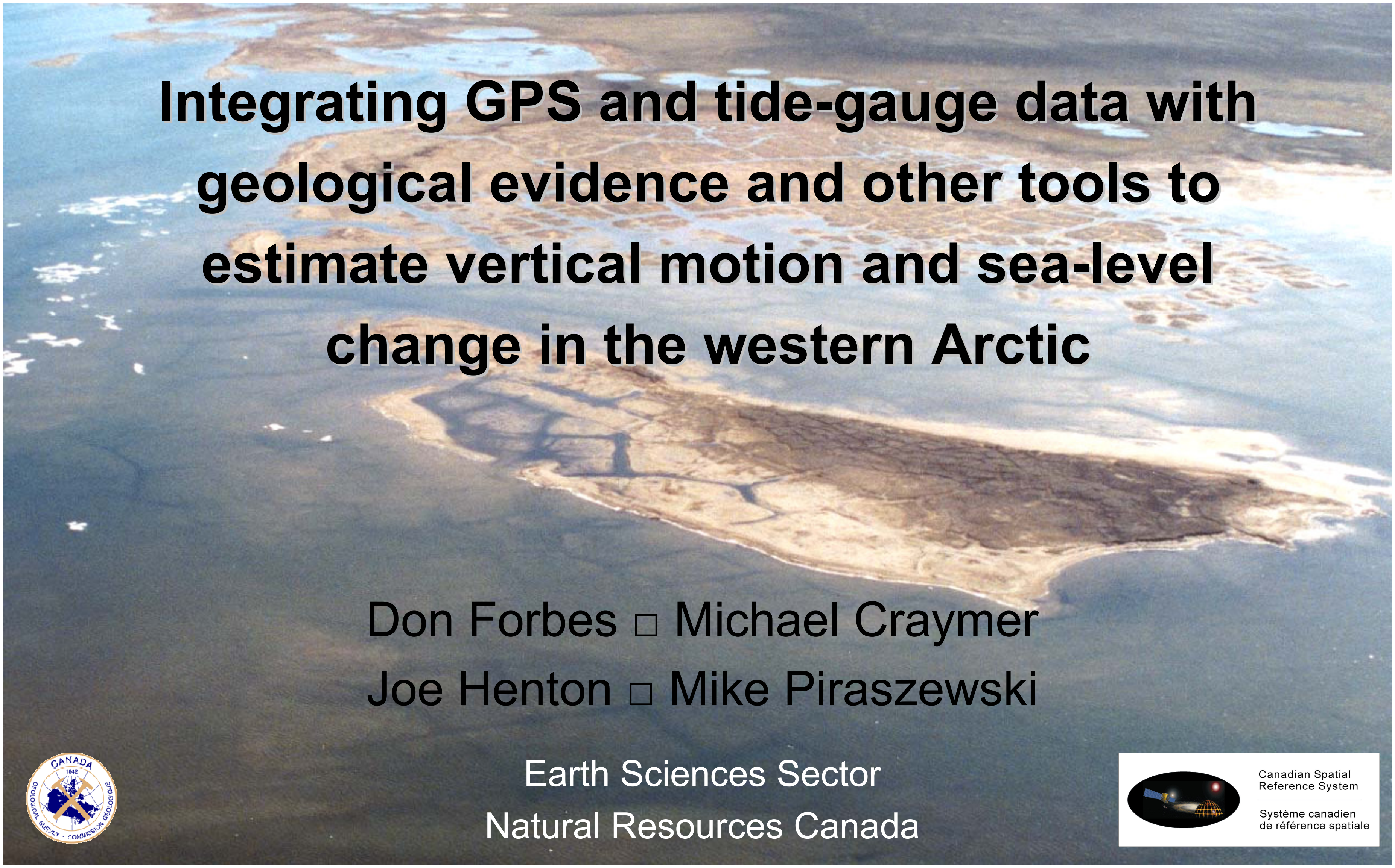

Integrating GPS and tide-gauge data with geological evidence and other tools to estimate vertical motion and sea-level change in the western Arctic

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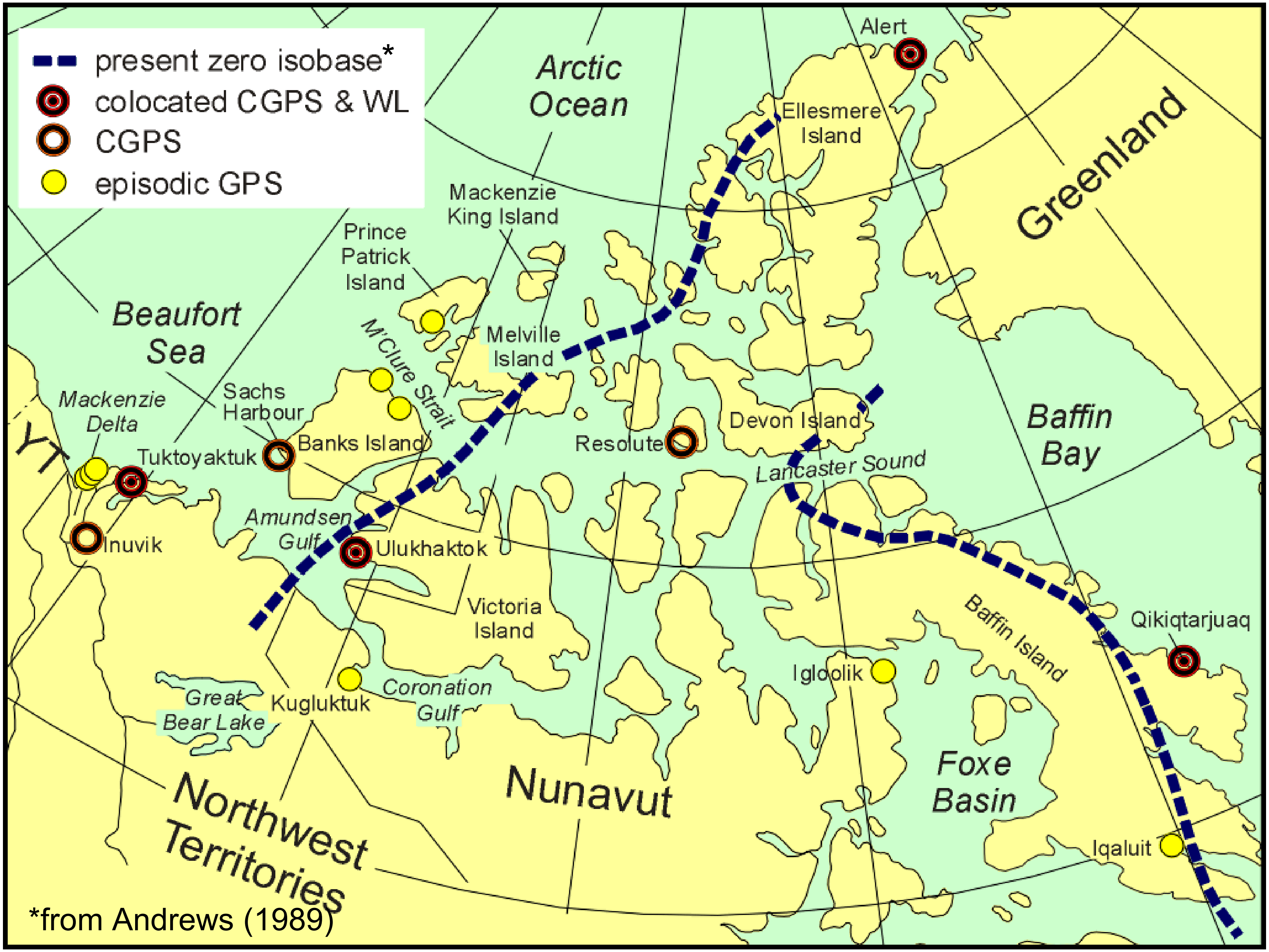
Système canadien de référence spatiale

