Analysis of unusual earthquakes using ‘legacy’ data

Meredith Nettles

John Wilding

Göran Ekström

“Securing Legacy Seismic Data to Enable Future Discoveries”
Albuquerque, Sept. 18—19, 2019

or,

What might we learn about glaciers, climate, and volcanos from legacy data?

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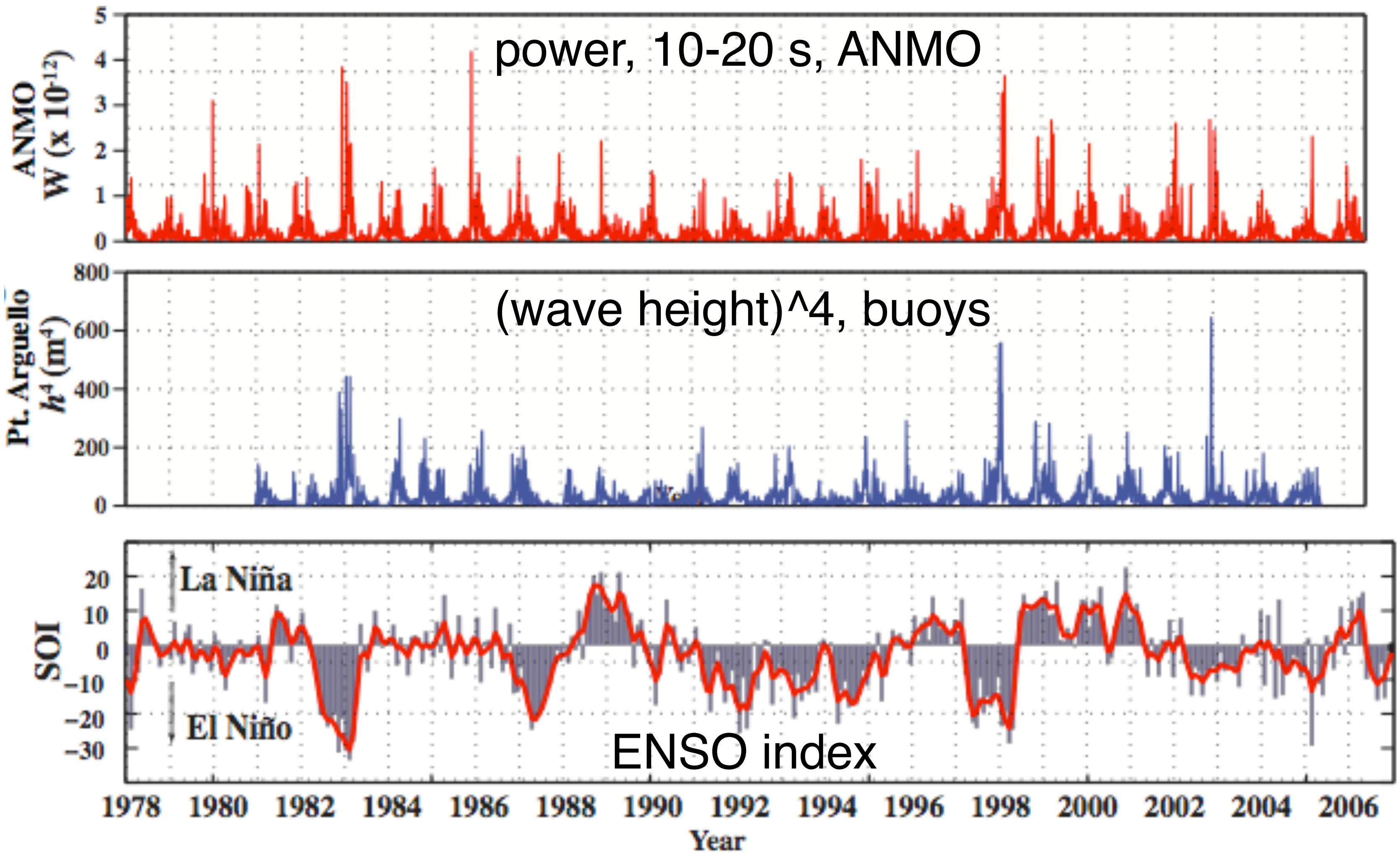
Relevance of seismic-analysis products for understanding of glaciers and climate

Earth structure:
response to surface (ice) loading — not addressed here

Seismic sources:
—noise and storm signals
—tectonic earthquakes
—glacial earthquakes

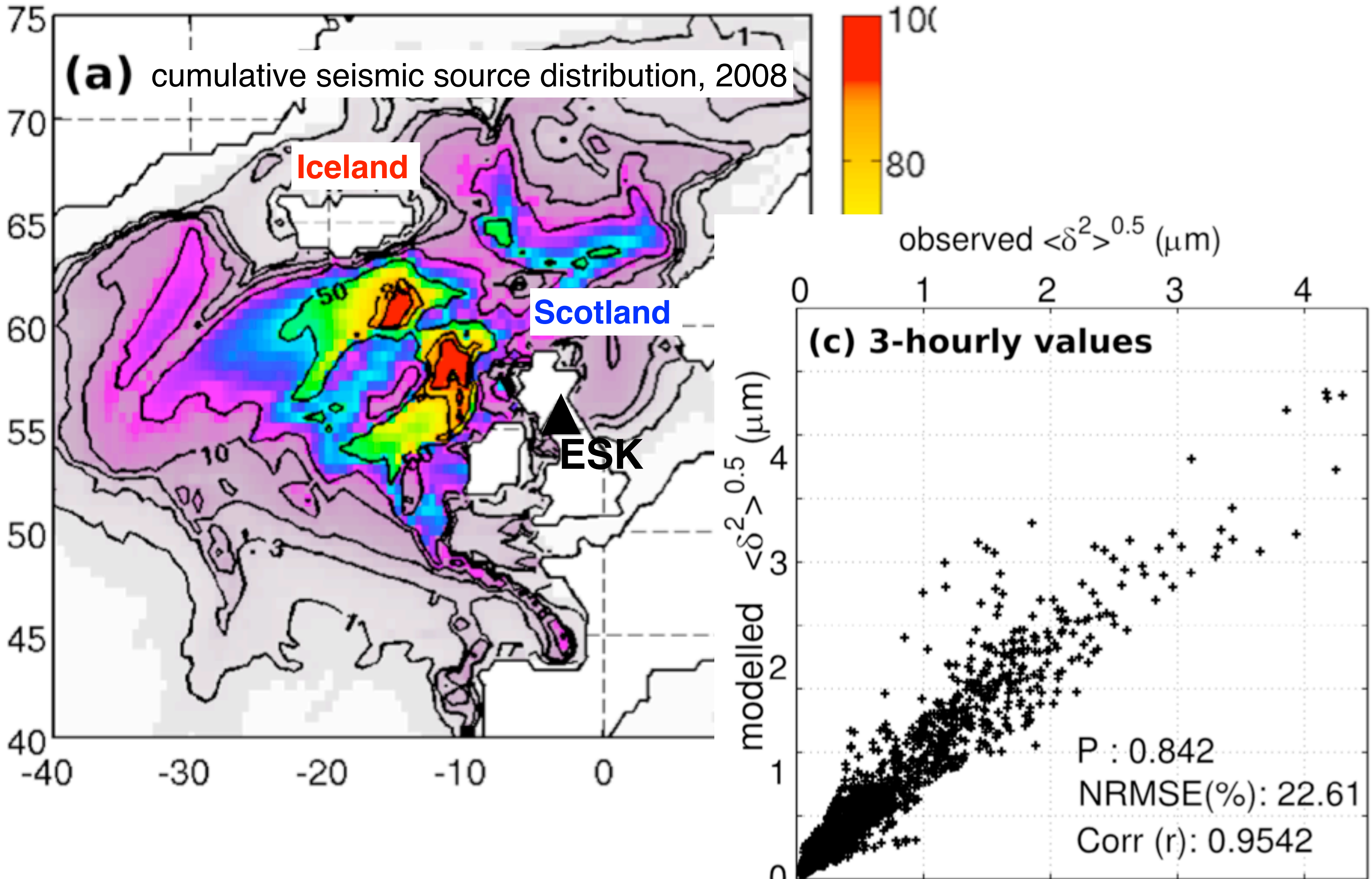
Seismic sources: noise and storms

observations sensitive to Pacific wave height



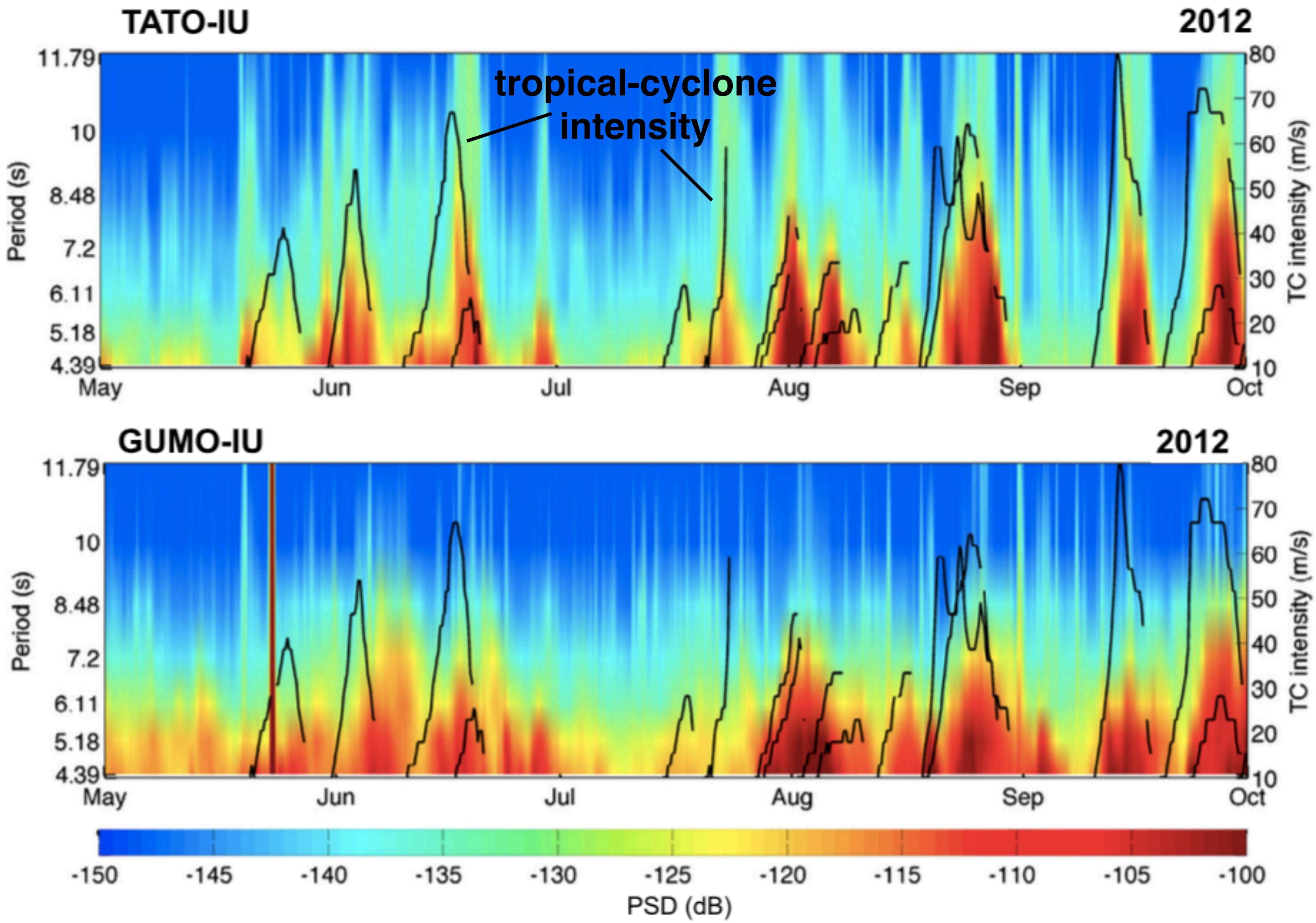
(Aster et al., 2008)

and North Atlantic sea state



(Ardhuin et al., 2012)

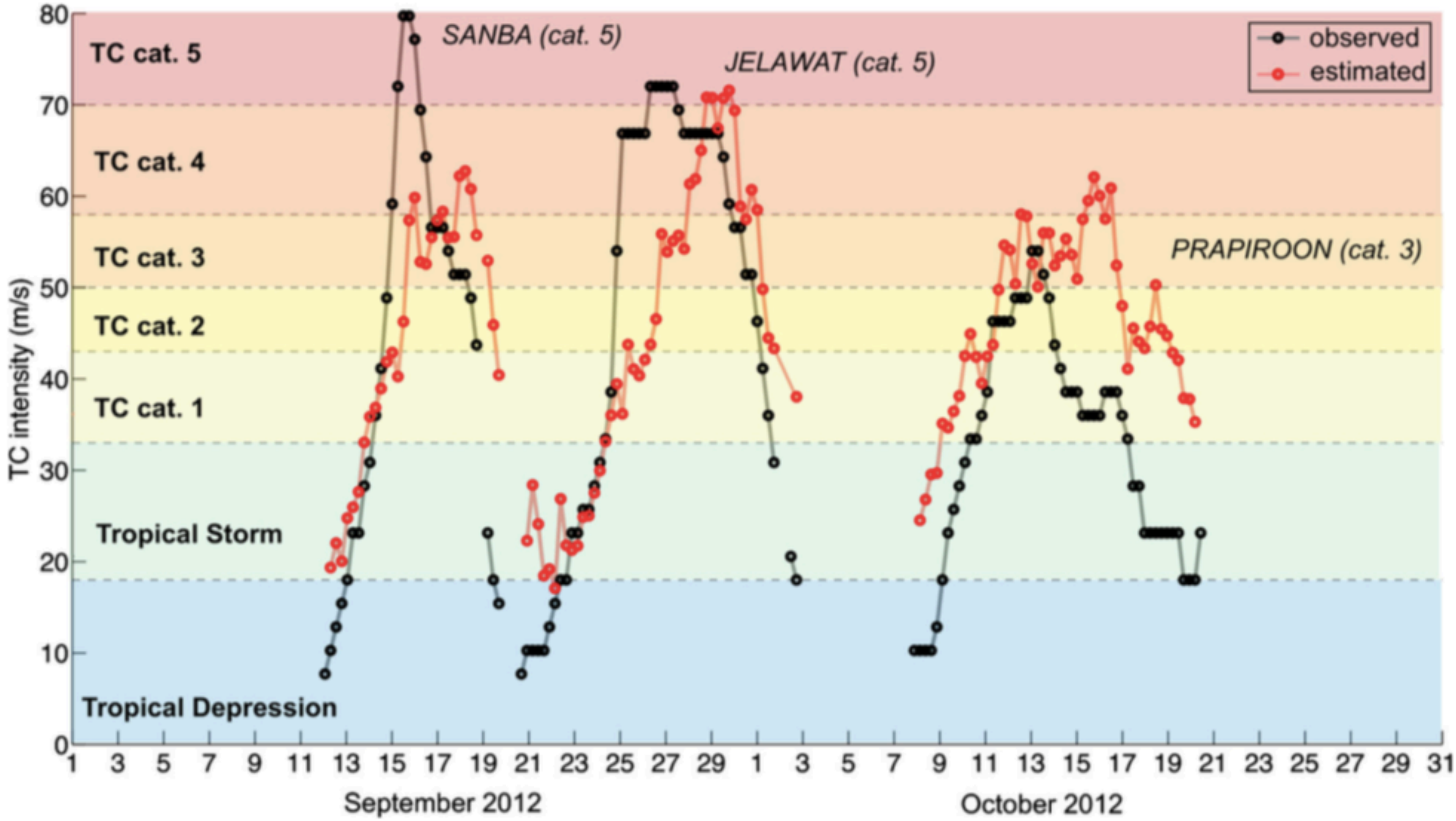
observations of tropical cyclones (hurricanes) in seismic noise



color scale: seismic noise level

(Gualtieri et al., 2018)

observations of tropical cyclones (hurricanes) in seismic noise



model based on data from 2000-2010

(Gualtieri et al., 2018)

