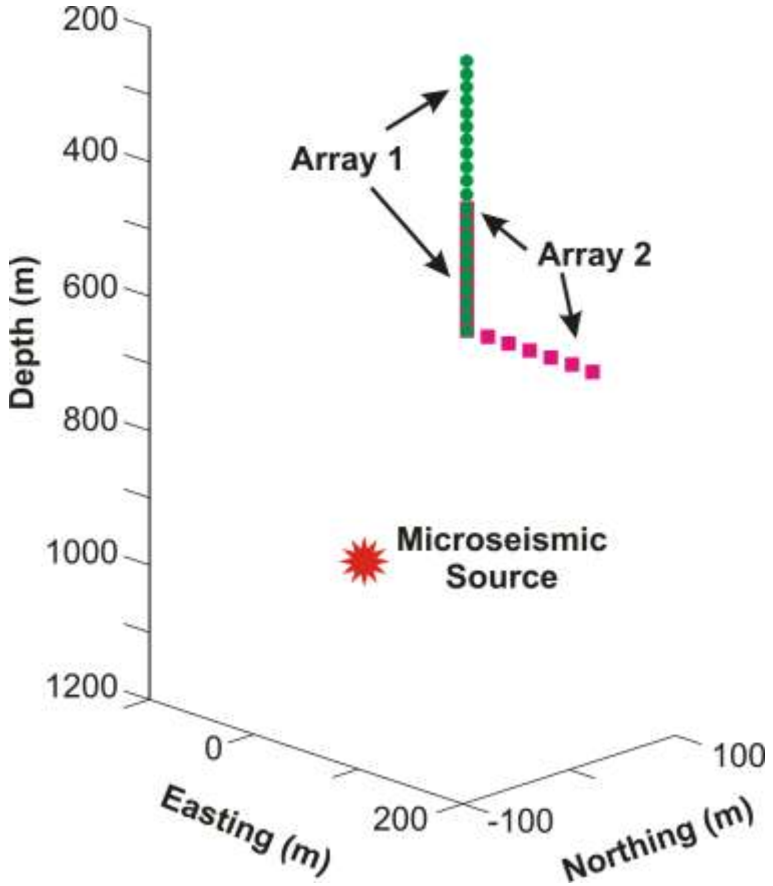
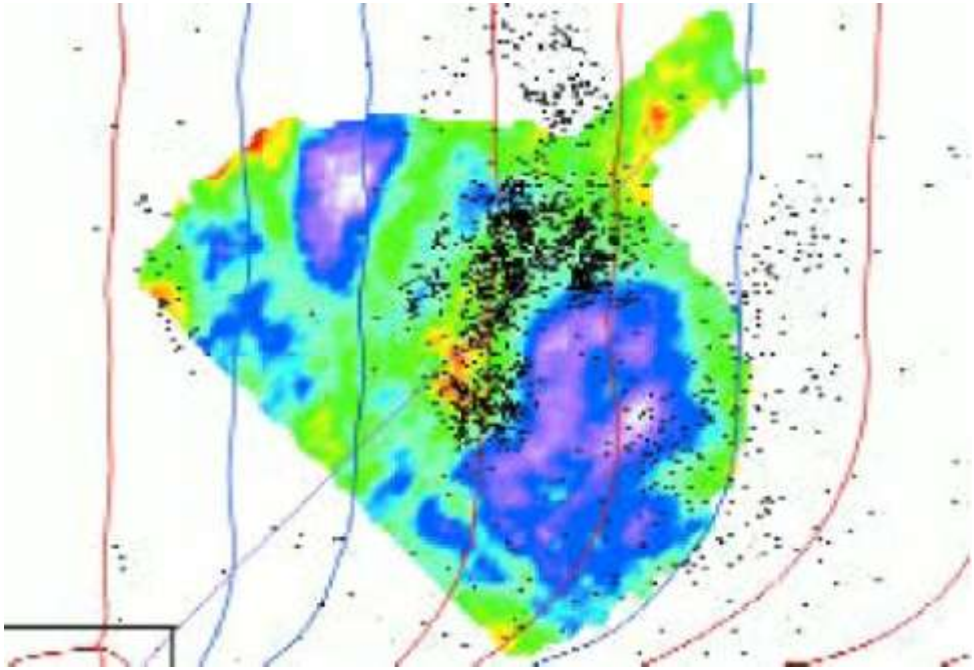
Resolution of microseismic moment tensors: A synthetic modeling study