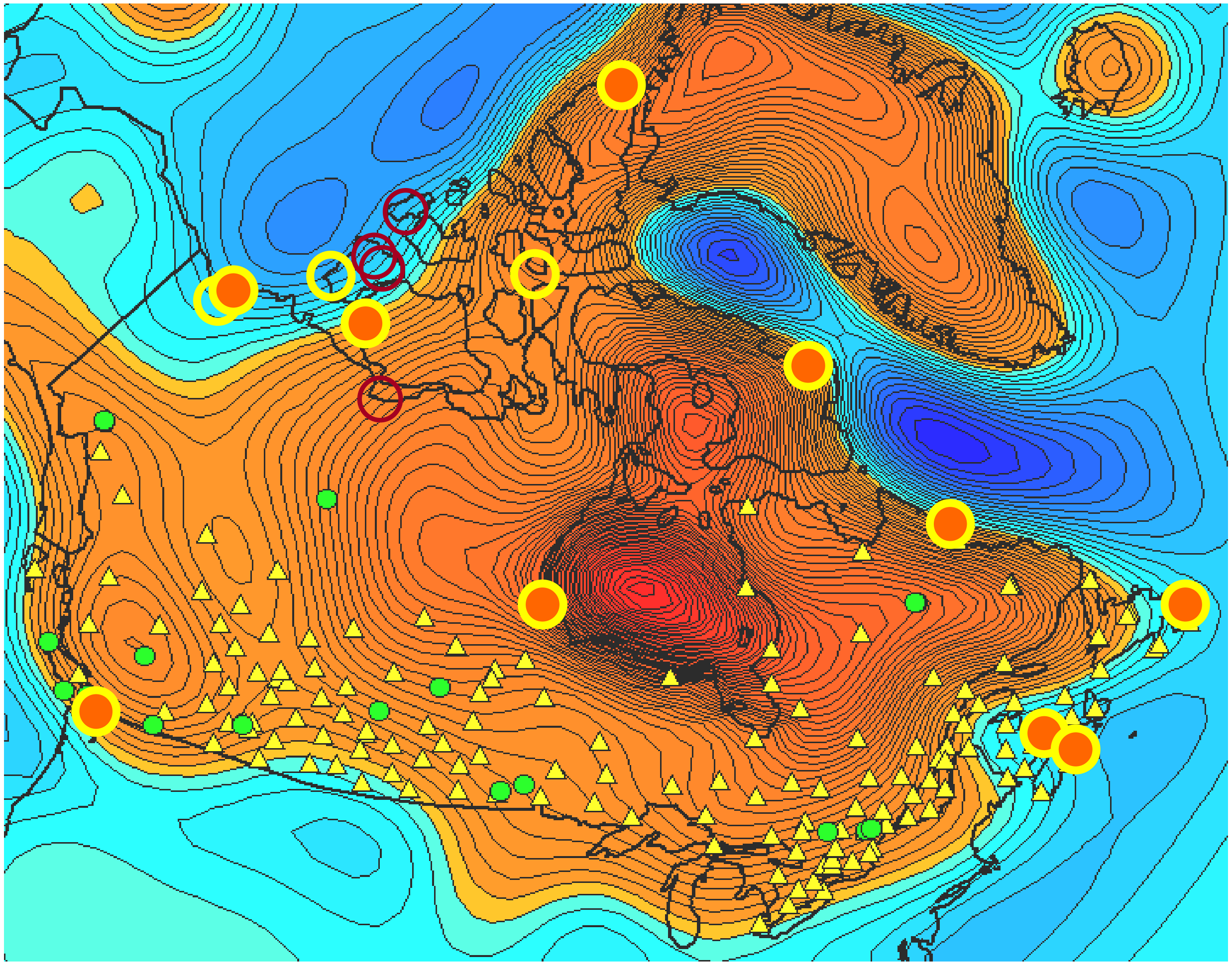
Abstract

Projections of future sea-level rise, flooding, and coastal erosion in the western Arctic require a good understanding of vertical motion and sea-level rise. Safe and sustainable hydrocarbon production in the Mackenzie Delta requires the same information on regional trends combined with estimates of delta loading, compaction, and future production-induced subsidence. A network of GPS stations has been established in the Canadian Arctic since 2001, including continuous GPS (CGPS) at Inuvik and Resolute and CGPS co-located with tide gauges at Tuktoyaktuk and Ulukhaktok (Holman). Over time, the data will enable independent measurement of vertical motion and sea-level change. Preliminary estimates of vertical motion range from 2.7±1.1 mm/a at Inuvik to positive values (uplift) at Ulukhaktok and Tuktoyaktuk (where the record is short and frost jacking is a possibility). Geophysical models suggest subsidence at all three sites. The short-term tide-gauge records at Ulukhaktok and Tuktoyaktuk show falling relative sea level (RSL), consistent with uplift, whereas flooded river outlets and submerged tundra polygons, among other evidence, point to a submerging trend. The long-term tide-gauge record at Tuktoyaktuk shows a 35-year RSL trend (1962-1997) of +3.6±1.8 mm/a. If regional sea-level rise in the Beaufort Sea has been comparable to the global trend during this interval, the implied motion at Tuktoyaktuk would be about 2±2 mm/a (subsidence), close to the 5-year GPS estimate at Inuvik. In the Mackenzie Delta, long-term sediment loading over the past 65 million years accounts for subsidence of about 0.2 mm/a. Compaction in the upper part of the modern delta is limited by 100 m of permafrost, but continues at greater depth and in thaw taliks below lakes deeper than 2 m. We show preliminary GPS results from the delta and examine some of the challenges of measuring these rates and the various components of subsidence on the complex delta surface.

Rationale

- Projections of relative sea-level rise, flooding, and coastal erosion in the western Arctic require a good understanding of regional vertical motion and sea-level rise
- Safe and sustainable hydrocarbon production in the Mackenzie Delta requires
  - regional trends in vertical motion & sea levels
  - estimates of delta loading, compaction, and future production-induced subsidence


present zero isobase*
colocated CGPS & WL
CGPS
episodic GPS
Arctic Ocean
Alert
Ellesmere Island
Greenland
Mackenzie King Island
Prince Patrick Island
Beaufort Sea
M'Clure Strait
Melville Island
Sachs Harbour
Mackenzie Delta
YT
Tuktoyaktuk
Banks Island
Resolute
Devon Island
Lancaster Sound
Baffin Bay
Inuvik
Amundsen Gulf
Ulukhaktok
Victoria Island
Baffin Island
Qikiqtarjuaq
Igloolik
Coronation Gulf
Great Bear Lake
Kugluktuk
Foxe Basin
Nunavut
Northwest Territories
Iqaluit
*from Andrews (1989)



Vertical velocity from ICE-4G model (W.R. Peltier, U of T)

co-located GPS and tide gauge

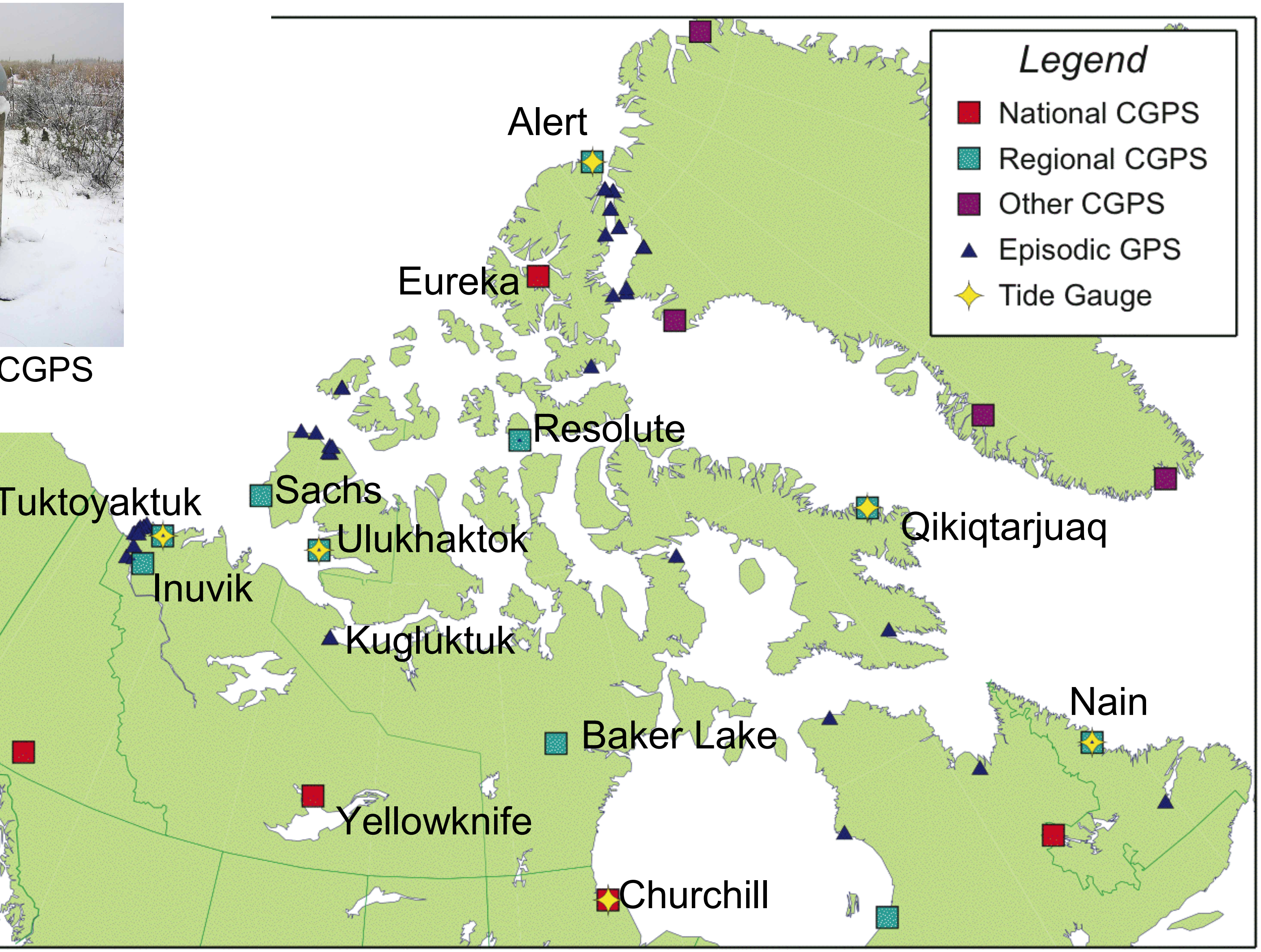
Arctic regional network of GPS sites

- established since 2001
- continuous GPS (CGPS):
  - Inuvik NT
  - Resolute NU
- CGPS co-located with CHS tide gauges:
  - Tuktoyaktuk NT
  - Ulukhaktok (Holman) NT
  - Alert NU
  - Qikiqtarjuaq NU
  - Nain NL

Over time, data are accumulating to enable independent measurement of vertical motion and sea-level change

