ABSTRACT BOOK

UNIVERSITY OF CALGARY

Imperial

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# GEOSCIENCE RESEARCH EXCHANGE

April 9th, 2021

GEOREX

# A message from the organizers

Welcome to the 2021 Geoscience Research Exchange (GeoREX) at the University of Calgary! We are proud to bring together a strong schedule of presentations and posters this year, covering a variety of topics in geosciences including hydrogeology, geochemistry, geophysics, and geology. We would like to thank our student presenters for pulling together an interesting and engaging series of presentations. And we would like to thank our keynote speakers Astrid Arts, Lauren Eggie, and Cin-Ty Lee for sharing their latest research with us.

Over the years, GeoREX has grown into an annual symposium that seeks to instill a culture of sharing and collaboration within the Department of Geoscience. Sharing our research in a multidisciplinary environment provides us all with an opportunity to explore new ideas and seek out new collaborative efforts, all while gaining critical experience in communicating the results of our research. We hope as always that GeoREX will continue to flourish and become a longstanding tradition for the students of the University of Calgary.

Last year, GeoREX had to be cancelled due to the unprecedented shutdown at the beginning of the Covid-19 Pandemic. After a year of closed offices, restricted field work, cancelled conferences, and many zoom meetings, we are pleased to offer this year's event in the now familiar online format. Even though our format may be different this year, we hope that the spirit of collaboration and pursuit of science advancement continue to make GeoREX special.

Finally, GeoREX would not be the same without the sponsorship of our amazing partners. We would like to express our gratitude to Cenovus Energy and Imperial. Without their support, this event would not be possible.

Welcome to GeoREX 2021, we hope you enjoy this experience!

Sincerely,
**The GeoREX Committee**
Katie Biegel, Simone Pujatti, Qin Zhang, Shihab Uddin,
and Fernando Berumen Borrego

# PROGRAM SCHEDULE

| Time | Program |
|---|---|
| 10:50 AM | **Opening Remarks** |
| | **Session 1: Reservoirs** |
| 11:00 AM | **Bob Lee**<br>The critical role of capillary forces in fluid saturation distribution and formation evaluation |
| 11:15 AM | **Brendan Kolkman-Quinn**<br>Time-lapse VSP monitoring of CO2 sequestration at the CaMI Field Research Station |
| 11:30 AM | **Ranya Algeer**<br>Identification of reservoir compartmentalization at the appraisal stage in the absence of dynamic data using integrated geochemical approach |
| 11:45 AM | **Morning Keynote Talk: Cenovus**<br>**Speaker: Astrid Arts**<br>Demographics in the GeoSciences – the evolving role of female geoscientists |
| | **Session 2: Hydrology** |
| 12:15 PM | **Sara Lilley**<br>Hydrogeological Characterization of an alpine karst spring in the Canadian Rockies |
| 12:30 PM | **Sarah Reid**<br>Investigation of soap hole formation using fluid flow and geomechanics modelling |
| 12:45 PM | **Tom Wilson**<br>Geochemical investigations of the Banff Hot Springs, Alberta |
| 01:00 PM | **Poster Session** |
| | **Pres1: Kaveer Hazrah**<br>Cations vs. Anions: Structural Changes in Apatite Solid Solutions, Ca10(PO4)6(F, Cl, OH)2 |

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| | **Pres2: Neil Fleming**<br>Groundwater well barometric efficiency application to free-phase gas detection and monitoring |
| | **Pres3: Brayden Ralph**<br>Watershed-Scale Characterization of Alpine Aquifer Systems |
| | **Pres4: Mahdi Hamidbeygi**<br>Understanding Induced Seismicity and Seismic Hazard in the Montney Formation |
| **01:30 PM** | **Afternoon Keynote Talk: Imperial**<br>**Speaker: Lauren Eggie**<br>Releasing the Pressure: Industry's First Horizontal Devonian Depressurization Well at the Kearl Oilsands Mine |
| | **Session 3: Geophysics and Geology** |
| **02:00 PM** | **Laleh Khadangi**<br>Using HVSR observations at the CaMI Field Research Station to estimate structural characteristics of a CO2 storage site |
| **02:15 PM** | **Kienan Marion**<br>A Not-So Quiet Place – Unpacking the 14 February 2021 Banff Earthquake |
| **02:30 PM** | **Collin Kehler**<br>Metamorphism of metapelites and metabasites within the aureole of the mid-Cretaceous White Creek batholith, Purcell Mountains, southeastern British Columbia |
| **02:45 PM** | **Collin Padget**<br>Pyrite and pyrrhotite in a prograde metamorphic sequence, Hyland River region, SE Yukon: implications for orogenic gold |
| | **Session 4: Geochemistry** |
| **03:00 PM** | **Qin Zhang**<br>Experimental Determination of the Kinetics of Glauconite Dissolution and Carbonation |

