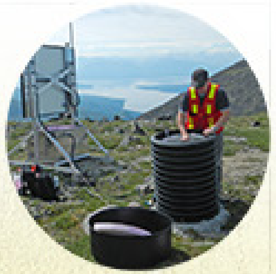
Natural Resources Canada
Ressources naturelles Canada

Geological Survey of Canada
Scientific Presentation 144

Public presentations (126th) of May 10th, 2022: Environmental Geoscience Program, current status of research projects for the 2019-2024 program cycle

J. Aubut Bernard[1], P.M. Outridge[2], H. Kao[3], C. Rivard[1], A.J. Desbarats[2], J. Jautzy[1], J.M. Galloway[4], and S. Larmagnat[1]

[1]Geological Survey of Canada, 490, rue de la Couronne, Québec, Quebec
[2]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
[3]Geological Survey of Canada, 9860 West Saanich Road, Sidney, British Columbia
[4]Geological Survey of Canada, 3303-33rd Street N.W., Calgary, Alberta

2022

Canada

Presented at: Public presentations (126th) May 10, 2022: Environmental Geoscience Program, current status of research projects (phase 2019-2024)

Date presented: May 2022

Permanent link: https://doi.org/10.4095/330891

This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).

Recommended citation

Aubut Bernard, J., Outridge, P.M., Kao, H., Rivard, C., Desbarats, A.J., Jautzy, J., Galloway, J.M., and Larmagnat, S., 2022. Public presentations (126th) of May 10th, 2022: Environmental Geoscience Program, current status of research projects for the 2019-2024 program cycle; Geological Survey of Canada, Scientific Presentation 144, 1 .pdf file. https://doi.org/10.4095/330891

Publications in this series have not been edited; they are released as submitted by the author.

Natural Resources Canada

Ressources naturelles Canada

Canada

Environmental Geoscience Program (EGP)
Presentation of research status for 7 out of 15 projects in 2021-2022

The goal of the EGP is to provide innovative scientific information that makes it possible to distinguish between the environmental effects of natural resource development and those produced by natural processes. As part of this mandate, developing new approaches in geoscience supports the responsible use and development of Canada's natural resources through informed decision-making.

The ultimate outcome of the EGP is to increase the effectiveness and efficiency of Canadian environmental regulation and oversight. In developing innovative geoscience for environmental stewardship, as well as increasing public and private sector access to research findings, decision makers have a greater capacity to carry out and review environmental assessments.

Due to the pandemic, research advancement occasionally faced delay due to laboratory closure and lack of fieldwork access. Nevertheless, the advancement of projects is documented herein and via the EGP YouTube account. The talks on this work were recorded during the public presentations via Zoom on May 10 and 17, 2022 are available via the following link:
https://www.youtube.com/channel/UCWiCrKnTeF-j_La6_Wc5NMA/playlists

Key words: *Clumped isotope geothermometry, induced seismicity, impacts on aquifers, diluted bitumen, modelling in oil sands region, marine oil spill, Mackenzie River Basin, climate change, UNEP global mercury assessment, geological storage of carbon, cumulative effects, permafrost degradation, permafrost geochemistry, dredge disposal at sea and regional assessment.*

Programme de géosciences environnementales (PGE)
Présentation de l'état d'avancement des recherches pour 7 des 15 projets en 2021-2022.

L'objectif du PGE est de fournir des informations scientifiques novatrices qui permettent de distinguer les effets environnementaux de l'exploitation des ressources naturelles de ceux produits par les processus naturels. Dans le cadre de ce mandat, le développement de nouvelles approches en géosciences soutient l'utilisation et le développement responsable des ressources naturelles du Canada par une prise de décision éclairée.

Le résultat ultime du PGE est d'accroître l'efficacité et le rendement de la réglementation et de la surveillance environnementale au Canada. En développant de la géoscience novatrice pour la gestion de l'environnement, ainsi qu'en augmentant l'accès des secteurs public et privé aux résultats de la recherche, les décideurs ont une plus grande capacité à effectuer et à examiner les évaluations environnementales.

En raison de la pandémie, l'avancement des recherches a parfois été retardé par la fermeture des laboratoires et le manque d'accès au travail sur le terrain. Néanmoins, l'avancement des projets est documenté dans le présent document et sur le compte YouTube du PGE. Les exposés sur ces travaux ont été enregistrés lors des présentations publiques via Zoom les 10 et 17 mai, 2022 et sont disponibles via le lien suivant: https://www.youtube.com/channel/UCWiCrKnTeF-j_La6_Wc5NMA/playlists

Mots clé: *Clumped isotope geothermometry, induced seismicity, impacts on aquifers, diluted bitumen, modelling in oil sands region, marine oil spill, Mackenzie River Basin, climate change, UNEP global mercury assessment, geological storage of carbon, cumulative effects, permafrost degradation, permafrost geochemistry, dredge disposal at sea and regional assessment.*

DAY 1 : May 10, 2022 // JOUR 1 : 10 mai, 2022

Ressources naturelles Canada
Natural Resources Canada

Filling Knowledge Gaps in Global Mercury Science - Research in Support of the UNEP Global Mercury Assessment

Combler les lacunes scientifiques sur le mercure mondial - Recherche à l'appui de l'évaluation mondiale du mercure du PNUE

Peter Outridge. May 2022



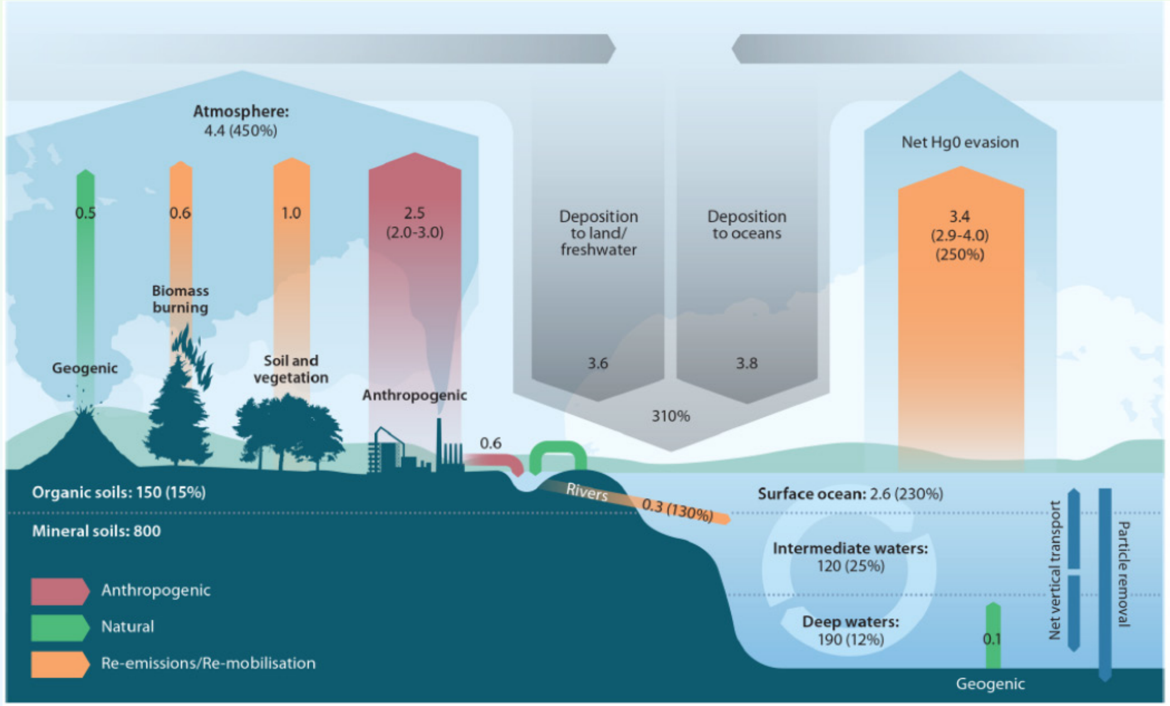

Canada

Activities

- 1. Volcanic mercury emissions
- 2. Deep-ocean trench mercury
- 3. Publications from AMAP 2021 Arctic Mercury Assessment

Project Context – Activities 1 & 2

- Importance of natural processes & sources in the global Hg story.
- Total geogenic Hg emissions to air poorly constrained (<1 – ~30% of anthropogenic emissions, i.e. <10 – 900 tonnes/yr).
- Iceland Hg studies 1970s support very high natural emission estimate
  - many 10,000s ng Hg/m^3.
- Oceans as largest final repository for Hg in environment. Rate poorly constrained by sampling (none until our study).



AMAP/UNEP (2018) Global Mercury Budget

ABSTRACT – 1. Volcanic Mercury Emissions

- Goal: Help fill key knowledge gap in natural Hg cycle (volcanic systems' emissions), a weakness in global Hg budget supporting Minamata Convention on Mercury, 2017.
- Focus on Icelandic volcanic systems (possible high Hg emitters).
- Progress on schedule.

Brock Edwards sampling gaseous Hg at Fagradalsfjall fissure eruption, Aug 2021

PROJECT MEMBERS – 1. Volcanic Mercury Emissions

- Peter Outridge, GSC P.L.
- Brock Edwards (NRCan RAP-PhD student)
- Feiyue Wang, U. Manitoba
- Melissa Pfeffer & Michelle Parks, Icelandic Met. Office
- Hamed Sanei, Aarhus U., Denmark
- Bruce Kjarsgaard, GSC

Progress (Apr '21- Mar '22)

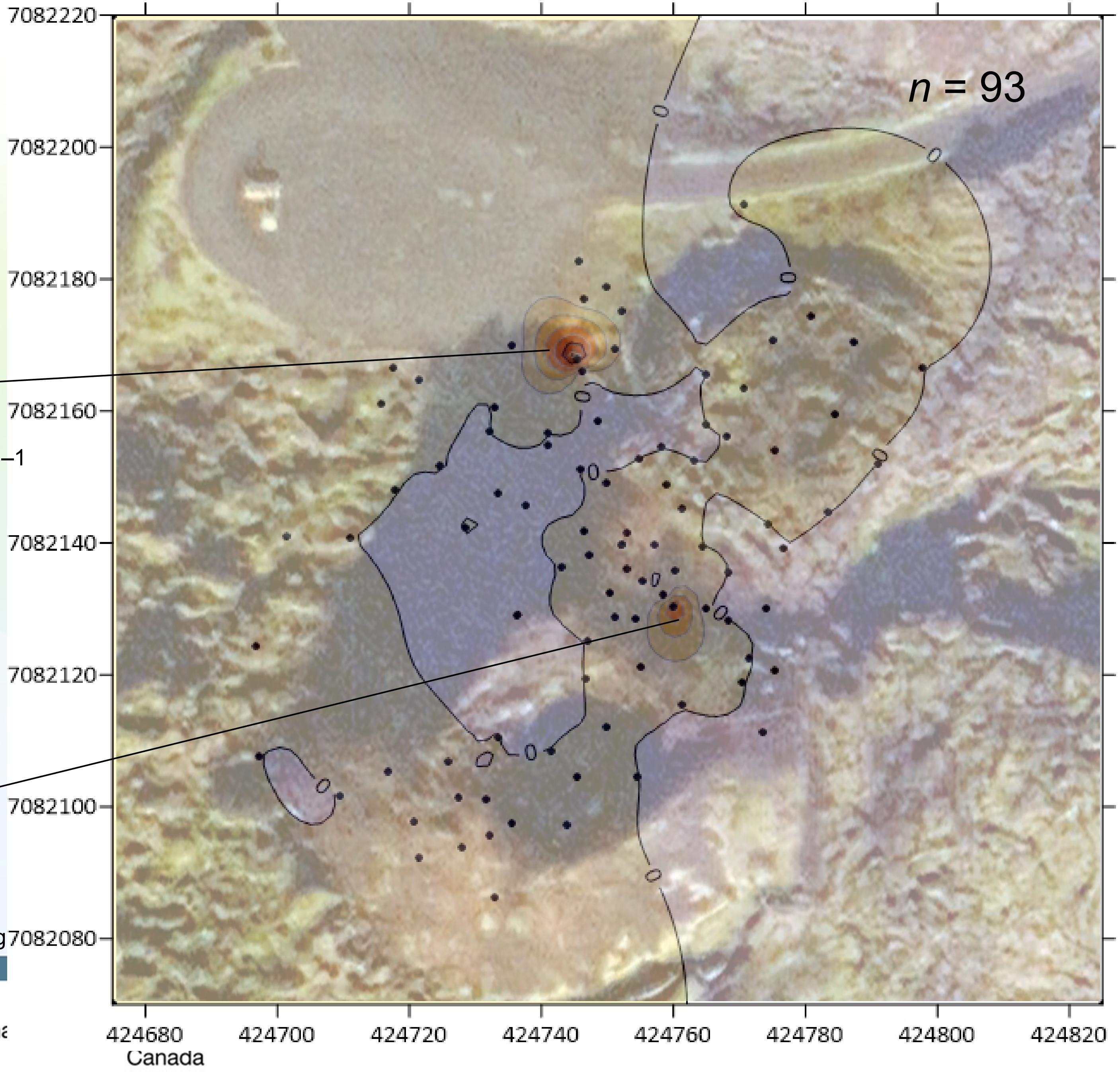
- Brock's PhD course work completed;
- 3rd Icelandic field trip (August 2021);
- passive & active sampling of gaseous Hg from erupting Fagradalsfjall fissure;
- Spatially intensive soil gas Hg measurements show previously unrecognized high subsoil Hg levels that may drive high fluxes into air;
- Sampling methods inter-comparison of gas Hg concentrations (new flux measurement method for soil Hg emissions adapted from volatile organics; active & passive samplers; real-time Lumex measurements vs samplers).

Eldvörp

ELD-59
ΔC= 2450 ng m^{-3}
Soil Hg content:
19,298 ± 2,618 ng g^{-1}

(Eldvörp median
1,071 ng g^{-1})

ELD-88
ΔC= 8655 ng m^{-3}
Soil Hg content:
7,056 ± 209.5 ng g^{-1}



Area average
0.21 x 10^{-6} g/m^2/d

Novel drone-based airborne sampling of volcanic plumes

Active sampling of particulate Hg (& other metals) directly within volcanic plumes

Brock Edwards & Evgenia Ilyinskaya (U. of Leeds, UK) preparing drone for sampling the Fagradalsfjall eruption plume, August 2021.

Activity 2. Deep-ocean trench mercury
Team members

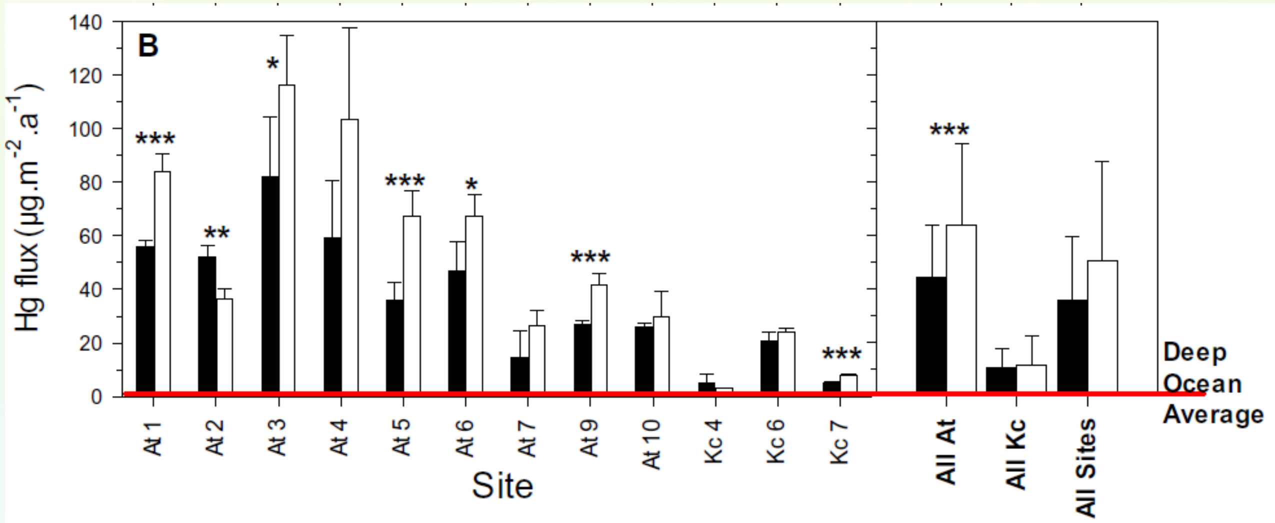
- Hamed Sanei, Aarhus U., Denmark
- Peter Outridge, GSC
- Feiyue Wang, U. Manitoba
- Ronnie Glud, U. Southern Denmark (Hadal Research Group)

Deep-ocean sediment core retrieval, Atacama Trench, Pacific Ocean, on board *Polarstern.*

- Sanei H, Outridge PM, Oguri K, Stern GA, Thamdrup B, Wenzhöfer F, Wang F, and Glud RN. 2021. High mercury accumulation in deep-ocean hadal sediments. **Scientific Reports** 11: 10970. doi: 0.1038/s41598-021-90459-1.

Deep-ocean (>6 km) sediment Hg fluxes may be many times higher than ocean models predict.

→ Reliability of the ocean models??



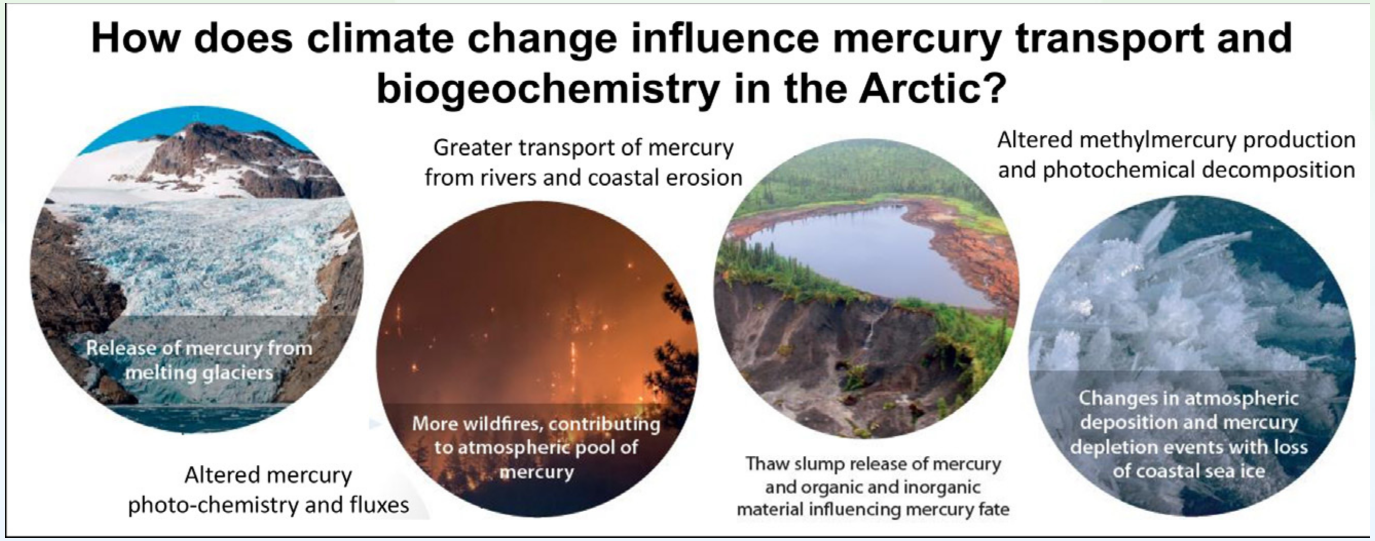
- 2,903 downloads since publication

- 98th percentile all natural science papers published since May 2021.

Activity 3. Publications from AMAP 2021

Dastoor A, Angot H, Bieser J, Christensen JH, Douglas TA, Heimbürger-Boavida L-E, Jiskra M, Mason RP, McLagan DS, Obrist D, Outridge PM, Petrova MV, Ryjkov A, St. Pierre KA, Schartup AT, Soerensen AL, Toyota K, Travnikov O, Wilson J, and Zdanowicz C. 2022. Arctic mercury cycling. **Nature Reviews Earth & Environment** doi.org/10.1038/s43017-022-00269-w.

Chételat J, McKinney MA, Amyot M, Dastoor A , Douglas TA, Heimbürger-Boavida L-E, Kirk J, Kahilainen KK, Outridge PM, Pelletier N, Skov H, St. Pierre K, Vuorenmaa J, and Wang F. 2022. Climate change and mercury in the Arctic: Abiotic interactions. **Science of the Total Environment** doi.org/10.1016/j.scitotenv.2022.153715



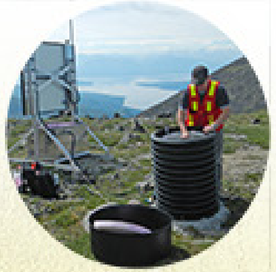
CONTACT DETAILS

- Peter Outridge
- Contact: Peter.Outridge@nrcan-rncan.ca

THANK YOU

Natural Resources Canada | Ressources naturelles Canada




Geological Survey of Canada
Scientific Presentation 02

Induced Seismicity Research Project:
Highlights of Accomplishments in 2021-2022
Projet de recherche sur la sismicité induite :
Faits saillants des réalisations en 2021-2022

H. Kao

May 10, 2022

Canada

ABSTRACT

The Induced Seismicity Research (ISR) project has a national scope with team members from NRCan offices in Sidney, Ottawa, and Quebec City. The Project establishes close collaboration with both public and private sectors, including provincial and local governments, crown corporations, professional organizations, and academia, to address critical knowledge gaps in the source process of induced earthquakes and to provide observation-based science to improve regulations on the development of unconventional hydrocarbon resources.

Key accomplishments during 2021-2022 include:

- Compilation of injection-induced earthquake (IIE) catalogues for west Canada;
- Publications of research results on source characteristics of significant IIE events in Canada;
- Development of innovative methodologies for detection and location of repeating earthquakes and precise earthquake focal depths;
- Enhanced IIE monitoring for major shale gas basins in BC and AB.
- Media interviews, including live programs by CBC and local radio stations, on significant IIE events and IIE research.

KEY PROJECT MEMBERS

- GSC Research Scientists and Supporting Staff
  - Sidney: Honn Kao (Project Leader), John Cassidy, Ramin Dokht
  - Ottawa: Don White, Maurice Lamontagne (Retired in Jan 2022)
  - Quebec: Nathalie Jacob, Joby Aubut Bernard and Christine Laberge (admin support)

- GSC Research Associates and Supports
  - Alireza Babaie Mahani and Ryan Visser (scientists funded by Geoscience BC)
  - Bei Wang (UVic PDF funded by Geoscience BC)
  - Fengzhou Tan and Chet Goerzen (UVic graduate students)
  - Amir Farahbod, Jesse Hutchinson, Adebayo Ojo, and Hongyu Yu (contractors and volunteers)

Collaboration Highlights

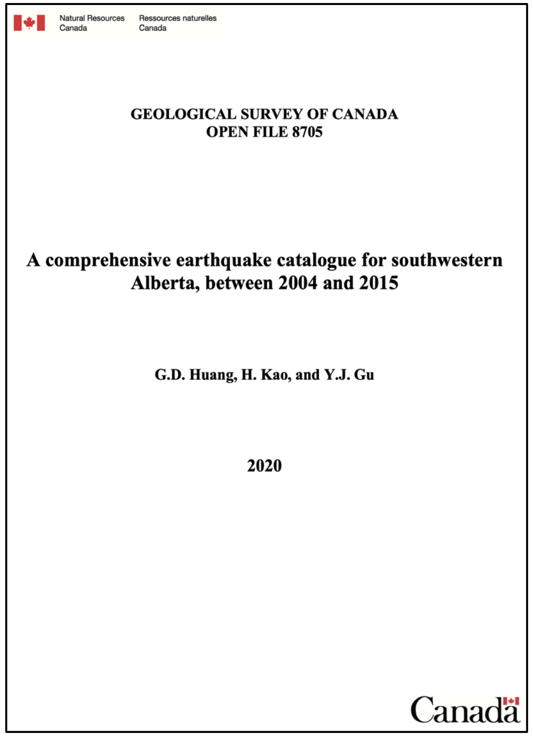
- Multi-lateral Collaboration on Induced Earthquake Study
  - Sign a collaborative agreement with Ovintiv Canada to establish a dense seismic array to study the source process of hydraulic fracturing-induced earthquakes at unprecedented resolution. This experiment received funding support from Innovation Solutions Canada ($400,500 in total) and logistical support from Symroc Inc., and BC Oil and Gas Commission.

- External Research Resources
  - $154,800 from Geoscience BC in support of the routine operation of seismograph stations and injection-induced earthquake (IIE) research in NE BC.
  - $135K contributed by the BC Seismic Research Consortium in support of IIE monitoring in the WCSB.

- Enhanced Local and Regional Seismograph Coverage of Western Canada
  - McGill University, University of Victoria, University of Calgary, Ruhr University Bochum (Germany), Geoscience BC, BC Oil and Gas Commission (BCOGC) and Canadian Association of Petroleum Producers (CAPP)

- Joint IIE Research and Publications
  - McGill University, University of Victoria, University of Calgary, Ruhr University Bochum (Germany), Geoscience BC, and BC Oil and Gas Commission

Comprehensive IIE Catalogues


Natural Resources Canada / Ressources naturelles Canada

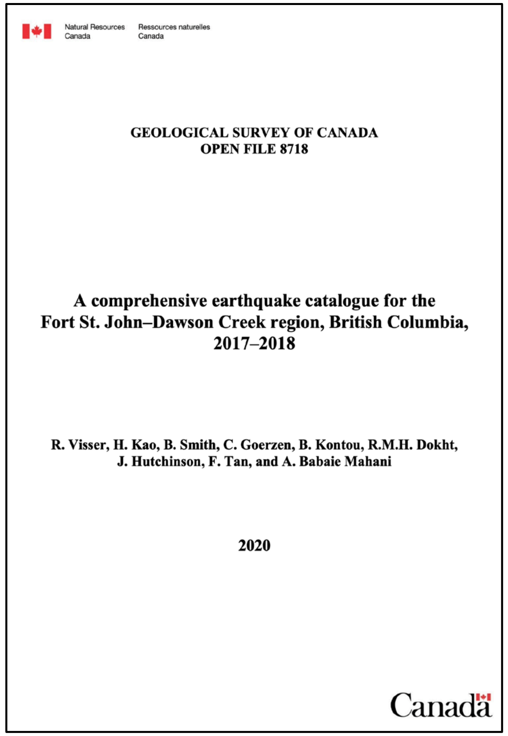
GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8705

A comprehensive earthquake catalogue for southwestern Alberta, between 2004 and 2015

G.D. Huang, H. Kao, and Y.J. Gu

2020

Canada


Natural Resources Canada / Ressources naturelles Canada

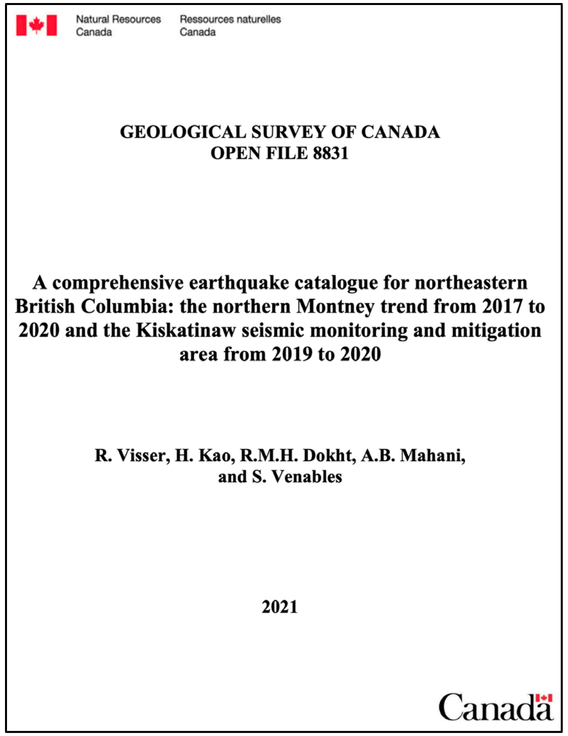
GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8718

A comprehensive earthquake catalogue for the Fort St. John–Dawson Creek region, British Columbia, 2017–2018

R. Visser, H. Kao, B. Smith, C. Goerzen, B. Kontou, R.M.H. Dokht, J. Hutchinson, F. Tan, and A. Babaie Mahani

2020

Canada


Natural Resources Canada / Ressources naturelles Canada

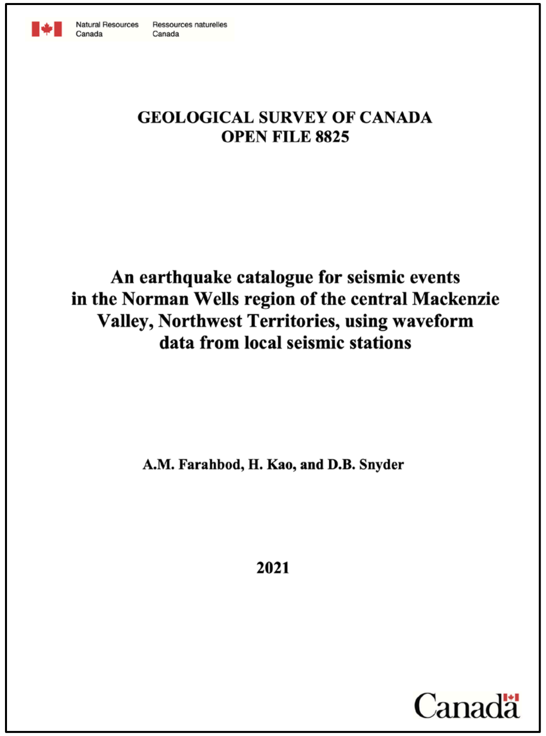
GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8831

A comprehensive earthquake catalogue for northeastern British Columbia: the northern Montney trend from 2017 to 2020 and the Kiskatinaw seismic monitoring and mitigation area from 2019 to 2020

R. Visser, H. Kao, R.M.H. Dokht, A.B. Mahani, and S. Venables

2021

Canada


Natural Resources Canada / Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8825

An earthquake catalogue for seismic events in the Norman Wells region of the central Mackenzie Valley, Northwest Territories, using waveform data from local seismic stations

A.M. Farahbod, H. Kao, and D.B. Snyder

2021

Canada

All IIE catalogues are published as Geological Survey of Canada (GSC) Open File Reports, freely available at NRCan's GEOSCAN database.
Daily earthquake catalogues are provided to BCOGC for regulatory purposes.

13 journal papers

Key Publications

AGU ADVANCING EARTH AND SPACE SCIENCE

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2020JB021362

Key Points:
- A clustering analysis is performed to investigate the spatiotemporal correlation between seismicity and injection activity in western Canada
- Seismotectonic state of the injection sites is quantitatively characterized using the estimates of the seismogenic index
- Statistical models are presented to forecast the magnitudes of the largest expected events induced by deep fluid injection

Supporting Information:

Spatiotemporal Analysis of Seismotectonic State of Injection-Induced Seismicity Clusters in the Western Canada Sedimentary Basin

Ramin M. H. Dokht[1], Honn Kao[1,2], Alireza Babaie Mahani[3], and Ryan Visser[1,3]

[1]Pacific Geoscience Centre, Geological Survey of Canada, Natural Resources Canada, Sidney, BC, Canada, [2]School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada, [3]Geoscience BC, Vancouver, BC, Canada

Abstract The observations of spatiotemporal distribution of seismicity in western Canada indicate that the occurrence of earthquakes is tied to the hydraulic fracturing operations and disposal of coproduced wastewater. In this study, we investigate the temporal changes in the frequency-magnitude distributions for multiple clusters of induced events in regions where the level of background seismicity is low. The induced events are clustered into six major groups using density-based spatial and soft clustering algorithms based on their epicenters. Each cluster is identified by different distributions of earthquake ... earthquakes ... the ... seismogenic ... agnitude ... d seismic ... ectonically

AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL093979

Key Points:
- We document a complex 3D source migration process with delayed mainshock triggering that is controlled by a local hydrogeological setting
- Poroelastic effects contribute to induced events but are probably insufficient to activate a large fault segment not critically stressed
- Rapid pore-pressure build-up can be very localized and lead to large earthquakes if adequate hydrological paths exist

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
H. Kao,
honn.kao@canada.ca

Citation:
Gao, D., Kao, H., Wang, B., Visser, R., Schultz, R., & Harrington, R. M. (2022). Complex 3D migration and delayed triggering of hydraulic fracturing-induced seismicity: A case study near Fox Creek, Alberta. Geophysical Research Letters, 49, e2021GL093979. https://doi.org/10.1029/2021GL093979

Received 20 APR 2021
Accepted 10 DEC 2021

Complex 3D Migration and Delayed Triggering of Hydr... Fracturing-Induced Seismicity: A Case Study Near Fox... Alberta

Dawei Gao[1,2], Honn Kao[1,2], Bei Wang[1,2], Ryan Visser[2], Ryan Schultz[3], and Rebecca M. Harrington[4]

[1]School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada, [2]Pacific Geoscience Centr... Survey of Canada, Sidney, BC, Canada, [3]Department of Geophysics, Stanford University, Stanford, CA, USA, ... University Bochum, Institute of Geology, Mineralogy, and Geophysics, Bochum, Germany

Abstract Earthquakes resulting from hydraulic fracturing (HF) can have delayed triggering re... injection commencement over a varied range of time scales, with the majority of $M \geq 4$ mainshock... near/after well completion. This poses serious challenges for risk mitigation and hazard assessmen... document a high-resolution, three-dimensional source migration process with delayed mainshock t... that is controlled by local hydrogeological conditions near Fox Creek, Alberta, Canada. Our result... poroelastic effects might contribute to induced seismicity, but are probably insufficient to activate ... segment not critically stressed. The rapid pore-pressure build-up from HF can be very localized an... of producing large, felt earthquakes if adequate hydrological paths exist. We interpret the delayed t... as a manifestation of pore-pressure build-up along pre-existing faults needed to facilitate seismic f... findings can explain why so few injection operations are seismogenic.

Plain Language Summary Fluid injection-induced earthquakes (IIE), especially those... mainshocks, are often observed to occur near or after well completion. Such delayed triggering rel... injection commencement poses serious challenges for both regulators and the energy industry to e... effective mitigation strategy for the potential seismic risk. In this study, we reveal a high-resolutio... three-dimensional pattern of IIE migration near Fox Creek, Alberta, Canada. The observed first-o... then-inward IIE sequence highlights the significance of hydrogeological networks in facilitating fl... migration and the associated seismic failure. The detailed spatiotemporal distribution of IIE sugge... effect of pore-pressure build-up from hydraulic fracturing (HF) can be very localized. The delayed... is a combined result of the fluid pressure migration and the current stress state of the hosting fault... from the HF wells. The findings from this study also provide plausible explanations on why only a... number of fluid injections are seismogenic.

scientific reports

OPEN

InSAR data revea... hydraulic fracturi... earthquake in Ca...

