CAPP CANADA'S OIL & NATURAL GAS PRODUCERS

Industry Shared Practices

Anomalous Induced Seismicity due to Hydraulic Fracturing

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The Canadian Association of Petroleum Producers (CAPP) represents companies, large and small, that explore for, develop and produce natural gas and oil throughout Canada. CAPP’s member companies produce about 80 per cent of Canada’s natural gas and oil. CAPP's associate members provide a wide range of services that support the upstream oil and natural gas industry. Together CAPP's members and associate members are an important part of a national industry with revenues from oil and natural gas production of about $101 billion a year. CAPP’s mission, on behalf of the Canadian upstream oil and natural gas industry, is to advocate for and enable economic competitiveness and safe, environmentally and socially responsible performance.

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Overview

As prudent and responsible operators active in the development and production of unconventional resources, it is important to gain a better understanding of types and sources of seismic activity. By supporting research at universities, partnering with federal and provincial agencies, and conducting our own on-site research, we are contributing to a better understanding of seismicity and the potential impacts of our operations on each unique geological setting. Evidence suggests that any induced seismicity caused to date by hydraulic fracturing in the Western Canadian Sedimentary Basin (WCSB), while occasionally felt, is generally deep, near the reservoir interval and poses no risk to health, safety or the environment.

CAPP and its member companies encourage approaches to managing potential seismic risk that are based on science, taking into account the local public exposure of such as felt events, operational factors, geological setting and historical baseline seismicity levels. We also support reasonable and prudent considerations of engineering standards and codes related to seismicity and structural integrity. We take a diligent risk-management approach toward studying and limiting the potential for anomalous induced seismicity caused by hydraulic fracturing in our operations.

Seismicity is a normal part of hydraulic fracturing. Typically, these seismic events are small (microseismic events), too small to be felt at the surface. In rare cases, estimated to be 0.15 per cent[1] of hydraulic fracturing stages completed in the Montney for example, seismic events can be large enough to be felt at the surface. These have not posed a threat to safety, structures or the environment in the WCSB. Seismic events felt at the surface and linked to human activities are often referred to as anomalous induced seismicity. This is the case in some areas in Alberta and northeast British Columbia where incidents of felt seismic events associated with hydraulic fracturing have been reported.

[1] Source: BC OGC, Investigation of Observed Seismicity in the Montney Trend, December 2014

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1 Purpose

Operators in CAPP’s seismicity committees have shared their experiences and knowledge to produce this document. It is designed to serve as a guide and describes current recommended practices for hydraulic fracturing induced seismicity risk appraisal, risk mitigation approaches, and key research and activities. Operators are encouraged to follow these recommended practices voluntarily.

These shared practices reflect the current state of knowledge and take into account areas of ongoing research to improve understanding. This document is therefore described as a “shared” rather than “best” practice. Any recommendations herein are superseded by regulatory requirements that exist in specific areas of operations.

The document provides information of use to operators in addressing the risk of induced seismicity. The shared practices are general in nature. Operators will need to adapt the shared practices to their specific situation. It is the responsibility of each operator to conduct their operations safely and in accordance with the circumstances of the particular operation

2 Risk Appraisal and Risk Mitigation

The key planning activities that guide the design and implementation of hydraulic fracturing operations where induced seismicity is a potential should be influenced by a comprehensive risk assessment and a corresponding monitoring and response plan suited to the specific location.

What follows is a discussion that will help lead to a substantiated and logical Pre-Completion Risk Assessment, and a presentation of recommendations for monitoring and appropriate operational responses.

2.1 Pre-Completions Risk Assessment for Anomalous Induced Seismicity Due to Hydraulic Fracturing

While most hydraulic fracturing operations do not trigger anomalous induced seismicity, it has occurred under certain conditions. This section highlights some of the factors that should be considered when designing and assessing hydraulic fracturing operations. As with all aspects of oil and gas operations, risks exist and should be evaluated to manage and mitigate the hazards.

A hazard is any source of potential damage or harm to people or property. The risk associated with a hazard is understood to be the product of the likelihood of the hazard to occur and its consequence as presented in Figure 1. That is:

Risk = Likelihood x Consequence

The consequence of a hazard is a measure of its impact. For ground motion associated with seismicity, this is primarily governed by the magnitude[2], the resultant ground motion generated at various epicentral distances and the effects of the ground motion on nearby infrastructure and/or the public.