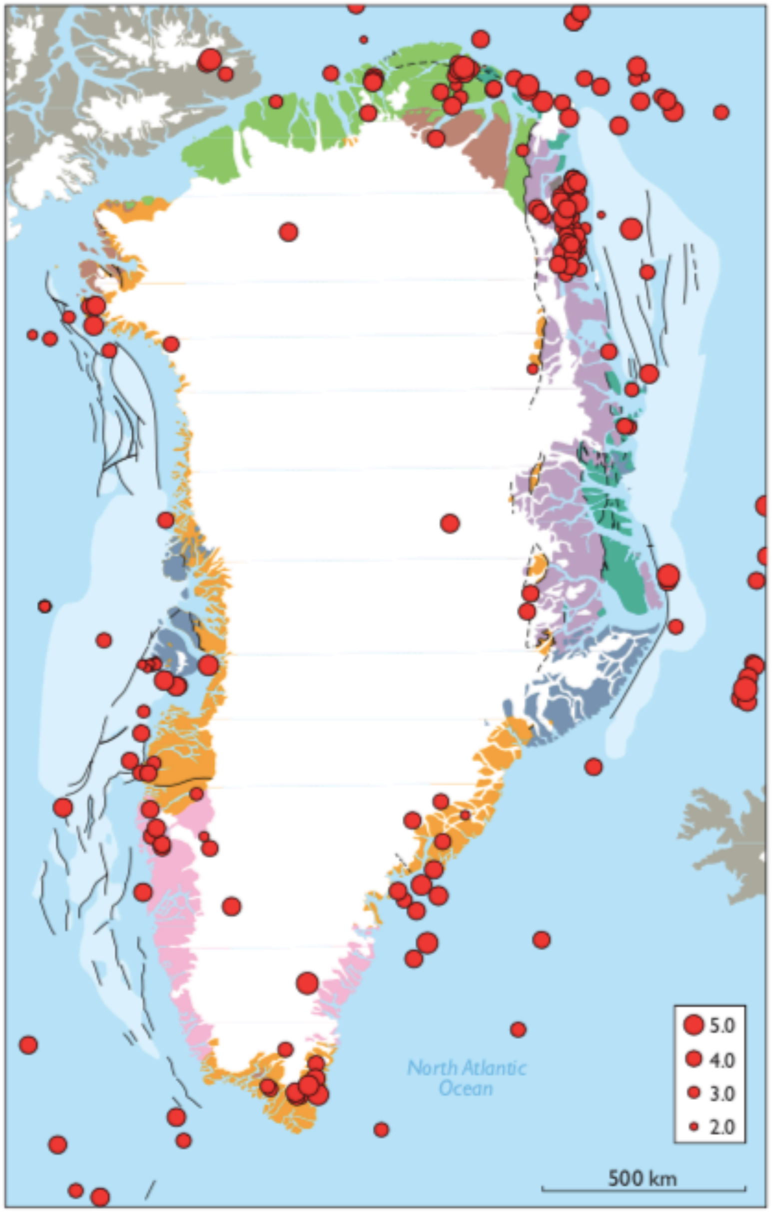
Possible to extend these (proxy) records of sea state and hurricane intensity to pre-digital era?

More seismic sources:

(Johnston, 1996)

- earthquakes due to ice unloading
- ice/earthquakes due to slip at glacier bed
- glacial earthquakes

Crustal earthquakes in Greenland, 1970-2005



(Larsen et al., 2006)

What is the stress regime?
Consistent with unloading, or "normal" plate interior?

Limited number of M 4-5 events;
extending earlier in time would help

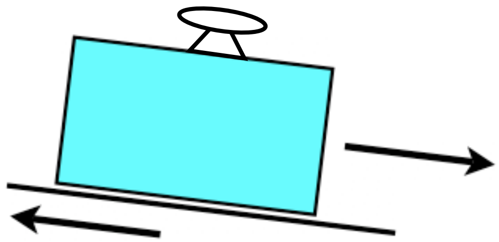
Events already cataloged;
CMT-type analysis likely possible

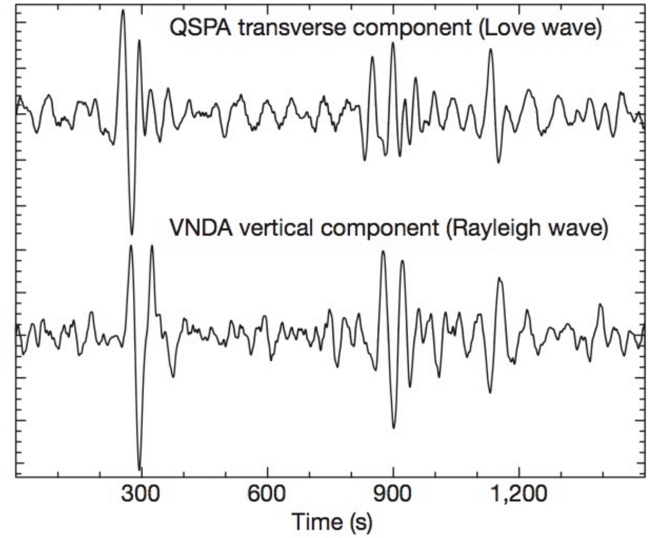
More seismic sources:

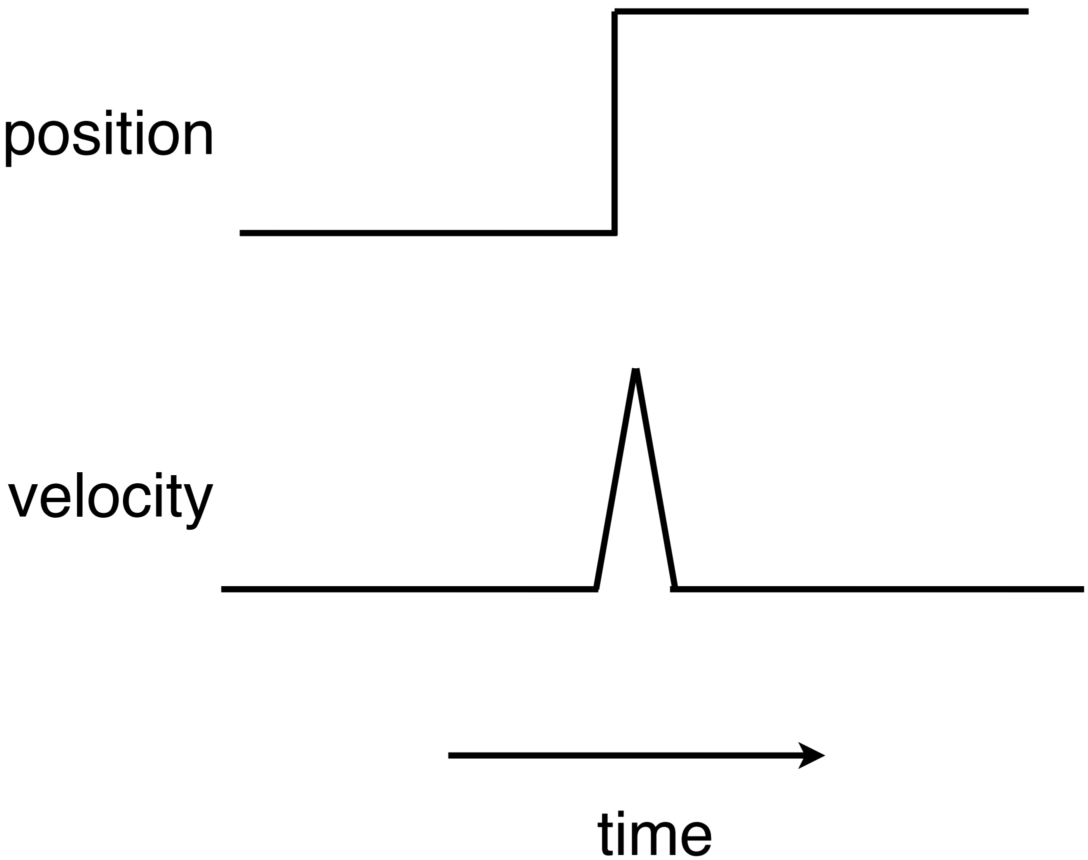
(Johnston, 1996)

- earthquakes due to ice unloading
- ice/earthquakes due to slip at glacier bed
- glacial earthquakes

Tidally modulated glacier lurching at Whillans Ice Stream, Antarctica:
Wiens et al., 2008



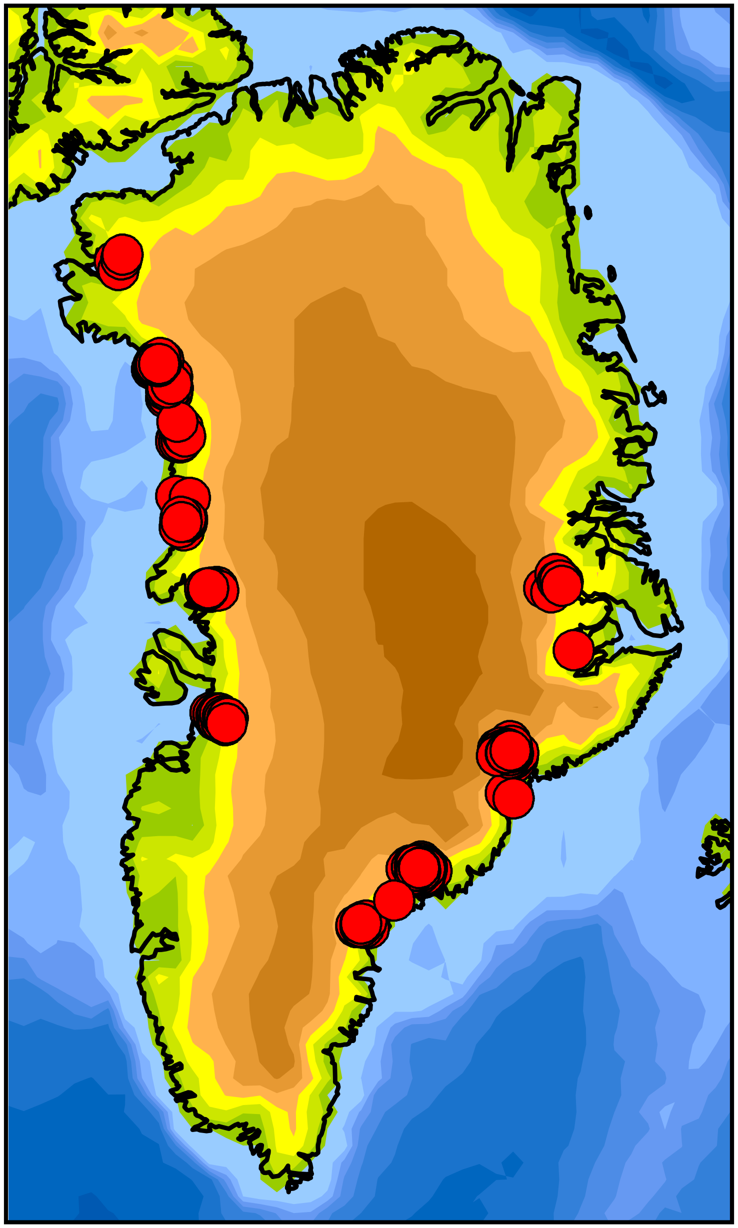




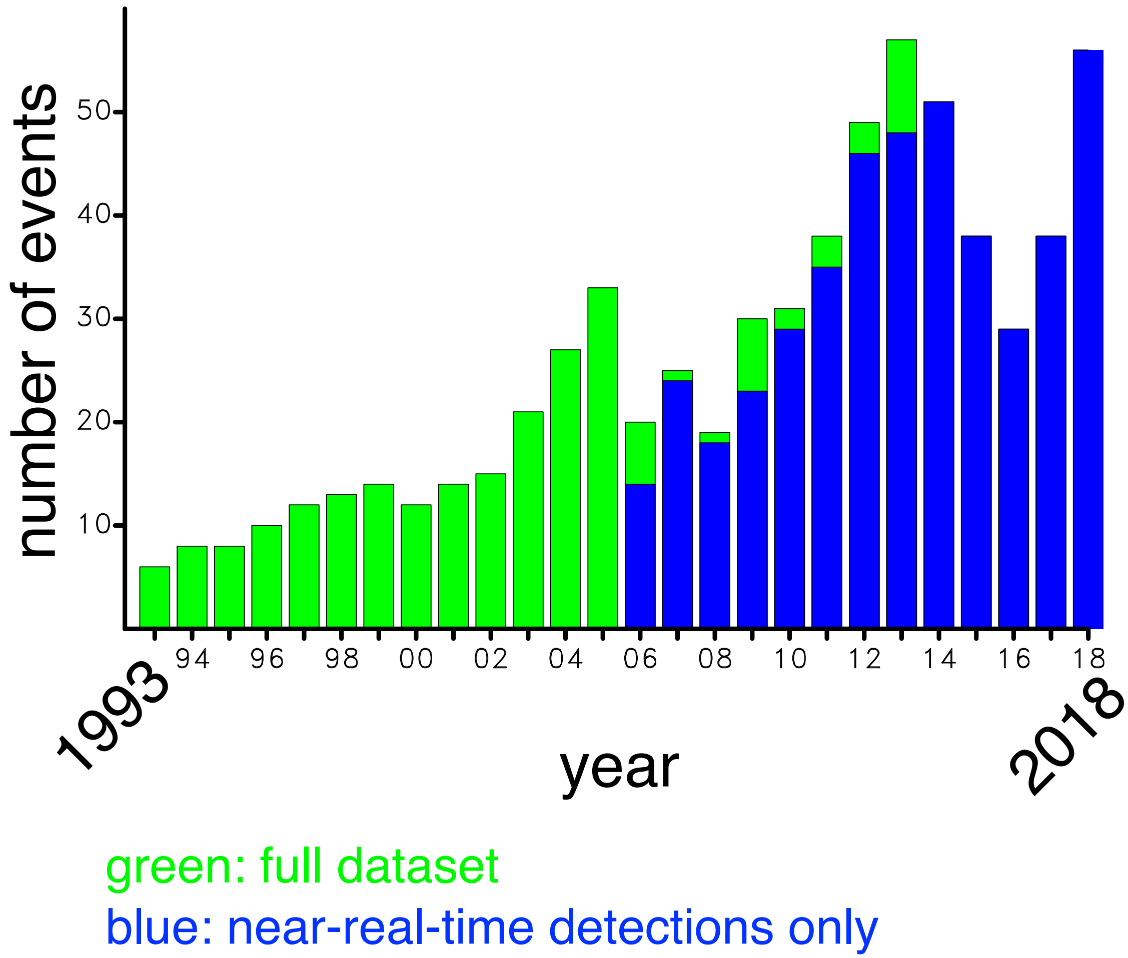
Changes from 2003-2010: events less regular as ice stream slows down upstream (Winberry et al., 2017)

How long have these things been going on?