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| **03:15 PM** | **David Terrill**<br>Teeth walk, teeth talk: Strontium isotope ratios in Centrosaurus enamel reveal evidence of long range migratory behaviour |
| **03:30 PM** | **Zhengqiang Che**<br>Probing the application of kinetic theory to Mg-phyllosilicate growth with Si isotope doping |
| **03:50 PM** | **Thank You Remarks for the Presentations** |
| **04:00 PM** | **Danielle Kondla Memorial Keynote Talk: Dr. Cin-Ty A. Lee**<br>Whole Earth Carbon Cycling, from source to sink, and implications for long term climate |
| **05:30 PM** | **Prizes and Closing Statements** |

## Cenovus Keynote

# Demographics in the GeoSciences – the evolving role of female geoscientists

*Astrid Arts*

The demographics of geoscience is changing in industry, government and academia. The first female geologist to receive a degree in Canada was Grace Anne Stewart in 1918 from the University of Alberta. Alice Wilson was the first female professional to work for the Geological Survey of Canada in 1919 and became the first female geologist when she received her PhD in1929. Helen Belyea was the first woman to work in the field for the Geological Survey of Canada in the 1950's. Through the lens of membership data from the Canadian Society of Petroleum Geologists we will look at the changing trends of age and gender in geology and its implications.

*Astrid will also be doing a Q&A about careers & life after university following her talk.

# Imperial Keynote

## Releasing the Pressure: Industry's First Horizontal Devonian Depressurization Well at the Kearl Oilsands Mine

*Lauren Eggie, MSc, GIT*

The Kearl Oilsands Mine project is located in the Athabasca Basin of northeastern Alberta. The ore body is composed of bitumen-saturated McMurray Formation sands that unconformably overlie the Beaverhill Lake Group, which contain brackish to saline aquifer units. While mining, Imperial must manage the Devonian aquifer below, to avoid uncontrollable influx of in-pit saline water.

In the lease area, the basal unit is overlain by ramp and reef/pinnacles of the Keg River Formation. The Keg River Formation was buried by evaporite and carbonate facies of the Prairie Evaporite, Watt Mountain, Fort Vermillion, Slave Point, and Waterways Formations. The evaporite units of the Prairie Evaporite Formation were dissolved during the Cretaceous and Quaternary, forming hypogenic karst and collapse breccias in the overlying units. This process is associated with enhanced porosity and permeability, creating a saline aquifer in the lowermost unit of the Prairie Evaporite Formation and in the underlying Keg River Formation ramp. At Kearl, this dissolution is expressed as complex diagenetic and faulted features that control aquifer connectivity to the overlying strata. These features are useful for the mine depressurization strategy, but are difficult to target using sparse 2D seismic data and limited deep well penetrations.

Traditionally, depressurization has been done with in-pit vertical pumping. However, this methodology presents some challenges, as these wells must be lowered as mining progresses and multiple wells are commonly needed. To mitigate these challenges, the Imperial team planned and drilled a horizontal well that had its surface location outside of the pit and would access a larger portion of the aquifer without needed multiple wells. Due to the sparsity of available data, planning the trajectory of this well involved application of regional Devonian understanding, targeting an existing deep Devonian well, and utilizing specialized LWD tools. During drilling of this well, we intersected interesting structural features that ultimately lead to the success of the well and furthered our understanding of the Devonian succession and potential diagenetic and structural controls on aquifer connectivity.