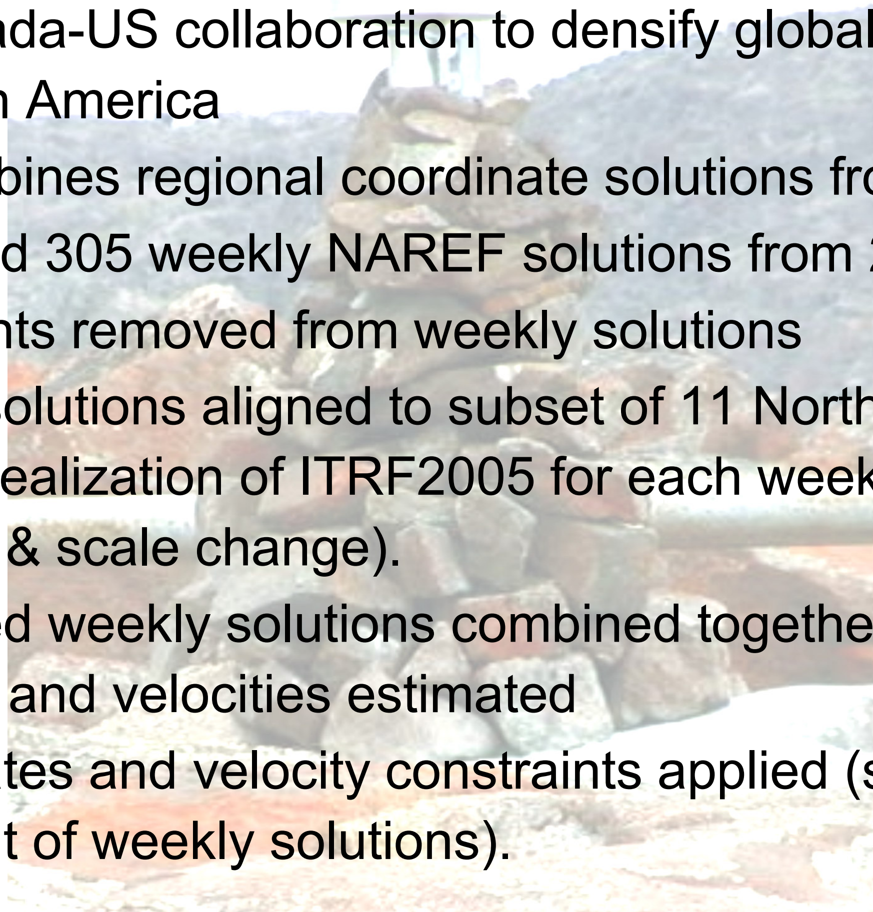
Arctic GPS & tide-gauge sites

Inuvik CGPS



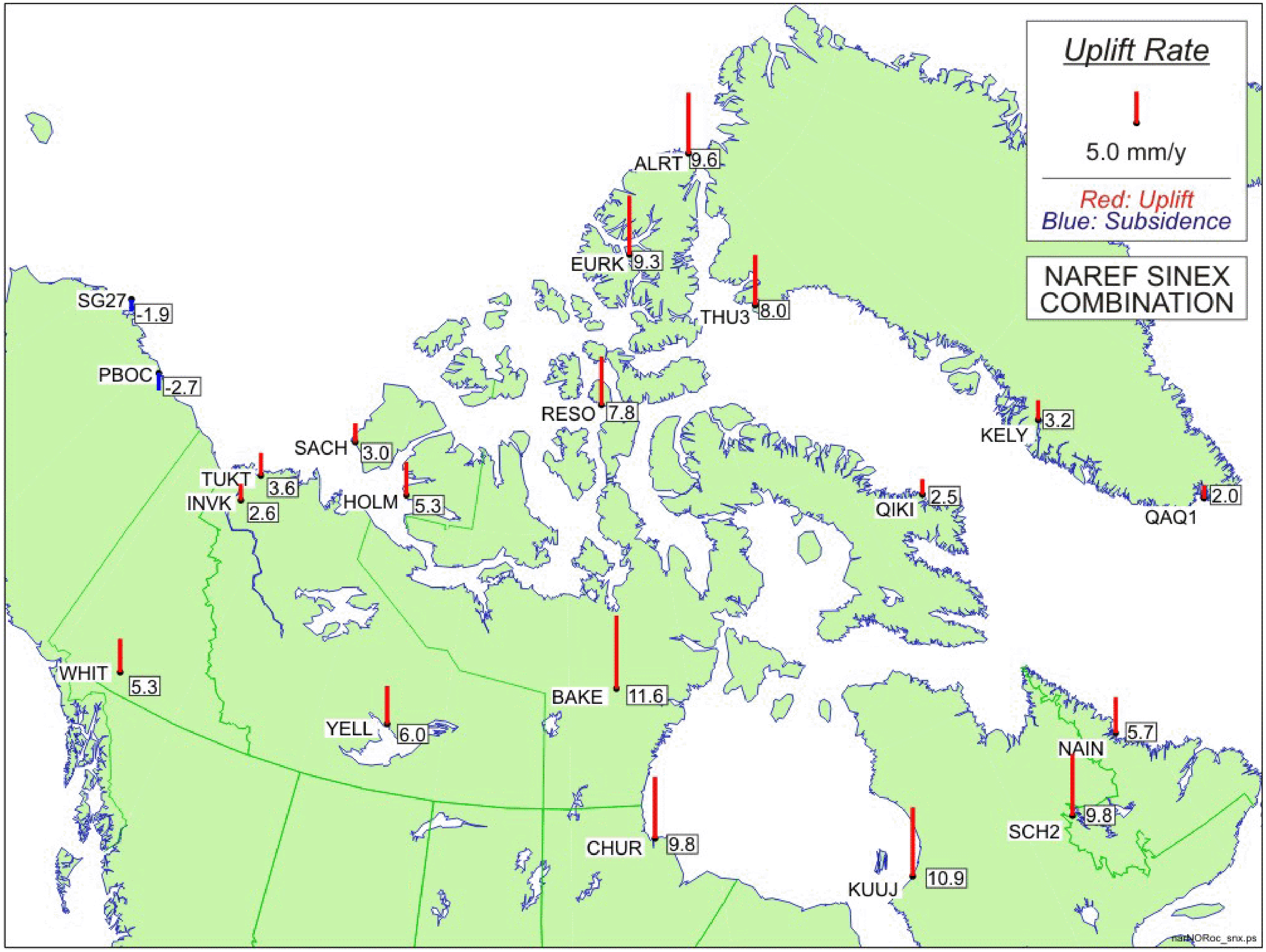
NAREF velocities

- NAREF = North American Reference Frame
  - Canada-US collaboration to densify global reference frame in North America
  - Combines regional coordinate solutions from several groups
- Combined 305 weekly NAREF solutions from 2001-2006
- Constraints removed from weekly solutions
- Weekly solutions aligned to subset of 11 North American sites in the IGS realization of ITRF2005 for each week (3 translations, 3 rotations & scale change).
- All aligned weekly solutions combined together (summation of normals) and velocities estimated
- Coordinates and velocity constraints applied (same as used in alignment of weekly solutions).



