SE05: Induced earthquakes: Source processes and hazard assessment

Conveners: Yajing Liu[1], and Rebecca Harrington[2]

Co-chairs: Yajing Liu[1], and Rebecca Harrington[2]

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Session Description

In the past decade, there has been a drastic increase in seismicity associated with fluid injection during unconventional oil and gas extraction in North America, including previously seismically quiescent areas. While pore pressure increase due to fluid diffusion is a commonly recognized conceptual mechanism for inducing earthquakes, the complex interaction between pore fluids, solid matrix stress and, if applicable, strength of a pre-existing fault, remains unclear. Regional seismic network and local dense arrays have been established and are starting to provide detailed information about the source process and ground motion of induced earthquakes. In this session, we invite contributions from studies on earthquakes potentially induced by various anthropogenic causes, including but not limited to, wastewater disposal, hydraulic fracturing, geothermal energy extraction, CO_2 sequestration and natural gas underground storage, and reservoir impoundment. We welcome studies using seismological and geodetic observations, geomechanical modeling, statistical analysis and laboratory experiments to address the source mechanism of induced seismicity, their distinctions and/or similarities to natural tectonic earthquakes, and seismic hazard assessment and mitigation.

Primary Affiliation: Solid Earth / Geodesy / Hydrology

NOTE: THIS DOCUMENT CONTAINS INFORMATION FOR ALL SESSION SUB-SECTIONS. PRESENTER ABSTRACTS ARE FOUND AT THE END OF THE DOCUMENT.

SCHEDULE MAY BE SUBJECT TO CHANGE.

ORAL SESSION SE05a

Chairs: Y. Liu & R. Harrington **Room: ESB 2012**

Wednesday, May 31st

TIME	AUTHORS	TITLE
9:00	H. Kao, R. Hyndman, Y. Jiang & L. Leonard (invited)	Tectonic Strain Rate and Injection-Induced Earthquakes (IIE) in western Canada: Implications for Short-Term and Long-Term Seismic Hazard Assessments
9:15	B. Wang, R. M. Harrington, Y. Liu, H. Kao & H. Yu	Static stress drop of the largest recorded M4.6 hydraulic fracturing induced earthquake and its aftershock pattern in the northern Montney Play, British Columbia, Canada
9:30	R. Wang, Y. J. Gu, Y. Chen & M. Zhang	The January 2016 Earthquake Sequence near Fox Creek and its Relation to Hydraulic Fracturing
9:45	Y. Vaezi & M. van der Baan	Interferometric time-lapse velocity analysis: Application to a salt-water disposal well in British Columbia, Canada
10:00	Y. Liu, K. Deng & R. Harrington	Poroelastic stress change and fault slip induced by fluid injection
10:15	K. Assatourians & G. Atkinson	Processed Ground-Motion Records for Induced Earthquakes for Use in Engineering Applications

ORAL SESSION SE05b

Chairs: Y. Liu & R. Harrington **Room: ESB 2012**

Wednesday, May 31st

TIME	AUTHORS	TITLE
16:00	M. R. Canales & M. van der Baan	Probabilistic Seismic Hazard Analysis for Induced Seismicity: suggested approaches and application to the Horn River Basin, Northeast B.C.
16:15	H. Ghofrani & G. M. Atkinson	Rates of Induced-Earthquake Activation in Western Canada and Implications for Hazard
16:30	G. M. Atkinson	Mitigation strategies to prevent damage to critical infrastructure due to induced seismicity

POSTER SESSION SE05

Chairs: Y. Liu & R. Harrington   Room: ESB Atrium

Tuesday, May 30th

Poster No.	AUTHORS	TITLE
P01-SE05	S. D. Thorpe, K. F. Tiampo, S. V. Samsonov, M. Shirzaei & P. J. González	Time series analysis of surface deformation associated with fluid injection and induced seismicity in Timpson, Texas using DInSAR methods
P02-SE05	J. Kubanek, Y. Liu & R. M. Harrington	Monitoring ground motion associated with fluid injection and earthquakes in the western Canadian sedimentary basin (WCSB)
P03-SE05	A. Amini, E. Eberhardt	An investigation on the effects of hydraulic fracturing injection volume and rate on the magnitude of induced seismic events