David W. Eaton and
Farshid Forouhideh
Department of Geoscience
University of Calgary

Motivation

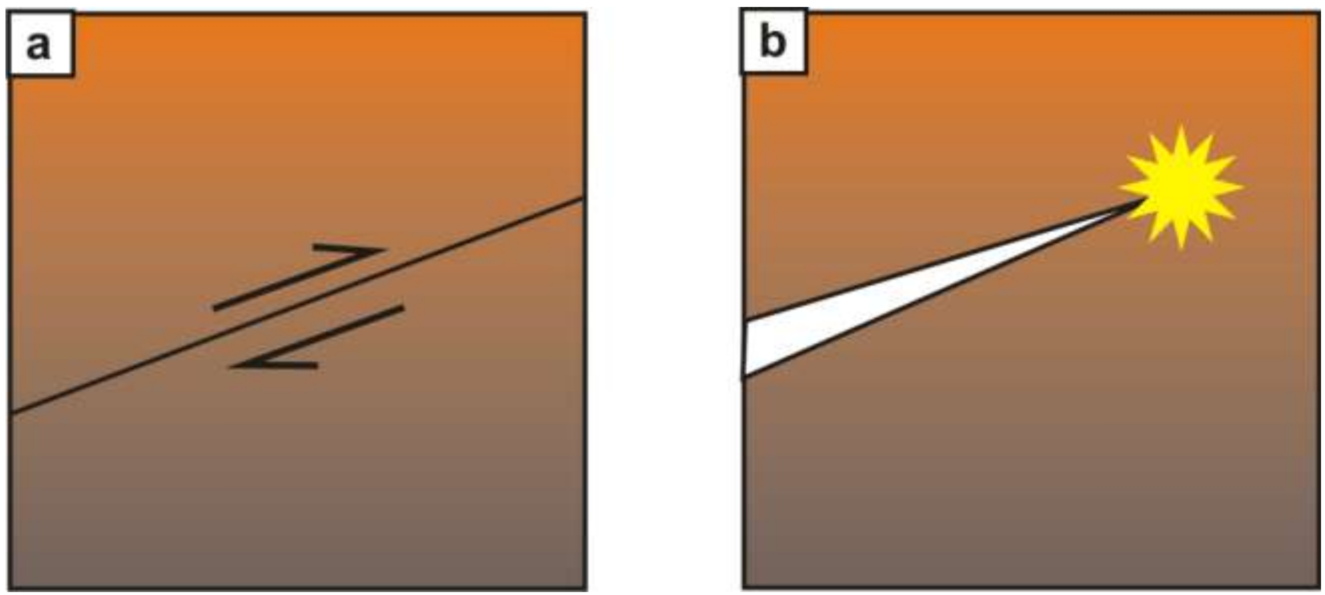


McGillivray, 2005

- Microseismic events are routinely generated for EOR and EGR operations, including hydrofrac stimulation for unconventional gas, and this cyclic steam stimulation heavy oil project in the Peace River area
- Stimulation is intended to create new fractures in order to enhance permeability