[2] Although ground motion is the key concern, the most commonly used measure of seismic event size is the magnitude scale. As such, most industry and regulatory Traffic Light/Stop Light approaches still use magnitudes as thresholds in their response plans. The magnitude value calculated depends on whether moment or local magnitudes are used, what phase is analyzed and how the equations are parameterized. In this document, magnitude is used to refer to any of these methods of calculating the size of a seismic event.

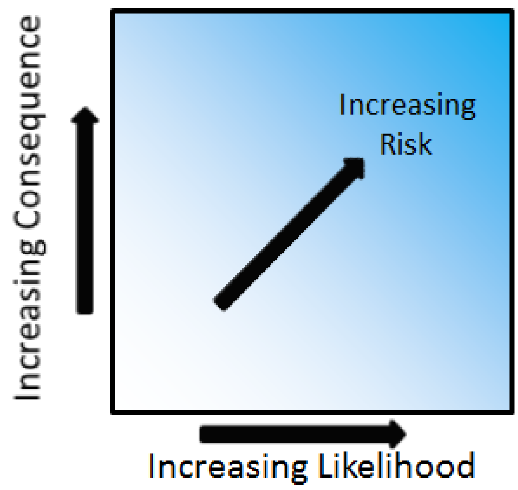


Figure 1: Risk Matrix

For decades seismologists have struggled to predict when and where seismicity will occur in long-standing geological systems with well known, essentially steady-state, tectonic stress. Natural seismicity is typically characterized based on historically observed seismicity and the assumption of a power law (Gutenberg-Richter) relationship between event magnitude and its frequency of occurrence that is normally derived over a significant period of time (years to decades) as shown in Figure 2-2.

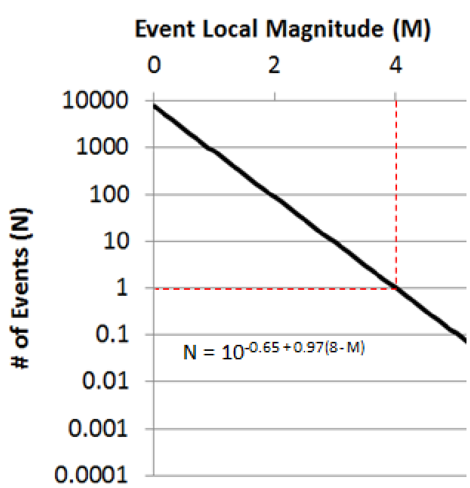


Figure 2: Gutenberg-Richter plot normalized for a single M=4.0 event

When short-term human activity, such as hydraulic fracturing, impacts a geological system, our ability to predict the number and magnitude of seismic events is challenged. However, there are factors we can consider when assessing the risk of induced seismicity caused by hydraulic fracturing, as identified in the following subsections.

2.1.1 Historical Seismicity

Checking data for historical seismicity will identify whether there has been natural or induced seismic activity near your area of operations. The occurrence of previous seismic activity indicates the geologic system may be stressed. This may raise the likelihood of seismic activity resulting from hydraulic fracturing, particularly if the historical seismicity is known to come from the depth near that of planned operations. In addition to the occurrence of seismicity, it is useful to identify the locations, spatial clustering/trends, focal mechanisms and the maximum magnitude that has occurred. These attributes provide further insight into the seismogenic character of the area.

The absence of seismic activity does not necessarily mean the geologic system is not critically stressed, as the dataset may suffer from poor or sparse array monitoring and may not have been capable of detecting the seismicity. If an area has not been targeted for development before, fracking operations may induce events for the first time, as natural seismicity often occurs on larger time scales that may not yet have been captured during any monitoring. Data should be chosen from longer historical records and collected from higher quality arrays when available. For a field/play scale perspective of the historical seismicity, it is helpful to first review the data (e.g., Natural Resources Canada, U.S. Geological Survey, Alberta Geological Survey) on a regional scale around operations to put the planned operation into the correct context.

2.1.2 In situ Stresses

The subsurface stress state is a key factor in assessing the likelihood of seismicity in a region. If the geologic system is not stressed, fault activation will not occur. Local estimates of the in-situ stress magnitudes and azimuths (principal stresses and pore pressure) at the target level should be made using available data. This may provide insight into how close the system is to failure for an optimally orientated fault and for any other fault orientations identified.