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SUBMITTED ABSTRACTS

SE05-01: Tectonic Strain Rate and Injection-Induced Earthquakes (IIE) in western Canada: Implications for Short-Term and Long-Term Seismic Hazard Assessments

Honn Kao[1,2], Roy Hyndman[1,2], Yan Jiang[1] and Lucinda Leonard[2]

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Abstract
Most injection-induced earthquakes (IIE) in western Canada are associated with the development of unconventional hydrocarbons. In this study, we investigate their relationship to the distribution of tectonic strain in this region. Data from regional and local seismograph networks were used to establish a comprehensive earthquake catalogue with over 4000 events between January 2014 and August 2016, 3.5 times that from routine catalogues. A database of regional injection parameters was also compiled for the same time period from industry and regulatory agency data. These databases were then compared to the distribution of tectonic strain rate from GPS measurements. The maximum tectonic strain is in the Cordillera, decreasing eastward but still significant in the foothill inside the Western Canada Sedimentary Basin, decreasing to low values further to the east. We find that the greatest natural seismicity is also in the mountains but, with the addition of IIE, the total seismicity in the foothill is greater. Moreover, many high-volume injection sites further to the east where the GPS-defined strain rates are insignificant have caused no IIE. We propose that the seismic pattern of relatively large IIE in the study area is strongly controlled by the tectonic strain. In the short term, the effect of injection can temporarily increase the likelihood of a major earthquake as the volume affected by high pore pressure becomes larger, increasing the probability of triggering a fault that has already accumulated significant elastic tectonic strain. In the long term, however, IIE for an extended period will deplete the available built-up strain, and may delay the next major earthquake. Therefore, a seismic hazard model for regions with IIE should incorporate the concept of varying probability due to short-term pore-pressure perturbations from injection and long-term conservation of strain energy from tectonic deformation. [291 words]

Presentation type: Oral Presentation

SE05-02: Static stress drop of the largest recorded M4.6 hydraulic fracturing induced earthquake and its aftershock pattern in the northern Montney Play, British Columbia, Canada

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

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3. Geological Survey of Canada, Pacific Geoscience Centre, 9860 West Saanich Road, Sidney, British Columbia, Canada

Abstract
The largest suspected fracking-induced earthquake to date occurred near Fort St. John, British Columbia on August 17, 2015, with a reported magnitude of Mw 4.6. Here we locate the mainshock and estimate the static stress release along with the four cataloged aftershocks. We use data from 8 McGill broadband seismometers installed approximately 50 km northwest from the epicenter of the mainshock and one permanent station (NBC5) established by the Natural Resources Canada (NRCan). They are the closest public seismic stations in the region. We calculate seismic moment (M_0) and spectral corner frequency (f_c) values estimated using both individual earthquake spectra and spectral ratios of event pairs to correct for travel-path attenuation and site effects. The corner frequency values estimated from P-wave spectra yield static stress drops ranging from 0.2 to 15 MPa, falling on the lower end of the range typically observed for tectonic earthquakes. Corner frequencies roughly follow constant a stress drop scaling. We also use a multi-station matched-filter (MMF) approach to detect an additional 290 smaller-magnitude aftershocks in the continuous waveforms for a period of 45 days following the mainshock. Due to the lack of azimuthal coverage of the 8 McGill stations, we apply a “grid search” to calculate the initial locations and origin times for all the 290 events, and use HypoDD to relocate them. We also perform waveform inversion to calculate the focal mechanism of the M4.6 mainshock and find it to be on an oblique fault with reverse motion.   We plan to combine our MMF-detected aftershocks with previously cataloged events, in order to investigate their spatial-temporal distribution and potential correlation with the hydraulic fracturing at the nearest wells.