Objective

Type II Type I



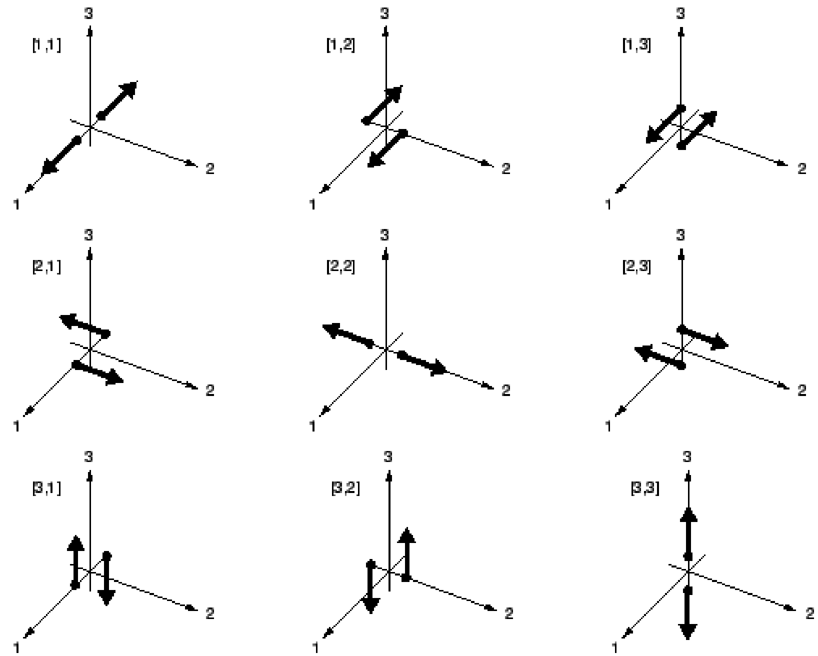
- Type I fractures (crack opening under tension) increase permeability, whereas type II (slip on an existing failure surface) do not.

- Our objective is to distinguish between microseismic events that produce these two types of fractures.

Seismic Moment Tensor

$$\mathbf{M} = M_0 \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$$

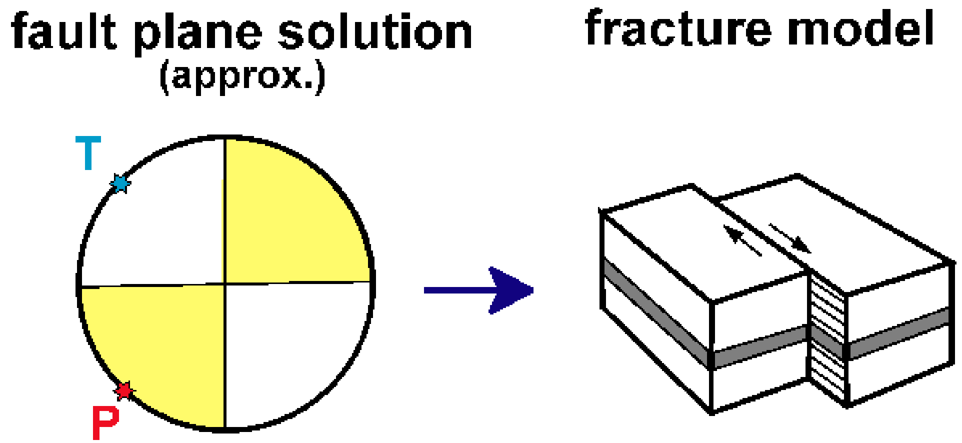
- A general representation of an earthquake source
- Each tensor component represents a force couple
- **M** is symmetric to ensure zero net torque; hence it has 6 independent components



Aki and Richards, 1980

Seismic Moment Tensor

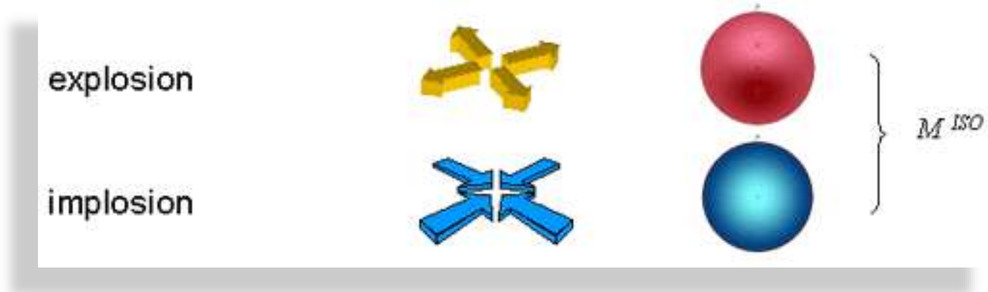
- Type II fractures be approximated by a double-couple



$$\begin{bmatrix} 0 & M_0 & 0 \\ M_0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Seismic Moment Tensor