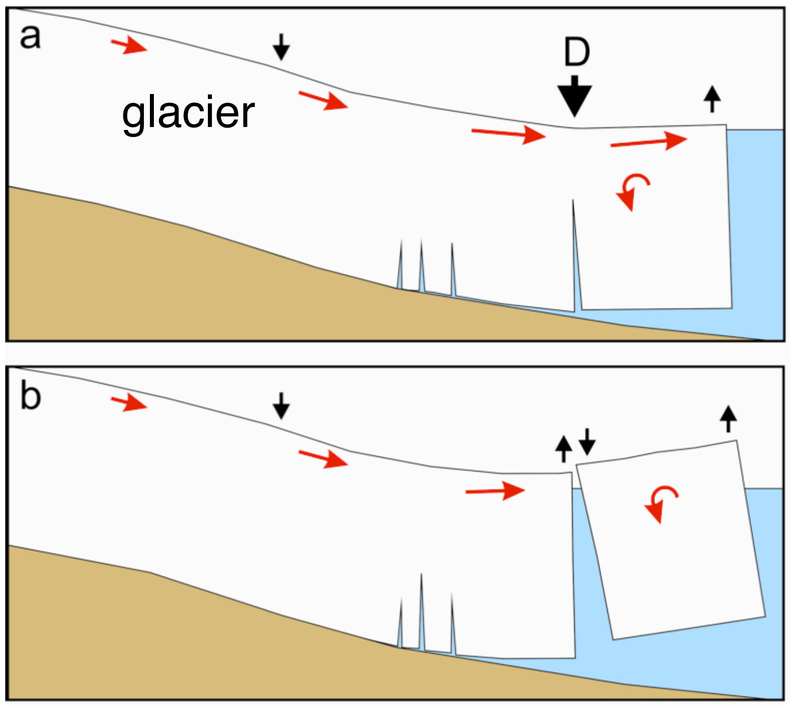
Glacial earthquakes in Greenland



(updated from Nettles and Ekström, 2010)



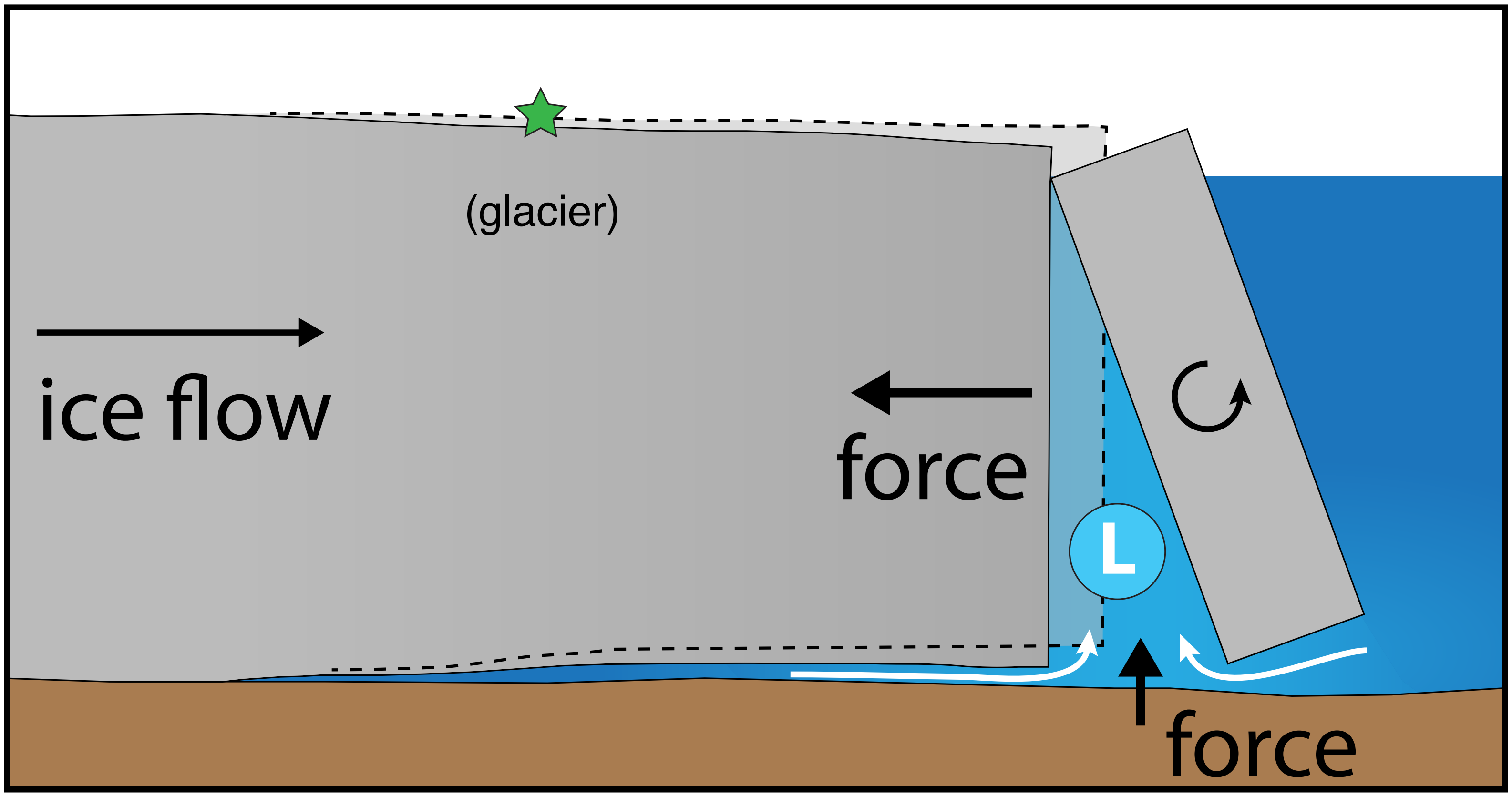
Glacial earthquakes:
Calving of (nearly) grounded ice through buoyancy-driven calving



(Murray et al., 2014)

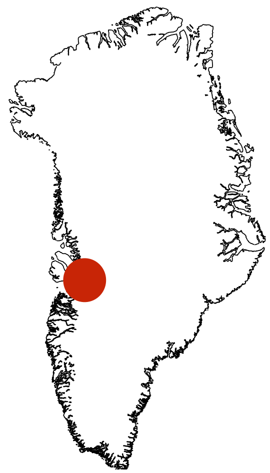
Earthquake source:

- horizontal force - reaction force due to iceberg acceleration away from glacier;
- vertical force - upward force due to dynamic pressure drop behind capsizing iceberg

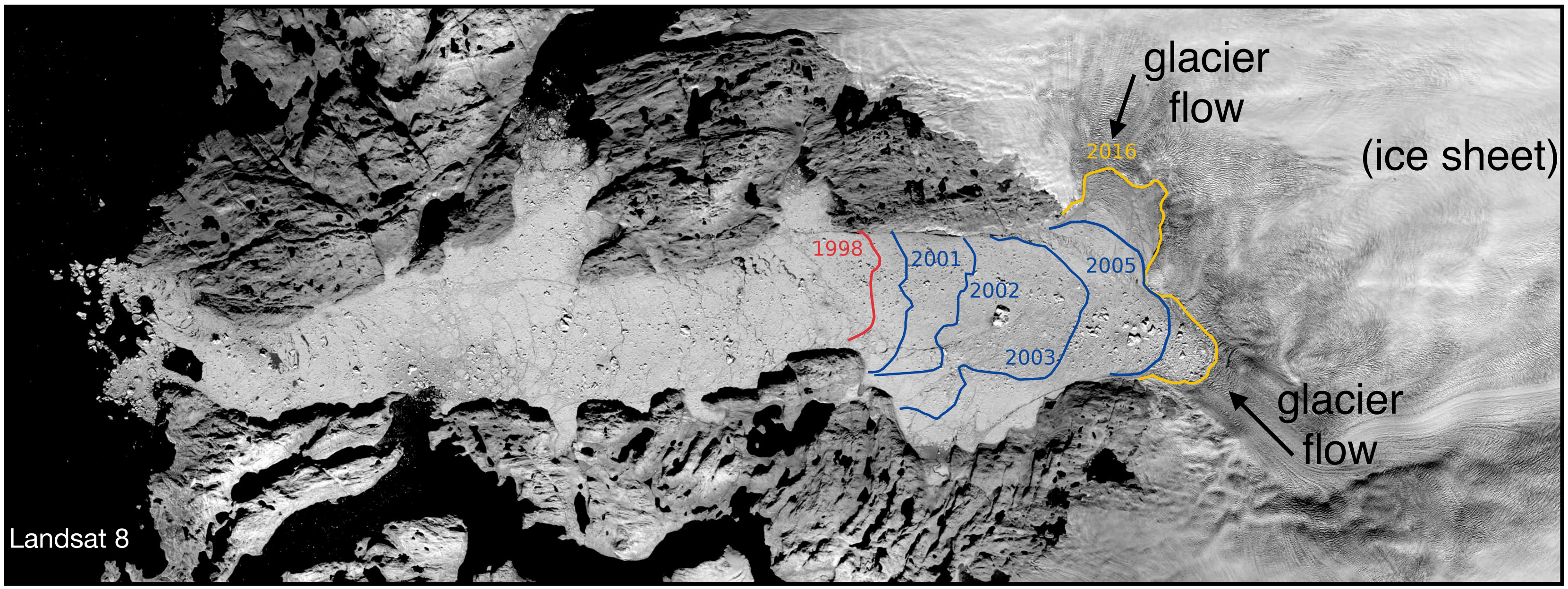


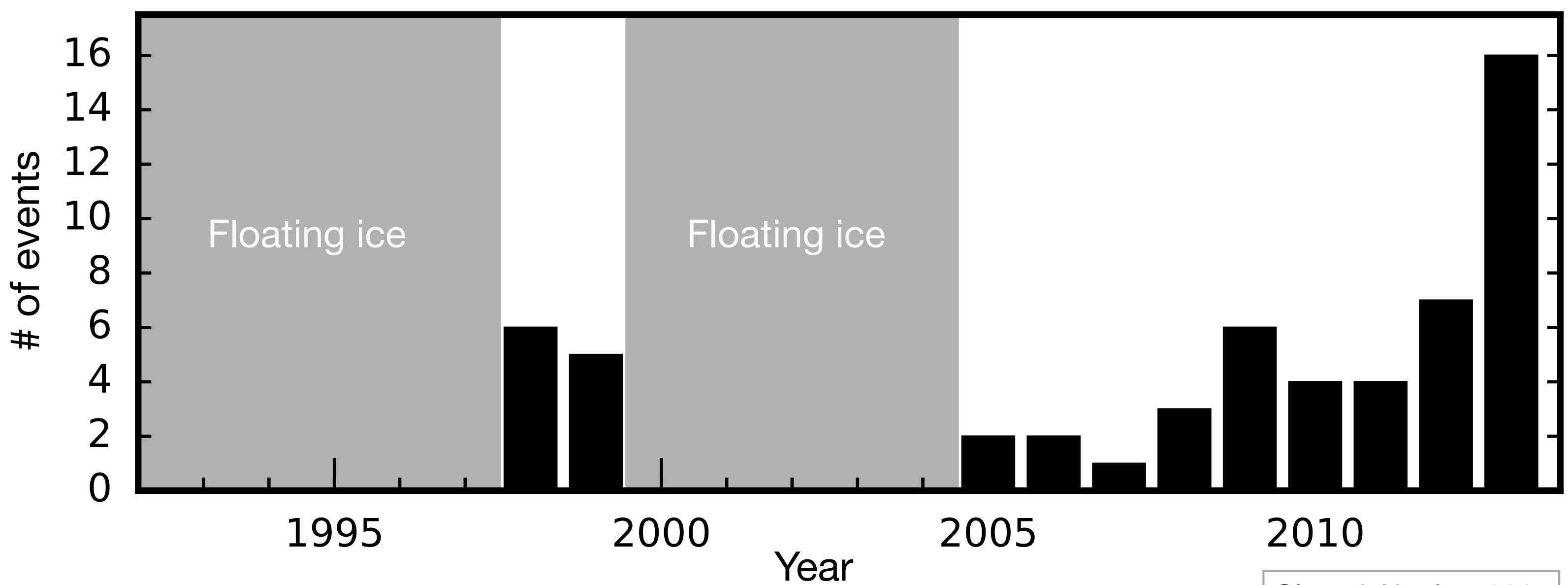
(Murray et al., 2015)

Glacial earthquakes occur during glacier retreat, and tell us the glacier grounding state



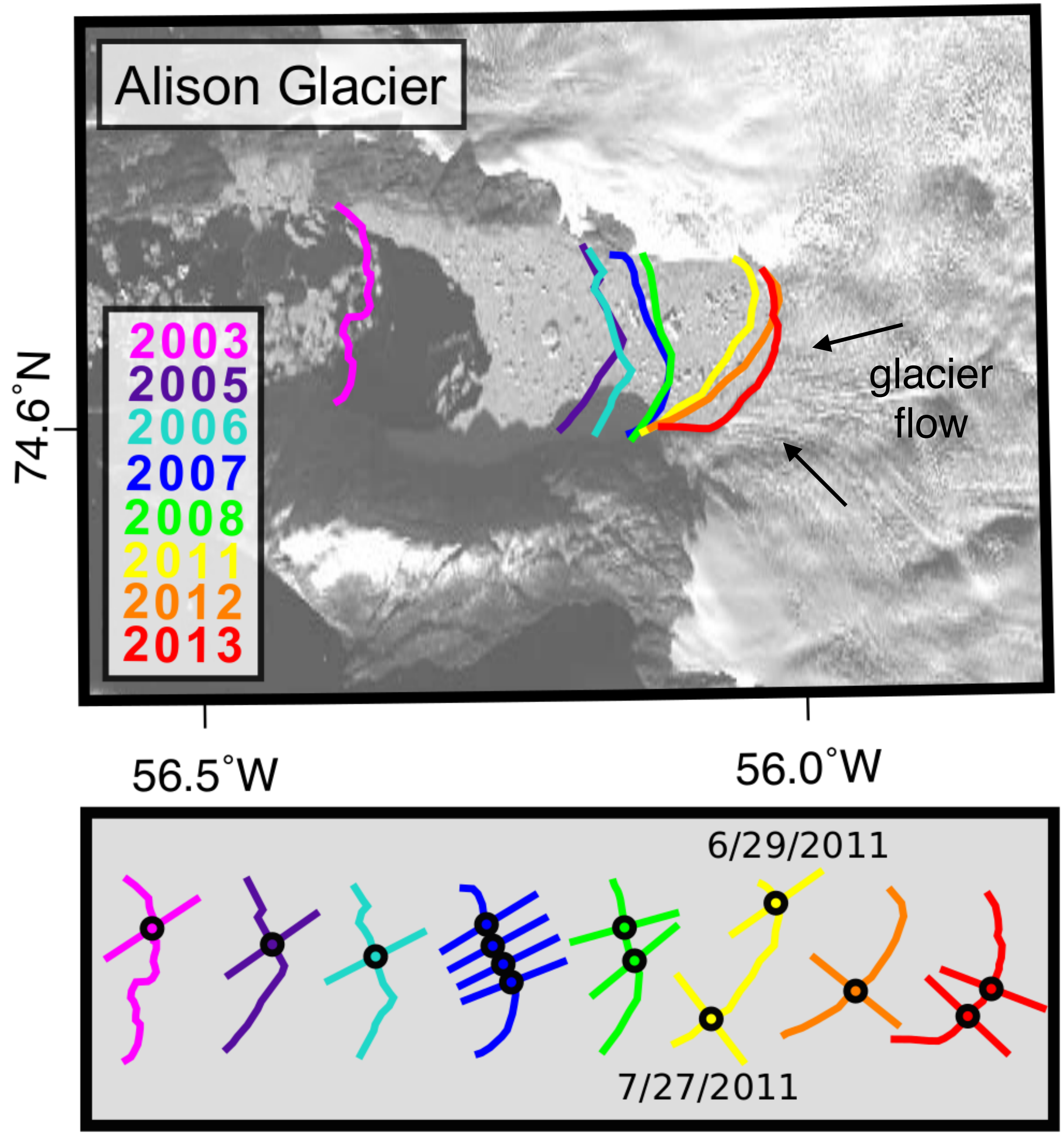
Jakobshavn Isbræ





Olsen & Nettles, 2017

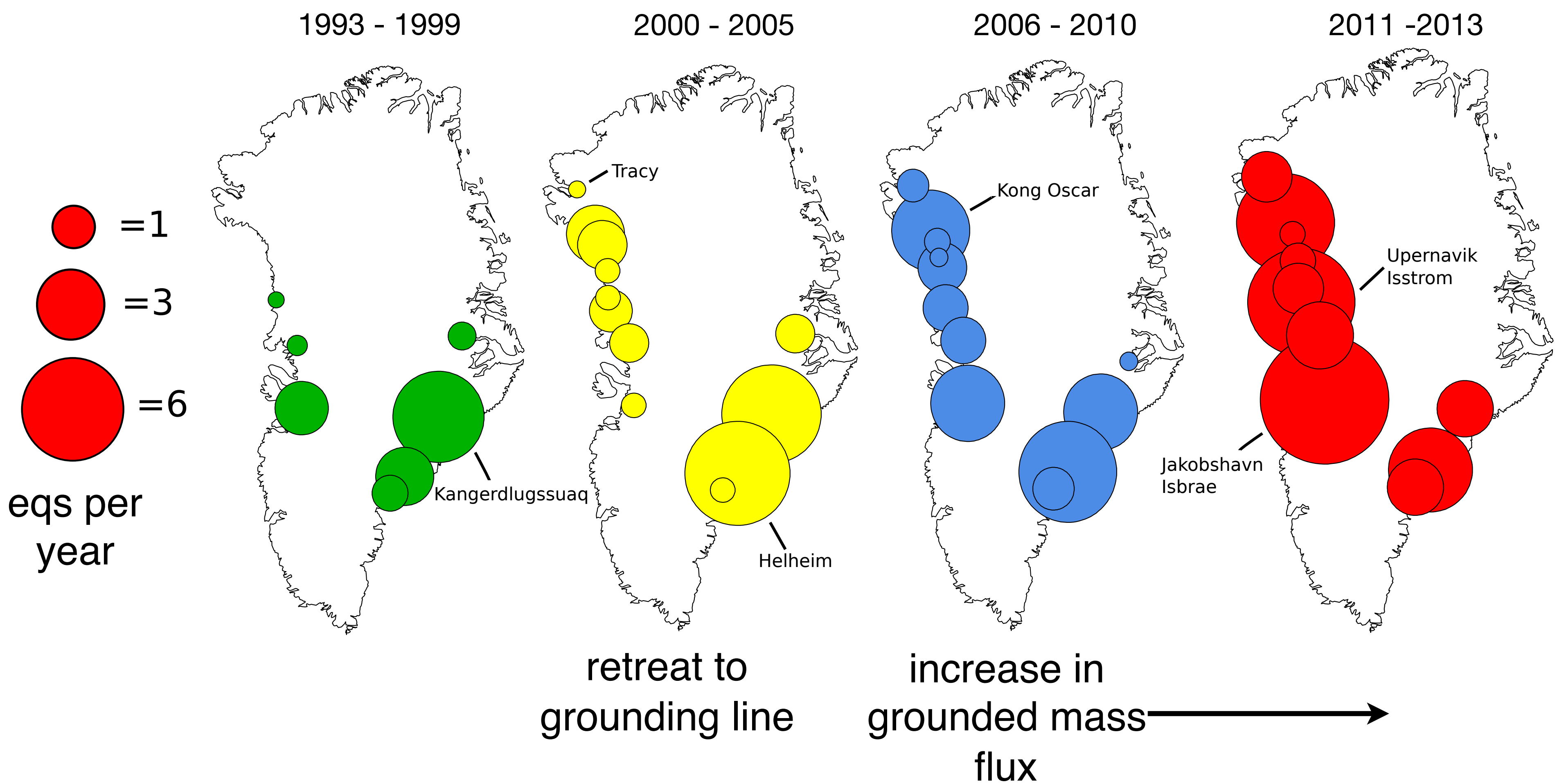
Glacial-earthquake locations track calving-front location, and force directions give geometry



bars: force directions (normal to glacier front)

