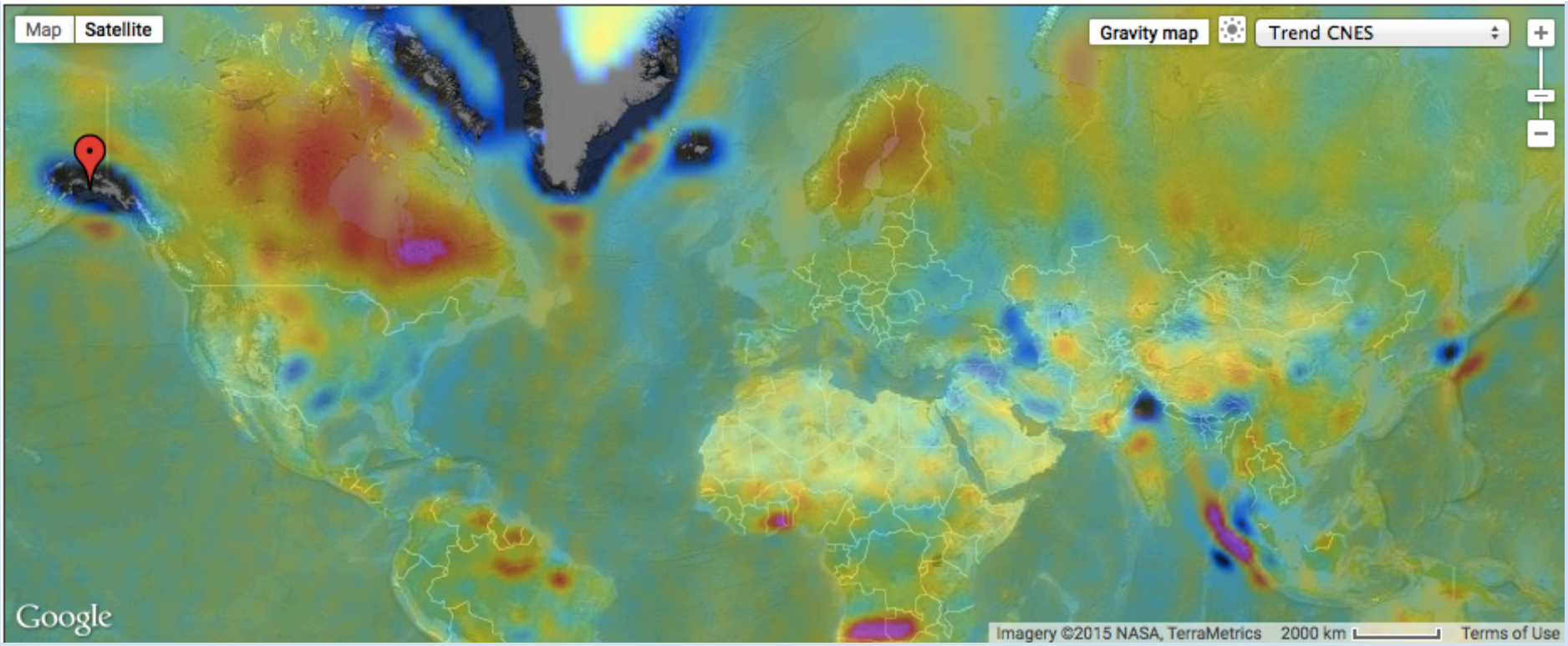


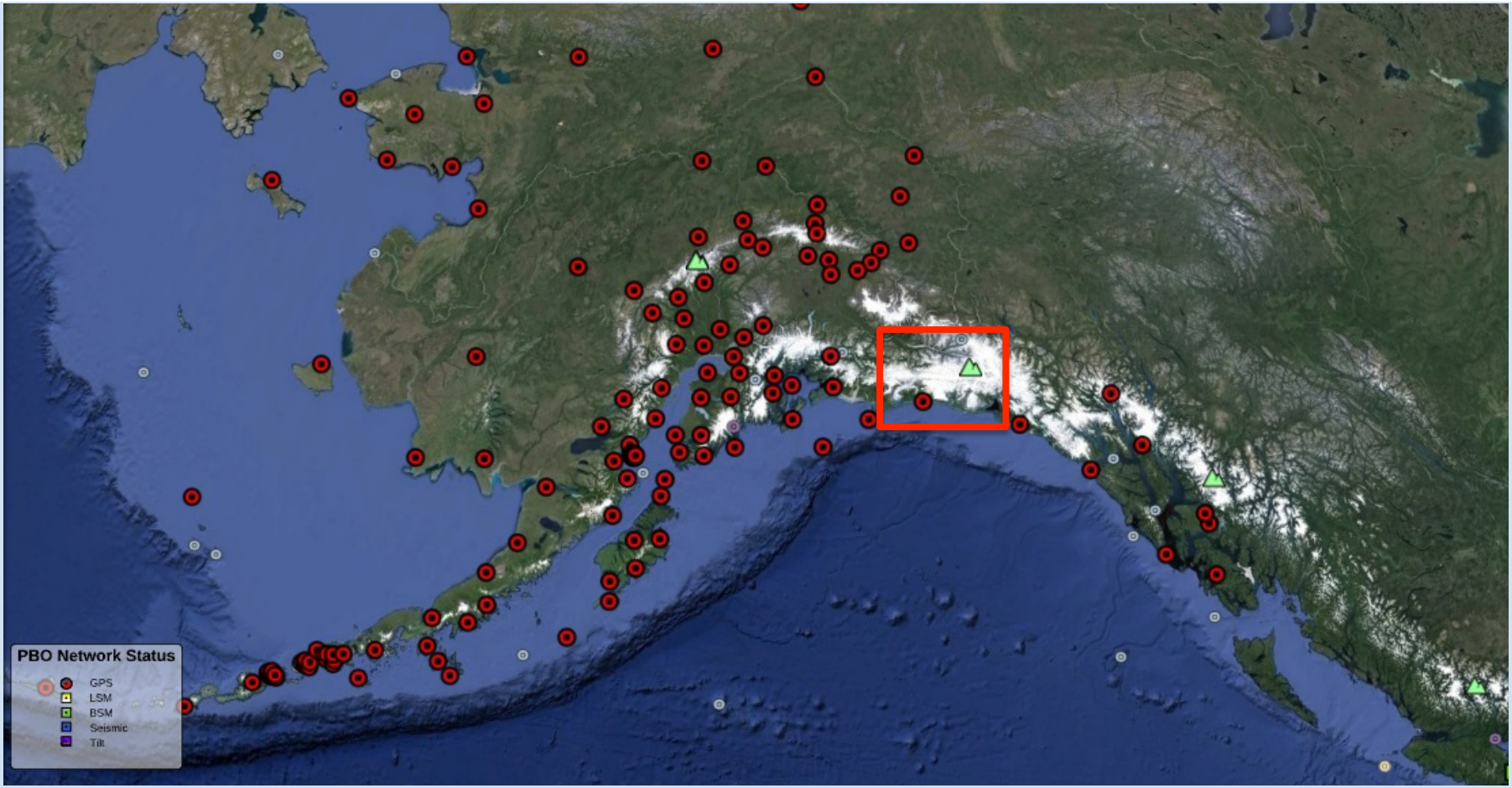
Cryospheric Fluctuations, Crustal Deformation and *Earthquakes*

Jeanne Sauber, NASA Goddard Space Flight Center

What are the different temporal and spatial scales of ice mass changes in southern Alaska?

How do they influence crustal deformation and earthquake occurrence?

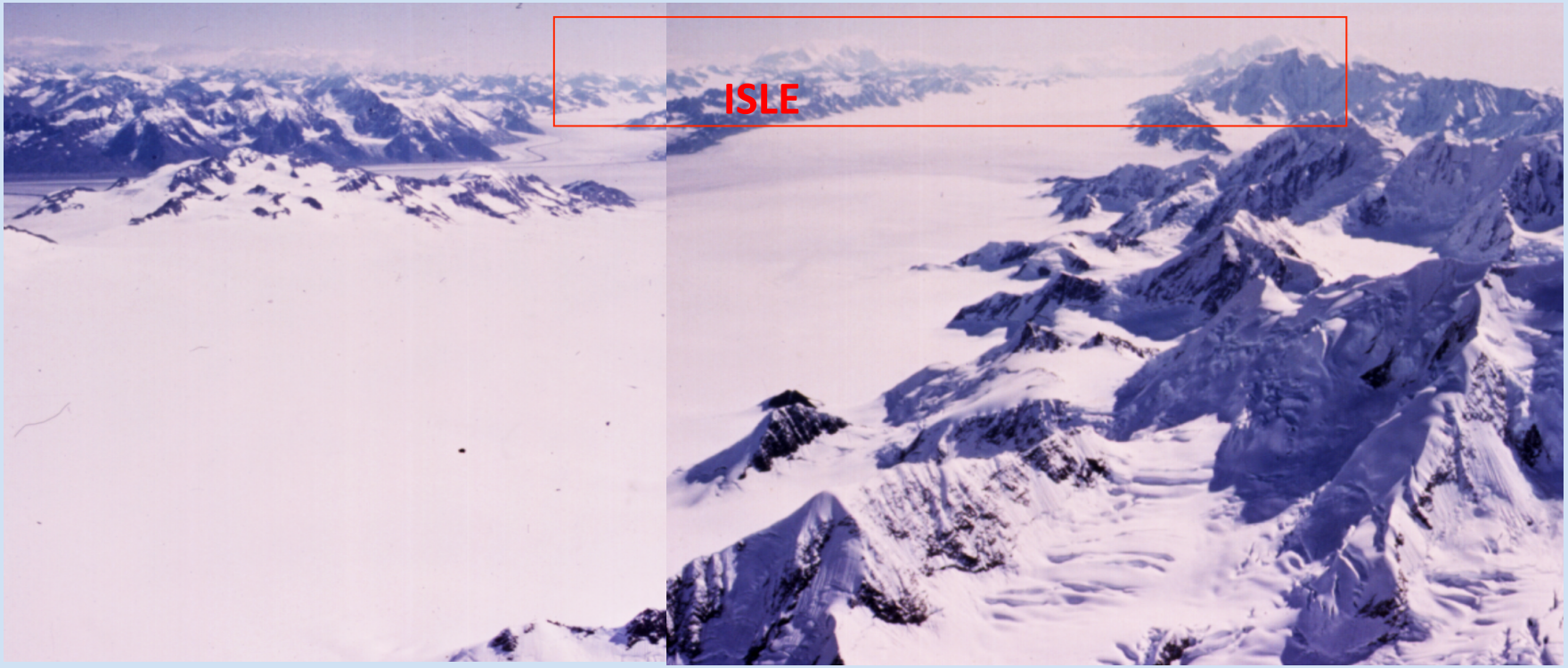
"Made with www.thegraceplotter.com, courtesy of CNES/GRGS"



