Investigations of Icequake Source Physics

Assessing the Link Between Englacial Fracturing and Glacial Floods

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Glacier Seismics

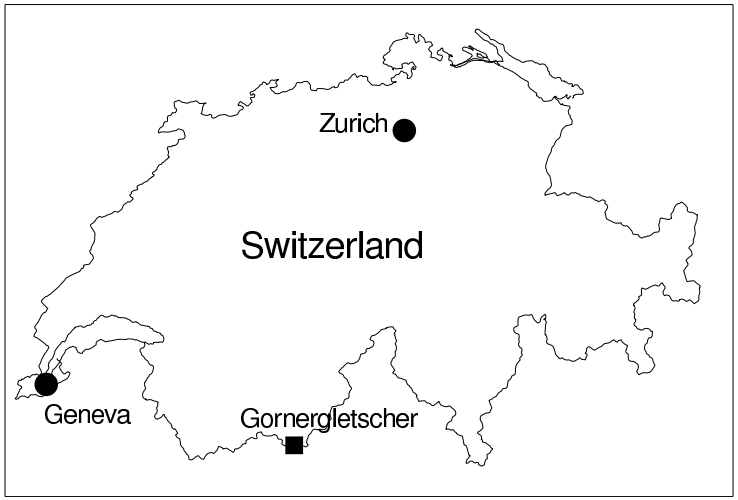
Icequakes

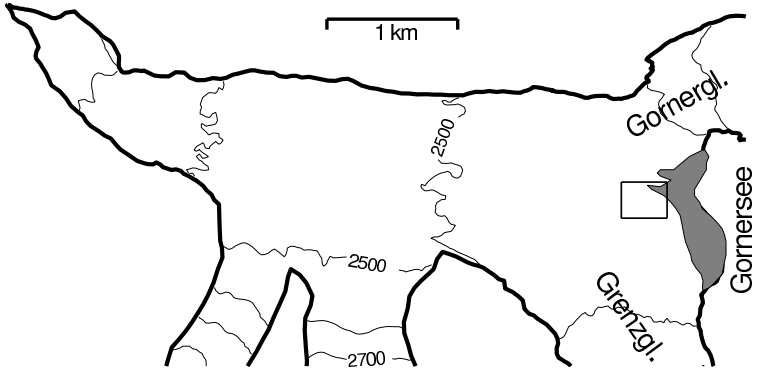
- Seismic signals within large masses of ice
- Due to straining within the ice
- Temperate glaciers:
  - Many thousand events per day
  - Occur at all depths
  - Hydrofracturing

Open questions

- Source mechanisms (compared to earthquakes)
- Source parameters (magnitude, volumetric changes, geometry)
- Connection to surface crevasses
- Connection to glacier hydraulics

Study of Jökulhlaup on Gornergletscher





Gornergletscher

- Second largest glacier in Switzerland
- 14km long
- 4500m-2200m above sea level
- Thickness up to 450m
- 3km retreat since 2nd half of 19th century
- Yearly filling and subglacial drainage of Gornersee

Gornersee outburst floods (Jökulhlaup)

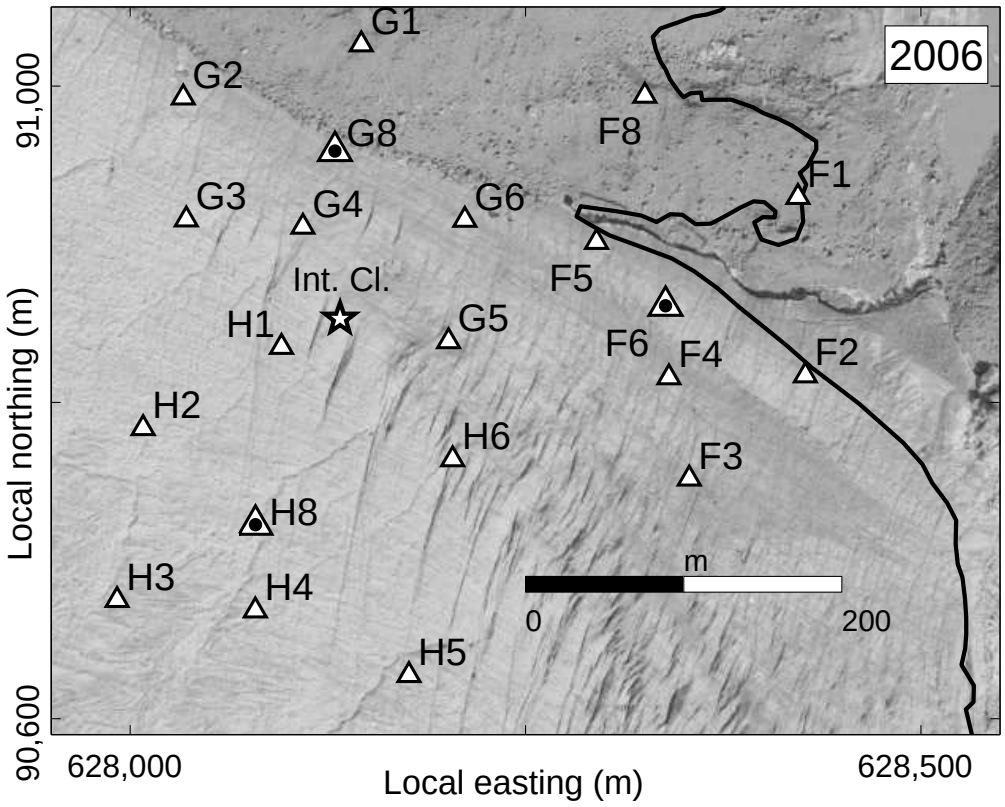
- Filling with melt water in spring
- Sudden drainage in June-July
- Lake volume ca. $4 * 10^6\ m^3$
- Sub- and intraglacial drainage
- Significant damage in Zermatt in the past
- Field campaigns during four drainages

A Relationship Between Glacier Outburst Floods and Icequakes?