- An explosive source can be represented by an isotropic moment tensor

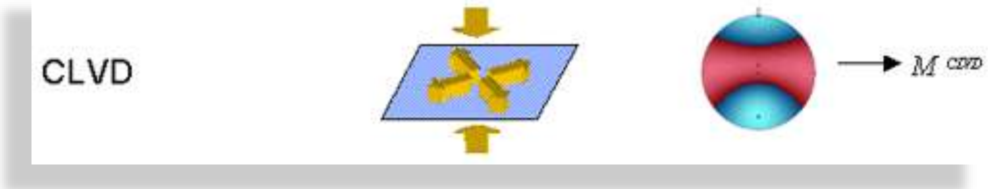


http://www.iwb.uni-stuttgart.de/grosse/aet/mti.htm

$$\begin{bmatrix} M_0 & 0 & 0 \\ 0 & M_0 & 0 \\ 0 & 0 & M_0 \end{bmatrix}$$

Seismic Moment Tensor

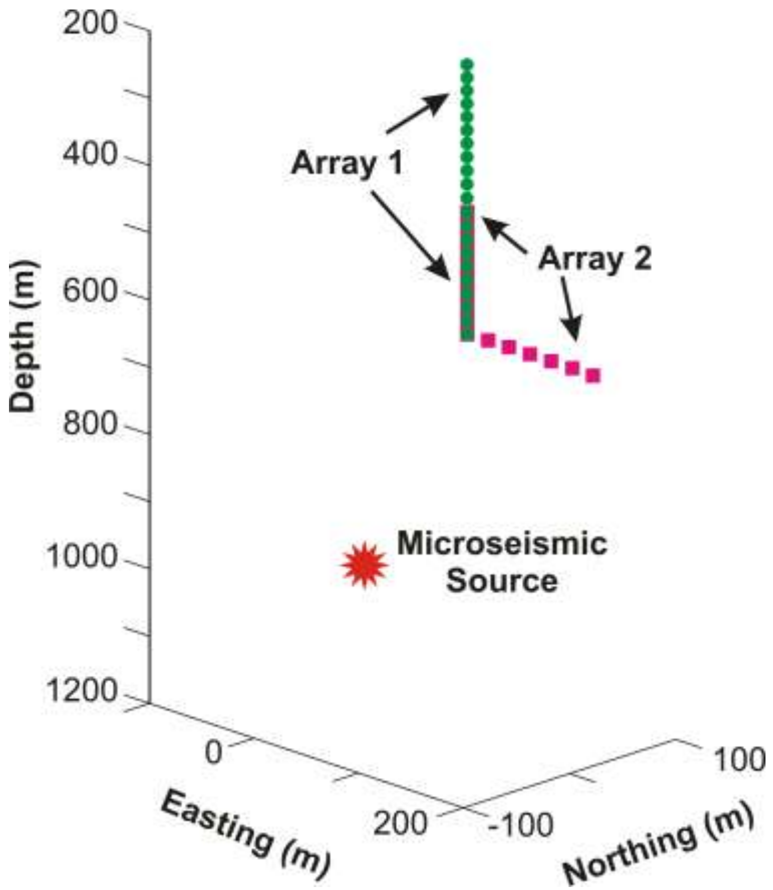
- A crack opening under tension (type I) can be represented by the sum of an isotropic moment tensor and a compensated linear vector dipole (CVLD)



http://www.iwb.uni-stuttgart.de/grosse/aet/mti.htm

$$\begin{bmatrix} M_0 & 0 & 0 \\ 0 & -2M_0 & 0 \\ 0 & 0 & M_0 \end{bmatrix}$$

Synthetic Modelling Geometry



- Two borehole array configurations were used to generate synthetic data, as illustrated here

