Deformation Measurements for Seismic Hazard Assessment

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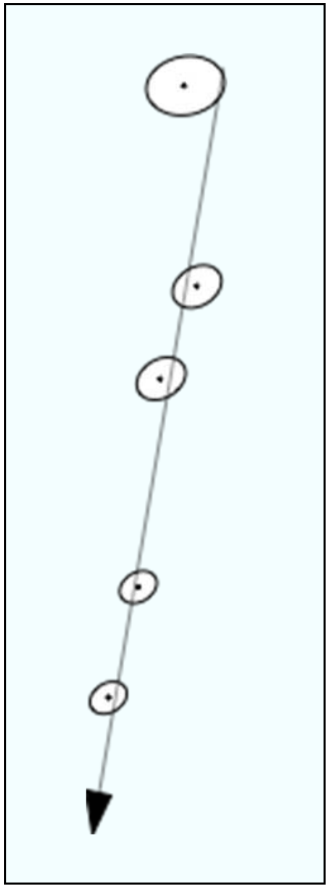
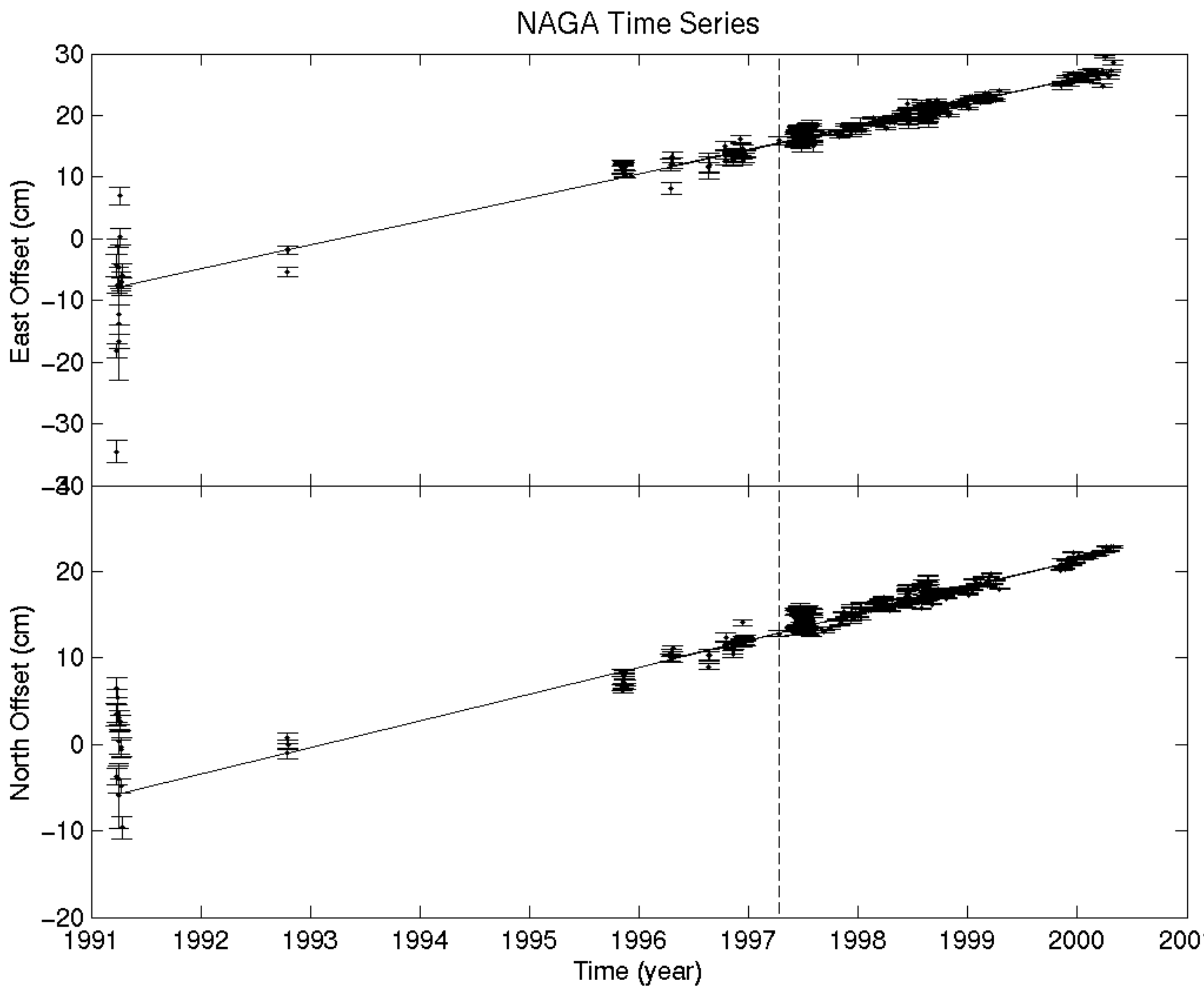
Global Positioning System

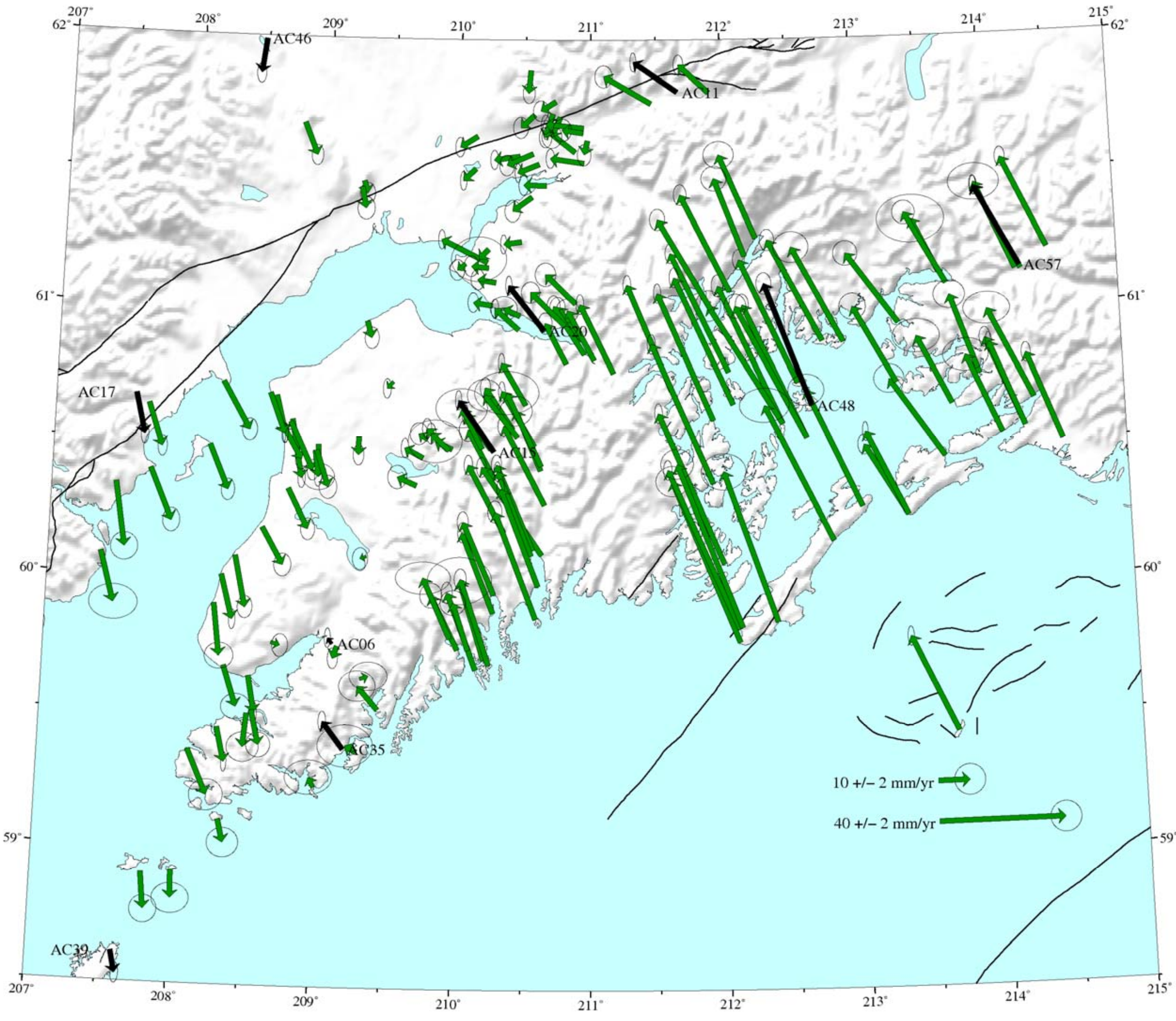
- Portable Surveying Equipment
- Precision of a few millimeters in 3D
- Repeated surveys measure motion of sites

Measuring the Crust

- GPS surveys repeated over time
- Series of positions records the motion of a point fixed to the crust
  - Plate motion
  - Deformation
  - Measurement noise
- Three Dimensions!




NAGA Time Series
East Offset (cm)
North Offset (cm)
Time (year)
30
20
10
0
−10
−20
−30
−40
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001



207°
208°
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60°
59°
AC46
AC11
AC57
AC20
AC17
AC48
AC15
AC06
AC35
AC39
10 +/− 2 mm/yr
40 +/− 2 mm/yr

Rates of Motion to Hazard

- Seismic hazard and risk roughly proportional to rates of motion
- All other things being equal, the frequency of earthquakes of a given size on a fault is proportional to the slip rate of the fault
  - Faster slip rate means shorter recurrence time
- Deformation data also help constrain size of seismogenic region on fault → maximum earthquake size

Outline

- Example of measuring motion before, during and after a major earthquake
  - 2002 Denali fault earthquake
- What this illustrates about general properties of faults
- Some examples from other parts of Alaska

2002 Denali Fault Earthquakes

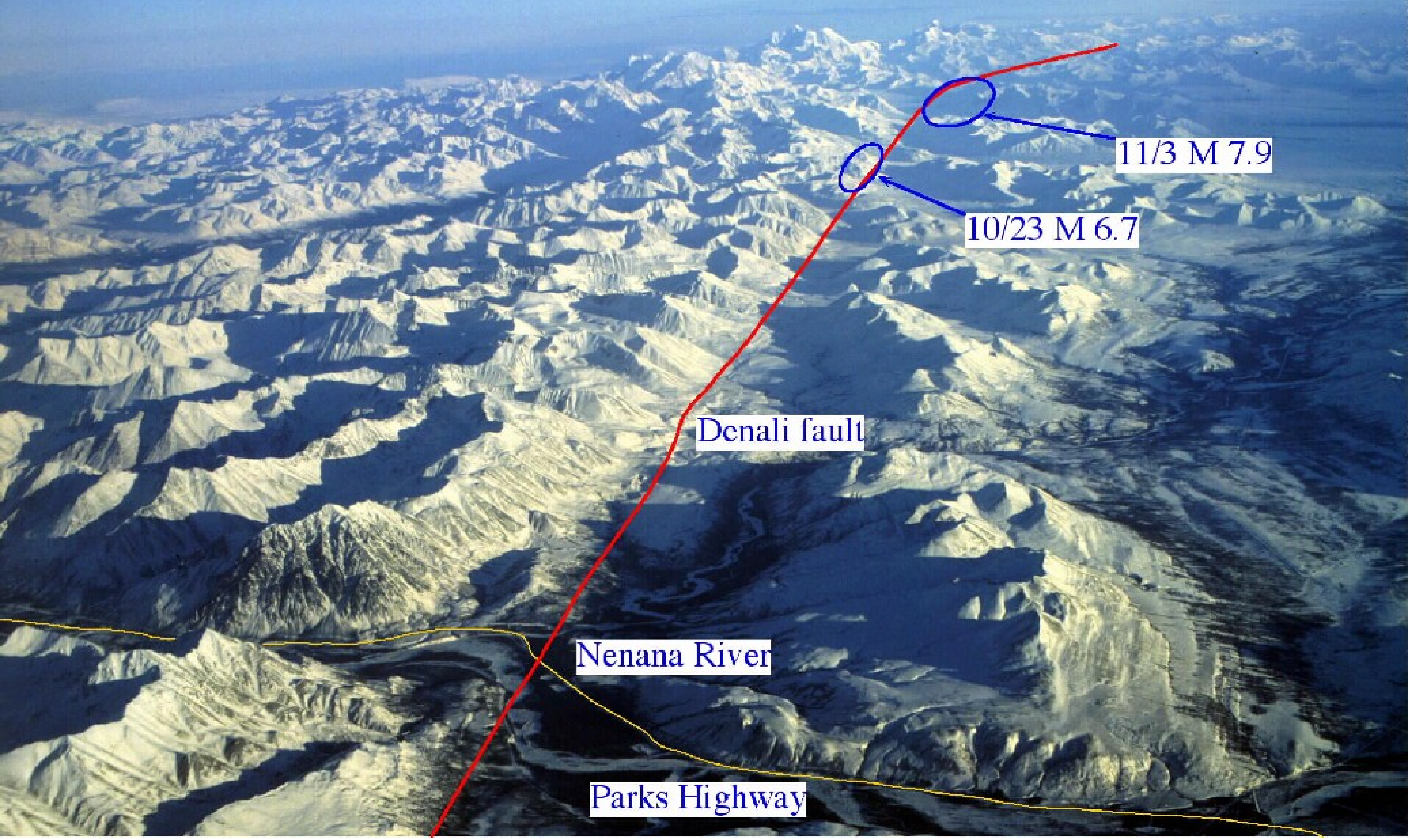
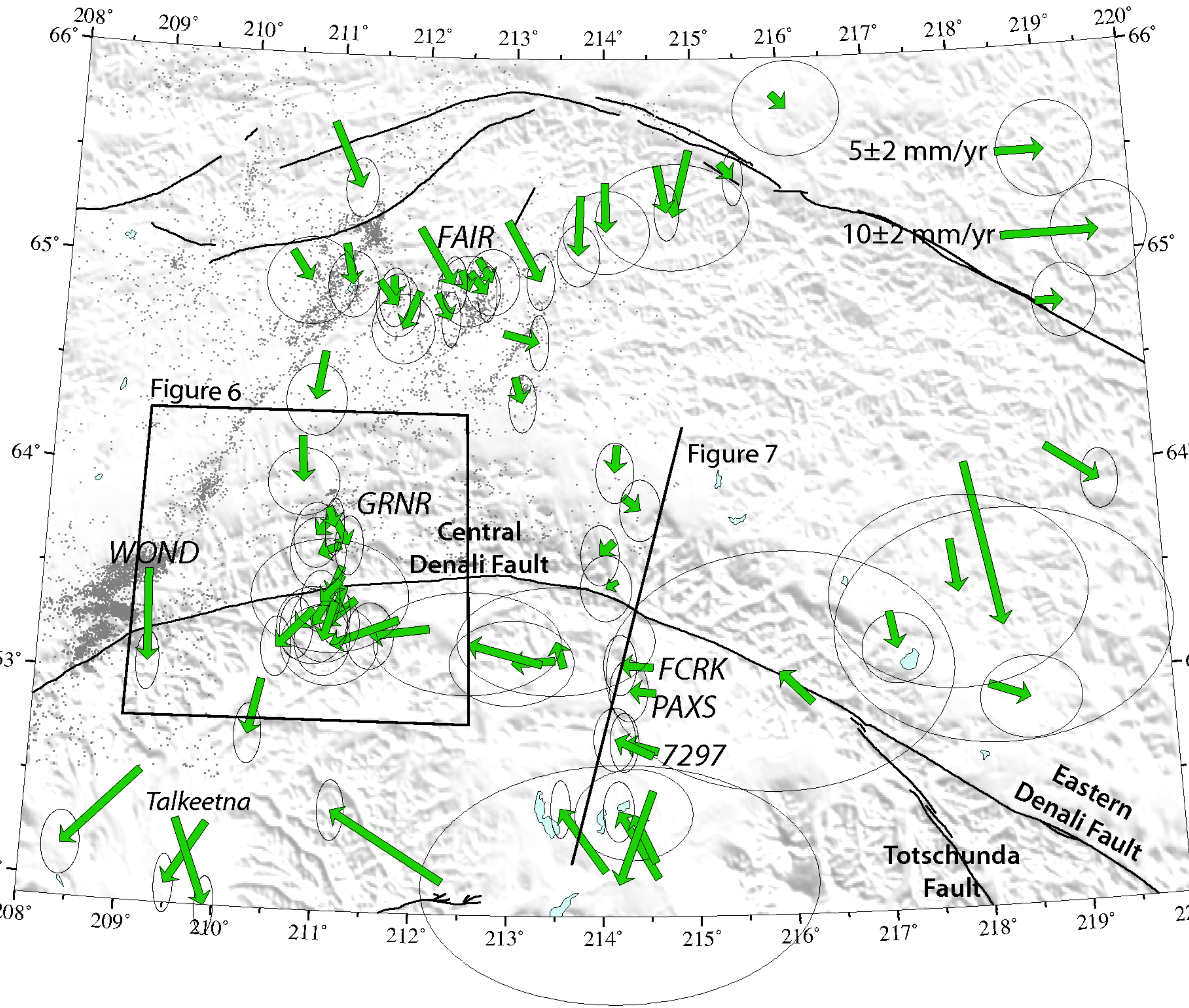