Background image:
Ulukhaktok CGPS

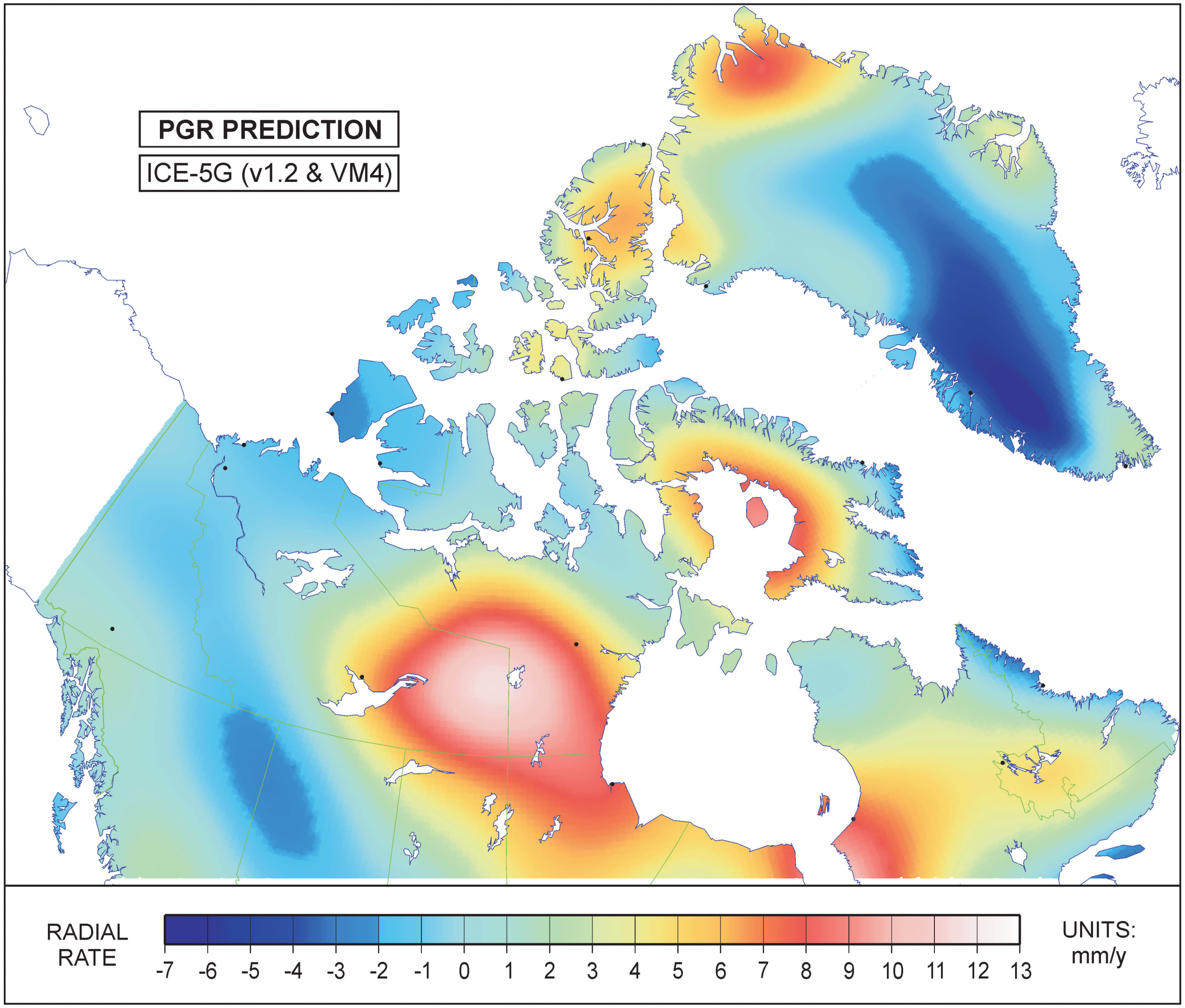
NAREF estimates of vertical motion



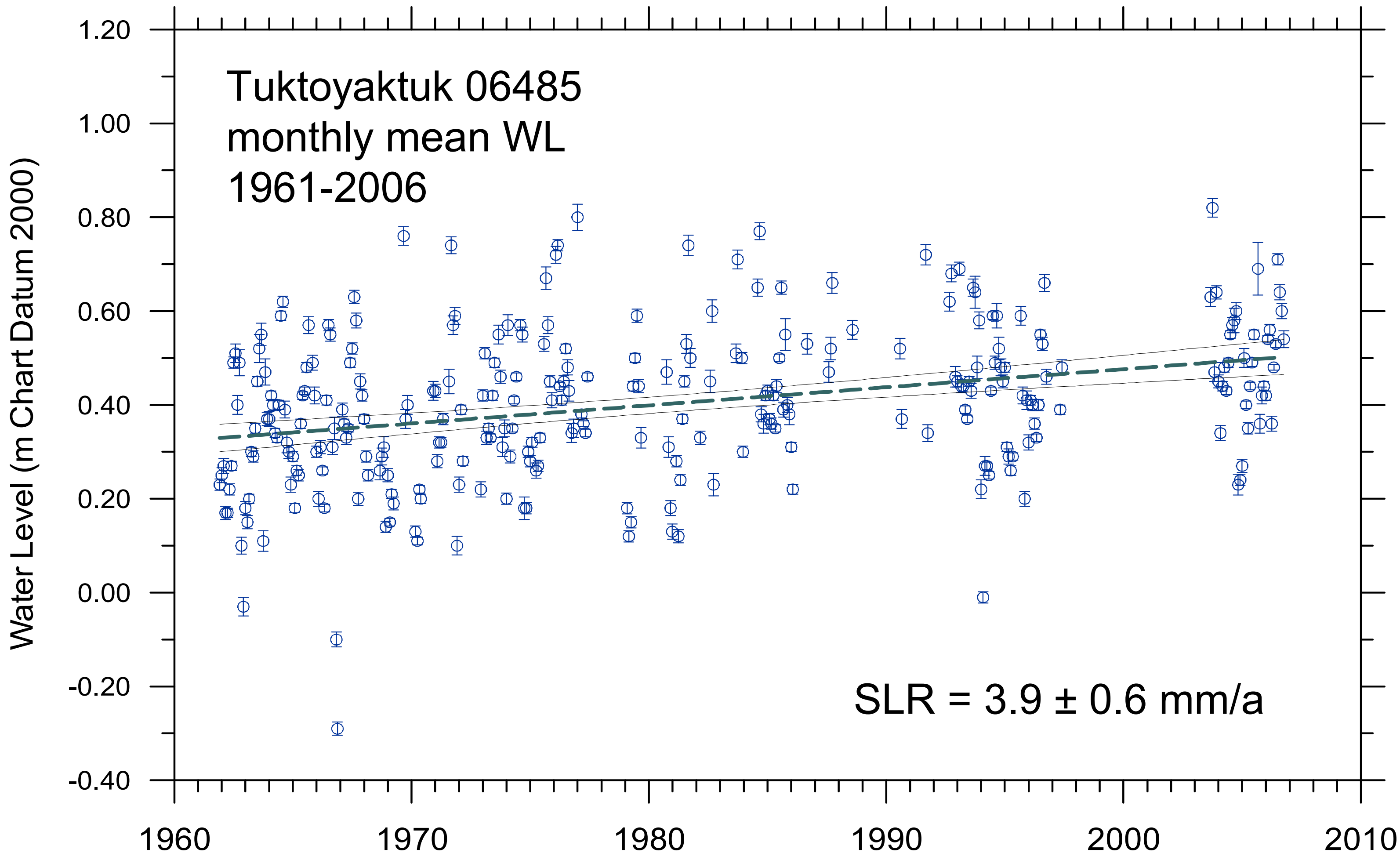
NAREF solutions in good agreement with rates from other groups:

GPS site	NAREF uplift (mm/a)	JPL uplift (mm/a)	SOPAC uplift (mm/a)
Alert	9.6 ± 0.4	11.9 ± 0.5	9.5 ± 1.6
Ulukhaktok	5.3 ± 0.2	5.3 ± 0.3	3.5 ± 1.6
Tuktoyaktuk	3.6 ± 0.4	1.0 ± 0.6	38 ± 2.0
Nain	5.7 ± 0.3	4.4 ± 0.3	N/A

Geophysical models suggest substantially lower rates and subsidence at a number of the sites

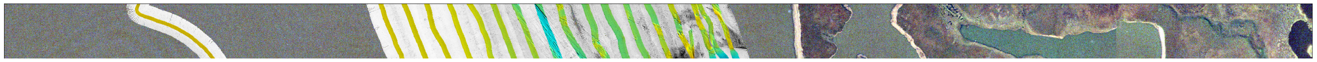


- Short-term tide-gauge records (overlapping with CGPS) at Ulukhaktok & Tuktoyaktuk are inconclusive due to the short time span
- The long-term tide-gauge record at Tuktoyaktuk shows a 35-year rising trend (1961-2006) of +3.9 ± 0.6 mm/a.

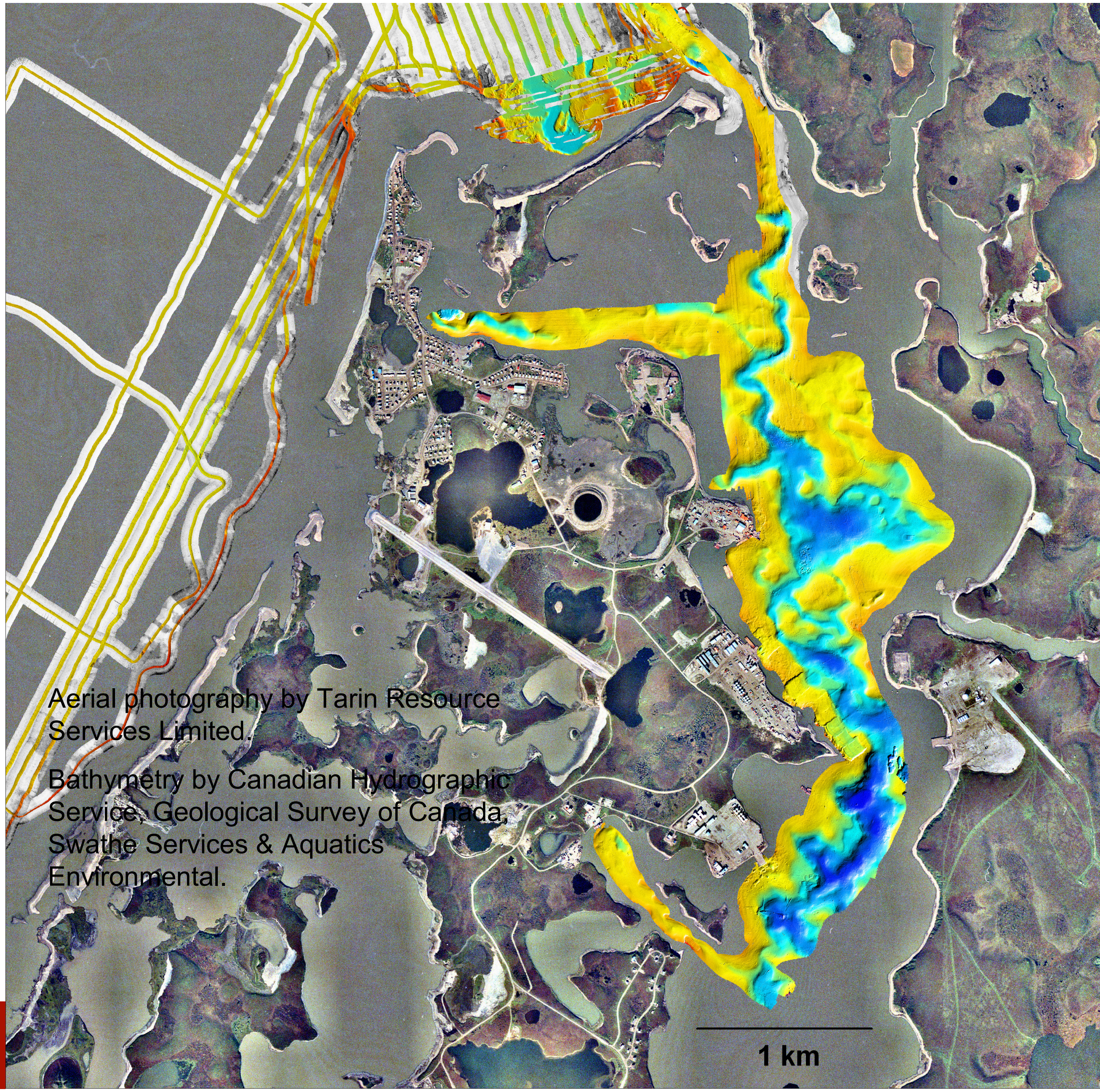


Coastal geomorphology also points to submergence – lines of evidence include:

