The Ubiquity of Seismology

Unexpected Science: New Approaches to Using Continuous Array Data

Focusing on Recent Discoveries From the Cryosphere Volcanoes and Rivers

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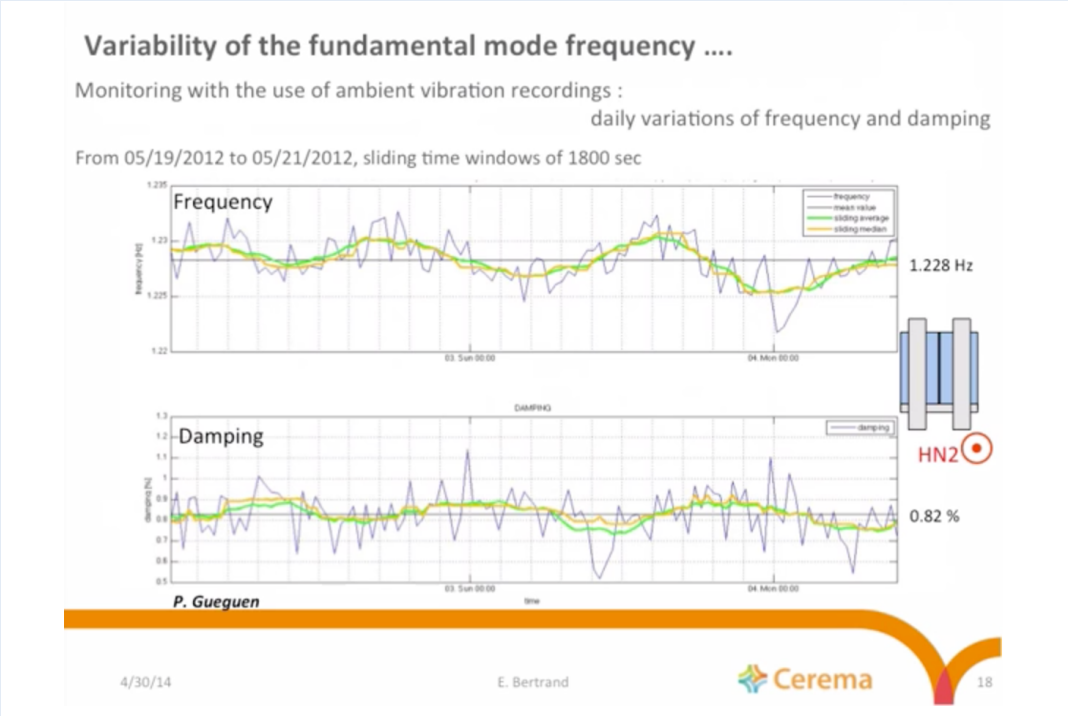
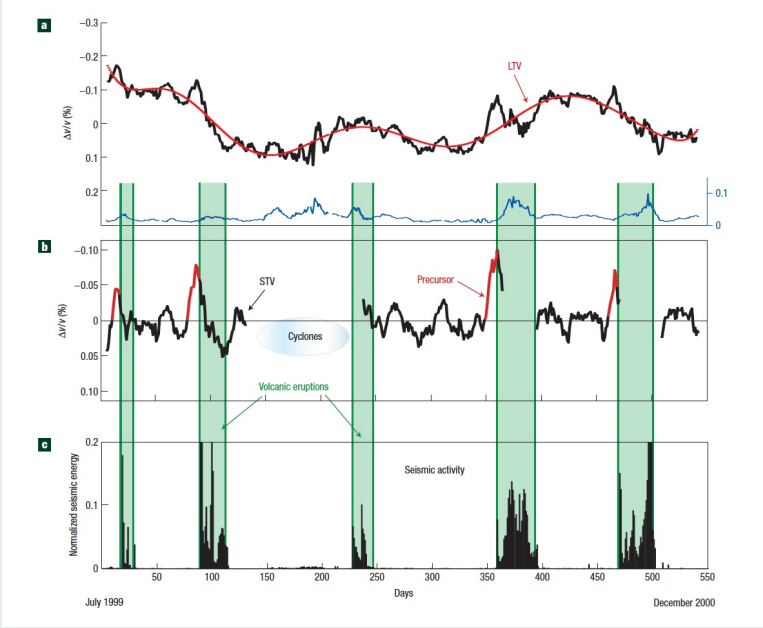
Special thanks to: Doug MacAyeal, Emile Okal, Rob Anthony, Hunter Knox, Julien Chaput, Seelye Martin, Kelly Brunt, Jeremy Bassis, Doug Wiens, Paul Winberry, Peter Bromirski, Andy Nyblade

The Ubiquity of Seismology

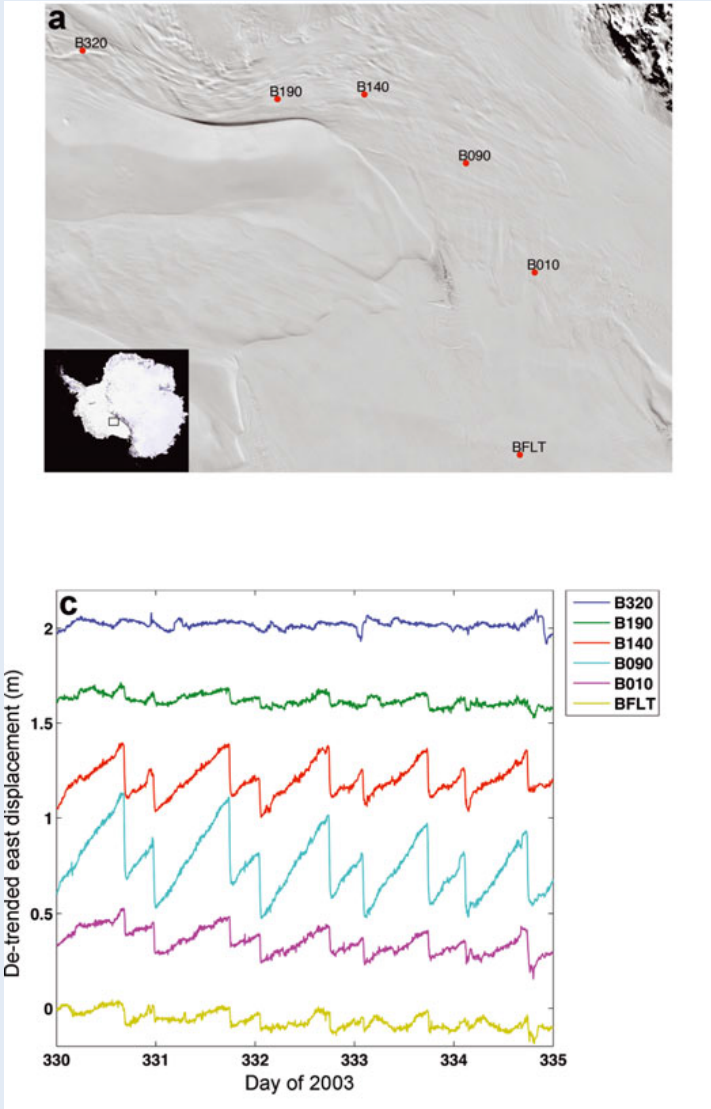
- The oceans, atmosphere, tectosphere, cryosphere, biosphere, and the civil structural environment are awash with elastic and gravity waves.
- Continuous data facilitates the discovery and understanding of source processes, structure, and interconnected processes on a tremendous range of scales and applications.



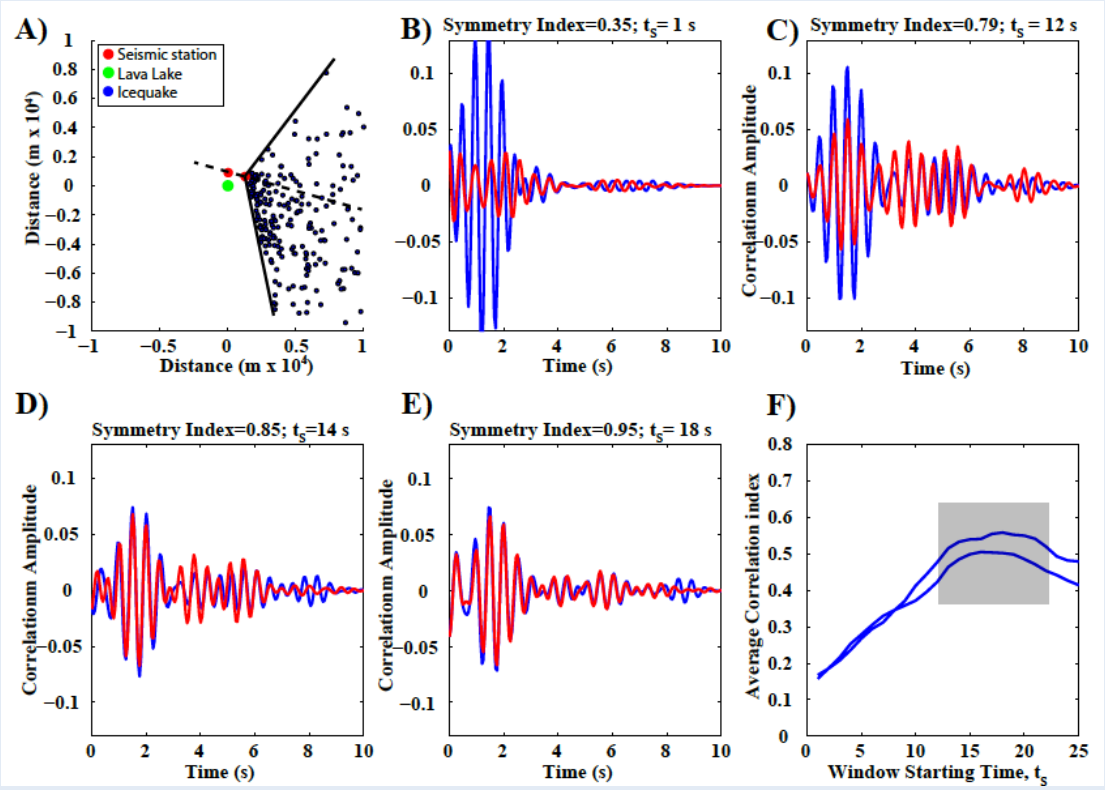
Time varying elastic/ anelastic response of a 19-storey building using ambient noise correlation (Bertrand, 2014).



Time varying elastic/ anelastic response of an active (Piton de la Fournaise) volcano (Brenguier et al., 2008). Eruptive indicated by green rectangles.

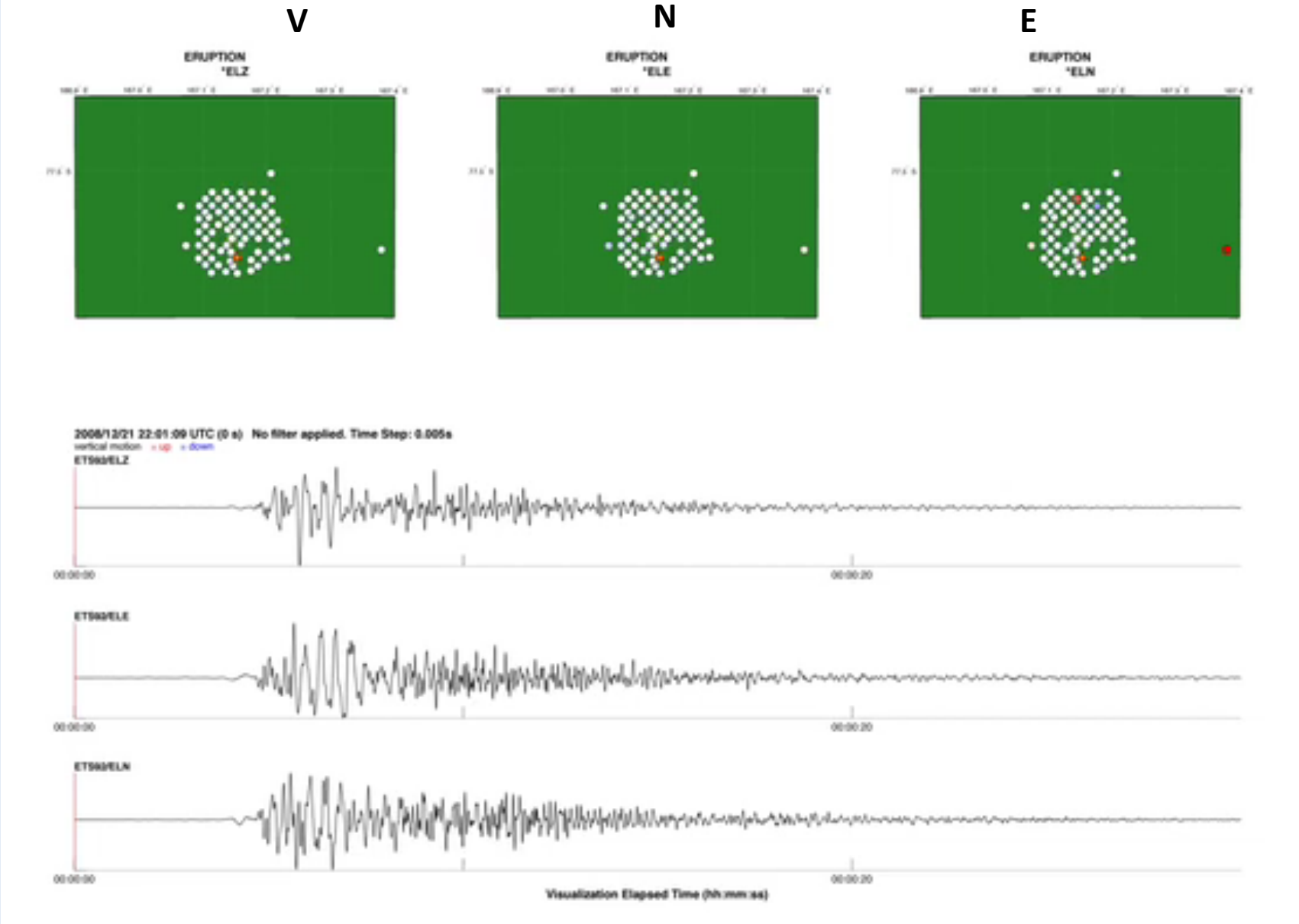


Tidally modulated slow slip (geodetically and long-period seismic) events on the Whillans Ice Stream, West Antarctica (Sergienko et al., 2009; Wiens et al., 2008).

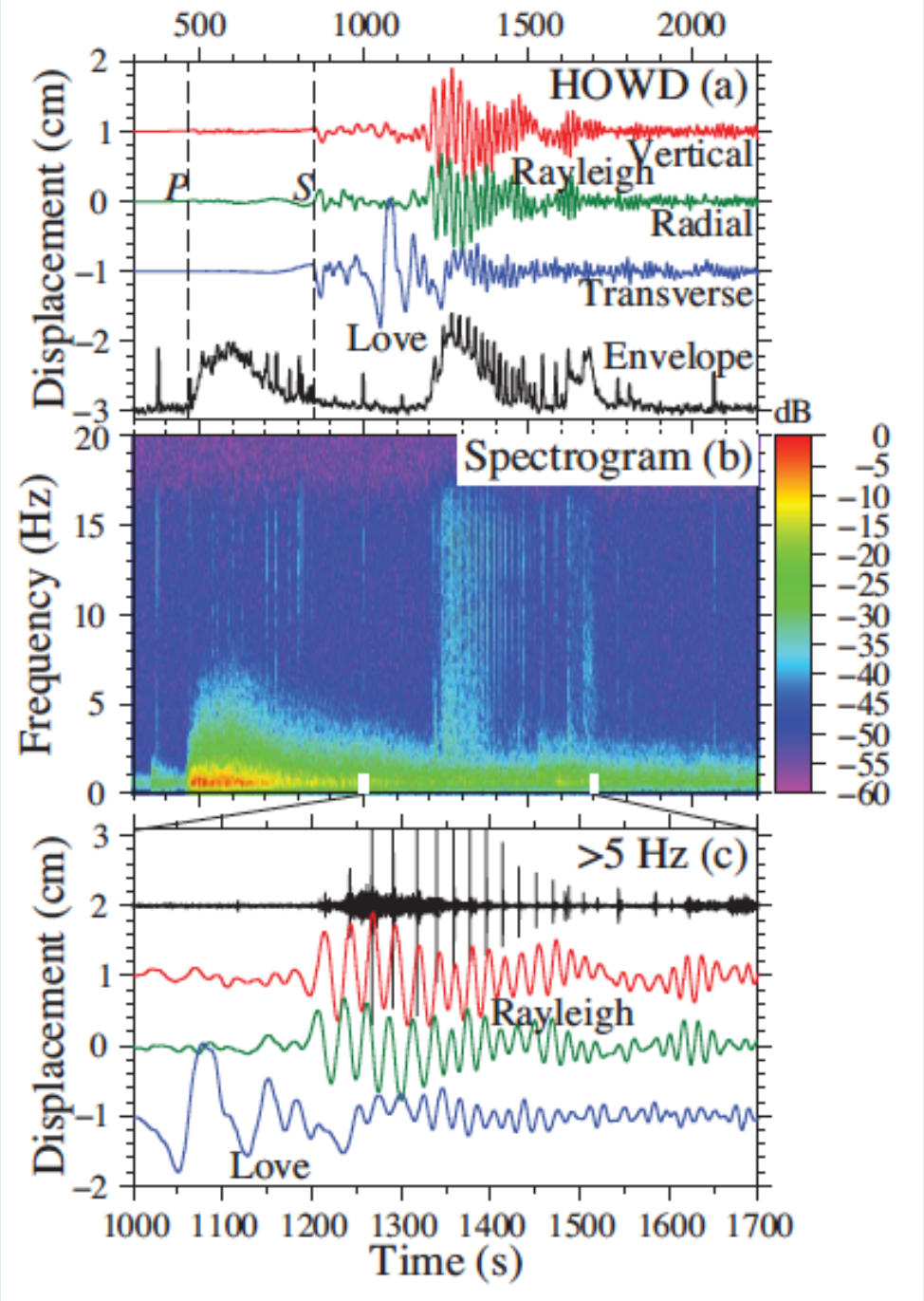


Correlograms recovered from coda waves produced by atmospherically-forced (temperature-driven) shallow icequakes, Mount Erebus, Antarctica (Chaput et al., 2014).