Photo Wes Wallace, UAF



5±2 mm/yr
10±2 mm/yr
FAIR
Figure 6
Figure 7
GRNR
WOND
Central
Denali Fault
FCRK
PAXS
7297
Talkeetna
Eastern
Denali Fault
Totschunda
Fault
208°
209°
210°
211°
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220°
66°
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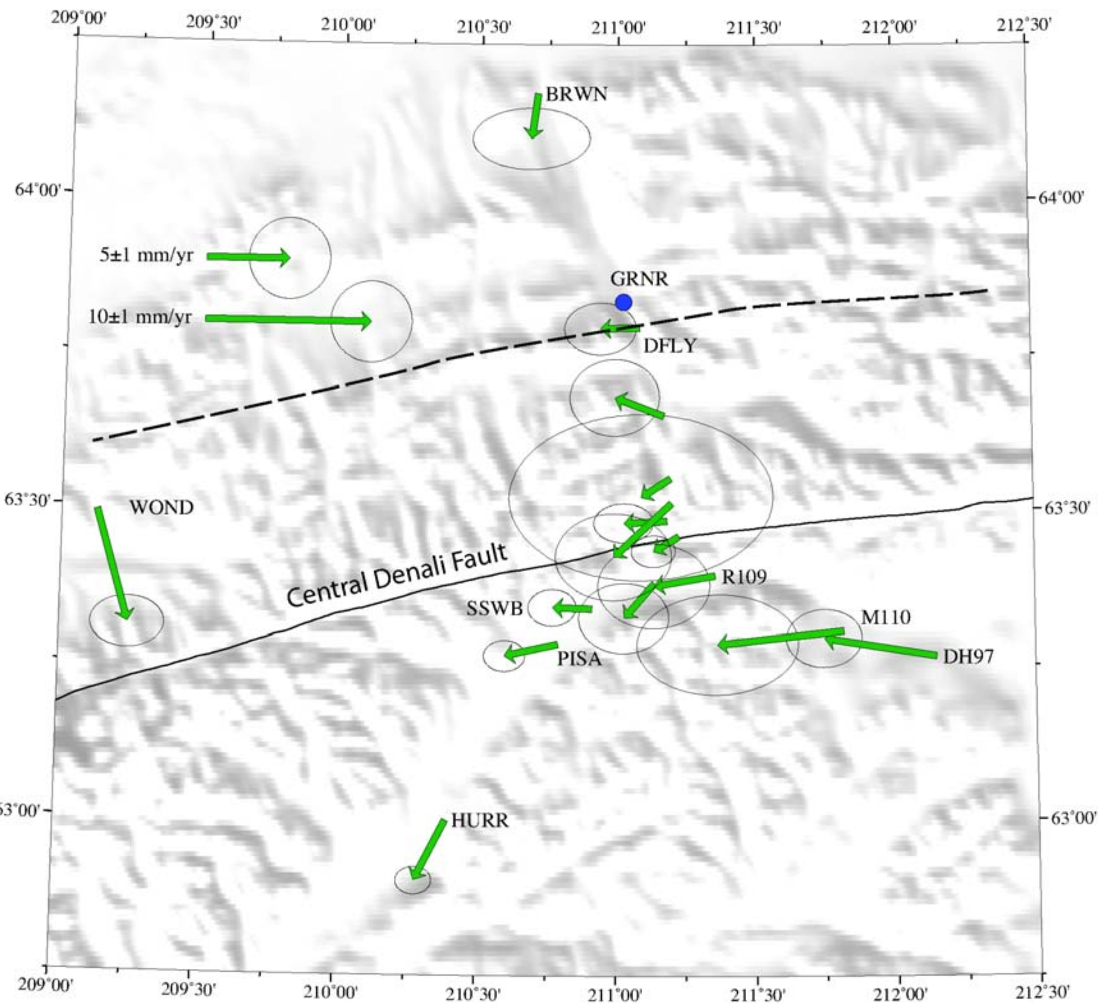
64°
63°
62°

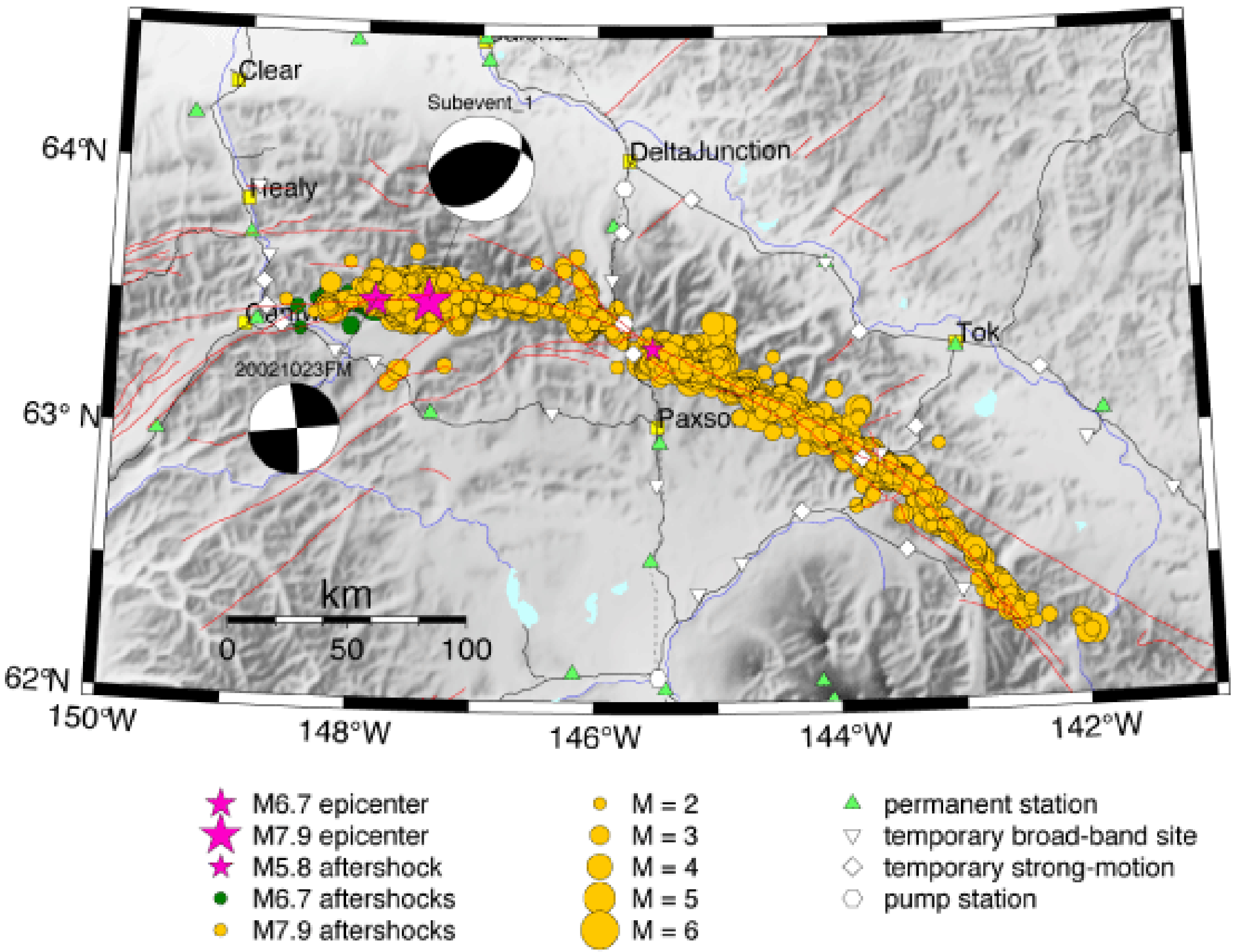
Deformation Across Denali Fault



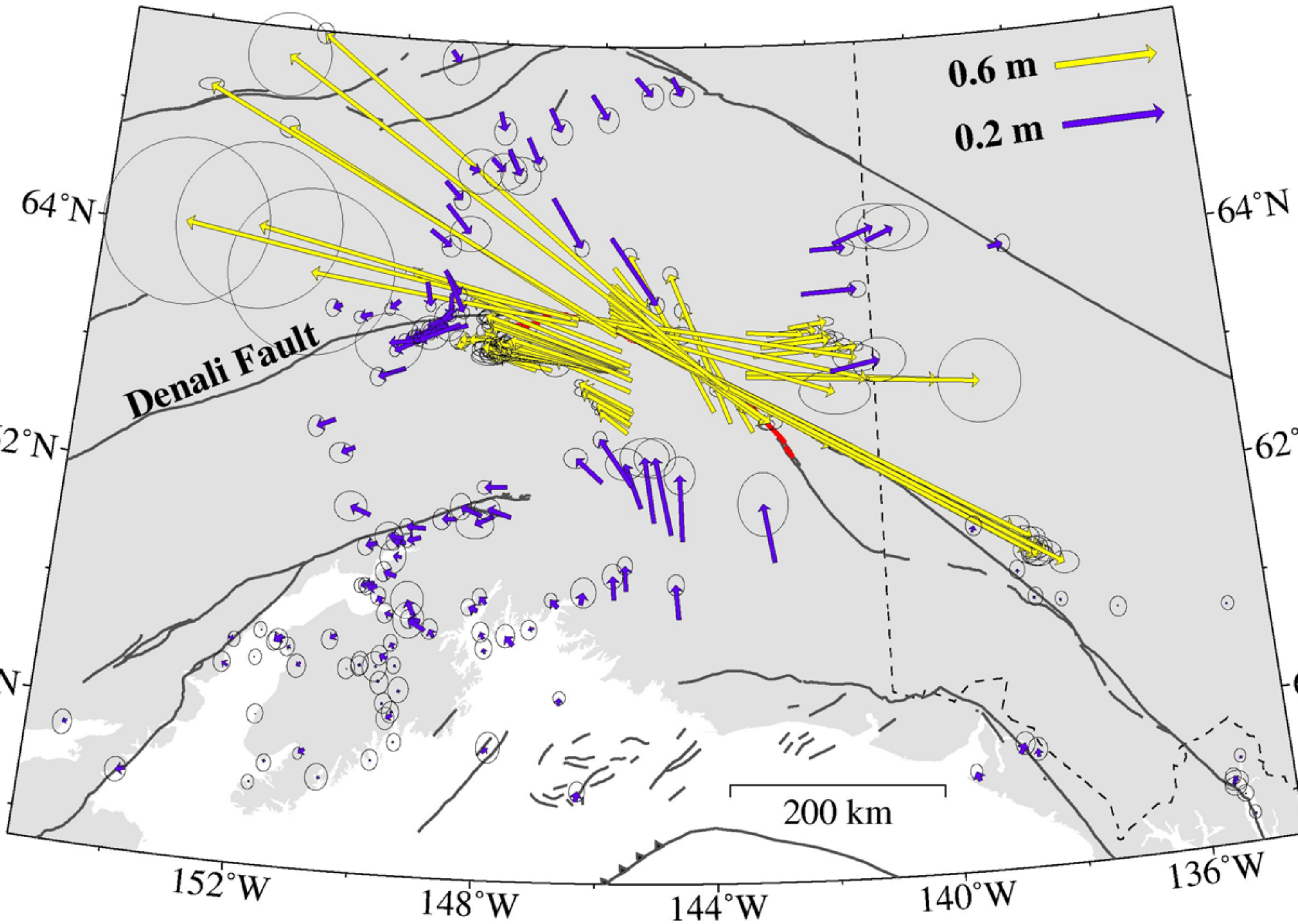
- 8 mm/yr total
- Possibly ~2-3 mm/yr on northern fault
- ~5-6 mm/yr on McKinley strand