- rising barrier crest elevations (Banks Island)



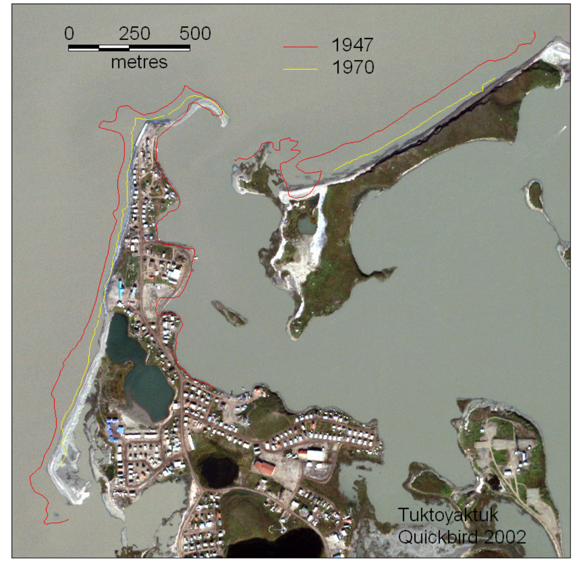
- flooded valleys (e.g. Tuktoyaktuk Harbour)



- submerged tundra polygons
  (e.g. Tuktoyaktuk Peninsula, Banks Island)

If sea-level rise in the Beaufort Sea has been comparable to the global trend for 1961-2006 (~2 mm/a)

- implied motion at Tuktoyaktuk is about [~2 – 3.9] ≈ -2 ± 2 mm/a (subsidence)



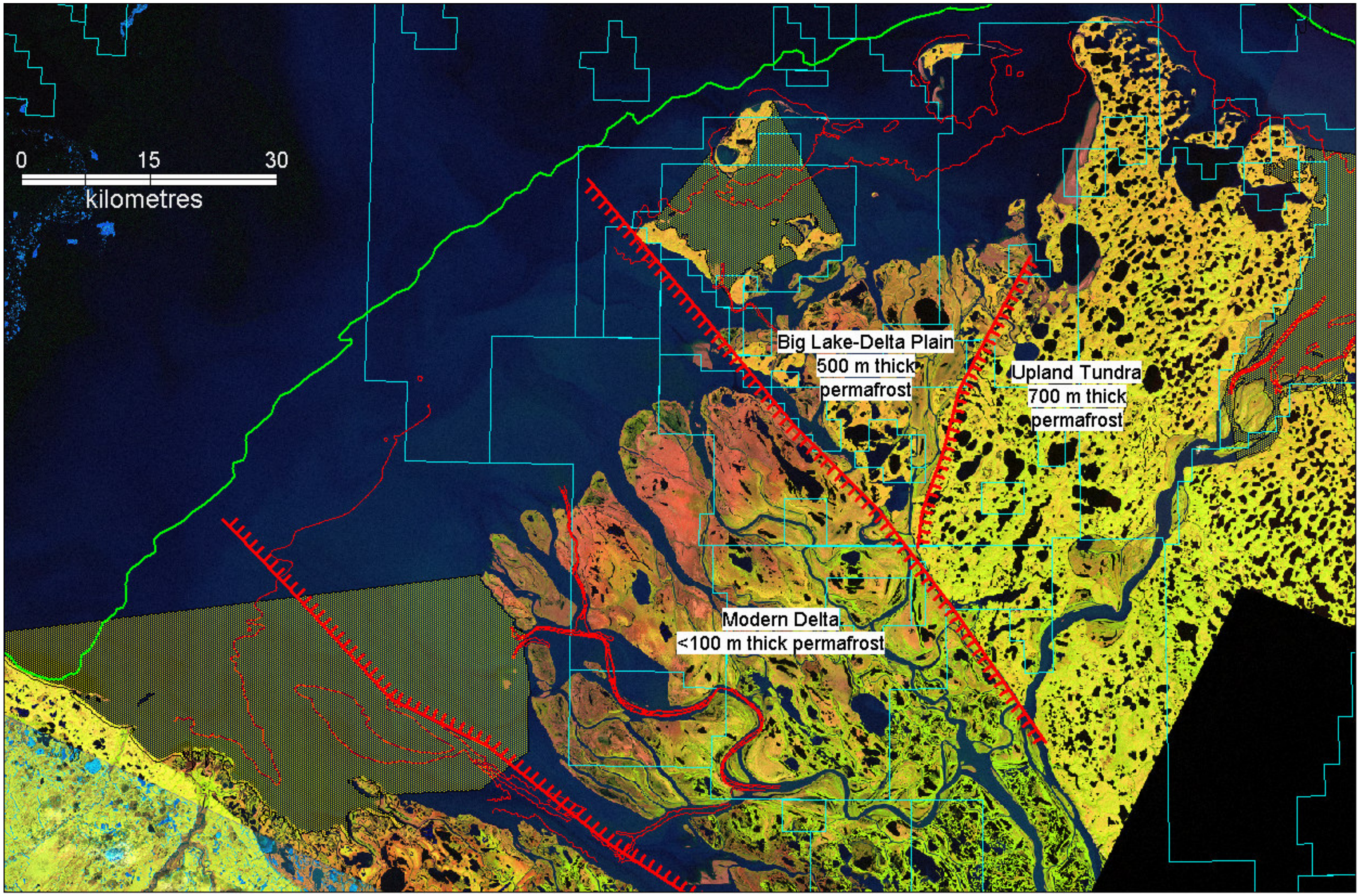
Substituting the NAREF value for uplift at Tuk into the relative sea-level solution

- gives an absolute sea-level rise of 7.5 ± 1.0 mm/a (seems unrealistic)

- … therefore the GPS solutions may be biased at higher latitudes due to reference frame issues (possibly mismodelled geocentre motion along the rotational Z axis)

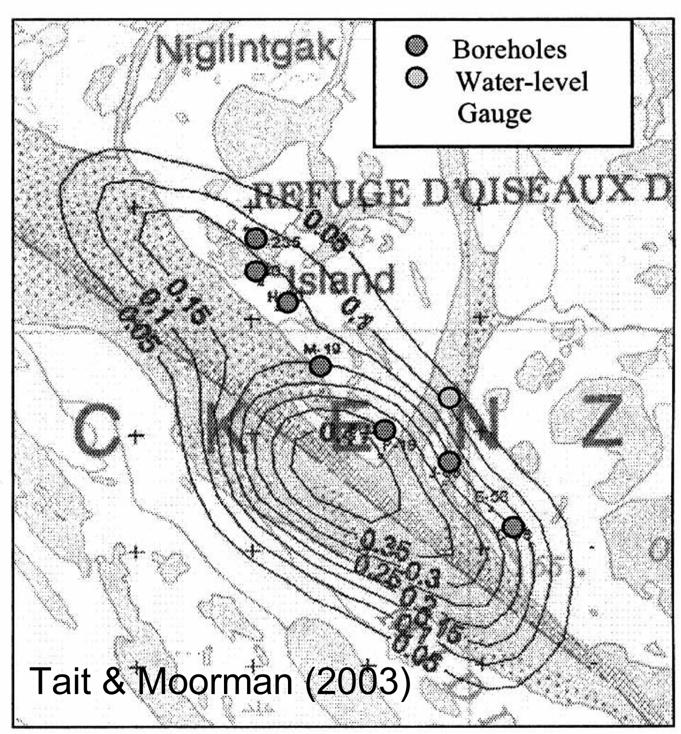
Subsidence in the Mackenzie Delta

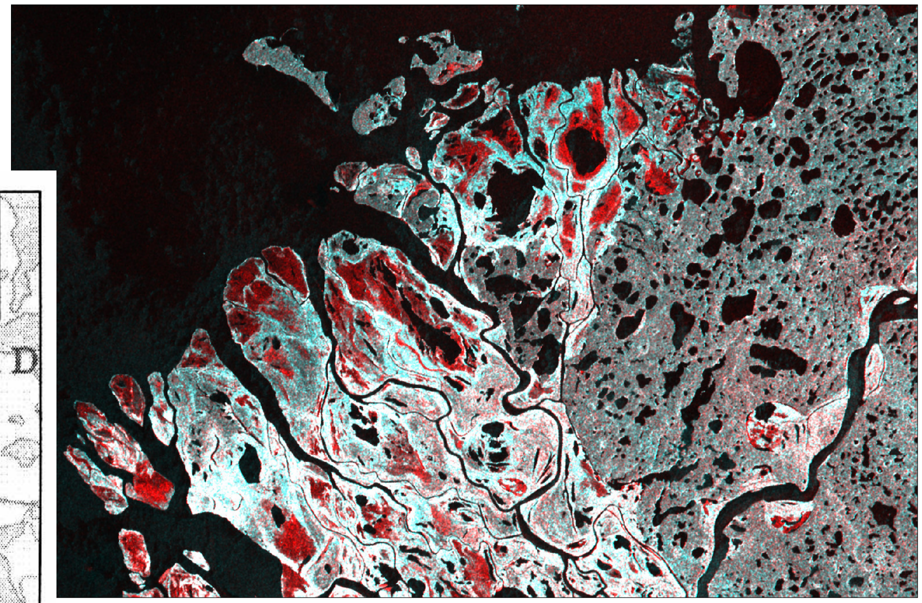
Long-term subsidence due to sediment loading adds a small component to the regional postglacial isostatic subsidence