... Wa... ...ting... ...ing... ...caus... ...ati... ...g hy... ...n o... ...duc... ...e o... ...ent... ...nes.

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

ELSEVIER

Spatiotemporal changes in seismic velocity associated with hydraulic fracturing-induced earthquakes near Fox Creek, Alberta, Canada

Adebayo Oluwaseun Ojo[a,*], Honn Kao, PhD[a,b], Ryan Visser[a,c], Chet Goerzen[b]

[a] Geological Survey of Canada, Natural Resources Canada, Sidney, British Columbia, Canada
[b] School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada
[c] Geoscience BC, Vancouver, British Columbia, Canada

ARTICLE INFO

Keywords:
Hydraulic fracturing
Coda wave interferometry
Seismic noise
Temporal velocity change

ABSTRACT

To characterize the subsurface geomechanical response to hydraulic fracturing (HF) activities, we study the spatiotemporal changes of seismic velocity during the completion of four HF wells in the Fox Creek area, Alberta, Canada. We estimate temporal velocity changes (dv/v) from ambient seismic noise recorded during the Tony Creek Dual Microseismic Experiment (ToC2ME) by comparing a 5-day stacked noise correlation function with a reference noise correlation function stacked over the deployment period. In the frequency band (0.1–0.4 Hz) most sensitive to the injection depths (~3.4 km), we observe daily dv/v that revealed alternating gradual velocity decreases and increases with magnitudes in the range of ±0.9%. We found a strong temporal correlation between the onset of velocity decreases and periods of intense seismicity, suggesting that the observed dv/v reductions are likely caused by stress-induced subsurface deformation due to elevated pore pressures, increased crack density, and ground shaking. A period of dv/v increase observed between the beginning and end of different well stimulation is attributed to crustal healing. Comparing the dv/v time series with injection parameters, we observed a 272.66% increase in induced seismicity and 50% more reduction in dv/v during the second injection phase that are correlated with 90.53%, 169.64%, and 4.34% increase in the injection volume, rate, and pressure, respectively. Our study provides valuable new information on the changes in reservoir elastic properties within the Western Canadian Sedimentary Basin. It also demonstrates that coda wave interferometry using data from dense seismic arrays near injection sites can be an additional tool for monitoring hydraulic fracturing operations.

nature COMMUNICATIONS

ARTICLE

Check for updates

https://doi.org/10.1038/s41467-021-26961-x OPEN

Fluid-injection-induced earthquakes characterized by hybrid-frequency waveforms manifest the transition from aseismic to seismic slip

Hongyu Yu[1,2✉], Rebecca M. Harrington[2], Honn Kao[1,3✉], Yajing Liu[4] & Bei Wang[1,3]

Aseismic slip loading has recently been proposed as a complementary mechanism to induce moderate-sized earthquakes located within a few kilometers of the wellbore over the time-scales of hydraulic stimulation. However, aseismic slip signals linked to injection-induced earthquakes remain largely undocumented to date. Here we report a new type of earthquake characterized by hybrid-frequency waveforms (EHWs). Distinguishing features from typical induced earthquakes include broader P and S-pulses and relatively lower-frequency coda content. Both features may be causally related to lower corner frequencies, implying longer source durations, thus, either slower rupture speeds, lower stress drop values, or a combination of both. The source characteristics of EHWs are identical to those of low-frequency earthquakes widely documented in plate boundary fault transition zones. The distribution of EHWs further suggests a possible role of aseismic slip in fault loading. EHWs could thus represent the manifestation of slow rupture transitioning from aseismic to seismic slip.

AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL092815

Key Points:
- There is no simple relationship between cross-correlation coefficient (CC) and interevent separation
- CC is affected by many factors and thus lacks the resolution to determine two events as true repeating or just neighboring

Misconception of Waveform Similarity ... Identification of Repeating Earthquakes

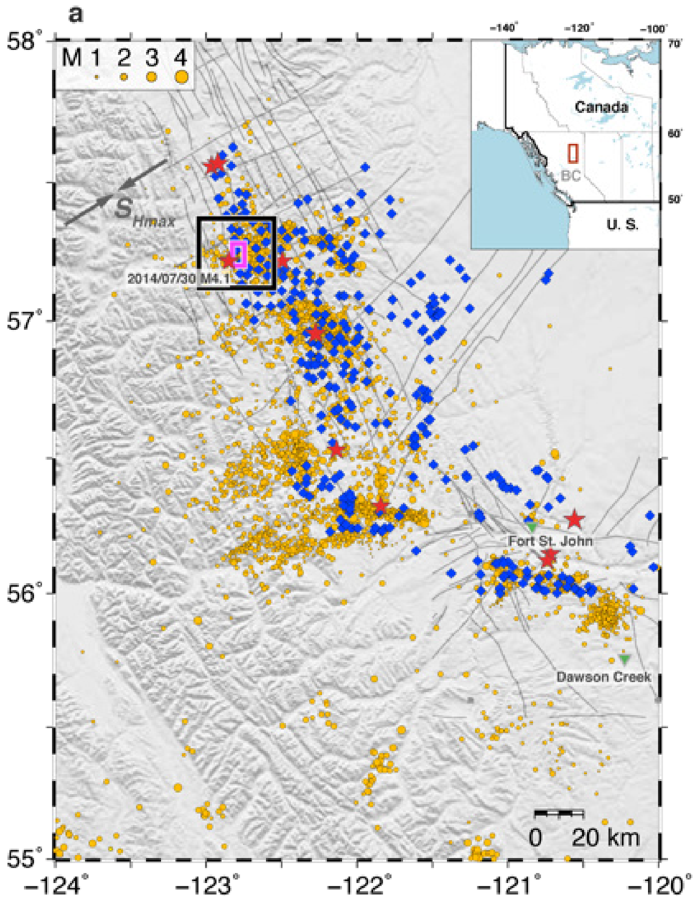
Dawei Gao[1,2], Honn Kao[1,2], and Bei Wang[1,2]

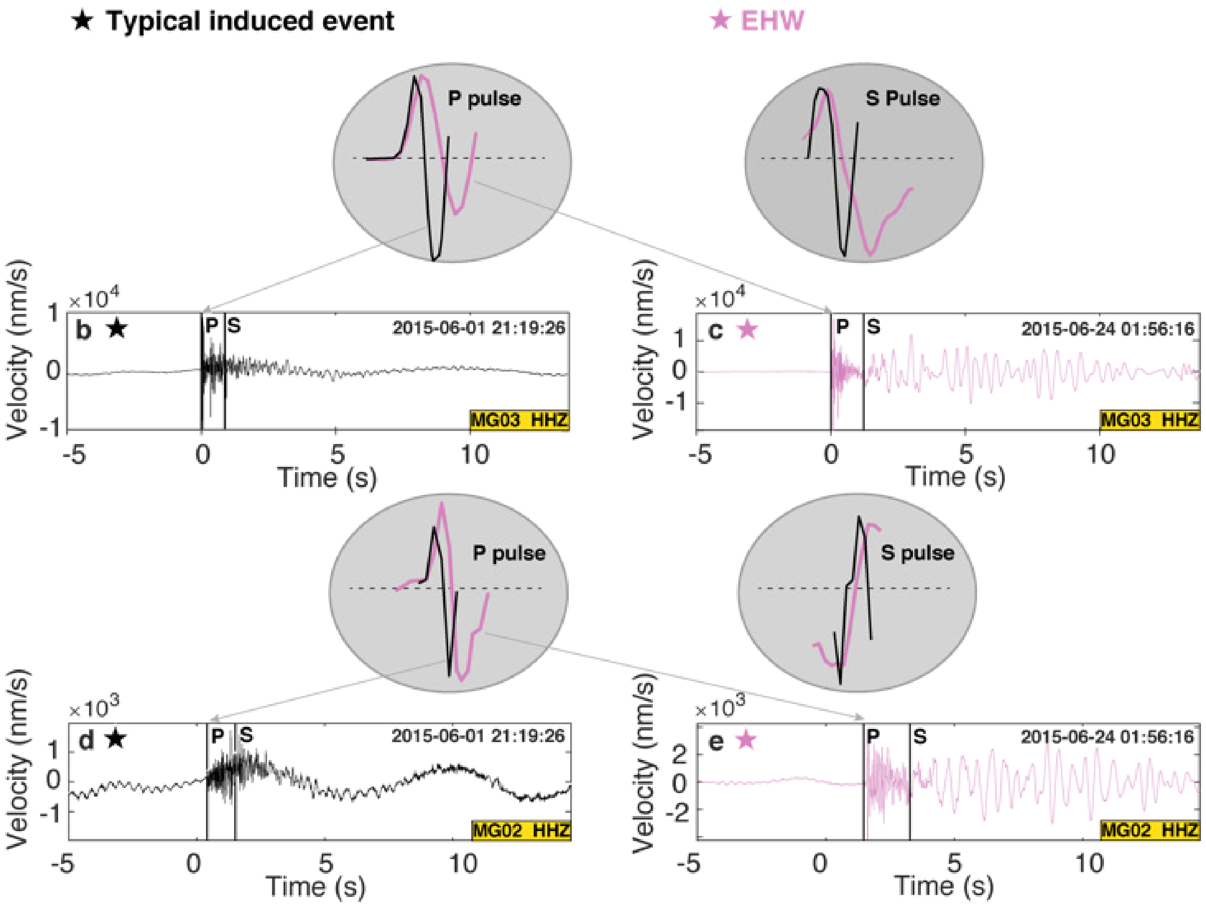
[1]School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada, [2]Pacific Geoscience Centre, Geological Survey of Canada, Sidney, BC, Canada

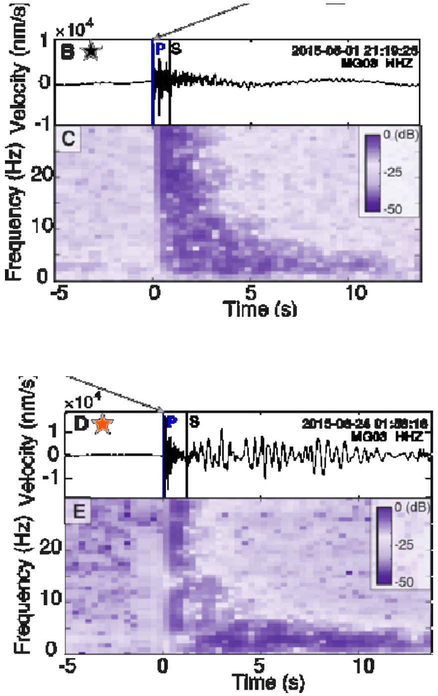
Abstract Identification of repeating earthquakes (repeaters) usually depends on waveform similarity

More Insight into the Seismogenesis of IIE

A new type of IIE: Earthquakes Characterized by Hybrid-frequency Waveforms (EHW)







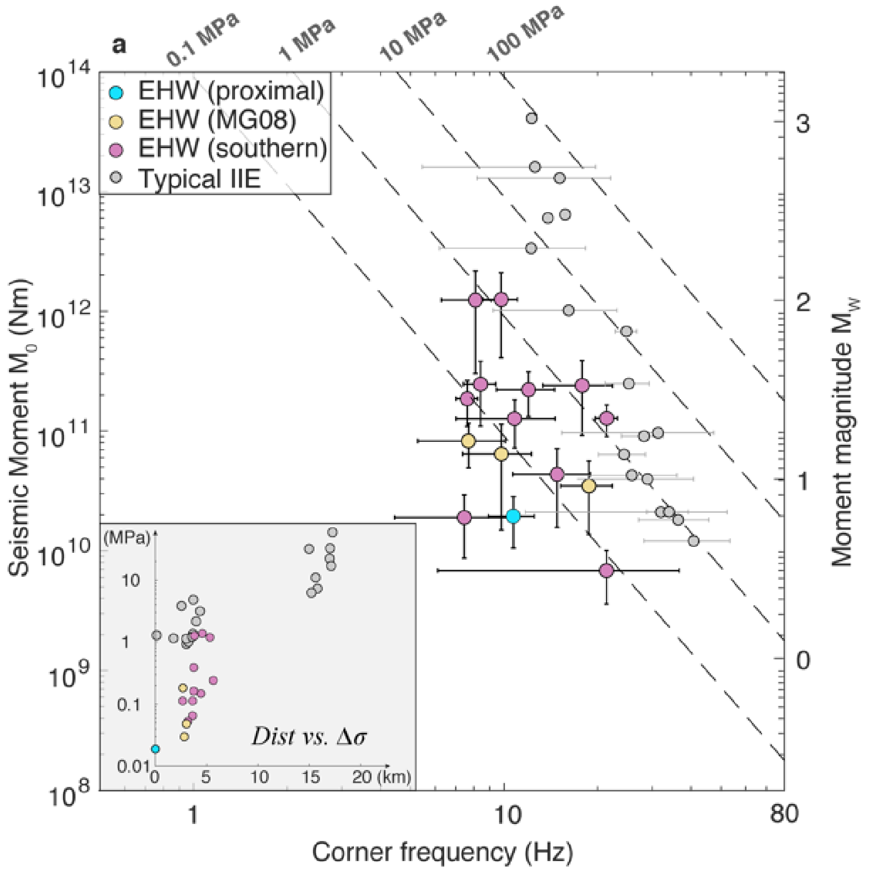
Broader *P* and *S* pulses

Long coda train with low-frequency content

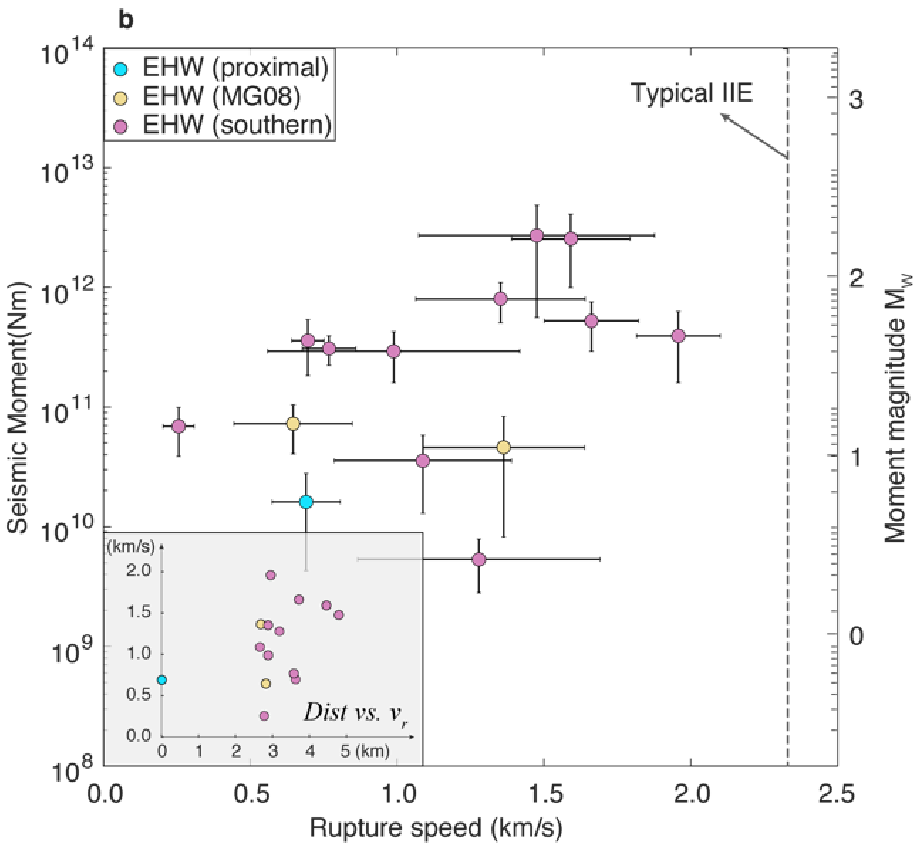
Yu et al. (2021, Nature Comm.)

Source Characteristics of EHWs

Lower Stress Drop



Slower Rupture Speed



Probably manifest the slow rupture transitioning from aseismic to seismic slip caused by injections.

Thus, EHW can be an important sign of increasing likelihood of seismic rupture.

Yu et al. (2021, Nature Comm.)

List of Published Papers and Reports

Eyre, T.S., S. Samsonov, W. Feng, H. Kao, and D.W. Eaton (2022). InSAR data reveal that the largest hydraulic fracturing-induced earthquake in Canada, to date, is a slow-slip event, *Science Reports*, *12*, 2043, doi:10.1038/s41598-022-06129-3.

Gao, D., H. Kao, B. Wang, R. Visser, R. Schultz, and R.M. Harrington (2022). Complex 3D migration and delayed triggering of hydraulic fracturing-induced seismicity: A case study near Fox Creek, Alberta, *Geophysical Research Letters, 49*, e2021GL093979, doi:10.1029/2021GL093979.

Yu, H., H. Kao, R. Visser, and B. Wang (2021). Form seismic quiescence to surged activity after decades of wastewater disposal: A case study in central-west Alberta, Canada, *Geophysical Research Letters,* 48, e2021GL095074, doi: 10.1029/2021GL095074.

Yu, H., R.M. Harrington, H. Kao, Y. Liu, and B. Wang (2021). Fluid-injection induced earthquakes characterized by hybrid-frequency waveforms manifest the transition from aseismic to seismic slip, *Nature Communications*, *12*, 6862, doi: 10.1038/s41467-021-26961-x.

Gao, D., H. Kao, and B. Wang (2021). Misconception of waveform similarity in the identification of repeating earthquakes, *Geophysical Research Letters, 48*, e2021GL092815, doi:10.1029/2021GL092815.

Ojo, A. O., H. Kao, R. Visser, and C. Goerzen (2021). Spatiotemporal changes in seismic velocity associated with hydraulic fracturing-induced earthquakes near Fox Creek, Alberta, Canada. *Journal of Petroleum Science and Engineering, 208*, 109390, doi:10.1016/j.petrol.2021.109390.

Babaie Mahani, A., S. Venables, H. Kao, R. Visser, M. Gaucher, R.M.H. Dokht, and J. Johnson (2021). Intensity of induced earthquakes in northeast British Columbia, Canada, *Seismol. Res. Lett., 92,* 3482-3491, doi:10.1785/0220210037.

Dokht, R.M.H, H. Kao, A. Babaie Mahani, and R. Visser (2021). Spatiotemporal analysis of seismotectonic state of injection-induced seismicity clusters in the Western Canada Sedimentary Basin, *Journal of Geophysical Research: Solid Earth, 126,* e2020JB021362, doi:10.1029/2020JB021362.

Kuponiyi, A.P., and H. Kao (2021). Temporal variation in cultural seismic noise and noise correlation functions during COVID-19 lockdown in Canada, *Seismol. Res. Lett., 92 (5)*, 3024-3034, doi:10.1785/0220200330.

Ojo, A.O., H. Kao, Y. Jiang, M. Craymer, and J. Henton (2021). Strain accumulation and release rate in Canada: Implications for long-term crustal deformation and earthquake hazards, *Journal of Geophysical Research: Solid Earth, 126*, e2020JB020529, doi:10.1029/2020JB020529.

Wang, B., A. Verdecchia, H. Kao, R.M. Harrington, Y. Liu, and H. Yu (2021). A study on the largest hydraulic fracturing induced earthquake in Canada: numerical modeling and triggering mechanism, *Bull. Seismol. Soc. Am., 111*, 1392-1404, doi:10.1785/0120200251.

Babaie Mahani, A., D. Malytskyy, R. Visser, M. Hayes, M. Gaucher, and H. Kao (2021). Well-log-based velocity and density models for the Montney unconventional resource play in northeast British Columbia, Canada, applicable to induced seismicity monitoring and research, *Seismol. Res. Lett., 92 (2A)*, 886-894, doi:10.1785/0220200213.

Ackerley, N., A.L. Bird, M. Kolaj, H. Kao, and M. Lamontagne (2022). Procedures for seismic event type discrimination at the Canadian Hazards Information Service, *Geol. Surv. Canada, Open File 8253,* ver. 1, 35 pages, doi:10.4095/329613.

Visser, V., H. Kao, R.M.H. Dokht, A. Babaie Mahani, and S. Venables (2021). A comprehensive earthquake catalogue for Northeastern British Columbia: The Northern Montney Trend from 2017 to 2020 and the Kiskatinaw Seismic Monitoring and Mitigation Area from 2019 to 2020, *Geological Survey of Canada Open File 8831*, one .zip file, doi:10.4095/329078.

Farahbod, A M; H. Kao, and D.B. Snyder (2021). An earthquake catalogue for seismic events in the Norman Wells region of the central Mackenzie Valley, Northwest Territories, using waveform data from local seismic stations, *Geological Survey of Canada Open File 8825*, one .zip file, doi.org/10.4095/328953.

Wang, B., Verdecchia, A., Kao, H., Harrington, R.M., Liu, Y. and Yu, H. (2021): Numerical modelling and triggering mechanism of the largest hydraulic fracturing–induced earthquake in northeastern British Columbia, Canada (NTS 094B/16); in Geoscience BC Summary of Activities 2020: Energy and Water, Geoscience BC, Report 2021-02, p. 31–44.

CONTACT INFORMATION

- Project leader: Dr. Honn Kao
- Webpage on Science.gc.ca: https://profils-profiles.science.gc.ca/en/profile/honn-kao-phd
- Email address: Honn.Kao@nrcan-rncan.gc.ca

THANK YOU!

Ressources naturelles Canada | Natural Resources Canada

Évaluation des impacts potentiels liés aux activités pétrolières et gazières sur les aquifères peu profonds dans la région de Fox Creek (AB) – mise à jour de mai 2022

Assessment of potential impacts of oil and gas development activities on shallow aquifers in the Fox Creek area (AB) – May 2022 update

Christine Rivard

Canada

ABSTRACT

A multidisciplinary and multi-institutional project was initiated in the Fox Creek area (west-central Alberta) in April 2019 to study environmental impacts of hydrocarbon development activities. The initial objective was to specifically study potential impacts on shallow groundwater. However, different Sectors within NRCan later identified the Fox Creek area as a region of interest for developing regional cumulative effects evaluation methods in support of new impact assessment legislation. As a result, the scope is now much broader and the project includes studies of vegetation, forest, snow cover, landscape evolution over time, and contributes to a woodland caribou habitat study. The project involves many collaborators from the federal and provincial governments, as well as from the academic community.This project is supported by the GGP and EGP programs and the Initiative on Cumulative Effects.

Project members 2021-2022

(including EGP, GGP and cumulative effects)

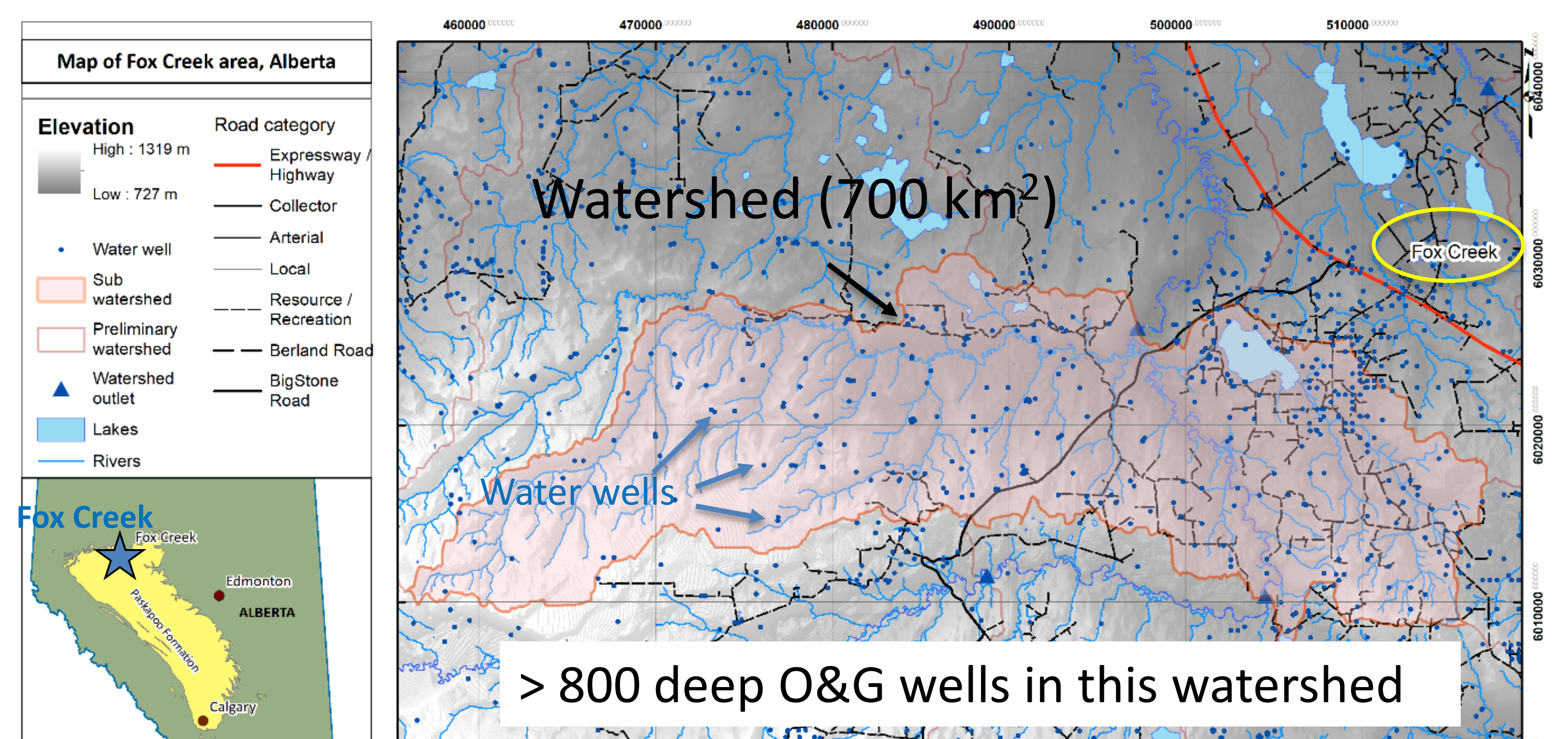
C. Rivard[1], C. Paniconi [2], E. Konstantinovskaya[3], O. Haeri Ardakani[1], H. Crow[1], G. Bordeleau[2], L.I. Guarin-Martinez[2,1], B.J. Meneses-Vega[1,2], D. Kononovs[3], D. Degenhardt[4], D. Alessi[3], B. Xu.[5], P. Leblanc-Rochette[1,6], R. Lavoie[6], D. Lavoie[7], S. Heckbert[8], D. Palombi[8], C. McClain[9], J. Lovitt[10], W. Chen[10]

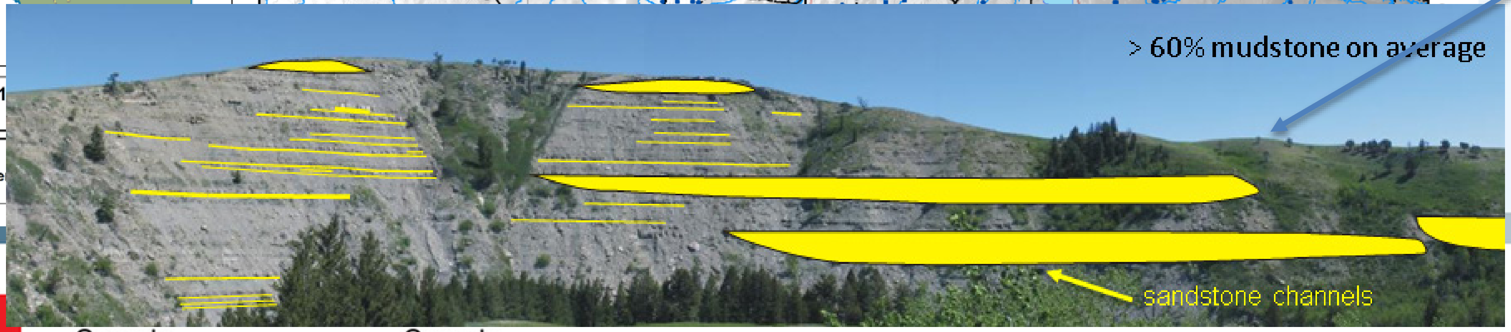
[1] *Geological Survey of Canada, Natural Resources Canada, Québec, QC; Ottawa, ON; Calgary, AB; and Victoria, BC;*
[2] *Institut national de la recherche scientifique – Eau Terre Environnement (INRS-ETE), Québec, QC*
[3] *University of Alberta, Department of Earth and Atmospheric Sciences, Edmonton, AB*
[4] *Canadian Forest Service, Natural Resources Canada, Edmonton*
[5] *Northern Alberta Institute of Technology (NAIT), Edmonton, AB*
[6] *Université Laval, École supérieure d'aménagement du territoire et de développement régional, Québec, QC*
[7] *Consultant, geologist, Quebec, QC*
[8] *Alberta Energy Regulator (AER) and Alberta Geological Survey (AGS), Edmonton, AB*
[9] *Alberta Environment and Parks (AEP)*
[10] *CCMEO, Natural Resources Canada, Ottawa, ON*

3 MSc students
1 PhD student

Description of the study area

Fox Creek, west-central Alberta: one of the most active regions for O&G production in the last 50 years





The study area is mainly forested and unpopulated

Elevations range from 785 to 1180 m

The regional aquifer is located in the Paskapoo Fm.: a complex succession of interbedded mudstone and siltstone with sandstone channels, and some coal seams

Project objectives

1) Characterize the regional shallow aquifer (GGP)
2) Study the intermediate zone integrity (EGP)

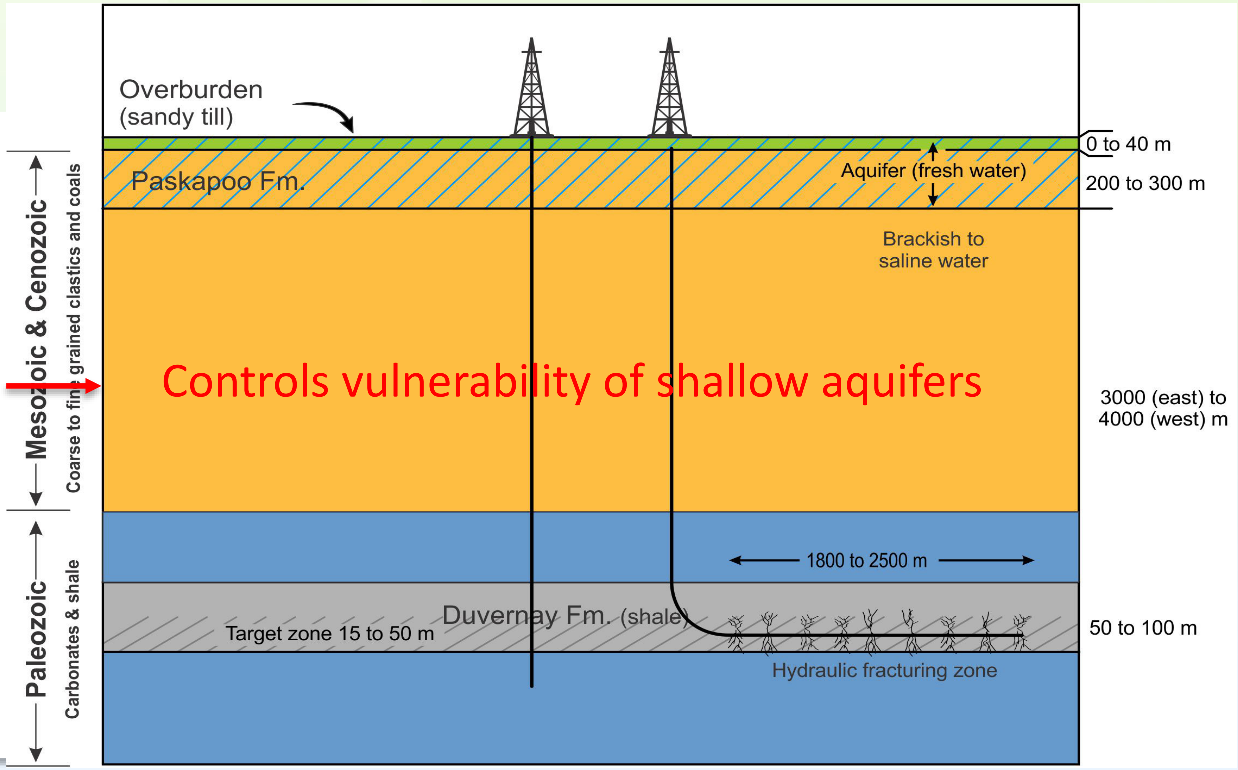
Mean water-well depth in the Paskapoo Fm: ≈50 m

Mean O&G well depth: ≈ 3500 m

Surficial aquifers

Intermediate zone

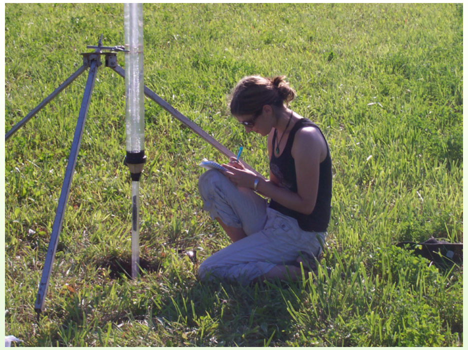
Zone targeted by the industry



3) Assess cumulative effects (CE)

Fieldwork in 2021-2022

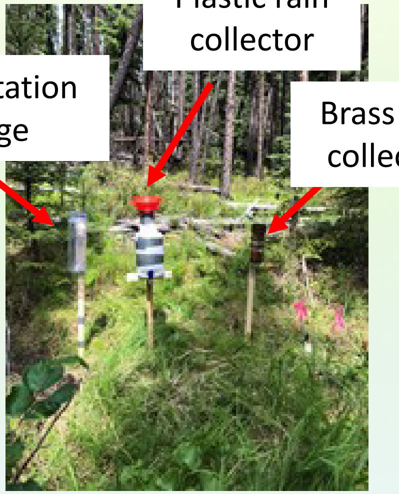
- 9 monitoring wells drilled in 2020 (35 - 90 m):
  - Permeability (slug) tests
  - Groundwater sampling (in MW and 13 water wells from O&G operators)
  - Download of pressure transducers
- Permeability tests in unconsolidated sediments
- Re-installation of the gauging station
- Installation of lysimeters, soil moisture sensors, rain gauges and rain collectors at 5 sites in vegetated and unvegetated (impacted) areas → monthly sampling
- Snow density and thickness were measured this winter.