Earthquake and Effects

Mainshock and Aftershocks

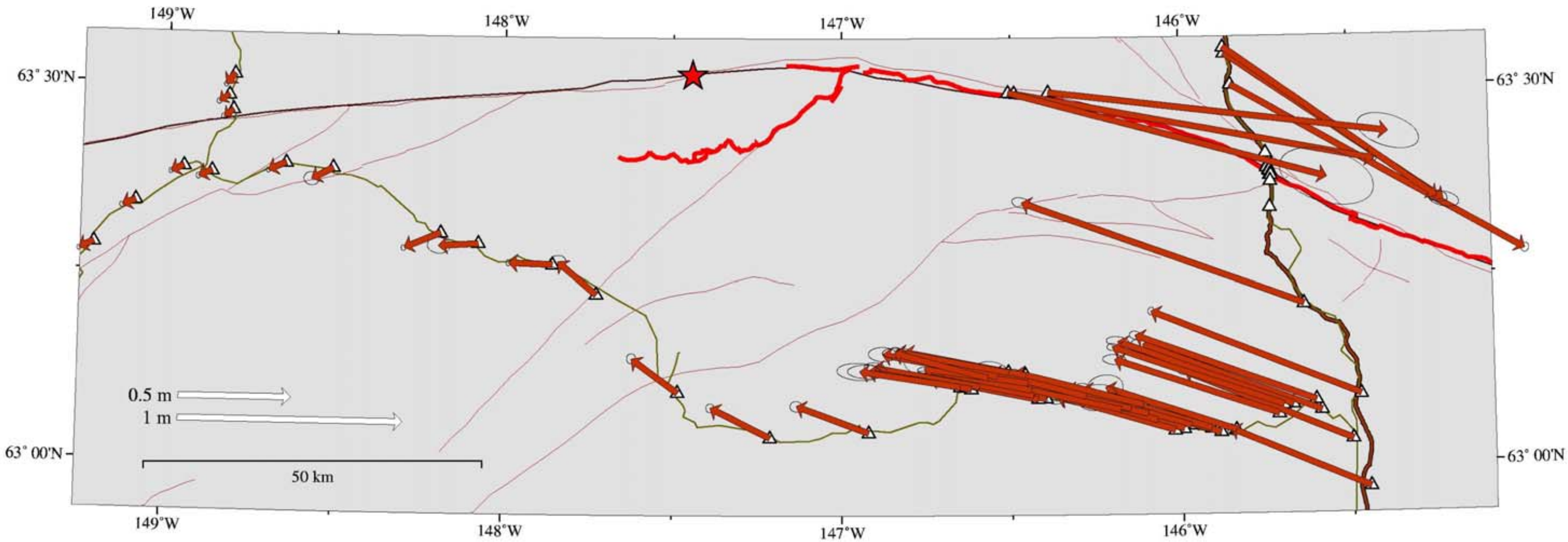


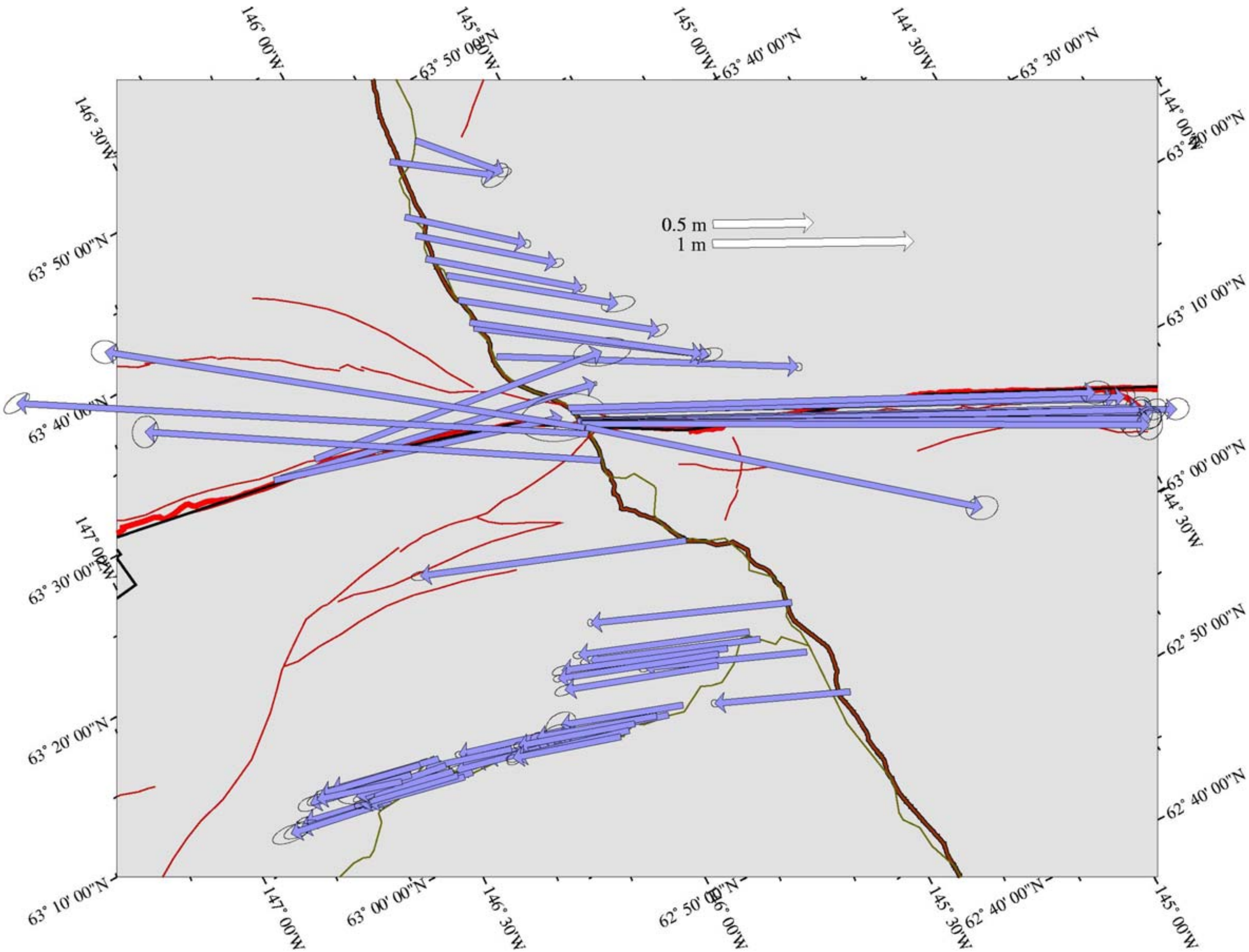
Coseismic Displacements - Horizontal



Two scales (3:1)

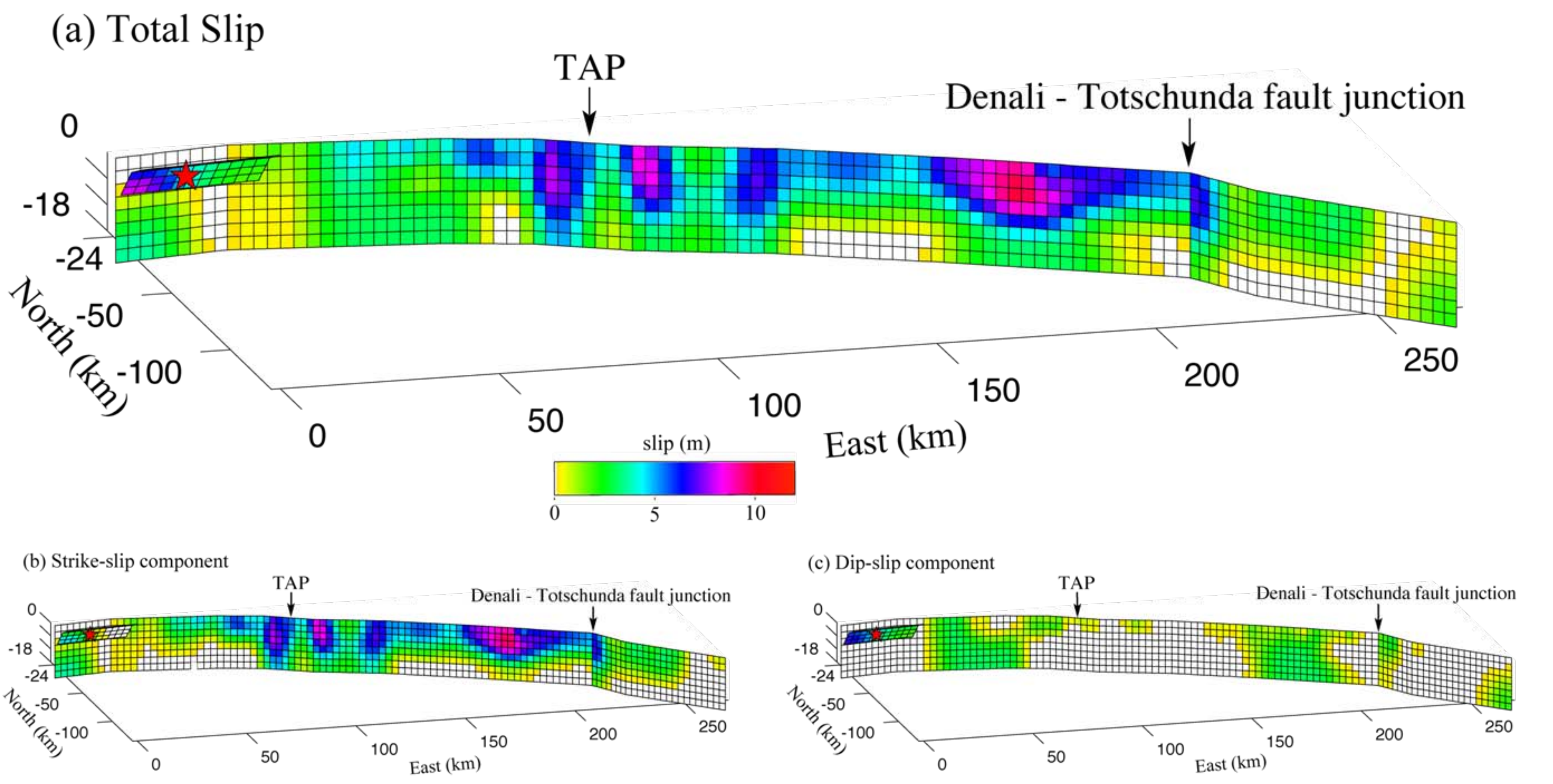
Western Part of Rupture





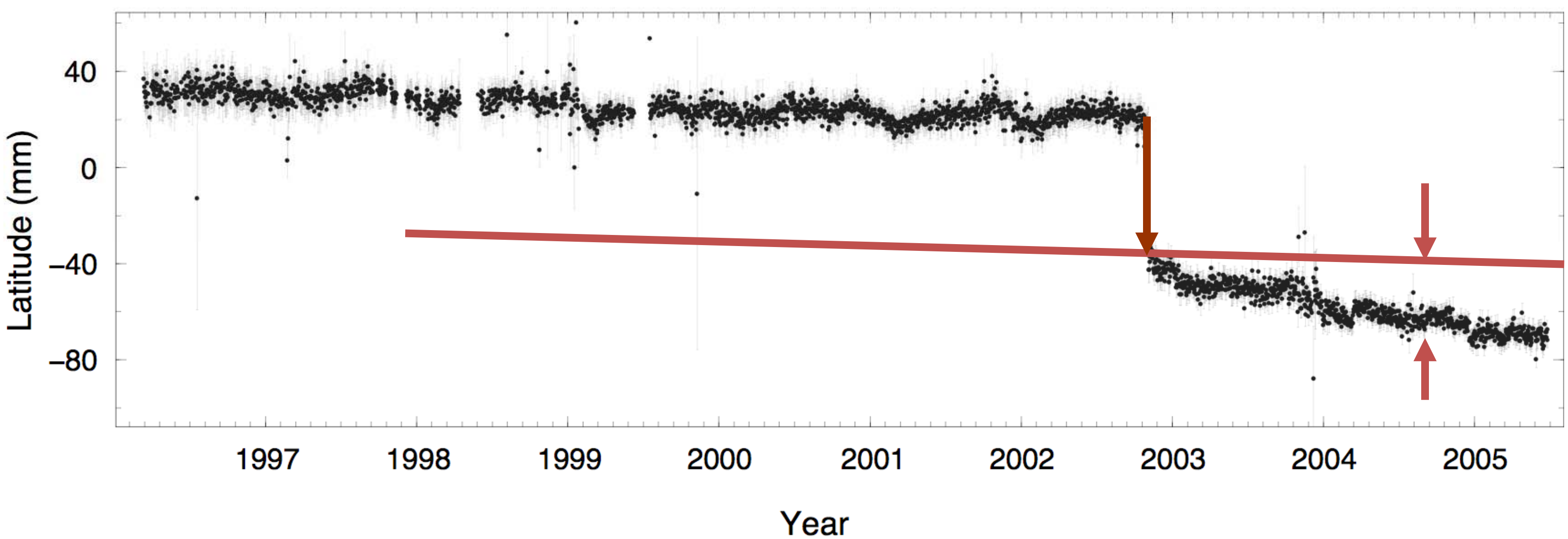
0.5 m
1 m
63° 50' 00"N
63° 40' 00"N
63° 30' 00"N
63° 20' 00"N
63° 10' 00"N
63° 10' 00"N
63° 00' 00"N
62° 50' 00"N
62° 40' 00"N
146° 00'W
145° 00'W
144° 30'W
146° 30'W
147° 00'W
146° 30'W
145° 30'W
145° 00'W

Coseismic Slip Model

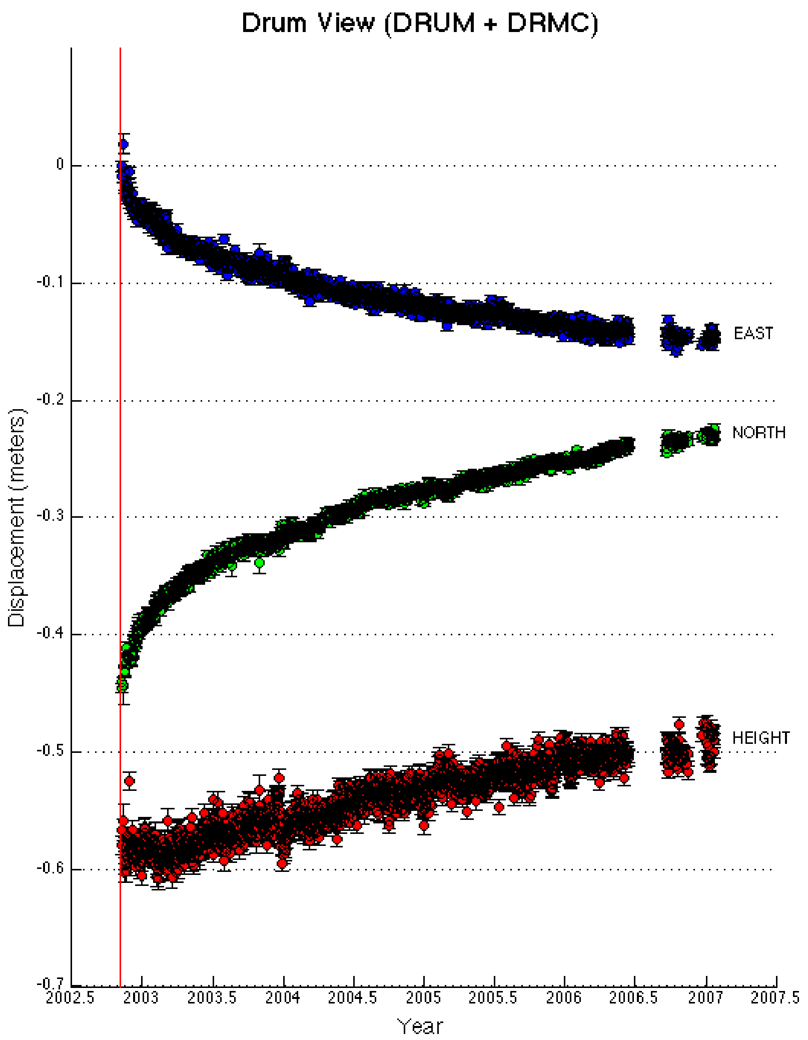


What is Postseismic Deformation?

- Transient deformation triggered by an earthquake
  - Afterslip on the fault zone
  - Viscoelastic relaxation of the mantle or lower crust
  - Poroelastic deformation associated with earthquake-driven fluid flow (changes elastic constants)