Glacier Outburst Floods ↔ Icequakes

- Change of icequake activity in response to lake drainage (?)
- Possibility of early warning (?)
- →Need for good characterization and understanding of icequakes and their source mechanisms

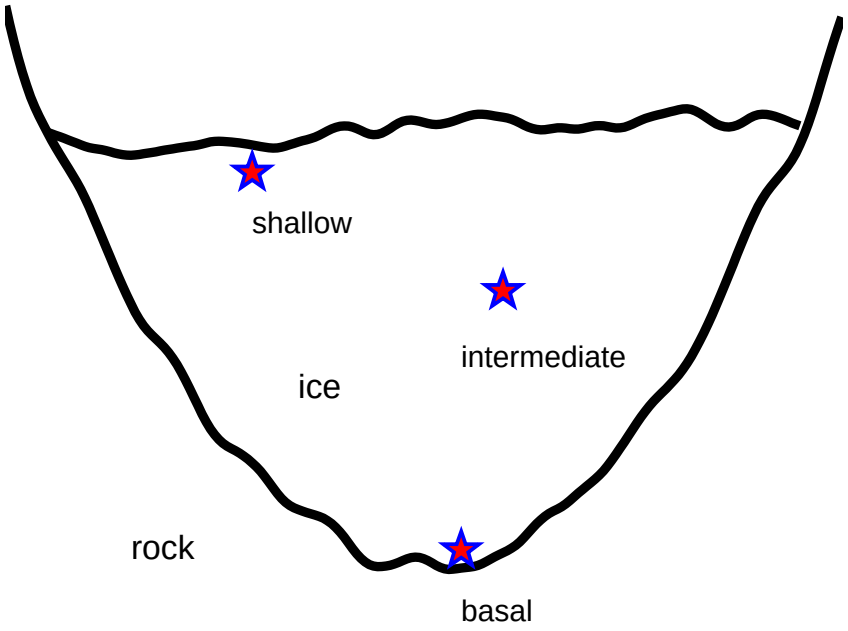
Seismic Measurements



Instrumentation

- ca. 24 seismometers
- Field measurements May-July each year
- Surface and borehole seismometers
- Trigger and continuous mode
- Unique data set: First time an alpine glacier has been instrumented with such a dense seismic network over an extended time period

Icequake Hypocenters



Shallow icequakes

- 30,000 per field campaign
- Surface crevasse zone (< 20 m)
- Compressive first motions at all azimuths (with exceptions!)
- Dominant Rayleigh wave

Intermediate icequakes

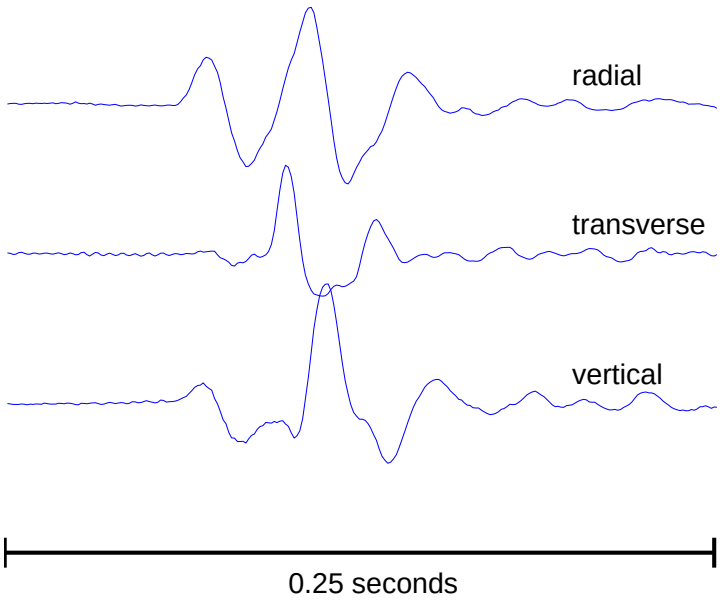
- 30 per field campaign
- Below crevassing zone
- Compressive first motions at all azimuths
- Dominant P- or S-wave
- Hydrofracturing
- Clusters found via crosscorrelation

Basal icequakes

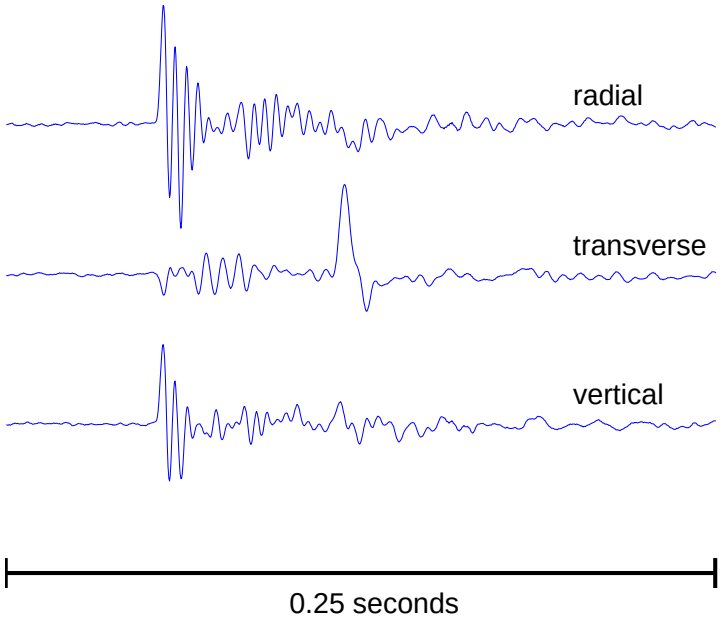
- 200 per field campaign
- Within 10s of meters of bed
- Compressive first motions at all azimuths (with exceptions!)
- Dominant P- or S-wave
- Hydrofracturing
- Clusters found via crosscorrelation

Icequake locations

Near-surface event



Intermediate event



- Duration ca. 0.1sec
- Frequency content as high as 200Hz
- Sampling frequency 1000-4000Hz
- $M_w = -2.0$ to -1.5

Seismic Moment Tensor

Idea: express source mechanism in terms of force-equivalents

$$u_n(\mathbf{x}, t) = \int \int_{\Sigma} m_{pq} * G_{np,q} \, \mathrm{d}\Sigma$$

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Variable Definitions

- $u_n(\mathbf{x}, t)$: ground motion
- Integration of fracture area Σ
- $*$: Temporal convolution
- G_{np}: n^{th} component of ground motion in response to a delta-function force impulse in the pth direction (Green's Function)
- $G_{np,q}$: q^{th} derivative of G_{np}
- m_{pq}: moment density tensor (symmetric)