(Olsen and Nettles, 2017)

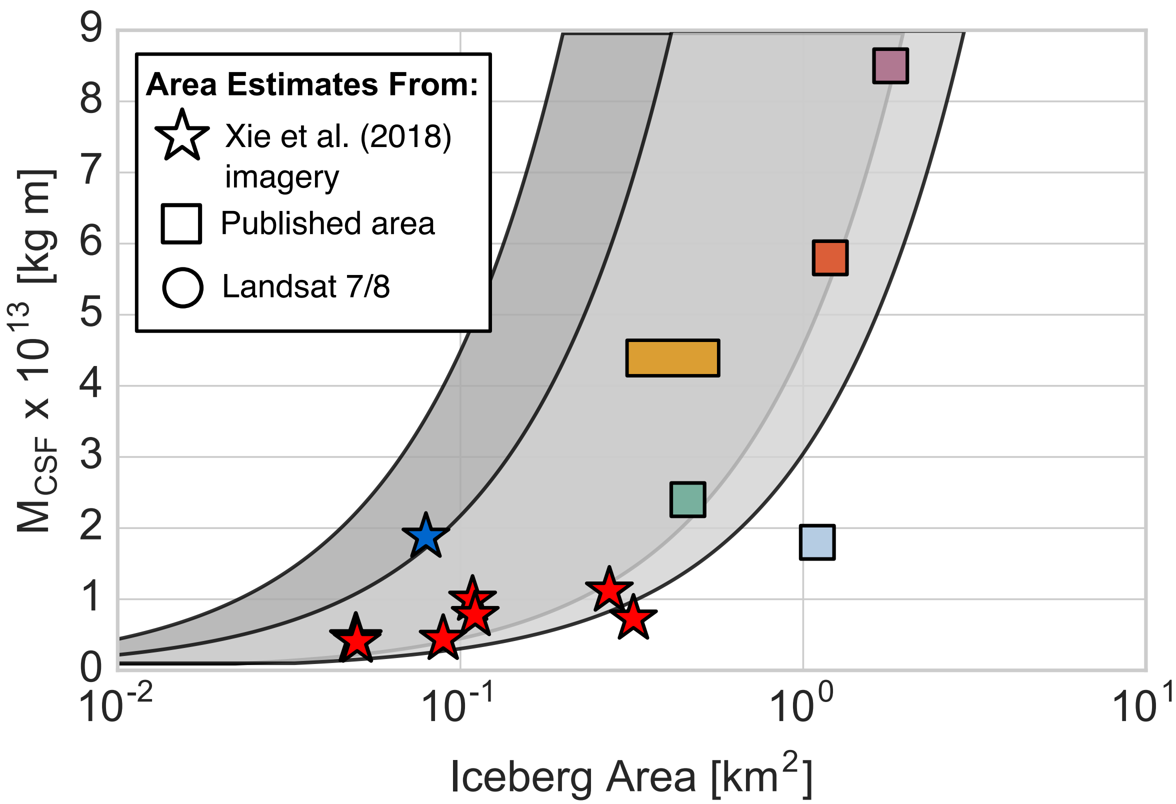
Evolution of glacial-earthquake production: links to glacier dynamics



(Veitch and Nettles, 2012; Olsen and Nettles, 2017)

Glacial-earthquake size is correlated with iceberg mass

earthquake size



iceberg size

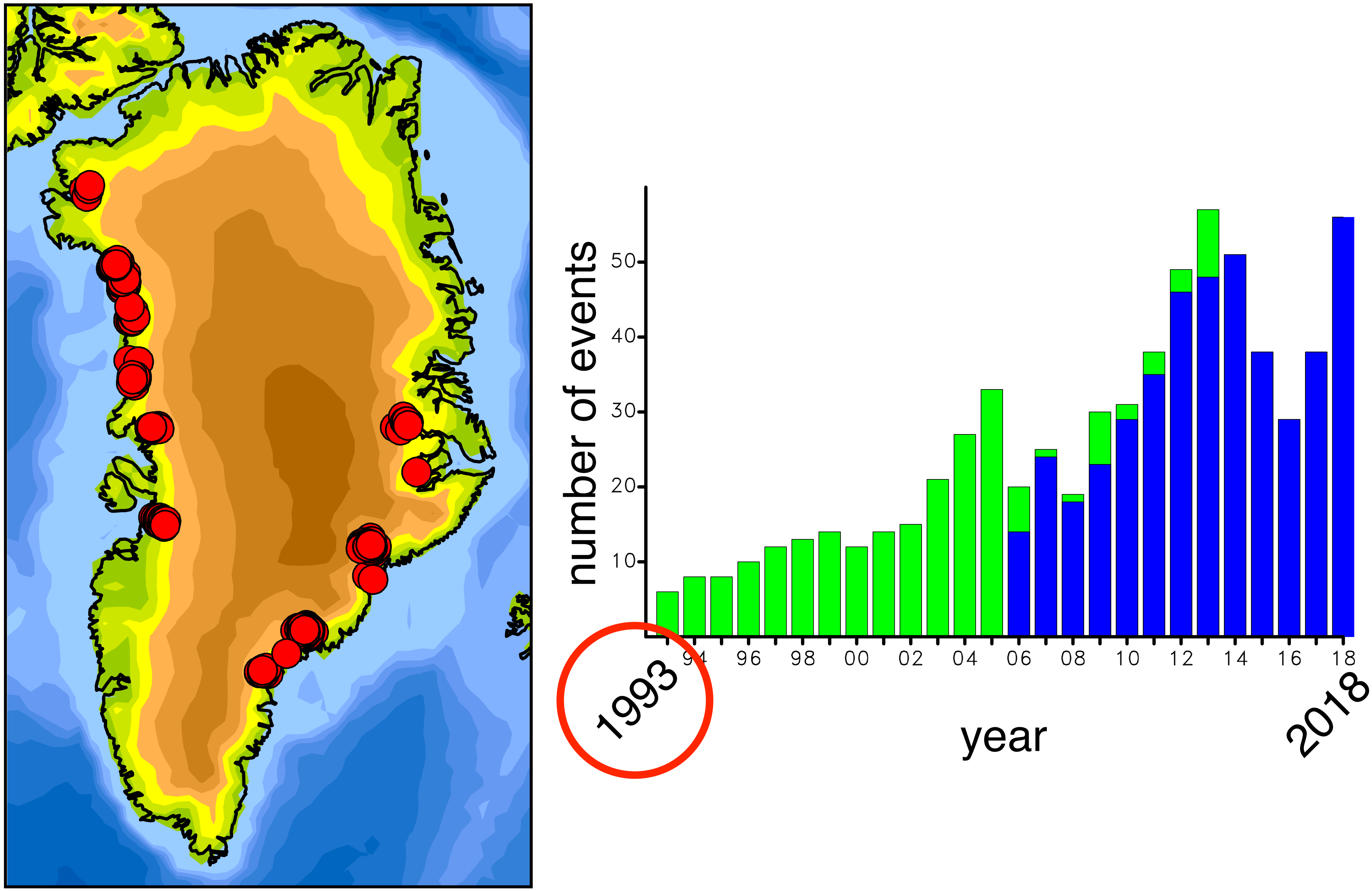
(Olsen and Nettles, 2019)

So, seismic signals give us information about
—timing of calving
—style of calving mass loss
—grounding state of glaciers
—geometry of calving fronts
—size of icebergs lost

Which tells us about
—glacier dynamics
—ice-ocean interactions
—ice-atmosphere interactions (probably)
—ice-front stability
—speed of ice-sheet response to climate changes
and maybe other things…

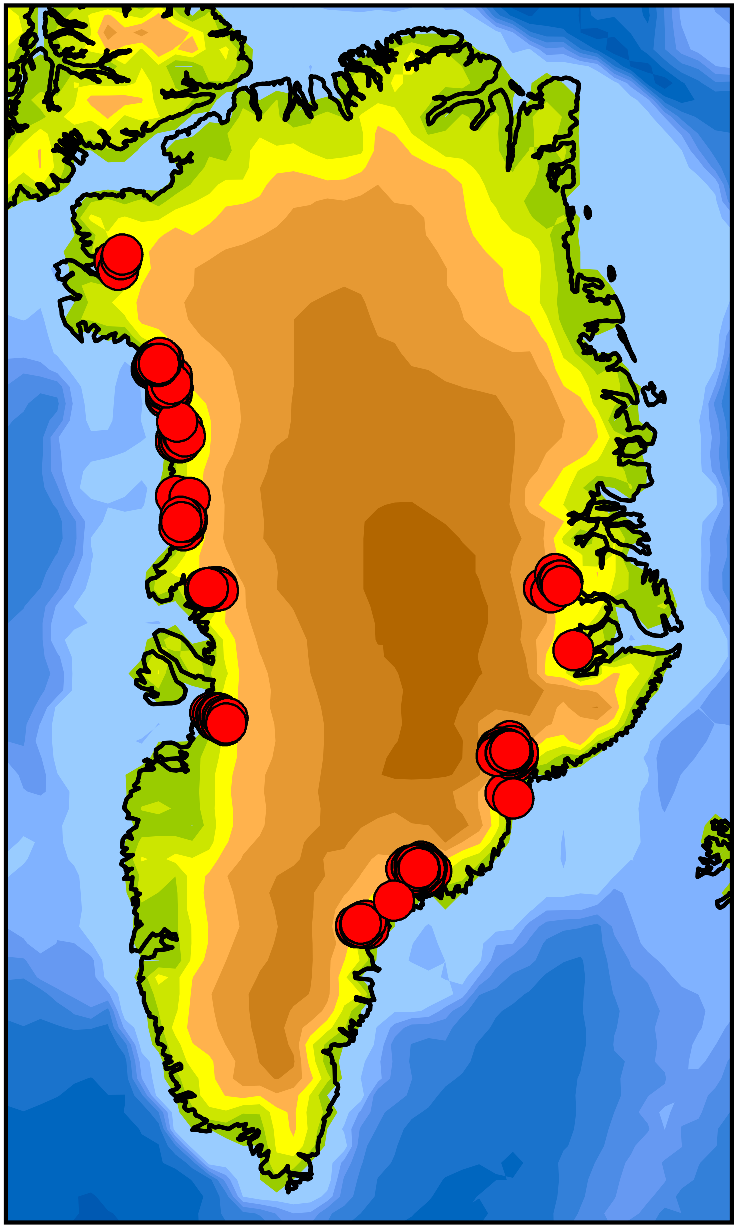
But!

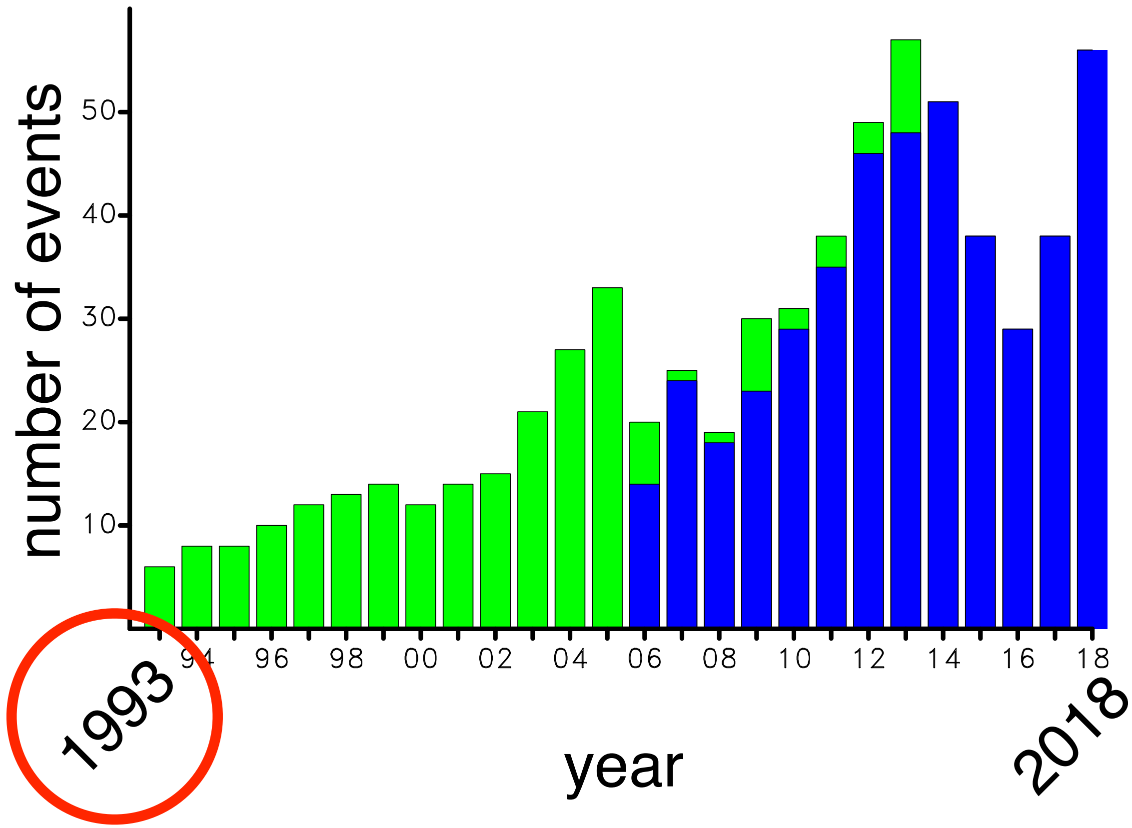
Glacial earthquakes in Greenland



(updated from Nettles and Ekström, 2010)

Glacial earthquakes in Greenland





What were the glaciers doing at earlier times?