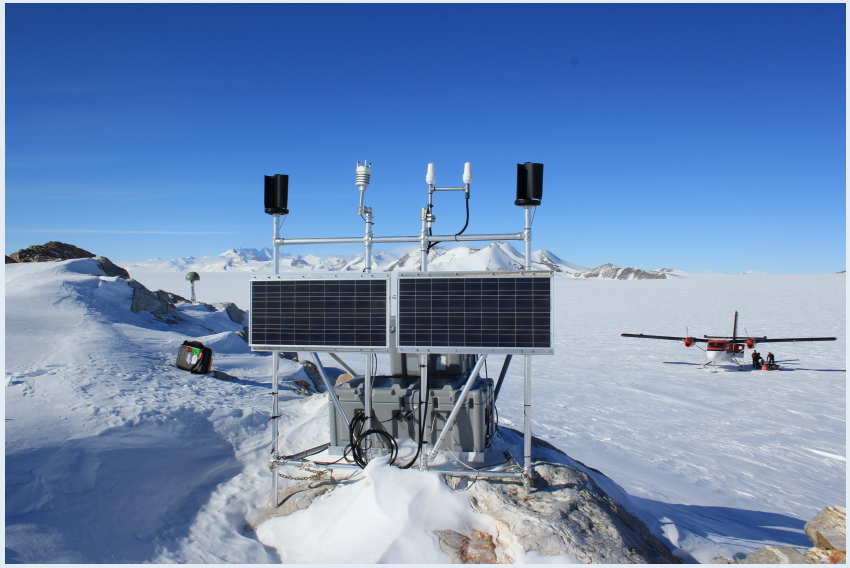
An Eruption Wavefield Viewed in Three Components



Nicole McMahon

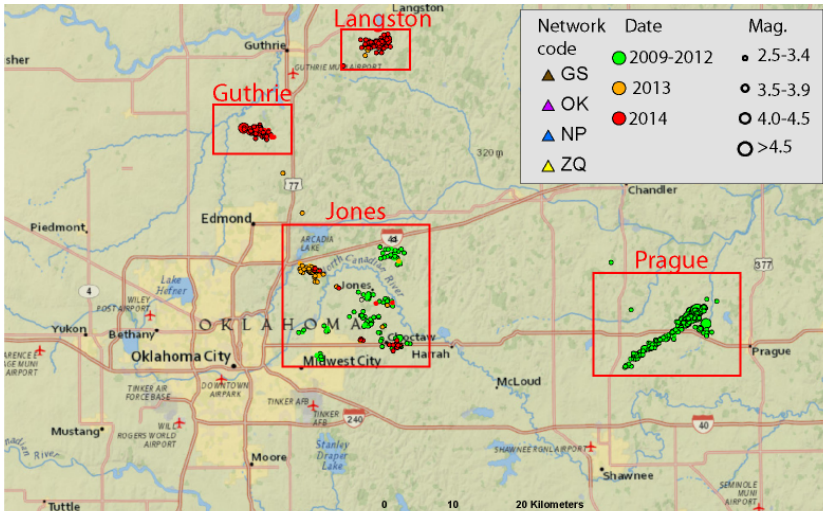


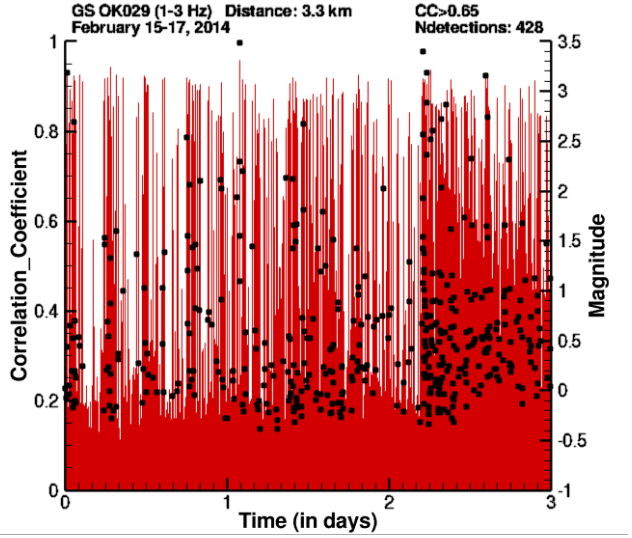
Icequakes triggered in the Antarctic ice sheet by Rayleigh waves from the Maule earthquake (Peng et al., 2014).

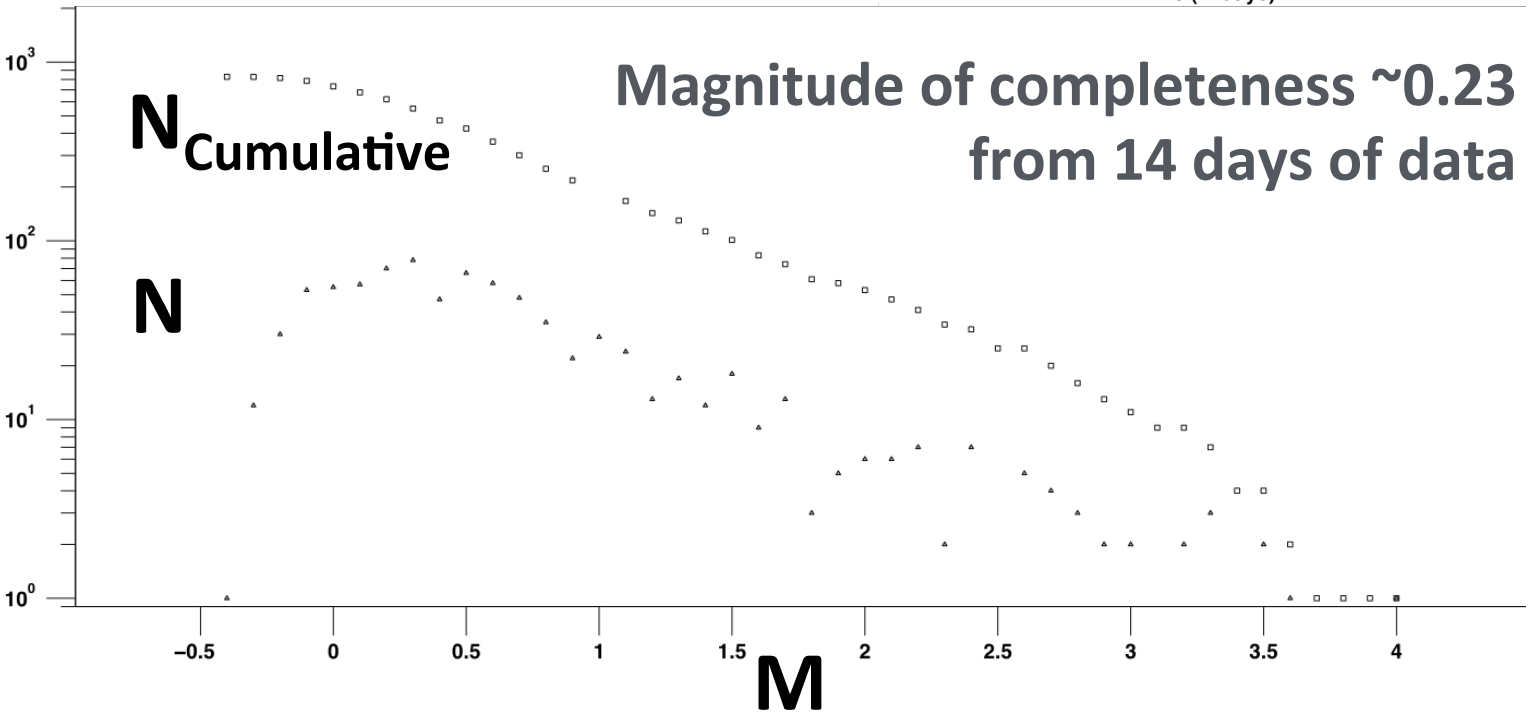


Howard Nunatak; Polenet.org

Anthropogenic earthquakes. Guthrie OK swarm; matched filtering detections from a single station calculated at NEIC (c/o Harley Benz)







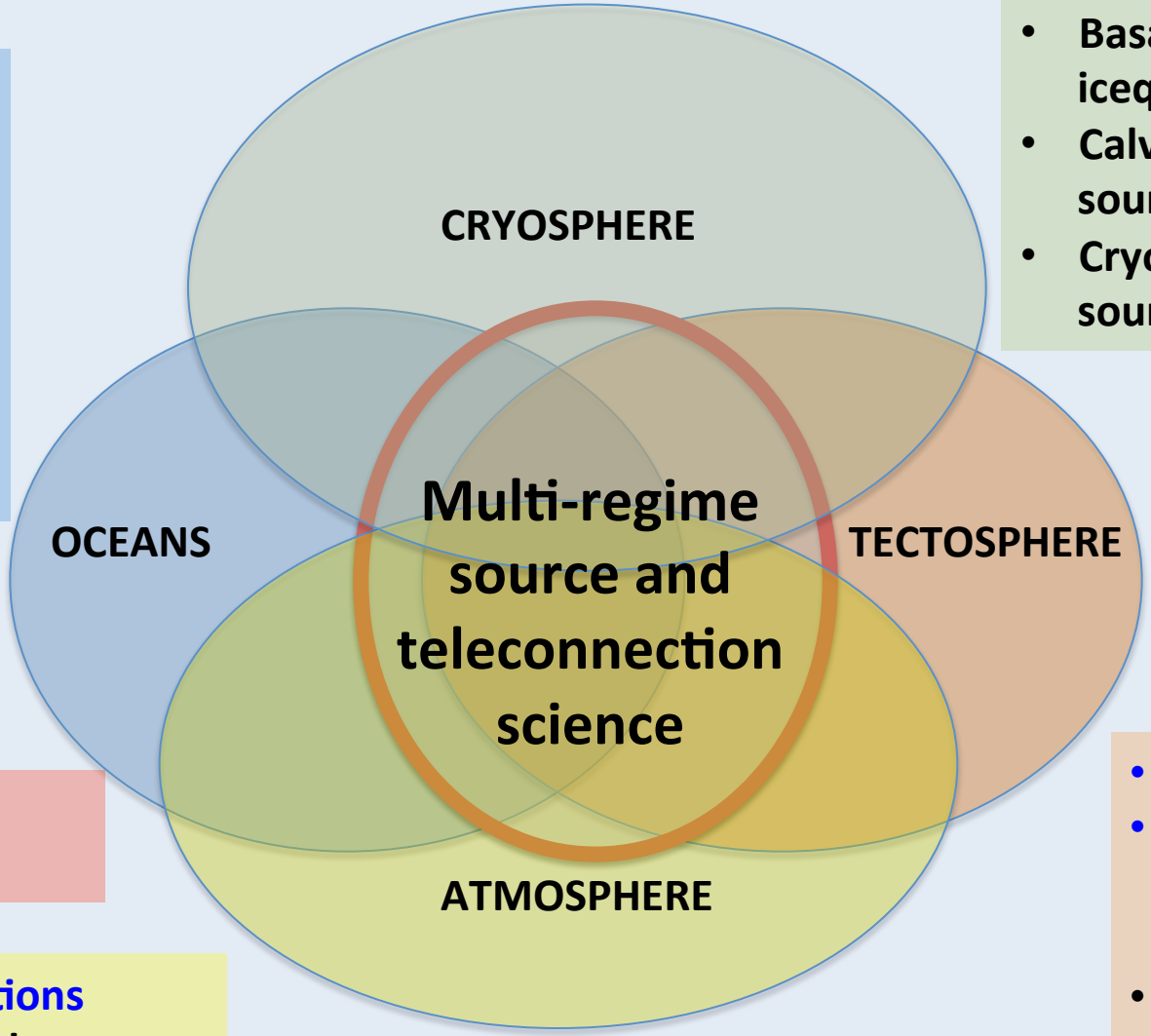
Other recent cryosphere-tectosphere-ocean examples of teleconnected processes affecting the cryosphere:

- Transoceanic destabilization of calving fronts and generation of megaicegergs by tsunamis (e.g., Brunt et al., 2011).
- Smooth tidal modulation of ice shelf flow (e.g., Brunt et al., 2010).
- Repeating and chaotic transitions in seismogenic glacial slip patches (P. Winberry, this meeting).

Global continuous seismic data facilitated the recognition and study of a huge range of natural elastic and gravity wave sources, propagation, and linkage phenomena

- Microseism sources.
- Hum sources.
- Gravity (surface and internal) wave sources.
- Tidal sources.

- Basal and internal icequakes
- Calving/iceberg sources/dynamics
- Cryohydrological sources



Anthropogenic forcings

- Volcanic eruptions
- Meteorological sources
- Bolides
- Atmospheric Gravity waves

Within the civil (built) environment too! (e.g., Building seismology)

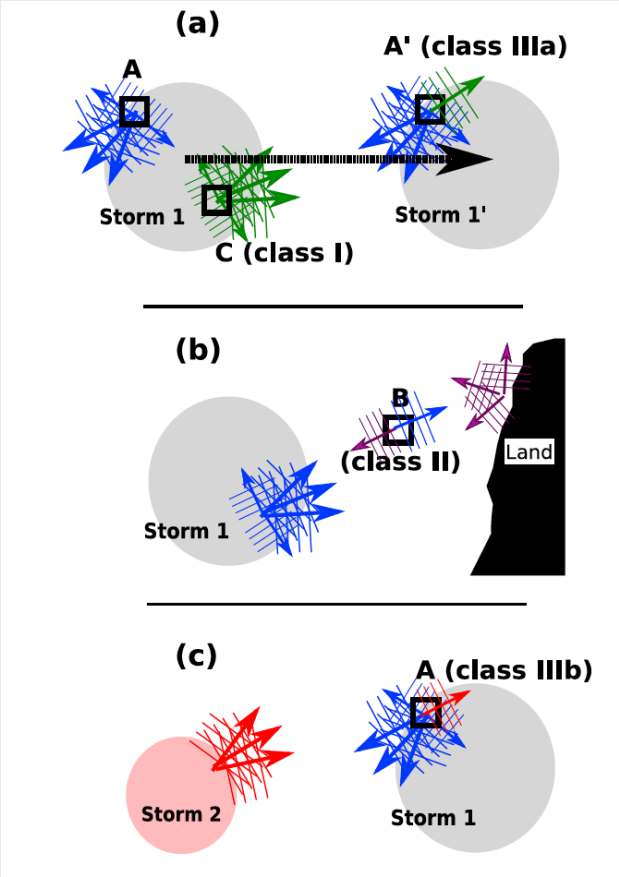
- Earthquakes
- Internal volcanic sources
- Tectonic tremor
- Fluvial seismology

Many of these phenomena occupy a continuum between "transient" and "continuous" signals

- **Examples include**
  - The microseism background punctuated by hour/day/season-long wave events.
  - Small tectonic, volcanic, or cryospheric events that can sometimes be discriminated with highly specific matched filtering or close-in recording.
  - Long-duration events with some internal stationarity and subject to envelope and other types of moving-window analysis (e.g., eruptions, pipeline explosions, tectonic and volcanic tremor, singing icebergs, …).