## Danielle Kondla Memorial Keynote

# Whole Earth Carbon Cycling, from source to sink, and implications for long term climate

*Dr. Cin-Ty Lee*

Climate on million-year timescales is controlled by a dynamic balance between degassing of carbon dioxide from the Earth's interior and the efficiency by which atmospheric carbon dioxide is removed through burial of organic matter and carbonate deposition. Mountain building events play an important role in modulating inputs and the efficiency of outputs from the ocean-atmosphere system. Here, we discuss the importance of magmatic orogens like the modern Andes or the Cretaceous continental arc that stretched across the western margin of North America. These orogens amplify $CO_2$ inputs when they are active, leading to greenhouse conditions. However, after magmatism ends, these mountains continue to serve as a source for silicate weathering, shifting the Earth system to cooler conditions. The rise and fall of mountains should thus lead to greenhouse-icehouse oscillations. Finally, we discuss the implications of Cretaceous magmatic orogens on the generation of organic-rich source rocks, which have had both positive and negative impacts to society.

# The critical role of capillary forces in fluid saturation distribution and formation evaluation

*Robert Lee, P.Geol., Centre for Applied Basin Srudies, University of Calgary, Per Pedersen, PhD, University of Calgary, Tom Moslow, PhD, University of Calgary*

The theories presented in this talk all arose from research since 2016 into understanding the massive volumes of bypassed oil pay in Mannville reservoirs such as the Clearwater. That specific research evolved into a framework model applicable to all reservoirs and particularly those that I classify as semi-conventional. This presentation introduces a completely new way to understand reservoirs.

My research indicates that electrostatic capillary forces are the largest controlling factor on resource distribution from basin to pore-scale, and play the dominant role in masking the recognition and understanding of semi-conventional oil resources. Every published capillary study for the oil industry focuses on pressure and other effects and their application for understanding and modelling production and recovery. My research looks at those studies in reverse to aid in understanding how capillary forces controlled migration, emplacement, and fluid saturation distributions, a primary interest of exploration geologists. Understanding these forces has implications for interpreting trapping, basin flow, drilling, well logs, core analyses, well testing, and production.

Capillary forces are permanent intrinsic electrostatic forces that control what happens at liquid/solid, liquid/gas, and liquid/liquid contacts. These electrostatic forces are small on an absolute scale but are powerful at the scale of pores and pore throats. Capillarity is defined as the intrinsic tendency of a reservoir to retain water because of electrostatic forces within pore systems and use it to describe relative differences between reservoirs. Any factors within a pore system that increase surface areas or decrease pore throat apertures, contribute to higher capillarity.

# Time-lapse VSP monitoring of CO2 sequestration at the CaMI Field Research Station

*Brendan J. Kolkman-Quinn*[1] *and Donald C. Lawton*[1,2]
[1] *CREWES, Department of Geoscience, University of*
[2] *Calgary Containment and Monitoring Institute, CMC Research Institutes, Inc.*

Alberta and Canada are facing challenges to make significant reductions in atmospheric greenhouse gas emissions and to meet nationally defined commitments to the COP21 Paris Agreement. Carbon Capture and Storage is considered an essential strategy for reducing global CO2 emissions. The Containment and Monitoring Institute (CaMI) operates a CO2 sequestration experiment near Brooks, AB. Vertical seismic profiles (VSP) have been acquired at the CaMI Field Research Station (FRS) for the purpose of time-lapse monitoring of the CO2 plume in the subsurface. These data were collected between 2017 and 2021 using 3-component geophones and Distributed Acoustic Sensing (DAS) fibers. This provided the opportunity to test different monitoring technologies and develop a time-lapse processing workflow. The geophone data possess a higher signal-to-noise ratio but poorer spatial coverage than the DAS data. Different DAS interrogators allowed for comparison of data quality, but decreased time-lapse repeatability. The best time-lapse results so far have been achieved with geophone data. The processing workflow involved RMS-normalization and match-filtering to balance amplitude and phase differences between different VSP surveys. Residual amplitudes in the time-lapse difference are currently stronger than any seismic anomaly caused by gas-phase CO2. Therefore, the definitive identification of the CO2 plume has not yet been achieved. However, this exercise provided valuable insight into the capabilities and challenges of the seismic datasets from the CaMI Field Research Station.

