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A Review of Exploration Tools and Techniques to Support the COSIA Land Challenge: Near Zero Footprint Seismic Exploration

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MAKING COMPLEX EASY

Executive Summary

Exploration for natural resources in the boreal forest is known to be a critical step in the discovery and delineation of future oil and gas reserves. This seismic acquisition has historically required a network of cut seismic lines to produce high quality subsurface images that can be used to guide business investments and decisions. Cut seismic lines have been critical for enabling efficient seismic programs across difficult terrain, providing a predictable template for estimating acquisition costs, and facilitating the movement of individuals safely and quickly in the event of an injury or medical emergency.

There is also growing awareness of the potential ecological impacts of cut seismic lines. Legacy seismic lines that have not returned to forest cover can double the movement efficiency of wolves, increasing the frequency of encounters with threatened woodland caribou. More recent low impact seismic lines, while much narrower than legacy seismic lines, may also fail to return to forest cover quickly. Low impact seismic lines also often occur at high densities, which may contribute to ecological concerns such as edge effects in boreal landscapes.

This report focuses on uniting the ecological and geophysical aspects of seismic lines within a single project to identify opportunities to advance near zero footprint seismic exploration within Canada's oil sands region. Member companies of Canada's Oil Sands Innovation Alliance (COSIA) have identified a land performance goal of increasing land-use efficiency and reducing the operating footprint intensity of in situ operations. To address the ecological impacts of seismic development, COSIA and its member companies have established a land challenge to achieve near zero footprint seismic operations. The specified goal of the land challenge is:

> *To investigate alternative exploration techniques that would help lead us towards zero land disturbance for in situ projects.*

This report is intended to take a creative, open-minded look at what options may be available to help oil sands operators shift towards near zero footprint seismic operations in the near future.

Approach

This report collates ideas and feedback related to the pursuit of near zero footprint seismic in four core ways: Interviews with progressive contractors and energy and petroleum company representatives, a global literature review of available and emerging technologies, a qualitative look at potential impacts of new technologies on cost, data quality, and health and safety metrics, and a workshop with environmental and geophysical staff at COSIA member companies.

Core findings

Through a comprehensive literature review five opportunities were identified for near zero footprint seismic:

1. **Modify and miniaturize existing methods:** Reducing the size of all types of equipment used for acquiring seismic data, including vibratory or explosive sources, receivers, and the practices used to deploy them. Pilot projects are promising.

2. **Leave the ground entirely by going airborne:** Deploying and retrieving all equipment from the air. Pilot projects currently exist for receiver deployment.
3. **Leave the ground entirely by going underground:** Deploying all equipment in existing wells (confining surface work to the well site itself). Pilot projects are showing promise in the limited case of 4D seismic monitoring at existing facilities.
4. **Use alternative seismic sampling theory:** Changing how the seismic waveform is measured by using emerging technologies (e.g., compressive sensing and gradient geophones). This strategy may offer incremental impact reduction by relaxing source and receiver density requirements.
5. **Accept a different definition of seismic data:** Recasting the definition of seismic data itself by using emerging technologies like Full Waveform Inversion. This strategy may offer incremental impact reduction by relaxing source and receiver density requirements.

Based on the experience of the authors, and on discussions with COSIA member company staff (including environmental staff and geoscientists), a “modify and miniaturize” approach is believed to have the most potential for significant changes to seismic footprint. Such an approach would see incrementally smaller cableless receivers being used in exploration programs, and more creativity with respect to seismic energy sources. Current seismic energy sources include explosive charges, vibroseis units, and an array of less powerful sources that are not as commonly used, such as accelerated weight drop devices and small firearm sources. Creativity in the area of energy source development could involve miniaturizing energy sources and applying smaller sources at a higher density, exploring the use of robotics, or exploring opportunities for aerial source deployment.

During discussions at the workshop associated with this project, COSIA member company staff noted there are four core drivers of current seismic approaches which need to be considered with respect to future innovations: safety for workers, cost efficiency and predictability, data quality, and the need to accurately model cap rock integrity to achieve regulatory requirements. Participants also identified opportunities associated with the pursuit of near zero footprint seismic, including opportunities to solve technically complex challenges and business opportunities associated with reducing exploration footprints. However, participants also acknowledged key constraints to innovation, including investment funding. The pursuit of near zero footprint seismic techniques is likely to require dedicated research and development funding to see progress and new insights.

It is also important to acknowledge there are many current concerns related to scalability, safety and potential cost implications of near zero footprint programs. These criteria must be evaluated when considering future technologies and innovations. However, on-the-ground pilots are advancing many of these ideas. For example, the Multiphysics Exploration Technology Integrated System (METIS) program, lead by Total, has advanced to a second pilot project for aerial and autonomous seismic programs. While the program costs remain high, the potential of the technology is proving increasingly valuable. BP has also recently announced the successful use of full waveform inversion in delineating a major oil deposit which had previously been overlooked in the Gulf of Mexico. This review suggests there are opportunities for COSIA member companies to advance technologies and techniques that could move seismic exploration programs towards near zero footprint practices.

Acknowledgements

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We would also like to thank the seven anonymous individuals who agreed to participate in the interviews for this project. Their insights and perspectives on the seismic industry were a valuable contribution to this report.

This project was a collaborative effort between Fuse Consulting Ltd. and RPS Energy Canada Ltd. (RPS). Additional contributions were made by Chris Rudling and Chris Helly (RPS Group) who assisted with the global literature review for this project. Kate Broadley (Fuse Consulting) developed the illustrations in this report.

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1. Introduction and Rationale

Exploration is a critical step in the discovery and delineation of oil and gas reserves within resource-rich areas of western Canada. In the oil sands region of Alberta, exploration activities are generally completed by cutting seismic lines and developing exploration pads to collect seismic data and core hole samples, respectively. Low impact seismic lines consisting of a maximum 3.75 m wide source line and a minimum 1.75 m wide receiver line have been used since the 1990s in Alberta. These lines have typically been cleared using mulching equipment (Figure 1).