Current distribution of cGPS stations in southern Alaska

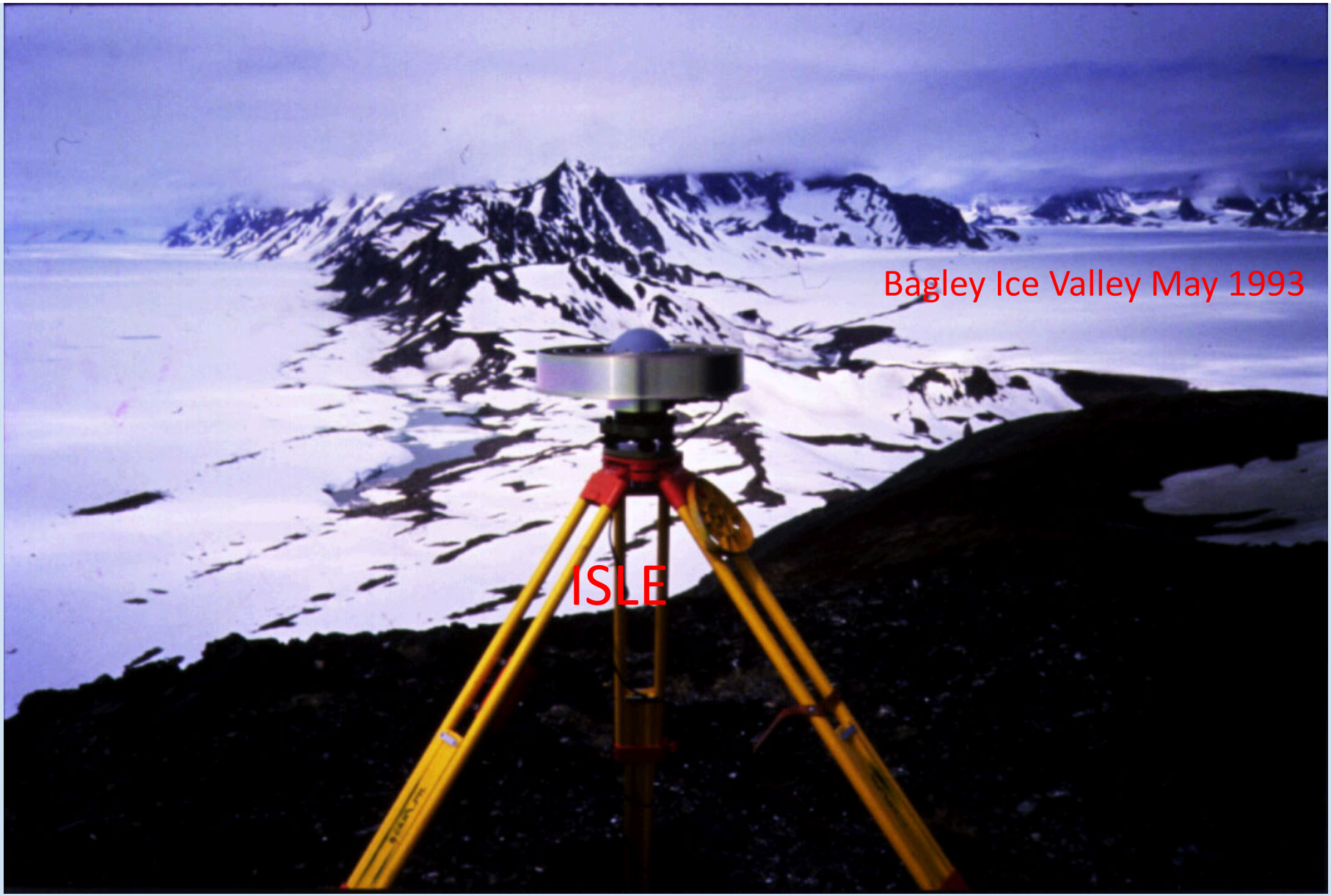
But first a little context for interpreting precise geodetic measurements with the Bagley Ice Valley as an example

Bagley Ice Valley – Spring 1982



•The USGS made trilateration measurements on regional networks across different portions of the subduction plate boundary zone in southern Alaska including the region above (*Savage and Lisowski,* 1988) to assess earthquake hazard.

•Also in the 1980's, as part of NASA's Crustal Dynamics Project, the first precise space-geodetic measurements of crustal deformation at southern Alaska sites were made in a global reference frame using mobile Very Long Baseline Interferometry (VLBI) (*Ma et al.,* 1990).



Global Positioning System receiver set up over geodetic mark that we measured multiple times to look for changes in position starting in May 1993.

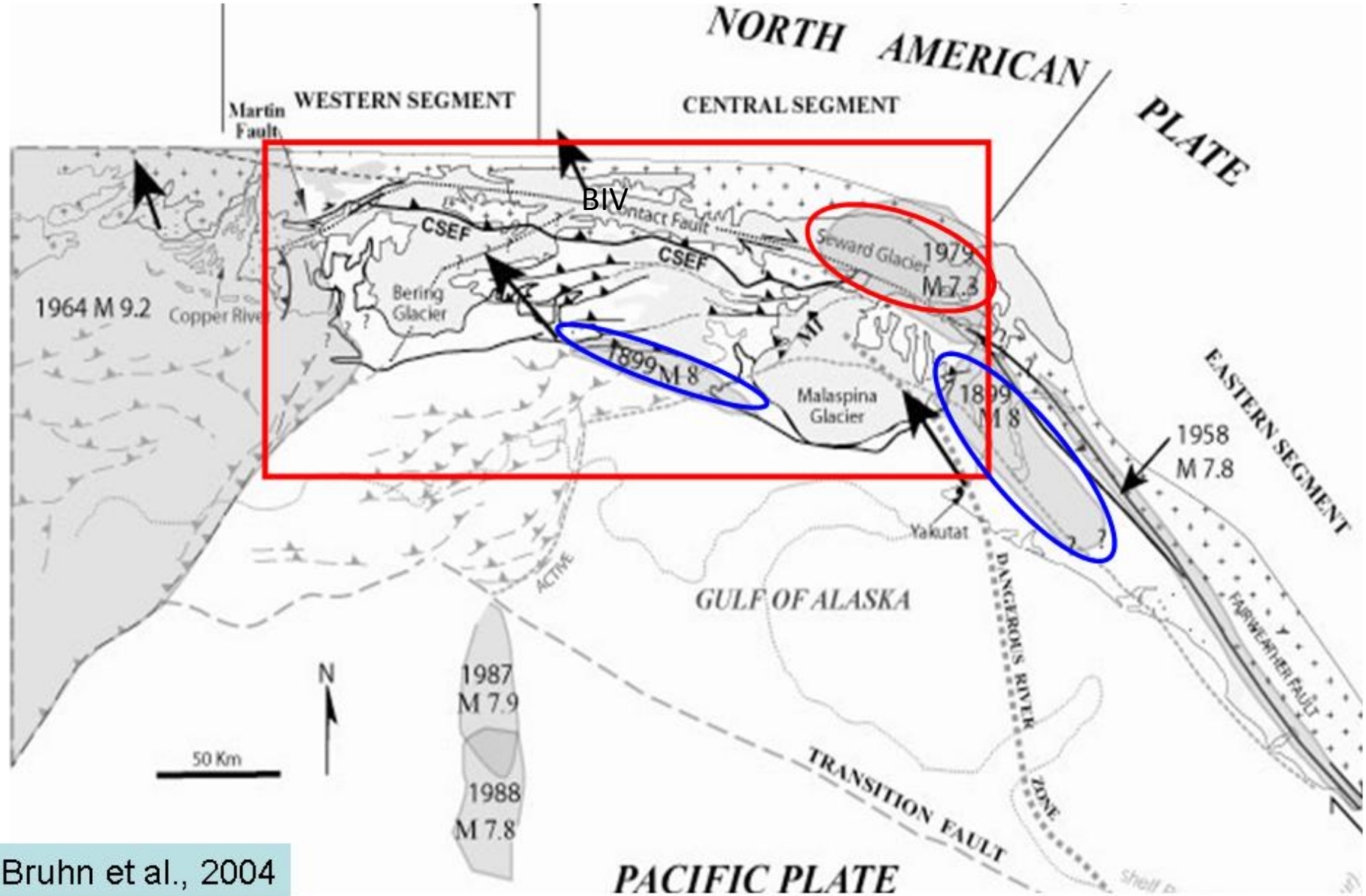
HOUSTON WE HAVE A PROBLEM

✓ ***Annual*** *variations in snow and ice on glaciers*: 1-8+ meters in ablation region, not well documented in accumulation region but 10s of meters estimated. Use NASA **GRACE** results (2002-present) and snow models to estimate the timing and magnitude of seasonal crustal deformation. **Evaluate seismic rate changes.**

✓: **Years** *Retreat* (meters/yr thinning in ablation region of glaciers). Also more frequent **glacier surges** with ice unloading in surge reservoir region and ice loading in surge receiving area. **Calculate predicted vertical and horizontal crustal deformation for warm years.**

✓ ***End of Little Ice Age (LIA) Wastage*** Most glaciers in southern Alaska have undergone km's of terminus retreat with up to 100-1000 meters of ice thickness change. We calculated the **stress changes associated with this wastage between ~1900-1979.**

---***Late Pleistocene deglaciation*** **Not** modeled here due to low asthenosphere viscosities, frequent large events in southern Alaska that alter stress. **Show calculated stresses associated with Late Pleistocene deglaciation and earthquake history for N America and N Europe.**

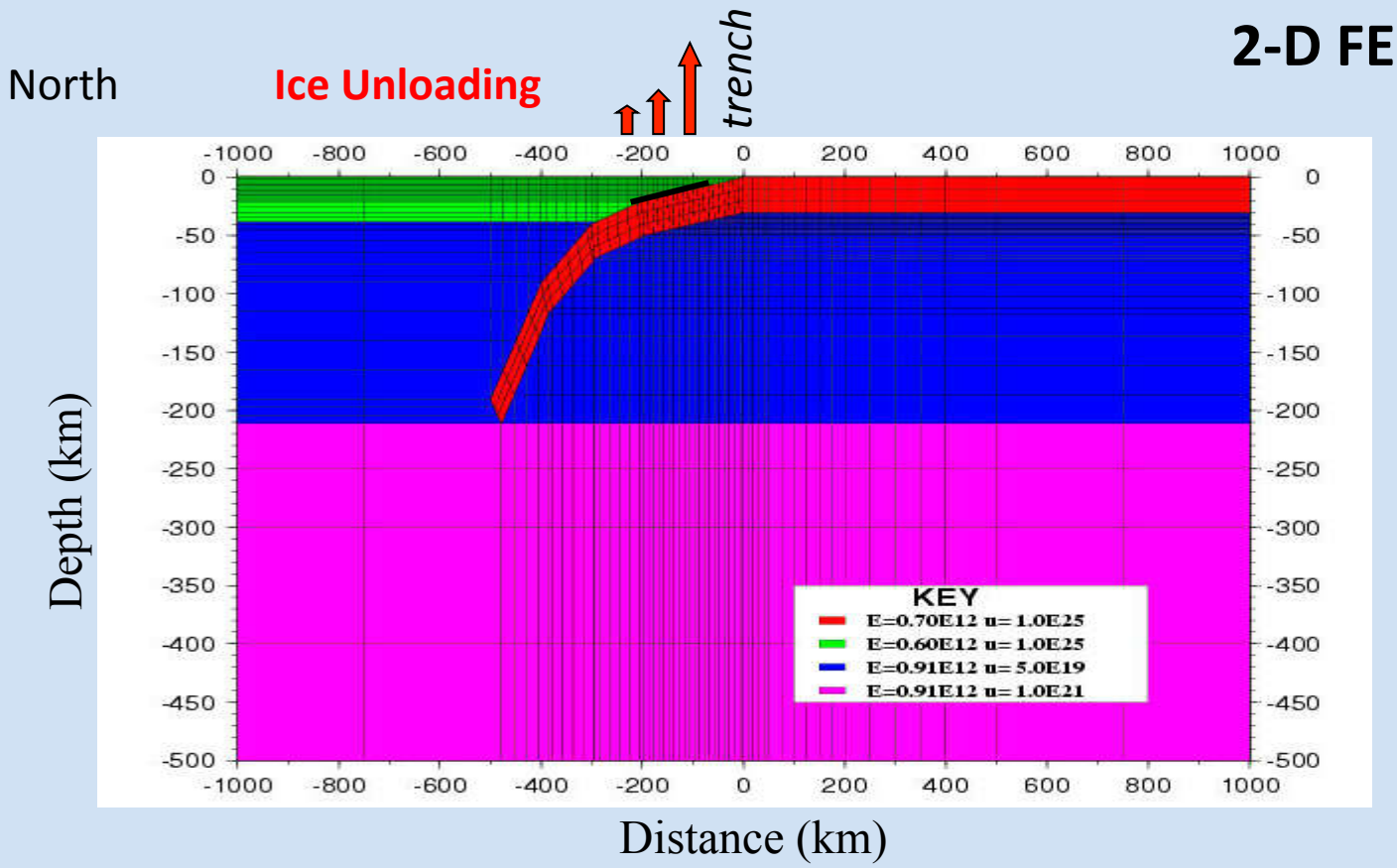


Bruhn et al., 2004

Decade to century scale glacier changes:

September **1899** earthquakes probably occurred on plate interface and on upper crustal faults.
1979 earthquake started on plate interface with reverse faulting but included strike-slip.