Results

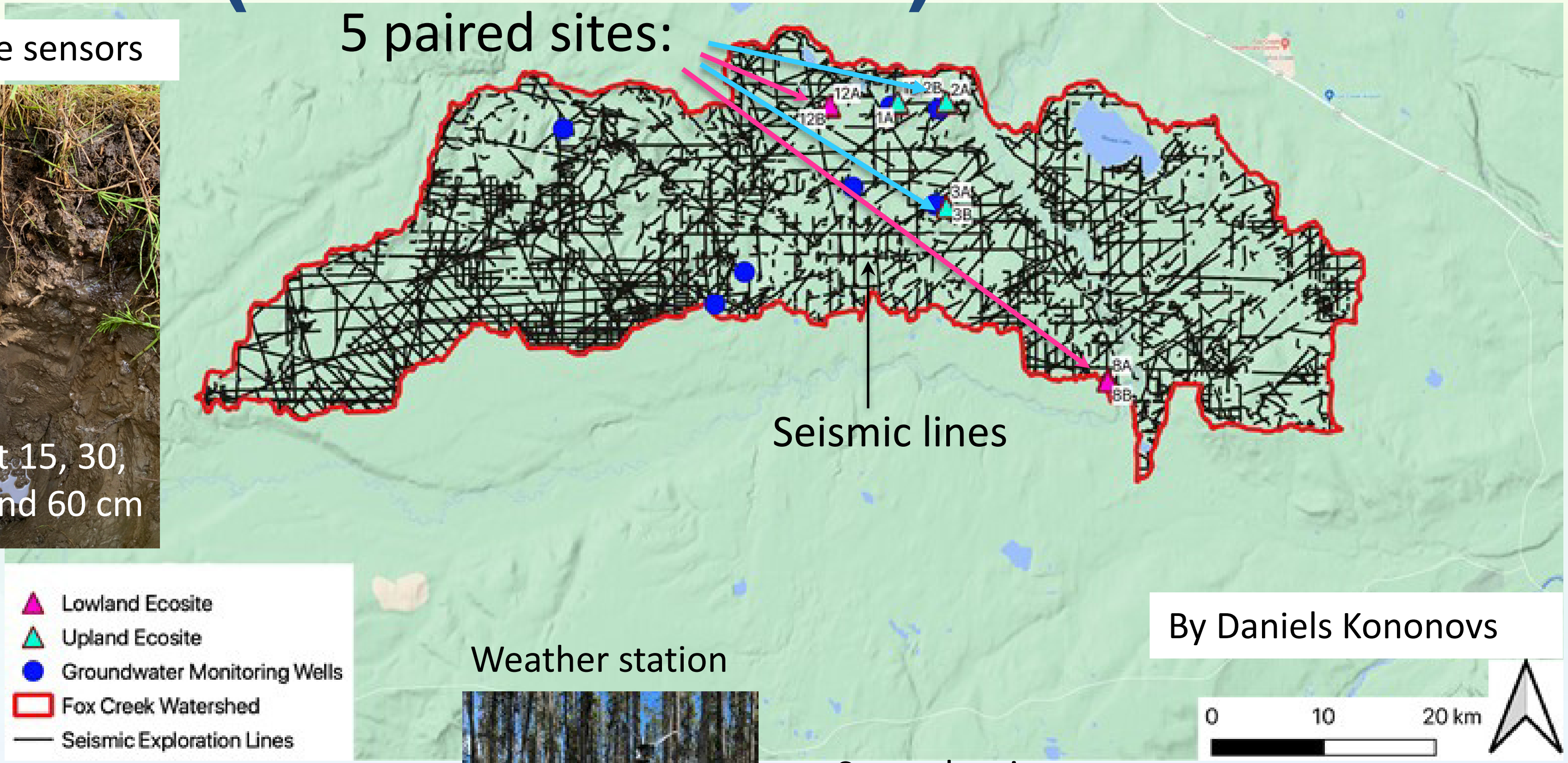
(some are preliminary)

Water budgets in vegetated and non-vegetated (seismic lines) areas

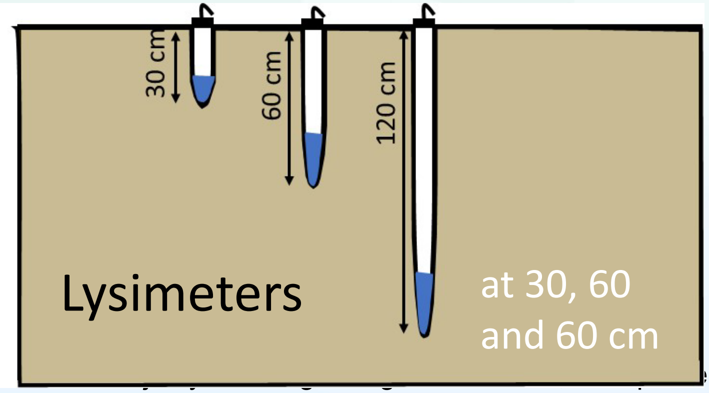


Soil moisture sensors

5 paired sites:



By Daniels Kononovs

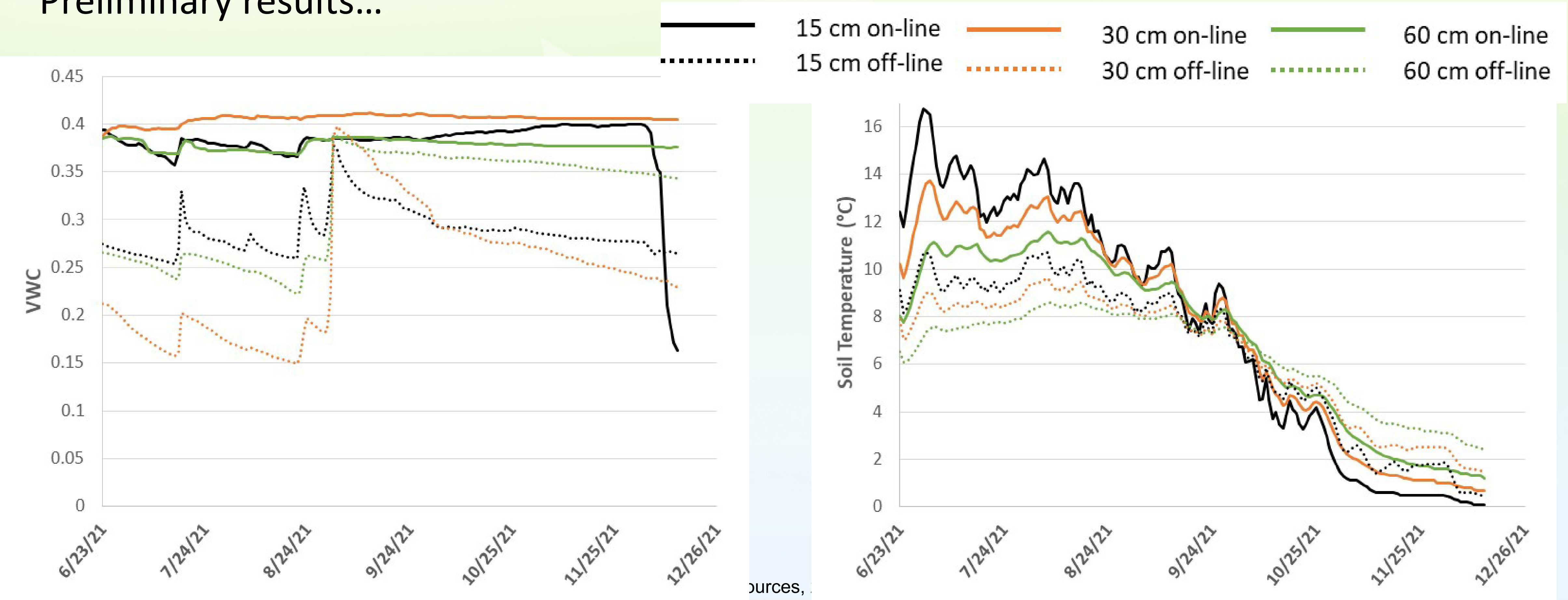


Weather station

Snow density measurement

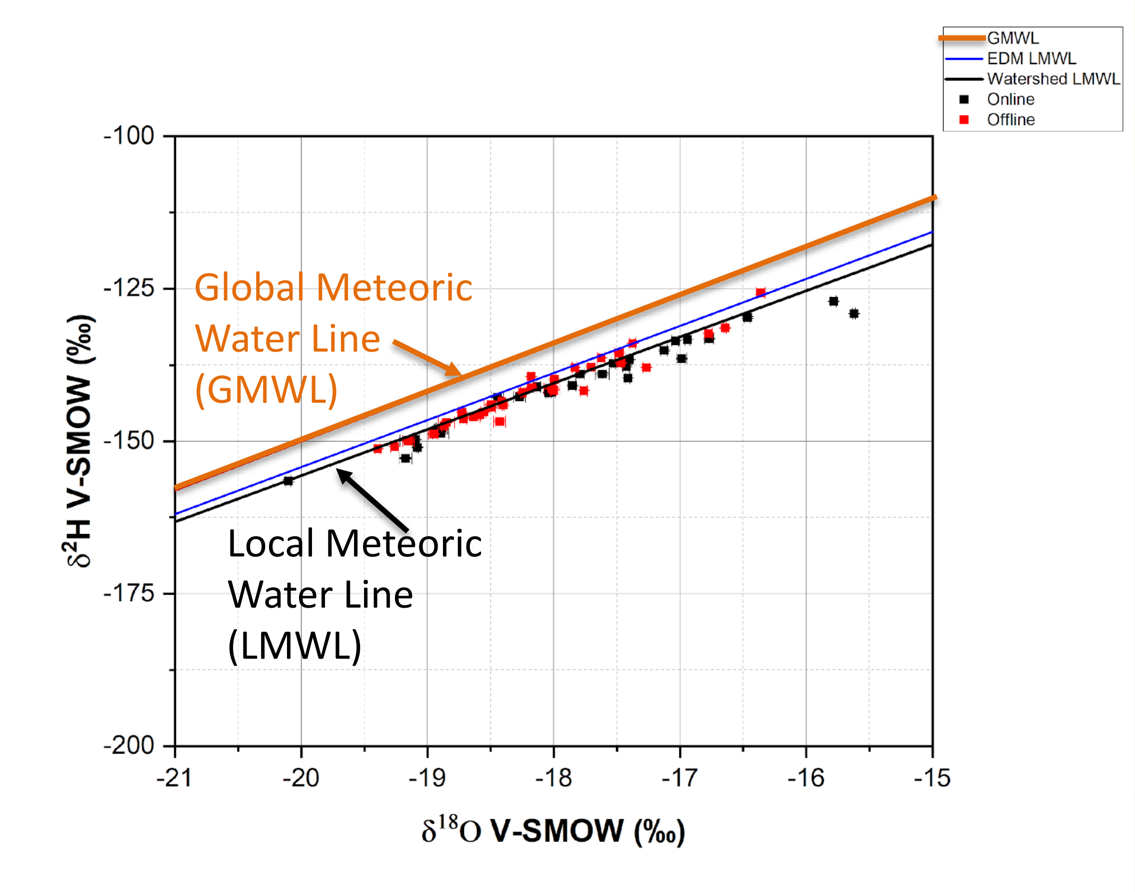
Water budgets in vegetated and non-vegetated (seismic lines) areas

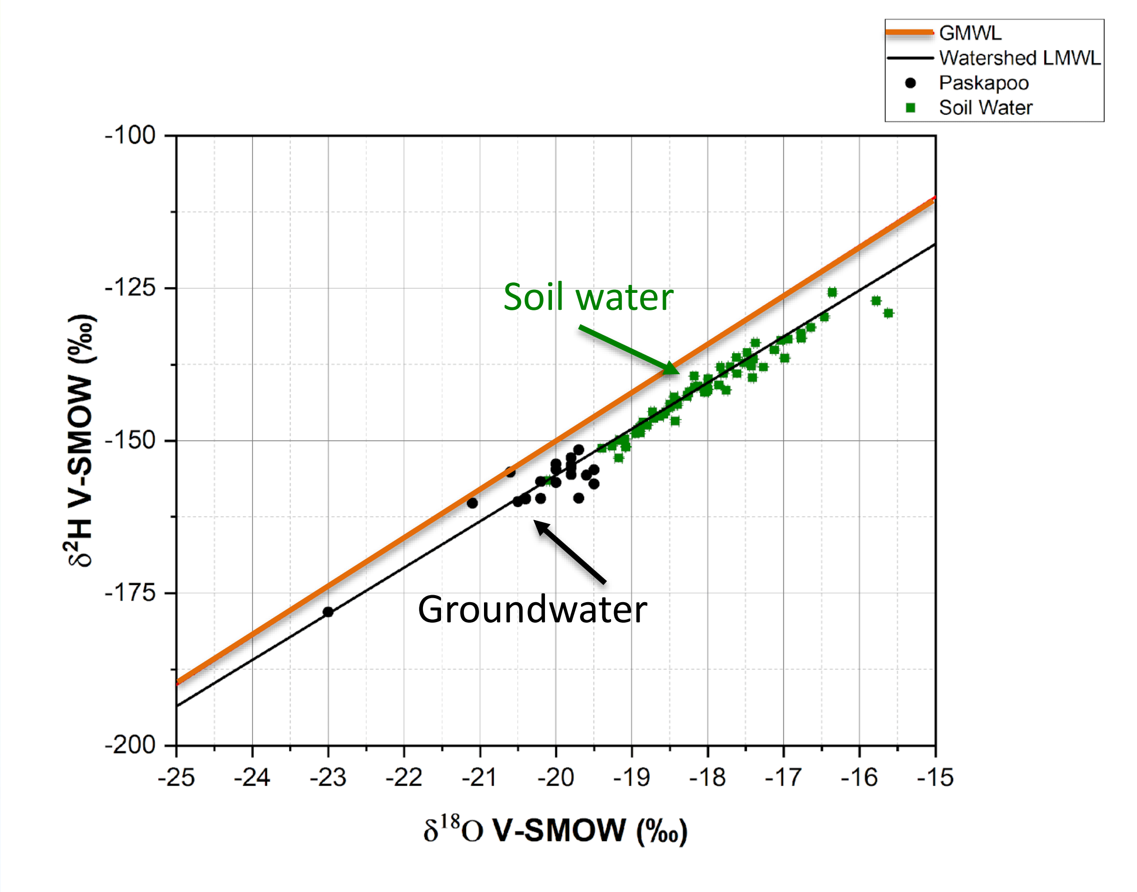
Preliminary results…



Meteoric line

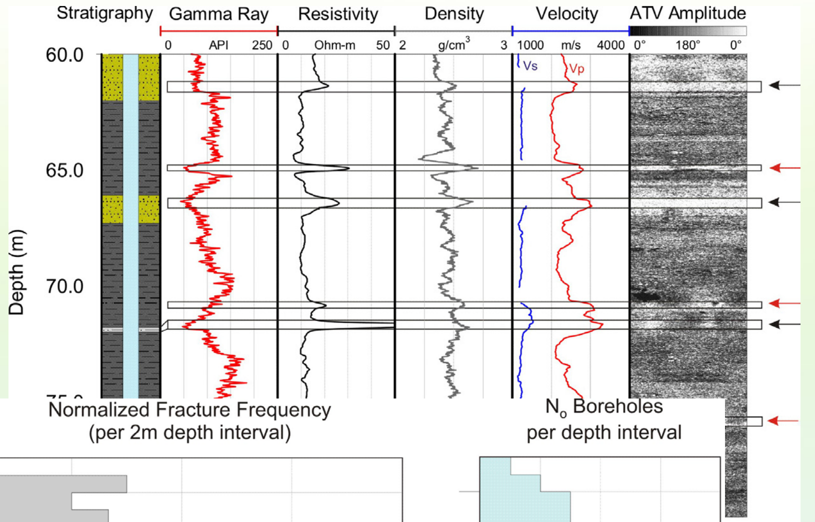
Samples collected over 6 months:



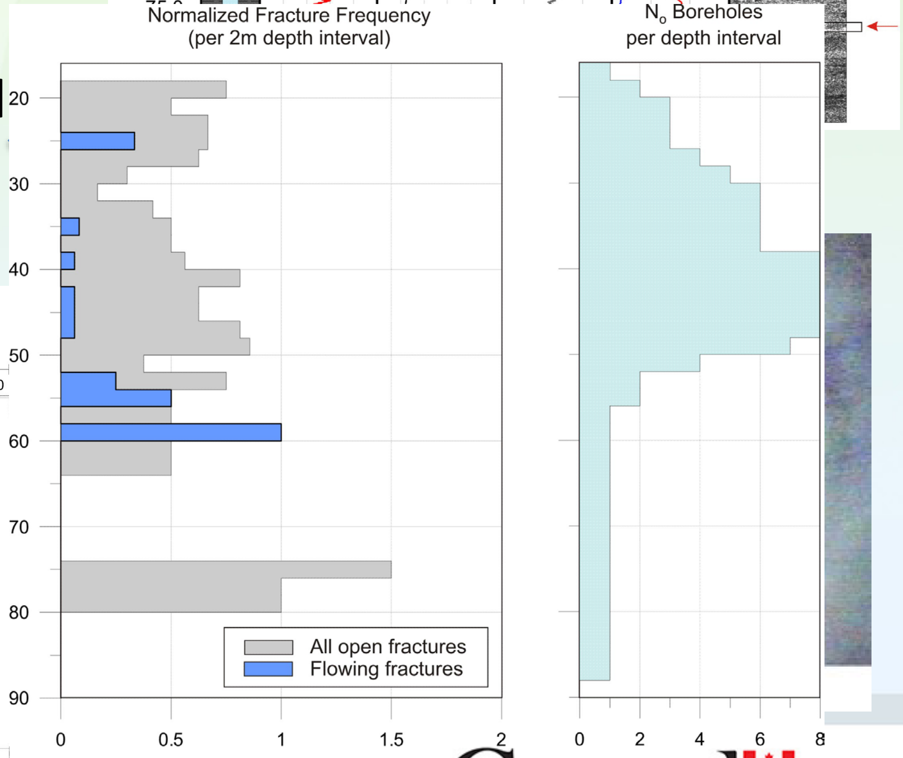


Borehole geophysical logging

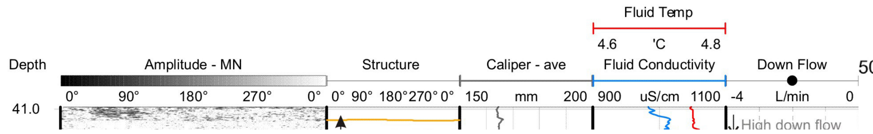
- Lithological logs:
  - indicated variability: helped refine stratigraphic logs;
  - identified the presence of a few high velocity/density/resistivity beds (mainly in sandstone), interpreted as cemented ➡ may represent barriers to vertical flow.



- The poorly consolidated rock of the Paskapoo Fm. caused wall roughness, affecting Vs and thus Young's Modulus (E) values.



- Downward flowing GW was observed in almost all the wells ➡ recharge conditions.

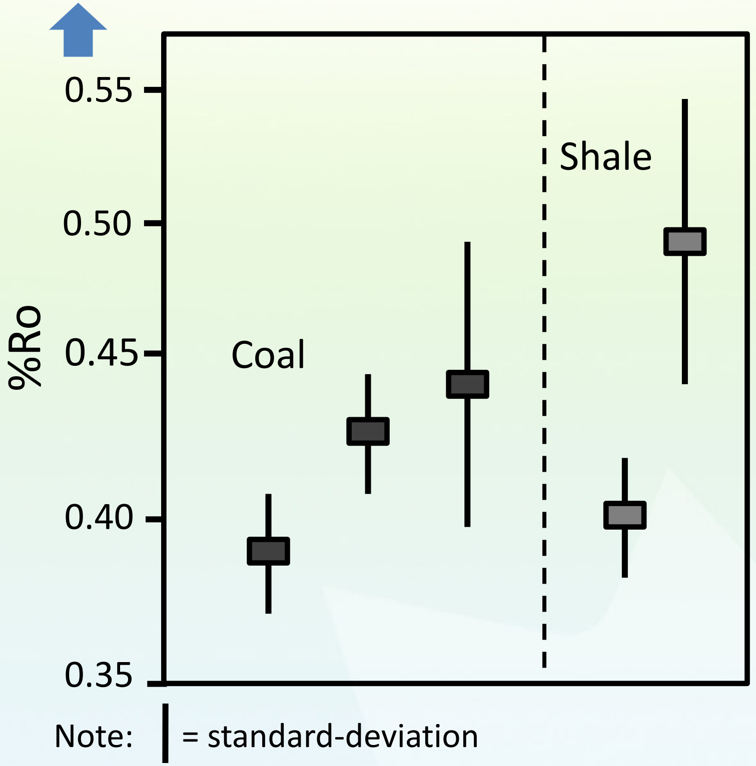


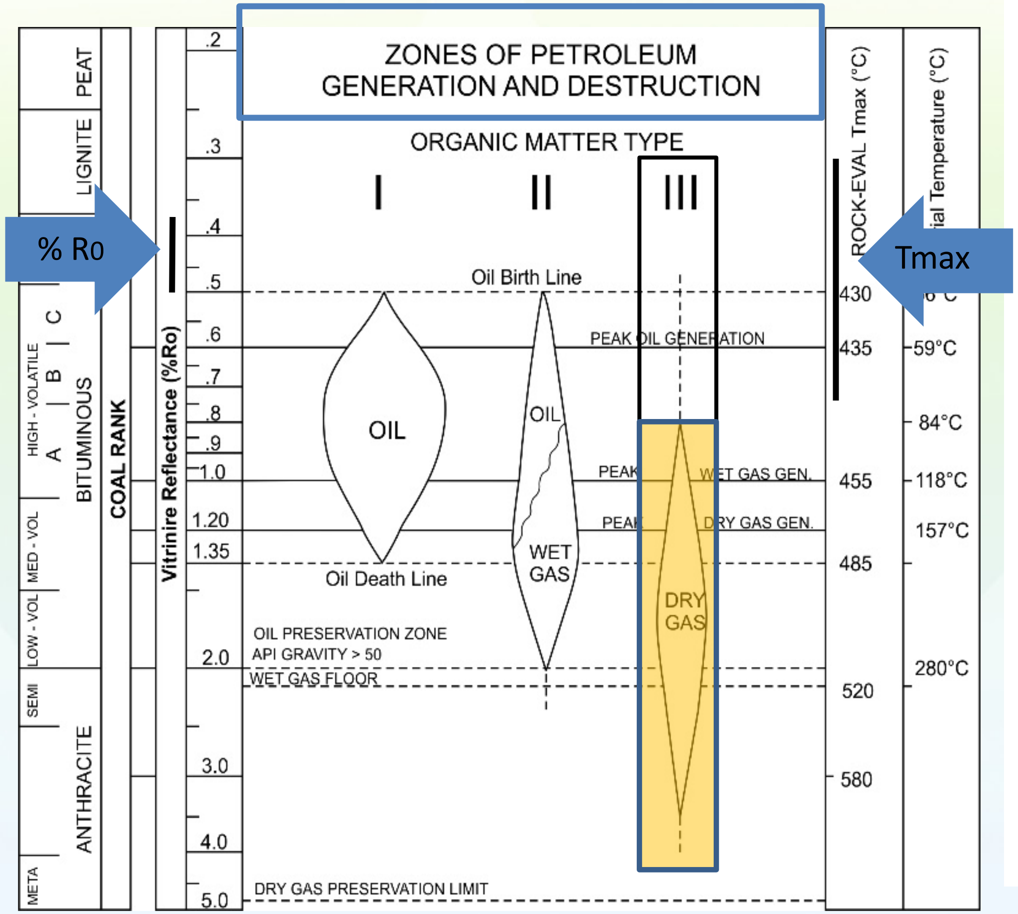
- Fluid pathways are interpreted to be mainly along discontinuous fractures and, to a lesser extent, through the sandstone matrix.
- The majority of open fractures observed were bedding-parallel, of which (5%) were interpreted as transmitting fluid.

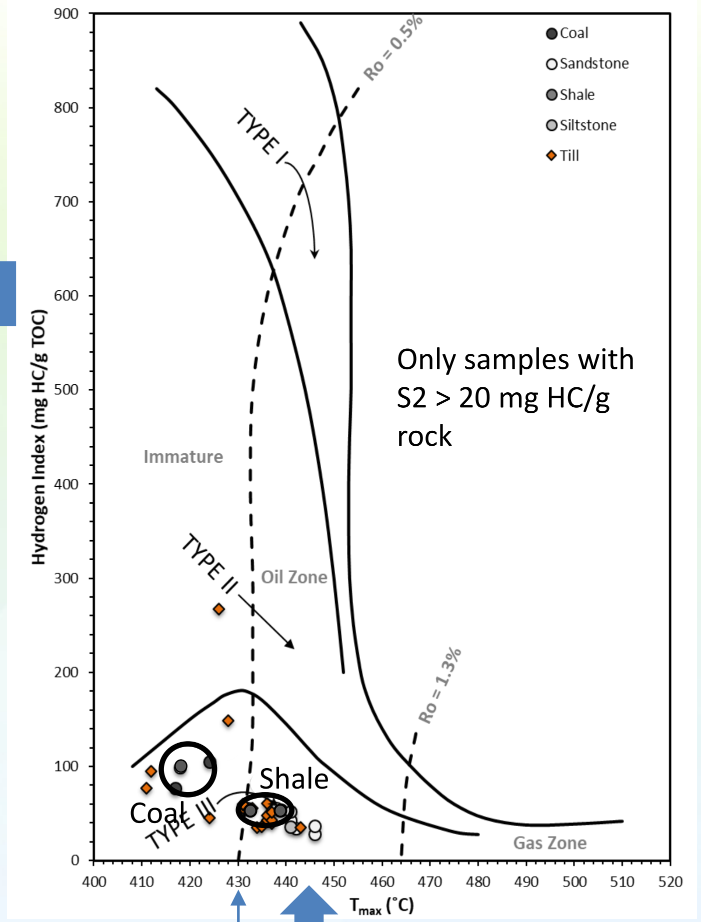
By Heather Crow

Geochemistry – shallow rock

Onset of hydrocarbon generation for Type III: 0.8 %Ro







Type I and II

Onset of hydrocarbon generation type III: 445°C

By Omid Haeri Ardakani

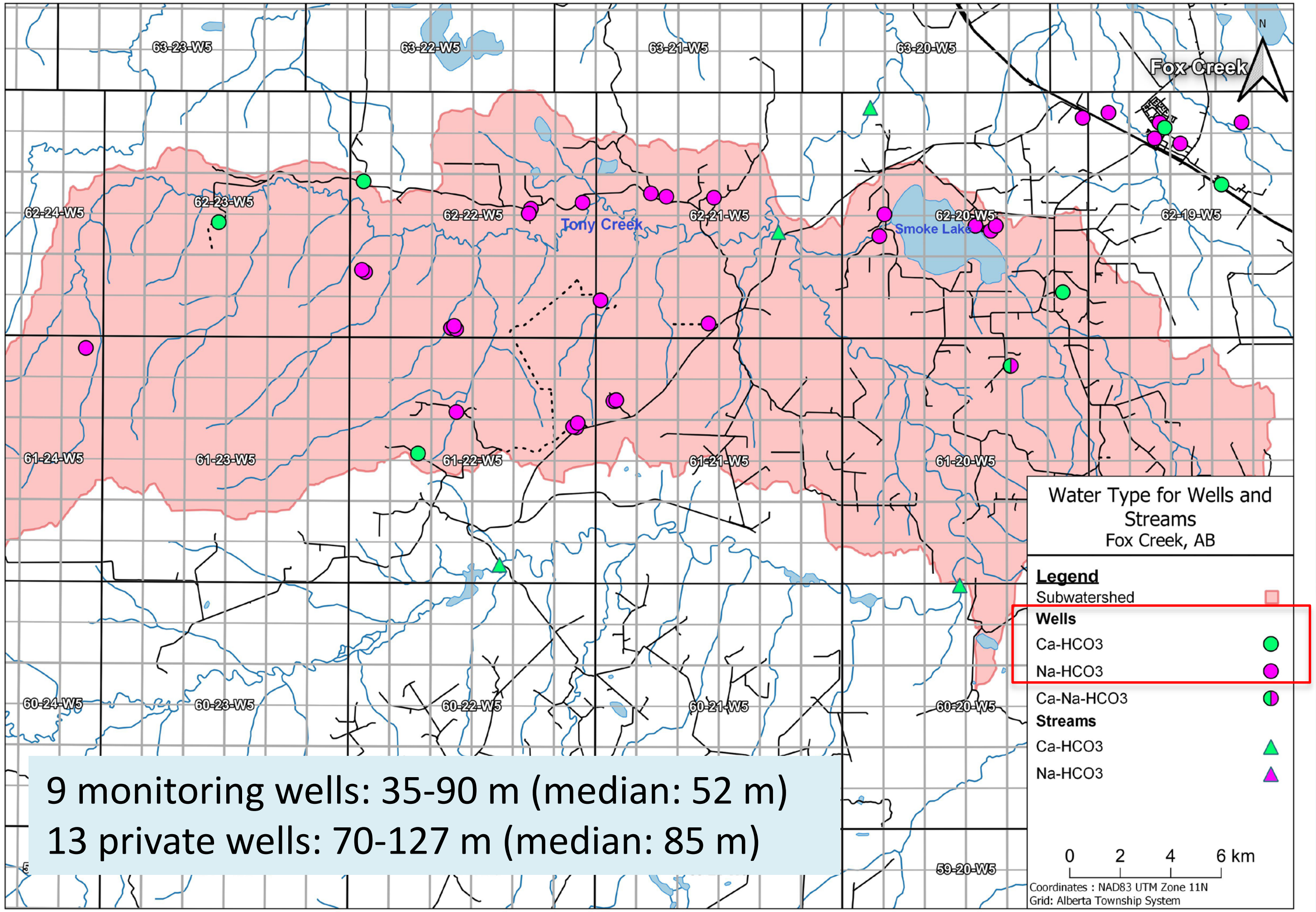
- Values found within the rock of shallow monitoring wells are well below the thermal conditions for thermogenic hydrocarbon generation.
- However, microbial gas production associated with OM in the coal seams (TOC: 5.8-8.8%) cannot be discarded.

Geochemistry - Groundwater

Map of water types

mostly $NaHCO_3$

moderately evolved GW



9 monitoring wells: 35-90 m (median: 52 m)
13 private wells: 70-127 m (median: 85 m)

Private wells (screened in sandstone) and monitoring wells (screened in shale)

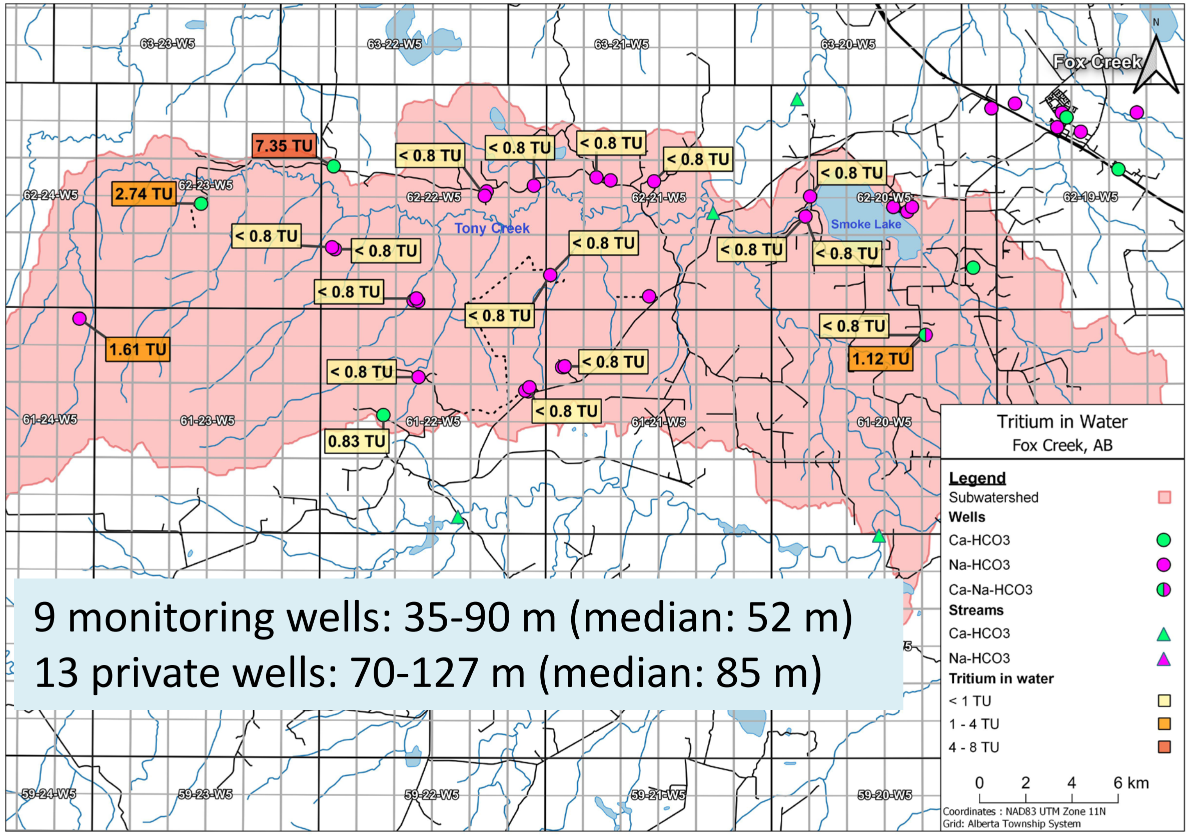
same water type

Only 4 wells contained dissolved methane: the deepest MW (90 m) and three private wells. All of **microbial** origin.

