COMPLEXITY OF GROUND DEFORMATION DUE TO NATURAL GAS WITHDRAWAL IN MACKENZIE DELTA

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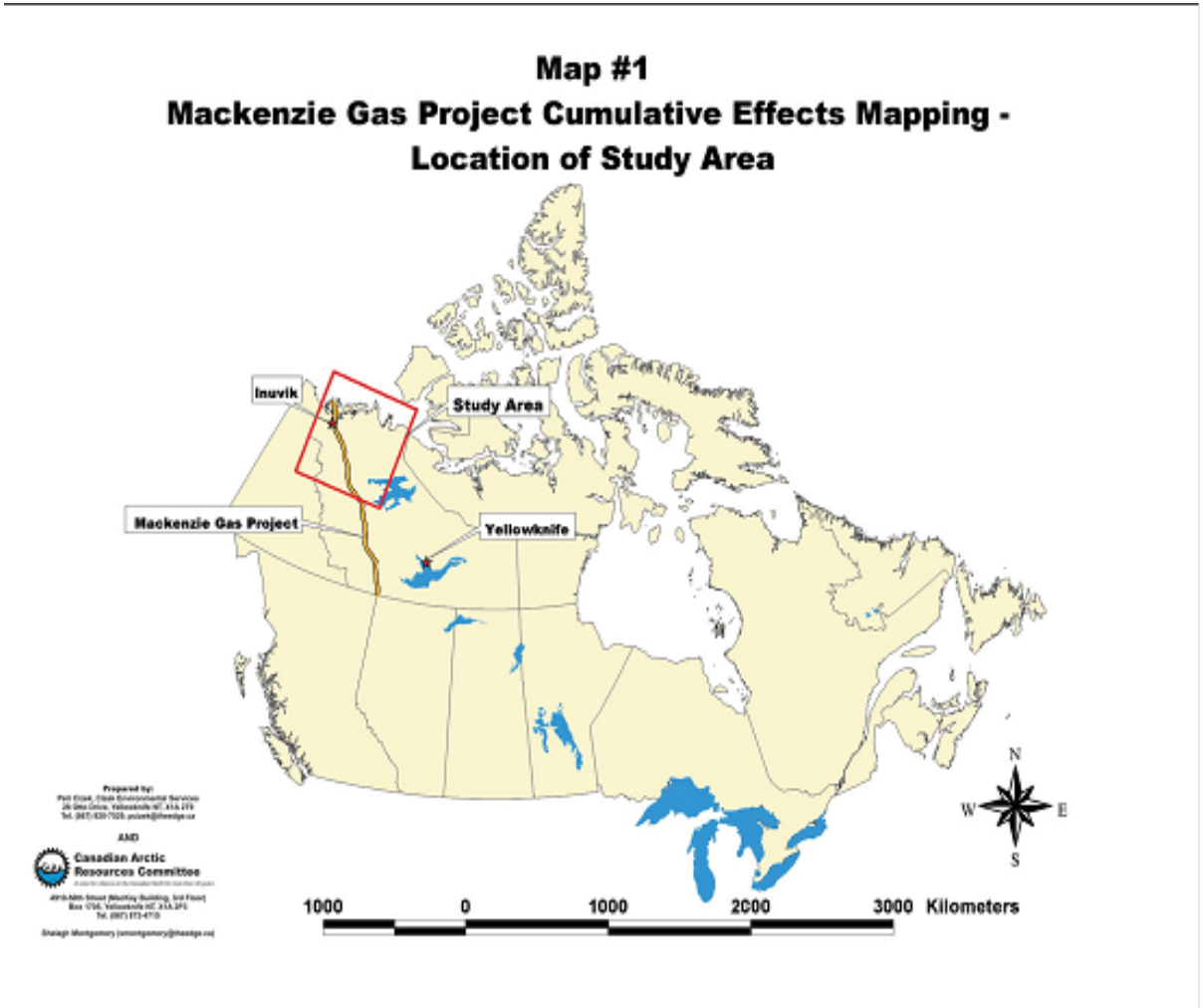
Mackenzie/Beaufort-Sea reserves of natural gas
10 Trillion m^3 (ca. 2% of world reserves)



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Mackenzie River

The Mackenzie River Watershed

one of the world's most spectacular wilderness areas,

is largely without roads, settlements, or development

- longest river in Canada at 1,738 km
- together with its headstreams:
  Peace and Finlay,

second longest river in North America at 4,241 km in length.