Figure 1. *An example of a mulcher used to clear recent seismic lines in the boreal forest.*

A core function of cleared seismic lines is to provide both an efficient and safe mechanism for collecting high quality seismic information. High densities of seismic lines permit efficient travel and predictable costs for seismic programs. Likewise, cleared lines provide important safety mechanisms – allowing control of ambient hazards and quick egress in the event of injury to personnel. Finally, current seismic practices have also resulted in a high degree of technical accuracy in seismic data, enabling both initial delineation of oil and gas resources (i.e., 3D seismic), accurate estimation of cap rock integrity to meet regulatory requirements, and to monitor changes in oil and gas deposits over time as oil is extracted (i.e., 4D seismic).

There is, however, growing concern about the potential ecological impacts of low impact seismic lines. Ecological implications related to the high density of low impact seismic lines have been documented, with particular emphasis on the amount of edge habitat created and changes to vegetation communities (Dabros et al., 2018) on cleared seismic lines (Figure 2). Researchers have also determined that recovery of trees and other vegetation on cleared low impact seismic lines is not guaranteed (Kansas et al., 2015), but rather is impacted by site conditions along cleared lines. The frequency of seismic acquisition (i.e., 4D seismic) is also projected to impact the rate of vegetation recovery along cleared seismic lines (Dabros et al., 2018). Concerns have also been identified with respect to potential methane emissions from seismic lines in the boreal forest driven by a reduction in peat height and an increase in water at the surface of peatlands (Strack et al., 2019).

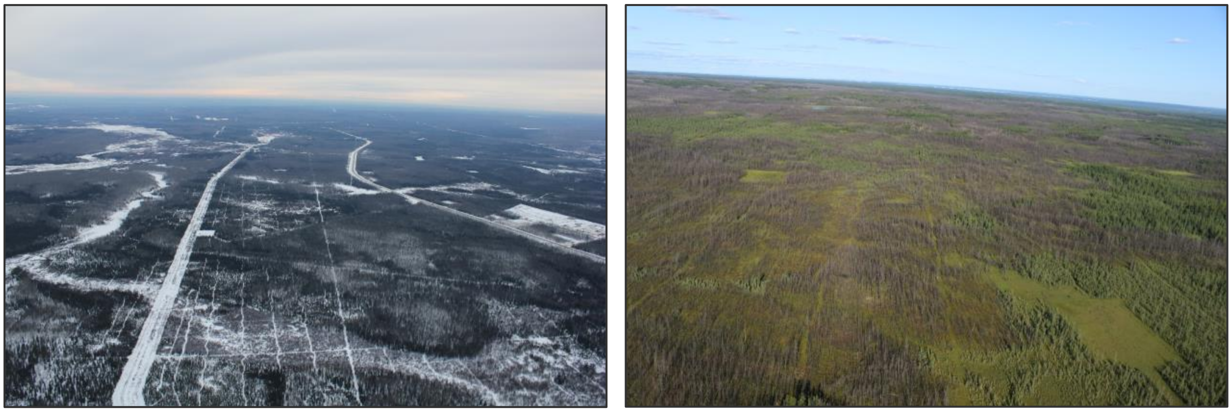

Figure 2. *Aerial imagery of low impact seismic lines in both winter (left) and summer (right) conditions.*

Historical seismic practices, created prior to the adoption of low impact seismic techniques, have also created a legacy of seismic lines in Alberta which have in many cases shown limited return to a forested condition. For example, historical seismic lines that are 30–40 years old, particularly those lines within lowland or dry upland ecosystems (van Rensen et al., 2015), have not returned to forest cover (Figure 3).

Figure 3. *An example of a legacy seismic line which has not returned to forest cover after 30–40 years. Photo courtesy of Woodlands North.*

While legacy seismic lines were reclaimed to regulations of the day, legacy seismic lines which have not recovered to a forested condition have been shown to present significant implications for important species like wolves and woodland caribou. Woodland caribou are a threatened species in Canada and legacy seismic lines have been shown to increase the risk of predation by wolves (Dickie, 2015). Legacy seismic lines increase wolf movement and speed across boreal landscapes and increase the frequency of encounters with, and predation of, woodland caribou (Latham et al., 2011). Reducing fragmentation from future and historical disturbances is therefore identified as a key theme in the federal recovery strategy for boreal populations of woodland caribou (Environment Canada, 2012).

It is important to acknowledge that legacy seismic lines (i.e., 8–10 m wide lines) do not reflect current seismic practices, but concerns related to woodland caribou have drawn attention to the high densities of low impact seismic lines within the boreal forest. Canada's Oil Sands Innovation Alliance (COSIA) and its member companies have, therefore, established a land challenge to achieve near zero footprint seismic operations. The specified goal of the land challenge is:

> *To investigate alternative exploration techniques that would help lead us towards zero land disturbance for in situ projects.*

To help reach the land challenge goal, COSIA member companies identified a need for an impartial review of current and future technologies that could assist in achieving the goal of near zero footprint seismic exploration. This report summarizes key findings from a global review of seismic exploration technologies that are either currently available or could become commercially available with additional research and investment. The specific goal of the project was to identify a series of potential tools and technologies that could lead towards zero footprint seismic operations, and complete an initial *first look* review, evaluating each tool\technology against criteria including: cost, safety, data quality and footprint reductions.

2. Summary of Current Baseline

In order to evaluate options for near zero footprint seismic exploration, it is important to have a clear understanding of current "best practices" as they relate to seismic exploration. This baseline of existing practices can then be used to effectively evaluate future technologies from the perspectives of cost, safety, data quality, and footprint. Current baselines for both low impact seismic line clearing practices and seismic data acquisition are documented in this section.

