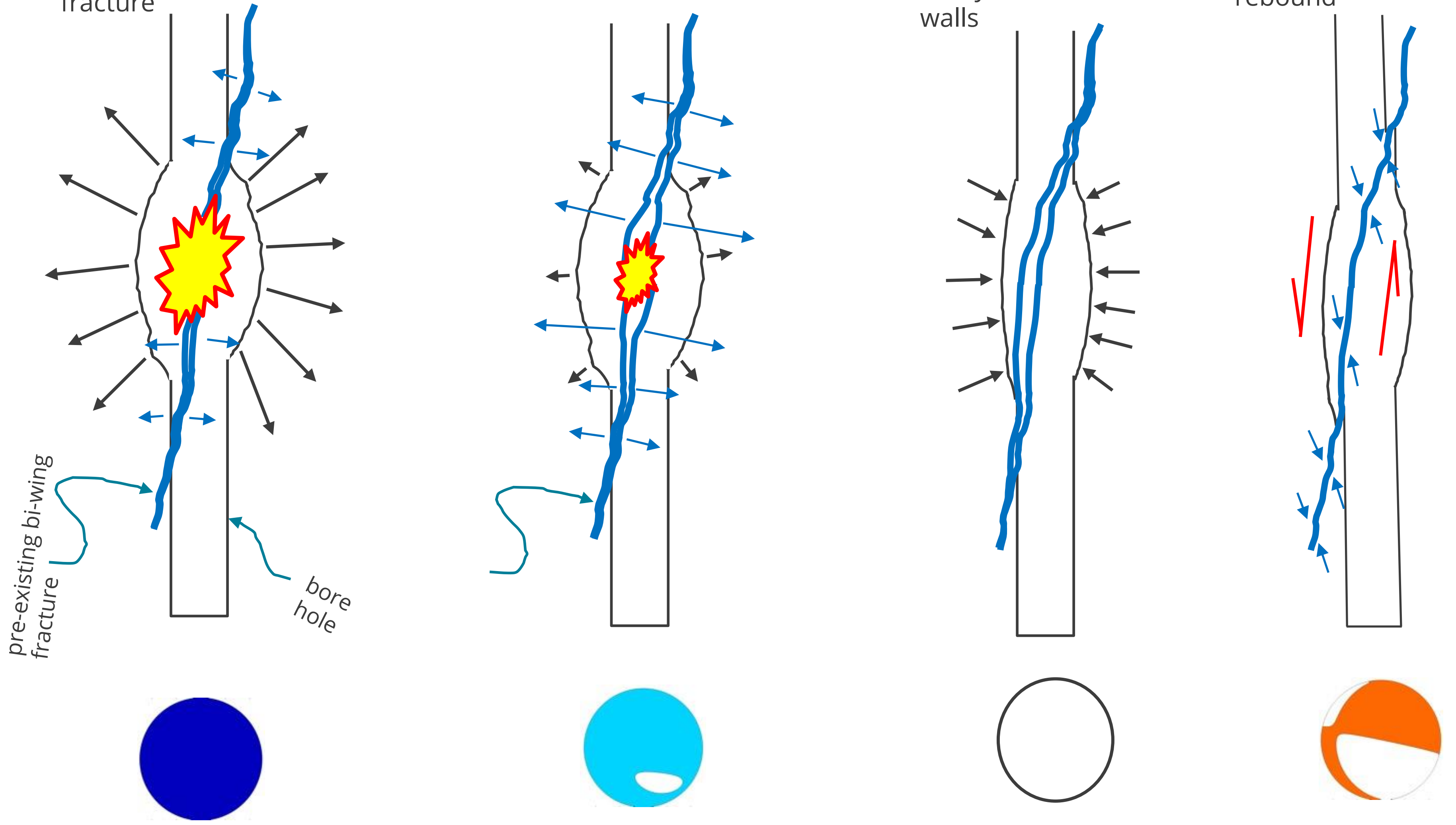



1: volumetric expansion starting at explosion initiation and slight opening of pre-existing bi-wing fracture

2: additional opening of bi-wing fracture at end of explosion

3: volumetric contraction due to elastic rebound of cavity and borehole walls

4: pre-existing fracture closes and shears at end of rebound



# Concluding remarks

- Conventional moment tensor inversion methods may not be appropriate for high frequency, local-scale seismic data from buried explosions
- Better to invert for the time-variable force couples corresponding to the moment tensor
  - Let the source time functions (or moment rate functions) be independent for each MT component
- Can decompose the time-varying source functions into source mechanisms and beachball diagrams which also evolve through time
- Analyzing a small explosion reveals a complex, time-evolving series of source mechanisms

# Acknowledgements


**SNL**

- Joseph Pope, Eric Robey, Taylor Myers, Giorgia Bettin, Lauren Wheeler, Venner Saul, Charles Choens, Mark Grubelich, Leiph Preston

**PNNL**

- Hunter Knox, James St. Clair, Christine Johnson, Chris Strickland, Kirsten Chojnicki, Tim Johnson, Justin Lowery, Parker Sprinkle, Josh Feldman, James Knox, Jeff Burghardt

**Silixa, LLC**

- Thomas Coleman, David Podrasky, Taylor Martin

***Thanks to NNSA Office of Defense Nuclear Nonproliferation for funding this work***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