2-D FEM Model used



5×10^{25} Pa s

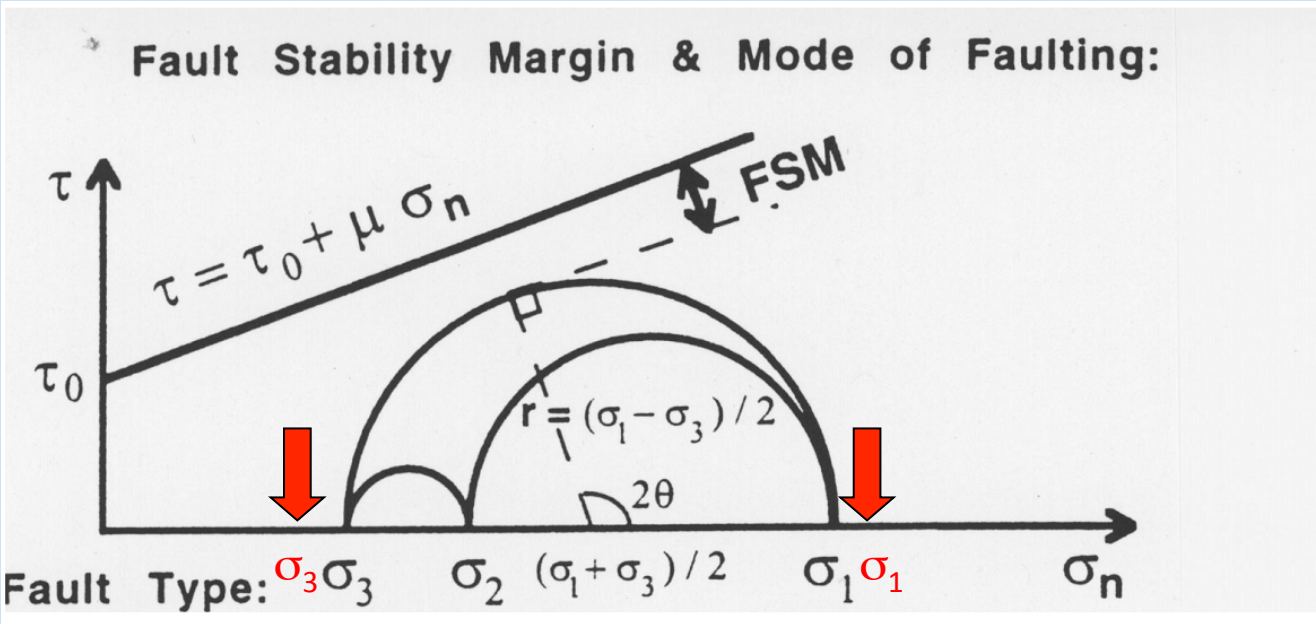
5×10^{19} Pa s

5×10^{21} Pa s

•Input the *cumulative* ice mass changes from **1899 to 1979** based on geologic field mapping by G Plafker and B Molnia.

•Calculate the subsequent stresses and change in fault stability on *Main Thrust Zone* and on the *surface (Sauber et al., 2000; Sauber and Ruppert, 2008).*

For incremental stresses due tectonic & glacial changes, assume Maxwell Solid. Plane strain Finite Element Model (FEM), TECTON 2-D *(Melosh &Raefsky,* 1981; details given in *Sauber et al.,* 2000) *Currently using CIG's Pylith FEM for snow/ice loading & unloading*



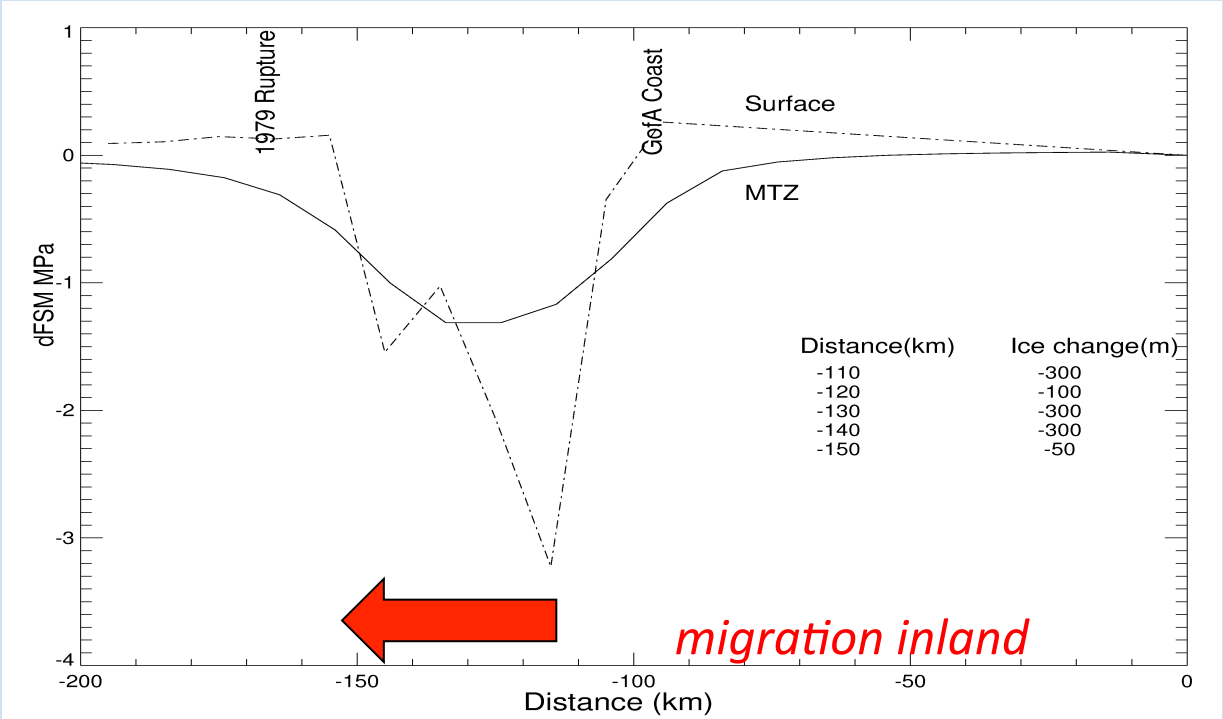
$\Delta\sigma_1$ due to tectonic loading is predicted to be **NNW-SSE to N-S**

$\Delta\sigma_1$ due to glacial wastage is predicted to be variable but generally oriented northward

$\Delta\sigma_3$ due to tectonic loading is predicted to be directed ***up,***
similar to the $\Delta\sigma_3$ for ice removal

τ= shear stress necessary to induce failure on main thrust zone (MTZ)
τ_O = the inherent shear strength
μ= coefficient of friction on fault surface
σ_n = normal stress on fault

Influence of Ice Mass Changes on Earthquakes



The cumulative decrease in **fault stability margin** due to glacial wastage between the 1899 (Yakataga earthquake, **M** = 8) and 1979 St. Elias earthquake (M =7.2) was **0.2 – 1.2** MPa over an ~80 km region above the main thrust zone (MTZ)

We hypothesize that the ice-mass change induced stresses would **promote** the time to fault instability, especially in regions undergoing rapid uplift rates and north-northwest horizontal motion (to be discussed later)

Sauber and Ruppert, 2008

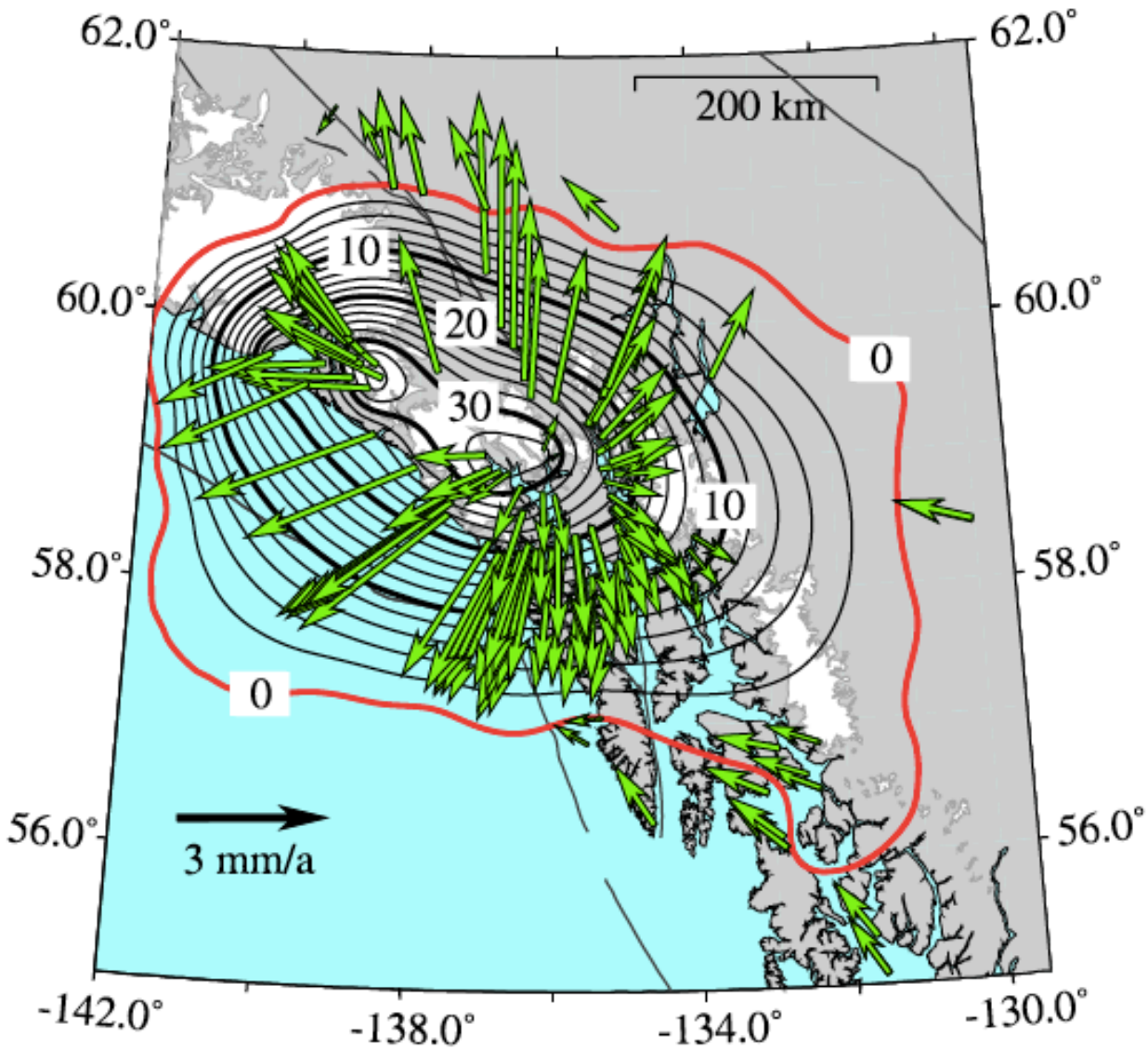


Figure 3. Glacial isostatic adjustment model predictions for southeast Alaska. Vectors show the horizontal motion while the contours show the vertical motion. Contour label units are mm/a (Figure S1 shows a larger version).

Elliott, Larsen, Freymueller, Motyka (2010) calculated the surface displacements due to the ice volume loss of 3030km^3 from the collapse of the Glacier Bay Ice Field (beginning ~1780).

Best-fit Earth parameters:

50 km **Lithosphere**

110 km **Asthenosphere** (viscosity 3.7 x 10^{18} Pa s)

Upper Mantle (viscosity 4.0 x 10^{19} Pa s)

What are the approximate stresses associated with continent scale deglaciation?

