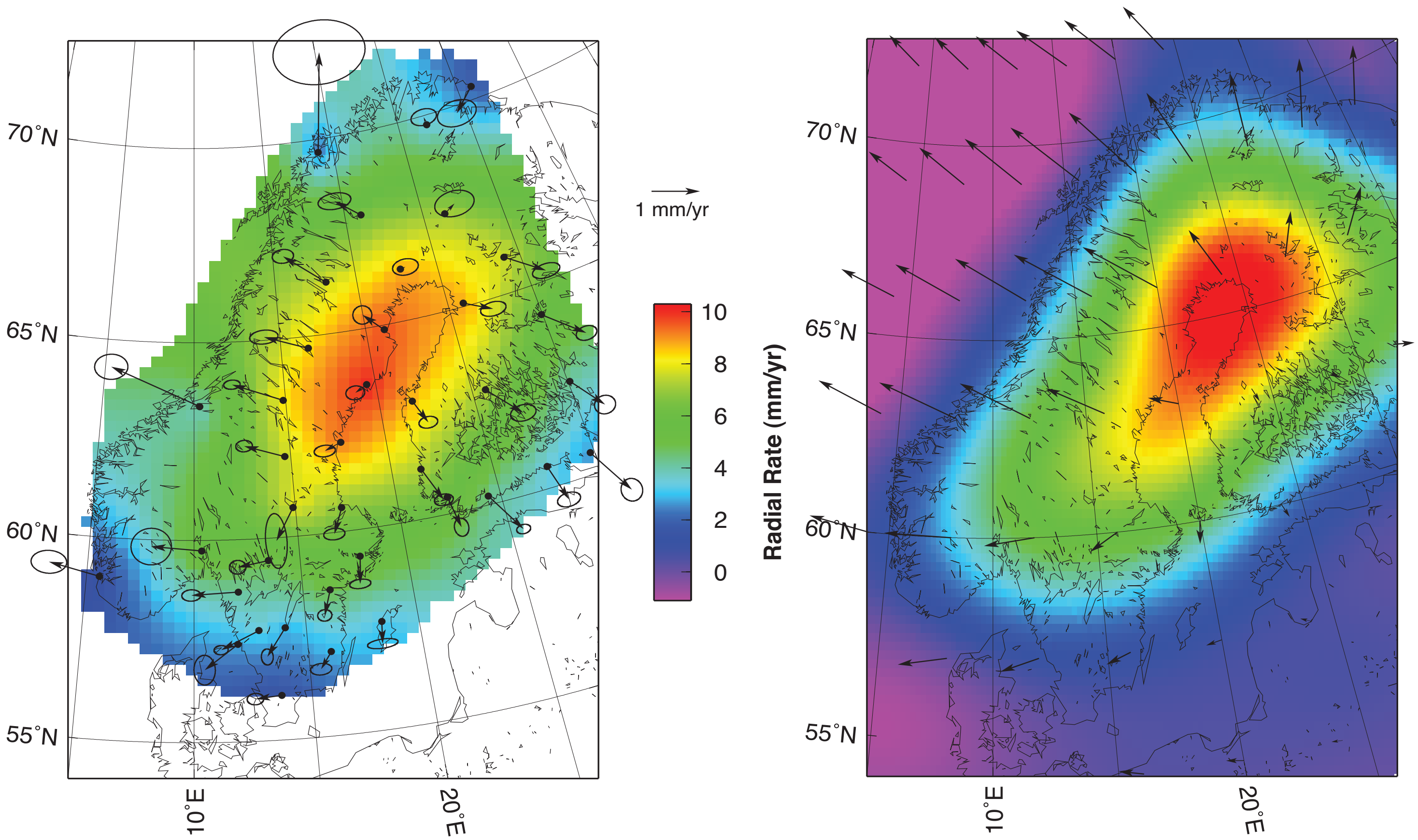
Glacial Isostatic Adjustment: Global (post-LGM) & SE Alaska (post-LIA)

GEOS 655 Tectonic Geodesy Jeff Freymueller

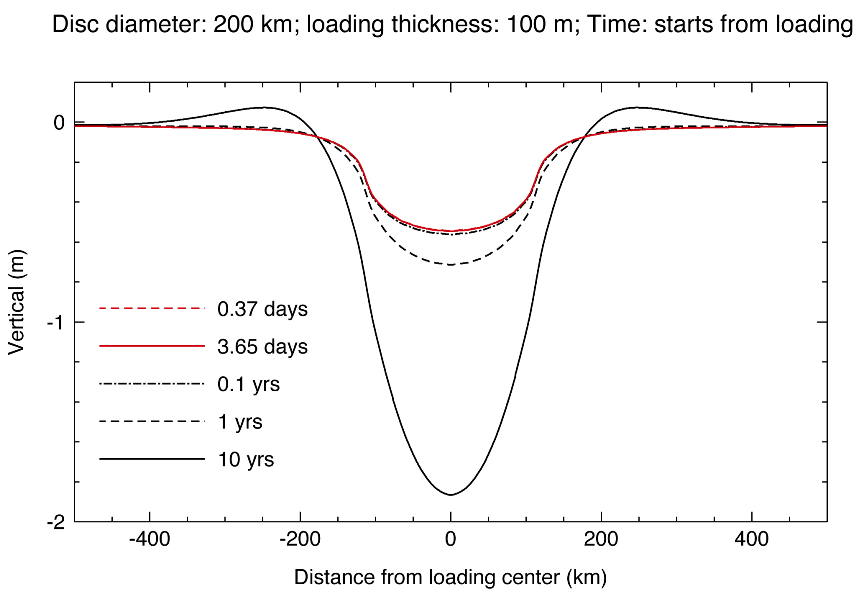
Glacial Isostatic Adjustment

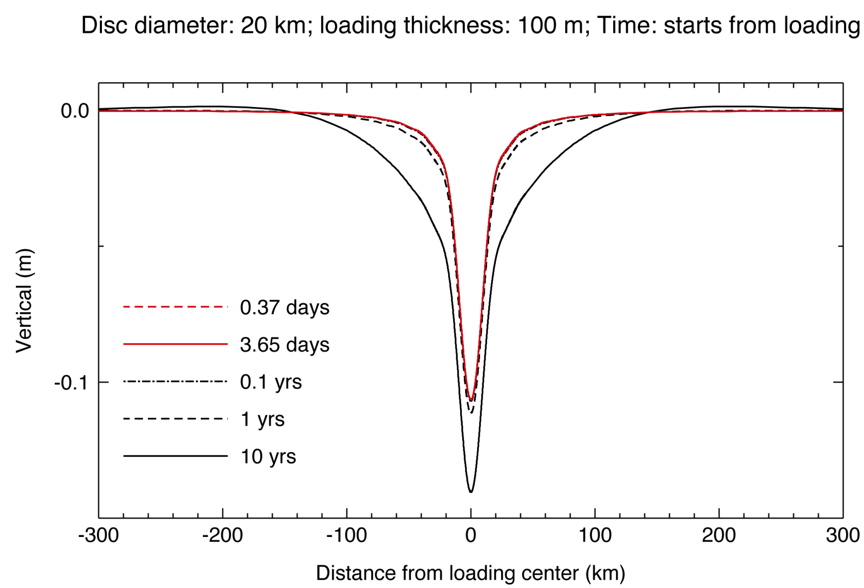
Glacial unloading after Last Glacial Maximum



Freymueller (2011), *Encyclopedia of Solid Earth Geophysics*

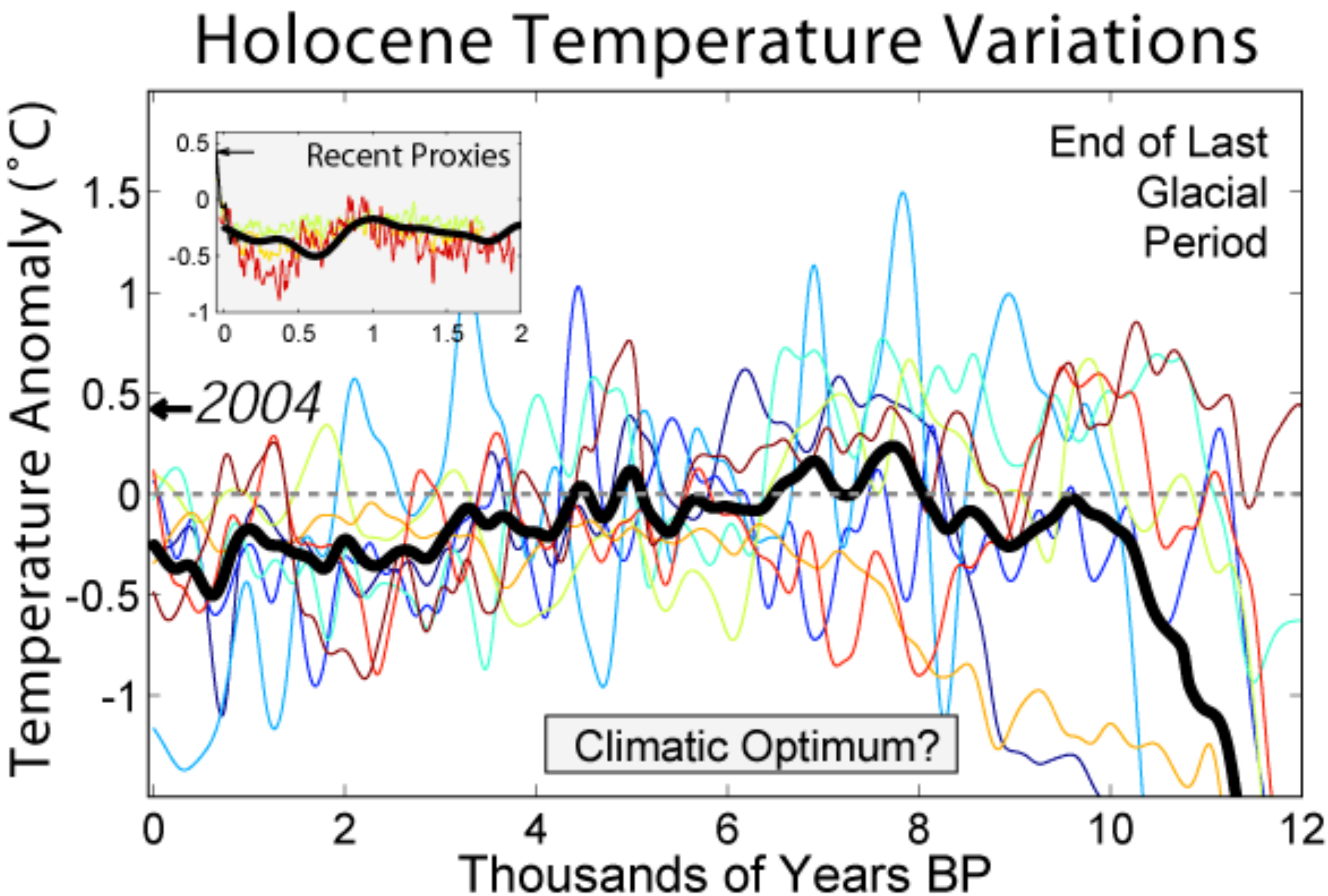
Response to Surface Loading



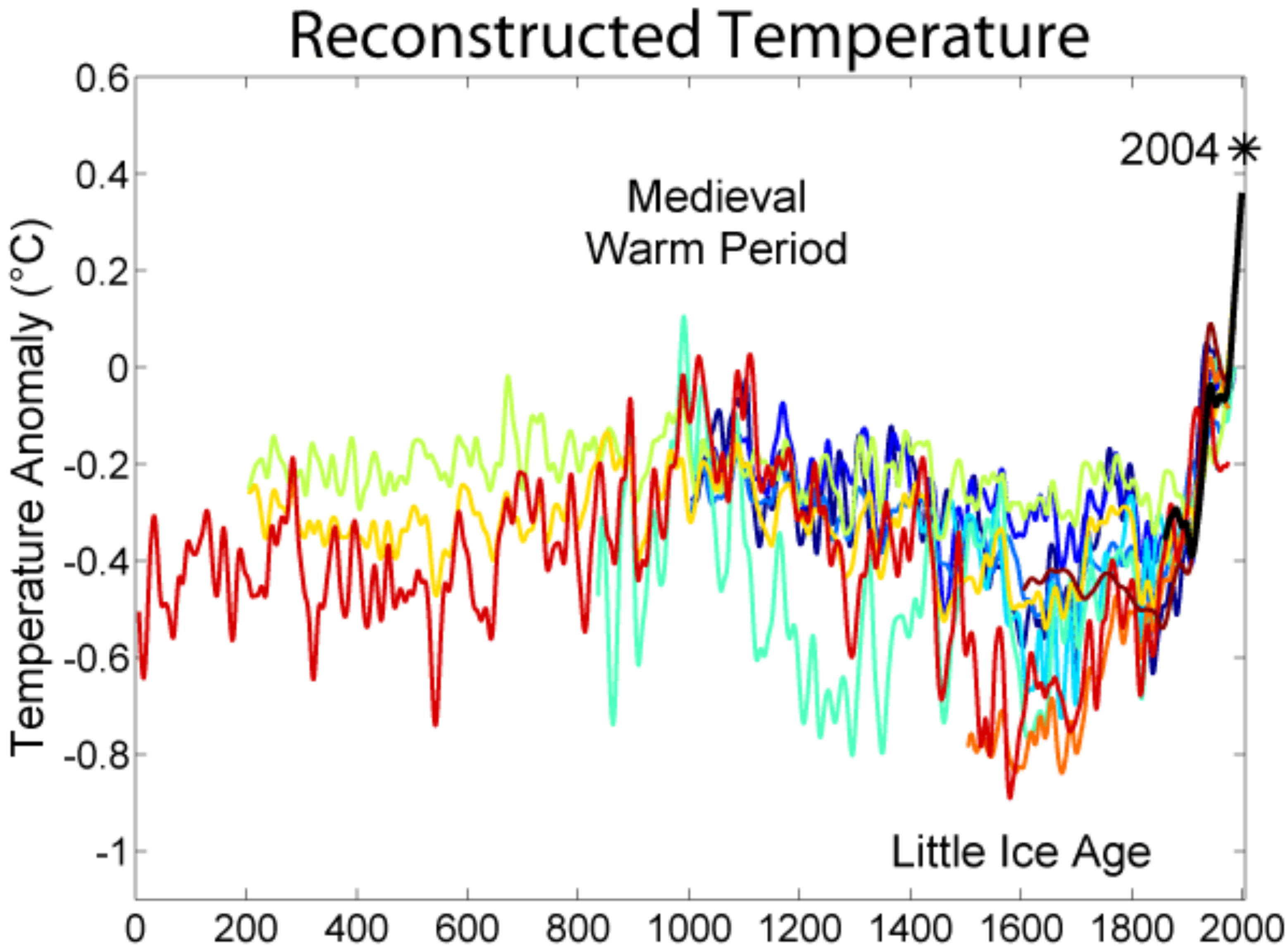


Outline

- Quaternary glaciation
- Glacial Isostatic Adjustment ("post-glacial rebound")
- Examples from the paleo ice sheets (Laurentide and Fennoscandia)
- Examples from Southeast Alaska
  - Special thanks to Chris Larsen
- What about Greenland and Antarctica?

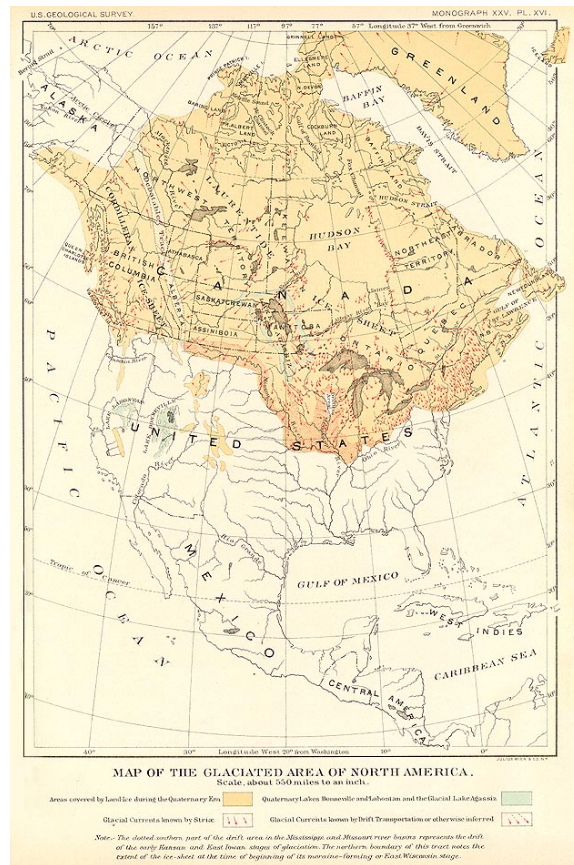


http://www.globalwarmingart.com/wiki/Image:Holocene_Temperature_Variations.png



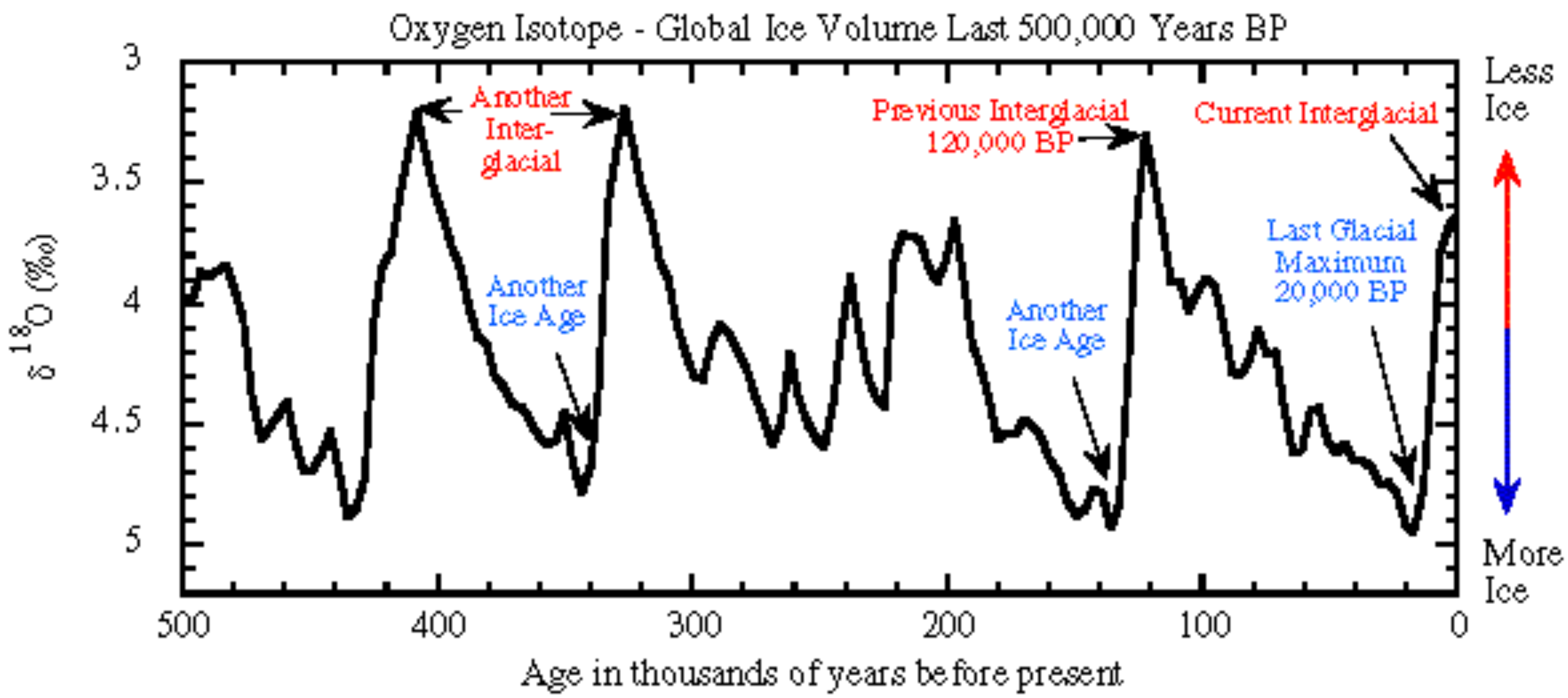
http://www.globalwarmingart.com/wiki/Image:2000_Year_Temperature_Comparison.png

Quaternary Glaciations

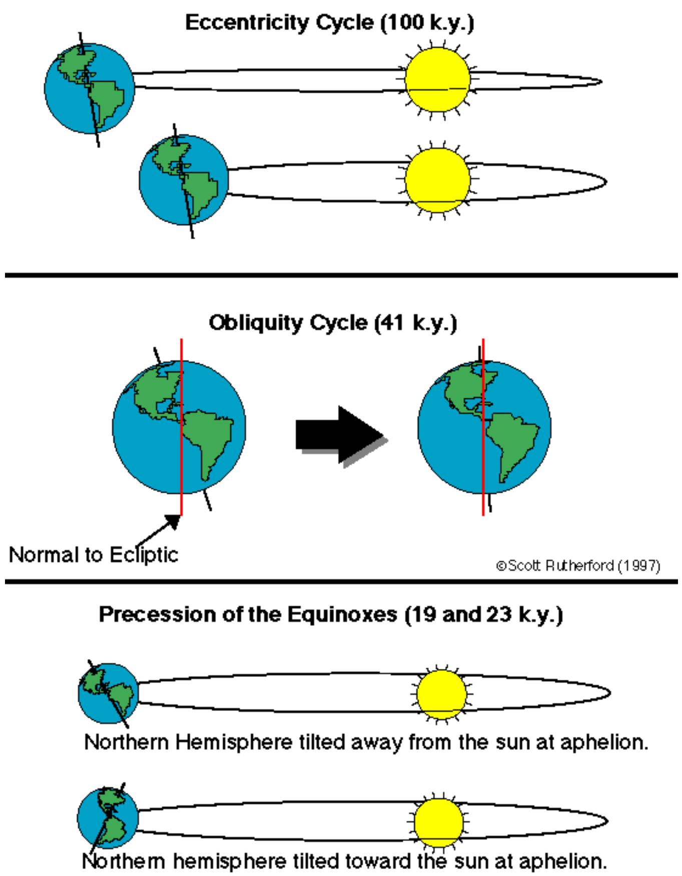


Time History of Glaciations

- Oxygen isotope variations record variations in the amount of ice
  - More ice means more O18 in the oceans.

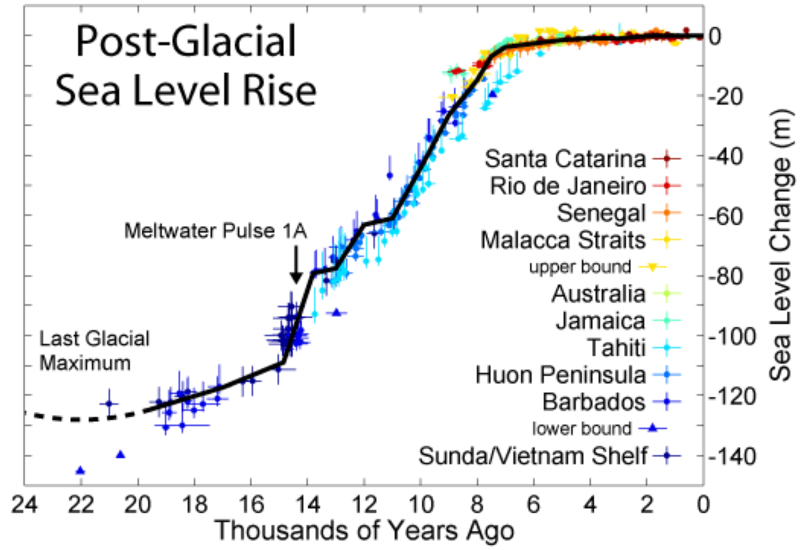


Why ~100,000 year cycle?

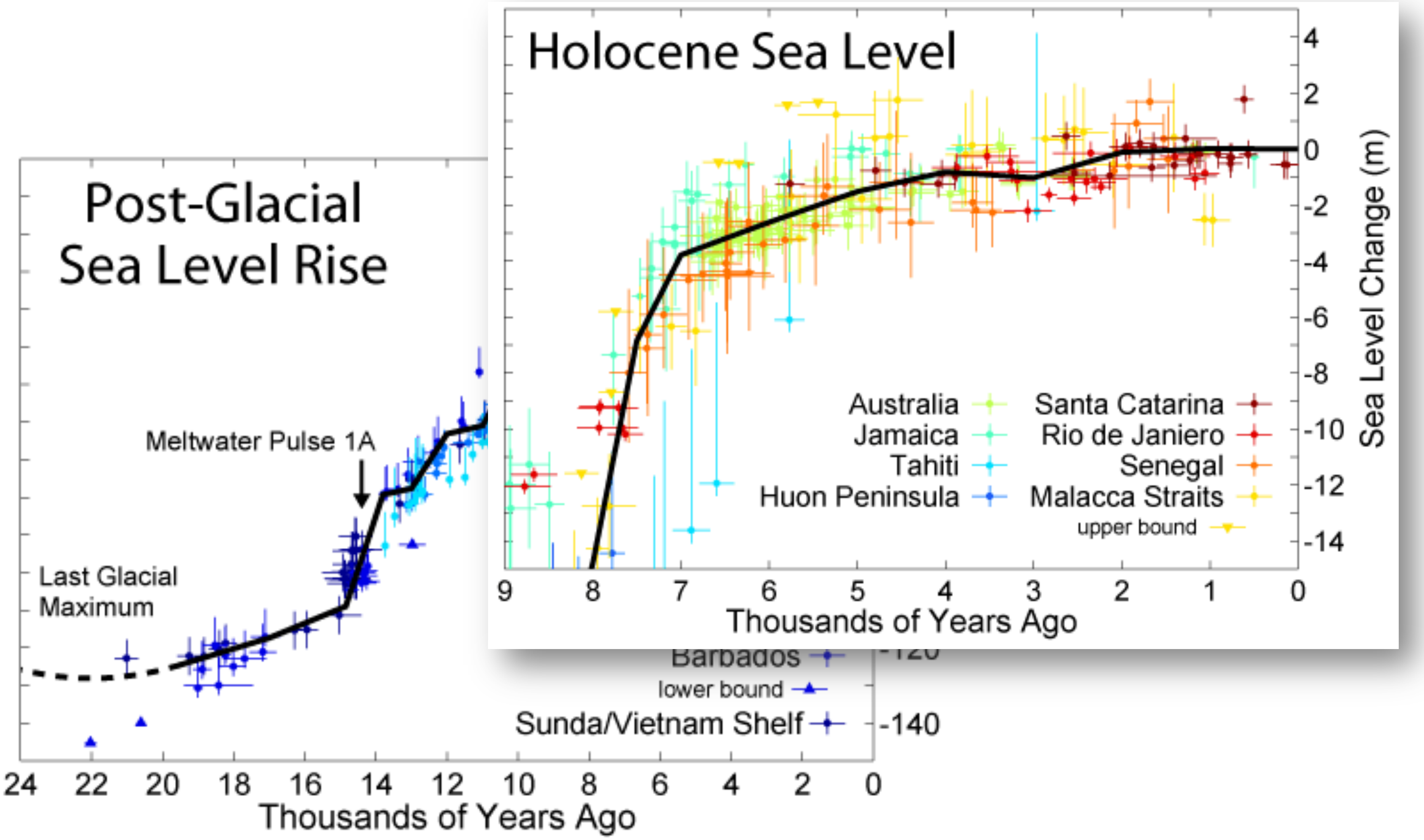


- "Milankovitch cycles"
  - Eccentricity of Earth Orbit
  - Obliquity cycle
  - Precession cycle
- Still, we have had glacial climate for only the last few million years

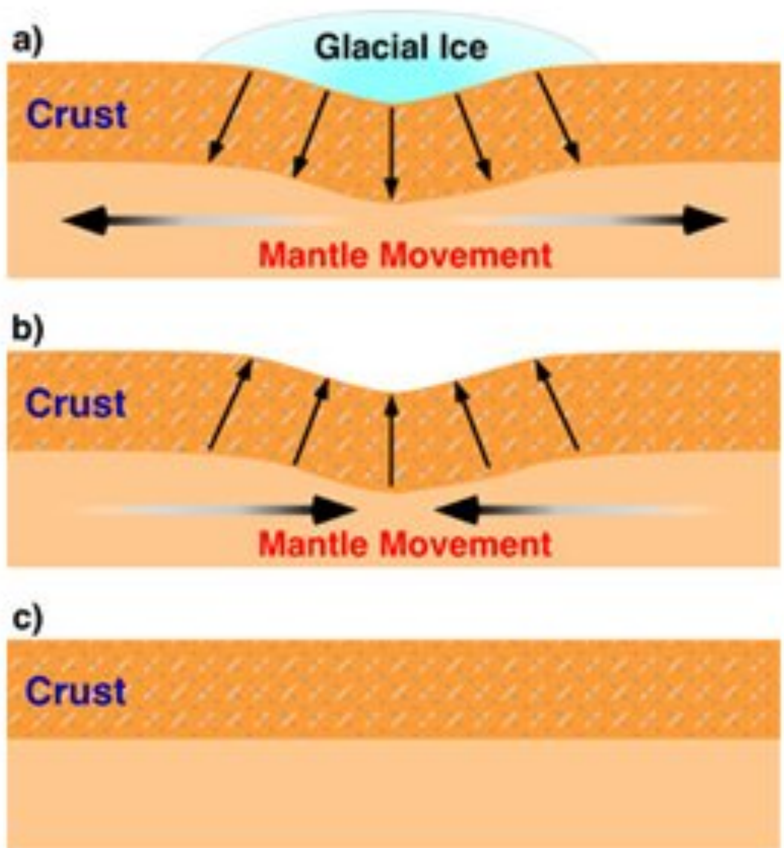
Constraints from Sea Level Rise



Sea Level Rise History

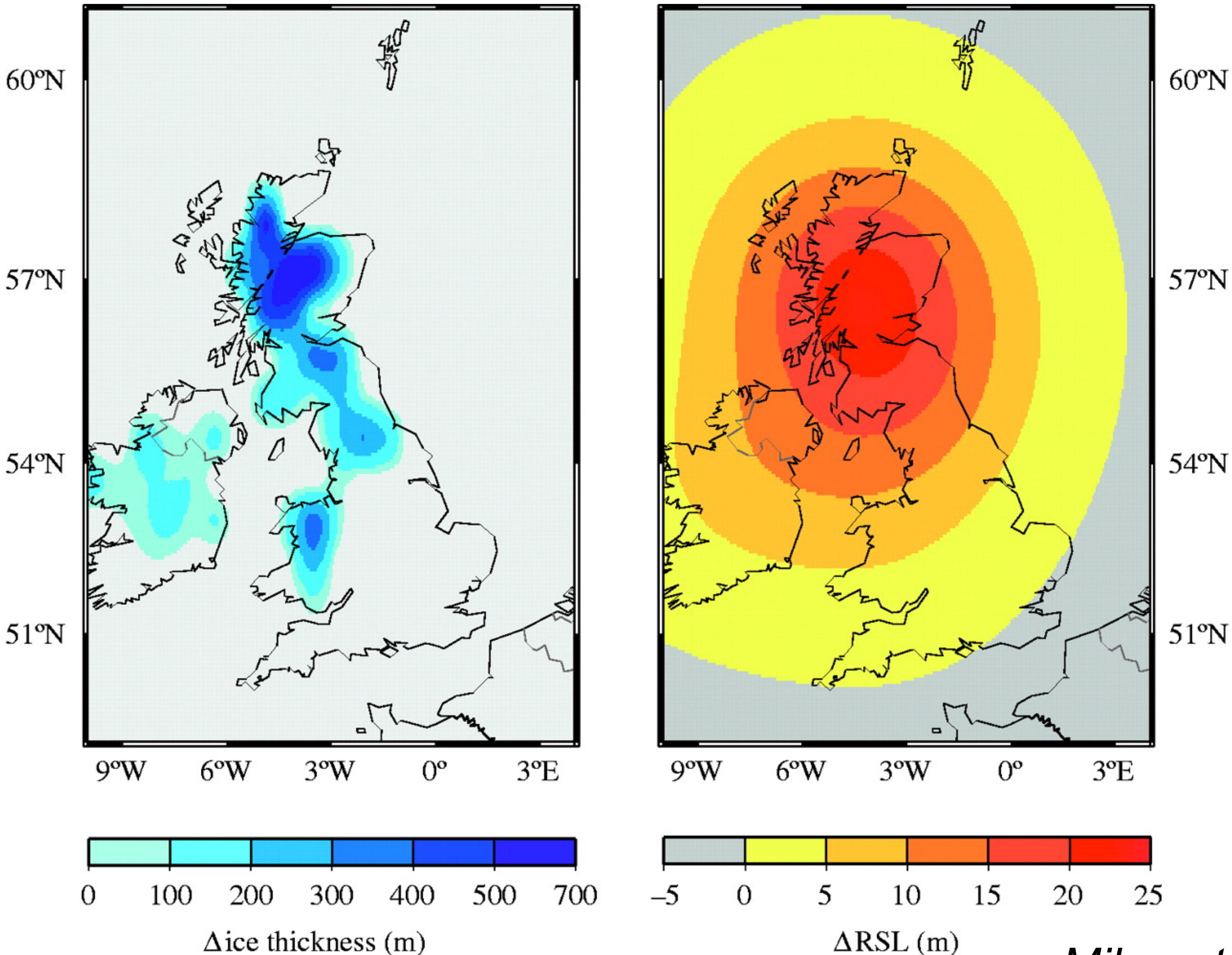


Glacial Isostatic Adjustment (aka "post-glacial rebound")