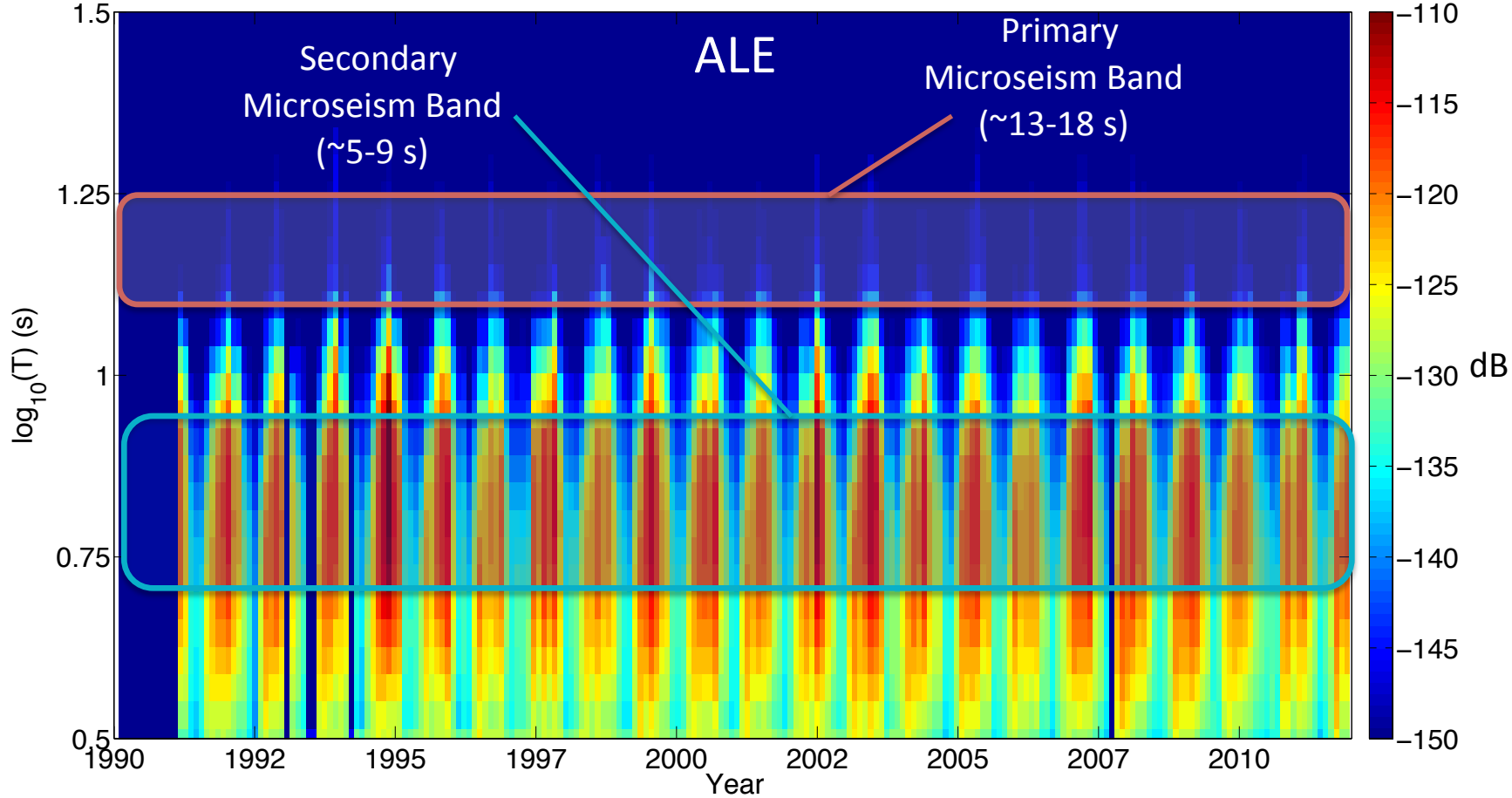
The Global Microseism

- Primarily (but not exclusively) Rayleigh waves generated by wave-coast (primary) and wave-wave (standing-wave; secondary) interactions.
- Microseism intensity can function as an integrative"storminess metric" that is sensitive to storm intensity and wind patterns, storm tracks, sea ice, (up to multidecadal) climate oscillations, …



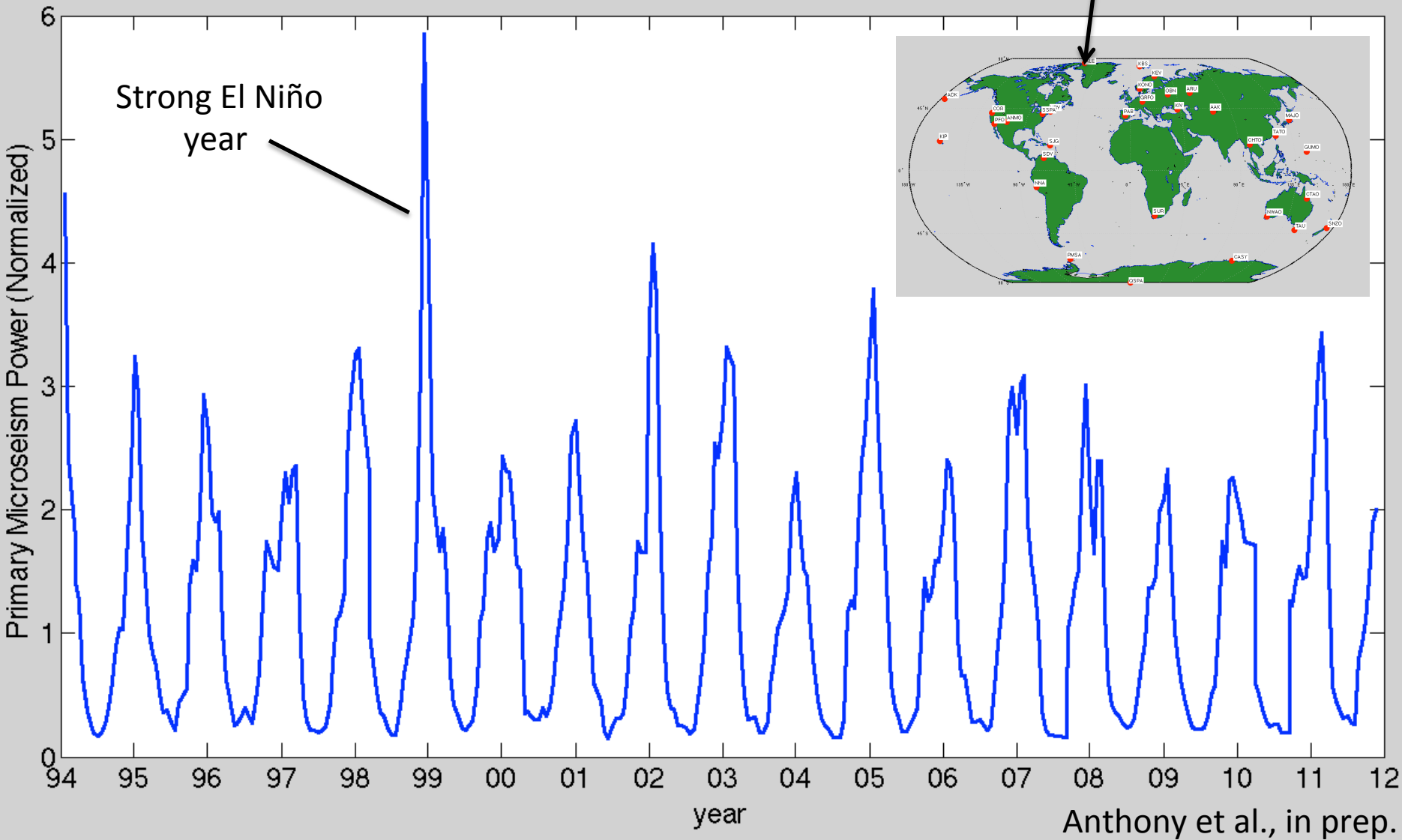
Secondary microseism source scenarios: Intra-storm (a); coastal reflection (b); interstorm microseism generating mechanisms (Ardhuin et al., 2011).

Analysis via Deciyear PSDs



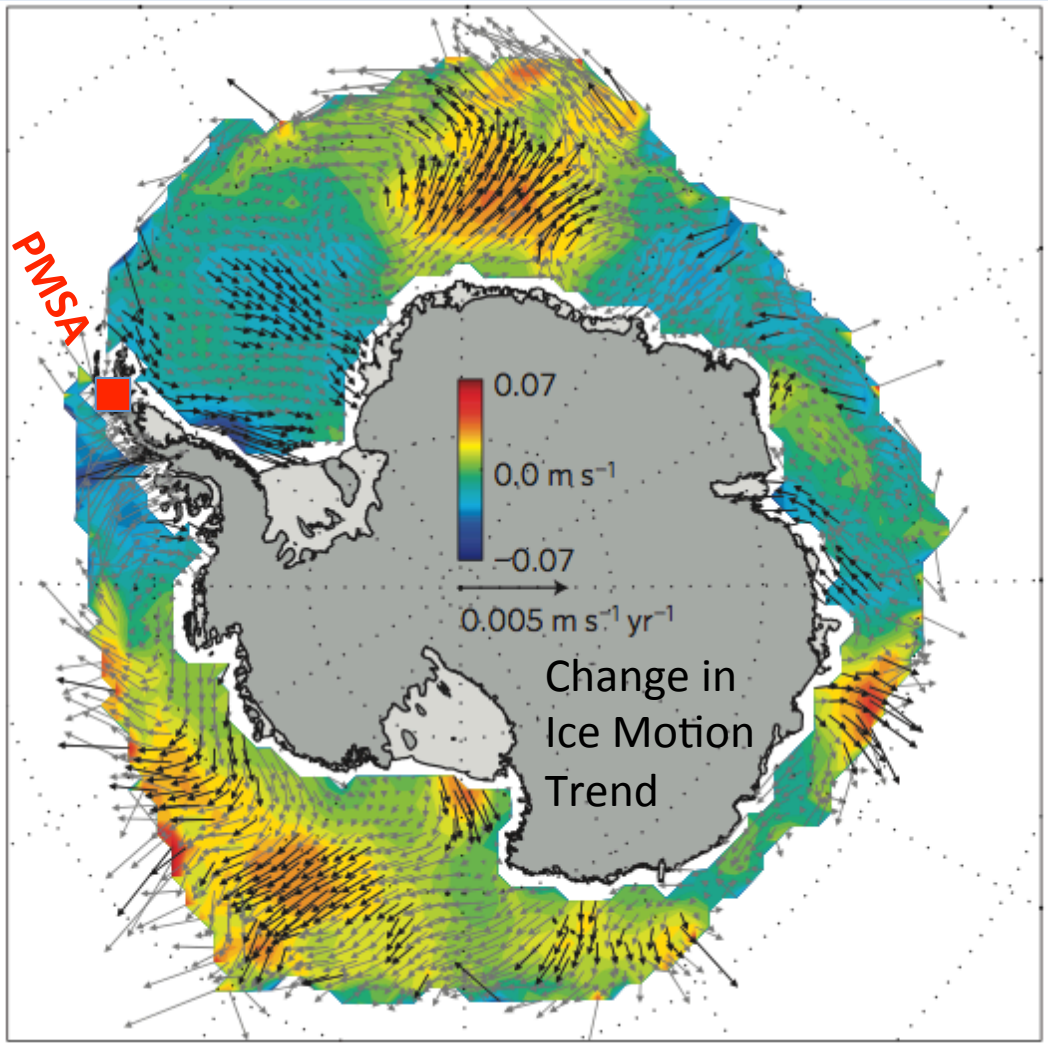
Anthony et al., in prep.

Primary Microseism Integrated Power Time Series



Anthony et al., in prep.

Changes in Sea Ice Concentration



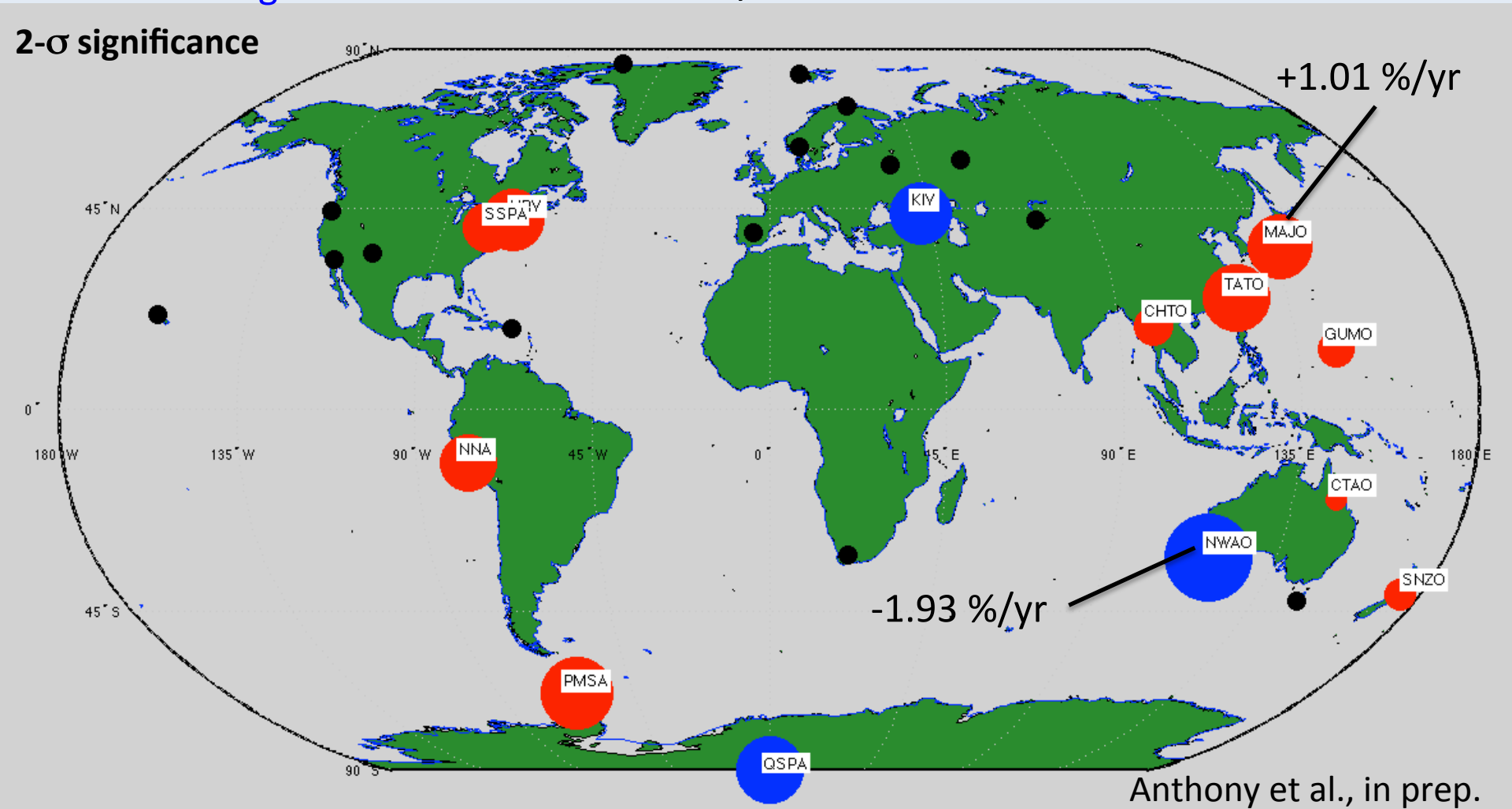
Holland and Kwok, 2012

- Over the past 2 decades the Southern Annular Mode has moved into a strongly positive phase (decreased pressure over Antarctica)
  - -> Deepens the Circumpolar Trough
  - -> Strengthens the circumpolar westerlies
  - -> Warming of the Antarctic Peninsula through "Santa Anna-style" wind regimes
  - => Reduced sea ice off of the Peninsula

Anthony et al., in prep.

Global Primary Microseism Power Trends for 1994-2013

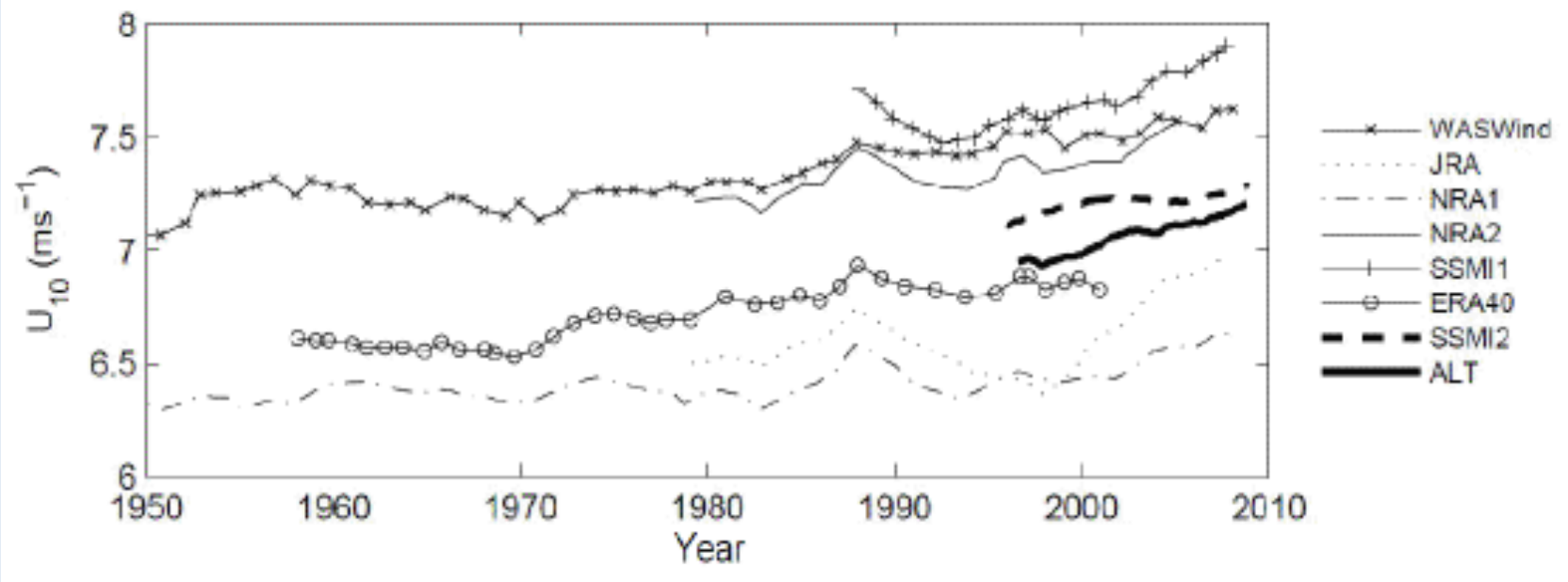
Decreasing Stations: 3 Stationary Stations: 15 Increasing Stations: 10



Anthony et al., in prep.