Mackenzie River is Canada's – and the world's – largest land ecosystem

The area is a pristine section of North America's Boreal Forest - a vast stretch of forests, lakes and wetlands

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Mackenzie River Habitat

- **Mackenzie River Watershed is woodland and barren ground Is home to:**
  - **caribou,**
  - **wolves,**
  - **lynx,**
  - **grizzly bears,**
  - **moose,**

- **The large marshy delta of the Mackenzie River provides habitat for:**
  - **migrating Snow Geese,**
  - **Tundra Swans, and**
  - **Brant**
  - **a breeding habitat for other waterfowl.**

- **The estuary is a calving area for Beluga whales.**

Mackenzie Gas Project (MGP)

Planned production of gas:

- **Niglintgak** area 28 billion m^3;
- **Taglu** area 85 billion m^3 ;
- **Parsons Lake** area 50 billion m^3

Environmental Impact at Niglintgak and Taglu

- **Main concern for Environment Canada**

Gas withdrawal will result in a compaction of the reservoirs and subsidence of the ground surface (ca. 800 km^2).

Subsidence = Flooding = environmental impact

The subsidence will cause flooding of several hundred hectars of low-lying land in the Mackenzie Delta,

causing the loss of a bird-nesting area in the Kendall Island Bird Sanctuary (KIBS).

Approval of the MG Project

If the MGP receives its approvals from Government of Canada, monitoring program of subsidence must be developed.

The monitoring is critical to:

- **verify predicted values of subsidence and**
- **determine impacts and adjustments to offsets if required.**

Some issues relevant to onshore production in the Mackenzie Delta

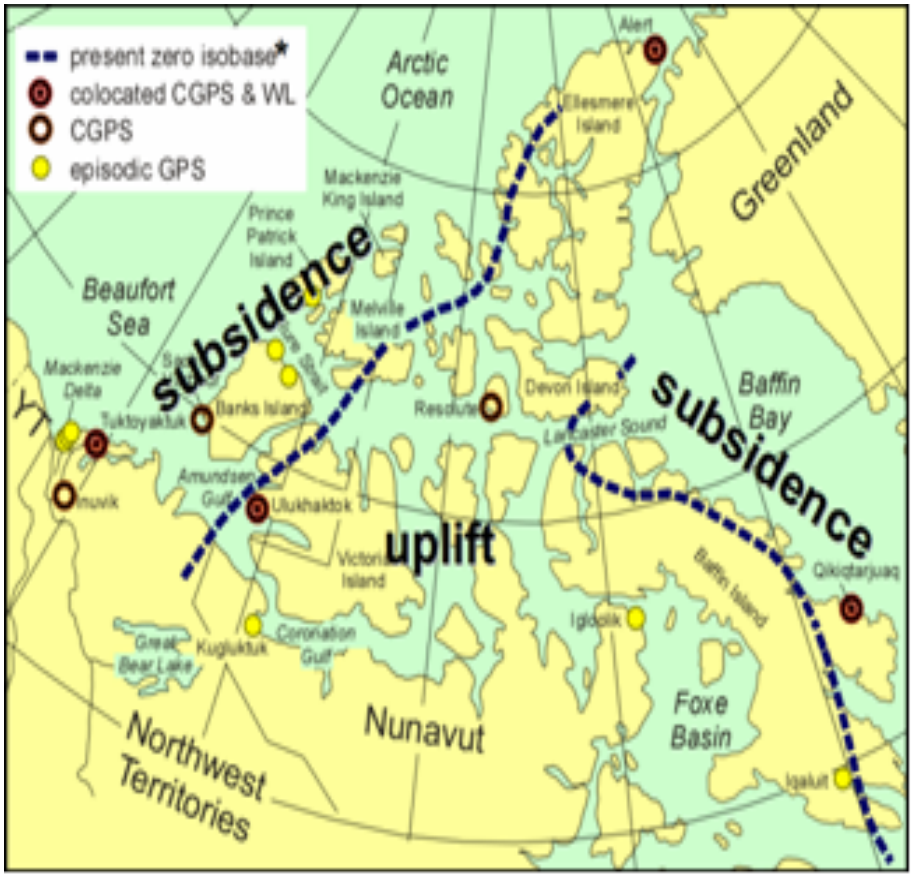
- Flooding hazards
  e.g. habitat inundation in KIBS;
  design freeboard for production facilities
- Sea-level rise
- Permafrost, ice-content, and other geotechnical properties affecting foundations and compaction processes in delta deposits
- Shoreline erosion
- Multiple sources of ground deformation (natural and gas production)