Geochemistry – Groundwater

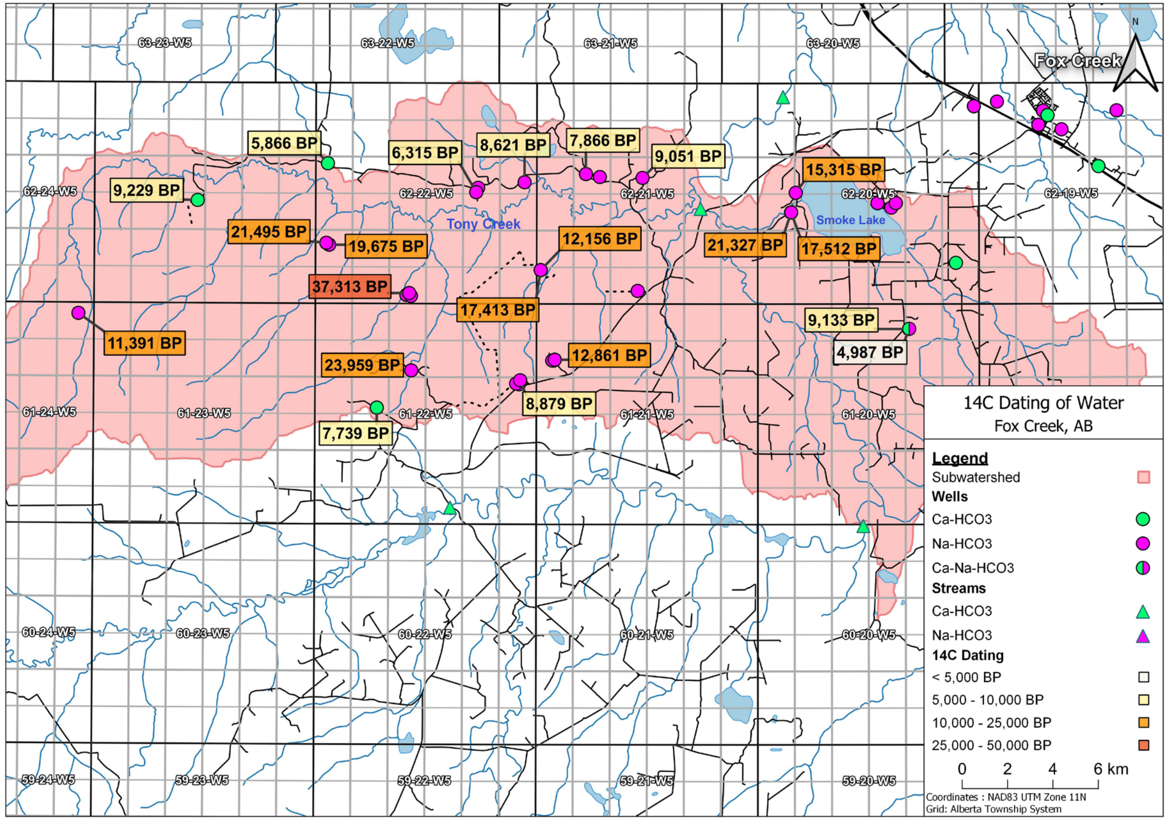
Dating

Tritium



9 monitoring wells: 35-90 m (median: 52 m)
13 private wells: 70-127 m (median: 85 m)

Uncorrected radiocarbon age (from the lab)



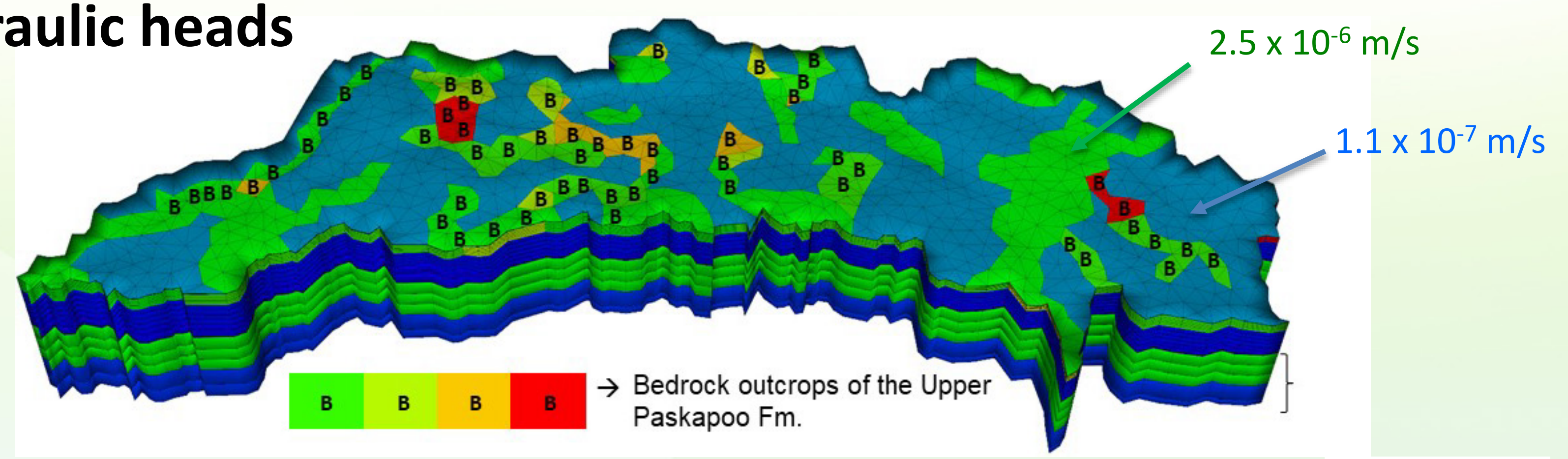
GW typically contains very little or no tritium and has uncorrected radiocarbon age between 5,000-10,000 years upstream and >10,000 years in the middle and downstream parts of the watershed

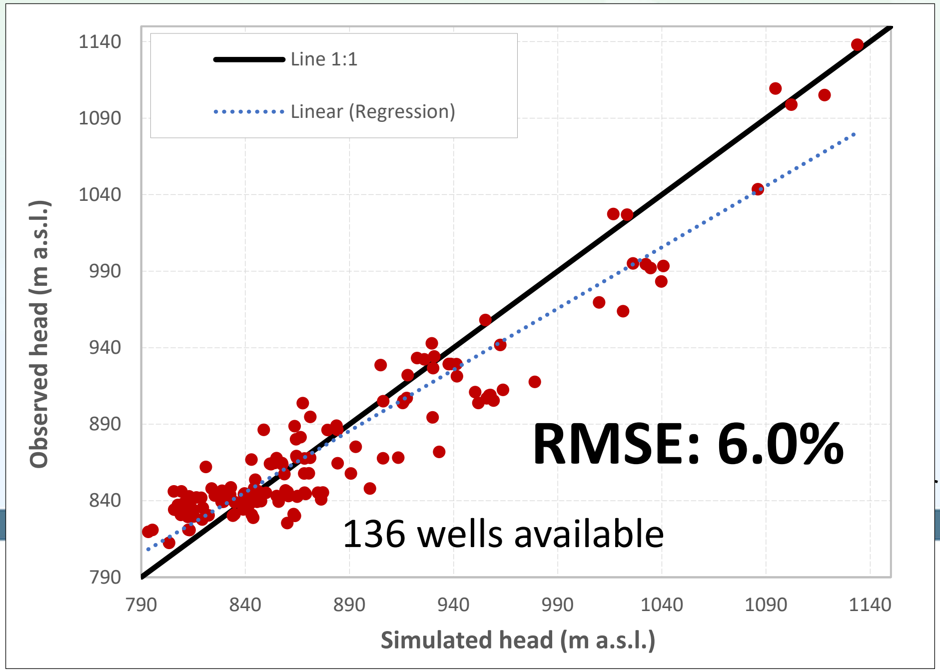
➡ GW is relatively old (contribution from outside the watershed) and little mixing with recent GW.

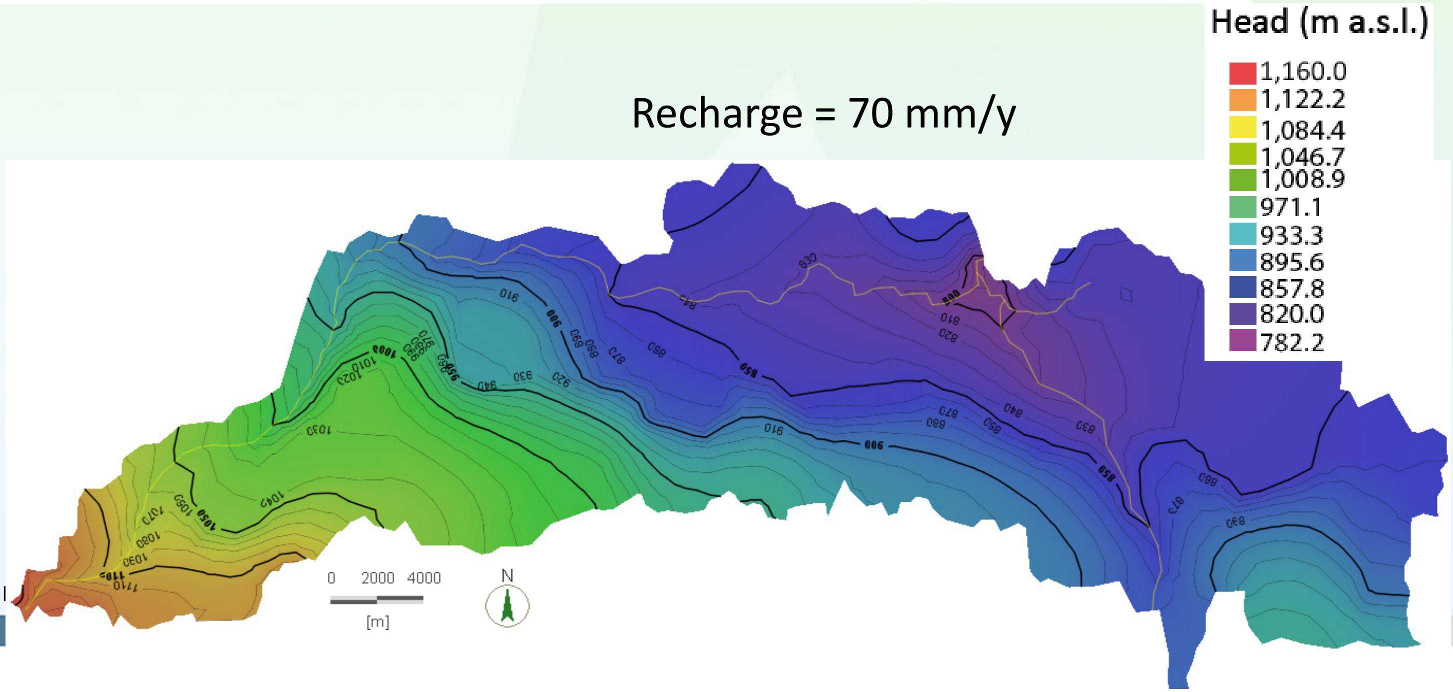
Hydrogeological modeling

3D FEFLOW model, RMSE and hydraulic heads

Geological formation		Kx=Ky (m/s)	K range from literature (m/s)
Upper Paskapoo (~100 m thick)	Min. value	2.5E-6	2.5E-6 – 1.0E-3 (Hughes et al., 2017)
	Max. value	6.0E-4	
Lower Paskapoo		1.46E-8	1.10E-10 – 3.00E-5 (Hughes et al., 2017)
Scollard		1.10E-8	9.53E-10 – 3.54E-6 (Riddell et al., 2009)
Battle (~10 m thick, not posible to visualize it)		8.70E-10	7.37E-10 – 1.34E-7 (Riddell et al., 2009)
Upper Wapiti (0-500 m depth)		2.60E-6	7.10E-6 – 3.8E-6 (IHS Markit, 2018)
Lower Wapiti (500-1000 m depth)		2.60E-8	2.6E-6 – 2.6E-8 (IHS Markit, 2018)





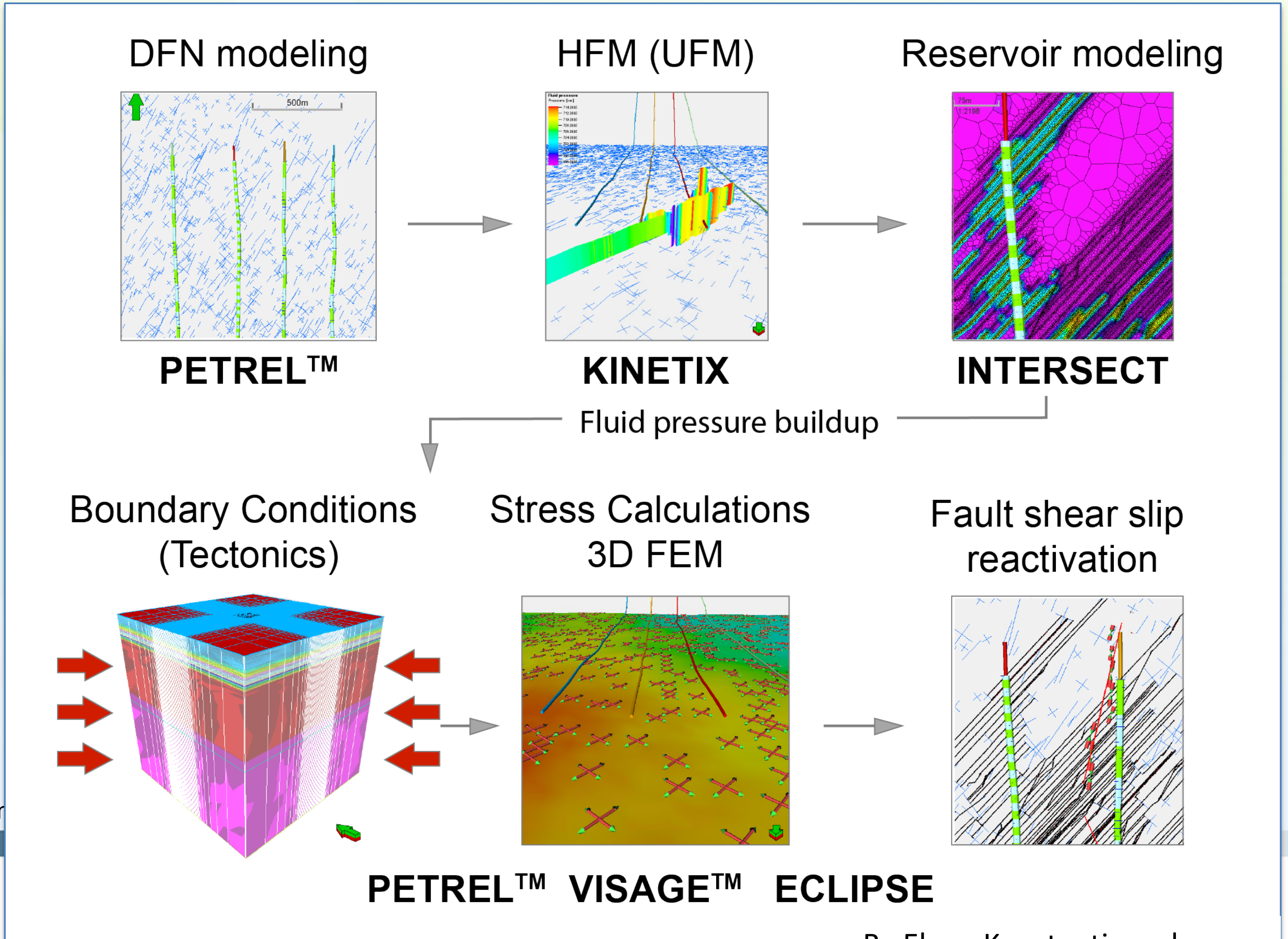


By Barbara Javiera Meneses Vega

Geomechanical model

Goal: to better understand the behavior of the intermediate zone (which controls upward fluid flow)

- **Discrete Fracture Network** (DFN) **modeling** to simulate the presence of natural fractures in the Duvernay Formation
- **Hydraulic Fracture Modeling** (HFM) to create complex fracture networks and subsequently an unstructured grid for fluid flow simulation
- **Reservoir simulation** to model fluid injection; validated by a history matching of fluid injection volume and bottomhole pressure data
- **3D coupled reservoir geomechanical modeling** to analyze fault mechanical instability



By Elena Konstantinovskaya

Geomechanical model

Discrete fracture network (DFN):

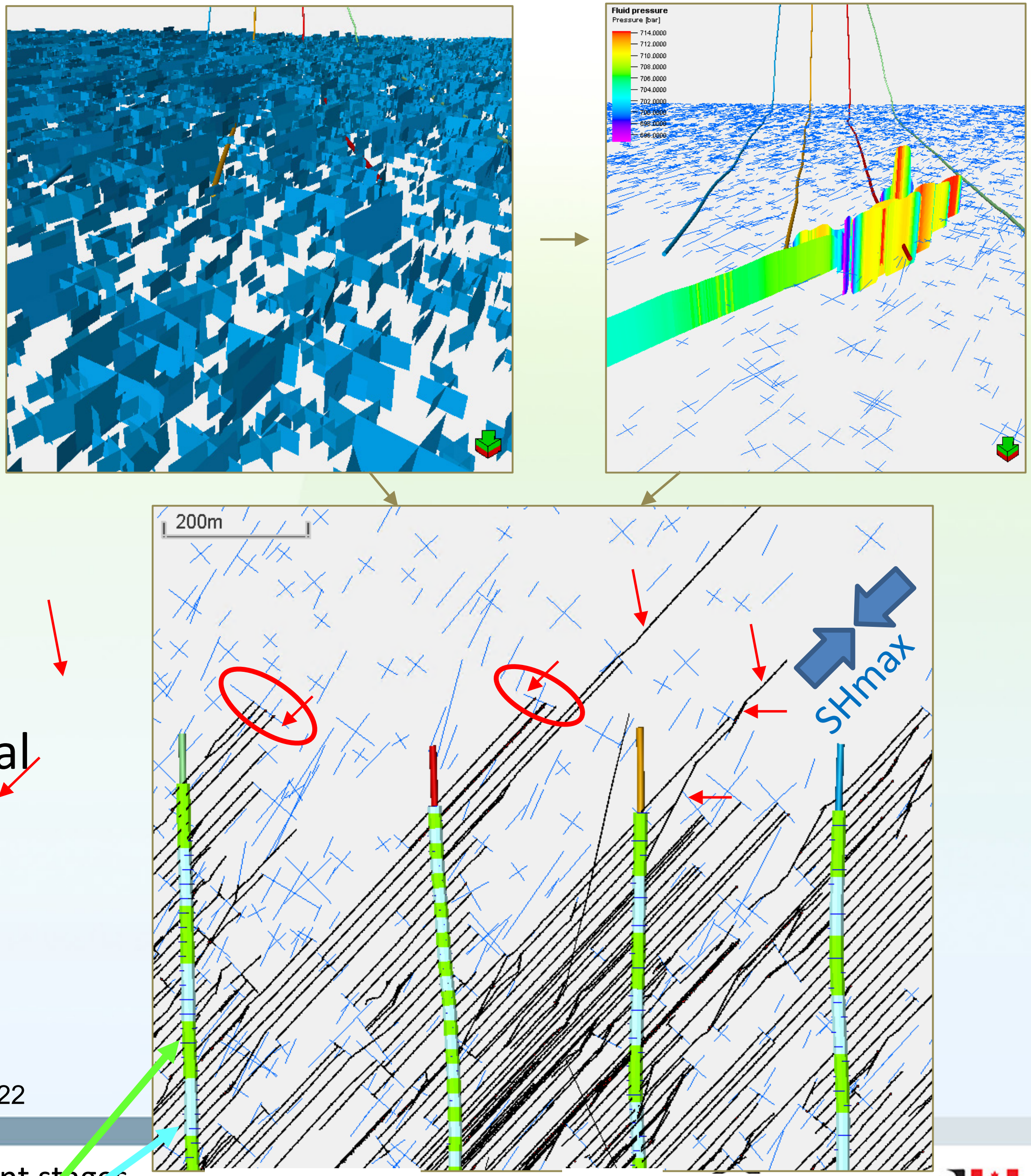
- 3 vertical fracture sets, oriented parallel (N43°E), orthogonal (N133°E) and at 13° to SHmax

Modelling of hydraulic fractures (HF):

- HFs are mostly oriented NE-SW, parallel to Shmax

- HFs are stopped at the intersection with orthogonal natural fractures (NFs) oriented NW-SE

- HFs branch and run along dilated or sheared orthogonal and oblique NFs



Different stages of HF

NFs (DFN)

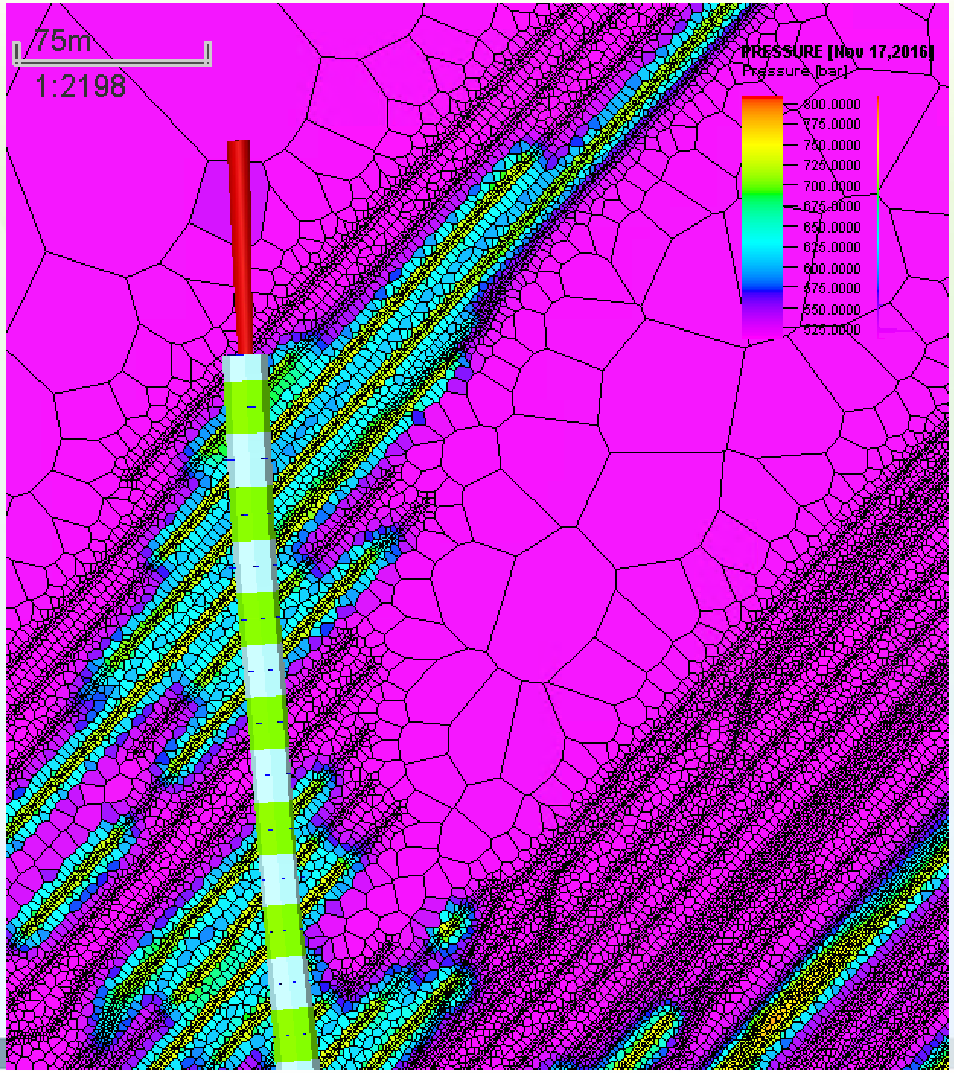
HFs

By Elena Konstantinovskaya

Geomechanical model

Reservoir simulations

- Bottomhole pressure (BHP) increases by of 20 MPa during hydraulic fracturing to reach 80-84 Mpa
- BHP is transmitted during HF through the complex HFs-NFs from injection wells to pre-existing fault zones
- HFs do not extend beyond the top of the Duvernay Fm., mainly due to contrasting geomechanical properties with the overlying unit.



By Elena Konstantinovskaya

Study on cumulative effects assessment

Conclusions:

Several obstacles for practitioners:

- lack of data or problems accessing it
- unclear government requirements and the lack of guidance despite the documents available

The fact that First Nations are not involved throughout the process and in the decisions ➡ frustration
On the other hand, their involvement requires a lot of time and energy ➡ need additional resources.

Recommendations:

Will require a lot of political will and open-mindedness, in order to limit, or even remedy these problems.

1) legislation to make data (including monitoring) publicly available
2) the legal requirement to monitor certain data (which could be used to re-evaluate operating permits)
3) developing long-term government plans to conduct regional assessments in different regions of the country.

by Philippe Leblanc-Rochette

CONTACT INFORMATION

- Christine Rivard
- Work phone number: 418-654-3173
  Christine.Rivard@nrcan-rncan.gc.ca

THANK YOU!

Ressources naturelles Canada | Natural Resources Canada

Cumulative Effects of Resource Development on Mining-Impacted Watersheds

Effets Cumulatifs du Développement Minier dans les Basins Versants Contaminés

Alexandre Desbarats

May 10 2022

Canada

ABSTRACT

Renewed exploration or development in historical mining districts, such as Cobalt, presents unique challenges for proponents and government regulators because of the cumulative nature of environmental impacts. To increase capacity to carry out or review environmental assessments, this project will develop geoscience methods for distinguishing environmental effects of new mining activity from complex existing background conditions in affected watersheds. Specifically, the project will develop means of unraveling the history of accumulated polymetallic contamination from multiple sources over multiple periods. This information and new data from mine wastes and mine drainage will be synthesized in the first geoenvironmental model for Ag-Ni-Co-As vein type deposits. Project results will be disseminated to key end users in order to improve the environmental assessment process and to ensure that decision makers have a better understanding of the cumulative nature of environmental impacts for sustainable mineral resource development.

Project Members and Collaborators

- Alexandre Desbarats (GSC-NC, leader)
- Michael Parsons (GSC-ATL)
- Jeanne Percival (GSC-NC)
- Jennifer Galloway (GSC-Cal)
- Alexandre Normandeau (GSC-ATL)
- Josué Jautzy (GSC-QC)
- Suzanne Beauchemin (Health Canada)
- Tom Al, Danielle Fortin (University of Ottawa)
- Heather Jamieson (Queen's University)
- Richard Goulet, Sean Langley, Asma Asemaninejad (CanmetMINING)

Beaver-Temiskaming tailings

Cumulative Effects Assessment in a Historical Mining Camp undergoing a new Exploration Boom: Scientific Questions

- How to assess environmental impacts of new resource development against a brownfield legacy of pervasive contamination due to 90 years of un-regulated mining activity?
- What was the pre-mining (bio)geochemical baseline of the soils, sediments, vegetation, and waters of the mineralized watersheds?
- Has the existing environment reached a new geochemical equilibrium after historical resource development activities?
- Are there geochemical thresholds (tipping points) that need to be considered in assessing cumulative effects?
- Can lake sediment cores provide a reliable chronology of different phases of resource development in a mining-impacted watershed?
- With reference to climate change, what effects will the environment have on past, current, and future resource development projects?

Task 0: Partnership building with mining industry (Desbarats, lead)

FY 2021-2022 Achievements (Year end):

- Partnership with Agnico-Eagle Mines (AEM): Liaison with company representative (Josée Brazeau).
- Collaboration with local consultants Story Environmental Inc. (SEI): Contracting out survey of mine water discharge flow and chemistry; in-kind support for drilling three core holes in mine tailings; in-kind logistical support (workshop access, sampling advice) for March 2022 lake sediment coring.

Canada

Task 1: Metal(loid) loading in groundwater discharge to surface waters (Desbarats, lead)

Task 1.2: Discharge of metal(loid)-impacted groundwater from mine openings: Locating and characterizing anthropogenic seeps of mine-impacted groundwater

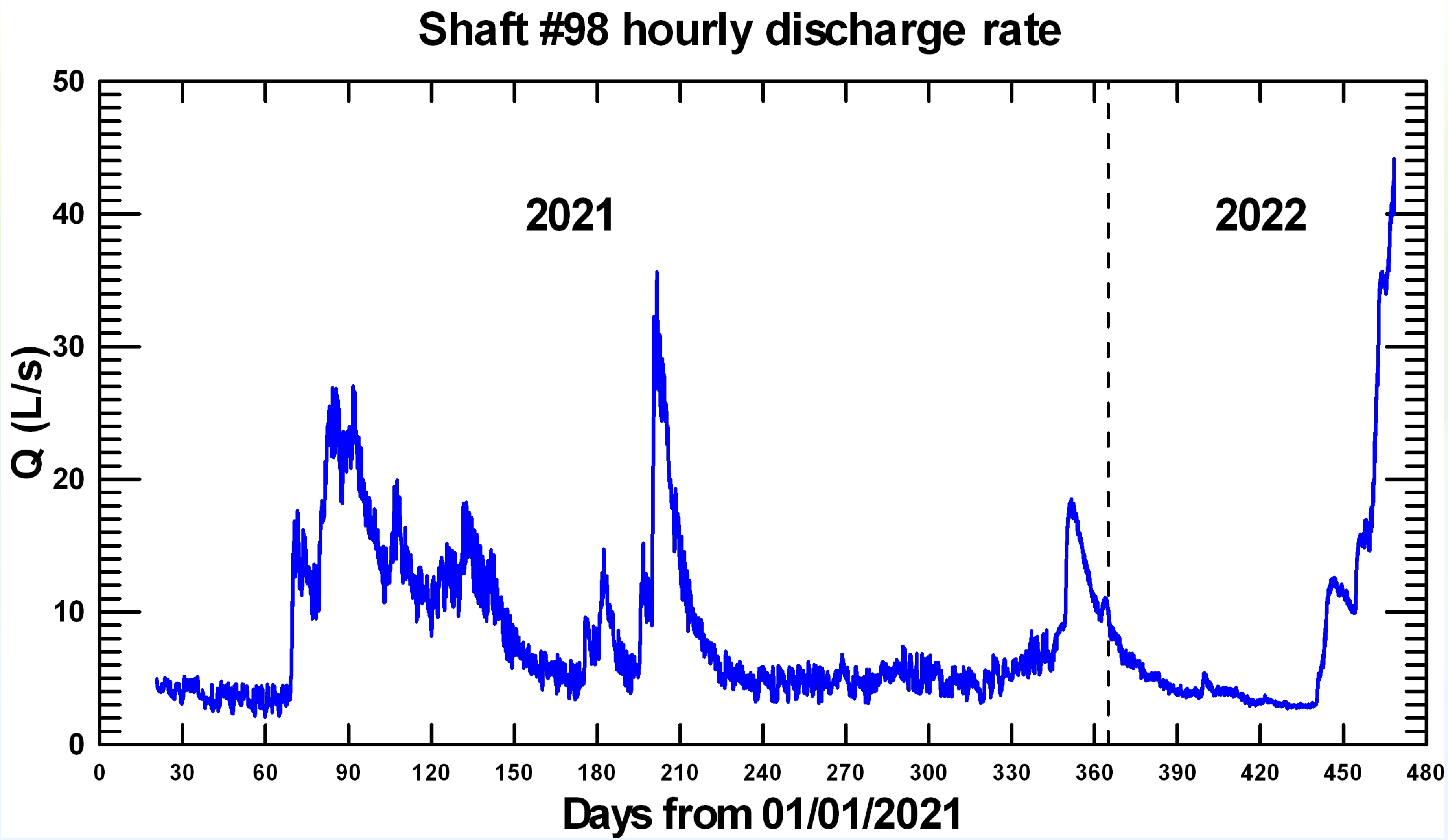
FY 2021-2022 Achievements (Year end):

Research question: Concentration-discharge relationships for point sources of mine drainage - How will metal(loid) mobilization be affected by extreme flow events related to climate change?

- High-frequency monitoring of flow and chemistry of contaminated mine waters discharging from Shaft #98 in the Cobalt camp – study ongoing

H-Flume at Shaft #98

Task 1.2: Discharge of metal(loid)-impacted groundwater from mine openings



Early mine water chemistry results (Dec 2021-Jan 2022):

As: 723-778 ppb
Co: 96-99 ppb
Ni: 75-77 ppb
Ag: 0.34-0.41 ppb
Zn: 54-57 ppb

Task 2: Stability of legacy contaminants in wetlands and lake environments (Parsons, lead)

Task 2.1: Sample mine wastes, sediments, and surface waters upstream and downstream of mining-impacted areas to evaluate the concentration and speciation of Ag, As, Co, Hg, Ni, and Sb in pre-mining and near-surface sediments and pore water.

Task 2.3: Micro-paleontological analysis (arcellaceans, diatoms, pollen) of lake sediments to evaluate the ecological response to legacy contamination, and the cumulative effects of mining and other development activities on aquatic biota.