Changes in Global Winds/Waves

- Recent reanalysis of diverse meterological datasets suggests average global wind speeds have increased over the past 50-60 years by 0.06-0.20 ms^{-1} $decade^{-1}$.
- Since meteorological waves are generated through ocean-wind interactions, this trend could impact global wave state and could be visible in multidecadal microseism records (e.g. Aster et al., 2008).
- Changes in global wave state has implications for:
  - Coastal Erosion and Flooding
  - Near Coastal Engineering
  - Shipping Routes
  - Cryosphere (sea ice and shelf) Stability
  - Evaporation Rates
  - Global Climate



Tokinaga and Xie, 2011; Young et al., 2011

Examples of Recurring Transient Events, Sometimes Merging into Tremor

This class of seismic events is associated with repeating or distributed processes incorporating very large numbers of subevents

- Tectonic
- Volcanic
- Cryospheric
- Fluvial
- Anthropogenic (e.g., Geoff Abers' talk yesterday).

Surprises from the Cryosphere

The availability of high-quality seismic data from Antarctica, Greenland, and a some other heavily glaciated areas (e.g., Alaska) has advanced (very) significantly in the past decade.

- As a result, wholly new types of seismic sources and detections have been identified, including:
  - calving seismicity at large (Greenland, Antarctica, Alaska) scales
  - tidally coupled and other repeating/quasi-repeating glacierquakes
  - teleseisically triggered icequakes
  - iceberg seismicity and tremor
  - Ocean wave signals (for ice-sited floating seismographs).

Mount Erebus, Antarctica; 5/28/02

High-amplitude tremor

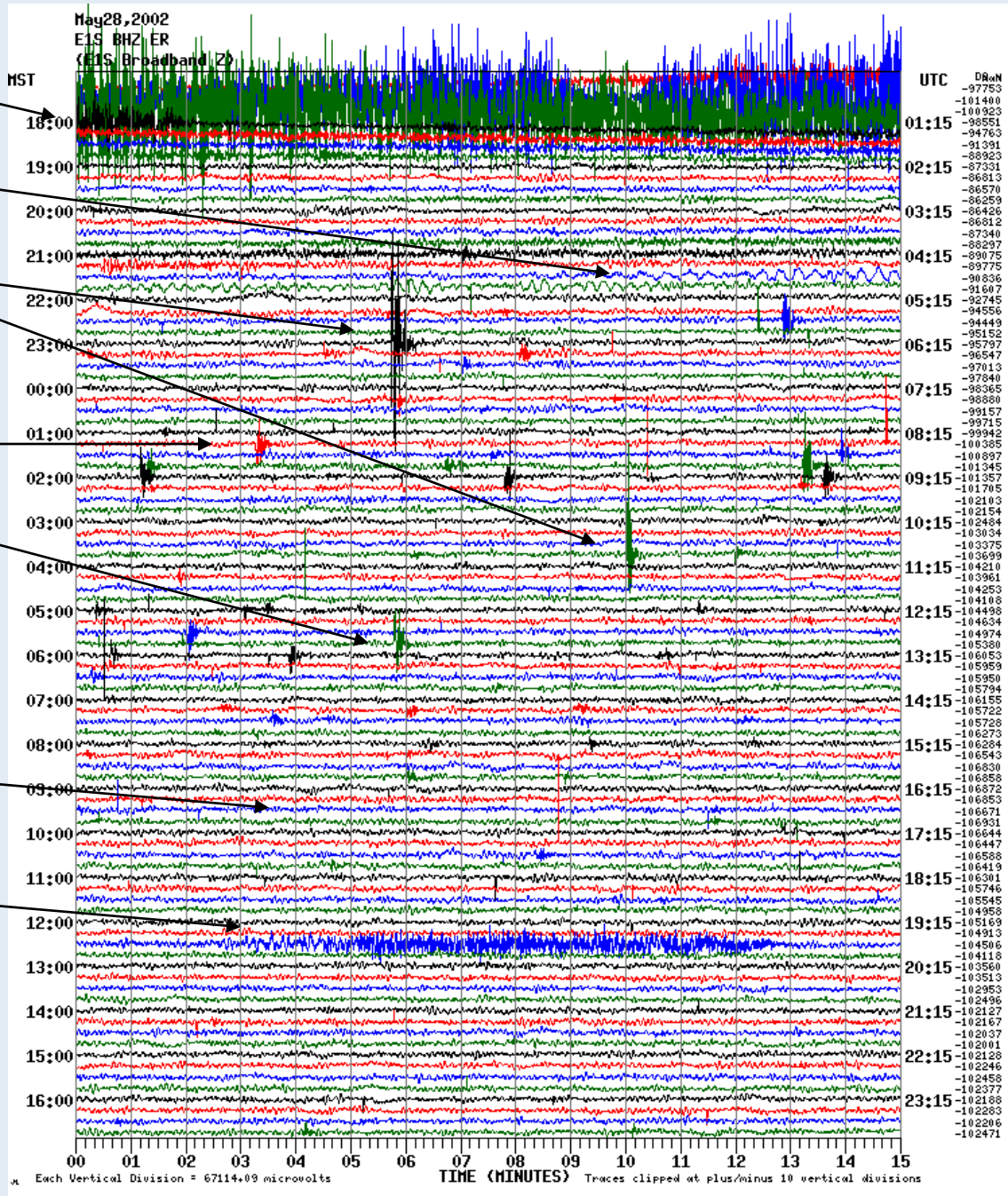
Teleseismic surface waves (Argentina, 6.0)

Strombolian explosions

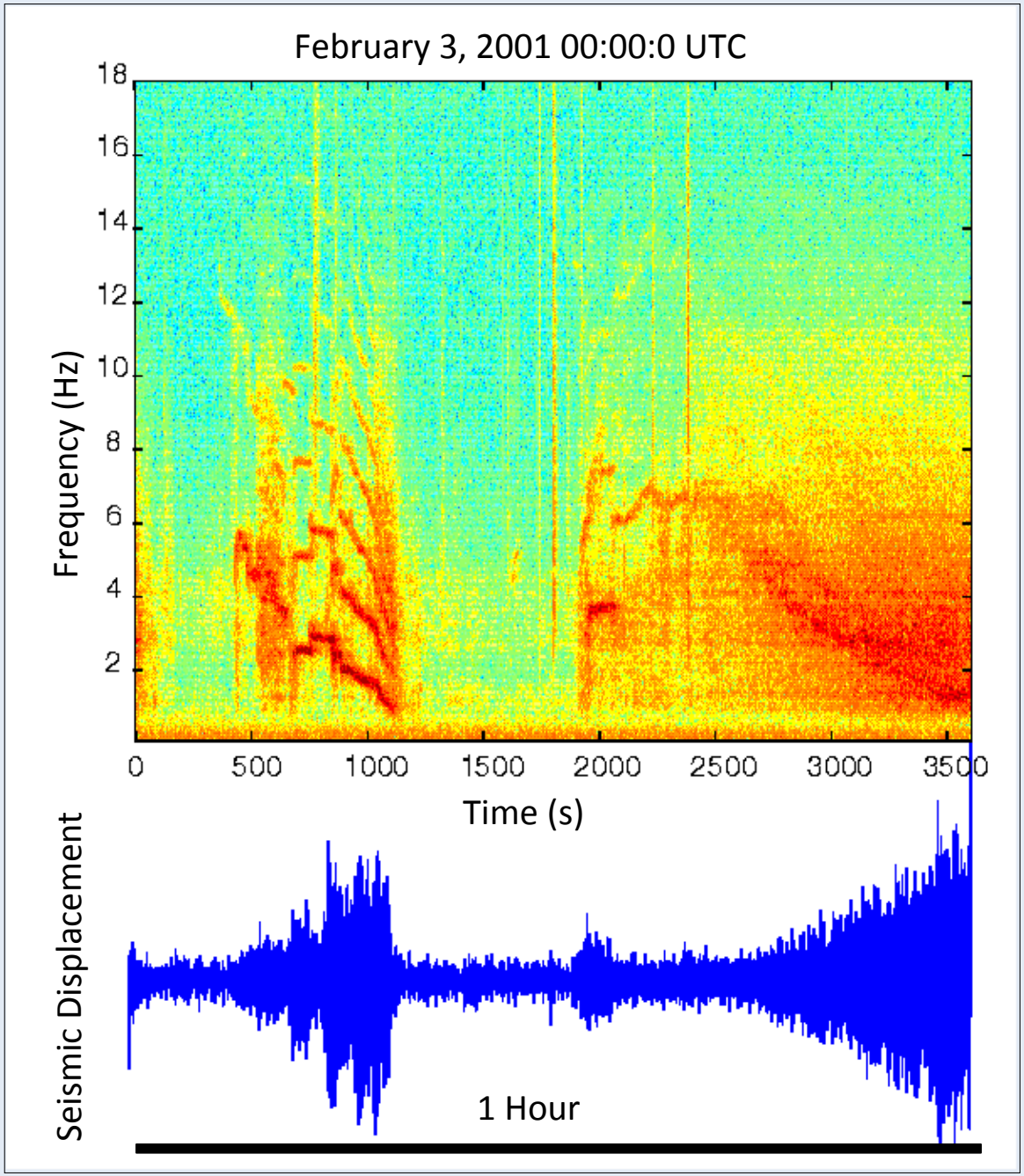
Icequakes

Oceanic microseism

Lower-amplitude tremor



Tremor in this case is non-volcanic…

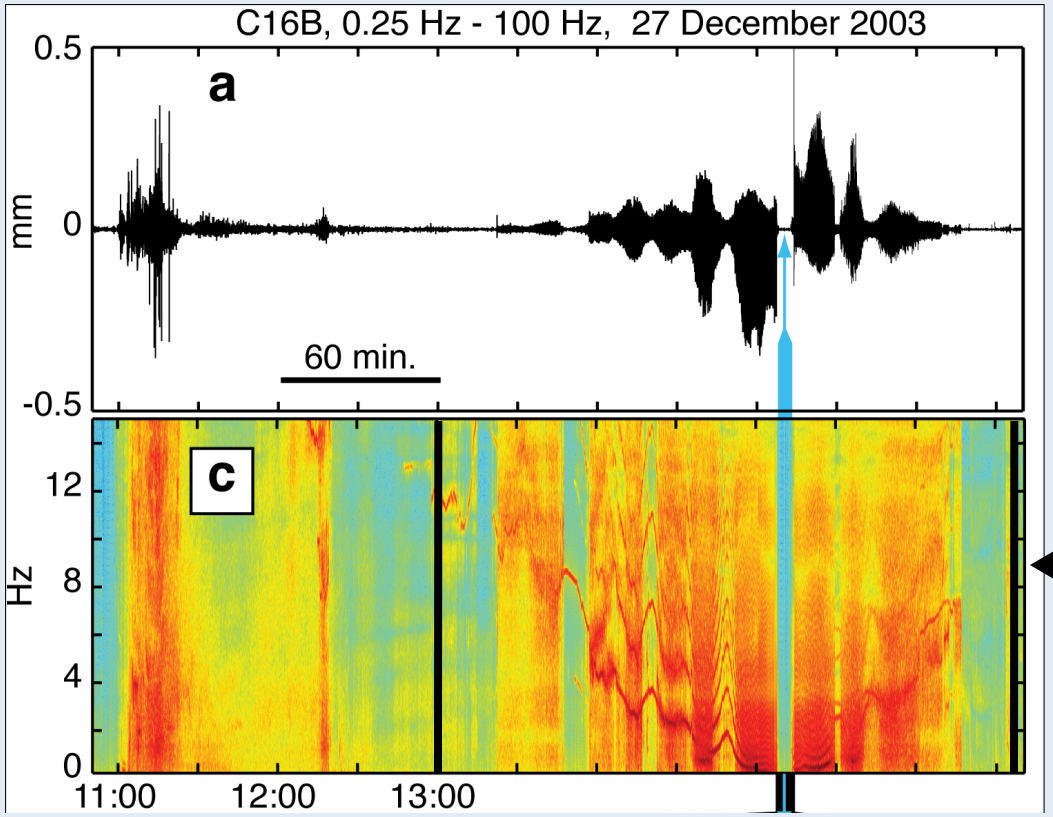


A complex tremor episode recorded on Mount Erebus (vertical ground motion).

Despite superficial similarities to volcanic tremor, it was soon determined that these signals were *not* being generated by the volcano.

100 x speed

Aster et al, 2004



"Reversing" events, as well as near-source observations were essential in determining the iceberg tremor mechanism.

200 x speed

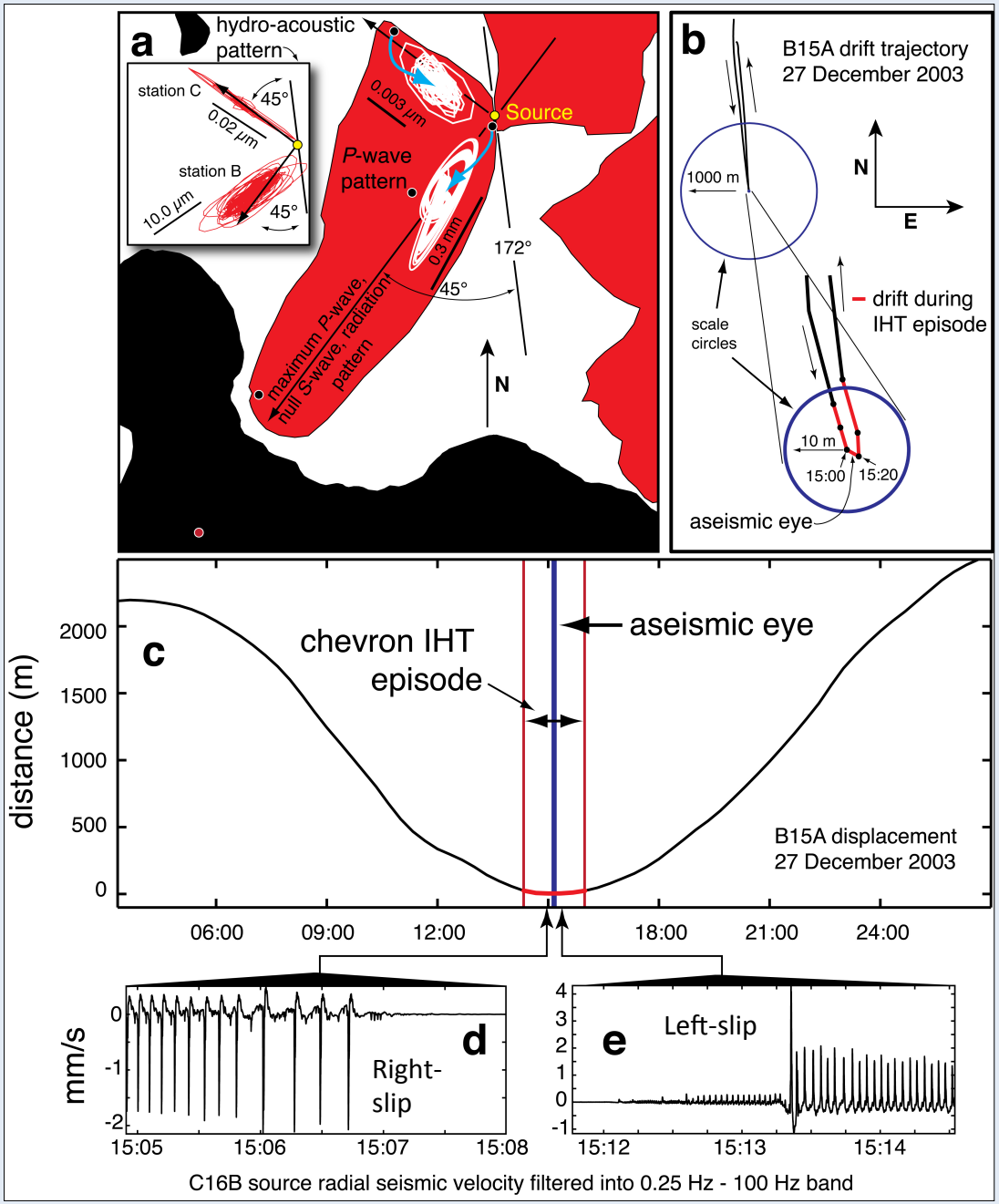
Tremor observed very close to the source from iceberg-deployed seismographs is revealed to consist of long sequences of impulses occurring at the tremor fundamental frequency.

$$\mathbf{F}[r\text{III}(rt)] = \text{III}(f/r), \text{ where}$$

$$\text{III}(rt) = \sum_n \delta(rt-n)$$

(the "Dirac Comb")