# Identification of reservoir compartmentalization at the appraisal stage in the absence of dynamic data using integrated geochemical approach

*Ranya Algeer*
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One of the major uncertainties at the appraisal and development stage of a petroleum reservoir is compartmentalization, which has an important bearing on the predicted economics of that reservoir. Assessing the extent of horizontal and vertical fluid connectivity among oil reservoir units at an early stage is a corner stone for robust design of optimum development plan and efficient management of petroleum asset throughout its life. In typical reservoir geochemistry studies, oils are compared & large fingerprint variations are taken as evidence that a barrier to fluid flow is present between wells. However, compositional variations might result from differences in the source of reservoired hydrocarbons and/or their thermal maturity level. Also, oil field additives (i.e., oil based mud OBM) causes fluid compositional differences that can be misinterpreted as compartmentalization.

In this study, six bottom hole oil samples collected from a Cretaceous reservoir were fingerprinted using C8-C20 hydrocarbons to assess compartmentalization within this reservoir. To rule out the possibility of variation in fluids composition due to differences in the origin and maturity of reservoired hydrocarbons or contamination with OBM, an integrated approach was implemented comparing the bulk properties and chemical composition of the reservoired gas & oil samples. Theoretically, OBM contaminants would be expected to affect the composition of oils, which is usually used to evaluate reservoir compartmentalization, but not the gas. Hence, the integrated approach have employed the gas composition as a key component in the assessment and independently identified multiple oil zones and confirmed compartmentalization within the studied reservoir. This approach has provided the first set of material and reliable data that unequivocally confirmed compartments within this reservoir in the absence of adequate dynamic production and geological data. The results help characterizing the reservoir and optimize Exploration and Production plans with optimum costs.

# Hydrogeological Characterization of an alpine karst spring in the Canadian Rockies

*Sara Lilley and Masaki Hayashi*
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Alpine karst aquifers have distinct hydrogeologic characteristics due to a lack of vegetative cover and higher hydraulic gradients. Rapid recharge from direct precipitation and high flow velocities generally lead to marked spring responses. Global air temperature is rising, resulting in less snow accumulation and shorter periods snow storage. A shifting climate may have significant impacts on karst groundwater availability, but little research has focused on alpine karst owing to a lack of data from these rugged landscapes.

The Watridge Karst Spring in Kananaskis, Alberta is a perennial spring at an elevation of 1870m that flows at up to 3.9 m3/s. The source of spring recharge has been contemplated by local hydrogeologists for decades. The spring discharges a disproportionately large volume of water compared to the topographically delineated watershed area, thus the aquifer is being regionally recharged from neighbouring watersheds. Two of the nearest watersheds to the spring (<10 km away) are suspected to recharge the aquifer based on indications of groundwater seepage; these are Birdwood Lakes and Burstall Creek. Birdwood Lakes are estimated to discharge groundwater at flow rate of approximately 10% that of the karst spring discharge. Burstall Creek discharges an uncharacteristically low volume of water compared to similar-sized local watersheds, suggesting that a portion of recharge is re-routed into the karst aquifer.

This study is an analysis of hydrological and geochemical data at high temporal resolution over a 4-year period. An understanding of recharge, storage, and transmission of groundwater can improve hydrological models of alpine karst aquifers.

# Investigation of soap hole formation using fluid flow and geomechanics modeling

*Sarah Reid, Rachel Lauer University of Calgary*

Soap holes were first identified >50 years ago as areas of localized surface weakness characterized by a thin and fragile crust covering sand, silt, clay and water. It was hypothesized that they form where groundwater is moving upward to the ground surface through unconsolidated sediment. Soap holes are ubiquitous across the prairies and manifest as either mounds or flat exteriors underlain by liquefied mud. They range in diameter from less than 1-m to several meters and can reach up to several meters in depth. Due to their thin and fragile crust, they pose a risk to farming equipment and livestock, with several farmers reporting loss of cattle and extensive portions of land that are no longer farmable. Previous work has provided hydrological and geochemical constraints to create a conceptual model for soap hole formation. In this conceptual model, pressurized water from an aquifer travels upward through preferential flow paths in glacial till to a lacustrine deposit at the ground surface. There, the combined effects of increased fluid pressure and clay dispersion cause the soil to liquefy and create a soap hole. This conceptual model is tested with a preliminary steady state numerical model of a soap hole using COMSOL Multiphysics. The numerical model shows an increase in pore pressure and stress within and below the soap hole relative to outside the soap hole. The model will continue to be developed to determine what characteristics are required for soap hole formation.