Qualitative and quantitative methods to help characterize the local stresses:

- Density log data
- Multi-arm caliper and FMI/OBMI log data
- Bore-hole collapse and loss of drilling mud circulation experiences
- Formation integrity tests
- Diagnostic fracture injection tests
- Microseismic data
- Attributes that include advanced pre-stack seismic attributes to predict zones of elevated local stresses from a combined mapping of 3D inversion for highly brittle zones with low minimum closure stress with 3D azimuthal differential shear anisotropy to assess elevated strain energy

2.1.3 Geological Fault Mapping

It is broadly understood that seismic events induced by human activity occur on previously existing faults in the subsurface. Faults that provide a pathway between the stimulated formation and brittle underlying formations and basement (where stored and differential stresses can be much larger than in the overlying sedimentary section) are of particular concern due to their potential to generate larger seismic events.

It can be challenging to identify existing faults, particularly faults with small offsets, vertical dip, or a strike-slip sense of motion. However, there are a number of technologies and methods available to industry that may be useful:

- FMI/OBMI log data and cross dipole shear logging
- Drilling cuttings
- Gamma ray logs from the horizontal well section (may detect vertical offsets of bedding)
- Microseismic data (may highlight minor fault re-activation trends)
- 2D/3D surface seismic data
- To assist in identifying subtle faults, it is helpful to use seismic attributes such as curvature, semblance and coherence to highlight structural features in the seismic data

Faults and structural features should be mapped within the target formation, as well as above and below the area of planned hydraulic fracturing. It may also be useful to map faults at deeper levels (e.g., crystalline basement). Basement features may help to identify controlling faults that have been nearly healed at the reservoir depth but may still exert a local influence. Gravity and magnetic data can be useful in identifying some of these larger scale basement features that may be difficult to resolve on most industry surface seismic data.

Although identifying faults near the area of hydraulic fracturing operations is good practice, industry experience on the use of fault mapping in B.C. and Alberta to date has been mixed. Seismicity with anomalous magnitudes tend to appear or cluster in zones. These zones may not correlate to areas of seismically mapped faults, suggesting a pre-existing fault exists but is not seismically discernable.

2.1.4 Operational Risk Factors

Operational risk factors in known areas of seismicity should be assessed to capture historical experience. This knowledge can be used to determine whether the planned hydraulic fracturing operations pose a risk. Examples of hydraulic fracturing operations that may affect the risk of seismicity are injection volume, pump rates, pressures and cumulative pad effects. Furthermore, adjacent operations may influence the assessment of risk due to the potential for localized communication and/or cumulative effects such as confining stresses.

2.1.5 Consequence

Although rare, induced seismic events can be felt by the public. As part of being a responsible operator, it is important to identify any communities near the area of operations and be prepared to respond to local concerns regarding felt events in addition to regulatory requirements.

Earthquake magnitude measures the seismic energy released; earthquake intensity estimates the degree to which the energy released is felt at surface as ground motion. The intensity of ground shaking is defined by the Modified Mercalli Intensity Scale (MMI). In the rare cases where induced seismic events are felt, intensities may range from II (up to 30 km away) to V (close to the epicenter). Table 1 shows MMI scale NRCAN and the USGS to use to quantify felt events.

Table 1: Description of the levels of Modified Mercalli Intensity (source USGS).[3]

Intensity	Shaking	Description/Damage
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Very strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.

[3] https://earthquake.usgs.gov/learn/topics/mercalli.php

Intensity	Shaking	Description/Damage
VIII	Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