After MacAyeal, Okal, Aster, Basis, 2008



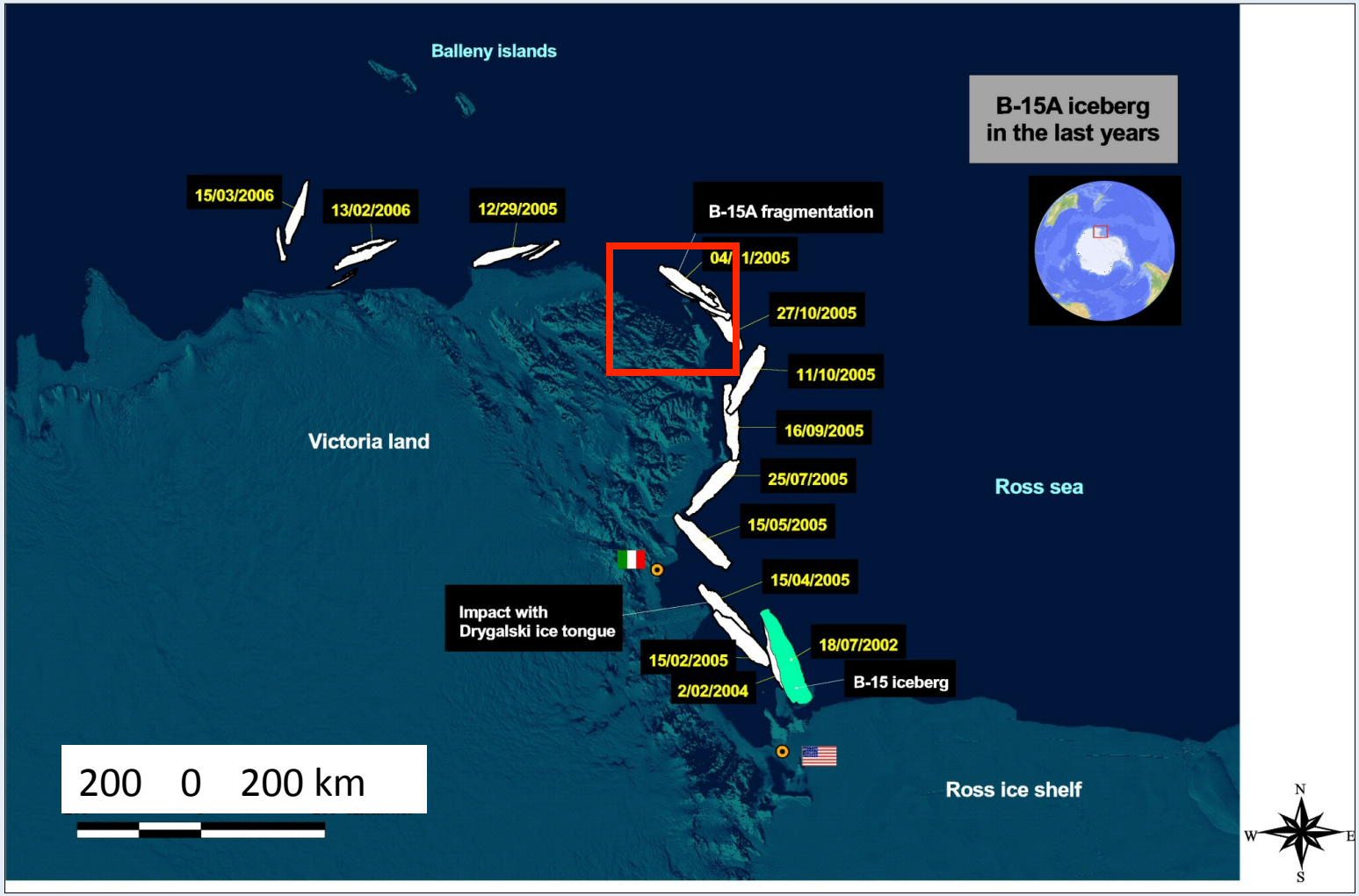
MacAyeal et al., 2008

Our studies have revealed that the tremor arises from tens of thousands of repeating icequake subevents per hour radiating seismoacoustic energy into both the iceberg and ocean.

- When B15A motion reverses; icequakes reverse polarity observed at station B.
- Seismic radiation pattern of P and S waves confirms that the subevents are strike-slip icequakes.

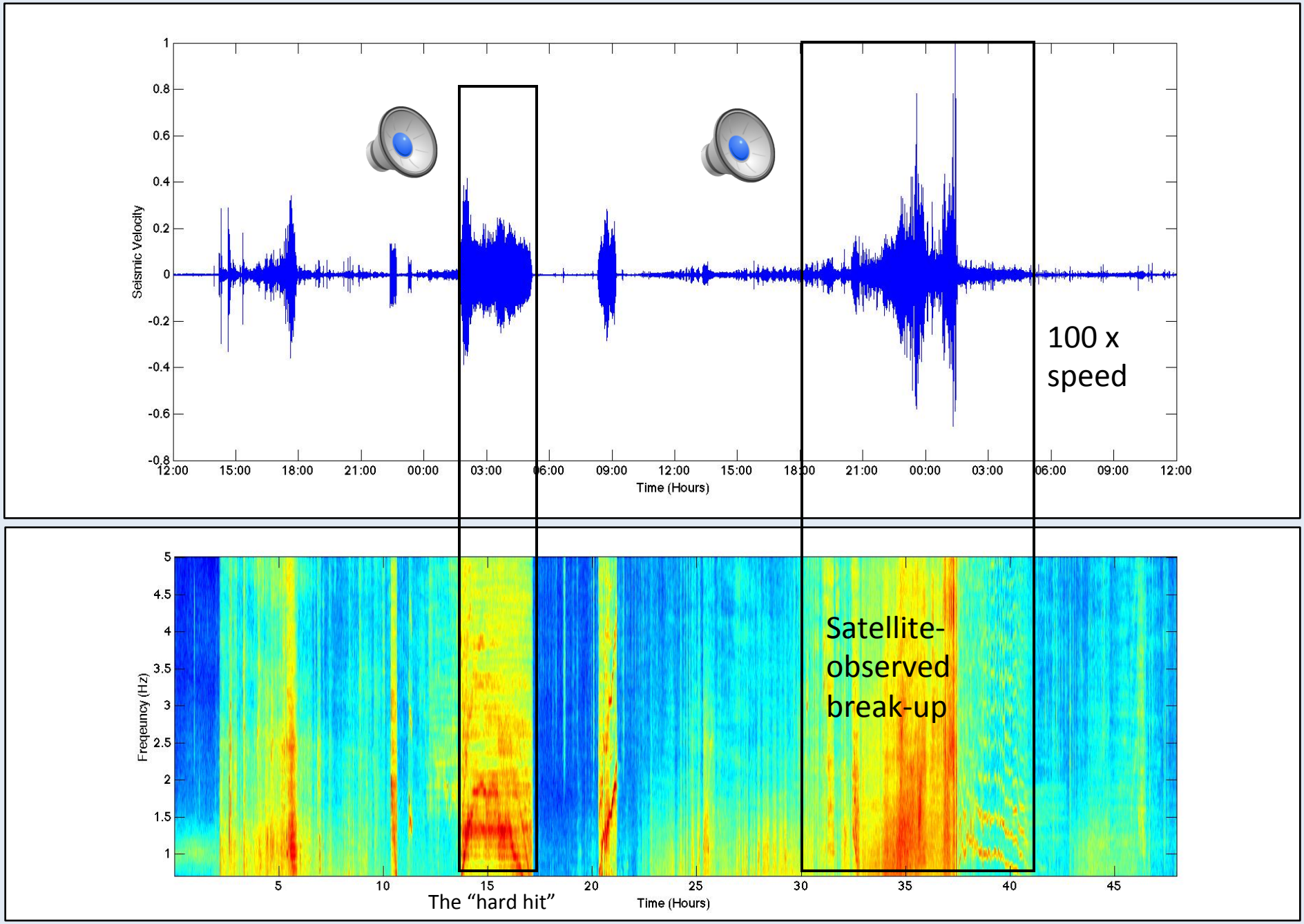
The Travels (and Travails) of B15A - Seismic signature of the breakup of Earth's largest iceberg.

- After splitting off B15B, B15J, and B15K, B15A finally left the Ross Island area in November of 2004, traveling over 700 km before its IRIS PASSCAL instrumentation was recovered.
- On October 27, 2005, B15A shattered off Cape Adare, Victoria Land.



Martin et al., in prep

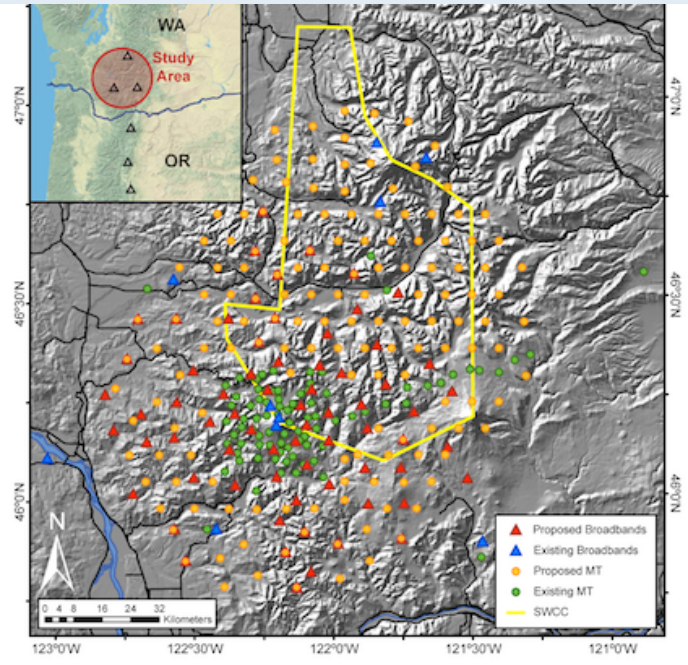
B15A Seismograms/Spectrograms During Break-up (48-hours)



Under the Volcano

- Volcanoes are still remarkably under-instrumented , and large eruptions are infrequent, but the is momentum building in the community to collect and analyze increasingly ambitious seismic data sets (e.g., iMush project, starting just after this workshop).
- We need more seismographs on volcanoes, and wider distribution of key data sets. Where unusually dense deployments exist (e.g. La Reunion, Erebus) new methodologies such as ambient and coda correlation imaging/ interferometry are being successfully implemented.

Anchorage pre-SSA volcano seismology workshop, April, 2014



iMush (Imaging Magma under Saint Helens; imush.org) proposed deployment.

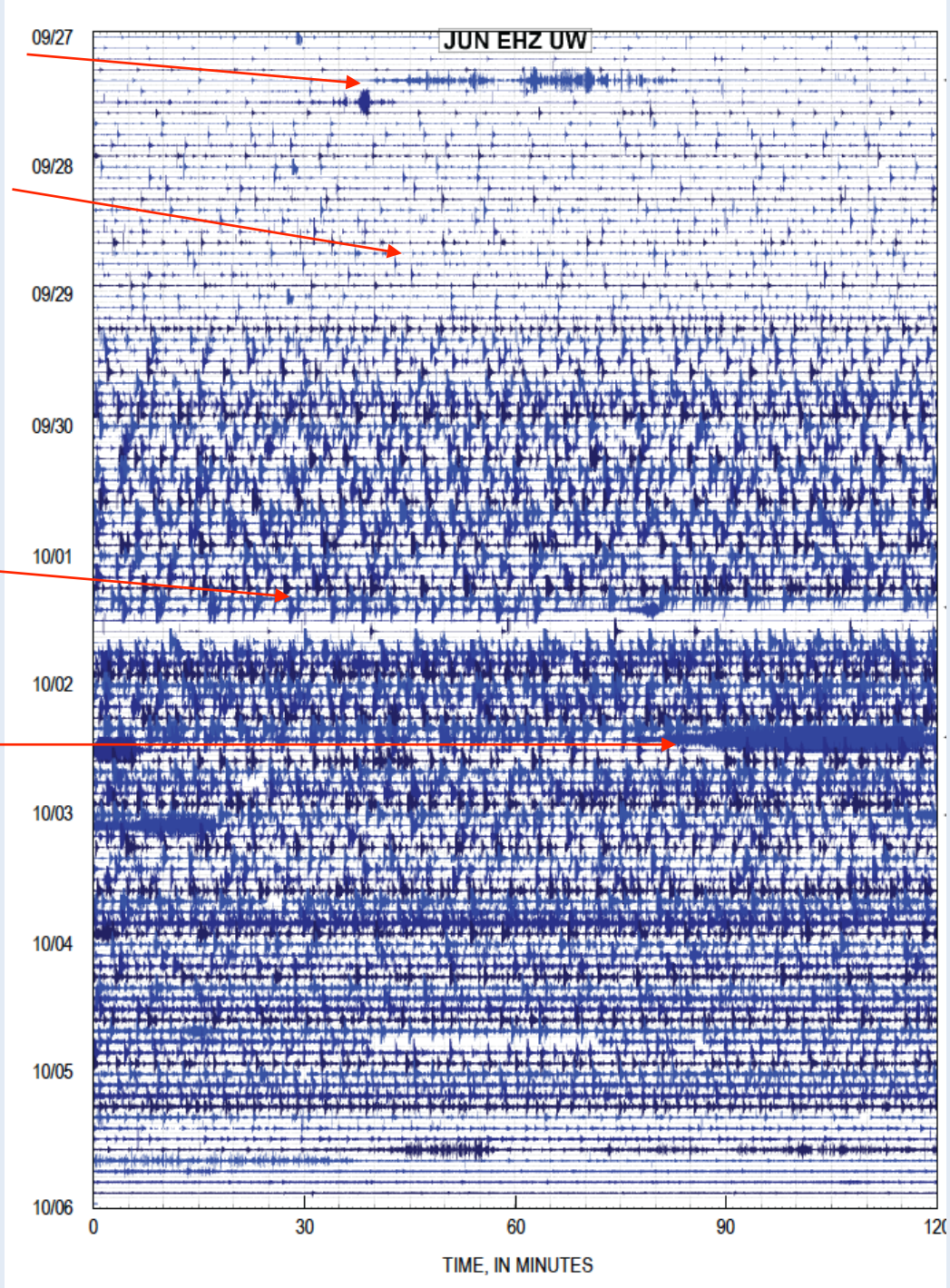
Mount St. Helens; September-October 2004.

Traffic(?)