- Adding weight of ice depresses crust, forces viscous mantle to flow out of the way
  - Instantaneous elastic response
  - Time-delayed viscous response
  - Timescale for viscous flow depends on ***relaxation time*** for mantle
- Removing ice reverses the process

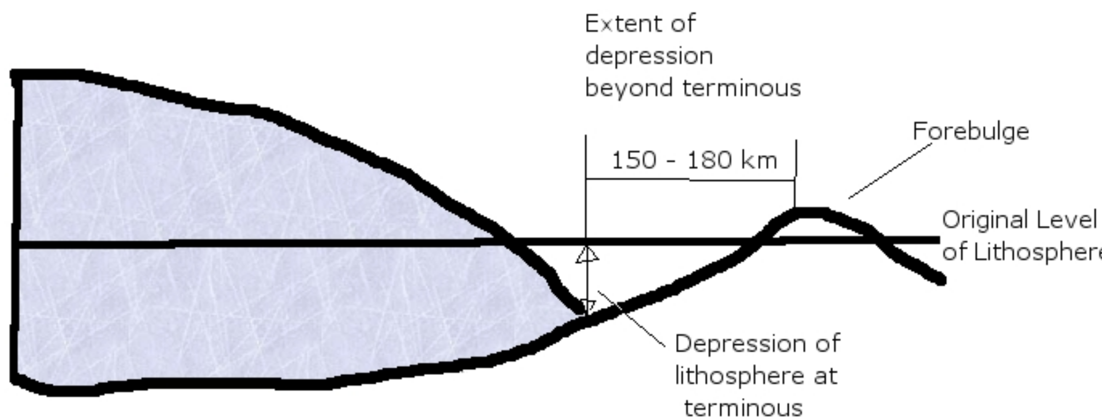
An Example – Scotland



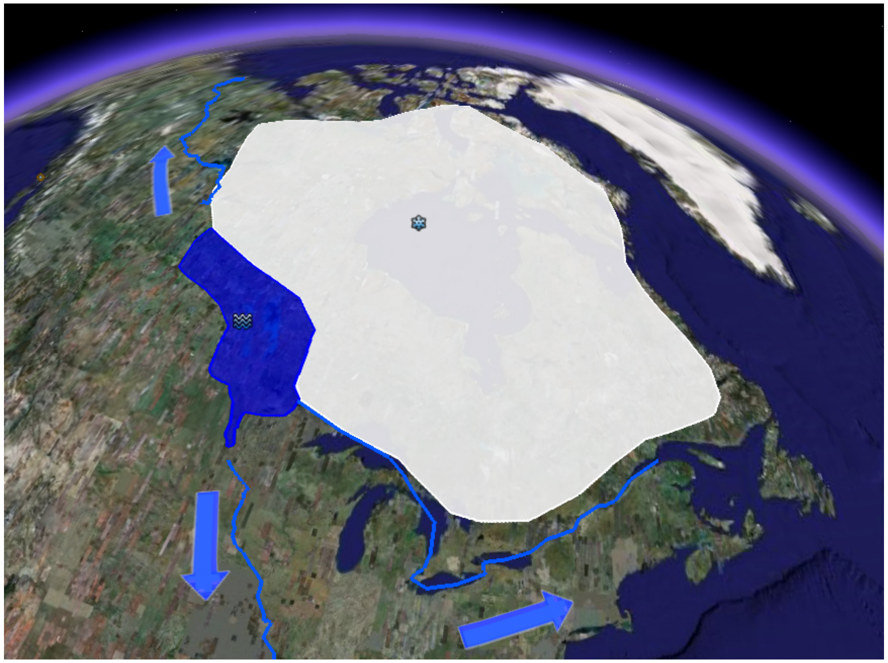
Milne et al. (2006)

Why GIA not PGR?

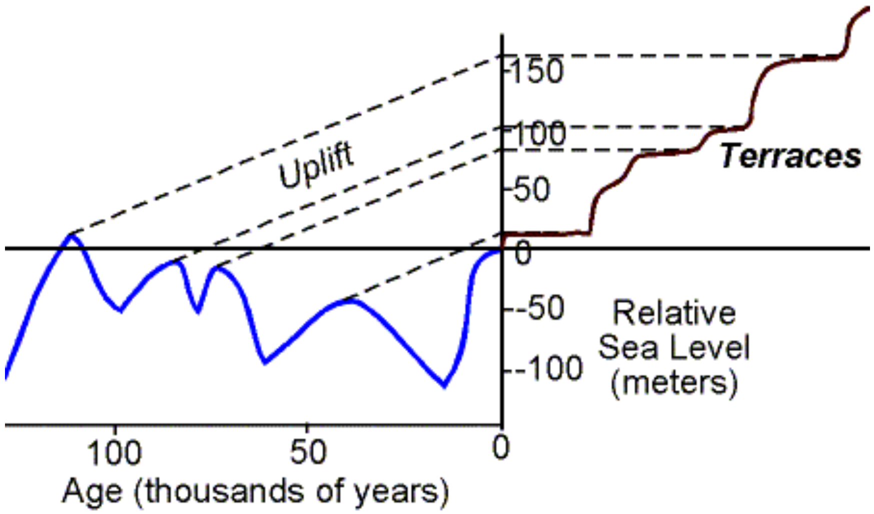
- The term Glacial Isostatic Adjustment is preferred because not all areas "rebound"
  - The depressed area is ringed by a flexural forebulge as load increases
  - The forebulge collapses after load is removed.



Deglaciation and Paleo-Shorelines



Hudson Bay Shoreline Terraces

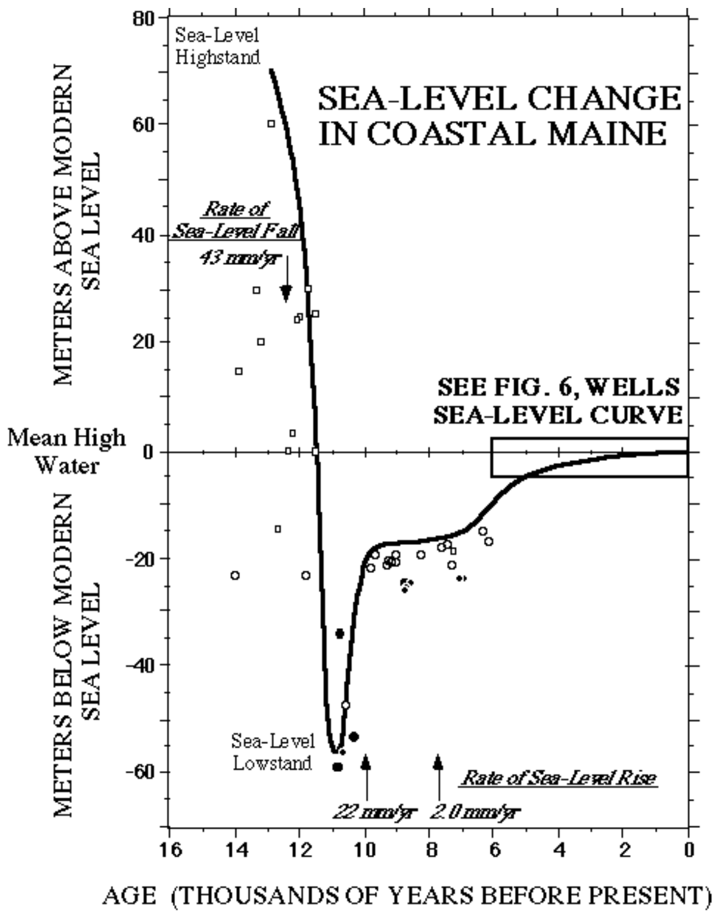


Hudson Bay Paleo-shorelines

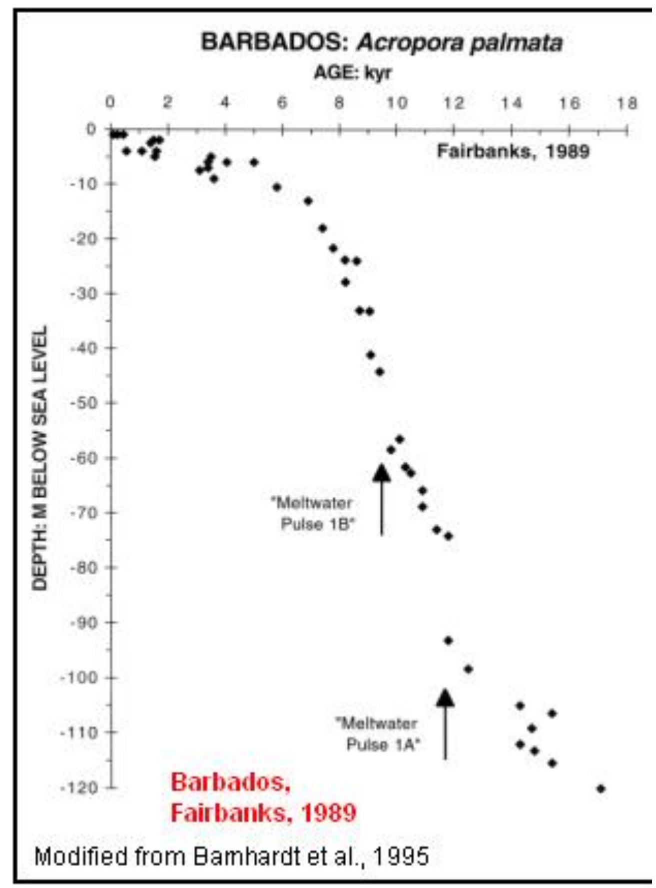
- Closely-spaced abandoned shoreline terraces mark uplift of the land (relative sea level fall)
- Rebound of areas formerly under the ice is in the 100s of meters.

Varied Sea Level Curves

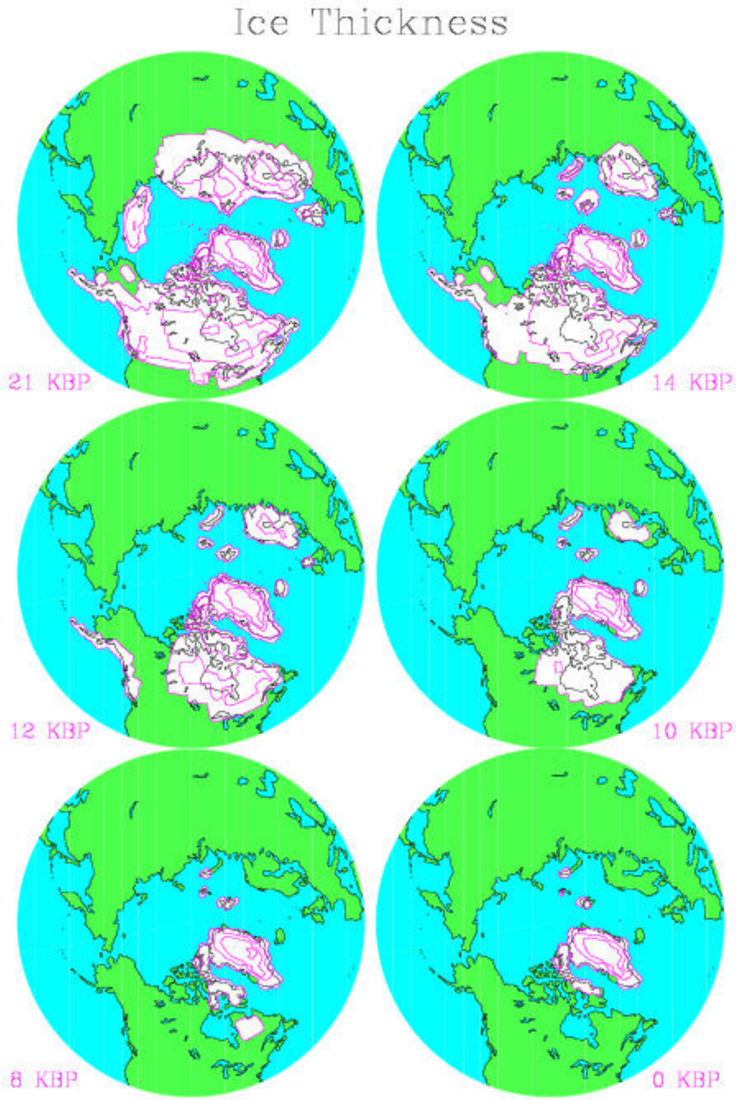
Proximal (Maine)



Distal (Barbados)



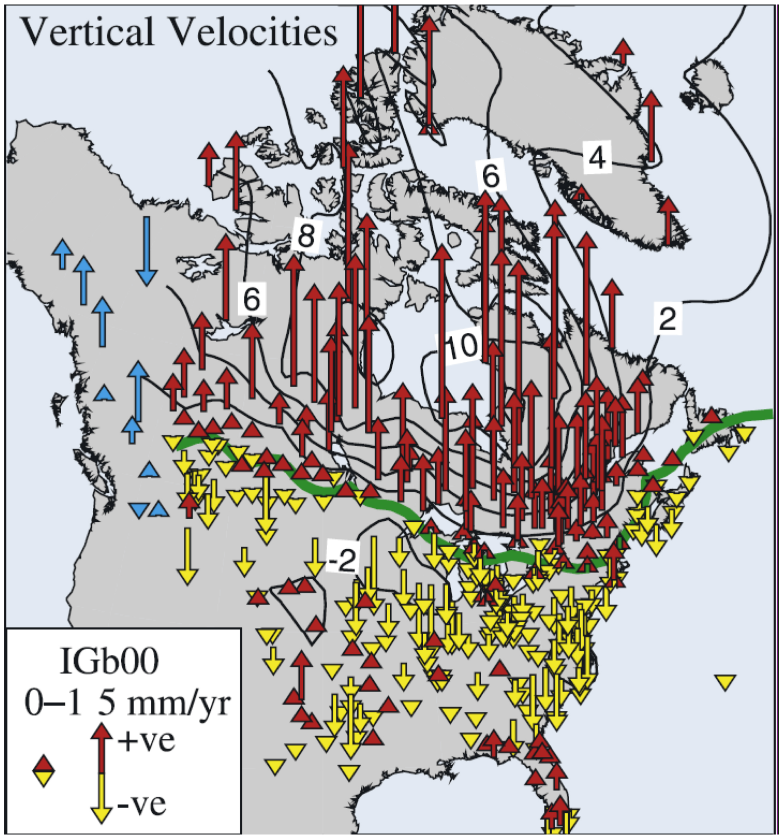
ICE Models



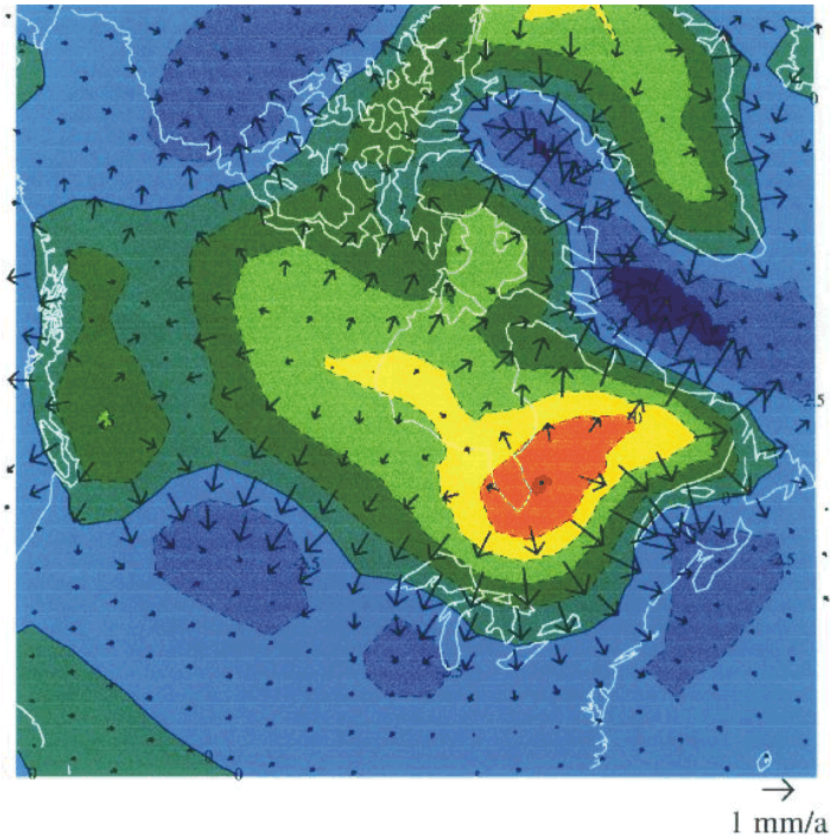
- Richard Peltier (U. Toronto) has developed a series of models over the years
  - ICE-1 to ICE-5G
  - Coupled to mantle viscosity models
- Constrained by sea level histories, including effects of GIA and sea level equation
- More recent models also attempt to integrate geodetic rates

Present-day Uplift

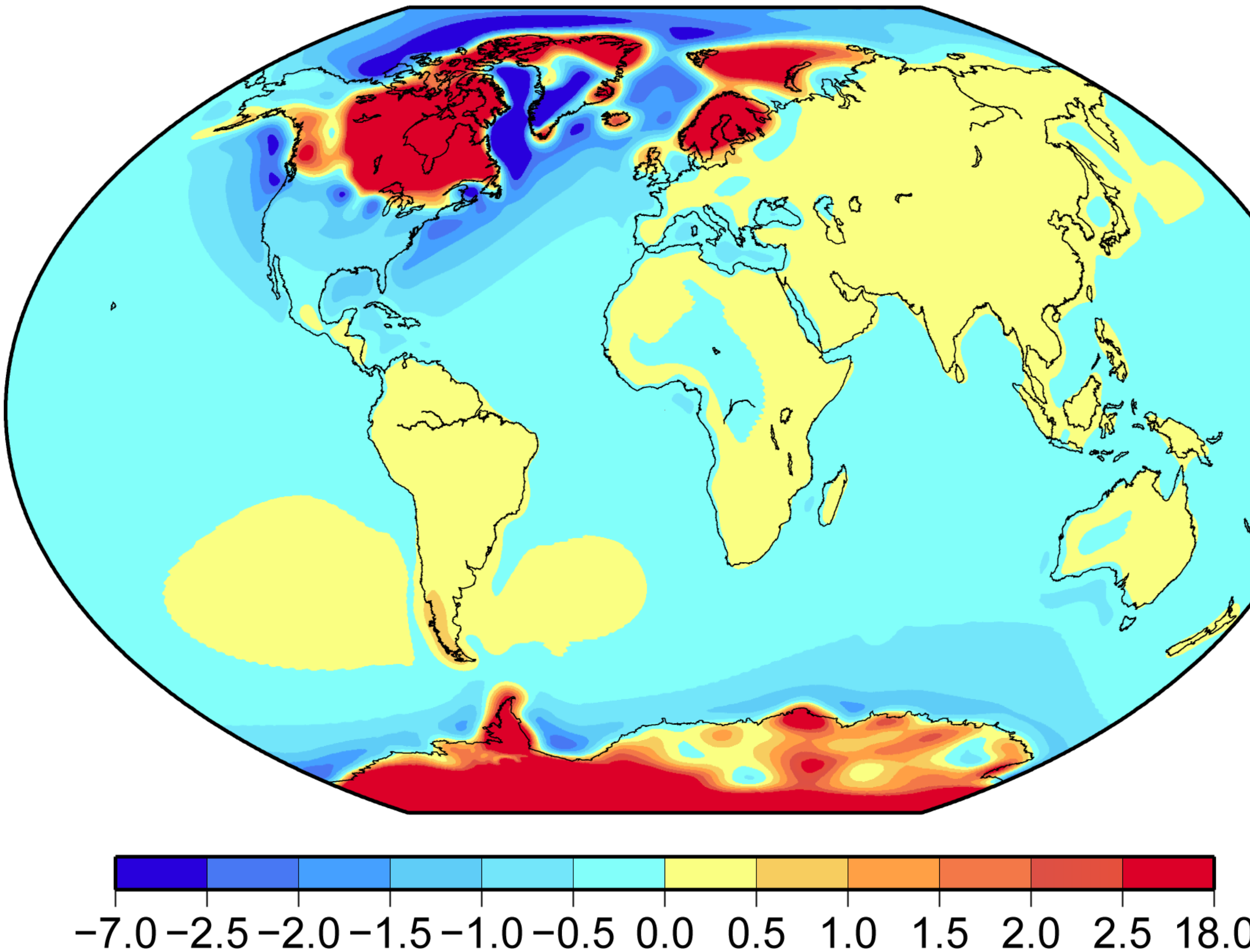
Observed (Sella et al., 2007)



Model (ICE-3G)

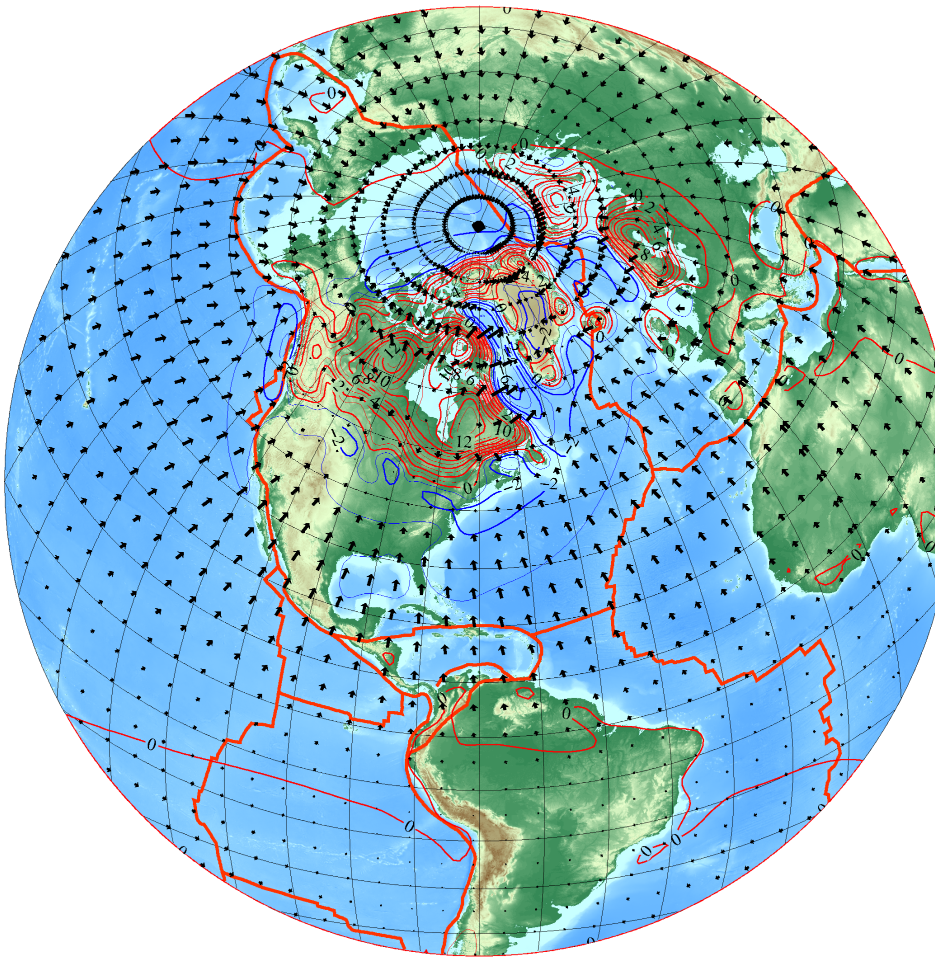


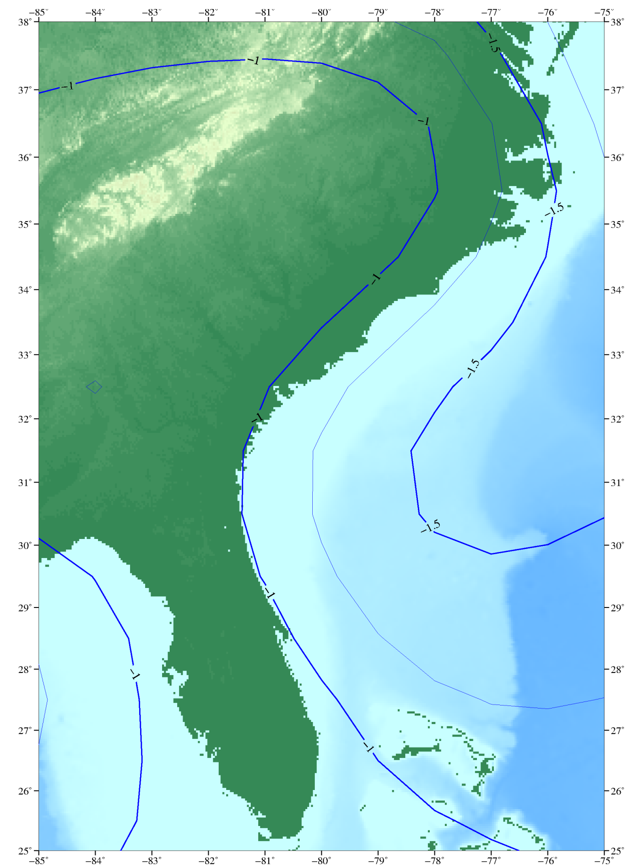
Global Pattern of Rebound:



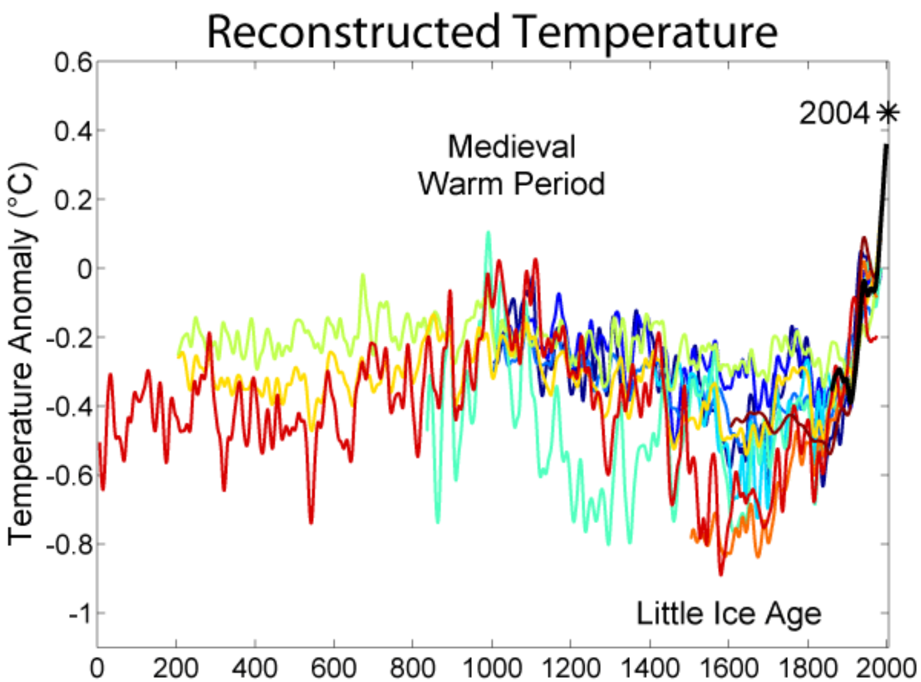
Milne et al. (2006)