Low Impact Seismic Baseline Practices

Legacy/historical practices for seismic line development included clearing lines as wide as 6–8 m (Figure 4a). However, current practices throughout much of the oil sands region consist of clearing 2.75 m to 3.00 m wide source lines with 1.75 m wide receiver lines (i.e., low impact seismic). These lines are applied at various densities during exploration programs. In some cases, lines are applied every 120 m in a grid pattern (Figure 4b). In other cases, the density of lines may increase to 30 m spacing or less in a grid pattern (Figure 4c) depending on the oil sands target depth.

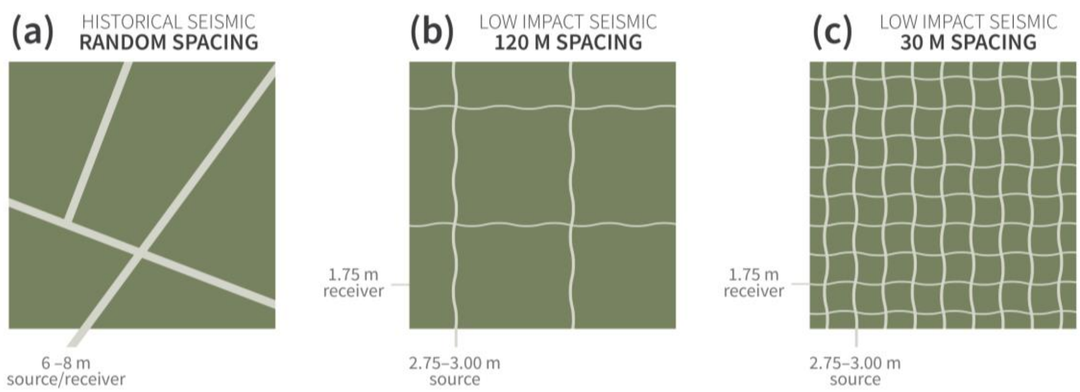

Figure 4. *The evolution of seismic lines in the boreal forest. a) Historical lines were cleared to up to 6–8 m in width. Recent practices include 2.75–3.00 m wide source lines with 1.75 m wide receiver lines, at spacing densities of b) 120 m to c) 30 m or less, depending on oil sands target depth.*

One of the unique challenges in the oil sands region is the relatively shallow depth of oil deposits, typically extending from 100 m down to 900 m below the ground surface. Seismic surveys must be able to accurately image shallow deposits; the depth of the deposit is a key driver of seismic line spacing. Shallower deposits require denser seismic line spacing to provide an accurate seismic image. Regulatory requirements also have a large influence on seismic program design. The Alberta Energy Regulator requires an accurate estimate of cap rock formation integrity (Alberta Energy Regulator, 2016), and seismic exploration provides this information in a manner that is acceptable to the regulator.

Once seismic lines have been cleared and data acquired, some lines may be resampled every year to provide "4D information" (the 4th dimension is elapsed time). Four-dimensional information helps companies monitor oil sands production and assess production efficiency over time as oil sands resources are extracted.

Low impact seismic operations are typically executed during frozen ground conditions to avoid damage to soils and in sensitive environments. Frozen conditions also generally provide better quality seismic data compared to unfrozen conditions.

Seismic Data Baseline

Current best practices for seismic data collection within the oil sands region of Alberta focus on collecting seismic data either through vibroseis or through blast programs. Vibroseis programs use specialized low footprint vibration source equipment to deliver seismic source energy along low impact seismic lines. Blast programs (also known as dynamite programs) use small shot hole drills to deliver seismic source energy in the form of small dynamite charges along low impact seismic lines. Both types of program require helicopter or ground based OHV support to deploy receivers and preparation of mulched lines to accommodate the sources and receivers required to conduct seismic surveys.

The above methods will typically deploy receivers and energy sources in a grid pattern, with source and receiver points laid out orthogonally along lines spaced as noted in Figures 4b and 4c. Sources, typically either dynamite charges or vibroseis units, are usually placed along the line at uniform intervals (e.g., every 20 m for in situ oil projects). Receivers are likewise placed along lines at uniform intervals (e.g., every 10 m for in situ oil projects).

Most seismic data are currently analyzed using an active source seismic reflection approach. This technique records a single simple reflection of sound energy off the below-ground geological formations. The output is a seismic image that guides interpretation of potential oil deposits below the surface.

3. Project Methodology

This project consisted of four phases:

- Interviews with a total of seven individuals with experience and expertise in seismic exploration.
- A global literature review focused on identifying both near-term and more theoretical ideas and opportunities to achieve the goal of near zero footprint seismic exploration.
- A “first look” at the potential health and safety, data quality, and cost implications of the range of potential technologies.
- A workshop with COSIA member company staff, including environmental and geophysical staff, to discuss the pursuit of near zero footprint seismic exploration and discuss near-term and future opportunities.

The methods and results from each phase of the project are detailed in the relevant sections of this report.

Interviews with Seismic Exploration Professionals

To complete the interview phase of this project, an initial list of interview candidates was proposed to COSIA. The list was based on experience, qualification and public reputation for relatively progressive and creative contributions to the field of seismic exploration. The list was then further refined with input from representatives of COSIA member companies. Twelve requests for interviews were made; seven individuals responded and were interviewed, two did not respond, and three declined.

The seven interviewees represented a broad diversity of organizations and had a combined 200 years of experience in seismic exploration and acquisition:

- Energy and Petroleum Companies (3)
- Seismic Contractors (2)
- Seismic Operations Management (2)

Some interviewees had experience in two or more of these categories over the course of their careers.

Each interview comprised eight questions and was designed to last 30 minutes (Appendix 1). In practice the initial two questions provided a framework for discussions that lasted up to 90 minutes.