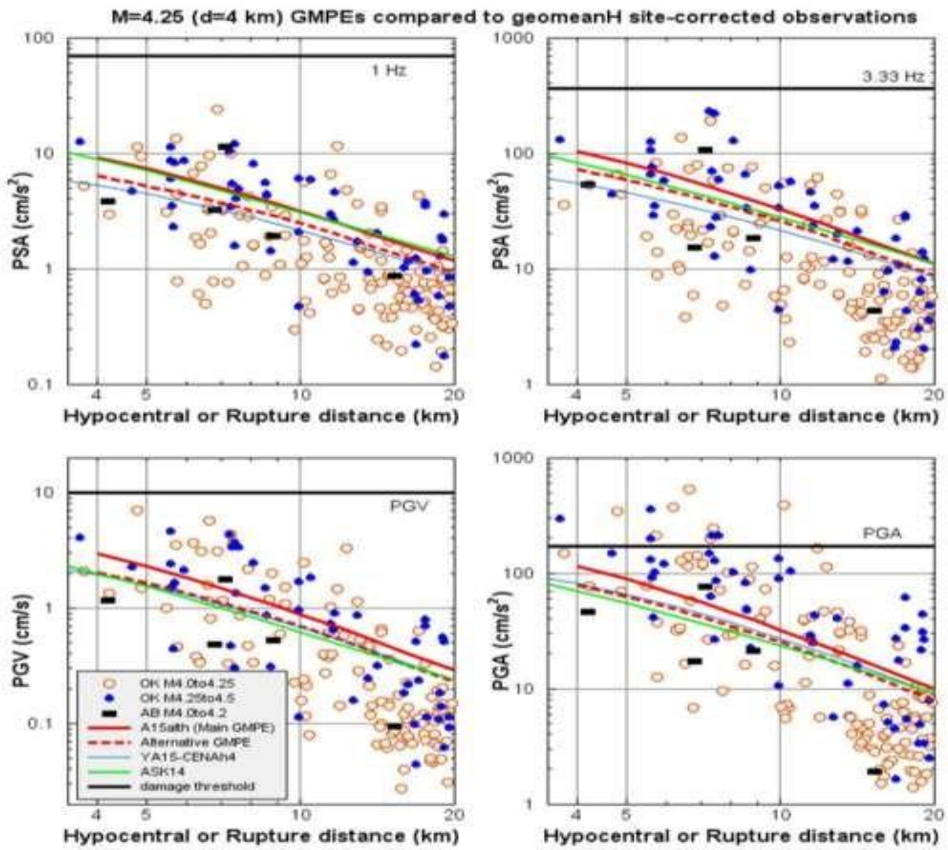
In addition to magnitude, intensity is determined by distance and depth, site amplification effects, and source radiation pattern. Site amplification effects due to site class vary considerably. A magnitude 4 event may not be felt at all on hard rock (class A) soil, whereas the same event may be felt a considerable distance away on soft (Class E) soil. Ground motion is described by both peak ground acceleration (PGA) and peak ground velocity (PGV). The degree to which events are felt is best measured by PGA, whereas the degree of damage is best measured by PGV. Table 2 relates PGA and PGV to Mercalli Intensity.

Table 2: Relationship between PGA, PGV, Damage potential and Intensity

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL. (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

As of April 2019, there have been six induced seismic events in Western Canada greater than magnitude 4.0, with the largest being 4.6. Some have been felt over a relatively large area, but there has been little or no impact to infrastructure. However, as part of a field level risk assessment, it is prudent to identify potentially susceptible critical infrastructure such as, but not limited to, dams, gas plants, power facilities, water towers, etc. Where warranted by risk such proximity to population centers, operators may consider use of a Ground Motion Prediction Equation (GMPE) that relates earthquake magnitude to ground motion vs. distance for a given region. This allows operators to set magnitude thresholds appropriate to the risk associated with pad being fractured, along with those required by regulation.

Figure 3: Observed horizontal-component ground motions (symbols) for induced events of M4.0 to 4.5 (converted to B/C site conditions) in Oklahoma and Alberta[4]



2.1.6 Final Risk Assessment

The overall risk associated with induced seismicity due to hydraulic fracturing operations is the result of a reasonable documented aggregate of all the risks, weighted appropriately for the area of operations. The combined effect of risk factors discussed above should result in risk categories based on how they rank. The responsibility of how to assess and aggregate the risk from each of these should be passed on to operators.

In summary, total risk increases with the following:

- Historical seismicity
- In situ stresses
- Discernible faults from geological mapping
- Operation risk factors due to activities on site and adjacent
- Consequence

[4] Atkinson, 2017, https://www.inducedseismicity.ca/wp-content/uploads/Atkinson2017-FACETS.pdf

2.1.7 Pre-Completions Operations Risk Review

Prior to initiating hydraulic fracturing operations and depending on the results of preceding risk assessment, it is good practice to hold a seismicity risk and seismicity mitigation planning review with key subsurface and well completion technical staff and decision makers. The review can align understanding of the risks and response protocols for the well or group of wells, and should:

- Review and document risk factors and their characteristics for the upcoming area of operations
- Finalize and document the prioritized mitigation response plan for consideration if seismicity events or trends occur
- Use the results of the risk review to finalize seismicity monitoring and response protocols for that operation

2.2 Seismic Monitoring and Response during Hydraulic Fracturing Operations

In areas of higher risk, it is important to establish an appropriate monitoring procedure based on the risk assessment for anomalous induced seismicity. Options for monitoring span publicly available regional data and a spectrum of industry monitoring solutions. Prior to hydraulic fracturing operations, the risk assessment should be incorporated into an appropriate monitoring and response documented plan. Below are suggestions for such a plan.