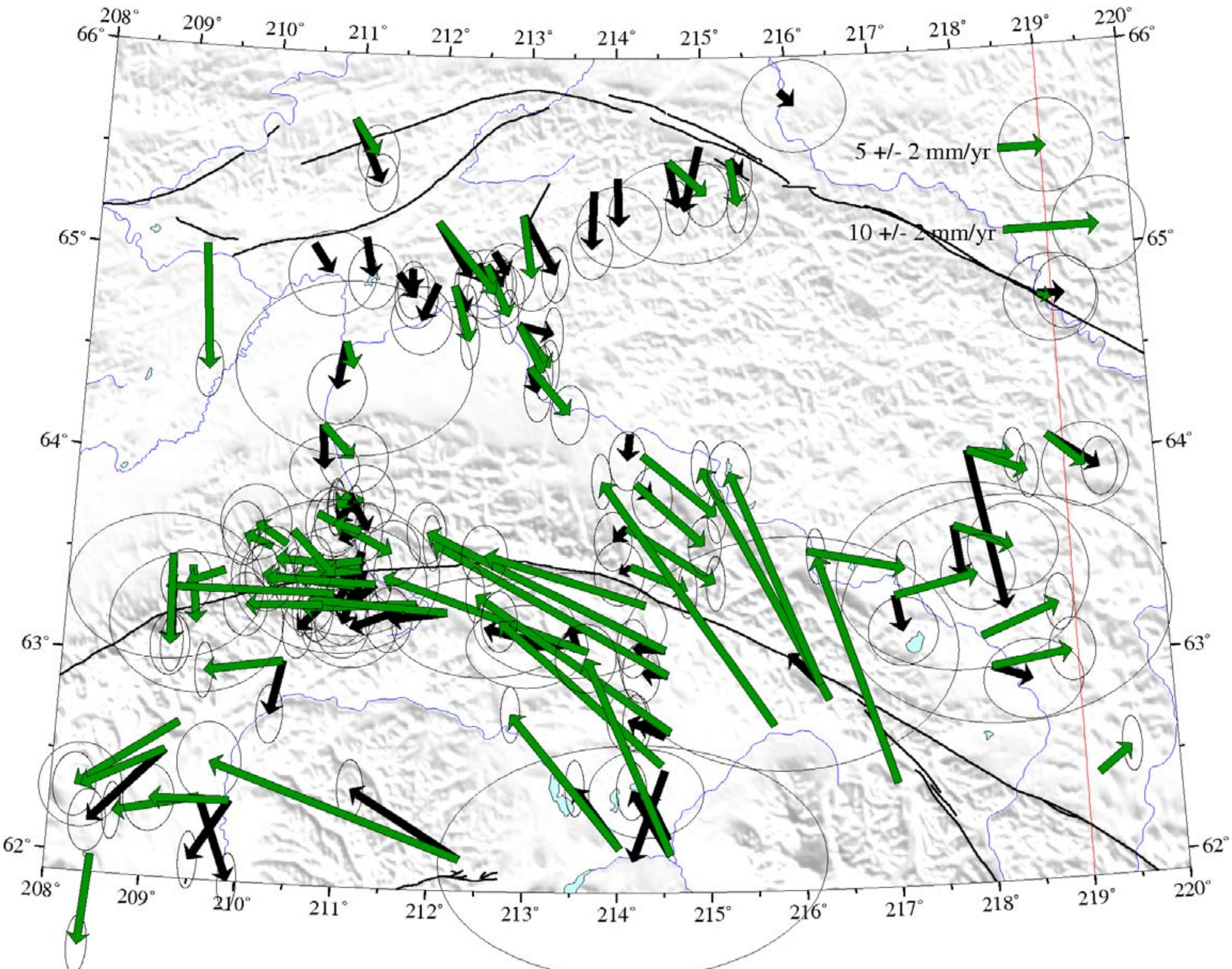


A Sample Postseismic Time Series

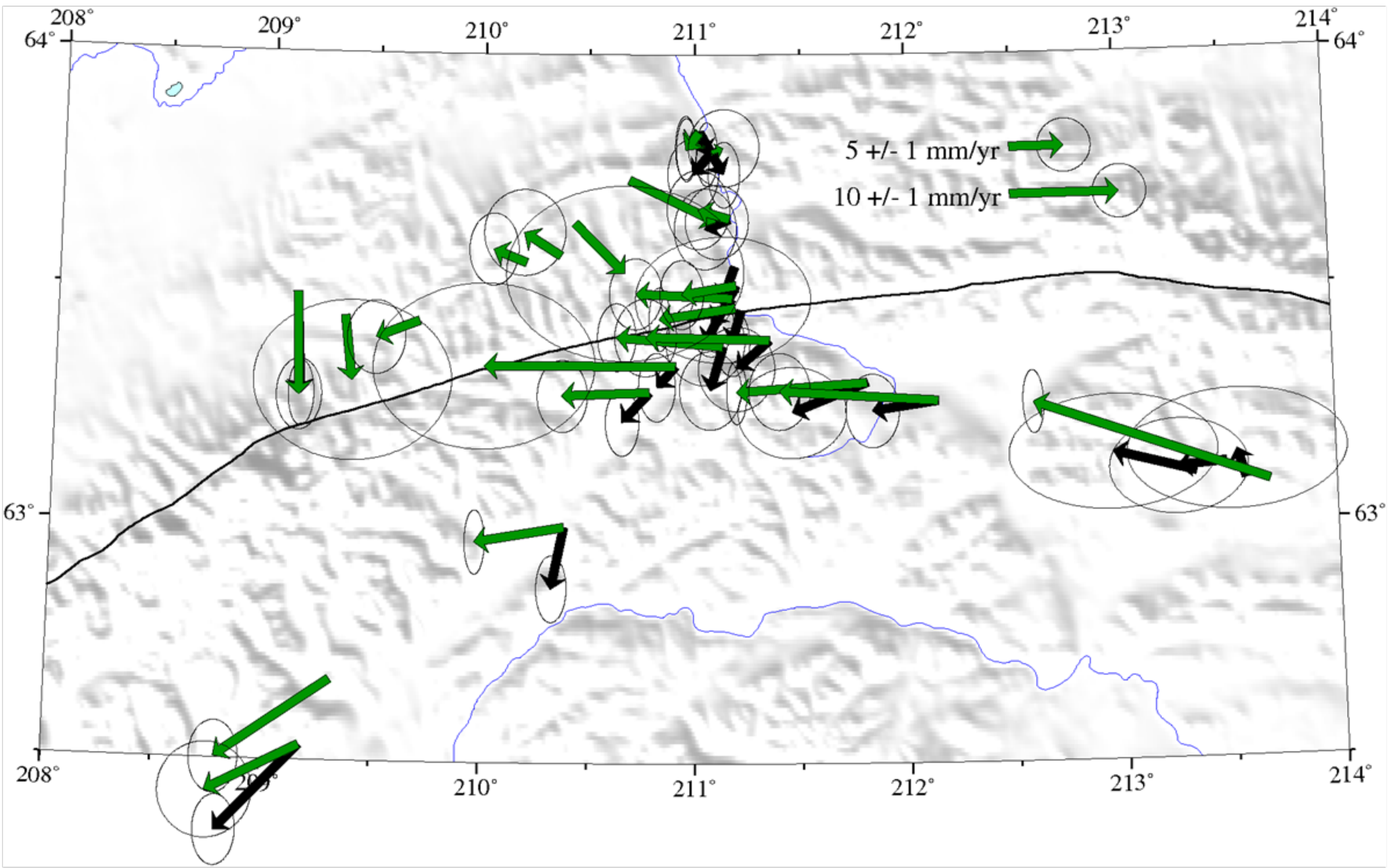


- Time series are shown with pre-earthquake trend subtracted (less than ~6 mm/yr relative to North America)
- Post-earthquake rates still >20 mm/yr
- Total 4-year displacement
  - 15 cm east
  - 20 cm north
  - 12 cm vertical

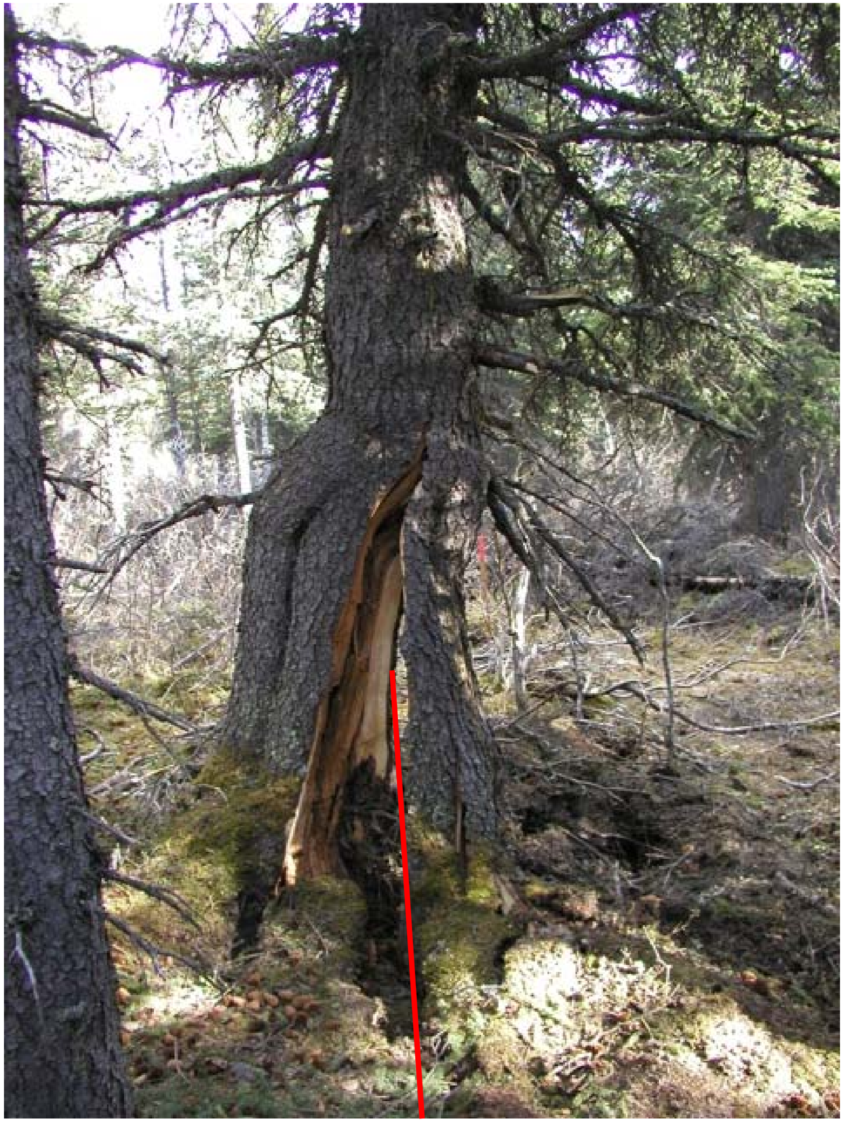
Postseismic Displacements



Postseismic Displacements



Faults

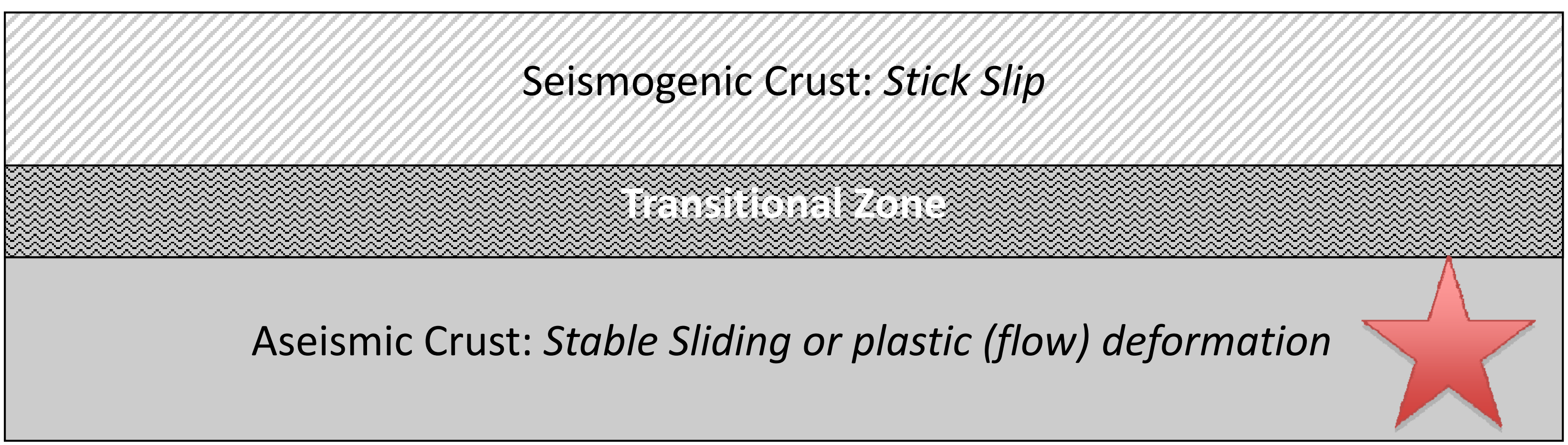


A View of a Fault

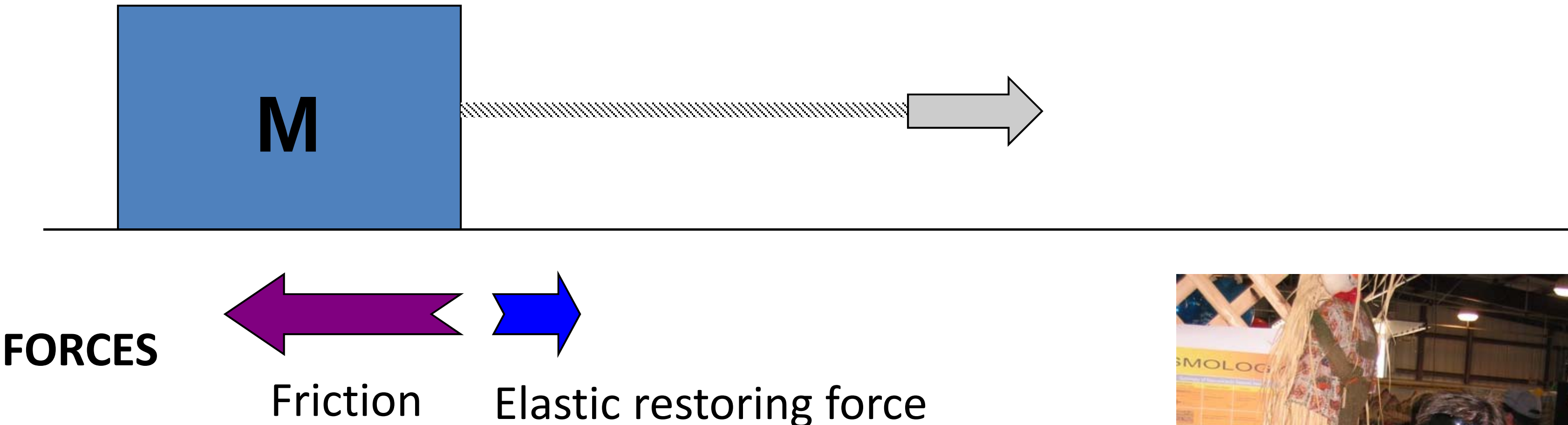
Can divide fault zone based on how fault slips

- *Seismogenic Crust* exhibits stick slip
- *Transitional Zone* may exhibit complex behavior
- *Aseismic Crust* exhibits stable sliding

- Crustal earthquakes involve slip of seismogenic crust and possibly transitional zone

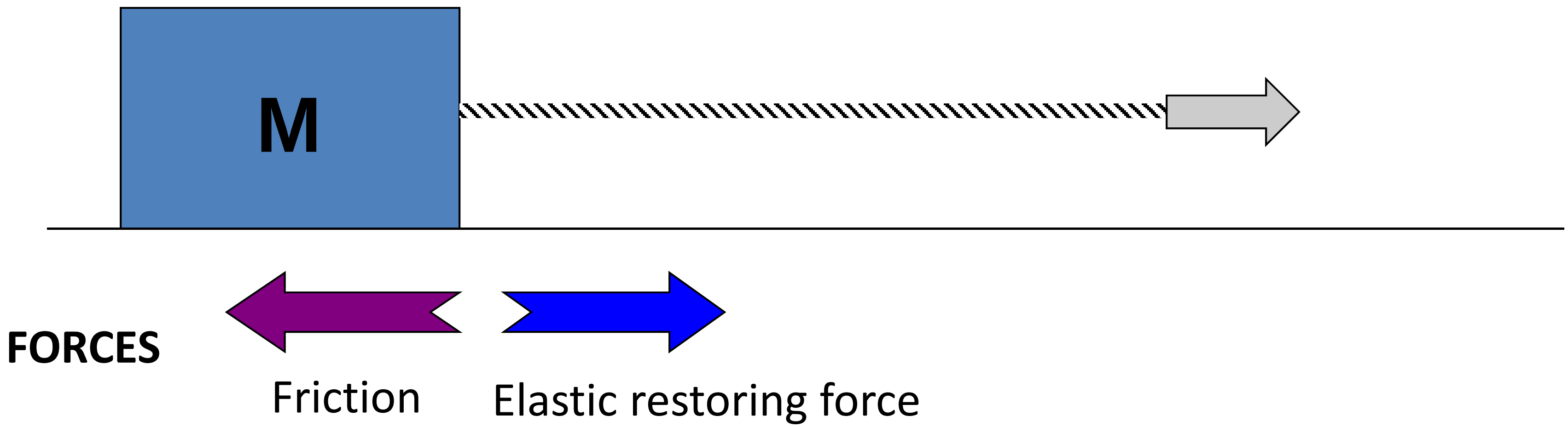


A Simple Analogue: Spring Slider



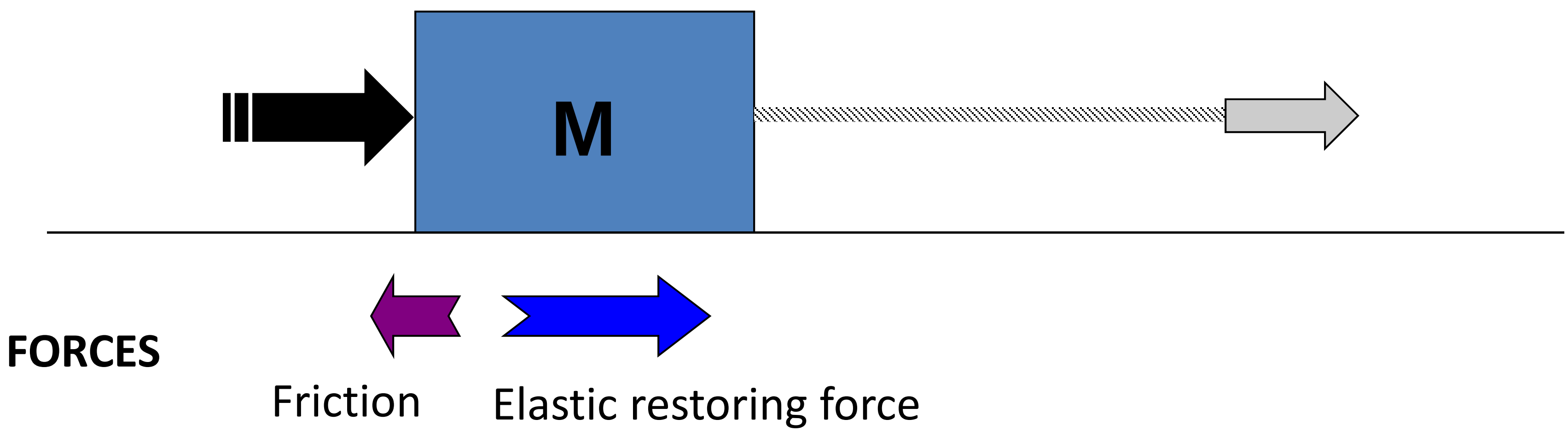
- Block is held in place by force of friction