Compaction causes additional subsidence in the Delta

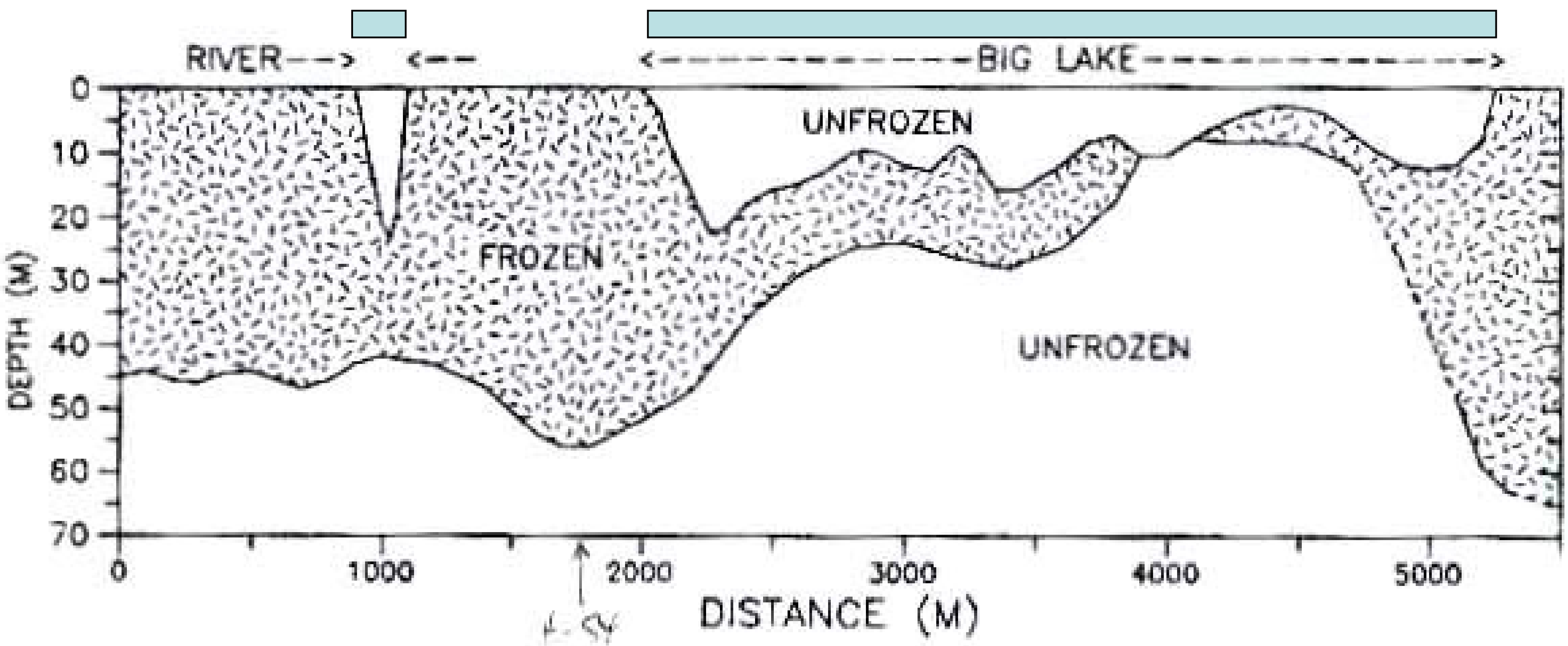
Compaction in the upper part of the modern delta is limited by <100 m of permafrost, but may continue at greater depth and in thaw taliks below lakes and channels

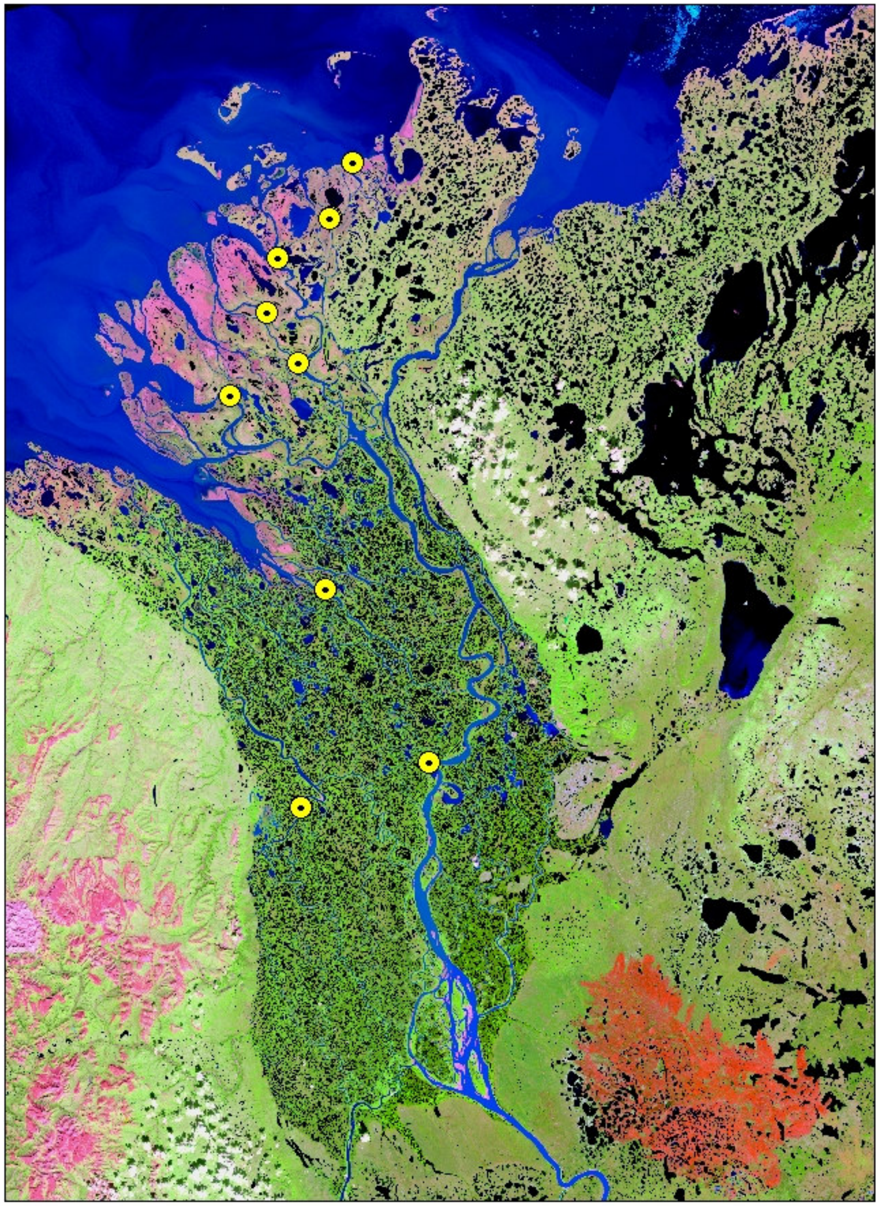




Induced subsidence expected due to fluid extraction once natural gas production begins

Compaction is greatly reduced in ice-bonded sediments



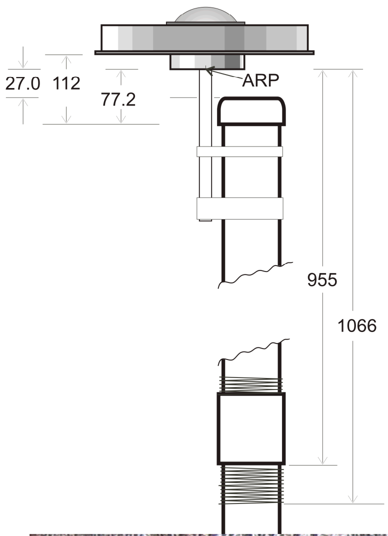


GPS epoch sites

- established in the Mackenzie Delta in 2004 and 2005
- monitor natural subsidence prior to gas production
- 9 sites across lower and upper Delta

Canada

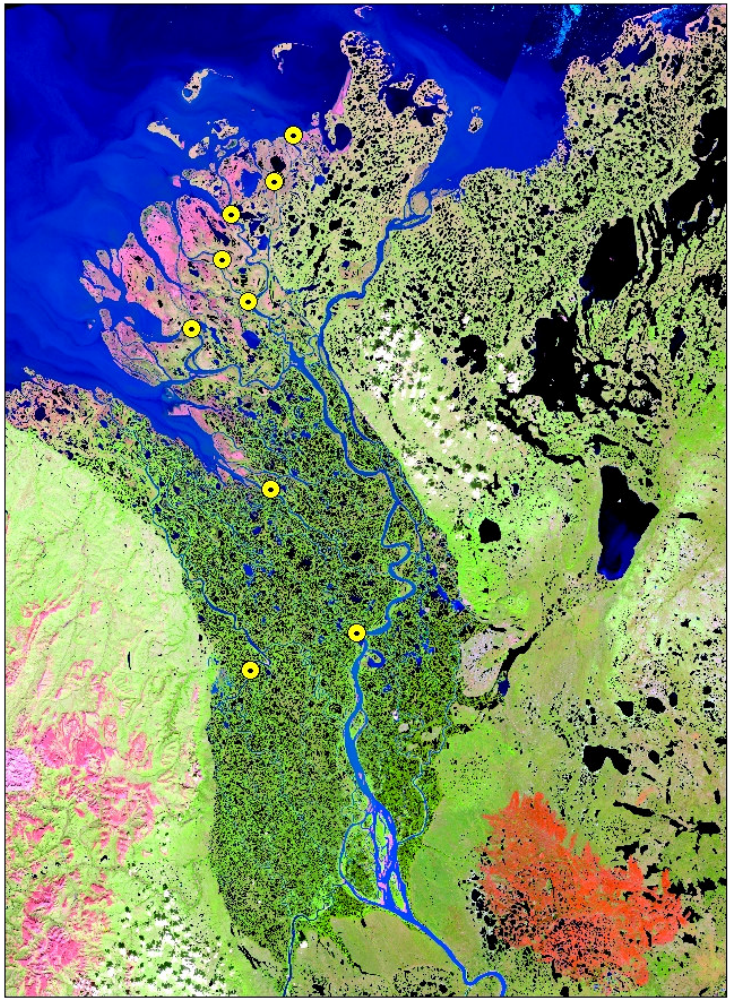
Kumak GSC M049004



- 3 sites on existing 3″ pipe (1992 GSC boreholes) to >300 m (but casing cut at shallow depth)
- 6 sites on 1″ pipe to ≥15 m
- Epochs twice per year since 2004 at 5 sites (one now abandoned) and since 2005 at remaining sites