2.2.1 Monitoring System

Monitoring for induced seismicity serves three main purposes:

- It provides the operator with an opportunity to identify elevated levels of seismic activity or clustering before an anomalous event occurs so that proactive operational changes can be implemented to mitigate the risk.
- If an anomalous seismic event occurs, real-time monitoring allows the operator to implement reactive operational changes quickly.
- Monitoring seismicity allows operators to learn more about the occurrence and behavior of anomalous induced seismicity to improve mitigation measures.

Monitoring will often use a national seismic network for detection and location of seismic events. In some cases, it may be preferred to supplement with a local network installed to have same-day or near real-time notification of seismic activity. Furthermore, apps are available for devices that provide real-time notifications of events that can be used to monitor the public arrays.

If a near real-time seismic monitoring program is scheduled for the well operations, the service provider should be instructed to immediately notify the operator’s onsite representative, consistent with their response protocol.

For hydraulic fracturing of wells in risk areas where the operator chooses to monitor, it is recommended to monitor during the well fracturing and for a period of time thereafter.

2.2.2 Operational Response: Roles/Responsibilities/Communications

Individuals who are key to the seismicity response system should be documented and their roles/responsibilities described.

Examples of important roles to identify:

- Seismic Monitoring Representative
  - usually a member of a seismic monitoring service provider
  - may be on call to respond to large seismic events detected in proximity to known well operations
  - confirms the occurrence, magnitude and determined location of an event of concern
- Monitoring Focal Point
  - operator staff (usually a geophysicist or engineer based in the office)
  - typically on call during operations
  - regularly checks the seismicity recorded by the national network or by a local network
  - initiates communication protocols (e.g., contacting the regulator and the field operations) and organizes an investigation into seismic events of concern
  - collaborates with an interdisciplinary team, develops a response/mitigation plan for submission and approval by the regulator (if required)
  - communicates the approved mitigation plan to the field completions engineer
- Well site Supervisor/Completions Superintendent
  - based in the field and oversees well site operations
  - executes the well operational responses/interventions and startup if operations were stopped during the investigation of the event of concern
- External Communications Focal
  - operating company staff
  - communicates with the public and media
- Decision Maker(s)
  - identifies who has the key decision-making role for yellow and red light situations
- Regulator
  - liaises with the regulator authority for well activities

2.2.3 Example Operational Response System

Table 3 provides an example Operational Response System for seismicity detected in the vicinity of hydraulic fracturing well operations. Operators may modify their thresholds and metrics (e.g., ground motion) to suit local operations.

Table 3: Example Operational Responses to Observed Seismicity based on AER's Subsurface Order No.2 in High to Moderate Risk Areas

Response Level	Observed Seismicity[5]	Recommended Operational Response
Level A	Local conditions may vary, but typically the seismicity would be less than magnitude 2.	• Continue with regular operations and monitoring. • Track potential trends in the location and magnitude of events. • Consider initiation of yellow light mitigations if trends indicate the potential for higher risk.
Level B	Seismic events between magnitudes 2 and 4 are being observed, or there is a trend toward events of larger magnitude with time.	• A response plan on-site prior to beginning operations. • Meet with the engineers and subsurface geological and geophysical staff to evaluate forward steps. The urgency on meeting with the team is subject to the level of seismicity observed. • Consider making operational changes to mitigate further seismicity. These include, but are not limited to: ○ Reducing the injection rate or treating pressure ○ Adjusting the type of fluid being pumped (e.g., slick water vs. gelled) ○ Skipping completion stages or diverting flow to move away from a re-activating fault ○ Flowback the well (to reduce the pressure in the system) ○ Moving to another well to allow time for gradual pressure depletion (returning at a later time) and conducting an analysis of seismic event magnitude or location trends near the problematic well.

[5] The seismicity levels in this table are provided as an example. At this time, there are four "traffic light protocols" in Western Canada, two in BC, and two in Alberta, with shutdown magnitudes of either 4.0 M_L or 3.0 M_L, depending on the specifics of the given area. Special regulations are also in place for some hydroelectric dams and gas storage facilities. If regulations are not already in place, operators are encouraged to consult with regulators and other operators regarding appropriate magnitude thresholds for a given region. Operators should set their response levels based on local operational conditions, regulatory requirements and internal protocols.