The Latest ICE-6G Model

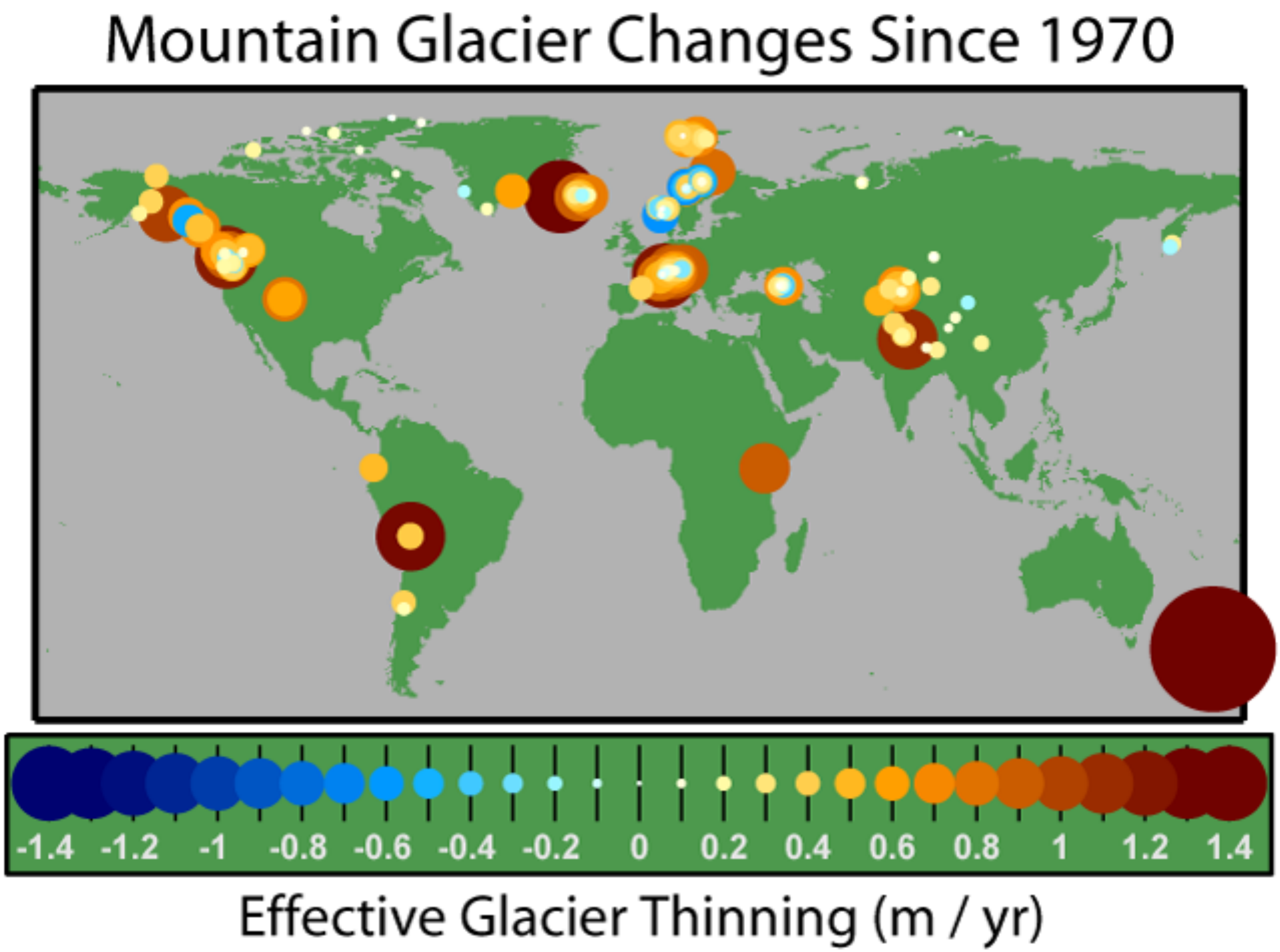




More Recent Changes – LIA to Present



- Most recent cold period was "Little Ice Age"
- Mountain glaciers advanced and gained mass
- Post-LIA melting began around 1800, accelerated through 20th Century



http://www.globalwarmingart.com/wiki/Image:Glacier_Mass_Balance_Map.png

Data from Dyurgerov and Meier (2005)

An Example: Patagonia

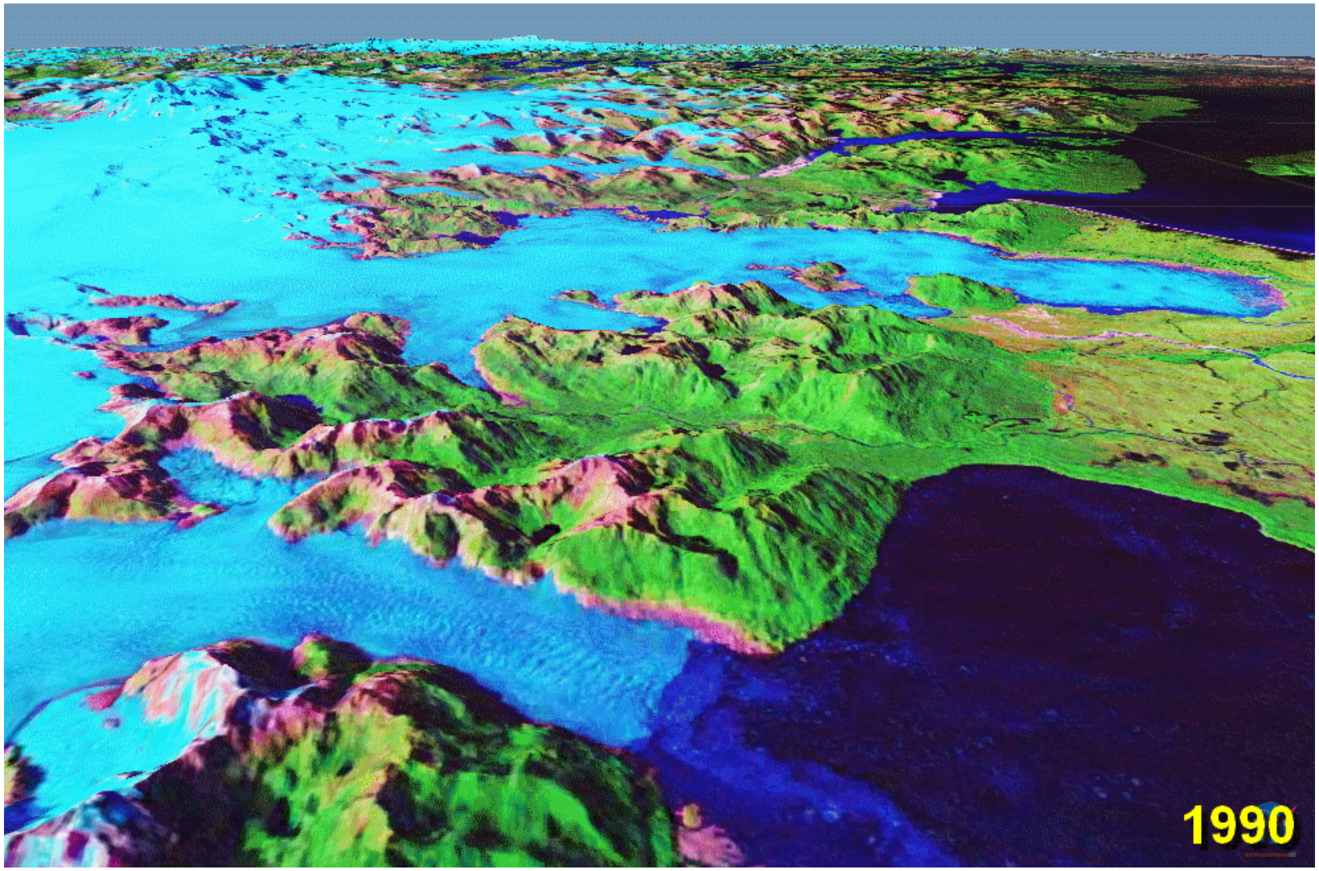
Ivins and James (2004)

- Rapid post-Little Ice Age retreat of glaciers
- GPS evidence for rapid uplift (Bevis et al., 2002)
- Ice load history known fairly well over last 1000 years and Holocene
- Located at end of a subduction zone, so lithosphere and mantle structure may be different from north to south.

Melting Patagonian Glaciers

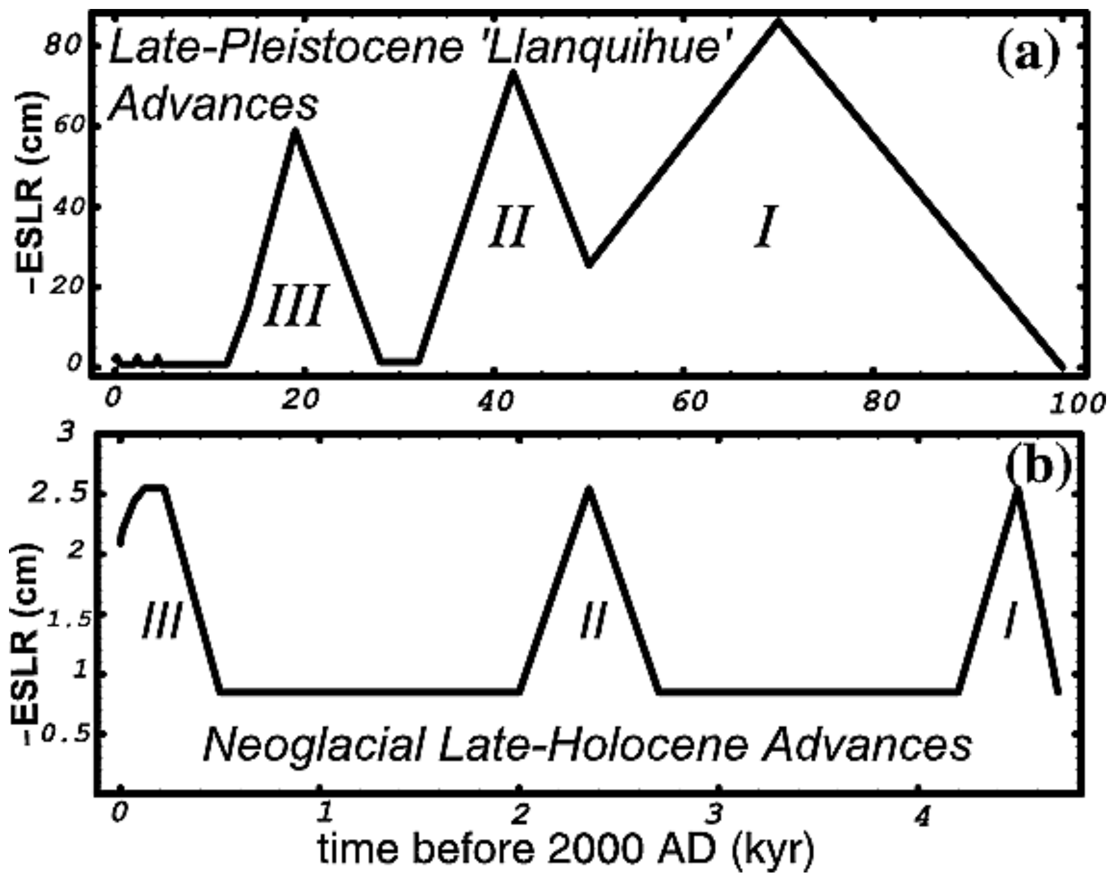
San Quintín Glacier

San Rafael Glacier



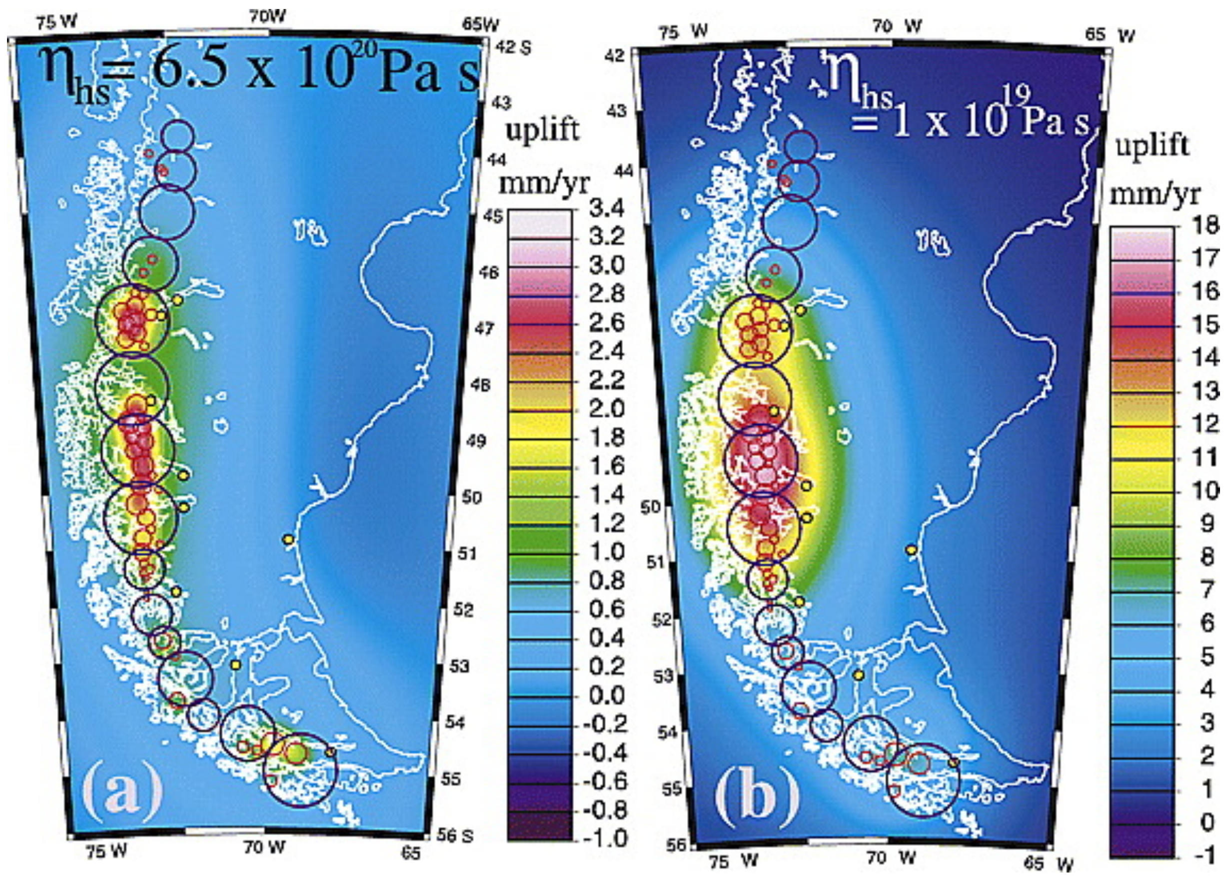
http://commons.wikimedia.org/wiki/Image:73.85851W_46.74169S.gif

Glacial History



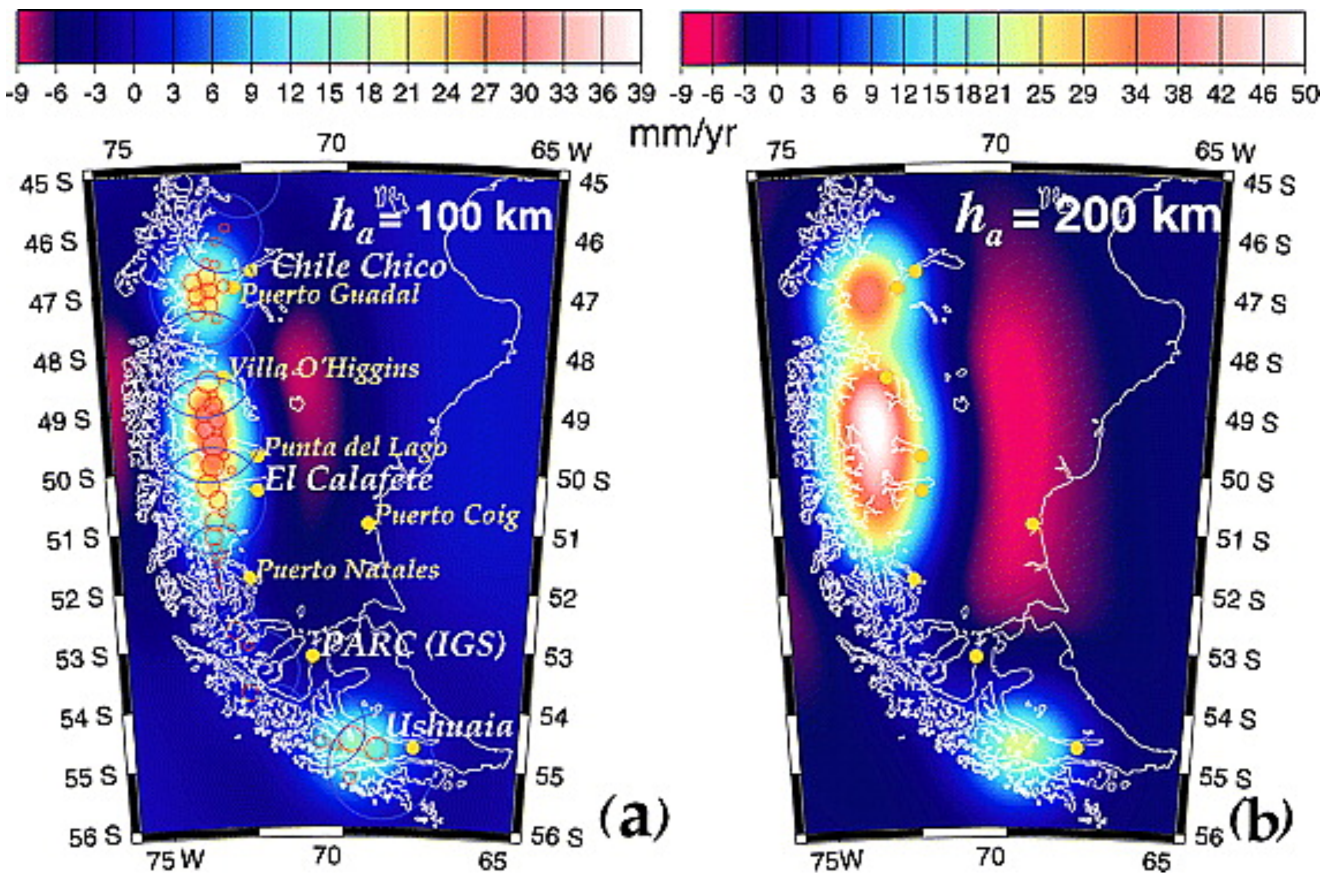
Ivins and James (2004)

Impact of Varying Viscosity



Ivins and James (2004)

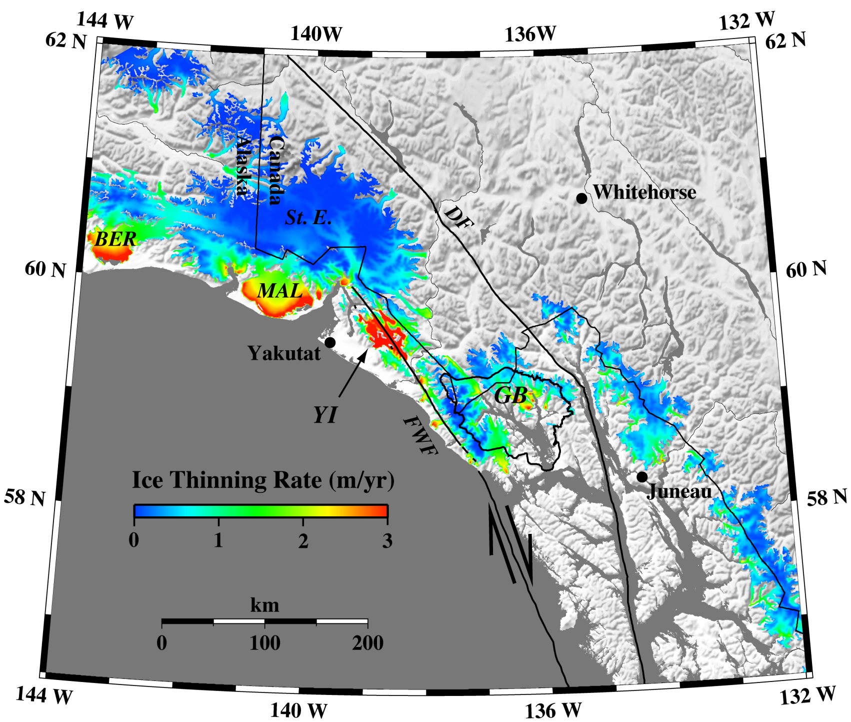
Impact of Low Viscosity Asthenosphere



Ivins and James (2004)

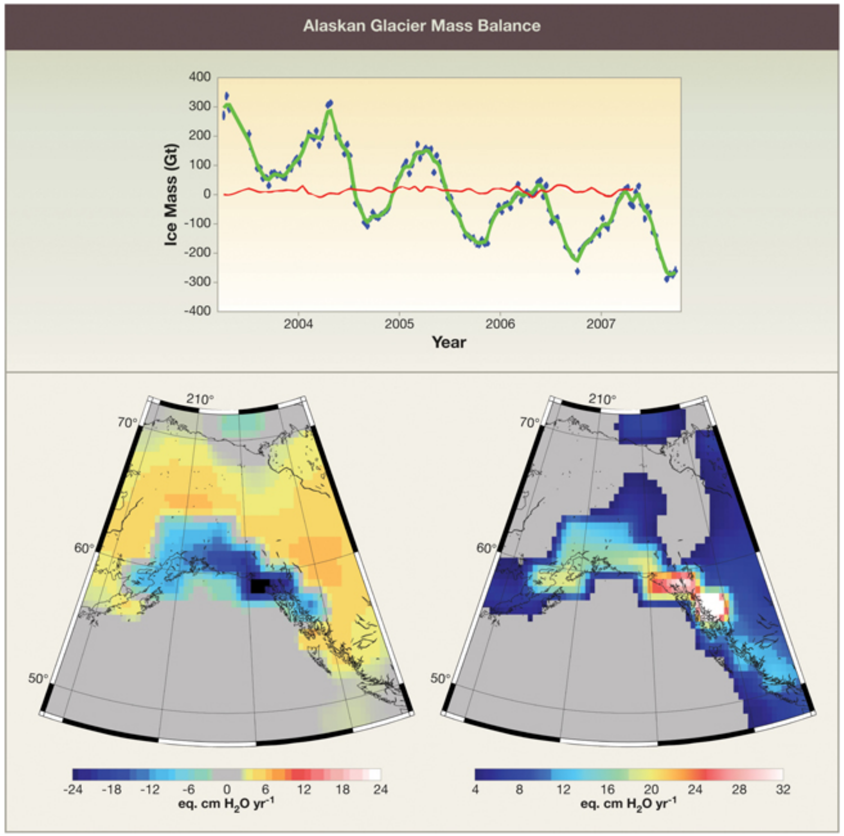
Present Changes, Alaska

From repeat glacial altimetry

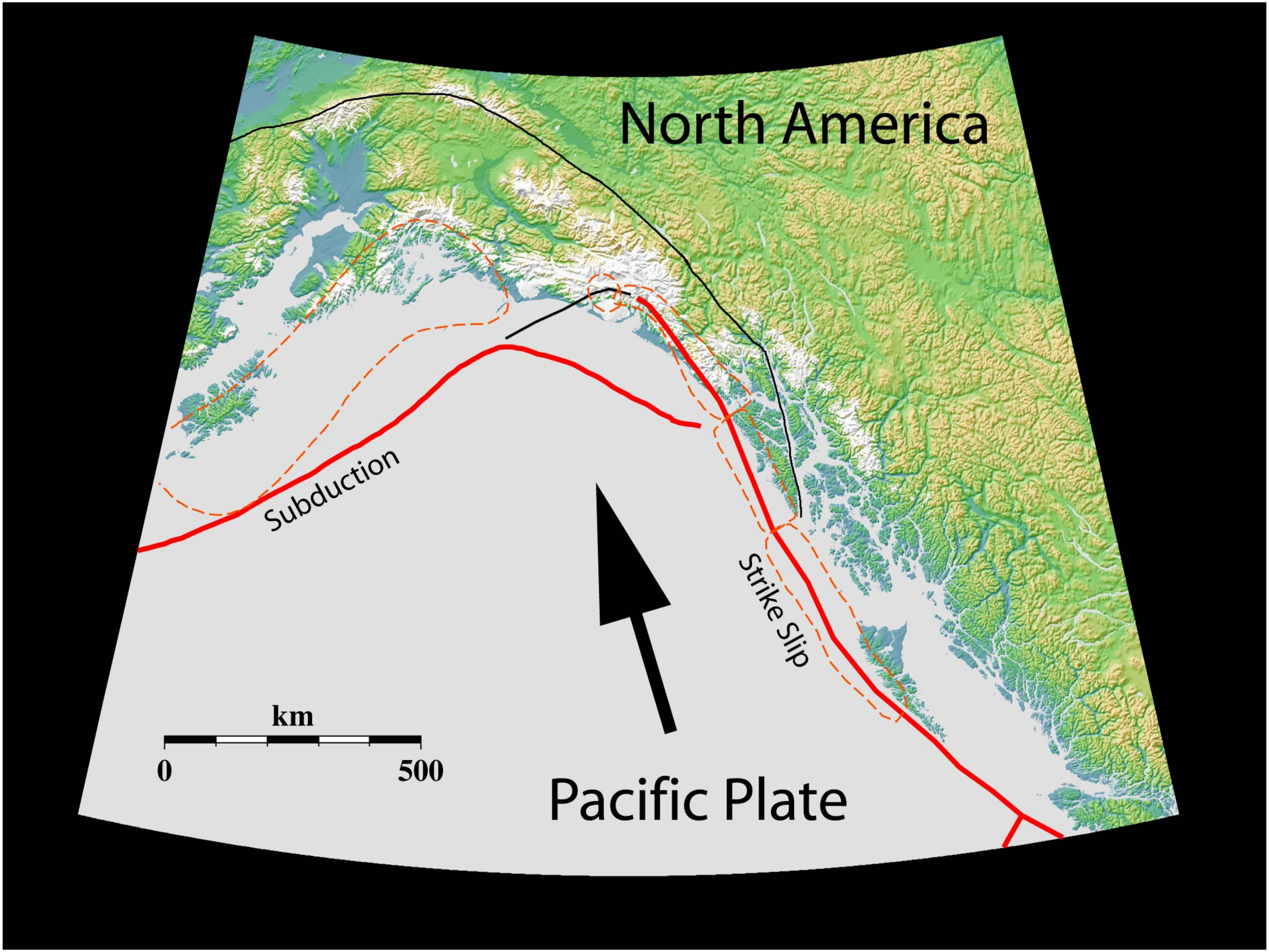


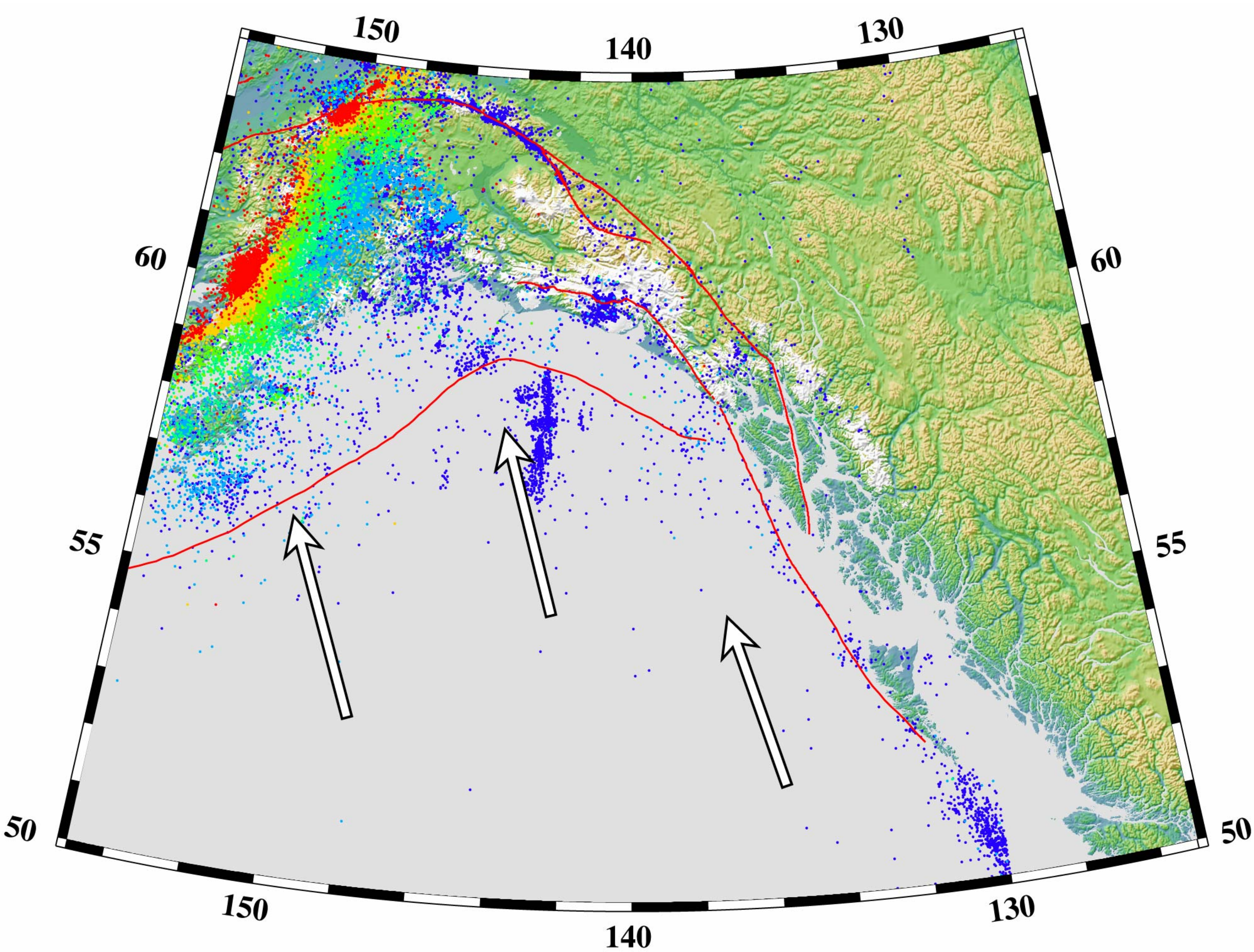
Arendt et al. (2002)