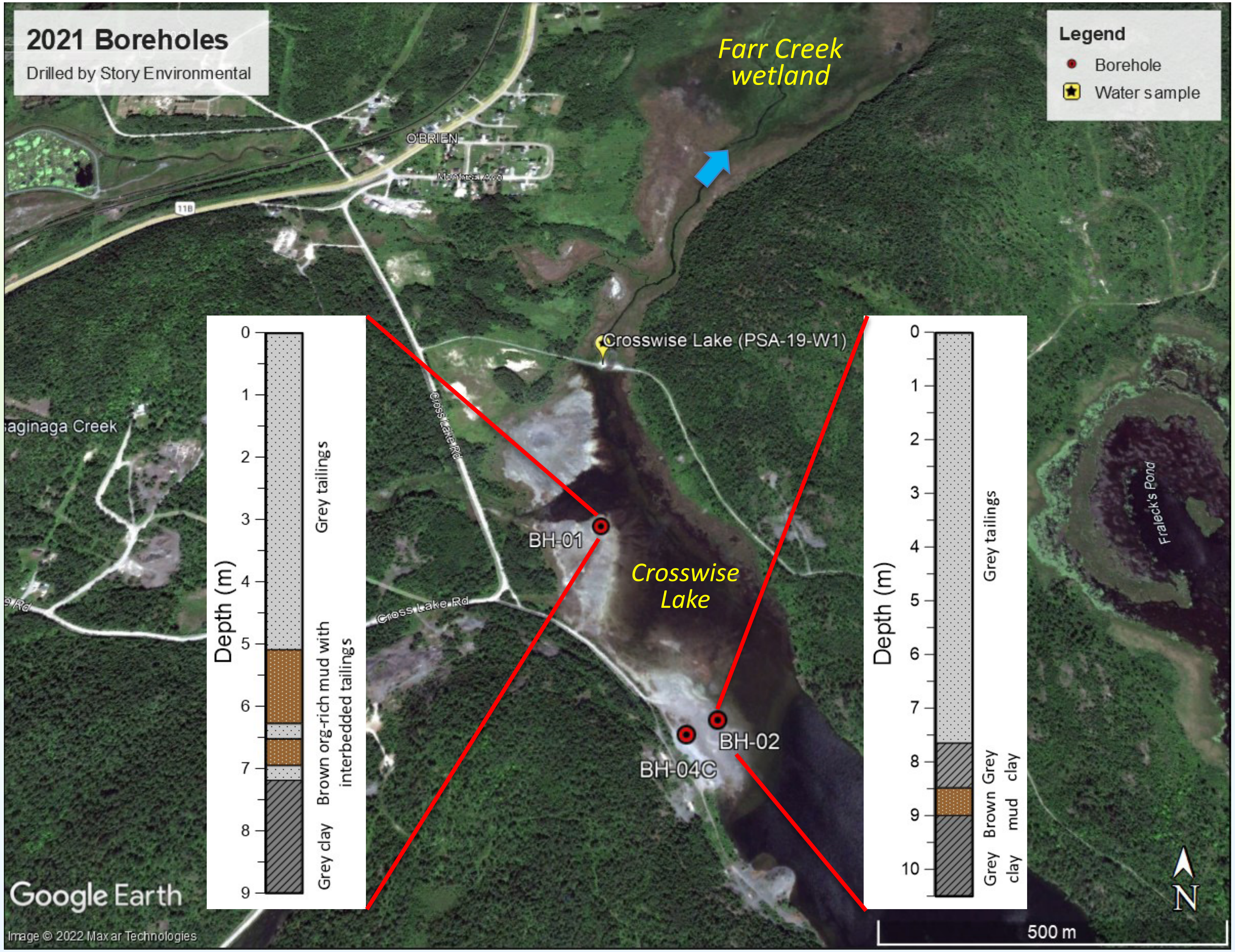
Sampling surface water at the outlet of Crosswise Lake, Cobalt, ON, June 2019

Task 2: Stability of legacy contaminants in wetlands and lake environments (continued)

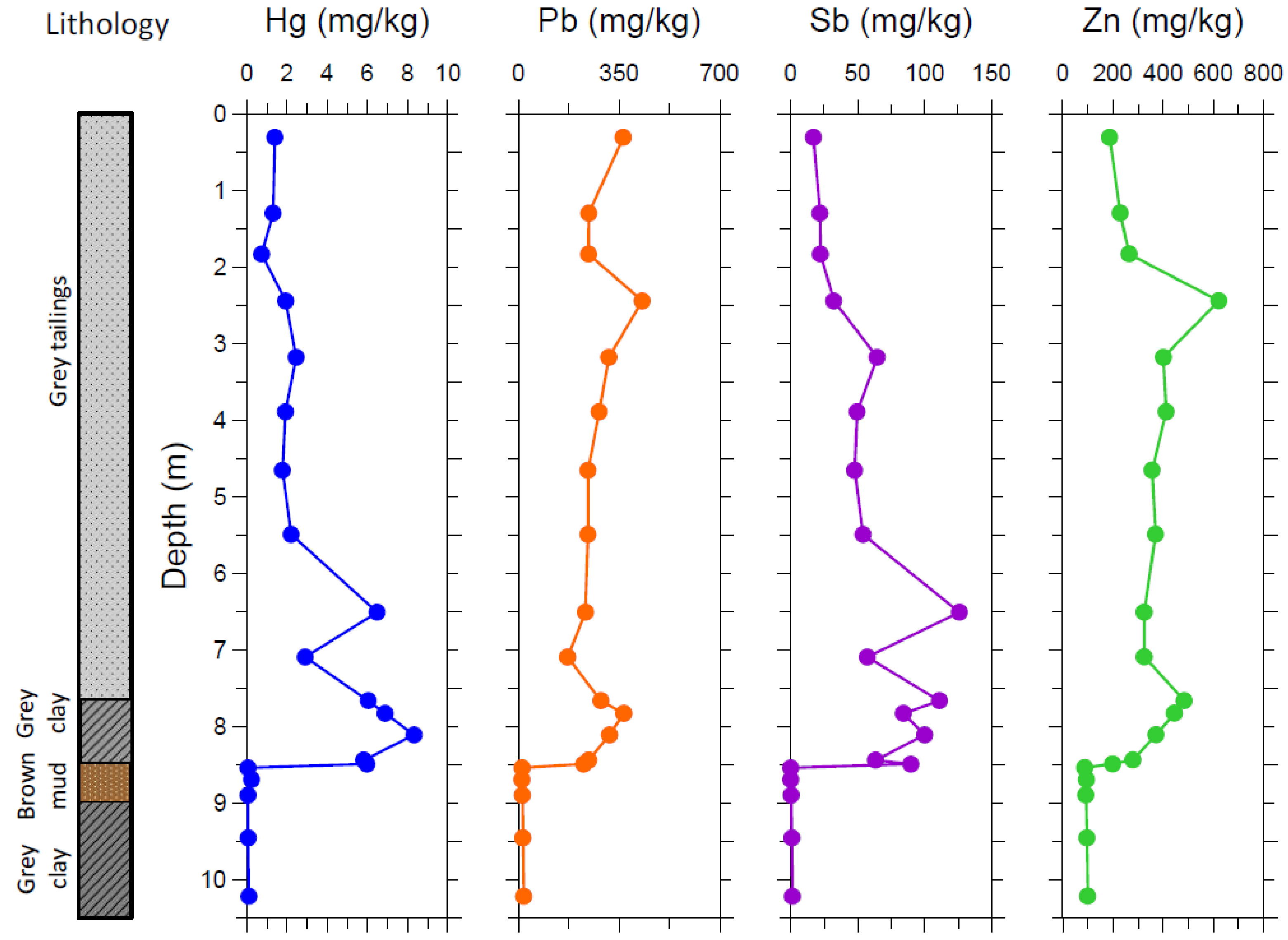
FY 2021-2022 Achievements (Year end):

- Tailings, organic-rich sediments, and glaciolacustrine clays subsampled from two 30’ boreholes drilled in Crosswise Lake in March 2021; geochemical, grain size, HAWK pyrolysis, and 14C analyses completed.
- Additional cored borehole drilled in Crosswise Lake tailings in October 2021 (at no charge to project); subsampled for geochemical and grain size analysis.
- Successful sediment coring program completed on Lake Temiskaming in March 2022. Collected duplicate cores from nine sites in water depths from 1 – 85 m.
- ***Parsons, M.B.***, *Geoenvironmental Characteristics of Canadian Critical Metal Deposits. Invited presentation for LMS Science-Policy Forum, April 15, 2021.*

- Tailings were discharged into Crosswise Lake and an adjacent wetland from at least five different mills between 1908 and 1970.
- Boreholes drilled in two tailings lobes in 2021 reveal ~ 5 - 7.5 m of tailings overlying brown organic-rich mud, and grey clay-rich glaciolacustrine sediments.
- Fine tailings and contaminated surface water flow northward into Farr Creek and discharge to Lake Temiskaming 7.5 km downstream.



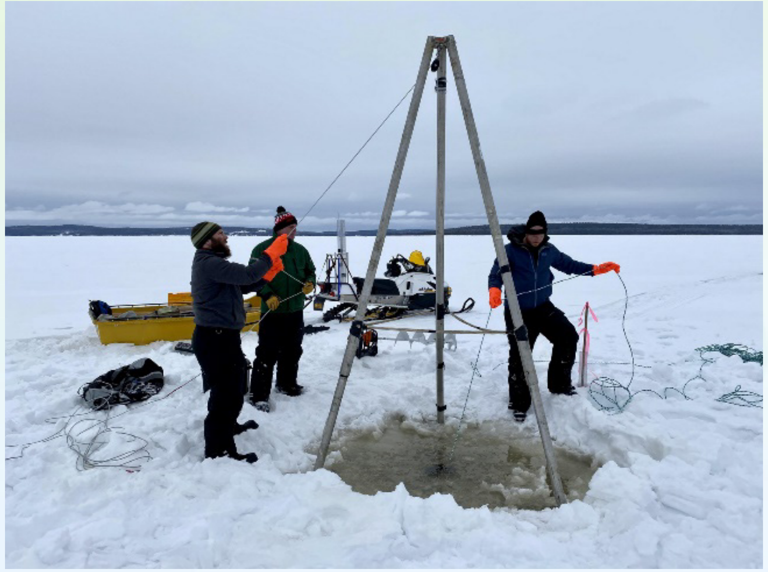
Metal(loid) concentrations in sediments in Borehole BH-02, Crosswise Lake, Cobalt, ON

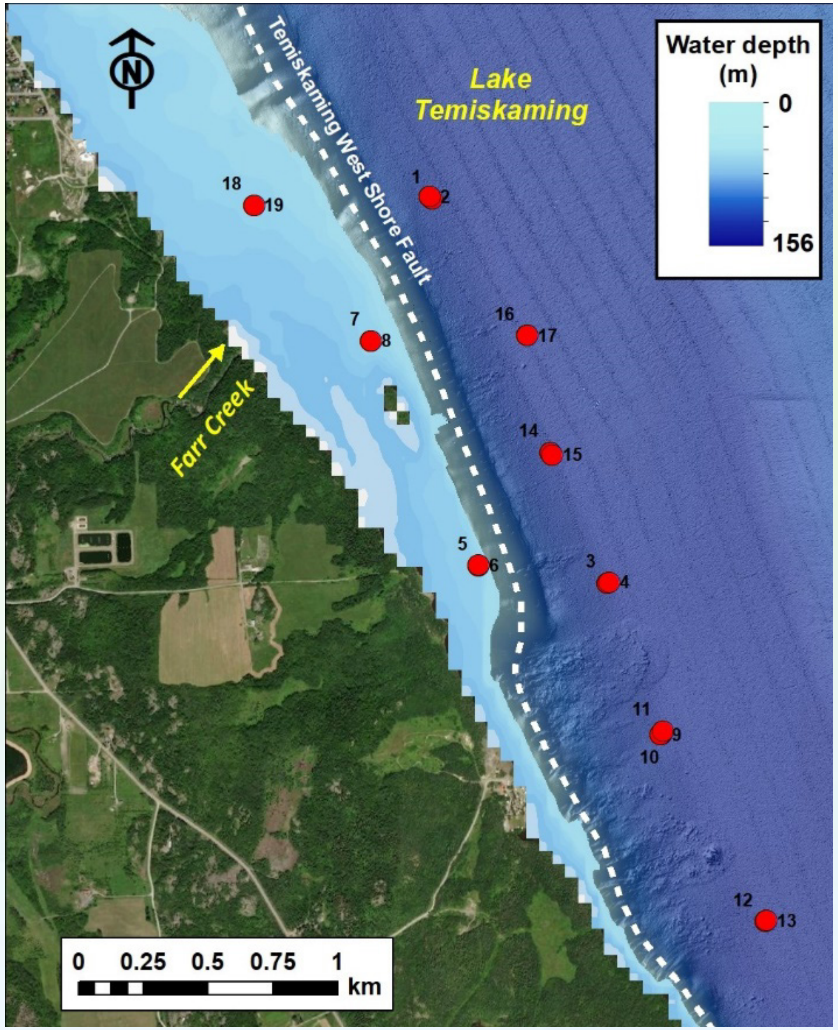


Tailings vs. Glaciolacustrine Clays
[min, max (median)]

Element	Tailings (mg/kg)	Glacial clays (mg/kg)
Ag	15 - 393 (60)	0.3 - 2.6 (1.0)
As	1220 - 4650 (2200)	10 - 66 (41)
Co	262 – 1060 (557)	14 – 33 (23)
Hg	0.26 – 8.33 (2.08)	0.04 – 0.24 (0.06)
Ni	99 – 853 (329)	33 – 64 (53)
Sb	9.1 – 126 (52)	0.21 – 1.4 (0.44)

Task 2: Stability of legacy contaminants in wetlands and lake environments (continued)





Sediment coring on Lake Temiskaming, March 7-11, 2022

Task 3: Mineralogical characterization of mine wastes and other solid phases (Percival, lead)

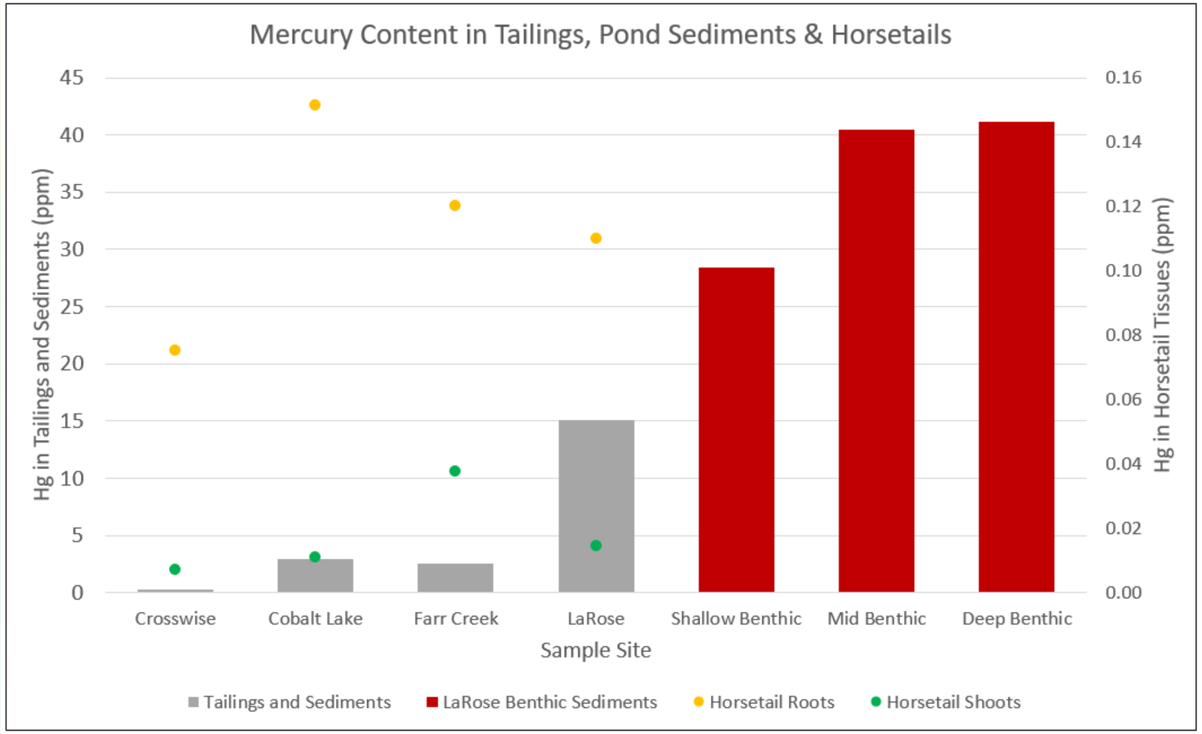
Task 3.1: Review and re-analysis of selected archived samples from earlier studies as a platform to define the mineralogical signature for the geoenvironmental ore deposit model.

Task 3.3: Micro-mineralogy of primary and secondary As, Co, Ni and Sb phases in high-grade tailings and mill waste to evaluate the solid-phase speciation of these elements and their long-term stability under weathering conditions and remediation scenarios.

FY 2021-2022 Achievements (Year end):

- Parsons with Heather Jamieson (Queen's) supervising M.Sc. Student (Melissa Turcotte) studying micro-mineralogy of mine tailings and effects of vegetation on metal mobility; EPMA analyses; SEM-MLA analyses; collection of new samples in the field in July 2021
- Archived ore samples retrieved from Hawthorne Road facility and shared with Jamieson and Bowell (Queen's) for detailed studies of pre- and post-oxidation of ores; sample preparation in progress for petrographic and SEM analyses (Percival)
- 3 invited presentations (Parsons); presentations at the GAC-MAC 2021 conference (Percival) and the Virtual Symposium 2021 on Mines and the Environment (Jamieson)

Task 3: Mineralogical characterization of mine wastes and other solid phases (cont'd)



Results from Queen's M.Sc. Student, Melissa Turcotte, EGP Student Day presentation, January 25, 2022

- M. Turcotte collected near-surface tailings and sediments from four sites in July 2021, and horsetails growing in mine tailings.
- Chemical and mineralogical analyses are nearing completion; shake flask extraction tests completed in April 2022.
- Forthcoming presentation at GAC-MAC in May 2022; on-track for M.Sc. thesis defense in late 2022.

Task 4: Best management practices for cobalt-rich tailings (Beauchemin, Health Canada, lead)

Task 4.2: Laboratory experiments under controlled conditions to elucidate health risks from metal(loids) in airborne dust from tailings impoundments.

FY 2021-2022 Achievements (Year end):

Research question: Inhalation exposure to metal mixtures in mining areas - contribution from surface soils/wastes to airborne fine ($PM_{2.5}$) and ultra-fine particles (UFP):

- Training of HQP on the newly acquired ICP-MS/MS instrument with integrated single-particle analysis module (sp-ICP-QQQ) for characterization of nanoparticles (NP)
- Method development for water extraction of NP from environmental samples using NP-spiked samples
- Method development for single-particle analysis using certified monometallic suspensions of relevant metal oxide nanomaterials

Task 5: Weathering processes in Cobalt-type Ag-Ni-Co arsenide tailings (T. Al, University of Ottawa, lead)

Task 5.1: Field sampling of in-situ weathering products of primary Ag-Ni-Co arsenide and sulphide minerals in mine tailings

Task 5.2: Detailed mineralogical investigations of weathering products and laboratory studies of metal(loid) mobilization

FY 2021-2022 Achievements (Year end):

- Mineralogical analyses of primary sulf-arsenides and secondary minerals in core samples from the Cart Lake tailings: reflected-light microscopy; SEM-EDS analyses; EPMA analyses
- M.Sc. student (Cole Fischer) thesis write-up on track

Cart Lake tailings

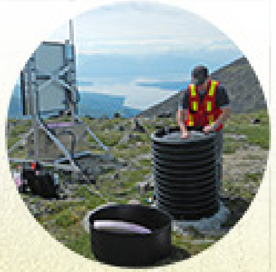
CONTACT INFORMATION

- Project leader: Alexandre Desbarats
- 613-995-5512 / 343-548-5571
- alexandre.desbarats@nrcan-rncan.gc.ca

THANK YOU!

Ressources naturelles Canada | Natural Resources Canada




Ring of Fire: Reconstructing long-term environmental records to support regional assessment

2022

Canada

Abstract

Ring of Fire (RoF) = large mineral deposits of Ni/Cu/Zn/Cr and PGM

- Located in one of the world's largest peatland system;
- Sensitive to climate change (Hadley et al., 2019) and anthropogenic stresses (Leclair et al., 2015)

Additional knowledge on environmental conditions required:

Pre-mining:

- Natural presence/behavior of metal(loid)s needs to be carefully assessed
- Baseline conditions response to climate change + remote anthropogenic stresses

Post-mining initiation:

- Changes to groundwater flow dynamic, geochemical fate of metal(loid)s in surface storage of tailings and waste rocks over time.
- Explore and develop environmental indicators adapted to the monitoring of RoF environment.

Project members

J. Jautzy[1], N. Benoit[1], J. Marion[1], M. Parsons[1], Paul Gammon[1], Pierre Pelchat[1], A. Desbarats[1], G. Légaré-Couture[2], P. Bergeron[1], M. Parent[1], J. Galloway[1], J. Ahad[1], B. Fosu[1], C. Bégin[1], É. Girard[1], E. Berryman[3], J. Girard[4], N. Sanderson[5], M. Garneau[5], M. Bunn[1], F. Letourneau[1], M. Nastev[1], A. Dixit[1], N. Balliston[6]

[1]*Geological Survey of Canada, Natural Resources Canada (NRCan)*
[2]*Canada Centre for Mapping and Earth Observation, Natural Resources Canada (NRCan)*
[3]*CanmetMINING, Natural Resources Canada (NRCan)*
[4]*Environment Canada*
[5]*Université du Québec à Montréal*
[6]*University of Waterloo*

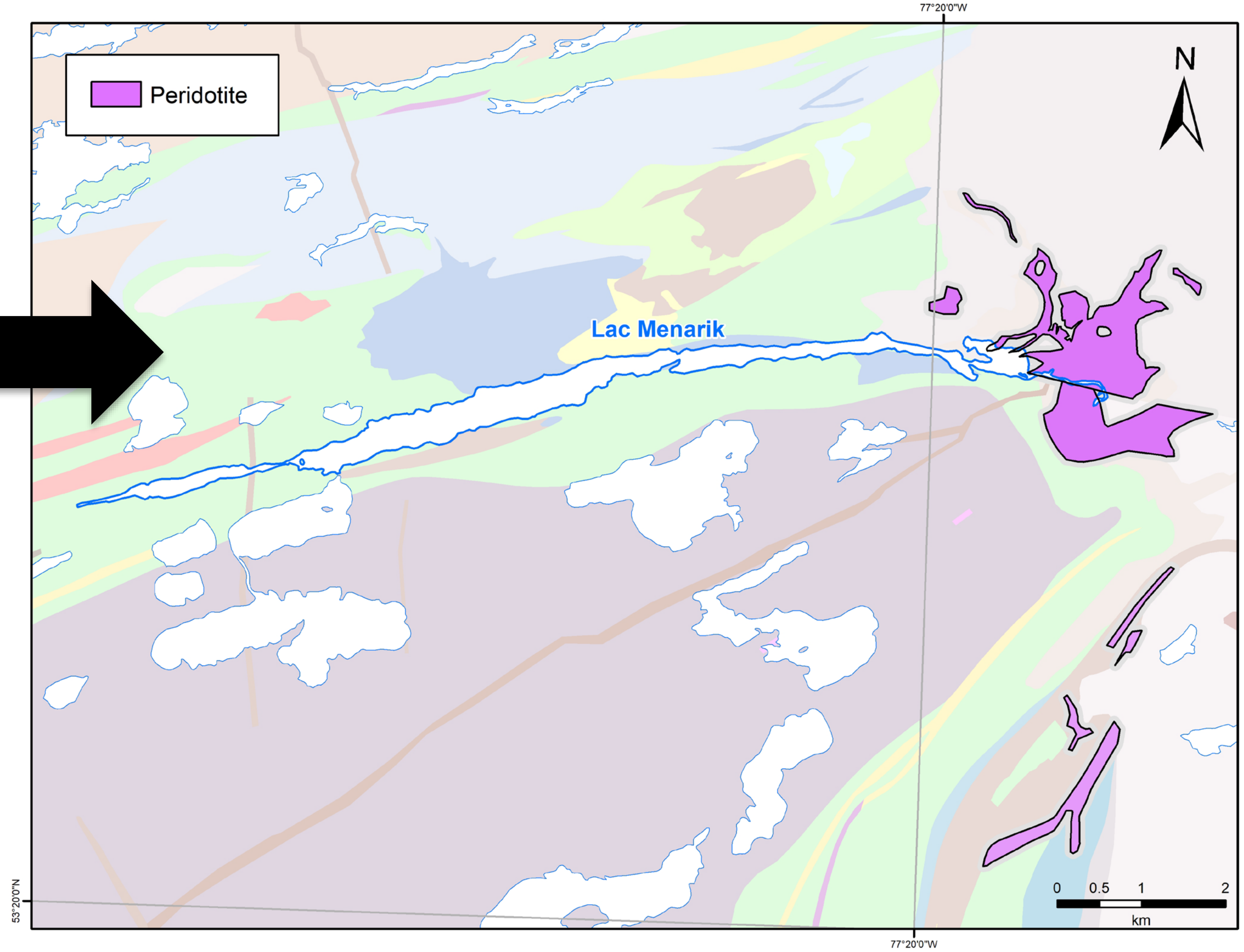
Activities

- Environnemental archives study on a pre-mining analog context of chromite deposit – Menarik lake (Qc): Field campaign / Sample preparation and analysis / Establishment of chronologies for the different archives;
- Hydrogeochemical study on a post-mining analog context of chromite deposits – Chaudière-Appalaches (Qc): Field campaign;
- Analytical development of Chromium speciation analyses in water, laboratory and real field development;

Pre-mining context

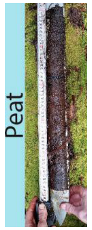
- Analog Cr-deposit context – Cr-mineralized outcrops in a boreal environment.

© Hi



Pre-mining context

Colocalized archives with ≠ complementary chronological scales.
Past climatic anomalies as analog to current climate change.

Peat  1000s yrs	Lake sediment  200-1000 yrs	Tree rings  50-200 yrs

Climate proxy

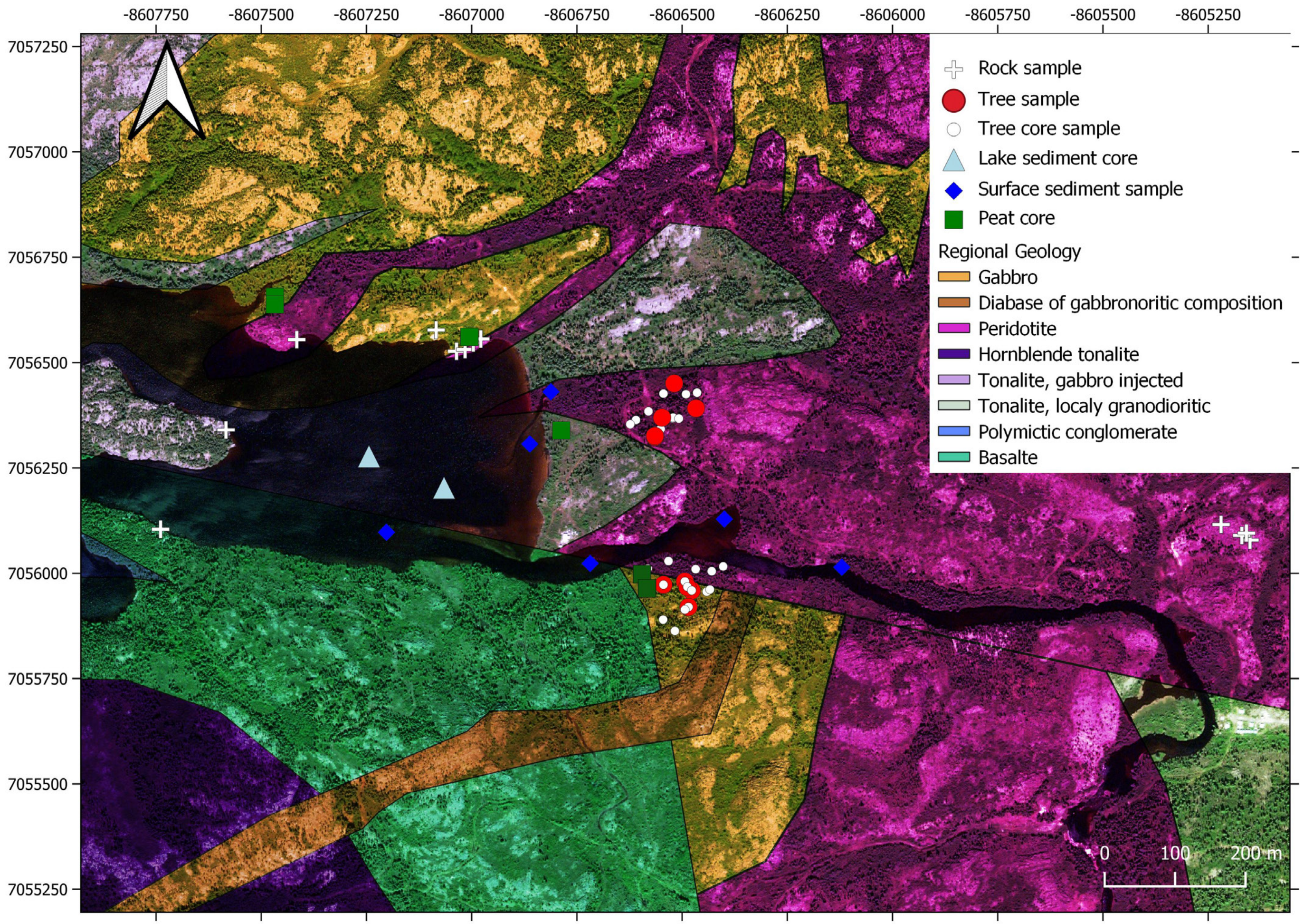
↕ *Link?*

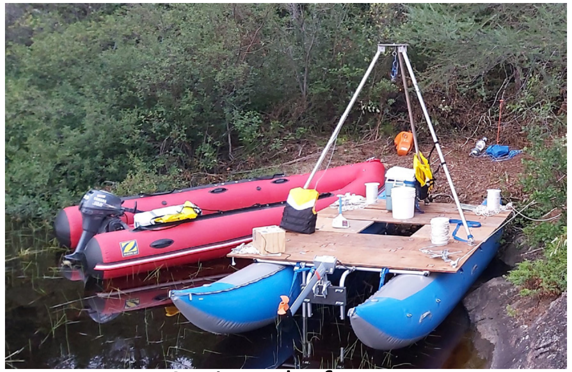
Record of Cr loading?

Test and development of new indicators:

- forest fire intensity
- natural level metallic loading

Field work: Pre-Mining Site





Coring platform

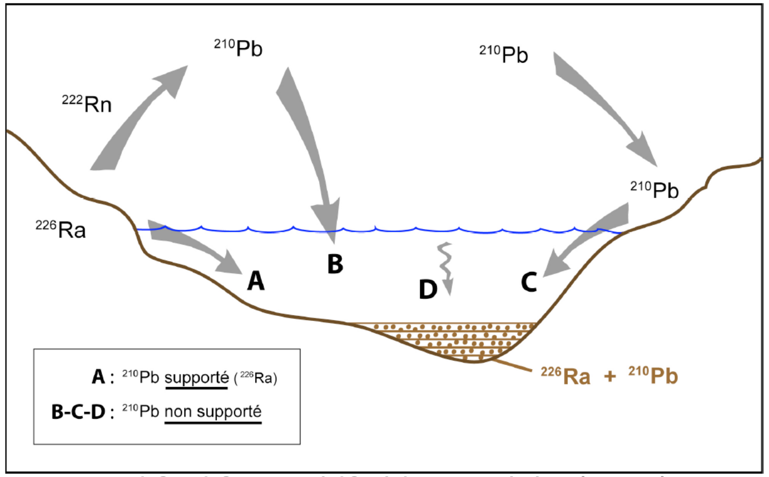
Blake Spruce sample

Sediment Cores

Minerotrophic peat sample

Chronologies

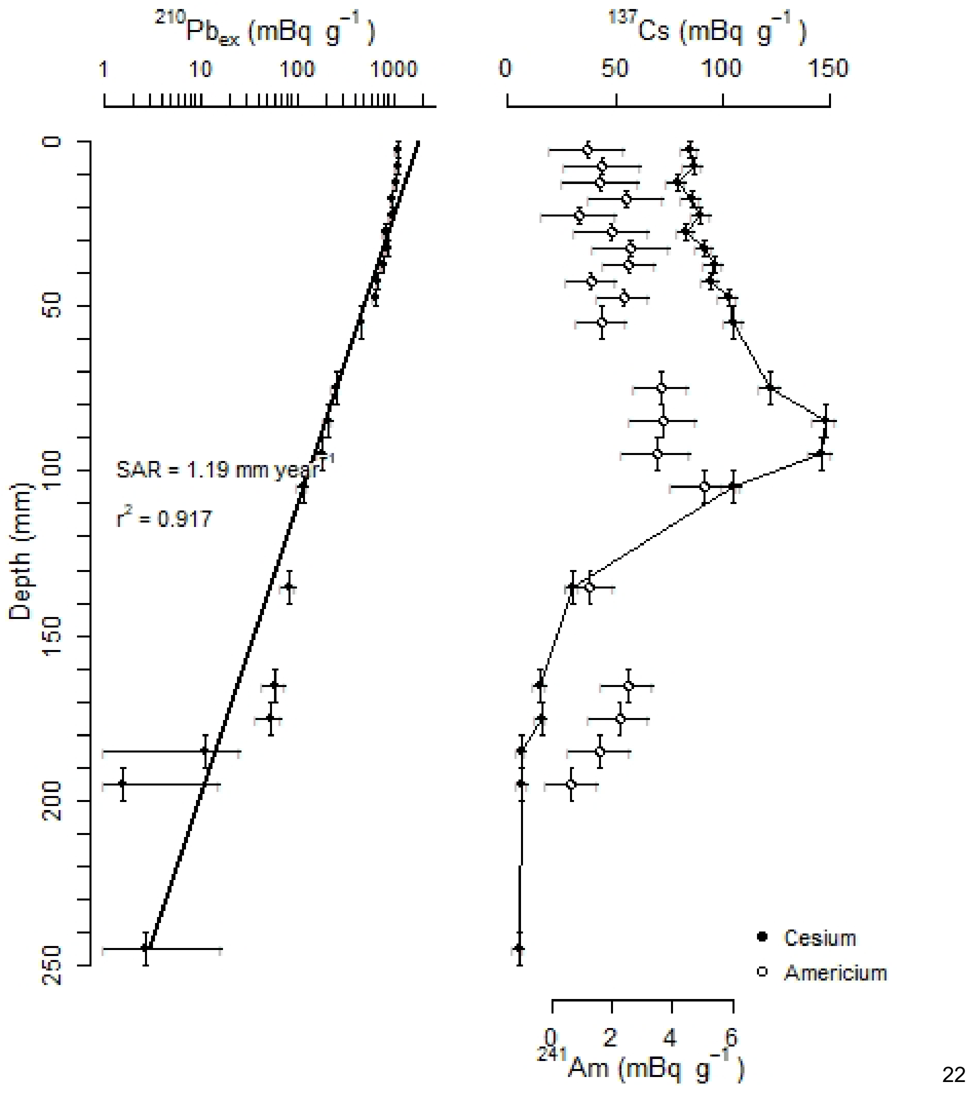
- Use of various isotopic systems or geochronometers to establish chronologies for the archives→ crucial step in order to be able to interpret proxies variations.
  - → Combination of ^{210}Pb ^{137}Cs, ^{226}Ra, ^{241}Am and ^{14}C for lake sediment cores and peat cores
  - → Test of various age model technique in order to provide the best age/depth relationship with appropriate uncertainties. (bayesian and linear)

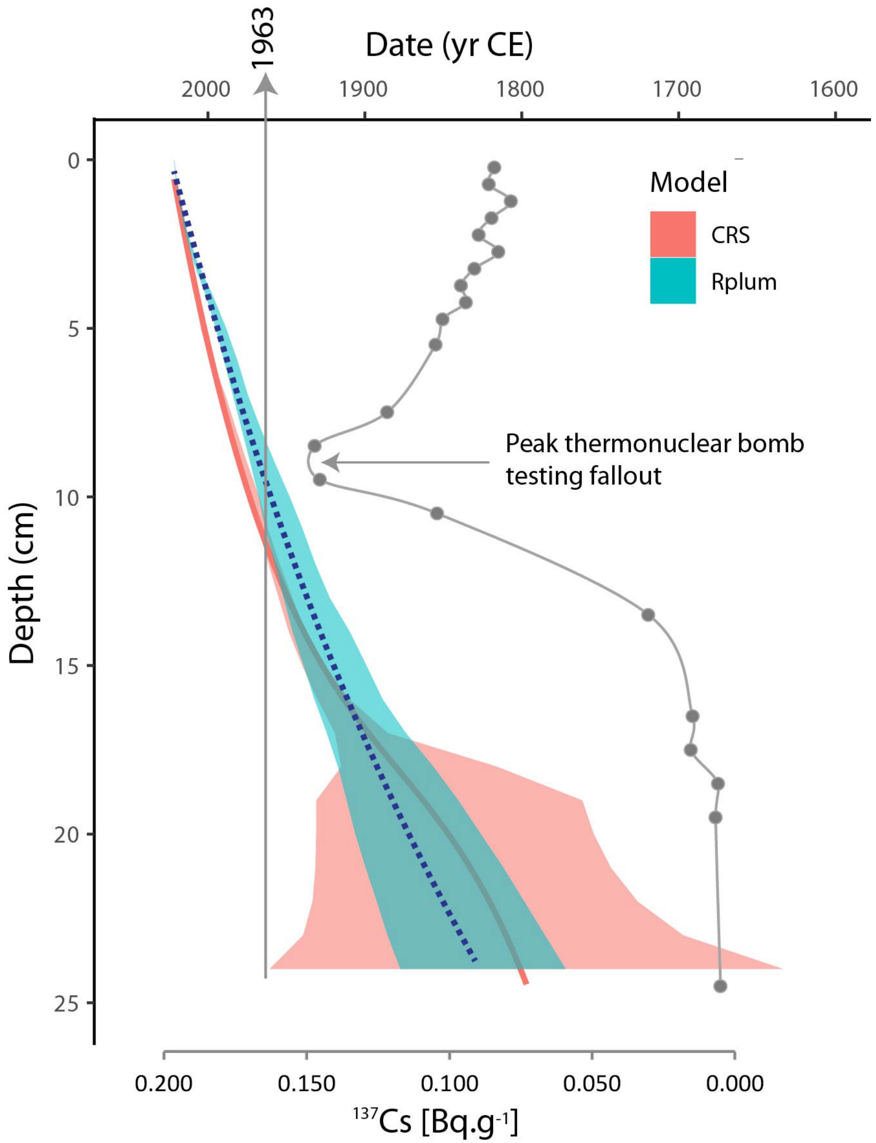


Modified from Oldfield & Appleby (1984)

- Tree ring counting for absolute datation in black spruce population sampled.

