Investigations of Icequake Source Physics
Assessing the Link Between Englacial Fracturing and Glacial Floods

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Strasbourg – March 4, 2008

J. Clinton, N. Deichmann, M. Funk
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. $4 \times 10^6 \, m^3$
- Sub- and intraglacial drainage
- Significant damage in Zermatt in the past
- Field campaigns during four drainages
A Relationship Between Glacier Outburst Floods and Icequakes?

- 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
Duration ca. 0.1 sec
Frequency content as high as 200Hz
Sampling frequency 1000-4000Hz
$M_w = -2.0 \text{ to } -1.5$
Seismic Moment Tensor

Idea: express source mechanism in terms of force-equivalents

\[ u_n(x, t) = \int \int_{\Sigma} m_{pq} * G_{np,q} \, d\Sigma \]
Seismic Moment Tensor

Idea: express source mechanism in terms of force-equivalents

\[ u_n(x, t) = \int \int_{\Sigma} m_{pq} \ast G_{np,q} \, d\Sigma \]

Variable Definitions

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

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\[ u_n(x, t) = \int \int_{\Sigma} m_{pq} \ast G_{np,q} \, d\Sigma \]

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Meaning and Significance
- \( G_{np} \): propagation of seismic waves
- \( m_{pq} \): ↔ 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

<table>
<thead>
<tr>
<th>name</th>
<th>example</th>
<th>deviatoric or isotropic?</th>
<th>representation of</th>
</tr>
</thead>
<tbody>
<tr>
<td>explosion (ISO)</td>
<td>$\begin{pmatrix} 1 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 1 \end{pmatrix}$</td>
<td>purely isotropic</td>
<td>explosion</td>
</tr>
<tr>
<td>double couple (DC)</td>
<td>$\begin{pmatrix} 1 &amp; 0 &amp; 0 \ 0 &amp; -1 &amp; 0 \ 0 &amp; 0 &amp; 0 \end{pmatrix}$</td>
<td>purely deviatoric</td>
<td>shear fault</td>
</tr>
<tr>
<td>CLVD</td>
<td>$\begin{pmatrix} 1 &amp; 0 &amp; 0 \ 0 &amp; -1/2 &amp; 0 \ 0 &amp; 0 &amp; -1/2 \end{pmatrix}$</td>
<td>purely deviatoric</td>
<td>various interpretations</td>
</tr>
<tr>
<td>crack</td>
<td>$\begin{pmatrix} 1 &amp; 0 &amp; 0 \ 0 &amp; 1 &amp; 0 \ 0 &amp; 0 &amp; 1/\nu^* - 1 \end{pmatrix}$</td>
<td>mixed</td>
<td>crack opening</td>
</tr>
</tbody>
</table>

$\nu_{\text{ice}} = 0.36$
Source Type Plots*

*Hudson (1989)
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
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 %)

<table>
<thead>
<tr>
<th>scheme</th>
<th>ev1</th>
<th>ev2</th>
<th>ev3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>57</td>
<td>59</td>
<td>62</td>
</tr>
<tr>
<td>Deviatoric</td>
<td>20</td>
<td>31</td>
<td>47</td>
</tr>
<tr>
<td>Crack + Double Couple</td>
<td>49</td>
<td>51</td>
<td>61</td>
</tr>
</tbody>
</table>
Intermediate Events: Full vs. Deviatoric Moment Tensor Inversion

Full Moment Tensor Inversion

- Tangential
- Radial
- Vertical

Deviatoric Moment Tensor Inversion

- Tangential
- Radial
- Vertical

Depth: 80m; bp: 30-70Hz; source-receiver distances: 50-300m, $\Delta V = 70$ cm$^3$
Intermediate Events: Full vs. Deviatoric Moment Tensor Inversion

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- Tangential
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Deviatoric Moment Tensor Inversion

