BANFF 2018 INTERNATIONAL INDUCED SEISMICITY WORKSHOP

October 24 – 26, 2018
Banff, Alberta, Canada
Banff Park Lodge WIFI code is: WUIS2018

For the workshop, we will use the Meetoo app to make it easy for everyone to share their ideas and opinions and most importantly, ask questions!

Alternatively, one of the CSUR volunteers will be in the audience with a microphone so do ensure you raise your hand if you wish to ask questions.

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DAY ONE: Wednesday, October 24, 2018 - Summit Assiniboine Room, Banff Park Lodge

15:00 – 15:15: Pradeep Talwani presents ‘Returning to Banff. The End of an Odyssey.’

The first international conference on induced seismicity held at Banff in 1975, was the beginning of my odyssey in understanding the mechanism of reservoir-induced seismicity. It was here that the role of pore pressures related with the impoundment of reservoirs was recognized as an important parameter in triggering the seismicity. Four decades later, I have learned that pore pressures flow from the reservoir to the hypocenters occurs by a process of diffusion along a small number of discrete fractures. Fractures associated with seismicity are associated with seismogenic permeability, $k_s$ ranging between $5 \times 10^{-16}$ and $5 \times 10^{-14}$ m$^2$. Modelling showed that there is threshold pore pressure for the occurrence of seismicity. Our studies disproved our initial thinking before the 1975 Banff meeting. The load of the reservoir is not the culprit, it was the always the pore pressure. Returning to Banff, my odyssey has come to an end.

BIO: Pradeep Talwani,

Distinguished Professor Emeritus of Geophysics, The University of South Carolina, Columbia, South Carolina; M.Sc. (Indian School of Mines, 1962); Ph.D. (Stanford University, 1973)

Employed with the University of South Carolina from 1973 to present.

I have been involved in the study of Reservoir Induced Seismicity (RIS) since 1974, with an emphasis on understanding its mechanism. Besides a study of RIS at six locations in South Carolina, I have visited and/or studied RIS in Brazil, Canada, China, Egypt, India, Spain and Viet Nam. These studies have been complemented by a study of injection-induced seismicity. Another area of my research involves Intraplate Earthquakes.

15:15 – 16:00: Bill Ellsworth presents ‘Induced Earthquakes: State of the Science 2018.’

Earthquakes of anthropogenic origin have become an important issue for society in many countries around the world, particularly in places where natural earthquakes are infrequent. We have seen that a wide range of industrial processes, including some that only produce small changes in fault stability, can induce them. Fortunately, induced earthquakes strong enough to cause structural damage or injury happen rarely. In most cases to date, the level of shaking presents more of a nuisance than a direct threat to life and property. Research conducted in the recent years into the physics of induced earthquakes has deepened our understanding of the underground conditions and perturbations favourable to trigger them. It has also led to the development of forecast model that provided guidance for managing induced seismicity once initiated. Despite the
progress, much remains to be done if we are to make prospective forecasts of the hazard before the onset of industrial activity.

**BIO:** William L. Ellsworth is a professor in the Department of Geophysics at Stanford University where he co-directs the Stanford Center for Induced and Triggered Seismicity. His research focuses on the seismological study of active faults, the earthquakes they generate and the physics of the earthquake source. He received B.S. in Physics and M.S. in Geophysics from Stanford University and his Ph.D. in Geophysics from MIT. He is a past President of the Seismological Society of America, a Fellow of the American Geophysical Union, and recipient of the Distinguished Service Award of the Department of the Interior.

16:00 – 17:30 **Poster Session - CASTLE ROOM**

18:00 – 20:00 **Icebreaker Reception sponsored by Western University & University of Southern California - ALPINE MEADOWS**

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**DAY TWO: Thursday, October 25, 2018 - Summit Assiniboine Room, Banff Park Lodge**

07:00 - 08:30 - **Breakfast Buffet - Glacier Salon**

08:30 – 10:00 **PROCESSES LEADING TO LARGE FAILURE EVENTS with Chair, Yehuda Ben-Zion, University of Southern California**

This session will discuss basic processes leading to transitions from ongoing small failure events to large earthquakes, and how to track approaching large events with recorded data. The discussed material will include perspectives from laboratory experiments, analysis of in-situ data and well-instrumented field experiments.

**BIO:** Yehuda Ben-Zion is a Professor of Geophysics at the University of Southern California. His research focuses on the physics of earthquakes and faults using a variety of theoretical frameworks and observational results. Ben-Zion received B.Sc. in physics and geology from the Hebrew University of Jerusalem in 1982 and Ph.D. in geophysics from the University of Southern California in 1990. He had visiting Professor positions in several institutions in Japan, Germany, Australia, France, Norway, China and the US. Ben-Zion is a fellow of...
the American Geophysical Union and received the Mercator fellowship from the German Research Society and the Humboldt Research Prize in geophysics.

08:30 – 08:55: Ilya Zaliapin of the University of Nevada, Reno will present ‘Localization Processes Leading to Large Failures: Analysis of acoustic emission and earthquake catalogues.’

This talk presents the recent findings on localization processes leading to large failures in natural and laboratory data. (1) We analyze Acoustic Emission (AE) data with the goal of quantifying the transition from distributed events to a system-size failure. Several datasets from different experiments provide information on the failure process in different rock types (granite, sandstone), loading conditions (constant loading rate vs. servo-controlled to maintain about constant AE rate) and sample properties (pre-existing notch vs. intact sample). We discuss several statistics that change significantly as system-size failure approaches. (2) We document how earthquake cluster characteristics (background rates, offspring productivity, regional cluster style) are related to physical properties of the crust (e.g., heat flow), seasonal variations of regional strain rates on the scale of hundreds of kilometres and climatic effects (e.g., equivalent water loads during a drought).