# Geochemical investigations of the Banff Hot Springs, Alberta

*Tom Wilson*[1]*, Rachel Lauer*[1]*, Masaki Hayashi*[1]

*(1: University of Calgary)*

In Banff National Park, located within the Front Ranges of the Canadian Rockies, nine thermal springs occur along a 4 km interval of the Sulphur Mountain Thrust (SMT) fault. In recent years the highest-elevation hot spring, Upper Hot Spring, has experienced flow stoppages from the late winter until the late spring causing operational interruption to a commercial spring-fed swimming pool. Occasionally, these flow stoppages extend to the lower elevation springs and directly threaten the habitat of Physella johnsoni, an endangered snail species. Previous research suggests that reduced freshwater contributions from the mountains adjacent to the SMT are the main cause of spring flow stoppages.

We use hydrological and geochemical investigations to provide constraints for regional scale hydrogeological models of the hot spring system. These models will be used to investigate the driving mechanisms behind spring flow and forecast future hot spring flow under future climate scenarios. From April 2019 until March 2020 we collected monthly water samples from each of the seven active hot springs. We analyzed: 137 of the collected samples for major ion chemistry and stable water isotopes, 21 samples for tritium concentration and radio-carbon age, and 10 samples for Strontium isotopes. Analysis of the Upper Hot spring flow, temperature and chemistry time series signals, along with geochemical modeling of the observed tritium concentration time series, suggests that the main features of the dynamics of the Upper Hot Spring can be simulated using simple binary mixing models.

# Cations vs. Anions: Structural Changes in Apatite Solid Solutions, Ca10(PO4)6(F, Cl, OH)2

*Kaveer S. Hazrah and Sytle M. Antao*

Apatite, Ca10(PO4)6(F, Cl, OH)2, is the most abundant phosphate mineral in the world with numerous uses in geology, materials science, biology, medicine, agriculture, and dentistry. The three main natural end members are fluorapatite (Ca10(PO4)6F2), chlorapatite (Ca10(PO4)6Cl2) and hydroxylapatite (Ca10(PO4)6OH2). Quantitative chemical compositions and backscattered electron (BSE) images on four natural apatite samples, from various locations, were obtained with an electron-probe microanalyzer (EPMA). Varying cation and anion content lead to distinctive zoning and unique crystal structures. The four samples were selected and studied with synchrotron high resolution powder X-ray diffraction (HRPXRD). All four samples observed a hexagonal structure (P63/m), consisting of a phosphate tetrahedron, a Ca1 polyhedron and a Ca2 polyhedron. The Ca1 site is a 9-coordinated system and the Ca2 site is a 6-coordinated with an addition anion containing either F, Cl and/or OH. Three of the four samples were found to be single phased fluorapatites with varying features and cation content. Two samples displayed unique zoning (1E9 and 1V5), however only 1E9 was found to be a multiphase apatite.
Sample 1E9 displayed two separate phases of fluorapatite and hydoxylapatite, with the OH residing at 0.224 Å and F placed on the mirror planes at 0,0, 1⁄4.

# Groundwater well barometric efficiency application to free-phase gas detection and monitoring

*Neil Fleming, Tiago Morais, Cathryn Ryan*
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Free-phase gas can enter aquifers due to well integrity failures and leakage around drilled boreholes of energy wells, or during mismanaged gas injection projects. These leaks are a source of greenhouse gas emissions and can negatively impact groundwater quality. In common practice, leaking gases are detected by measuring surface gas concentrations or emissions, or (rarely) through specific groundwater geochemical changes. Continuous transducer-measured groundwater levels offer an alternate means of assessing the presence and spatial extent of free-phase gas incursion into aquifers.

The water level in groundwater wells is known to respond to changes in atmospheric pressure loading, to a varying degree depending on the ratio of water pressure change to atmospheric pressure change that is known as barometric efficiency. Previous researchers have identified that this barometric efficiency depends on the compressibility of both the aquifer formation and the pore fluids. Since free-phase gas is substantially more compressible than water, small free-phase gas pore saturations will impact the aquifer barometric efficiency.

Here, we present barometric efficiencies calculated from hourly water level measurements at four monitoring wells, all completed within an unconfined aquifer. The monitoring wells surround an energy well with known gas migration outside the surface casing. Our calculations indicate that the barometric efficiency is higher nearer to the energy well, which is consistent with a higher gas saturation. These findings reveal potential applications of water level and barometric efficiency data for long term monitoring and detection of free phase gas leakage into surface aquifers.