(updated from Nettles and Ekström, 2010)

Can we do analysis on pre-digital data?

what is feasible now: modern, full-waveform analysis of (similar) events

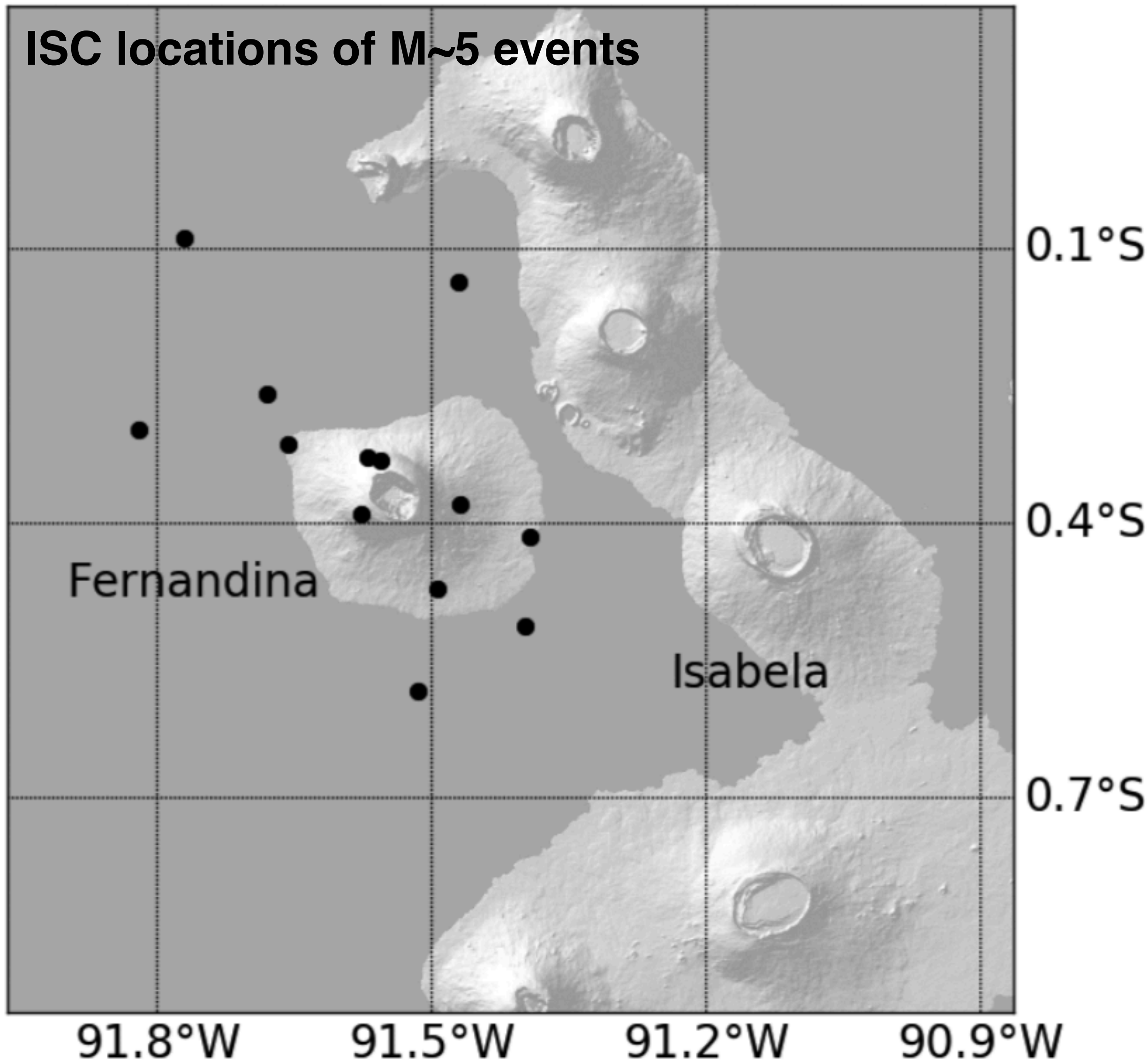
what is not feasible now: detecting the events

what is feasible now

an analog, and some additional, volcanic, motivation for preserving records:

caldera collapse at Fernandina Volcano, Galápagos Islands, 1968

Galápagos Islands (Fernandina) caldera collapse, 1968



(Wilding et al., in prep)

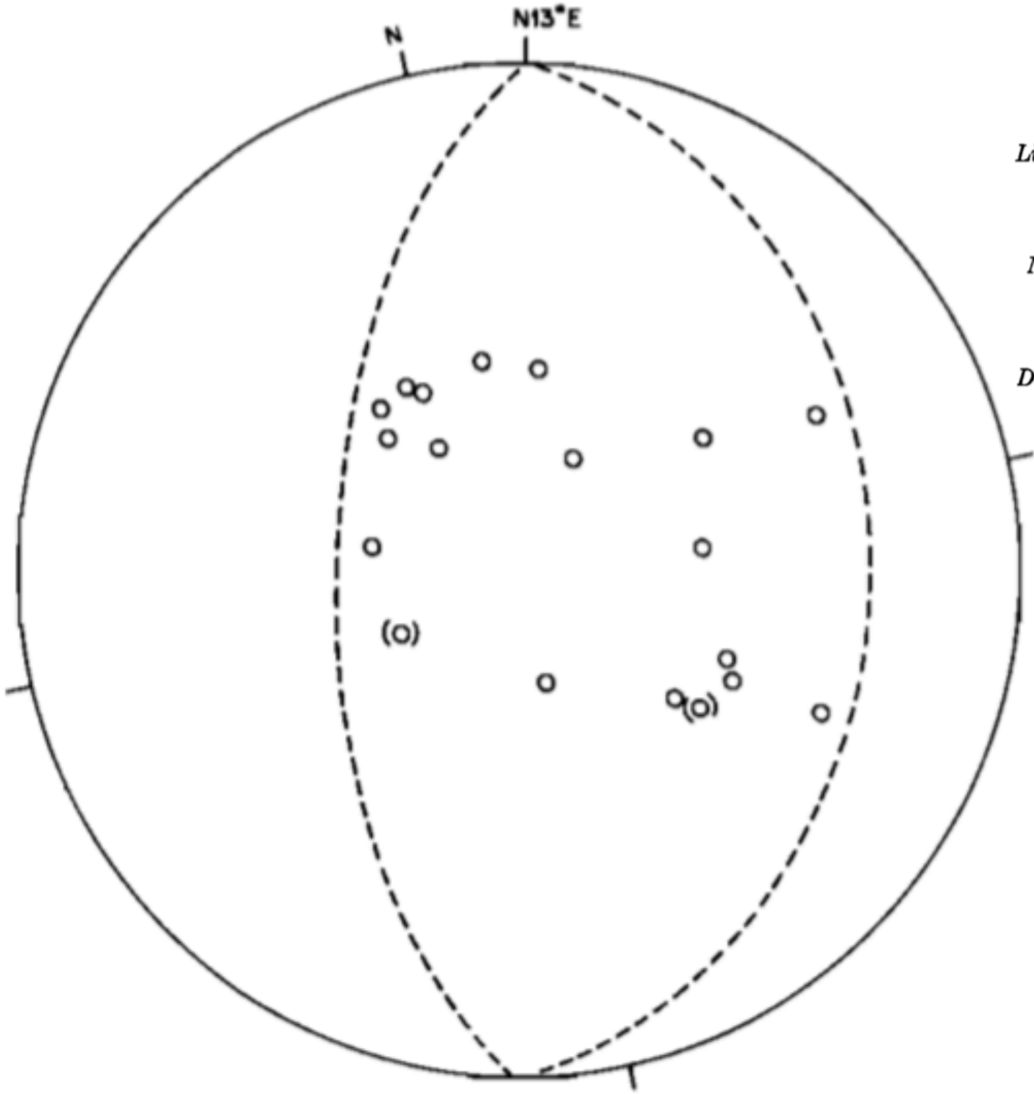


Fig. 16. The first motion pattern of the largest event of the swarm plotted on an equal area projection of the lower focal hemisphere. Dilatations are plotted as open circles. A possible fault plane orientation is shown by the dotted lines, but it is by no means unique. (Filson et al., 1973)

Seismicity of a Caldera Collapse: Galapagos Islands 1968

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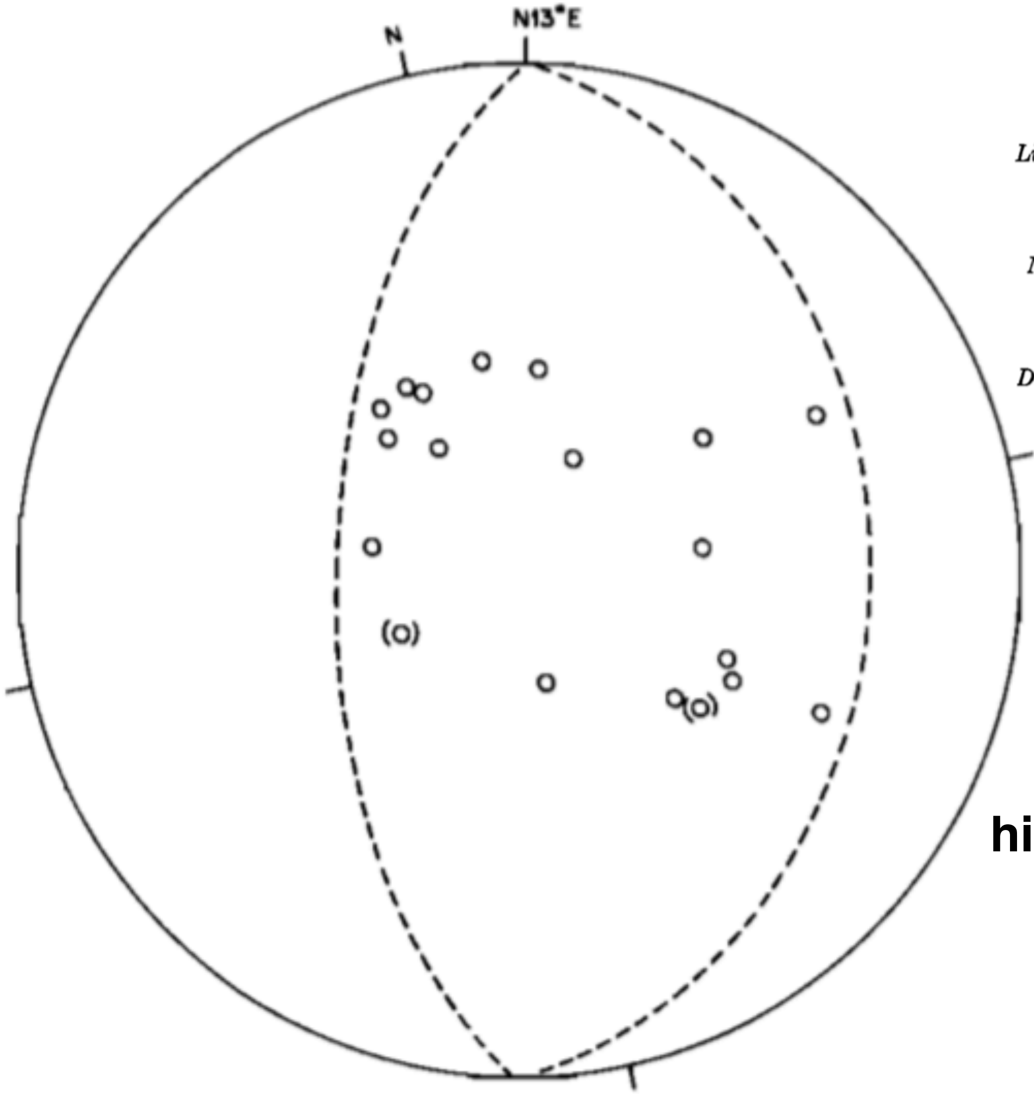

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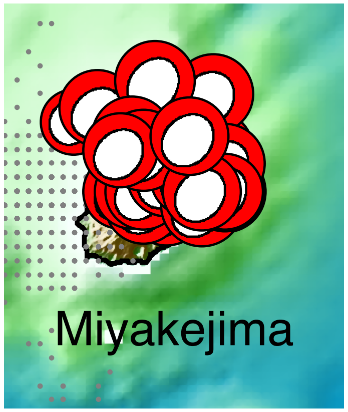
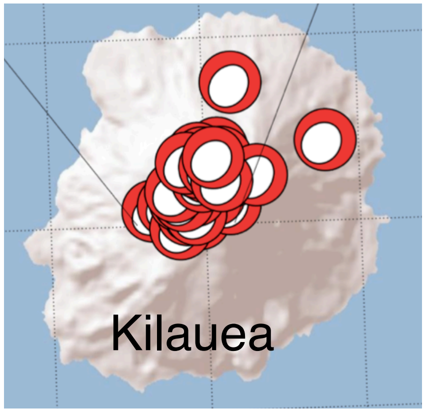
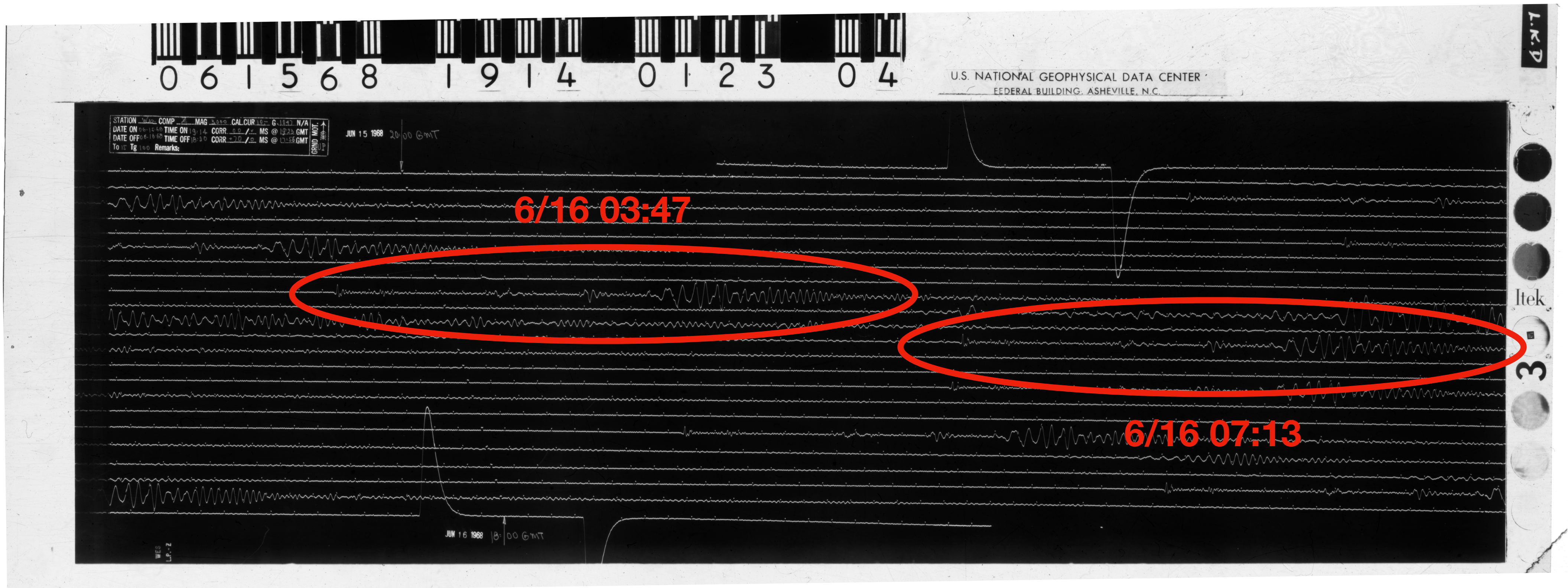
other collapse sequences have highly non-double-couple focal mechanisms



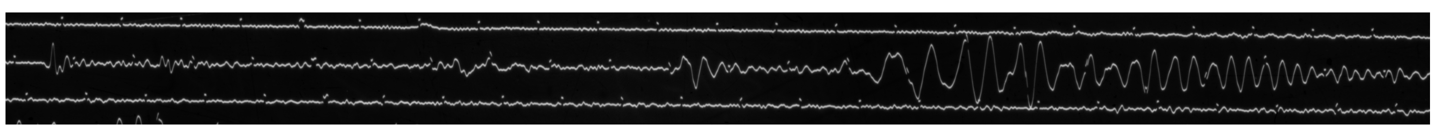


CMT analysis from digitized WWSSN records

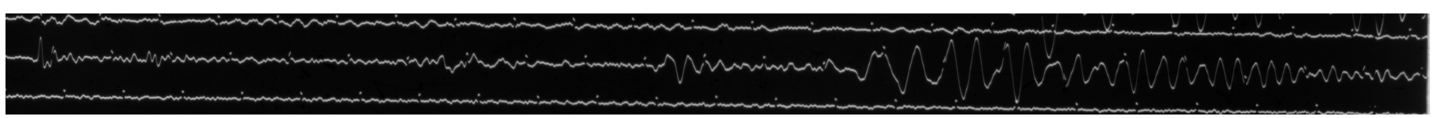
WES = Weston, MA
distance = 46.2°



6/16 03:47



6/16 07:13



(Wilding et al., in prep)