BIO: Ilya Zaliapin's bio follows:

Education: 1999 PhD in Physics and Mathematics, Russian Academy of Science, MITPAN. Advisors: Vladilen Pisarenko, Vladimir Piterbarg; 1995 MSc in Mathematics and Applied Mathematics (Probability and Statistics), Lomonosov Moscow State University, Department of Probability Theory, Advisor: Vladimir Piterbarg

Position: Professor, Director of Statistics and Data Science PhD program

Interests include: Self-similar trees, network transport; Aggregation (coagulation) processes; Delay Equations; Multiscale methods of time series analysis; Random sums of heavy-tailed variables; Statistical seismology, geo-statistics; Statistical consulting.

08:55 – 09:20: Georg Dresen, Professor of Geology, University of Potsdam and Section Geomechanics and Rheology German Research Centre of Geosciences presents ‘Damage evolution is leading to dynamic failure in rocks- observations from laboratory tests.’

Induced seismic events close to reservoir depths can lead to ground motions large enough to be felt at the surface, which raises significant public concern. Such events with relatively larger magnitudes are commonly connected to the reactivation of preexisting faults. We study fault
reactivation and creation in laboratory earthquake-analog systems and record seismic energy release over series of seismic cycle.

Natural and laboratory faults typically display characteristic structural patterns that evolve in space and time resulting in complex anastomosing networks of slip zones showing aspects of band-limited self-similarity across a broad range of spatial scales. Individual slip surfaces show varying roughness and are embedded in zones of distributed damage. Field studies and laboratory experiments suggest that structural heterogeneity and fault zone roughness may affect seismic characteristics such as earthquake magnitudes, recurrence intervals, b-values, radiated energy, and stress drops.

**BIO: Georg Dresen** is a Professor of Geology at the University of Potsdam and headed the Geomechanics and Rheology group at the GeoForschungsZentrum Potsdam from 1992-2017. He finished his PhD in Structural Geology at the University of Bonn in 1984 and his Habilitation in 1990. Between 1989 and 1993 he was a research scientist in the rock physics group at Department of Earth, Atmospheric and Planetary Sciences at MIT, Cambridge, Mass.

His research interests comprise rock mechanics and geomechanics, wellbore stability problems, reservoir stimulation and induced seismicity, physics of earthquakes and faulting, scaling relations of geological processes, the macroscopic constitutive behaviour of rocks and rock transport properties. He is co-PI of an ICDP fault drilling project at the North Anatolian Fault (Turkey) and involved in several industries- and EU-funded projects focusing on geomechanics, unconventional reservoir rocks and geothermal energy is the co-founder of two start-up companies active in geomechanics and microseismics.

**09:20 – 09:45: Ze’ev Reches of Oklahoma University presents ‘Seismic reactivation of basement structures in Oklahoma.’**

The recent seismicity in Oklahoma was attributed to reactivation of pre-existing basement faults by wastewater injection. However, the pattern, properties and even existence of these faults are practically unknown. Here, we characterize these unknown features and demonstrate that the geometry, structure and mechanical stability of Oklahoma basement faults make them critically susceptible to seismic reactivation. First, our outcrop and satellite mapping revealed widespread networks of fractures and faults with NE and NW trends that are strikingly like the trends of recent earthquake lineaments. Second, our 3D seismic analyses of basement structure show steeply-dipping faults that penetrate the lower parts of the sedimentary sequence; these faults could serve as pathways for wastewater migration. Finally, rock-mechanics testing under in-situ conditions down to 9 km depth indicates that Oklahoma basement rocks become seismically unstable at 3-6 km depth interval, which is the dominant hypocentral depth of the recent earthquakes.

Affiliations: School of Geology and Geophysics, University of Oklahoma, Norman, Oklahoma, USA. Oklahoma Geological Survey, Norman, Oklahoma; Currently: US Geological Survey, Menlo Park, CA, USA.

BIO: Professional Preparation of Ze’ev Reches


09:45 – 10:00 Q&A with Panel

10:00 – 10:30 Coffee Break and Poster Session

10:30 – 12:45 Hazard and Mitigation with Chair, Dr. Gail Atkinson, Western University

Hazards to infrastructure and their mitigation are explored from several perspectives. These include hindcasting of induced-seismicity hazard based on observations (such as 1-year hazard maps) and developments in forecasting models based on operational parameters and geological susceptibility, including machine-learning approaches. Improvements to hazard models to better account for spatial and temporal clustering behaviours are also explored.

10:30 – 10:50: Mark Petersen of the USGS presents ‘The USGS Induced-Seismicity Hazard Mapping Program.’

The 2018 one-year probabilistic seismic hazard forecast for the central and eastern United States from induced and natural earthquakes is developed using the same probabilistic seismicity-based methodology as applied in the two previous forecasts. Rates of earthquakes across the U.S. have steadily declined over the past 3 years, especially in areas of Oklahoma and southern Kansas where fluid injection has decreased. The seismicity pattern in 2017 was complex with earthquakes more spatially dispersed than in the previous years. Some areas of west-central Oklahoma experienced increased activity rates where industrial activity increased. Earthquake rates continue
Almost all earthquakes occurred within the highest hazard regions of the 2017 forecast. Fine details and variability between the 2016–2018 forecasts are obscured by significant uncertainties in the input model. These short-term hazard levels are like active regions in California.