Presentation type: Oral Presentation / Poster

SE05-03: The January 2016 Earthquake Sequence near Fox Creek and its Relation to Hydraulic Fracturing

Ruijia Wang[1†], Yu Jeffrey Gu[1], Yunfeng Chen[1], Miao Zhang[2]

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Abstract
With a reported Richter magnitude of 4.8, the January 12, 2016 earthquake near Fox Creek is the largest event in Alberta during the past decade. This earthquake, which was suspected to be induced by hydraulic fracturing, triggered the "stoplight" according to provincial energy regulations (traffic-light protocol) and led to the suspension of a nearby injection well. In this study, we examine the hypocenter location of this earthquake, and the results are consistent with an anthropogenic origin. The focal mechanism determined from full moment tensor inversions suggests a strike-slip mechanism with limited (~22%) non-double-couple components. The candidate fault orientations, which are predominately N-S and E-W trending, are consistent with the results from double-couple forward modelling and P-wave first motion analysis. This source solution is supported by similar analyses of several other **M**~4 events in this region. Through waveform correlation analysis of near-source station (distance <10 km) records we are able to identify over 400 smaller (**M**<2) earthquakes within two weeks. They are closely distributed around the hydraulic fracturing well at depths between 2.5-4.5 km, comparable to the injection depth (3.5 km). The spatial distribution of this earthquake cluster further suggests that 1) N-S is the true orientation of the potential fault system and 2) the earthquakes were induced by a well close to, but different from, the one that triggered an earlier (January 2015) earthquake swarm. The temporal distribution of the seismicity indicates that the majority of these events took place during the simulation phase, showing near-instantaneous response to the injection activity. In short, our integrated study of the January 2016 sequence offers critical insights to the nature of induced earthquakes in the Fox Creek region.

Presentation type: Oral presentation preferred

SE05-04: Interferometric time-lapse velocity analysis: Application to a salt-water disposal well in British Columbia, Canada

Yoones Vaezi[1] and Mirko van der Baan[1]

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Abstract
There is an increasing need to obtain comprehensive knowledge about the subsurface and its temporal changes for exploitation of natural resources, storage of waste, or subsurface construction. In a salt-water disposal setting, injection and movement of fluids in geologic formations cause changes in seismic velocities and attenuation, resulting in changes in seismic wave scattering and propagation. The changes in seismic velocities can be associated with changes in fluid saturation and pore pressure, opening or enlargement of cracks, or induced stress variations. Passive methods based on ambient seismic noise, in general, present an effective approach to accomplish the important task of long-term monitoring. Here, we investigate the possibility of passive monitoring of a salt-water disposal well and its surroundings located in British Columbia using continuously–recorded ambient seismic noise. We are especially interested in seismic velocity variations induced by a reduction of injection pressure in an effort to mitigate the elevated level of seismicity, most likely associated with the injection of large volumes of salt water. We use the method of passive image interferometry to estimate the relative velocity variations from the time shifts measured between consecutive crosscorrelation functions for each station pair in a surface array composed of 5 broadband seismometers. Preliminary results show that among the station-pair paths that are analyzed some represent clear systematic changes of velocities on the order of 0.1% during the period of interest when the injection pressures were reduced. The probable driving mechanisms responsible for the velocity increase or decrease coincident with injection pressure changes are reduced pore pressures or lowered poroelastic stresses beyond the injection wellbore, respectively. As opposed to injection pressures, hydrologic data (e.g., snow and rain fall) and noise energy trends do not correlate with the estimated relative velocity variations.