Global Literature Review

To complete the literature review, RPS Group staff conducted internet searches for articles, peer-reviewed papers, and conference abstracts. As a global consultancy, RPS Group has observed that different regions (e.g., Europe, North America) have slightly different technical solutions to similar problems. For example, many geophysicists will recognize that seismic inversion is practiced slightly differently in Canada compared to the United Kingdom. Recognizing these differences, two small groups of reviewers were deployed, one located in Calgary, Alberta and the other in London, UK to ensure a broad review was undertaken. The London team focused on Europe and the Middle East, and the Calgary team focused on Canada, the United States and Asia.

The searches were conducted using several search phrases established to achieve the project objectives. Searches were conducted through the following organizations:

- Society of Exploration Geophysicists (SEG)
- Canadian Society of Exploration Geophysicists (CSEG)
- European Association of Geoscientists and Engineers (EAGE)
- One Petro
- American Association of Petroleum Geologists (AAPG)

Additional resources were also identified from the reference sections in documents, active links available to reviewers on organizational websites, or through the interview process completed as part of this project.

Approximately 240 abstracts were reviewed. From the 240 abstracts, 35 papers were selected for further consideration. Review and ranking of the 35 papers led to the selection of 15 priority papers and four United States patents as representative of the overall trends observed in the literature with respect to reducing seismic exploration footprints.

Search terms used to complete the global literature review of seismic exploration tools and techniques:

- Green seismic acquisition
- Zero impact seismic
- Zero footprint seismic
- Low impact seismic
- Reduced receiver spacing
- Onshore "seismic source" Environment
- "Environmental footprint"
- "METIS"
- "reduced footprint source"
- "zero footprint"
- Land "seismic source" Environment
- shaped charge seismic source
- PinPoint
- FWI
- Compressive sensing
- interferometry
- zero AND impact AND acquisition AND land AND Environmental
- Gradient geophones
- Gradient seismic
- Non Nyquist – Shannon sampling

Review of Implications of New Technologies

An initial review of the health and safety, cost and data quality implications were then completed for each potential technology identified through the literature review. The scope of this project did not enable an exhaustive quantitative review of implications on health and safety, cost and data quality. However, a qualitative review was completed by four RPS Group staff geophysicists, all of whom have considerable experience developing and delivering on-the-ground seismic exploration programs. These individuals indicated the expected positive effect of each new technology on health and safety, cost, and data implications using a rank from 1 to 10 (assuming all other ranking categories are “satisfied”). Each category’s average rank is presented in this report.

COSIA Member Company Workshop

The workshop approach was developed by Matthew Pyper (Fuse Consulting Ltd.) in consultation with a multi-organization planning committee. Workshop planning committee representatives included: Ted Johnson (Cenovus), Robert Albricht (ConocoPhillips), Jack O'Neill (COSIA), Natalie Shelby-James (COSIA), Clayton Dubyk (CNRL), Mark Nergaard (CNRL), Michelle Young (Imperial), Megan Boutin (Suncor), Christine Daly (Suncor), and Peter Vermeulen (Suncor).

The main goal of the workshop was to create an open space in which representatives of COSIA member companies could discuss challenges and opportunities associated with near zero footprint seismic exploration. The workshop was structured to encourage participants to share their views on the topic of near zero footprint seismic exploration, and to discuss creative ideas for how to realize this goal over time. A secondary goal of the workshop was to produce and prioritize a list of ideas to help achieve the goal of near zero footprint seismic exploration. This list of priorities could help guide future discussions about how COSIA and COSIA member companies should prioritize funds to address the COSIA Land Challenge.

It was particularly important to ensure geophysical and environmental staff were able to hear each other's perspectives and exchange ideas. The approach drew on Art of Hosting techniques and made use of the Chaordic Stepping Stones process for discussing workshop goals, desired outcomes, limiting beliefs, and required participants (Corrigan, 2016). These inputs were used to select a range of facilitation techniques that matched the desired goals and outcomes of the workshop.

Facilitation techniques were specifically selected to create energy and creativity among participants and to allow for the "outside of the box" style of thinking needed to address the ambitious COSIA Land Challenge. A key idea that was presented to participants by the facilitator throughout the workshop was that of "limiting beliefs": participants were encouraged to be aware of what beliefs may be limiting their ability to think creatively, and to set these aside during the workshop discussions.

The following components were used to structure the event:

1. Pre-workshop reading materials (draft literature review)
2. Keynote remarks
3. World Café discussions
4. 25/10 ranking exercise
5. Small group discussions
6. Final reflections

The morning sessions (keynote remarks and World Café) allowed participants to openly discuss and brainstorm ways to achieve near zero footprint seismic exploration. This exercise led directly into the 25/10 exercise, which was designed to help participants identify their preferred options for advancing the pursuit of near zero footprint seismic.

In the 25/10 exercise, each participant wrote their chosen idea on an index card. The group exchanged cards multiple times, ranking the idea on a scale of one to five each time – with a rank of one being "I don’t like this idea,” and a rank of five being “I love this idea.” After cards were exchanged and ranked five times, the total rankings were added up to get a cumulative score, with a potential maximum score of 25 (i.e., an idea that was ranked a “five” every time it was exchanged).

After the scoring was complete, the top-ranked ideas were identified and listed in order of ranking by the group. Based on this process, the four highest-ranked ideas were selected to continue to the next step of the workshop.

To further develop the top four ideas generated by the 25/10 exercise, participants each selected a topic to discuss in small groups. The goals of this portion of the workshop were for the groups to consider the feasibility of the idea, including possibilities to overcome its associated challenges, and suggest some potential next steps to help advance it. At the conclusion of this exercise, the note-taking template from each group was posted for the rest of the participants to review and ask questions. The ideas generated from the 25/10 exercise, and the results from these small group discussions, were used as key inputs into this report.