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Meaning and Significance

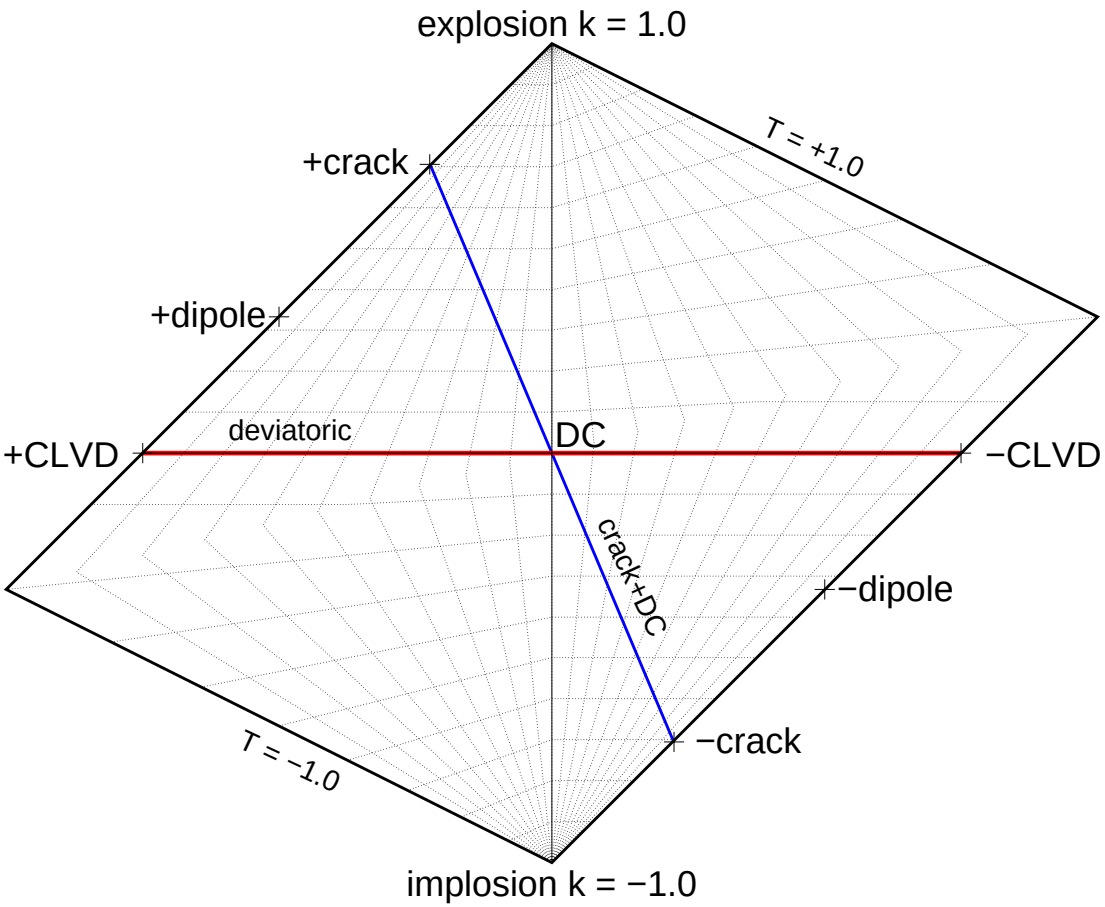
- G_{np}: propagation of seismic waves
- m_{pq}: $\leftrightarrow$ source mechanism
  - Magnitude of event
  - Nature of Failure
  - Orientation of fault planes
  - Isotropic: Volume change of fracture region
  - Deviatoric: NO volume change of fracture region

Examples for Moment Tensors

name	example	deviatoric or isotropic ?	representation of
explosion (ISO)	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$	purely isotropic	explosion
double couple (DC)	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	purely deviatoric	shear fault
CLVD	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \text{-1/2} & 0 \\ 0 & 0 & \text{-1/2} \end{pmatrix}$	purely deviatoric	various interpretations
crack	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1/\nu^* - 1 \end{pmatrix}$	mixed	crack opening

$^*\nu_{\text{ice}} = 0.36$

Source Type Plots*



*Hudson (1989)

Moment Tensor Inversion

Goals

- Invert 3 component seismograms of icequakes
- Determine source parameters

Strategy

- Try full and constrained inversions:
  - Full
  - Deviatoric
  - Crack+DC
- Evaluate inversion results via source-type plots
- Consider information from first motions, crevasse patterns, etc.
- Evaluate inversion performance via variance reduction

Moment Tensor Inversion

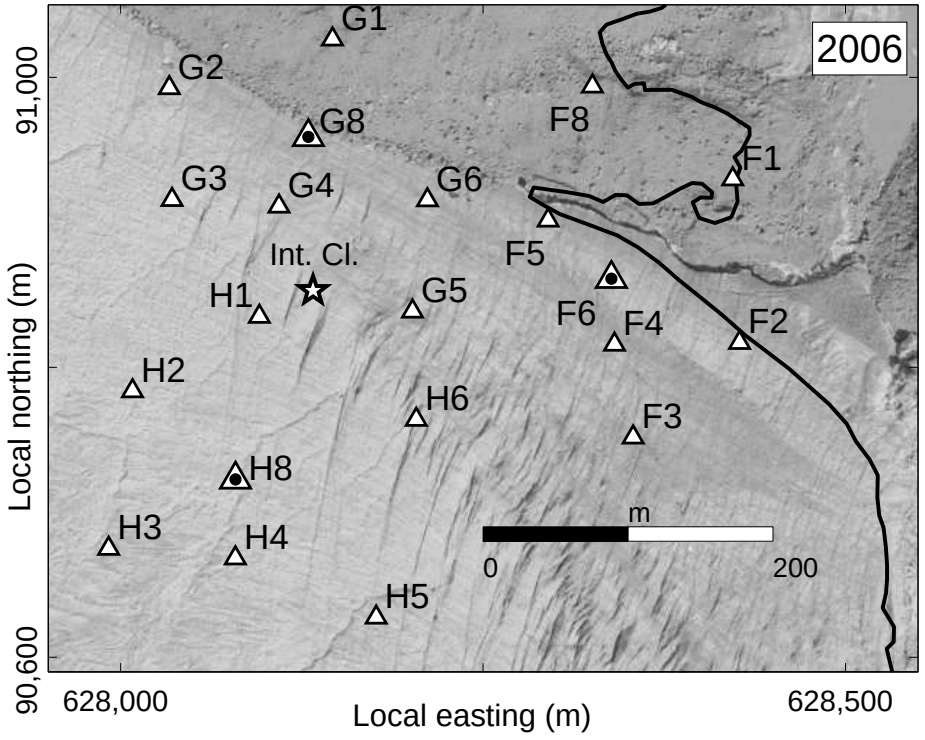
Numerical inversion tools for tectonic earthquakes (Dreger (1994) and Minson, Dreger and others (2007))