Co-Authors: Charles Mueller, USGS & Morgan Moschetti, USGS

BIO: Dr. Mark D. Petersen is a regional coordinator for the U.S. Geological Survey’s (USGS) Earthquake Program and chief of the U.S. National Seismic Hazard Project. Dr. Petersen led the development of the 1996 (California Geological Survey) and 2002 (USGS) versions of the California Seismic hazard maps and 2008, 2014, and 2018 versions of the U.S. National Seismic Hazard Models that are applied in building codes, risk assessments, and public policy. He developed 3 one-year USGS forecasts for the Central and Eastern U.S. for induced and natural earthquakes.


A sharp increase in the frequency of earthquakes near Fox Creek, Alberta began in December 2013 in response to hydraulic fracturing. Using a hydraulic fracturing database, it was shown that seismic productivity scales linearly with injection volume and that geological factors play a prominent role in seismic productivity, as evidenced by spatial correlations. To account for these geological factors, we train a machine learning algorithm to systemically evaluate tectonic, geomechanical, and hydrological proxies suspected to control induced seismicity.

Feature importance suggests that proximity to basement, in situ stress, proximity to fossil reef margins, lithium concentration, and rate of natural seismicity are among the strongest model predictors. Our derived seismogenic potential map faithfully reproduces the current distribution of induced seismicity and is suggestive of other regions which may be prone to induced earthquakes. The refinement of induced seismicity geological susceptibility may become an important technique to identify significant underlying geological features and address induced seismic hazard forecasting issues.

Co-Authors are Ryan Schultz, Steven Pawley, Tiffany Playter, Hilary Corlett, Todd Shipman, Steven Lyster, and Tyler Hauck.

BIO: Ryan Schultz has been a seismologist at the Alberta Geological Survey in Edmonton, Alberta for close to seven years.
11:10 – 11:40: Norm Abrahamson of UC Berkeley presents ‘Evaluation of Deformation Hazard for Dams from Induced Seismicity.’

Authors: N. Abrahamson and C. Hale

Abstract: The effect of induced seismicity on the seismic risk of the earth dams is evaluated using a simplified approach to estimating seismic deformation of embankment dams combined with a probabilistic hazard analyses for induced earthquakes and for naturally occurring earthquakes. Hale (2018) developed a simplified model of the impulse response of the sliding mass based on an equivalent linear approach. The Abrahamson et al (2014) GMPE is modified to be applicable for induced earthquakes. Specifically, the short-period ground motion at distances less than 20 km is significantly increased compared to the Abrahamson et al (2014) GMPE for crustal earthquakes. The deformation is estimated by combining spectrum-compatible time histories for the input motion with the impulse response of the sliding mass and then computing a Newmark displacement. Although simplified, this approach allows the full frequency range of the input motion to be considered in the estimation of the deformation rather than using a single ground motion parameter such as PGA or PGV. This is important for induced earthquakes due to the enriched high-frequency content of induced earthquakes compared to current GMPEs for crustal earthquakes. Deformations from deterministic scenarios for a range of magnitudes, distances, and yield accelerations are computed for dam heights from 25 ft to 150 ft. Comparing these deformation with the available freeboard allows for setbacks to be selected. In addition, an example of a probabilistic analysis of the deformation hazard is shown which shows the increase in the deformation hazard due to the addition of the induced seismicity.

BIO: Dr. Abrahamson is an engineering seismologist with expertise in ground-motion models, seismic hazard, and seismic risk. This year, he retired from PG&E after 22 years as the technical manager for PG&E seismic research program on the seismic studies for application to PG&E's nuclear power plants, dams, office buildings, gas pipelines, and electric grid. He is currently an adjunct professor in the civil engineering departments at UC Berkeley and UC Davis. He also serves as a consultant for seismic hazard and seismic risk studies for nuclear power plants, dams, and bridges around the world.

11:40 – 11:55: Gail Atkinson of the University of Western Ontario presents ‘A brief overview of induced-seismicity ground motions in western Canada and the central United States.’

The implications of the motions for hazard assessment are summarized, along with the challenges for mitigation.
BIO: Gail Atkinson conducts research at the engineering-seismology interface. She has authored over 200 research articles on earthquake ground motions and seismic hazards and has also been active in the development of seismic design regulations for buildings, dams and nuclear power plants. Professor Atkinson has served as President of both the Seismological Society of America and the Canadian Geophysical Union, is a member of the U.S. National Earthquake Prediction Evaluation Council, and a Fellow of Royal Society of Canada. She currently holds the NSERC/TransAlta/Nanometrics Industrial Research Chair in Hazards from Induced Seismicity.

11:55 – 12:30 Q&A with Panel

12:30 – 14:00 Lunch Break in the Glacier Salon and Poster Session - CASTLE ROOM

14:00 – 15:30 High-quality datasets: Hits and Misses. An interactive session with shorter talks focusing on possible uses of presented datasets with Chair, Dr. David Eaton, University of Calgary

Acquisition of high-quality datasets has provided insights into underlying processes, ground-motion relationships and traffic light protocols for induced seismicity. The advent of large-N geophone arrays offers new opportunities to characterize source-processes and wave fields. There are some challenges, however, that hinder high-quality data acquisition, including lack of access to sufficient proprietary data and suitable field locations. This session will cover recent successes as well as a retrospective look at remaining challenges.