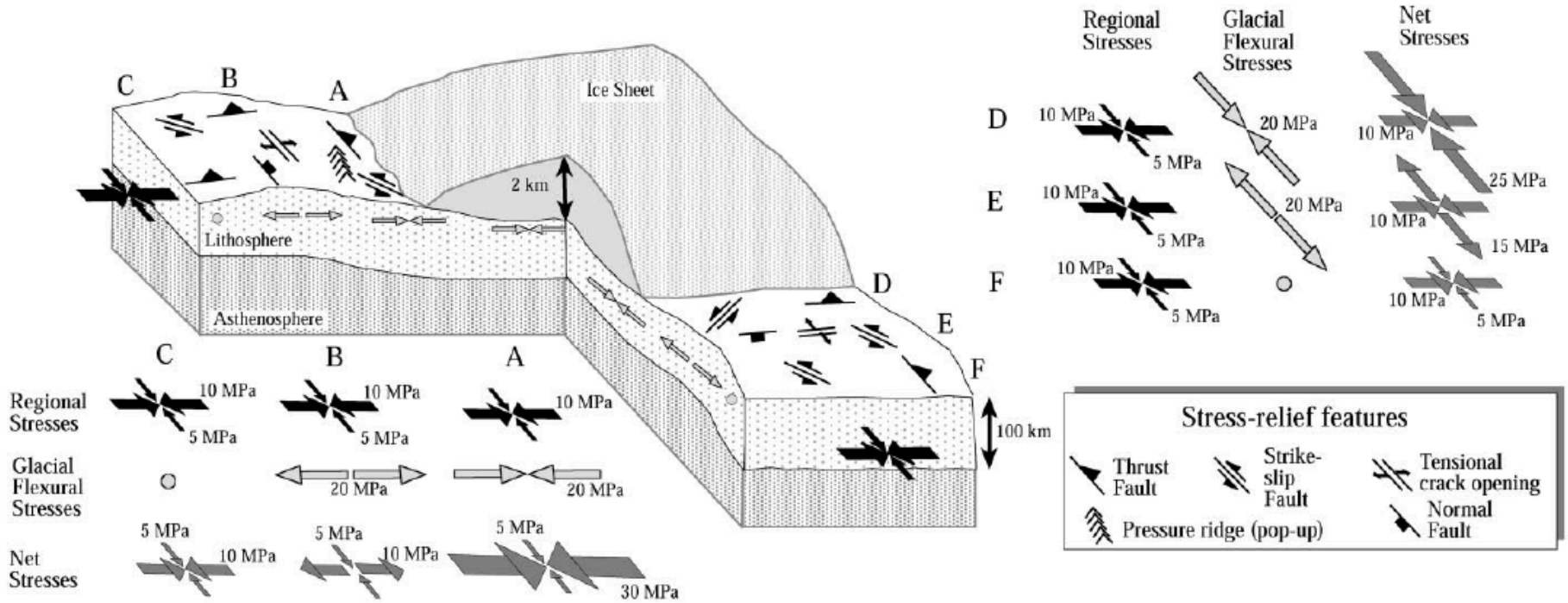
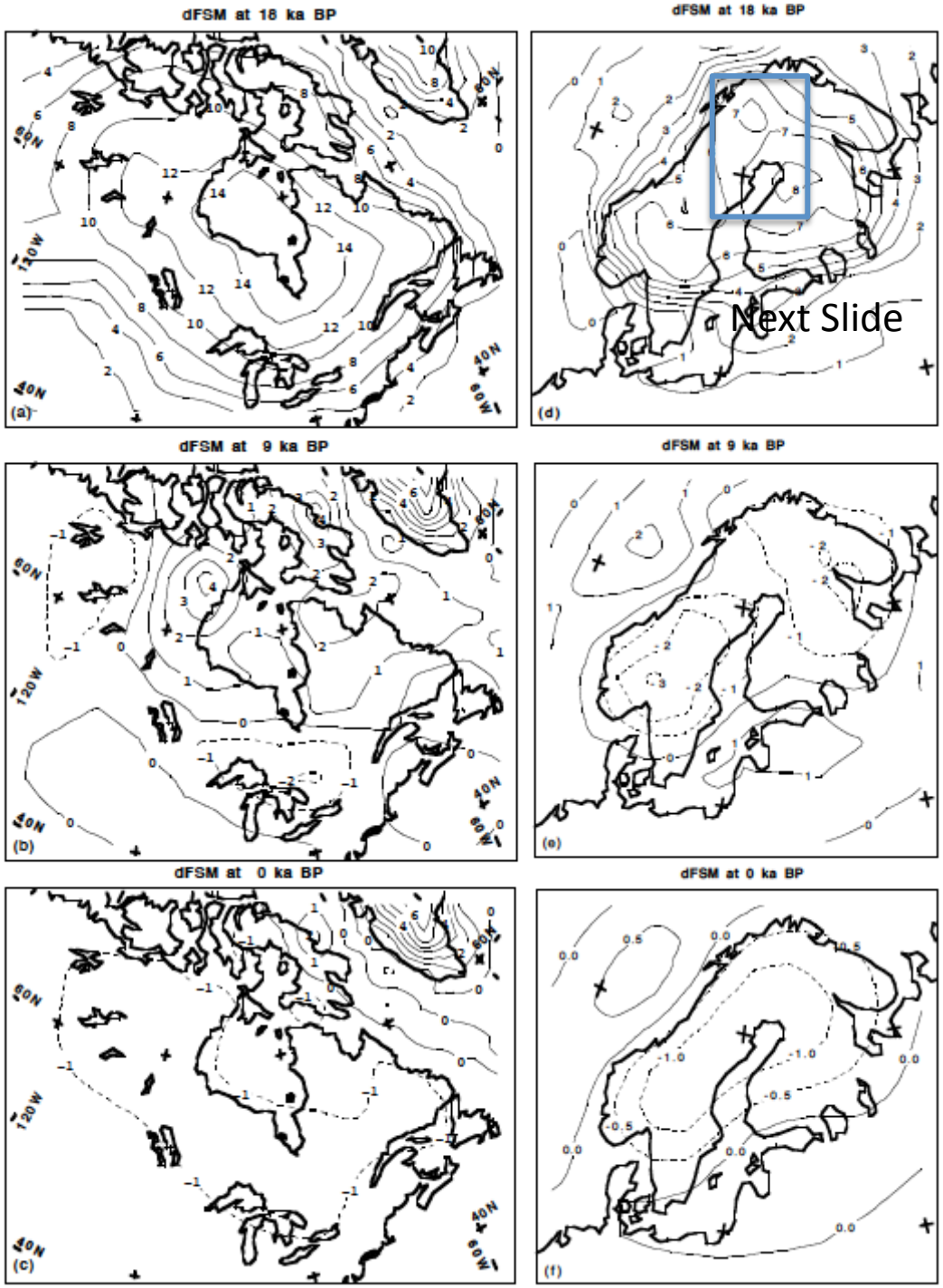


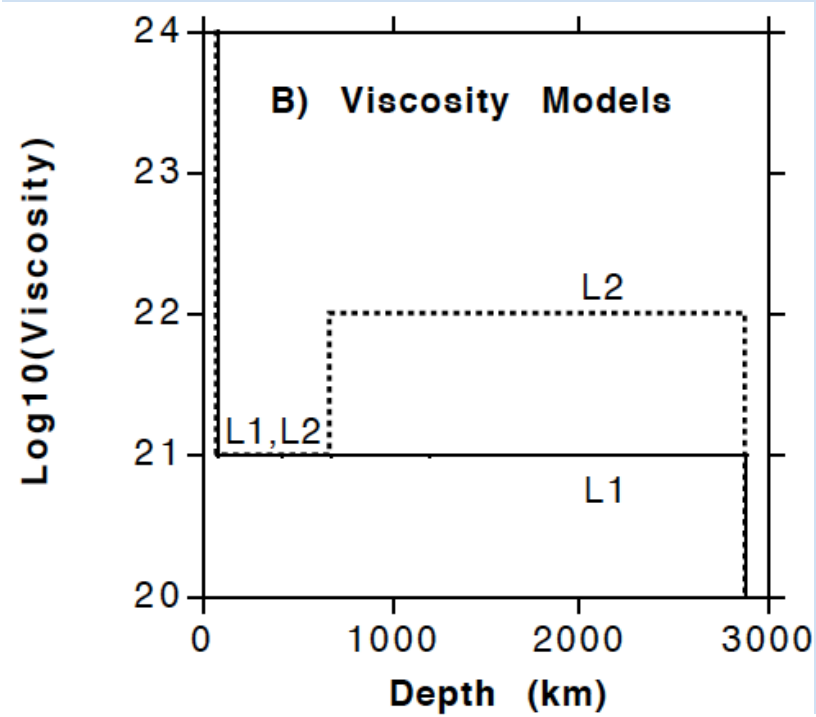
Fig. 1. Conceptual model for near-surface postglacial stresses during deglaciation. The exploded block model illustrates how the superimposition of changing glacial flexural stresses (light grey arrows) on a uniform regional tectonic stress field (black arrows) results in contrasting resultant stress states (dark grey) and different styles and orientations of stress-relief phenomena at the ice margin (A and D), the forebulge (B and E) and the undeformed foreland (C and F). Modified from Adams (1989a) after Walcott (1970). Note the considerably exaggerated vertical scale difference between the lithosphere thickness and the ice sheet thickness.

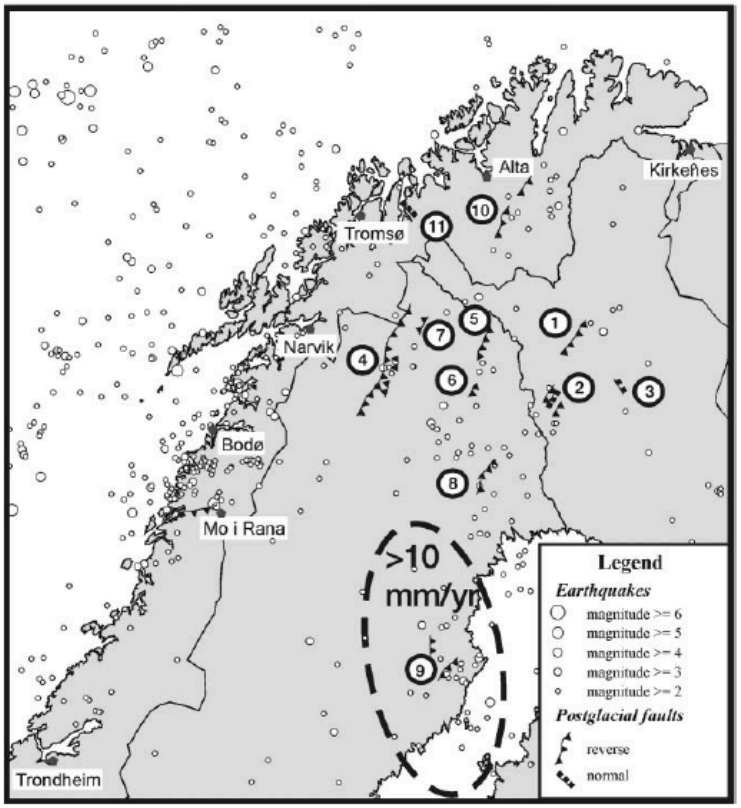
From Stewart, Sauber, Rose, QSR, 2000



Spatio-temporal variation in dFSM in N. America and N. Europe at 3 time periods at a seismogenic depth of ~12km. Model L1 (below) was used. Contours are in MPa (*Wu*, 1998)

At present both regions are still undergoing uplift (GRACE & GPS)





Based on earlier studies, post-glacial faulting (left) in the Lapland Fault Province appear to have much larger displacements, and much greater lengths, than the Canadian equivalents.

However, in both regions, most of the reported post-glacial faults are thrust faults (*Wu*, 1998; summary in *Stewart et al., QSR volume,* 2000)

No.	Fault	Country	Length (km)	Max. scarp height (m)	Scarp height/fault length ratio	Trend	Type	Moment magnitude	Ref.
1.	Suasselkä	Finland	48	5	0.0001	NE–SW	reverse	7.0	Kujansuu (1964)
2.	Pasmajärvi-Venejärvi	Finland	15	12	0.0008	NE–SW	reverse	6.5	Kujansuu (1964)
3.	Vaalajärvi	Finland	6	2	0.0003	NW–SE	??	6.0	Kujansuu (1964)
4.	Pärve	Sweden	150	13	0.0001	NE–SW	reverse	7.6	Lundquist and Lagerbäck (1976)
5.	Lainio-Suijavaara	Sweden	55	30	0.0005	NE–SW	reverse	7.1	Lagerbäck (1979)
6.	Merasjärvi	Sweden	9	18	0.002	NE–SW	reverse	6.3	Lagerbäck (1979)
7.	Pirttimys	Sweden	18	2	0.0001	NE–SW	reverse	6.5	Lagerbäck (1979)
8.	Lansjärv	Sweden	50	22	0.0004	NE–SW	reverse	7.1	Lagerbäck (1979)
9.	Burträsk-Bastuträsk	Sweden	60	~ 10	0.0002	NE–SW	??	7.1	Lagerbäck (1979)
10.	Stuoragurra	Norway	80	7	0.0001	NE–SW	reverse	7.3	Olesen (1988)
11.	Nordmannvik	Norway	3	1	0.0003	NW–SE	normal	5.7	Tolgensbakk and Sollid (1988)