# Watershed-Scale Characterization of Alpine Aquifer Systems

*Brayden[1] Ralph and Masaki Hayashi[1]*
*[1]Department of Geoscience, University of Calgary, Calgary, Alberta, Canada*

Major rivers that originate in mountainous areas provide the main water supply and generate hydropower for more than one third of the world's population. In western North America, the spring melt of snow and ice, in addition to inputs from rainfall, cumulatively generate a high-flow period in these rivers that lasts four to five months of the year. During the remaining seven to eight months however, the flow in these rivers is solely sustained by groundwater discharge from mountain headwaters. Recent studies have identified several alpine landforms, including talus slopes, moraines, rock glaciers, and alpine meadows as the main units responsible for storing and discharging groundwater in these environments and have further classified them as alpine aquifers. The main objective of this research is to design a new geospatial workflow that will be able to map different aquifers that are common in alpine watersheds. This will be accomplished by initially developing a deep learning classifier that can identify the size and spatial distribution of these aquifers based upon high-resolution satellite imagery of the given watershed. Once the size and spatial distribution of the different aquifers have been identified, representative storage and discharge characteristics will be assigned to each aquifer from existing field data, so that the entire watershed's storage and discharge characteristics can be determined. The final refined workflow will efficiently up-scale our current knowledge of alpine aquifer systems and be used to better predict and quantify their contributions to the year-round flow regime of major rivers.

# Understanding Induced Seismicity and Seismic Hazard in the Montney Formation

*Hamidbeygi, M. Dettmer, J.*

Induced seismicity has been studied for decades but the details of fault activation remain a challenging area of research. In the Montney, complex tectonic structures, including graben and flower structures, are present where hydraulic fracturing operations take place. This unique combination requires careful studies of microseismic and induced seismic events for economic and public risk management. Since the region has barely been experiencing natural earthquakes, any sort of precautions, and conservative actions haven't been taken to increase public safety. So, in order to reduce public risk of earthquakes and help the regulators operate fluid injection in safer ways, I determined the seismic event's mechanisms using a probabilistic inference to better understand rupture processes, and use them in the processes of determining predominant stresses in the region. What's more, estimates of the spatial variability of stress will inform an interpretation of how induced events relate to the tectonic setting and fluid injection operations in the study area. Moreover, the software I utilize to find solutions to earthquake and stress inversions is BEAT (Bayesian Earthquake Analysis Tools), which is an open-source Python-based program. I have produced probabilistic focal mechanism for the Nov 30, 2018 event with ML=4.2 using BEAT. The results indicate that the complex earthquake mechanism can be explained with a simple rupture model. Therefore, this event likely activated an existing tectonic fault with thrust mechanism that is nearly planar.

# Using HVSR observations at the CaMI Field Research Station to estimate structural characteristics of a $CO_2$ storage site

*Laleh Khadangi, PhD Student, University of Calgary; Hersh Gilbert, University of Calgary; Marie Macquet, CMC Research Institutes; and Don Lawton, CMC Research Institutes*

Injection of liquefied $CO_2$ changes the pore pressure and subsequently stress state in the geological formations, which in return can lead to faulting, induced seismicity, and leaks. To establish a secure $CO_2$ injection operation, continuous monitoring of structural variations is crucial. Ambient seismic noise provides a mean to monitor $CO_2$ injection sites. In this study, horizontal to vertical spectral ratio (HVSR) curves are obtained using the ambient seismic noise to estimate the fundamental frequency ($f0$) in the CaMI Field Research Station (FRS), in Brooks, Alberta. An array of 3-component 10 Hz geophones along with a few broadband seismometers are deployed within a 1 by 1 km area surrounding the injection well. In the HVSR method, the continuous trace is split into time windows and then the horizontal-to-vertical Fourier spectrum ratio of ground motion is calculated for each segment of time. This technique is sensitive to impedance contrast between soil and bedrock layers and can be used to estimate the shear wave velocity and thickness of the resonating layer. Observations at the FRS show that the ambient seismic noise field exhibits two peak frequencies at 2-3 Hz and 7-8 Hz. We observe the same peak frequencies on data recorded by both the 10-Hz geophones and broadband seismometers. We suggest that the peak at 2-3 Hz, which shows slight temporal and spatial variations across the array, is the fundamental frequency of the site. The next step is to link these variations in the HVSR peaks to perturbations in temperature, fluid flow, and pore pressure changes.