14:00 – 14:15: Honn Kao, PCG of the Geological Survey of Canada, Natural Resources Canada presents ‘The Improvement of Regional Seismograph Networks in Northeast BC and Western AB: Impact on Regulations of Unconventional Hydrocarbon Development.’

By establishing close collaborations with many partners, including regulators, government research organizations, universities, professional societies, and the energy industry, significant improvement has been made to enhance the earthquake monitoring capability of the regional seismograph network in NE BC and W AB. As a result, the overall magnitude of completeness of the earthquake catalogue for the region has improved by about one magnitude unit, dropping from ML≥2.5 to ~1.5. The improved earthquake monitoring has dramatically enhanced the performance of regulatory agencies by allowing regulators to 1) better identify and define “sweet spots” of IIE; 2) strengthen earthquake monitoring requirements for specific sites; 3) rapidly respond to media and public inquiries about possible felt IIE; and 4) understand the full impact/consequence of ground shaking caused by individual IIE events.
BIO: Honn Kao obtained his BSc in Geophysics from the National Central University, Taiwan, in 1985, MSc and Ph.D. in Geophysics from the University of Illinois at Urbana-Champaign in 1991 and 1993, respectively. He was recruited by the Institute of Earth Sciences (IES), Academia Sinica, Taiwan, as an Assistant Research Fellow immediately after finishing his Ph.D. study. During his initial years in IES, he oversaw establishing the Broadband Array in Taiwan for Seismology (BATS). He was promoted to Associate Research Fellow in 1996 and then Research Fellow in 2000. He was awarded the Outstanding Research Award of the National Research Council twice (1999 and 2001). In 2001, he was awarded the Distinguished Youth Medal of the Republic of China. He joined the Geological Survey of Canada in 2002 as a research scientist working on earthquake source characteristics and seismogenic structures. In 2006, he was appointed by the School of Earth and Ocean Sciences, University of Victoria, as an Adjunct Professor. He has served as an Associate Editor of the Journal of Geophysical Research between 2011 and 2017. He was also a member of the Editorial Board of the International Journal of Geophysics between 2012 and 2017. Currently, he is the leader of the Induced Seismicity Research Project of Natural Resources Canada.

14:15 – 14:30: Elizabeth Cochran of the U.S. Geological Survey will present ‘Trials and triumphs of a large-N seismic array to survey injection-induced earthquakes in northern Oklahoma.’

Temporary seismic deployments that capture ephemeral earthquake sequences provide datasets to explore a range of slip processes. Deployments typically include several-to-tens of seismic sensors; however, new technologies allow for arrays of hundreds-to-thousands of sensors. The LArge-n Seismic Survey in Oklahoma (LASSO) is a month-long deployment of 1,833 vertical-component nodes in a region of induced seismicity in northern Oklahoma. The raw dataset of 500 sample-per-second continuous data is 8.7 Tb, effectively requiring the use of high-performance computing for standard analyses. We develop a catalogue of nearly 10,000 events. This catalogue is used to explore the spatiotemporal evolution of seismicity, with a focus on fault segments that host larger (M2.5+) earthquakes during the deployment period. We find evidence for delayed dynamic triggering following teleseismic phase arrivals. For larger events, we examine how dense data may reduce uncertainties of source property estimates.
**BIO:** Elizabeth Cochran is a geophysicist with the US Geological Survey in Pasadena, California. As an observational seismologist, her research ranges from studying the detailed behaviour of fault slip to developing new techniques to densely observe earthquakes.

Dr. Cochran conducts detailed studies of aftershock behaviour, fault zone properties, and deep seismic slip (tremor). After a large earthquake, large numbers of seismic stations are installed near the mainshock to record the hundreds to thousands of aftershocks that will occur over the subsequent months. These data are then used to image fault structure and study the small-scale details of fault complexity and damage zones around faults. The work has shown that fault structures can exhibit highly complex slip behaviour. And, faults tend to localize on zones that are 100m - 1 km wide and severely damaged compared to surrounding, intact rock.

She is also currently investigating new techniques to densely monitor strong ground motions in urban areas. The Quake-Catcher Network is a collaborative research effort that uses low-cost MEMS sensors connected to personal computers or other devices in homes, offices, and schools. The data collected by these sensors may be used to augment the existing seismic networks to aid in the study of earthquake rupture processes, block-by-block variations in ground motion, and may even provide useful data for earthquake early warning systems currently being developed for California and the Pacific Northwest.

14:30 – 14:45: Emrah Yenier of Nanometrics will present ‘Insights from High Quality Datasets on Induced Seismicity Risk Management.’

The result from any analysis is directly controlled by the quality of the data inputs. When it comes to induced seismic risk management and mitigation, accurate and complete seismic catalogs generated in near real-time are critical to the utility and practicality of seismicity attribute forecasts. In this study we demonstrate the importance of catalog quality for successful seismic risk assessment and mitigation. We also discuss different published seismicity forecasting models and evaluate their performance for number of datasets.

To understand the sensitivity and reliability of forecasting models to the data quality, we compared observed and forecasted seismicity for local and regional arrays. We also assessed the estimated seismicity with and without applying advanced event detection and location techniques on the local arrays. The results show that a fine-tuned enriched catalog is the most important requirement to drive a reliable risk management application.