"Drumbeat" repeating events

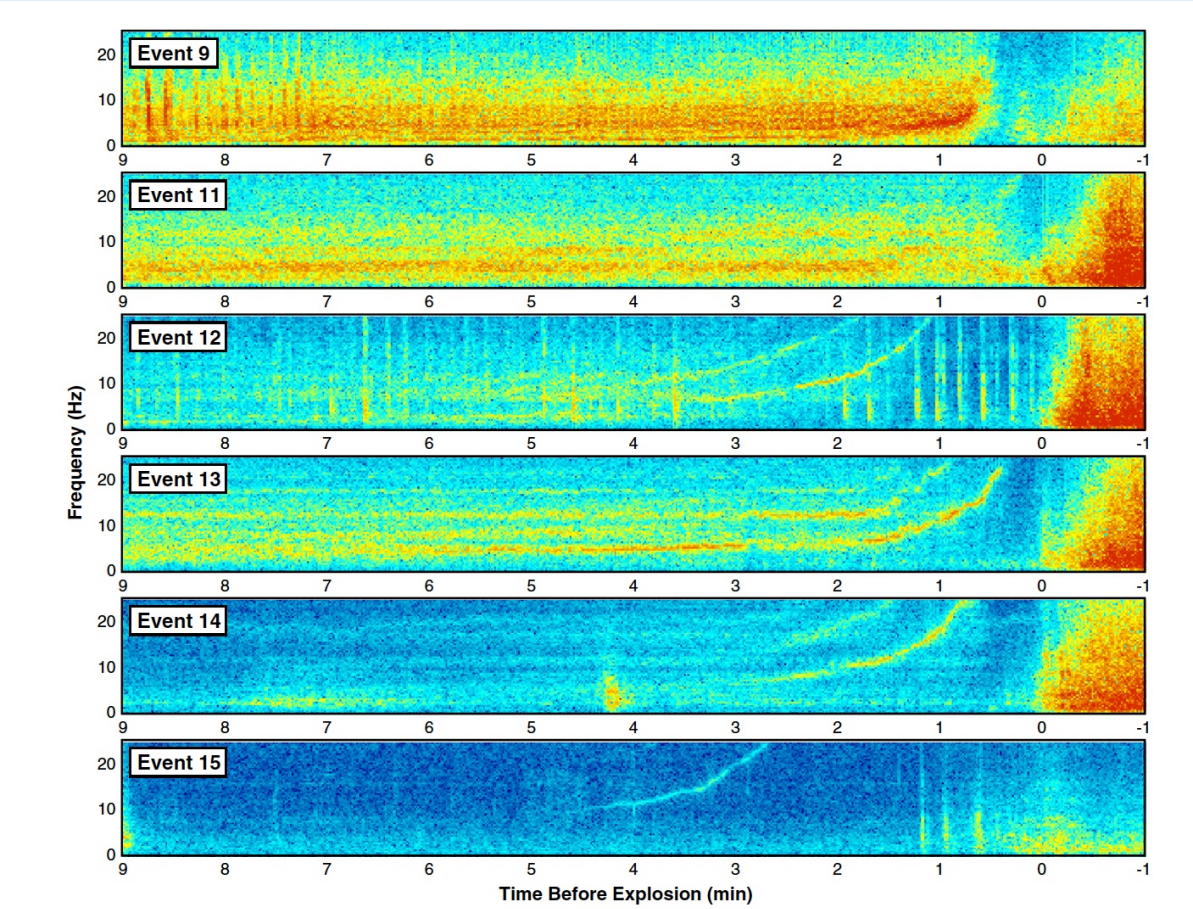
"Drumbeat" overlapping events

Tremor



Moran et al., 2008

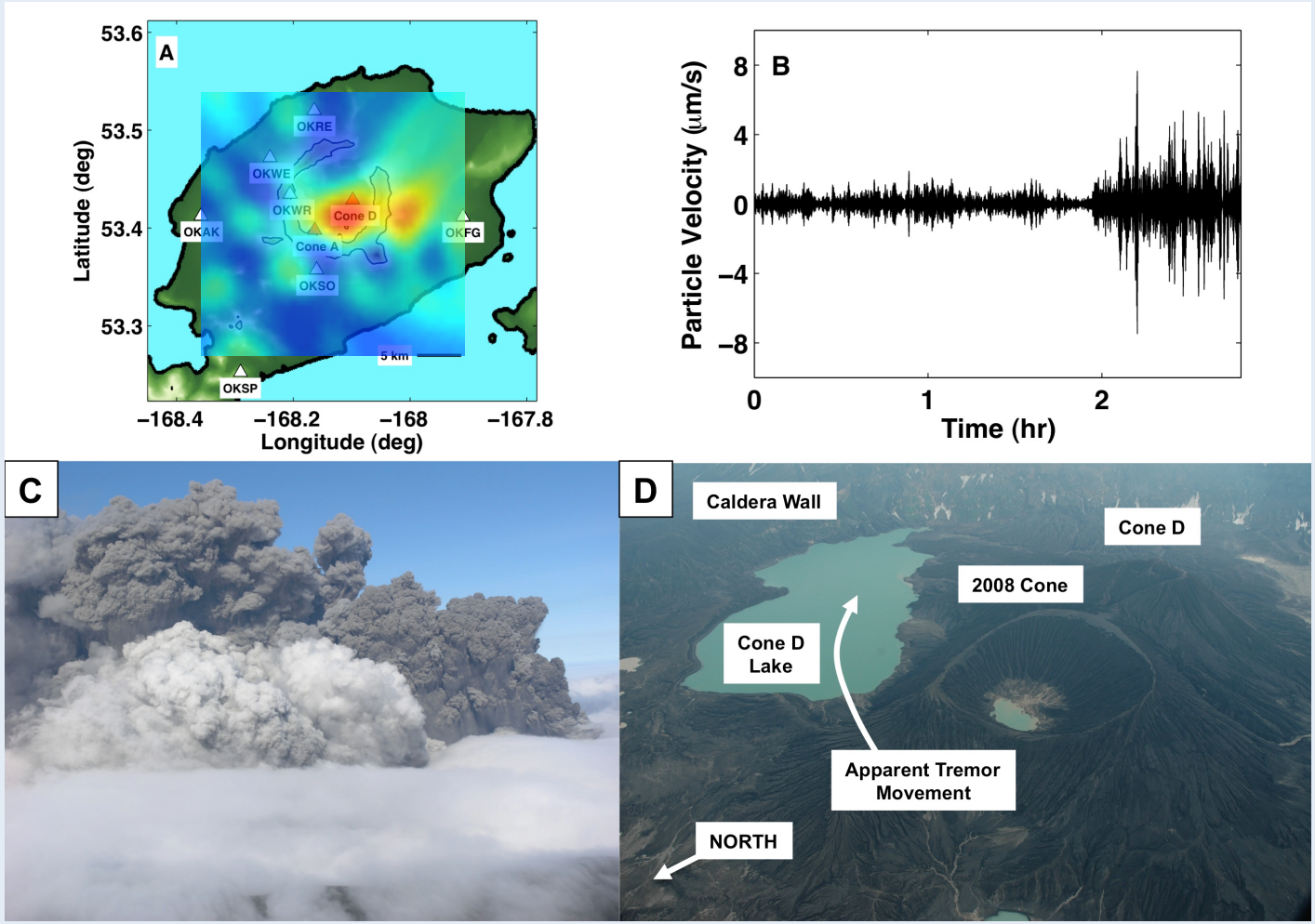
What Causes Harmonic Tremor (resonance or Dirac comb?)



2009 eruption of Redoubt Volcano (Dmitrieva et al., 2013; Hotovec-Ellis et al., 2012. "Gliding" tremor approaching 30 Hz favors a distinct and compact (e.g., stick-slip) underlying mechanism.

Time-evolving localization of tremor (long period/close stations!)

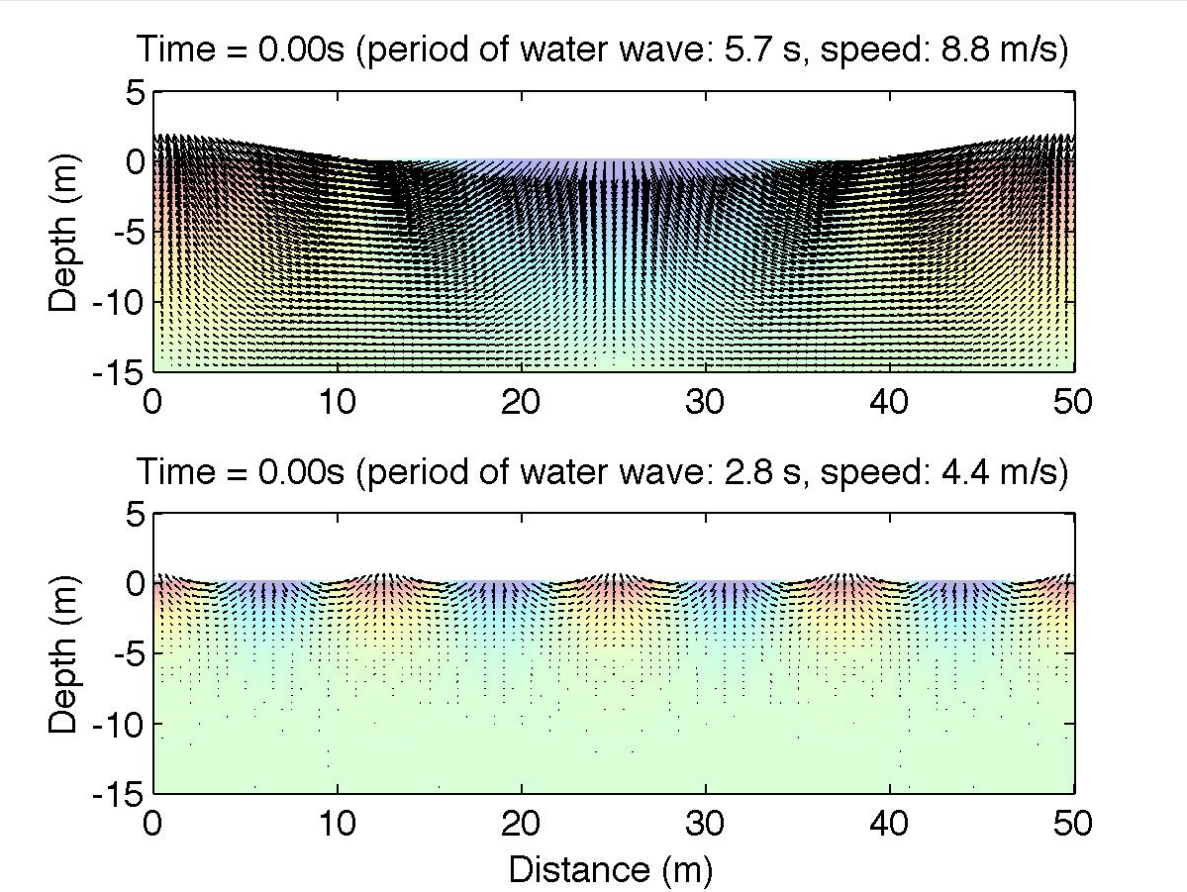
- 2008 eruption of Okmok volcano identification of the source as Rayleigh wave dominated and short (e.g. 5 km) ray paths allowed for localization of a moving near-surface tremor source at periods of several s.



You still can learn a lot from a few exceptionally sited stations!

Haney, 2014

Long-period signals recorded on ice-sited floating seismographs…



"Deep" water wave propagation ($h >> \lambda$) is dispersive with group velocity

$U = g/(4\pi f)$

so group travel time, t, as a function of distance, D, is

$t = D/U = 4\pi f D/g$

and

$dt/df = 4\pi D/g$

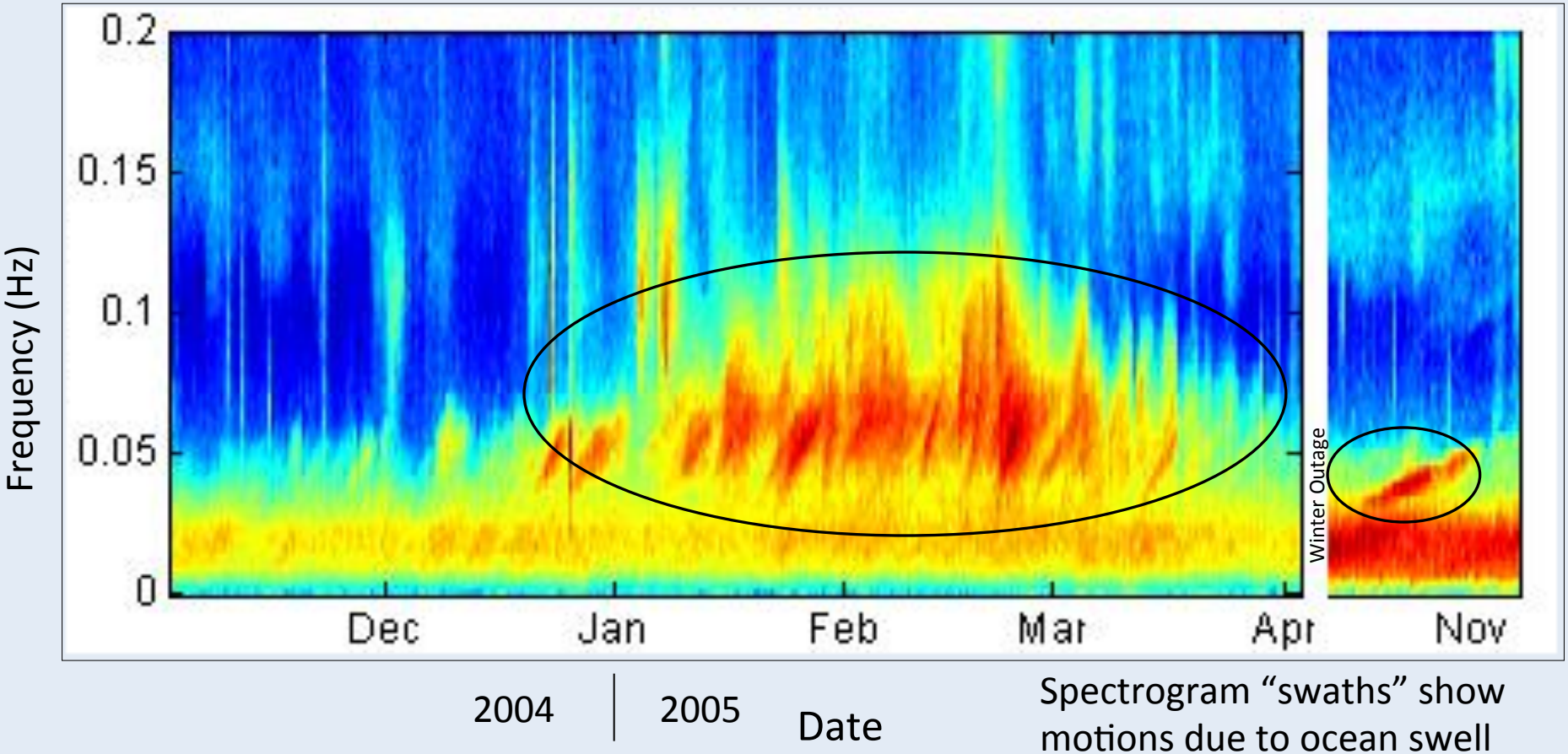
Swell source distances are thus proportionate to the slopes of their dispersed seismogram spectrogram swaths.

$D = g/(4\pi)(df/dt)^{-1}$

e.g., an ~30 s swell group propagates at ~23.5 m/s (~55 miles/hr).

Broadband seismographs atop large tabular ice bodies not only record elastic waves but also function as exquisitely sensitive buoys.

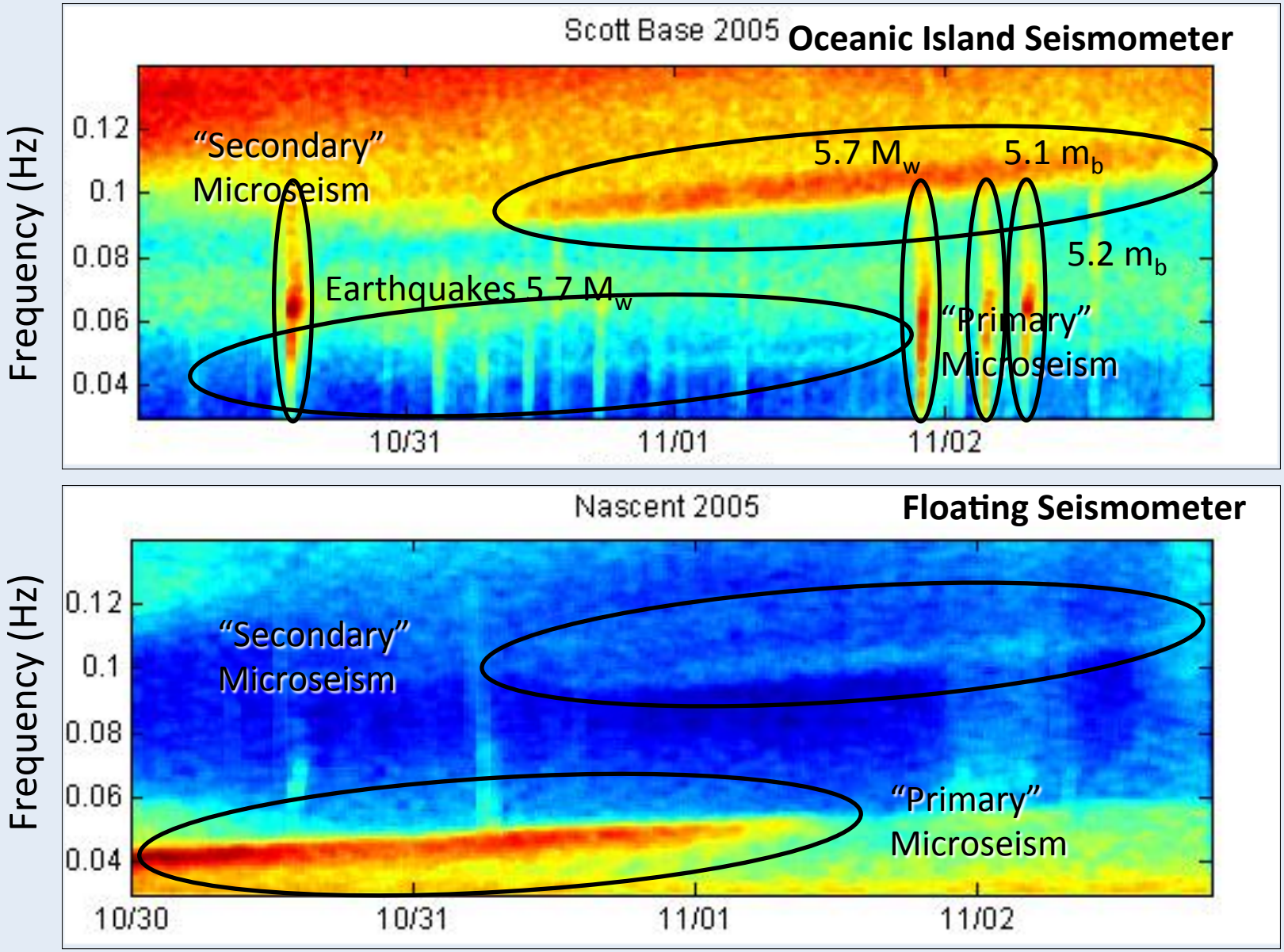
An ocean-wide record of dispersed wave events from a single broadband seismograph on Nascent Iceberg at the edge of the Ross Ice Shelf.