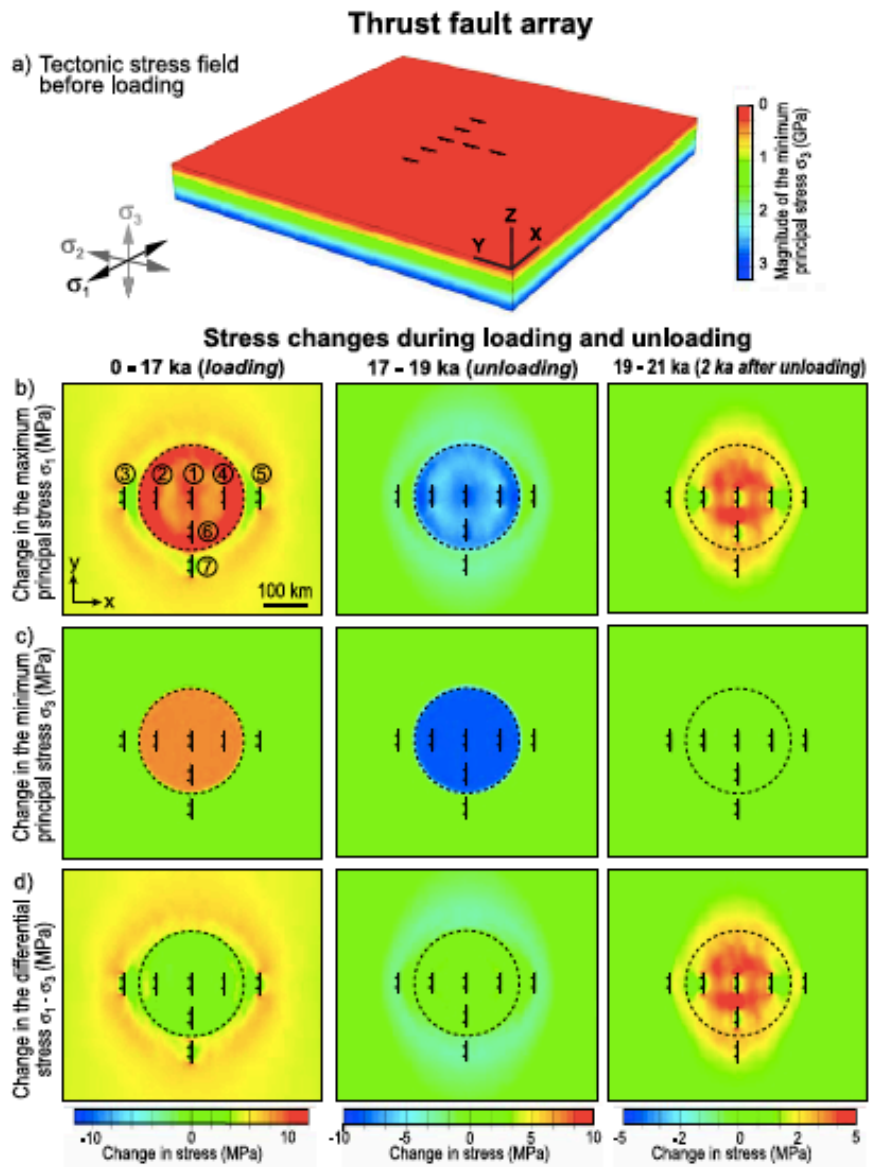
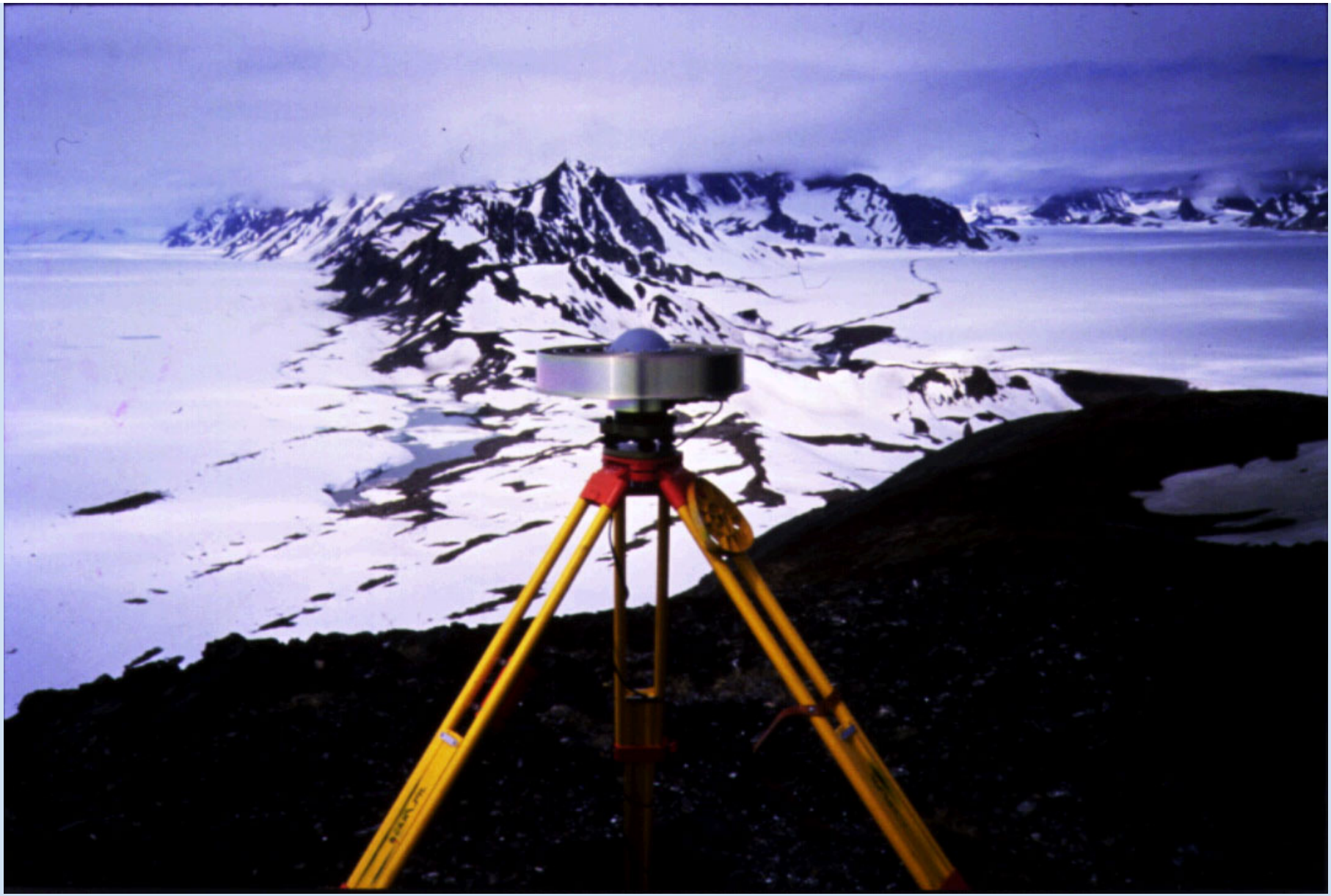


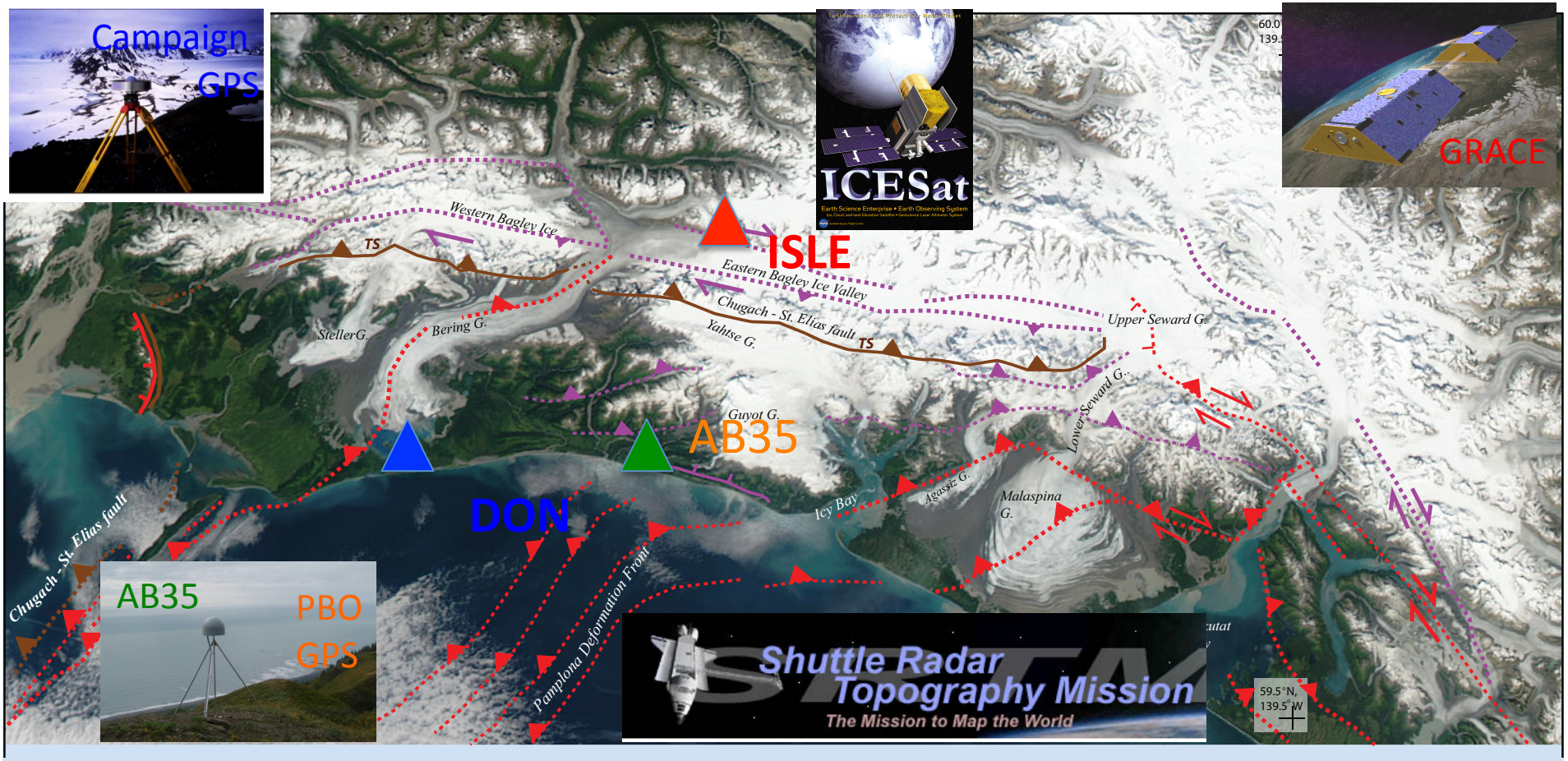
Figure 7. Stress evolution in the thrust fault model. (a) Tectonic stress field before loading. Arrows show the orientation of the maximum principal stress σ_1, the intermediate principal stress σ_2, and the minimum principal stress σ_3. Perspective view of the model with contour plot showing the magnitude of the vertically oriented principal stress, which is σ_3 in the thrust fault model. (b–d) Contour plots showing in map view the change of the magnitudes of σ_1, σ_3, and the differential stress $\sigma_1 - \sigma_3$ at 2 km depth. The stress changes shown occur over 2-ka-long time intervals during loading (0–17 ka), unloading (17–19 ka) and after completion of unloading (21–19 ka). Dip of the faults is 45°. Dashed lines mark the outline of the model ice cap.

Hampel et al, JGR, 2009 used 3-D F.E.M. to investigated how *arrays of normal & thrust faults* near a growing and subsequently melting ice cap are influenced in their slip evolution. Their results indicate that regardless of fault dip both types of faults experience a **decrease** in slip rate during ice cap growth and an ***increase*** in slip during ice cap wastage IF located below ice cap.

Steffen et al., 2014 used a F.E.M. to predict the fault slip, activation time and the number of major seismic events.