4. Current Realities and Perceptions of Near Zero Footprint Seismic

Current Realities

In the context of exploring near zero footprint seismic exploration, it is important to consider current realities driving the use of broadly accepted practices. These current realities can help to better understand accepted practices and provide a baseline for considering future opportunities to work towards near zero footprint seismic exploration. Current approaches to seismic exploration, largely utilizing low impact seismic lines, have revealed several important factors that bring stability to existing seismic exploration programs. These factors include:

Safety
In the event of an injury or illness, linear low impact seismic lines provide a clear, predictable path for operators to extract and transfer individuals and to get these individuals to support mechanisms and high-grade access routes or medical staging areas as quickly as possible. Companies work towards the shortest possible response time within Occupational Health and Safety regulatory requirements to ensure the safety of all field personnel.

Cost
Low impact seismic lines have been widely used in the oil sands area of Alberta for the past 20–30 years. The use of low impact seismic lines, combined with adoption of regular grid patterns spaced at 30–200 metre intervals (depending on oil sands target depth), has created an efficient and predictable system for seismic exploration contractors. This results in the ability to accurately predict costs for providing exploration services and has also helped drive efficiencies from a cost perspective. This cost efficiency has been critical for the oil sands industry, particularly during times of fiscal restraint.

Imaging
Oil sands reservoirs are characterized by being much closer to the surface than most conventional oil and gas deposits. The shallow nature of the oil sands reservoirs requires tightly spaced lines to create the subsurface image required to create an accurate picture of the underlying deposits. In addition, having high quality data can facilitate more accurate delineation of target zones for wells, and can help reduce future development footprints by accurately delineating resource deposits.

Cap Rock Integrity
Under direction from the Alberta Energy Regulator (Alberta Energy Regulator, 2016), companies are required to demonstrate that cap rock integrity requirements can be met within areas proposed for in-situ oil sands development. Companies have acknowledged the density of seismic programs is driven by both regulatory requirements to model cap rock integrity and company requirements to accurately model resource deposits. It is, therefore, important to note that current regulations requiring modelling of cap rock integrity may hinder any future requirements to reduce seismic densities and footprints.

Reclamation and Restoration

Current guidelines in the province of Alberta require all refuse and debris to be cleared from low-impact seismic programs. Watercourse crossings must also be removed and evidence of the absence of erosion must be provided. There are currently no specified criteria for the required rate of recovery or vegetation species that must be present following low-impact seismic development, except for exploration pads. Legacy seismic lines have received more focus for restoration as they are known to facilitate movement of wolves within woodland caribou habitat. Numerous voluntary company programs are in progress to restore these legacy seismic lines within woodland caribou ranges.

The current realities provide a baseline for evaluating potential future innovations. Approaches that move towards near zero footprint techniques must have mechanisms to move injured people safely and quickly and must provide reliable information for cost, data quality and cap rock integrity.

Perceptions of Near Zero Footprint Seismic

The Potential of Near Zero Footprint Seismic (Interview Results)

Interviews with seismic exploration experts outside of COSIA member companies provided perspectives that were not captured during the workshop. The interviews with these individuals provided an additional opportunity to have open conversations about challenges and opportunities related to exploration tools and techniques available to achieve near zero footprint seismic exploration.

There were five consistent trends that emerged from the interviews with seismic exploration professionals outside of COSIA member companies:

- Every interviewee indicated zero footprint was technically and practically possible, either now or in the future.
- Every interviewee indicated data quality should not be compromised by near zero footprint seismic with the correct investments and development of approaches.
- Every interviewee indicated that if a shift were to happen to near zero footprint seismic, health and safety issues would not be a significant barrier to implementation.
- Every interviewee indicated that a primary obstacle to zero footprint seismic was “investment” – money and engagement. They also acknowledged this is a significant obstacle considering the current pressures within the industry, in both energy and petroleum and supply companies, for driving down costs and increasing competitiveness.
- With one exception, every interviewee indicated that zero footprint seismic acquisition will cost more than low impact seismic.

The almost uniform response by interviewees that near zero footprint seismic is attainable requires additional explanation. Interviewees indicated that with sufficient funding and time, an exclusively hand-cut seismic exploration program could be planned and executed. Interviewees also acknowledged obstacles, including cost, health and safety changes and scalability concerns.

Interviewees also noted that from a data quality and a health and safety perspective, there were no obvious barriers to implementation based on their professional experiences. Interviewees acknowledged, however, that they had not conducted thorough studies to evaluate the potential impacts of near zero footprint seismic exploration programs on data quality and health and safety programs (Table 1).

Table 1. *Summary of interview results. Interviewees have been anonymized to protect their identities.*

Interview	Is Zero Footprint Possible?	How Close to Zero Footprint Are We?*	Obstacles (Selected)	Data Quality Effect	Health and Safety Implications
1	Yes	100%	Research and development investment by seismic companies and oil and gas companies. Pilot studies and research and development need more investment. Lost knowledge through individuals retiring.	Not anticipated – confirmation through study required	Not anticipated – confirmation through study required
2	Yes	100%	Seismic acquisition pricing, profit margins and lack of contractor ability/client willingness to invest in "new". Lost knowledge related to low density, man portable sources.	Not anticipated – confirmation through study required	Not anticipated – confirmation through study required
3	Yes	100%	Preplanning effort. Lack of "organic design" (i.e., design that includes but is not limited to fold, trace density and speed). Funding and awareness to undertake organic design efforts.	Not anticipated – confirmation through study required	Not anticipated – confirmation through study required
4	Yes	90% (100% within 5–10 years)	Inertia and comfort with the familiarity and predictability of current practices. This drives how seismic is funded. Zero footprint operations require more decisions and responsibility from a seismic crew and this means more training and higher cost.	Not anticipated – confirmation through study required	Not anticipated – confirmation through study required

Interview	Is Zero Footprint Possible?	How Close to Zero Footprint Are We?*	Obstacles (Selected)	Data Quality Effect	Health and Safety Implications
5	Yes	100%	Lost knowledge. Both in line preparation practice and low-density sources. Training costs.	Not anticipated – confirmation through study required	Not anticipated – confirmation through study required
6	Yes	100%	Investment and experimental engagement by both client and contractor. Need to know we are in this together! But current cost constraints are a real impediment to early adoption and experimentation.	Not anticipated – confirmation through study required	Not anticipated – confirmation through study required
7	Yes	100%	Successful pilot projects need to be scaled to commercial levels. Innovation momentum must be maintained. Communicating success builds and maintains momentum.	Not anticipated – confirmation through study required	None that cannot be successfully mitigated.