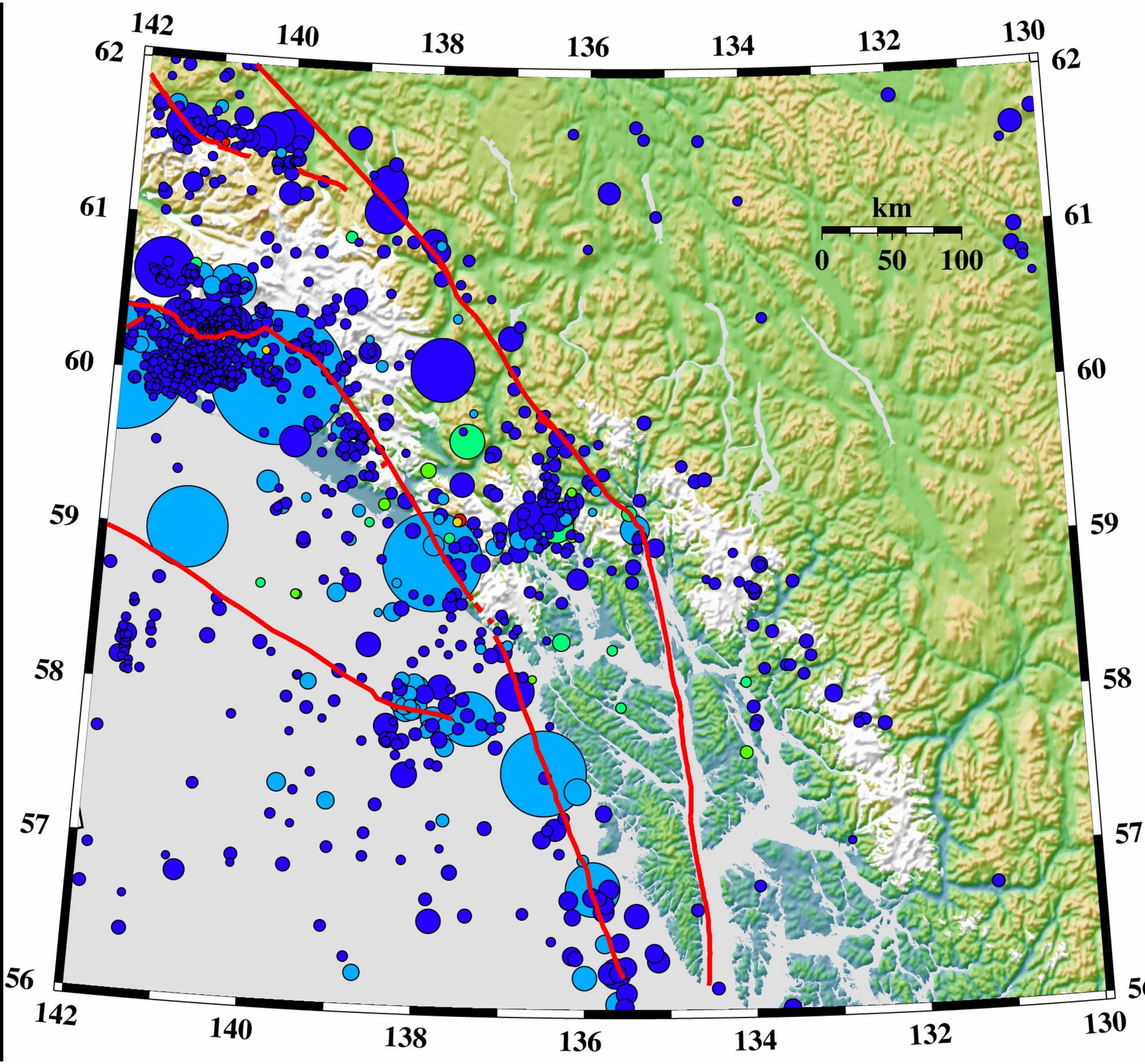
From geoid changes (GRACE)



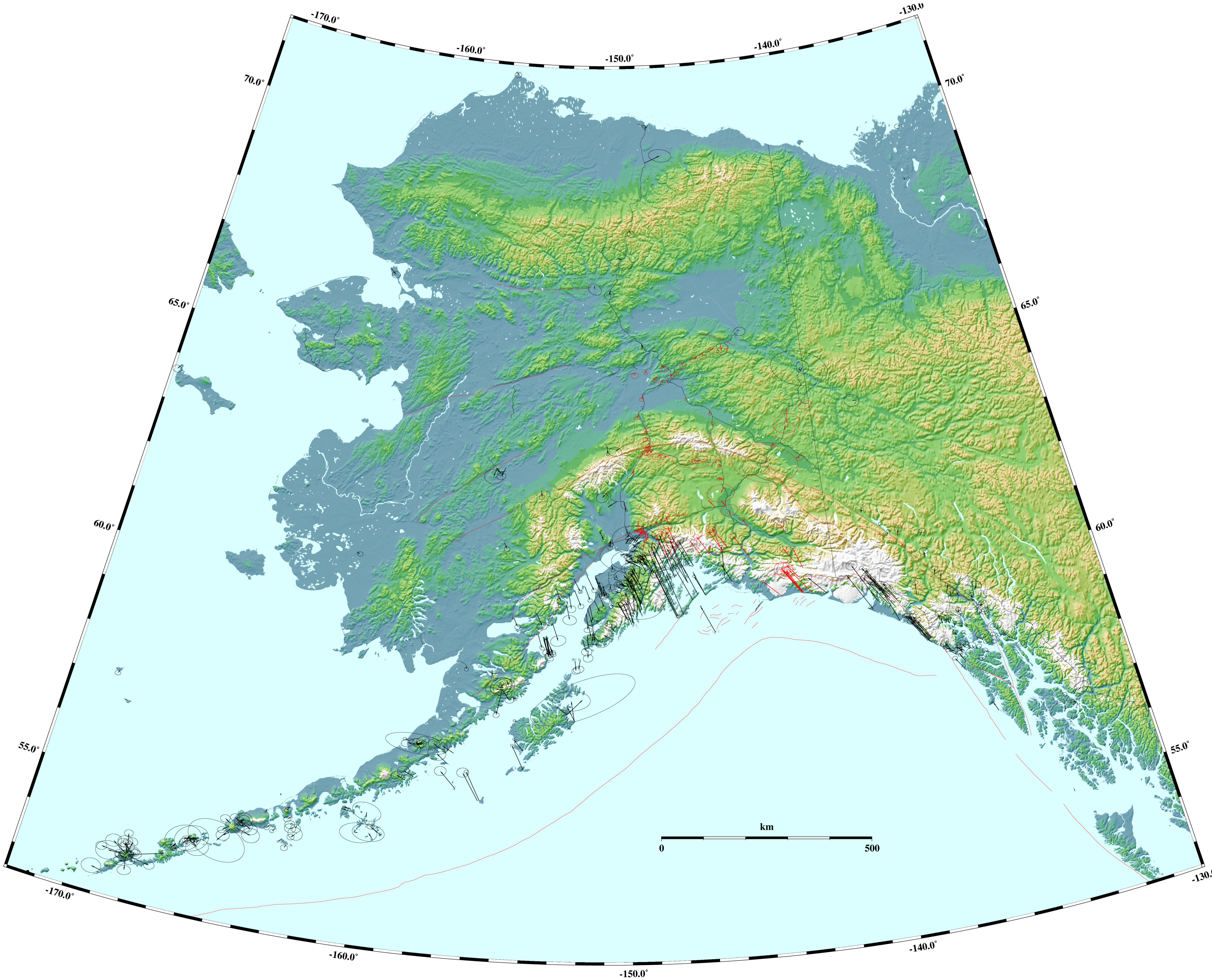
Luthcke et al. (2008)


North America
Subduction
Strike Slip
km
0
500
Pacific Plate

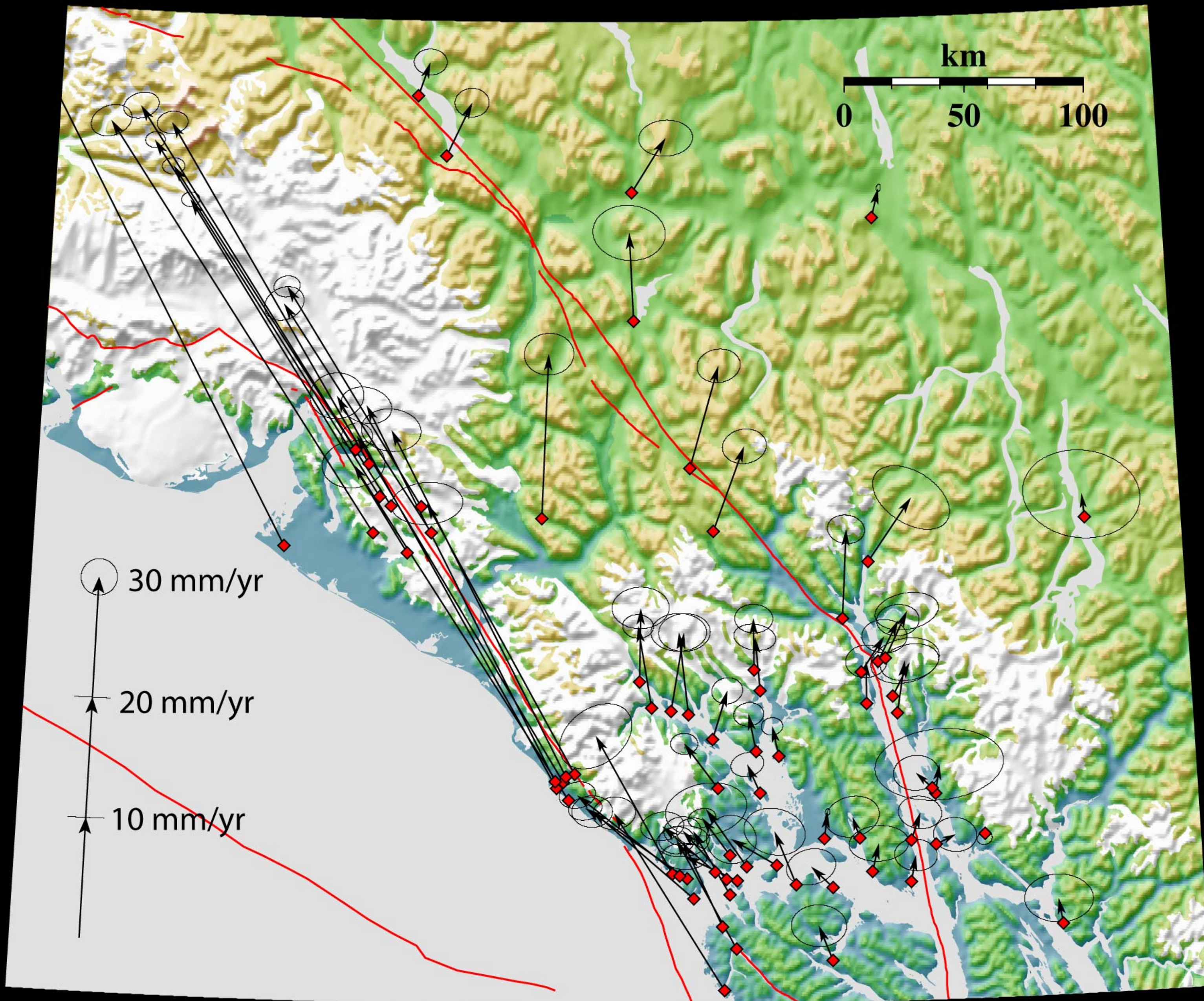

150
140
130
60
60
55
55
50
50
150
140
130

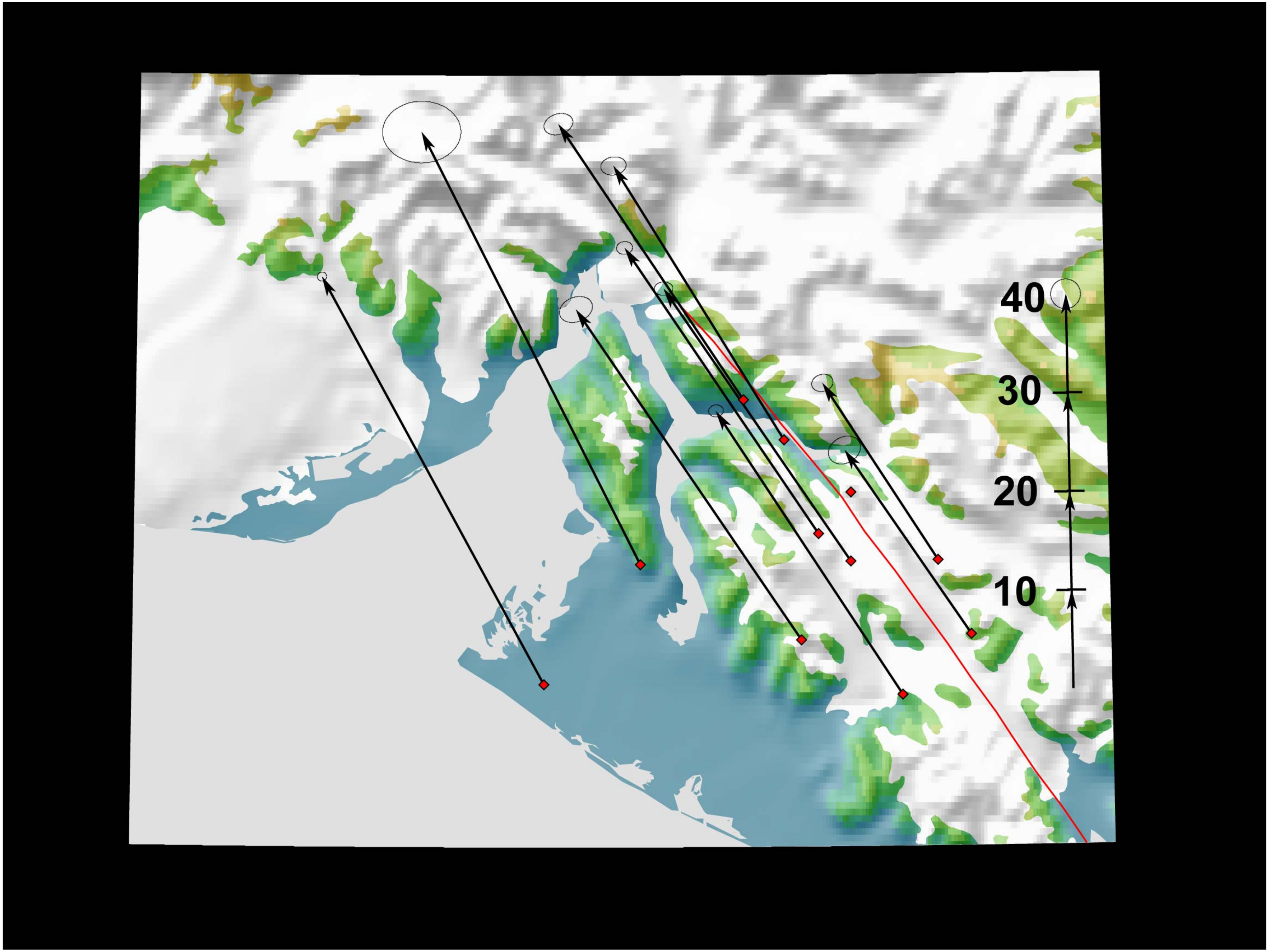


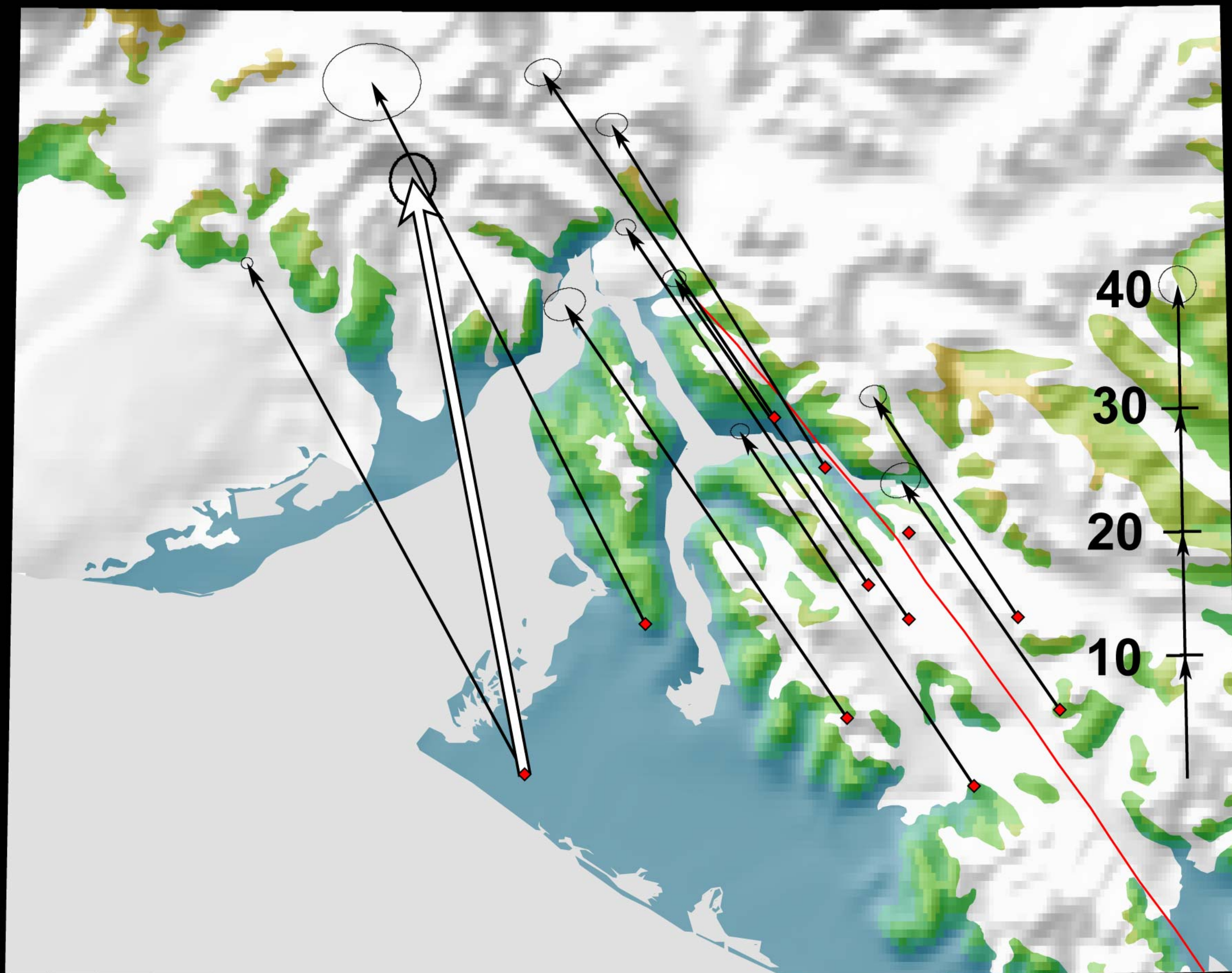
142
140
138
136
134
132
130
62
61
60
59
58
57
56
km
0
50
100



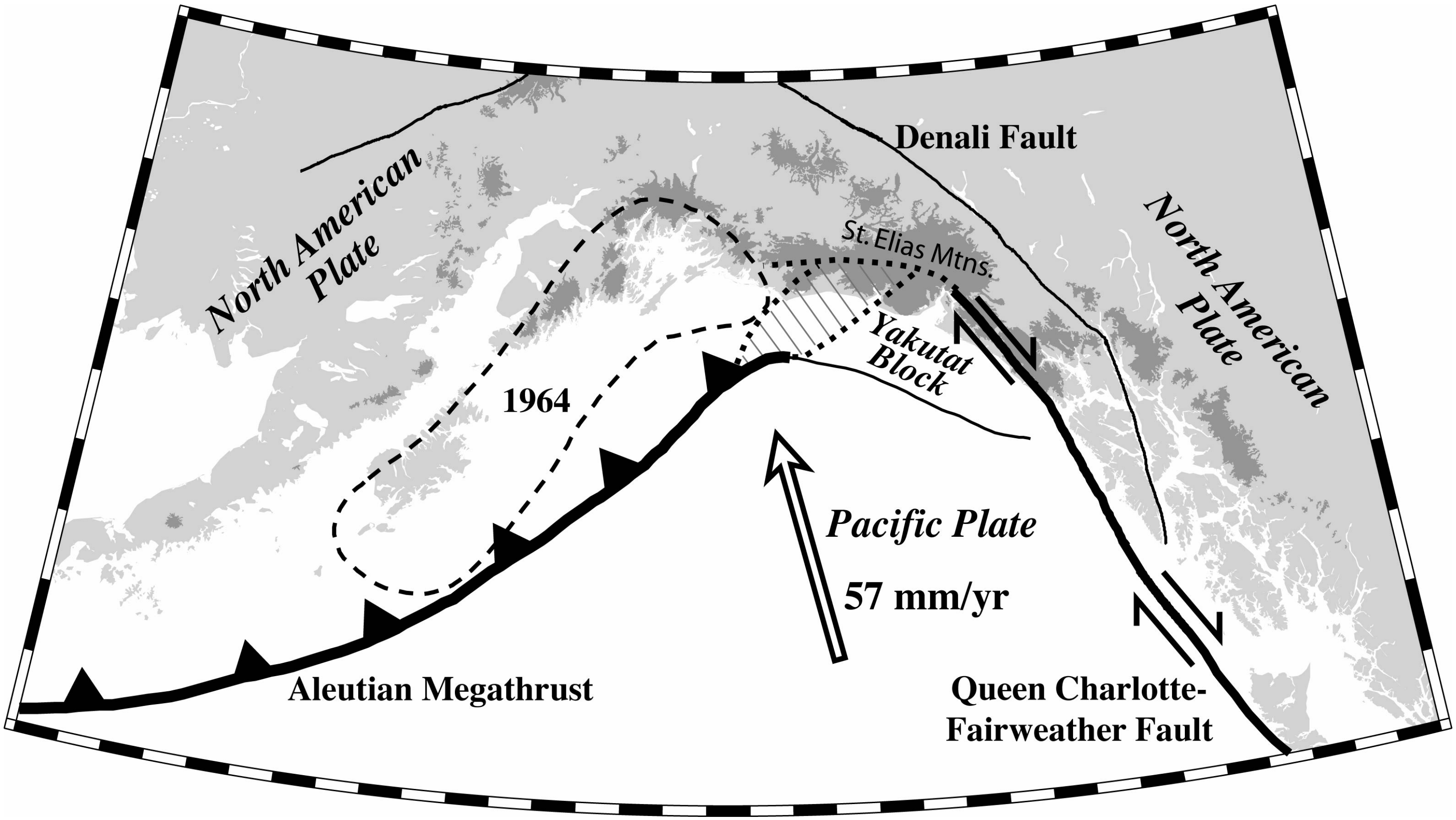
-170.0°
-160.0°
-150.0°
-140.0°
-130.0
70.0°
65.0°
60.0°
55.0°
70.0°
65.0°
60.0°
55.0°
-170.0°
-160.0°
-150.0°
-140.0°
-130.0°
km
0
500


