Seismic detection and study of environmental processes in the hydrosphere and cryosphere

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Environmental processes are a new science focus

Huge interest in global change - the world is 4D!
Interdisciplinary science is not passive and active seismologists working together!

Minimum Sea Ice, 1979
Minimum Sea Ice, 2005

How can seismology contribute?
Examples:  Ice streams, glaciers, icebergs
           Ocean storms
           Ocean ridge hydrothermal systems
Is seismology important for studying global change?

“Glaciers and ice sheets are the components of the natural surface environment that are expected to change the soonest in response to environmental change."

“These changes all involve mass movements that may both be monitored and investigated using seismological techniques.”

“So far, seismology is only scratching the surface of glaciology; there is likely to be a lot of opportunity to learn about ice-sheet/climate interaction through the vision of seismology...”

Doug MacAyeal, glaciologist, U Chicago

To a fool with a hammer, All the world is a nail
Seismic characterization of glacial processes

Mechanics of basal sliding:
- why low friction?
- what causes stick-slip?

Mechanics of calving:
- Ice shelf break up?
Glacial “stick-slip”: Whillans Ice Stream, Antarctica

Location

Seismic moment = $\mu DA = 3 \times 10^{19}$ N-m
(Mw ~ 7.0 earthquake)


Seismograms
- Two slips/day
- Duration ~25 min
- 1st pulse onset
- Last pulse is stopping phase

GPS data
- Two slips/day
- ~40 cm each
- Tidally triggered
- Slip area is 200 x 100 km
Whillans Ice Stream Stick-Slip

Upper figure shows slip velocity from GPS receivers on the ice Stream.

Lower figures show seismogram from South Pole (QSPA) 650 km away.

Slip initiates at the same location for every event;

Rupture origin represents an “asperity” in the bed.

Movie by Paul Winberry
GPS data from Sridhar Anandakrishnan & the TIDES project.
Waveform modeling of slip onset

Method:

- Assume double couple @ 1 km depth
- Compute synthetics with reflectivity algorithm, regional structure [Lawrence et al., 2006]

Results:

- Amplitudes well fit by fault shallowly dipping down the ice stream
- If extended out ~ 20 minutes gives expected seismic moment (Mw 7.0) within an order of magnitude
- Exact shape, seismic moment highly non-unique due to band-limited signal
- Later two arrivals more complex, presumably due to interference from stopping phases from different regions

Greenland Glacial Earthquakes – large calving events?

Northern Hemisphere
Long-Period Glacial Sources
Ekstrom et al., [2006]

- Located where outlet glaciers meet the coast
- Have sources with ~ 50-100 s duration
- Consistent with motion in the direction of ice movement
- Recent results show events simultaneous with iceberg calving at the seacoast
- Motion limited to near the calving front

Mechanical calving model for glacial earthquakes
Tsai et al., 2008
Calving of Greenland Outlet Glaciers (Jakobshavn)

Movie by J. Amundson
25 times actual speed
Seismogram converted to audio
Iceberg Harmonic Tremor

Map of icebergs and seismic deployment

- Very large icebergs located near McMurdo
- Harmonic tremor detected at land stations
- Seismographs installed on berg C16
- Source localized to a collision zone
- Tremor well recorded by stations on iceberg

Typical tremor record

strange “aseismic eye”

MacAyeal et al., 2008
The mechanism of iceberg tremor

Tremor Details

- Tremor caused by "stick-slip" between icebergs
- Made up of many small slips
- Interslip time varies with velocity, giving various harmonics
- Tides cause the berg to stop and reverse direction
- "Aseismic Eye" corresponds to the stopping time

Iceberg Motion

MacAyeal et al., 2008
The Goal: Understanding the mechanics of ice shelf collapse

Richard Alley: the worst case scenarios of sea level rise in the next 100 years are associated with ice-shelf collapse.
Major glaciological questions that seismology should help solve – Doug MacAyeal

• Ice stream flow mechanisms:
  what causes speed up and slow down
  do ice streams (other than Whillans) show stick-slip?
  what controls stick-slip behavior?