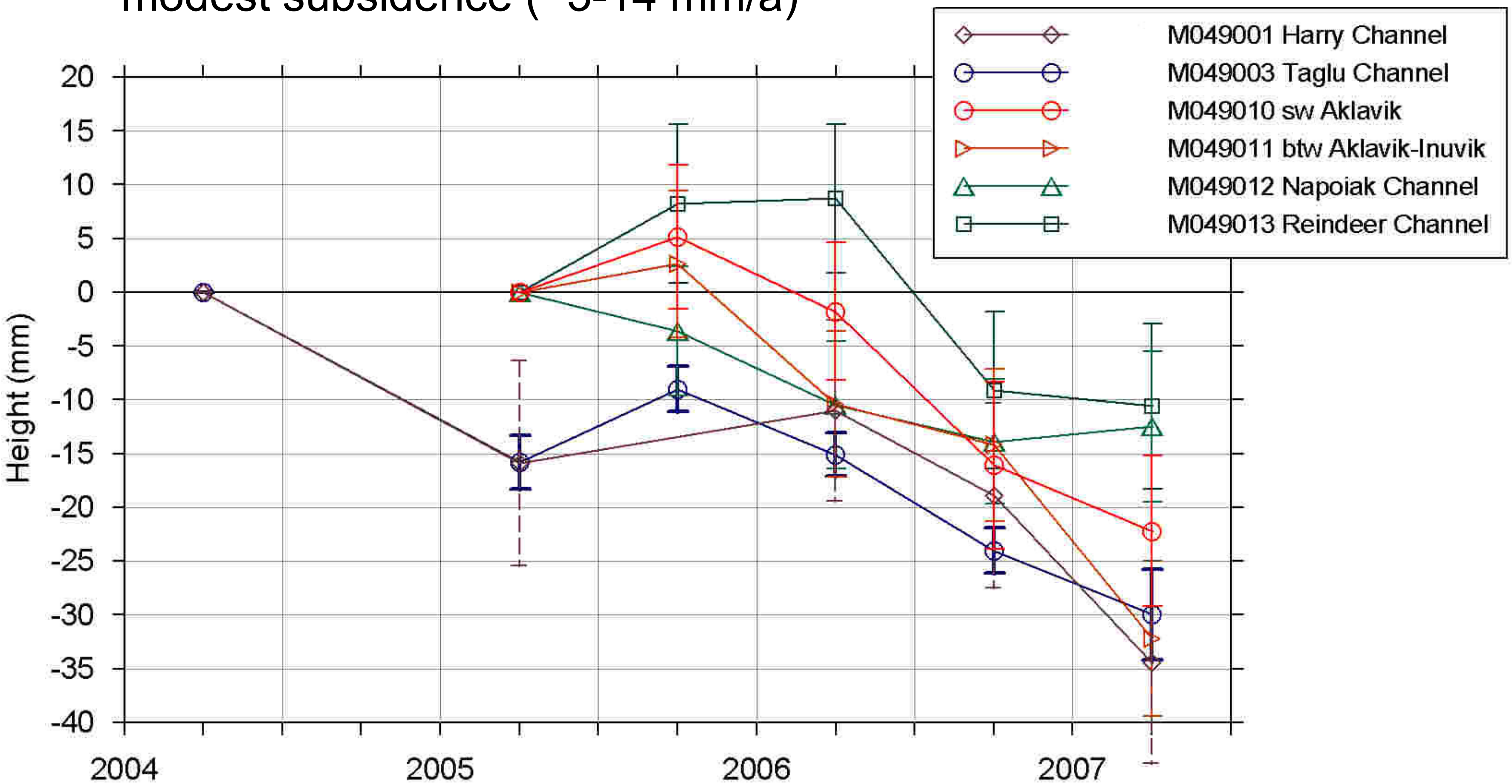
Episodic GPS processing

- same as CGPS solutions
- Bernese GPS Software v5.0 (latest version)
- multiple 24 h observation sessions
- double-differenced obs, 30 s sampling, 10° elevation cutoff
- IGS precise orbits & EOPs fixed
- tropospheric zenith delays estimated
- Neil dry+wet mapping function
- FES2004 ocean loading model (adopted by IGS)
- YELL constrained to ITRF2000 coords at 2002.0 for all epochs

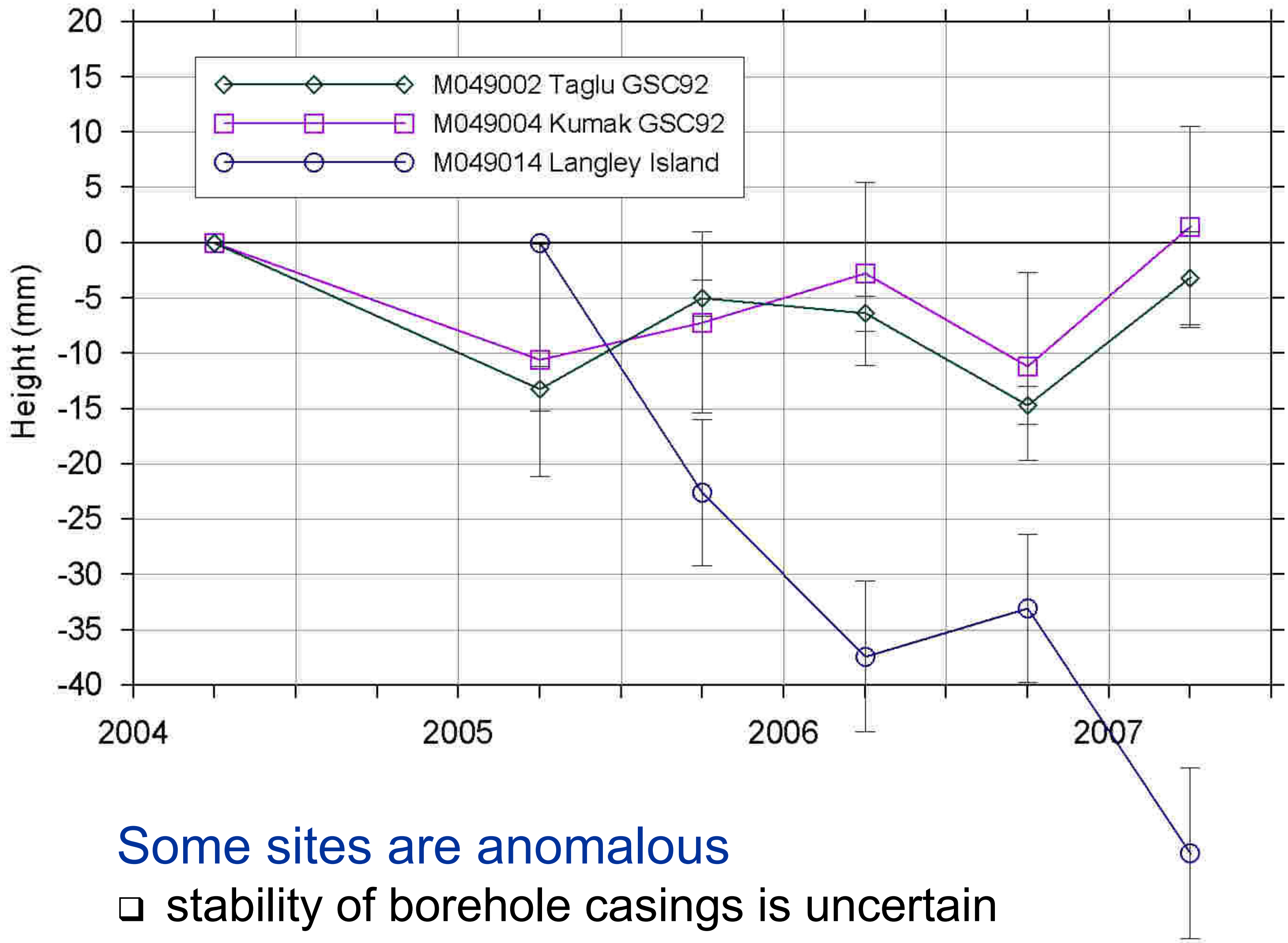


Preliminary GPS results in the Delta

Six sites show similar trends* suggesting modest subsidence (~3-14 mm/a)