In the next step, we evaluated published seismicity forecasting models by playing back 30+ datasets generated from hydraulic fracturing monitoring. Three prediction models are used to estimate maximum magnitude and one for evaluation of number of events larger than a threshold.
magnitude. Our findings show that in general maximum magnitude estimates from different models are nearly identical and in a good agreement with the observed seismicity. We also discussed the limitation of the models where for few cases the seismicity forecasts were not very successful. Our investigation in the effect of the injection volume on seismicity and maximum magnitude estimations reveals that as the seismogenic index and seismicity statistics are estimated in every time step, the forecasts lost their sensitivity to the injection volume over time.

To improve the practicality of seismicity forecasts, all observations and estimations are presented in a dashboard environment with the objective of providing effective real-time operational risk mitigation feedback.

**BIO:** With over 10 years’ experience in engineering seismology applications, Emrah Yenier specializes in ground motion modelling and seismic hazard analysis. He is the Engineering Seismology Lead with Nanometrics Inc., in Ottawa, Canada, where he is responsible for the management and development of models for earthquake source, attenuation and site processes for use in engineering practices. He has co-authored over 15 scientific papers and has participated in several collaborative research projects, including the Turkish National Strong Motion Project, Seismic Harmonization in Europe, and the Next Generation Attenuation–East. Emrah received BSc. and MSc. degrees in Civil Engineering from Middle East Technical University, Turkey and holds a Ph.D. degree in Geophysics from Western University, Canada.

14:45 – 15:00: David Eaton, NSERC/Chevron Industrial Research Chair in Microseismic System Dynamics, Department of Geoscience at the University of Calgary will present ‘Insights from the joint interpretation of dense array observations and 3D multicomponent seismic: The ToC2ME experiment, Fox Creek, AB Induced Seismicity from a Regulatory Perspective.’

Authors: David Eaton and the ToC2ME working group

The Tony Creek Dual Microseismic Experiment (ToC2ME) is a field program that employed a diverse set of sensors to record a hydraulic-fracturing program within a region of known susceptibility to induced seismicity west of Fox Creek, Alberta. The acquisition systems consisted of a 68-station shallow borehole array, six broadband seismometers and one strong-motion accelerometer. Analysis of the dataset is ongoing; to date, 20,000 events (M-1 to M3.2) have been detected over a 5-week period, including 530 high-quality moment tensors. The largest events have strike-slip mechanisms and are located several hundred metres above the treatment zone (~ 3.2 km depth) along a series of well-defined N-S lineaments. Integration of regional stress information...
with stress inversion results using moment tensors indicates that activated faults required a ~11-17 MPa pore-pressure increase to induce slip. A coincident 3-D multicomponent seismic survey provides a rare opportunity for detailed correlations between induced seismicity and pre-existing faults. Despite being nearly parallel to activated faults and proximal to the injection, fault strands that are most conspicuous in the 3D seismic data were not activated. There is evidence, however, that seismogenic faults have a local stress signature that is distinct from stable (cemented?) pre-existing faults.

**BIO:** Professor David Eaton holds the NSERC/Chevron Industrial Research Chair in Microseismic System Dynamics in the Department of Geoscience at the University of Calgary. Together with graduate students and postdoctoral fellows, his work focuses primarily on the advancement of research, education and technological innovations in microseismic methods and their practical applications for resource development, with a secondary focus on the deep lithospheric structure of continents. In 2007, he rejoined the University of Calgary as Head of the Department of Geoscience, after an 11-year academic career at the University of Western Ontario. His postdoctoral research experience included work at Arco’s Research and Technical Services (Plano, Texas) and the Geological Survey of Canada (Ottawa). He has over 140 publications in peer-reviewed journals and books, including articles in Nature and Science, as well as a recently published textbook on Passive Seismic Monitoring of Induced Seismicity.

15:00 - 15:30 Q&A with Panel

15:30 – 17:00 Refreshment Break and Poster Session - CASTLE ROOM

FREE NIGHT TO EXPLORE BANFF FOR ATTENDEES

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DAY THREE: Friday, October 26, 2018 - Summit Assiniboine Room, Banff Park Lodge

07:00 - 08:30 - Breakfast Buffet - Glacier Salon

08:30 – 12:30 Regulatory and Policy Approaches with Chairs, Shawn Maxwell, Newfield Resources and Dan Allan, Canadian Society for Unconventional Resources

Regulators, policy-setters, and operators from various jurisdictions will compare and discuss regulations regarding objectives, technical assumptions and practical application. Regulations are typically based on traffic light protocols although the details of implementation, including magnitude thresholds and responses, vary significantly in different locations.
08:30 – 08:35 Opening comments by session co-chairs, Shawn Maxwell & Dan Allan

Dan Allan, President and CEO
Canadian Society for Unconventional Resources

Mr. Allan is a registered professional geologist with 40 years of diverse industry experience working in both Canada and the United States. He is a graduate of McGill University with an honours degree in Geological Sciences. Mr. Allan has held executive management positions in numerous oil and gas companies over the last twenty years. These have included both large and smaller organizations, including being the President and CEO of several publicly listed energy firms.

Mr. Allan has extensive experience in unconventional resource exploration and development having worked on projects throughout North America. Mr. Allan is the former chairman of the board for CSUR, is a member of the Canadian Society of Petroleum Geologists, the American Association of Petroleum Geologists and is a registered Professional Geologist in both the province of Alberta and the state of Wyoming.