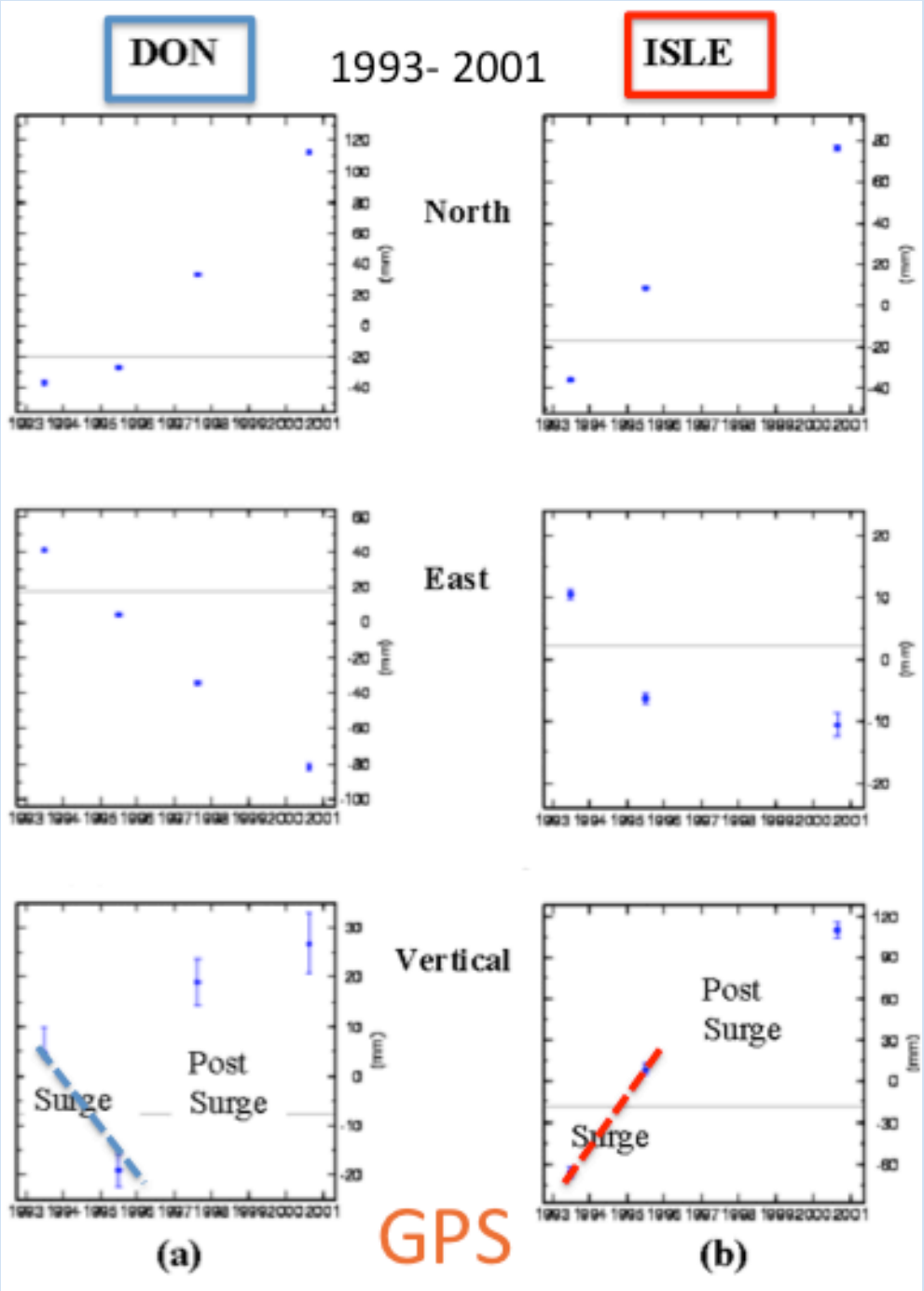


Shorter-term Changes: Crustal deformation and seismic rate



•The major faults within the upper crust are either **under** or near large glaciers.
SO, GPS measurements of surface displacement include the viscoelastic response to ice mass changes:

•Glacier surges + tectonic strain —observed GPS displacements at ISLE and DON
•Predicted horizontal and vertical displacements due to average annual changes
•Seasonal variations and seismic rate changes



The GPS station positions for both sites are predicted to move to the north-northwest (NNW) and up due to (steady) ***tectonic*** forcing (PCFC relative NOAM)

1993-1995 surge interval versus post-surge time period, 1996-2001:

- A higher **uplift** rate for ISLE. Site is moving faster to the northwest. Ice unloading to the south of the site would cause uplift & north directed motion.

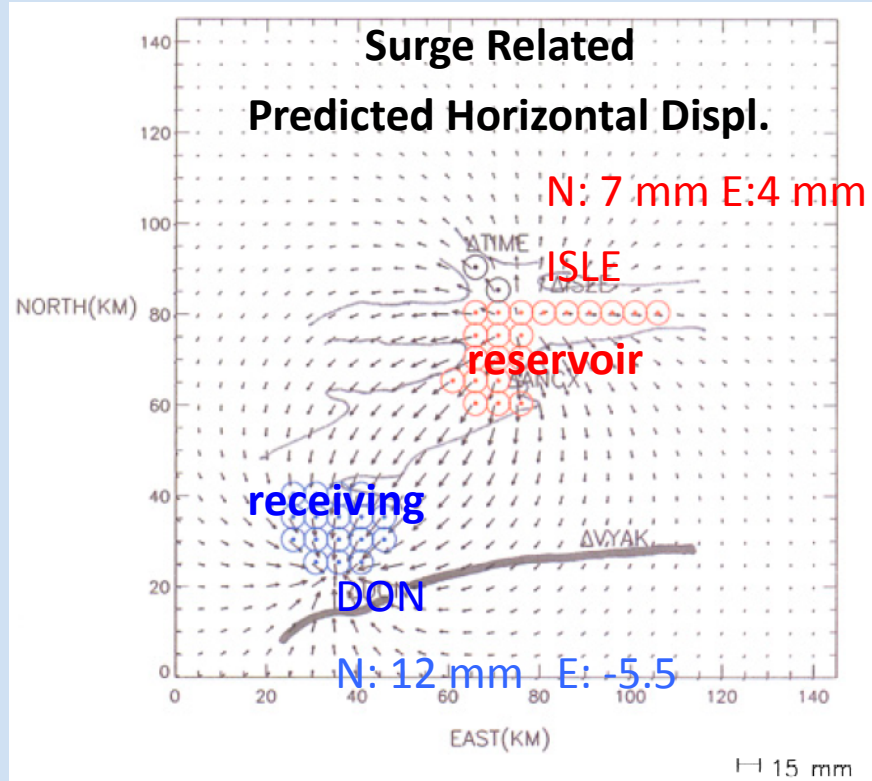
- In contrast, the station DON is undergoing vertical subsidence during the surge but uplift subsequently (as predicted for tectonic loading). The rate of the northward motion is lower during the surge.

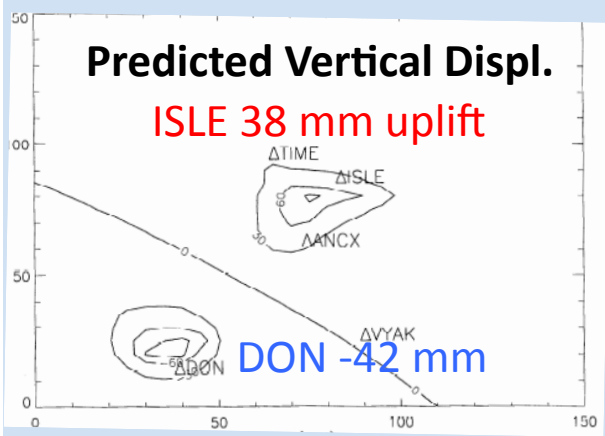
1993-1995 Bering Glacier Surge: A Solid Earth Geophysicist View

Represent 10s of meters of drawdown (unloading) in surge **reservoir** and thickening & terminus advancement in **receiving/** terminus (loading) region as **disc loads**

As a "local load", use elastic half-space model or radially stratified, gravitating Earth model to predict vertical and horizontal displacements [Farrell, 1972].

*Elliott et al.,*2013 estimates of **horizontal** site velocities between 2005-2008:
DON: ~43 mm/yr @N30°W
ISLE: ~20 mm/yr @N14°W



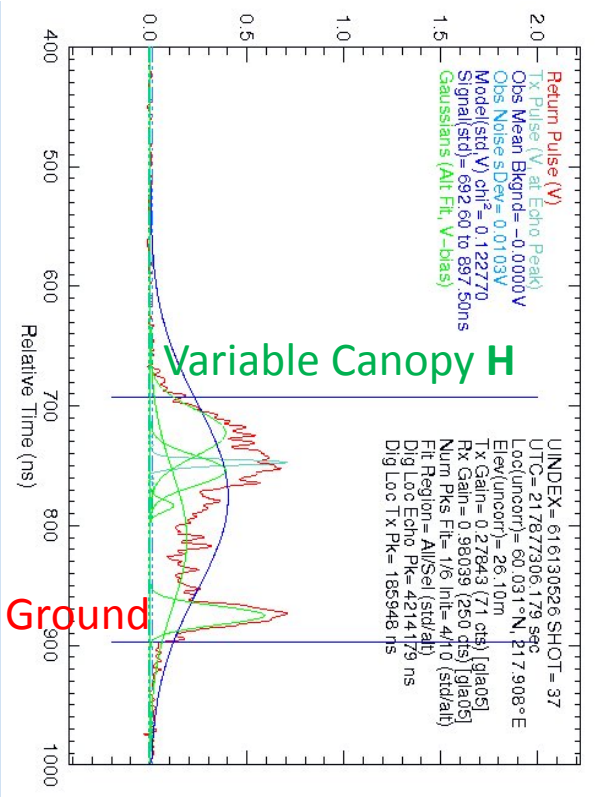


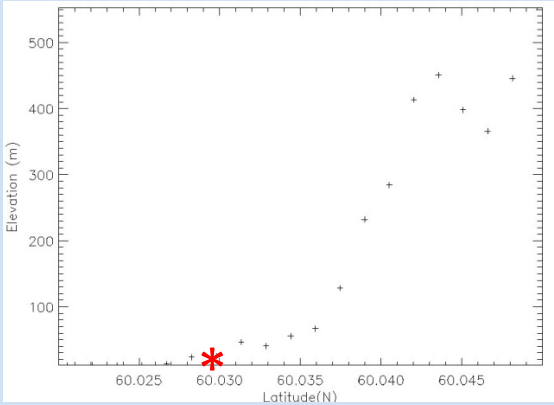
Sauber et al., 2000

Assumptions & Limitations in predicted values:

1. 1993-1995 net transfer of ice mass from surge **reservoir** to receiving area over the duration of surge is **equal** (~14km^3). GPS motions reflect magnitude of (un)loading & can be used to *invert* for process scaling factor.
2. **Ignores seasonal snow/ice build-up & summer melting. Horizontal component is complex due to tectonic strain as well as possible push moraine toward DON due to surge .**

Right: Example **ICESat** Waveform





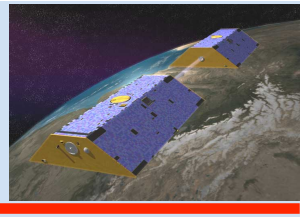
ICESat-1 penetrated canopy but density of observations was not optimal, albeit useful!

Above: Photo of marine terraces from coastal region west of Icy Bay and the Malaspina Glacier, Alaska, Includes the 1899 **M**=8 earthquake aftershock zone

Thick coastal forest and brush mask important aspects of the geomorphology on aerial photographs, standard DEM, and X, C-band synthetic aperture radar (SAR) images.

Sauber et al., 2010

Land ice mass evolution from GRACE



- 41,168 equal area ***1-arc-degree*** mascons are directly estimated from GRACE KBRR L1B data with spatial and temporal exponential taper constraints applied.
- ***10-day*** temporal resolution
- *Spatial constraint:* 100 km correlation distance
- *Temporal constraint:* 10-day correlation
- **Gulf of Alaska glacier region (61 mascons)**

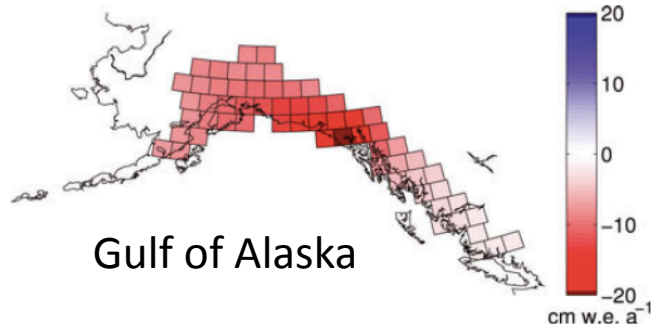


Fig. 15. The GOA mascon trends computed from the v12 mascon solution corrected with the ICE5G_Paulson GIA model and the Larsen LIA model over the time period 1 December 2003 to 1 December 2010.