- Full moment tensor inversion ($ISO + DC + CLVD$): Standard inversion of moment tensor with 6 unknowns
- Deviatoric moment tensor inversion ($DC + CLVD$): Standard inversion subject to constraining the isotropic components to be zero
- $Crack + DC$ inversion: Grid search of orientation of fault planes as well as individual strengths of crack and DC component

Scaling from glacier to tectonic dimensions

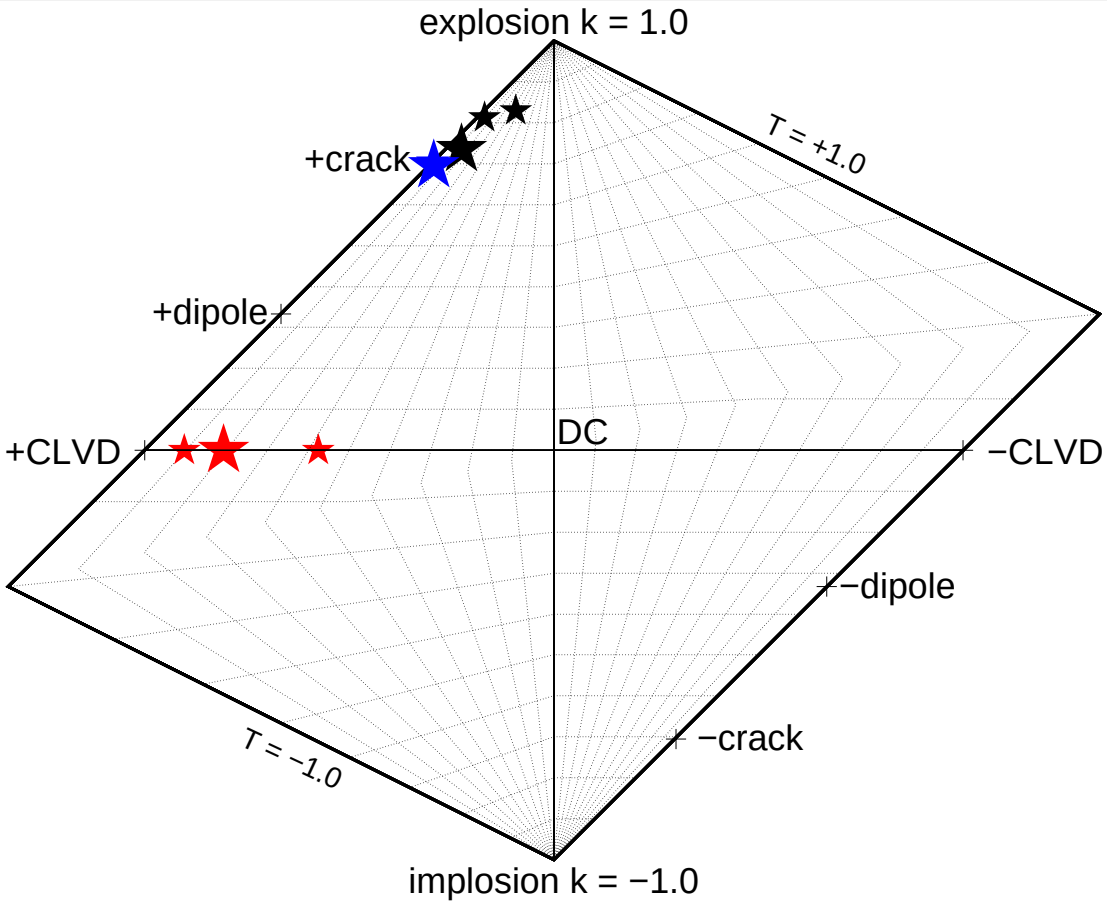
- Much higher frequencies and shorter wavelengths for icequake signals
- Scale frequencies and glacier dimensions by 1000
- Seismic velocities and source physics do not change
- Green's Functions determined using Saikia (1994) for a half space, and layer over a half space (sufficient model for a glacier)

Case Study: Intermediate Events



- Recorded in 2006
- Found with cross-correlation search
- 3 events within 3 hours
- 80m depth (basal depth: 120m)
- All compressive first motions (typical for crevasse openings)
- Impulsive P-arrivals