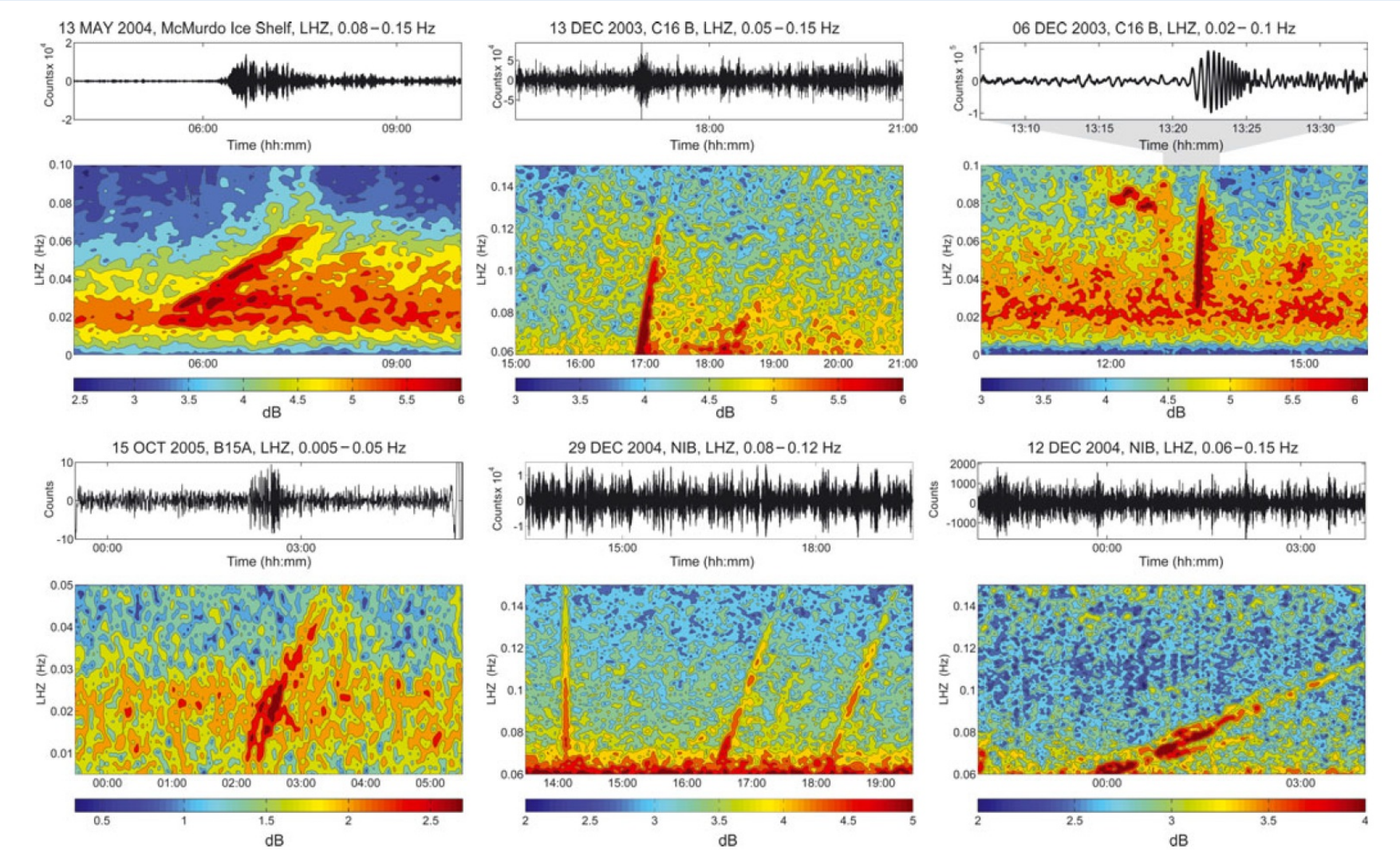
Nascent Iceberg 5+-month vertical seismic record (a floating seismometer at the edge of the Ross Ice Shelf).

Spectrogram "swaths" show motions due to ocean swell from global storms - (the "primary" component of the global microseism).

Complementary features of ice-sited (floating) and land-sited broadband seismic signals

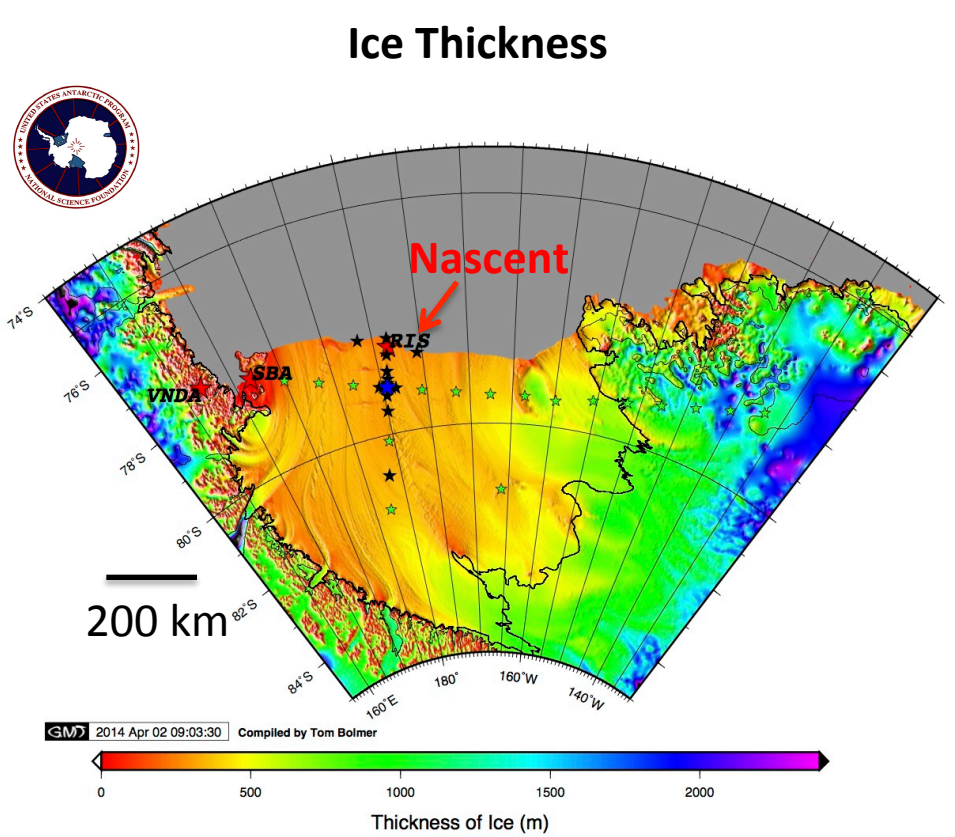


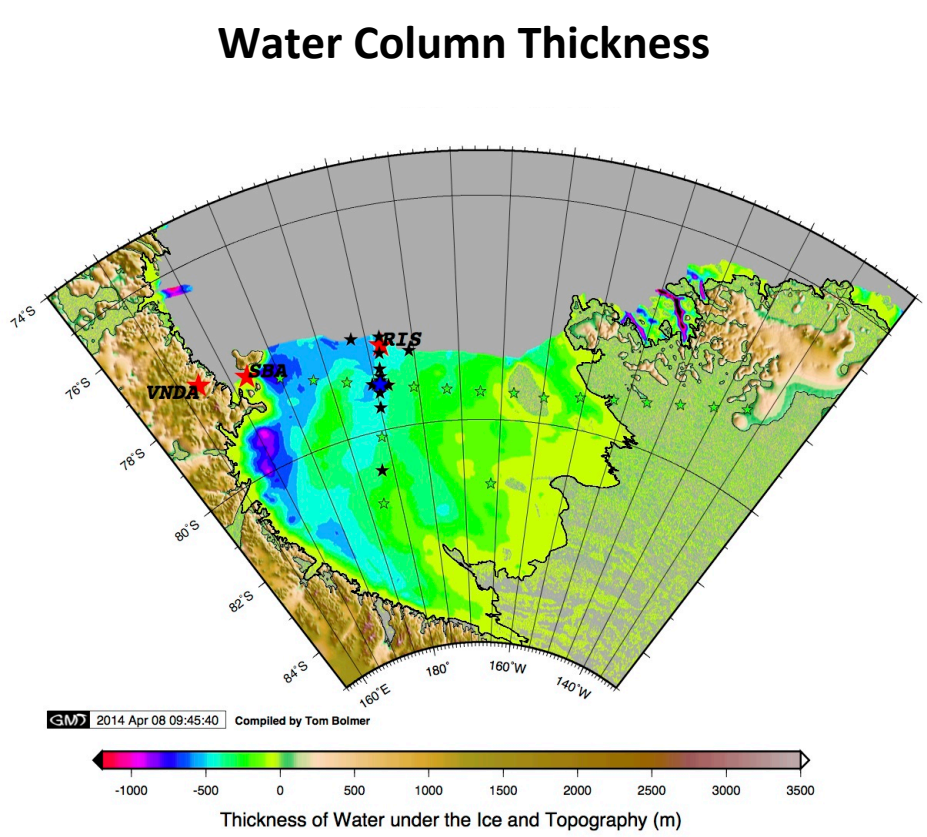
Nascent-recorded glaciogenic events (around 200/year). Hypothesized to be caused by small-scale calving and wasting of icebergs and ice-shelves, iceberg collisions, and possibly ice-shelf rifting or basal crevasse formation (some events are also temporally correlated with iceberg tremor).



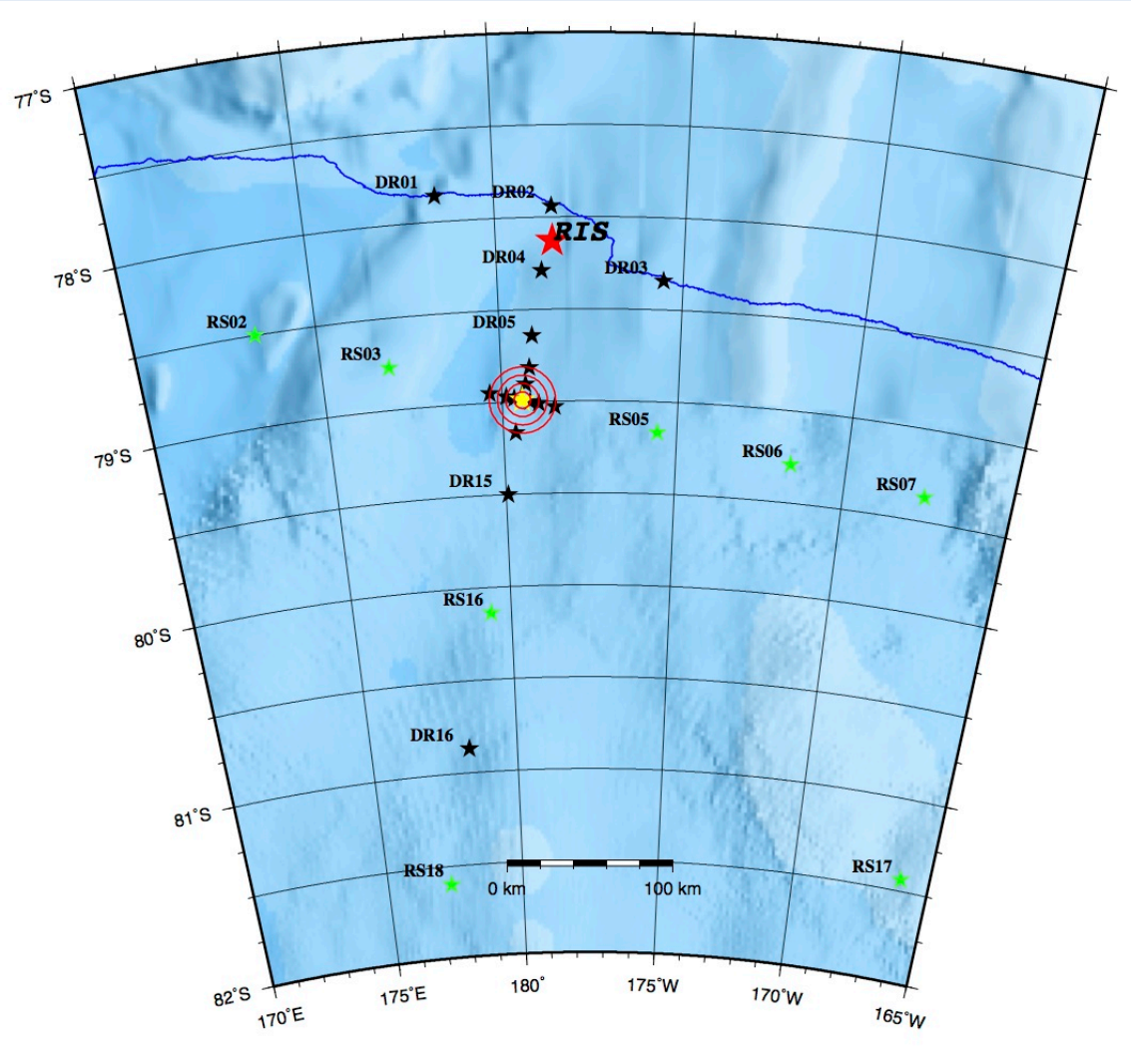
MacAyeal et al., 2009.

The next generation of ice-sited broadband data: Dynamical Response of the Ross Ice Shelf to Wave Induced Vibrations/Mantle Structure and Dynamics of the Ross Sea (2014-2016)



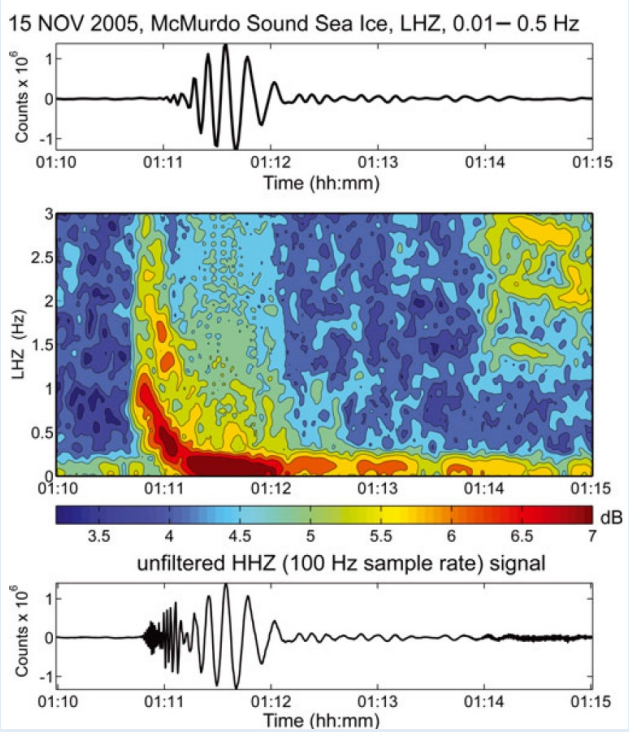


Broadband seismographs with an embedded array



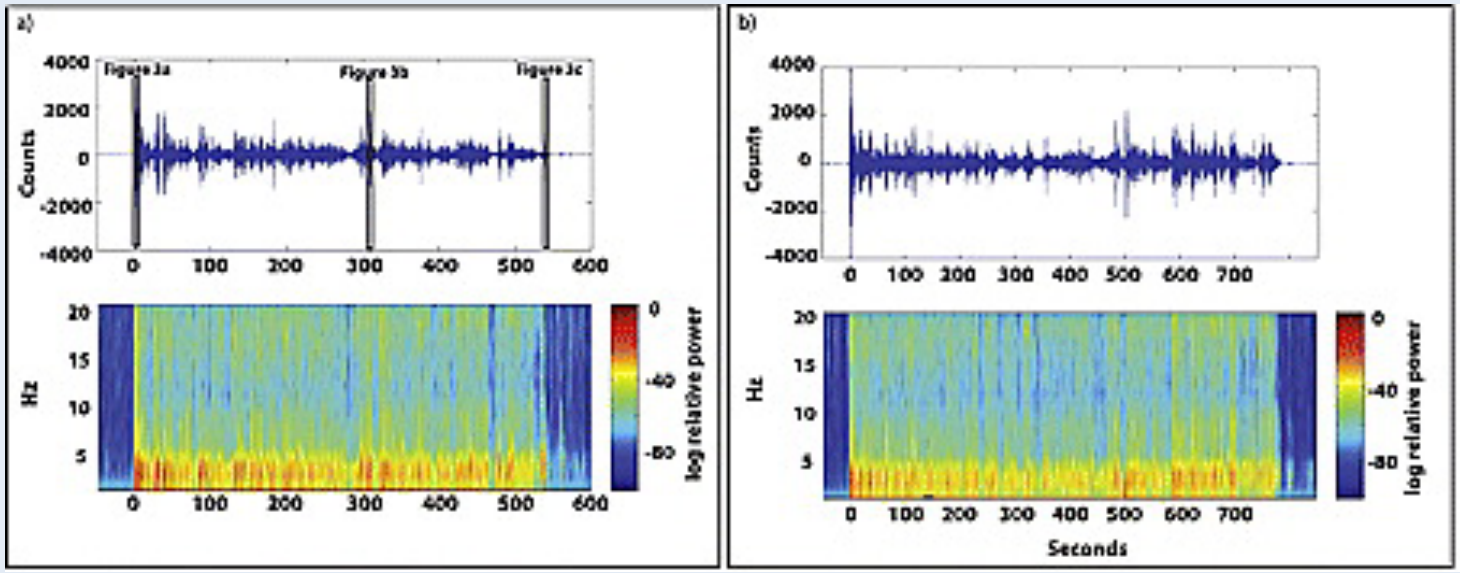
RISSS (Ross Ice Shelf Seismic Studies) Science Goals:

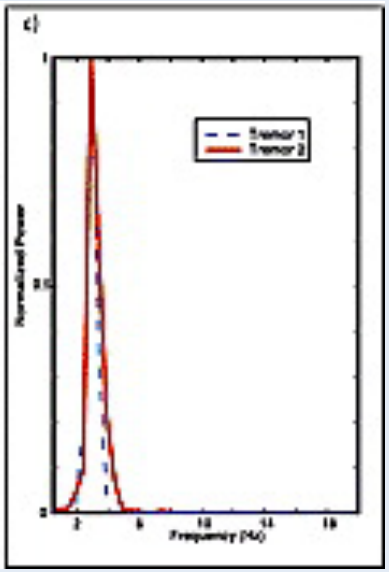
- Ocean gravity wave/ice shelf coupling
- Ice shelf flexural waves
- Internal ice shelf events
- Ross sea/West Antarctic Rift System crust/mantle structure
- Local and regional calving
- Basal events
- Regional iceberg seismicity

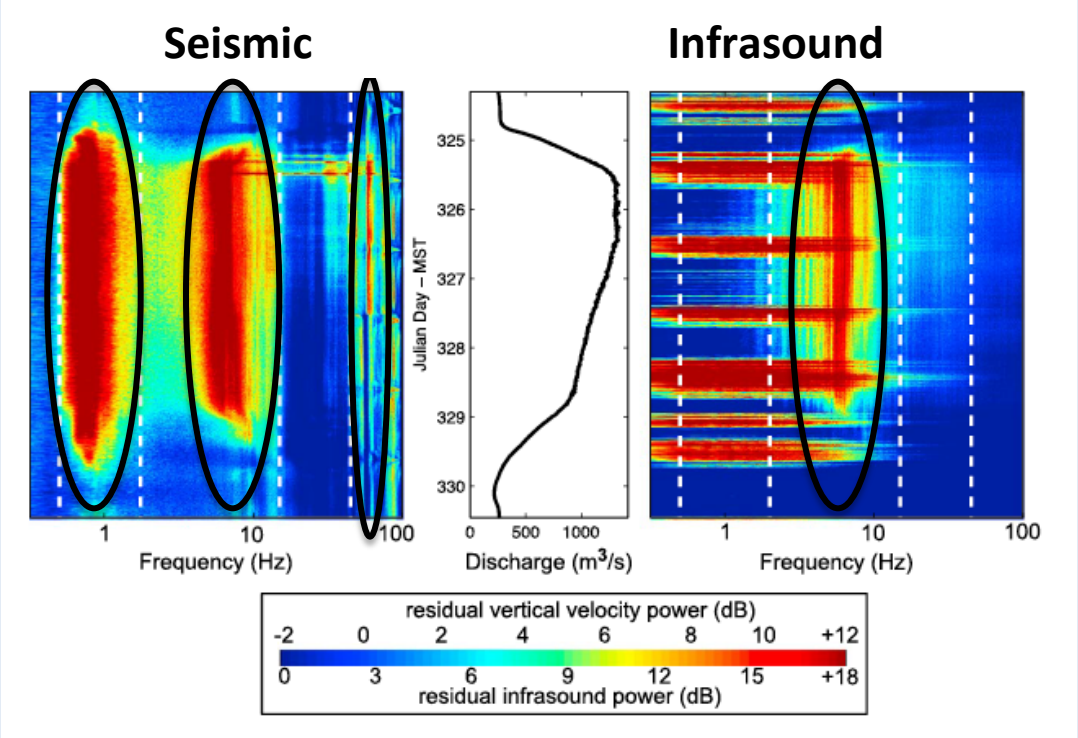


Anomalously dispersed flexural waves recorded on McMurdo sea ice (c/o D. MacAyeal).