Presentation type: Oral Presentation / Poster

SE05-05: Poroelastic stress change and fault slip induced by fluid injection

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Abstract
Solid matrix stress and pore pressure changes due to fluid injection are key factors for inducing earthquakes on pre-existing faults. In this study, we first present poroelastic stress modeling results for multi-stage hydraulic fracturing and wastewater disposal scenarios, with applications to induced earthquakes near Fox Creek, Alberta and Cushing, Oklahoma, respectively. In both cases, the shear and normal stresses critically influence the Coulomb stress regimes and consequently seismicity distribution, despite their relative amplitudes to the pore pressure increase in the two types of injection scenarios. We further introduce the poroelastic stress changes as perturbations to a nearby, pre-existing fault governed by the rate-state friction to simulate conditions for inducing aseismic and seismic slip. In the application to the December 2013 earthquake sequence near Fox Creek, we find that slip on the fault evolves in a manner similar to the onset of seismicity. For a modeled 15-stage HF that lasts for ~ 10 days, fault slip rate starts to accelerate after 3 days of fracking, and rapidly develops into the seismic range with V_{max} > 5 mm/s, which temporally coincides with the onset of seismicity. Fault slip rate continues to evolve and remains high (but below the seismic threshold) for several weeks, which may explain the continued seismicity after shut-in. By comparison, fault slip rate quickly decreases to the pre-fracking level when perturbations are instantaneously returned to zero at shut-in. Furthermore, when perturbations are removed just a few hours after the fault slip rate starts to accelerate (that is, fracking is terminated prematurely), only aseismic slip is observed in the model. Our results thus suggest the design of HF stages and flow-back strategy, either allowing stress perturbations to passively dissipate in the medium or actively reducing to the pre-fracking level, is critical for inducing seismic versus aseismic slip on pre-existing faults.
[300 words]

Presentation type: Oral Presentation / Poster

SE05-06: Processed Ground-Motion Records for Induced Earthquakes for Use in Engineering Applications

Karen Assatourians[1] and Gail Atkinson[1]

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Abstract
We compile and process an electronic database of ground motions recorded on accelerometers and broadband seismographic instruments for induced earthquakes of **M**≥4 at distances <50 km in central and eastern North America. Most of the data are from Oklahoma, with some records from Alberta. Our focus is on the subset of available records that are of most interest for engineering analyses aimed at evaluation of the potential hazards from induced events. We considered all records to 50 km for events of **M**≥4.5. For events of **M**4 to 4.5, we select records at close distance (<15 km), having good signal strength (PGA >~3%g), in order to allow high-quality time histories to be obtained. The selected records are windowed, filtered and instrument-corrected to compile a set of records having acceptable acceleration, velocity and displacement time histories. The records and their response spectra are provided as electronic files. We note that the record set is not suitable as a response spectra database for development of ground-motion prediction equations, because for **M**<4.5 the record selection is biased to records with higher amplitudes. Rather, the intended use of the records is as seed records, which can be readily scaled in the time domain to approximately represent induced-event target scenarios.

Presentation type: Poster

SE05-07: Probabilistic Seismic Hazard Analysis for Induced Seismicity: suggested approaches and application to the Horn River Basin, Northeast B.C.

Mauricio Reyes Canales[1*], Mirko van der Baan[1]

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Abstract
Large-magnitude induced seismicity associated with shale oil and gas production is a growing concern for operators, regulators and the public in general. Probabilistic Seismic Hazard Analysis (PSHA) has been used to quantify the hazard for natural events. However, some important challenges are associated with the assessment of human-induced seismic hazard; these include lack of understanding of source depths, magnitude-frequency distribution, the maximum magnitude, the nonstationary behavior of the induced seismicity, and the appropriate Ground Motion Prediction Equations. We describe novel methodologies to evaluate the seismic hazard caused by induced earthquakes. The first method (Observational model) uses observed earthquake catalogs to obtain relevant seismic parameters for past induced seismicity and then calculates the hazard. The second method (Predictive model) uses additional information, such as the statistical characteristics of microseismic events and the in-situ state of stress to predict some of the seismic parameters necessary to estimate hazard. The advantage of the predictive approach is that it permits to explore how different hydrocarbon depletion and drilling completion scenarios may affect future hazard. To illustrate these methodologies, we selected an area with recent induced seismic activity: The Horn River Basin, Northeast British Columbia. Our preliminary results indicate increased hazard during the period of active hydraulic fracturing treatments due to the addition of human-induced events in a region with a low level of background seismicity. The current analysis is conditioned to the assumption of stationarity in the calculations, and the results are only valid for short-term hazard forecasts. [244 words]

Presentation type: Oral Presentation

SE05-08: Rates of Induced-Earthquake Activation in Western Canada and Implications for Hazard

Hadi Ghofrani[1], Gail M. Atkinson[1]