km
0
50
100
30 mm/yr
20 mm/yr
10 mm/yr

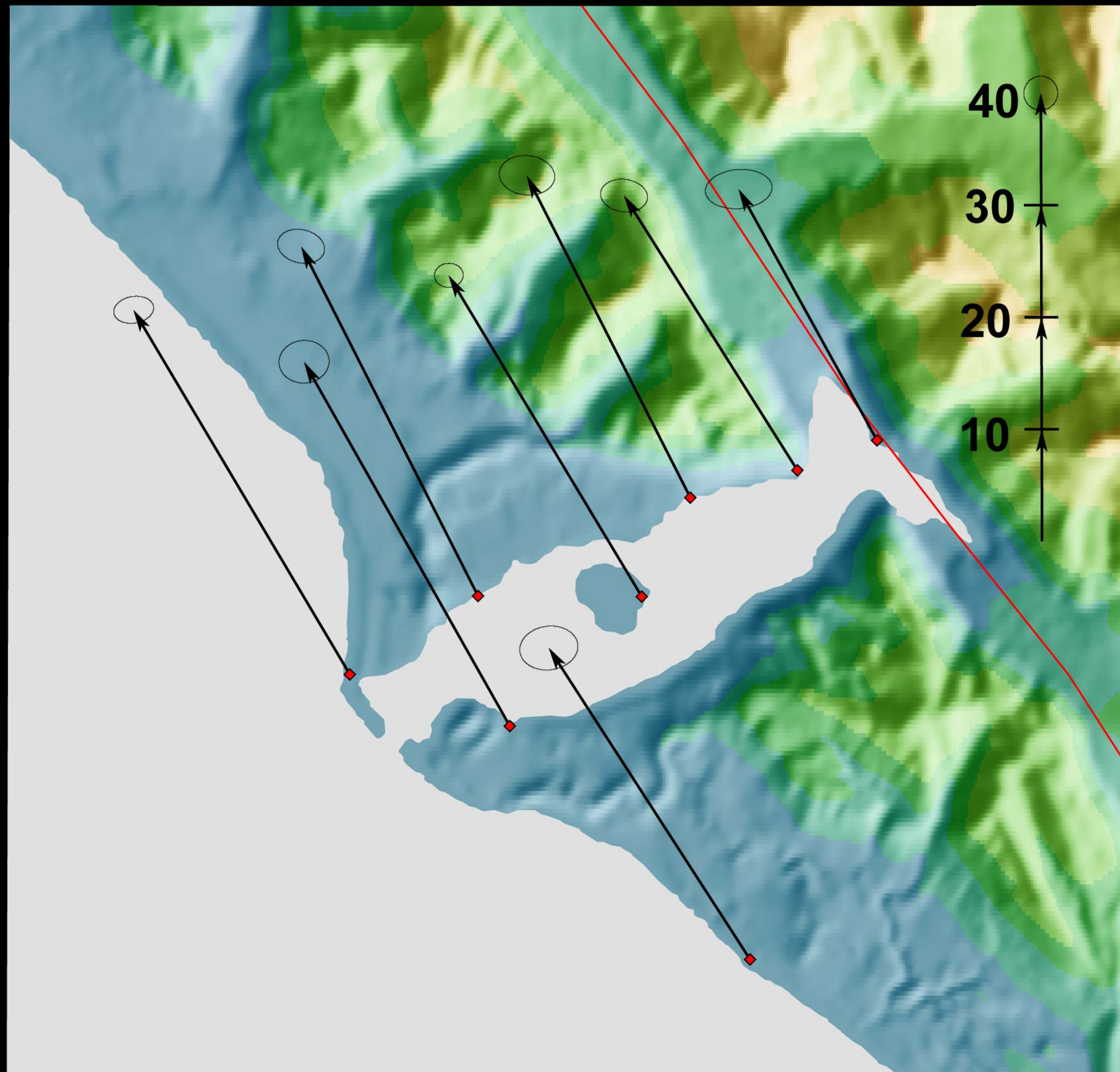

40
30
20
10

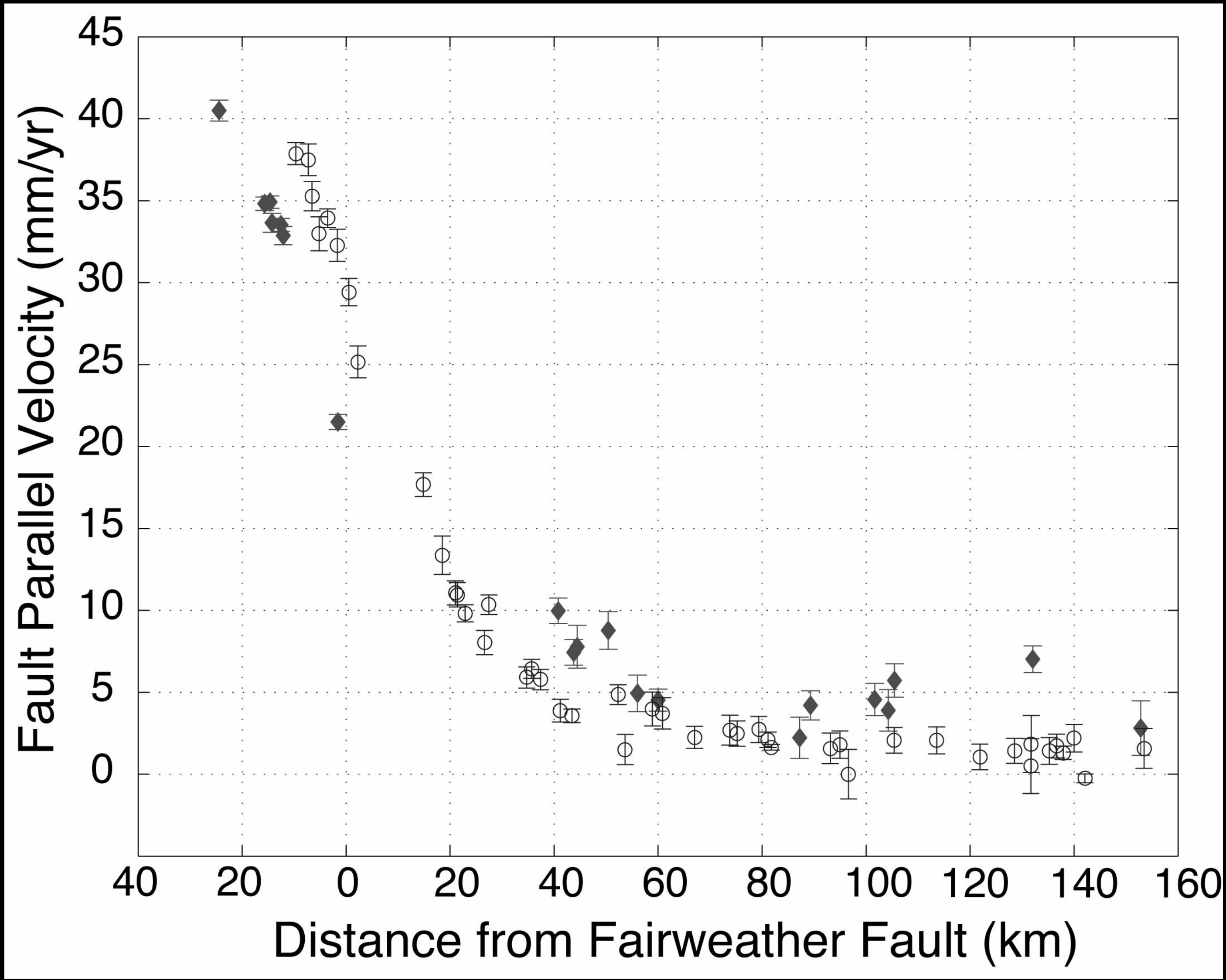


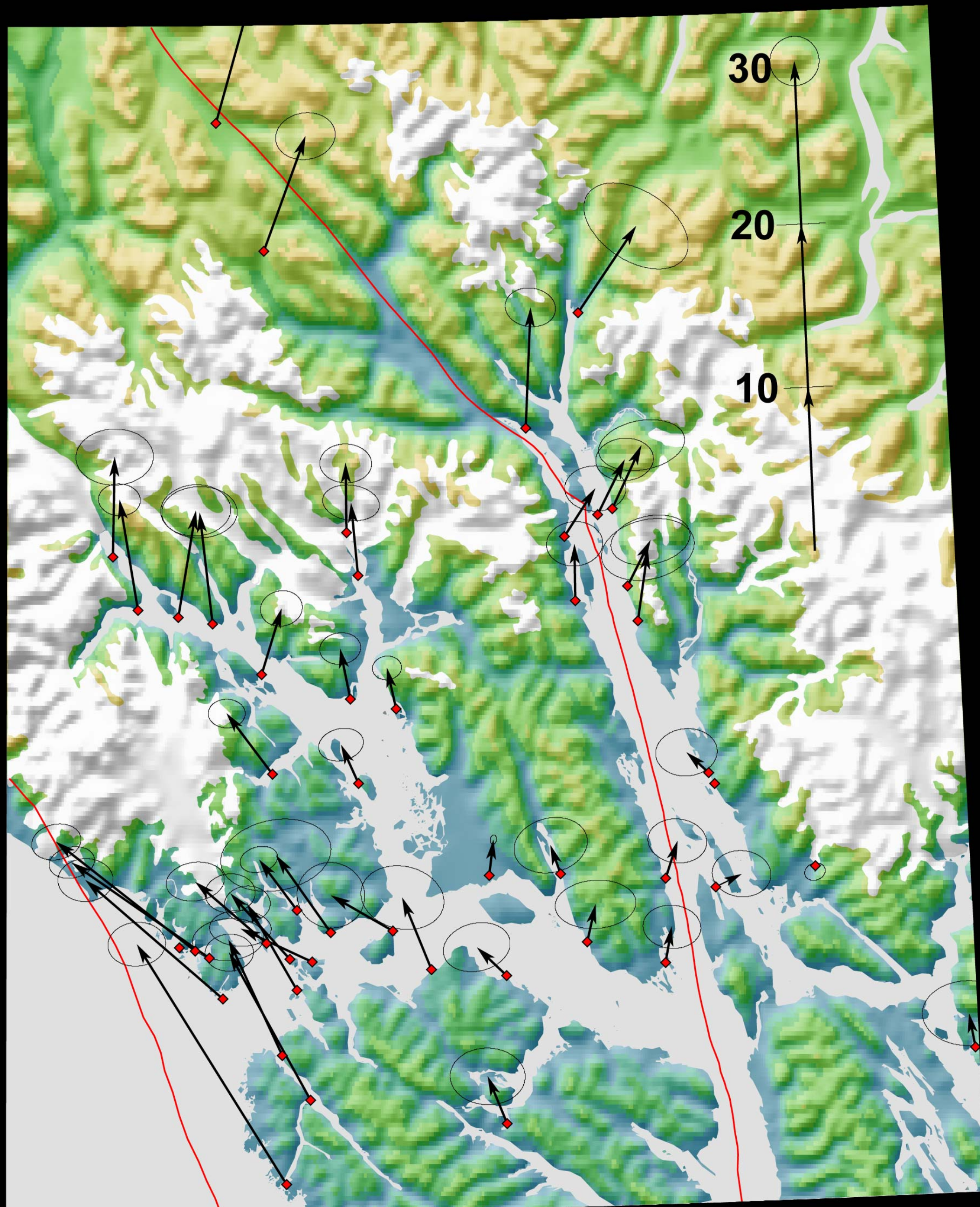
40
30
20
10

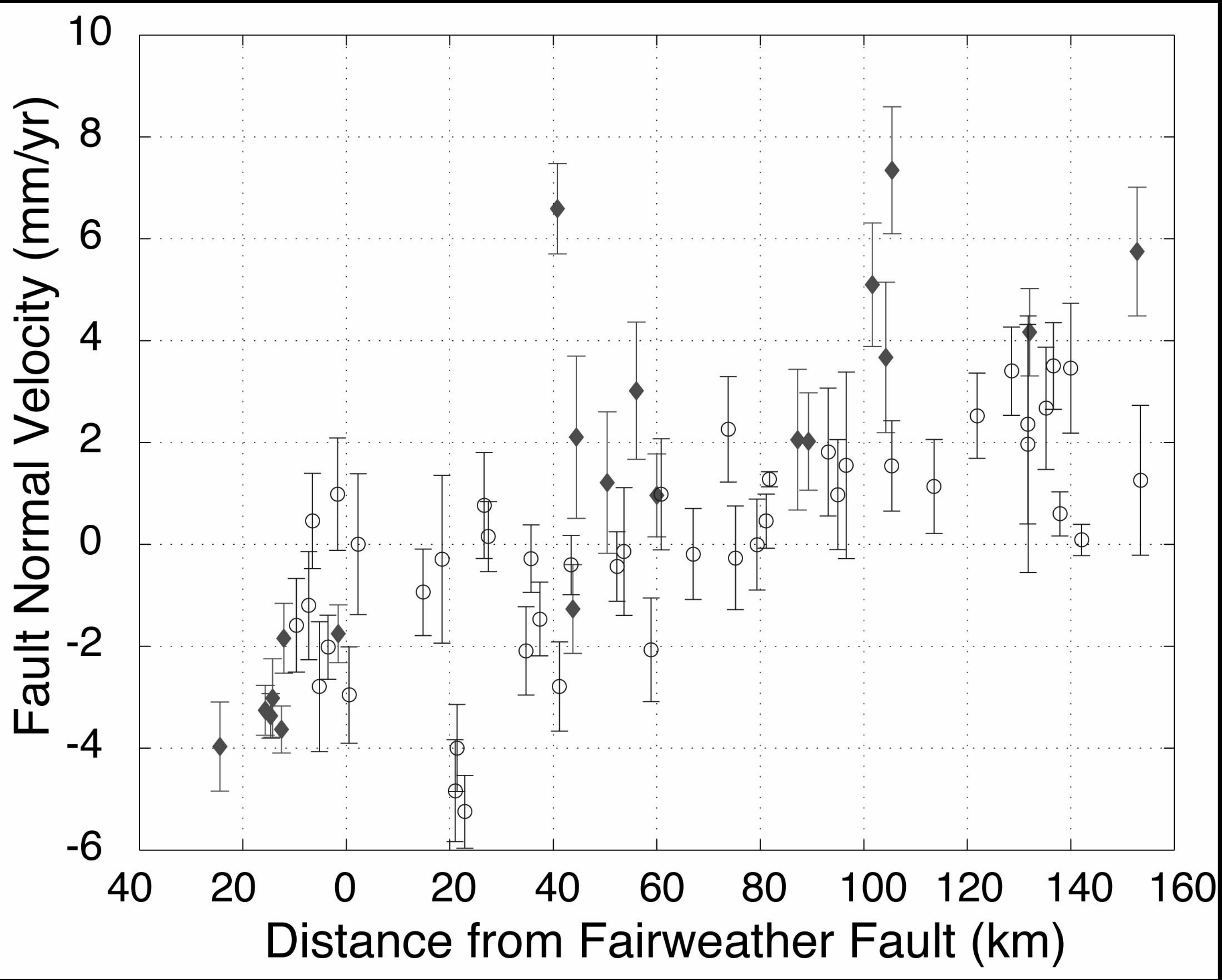


North American Plate
Denali Fault
St. Elias Mtns.
North American Plate
Yakutat Block
1964
Pacific Plate
57 mm/yr
Aleutian Megathrust
Queen Charlotte-Fairweather Fault

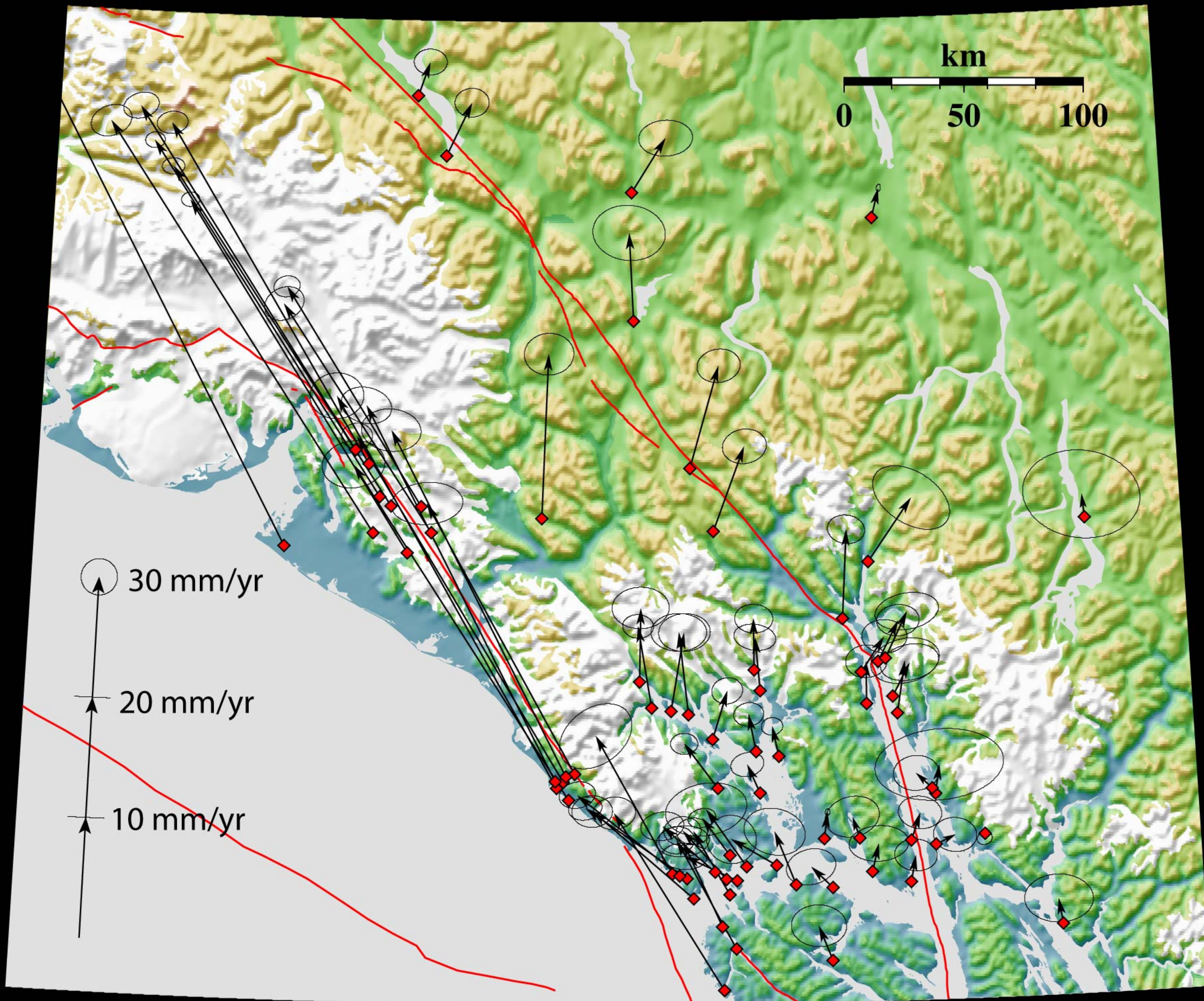

40
30
20
10


Fault Parallel Velocity (mm/yr)
45
40
35
30
25
20
15
10
5
0
40
20
0
20
40
60
80
100
120
140
160
Distance from Fairweather Fault (km)

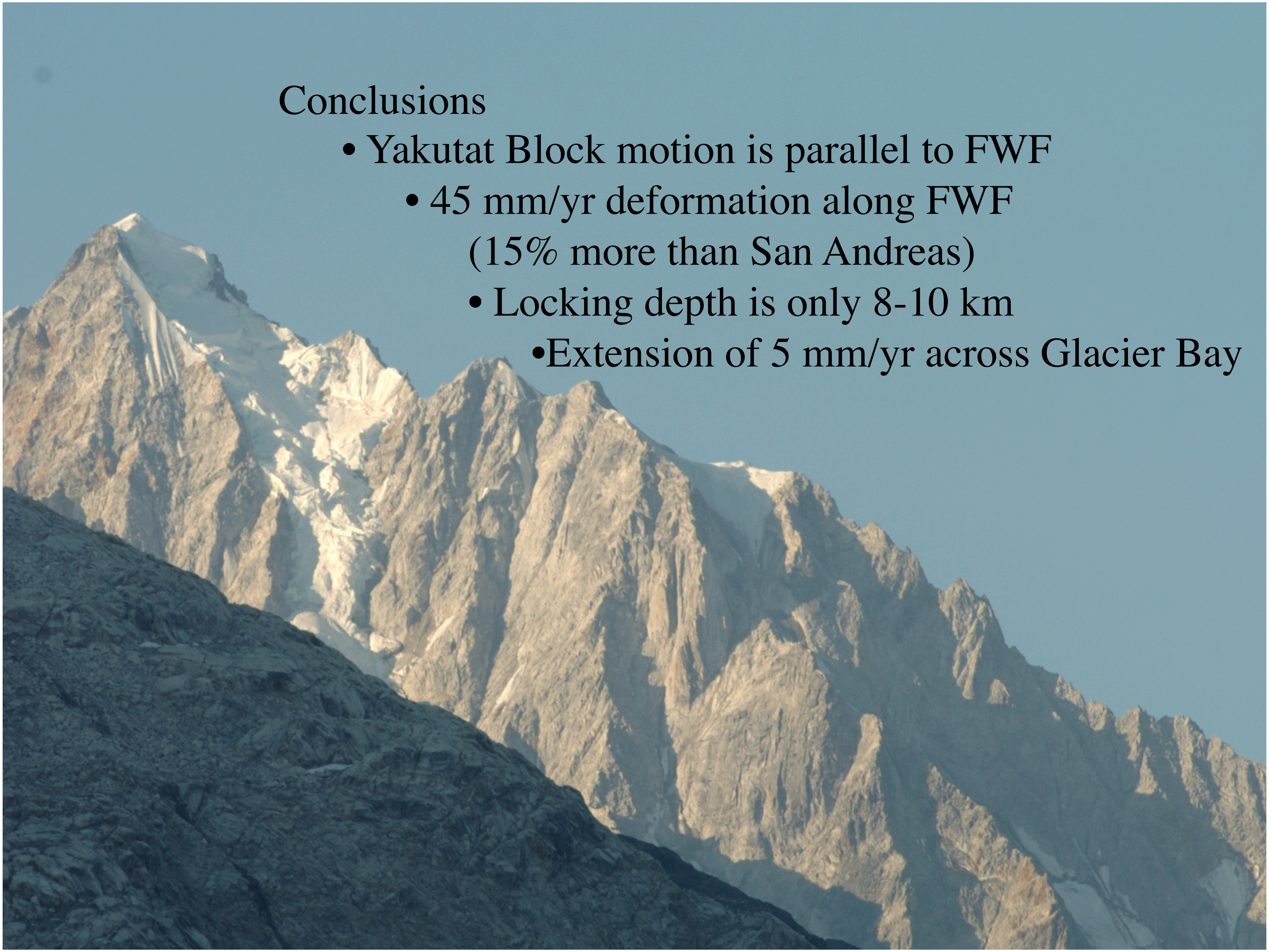

30
20
10

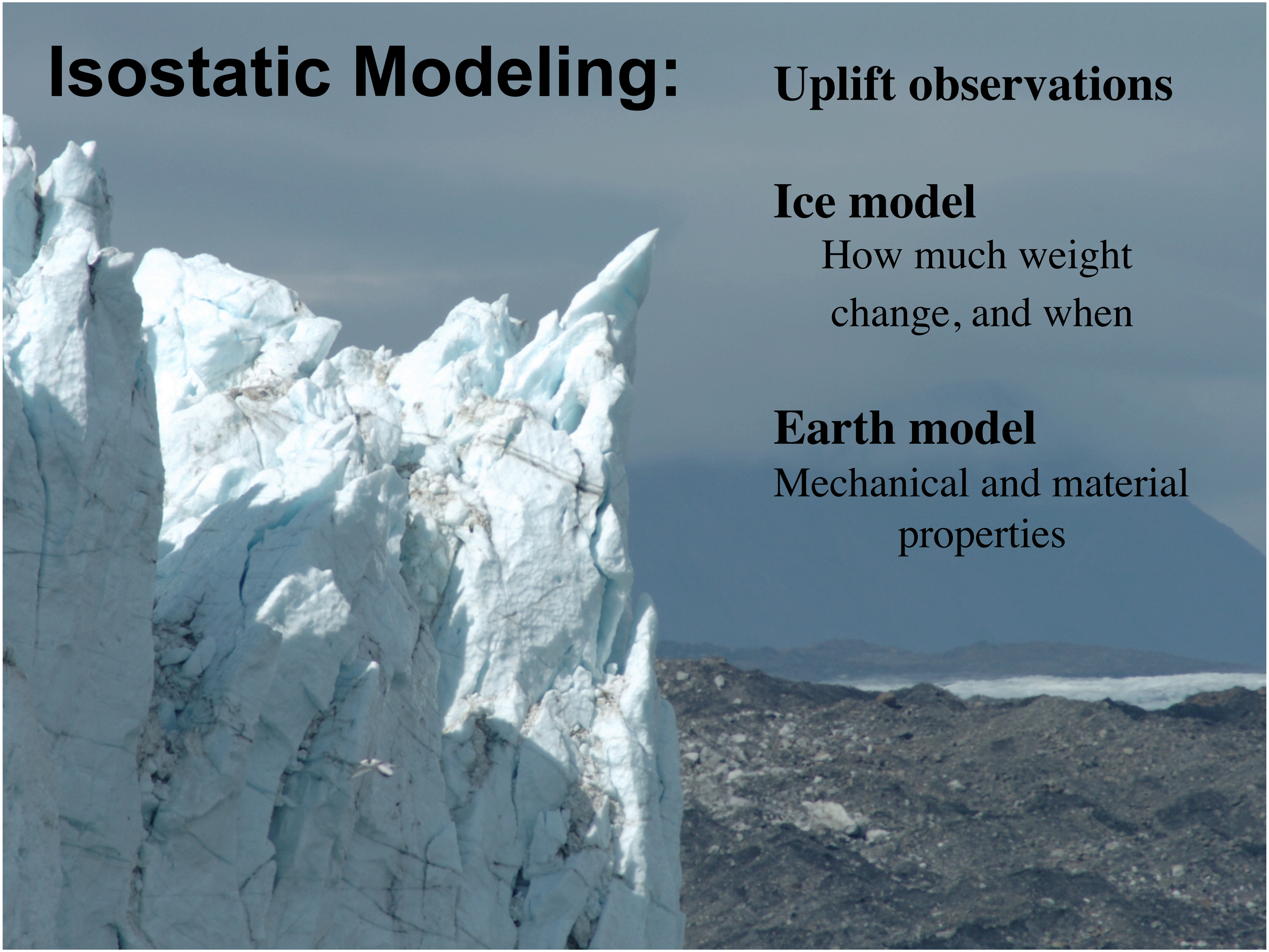


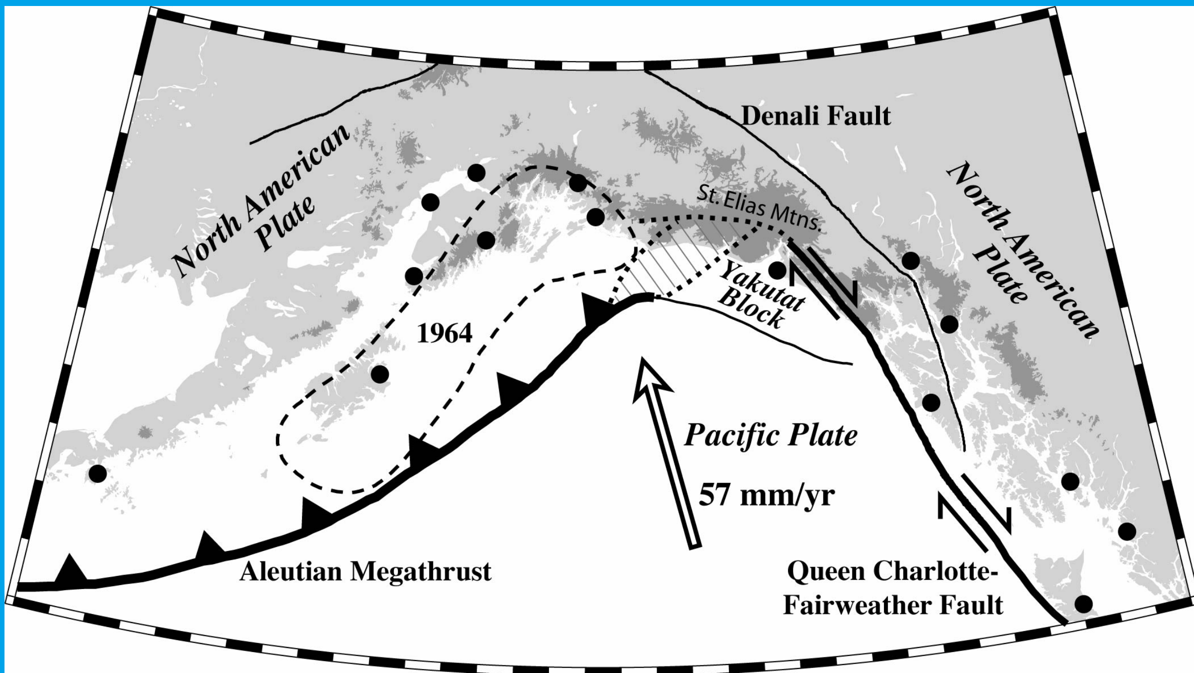
10
8
6
4
2
0
-2
-4
-6
Fault Normal Velocity (mm/yr)
40
20
0
20
40
60
80
100
120
140
160
Distance from Fairweather Fault (km)



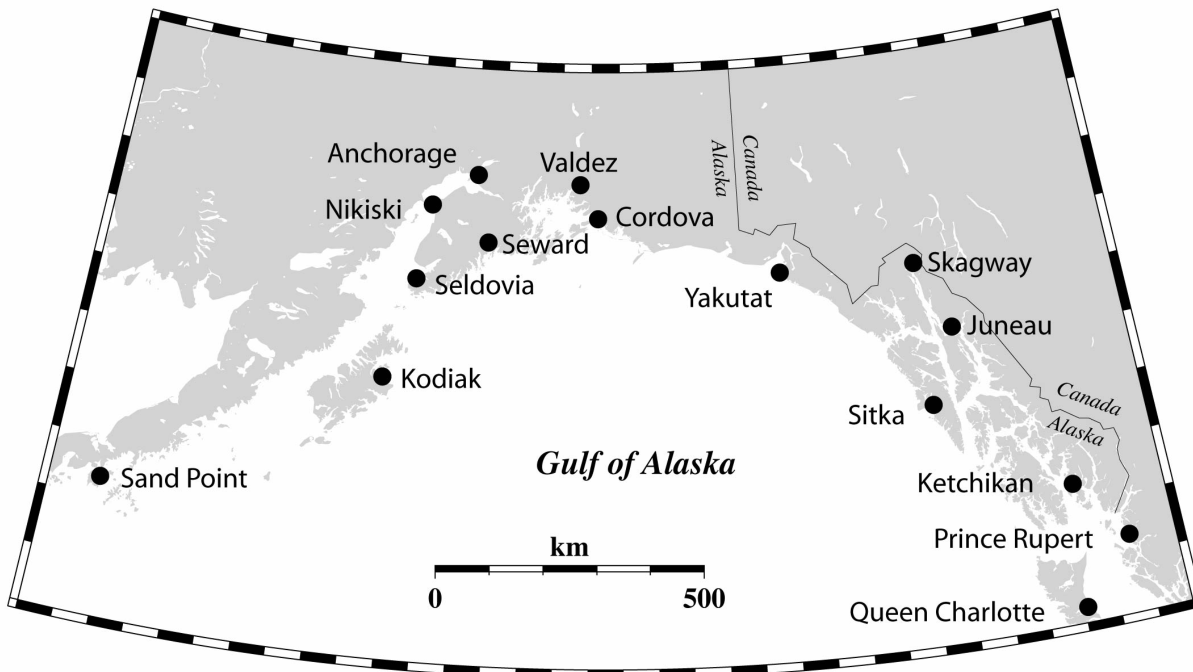
km
0
50
100
30 mm/yr
20 mm/yr
10 mm/yr

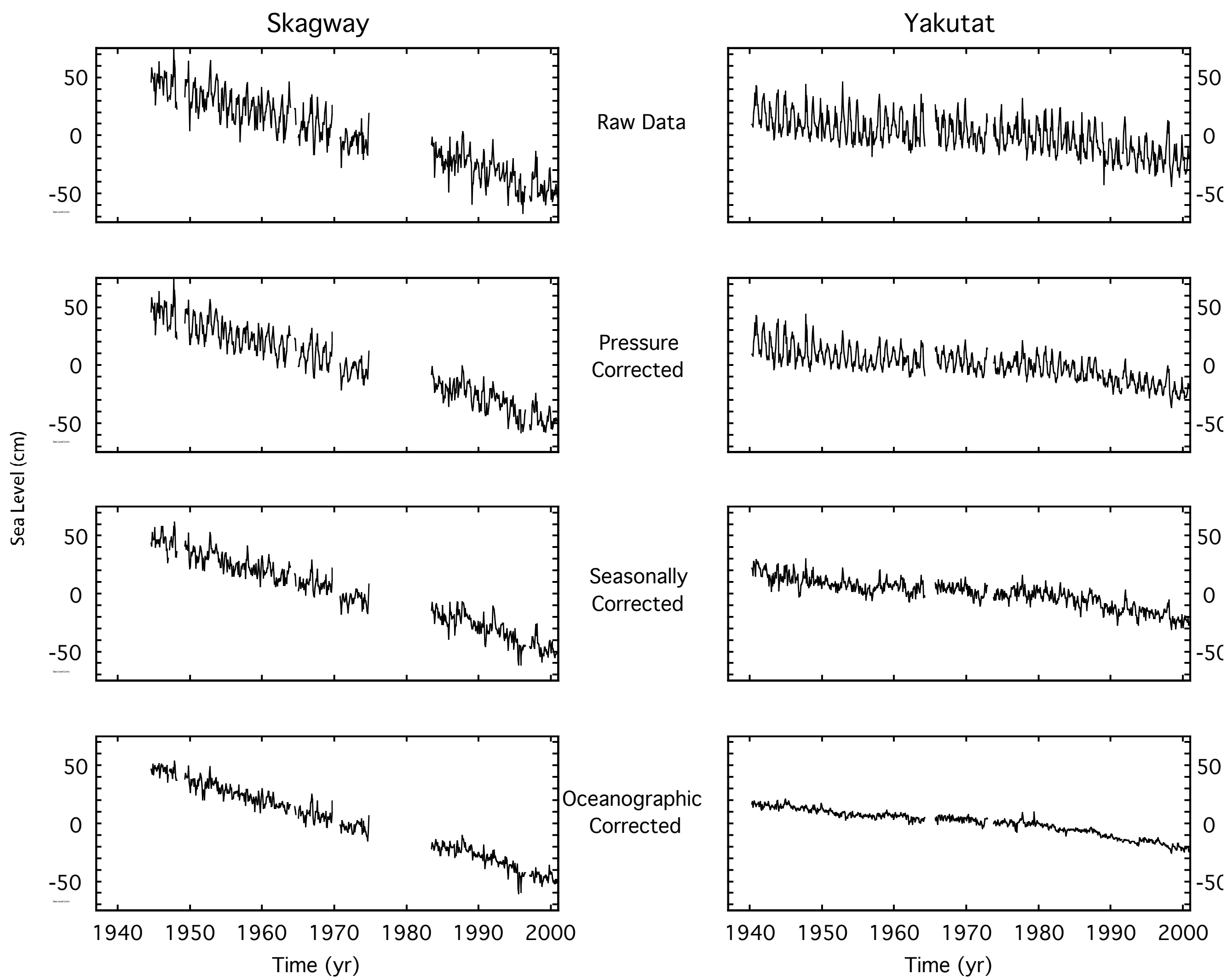

Conclusions
• Yakutat Block motion is parallel to FWF
• 45 mm/yr deformation along FWF
(15% more than San Andreas)
• Locking depth is only 8-10 km
•Extension of 5 mm/yr across Glacier Bay


Isostatic Modeling:
Uplift observations
Ice model
How much weight change, and when
Earth model
Mechanical and material properties

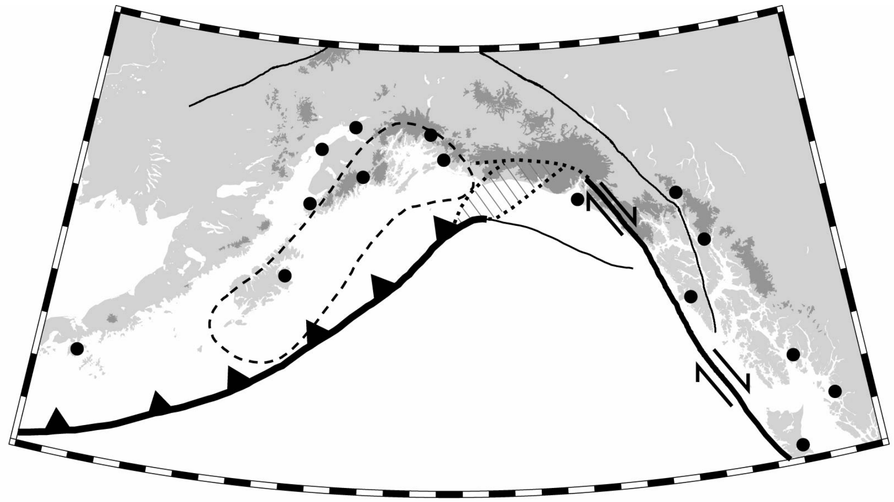


Permanent tide gauge sites

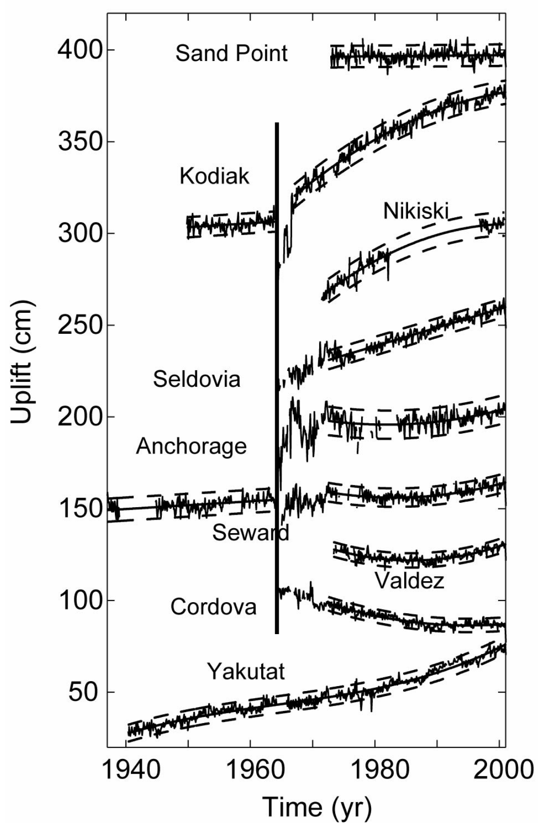



Skagway
Yakutat
Raw Data
Pressure Corrected
Seasonally Corrected
Oceanographic Corrected
Sea Level (cm)
50
0
-50
1940
1950
1960
1970
1980
1990
2000
Time (yr)
Time (yr)

