Seismic survey considerations in glaciology.

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Why seismics on ice?

Characterizing subglacial conditions/geology

Landseismics, the job:
- Drilling shots
- Preparing charges
- Staking geophones
- Many hands needed

Problems with landseismics:
- Labour intensive.
- Small coverage.

Can we fix this? We try
Seismic hardware and operational areas

• Large set-up, covers the ice sheet and shelf:
  - Source: Failing Y1100: 120kN p-wave vibrator, 10-110Hz
  - Source: Envirovib: 66kN p-wave vibrator, 5-300Hz
  - Receiver: 1500m, 60ch snow streamer, gimbaled 14Hz p-geophone arrays.

• Small set-up (transportable by helicopter), covers ablation zone, ice streams, mountain glaciers:
  - Source: minivib Elvis: 450N p and s-wave vibrator, 5-320Hz
  - Receiver: 300m streamer, 96ch gimbaled 30Hz p-geophones

Both set ups can cover the entire ice sheet.

Figure ipcc 5
Seismic equipment

Top: Failing Y1100 vibrator on skis + 1.5 km snow streamer.

Middle: Tracked vibrator Envirovib on a PE sled.

Bottom: Minivibrator Elvis + 300m snow streamer.
Vibroseis principle 1: the sweep
Vibroseis principle 2: a 3 reflector case

Vibroseis Response and Correlation

- $sw(t)$, Pilot (Vibroseis source sweep)
- $e(t)$, Spike series (Earth response)
- $u(t)$, Uncorrelated seismogram
- Sum of reflection responses = convolution of $sw(t)$ and $e(t)$
- $s(t)$, Seismogram = correlation of $sw(t)$ and $u(t)$
Vibrating in practice

- 1\textsuperscript{st} 10 s sweep to compact the firn.
- 2\textsuperscript{nd} sweep first recording.
- 3\textsuperscript{rd} sweep second recording.
2010, vibrator seismics on Ekström Ice Shelf

- Wide angle seismics, shelf is thin, streamer is long.
- Channel distance 25m => spatial aliasing large offsets.
Shortcomings for shallow target depths

\[ \Delta t: \text{sample rate} \]
\[ \Delta x: \text{channel spacing} \]
\[ \nabla: \text{channel} \]
\[ \#: \text{sweep} \]
\[ \Delta: \text{CDP} \]

Spatial aliasing:
\[ \lambda_x < 2\Delta x \text{ or } f > 1/(2\Delta x) \]

No spatial aliasing:
\[ \lambda_x > 2\Delta x \text{ or } f < 1/(2\Delta t) \]

Detail, p-wave cancels out at large incidence:
\[ gph8 + gph7 + 25 \text{ m} + gph2 + gph1 = 1 \text{ Ch} \]
Quick and dirty solution:

- Streamer in loop, 12.5m channel spacing
Explosive vs Vibrator on the shelf

- Left: Field record Vibroseis (streamer in loop).
- Middle: Explosive vs Vibroseis, notice resolution and penetration.
- Right: Amplitude spectra Explosive and Vibrator (10-100Hz).

Eisen et. al EOS 2010
Explosive vs Vibrator under the shelf

- Left: 2 hydrophones, two sweeps, one shot. Time vs amplitude.
- Right: Amplitude vs distance, maximum peak level almost equal, sound exposure level vibrator stronger.
60km shelf survey 2011

• Discovery of Explora Wedge, a volcanic wedge that formed during Gondwana break-up.
• Vibroseis penetrates well in base.
  – 300m thick shelf.
  – 600m of sea water.
  – At least 2km deep data visible.
  – Good source control.
• High production, 20km/day, 8 fold data.
  – Ideal tool for shelf surveys like ANDRILL.

Kristoffersen et. al JGR 2014
Halvfarryggen a coastal dome

- Vibrator 10-100Hz vs explosives (400g)
- Penetration good, resolution less as explosives.

7.7km Kirchhoff Migration

base

at least 12 internal reflections visible with explosives.

Hofstede et. al AG 2013
Ekströmisen survey 2014

- 420 km seismic survey
- Vibrator + 1.5km snow streamer
- 5 persons
- Four weeks of data collection

<table>
<thead>
<tr>
<th>fold</th>
<th>shot interval (m)</th>
<th>time/shotpoint (min)</th>
<th>production rate (km/h, km/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750</td>
<td>10</td>
<td>4.4, 40</td>
</tr>
<tr>
<td>2</td>
<td>375</td>
<td>6.3</td>
<td>7, 33</td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>4.5</td>
<td>3.3, 30</td>
</tr>
<tr>
<td>6</td>
<td>125</td>
<td>3.5</td>
<td>2.2, 20</td>
</tr>
</tbody>
</table>

Track vehicle

1.5km, 60ch snow streamer
Envirovib on PE sled

Eisen et. al Polar Science 2014
Sea bottom from the shelf
Onset of an ice stream channel

Flow direction:
from viewer

Englacial layering

Ice-bed reflections

TWT/S

0.40
0.60
0.80
1.00

65 150 250 350 450 550 650 750 850 950

Bedrock elevation (m)

0 500 1000 1500

FB1401

FB1402

EKSEIS 2013/14

Neumayer

Obs. Olymp

Obs. Watzmann

DML94

DML95

DML96

DML97

−1000
−500
0
500
1000
Projects with small seismic set up

- Alpine saddle, Colle Gnifetti
- Two locations on Russell Glacier, a land terminating glacier in West Greenland
- Tide water glacier Store Glacier in Uummannaq Fjord