A Simple Analogue: Spring Slider



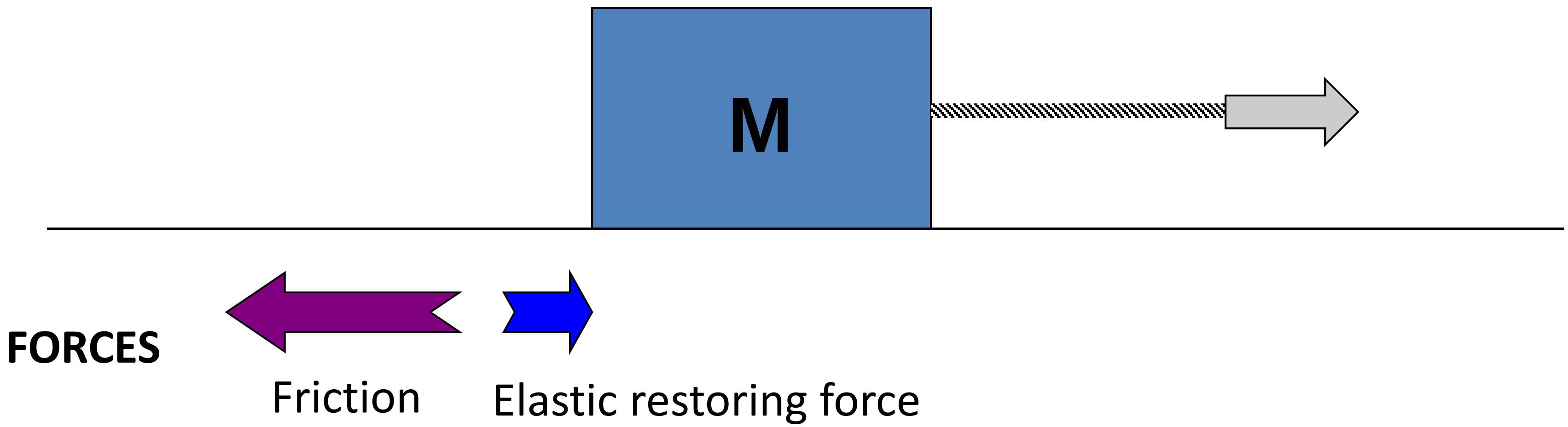
- Block is held in place by force of friction
- Moving load point increases elastic force

A Simple Analogue: Spring Slider



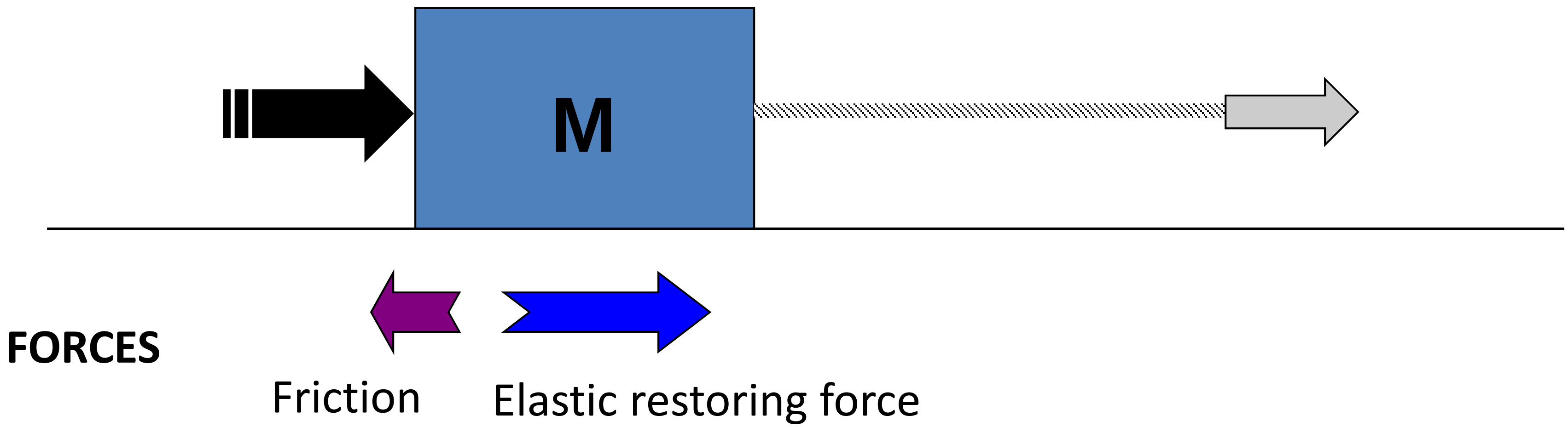
- Block is held in place by force of friction
- Moving load point increases elastic force
- Slips when elastic force exceeds friction

A Simple Analogue: Spring Slider



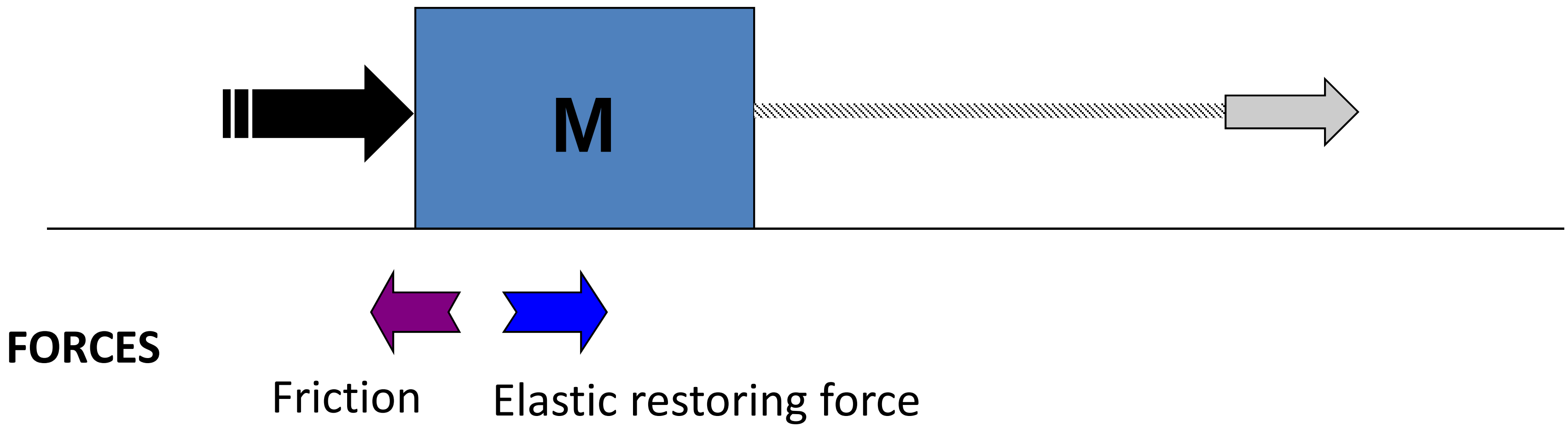
- Block is held in place by force of friction
- Moving load point increases elastic force
- Slips when elastic force exceeds friction

Frictional Instability



- Velocity-weakening (dynamic < static friction)
  - $F_e > F_f$; block accelerates
  - Velocity increases, F_f decreases; block accelerates more
  - Fe decreases with slip, in few seconds $F_e < F_f$; block decelerates
  - Velocity decreases, F_f goes up; block decelerates and stops

Alternative: Stable Sliding



- Velocity-strengthening (dynamic > static friction)
  - $F_e > F_f$; block accelerates
  - Velocity increases, F_f increases; acceleration stops
  - But velocity then remains the same
  - Velocity reaches equilibrium with shear stress

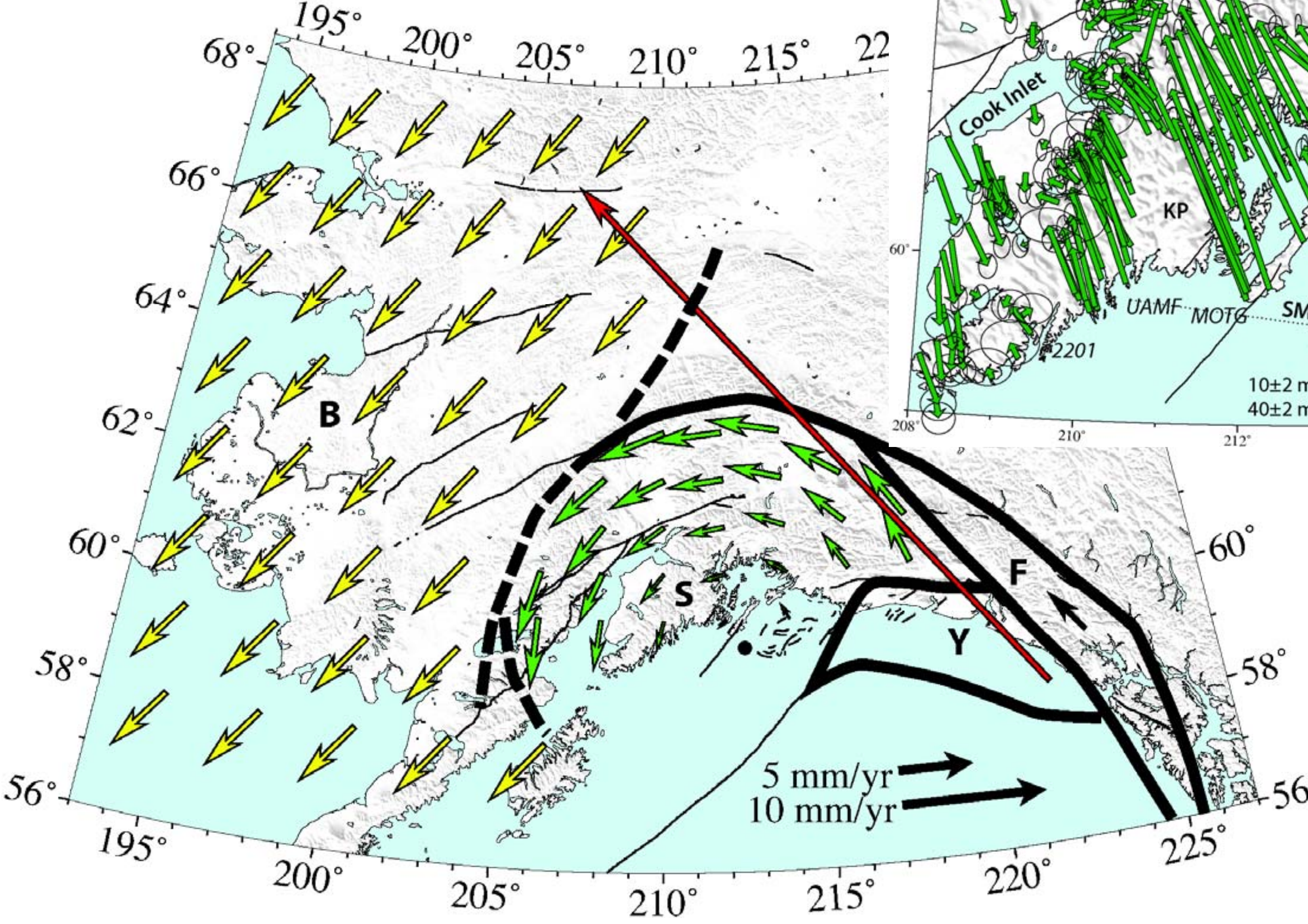
A Simple “Earthquake Cycle” Model

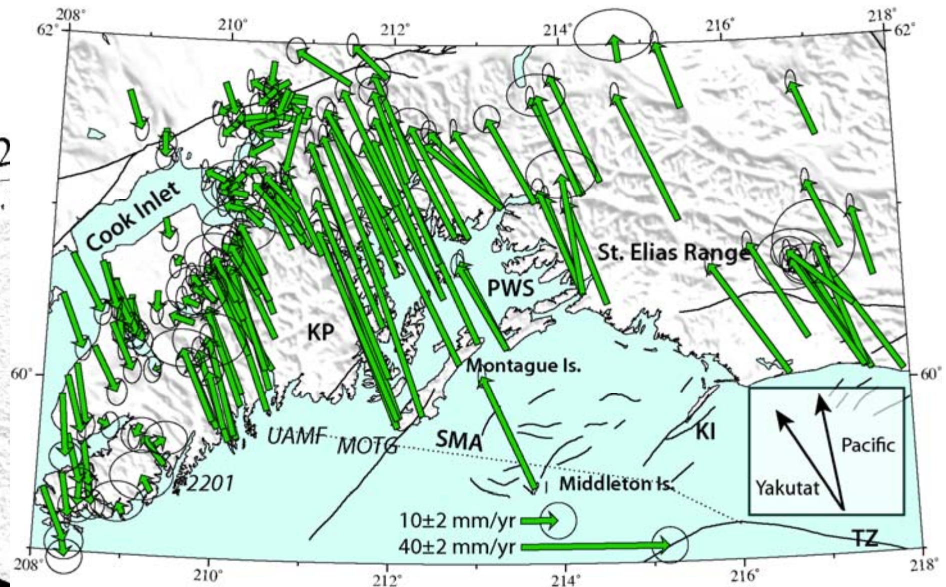
- Based on the spring-slider analogue model
- Between earthquakes:
  - Shallow fault is locked
  - Deeper fault is creeping at long-term slip rate
  - Stress builds up: elastic strain energy stored in crust
- During earthquake, shallowfault slips
  - Stress on fault reduced
- Cycle repeats forever

Shallow Locked Fault Causes Deformation Away from the Fault

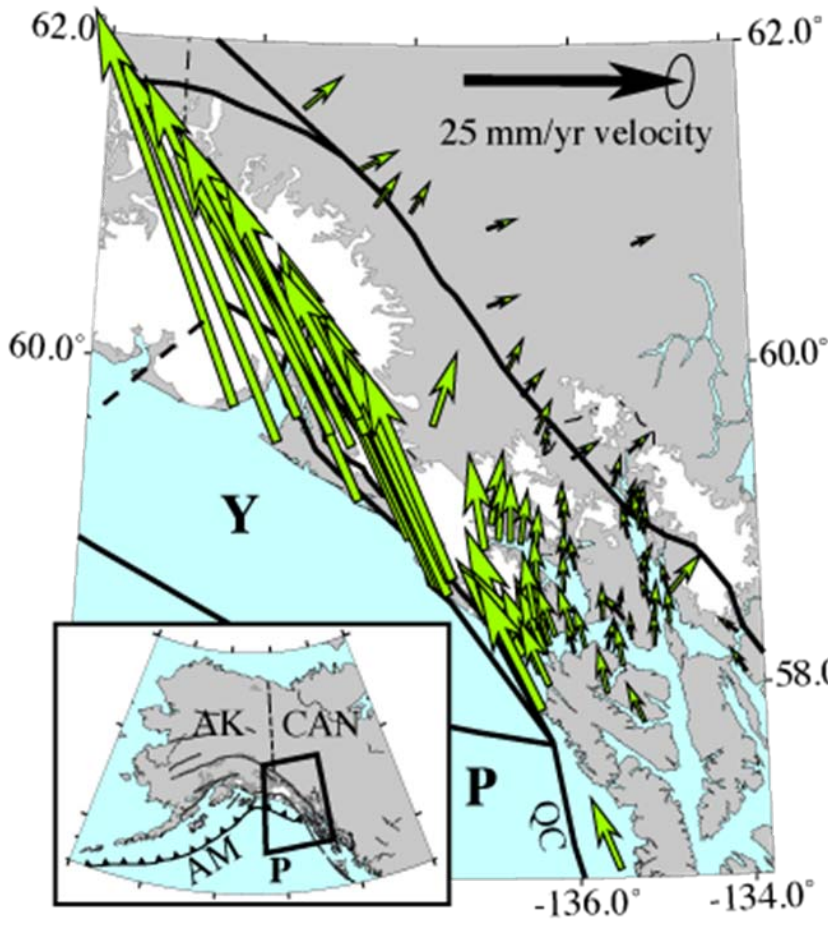
- Earth deforms as elastic body over short timescales
- Locked shallow fault + slipping deep fault produces elastic strain in vicinity of fault
  - Most important close to fault
  - Far from fault, motion is same as rigid blocks
- Simple numerical models allow us to compute effects of fault slip
- When there are multiple faults, it can be difficult to separate the effects of each one.