Non-linear sea level trends in transition and subduction zones

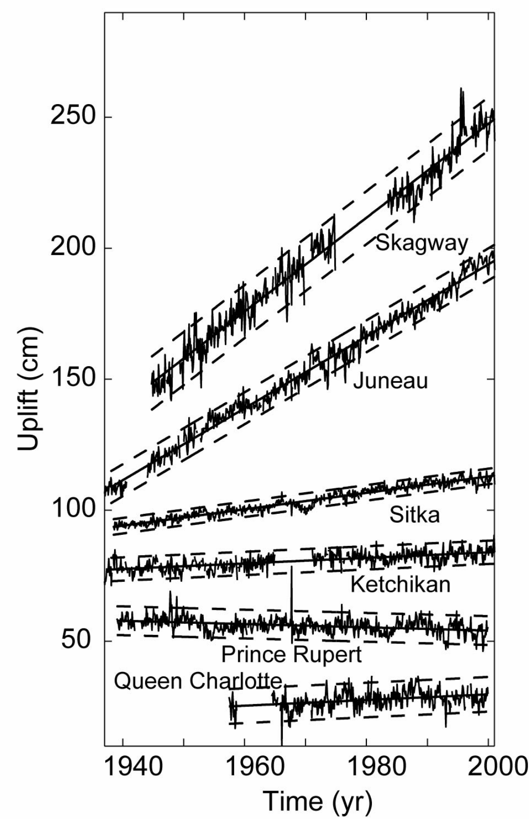


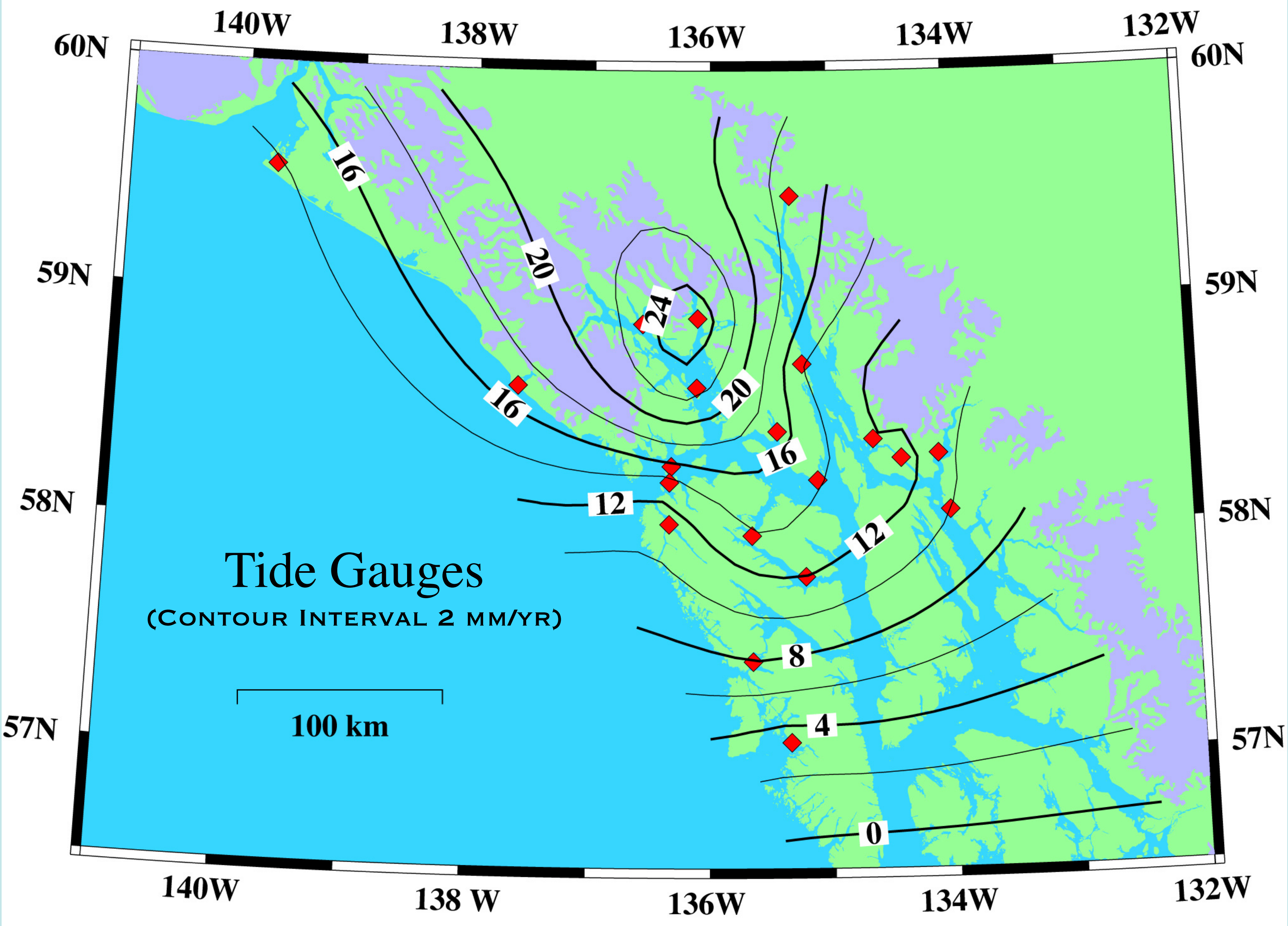
Linear sea level trends along strike-slip boundary

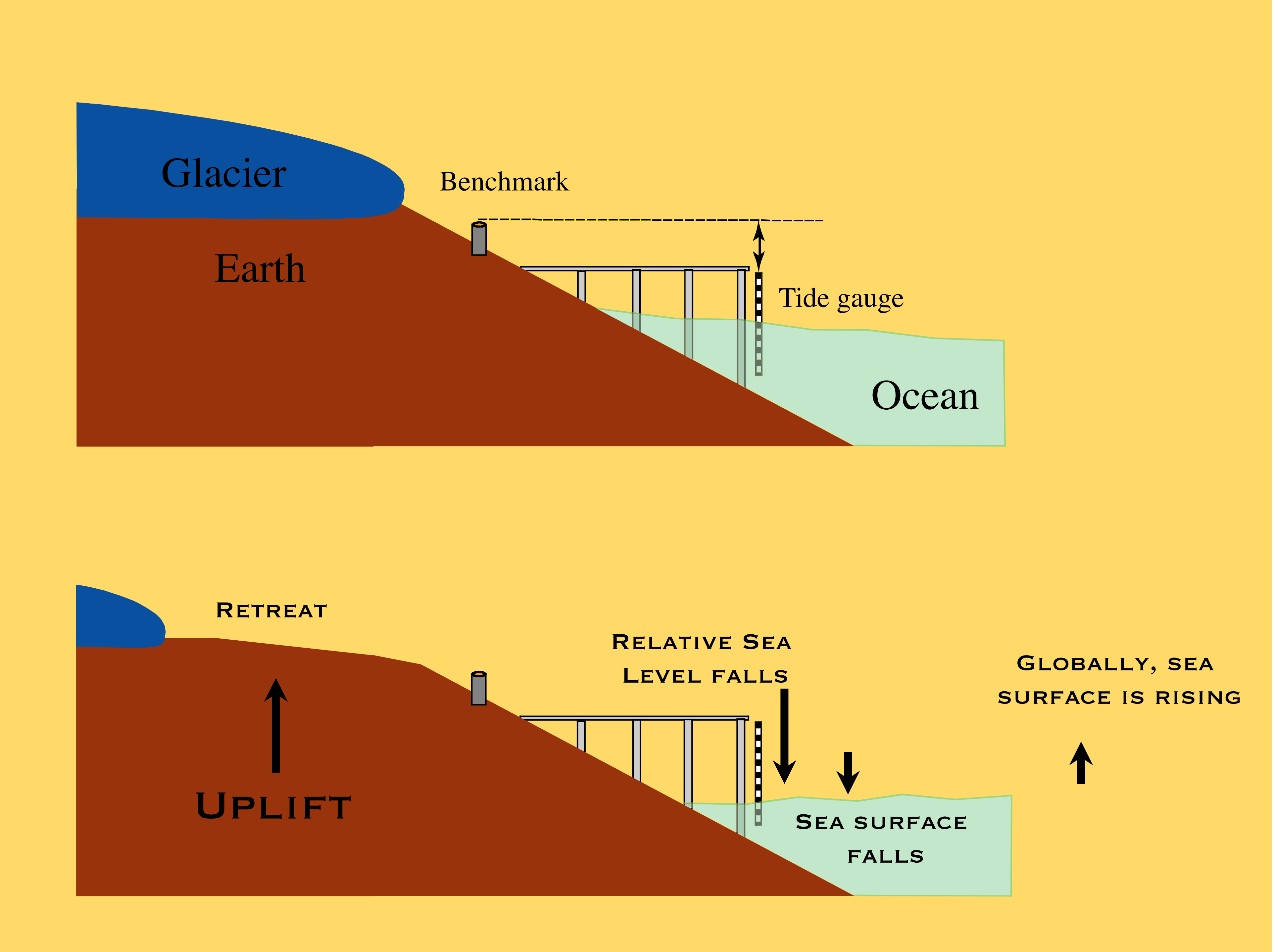


Tectonic influence on long term uplift records is strongest following the 1964 earthquake

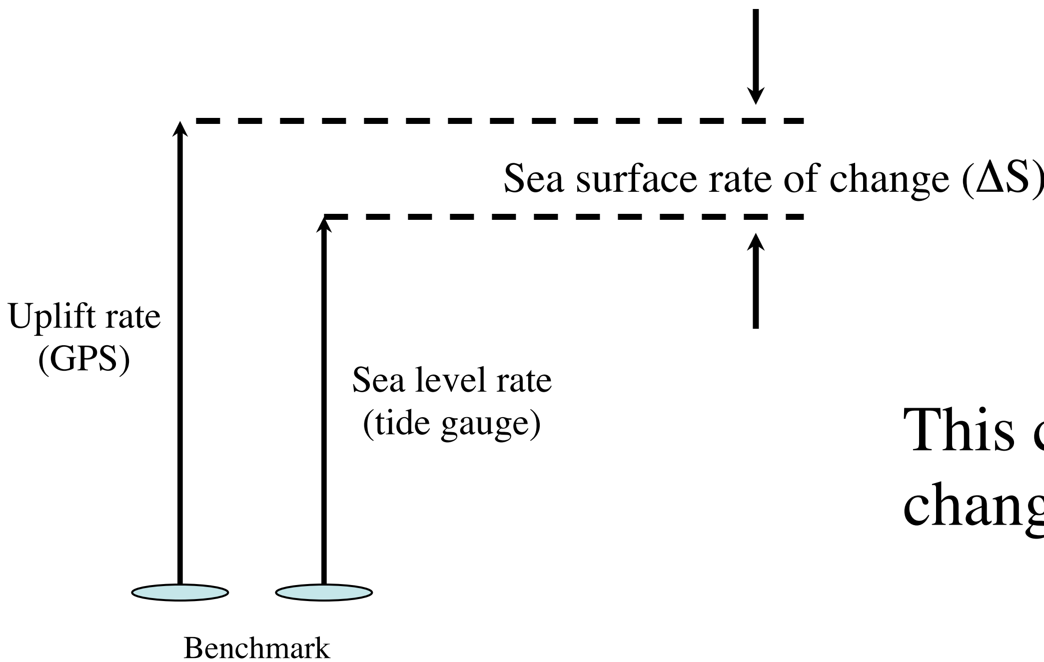
Steady rates in SE Alaska are much faster than "reasonable" long-term tectonic uplift




Tide Gauges
(Contour Interval 2 mm/yr)
100 km
140W
138W
136W
134W
132W
60N
59N
58N
57N
24
20
16
12
8
4
0

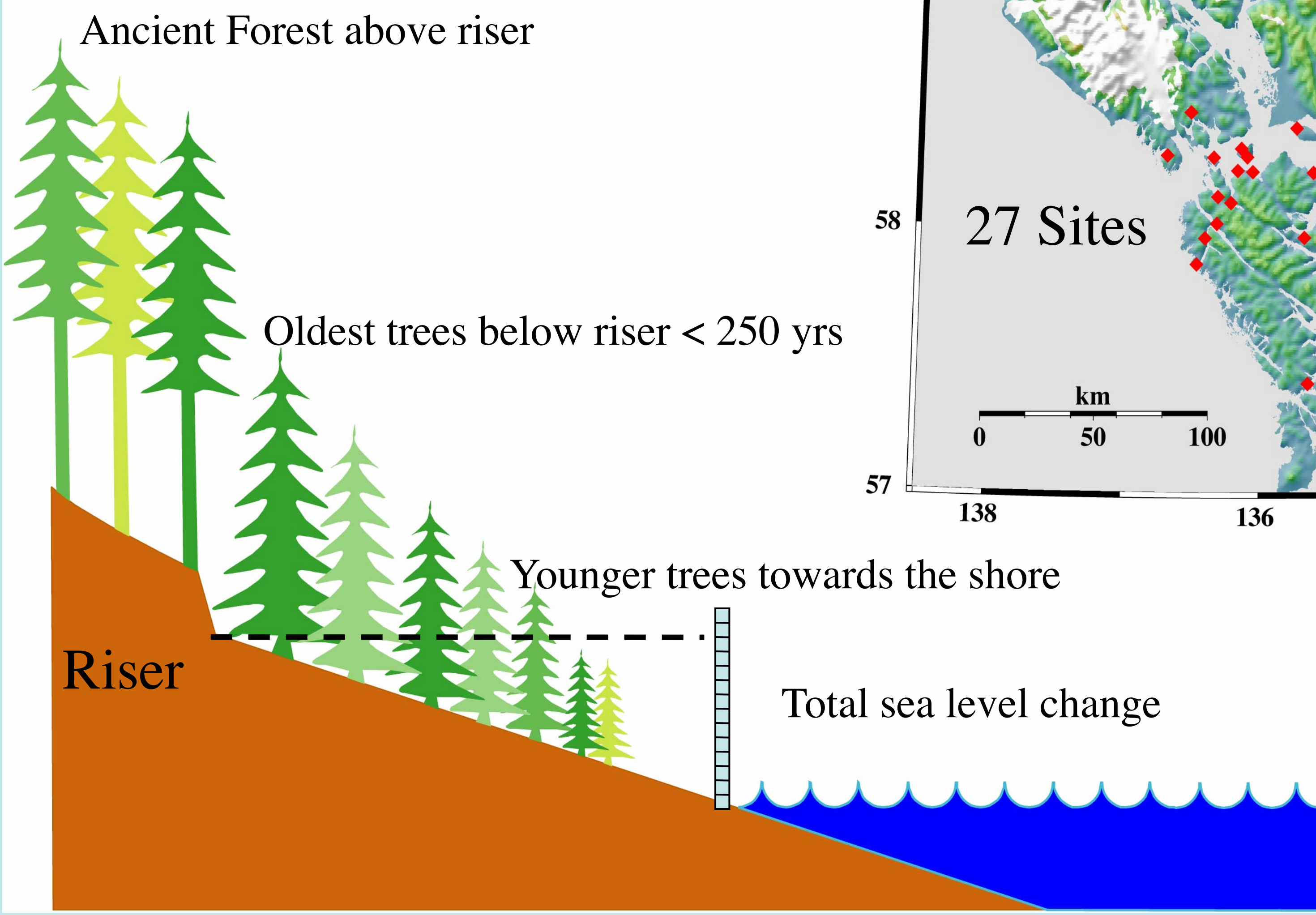

Glacier
Earth
Benchmark
Tide gauge
Ocean
Retreat
Uplift
Relative Sea Level falls
Sea surface falls
Globally, sea surface is rising

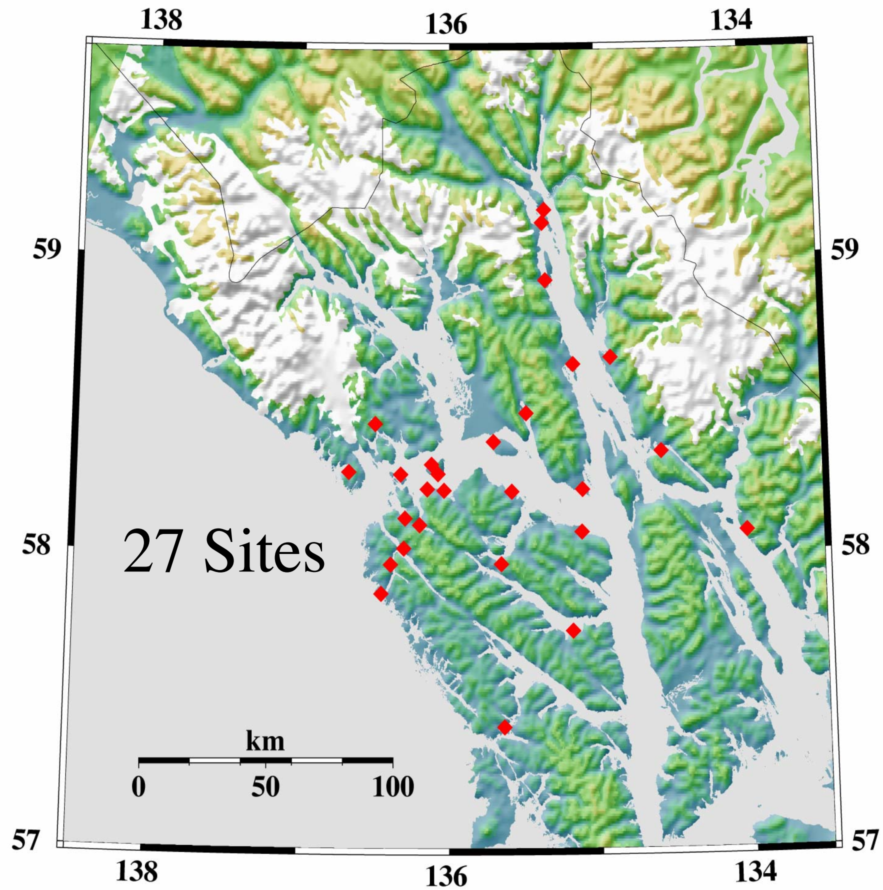
Where we have both GPS and tide gauge data:
Find the difference between rates.

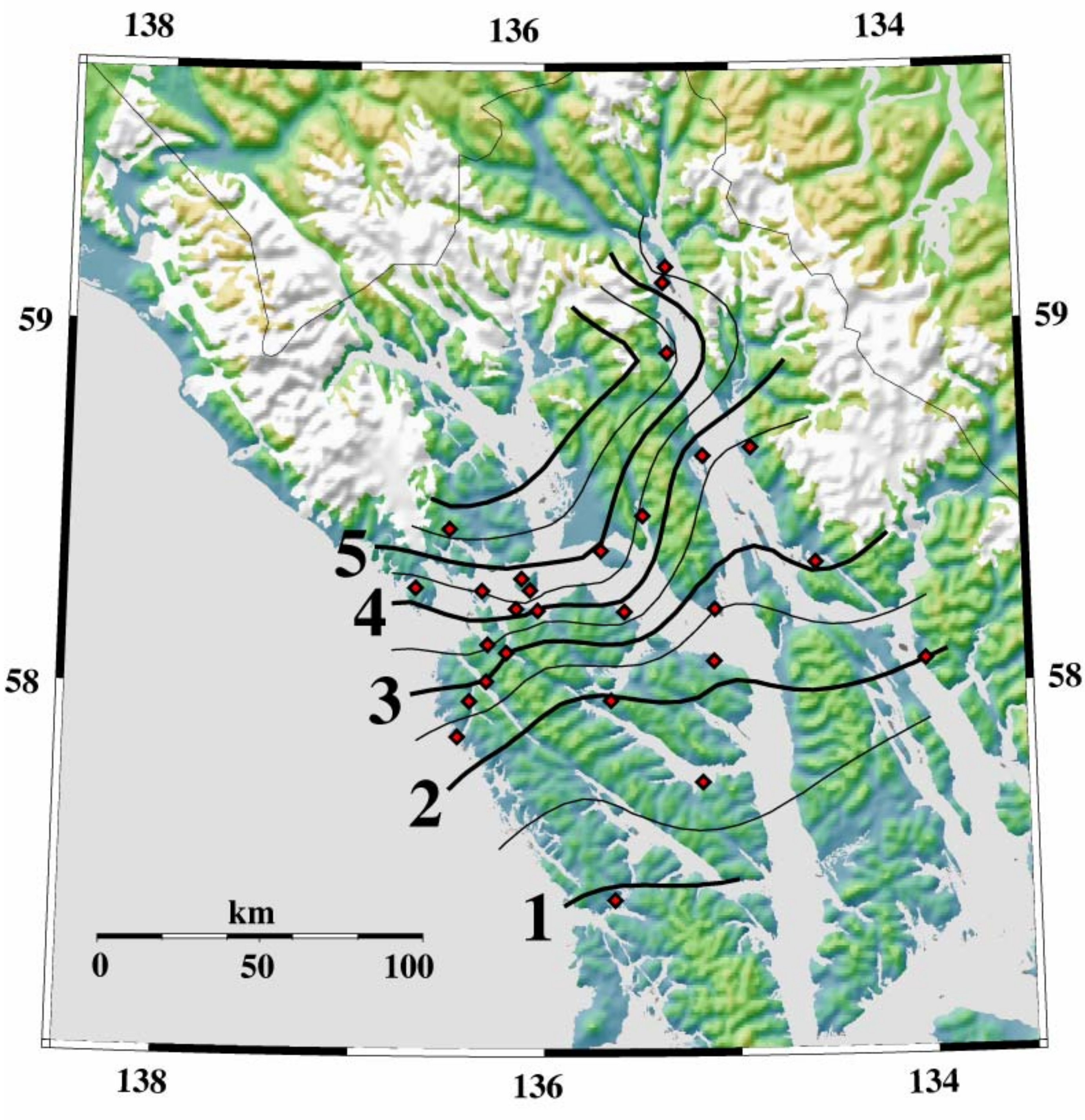


This could tell us the rate of change of the geoid…

Raised shorelines



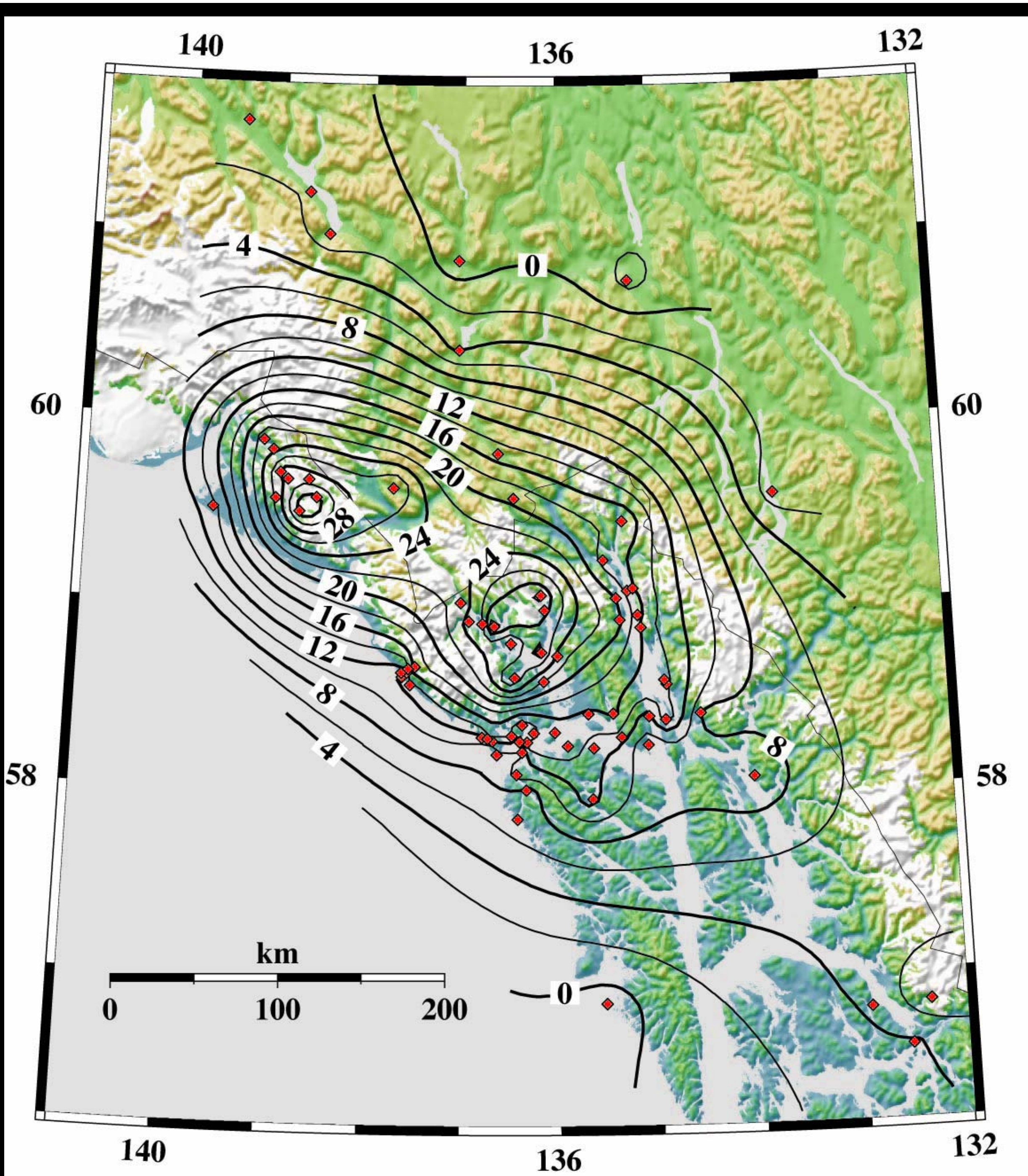




Total Sea Level Change Over the last ~250 yrs

Measurements range up to 5.5 m

σ = 0.25 m



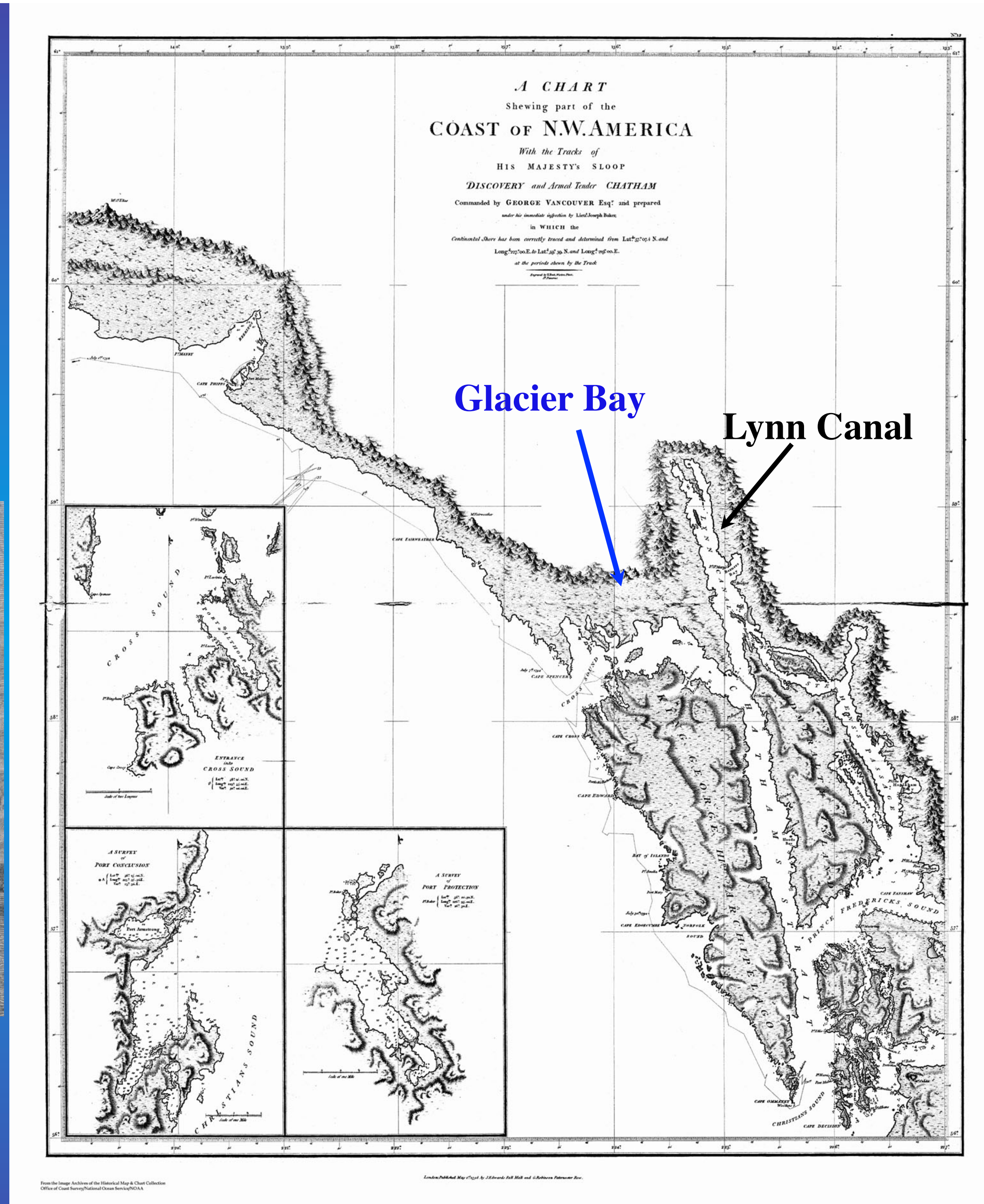
GPS uplift rates

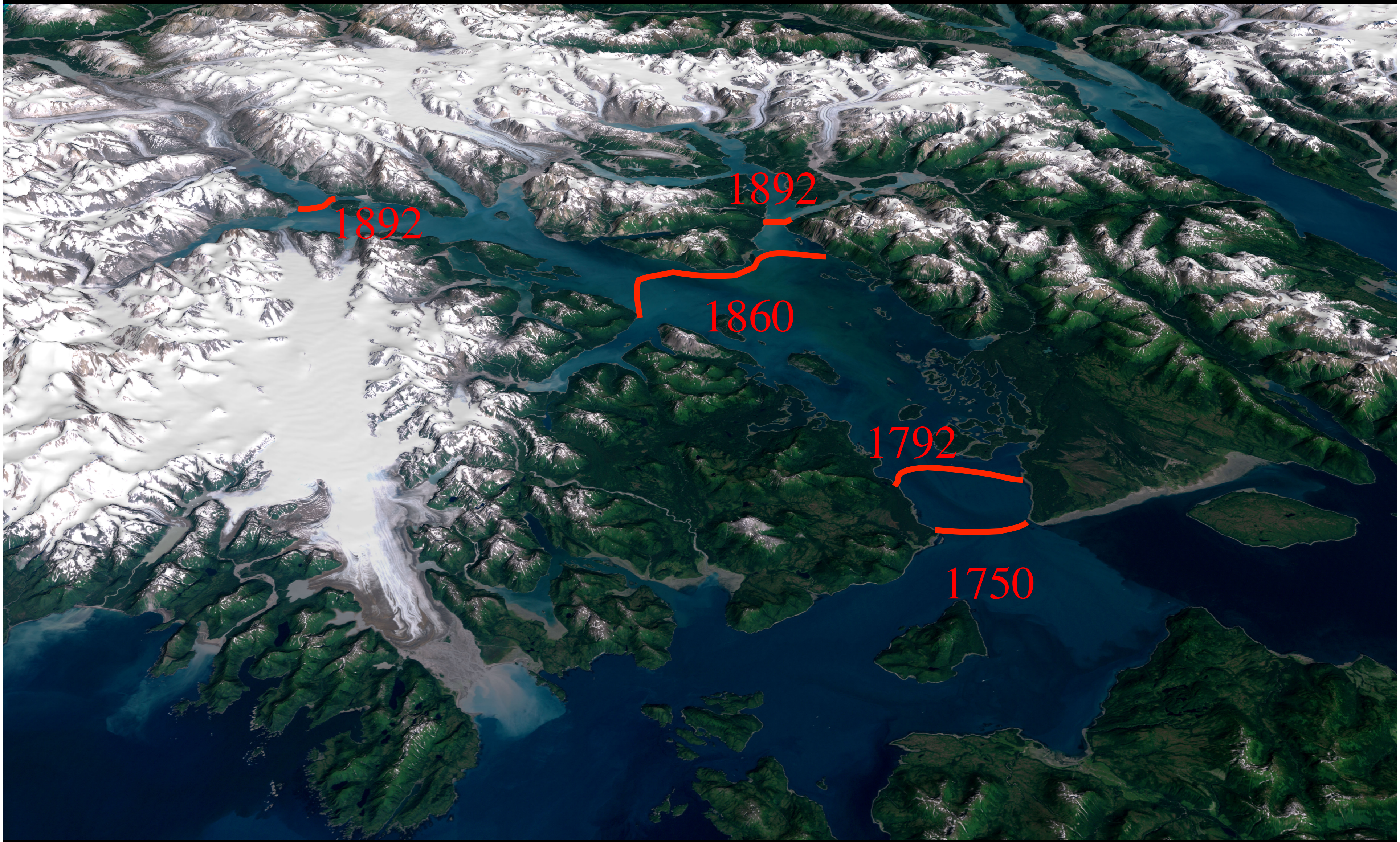
76 sites, 5 years of campaign measurements

Peak uplift rates 30-32 mm/yr

Average σ = 1.8 mm/yr
Max σ = 4 mm/yr

What was the extent and thickness of the Little Ice Age Glacier Bay Icefield?