Results - Lake





Various age models tested against chronostratigraphic marker 1963 ^{137}Cs max fallout.

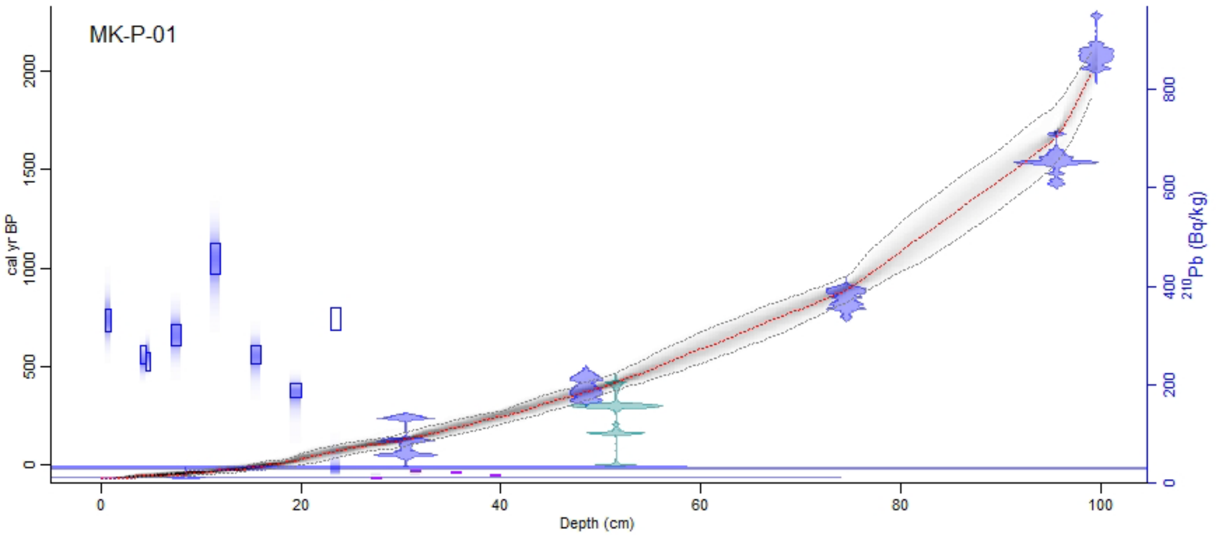
Bayesian model fits perfectly

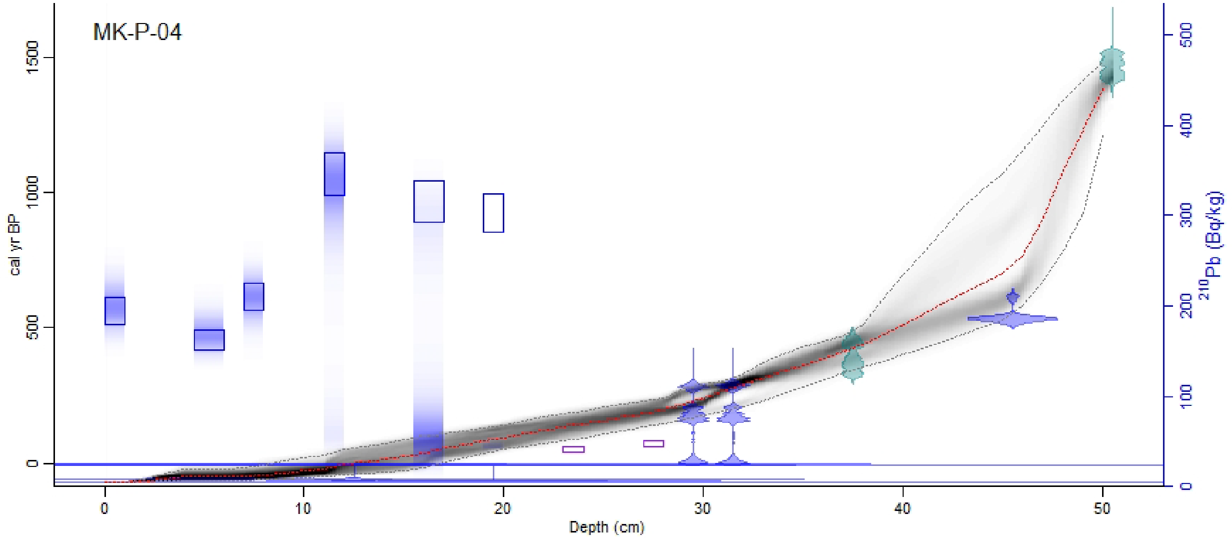
= reliable age model covering the Anthropocene with better contraints on uncertainty at depth

= better anchors for ^{14}C dates in the remaining 35cm of sediment core.

Appleby & Oldfield (1978)
Aquino-Lòpez et al. (2018)

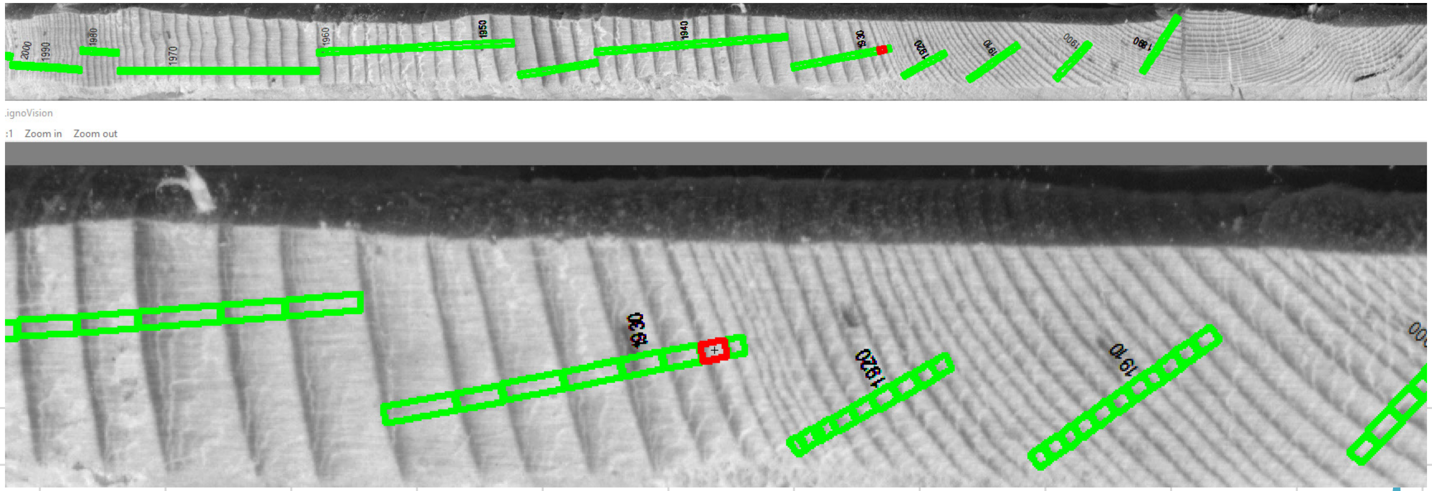
Results - Peat





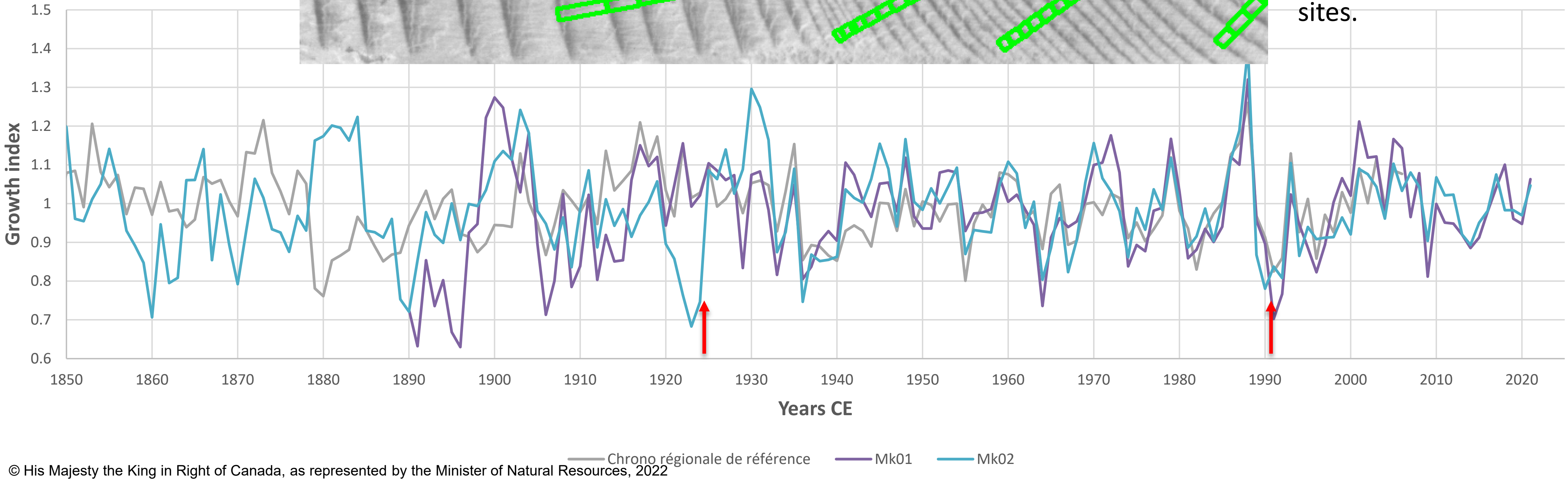
Both sites span millenial time scale with opportunity to explore the effect of the Medieval Climatic Optimum on natural metal(loid)s mobility. The resolution of the Anthropocene portion of the core ~ comparable to the lake sediment record.

Results - Tree



Mid 20’s : ecological stress inducing a significant growth reduction only for MK02.

Early 90’s: possible impact of PinaTubo volcanic eruption impacting both sites.



Conclusion

- Field work completed;
- Preliminary chronologies established and various archives will cover appropriately different climatic changes with various time resolution. This will allow to put in perspective the proxy profiles with know climatic events (MCO, LIA, etc.)
- On track to bring insight on the sensitivity of these different archives on the long term evolution of metals in these type of environments.

Contact Information

- josue.jautzy@canada.ca
- nicolas.benoit@canada.ca

Thank you / Merci!

Ressources naturelles Canada | Natural Resources Canada

Long-term hydrological dynamics of Canada’s largest watershed: The Mackenzie River Basin

Dynamique hydrologique à long terme du plus grand basin versant du Canada: le basin du fleuve Mackenzie

Canada gwizhìt chuu tł’it gwiinchii goo’aii gwats’àt chuu niinlaii nits’òo gwizhìt goo’aii k’iighè’ nikhwinagoo’ee yeendoo nits’òo gwihee’ah: Nagwichoo Njik Gwizhìt Khehłat Niinlaii

Jennifer Galloway and team

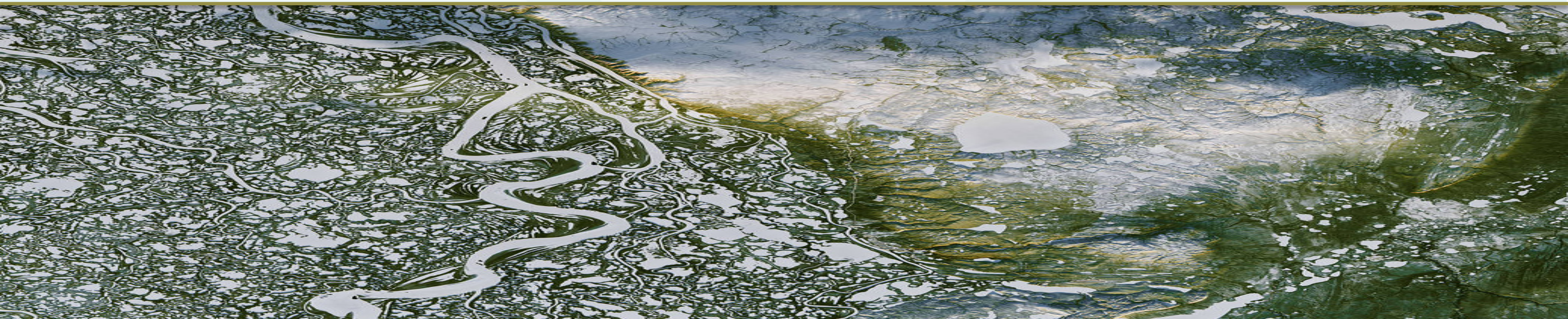
May 10, 2022

Canada

ABSTRACT

- The Mackenzie River (*Deh-Cho, Kuukpak, Fleuve de Mackenzie*) Basin (MRB) is one of the World's largest (4200 km long) and most important freshwater ecosystems
- Climate change is disproportionately affecting high northern latitudes
- How will climate change affect water quantity in the MRB?
- This project will examine long-term trends and cycles to develop predictive ecohydrological models

NASA Earth Observatory Joshua Stevens. LandSAT82 2016 data from USGS

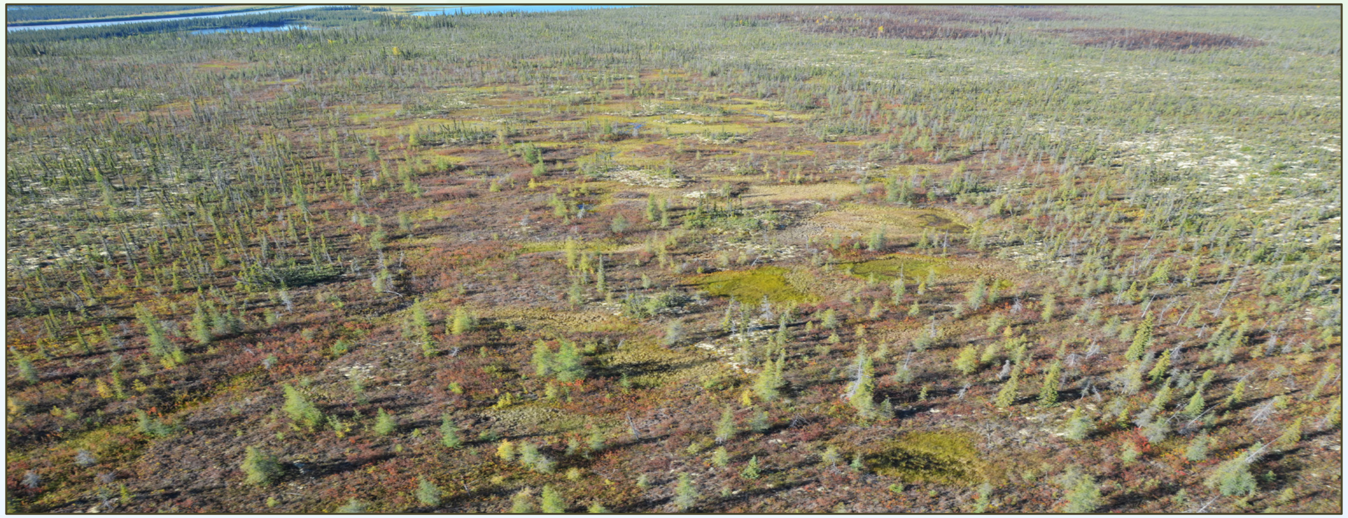


PROJECT MEMBERS

Internal	Galloway, Jennifer (GSC-C)
	Hadlari, Thomas (GSC-C)
	Ardakani, Omid (GSC-C)
	Bringué, Manuel (GSC-C)
	Wolfe, Steve (GSC-N)
	Morse, Peter (GSC-N)
	Parsons, Michael (GSC-A)
	Colmenares, Jaime Rafael Cesar (GSC-C)
	Crowley, John (Canadian Geodetic Survey, NRCan)
External	Falck, Hendrik (GNWT)
	Lantz, Trevor (University of Victoria)
	Shotyk, William (University of Alberta)
	Patterson, R. Tim (Carleton University)
	Swindles, Graeme (Queen's University, Belfast)
	Gałka, Mariusz (University of Łodz)
	Lord, Sarah (Gwich'in Renewable Resources Board, now DFO)
	Snowshoe, Sharon (Gwich'in Tribal Council, Dept. of Cultural Heritage)
	Clarke, Leon (Manchester Metropolitan University)
HQP	Andrii Oleksandrenko (PhDs) (U of Alberta)
	Jackie Ziegler (PDF) and Hanna Travers-Smith (MSc) (University of Victoria)
	Naomi Weinberg (MSc) and Anne Nguyen (PhD) (Carleton)

Funding: GSC's Environmental Geoscience Project, ArcticNet (Project #51) (FY 19-20 to 22-23; Galloway), NERC (Clarke), Polar Continental Shelf Project (Galloway), in-kind Gwich'in Renewable Resources Board (Lord) and Gwich'in Tribal Council, Department of Cultural Heritage (Showshoe)

This research occurs under NWT Science License #16737 and application #4705



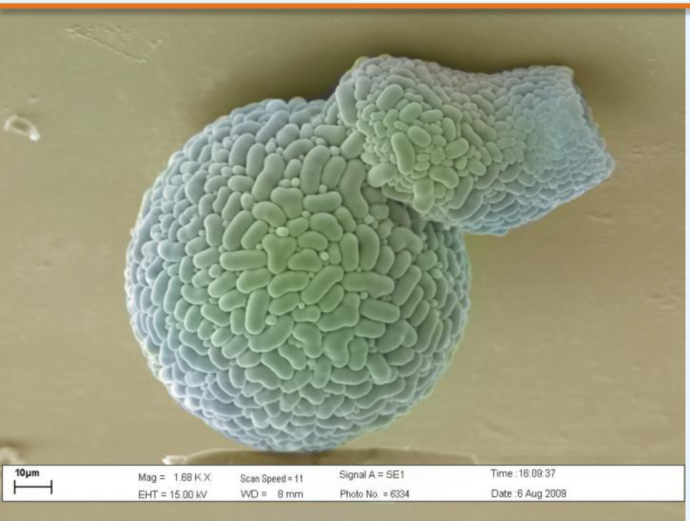
PROGRESS TO DATE

- 11 peat cores collected
- 100 vegetation samples and depth to water table measurements from 8 sites within and outside of the Gwich'in Settlement Area
- Analysis of core samples for HAWK pyrolysis, Hg analysis, inorganic geochemistry, age dating, stable isotopes, and paleontological analysis (testate amoebae, pollen, spores, charcoal, plant remains)
- Traditional Knowledge study based on synthesis of previously documented knowledge related to water levels in the Gwich'in Settlement Area (synthesized semi-structured interviews exploring hydrological dynamics in the Gwich'in Settlement Area; compilation of the Department of Cultural Heritage's archives for information on changing water level and the cultural significance of regional waterways)

TO

- Reconstruct depth-to-water table (quantitative), fire and vegetation history, chemical change, hydrological change, and synoptic-scale climate patterns (e.g., Pacific Decadal Oscillation) over millennia, that may drive future water quantity and quality change in the MRB

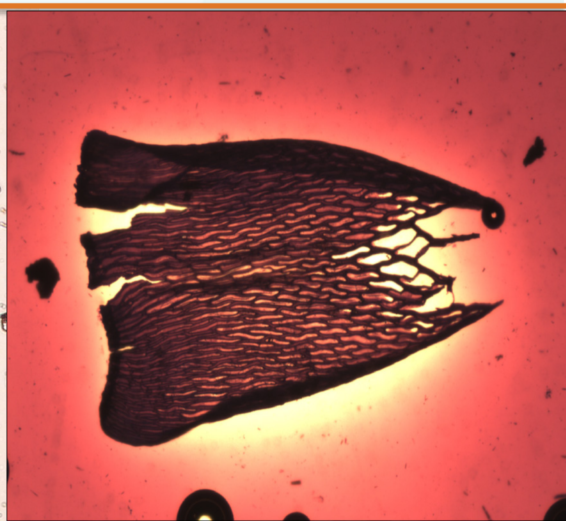
Lesquereusia epistomium survives peat fires
(credit: Yuri Mazei)



Picea (spruce) pollen (~125 µm)
(credit: Neotoma database)

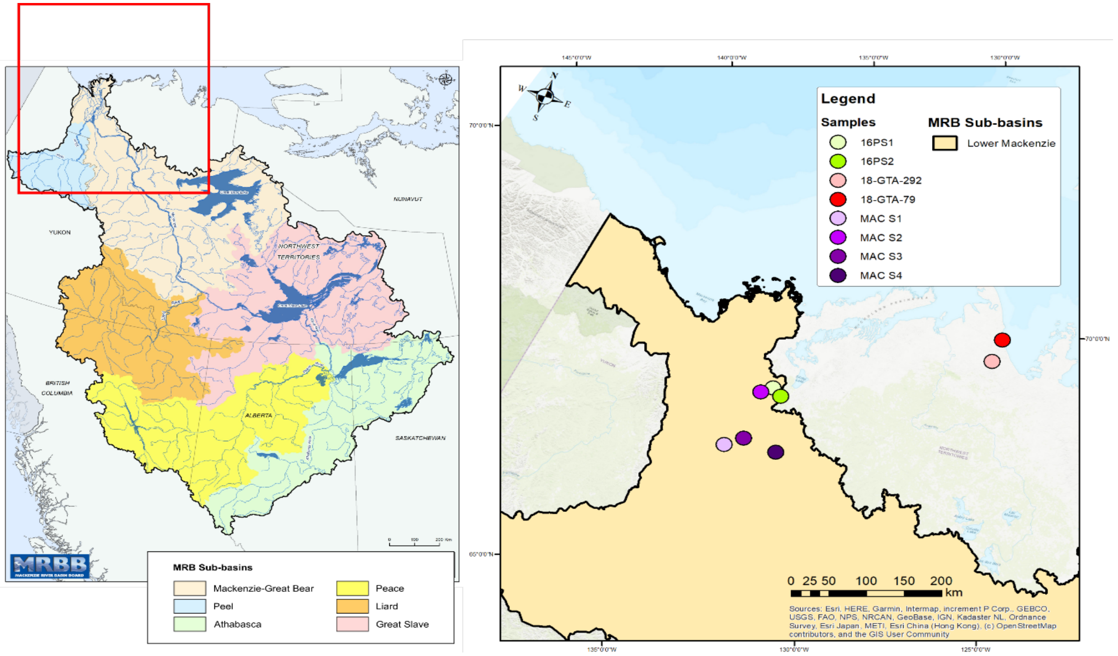
Microscopic charcoal
(credit: Mathewes et al. 2019 Vegetation History and Archaeobotany)

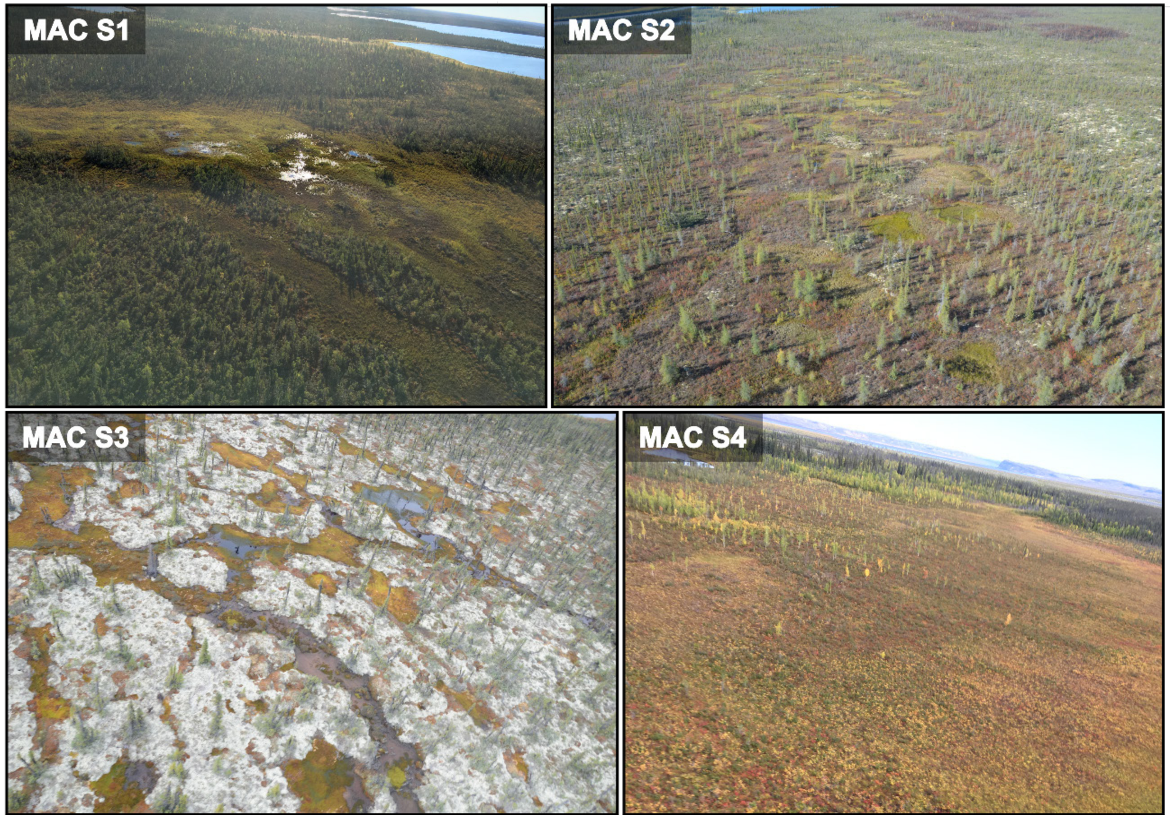
Sphagnum riparium
(credit: Mariusz Gałka)



Peat cores

11 peat monoliths collected from within (*n*=6) and outside (*n*=2) of the Gwich'in Settlement Area (GSA); 8 are being used for the study; and of these, 4 "MAC" cores collected with purpose-built titanium coring device by the Gwich'in Renewable Resources Board are being used for detailed study



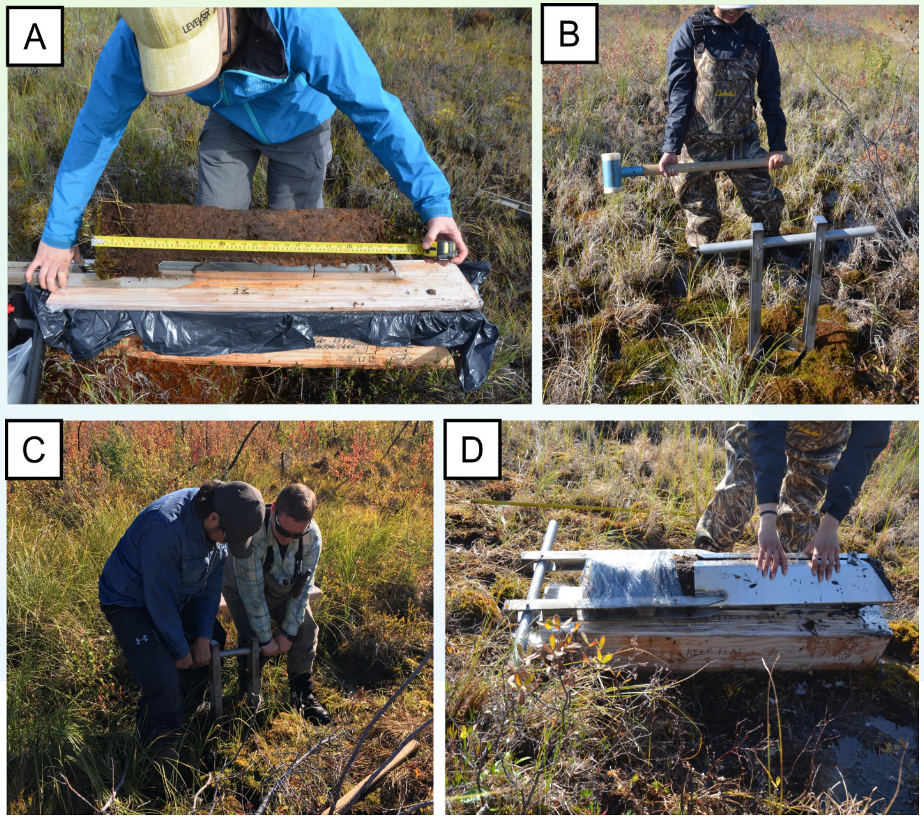


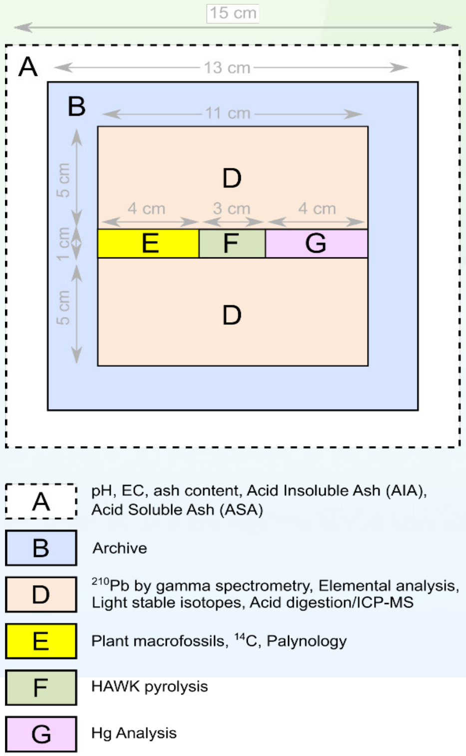
(L) Map of the MRB and peat core locations. The red box outlines the map boundary on the right. Modified from MRBB and EETSD, 2017. (R) site photos of MAC S1 – Mackenzie Site 1; MAC S2 – Mackenzie Site 2; MAC S3 – Mackenzie Site 3; MAC S4 – Mackenzie Site 4; photo credits S. Lord (2020)

Peat cores

(R) Site photos from the collection of the MAC cores by the Gwich'in Renewable Resources Board team in 2020. A) Steve Anderson measuring Site 1 Core 1, B) Julienne Chipesia using the titanium corer, C) Sarah Lord and Jason Blake McLeod using the titanium corer, D) Julienne Chipesia extracting Site 2 Core 1. Photo credits: S. Lord, 2020.

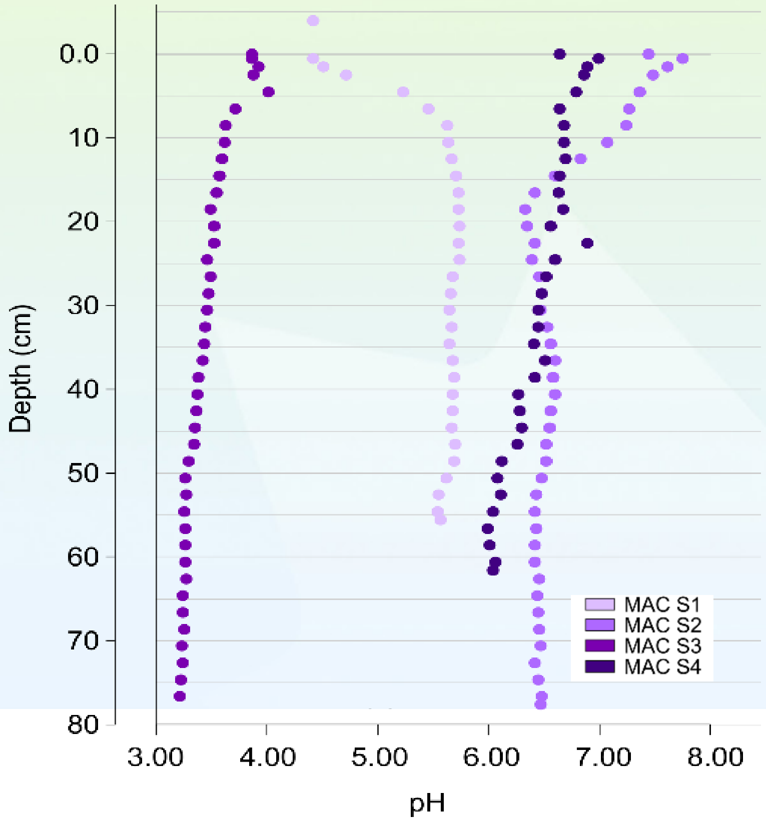
(L) Slicing and sub-sampling protocol devised by the SWAMP laboratory, University of Alberta for MAC cores sliced at 1-cm intervals and showing division of living layer from peat. Photo credit: A. Oleksandrenko, 2020, University of Alberta.