*Percent values indicate the degree to which zero footprint is thought to be possible given current technology. A value of 100% indicates that zero footprint seismic is theoretically possible today.

Throughout the interviews, much of the discussion focussed on modifying current practices. Another important observation from the interviews was that moving to near zero footprint seismic requires increasing levels of engagement between contractors and companies. Interviewees noted that near zero footprint seismic will require more pre-planning, a more highly trained workforce, and a collaborative client/contractor approach aimed at achieving broad goals (e.g., related to impact, health and safety, data quality, social narrative, etc.). One of the implications is that near zero footprint seismic data will come at a higher initial cost to implement relative to low impact seismic data. One interviewee estimated an increase of 35% to 50% above current costs. Another interviewee noted that it currently costs about $3,500 for basic training for each crew member annually, and that a more skilled workforce and higher training costs would be required to deliver near zero footprint seismic programs.

An additional observation was that a move to near zero footprint seismic could expand the seismic season because it would use smaller and lighter equipment. Manually carrying equipment, while labour-intensive, may not require frozen conditions to facilitate access. An expanded seismic season may represent an opportunity to revisit seismic program economics and may provide savings through increased flexibility with respect to acquisition timing. For example, data required for a fourth quarter decision could be acquired in the third quarter rather than in the first quarter. All-season seismic acquisition, if technically viable, may have a positive impact on project cash flow and may positively affect contractor cash flow.

Interviewees also focussed on the realities of current economics within the oil and gas industry in Canada. Several interviewees noted that reductions in the scale and frequency of seismic exploration, and funds available for seismic data collection, have resulted in a reduced number of seismic contractors in Canada. In the past decade, there has been a reduction from roughly ten contractors to three. One interviewee also noted that commercial bank lending has not been available to seismic acquisition companies in Canada for several years – at a time when loans are inexpensive for most enterprises, they are expensive for seismic companies due to industry-specific risks. Interviewees, including those with current or recent experience at energy and petroleum companies, noted that most contractors are hesitant to include more innovative approaches that may carry higher costs due to concerns that their bids may be viewed as uncompetitive.

Several interviewees expressed that the technology and operational practices required to achieve zero or near zero footprint have been known for decades. Examples provided include heli-portable shot hole drills that, combined with hand carried receivers, could achieve very close to zero footprint seismic. Interviewees also indicated that a limited supply of very small but otherwise conventional shot hole drills capable of operating on 1.75 m lines are currently available.

The interviewees were clearly passionate about the topic of near zero footprint seismic exploration.

COSIA Member Responses and Perceptions (Workshop)

The workshop with COSIA member companies allowed environmental and geophysical representatives to share their perspectives on the challenges and opportunities associated with the pursuit of near zero footprint seismic exploration. This was a critical step for understanding the experiences and perspectives of COSIA member companies, and for helping to ground the optimism of future technologies with an open discussion of operational realities and constraints.

Four themes emerged from small group discussions about challenges: safety requirements and cost implications, data quality, communications and perceptions, and collaboration within and among companies and with other stakeholders (e.g., other industries, government).

Participants also indicated there are opportunities for “wins” with respect to many different aspects of near zero footprint seismic exploration. Participant reflections and perspectives on opportunities were grouped into three themes: business opportunities, professional opportunities, and personal opportunities.

The main observations from the workshop were that both environmental and geophysical staff feel motivated about the challenge of achieving near zero footprint seismic. However, they also acknowledged that it is critical to manage expectations and realities such as cost, scalability and safety, and it will take time to address these concerns. Participants emphasized that to manage risks and maintain competitiveness in the industry, a wide range of options must be permitted for achieving near zero footprint seismic. Being forced to use a single technology, or single vendor, would be potentially detrimental to the competitiveness and innovation within the seismic exploration industry.

Participants also discussed a range of potential opportunities for achieving near zero footprint seismic goals, and these opportunities are discussed in the next section of the report.

5. Opportunities for Achieving Near Zero Footprint Seismic

Two approaches were used to identify near-term and longer-term opportunities, as well as practical and theoretical opportunities for achieving near zero footprint seismic. First, the authors reviewed the academic literature to identify potential near-term and future opportunities available to COSIA member companies. Second, environmental and geophysical staff from COSIA member companies were asked to brainstorm their best ideas for achieving near zero footprint seismic and the top ideas that emerged underwent more focused discussion at the workshop associated with this project.

Results from a Global Literature Review

A key aspect of this project was to expand the search for seismic exploration technologies to a global scale. This was addressed through a review of peer-reviewed publications and conference proceedings related to near zero footprint seismic exploration. Recent press releases were also scanned to highlight emerging technologies from corporate research and development programs. The literature review included a broad search of forward-looking and currently available seismic technologies, including both field-based approaches to capturing data (e.g., geophones, seismic wave creation) and emerging tools to process and obtain more information from seismic wave data.

Core Findings

Five broad strategies demonstrated strong potential to help realize the goal of near zero footprint seismic exploration either now or in the future (Table 2). Each is discussed in more detail in this section.