Response Level	Observed Seismicity[5]	Recommended Operational Response
Level C	Seismic events greater than magnitude 4 are observed, or ground motion is felt at the surface.	• Execute a controlled well shutdown and suspend further operations until an appropriate course of action is determined and approved by the operating company decision maker and the regulator as required.

3 Areas of Active Research

The science for anomalous induced seismicity is complex, and research and understanding are evolving rapidly. CAPP operators are engaged in a wide range of research in Canada and globally. Several scientific questions have been postulated and are being investigated. As the scientific community learns more, it is expected new avenues of research will emerge.

CAPP members are conducting and supporting several research efforts to improve how risk from anomalous seismicity is identified and mitigated. Work is undertaken through research organizations and academic/industry consortia. CAPP member companies also contribute data and technical knowledge to support academic research. It is important to understand and identify knowledge gaps, and show regulators how operators are supporting consortium research on anomalous induced seismicity.

Collaborative research on induced seismicity is conducted under the leadership of:

- Microseismic Industry Consortium (Universities of Alberta and Calgary)
- Western University
- Center for Integrated Seismicity Research (University of Texas Bureau of Economic Geology)
- Stanford Center for Induced and Triggered Seismicity (Stanford University)
- Massachusetts Institute of Technology
- Southern Methodist University
- Miami University

While the geomechanics of natural seismicity are generally understood, induced seismicity from fracturing requires further research. Linking geomechanics to operational activity is in its early stages. Ideally, deterministic models could be built from the mechanisms of induced seismicity that would predict when and where an anomalous induced seismic event will occur. This is unlikely in the near term.

CAPP members, in collaboration with academia, have identified these research priorities:

- Magnitude standardization
  - Need for magnitude standardization for effective regulatory enforcement and consistent communication to the public. Local (e.g., Richter magnitude) vs. moment magnitudes can be confusing and misleading.

- Subsurface characterization
  - How can areas prone to larger seismic events be identified/predicted?
  - The roles of pore pressure and stress effects on inducing events.
- Understanding seismicity effects at surface
  - Given that the ground motion relationship with induced seismic events is locally variable, data acquisition and analysis may be needed to accurately predict ground motion in any specific area
  - Relationship of ground motion to magnitude and effects on infrastructure.
- Establishing effective operational mitigations

4 Industry and Regulator Interactions

Effective interactions among operators and between operators and the regulator are essential to the successful development of resources in an economic and socially responsible manner. This section highlights the various interfaces when dealing with anomalous induced seismicity due to hydraulic fracturing.

4.1 Industry/Regulator Interface

The regulator's role includes ensuring industry compliance with provincial legislation to protect the public interest.

The industry's goal is to manage and continue operations safely and effectively while reducing the risks associated with anomalous induced seismicity (CAPP Hydraulic Fracturing Operating Practices, 2012). Operators who are hydraulically fracturing should follow these guidelines, comply with regulations, and communicate clearly and directly with the regulator.

When interacting with the regulator, industry operators should:

- Be professional and objective
- Listen to requests and provide appropriate responses in a timely manner
- Respect public concerns about anomalous induced seismicity
- Provide accurate, clear and concise information
- Be clear on what is considered fact, being evaluated or investigated, and what is not known at that time
- When requested, provide the regulator with local surface array information, located event information and reports of felt seismic events to assist with anomalous induced seismicity event analysis
- Ensure permissions and confidentiality agreements exist to share information
- Incorporate lessons learned into future plans, which includes understanding how communication takes place

4.2 Industry/Industry Interface

Operators new to an area are encouraged to speak with other operators nearby who have experience with and knowledge of hydraulic fracturing and induced seismicity in the area. Operators are encouraged to share experiences and provide information about practices. CAPP's Induced Seismicity Steering Committee can also provide resources to assist with the planning and preparation phase.

Methods to build this working relationship could include:

- Sharing information to better understand the mechanisms of anomalous induced seismicity and mitigate risk
- Sharing information on the levels of ground motion experienced by nearby populations and any impacts on infrastructure
- Communicating new research findings and experiential learnings
- Communicating the uncertainty that exists in certain research areas (some relationships are not understood and explain that relevant research is underway)