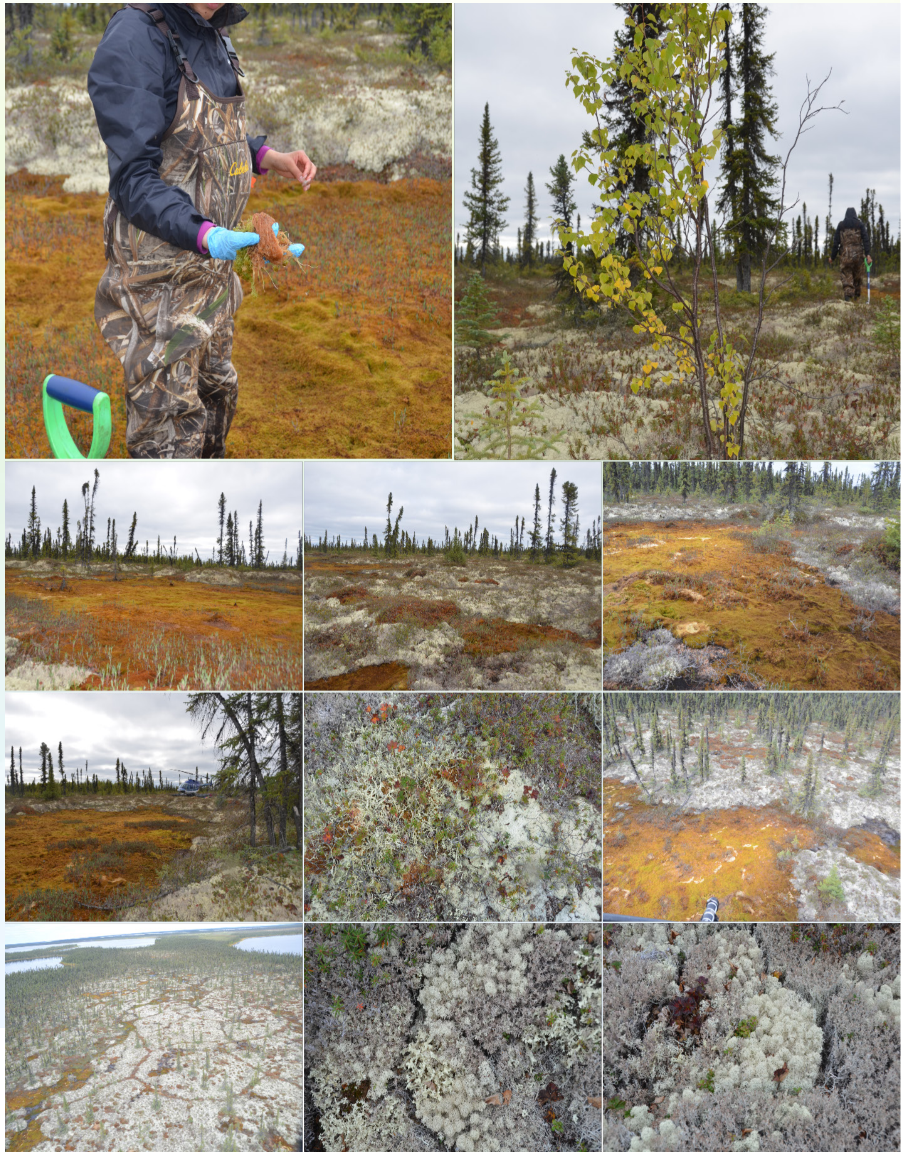


Peat cores

The MAC S3 peatland is ombrotrophic (pH < 4). This environment is ideal for reconstruction of atmospheric metal accumulation and paleoclimatic reconstruction; other sites received input from connected surface waters and/or groundwater.

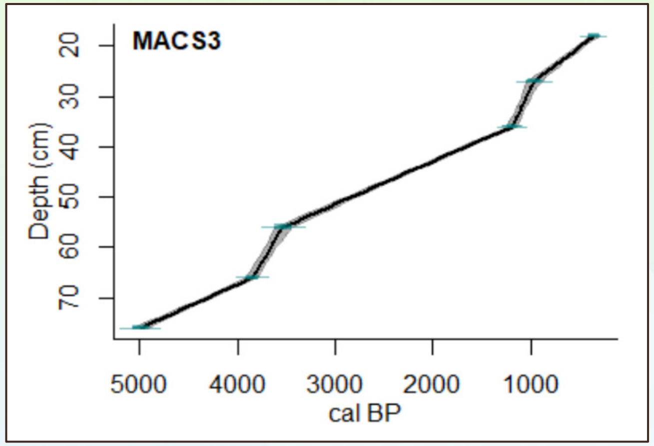


MAC S3 surface moss, vegetation, and depth to water table measurements. Photo credits: S. Lord, Gwich'in Renewable Resources Board, 2020.

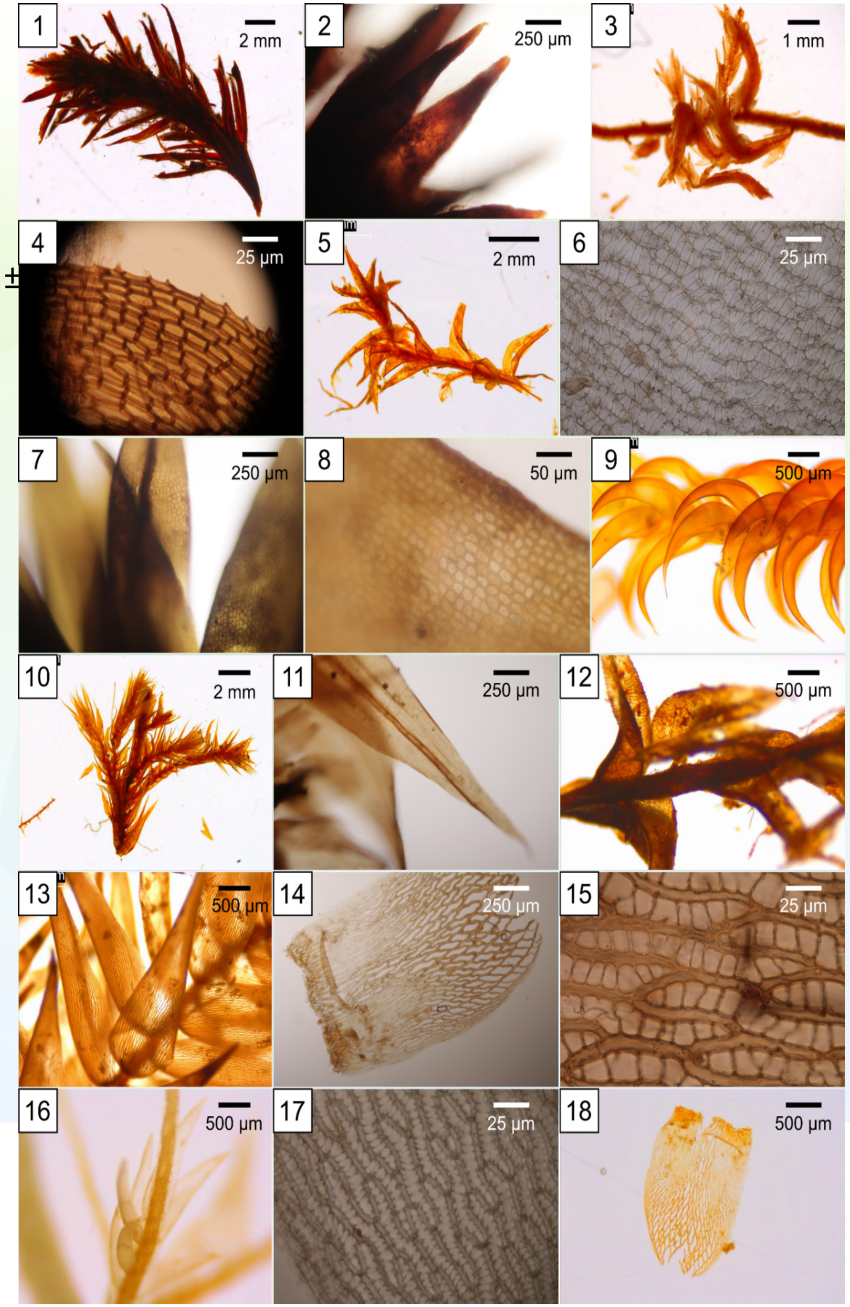


Peat cores

- 57 plant macrofossils submitted for AMS ^{14}C dating
- The youngest basal date returned was 214 ± 27 cal yr BP and the oldest basal date was 4993 ± 41 cal yr BP (the ombrotrophic bog MAC S3)



Age depth model (CLAM; Blaauw, 2010) of the MAC S3 core calibrated to cal BP using the IntCal20.14C curve (Reimer et al., 2020)



Representative plant macrofossils from each peat core/monolith that were selected for AMS ^{14}C dating. 1) 16PS1 0-5 mm – *Dicranum*? sp.; 2) 16PS1 80-85 mm – *Dicranum*? sp.; 3) 16PS2 55-60 mm – *Sphagnum* sect. *Acutifolia*; 4) 18-GTA-79 4-5cm – *Meesia triquetra*; 5) 18-GTA-79 4-5 cm – *Meesia triquetra*; 6) 16PS2 285-290 mm – leaf cells of *Sphagnum* sect. *Acutifolia*; 7) 18-GTA-79 12-13 cm – *Aulacomnium palustre*; 8) 18-GTA-79 12-13 cm – characteristic leaf cells of *Aulacomnium palustre*; 9) MAC S3 2E 0-1 cm – *Scorpidium* sp.; 10) 18-GTA-292 0-1 cm – *Tomentypnum nitens*; 11) 18-GTA-292 0-1cm – *Tomentypnum nitens*; 12) MAC S4 3E 1-2 cm – *Meesia triquetra*; 13) MAC S1 57E 55-56 cm – *Sphagnum lindbergii*; 14) MAC S1 57E 55-56 cm – stem leaf of *Sphagnum lindbergii*; 15) MAC S1 57E 55-56 cm – leaf cells of *Sphagnum lindbergii*; 16) MAC S3 2E 0-1 cm – *Sphagnum balticum*; 17) MAC S3 2E 0-1 cm – leaf cells of *Sphagnum balticum*; 18) MAC S3 8E 6-7 cm – stem leaf of *Sphagnum riparium*.

HIGHLIGHTS

- Plain language summary of a GSC Open File (Nguyen et al., in prep.) translated into Gwich'in

- Gwich'in Renewable Resources Board (GRRB) (Lord) presented a plain language summary of the project at the RRC meetings in the communities of Inuvik, Fort McPherson, Aklavik, and Tsiigehtchic in June, 2021

- GRACE satellite data analysis (unpubl.) for the Gwich'in Settlement Area (Output on: 19-Jan-2022, Produced by: John W. Crowley, Canadian Geodetic Survey, Natural Resources Canada, Correlated errors removed using: Crowley and Huang (2020), https://doi.org/10.1093/gji/ggaa104, Region geometry defined by: GSR_250k.kmz, Destriped solution used: R_GRCE_JI_CSRRL06_RV2_UFE0_GIA8, Destriped results file produced on: 12-Jan-2022 14:38:56, GIA Correction Applied, Model 8 used) of time series from 2002 to 2021 shows that the GSA has experienced a reduction in water storage capacity (of approximately 2 cm per year) over this time interval, but especially pronounced since 2017

- Landsat satellite imagery was used to map interannual changes in over 5000 lakes and ponds in the Lower Mackenzie Plain between 1985 and 2020. The overall surface area of lakes in the study region has decreased, driven by losses in larger water bodies. Smaller lakes tended to increase in area over time, likely responding to increases in precipitation. Lakes in regions impacted by wildfire are more likely to decrease in the area. Declines in lake area following wildfire persisted for approximately 20 years after the fire, suggesting that wildfire is likely an important driver of change for lakes in subarctic environments underlain by permafrost (Travers-Smith et al., 2021)

- A portable extruder for subsampling of sediment cores was developed for field use. The device can be used to subsample lake sediments at 1-mm resolution (Patterson et al., 2021)

- Project has supported 1 PDF, 2 Phds, 2 MScs, local Gwich'in youth and community members, and a staff member at the Gwich'in Tribal Council, Department of Cultural Heritage

Photo: Paul Vecsei

HIGHLIGHTS

- Plain language summary of field work presented at Regional Resource Council Meetings, June, 2021, in communities of Aklavik, Inuvik, Tsiigehtchic, and Fort McPherson (IRIS-1), by Sarah Lord of the Gwich'in Renewable Resources Board. Plain language summary document provided in English and Gwich'in.
- Nguyen, A.V., Oleksandrenko, A., Lord, S., Patterson, R.T., Shotyk, W., Clarke, L., Galka, M., Swindles, G.T., Galloway, J.M. 2022 (in preparation). Mid-project summary of "climate controls on the long-term hydrological dynamics of the Mackenzie River Basin Project". Geological Survey of Canada Open File (in preparation), 74 pp.
- Polar Data Catalogue Upload Feb. 2021 for P51. Polar Data Catalogue; CCIN-13261-Long-term hydrological change of the Gwich'in Settlement Area, Mackenzie River Basin
- Miller, C.B., Parsons, M.B., Jamieson, H.E., Ardakani, O.H., Patterson, R.T., Galloway, J.M. 2021. Mediation of arsenic mobility by organic matter in mining-impacted sediment from sub-arctic lakes: Implications for climate warming on contaminant mobility. Environmental Earth Sciences 81:137.
- Travers-Smith, H.Z., Lantz, T.C., Fraser, R.H. 2021. Surface water dynamics and rapid lake drainage in the western Canadian subarctic (1985-2020). Journal of Geosphysical Research Biogeosciences 126, e2021JG006445
- Patterson, R.T., Nawaf, N.A., Tremblay, S., Galloway, J.M. 2021. A portable extruder for precision high-resolution subsampling of unconsolidated sediment cores. Journal of Paleolimnology 67: 183-189.
- Mullan, D. J., Barr, I.D., Flood, R.P., Galloway, J.M., Newton, A.M., Swindles, G.T. 2021. Examining the Viability of the World's Busiest Winter Road to Climate Change Using a Process-Based Lake Model. Bulletin of the American Meteorlogical Society: E1464.
- Rousten, C.C., Kaufman, D.S., McKay, N.P., Erb, M.B., Arcusa, S.H., Brown, K.J., Kirby, M.E., Marsicek, J.P., Anderson, R.S., Jiménez-Moreno, G., Rodysill, J.R., Lachniet, M.S., Fritz, S.C., Bennet, J.R., Goman, M.F., Metcalf, S.E., Galloway, J.M., Schoups, G., Wahl, D.B., Morris, J.L., Staines-Urias, F., Dawson, A., Shuman, B.N. 2020. A multiproxy database of western North American Holocene Paleoclimate records. Earth System Science Data 13: 1613-1632.
- Nguyen, A.V., Oleksandrenko, A., Lord, S., Gałka, M., Galloway, J.M., Shotyk, W., Clarke, L., & Patterson, R.T. 2022. Reconstructing the Hydrology of the Mackenzie River Basin: Preliminary Results. Environmental Geoscience Program (EGP) Student Day Event, Geological Survey of Canada, Online. January 25, 2022.
- Nguyen, A.V., Galloway, J.M., Lord, S., Clarke, L., Gałka, M., & Patterson, R.T. 2021. Testate amoebae as a proxy for reconstructing paleohydrological changes in the Mackenzie River Basin, Northwest Territories. 9 ¾ International Symposium for Testate Amoebae (ISTA), International Society of Testate Amoeba Researchers (ISTAR), Online. October 18-20, 2021.
- Oleksandrenko, A., Lord, S., Noernberg, T., Shotyk, W., Galloway, J.M. 2022. Importance of site selection for studying trace elements and fallout radionuclides. University of Alberta, ALES GSA Symposium, February 22, 2022.

Photo: Paul Vecsei

CONTACT INFORMATION

Jennifer Galloway

https://www.researchgate.net/profile/Jennifer_Galloway2;
https://scholar.google.ca/citations?user=x6SQcrsAAAAJ&hl=en

Jennifer.Galloway@nrcan-rncan.gc.ca

THANK YOU!

Ressources naturelles Canada | Natural Resources Canada

Dynamic reservoir assessment to support CO2 sequestration in carbonate reservoirs / Évaluation dynamique des propriétés réservoir des carbonates pour la séquestration de CO2

Institut national de la recherche scientifique

Stéphanie Larmagnat

May 10, 2022

Canada

ABSTRACT

This project uses carbonate rock samples from quarry exposures in Quebec to appraise CO_2 sequestration potential in carbonate reservoirs, a type of reservoir widespread across Canada. It will deliver a novel multi-parameter reservoir assessment approach applicable to on-site sequestration for CO_2 producers in Canadian sedimentary basins.

The project combines clumped isotopes and U/Pb dating of calcite to document the porosity evolution, dry/saturated petrophysical measurements to derive the effective porosity, geophysical and geochemical monitoring of mineral carbonation experiments using medical Computed-Tomography (medCT) and micro-CT under varying reservoir conditions (temperature, pressure, saturation). Clumped isotopes and U/Pb dating will deliver a refined diagenetic history of the carbonates. The combination of medCT and micro-CT will allow determining the scale of spatial heterogeneities that influence the effective porosity, a key parameter for CO_2 storage. The suite of geochemical, geophysical and CT tools will enable to track mineral precipitation, diagenesis and CO_2 distribution.

This innovative reservoir characterization approach will benefit to government initiatives aiming to reach net zero CO_2 emission and limit future climate change.

PROJECT MEMBERS

GSC – Québec division

Stéphanie Larmagnat, Sedimentary Geology
Mathieu J. Duchesne, Geophysics
Nicolas Pinet, Structural Geology
Josué Jautzy, Geochemistry

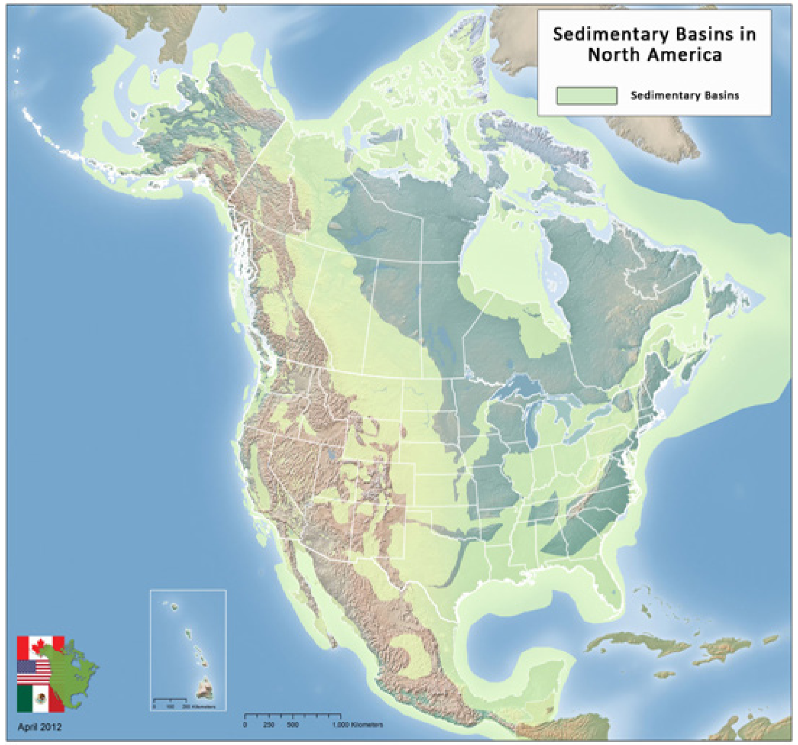
INRS – Centre Eau Terre Environnement

Louis-Cesar Pasquier, Geochemistry and CO_2 Capture & Storage
Bernard Giroux, Geophysics
Pierre Francus, Sedimentology
Mathieu Des Roches, CT-scanning
Ehsan Vosoughi, PhD student, Geophysics
Arnault Baldassari, PhD student, Geochemistry
Jasmin Raymond, Geothermal Energy
Michel Malo, Emeritus, Structural Geology and CO_2 Storage

- **12 persons**
- **6 disciplines**
- **2 PhD students**

Context

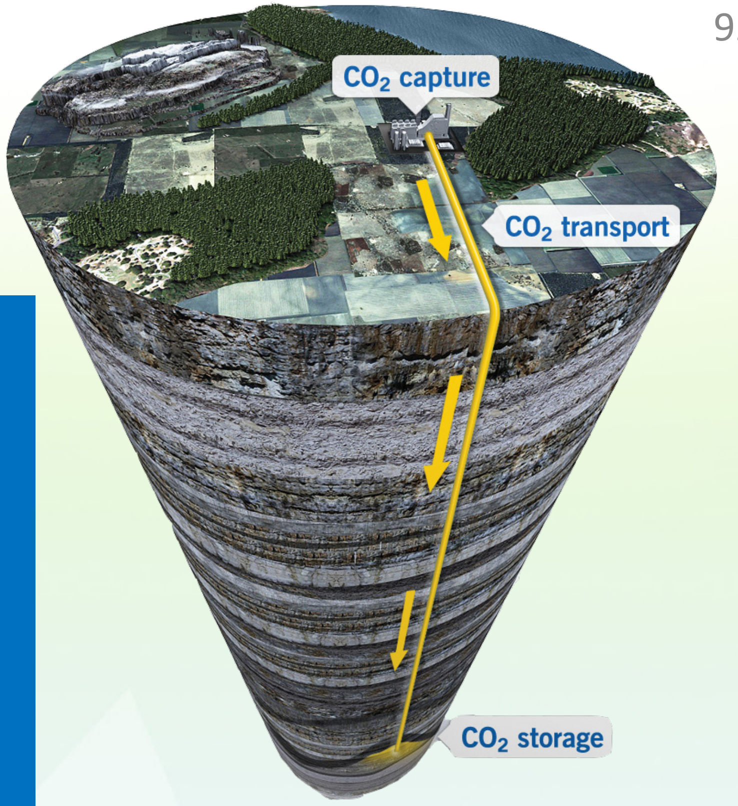
Preparing the canadian CCUS picture in 2050 ?



https://www.nrcan.gc.ca/energy/publications/16226

3 keys components to geological storage

- capacity
- integrity
- injectivity



https://www.globalccsinstitute.com/resources/ccs-image-library/

Importance of exploring a wider range of geologic storage options within canadian sedimentary basins (e.g. low porosity, low permeability carbonates)

Three main objectives

- Objective 1 & 2 uses reference rock samples to develop new, lab-scale **methodologies to better characterize the reservoir sequestration potential of sedimentary units at depth**
  - **(1) CO_2 injections tests and geochemical assessments reactivity**
  - **(2) Testing geophysical tools to monitor CO_2 injection**
- Objective 3 focuses on a **surface analog in eastern Québec** to develop **new tools to reconstruct porosity history in carbonates**

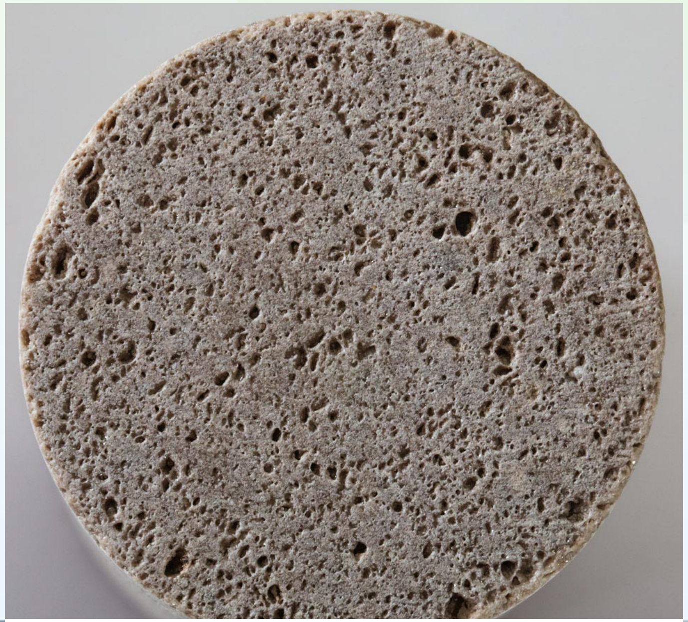
Reference rock material

Sedimentary rocks common within sedimentary basins in North America

Exp #	Sample	V_{pore} (cc)	Porosity (%)	Perm. (mD)
1	IN-15-1	10.3	12.4	5.1
2	SI-15-1	11.4	13.9	0.9
3	BE-15-1	15.8	19.0	175.0
4	WI-15-1	7.5	9.3	9.0
5	CA-15-1	0.2	1.1	0.009

Ex. Indiana Limestone ($CaCO_3$)

Ex. Berea Sandstone (SiO_2)

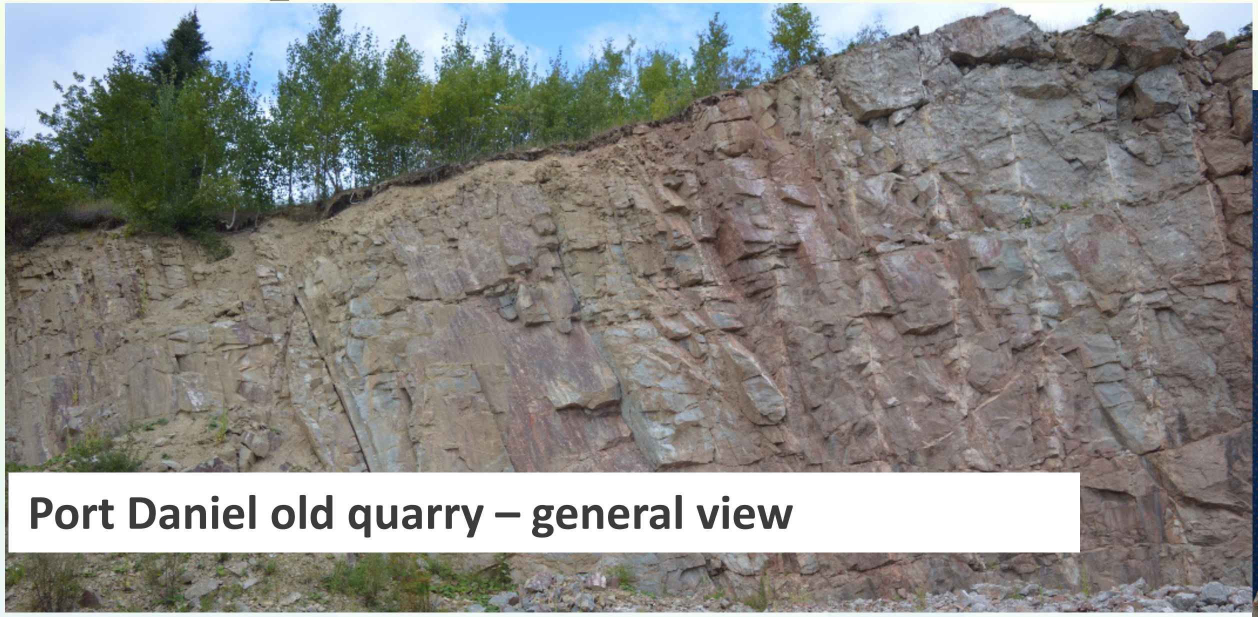


Ex. Silurian Dolomite ($CaMg(CO_3)_2$)

https://kocurekindustries.com/

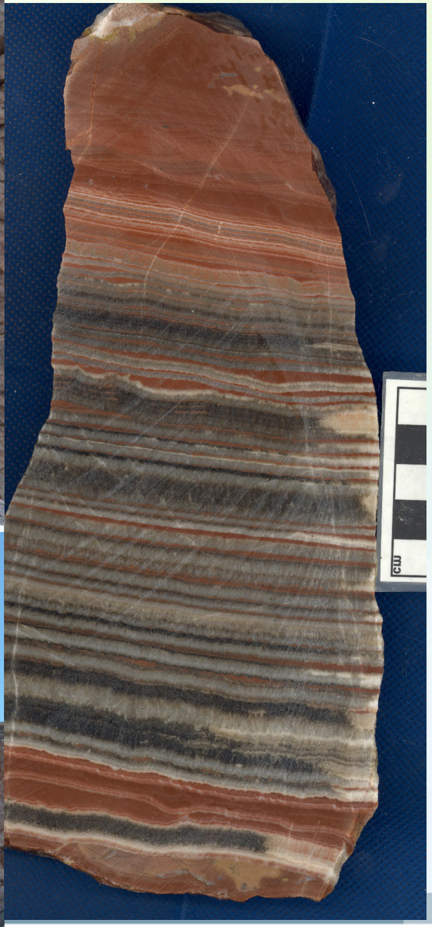
Surface analog in eastern Quebec

Large CO_2 emitter in eastern Canada (≈ 6 % of Provincial Emissions in 2019)



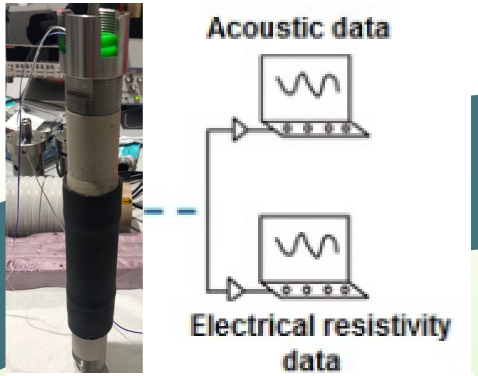
Port Daniel old quarry – general view

Mc Innis quarry – Karst features



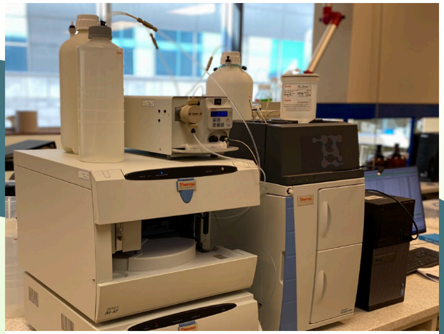
- Gaspé peninsula, Qc
- Mc Innis Quarry & cement plant
- Limestone and dolostones
- Paleozoic, Silurian
- Average thickness

Methods

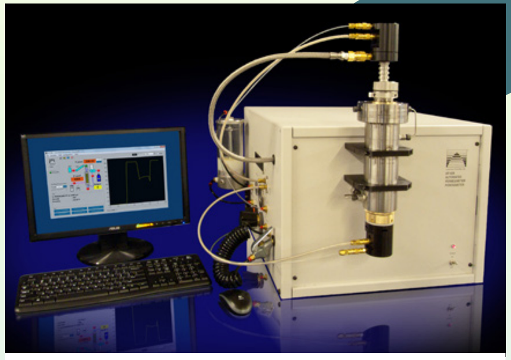


Geophysics

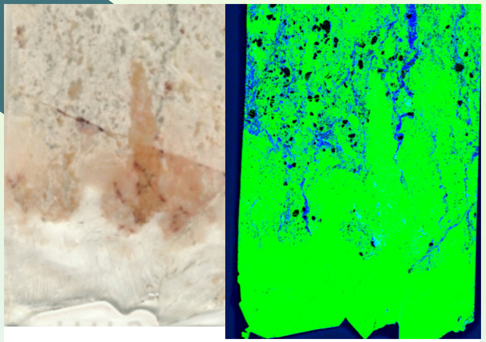
ICP AES



HPLC, TOC



Petrophysics

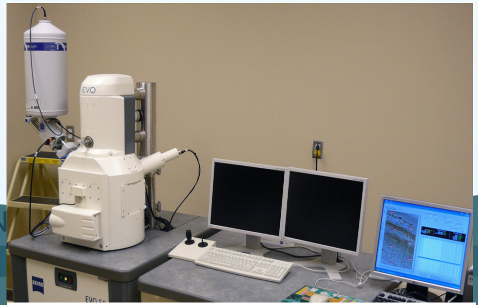


Petrography + µXRF

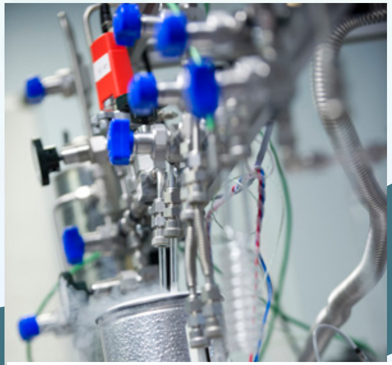
- **Pluridisciplinary**
- **Multi-scale**
- ***In situ***
- **Real-time** (whenever possible)