Shawn Maxwell, Geophysical and Geomechanical Advisor
Newfield Resources, The Woodland, Texas, USA

Mr. Maxwell is the Geophysical and Geomechanical advisor for Newfield Resources, based in The Woodlands. Previously he was President and Chief Technology Officer for Itasca IMaGE, Chief Geophysicist and Microseismic Advisor for Schlumberger, led microseismic development at Pinnacle Technologies (Halliburton) and ESG, and served as a Lecturer at Keele University in England. Shawn was awarded a Ph.D. specializing in microseismology from Queen’s University in Kingston, Canada.

08:35 – 09:00: Rick Simmers, Chief of the Ohio Department of Natural Resources ‘Division of Oil and Gas Resources Management will present ‘Induced Seismicity from a Regulatory Perspective.’

Induced seismic events from deep well fluid disposal or well completion operations, although rare, do occur. Regulatory programs must be able to monitor and evaluate data in real-time and be prepared to make informed regulatory decisions on short notice. The regulated community may realize adverse economic impacts from these actions. There may be a safety or functional issues that delay cessation of operations that could have induced seismic events.
The public expects the regulator to protect human health and safety, and the environment and may expect or demand quick regulatory action.

What data is necessary to make such decisions? What legal authority does the regulatory agency have? What is an appropriate regulatory action for the induced seismic event? What data could the company provide to assist the regulator in the review? What precautions have the company initiated to minimalize the risk? Is the seismic monitoring network adequate to effectively evaluate the cause?

These are but a few of the questions a regulator must consider. The regulated community should be prepared to respond to an induced seismic event with sound data and an appropriate mitigation plan. It is in everyone’s best interest to be prepared before any action is necessary.

**BIO: Rick Simmers** is Chief of the Ohio Department of Natural Resources’ Division of Oil and Gas Resources Management. He is responsible for enforcing Ohio’s laws related to oil and gas drilling, production, plugging, orphan wells, solution mining, enhanced recovery, gas storage and underground injection control operations. An ODNR career employee, Simmers began working for the Oil and Gas Program in 1985. Over the years he has served as a staff geologist, groundwater investigator, acting chief and statewide field enforcement administrator.

Simmers earned both a Master of Science degree and bachelor’s degree in geology from the University of Akron. He also holds a bachelor’s degree in biology from the University of Akron. He is currently serving as Ohio’s representative to the Interstate Oil and Gas Compact Commission and has also served on the Ground Water Protection Council.

**SESSION on the BC MONTNEY**

09:00 – 09:10: Stuart (Stu) Venables, British Columbia Oil & Gas Commission presents ‘A short synopsis of the current regulatory climate and an overview of potential regulatory enhancements.’

09:10 – 09:40: Stuart (Stu) Venables of the British Columbia Oil and Gas Commission presents ‘Induced Seismicity: Observations, Research and Oversight in British Columbia.’

A detailed review of seismic activity in BC related to both hydraulic fracturing and disposal activities. The emphasis of the talk will be to scrutinize the various parameters associated with induced seismicity and emphasize the requirement for site-specific solutions.
**BIO:** Stuart (Stu) Venables grew up in Ottawa, Ontario. He obtained a B.Sc. in Geology from Acadia University graduating in 1999. Upon graduation, Mr. Venables moved to Calgary, Alberta where he worked for a variety of E&P and M&A firms from small 5-person operations to large, multinational corporations and banking firms. In 2010, he left Calgary and moved to Victoria, British Columbia where he accepted a position with the BC Oil & Gas Commission (Commission). Since 2010, Stu has worked for the Commission as a Senior Petroleum Geologist and taken on a variety of issues including the launch and on-going oversight of fracfocus.ca and implementing the first fracture fluid disclosure regulations in Canada. Currently, his primary focus is the regulatory approach, oversight and mitigation of induced seismicity. Stu Venables is a registered Professional Geologist with APEGBC.

**09:40 – 10:00:** Lindsay Miller of Progress Energy presents ‘Progress Energy – An operator’s perspective on the nature of induced seismicity in the Montney field and the ever-evolving challenges for the regulatory body.’

Since 2014, Progress Energy has been using a 17-broadband station array to monitor induced seismicity over its operating land base. Progress installed the 17-broadband station array to monitor and assess induced seismicity during operations. On a few select pads, the company also obtained surface microseismic. In reviewing these data sets, Progress Energy has been looking to identify any repeatable patterns of induced seismicity and felt events. Could these patterns help the regulating government body in determining a blanket approach to best regulate operations in the Montney field?

**BIO:** Lindsay Miller, BSc., joined Progress Energy in 2013 to work with conventional and unconventional assets within Western Canada. Lindsay works with the asset team to deliver operational geophysical support; including, seismic interpretation to aid the drilling and completions team with well programs and geo-hazard assessments. Previously she worked on conventional international exploration at Talisman Energy, her work involved regional interpretation for oil and gas exploration. Lindsay is an active member of CSEG, SEG, AAPG, and, on behalf of Progress Energy, sits on the CAPP B.C. Induced Seismicity Working Group committee. Lindsay graduated with a Bachelor of Science in Geophysics from the University of Calgary in 2007. Outside of work, Lindsay can be found playing hockey, skiing, and rodeoing with her horses in the summer.