Natural Ground Deformation in Mackenzie Delta

- Postglacial isostatic adjustment
- Tectonic movements
- Degradation of permafrost due to warming trend and long-term settlement effect
- Changeable sedimentation loading
- Water surges and seasonal floodings

Challenge: separation of ground subsidence due to gas withdrawal from natural deformations

Subsidence/Uplift due to Isostatic Postglacial Adjustment or Tectonic Movements



45 years of water level records at Tuktoyaktuk show:

relative sea level rising

+ 3.5 mm/yr

10 years of continuous GPS records at Tuktoyaktuk show:

ground subsidence– 2.8 mm/yr

with respect to Active GPS in Inuvik, 120 km south

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GPS Surveys 2005-2009 in Mackenzie Delta

- Bi-annual Surveys at 15 stations

- **Drilled-in pipes (25 mm diam.) to the depth of 10 m to 30 m in permafrost**
- **Observation sessions: 3 days**
- **Average (8 stations) area subsidence:**

- 3.7 mm/year

with respect to Inuvik GPS (in bedrock) or

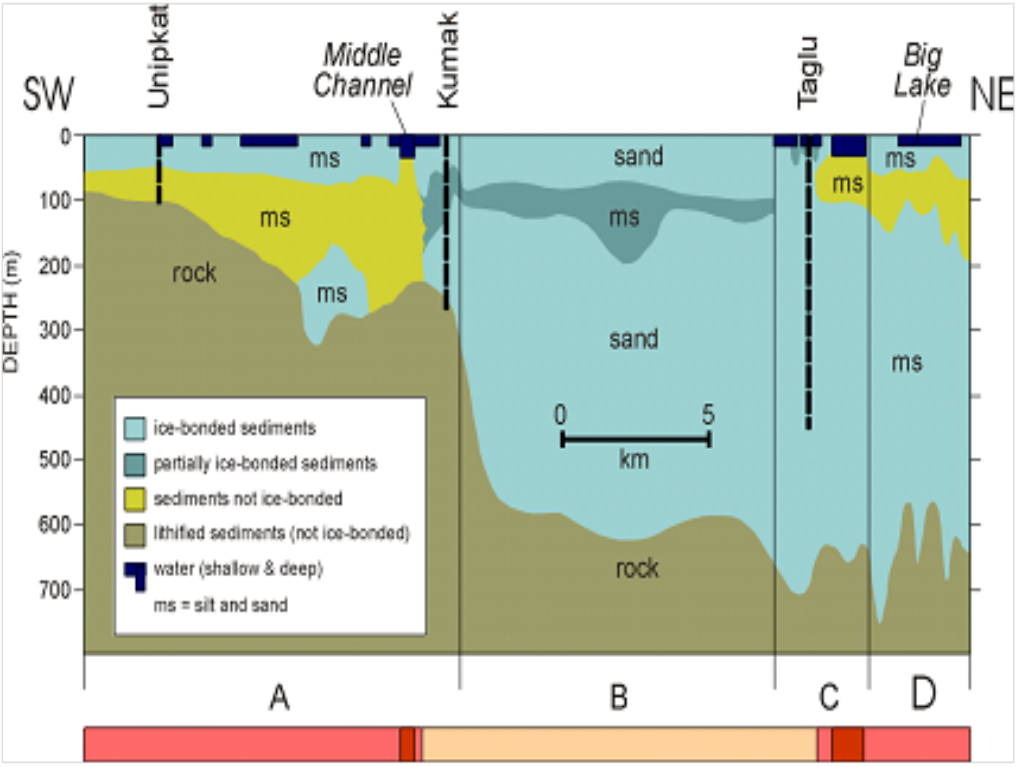
– 2.0 mm/yr

With respect to ITRF2005

D-InSAR Application

Preliminary application of D-InSAR not successful due to temporal decorelation

Seasonal and Long-term Deformation of Permafrost



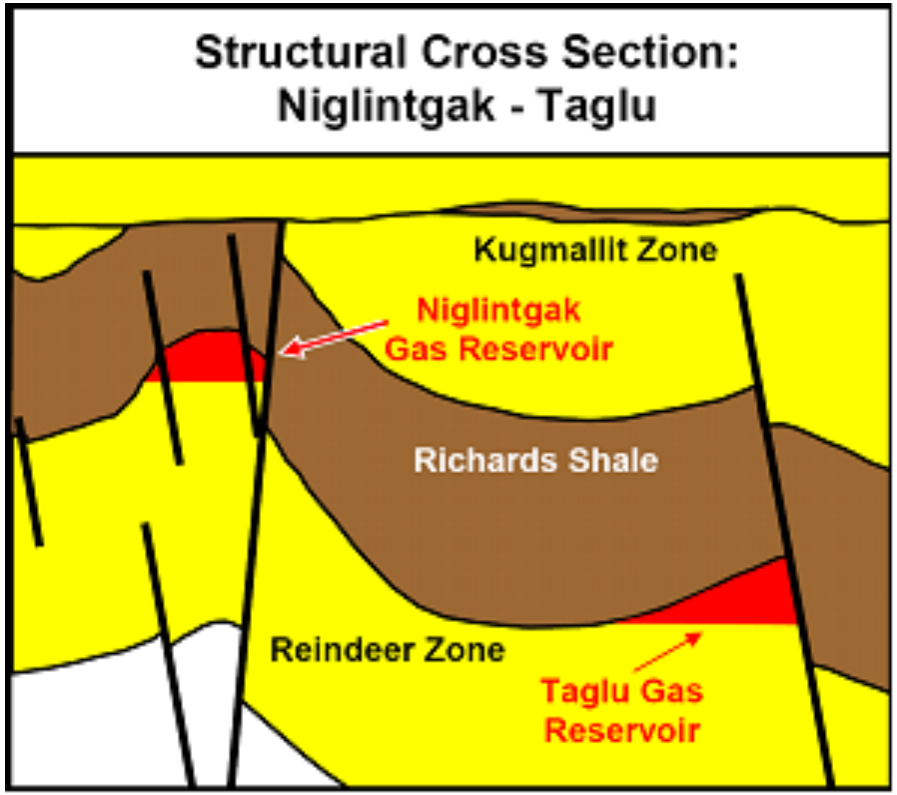
In the Mackenzie Delta, the air and ground temperature is increasing (1°C-13y)