…and Fluvial Seismology





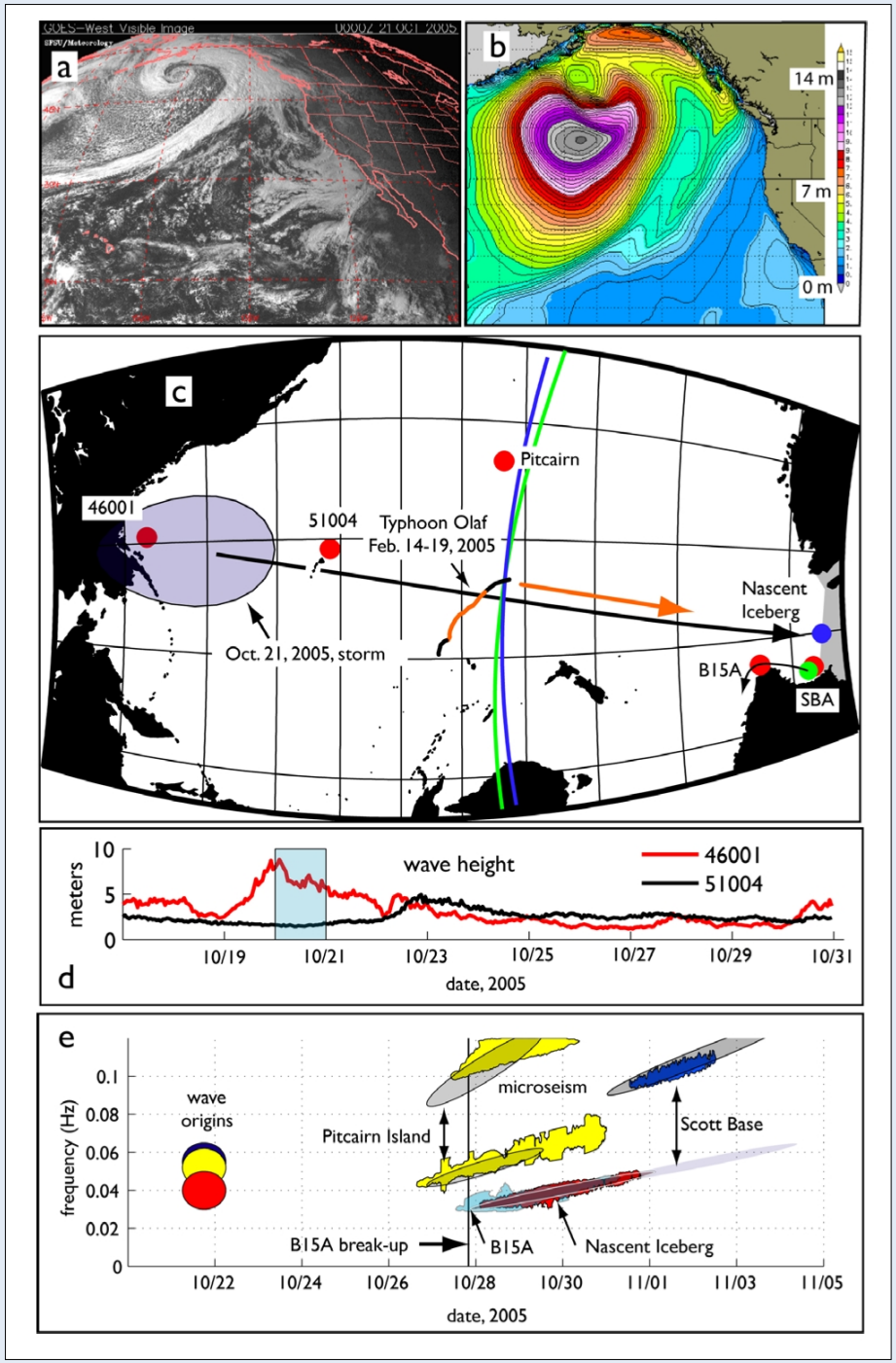


Winberry et al., 2009, Seismic observations of transient subglacial water-flow beneath MacAyeal Ice Stream, Antarctica.

Schmandt et al., 2013, Multiple fluvial process detected by riverside seismic and infrasound monitoring of a controlled flood in Grand Canyon.

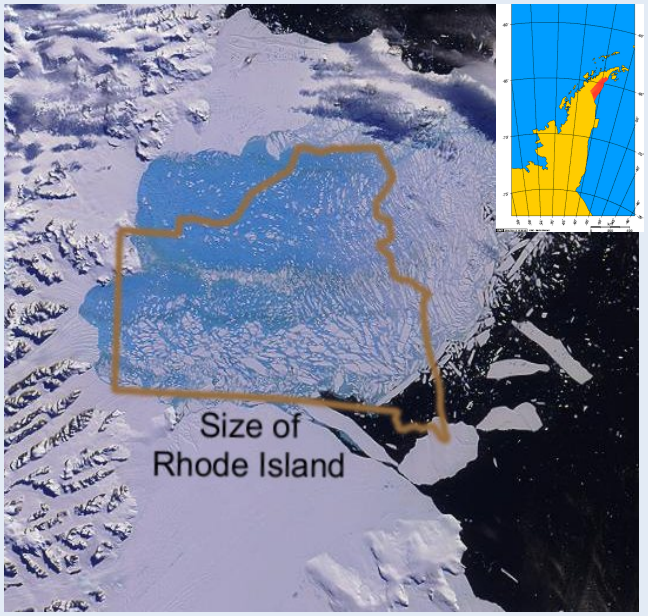
Summary

- Continuous, near-source, and generally expanded seismographic coverage of ocean, volcanic, and cryospheric sources of ground/ice motion have illuminated new process classes that span the continuum between “transient” and “stationary” behavior.
- Seismic/gravity wave source/propagation/process interactions between solid earth, ice, oceans, and atmosphere are revealing new types of sources and unexpected teleconnections.
- Deploying at near-to-source distances often provides critical information to discriminate between competing source models (more so than simply larger numbers of distant stations).
- Investments in producing well-curated seismographic data will produce scientific dividends for many decades to come.



•Although it seems safe to say that B15 broke up because it ran aground, it is interesting that it was also agitated at this timet by storm swell from a remarkable Gulf of Alaska storm?

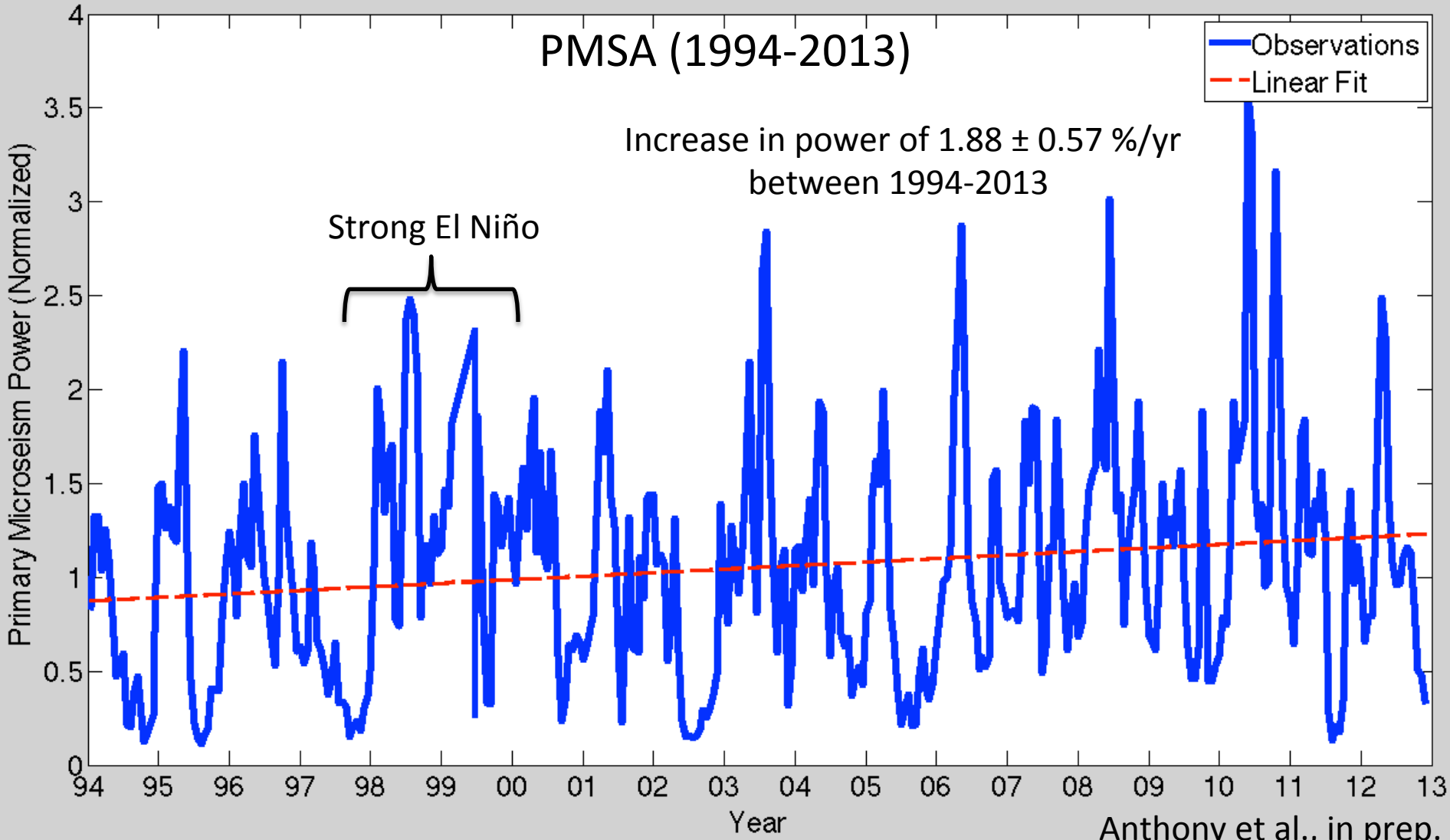
•How does swell generally affect the ice shelves? It certainly affects sea ice to ranges that have recently been shown to be linear (rather than exponential) for large wave events (Kohout et al., 2014).



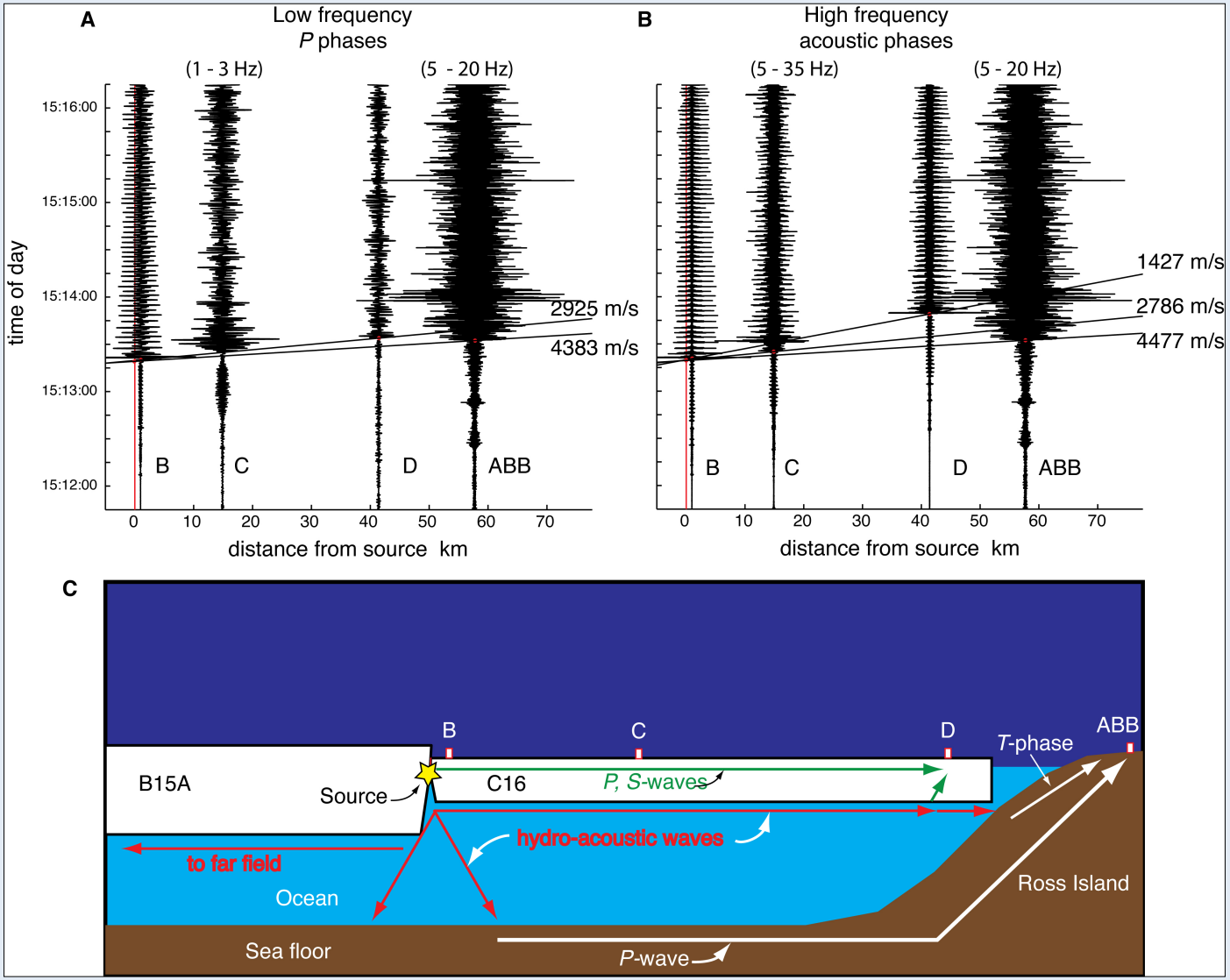
Larson B Ice Shelf, Antarctic Peninsula, 2002.

After MacAyeal et al., 2006; 2009

A remarkable number of 20-year microseism intensity records have significantly nonzero L1 and/or L2 slopes. Need to sort out effects due to storm intensity, storm track variation, sea ice (polar), ENSO/PDO/NAO/other effects.



Anthony et al., in prep.



P_{hydro} (T phase)

P_{ice}

$P_{solid\ Earth}$

Polarizations and observed propagation speeds of various signals enabled us to identify individual subevent seismic phases (P_{ice}, S_{ice}, P_{hydro}, $P_{solid\ Earth}$).

MacAyeal et al., 2008

Examples from the Cryosphere, Science Motivations

- Revealing and understanding dynamic processes and teleconnections affecting the past/present/future evolution of glaciers, ice sheets, and ice shelves. Processes include effects due to:
- Basal melt
- Geothermal heat flux
- Mantle viscosity and its lateral variation
- Ocean wave/tidal influences
- Englacial and subglacial flow/hydrofracting/melting/freezing
- Surface ablation
- Glacial/ice sheet/ice shelf collapse/retreat/advance mechanisms

Ongoing Microseism Research

- Directionality effects and constraints affecting its use as an ambient background source for Green's function estimation and structural imaging.
- Source modeling.
- Earth's "hum".
- Microseism generation of global Love and body waves.