Intermediate Events: Source Type Plots

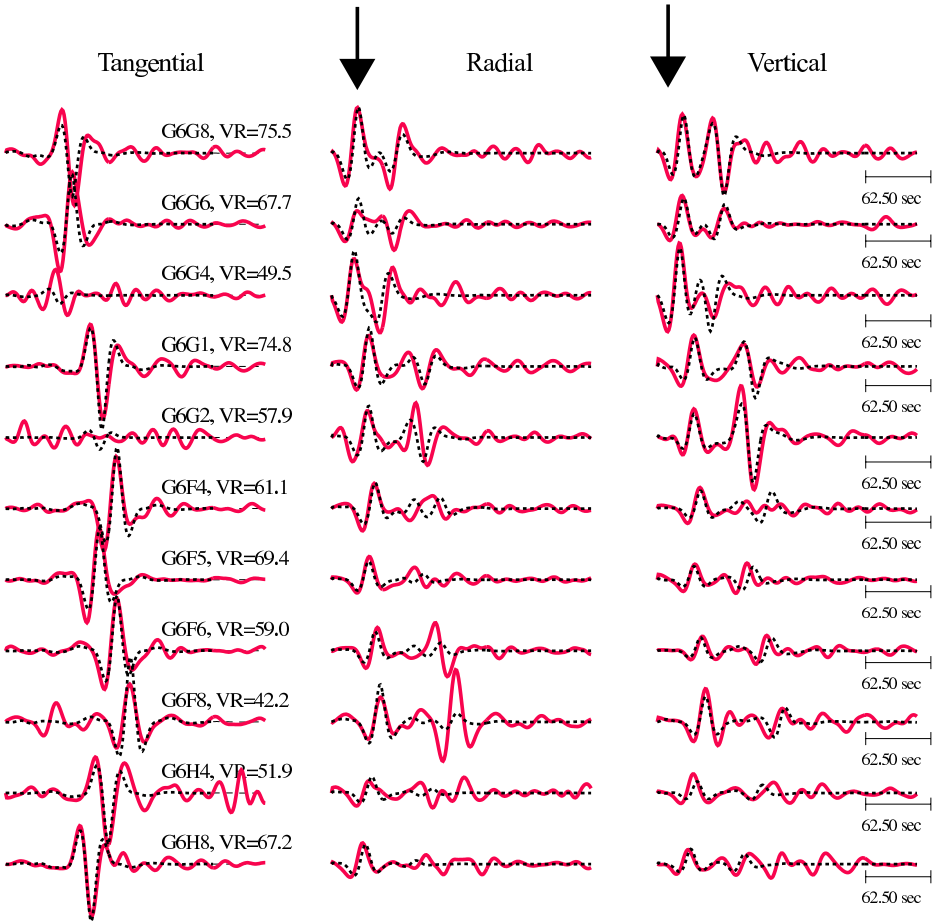


Variance Reductions (in %)

scheme	ev1	ev2	ev3
Full	57	59	62
Deviatoric	20	31	47
Crack + Double Couple	49	51	61