CMT analysis from digitized WWSSN records

*thanks to J. Wilding

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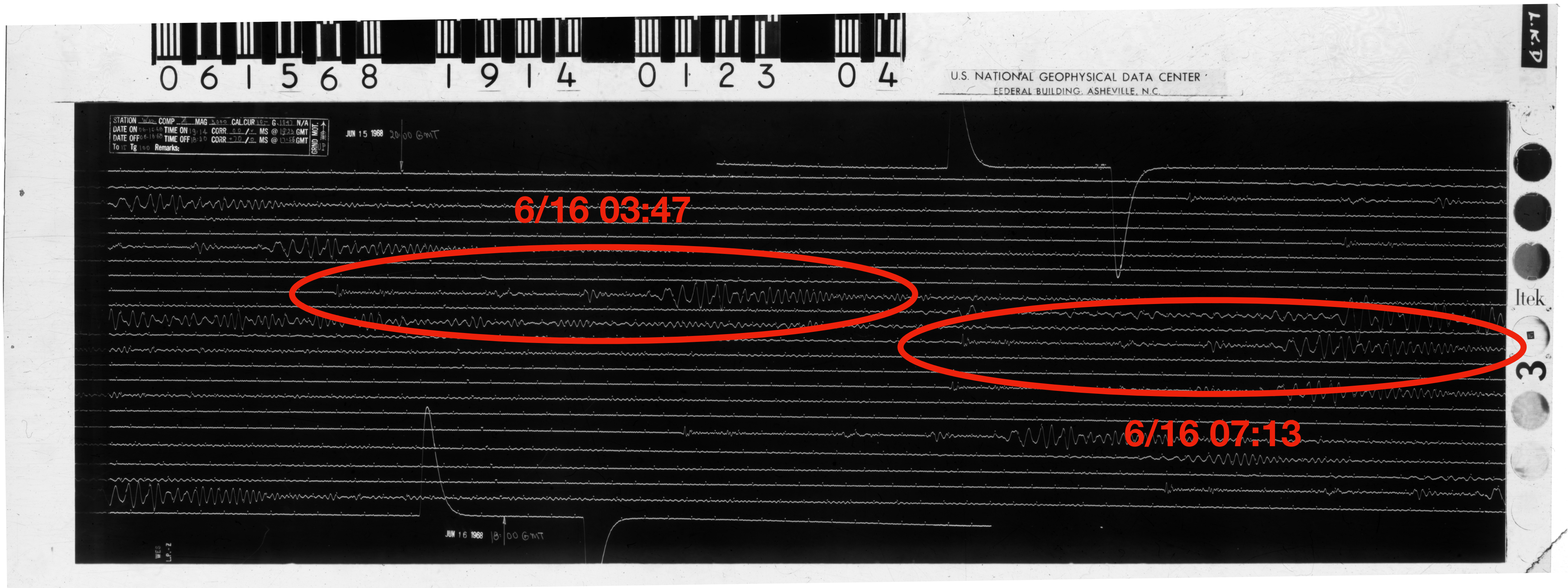

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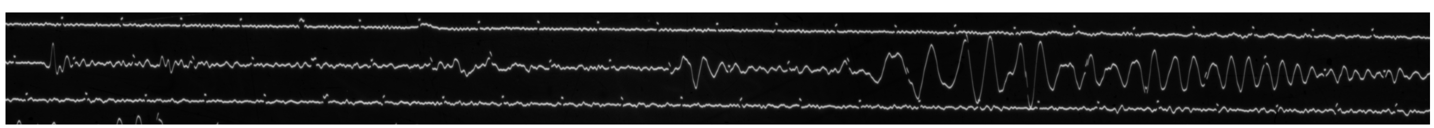
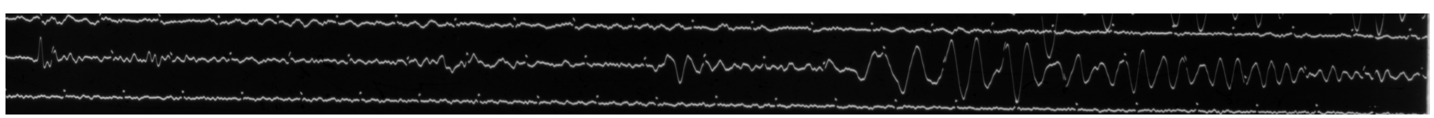


6/16 07:13



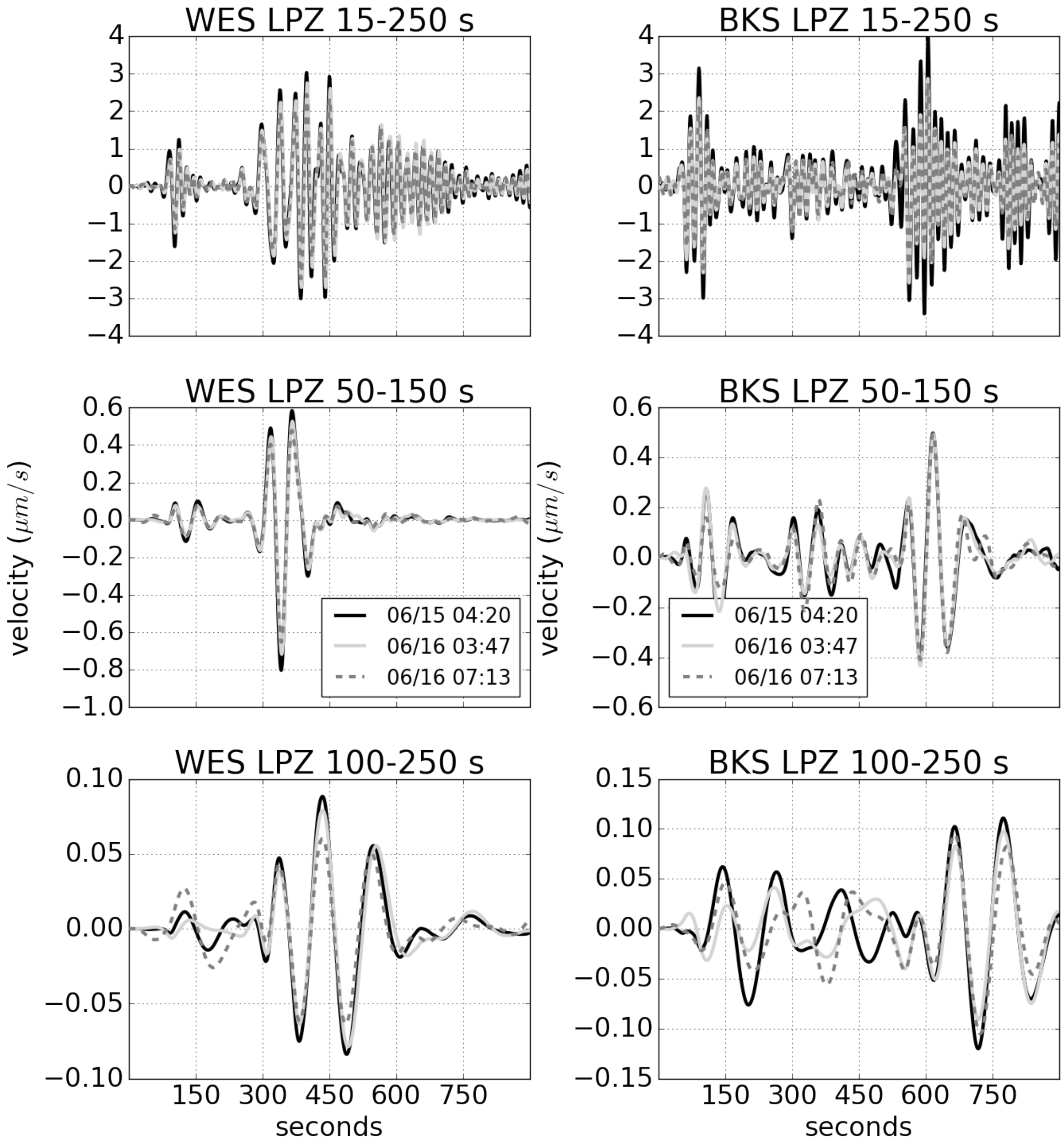
(Wilding et al., in prep)

Digitization using DigitSeis (Bogiatzis & Ishii, 2016; Lee, 2018)

Repeating events have consistent digitized signal across several period bands

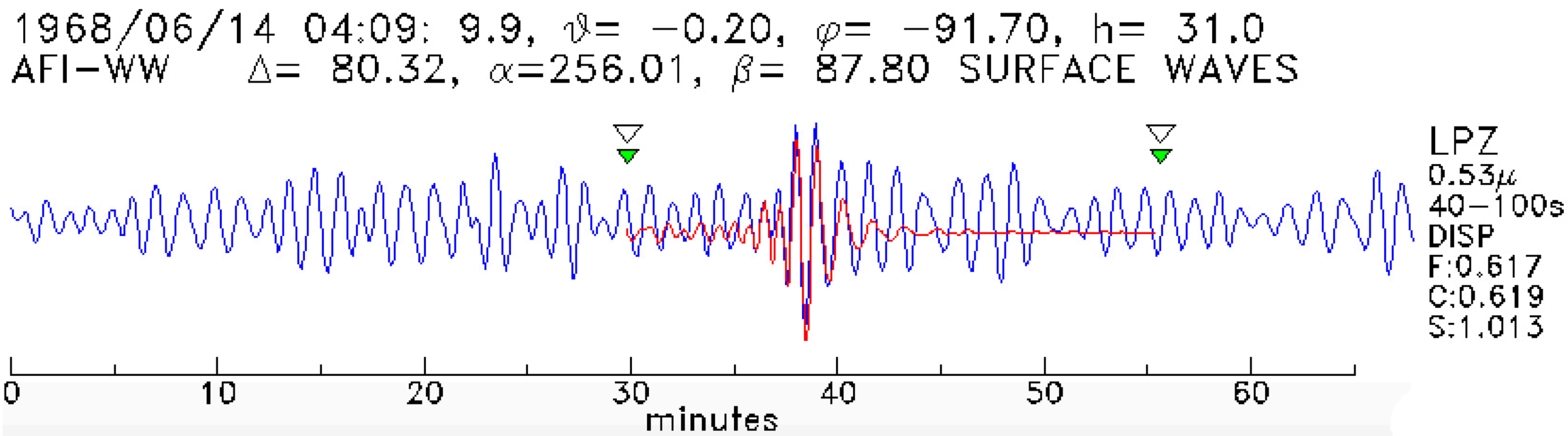
WES = Weston, MA
distance = 46.2°

BKS = Berkeley, CA
distance = 47.7°



(Wilding et al., in prep)

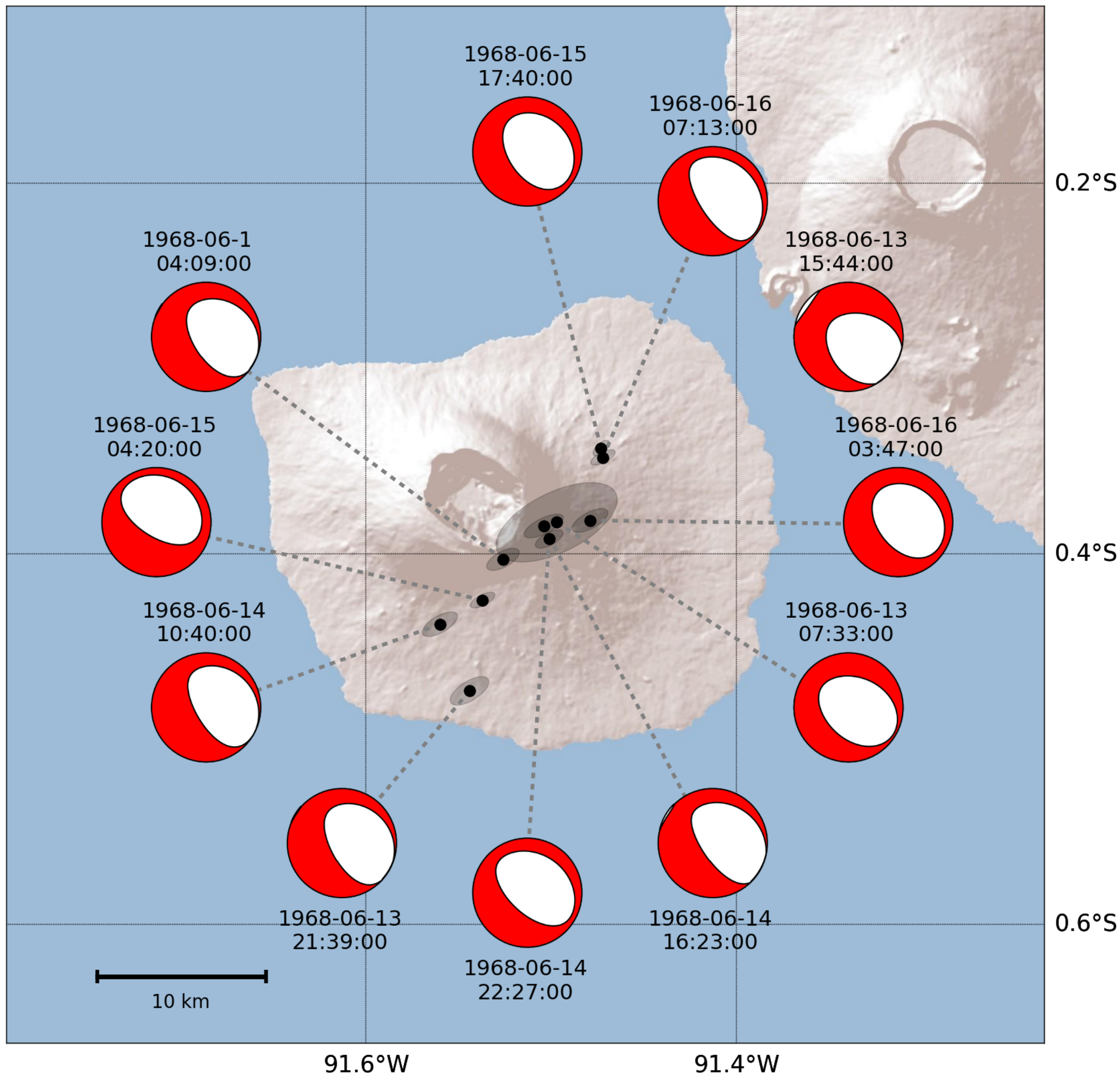
Waveform fitting for CMT analysis: intermediate periods, with corrections for dispersion



CMT project standard procedure for events of M ~4.2—6: tectonic, volcano-tectonic, glacial, landslide, bolide…

(Wilding et al., in prep)

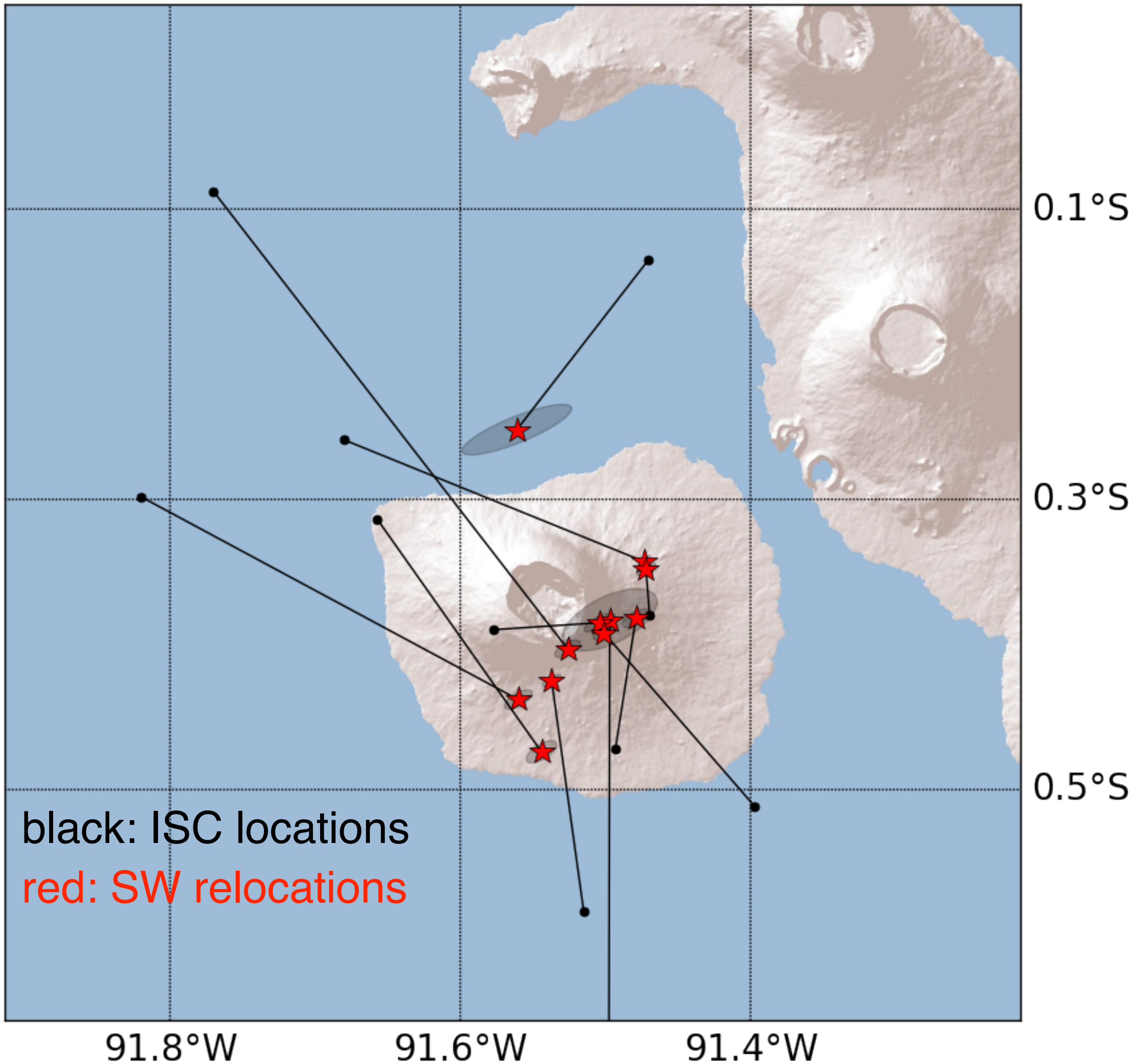
CMT results (6-10 stations, ~15–30 components)