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Hydraulic fracturing plays a significant role in triggering seismicity in the Western Canada Sedimentary Basin (WCSB; Atkinson et al., 2016; Bao and Eaton, 2016). Since 2010, most of the regional earthquakes of moment magnitude (**M**) ≥ 3 in WCSB are highly correlated in time and space with horizontally-fractured wells. We develop a statistical model of the likelihood that horizontally-fractured wells in the WCSB will trigger earthquakes of **M** ≥ 3 using the concept of cellular seismicity. Our aim is to facilitate the forecasting of induced-seismicity potential for future HF operations, for use in hazard analyses. This differs from an exercise aimed at identifying individual wells that initiated past sequences. For future operations, we are interested in the probability that a significant sequence of events may be triggered. The rate of seismicity in a probabilistic seismic hazard analysis (PSHA) for induced seismicity is the product of the activation probability and the conditional earthquake rate. Thus changing the activation probability is equivalent to changing the seismicity rate parameter, which significantly impacts the expected ground motions (Atkinson et al., 2015). We use statistical metrics to estimate the regionally-averaged probability that hydraulic fracture operations will be associated with **M** ≥ 3 seismicity within a 10 km-grid cell; this provides an estimate of the prior probability of inducing seismicity by commencing operations in a small area. For the geological setting and operational parameters in the WCSB, the likelihood that hydraulic fracture operations in an area of 10 km radius will be associated with **M** ≥ 3 earthquakes is 0.010 to 0.026, at the 95th percentile confidence limit. This is the likelihood averaged over the entire region. In some areas the rate is significantly higher than average, while in others it is lower. Monte Carlo simulations confirm that the observed correlations are extremely unlikely (<<1%) to have been obtained by chance. Proximity to a disposal well, and proximity to the Swan Hills Formation, which has been suggested as a proxy for basement faulting, appear to increase the likelihood that hydraulic fracturing will trigger seismicity.

Presentation type: No preference

SE05-09: Mitigation strategies to prevent damage to critical infrastructure due to induced seismicity

Gail M. Atkinson

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Abstract
There has been a significant increase in the rate of felt earthquakes in western Alberta and eastern B.C., which has been associated with hydraulic fracturing and wastewater disposal. The increased rate of seismicity and the potential for localized strong ground motions from very shallow events poses an increased hazard to critical infrastructure such as major dams – particularly for older high-consequence structures in areas of previously-low seismicity. This presentation overviews the factors that affect the likelihood of damaging ground motions and examines their implications for hazard. A mitigation strategy is developed to meet reliability targets. For critical facilities, an effective strategy includes: (i) an exclusion zone having a radius of ~5 km (at all depths); and (ii) a monitoring-and-response protocol to track the rate of events at the **M**>2 level within 25 km, and trigger adjustments to operational practices if this rate exceeds an acceptable level. An exclusion zone provides a deterministic safety margin to ensure the integrity of those few facilities whose failure consequences are simply unacceptable. Real-time monitoring tied to a response protocol can be used to control the rate of significant induced events on a regional basis and thereby limit the ground-motion hazard more broadly.

Presentation type: Oral Presentation

SE05-10: Time series analysis of surface deformation associated with fluid injection and induced seismicity in Timpson, Texas using DInSAR methods

Simon D. Thorpe[1*], Kristy F. Tiampo[1], Sergey V. Samsonov[2], Manoochehr Shirzaei[3], Pablo J. González[4]