# A Not-So Quiet Place – Unpacking the 14 February 2021 Banff Earthquake

*Kienan P. Marion, University of Calgary*
*David W. Eaton, University of Calgary*
*Rebecca O. Salvage, University of Calgary*

"It was like an explosion" – on 13th February 2021 at 6:33 PM MT (T2021-02-14 01:33:10 UTC), locals in downtown Banff reported a loud boom and felt shaking for several seconds. The culprit was a magnitude 3.9 earthquake 6 km NNW of the town, deep underneath Cascade Mountain in Banff National Park. Alberta rarely experiences natural earthquakes due to the province's intraplate tectonic setting, and an event of this size is uncommon. There is a paucity of earthquake monitoring stations in the immediate vicinity, making it difficult to analyze this event.

We present our analysis of this earthquake, combining data from 34 public stations with a broadband seismometer array installed by the University of Calgary as a part of an induced seismicity monitoring project near Condor, Alberta. We produced a focal mechanism that was consistent with slip along a right-lateral strike-slip fault, oriented NNE and centered in the basement beneath Cascade Mountain.

Most natural earthquakes in Alberta are thought to be associated with thrust-fault systems generated by the Laramide orogeny, which are typically found in Mesozoic and Paleozoic strata. We conclude that the Banff earthquake may have been triggered by movement in the Precambrian basement, as evidenced by its depth and orientation – it parallels the strike of the Rimbey Magmatic Zone. The installation of another broadband seismometer in this region would greatly enhance monitoring efforts and our understanding of seismicity in this area, since smaller earthquakes that are likely occurring here are not being picked up on the regional seismic network.

# Pyrite and pyrrhotite in a prograde metamorphic sequence, Hyland River region, SE Yukon: implications for orogenic gold

*C.D.W. Padget,[1] D.R.M. Pattison,[1]*
*D.P. Moynihan,[2] O. Beyssac[3]*

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The distribution of Pyrite and pyrrhotite is documented within an andalusite-sillimanite type (high-temperature, low-pressure) metasedimentary succession exposed in the Hyland River region of southeastern Yukon, Canada. The pyrite-pyrrhotite transition occurs over an interval in the chlorite and biotite zones. A pyrite-out isograd terminates the transition in the upper part of the biotite zone or the lowest grade part of the staurolite zone. The rocks' pressure and temperature conditions were estimated from phase equilibria modelling and Raman spectroscopy of carbonaceous material (RSCM) thermometry. Modelling indicates pressures of 3.7–4.1 kbar with temperatures of ~425˚C at the biotite isograd, 560–570˚C for chlorite-out/porphyroblast-in, ~575˚C for andalusite-in, 575–600˚C for the sillimanite isograd, and 645–660˚C at the K-feldspar + sillimanite isograd. RSCM temperature estimates show chlorite zone samples down to 420˚C, the biotite isograd at 500˚C, porphyroblast-in/chlorite-out in the range 525–550 ˚C, andalusite isograd at ~550˚C, and sillimanite isograd at 580˚C, showing good agreement with phase equilibria apart from the biotite isograd. These results suggest the pyrite-pyrrhotite transition extends from ≤420˚C to ~560˚C. Over this ~140˚C interval, thermodynamic modelling shows 0.6 wt. % H2O is released through metamorphism. A gradual release of fluid in the biotite zone is interpreted to have broadened the pyrite-pyrrhotite transition relative to predictions from modelling. Samples from the transition zone contain lower Au values than unmetamorphosed/lower grade rocks in the region. This suggests Au was removed from the rock at conditions below the pyrite-pyrrhotite transition (<420˚C). The upper chlorite zone and higher-grade metamorphic rocks of the Hyland River area do not appear to be a plausible source for orogenic gold.