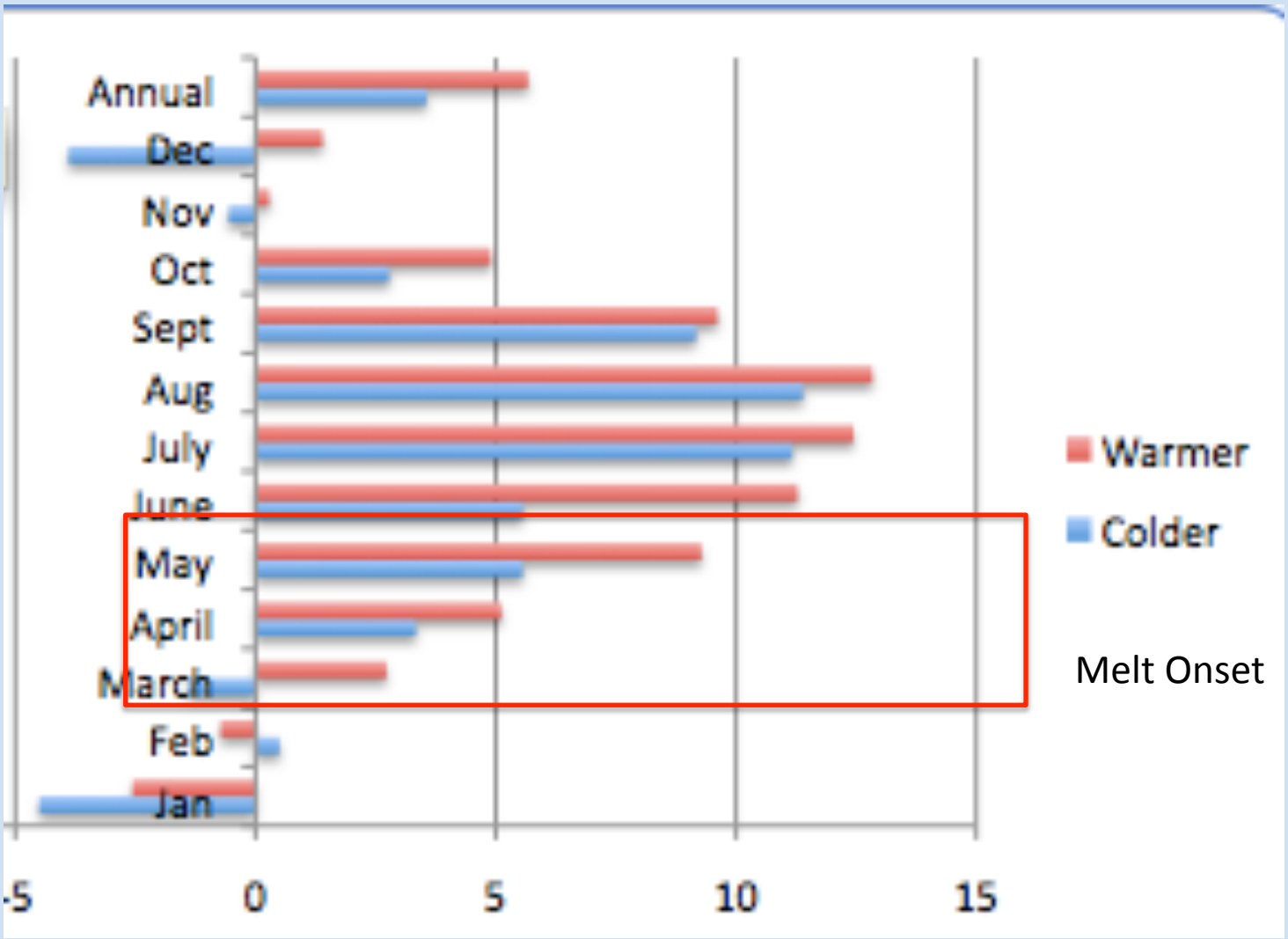
Overall G of Alaska Trend = -69 ± 11 Gt a^{-1}

Note **variability** in peak to peak seasonal amplitude and annual net balance (2005 versus 2012 balance year).

GSFC Mascon solution, Luthcke et al., *J. of Glaciology*, 2013

Yakutat NWS:

Average Monthly Temperature (°C)



Average Monthly Temperature for 2005 (Warmer) versus 2012 (Colder)

NOTE: March 2005 temperatures are +3°C whereas March 2012, -2°C

Land Surface Temperature (LST) from Terra MODIS:

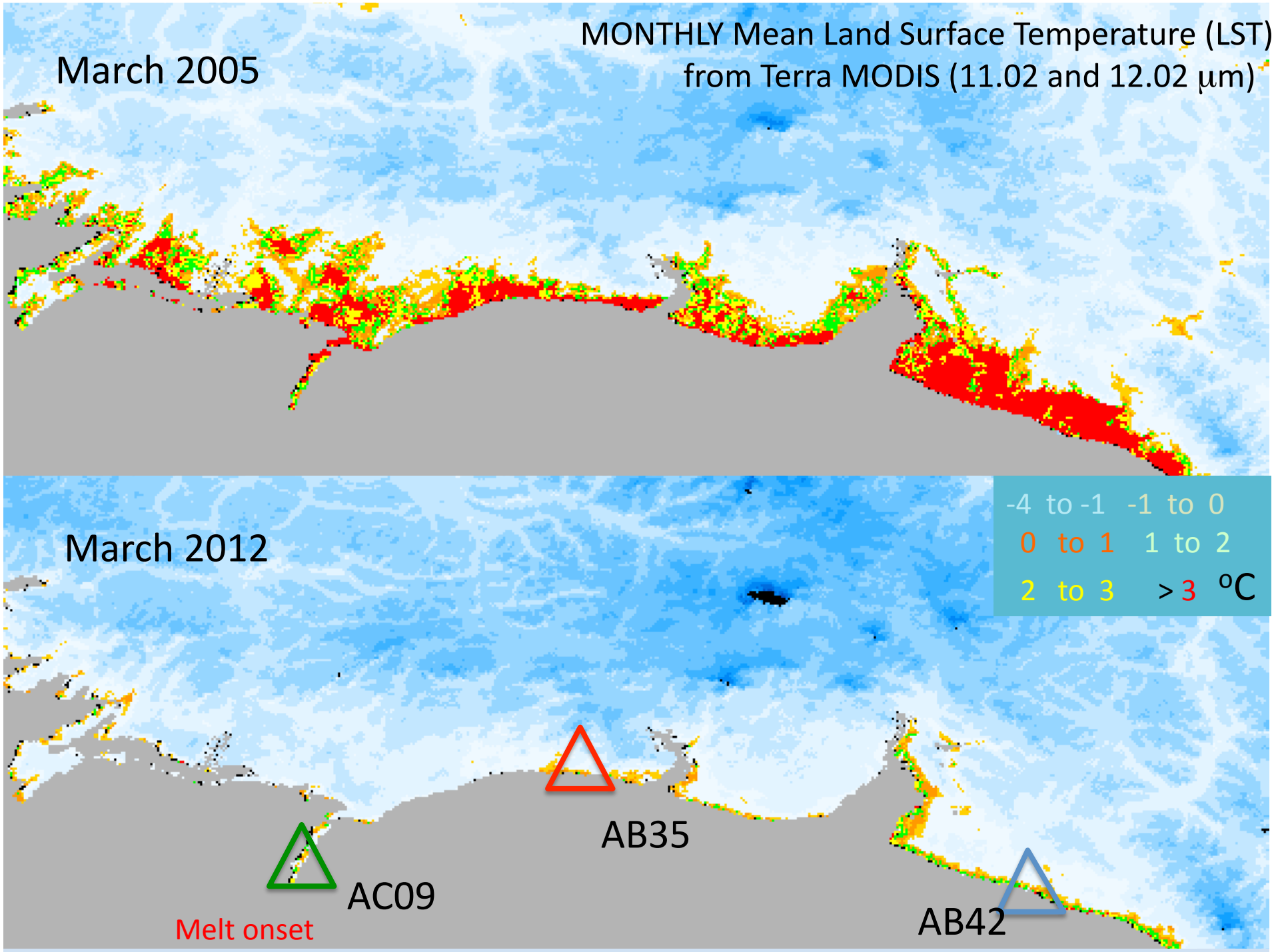
• Used Terra MODIS Channels 31 and 32 centered on 11.02 and 12.02 μm, respectively, are used to produce Land Surface Temperature (LST, MOD11A1) products; the cloud mask that is used in MOD11A1 is generated from another standard product, MOD35 [e.g. Hall et al., 2012, **].

•The monthly mean temperature (per 1 km pixel) for a swath through southern Alaska is given in the next several figures. The number of values used to estimate a **monthly mean** ranged from **5-14 days**. Cloud cover in southern Alaska precludes use of LST for many days.

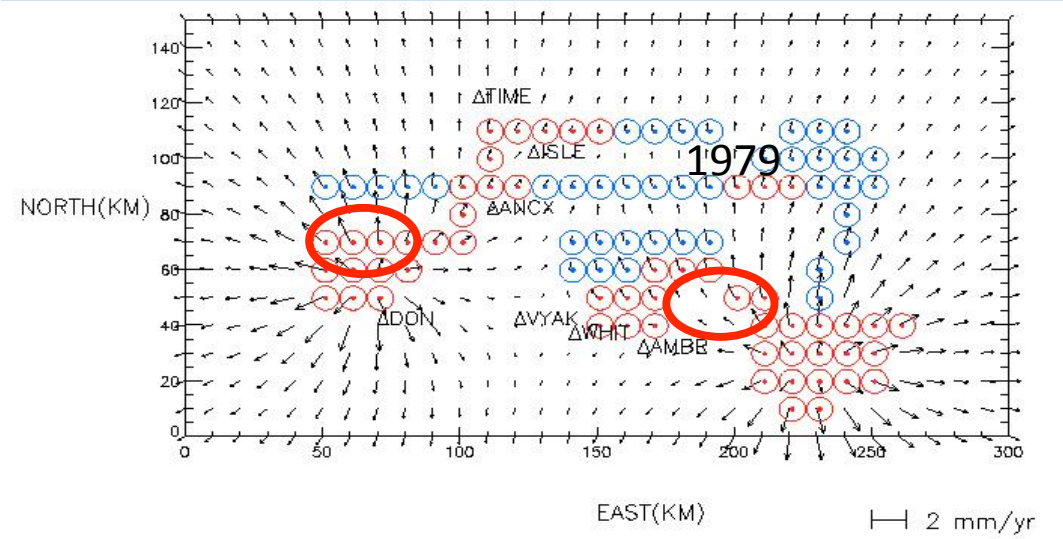
•The uncertainties in satellite-derived LST from multiple sensors have been evaluated in Greenland and over other snow- and ice-covered surfaces including mountainous regions [Hall et al., 2012; Forsythe et al., 2012; Koenig and Hall, 2010]**.**

Here we use the MODIS derived LST values to contrast differences in the timing and spatial evolution of melt onset/warmer temperatures for one month, March in 2005 and 2012.

Sauber et al., Fall AGU 2013

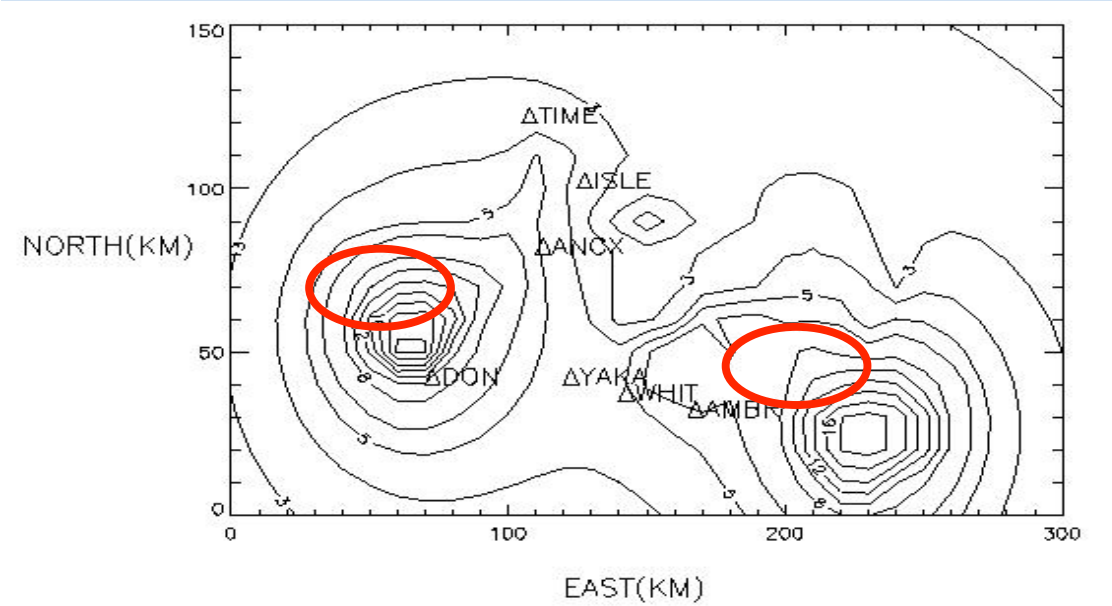

MONTHLY Mean Land Surface Temperature (LST)
from Terra MODIS (11.02 and 12.02 μm)
March 2005
March 2012
-4 to -1
-1 to 0
0 to 1
1 to 2
2 to 3
> 3
°C
AB35
AC09
Melt onset
AB42

2002-2006 example of predicted horizontal and vertical *elastic* displacements per year of the solid Earth associated with **average annual** wastage of the coastal glaciers.