Degradation of ice-rich non-homogeneus permafrost can lead to surface subsidence

Depth 700m at Taglu and 0-200m under water

Prediction of Ground Subsidence Due to Gas Withdrawal

Complexity of Faulting



Taglu: 5 stacked gas pools at 2400m -3200m

Niglintgak- 900m

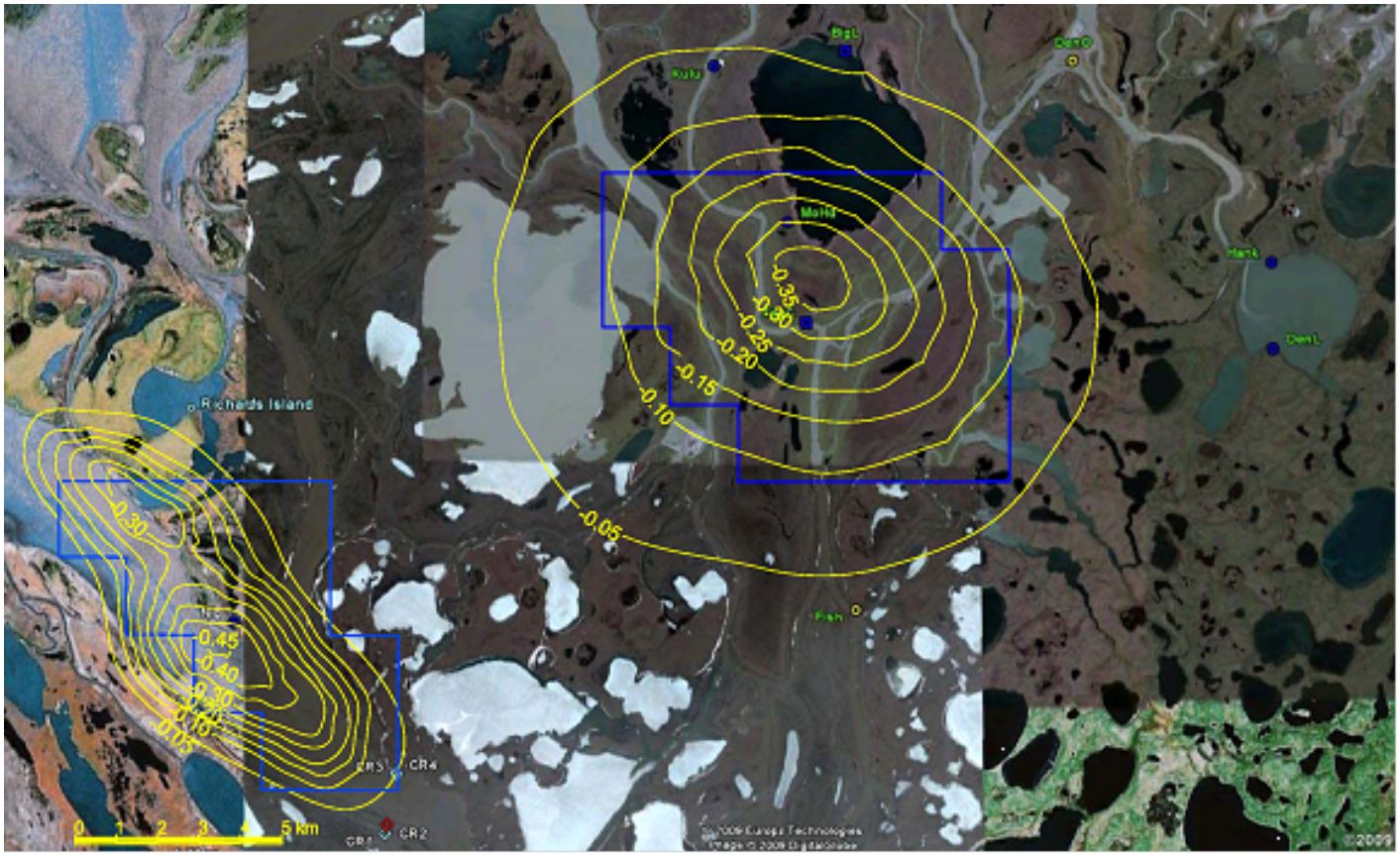
- **In-situ geomechanical parameters of the reservoir and overburden rocks are not well known.**
- **Laboratory tests may give too optimistic values.**

Prediction analysis

- FEM analysis gave a maximum expected subsidence estimated at ca. - 0.5 m/ 25 years
- larger values may be expected
- NEED FOR MONITORING

Predicted Ground Subsidence using FEM

Taglu --0.38 m and Niglintgak-- 0.45m Area -- 800 km^2



Monitoring Requirements

- sub-centimetre accuracy of displacements at 95% confidence level;
- three-dimensional information to be able to separate various causes of deformation;
- reliable
- robust to withstand the harsh conditions of the region, and
- must take under consideration the difficult and expensive access to the area either by
  - boat (slow and limited access to some points) during the short summers,
  - helicopter ($10,000/day),
  - by ice roads in the late winter (maintained only till the beginning of April).