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Abstract
In recent years, there has been a rise in unconventional oil and gas production in North America. Simultaneously, an increase in seismicity rate has been observed in this region, leading to the general consensus that both processes are linked resulting in induced seismicity (Ellsworth, 2013). As fluid is pumped into deep formations, the state of stress within the subsurface changes, potentially reactivating pre-existing faults and/or causing subsidence or uplift of the surface. Therefore, hydraulic fracturing and/or fluid disposal injection can significantly increase the seismic hazard to communities and structures surrounding the injection sites (Barnhart et al., 2014; Shirzaei et al., 2016). On 17th May 2012 a Mw4.2 earthquake occurred near the city of Timpson, Texas and has been linked with wastewater injection operations in the area (Shirzaei et al., 2016; Frohlich et al., 2014). This study aims to relate, both spatially and temporally, wastewater injection operations to seismicity near Timpson using differential interferometric synthetic aperture radar (DInSAR) analysis. Satellite-based geodetic methods such as DInSAR provide frequent measurements of ground deformation at high spatial resolution. Using the Canadian RADARSAT-2 and Japanese ALOS satellites, images were stacked to generate highly coherent interferograms. Results from this study are presented as a set of time series, produced using the Multidimensional Small Baseline Subset (MSBAS) InSAR technique that reveal the spatial and temporal relationship between well injection activity and associated induced seismicity in the region. Future work will utilise these time series to model subsurface fluid flow, providing important information regarding the nature of the subsurface structure and associated aquifer due to fluid injection.

Presentation type: Poster

SE05-11: Monitoring ground motion associated with fluid injection and earthquakes in the western Canadian sedimentary basin (WCSB)

Julia Kubanek[1], Yajing Liu[1], and Rebecca M. Harrington[2]

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Abstract
In the last five years, the number of earthquakes induced by hydraulic fracturing has increased drastically in North America. Whereas seismicity in the central U.S. is mostly related to high-volume injection of wastewater, a larger proportion of seismicity in the western Canadian sedimentary basin (WCSB) has been correlated with fracking along wells. We present here the outline and first results of our new research project aiming to investigate how fluid injection are linked to seismic activity. As a first test site, we have chosen the area around Fort St. John in the WCSB in northeast British Columbia where a Mw 4.6 earthquake occurred on 17th August 2015. It is the first time that dense seismic and geodetic observations will be used together with groundwater isotope geochemistry monitoring, and poroelasticity and fault slip models to achieve high-resolution information about induced event sources. To monitor the surface deformation caused by injection, we will employ GPS data as part of the integrated seismo-geodetic system which we plan to install in the area around Fort St. John. In addition, large archives of SAR data, including the Canadian RADARSAT-1 and 2, ERS-1 and 2, ENVISAT, and Sentinel 1A and B (all from the European Space Agency) will be analyzed to detect surface deformation due to fluid injection in our study area. We also plan to install corner reflectors, i.e., trihedral radar reflectors constructed by three mutually orthogonal plates in areas where natural persistent scatters are sparse, e.g., in remote areas of dense vegetation. The strong backscattered response they provide will facilitate interferometric processing deriving surface displacements on the submillimeter level. The joint data analysis will enable the identification of possible precursory signals for seismic activity related to hydraulic fracturing and wastewater disposal that can be applied in hazard assessment.

Presentation type: Poster

SE05-12: An investigation on the effects of hydraulic fracturing injection volume and rate on the magnitude of induced seismic events

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Abstract
Hydraulic fracturing is a technology that is used to increase production from unconventional oil and gas reservoirs. When performing hydraulic fracturing, high pressure fluid is pumped into different sections of well to break reservoir rock and create fractures in order to increase the stimulated reservoir volume and therefore increase production. Hydraulic fracturing, however, is not without side effects. Among the issues related to hydraulic fracturing, induced seismicity has gained a lot of public and governmental attraction around the world in the last decade especially due to natural gas production from shale gas reservoirs. One of the topics related to induce seismicity research, is to study the magnitude of induced seismic events. Induced seismic events have very low magnitudes most of the time but there have been reports of large earthquakes that have even caused damages to residential buildings. Therefore, it is important to study the parameters that influence the magnitude of these events. This study will investigate the effects of operational factors such as injection rate and volume on the magnitude of induced seismic events. To do so, a series of hydraulic fracturing laboratory experiments will be performed on cylindrical samples with precut planes in them to simulate injection on a fault plane. These experiments will be monitored with acoustic emission activity and the results will be analyzed based on number, magnitude distribution and focal mechanism of acoustic emission events. In parallel, a series of advanced numerical models using the distinct element code UDEC will be performed to investigate the effects of injection rates and volumes on the magnitude of induced seismic events on reservoir scale.

Presentation type: Poster