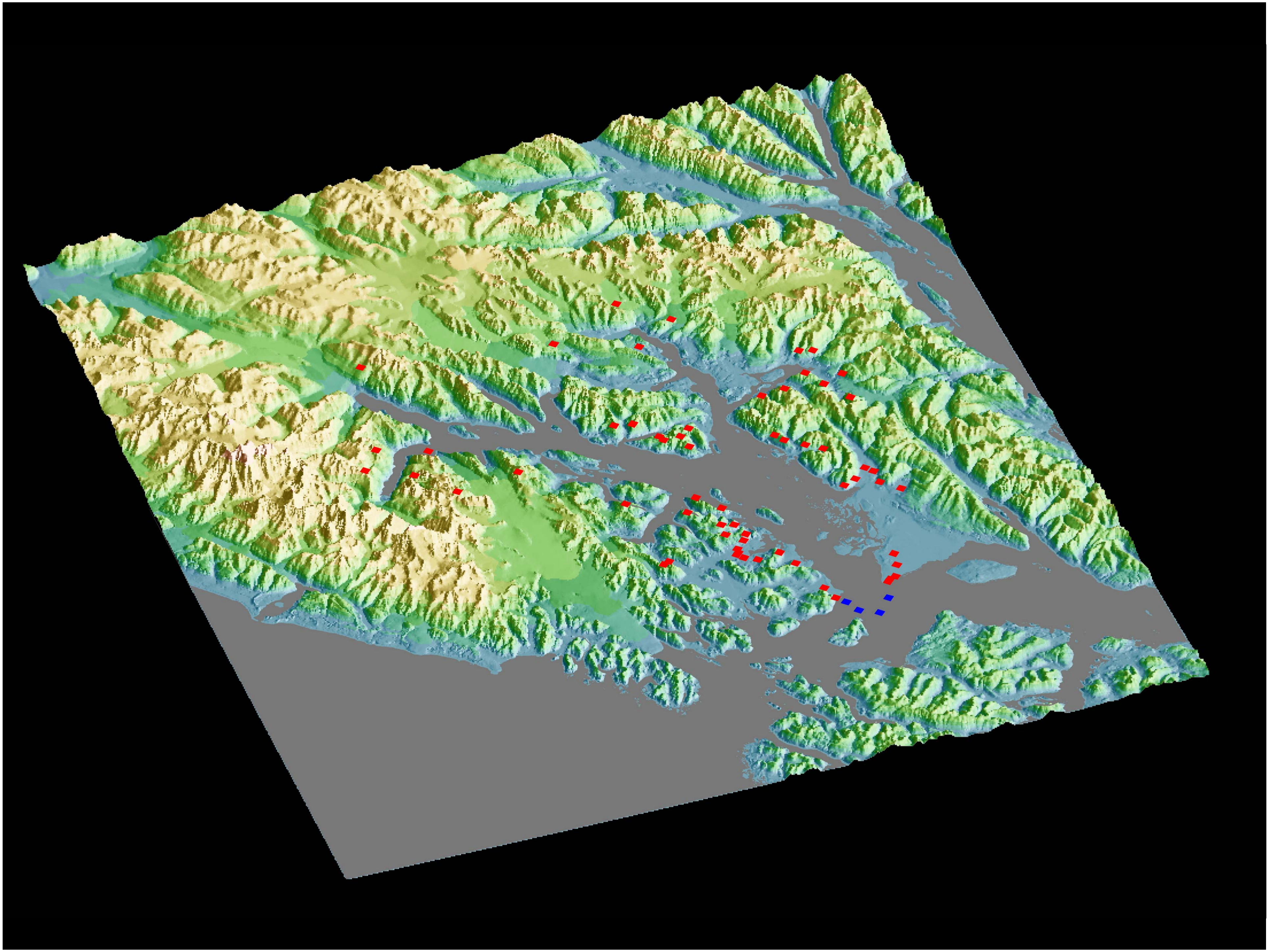


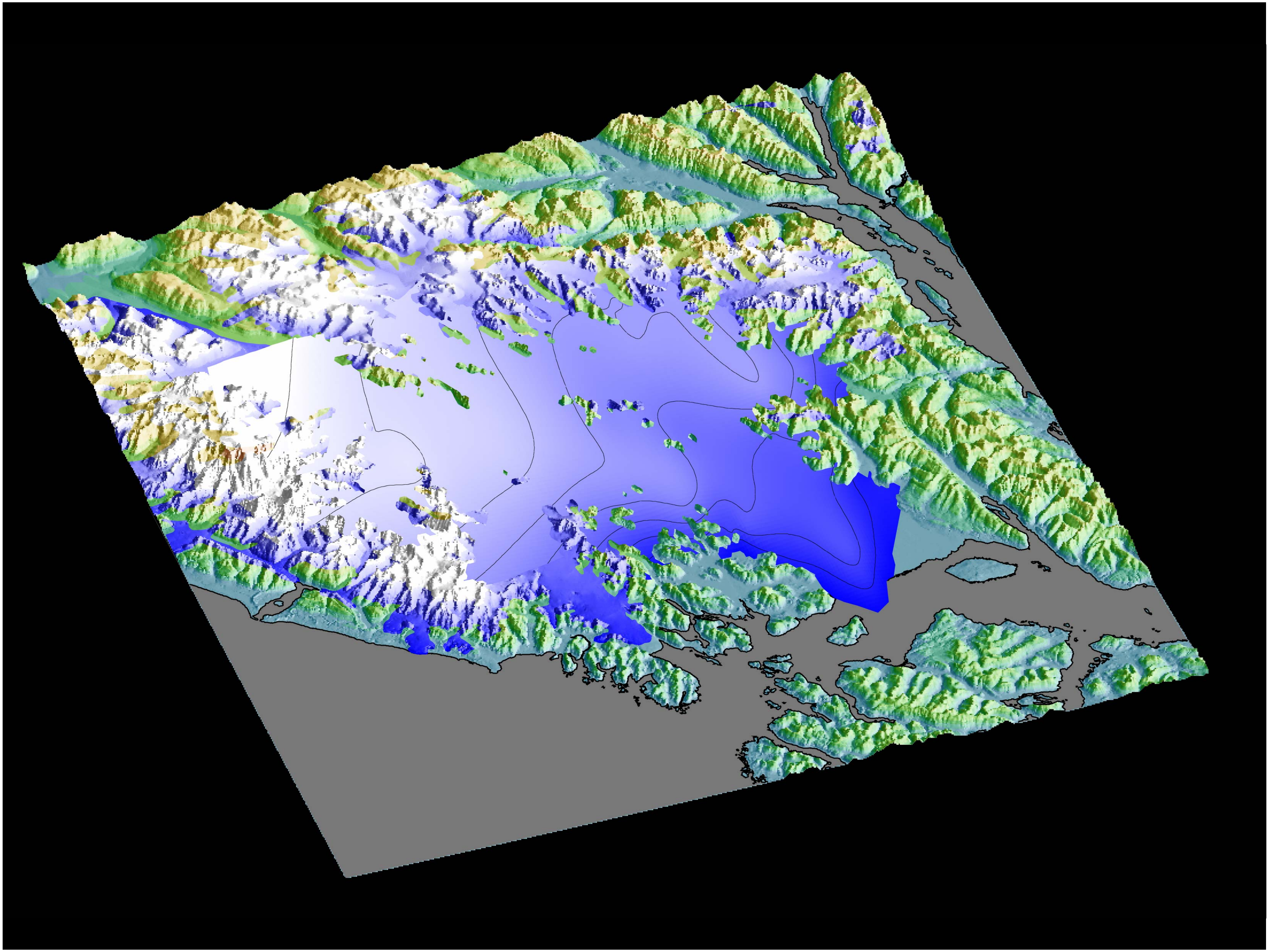

1892
1892
1860
1792
1750

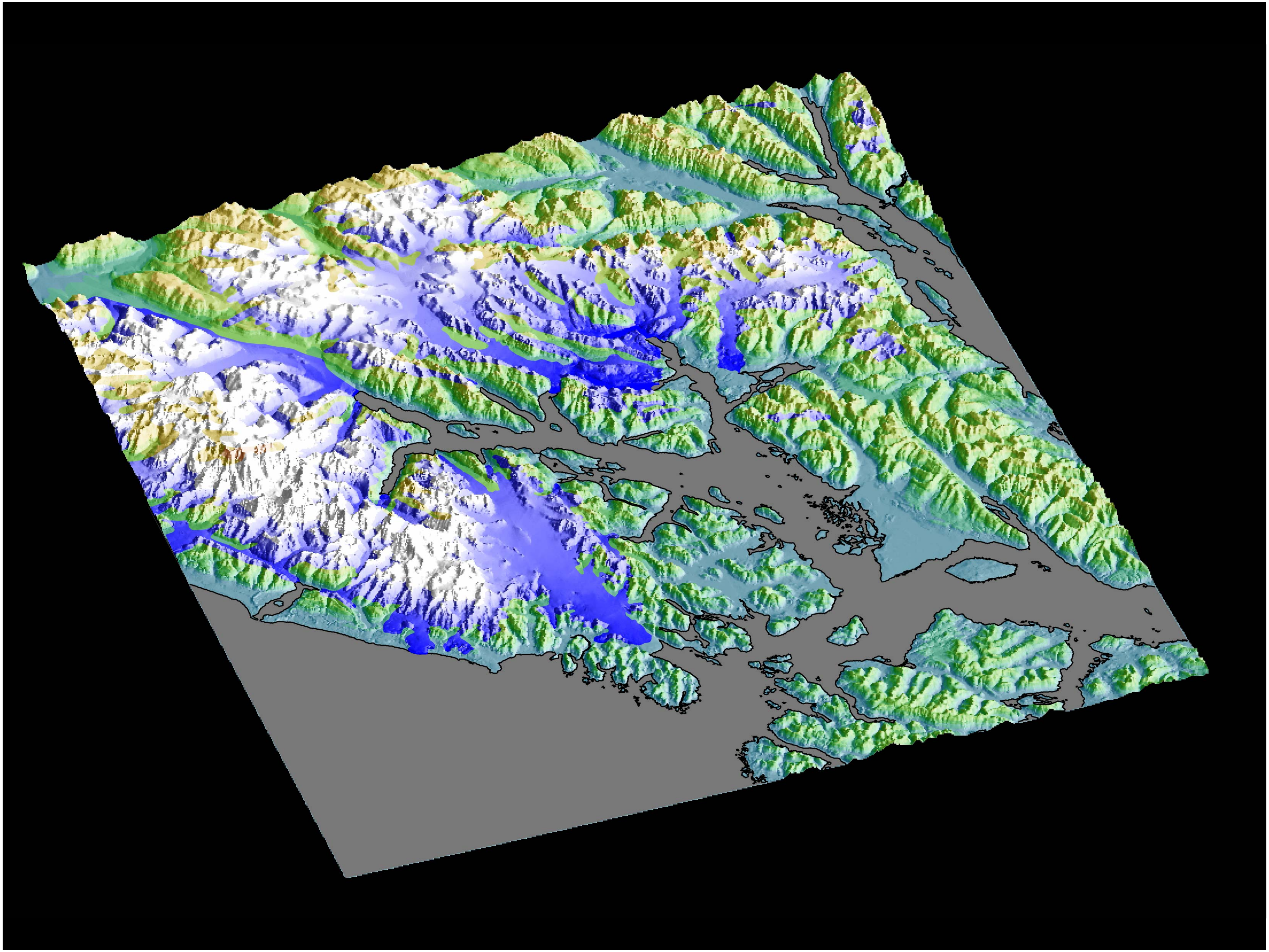
Upper West Arm
moraine at 1500 m

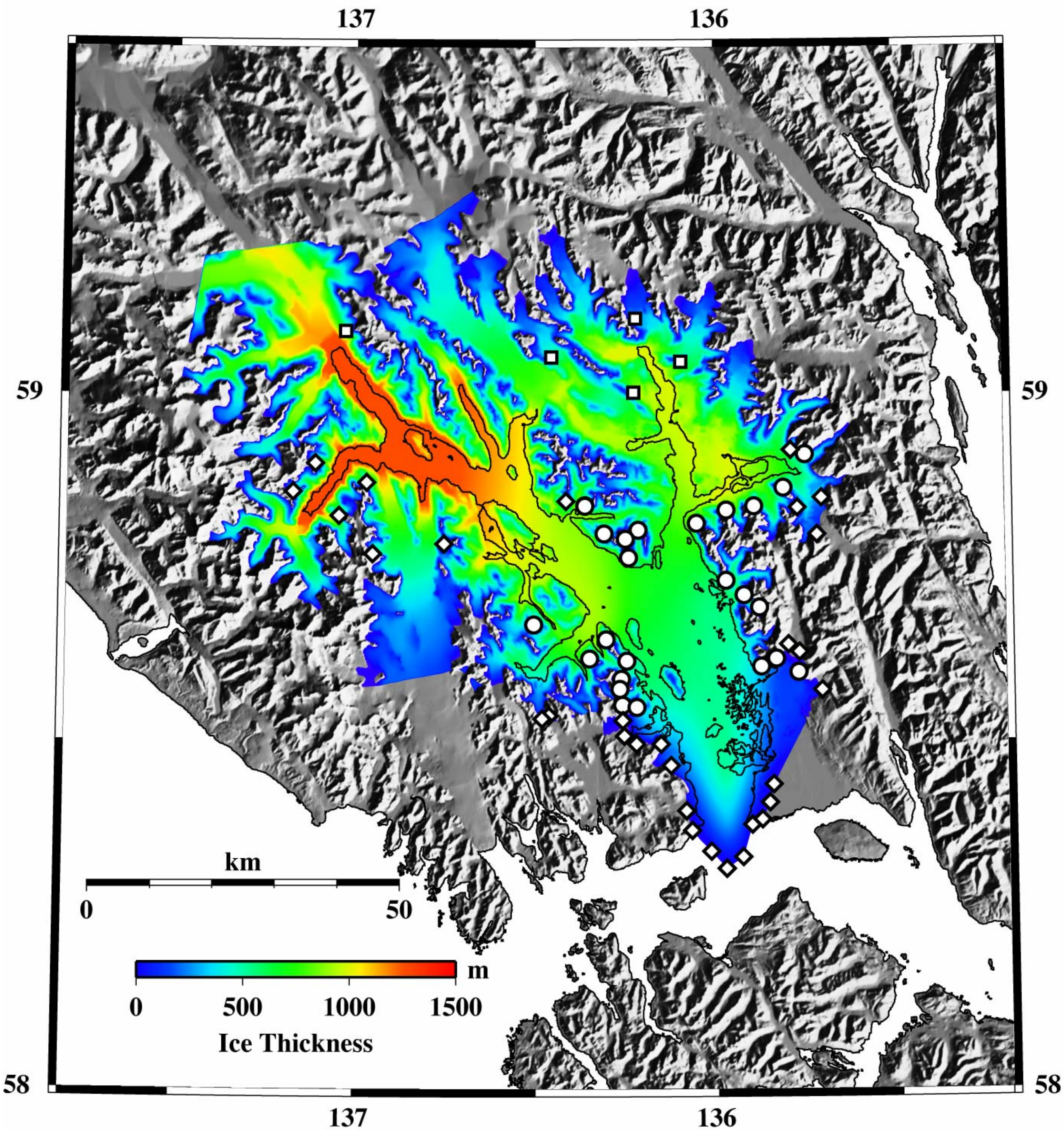
Berg Creek Trimlines
(Near Endicott Gap)

John Hopkins Inlet   Till deposit at 1500 m





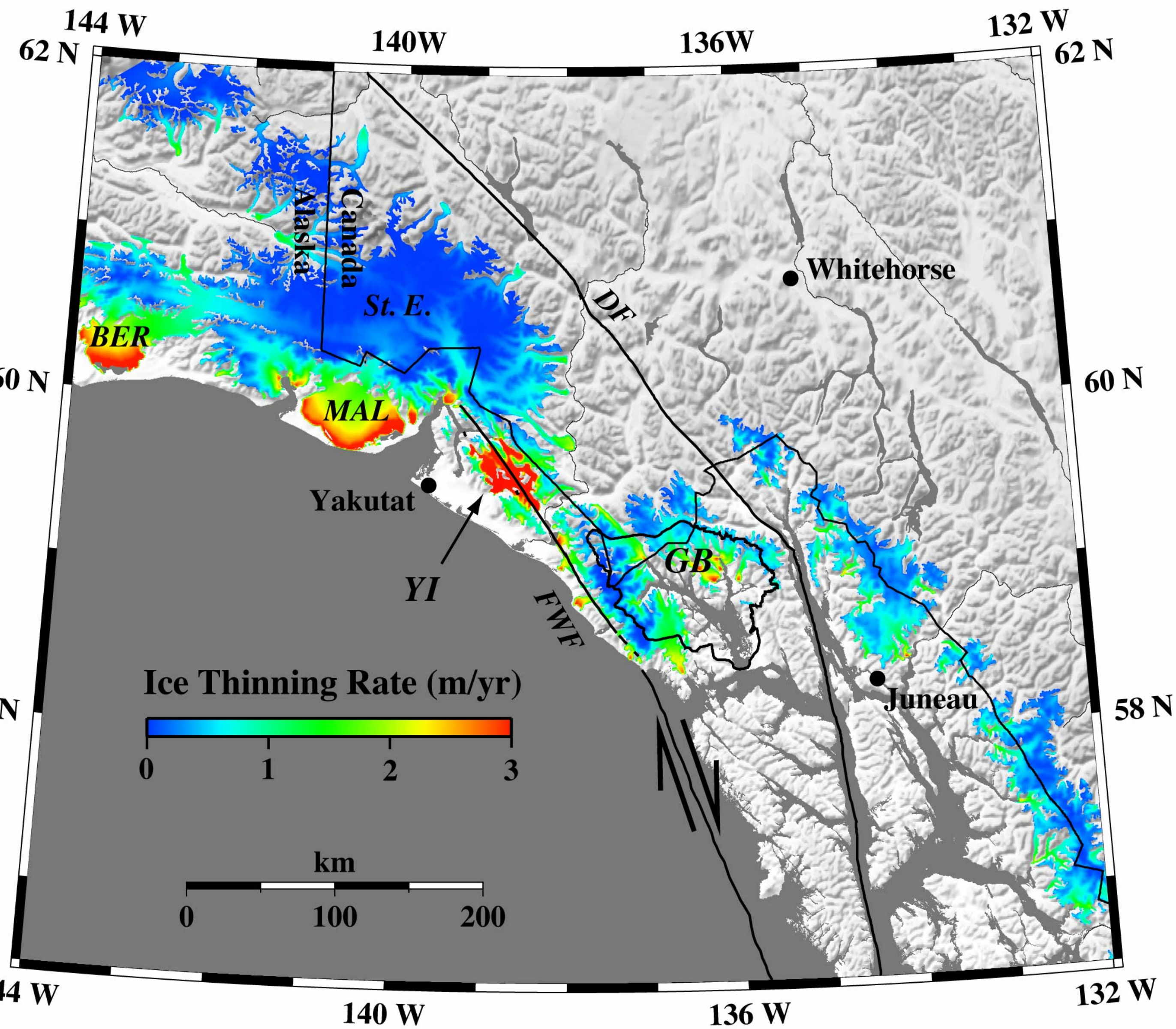




Ice Thickness Change Since Little Ice Age

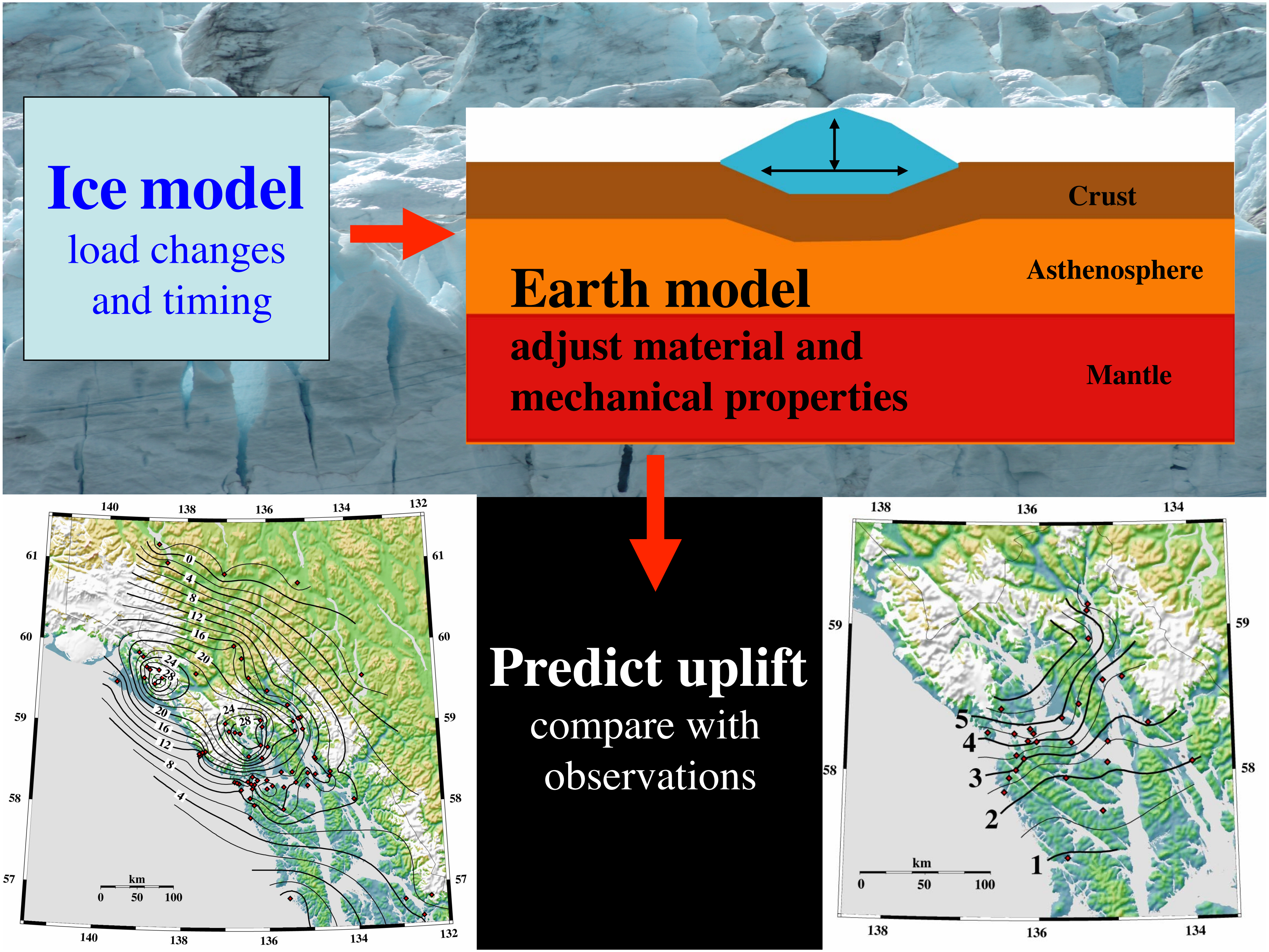
Total Volume 3000 km^3

Global Sea Level Equivalent = 8 mm



20th Century Regional Ice Loss

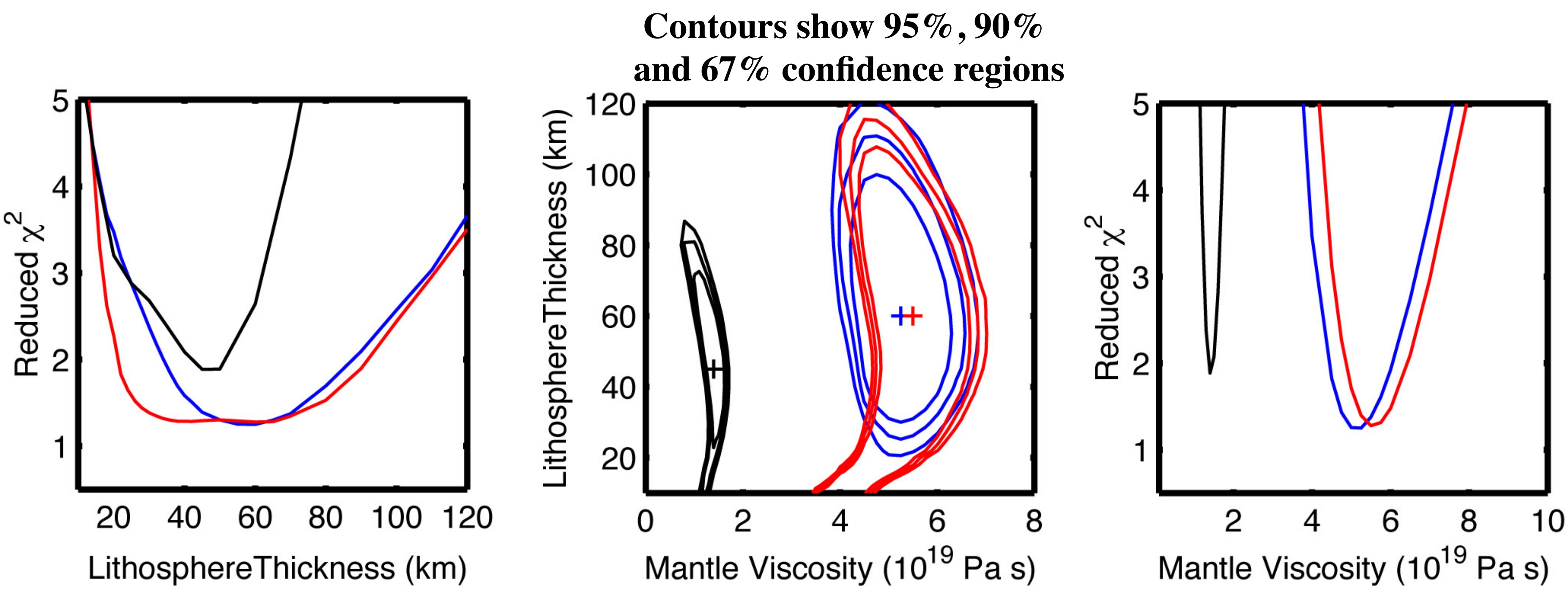
Additional 5800 km^3


Ice model
load changes
and timing
Crust
Asthenosphere
Earth model
adjust material and
mechanical properties
Mantle
Predict uplift
compare with
observations
km
0 50 100
km
0 50 100
1
2
3
4
5