Choice of Monitoring Technique

Considered:

- GPS (+ GLONASS + Galileo, if applicable)
- D-InSAR and CR-InSAR (with corner reflectors)
- Leveling
- Geotechnical Instruments (e.g. array of tiltmeters)

Selected:

- GPS for sub-surface monitoring with drilled-in pipes (63 mm diam.) to the depth of 15 m
- D-InSAR for monitoring total surface subsidence (if temporal coherence is achieved).

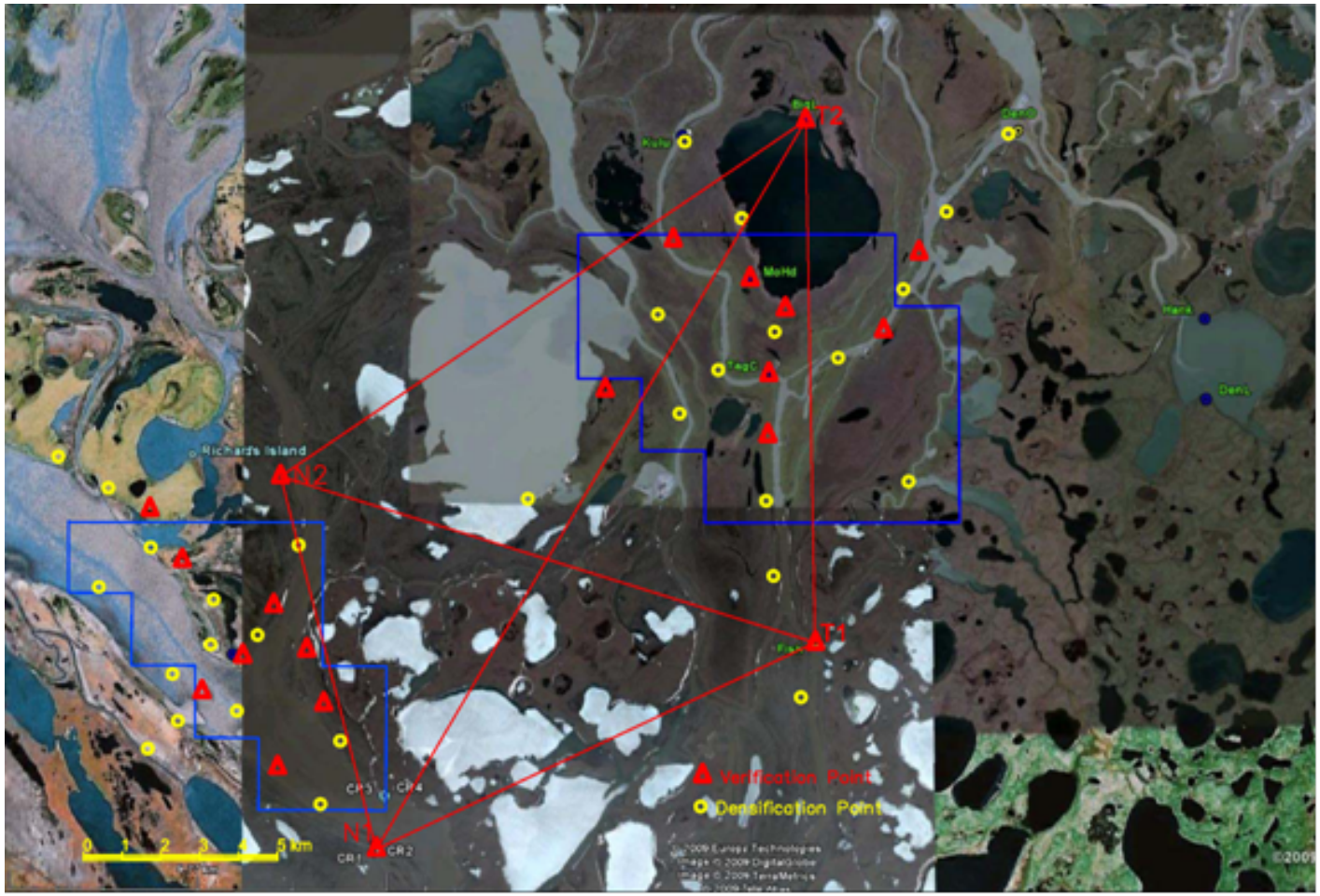
Design of the Monitoring Scheme

GPS – 50 points

red pts. observed annually

yellow pts. observed every 3 years)

with 4 local reference points



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Design of GPS Surveys

- 50 points observed using differential method with respect to 4 Local Control Points