Table 2. *Summary of core results from a global review of near-term and longer-term technologies that could help achieve the goal of near zero footprint seismic exploration.*

Strategy	Approach
Modify and miniaturize existing methods	This approach would seek to decrease seismic exploration footprints by reducing the size of all types of equipment used for acquiring seismic data. This includes vibratory or explosive sources, receivers, and the practices used to deploy them.
Leave the ground entirely by going airborne	This conceptually simple but practically complex strategy would reduce seismic exploration footprints by going airborne. In these scenarios, seismic equipment would be deployed and retrieved from the air. In some cases, source charges may also be delivered from the air.
Go underground by using existing footprints and well bores	A complex but potentially effective alternative for collecting seismic data within developed areas would consist of underground deployment of seismic technologies within existing wells (confining surface work to the well site itself). Pilot projects are showing promise in the limited case of 4D seismic monitoring at existing facilities.
Use alternative seismic sampling theory	Changing how the seismic waveform is measured by using emerging technologies (e.g., compressive sensing and gradient geophones) may offer incremental impact reduction by relaxing source and receiver density requirements.
Accept a different definition of seismic data	Recasting the definition of seismic data itself by using emerging technologies like Full Waveform Inversion (FWI). These technologies may offer incremental impact reduction by relaxing source and receiver density requirements.

1. Modify and Miniaturize

Of the 35 papers selected for further consideration in this report, 19 (54%) involved some variation of the Modify and Miniaturize strategy.

In general, a modify and miniaturize strategy is characterized by manipulation of two elements:

1. Source deployment
2. Receiver deployment

The papers reviewed generally indicated that receivers are easier than sources to miniaturize. Receiver systems that do not require cables are common, and there is a clear progression towards lighter, smaller housings and longer battery life for receiver units (Figure 5).

Figure 5. *The new Nimble Node is an example of continuing miniaturization of wireless receiver technology. The device is light and compact, dramatically improving deployment, retrieval and transportation. As shown in Ourabah et al. (2019).*

As evidence of this progression, a paper was recently presented at the 2019 European Association of Geoscientists and Engineers Conference in London (June 3–6, 2019), entitled *A Comparative Field Trial of a New Nimble Node and Cabled System in a Desert Environment* (Ourabah et al., 2019). The authors demonstrated that data quality obtained from a very small node (150 grams) equipped with a Piezoelectric accelerometer is comparable to data obtained with traditional cabled receivers. In general, Canadian seismic acquisition has seen an early adoption of cableless receiver technology. One provision is that most cableless receivers record only compressional wave energy.

The miniaturization of source deployment is a more complicated undertaking than receiver miniaturization. Seismic source generation requires devices capable of providing sufficient acoustic energy into the ground. A clear implication, therefore, is that source devices will be larger than receivers. Within the literature, very small explosive sources have been developed and many of these small explosive sources use a firearm type geometry. In these technologies, the charge is typically a variant of a shotgun cartridge detonated in a chamber very near the ground surface that will either move a projectile rapidly into the ground (a form of accelerated weight "drop") or simply rely on the expanding gas of the detonation to impart energy into the ground (Miller et al., 1994). A recent entry in this field is the PinPoint source developed in Canada and patented in the USA (# US 10,247,837 B2) by Explor. A legacy example is commonly referred to as a "Betsy gun". Patents also exist for the use of small directional charges (like a perf gun charge) as reflection seismic energy sources (US 6,419,044; Schlumberger).

Very small vibratory sources also appear in the literature (Berron et al., 2014; Lopez et al., 2015). Most employ some variant of a piezoelectric vibrator driving a small reaction mass. At least three different US patents have been granted for devices using piezoelectric oscillation as a seismic reflection energy source: US 5,115,880; Standard Oil (expired), US 4,850,449 (also assigned to Standard Oil, but applied mainly to large mass sources), and US6,488,117 (Owen). In principle, any vibrating mass coupled to the ground can serve as an energy source – this is the idea behind the commonly used vibroseis source.

Piezoelectric materials, typically crystalline, accumulate and release electrical charge when deformed by mechanical stress. Conversely, applying electrical charge to piezoelectrical materials can induce deformation. Piezoelectric materials are in common industrial use: medical ultrasound machines use a piezoelectric transducer – a device that acts as both source and receiver. Piezoelectric materials can be contrived to either detect or generate vibration, making them potentially useful as both seismic sources and seismic receivers. Low power requirements make piezoelectricity an attractive, though experimental, technology for a miniaturize strategy. Interviewees also indicated that a combined receiver/small vibrator “node” was built and tested in the US several years ago (unpublished).

Due to the fact that source charges are required to deliver sufficient acoustic energy, miniaturization of seismic sources does have physical limitations: if the source has truly insufficient energy release, then recovering reflections in the presence of ambient noise will be problematic (i.e., receivers will have a difficult time assessing source versus ambient signals). However, some researchers (Meunier et al., 2001; Berron et al., 2014; Lopez et al., 2015; Caporal et al., 2017) have employed a promising “energy density strategy” involving low vibration source energy over a long period of time. This strategy trades off the conventional approach of high energy over a short period of time, for low energy over more time. These studies suggest that high quality seismic data can be achieved by releasing smaller source energy either over longer periods of time (vibratory sources) or more often (explosive or impact sources). By extending the vibration time (or increasing the number of small discrete “drops” or explosive “pops”), signal and noise deficiencies that would otherwise appear in the data with a low energy seismic source are overcome, and data quality outputs are comparable (Figure 6).

This example shows the potential of reconsidering conventional seismic acquisition approaches.