Intermediate Events: Full vs. Deviatoric Moment Tensor Inversion

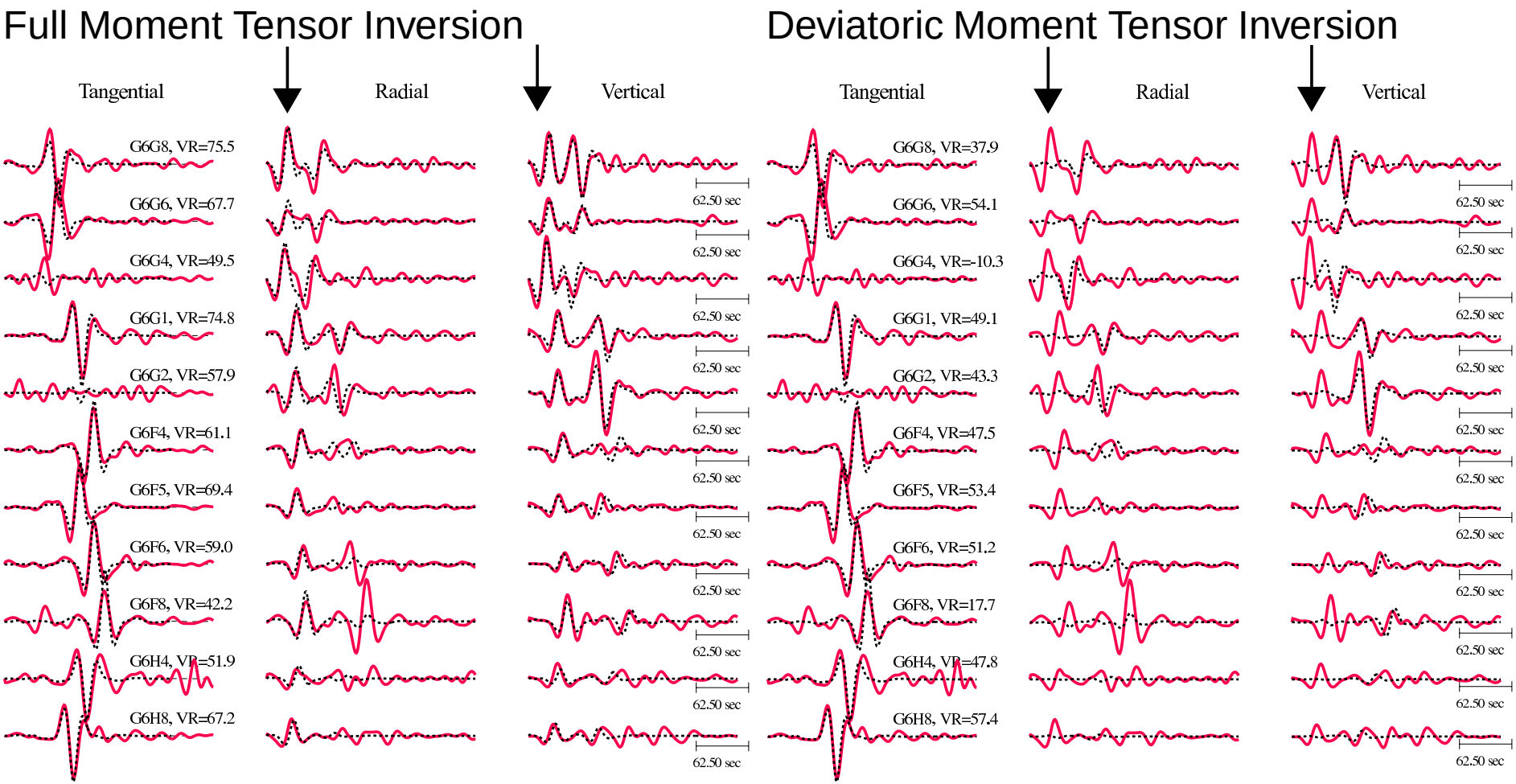
Full Moment Tensor Inversion



Deviatoric Moment Tensor Inversion

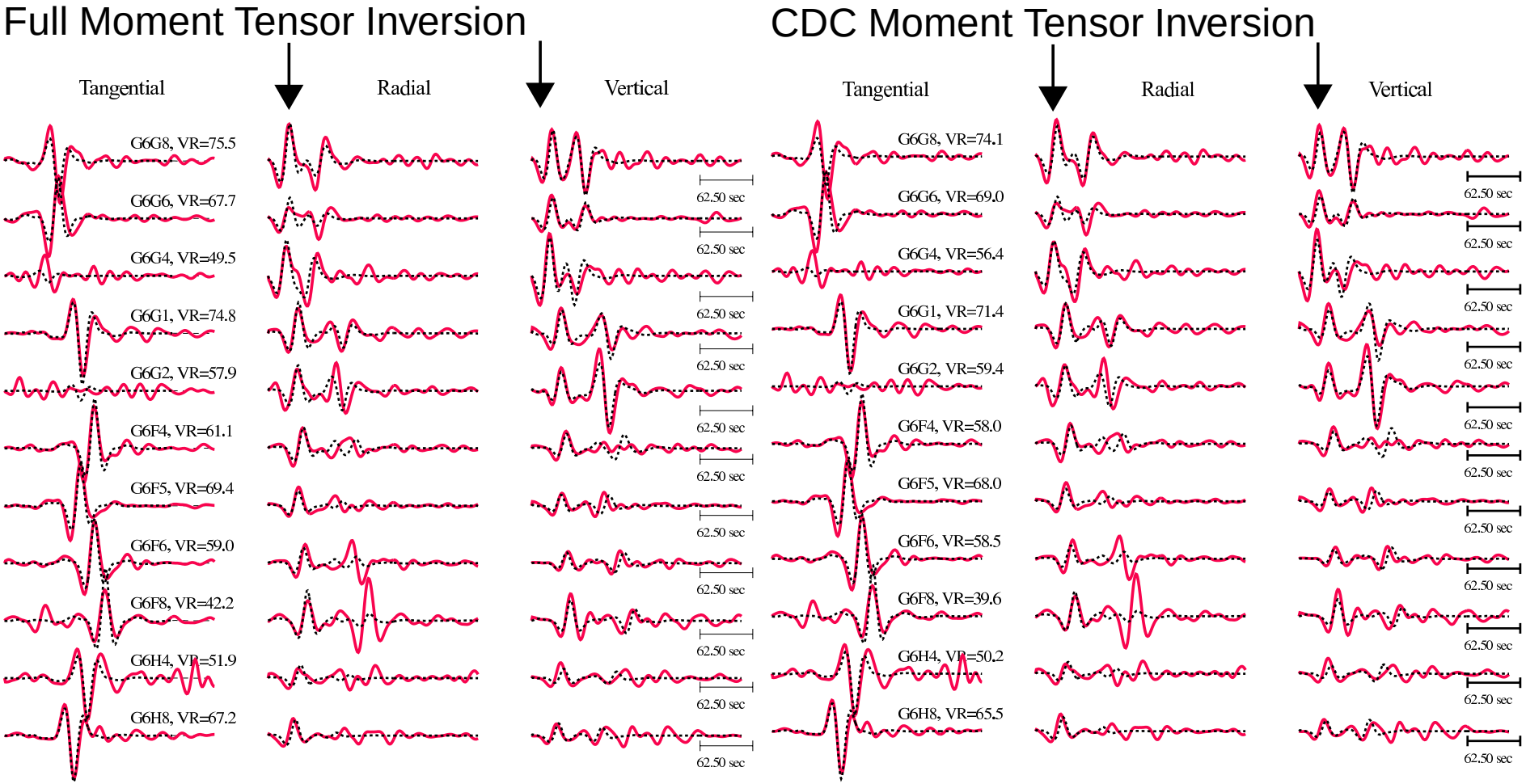
depth: 80m; bp: 30-70Hz; source-receiver distances: 50-300m, $\Delta V = 70$ cm^3

Intermediate Events: Full vs. Deviatoric Moment Tensor Inversion



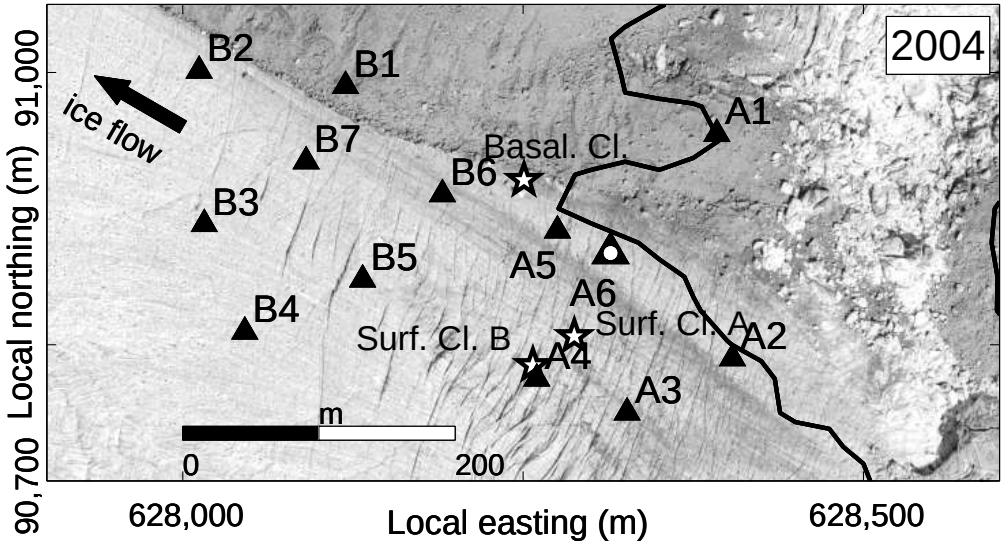
depth: 80m; bp: 30-70Hz; source-receiver distances: 50-300m, $\Delta V = 70$ cm^3

Intermediate Events: Full vs. CDC Moment Tensor Inversion



depth: 80m; bp: 30-70Hz; source-receiver distances: 50-300m, $\Delta V = 70$ cm^3