**10:00 – 10:15 Q&A with Panel**

**10:15 – 10:45** Coffee Break and **Poster Session - CASTLE ROOM**
SESSION on the DUVERNAY


The Alberta Energy Regulator is unique in the world as being the home of a world-class geological survey – the Alberta Geological Survey (AGS). Because the AGS is embedded in the energy regulator, applied science and knowledge can flow into regulatory response and design in real time when a subsurface event unfolds. In a similar way, resources and direction can flow into the AGS from the AER in real time as well to direct geologists and geophysicists to immediately turn their applied research programs and expertise to areas of immediate provincial priority. This is exemplified by the rapid growth of AGS applied research into Alberta seismicity from one experimental seismometer and no full-time seismology staff in 2008 to running a regional monitoring network of over 52 stations, including 14 AGS own seismic stations today with a team of three applied seismologists supporting AER real-time response to induced seismicity while producing research published in the highest quality scientific journals today. This success story built on the experience of AGS in building and running the Turtle Mountain-Frank Slide active landslide-monitoring system starting in 2003, going from no monitoring at all then to a world-renowned landslide observatory and real-time monitoring system that operates to this day.

**BIO:** Carol Crowfoot has been monitoring energy markets since 1981 and has been with the Alberta Energy Regulatory (AER) since 2007. Ms. Crowfoot is the AER’s executive vice president of the Strategy and Regulatory Division. She is responsible for leading the organization to the successful execution of its strategy, ensuring organization standards are developed and followed when designing risked-based regulatory requirements, and delivering energy information, independent analysis, and supply-and-demand forecasts for Alberta commodities to all stakeholders.

Ms. Crowfoot started her career at GLJ Petroleum Consultants. Through this work, she was responsible for monitoring and understanding the fundamentals of supply, demand, and transportation issues in energy markets. She also provided commentary regarding market trends and participated in regulatory hearings and civil proceeding as an expert witness. In addition to her duties with GLJ Petroleum Consultants, in 2002 Ms. Crowfoot was named the president of GLJ Energy Publications Inc., a firm specializing in market information and analysis of the North American natural gas industry.

Throughout her career, Ms. Crowfoot has been a frequent presenter to industry conferences including the Canadian Energy Research Institute Natural Gas Conference, numerous Canadian Institute conferences, the Economics Society of Calgary technical seminars, Canadian Society of Petroleum Geologists conventions, and Petroleum Society technical luncheons.

Reactive tools are the most common practices used to manage induced seismicity, such as traffic light protocols or ground motion thresholds. Recent findings have suggested that areas of susceptibility can be identified through multi-variant analysis of receptors and predictors, therefore recognizing areas that can be managed to avoid induced seismic events. Using an avoidance approach assumes a geological hazard as the main cause of induced seismicity, which requires evaluation of risk for future development of oil and gas activity or mitigation for existing activity. Avoidance has been attempted in Oklahoma, through subsurface fault maps detailing the hazards and there is some exploration of avoidance tools in other regulatory jurisdictions. This talk will discuss the possibilities of avoidance strategies for induced seismicity.

**BIO:** Todd Shipman, PhD., Landscape and Geological Hazards Manager with the Alberta Geological Survey has a master’s degree in Geology from Northern Arizona University 1999 and a Ph.D. from the University of Arizona in Geoscience 2004. Todd worked at the Arizona Geological Survey until 2009, where he developed the first earth fissure monitoring program for the State of Arizona. In 2010, he started work at the Alberta Geological Survey, where he became manager of the Landscapes and Geohazards Group. Todd was one of the authors of Subsurface Order #2 and currently manages the group that operates the RAVEN seismic network.


Chevron Canada Limited has been an active operator in the Kaybob Duvernay play since the early exploration days of the late 2000's. Chevron has worked extensively with the regulator, other operators and academia to collaborate and accelerate the advancement of our knowledge on seismicity related to hydraulic fracturing operations in the Duvernay. Our monitoring and mitigation protocols to manage the risk have adapted over time as knowledge has accumulated. A significant focus has been to provide key early recognition of risk features and trends and to provide a more detailed characterization of anomalous seismicity.
BIO: John Evans is a Senior Staff Geophysicist in the Kaybob Duvernay asset team at Chevron Canada. During his 30+ year career with Chevron, John has worked on many different exploration and development subsurface teams in several locations including Calgary, St. John’s and Houston. For the last 10 years, his work has focused on exploration and development of unconventional heavy oil and shale assets.

11:45 – 12:05: Daniel Ciulavu, Shell Canada presents ‘Induced Seismicity. HF Regulations, Shell Approach.’

BIO: Daniel Ciulavu is a structural geologist with a MSc degree in Geology and Geophysics from University of Bucharest, Romania, and a PhD in Geology from Vrije Universiteit, Amsterdam. Daniel worked as a consultant in structural geology in Europe, Asia, and the US.

In 2001, Daniel was a Senior Fulbright Fellow at the University of Texas at Dallas, before joining Shell Canada in 2002 as a geologist/structural geologist. Since then, he has held various roles from Foothills Central manager to Geosciences Advisor for Shell properties in Alberta. Presently, Daniel works as an explorationist in the Duvernay play.

12:05 – 12:30 Q&A with Panel

12:30 – 13:30 Lunch Break in the Glacier Salon and Poster Session - CASTLE ROOM

13:30 – 15:00 Data Mining with Novel Analysis Techniques

Chair: Yehuda Ben-Zion, University of Southern California and David Eaton, University of Calgary

The rapid increase in the quantity and quality of recorded seismic data sets and development of data mining techniques increase significantly the ability to extract robust information on the occurrence and properties of small earthquakes. Discussed techniques and applications include advanced use of templates and machine learning to develop detailed seismic catalogues and derive source properties of small events.