Synthetic Modelling Geometry

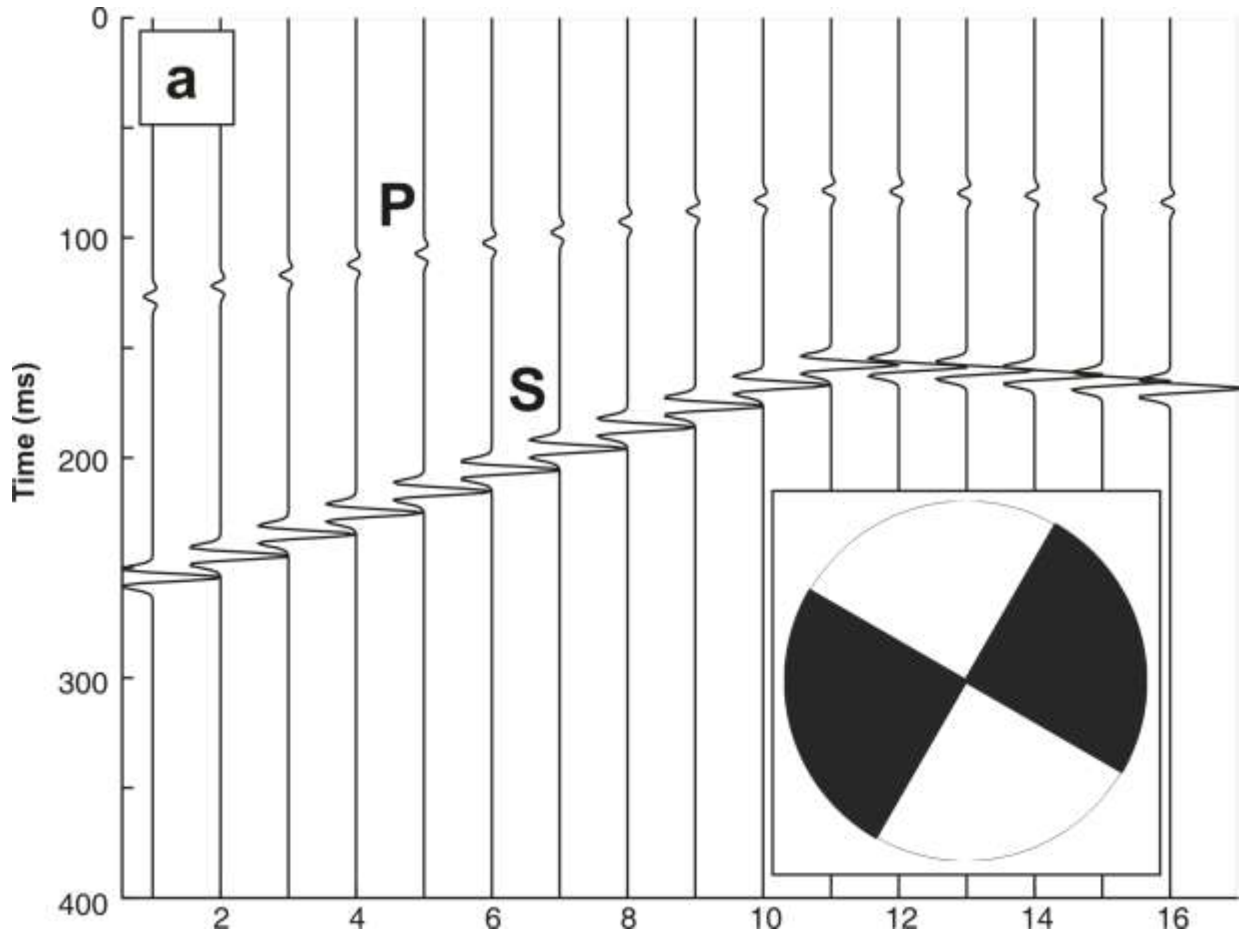
Synthetic seismograms were computed for a homogeneous medium using the following formulas:

$$u_i^P(x,t) = \left(4\pi\rho\alpha^3\right)^{-1}\left[\gamma_i\gamma_j\gamma_k r^{-1}\right]\dot{M}_{jk}\left(t - r/\alpha\right)$$