$\Delta\varepsilon_{11}$ due to tectonic loading is predicted to be **NW-SE** to **N-S**

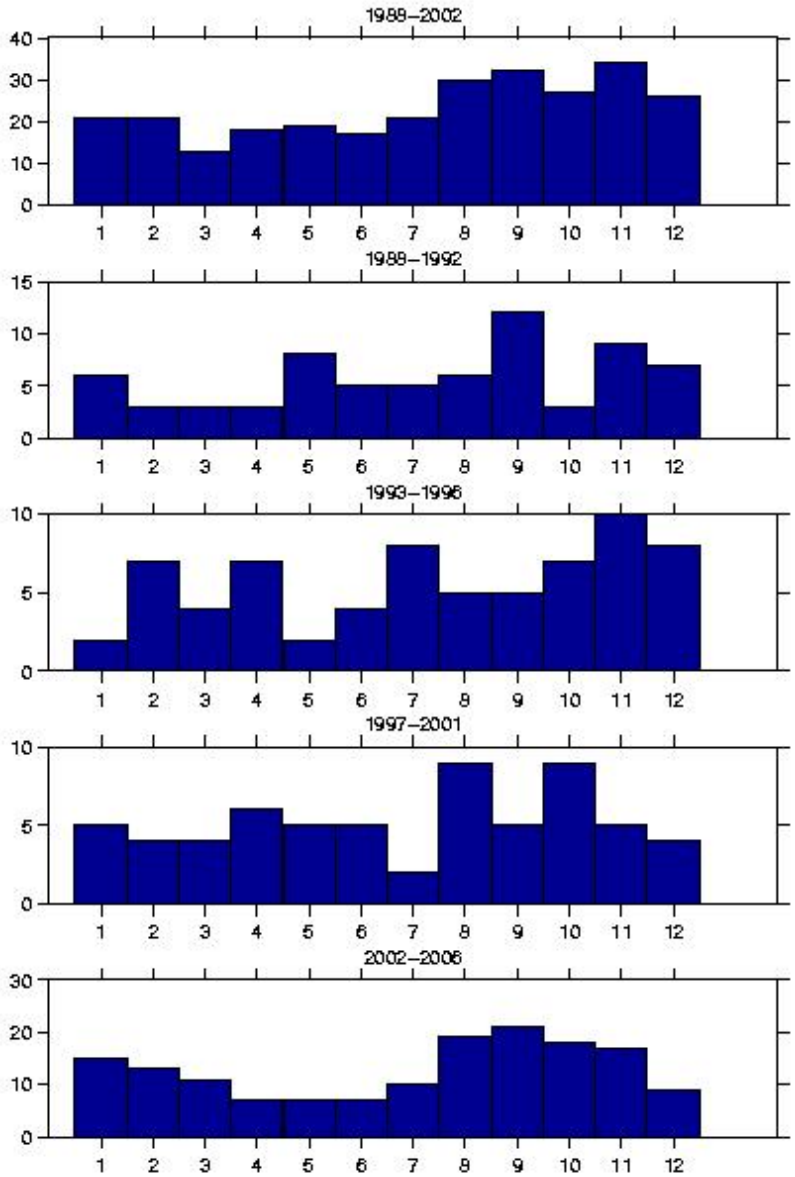
Note displacements away from region of ice thinning dominate the incremental changes.

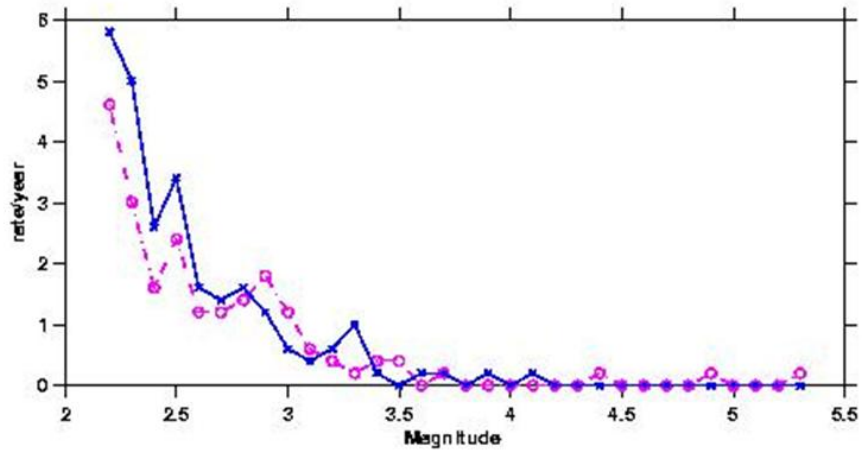


The red ellipses show an examples of a region where the calculated *incremental* displacements are similar to the orientation of tectonic strain.

$\Delta\varepsilon_{33}$ due to tectonic loading is predicted to be directed ***up***

Sauber and Ruppert, 2008

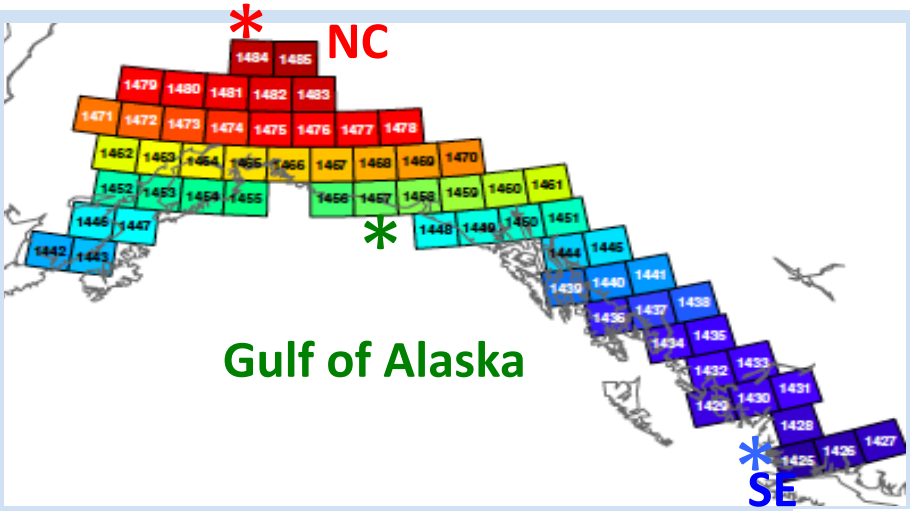




The earthquake rate/year in 0.1 magnitude bins for the reference time period (1988-1992, o- purple dashed) and the 2002-2006 (x-blue solid) for the Icy Bay region.
NOTE: the warmer time period has more events between M > 2.2 (threshold) and M <2.8 than the reference time period.

Tectonic earthquakes (left) as a function time (month) for the all (top) and three different time periods (lower three).

Sauber and Ruppert, 2008



Regional Variability:

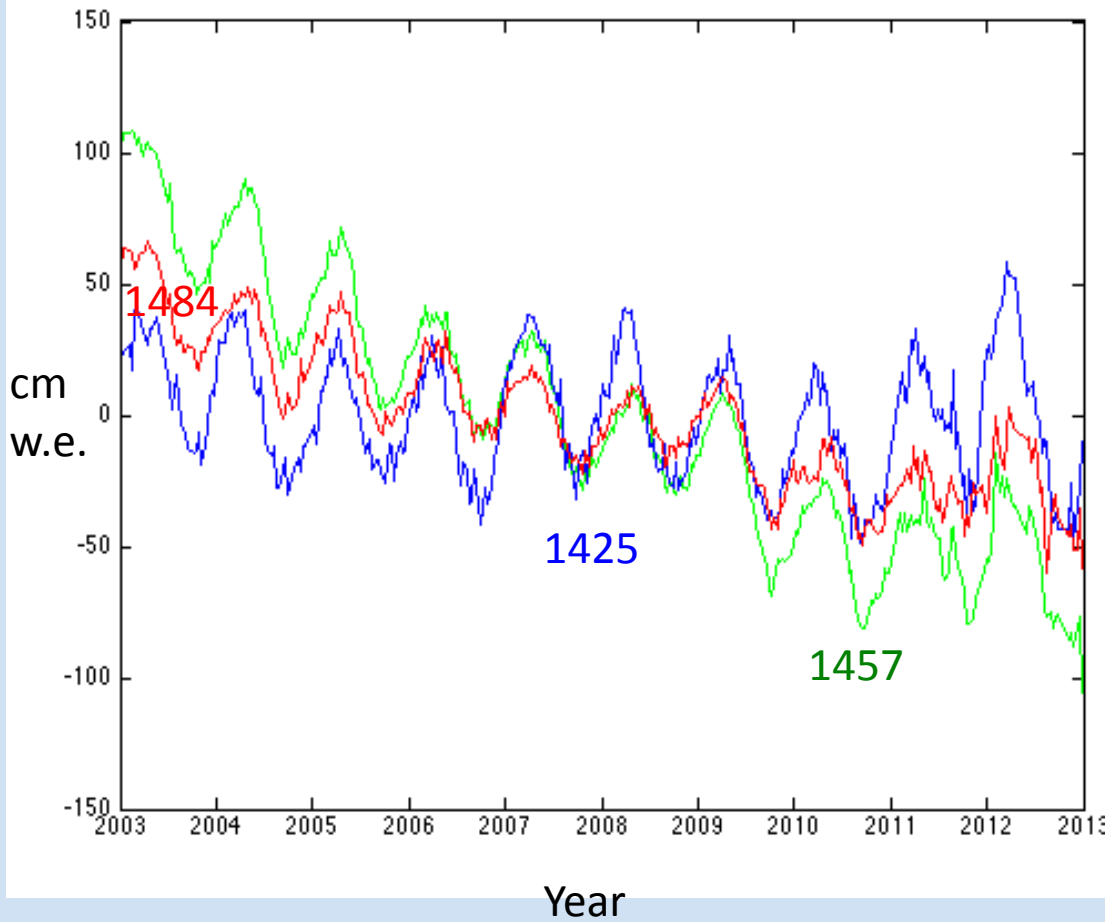
Mascon 1425, South Eastern Alaska:
Large seasonal, up to 100 cm w.e. (p to p)
Small 10 year-trend in ice mass loss

Mascon 1457: Central Coastal (study area)
Moderate seasonal, 50 -75 cm w.e.
Largest 10-year trend

Mascon 1484: North Central
Smaller seasonal signal
Moderate 10-year trend

Seasonal signal more important in different areas

Sauber et al, Fall AGU, 2013



Implications:

How do the different temporal and spatial scales of cryospheric change influence crustal deformation and earthquake occurrence?

Results suggested that a cumulative decrease **in fault stability margin** due to glacial wastage between 1899 (Yakataga earthquake, $M_W = 8.1$) and 1979 in the region of the St. Elias earthquake ($M_S = 7.2$) was up to 0.2-1.2 MPa over an 80 km region. Implication: *The cumulative ice loss over the last 100+ are large in localized regions and could "promote in time" moderate earthquakes on upper crustal faults.*

The frequency of small tectonic events in the Icy Bay region increased in the 2002-2006 warmer time interval; we tested whether this was due to the Denali earthquake or a significant increase in the rate of ice wastage. Ice changes are our preferred mechanism.

To use the exquisite set of new cGPS data from southern Alaska to evaluate earthquake hazard will require careful estimates of the crustal deformation due to cryospheric fluctuations on a variety of spatial scales and a rheologically complex Earth model.

Summary II

How does cryosphere mass change on times scales of months to years in southern Alaska?

1. The individual GRACE mascons located in distinctly different regions capture important inter-annual variations in the magnitude of the seasonal signal wastage trend.

2. These GRACE differences are important for estimating the timing and magnitude of broad-scale differences between regional GPS sites; however, more local estimates of changes in snow/ice extent and magnitude are needed to model cryosphere signal in GPS time series.

As estimated from EarthScope GPS data and FEM modeling, how do the surface displacements due to inter-annual and seasonal cryosphere mass change compare to tectonic displacement rates?

1. In the study region the surface horizontal displacements due cryosphere changes are generally <10% of the tectonic displacements whereas the vertical displacements can be comparable or than the predicted tectonic uplift rates (localized regions **near** glaciers).

2. *With a longer history of continuous GPS, and careful management of the sites, we will be able to use GPS derived changes in vertical and horizontal displacements to constrain process oriented cryosphere changes and provide better estimates of earthquake hazard.*