  24 h– 48 h long sessions

- Local Control Points linked:

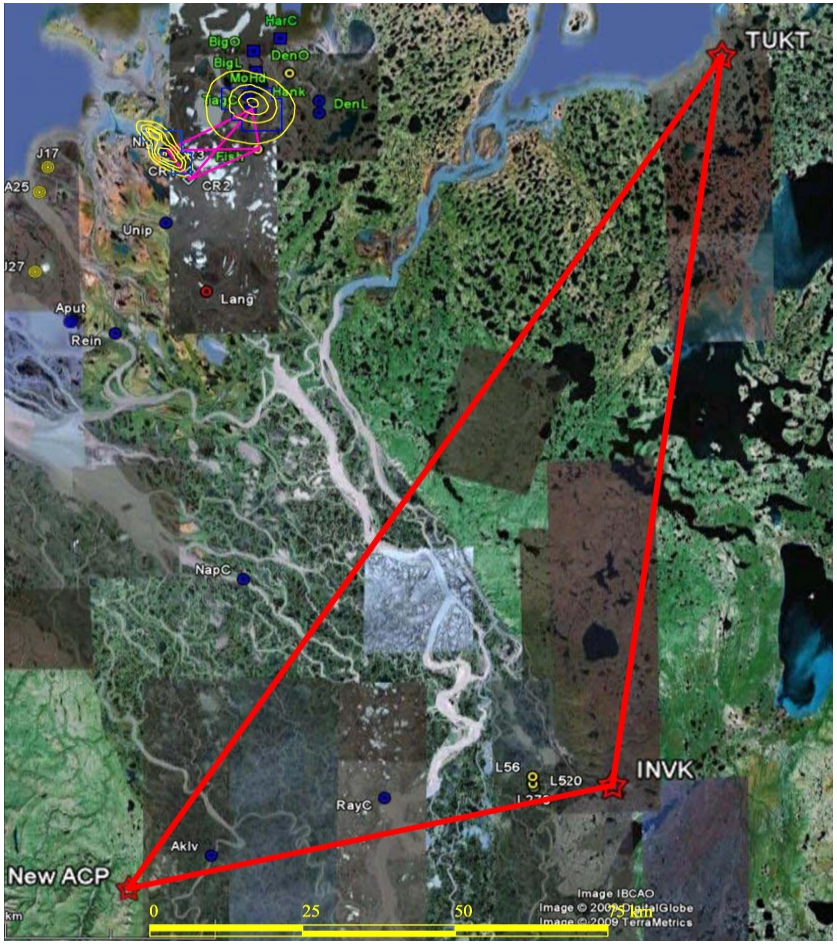
  either by differential measurements to 3-4 regional GPS

  active stations or

  directly to ITRF by

  using the **Precision Point Positioning (PPP)** method with 3-6 days of observations at each control point

Connecting Surveys to Regional Active GPS Network



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GPS +InSAR

- **If GPS is used alone, it will provide information only on the sub-surface (15 m deep) movements.**

- **More research is required on the use of D-InSAR to determine the total surface subsidence due to both natural causes and due to gas withdrawal**

Conclusions

Challenges to the separation of effects of ground subsidence

due to the gas withdrawal

from natural ground deformation phenomena

degradation of permafrost,

post-glacial rebound, and

sedimentation loading

Conclusions

Design of geodetic monitoring schemes, besides the accuracy and reliability requirements must consider:

the harsh conditions of the northern region and difficult and expensive access to the area.

GPS with deep monumentation in permafrost is considered as the main technology

If additional tests on obtaining temporal coherence will give positive results,

conventional InSAR technology will be added to the monitoring scheme to provide spatially continuous information on the total surface subsidence.