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- Vertical

Depth: 80m; bp: 30-70Hz; source-receiver distances: 50-300m, $\Delta V = 70$ cm$^3$
Intermediate Events: Full vs. CDC Moment Tensor Inversion

**Full Moment Tensor Inversion**

- Tangential
  - C6G8, VR=75.5
  - C6G6, VR=67.7
  - C6G4, VR=49.5
  - C6G1, VR=74.8
  - C6G2, VR=57.9
  - C6F4, VR=61.1
  - C6F5, VR=69.4
  - C6F6, VR=59.0
  - C6F8, VR=42.2
  - C6H4, VR=51.9
  - C6H8, VR=67.2

- Radial

- Vertical

**CDC Moment Tensor Inversion**

- Tangential
  - G6G8, VR=74.1
  - G6G6, VR=69.0
  - G6G4, VR=56.4
  - G6G1, VR=71.1
  - G6G2, VR=59.4
  - G6F4, VR=58.0
  - G6F5, VR=68.0
  - G6F6, VR=58.5
  - G6F8, VR=59.6
  - G6H4, VR=50.2
  - G6H8, VR=65.5

- Radial

- Vertical

**Details:**

- Depth: 80m; bp: 30-70Hz; source-receiver distances: 50-300m, \( \Delta V = 70 \text{ cm}^3 \)
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 %)

<table>
<thead>
<tr>
<th>scheme</th>
<th>ev1</th>
<th>ev2</th>
<th>ev3</th>
<th>ev4</th>
<th>ev5</th>
</tr>
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<tbody>
<tr>
<td>Full</td>
<td>74</td>
<td>63</td>
<td>71</td>
<td>65</td>
<td>74</td>
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<tr>
<td>Deviatoric</td>
<td>71</td>
<td>58</td>
<td>66</td>
<td>57</td>
<td>68</td>
</tr>
<tr>
<td>Crack + Double Couple</td>
<td>75</td>
<td>62</td>
<td>72</td>
<td>65</td>
<td>73</td>
</tr>
</tbody>
</table>
Surface Cluster B Events: Source Type Plots

Variance Reductions (in %)

<table>
<thead>
<tr>
<th>scheme</th>
<th>ev1</th>
<th>ev2</th>
<th>ev3</th>
<th>ev4</th>
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</tr>
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<tbody>
<tr>
<td>Full</td>
<td>74</td>
<td>73</td>
<td>72</td>
<td>77</td>
<td>74</td>
</tr>
<tr>
<td>Deviatoric</td>
<td>74</td>
<td>73</td>
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<td>77</td>
<td>74</td>
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<tr>
<td>Crack + Double Couple</td>
<td>72</td>
<td>74</td>
<td>66</td>
<td>75</td>
<td>72</td>
</tr>
</tbody>
</table>
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
  \[ \rightarrow \text{Moment tensor only determined uniquely up to a scaling factor} \]
- Need to scale moment tensor to get magnitudes
Moment Tensor Scaling

Determination of scalar moment

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

\[
M_0 = \frac{4\pi \rho_\chi^{1/2} \rho_\xi^{1/2} \beta_\chi^{1/2} \beta_\xi^{5/2}}{F_{\theta\phi}^{SH} S_{SH}^{SH}} R \int_0^T u^{SH}(\tau) d\tau
\]  

- 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:

  $$M_0 = \frac{|m_1| + |m_3|}{2}$$  \hspace{1cm} (2)

- For source with isotropic component:

  $$M_0 = \frac{\text{trace}(M)}{3} + m_1$$  \hspace{1cm} (3)

## Volumetric changes

$$\Delta V = M_{iso}(\lambda + 2\mu/3),$$  \hspace{1cm} (4)

- $\lambda$ and $\mu$ are the Lamé parameters
- Crack volume
## Source Geometry AND Magnitude

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

- 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
- → 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 ↔ fault plane orientations
- Attempt to correlate source mechanisms / magnitudes and lake drainage