Black = Raised Shorelines

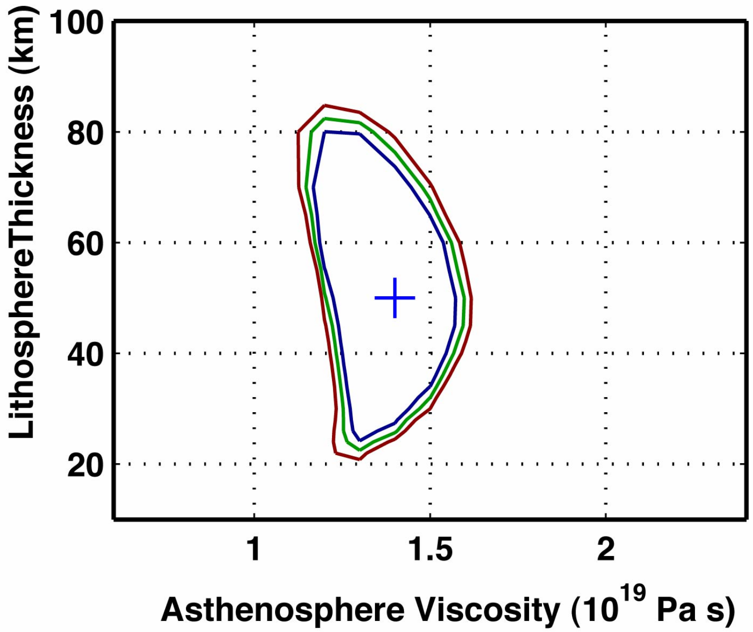
Red = GPS

Blue= Tide Gauges

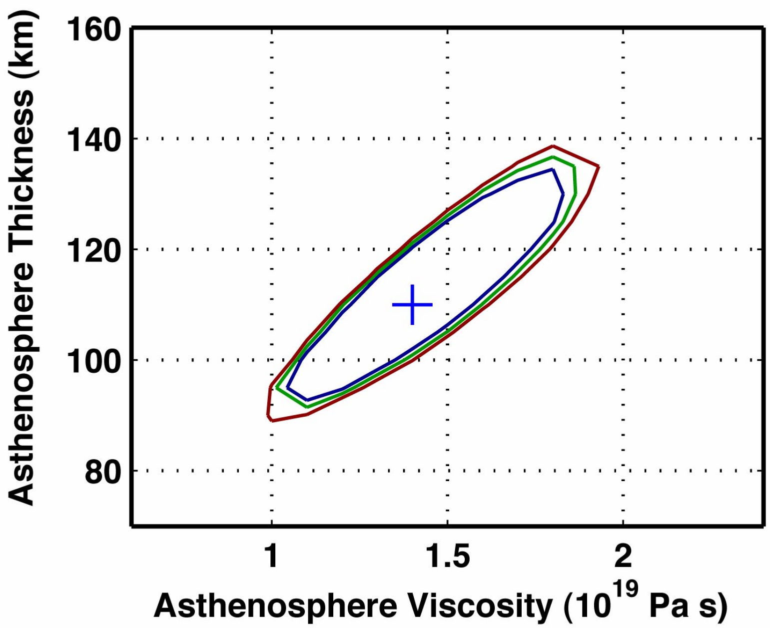


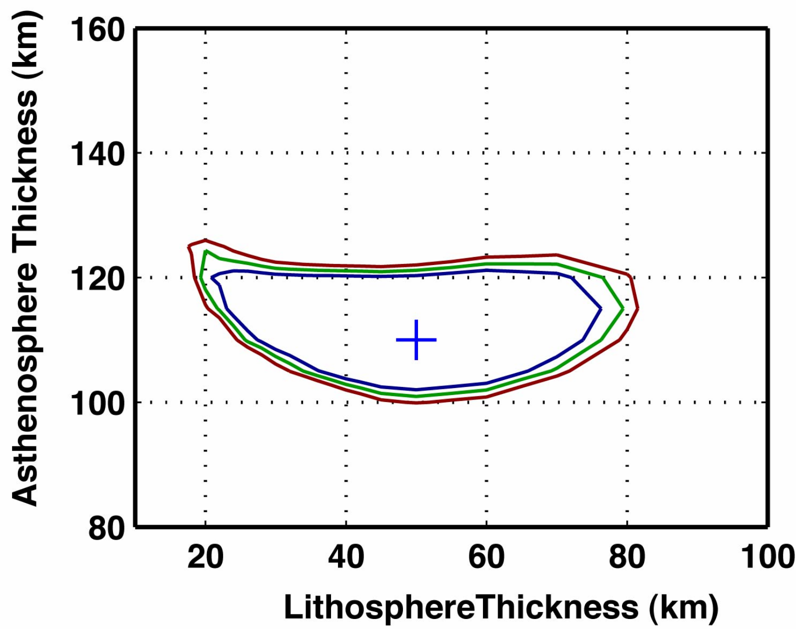
Misfit over all data

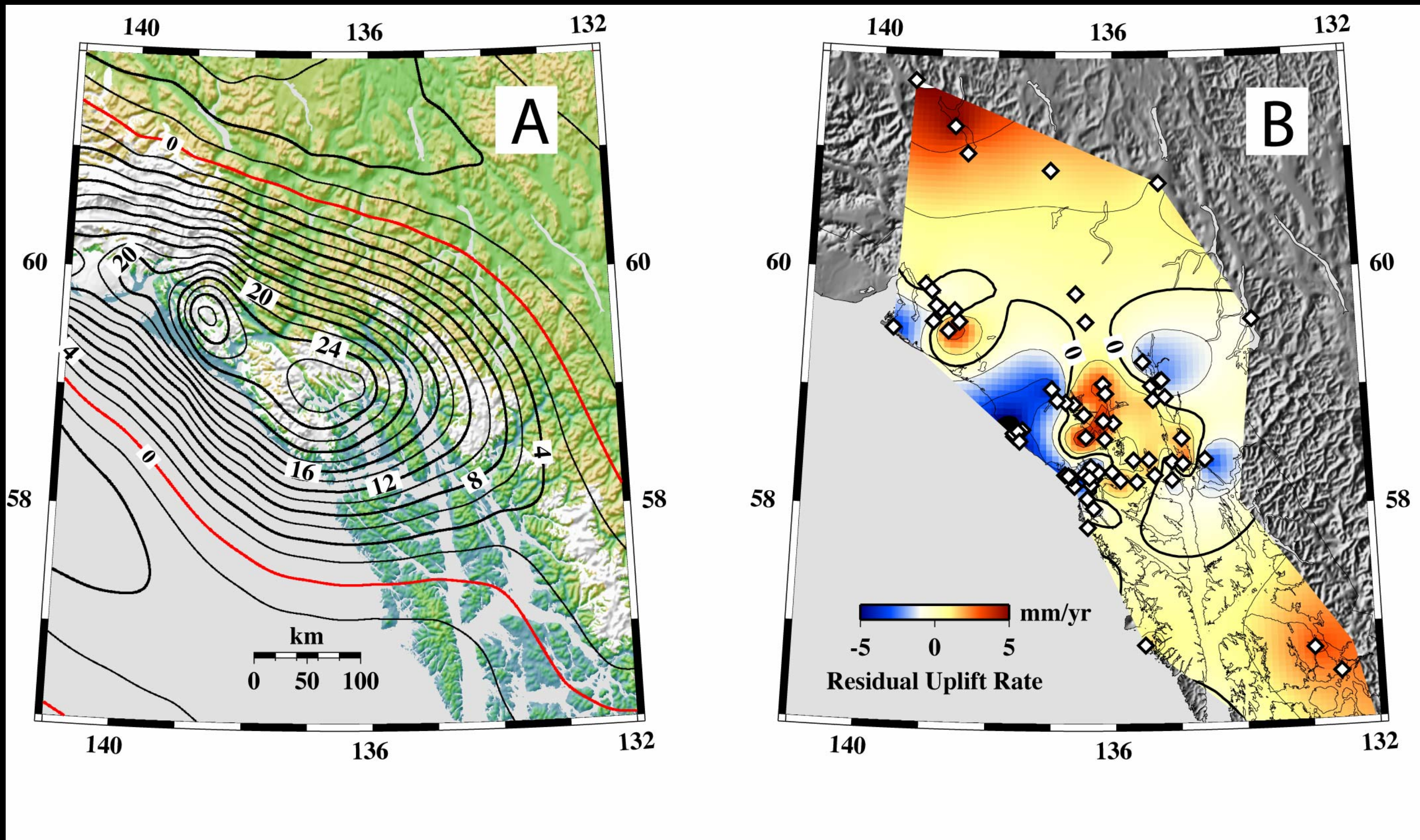
Best fit model
Lithosphere 50 km thick
Asthenosphere 110 km thick
With viscosity=1.4x10^{19} Pa s



CONTOURS:
Red=95% confidence
Green=90% confidence
Blue=68% confidence

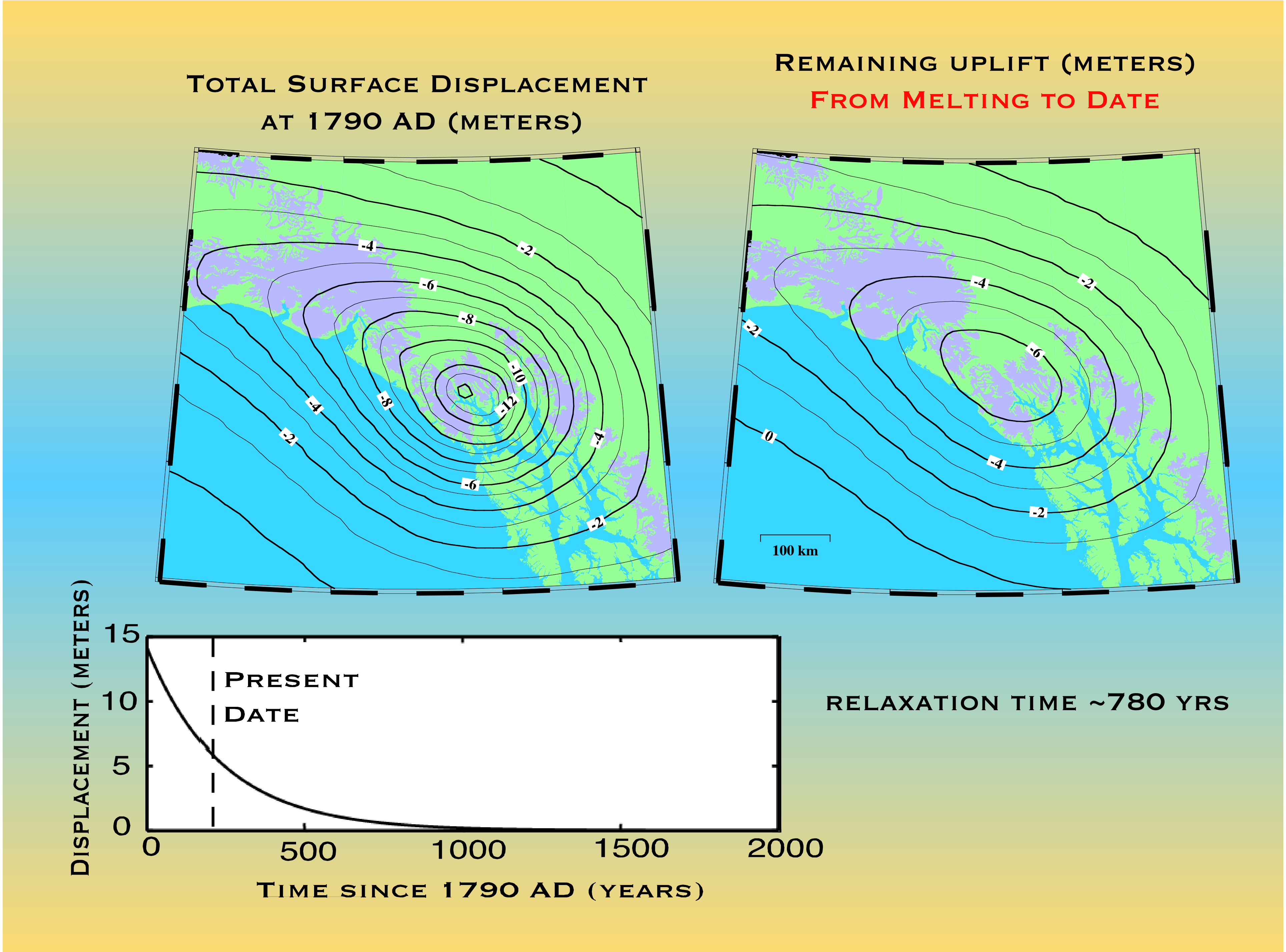






Predicted uplift rate

Difference between model and observations


Total Surface Displacement
at 1790 AD (meters)
Remaining uplift (meters)
From Melting to Date
-2
-4
-6
-8
-10
-12
0
100 km
Displacement (meters)
15
10
5
0
500
1000
1500
2000
Present
Date
Time since 1790 AD (years)
relaxation time ~780 yrs

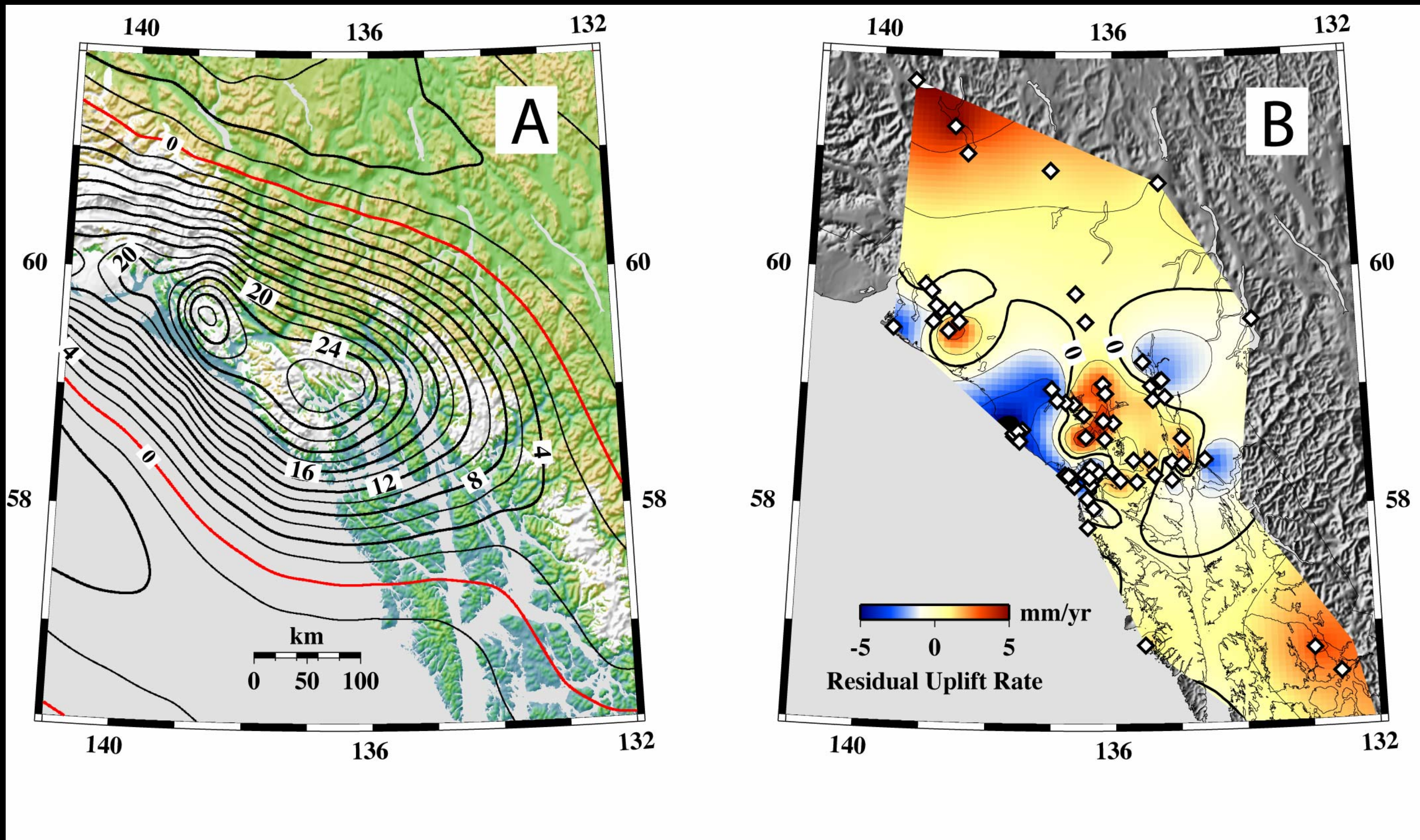
Conclusions

Rapid Uplift, up to
• 30-32 mm/yr uplift rates
• 5.7 m of sea level change over ~250 yrs

Large volume of ice lost since Little Ice Age
• 3000 km^3 in Glacier Bay
• 5800 km^3 Regionally

Glacial rebound models can fully explain the observed uplift.

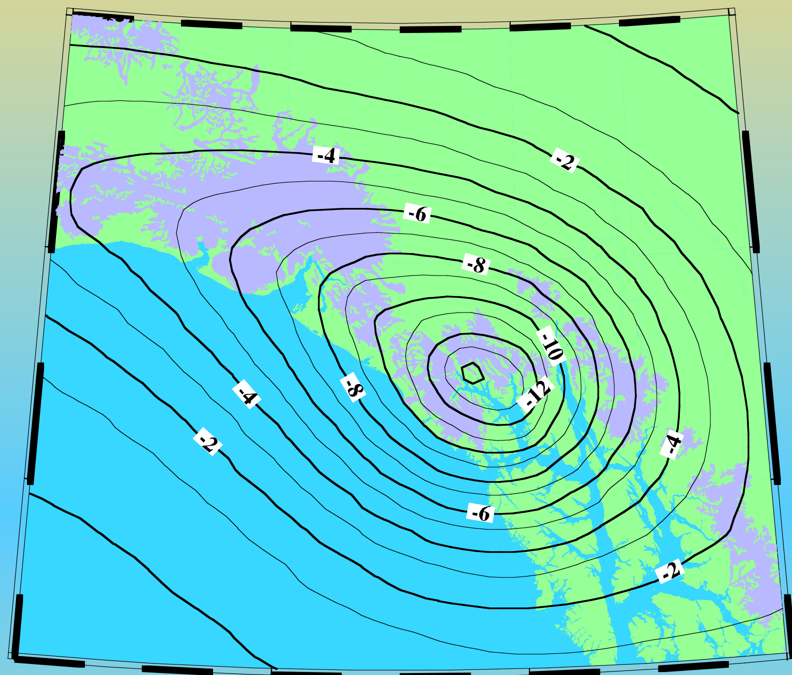
Rebound will continue for 700 to 800 years as a result of ice already lost.



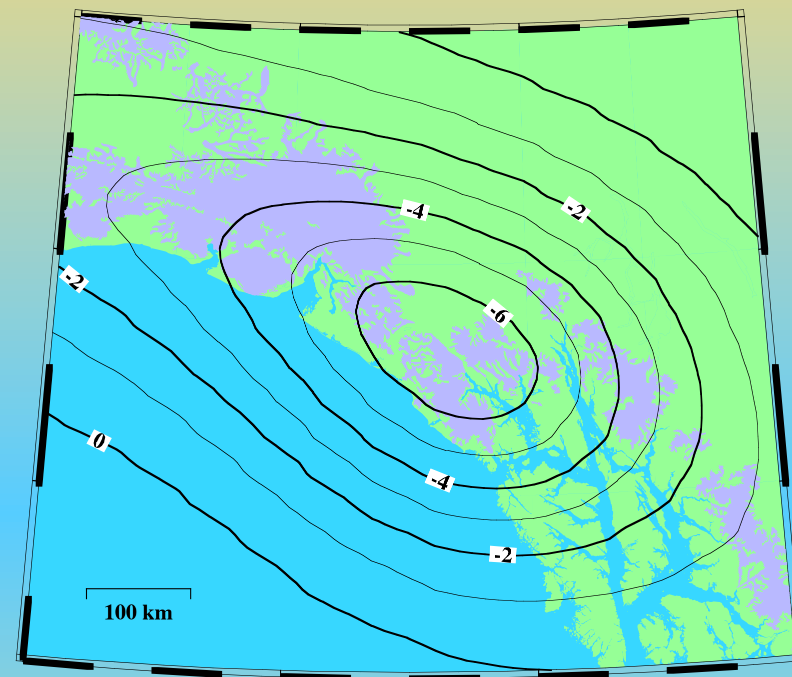
Predicted uplift rate

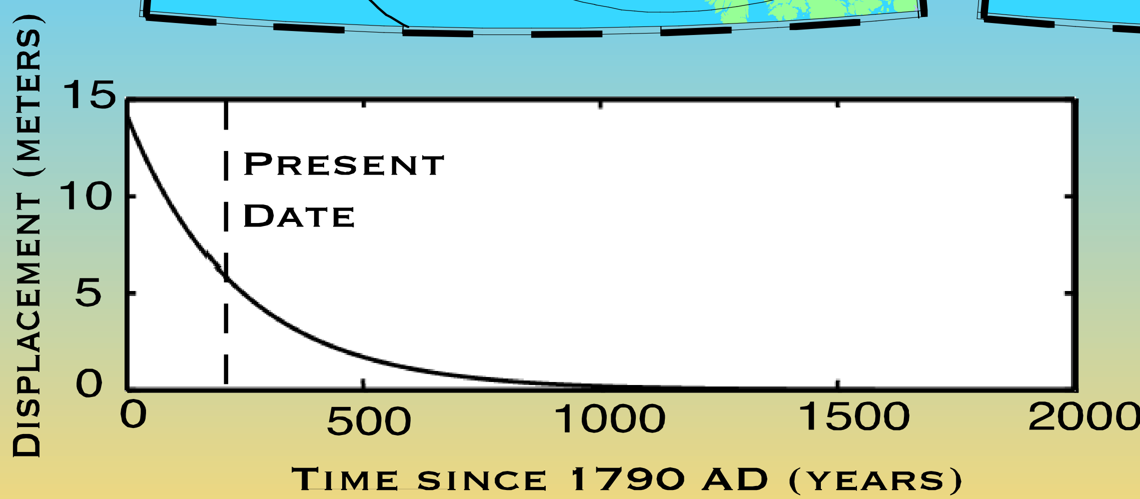
Difference between model and observations

Total Surface Displacement at 1790 AD (meters)

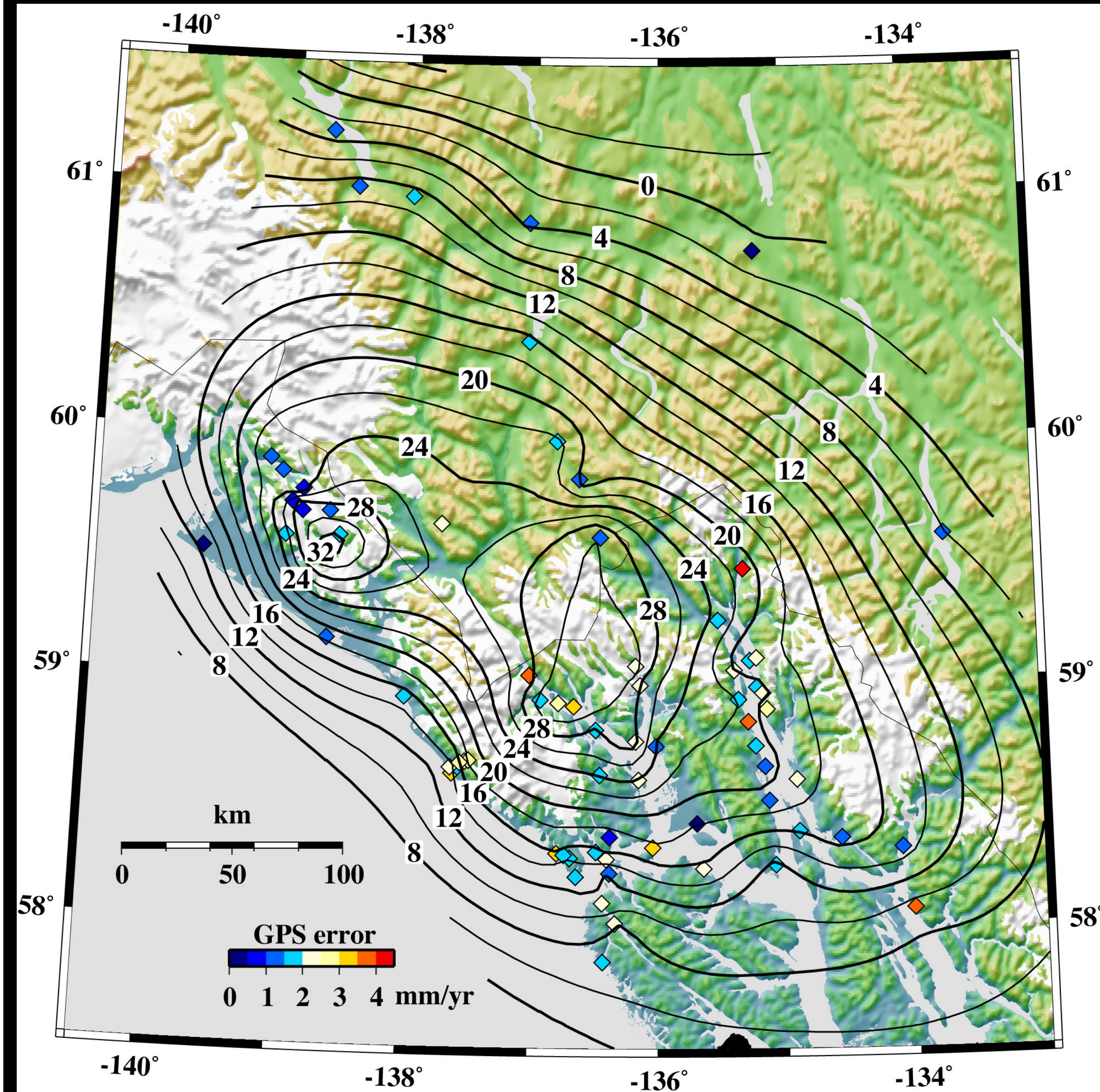


Remaining uplift (meters) From Melting to Date





relaxation time ~780 yrs

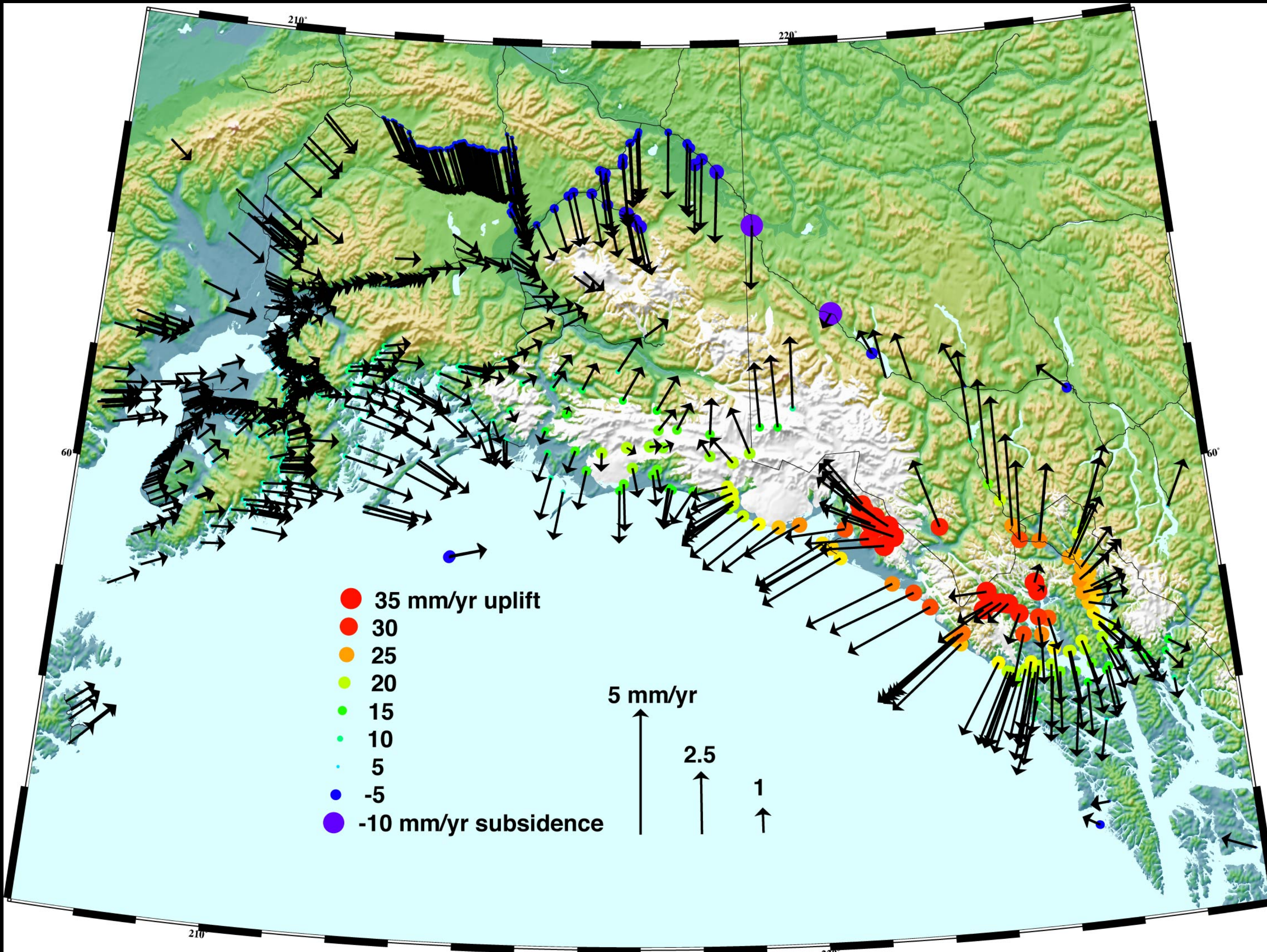


Rapid viscoelastic uplift

GPS rates up to 32 mm/yr

Uplift will continue for centuries…

From Chris Larsen



210°
220°
60°
60°
35 mm/yr uplift
30
25
20
15
10
5
-5
-10 mm/yr subsidence
5 mm/yr
2.5
1
210
220

General Viscoelastic Theory

General parameter equation

$$R = \frac{a}{M_e} \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{4\pi a^2}{2l+1} \int_{-\infty}^{t_p} L_{lm}(t) \left[R_l^E \delta(t_p - t) + \sum_{k=1}^{K} R_l^k e^{-s_l^k (t_p - t)} \right] dt Y_{lm}(\theta, \phi). \qquad (1)$$

Geoid height rate of change

$$\dot{N}^{\mathrm{CUR}} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \dot{N}_{lm}^{\mathrm{CUR}} Y_{lm}(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \frac{a}{M_e} \frac{4\pi a^2}{2l+1} \left(1 + k_l^E\right) \dot{L}_{lm}^{\mathrm{CUR}} Y_{lm}(\theta, \phi), \qquad (2)$$

Wu et al. (2002)

- a and Me are the radius and mass of the Earth.
- L(theta, phi, t) represents the harmonic expansion of the surface density of the load mass including the meltwater distributed in the oceans.
- Ylm are the fully normalized spherical harmonic functions.
- RlE are the lth degree coefficients of the direct and elastic effect (RlE = 1 + klE for geoid, RlE = hlE for uplift, klE and hlE are the usual elastic load Love numbers)
- Rlk and slk are the amplitude and inverse decay time of the kth relaxation mode. In the second equation they assume one relaxation mode (no sum over k).