Mw 4.6—5.6

(Wilding et al., in prep)

Event relocation using surface-wave cross-correlation



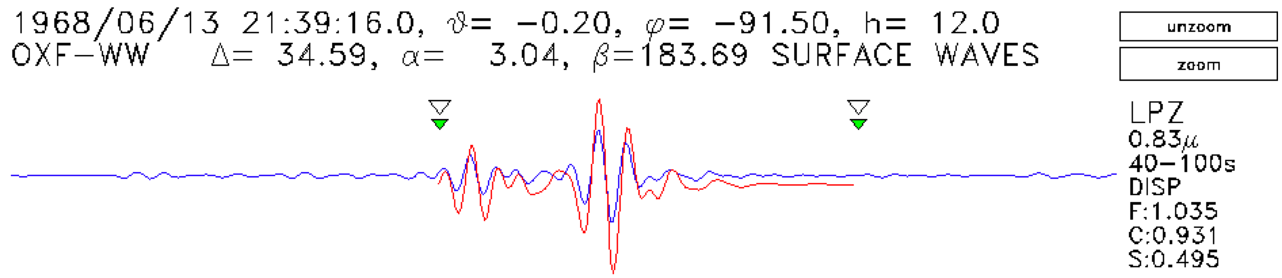
(Wilding et al., in prep)

Metadata!

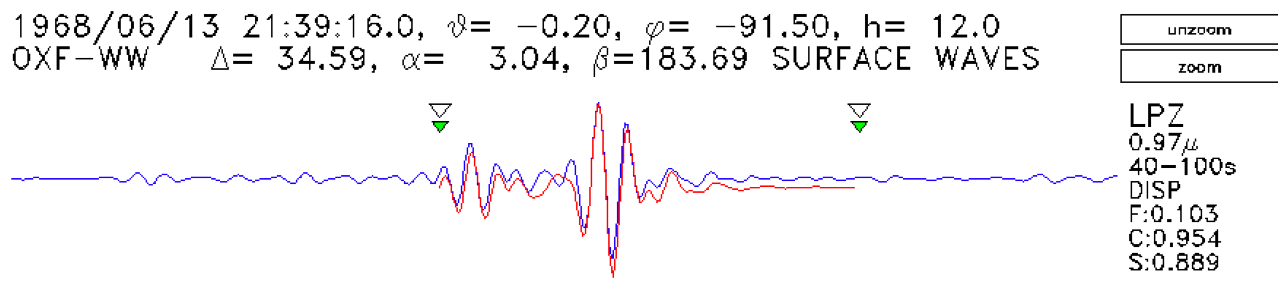
Quantitative waveform analysis requires highly accurate instrument response information

Importance of correct metadata

OXF LP instrumentation magnification factor hand-labeled at 3000



Corrected to 1500

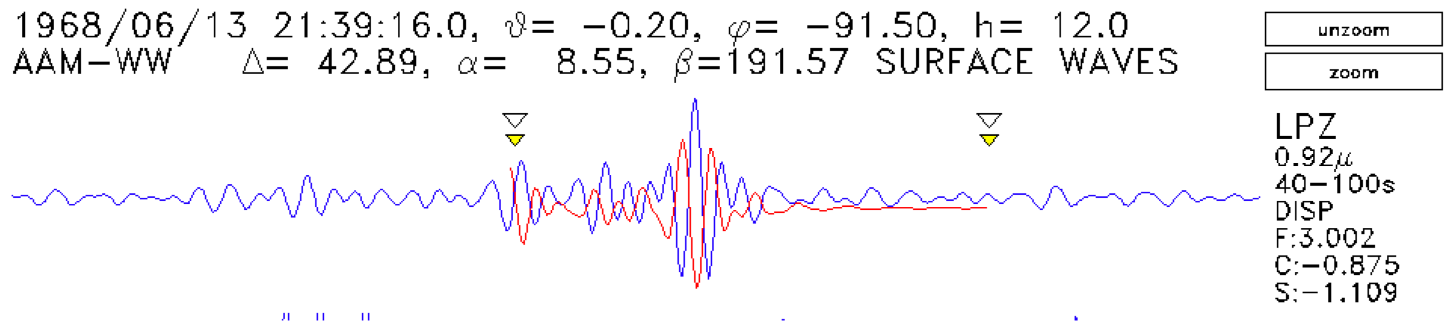


From WWSSN Data Users Guide: “Often, the level of microseismic activity is seasonal and the magnifications at some stations were adjusted accordingly.”

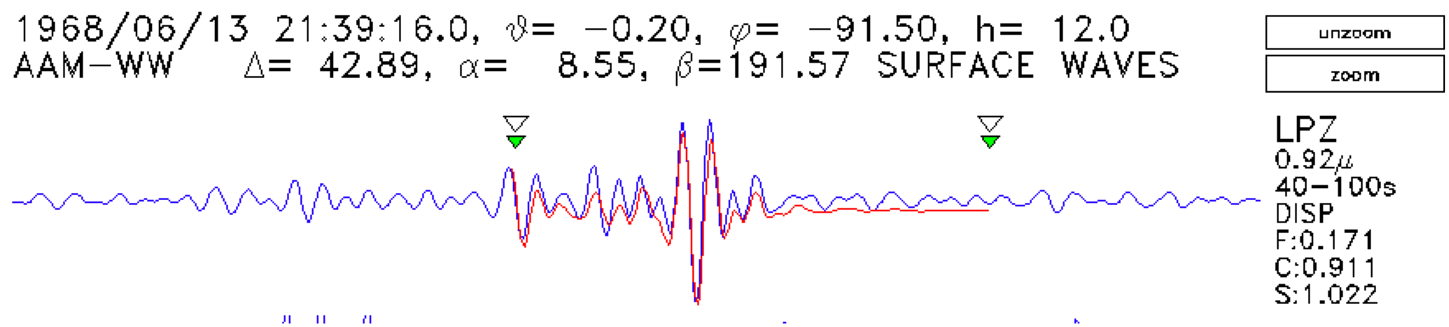
Peterson and Hutt, 2014

Importance of correct metadata

AAM Z-component displays reversed polarity

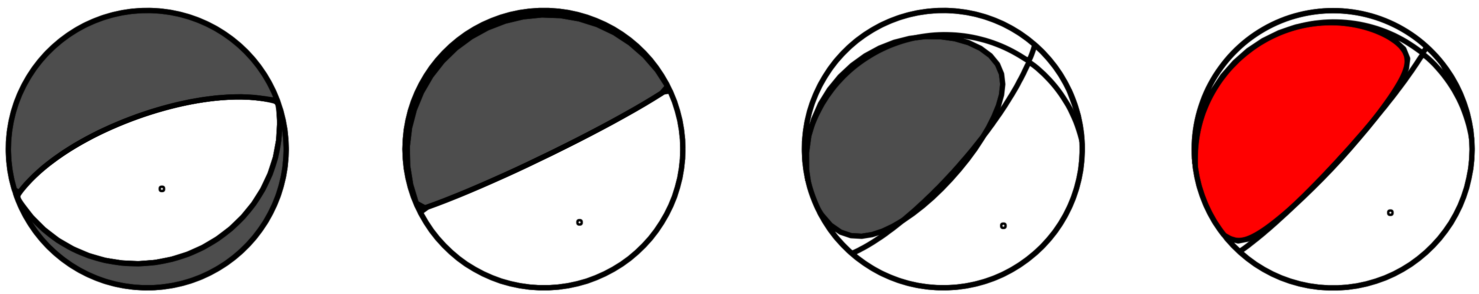


Corrected polarity

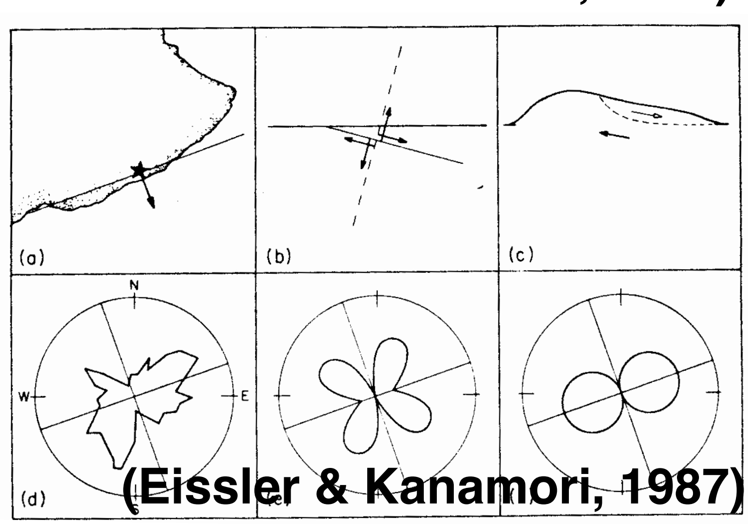


Another example: the 1976 Kalapana, Hawaii earthquake

Underthrusting, normal faulting — or a landslide?



1.8e20 N-m (Ando, 1979)	**1.2e20 N-m (Furumoto & Kovach, 1979)**	**1.4e20 N-m (Kawakatsu, 1989)**	**3.8e20 N-m (Nettles & Ekström, 2004)**



(Eissler & Kanamori, 1987)

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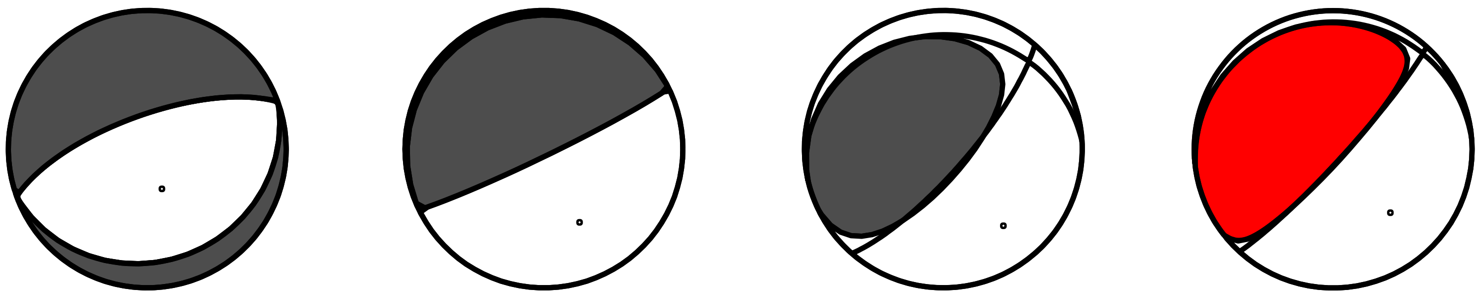

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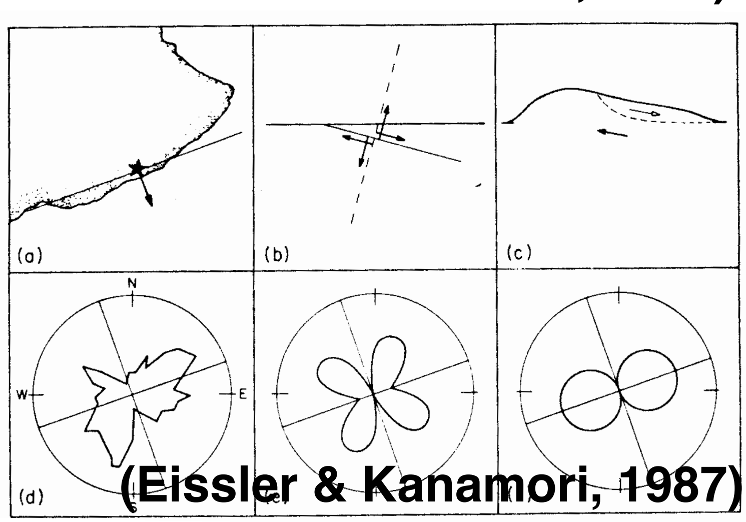


(Eissler & Kanamori, 1987)

New result consistent with seismic data, tsunami heights, geology — no need for landslide to explain data….

after recalibration of entire HGLP network!

Metadata!

Quantitative waveform analysis requires highly accurate instrument response information

back to glacial earthquakes

what is not feasible now: detecting the events

events are slow — no visible SP body waves

same is true for some caldera-collapse events,
and for landslides

How we do it today:

Detection of seismic sources using long-period surface waves

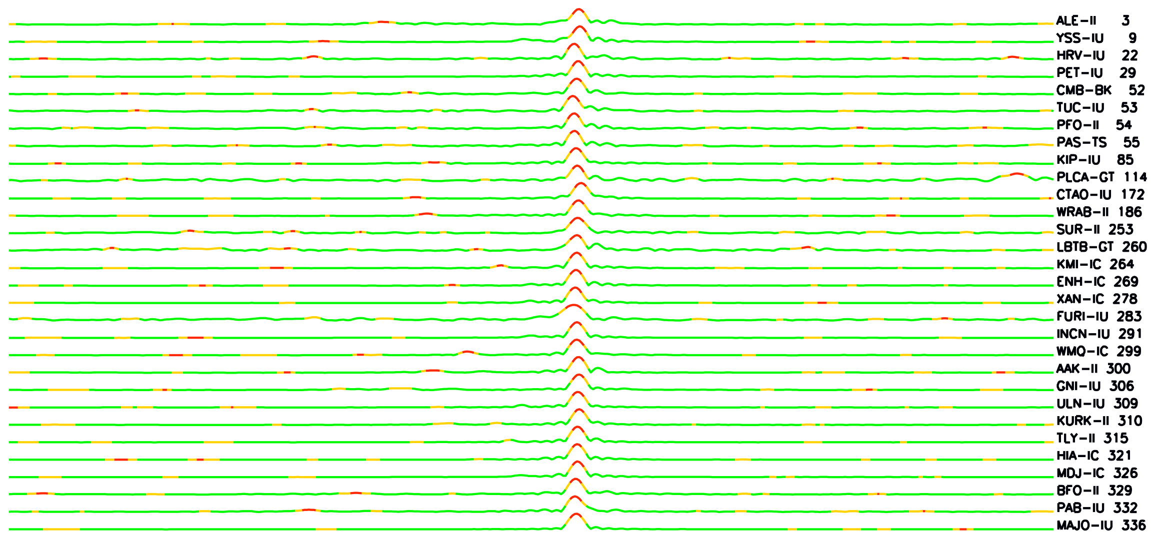
1. Collect seismograms from the GSN
2. Low-pass filter, 35-150 s period
3. Select a target location
4. Calculate dispersion curves to all stations