* All rates relative to Yellowknife where uplift ≈ 6 mm/year

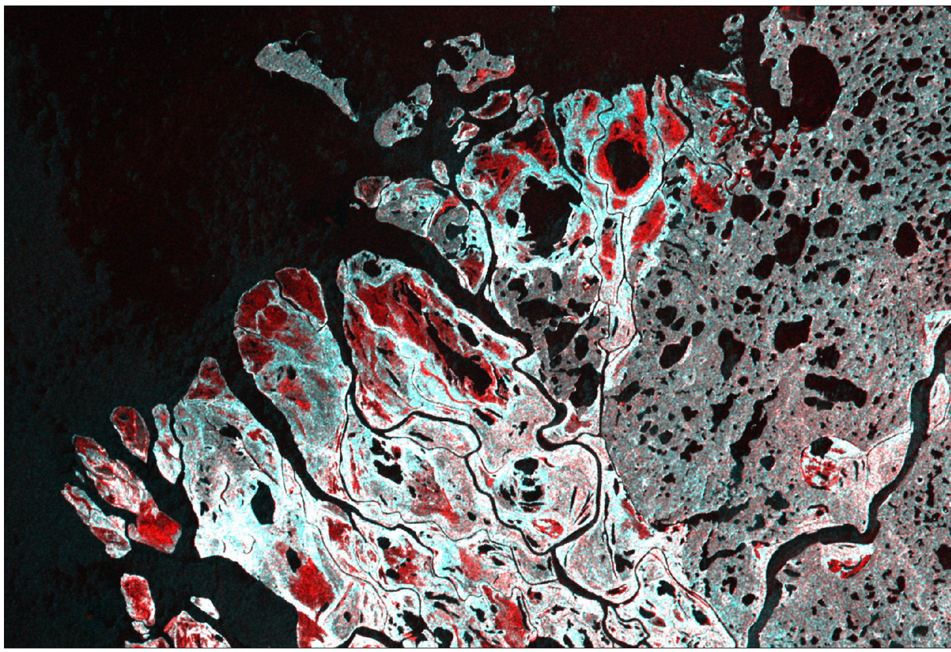


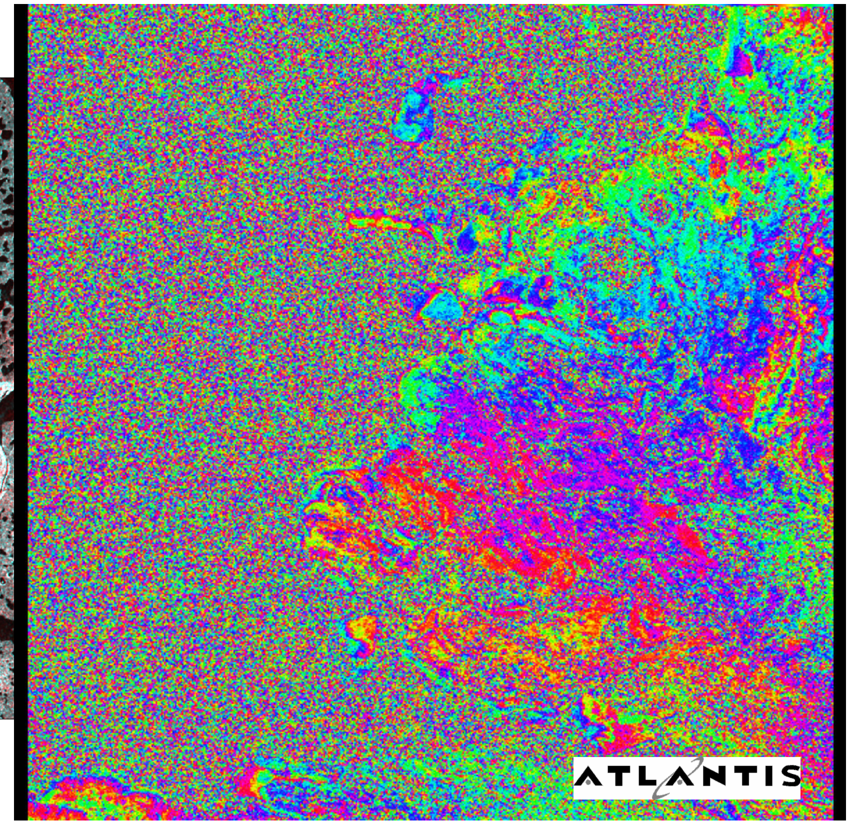
Some sites are anomalous

- stability of borehole casings is uncertain
- Langley Island rapid subsidence unexplained

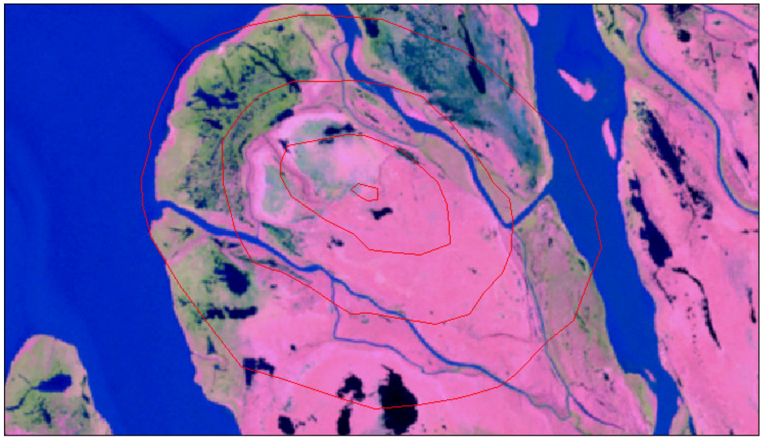
Work is beginning to densify estimates of vertical motion in the Mackenzie Delta using InSAR

- Initial trial 2 years ago showed low coherence
- Propose to use permanent scatterer technique with reflectors
  (in collaboration with S. Mazzotti and PDF)

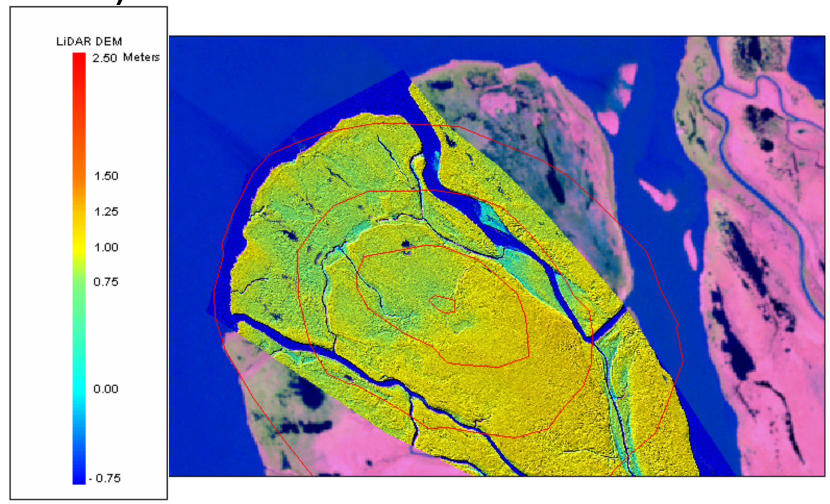


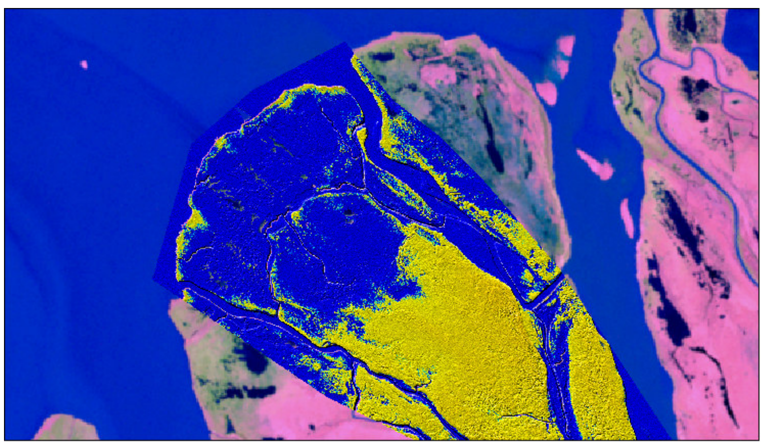


LiDAR DEM for modelling subsidence impacts on flood risk
(in collaboration with P. Marsh, EC, and others)

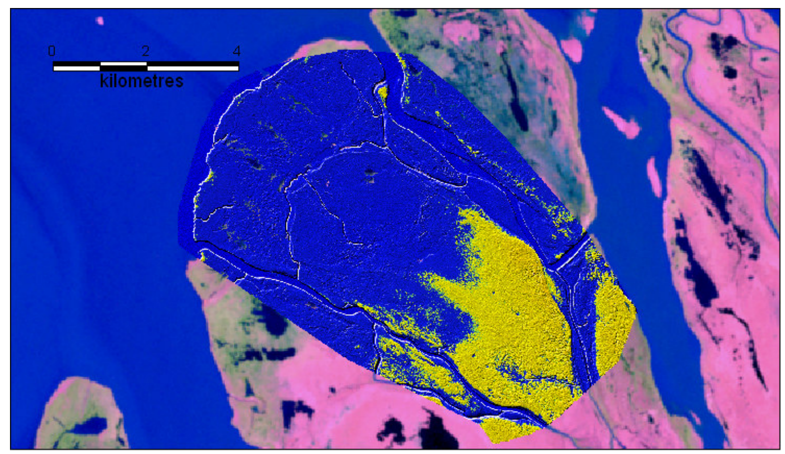


Hypothetical subsidence bowl on outer delta





1m (CGVD28) surge on original topo



1m (CGVD28) surge on subsided topo

Summary

- Network of CGPS and episodic sites established throughout the Arctic - preliminary trends after $\leq$ 6 years
- NAREF vertical motion estimates are consistent with other GPS analysis centres
- Geophysical, geological, and tide-gauge evidence suggests NAREF vertical motion is positively biased at higher latitudes (investigating further)
- GPS results from the modern Mackenzie Delta suggest modest subsidence (compaction > expected?)
- A combination of methods (GPS, InSAR, LiDAR) is needed for monitoring subsidence and and mapping flood risk on the Delta