Micro-CT

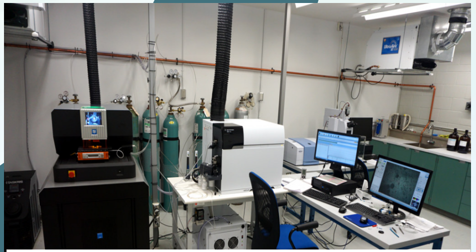
Med-CT



MEB



Clumped isotopes

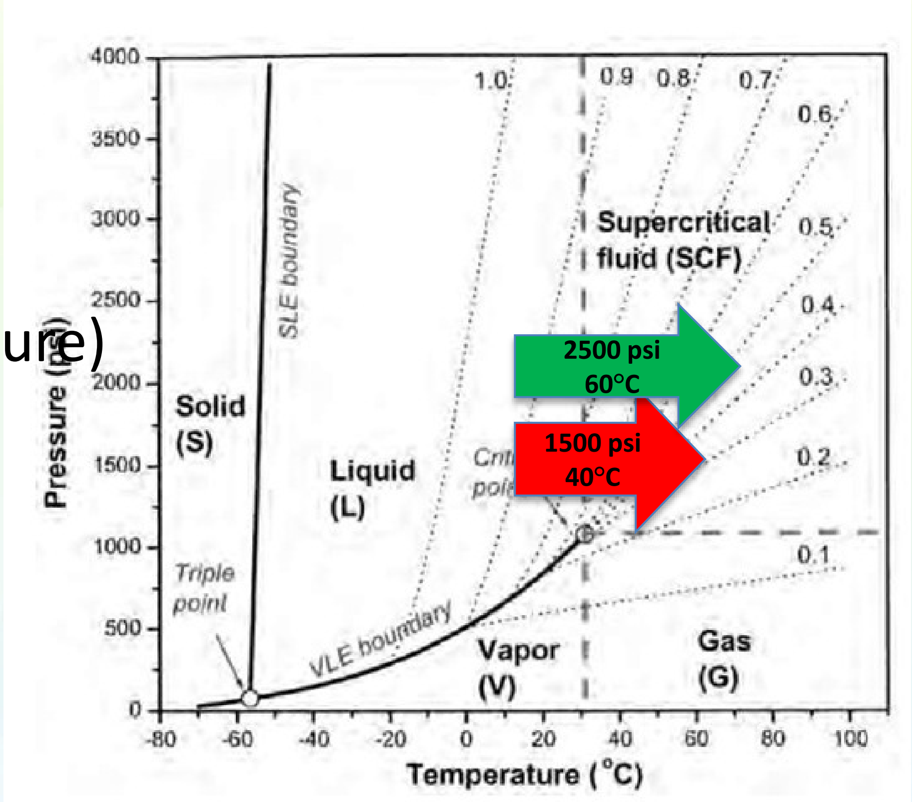


LA-ICPMS
U/Th dating

Objective 1 - CO_2 injections tests and geochemical reactivity

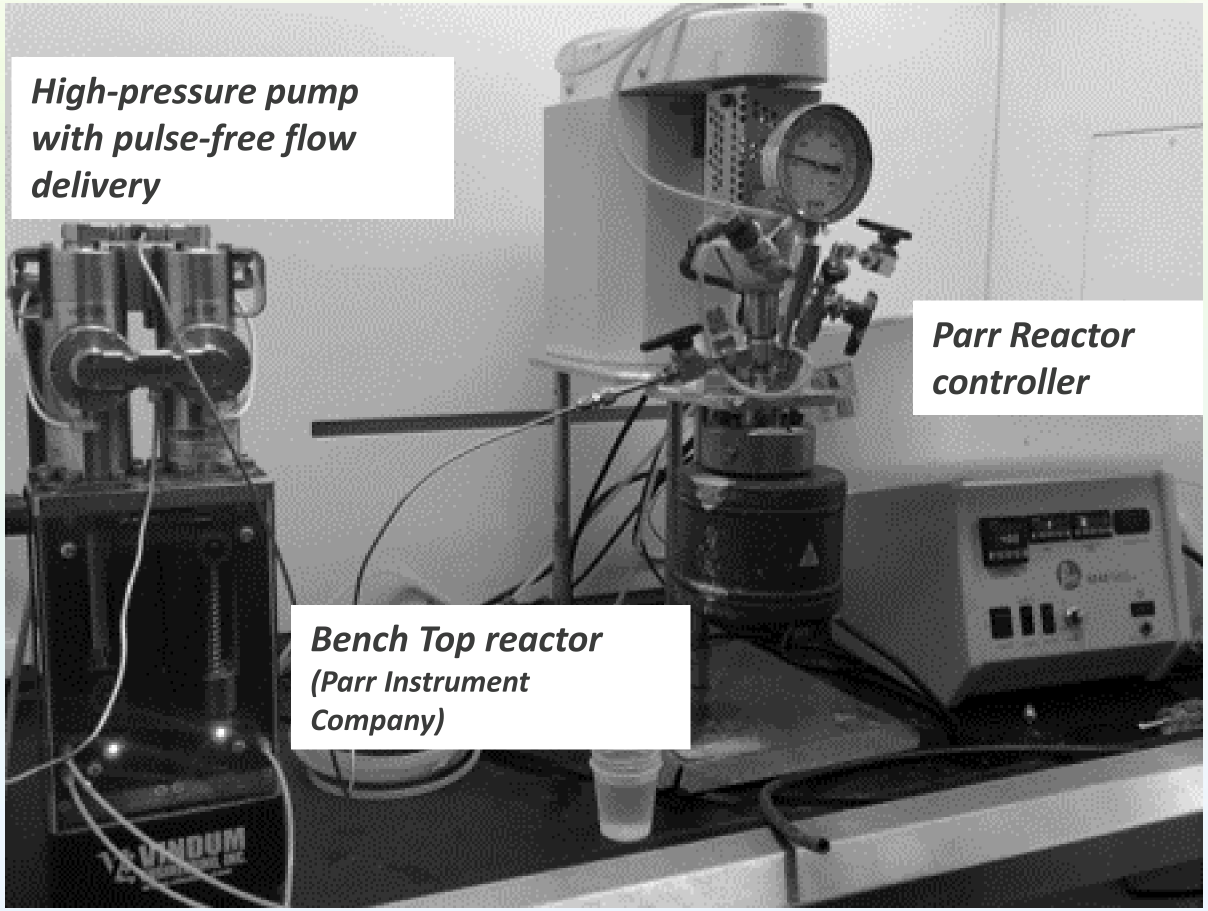
Goals and challenges

- **Three lithologies selected to test protocols**
- Samples **saturated with brines** (recipes from literature)
- **Carbonation reactor** = pressurized and controlled temperature vessel
- **CO_2 in supercritical conditions** (>1500 psi; 40 °)



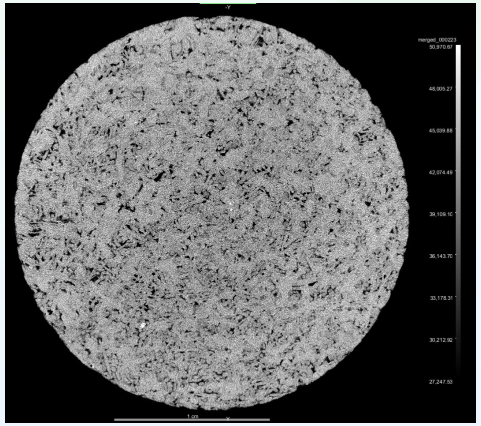
https://www.itec-es.co.jp/English/co2/co2_00.html
Note *1 Mpa = 145 psi*

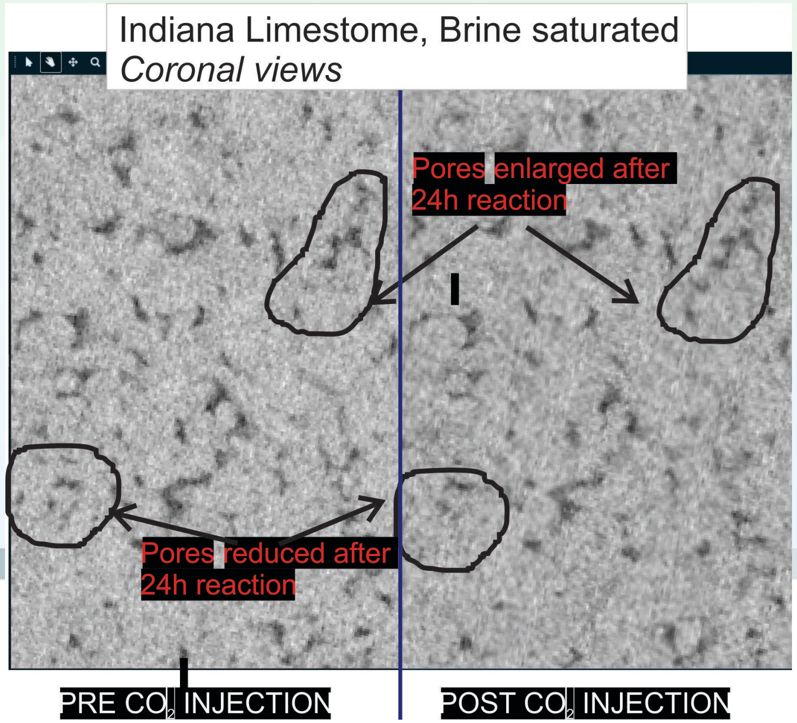
Objective 1 - CO_2 injections tests and geochemical reactivity



Results

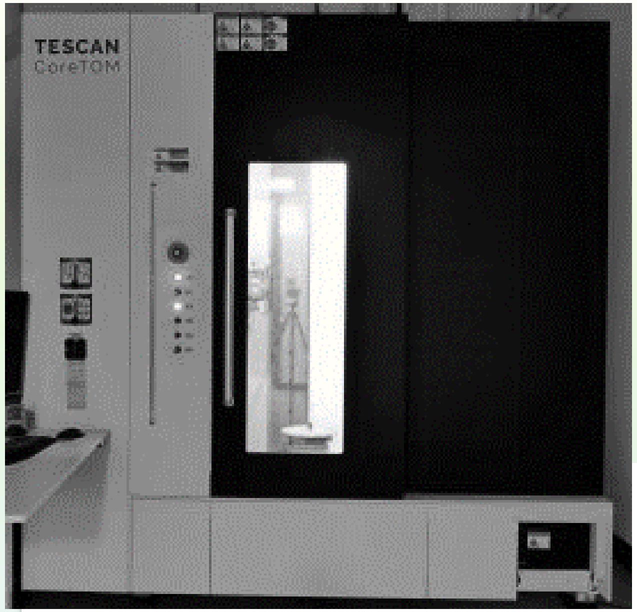
- 2 tests runs on Indiana Lst
- Pre/post micro-CT imaging
- Brine collected and filtered after injection test
- Pre/post poroperm measurements





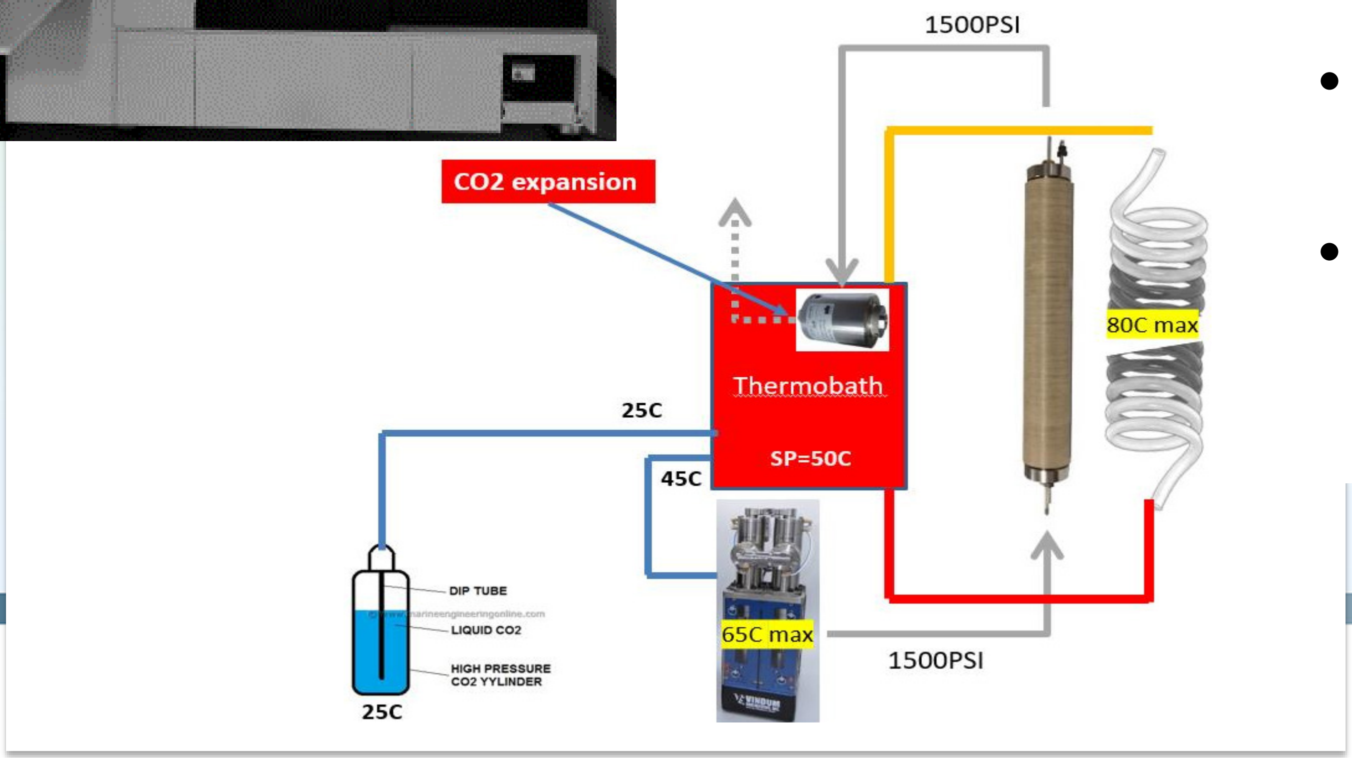
Objective 2- Geophysical tools to monitor CO_2 injections

Micro-CT



https://ctscan.ete.inrs.ca/en

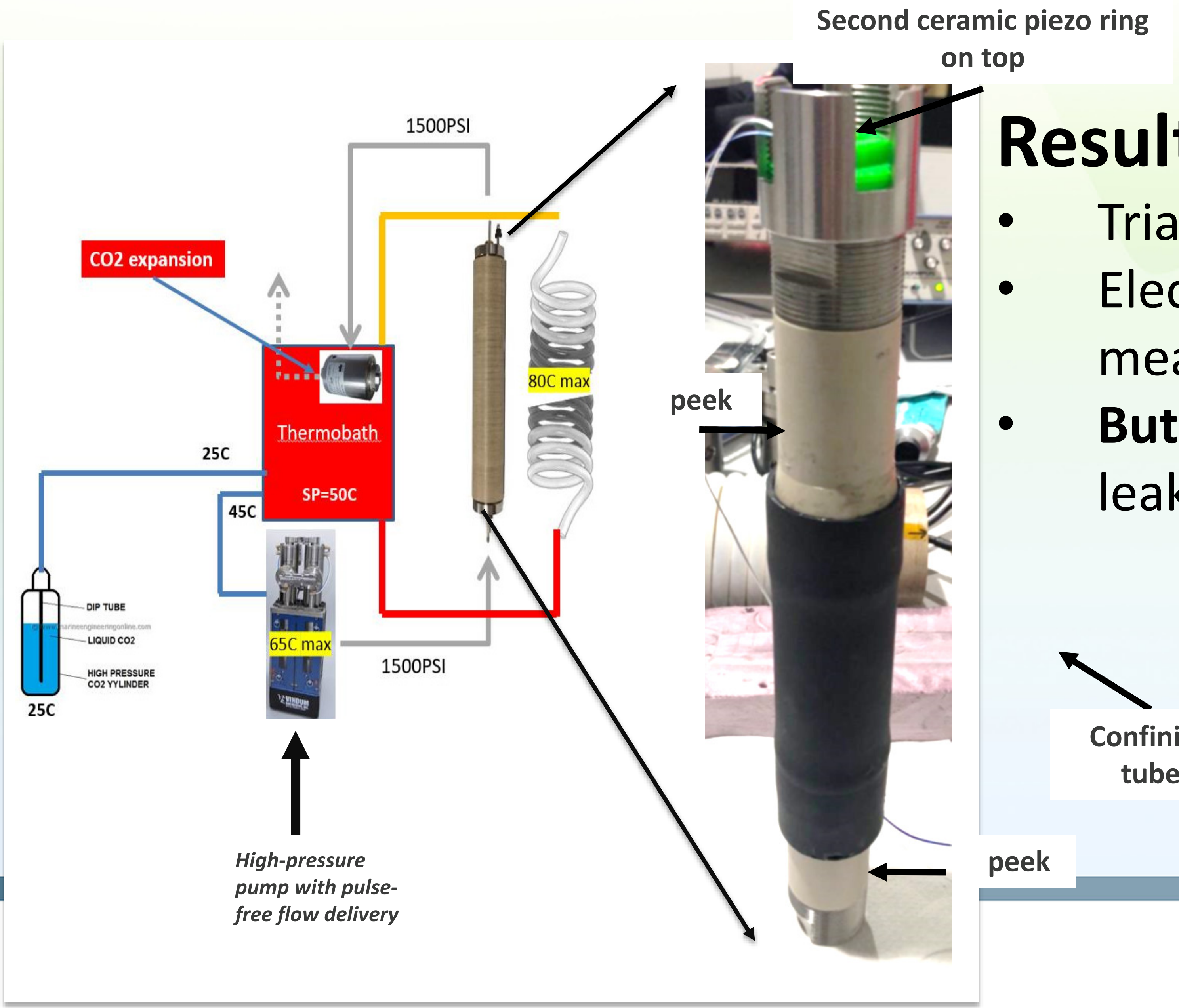
Joint interpretation of elastic-electrical data combined with micro-CT images has the potential to reveal new aspects of fluid-rock interaction



Goals and challenges

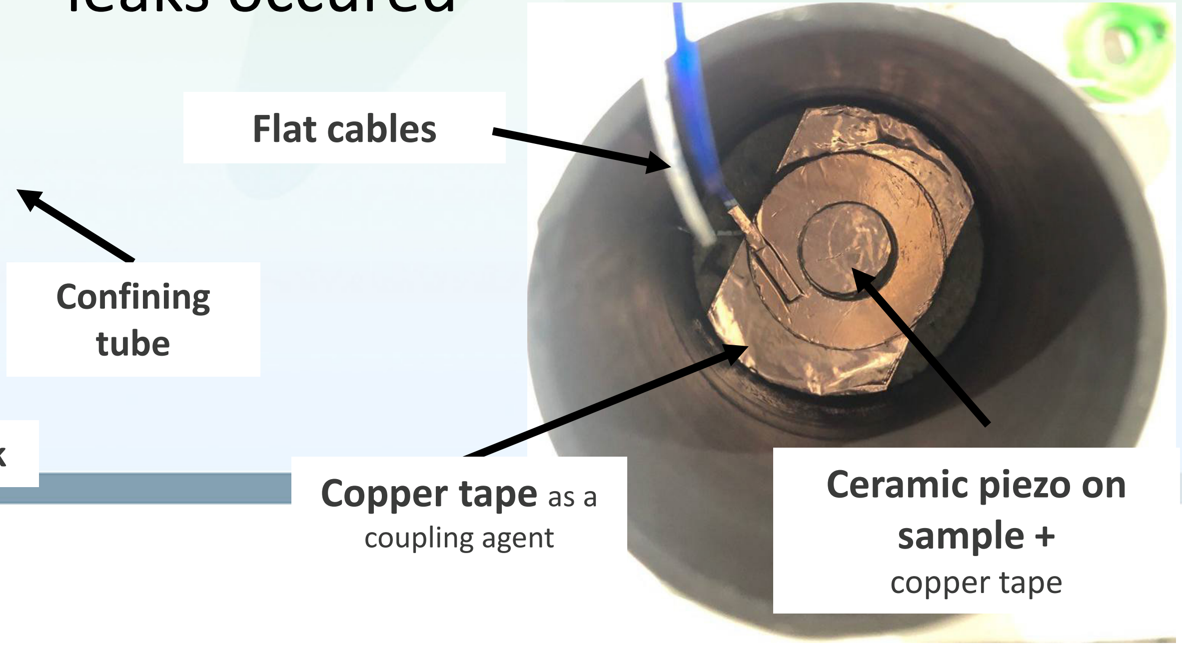
- Ultrasonic Acoustic and Electrical measurements
- Resistivity Both monitored during the micro-CT acquisitions
- Both working at pressure and temperature consistent with reservoir conditions

Objective 2- Geophysical tools to monitor CO_2 injections

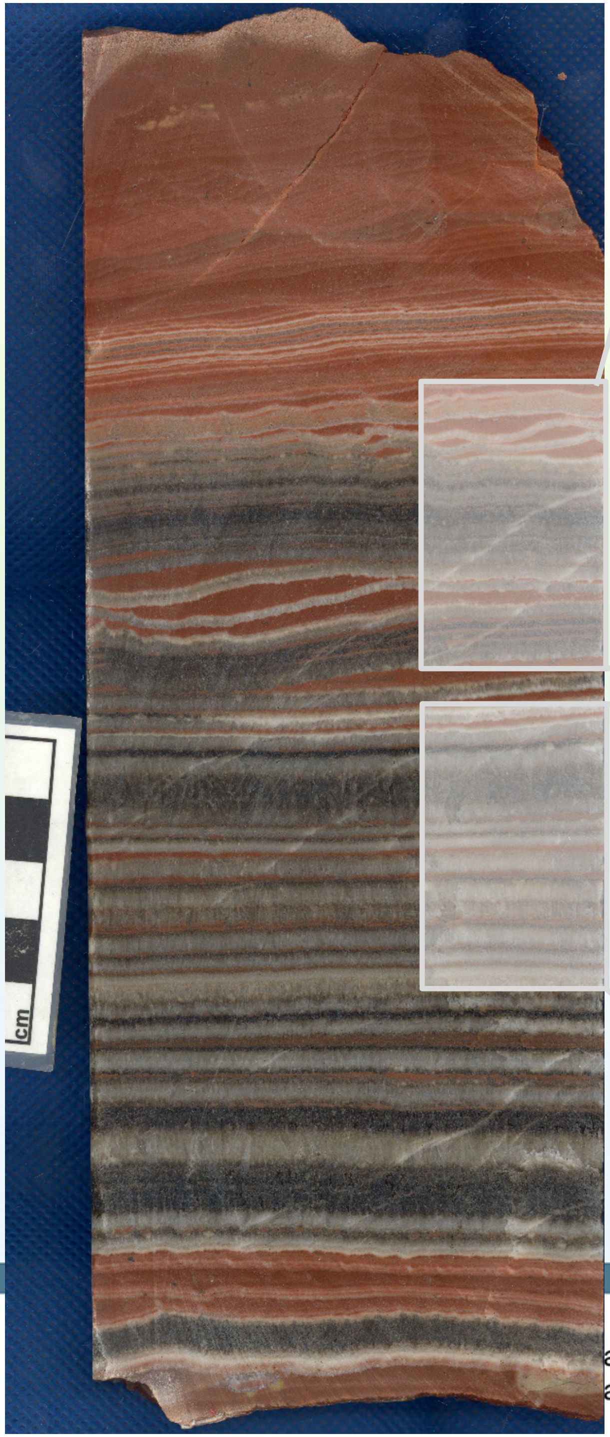


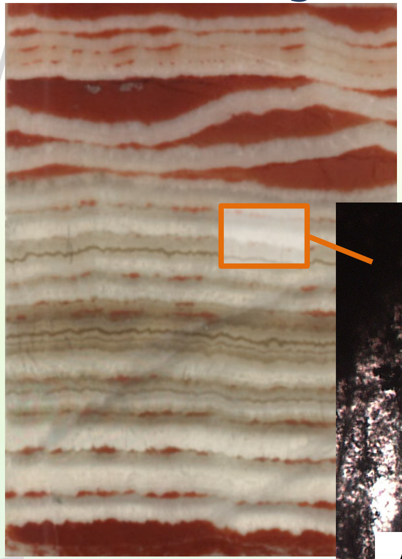
Results

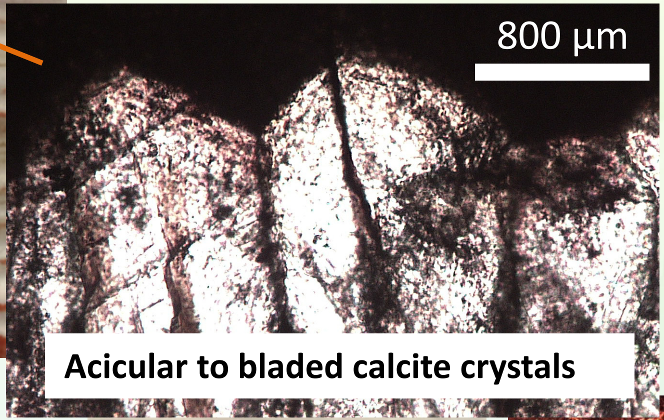
- Trial and error for custom made setup
- Electro-elastic properties of sample are measured
- **But** during injection, confining fluid leaks occured



Objective 3 - Reconstruct porosity history in carbonates

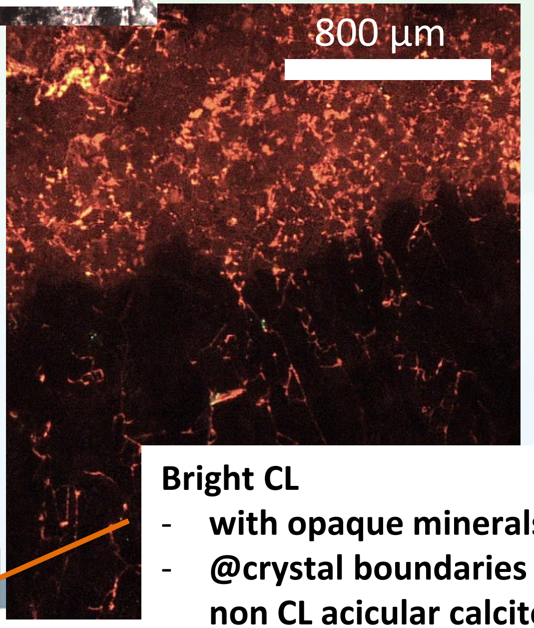




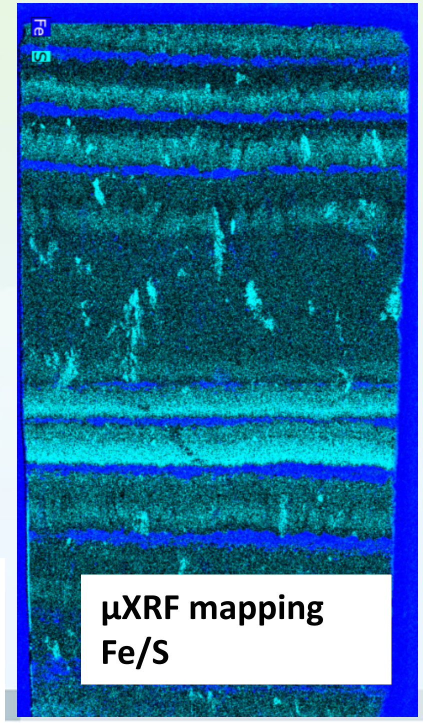


Speleothems samples – Mc Innis

- Mainly calcite, with minor Mg content
- Laminated karst with sulphate minerals



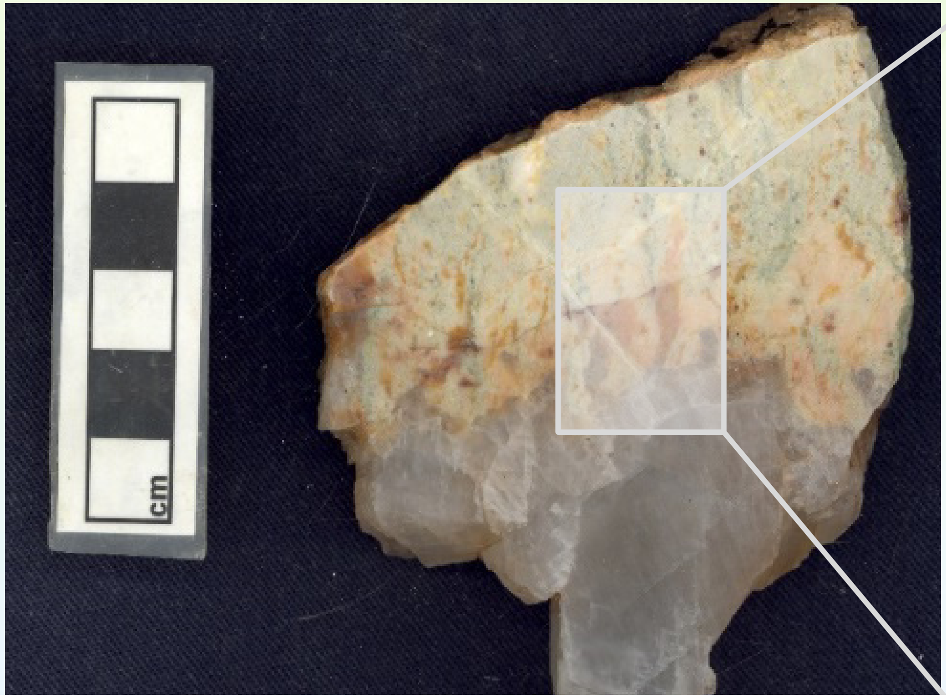
Bright CL
- **with opaque minerals**
- **@crystal boundaries in non CL acicular calcites**

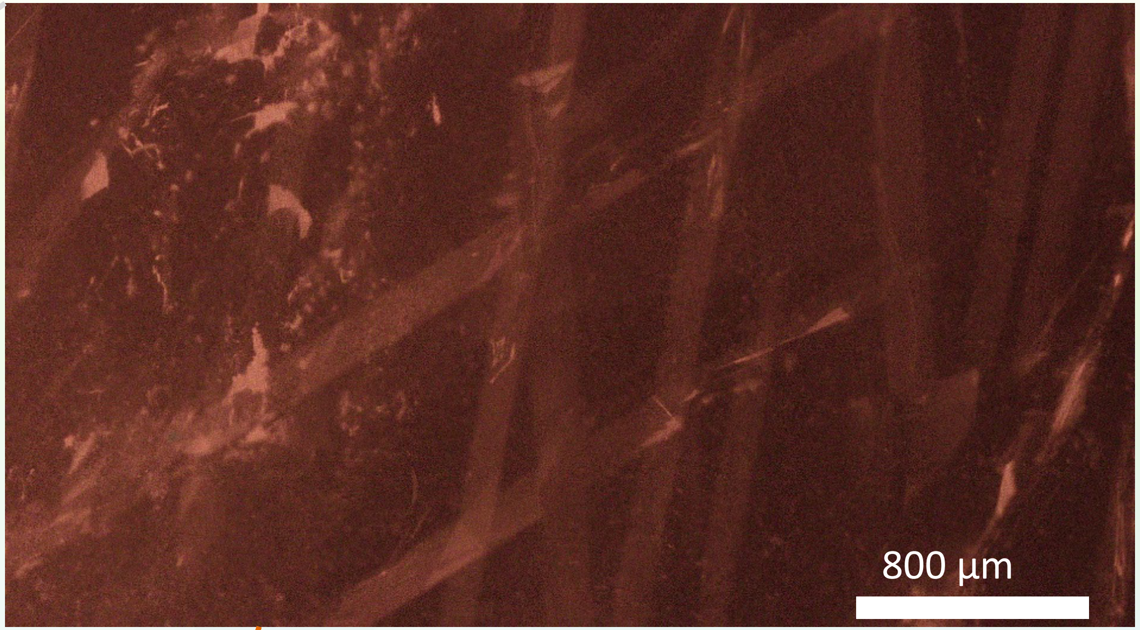


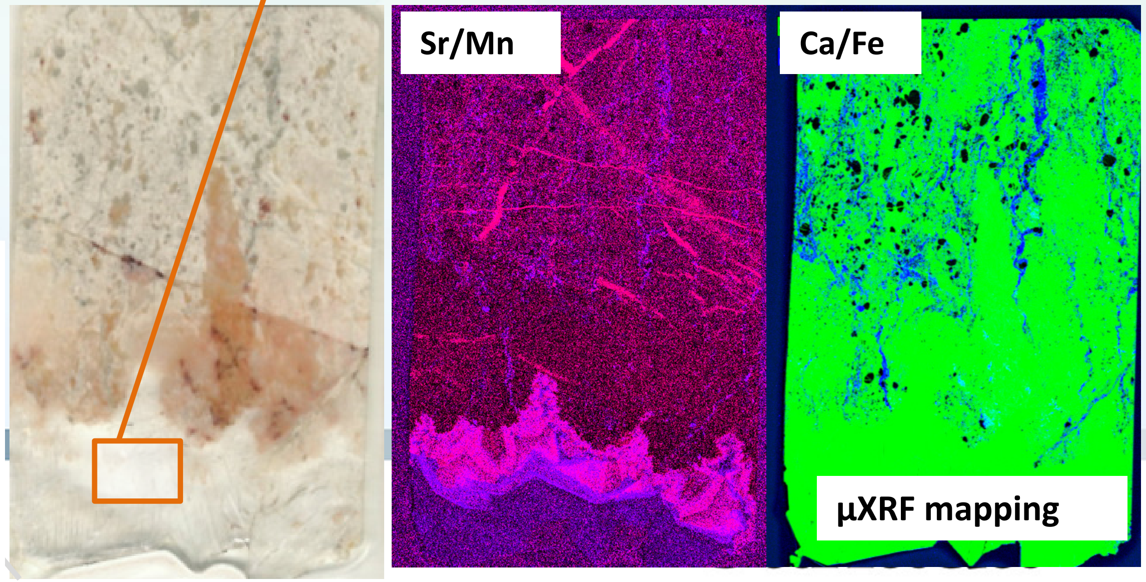
Objective 3 - Reconstruct porosity history in carbonates

Speleothems samples – Port Daniel (old quarry)

- Large void-filling calcite cements







- Mn-rich calcite within fracture
- Sr-rich calcite within fracture (2 generations)
- Fe-depleted late cement in karst (possibly 2 phases)

Next steps

Objective 1 - CO_2 injections tests and geochemical reactivity

- Reproduce CO_2 injections in reactor for additional lithologies and test higher reservoir pressure and temperature (2500 psi; 60 C)

Objective 2 - Geophysical tools to monitor CO_2 injections

- Upgrade the core-holder setup to avoid leakages under confining conditions
- Run CO_2 injection experiments comparable to those of objective 1 with *in situ* electric and acoustic monitoring and imaging under micro-CT

Objective 3 - Reconstruct porosity history in carbonates

- Interpret all petrographic and geochemicals results on surface analog
- Combine in comprehensive porosity history
- Explore additional examples of surface analogs to test the methodology

CONTACT INFORMATION

- **Stéphanie Larmagnat, PhD**
- Phone number (418) 654-1463
- Email stephanie.larmagnat@NRCan-RNCan.gc.ca

THANK YOU!

For additional information about the EGP, please contact // Pour plus de détails sur le PGE, veuillez contacter :

Gilles Cotteret (Program Manager) gilles.cotteret@nrcan-rncan.gc.ca OR/OU
Joby Aubut Bernard (Program Planning & Coordination) joby.aubutbernard@nrcan-rncan.gc.ca
Réjean Couture (Division Director): rejean.couture@canada.ca

For additional information about the science, please contact // Pour plus de détails sur la science, veuillez contacter :

Project Topic	Project Leader
Global mercury science	peter.outridge@canada.ca
Induced seismicity	honn.kao@canada.ca
Oil & gas development impacts in Fox Creek	christine.rivard@canada.ca
Mining-impacted watershed	alexandre.desbarats@canada.ca
Regional assessment of Ring of Fire	josue.jautzy@canada.ca
Hydrological dynamics of the Mackenzie River Basin	jennifer.galloway@canada.ca
Carbonate reservoir assessment to support CO_2 sequestration	stephanie.larmagnat@NRCan-RNCan.gc.ca

Follow us on YouTube! // Suivez-nous sur YouTube!

EGP YouTube page // Page Youtube du PGE