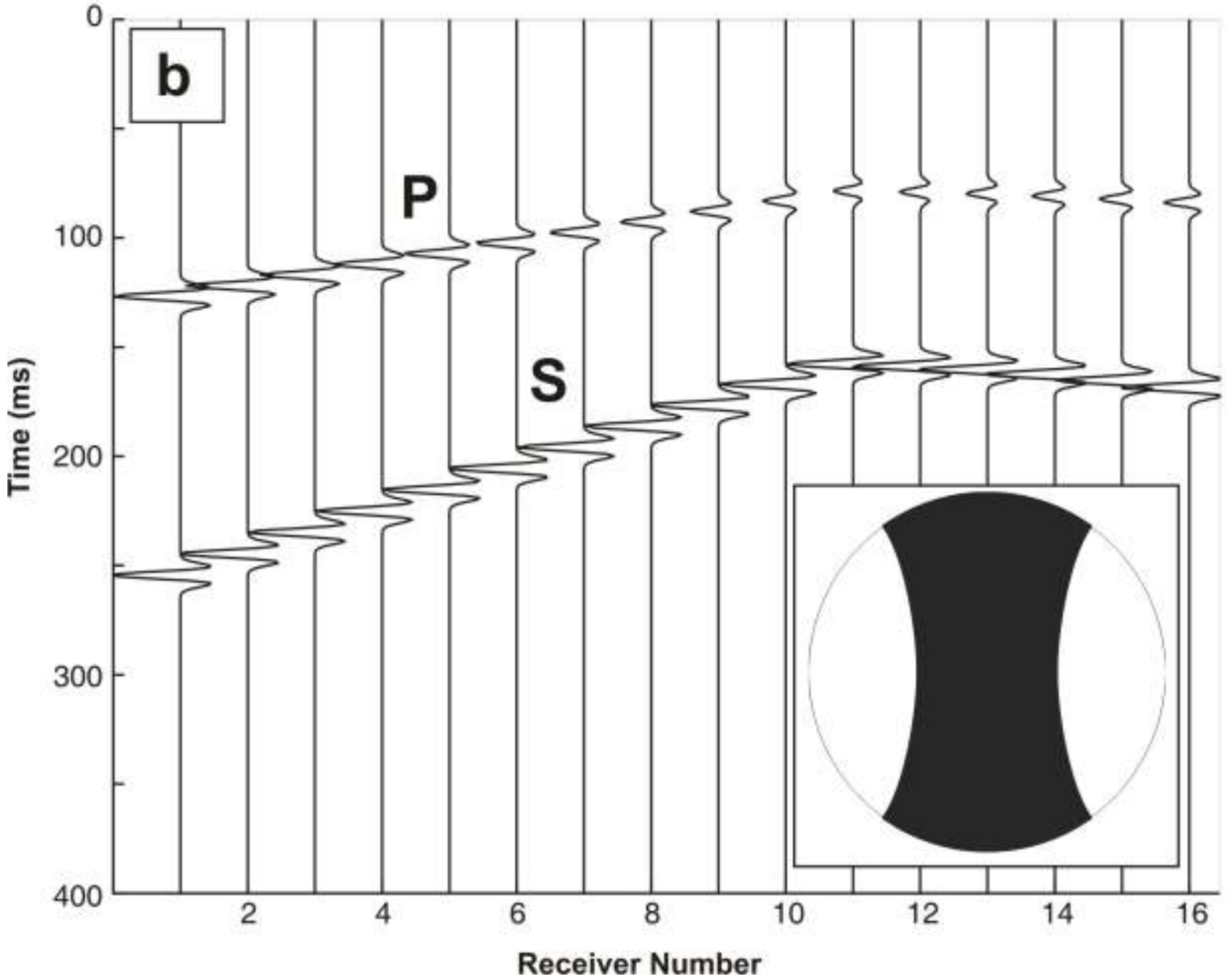
$$u_i^S(x,t) = \left(4\pi\rho\beta^3\right)^{-1}\left[(\delta_{ij} - \gamma_i\gamma_j)\gamma_k r^{-1}\right]\dot{M}_{jk}\left(t - r/\beta\right)$$