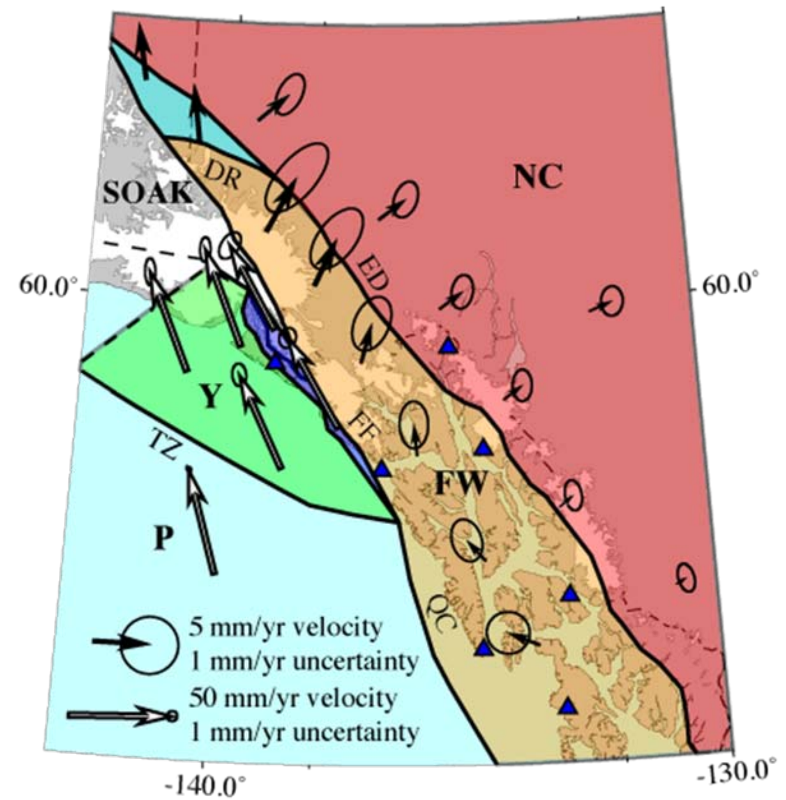
Broad-Scale Deformation of Overriding Plate

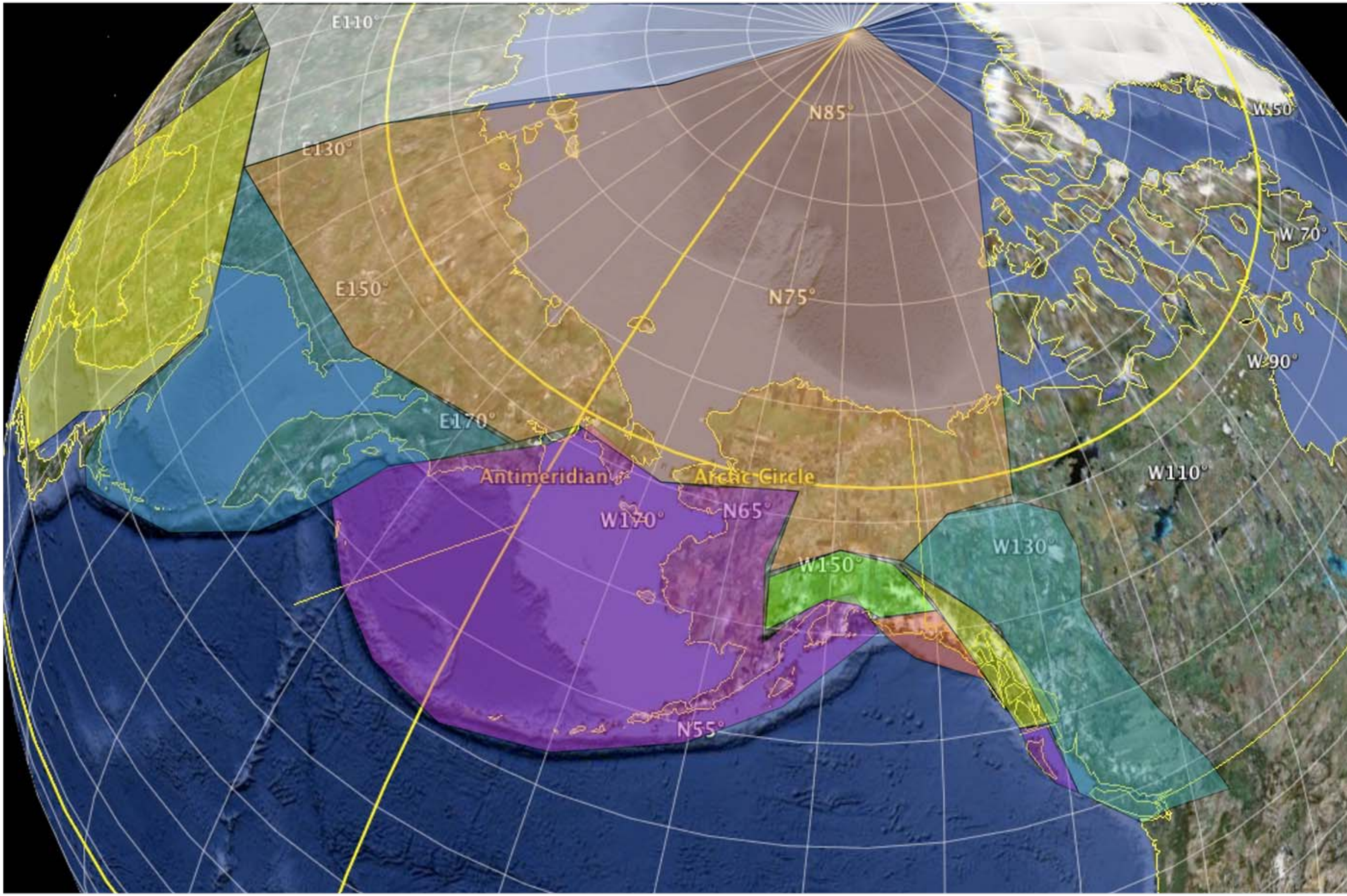




Southeast Alaska Block Model

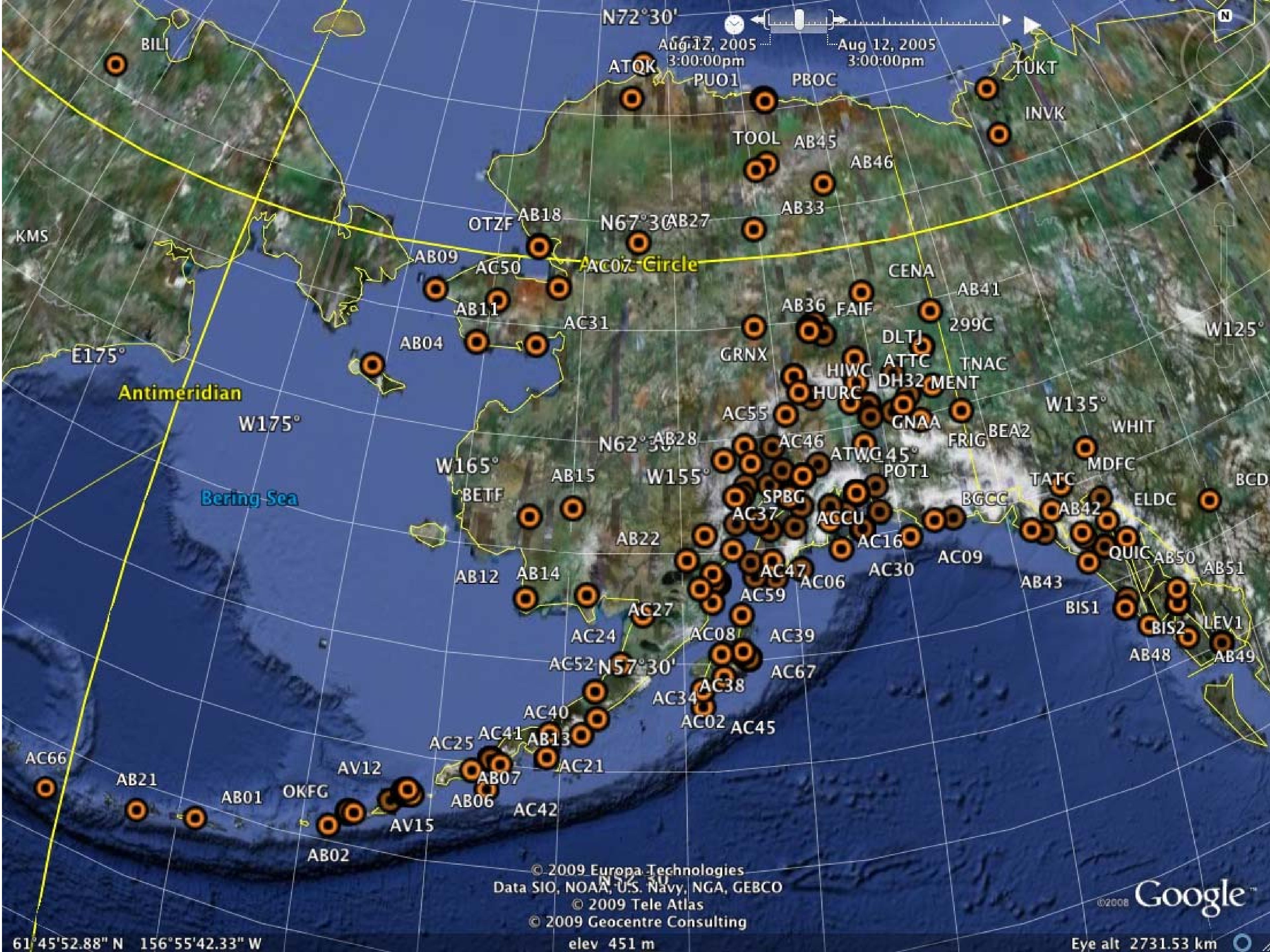





E110°
E130°
N85°
W 50
W 70°
E150°
N75°
W 90°
E170°
W110°
Antimeridian
Arctic Circle
N65°
W170°
W130°
W150°
N55°

Summary

- We can measure rates of motion of Earth's crust using repeated GPS measurements, and relate these to slip on faults, or models for the motion of crustal blocks.
- Rates of slip on faults are directly related to seismic hazard
- GPS velocities also provide information about the width and extent of the seismogenic region of faults
- The information provided by geodesy is a bit different from the data usually used for hazard estimation
  - Methodology to fully incorporate this information into formal seismic hazard estimates is still being developed


N72°30'
Aug 12, 2005
3:00:00pm
Aug 12, 2005
3:00:00pm
BILI
ATQK
PUO1
PBOC
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AB45
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N67°30'
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AB09
AC50
AC07
Arctic Circle
CENA
AB41
AB11
AC31
AB36
FAIF
299C
AB04
GRNX
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W125°
E175°
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HIWC
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HURC
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AB15
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TATC
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AB13
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AC66
AB21
AV12
AB07
OKFG
AB01
AB06
AC42
AV15
AB02
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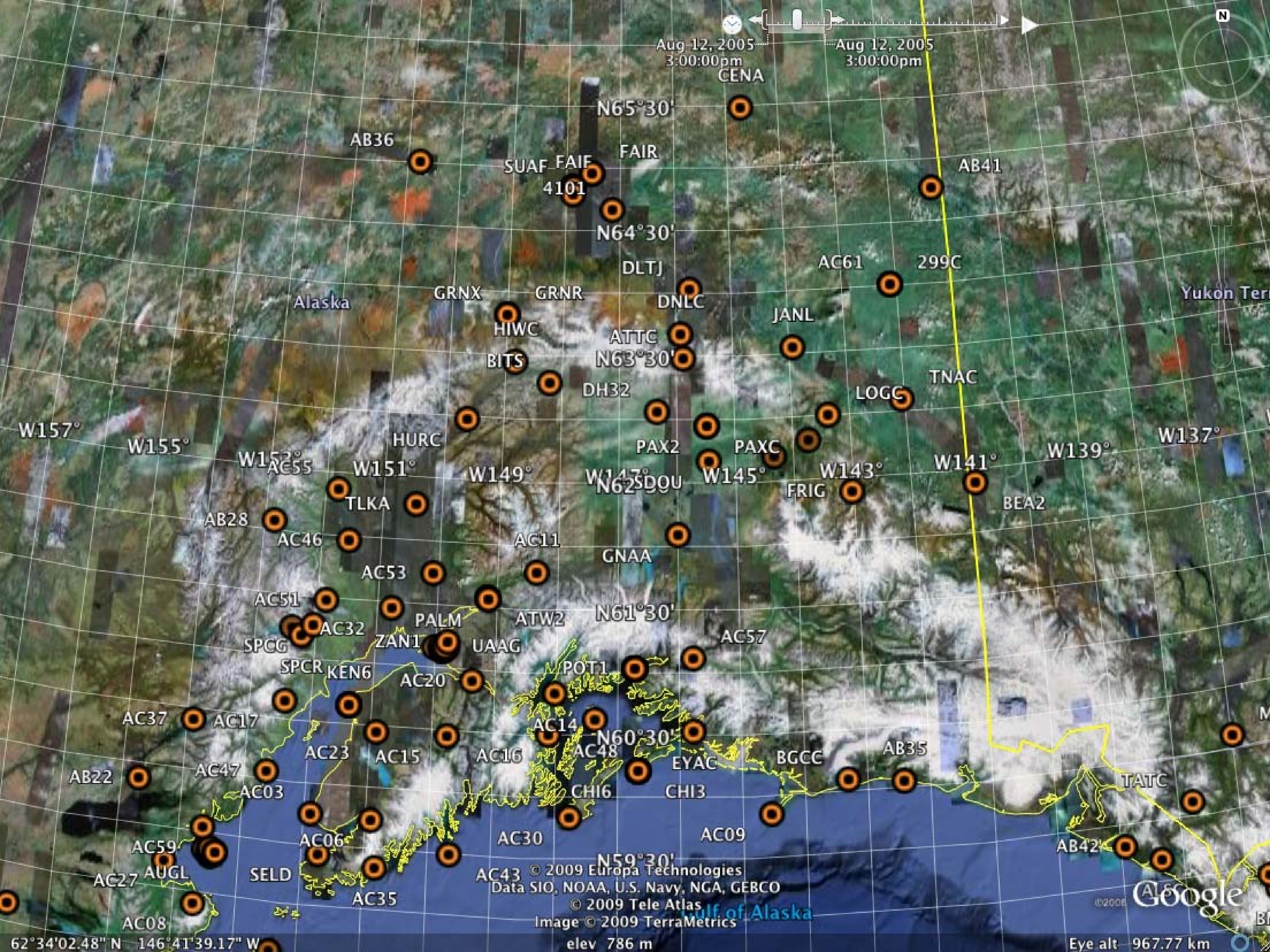
©2008 Google
61°45'52.88" N 156°55'42.33" W
elev 451 m
Eye alt 2731.53 km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Aug 12, 2005 3:00:00pm
CENA
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GRNR
DNLC
Yukon Terr
JANL
HIWC
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AUGL
SELD
AC43
N59°30'
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AC08
Gulf of Alaska
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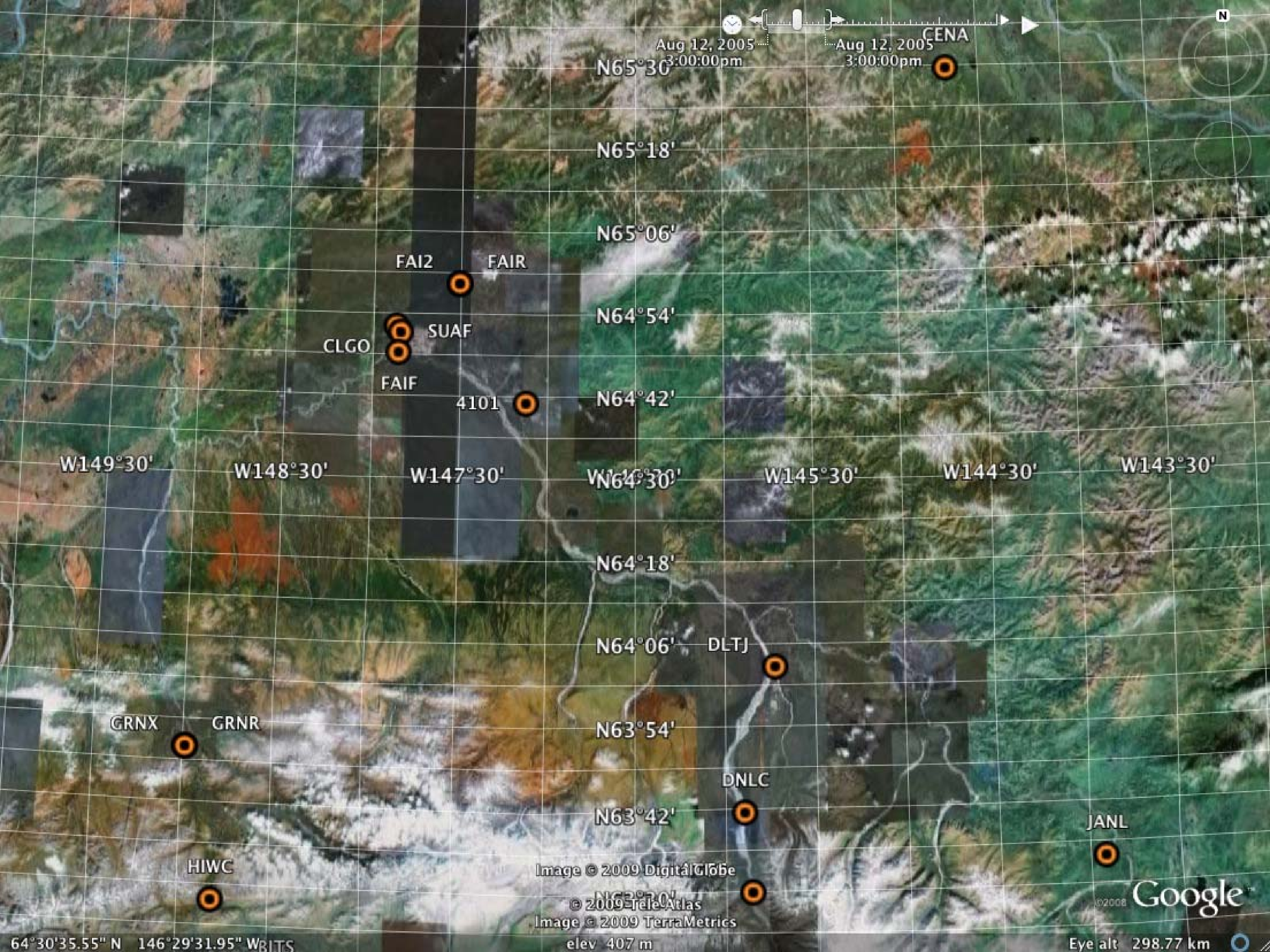
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2009 Tele Atlas
Image © 2009 TerraMetrics
Google
62°34'02.48" N 146°41'39.17" W
elev 786 m
Eye alt 967.77 km



Aug 12, 2005
3:00:00pm
Aug 12, 2005
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CENA
N65°30'
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FAI2
FAIR
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CLGO
FAIF
4101
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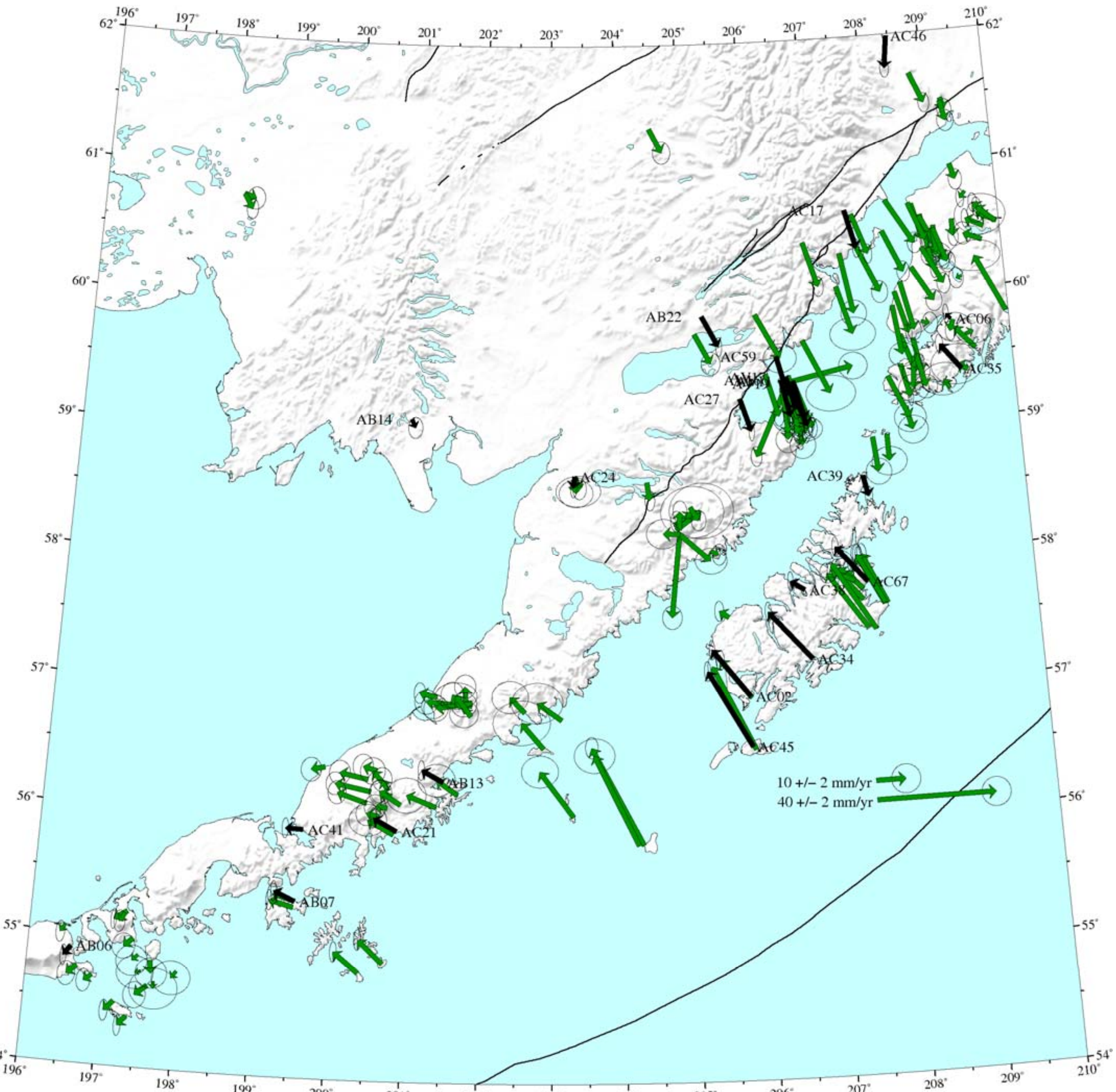
W149°30'
W148°30'
W147°30'
N64°30'
W145°30'
W144°30'
W143°30'
N64°18'
N64°06'
DLTJ
GRNX
GRNR
N63°54'
DNLC
N63°42'
JANL
HIWC
Image © 2009 DigitalGlobe
© 2009 Tele Atlas
Image © 2009 TerraMetrics
Google
64°30'35.55" N 146°29'31.95" W
elev 407 m
Eye alt 298.77 km



AC46
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10 +/– 2 mm/yr
40 +/– 2 mm/yr
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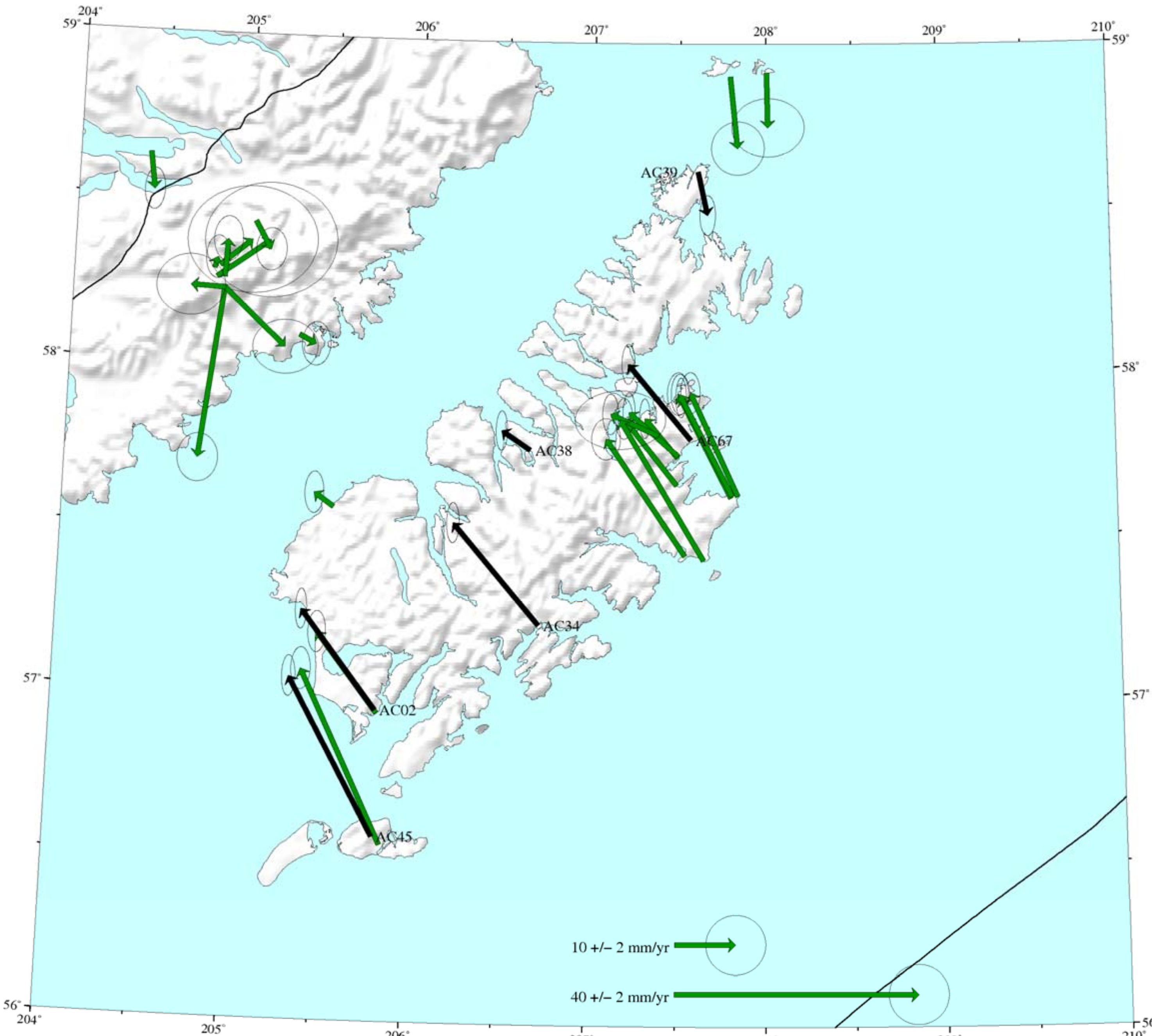

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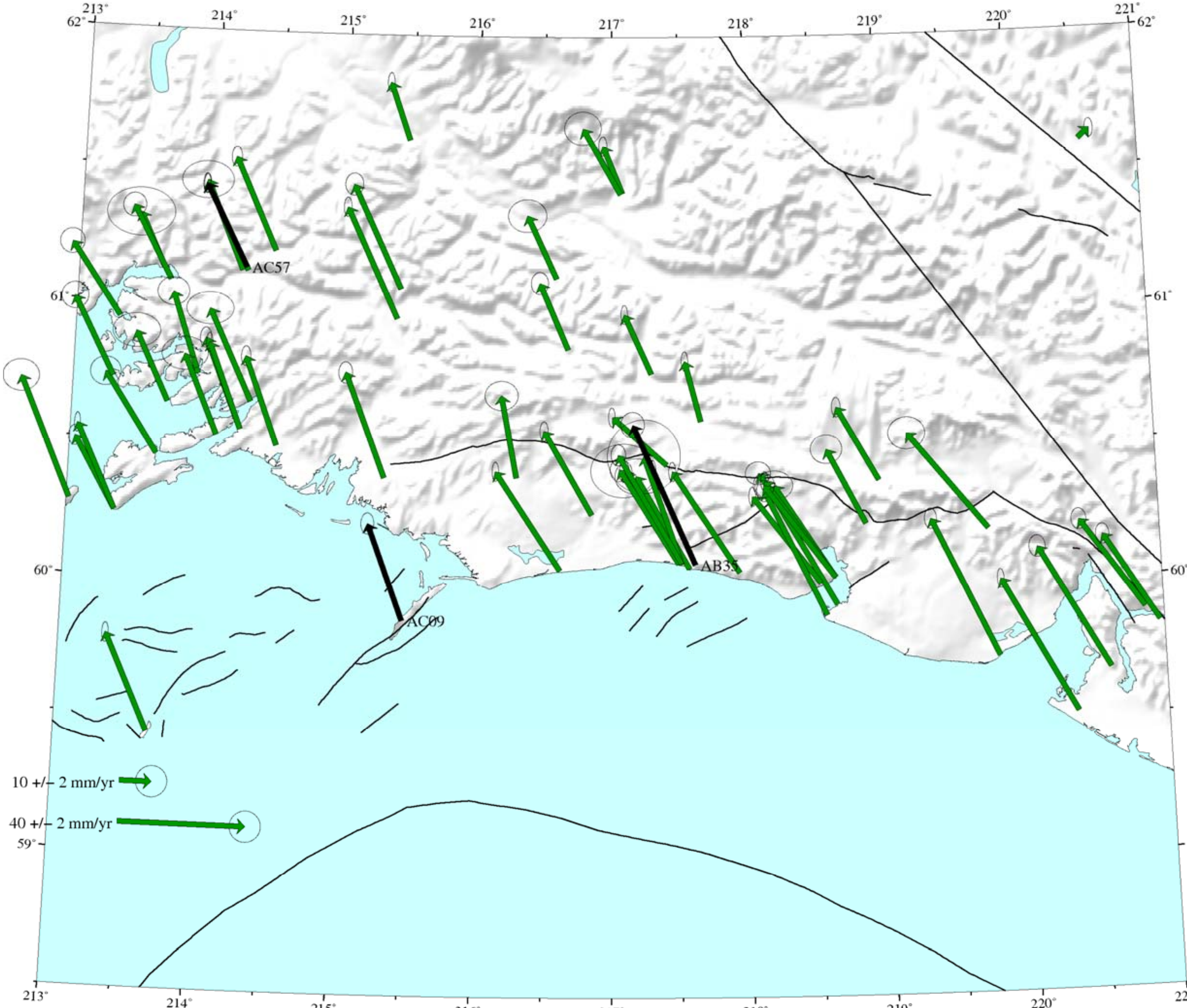
10 +/− 2 mm/yr
40 +/− 2 mm/yr



213°
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AC57
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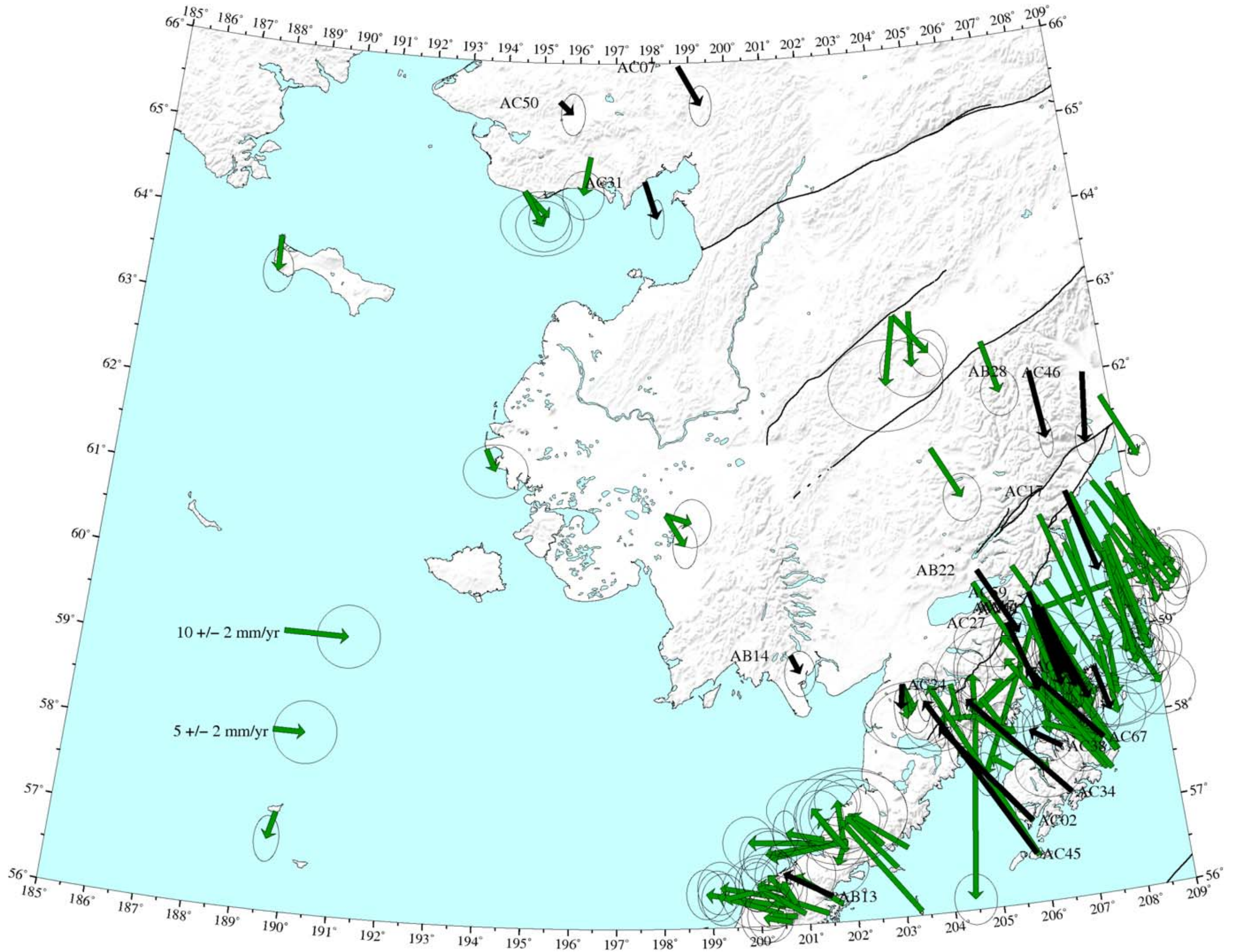
AB35
10 +/- 2 mm/yr
40 +/- 2 mm/yr


AC07
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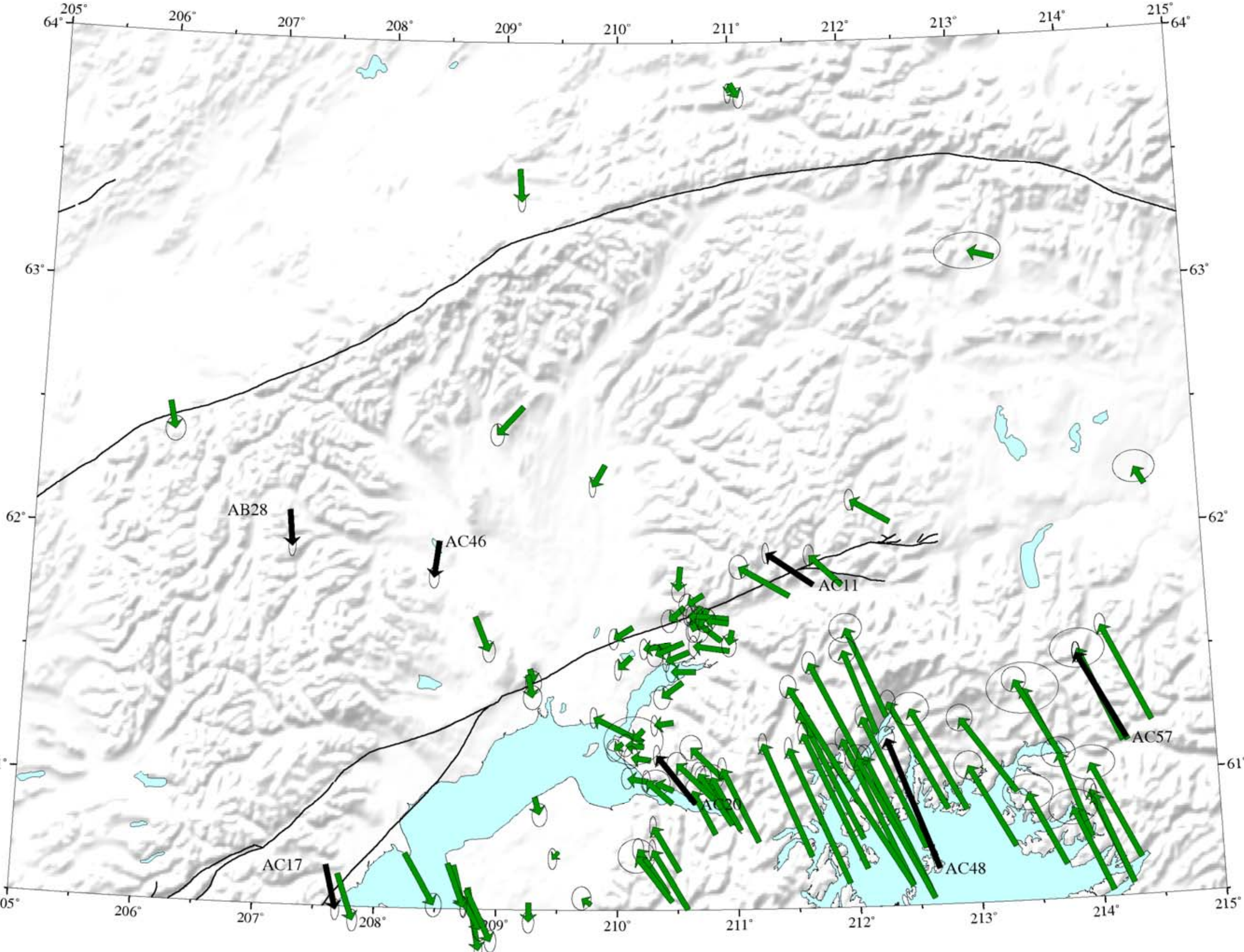
AC02
AC45
AB13
10 +/– 2 mm/yr
5 +/– 2 mm/yr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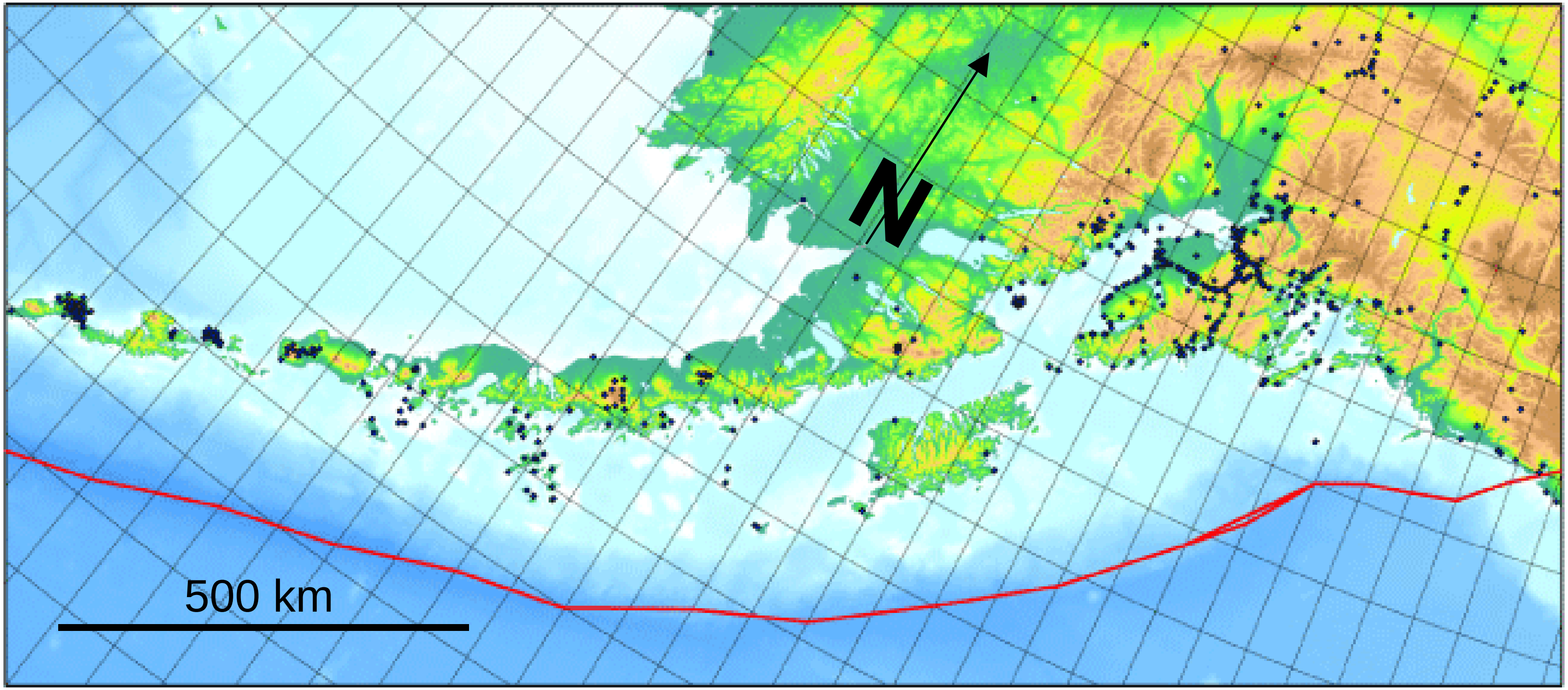
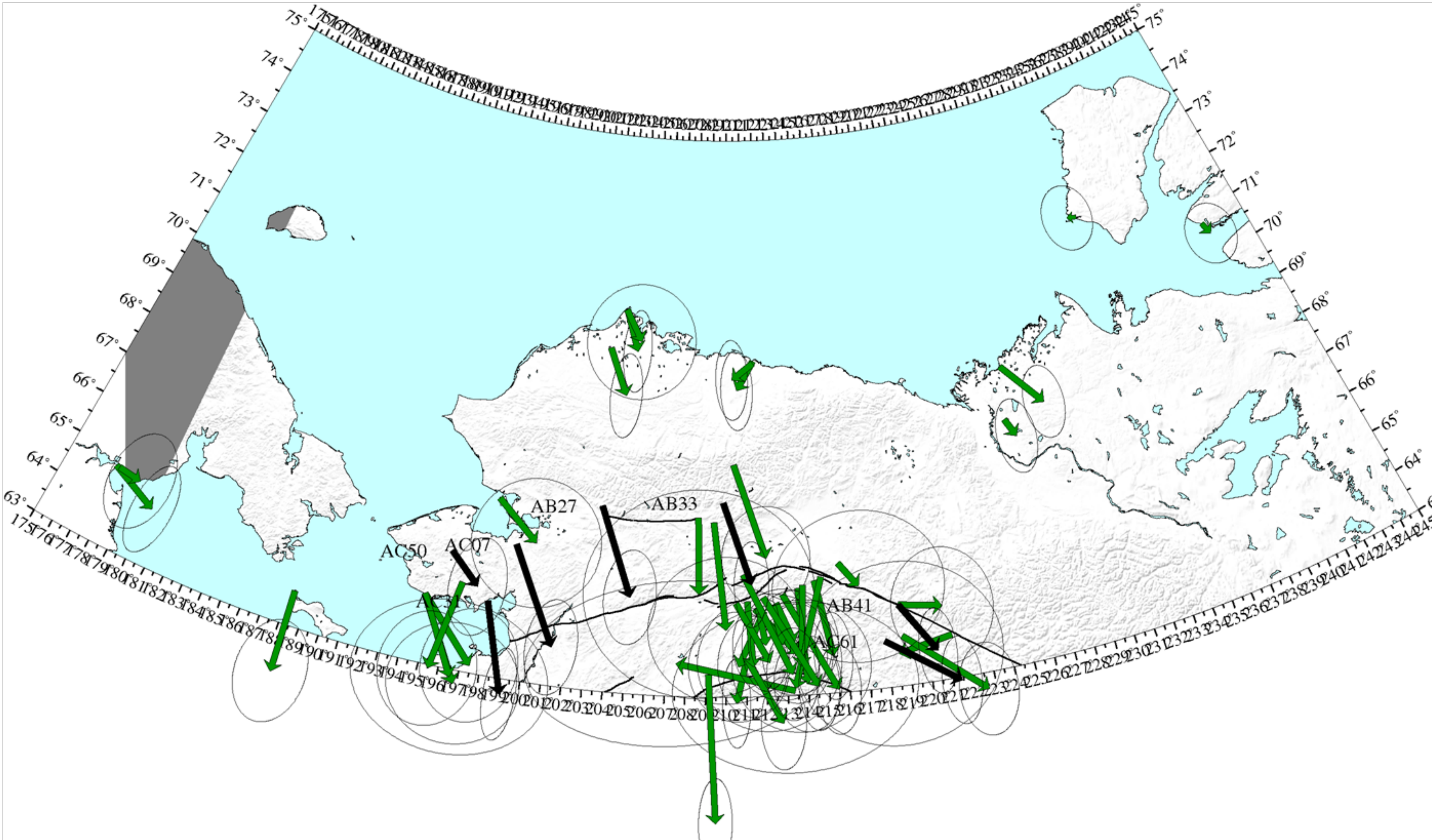
Tectonic and Earthquake Effects in Southern Alaska




AB27
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