Microseismicity often conveys the most direct information about active processes in the earth’s subsurface. However, routine network processing typically leaves most earthquakes uncharacterized. These “sub-catalogue” events can provide critical clues to ongoing processes in the source region. To address this issue, we have developed waveform-based processing that leverages the existing catalogue of earthquakes to detect and characterize events absent in routine catalogues. Using large-scale waveform cross-correlation between cataloged events with the continuous data stream, we 1) identify events with similar waveform signatures in the continuous data across multiple stations, 2) precisely measure relative time lags across these stations for both P- and S-waves, and 3) estimate the relative polarity between events by the sign of the peak absolute value correlations and its height above the secondary peak. This final step facilitates robust focal mechanism estimation for large populations of tiny earthquakes, addressing a common shortcoming in microseismicity analyses (Shelly et al., JGR, 2016). Depending on the application, we can characterize 2-10 times as many events as included in the initial catalogue. Application to a 2014 swarm in Long Valley Caldera, California, illuminates complex patterns of faulting that would have otherwise remained obscured. Together, these patterns imply strong interactions between fluid diffusion and faulting processes in the crust.

**BIO:** David R. Shelly is a research geophysicist in the Geologic Hazards Science Center, U.S. Geological Survey, Golden, Colorado. His research interests include earthquake swarms (and associated fluid-faulting interactions) and tectonic tremor. To gain insight into these processes, he has worked to develop new techniques for earthquake detection, source location, and focal mechanism determination, applicable to large populations of microseismicity.


With the volume of seismic data recorded around the world growing rapidly by the year, reliable automated techniques are becoming increasingly relied upon for extracting the usable scientific signal. Such automated methods, however, generally lag in performance compared with the capabilities of expert seismologists. Here, we develop a framework for generalized seismic phase detection using technology from artificial intelligence that learns directly from seismograms without the need for feature extraction. We utilize millions of manually determined phase picks to train deep neural networks to detect P and S body waves, localize onset times, and determine first-motion polarities. The networks are shown to perform as well, or better, than professional seismic analysts due to their ability to generalize entire waveform archives. This enables the trained models to be applied to data from completely different tectonic regimes or too large magnitude events without representation in the training set.
We separately develop a deep learning approach to seismic phase association, which is the task of linking together phase detections on different sensors that originate from a common earthquake. This fundamental task is challenging because the number of sources is unknown, and events frequently overlap in time. We train recurrent neural networks to link phases together that share a common origin by examining tens of millions of synthetic example sequences. The method is simple to apply to any tectonic regime and can naturally incorporate errors in arrival time picks. Rather than tuning a set of ad hoc parameters to improve performance, the results are improved by adding examples of problematic cases to the training dataset for the network to learn from. The developed techniques are expected to significantly improve the resolution of seismicity catalogues, stabilize real-time seismic monitoring, and streamline the automated processing of large seismic datasets.

**BIO:** Zachary Ross is a Postdoctoral Scholar in Geophysics at the California Institute of Technology. He previously received a Ph.D. in Geophysics from the University of Southern California, and a B.S. in Physics from the University of California, Davis. His research interests are in detection and picking of seismic waves with artificial intelligence, high-resolution imaging of fault zones, relationships between earthquake rupture processes and properties of fault zones, and algorithms for improved automated analysis of large seismic datasets.

14:20 – 14:45: Grzegorz Kwiatek of GFZ, Potsdam Germany presents ‘Limits on detection and analysis of small (induced) earthquakes.’

1. GFZ German Research Centre for Geosciences, Potsdam, Germany; 2. Free University, Berlin, Germany; 3. University of Southern California, Los Angeles, United States

We investigate theoretical limits on detection and reliable estimates of source characteristics of small induced and natural earthquakes using synthetic seismograms for shear/tensile dislocations on kinematic circular ruptures, observed seismic noise and properties of several acquisition systems typically used in industrial monitoring (instrument response, sampling rate). Simulated source time functions for shear/tensile dislocation events with different magnitudes, static stress drops, and rupture velocities provide estimates for the amplitude and frequency content of P and S phases at various observation angles. The source time functions are convolved with a Green’s function for a homogeneous solid / 1D velocity model assuming given P-, S- wave velocities and attenuation coefficients and a given instrument response. The synthetic waveforms are superposed with average levels of the observed ambient seismic noise up to 1 kHz. The combined seismograms are used to calculate signal-to-noise ratios and expected frequency content of P and S phases at various locations.
The synthetic simulations of signal-to-noise ratio reproduce observed ratios extracted from several well-recorded datasets of induced seismicity (mining, geothermal stimulation, fracking) with magnitudes ranging from $M_W-3$ to $M_W5$. The results provide guidelines on detection of small seismic events in various geological environments, along with information relevant to reliable analyses of earthquake source properties, ground motion assessment and earthquake scaling relations.

**BIO:** Grzegorz Kwiatek is a Senior researcher at Section 4.2: Geomechanics and Rheology of the GFZ German Research Centre of Geosciences in Potsdam, and Free University in Berlin. His background is Environmental Geophysics, with a focus on physics of earthquake source, earthquake scaling relations, and geomechanics. His research covers seismo-mechanical studies in a broad range of earthquake scales from analysis of acoustic emission activity recorded in laboratory experiments on rock samples and in the in-situ geomechanical laboratories to seismicity induced by exploitation of geo-reservoirs.

14:45 – 15:00 Q&A with Panel

15:00 – 16:00 Refreshment Break and [Poster Session - CASTLE ROOM](#)

16:00 – 17:00 Closing Panel Discussion

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**Thank you for attending the Banff 2018 International Induced Seismicity Workshop.**

**Safe travels home!**