Lay and Wallance, 1995

Synthetic data: double couple



Synthetic data: CLVD



Resolution estimation

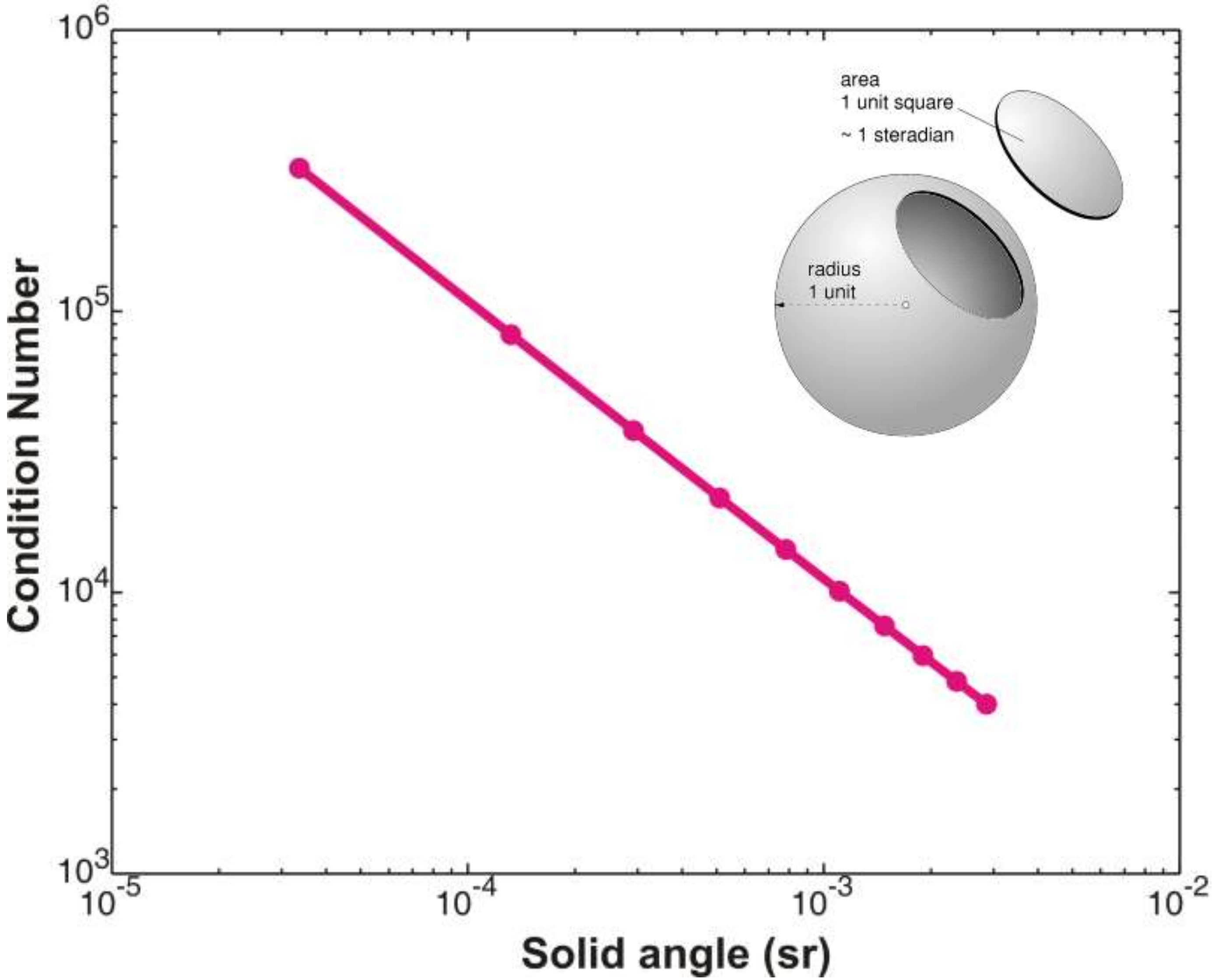
$$\mathbf{d} = \mathbf{A}\mathbf{m}$$

where $\mathbf{d} = (a_1{}^P, a_2{}^P, a_3{}^P, a_1{}^S, a_2{}^S, a_3{}^S)^{\mathrm{T}}$ defines the observed amplitudes of the *P*- and *S*-wave direct arrivals and $\mathbf{m} = (M_{11}, M_{22}, M_{33}, M_{12}, M_{13}, M_{23})^{\mathrm{T}}$ defines the independent components of the seismic moment tensor.

A least-squares solution to this over-determined system can be obtained using the generalized inverse,

$$\mathbf{m} = \mathbf{A}^{-\mathbf{g}}\,\mathbf{d} \quad = (\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{d}$$

Condition number



The condition number of A^TA is found to be inversion proportional to the solid angle subtended by the receiver array

Conclusions

Synthetic tests show that in order to solve for the complete moment tensor, the following conditions must be satisfied:

1) the receiver array must subtend a nonzero solid angle, viewed from the source;

2) 3-C observations are required;

3) both P- and S-wave amplitudes are required

GeoScience