Case Study: Near-Surface Events



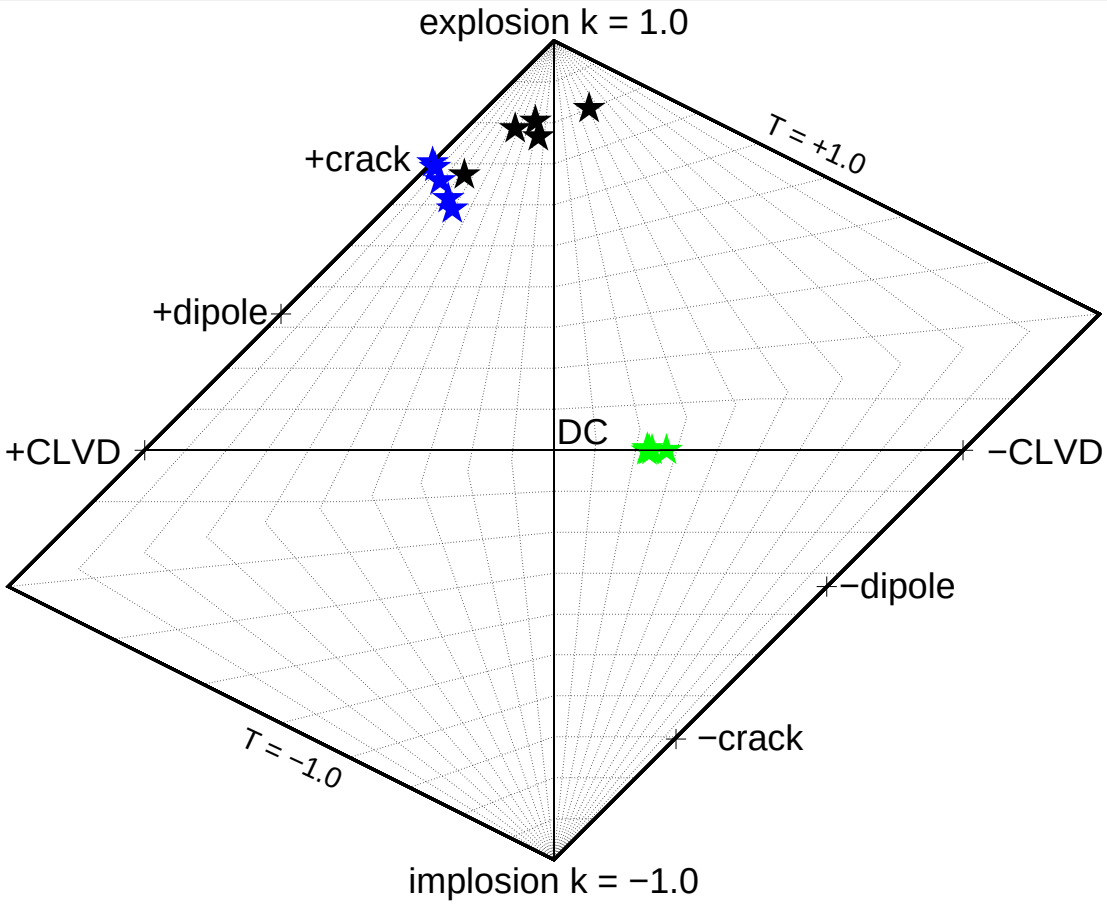
Typical Shallow Icequake (cluster A)

- Recorded in 2004
- Found with cross-correlation search
- 5 events within 24 hours
- Only compressive first motions (typical)
- Large Rayleigh Wave

Typical Shallow Icequake (cluster B)

- Recorded in 2004
- Found with cross-correlation search
- 5 events within 5 hours
- Quadrantal pattern of first motion (untypical)
- Small Rayleigh Wave

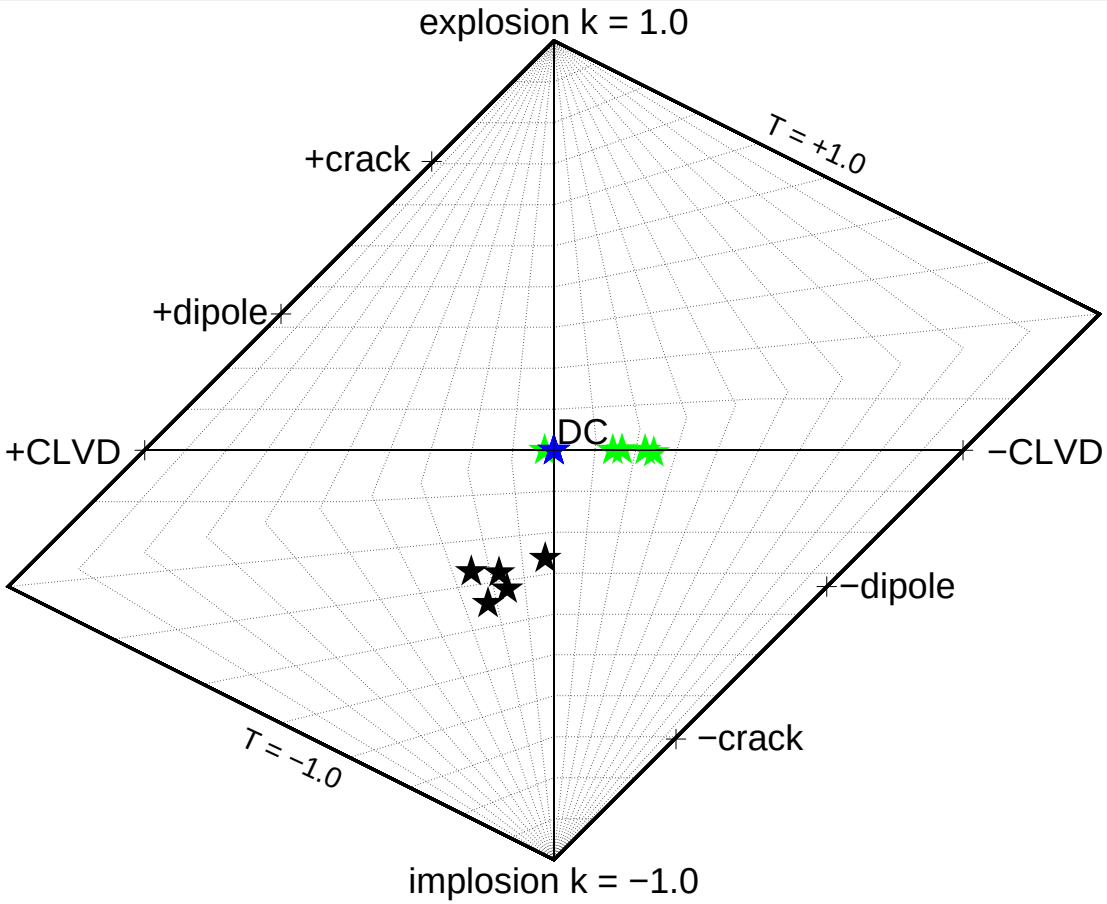
Surface Cluster A Events: Source Type Plots