⋮

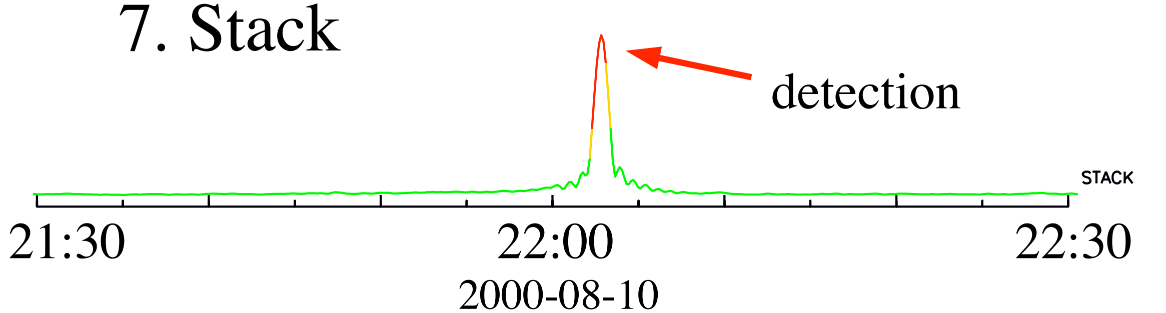
(Ekström and Nettles, 2002; Ekström, 2006)

5. Deconvolve propagation effects from all seismograms (Φ_P , A_Δ , A_Q)

6. Calculate envelope function



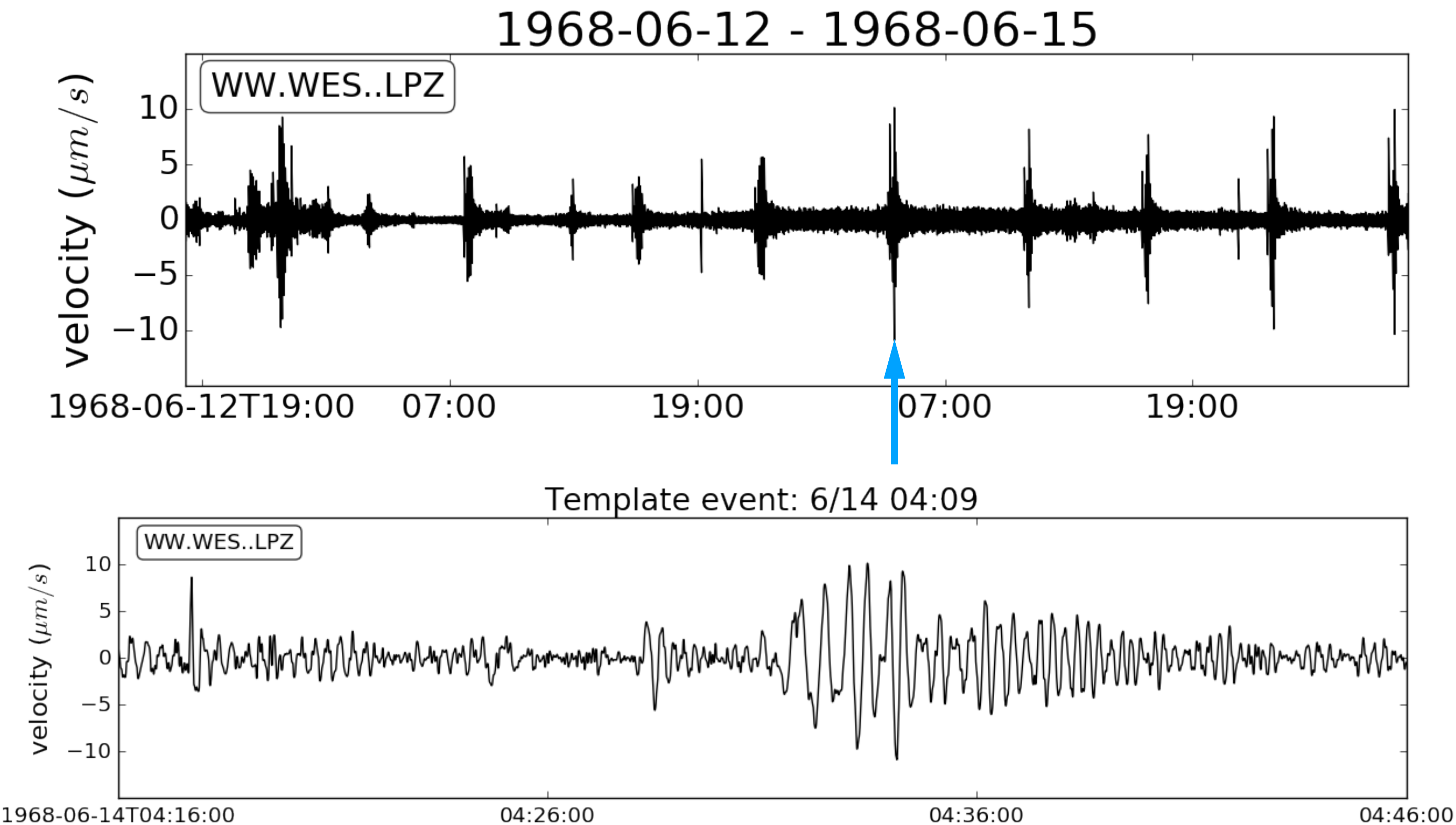
7. Stack



8. Detect source pulse using matched filter

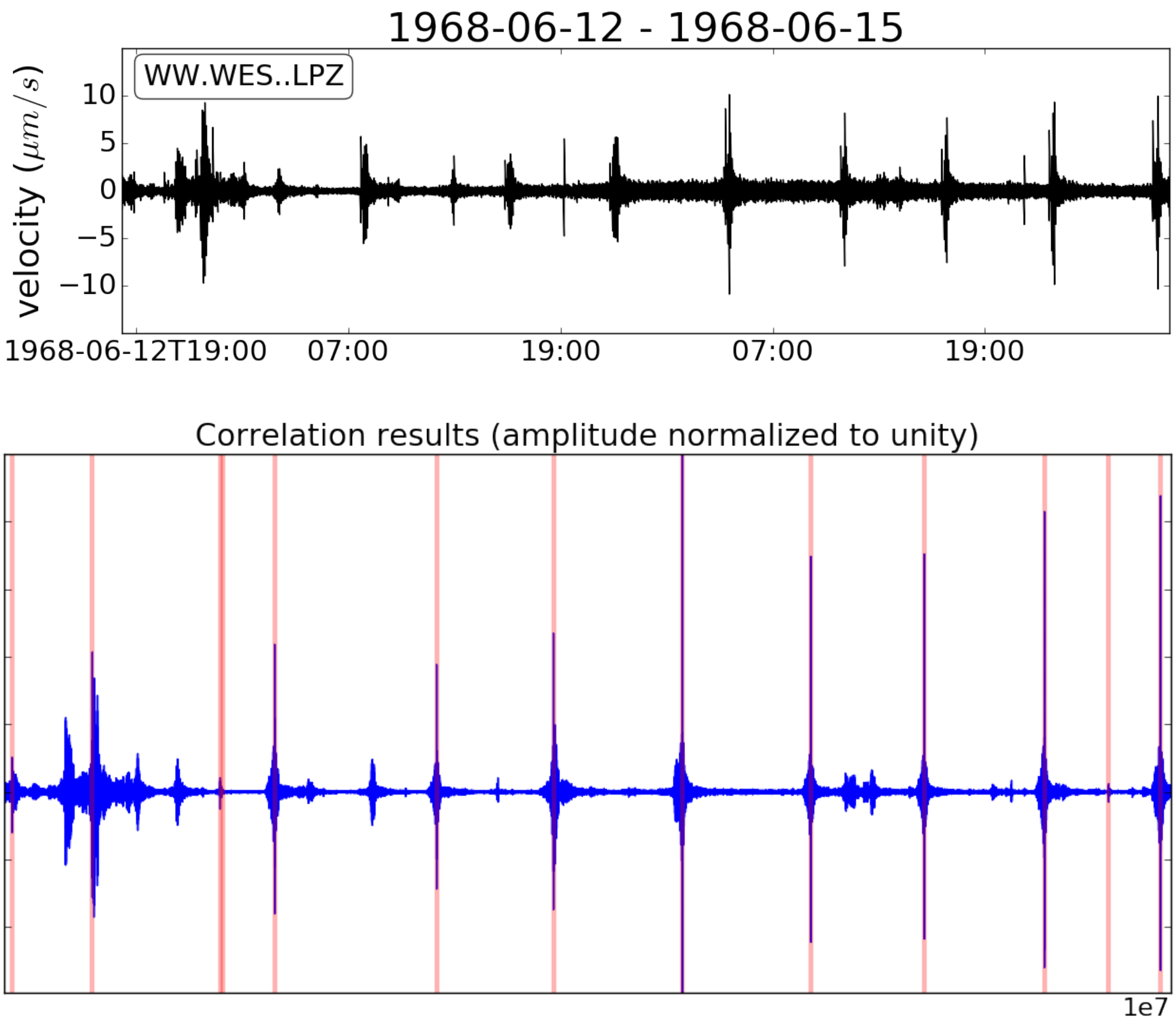
(Ekström and Nettles, 2002; Ekström, 2006)

Fernandina: template matching with continuously digitized data
60 hours of data, one station, one component
(only 12 hours of digitizing! super fast!)



(Wilding et al., in prep)

Fernandina: template matching with continuously digitized data



(Wilding et al., in prep)

what is not feasible now: detecting the events

but maybe there is a “cheaper” way to do it; and, probably, current approaches will get cheaper

a final, inspirational, non-seismic example, from Greenland and Denmark

air-survey photos of Greenland: collected, used to make maps, classified, "archived" in an old fort, forgotten… rediscovered, and re-used for modern analysis!

(Bjørk, Kjær, et al., 2012)

Figure 1 : Historical aerial photographs from the seventh Thule Expedition, 1933.

From: An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland

The oblique photographs were recorded from a Heinkel MKII hydroplane and show the Helheim Glacier (SEGL014). Images (no. 20.907–20.910) were recorded from left to right at 4,000 m elevation.

(Bjørk, Kjær, et al., 2012)

Table 1 | Images and sources used in this study.

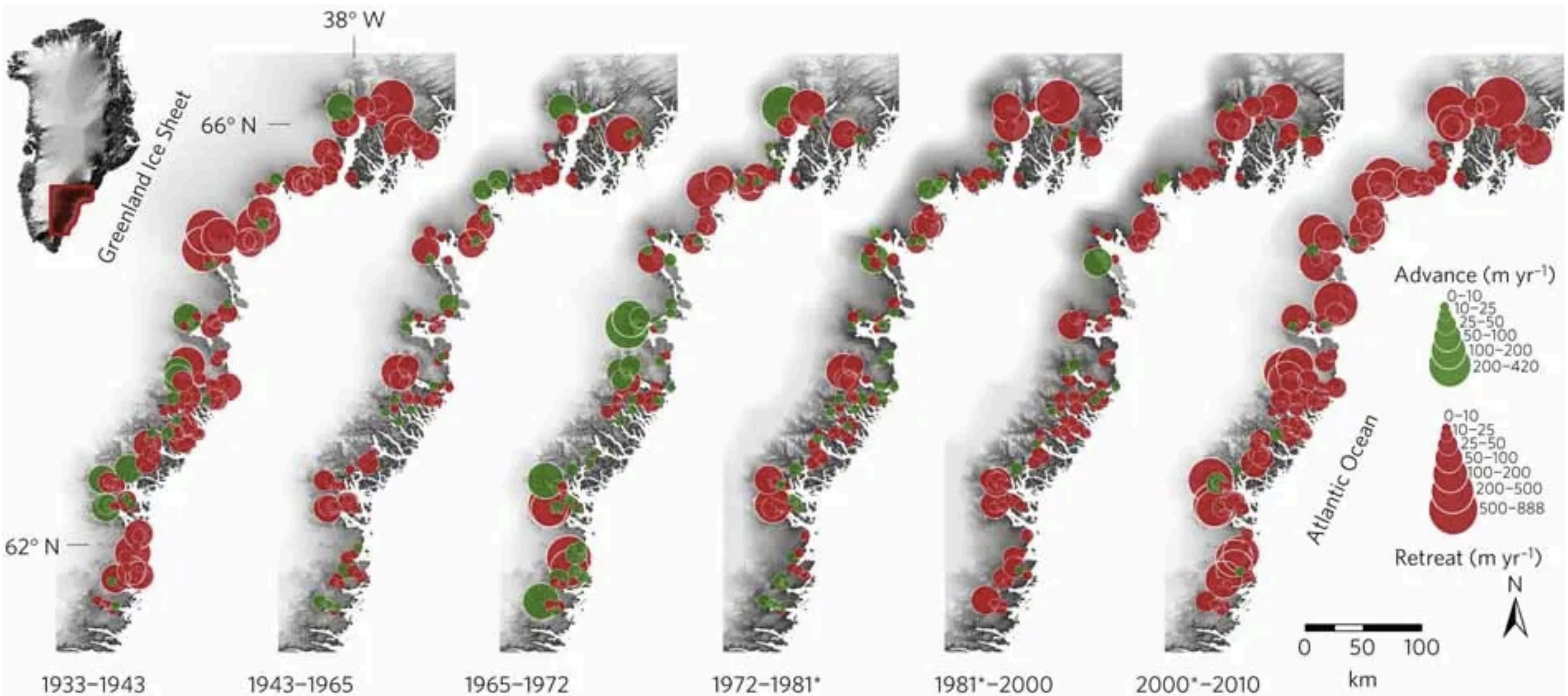
Year	Date	Data type	Source	Ground resolution	Number of images used
1931	20 July	Oblique aerial	BAARE	<60 m	36
1932	August	Oblique aerial	Seventh Thule	<60 m	9
1933	August	Oblique aerial	Seventh Thule	<60 m	212
1933	Late July	Terrestrial	Seventh Thule	n.a.	4
1943?	End of melt season	Vertical aerial	USAAF/USN	~1.7 m	124
1965	Late July	Satellite	Corona	0.61 m	28
1972	Early September–early October	Satellite	Landsat 1 MSS	60 m	9
1981/1985	Late July	Vertical aerial	KMS	4 m (ortho)	311
2000	August	Satellite	Landsat 7 ETM +	15 m (pan)	8
2010	Late July/August	Satellite	Landsat 7 ETM +	15 m (pan)	9

KMS, National Danish Survey and Cadastre; USAAF/USN, United States Army Air Force/United States Navy; n.a., not applicable. The ground resolution of the oblique aerial images vary within the frame of the image; only images within a ground resolution of 60 m or better have been used owing to the relative higher uncertainties in rectifying the oblique images. 1981/1985 vertical aerial images from KMS were scanned at a resolution of ~2 m. The Landsat 7 scenes have a spatial resolution of 30 m and were pan-sharpened to a resolution of 15 m using the panchromatic band 8. The exact time of recording remains uncertain for the USAAF/USN images (see Supplementary Information); based on the snow conditions, images must have been recorded at the end of the melt season.

aerial, terrestrial; front-mounted, rear-mounted, handheld cameras; times and dates sometimes not known; ground control in a glaciated region, with changing snow conditions ; etc….

Figure 2: Frontal changes of southeast Greenland glaciers.

From: An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland



(Bjørk, Kjær, et al., 2012)

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SCIENTIFIC DATA

OPEN

SUBJECT CATEGORIES

» Cryospheric science

» Geomorphology

» Climate and Earth system modelling

Data Descriptor: Digital elevation model and orthophotographs of Greenland based on aerial photographs from 1978–1987

Niels J. Korsgaard[1], Christopher Nuth[2], Shfaqat A. Khan[3], Kristian K. Kjeldsen[1,4], Anders A. Bjørk[1], Anders Schomacker[1,5] & Kurt H. Kjær[1]

Received: 04 December 2015

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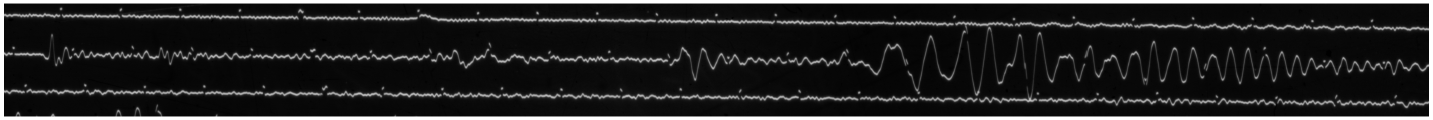
Wow.

1968/6/16 03:47



Recap:

Lots to be done for study of
—smaller, interesting earthquakes
—glaciers and climate
—volcanos
—landslides

If we can access
— high-quality data
— accurate, complete metadata

1968/6/16 07:13