# Experimental Determination of the Kinetics of Glauconite Dissolution and Carbonation

*Qin Zhang and Ben Tutolo*

Geologic carbon storage (GCS) in sedimentary basins is a promising method for CO2 disposal due to the global distribution of sedimentary basins with pre-existing injection infrastructure. Determination of mineral dissolution and precipitation kinetics is critical to the successful disposal of CO2 in reservoirs because the storage capacity is determined by the conversion rates of CO2 to carbonate minerals. Glauconite carbonation has been suggested as an important mechanism for GCS, however, previous research has invariably suffered from the almost completely unconstrained rates of glauconite dissolution and carbonation under relevant conditions. Modeling studies thus applied the kinetics of other clays as proxies for glauconite, such assumptions could lead to a vast range of uncertainties, which will be compounded when coupled to carbonate precipitation.

To fill this significant knowledge gap, we have undertaken a study to quantify the rates of glauconite dissolution and carbonation. We developed a new, mixed-flow reactor apparatus to explore the kinetics of glauconite dissolution under strictly controlled anaerobic conditions at pH ranging from 2 to 10 and temperatures ranging from 24 to 80 °C. Temporal evolution of the differences between the inlet and outlet solution aqueous cation concentrations during glauconite dissolution experiments have been analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES). BET surface area-normalized rates exhibit stoichiometric or close-to-stoichiometric glauconite dissolution for all elements except for Al. The kinetic data we present will provide vital insights in the development of quantitative reactive-transport models to predict the fate of CO2 in glauconite-bearing GCS reservoirs.

# Teeth walk, teeth talk: Strontium isotope ratios in Centrosaurus enamel reveal evidence of long range migratory behaviour

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The badlands of Alberta are home to one of the world richest deposits of dinosaur fossils, including spectacular bonebeds containing the remains of hundreds or even thousands of individuals. Perhaps the most well known of these bonebeds is Bone Bed 43 at Dinosaur Provincial Park, a football field-sized area containing the remains of more than 200 individual of Centrosaurus apertus. While the site has been identified as a probable mass-death assemblage of a travelling herd, less is known regarding where they may have travelled from before reaching their final resting place. One approach to this question is to analyze strontium isotope ratios, as strontium isotopes preserved in bones and teeth reflect the environment in which an animal is living. Tooth enamel is a particularly good target for this type of analysis in fossil materials due to its resistance to diagenetic alteration. Here we present strontium isotope ratio data preserved in the enamel of Centrosaurus individuals from Bone Bed 43 and compare them to previously published strontium isotope ratios from fossil materials from Dinosaur Provincial Park and other coeval fossil localities around the province. Our data show a strong likelihood that most Centrosaurus individuals from Bone Bed 43 migrated at least 200 km before arriving in the Dinosaur Provincial Park Area.

# Probing the application of kinetic theory to Mg-phyllosilicate growth with Si isotope doping

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The principle of detailed balance (PDB) played a defining role in the derivation of the widely-used Transition State Theory rate law equation and serves as an important link between geochemical kinetics and thermodynamics. Although significant strides have been made in applying the PDB to simple systems (e.g., SiO2-water), experimental verification of the PDB is lacking for more complex minerals such as the phyllosilicates. Here, we use 29Si isotopic doping techniques to quantify the rates of reaction between amorphous Mg-silicate and supersaturated solutions. The results show that the ratio of the forward and backward reaction rates approach unity as the saturation state of the solution approaches the apparent solubility of amorphous Mg-silicate. Both precipitation rates coupled with equivalent dissolution rates and precipitation rates coupled with negligible dissolution rates appear to obey the same rate function over the degrees of supersaturation we explore, indicating that the elementary step limiting the rate of precipitation remains the same. Accordingly, our results demonstrates that the PDB is applicable to amorphous Mg-silicate-water reactions, thereby reenforcing the use of TST rate equations to describe growth of Mg-phyllosilicates, and perhaps other phyllosilicates. The experimental data can also be taken as evidence that the apparent solubility of amorphous Mg-silicate, a concept previously explained using the kinetic theory of nucleation and growth, also has a thermodynamic meaning, in that it represents a quasi-equilibrium with the poorly crystalline phase. The measured, non-negligible forward and backward rates suggest that, even in this quasi-equilibrium state where little if any net reaction is occurring, isotopic signatures can be reset. Moreover, the significant discrepancy between the heterogeneous growth rates (net reaction rates) on the amorphous Mg-silicate substrate versus those measured on crystalline talc substrates indicates that mineral crystallinity likely plays a key role in mineral growth during diagenesis.

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