Variance Reductions (in %)

scheme	ev1	ev2	ev3	ev4	ev5
Full	74	63	71	65	74
Deviatoric	71	58	66	57	68
Crack + Double Couple	75	62	72	65	73

Surface Cluster B Events: Source Type Plots



Variance Reductions (in %)

scheme	ev1	ev2	ev3	ev4	ev5
Full	74	73	72	77	74
Deviatoric	74	73	71	77	74
Crack + Double Couple	72	74	66	75	72

Moment Tensor Scaling

MT inversion gives ...

- ... source type
- ... source geometry

MT inversion does not give ...

- ... magnitudes
- ... source dimensions

Implication of scaling

- Frequencies and source-receiver distances scaled
- Amplitudes need to be scaled, too
- $\rightarrow$ Moment tensor only determined uniquely up to a scaling factor
- Need to scale moment tensor to get magnitudes

Moment Tensor Scaling

Determination of scalar moment

- Scaling of scalar moment
- For double-couple sources:

$$M_0 = \frac{4\pi \rho_x^{1/2} \rho_\xi^{1/2} \beta_x^{1/2} \beta_\xi^{5/2}}{F_{\theta\phi}^{SH} S^{SH}} R \int_0^T u^{SH}(\tau)\, d\tau \qquad (1)$$

- Material constants of source and receiver region
- SH-wave ground motion u^{SH}
- Hypocentral distance R
- Integration over S-wave period
- Radiation pattern $F_{\theta\phi}^{SH}$

Moment Magnitude and Volumetric Changes

Scalar moment

- Moment tensor M
- m_1 and m_3 largest and smallest eigenvalue
- For deviatoric source:

$$M_0 = \frac{|m_1| + |m_3|}{2} \tag{2}$$

- For source with isotropic component:

$$M_0 = \frac{trace(\mathbf{M})}{3} + m_1 \tag{3}$$

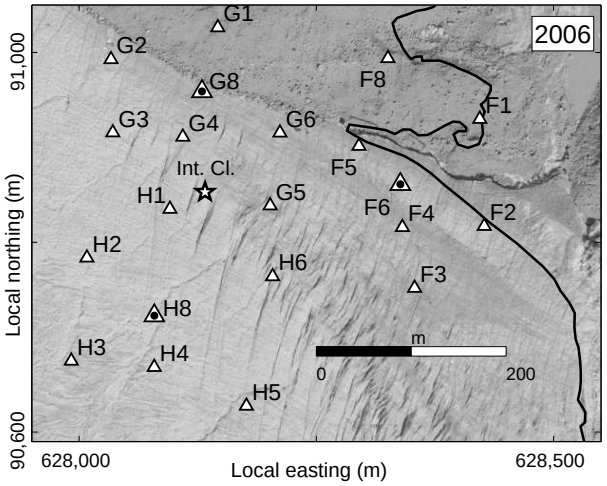
Volumetric changes

$$\Delta V = M_{iso}(\lambda + 2\mu/3), \tag{4}$$

- λ and μ are the Lamé parameters
- Crack volume

Source Geometry AND Magnitude

Event	Strike	Dip	Rake	ΔV (cm^3)	M_w
SURF_A 1	40	50	-60	280	-1.5
SURF_A 2	198	80	108	110	-1.8
SURF_A 3	202	78	105	400	-1.4
SURF_A 4	215	85	50	140	-1.7
SURF_A 5	36	86	-28	270	-1.5
SURF_B 1	208	68	156	0	-1.7 (-1.6)
SURF_B 2	208	73	152	0	-1.7 (-1.6)
SURF_B 3	200	70	156	0	-2.2 (-2.1)
SURF_B 4	202	72	144	0	-1.7 (-1.6)
SURF_B 5	202	67	150	0	-1.8 (-1.7)
INT 1	31	60	-124	120	-1.8
INT 2	32	64	-10	120	-1.8
INT 3	40	65	136	100	-1.8



- Strike consistent with crevasse pattern
- Surf. Cl. B: Fault planes consistent with first motions

Summary of Inversion Results (Shallow Events)

Near surface events

- Crack type (vast majority of signals)
  - Only compressive first arrivals
  - Crack+DC fit as good as full moment tensor inversion (VR 70%)
  - Crack+DC model dominated by crack component
  - Deviatoric inversion slightly worse, but satisfactory fit (VR decrease of 5%), similar to findings by Minson (2007)
- DC type (small subset of signals)
  - Indicated simple strike slip
  - Quadrantal pattern of first motions
  - Crack+DC fit as good as full moment tensor inversion (VR 70%)
  - Crack+DC model dominated by DC component
  - Deviatoric fit as good as others
  - Same mechanism as by first motions

Summary of Inversion Results (Deep Events)

Intermediate Icequakes

- Only compressive first arrivals
- Crack+DC fit as good as full moment tensor inversion (VR 50-60%)
- Crack+DC model dominated by crack component
- Likely crevasse opening
- $\rightarrow$ Hydrofracturing

Basal Icequakes: State of the Art

- Attempted full moment tensor inversion without bed and with horizontal bed
- Satisfactory fit quality ($VR = 57\%$)
- Fit quality best for homogeneous halfspace !!!
- Likely crevasse opening
- More work to be done ...

Results and Outlook

Results

- Successful application of regional moment tensor inversion scheme to glacier seismicity via simple scaling relationship
- Three types of inverted events:
  - Crack-like events at intermediate depths
  - Crack-like surface events
  - DC-like surface events
  - Strike and dip consistent with crevasse patterns

Results and Outlook

Outlook

- Invert more icequakes
- Basal events
  - Try to estimate effect of bed
  - Employ 2D or 3D Green's Functions
- Relative icequake locations $\leftrightarrow$ fault plane orientations
- Attempt to correlate source mechanisms / magnitudes and lake drainage