Work in progress:
Colle Gnifetti, at 4500m altitude

Used Elvis as a source for Both P and S-wave survey.
A mini ice-cap, no melt
Comparing S and P data:

Polom et. al NSG 2014
Poisson ratio ($\nu$) from P and S data

P and S data $\rightarrow$ Poisson ratio $\rightarrow$ Fracture mechanics

Plate et al. 2012
Summer speed up August 2006-September 2004:

- sheet: 50-100%
- outlet: < 15%

=> Check the basal conditions of the sheet at Russell

Joughin et al. 2008
Dynamics of SHR Russell Glacier

Data: courtesy R.S.W. van de Wal

Adjusted from Doyle et al, GRL 2014
Reintroducing a British approach, May 2014.
Slow but steady
Contact with the ice?
May 2014: variation in Vs and Vp caused by water content of the ice matrix?
Plot Vs along the main line SHR

For Vp as well, => water content

Variation of Vs along main line Russell Glacier
Bed Russell May 2014:

- Bed contact
- Glacier transported sediments
• Russell, SHR:
  – Process Amplitude vs Offset (AVO) data to recover the reflection coefficient.
  – Compare seismic data from September 2013 and May 2014.
Site SPG, a drainage lake?

Example of radar profile

(RS22–RS21)

Processing:
Lowpass filtered,
normal move-out corrected.
Using 168 m/µs in depth conversion

data: Rickard Petterson
Russell September 2013, ideal circumstances:
consolidated till
23-fold area crossing
dilatated till
water body
dilatated till
crossing
bed contact
dilatated till
water body
bed contact
line 20130522, 1000m

polarity reversal

polarity reversal

reflector 1

reflector 2

reflector 3

subglacial sediments

subglacial sediments
Subglacial Access and Fast Ice Research Experiment (SAFIRE)

Store glacier, 2\textsuperscript{nd} largest glacier (ice flux) in West Greenland

- Identify and characterize the basal mechanical and hydrological conditions
- Determine the role of basal processes in modulating ice flow and calving
- Locate potential drilling location sediment samples
July 2014, survey area Store Glacier
What was recorded

- Streamer and shot move
- Shots, streamer at fixed location
Store Glacier, parallel ice flow line

line 20140513, 2000m

thermistor string

englacial reflection

bed contact

sediments?

weak bed contact
Store Glacier, parallel ice flow line 20140513, 2000m

- Thermistor string
- Englacial reflection
- Bed contact
- Weak bed contact
- Sediments

E-W line 20140513, 2000m
Englacial reflection

Expected ice base

Thermistor string

Bed contact

Streamer location

V-ice = 3900 m/s

V-ice = 4000 m/s

V-ice = 4100 m/s

2000 m
My questions:

• Bed reflector deeper than encountered, why?
  – Timing delay?
  – Low velocity surface layer? I did encounter a slow HF direct wave Vp 2400m/s to 3000m/s. Shallow layer, app 20m.

• Different Vp values, why?
  – Vp stack ≈ 4100m/s (bed, far offset)
  – Vp stack ≈ 4000m/s (englacial, far offset)
  – Vp hor ≈ 3690m/s (diffraction)

• Water content in ice? Unlikely, fast ice = cold ice
Your questions?

Thank you
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Thanks to Alun Hubbard and the SAFIRE group for giving me this opportunity.
Vrefrac = 3690 m/s
Vdirect = 3100 m/s
6-fold example of the Common Mid Point (CMP) method.

Separation between midpoints is
1/2 separation between geophone groups
Common Midpoint Method (CMP Method)

geophone groups

Shotpoint # 2

#6  #5  #4  #3  #2  #1

Midpoints
Common Midpoint Method (CMP Method)

geophone groups

Shotpoint # 3

Midpoints
Common Midpoint Method (CMP Method)

geophone groups

#6  #5  #4  #3  #2  #1

Shotpoint #4

Midpoints
Common Midpoint Method (CMP Method)

geophone groups

#6  #5  #4  #3  #2  #1

Shotpoint # 5

Midpoints
Common Midpoint Method (CMP Method)

gleophone groups

#6  #5  #4  #3  #2  #1

Shotpoint # 6

Midpoints
Common Midpoint Method (CMP Method)

geophone groups
#6 #5 #4 #3 #2 #1

Shotpoint #7

Midpoints
Common Midpoint Method (CMP Method)

g eofphone groups

Shotpoint # 8

#6  #5  #4  #3  #2  #1

Midpoints
Common Midpoint Method (CMP Method)

geophone groups

#6  #5  #4  #3  #2  #1

Shotpoint # 1

Midpoints
Common Midpoint Method (CMP Method)

geophone groups

#6  #5  #4  #3  #2  #1

Midpoints

Shotpoints #1
Shotpoints #2
Common Midpoint Method (CMP Method)

geophone groups

#6  #5  #4  #3  #2  #1

Midpoints

Shotpoint # 1
Shotpoint # 2
Shotpoint # 3

Shotpoint # 1
Shotpoint # 2
Shotpoint # 3
Common Midpoint Method (CMP Method)

geophone groups

#6  #5  #4  #3  #2  #1

Midpoints

Shotpoint # 1
Shotpoint # 2
Shotpoint # 3
Shotpoint # 4

Shotpoint # 1
Shotpoint # 2
Shotpoint # 3
Shotpoint # 4
Common Midpoint Method (CMP Method)

geophone groups

Shotpoints # 1-8
Common Midpoint Method (CMP Method)

Fold or Multiplicity is the number of times that the same midpoint is sampled by different shots and different receivers.

Signal-to-Noise increases as the square root of the fold.
Drill site, why seismics in summer sucks: