Deciphering tectonic, isostatic, oceanic, and anthropogenic signals in combined GPS, absolute gravity, InSAR, and tide gauge data in the northern Cascadia subduction zone

Stephane Mazzotti, Tony Lambert,
Joe Henton, Herb Dragert, Mike Schmidt

Geological Survey of Canada (NRCan)
Geodetic Survey Division (NRCan)
University of Victoria

Outline

Northern Cascadia tectonics - Hz and Vt GPS

GPS / absolute gravity integration – Subduction dynamics

GPS / absolute gravity / tide gauges – Oceanic signals

(InSAR – Local anthropogenic processes)

Northern Cascadia Subduction Zone

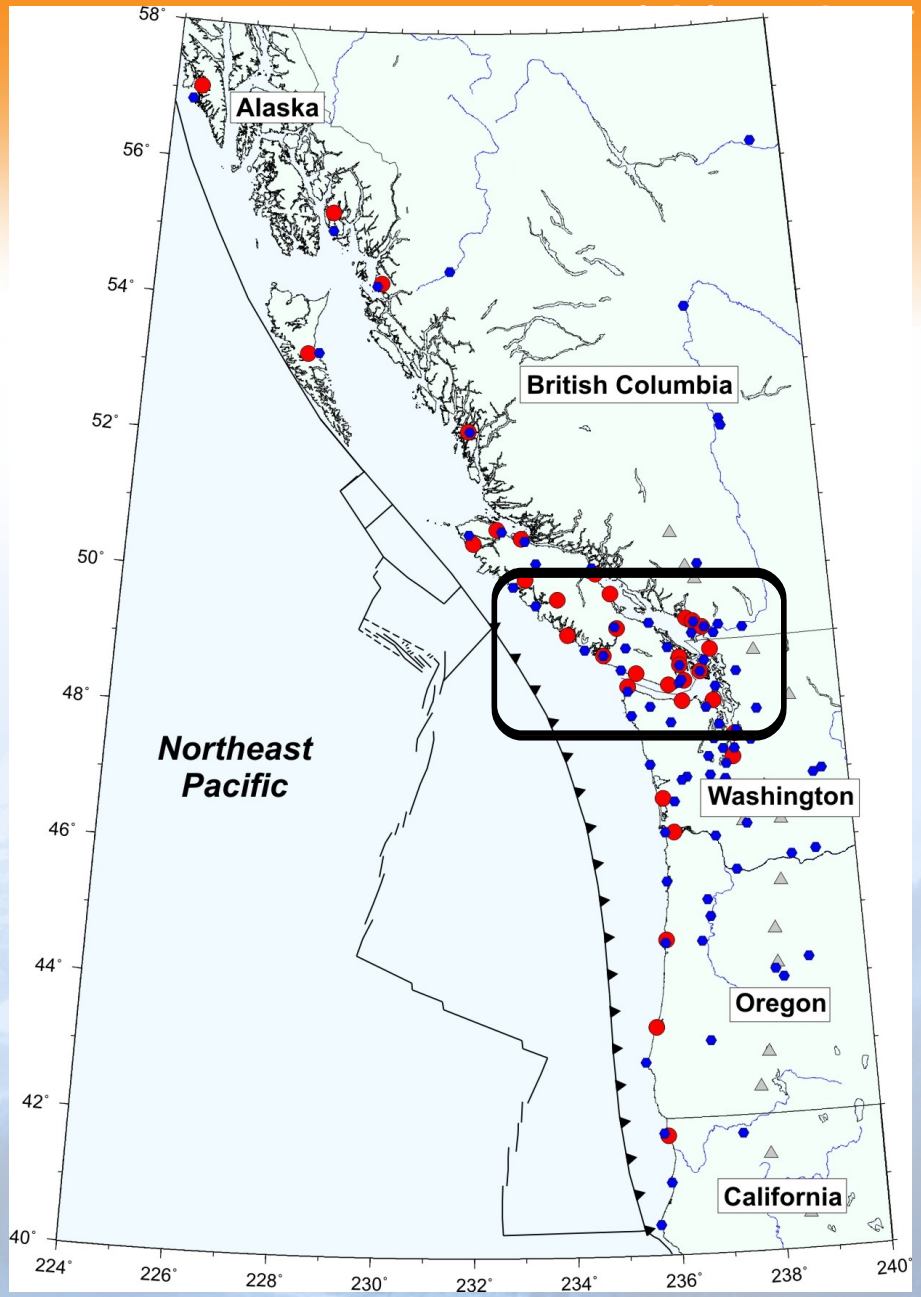
SW British Columbia – NW Washington State

18 tide gauge stations
110 – 13 yrs

30+ permanent GPS stations
15 – 2 yrs

5 absolute gravity stations
16 – 11 yrs

4 “collocated” tide gauge + GPS + abs. G



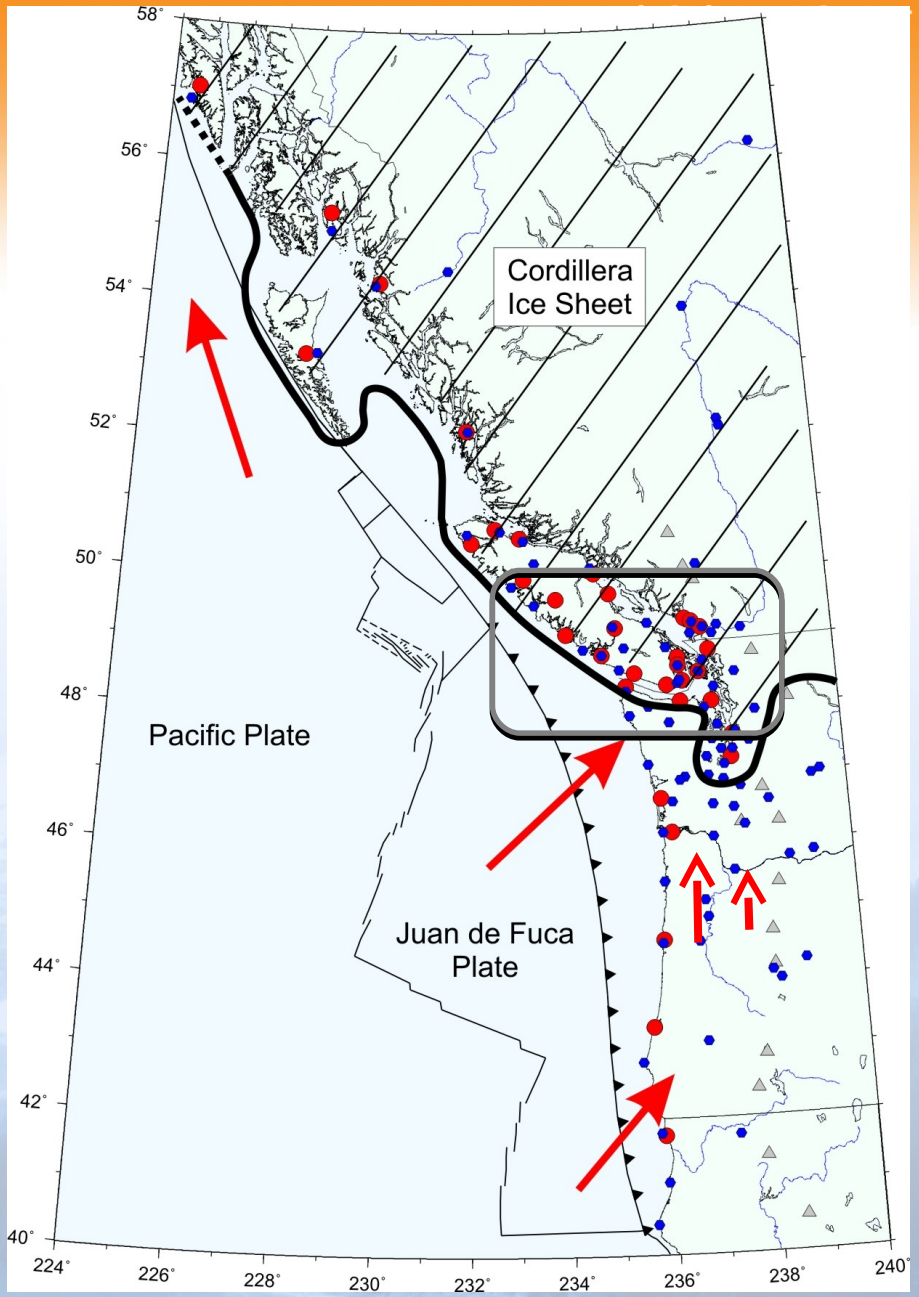
Northern Cascadia Subduction Zone

SW British Columbia – NW Washington State

Active plate boundary – Juan de Fuca plate subduction 35-45 mm/yr

Ongoing forearc tectonics – forearc sliver migration 5-10 mm/yr

Rebound from Cordillera Ice Sheet during last glaciation

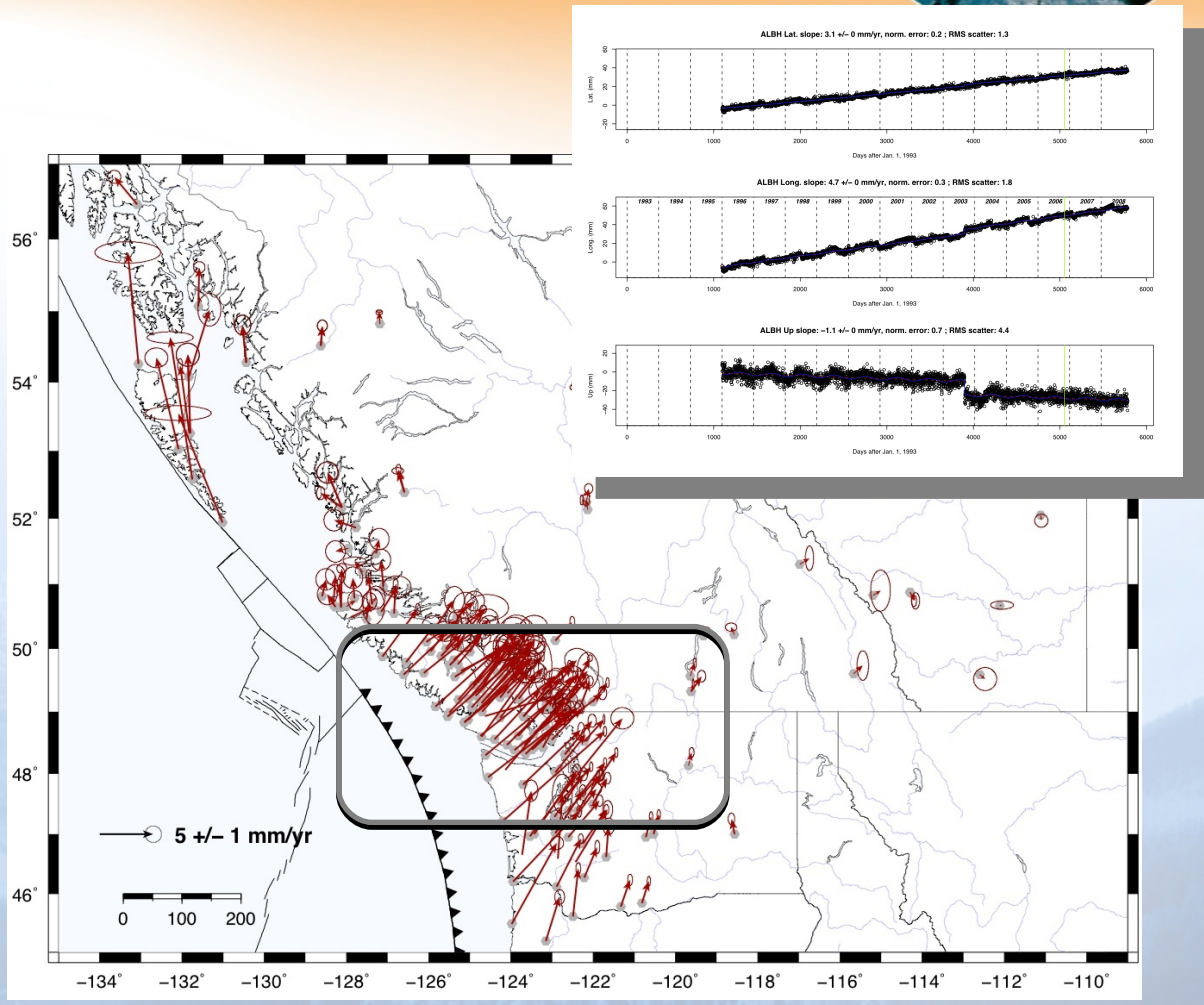


Horizontal GPS – Subduction Loading

Permanent and campaign GPS sites

Main signal: Interseismic loading of the forearc from the locked subduction thrust

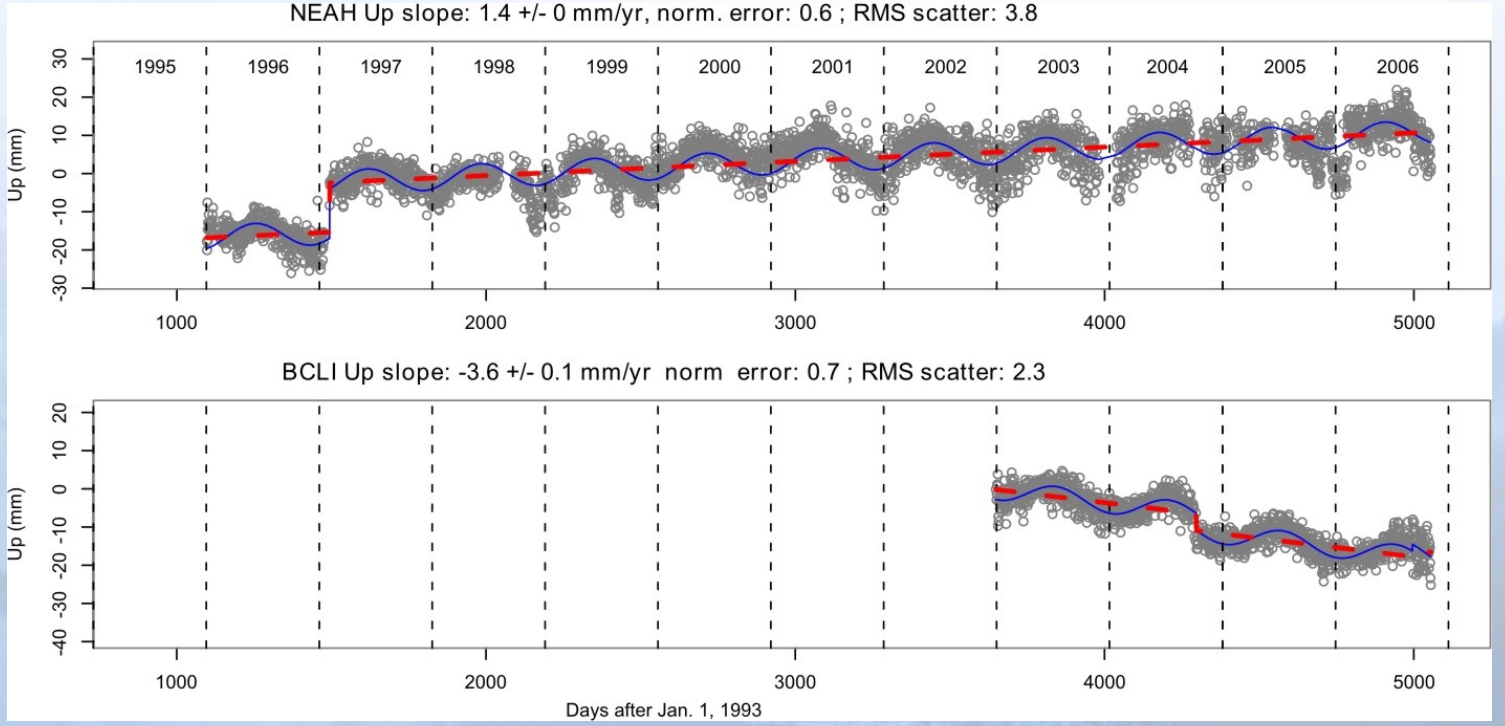
(strain accumulation towards next M~9 earthquake)



Vertical Land Motion

Vertical GPS time series

- 16 to 4 years
- Daily scatter (RMS) 2-5 mm
- Offsets, annual signals
- Trends resolved at 0.5-1.0 mm/yr level after 4-5 years



Vertical Land Motion

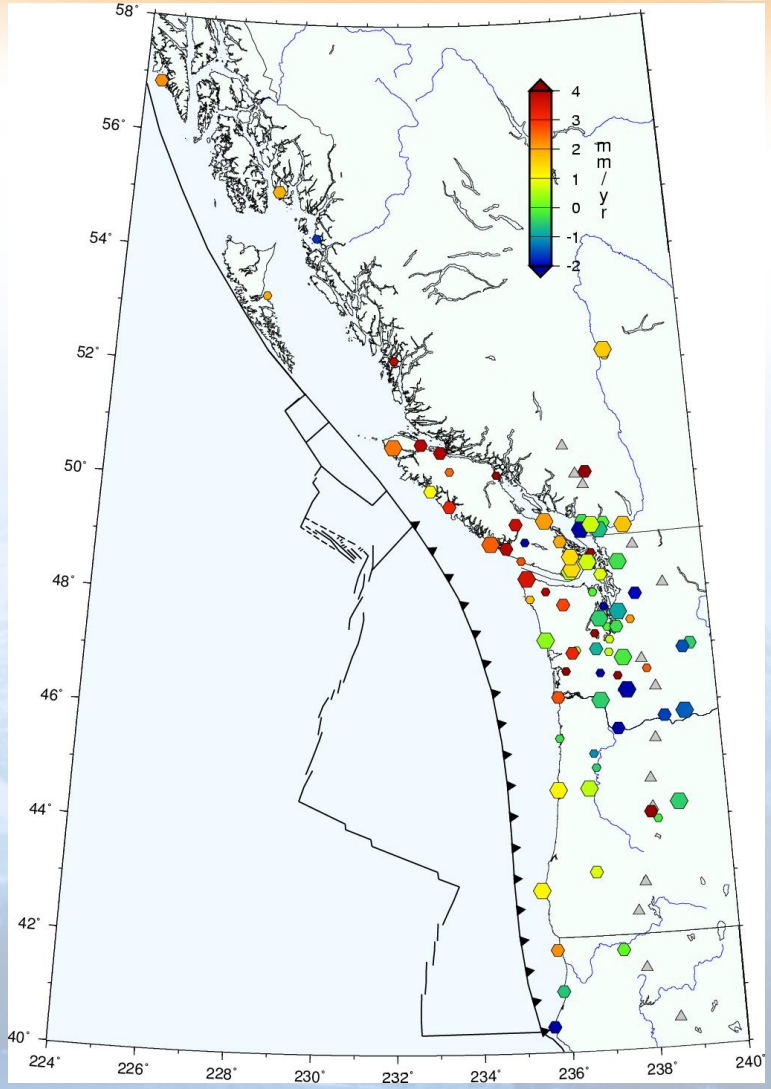
GPS vertical velocities in global “absolute” reference frame (ITRF2000)

First order-signal:

- 2 – 4 mm/yr uplift on West Coast
- ~0 mm/yr inner forearc

Lots of second-order complexity

- Along-strike variability
- Local subsidence



Vertical Land Motion

GPS vertical velocities in global “absolute” reference frame (ITRF2000)

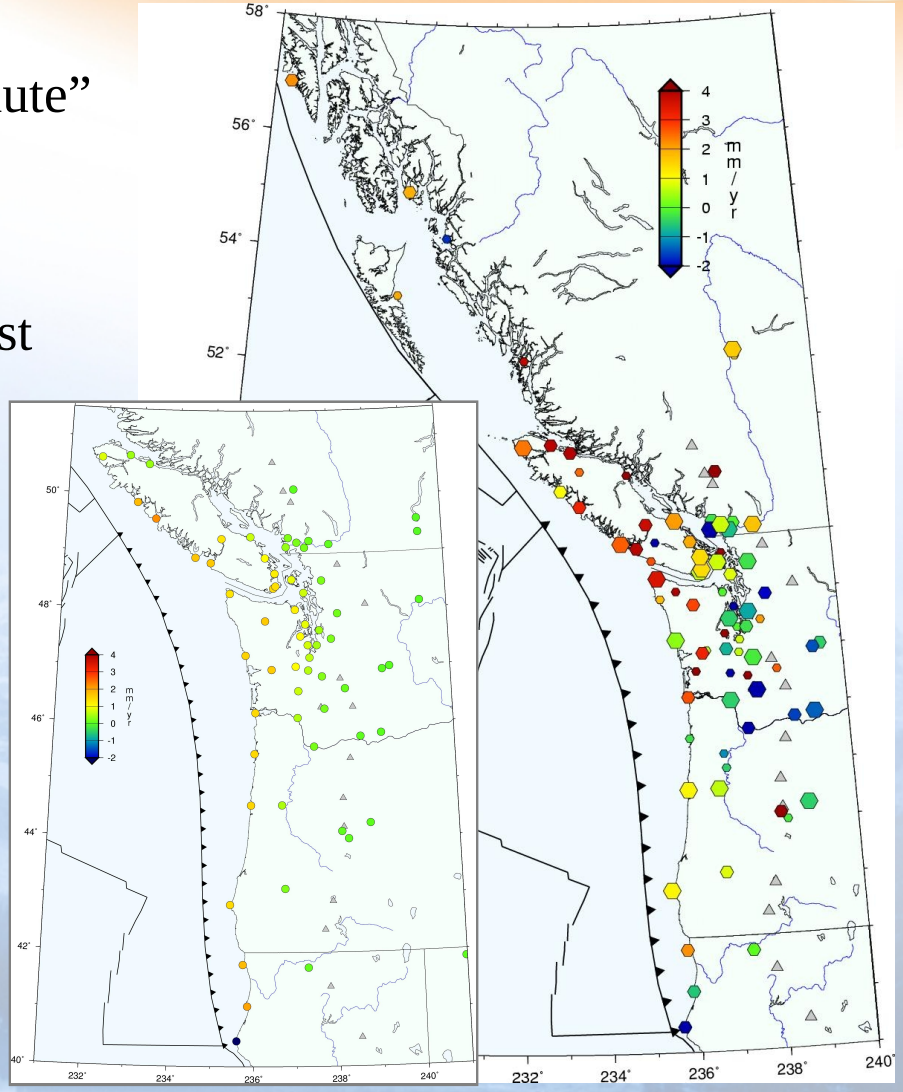
First order-signal:

- 2 – 4 mm/yr uplift on West Coast
- ~0 mm/yr inner forearc

Lots of second-order complexity

- Along-strike variability
- Local subsidence

Subduction loading only accounts for 50-75% of the vertical GPS signal



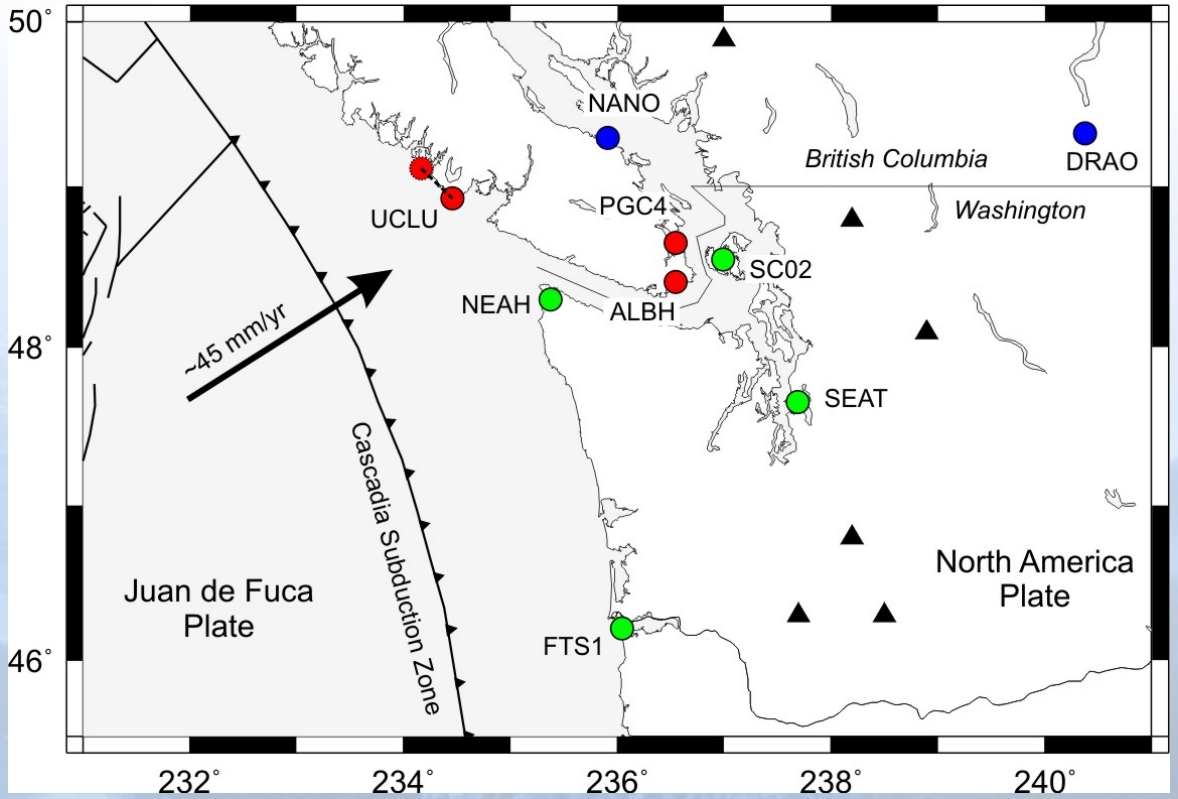
GPS / Absolute Gravity Integration

Collocated or nearby tide gauge, GPS and absolute gravity sites

3 TG – GPS – AG

2 GPS – AG

4 GPS – TG



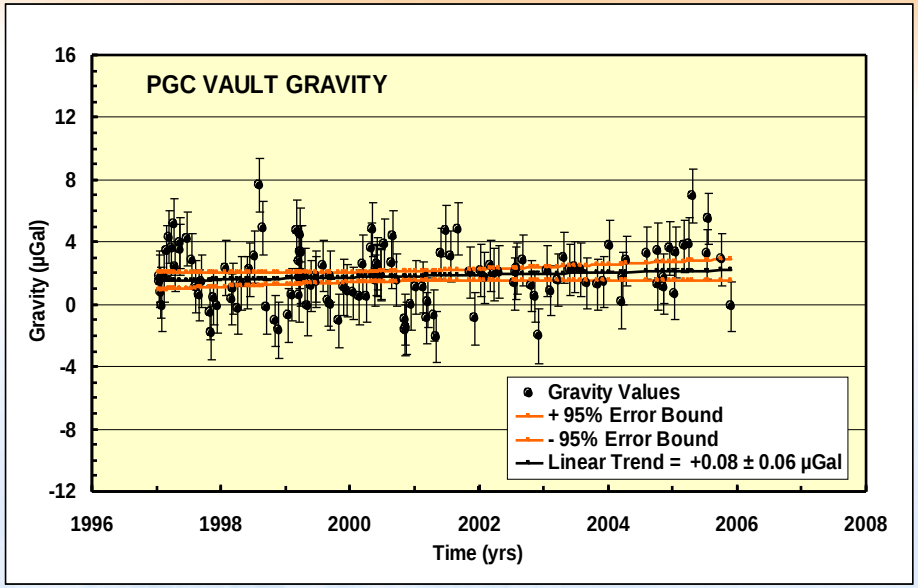
GPS / Absolute Gravity Integration

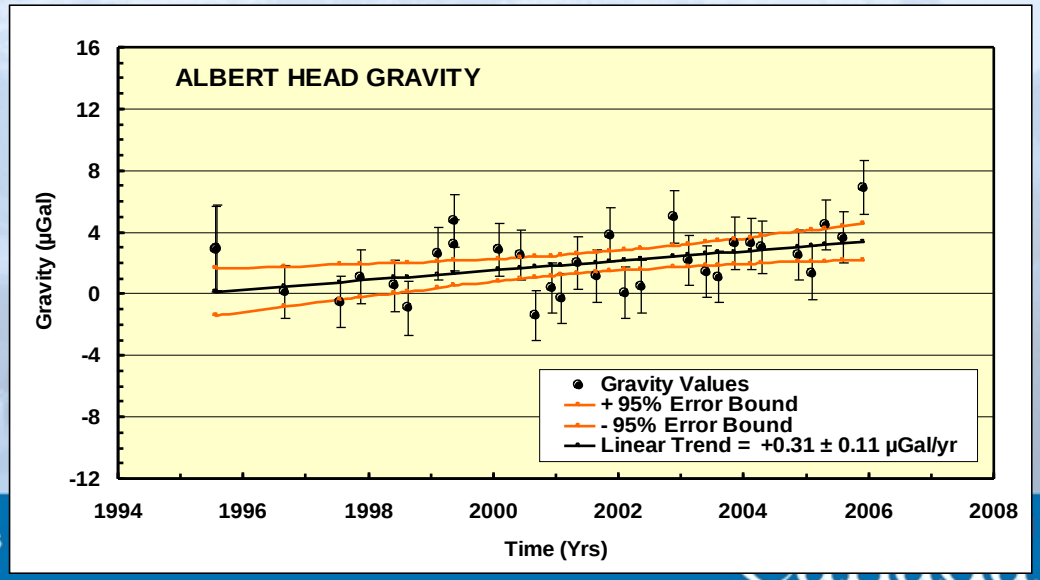
Absolute Gravity measurements at five sites since 1995/1997

Typical series: several (min. four) 24-hr surveys per year

Corrections for:
- Solid Earth & ocean tide loading
- Atmospheric pressure
- Soil moisture (probe data + leaky bucket model)
- Annual & inter-annual signals

Resolution of ± 0.1-0.2 µGal/yr
(equiv.) ± 0.5-1.0 mm/yr

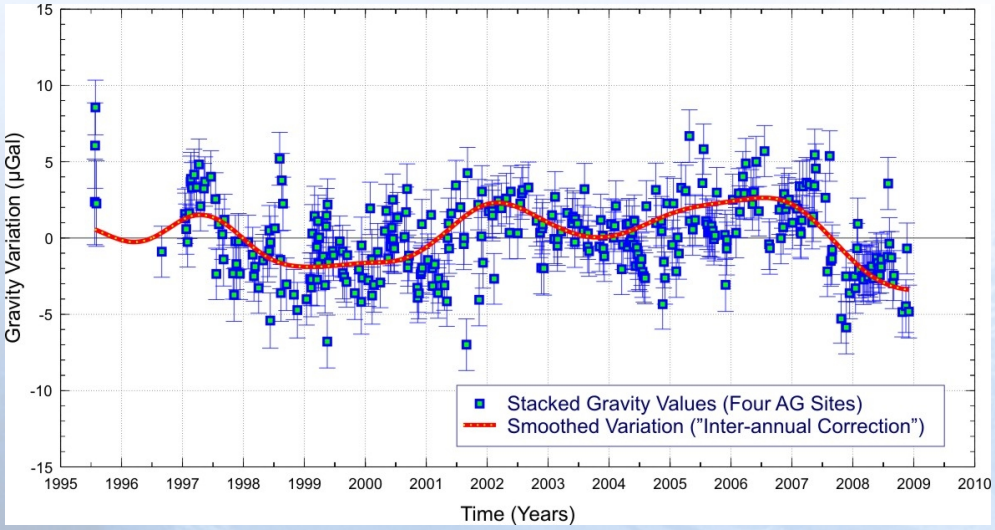




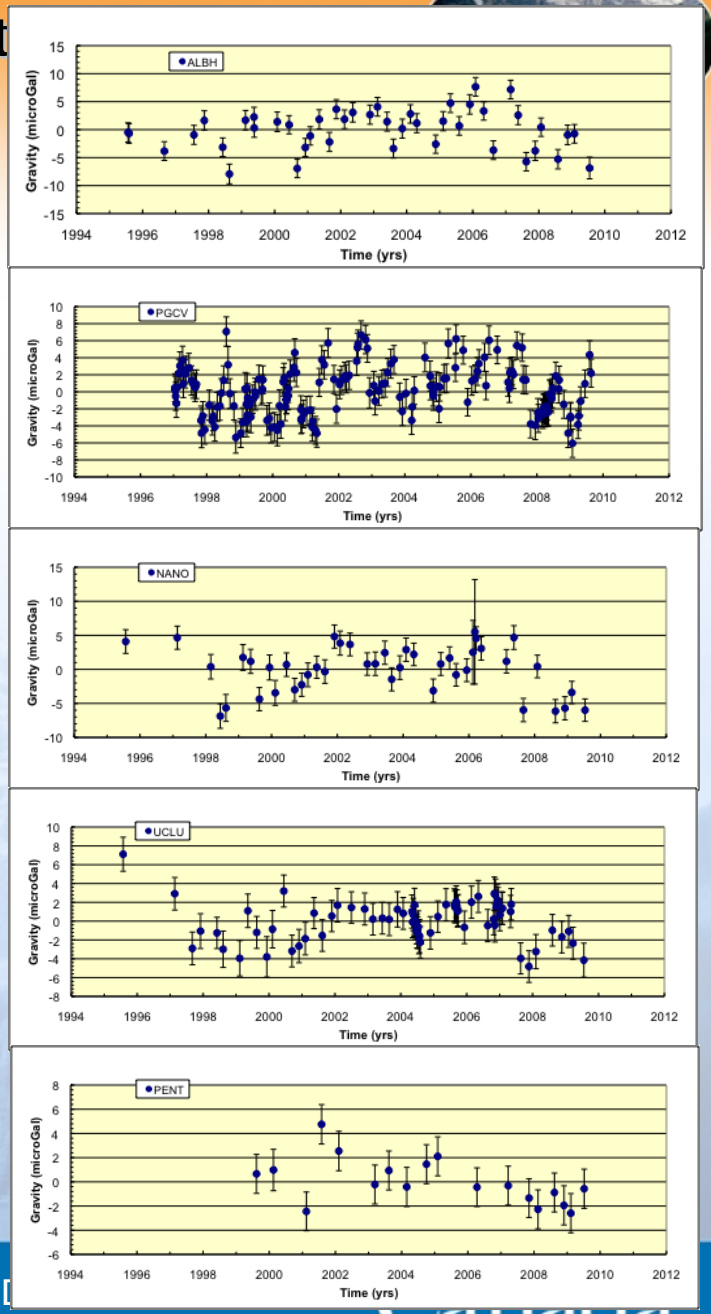
GPS / Absolute Gravity Int

Significant inter-annual signal
2-5 μGal over 3-5 years

(can affects trends)



Similar to inter-annual in mid-continent data
(cf. poster)



GPS / Absolute Gravity Integration

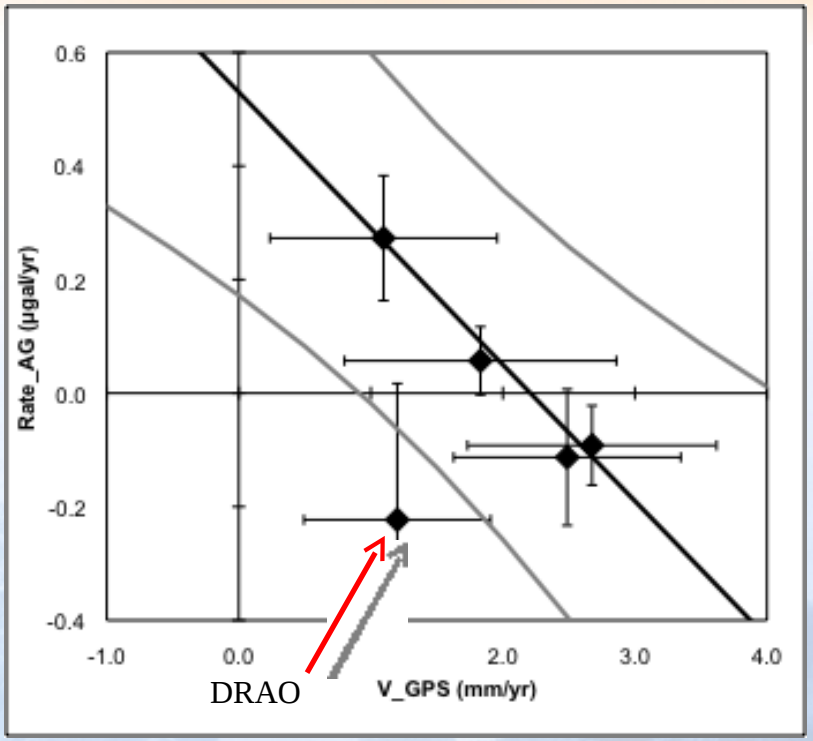
5 AG – GPS sites

4 sites in subduction zone forearc (95% confidence intervals, 3DF) :

- g/h ratio = -0.24 ± 0.13 μGal/mm

- offset = 0.53 ± 0.30 μGal/yr
  2.2 ± 1.3 mm/yr

1 site in Cordillera (back-arc) goes through 0 intercept



GPS / Absolute Gravity Integration

8 AG – GPS sites

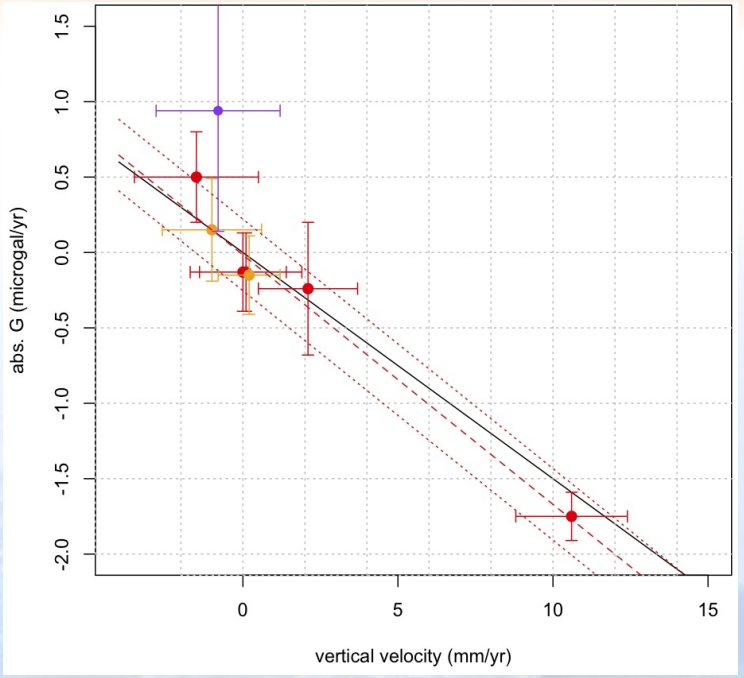
Mid-continent North America:

- g/h ratio = -0.16 ± 0.03 μGal/mm

- offset = 0.01 ± 0.8 μGal/yr

Slope consistent with postglacial rebound theoritical value (-0.15)

<u>No significant offset</u>



Cf. Poster

GPS / Absolute Gravity Integration

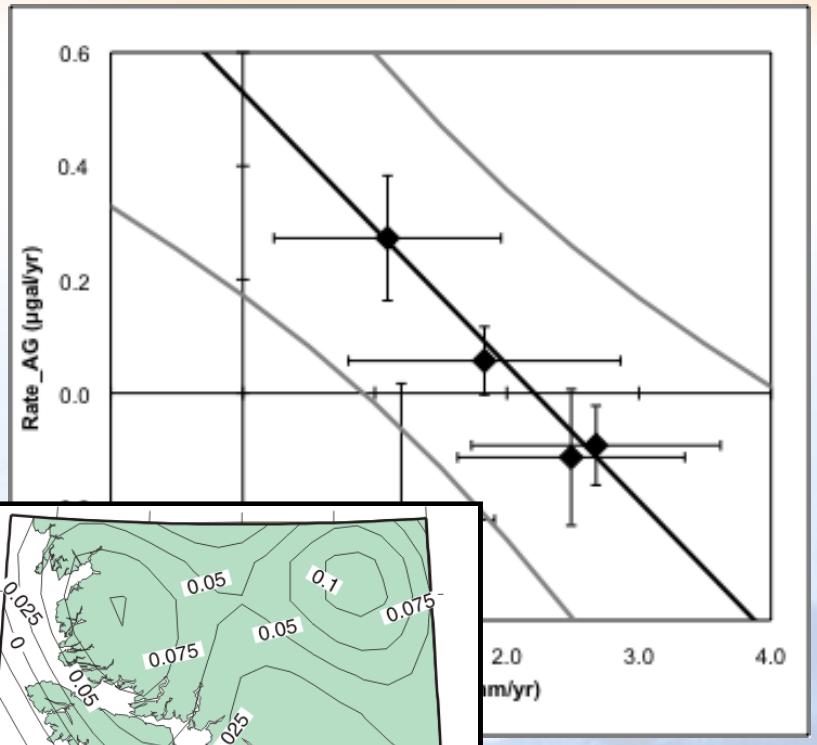
5 AG – GPS sites

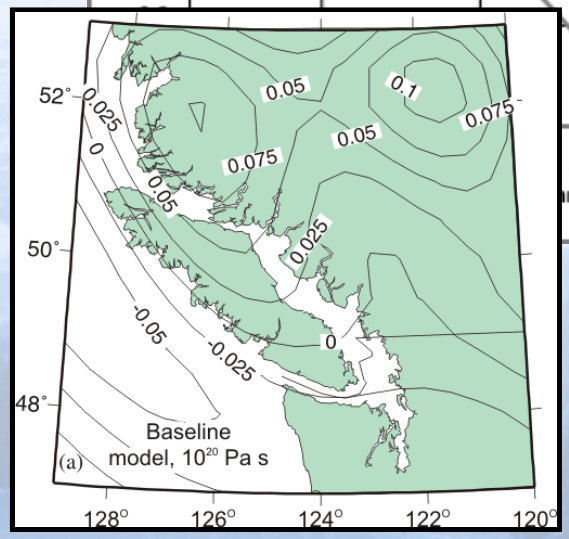
g/h ratio = -0.24 ± 0.13 μGal/mm

Consistent with subduction thrust theoretical value (-0.2 μGal/mm)

Consistent with no ongoing postglacial rebound due to low back-arc mantle viscosity (< 10^{20} Pa s)

>> Present-day PGR uplift rates less than 0.5 mm/yr





James et al., 2002

GPS / Absolute Gravity Integration

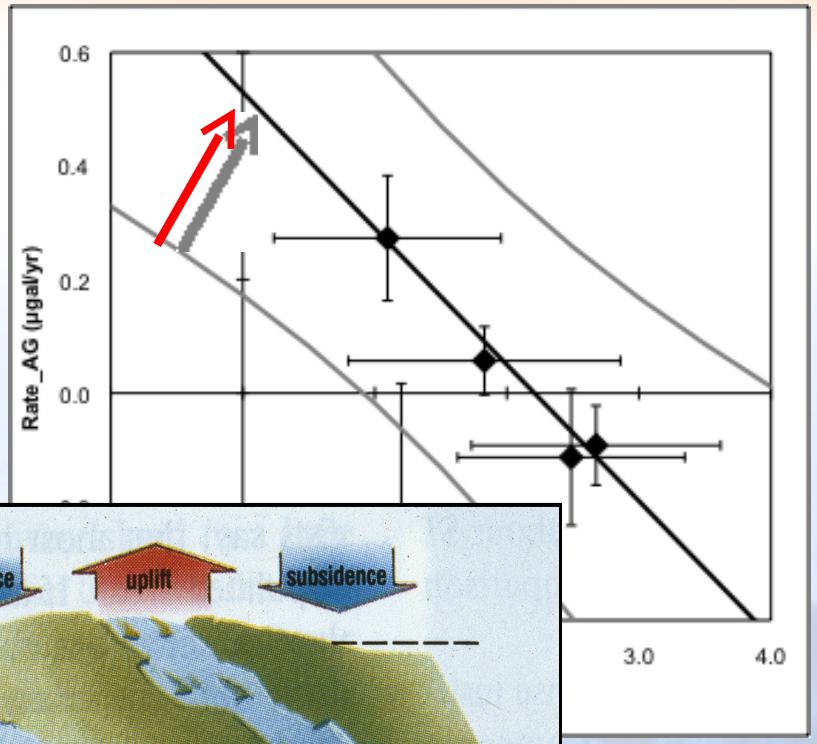
5 AG – GPS sites

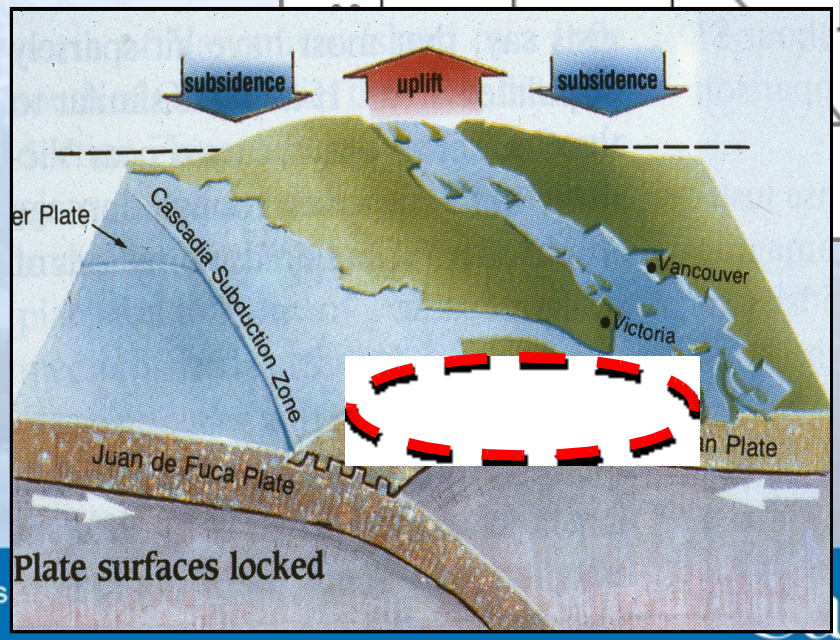
Offset = 0.53 ± 0.30 μGal/yr

Inelastic shortening of the forearc during interseismic period (e.g. closing of fracture void)

~0.2 μGal/yr

(shortening rate ~50 x 10^{-9} yr^{-1},
30 km thick crust, ρ=2.67 g/cm^3)



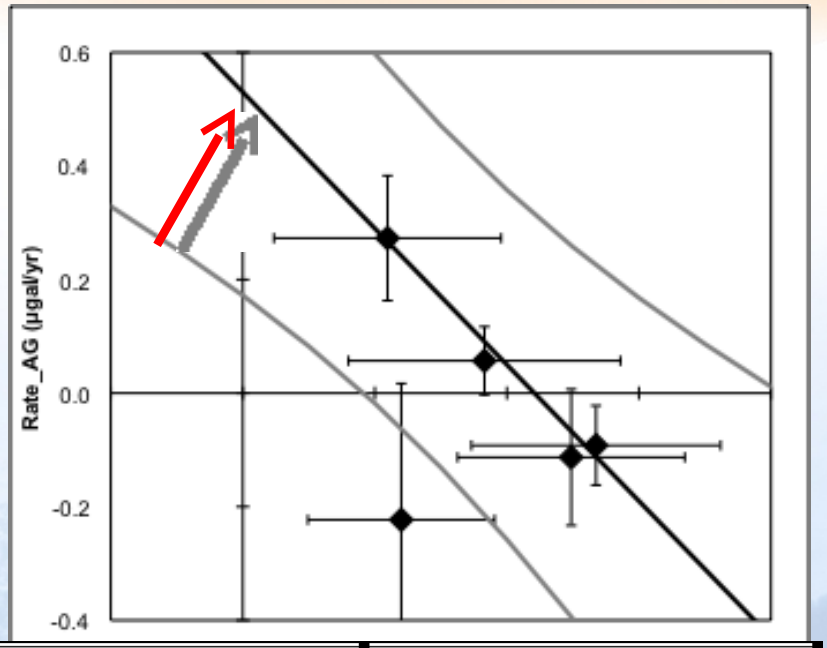


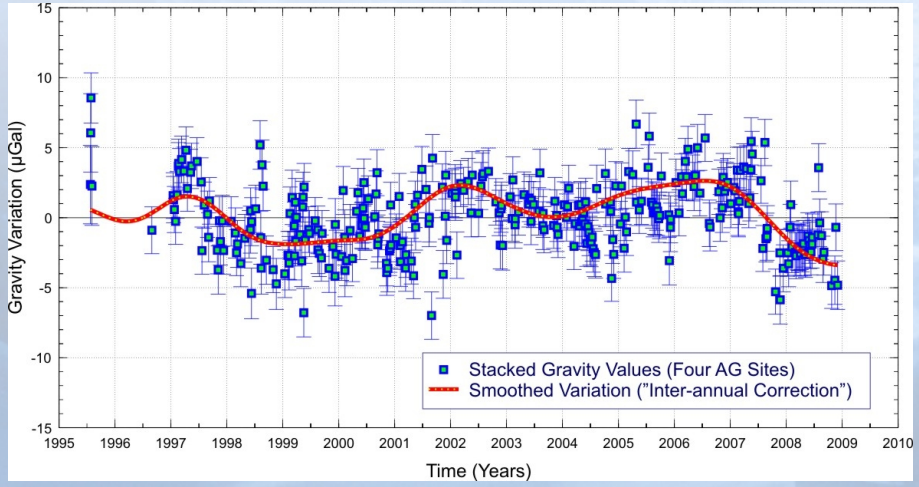
GPS / Absolute Gravity Integration

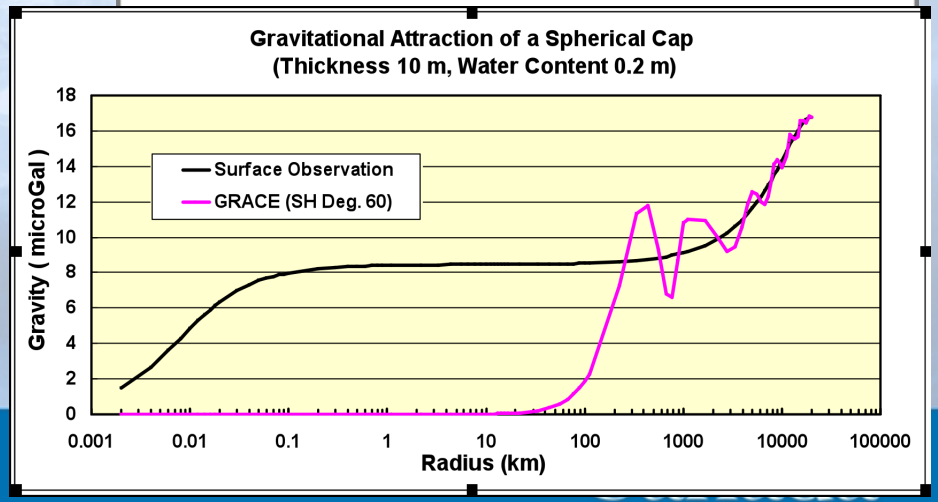
5 AG – GPS sites

Offset = 0.53 ± 0.30 μGal/yr

Increase of groundwater storage / moisture by ~10 mm/yr. Long-period large-scale inter-annual? (cf. poster)







GPS / Absolute Gravity Integration

5 AG – GPS sites

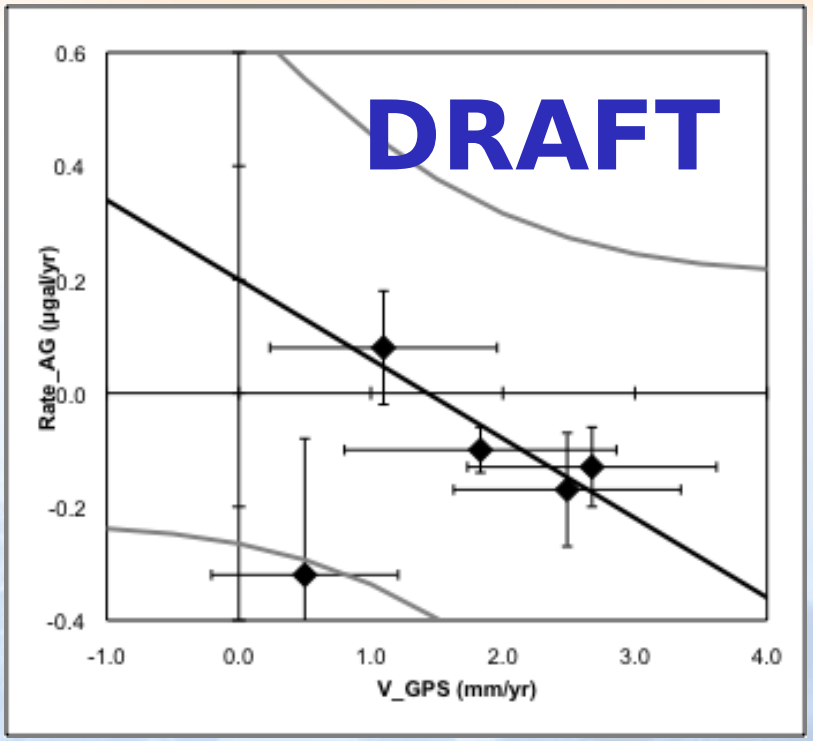
Preliminary update of abs. G and GPS rates (ITRF2005):

- g/h ratio = -0.14 ± 0.04 μGal/mm

  <u>not consistent with theory</u>

- offset = 0.20 ± 0.39 μGal/yr
  1.4 ± 2.8 mm/yr

  not significant – but still

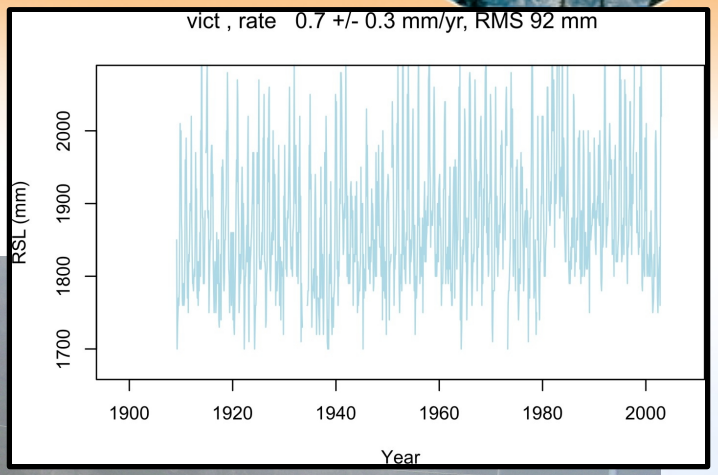


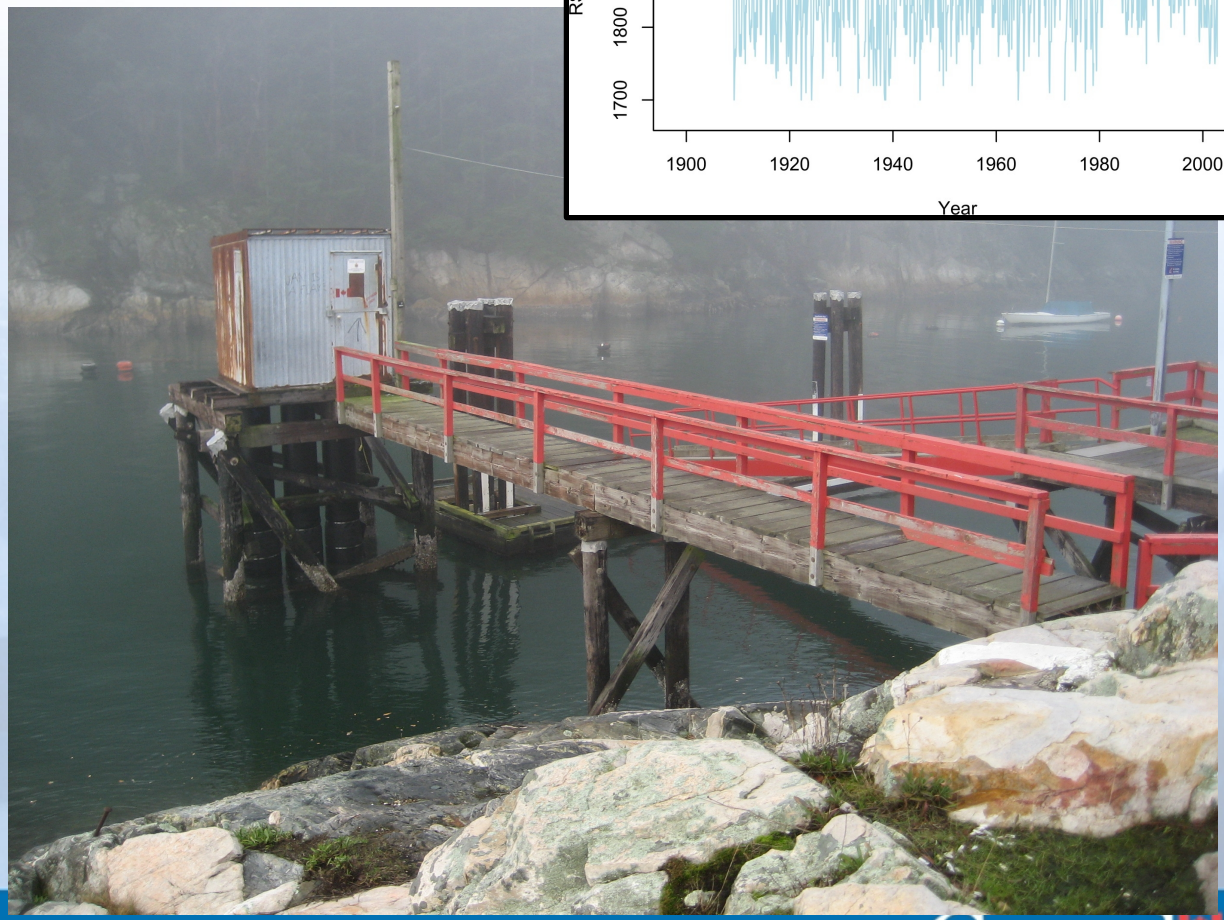
GPS / AG / Tide Gauge Integration

Integration with tide gauge data

- A proxy for vertical land motion

- An indicator of past and future regional sea-level changes





GPS / AG / Tide Gauge Integration

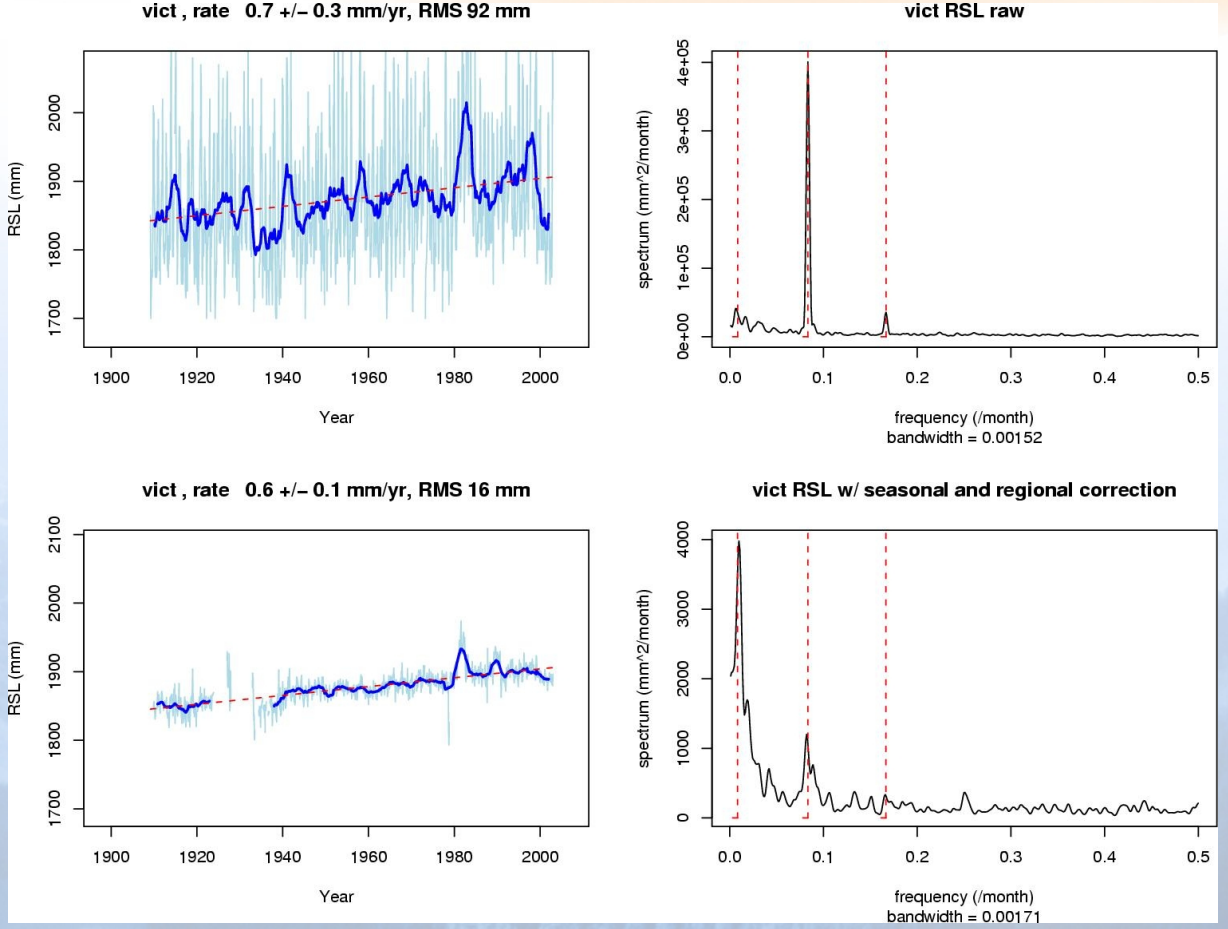
TG data processing:

- Monthly MSL values
- Atm. Loading and seasonal correction
- Regional common-mode correction

=> 70-80% variance reduction

=> Stable rate for short series

Colored-noise standard errors based on frequency spectrum

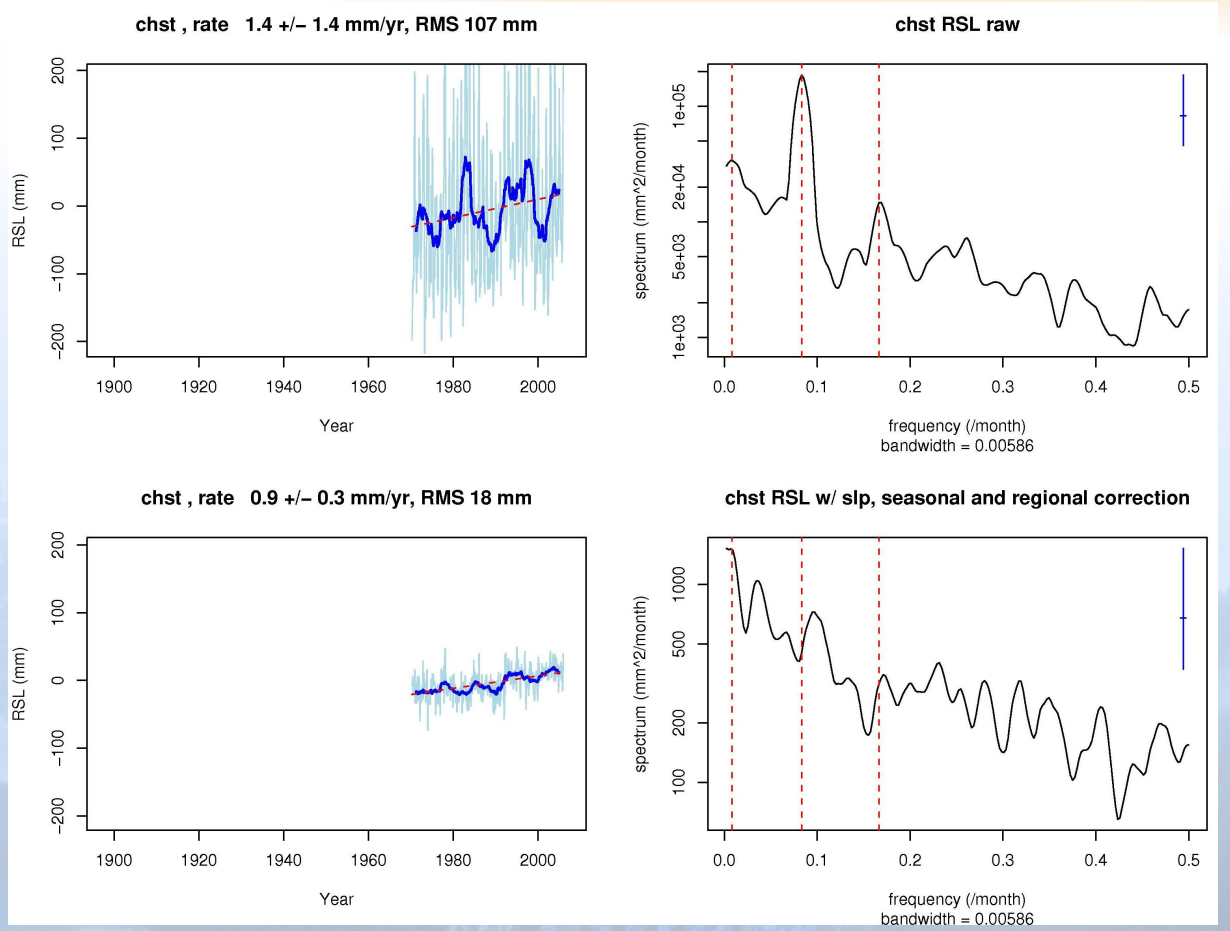


GPS / AG / Tide Gauge Integration

- Regional common-mode correction

Specially important for short (<30 yr) series with strong inter-annual signals (e.g. El Niño)

Impact on trend of up to 0.5-1.0 mm/yr



GPS / AG / Tide Gauge Integration

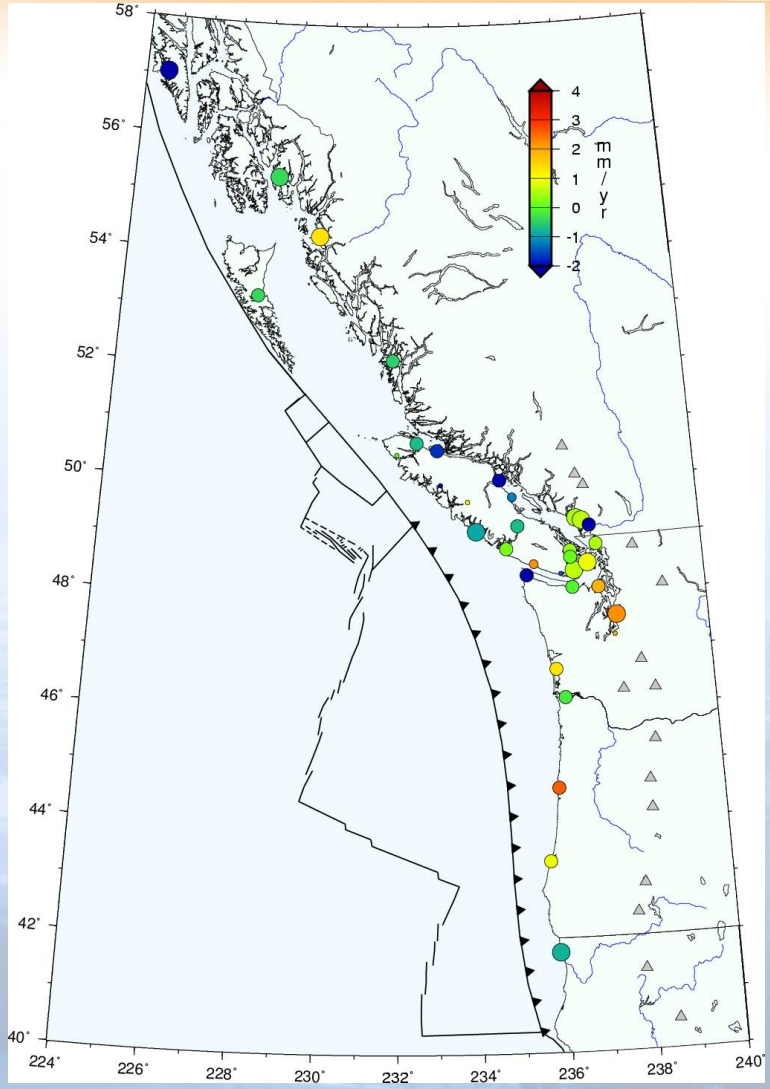
20th century RSL rates

MSL data since 1900 (longest) – 1975 (shortest)

West Coast (Tofino)
0 to -2 mm/yr RSL fall

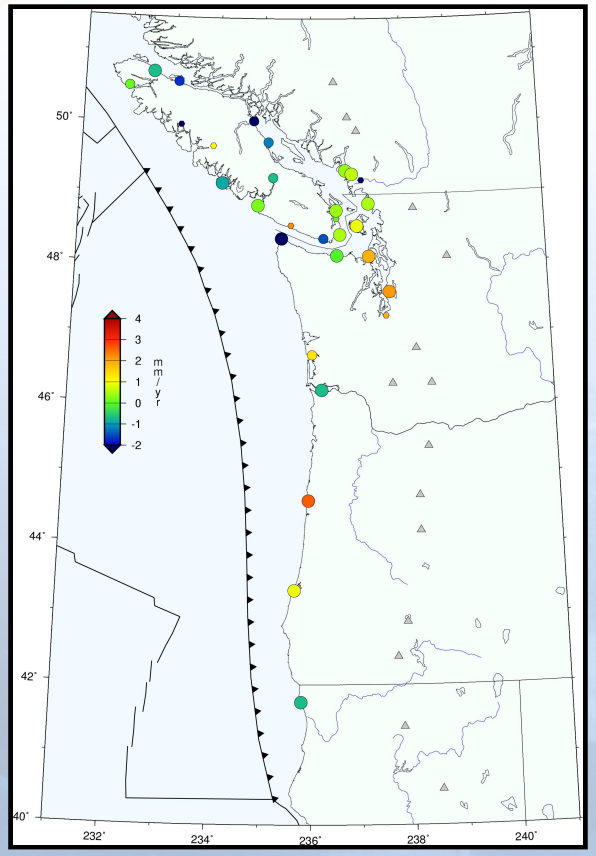
Strait of Georgia (Victoria)
0 to 0.5 mm/yr RSL rise

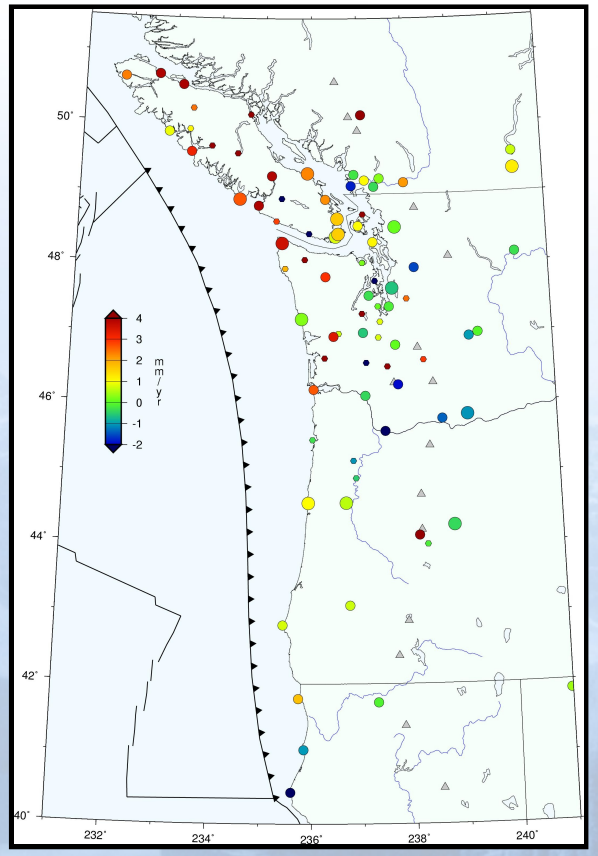
Puget Sound (Seattle)
2 mm/yr rise

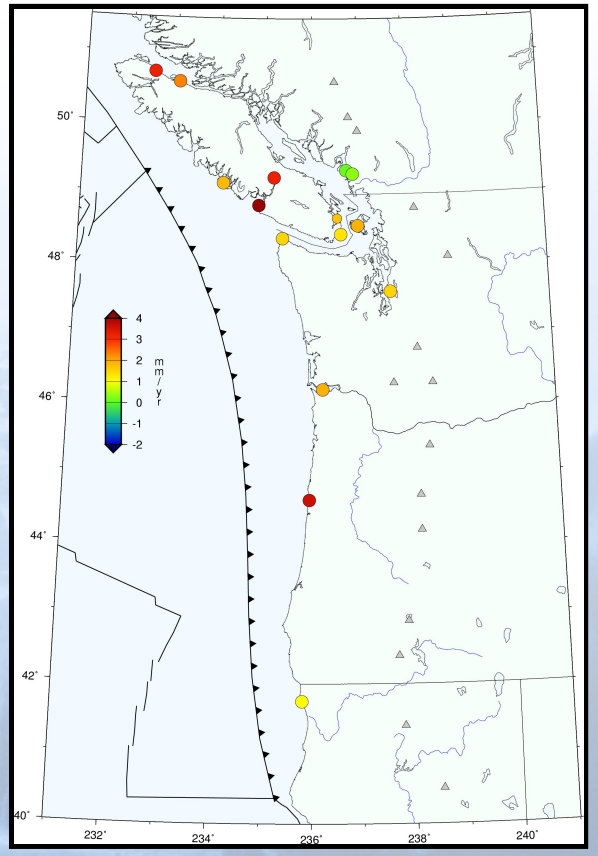


GPS / AG / Tide Gauge Integration

Tide gauge RSL - GPS V_{UP} = Regional sea-level







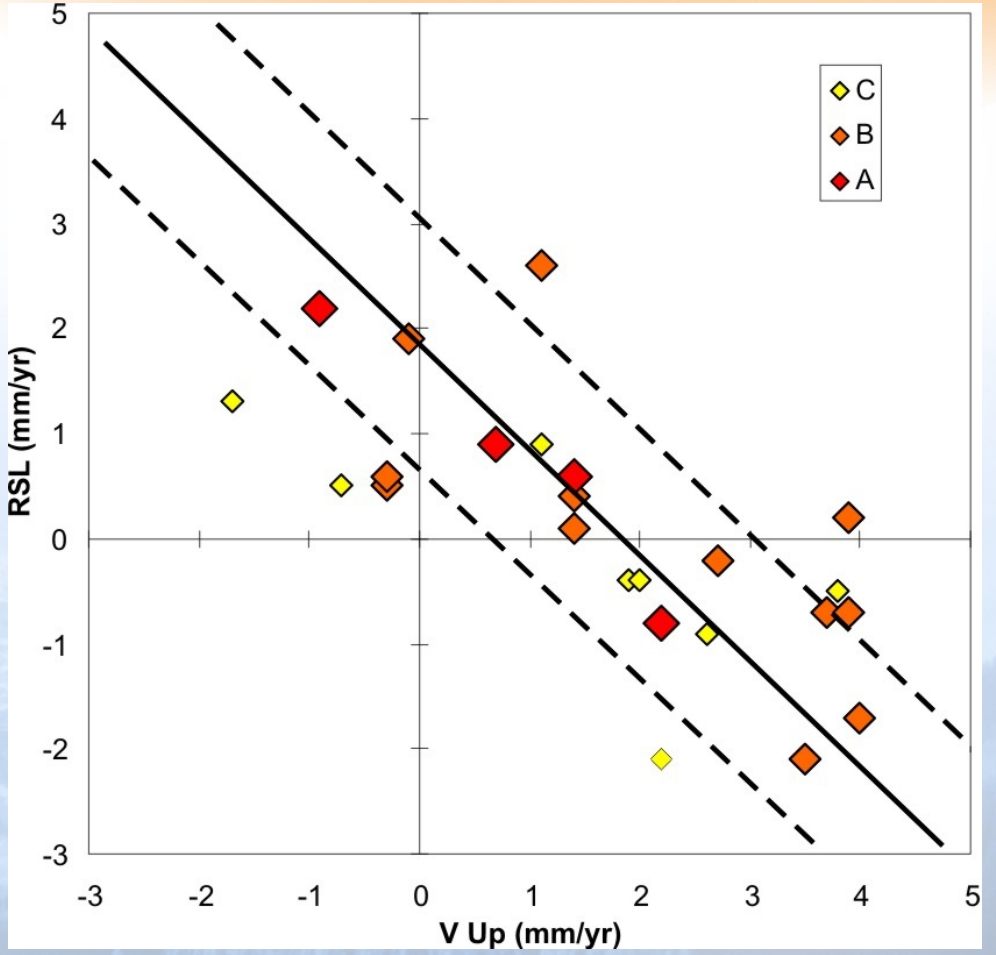
GPS / AG / Tide Gauge Integration

20th century rate of regional absolute sea-level rise (ITRF2000):

1.8 ± 0.2 mm/yr

Similar to global 20th century mean

Scatter of 1.2 mm/yr, with few significant outliers



GPS / AG / Tide Gauge Integration

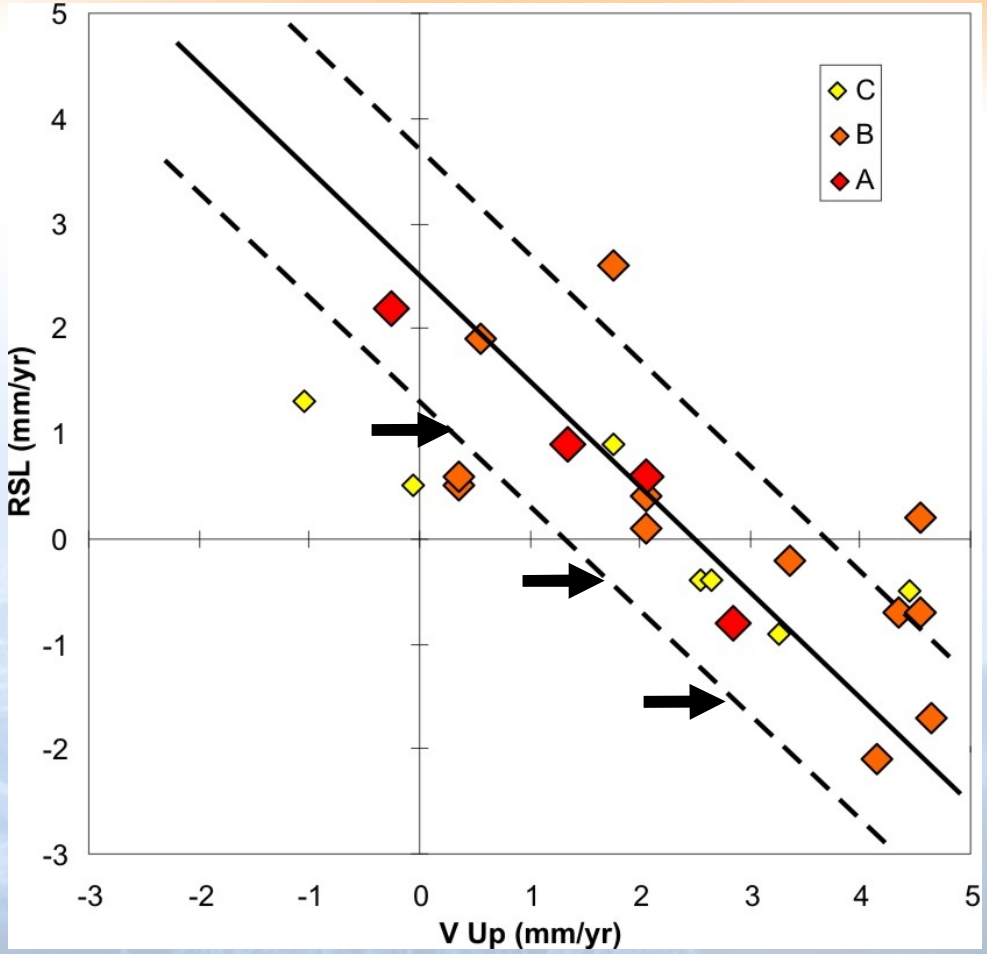
20th century rate of regional absolute sea-level rise in ITRF2000:

1.8 ± 0.2 mm/yr

In ITRF2005

2.6 ± 0.2 mm/yr

Issue of reference frame & absolute rates



GPS / AG / Tide Gauge Integration

20th century rate of regional ASL rise in ITRF2000:

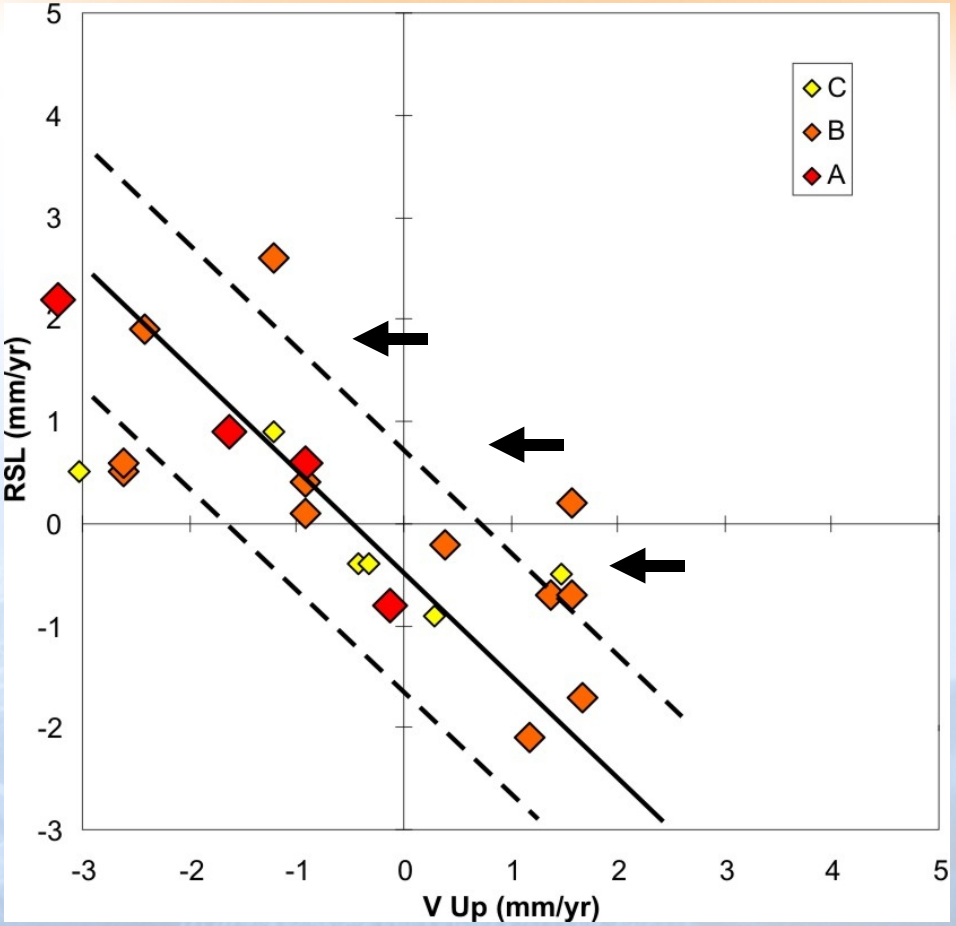
1.8 ± 0.2 mm/yr

In ITRF2005

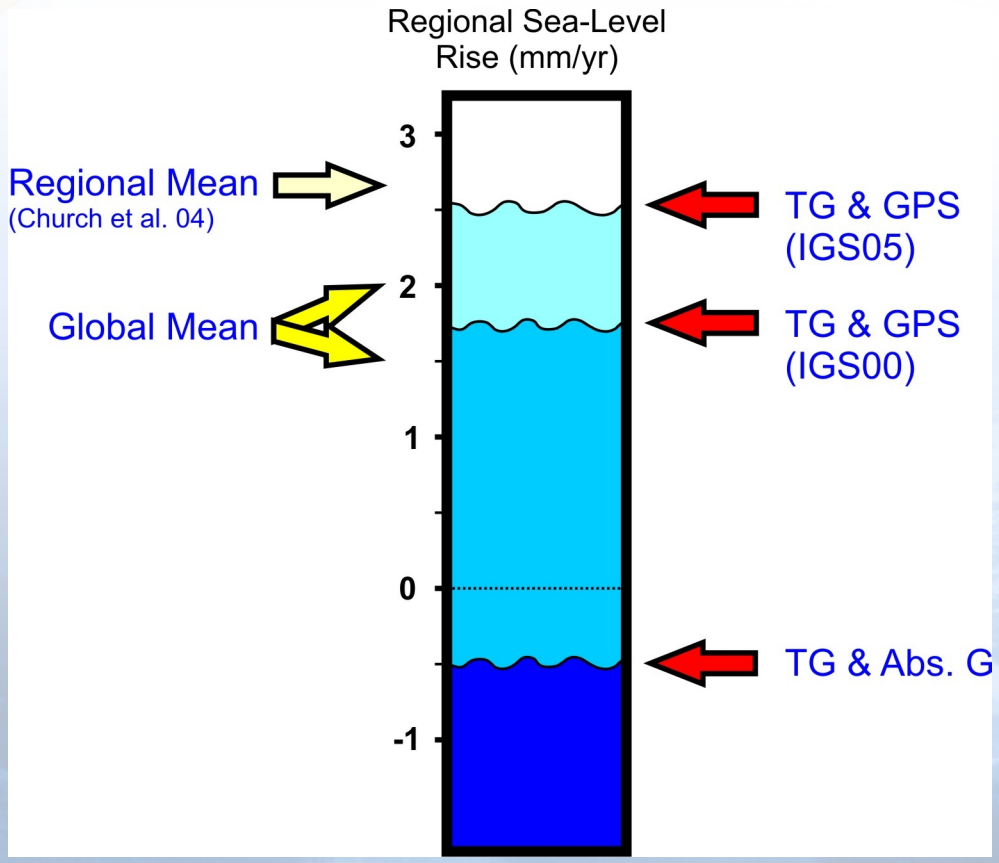
2.6 ± 0.2 mm/yr

Aligned to absolute gravity

-0.4 ± 0.5 mm/yr



GPS / AG / Tide Gauge Integration



North Cascadia Sea Level Rise

GPS (IGS00)

1.8 ± 0.2 mm/yr

GPS (IGS05)

2.6 ± 0.2 mm/yr

GPS / AG & tide gauge

-0.4 ± 0.5 mm/yr

GPS / AG / Tide Gauge Integration

1993-2003 rate of regional ASL rise (raw):

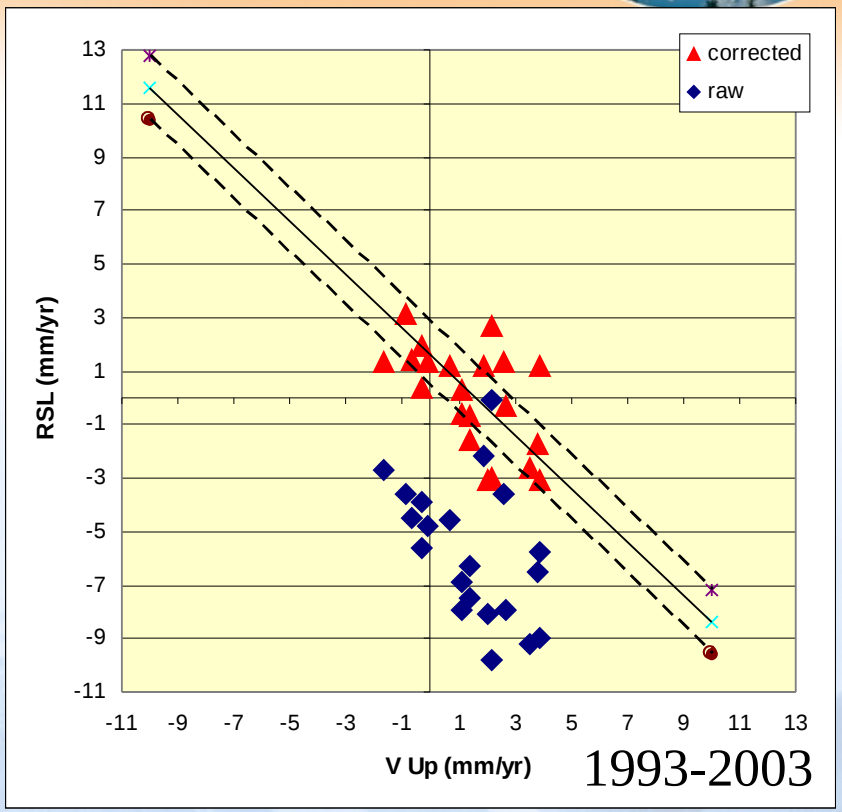
-4.4 ± 0.6 mm/yr

In agreement with altimetry results. But need more detailed comparison

After correction for regional common-mode:

1.7 ± 0.4 mm/yr

Similar to 20th century mean



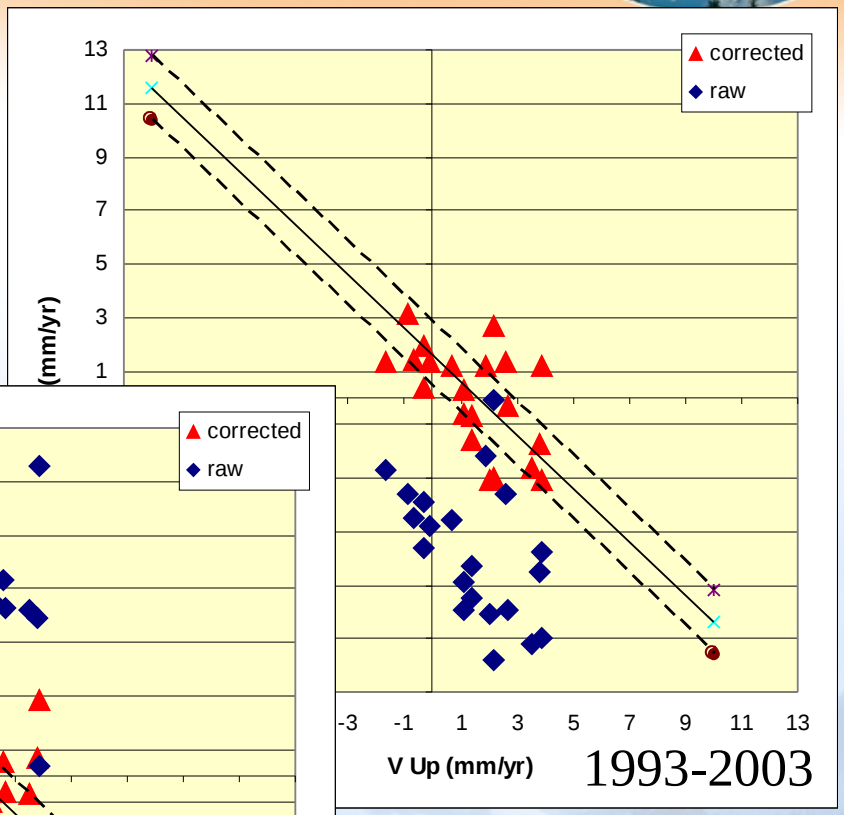
GPS / AG / Tide Gauge Integration

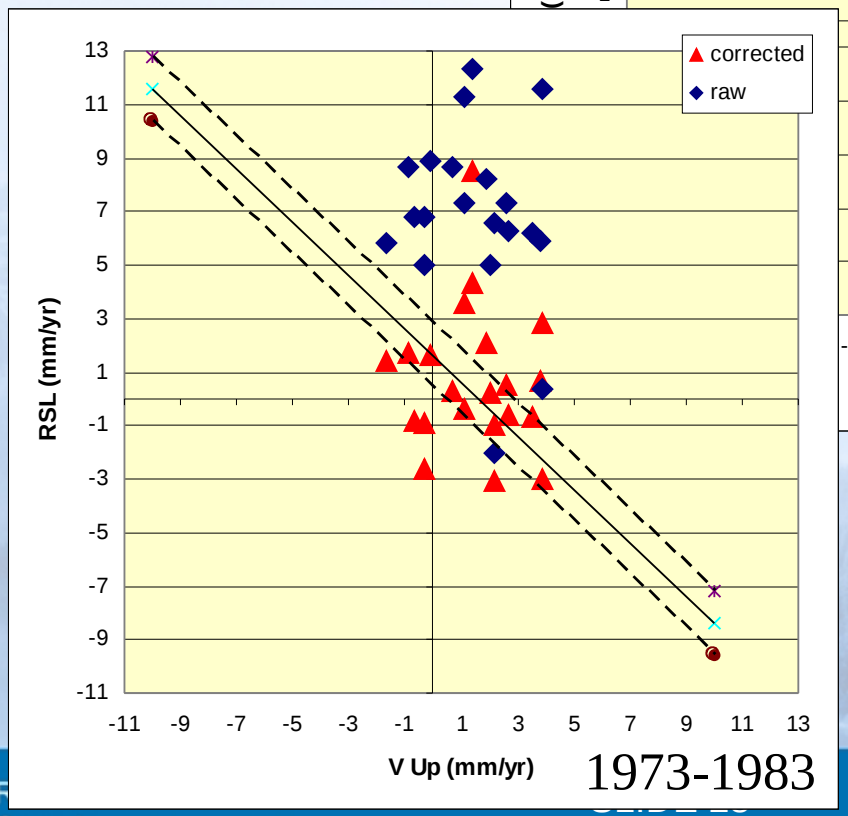
Raw regional ASL rates:

93-03: -4.4 ± 0.6 mm/yr
73-83: 9.6 ± 1.3 mm/yr

Compare with regional oceanic signals (Tp, sal.)

=> Coastal ENSO effects



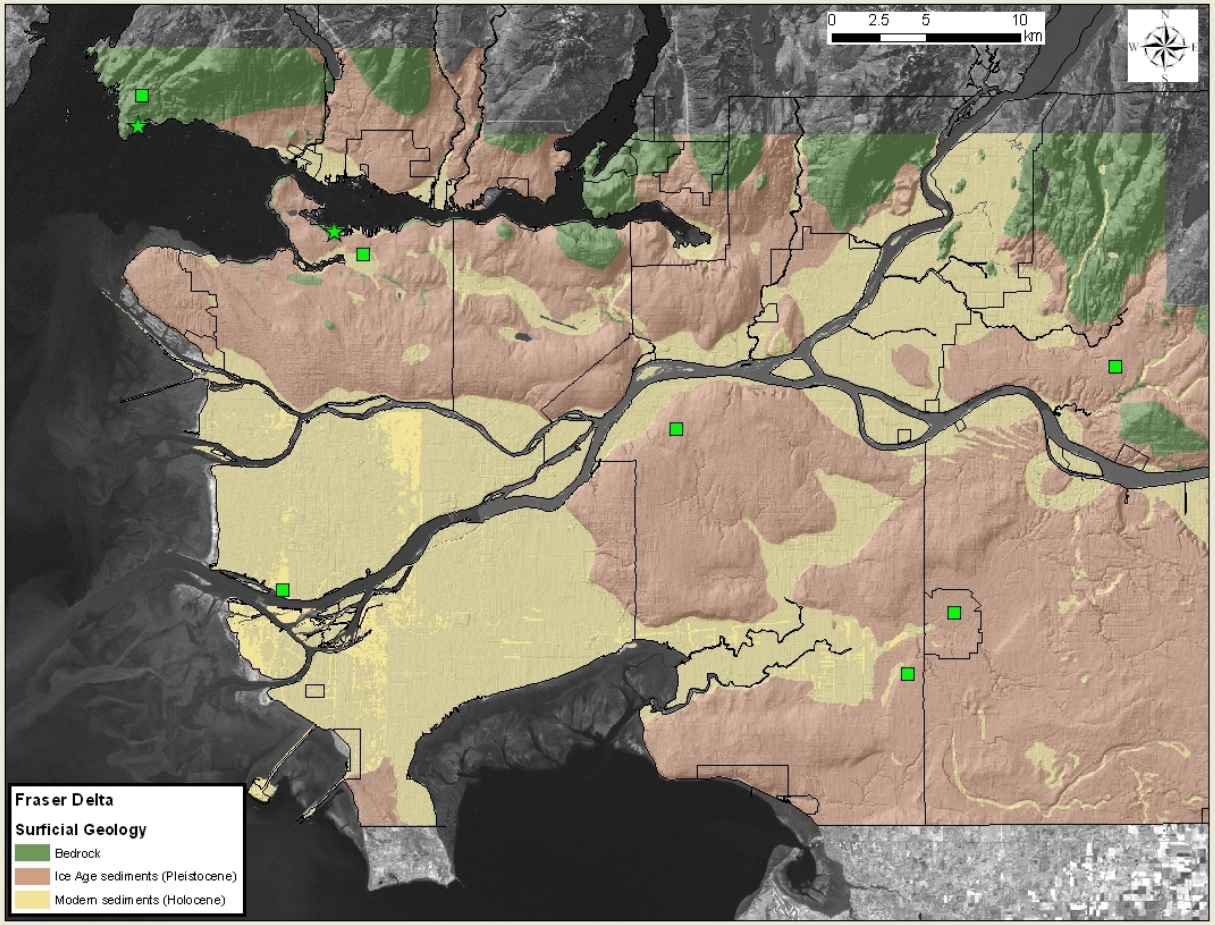


Tectonics vs. Anthropogenic Signals

Local study of subsidence and relative sea level rise

Fraser River Delta – Greater Vancouver

Combination of GPS, absolute G, InSAR, leveling, tide gauge



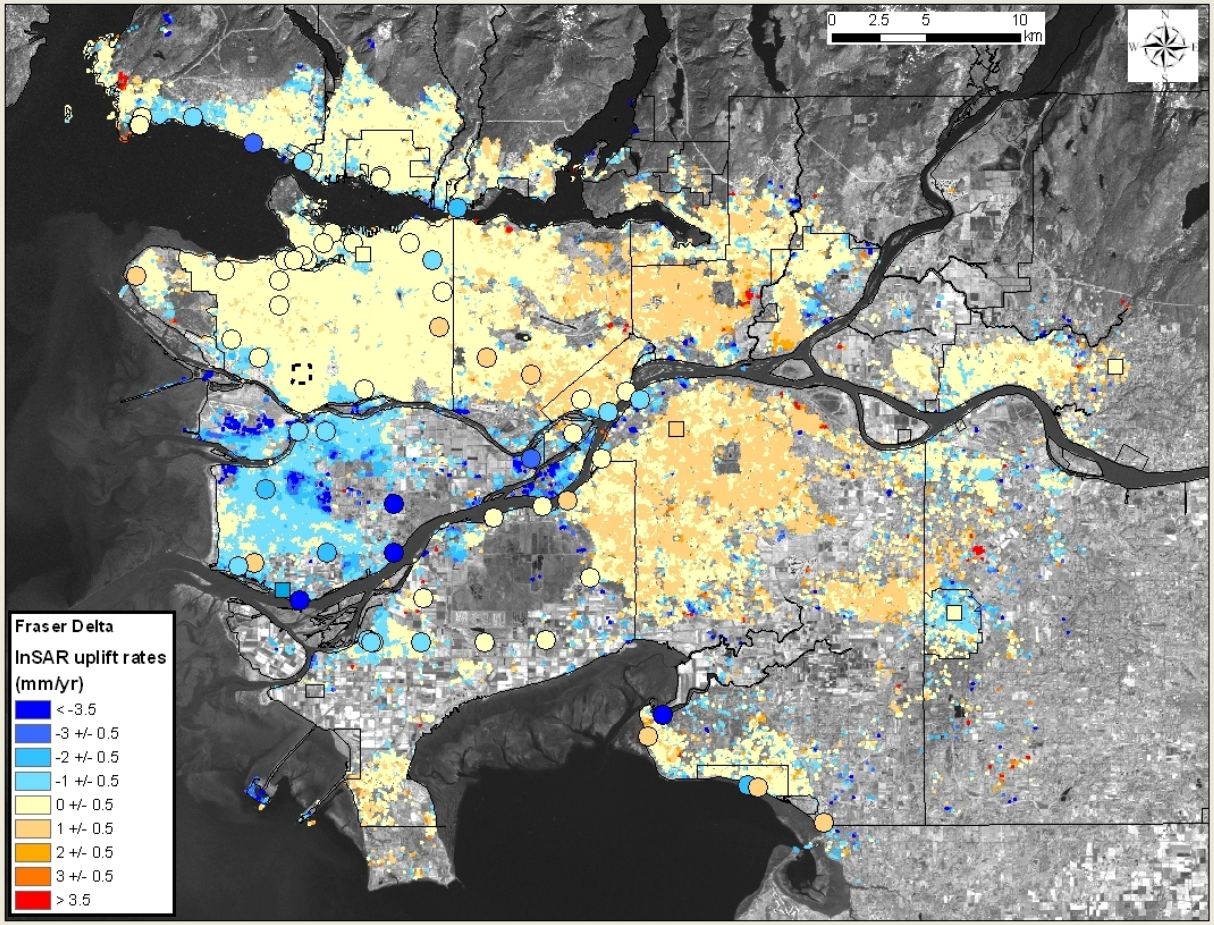
Regional and Local Projections

InSAR provides a high-resolution map of land motion

GPS provides the alignment to global frame / mean sea level

Subsidence of Fraser Delta average 1-2 mm/yr

5-10 mm/yr in regions of anthropogenic induced compaction



Regional and Local Projections

Subsidence & RSL in Fraser Delta by 2100

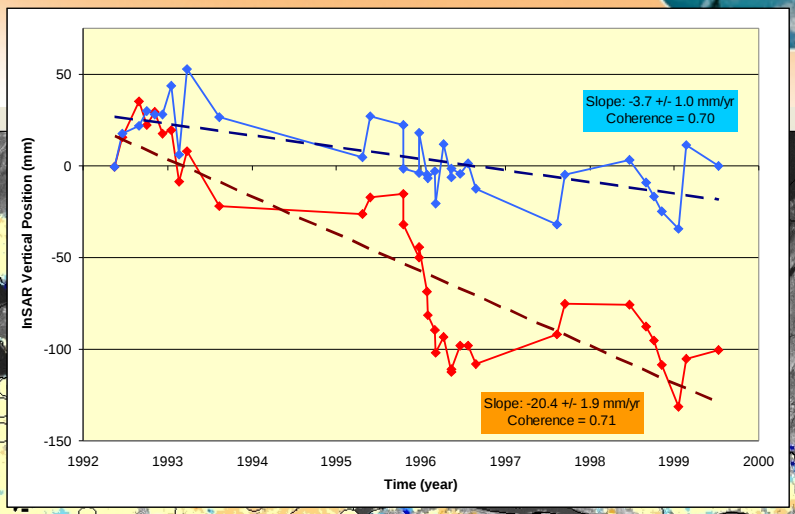
Linear response:

- Subsid.: 10-30 cm

Non-linear response:

- Subsid.: 50 cm over 2-3 yr

Local loading response



Conclusions

Vertical GPS and absolute gravity data in combination have potential for constraining the dynamics of tectonic systems (e.g. inelastic strain in subduction zone)

Requirements / Limitations:

- High-quality monuments and data acquisition

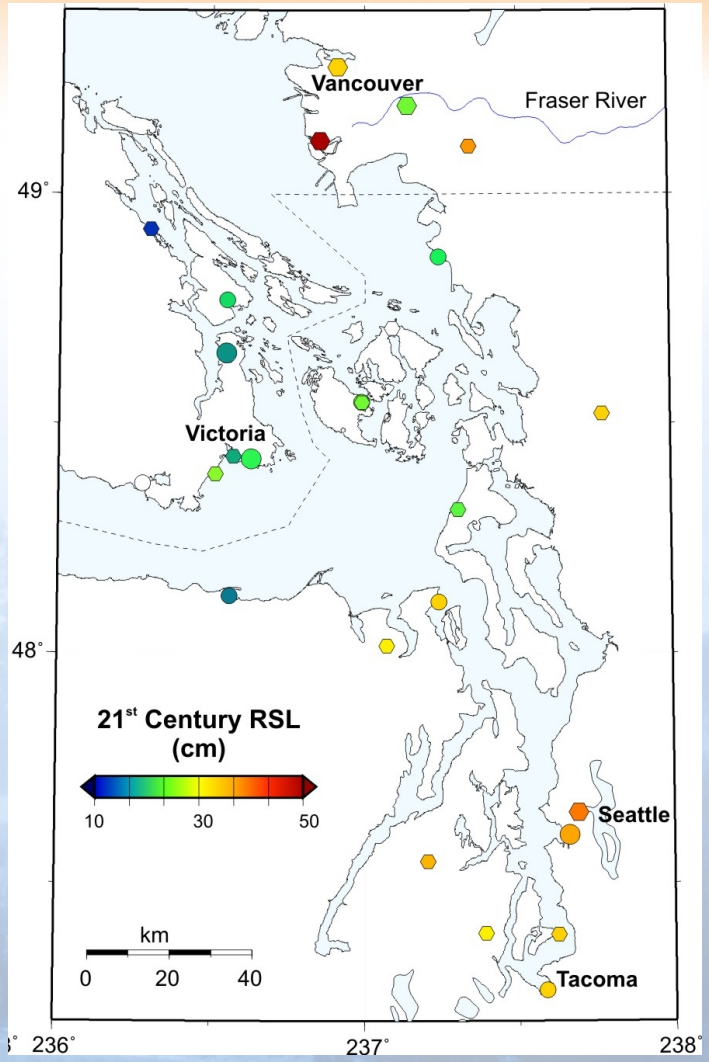
- Long-tem AG time series (10+ yr) with hydrology monitoring

- Proper alignment to a well-defined global reference frame uncertainties of ~1 mm/yr in RF translate directly in interpretations (e.g. sea-level)

- Combination with high-resolution local studies for anthropogenic / hydrology processes

Regional and Local Projections

Location		Tech.	Q	RSL rise (cm)		
				Mean	5%	95%
Prince Rupert		TG	2	25	13	37
Victoria		TG	3	19	7	31
		GPS	3	17	1	34
Vancouver		**GPS**	**2**	**33**	**14**	**52**
		TG	**2**	**19**	**7**	**31**
Fraser River Delta		GPS / InSAR	2	50	32	68



An Examination of the Factors Affecting Relative and Absolute Sea Level in Coastal British Columbia, *Canadian Technical Report of Hydrography and Ocean Sciences 260*