• What is the mechanism of Greenland “glacial earthquakes”?
  How are they related to calving events?
  What can they tell us about calving?
  Can these events be used as a proxy for glacier discharge?

• What can seismology tell us about collapsing ice shelves?
  What are the enabling conditions for ice shelf collapse?
  Are there seismic precursors to ice shelf collapse?

• What are the hydrological conditions beneath ice sheets?
  ephemeral lakes and streams exist beneath ice sheets
  what types of seismic signals are associated with meltwater transport?
Simultaneous deployment of broadband seismic stations around Antarctica during the International Polar Year (IPY)

Total number of stations deployed during IPY is on the order of 100

Initial sites deployed during 2007-2008

Some stations have co-located GPS and weather instruments

Year-around operation of seismic stations throughout Antarctica for the first time

Polenet seismic stations deployed during IPY; not all coastal stations are shown
Polar Seismic Instrumentation
developed by IRIS-Passcal Instrument Center

- Sensor: Trillium 240 or Guralp 3T - operates to -55C
- Datalogger: Quanterra Q330 with solid state recording
  operates to -45C
- Power source is solar panels (summer) and primary lithium
  batteries (winter)
- Total power required ~ 2 Watts
- Datalogger, batteries, and sensor enclosed in buried insulated
  vaults to maintain temperature 15-20 C above ambient

Needed: improvements in portability, data return
Seismic “Noise” and Oceanic Storms

Beamformed Seismic Data

Significant Wave Height (Topex-Poseidon)

Winter

Summer

Rhie and Romanowicz, Nature, 2004
Grid search for source locations, maximizing stack Amplitudes at F-NET, BDSN and 10 stations in Europe

Time interval: 6 hours on 2000.031

Rhie and Romanowicz 2006
Seismic studies of ridge hydrothermal vents

- Mid ocean ridge hydrothermal systems contain entire ecosystems
- Vitally important for planetary evolution and perhaps origin of life
- Yet very little is known about these systems
- Much of what is known comes from OBS studies

Photo by D. Kelley
Hydrothermal flow patterns from microseismicity

Previously thought that recharge happened off-ridge
- Microseismicity at 1-1.5 km depth is due to thermal cracking
- Pattern of microseismicity shows recharge occurs from downwellings elsewhere along the strike of the ridge

Needed: Investments in ocean bottom seismology

Ocean Seismic Network – 1990’s plan

Needed: a feasible plan for long-term seismographs in the oceans

Current OBS pool

Needed: more OBSs, increased reliability, buried OBSs
Conclusions

• Seismology is highly important for a variety of “environmental change” problems
• Examples:
  Ice streams
  Icebergs and ice shelves
  ocean storms
  ridge hydrothermal systems
• Seismic sensors should be a part of multidisciplinary environmental sensor networks
• Further progress requires additional investments in instrumentation for the polar regions and oceans
Post-Glacial Rebound Dependence on Mantle Viscosity

Low viscosity: short-term memory - Holocene

High Viscosity: LGM
Peak rates ~ 9-10 mm/yr

Seismic Tomography suggests strong lateral variations

Ivins & James 2005

Danesi & Morelli 2001
Seismological Constraints on Mantle Temperature and Viscosity Structure

Seismic Velocity

Inferred Temperature Profile

Inferred Temperature

Shapiro and Ritzwoller [2004]
Modeling seismic wave generation

Single Force

- Ice Stream
- Bed
- Slip initiation: Horizontal Force opposite motion
- Slip termination: Horizontal Force in direction of motion

Ice Stream is external to the Earth; exerts force on Earth’s surface

Double Couple

- Ice Stream
- Bed
- Ice Stream is part of the elastic earth; model as a dislocation in an elastic medium