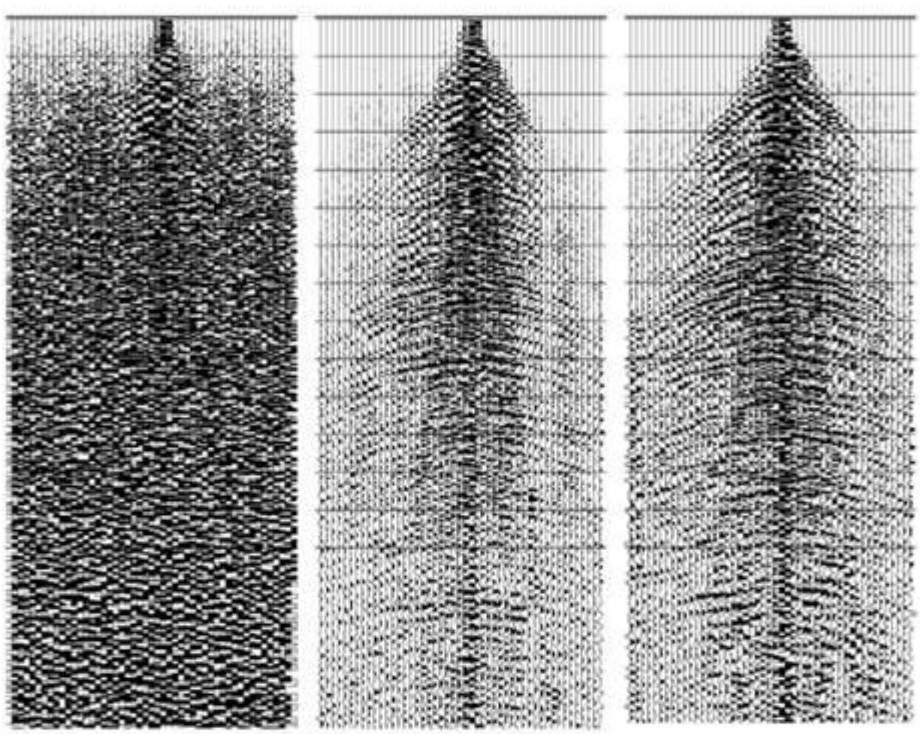

Figure 6. *Comparison of different sources over time. Left: a low intensity source with one sweep over 26 seconds. Center: the same low intensity source with 1280 sweeps over 33,280 seconds. Right: a hydraulic vibrator showing 1 sweep over 26 seconds. As shown in Meunier (2002), Figure 6.*

A final technique observed in the literature addressing source deployment revolves around the notion of eliminating the need for sources all together. The theory suggests that reliable seismic data could be obtained simply by using ambient noise that is generated at a location, such as vibrations from a nearby road. While this may seem an unlikely approach, it has been shown to be a viable strategy in academic studies. The technique is called seismic interferometry and is based on an assertion made by Dr. Jon Claerbout (1968).

Claerbout's statement is shown below as presented by and quoted directly from Curtis et al. (2006) who refer to it as Claerbout's "phenomenal conjecture".

> *That the cross correlation of noise traces recorded at two different receiver locations in three-dimensional, heterogeneous media gives the response that would be observed at one of the locations if there was a source at the other.*
>
> ***In other words, simply by listening to noise at two receivers, we can construct the signal that would have been observed if we had used a source at one of the receiver locations.***
>
> *This method to construct artificial seismic sources was demonstrated and proven years later (e.g., Rickett and Claerbout demonstrated its application to helioseismological data in 1999).*

A recent pilot test of this seismic interferometry approach was recently conducted at Schlumberger's Cambridge research facility. This test project used ambient noise to produce seismic reflectivity profiles (Figure 7). Ambient noise was primarily generated by traffic (public roadways adjacent to the survey location) (Edme and Halliday, 2016). The authors conclude that "comparison between the interferometry approach and an active source suggested that [interferometry] was able to recover shallow reflections visible in the active source data set." Note that, given seismic velocities similar to those typically encountered in the Mesozoic strata in the Western Canadian sedimentary basin, a time of 340 ms (the deepest black arrow in Figure 7) would be roughly equivalent to 340 meters total vertical depth (TVD).

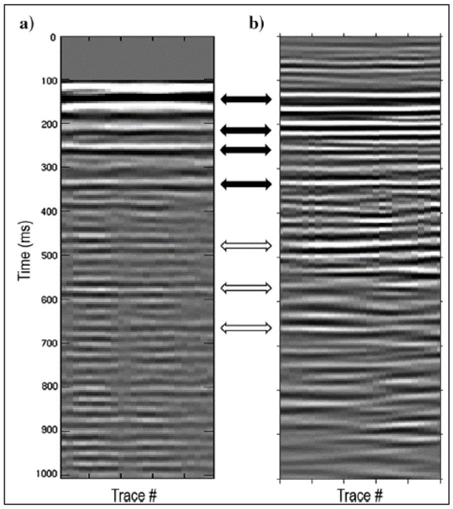

Figure 7. *An example of image capture using the seismic interferometry approach generated via ambient noise. The image on the left shows the interferometry (ambient noise) image, while the image on the right shows a traditional 'active source' seismic image. The authors annotate the image with black arrows indicating reflections that are obviously correlated, and white arrows for reflections that may be correlated but require additional analysis. As shown in Edme and Halliday (2016).*

Characteristic traits of the Modify and Miniaturize strategy are a higher density of small, cableless receivers and a higher density of lower strength explosive/impact sources, or to have lower strength vibratory sources deployed over a longer period of time. Both approaches show potential based on the published literature and sufficient evidence exists to warrant experimental trials of these techniques.

2. Go Airborne

Of the 35 papers selected for further consideration in this report, eight (~23%) involved some application of an airborne strategy for seismic exploration. The proportion is perhaps misleading as three papers referenced a single project and technology.

The basic strategy for going airborne, and avoiding source footprints, requires two constituent elements:

1. Source deployment
2. Receiver deployment

Much like for the Modify and Miniaturize strategy, and for the same reasons, receiver deployment is the easier of the two elements to realize.

One of the more advanced of the emerging approaches identified in the literature capitalizes on drone technology to deploy receivers. The most publicized project is the METIS project being delivered by TOTAL (Figure 8). This project, located in Papua New Guinea, seeks to use drones and airships to deploy receivers in sensitive and complex terrain. TOTAL has successfully piloted receiver deployment using drones paired with ancillary technology for health and safety purposes. The technology has also recently been announced for use in a second pilot project, this time in Abu Dhabi.

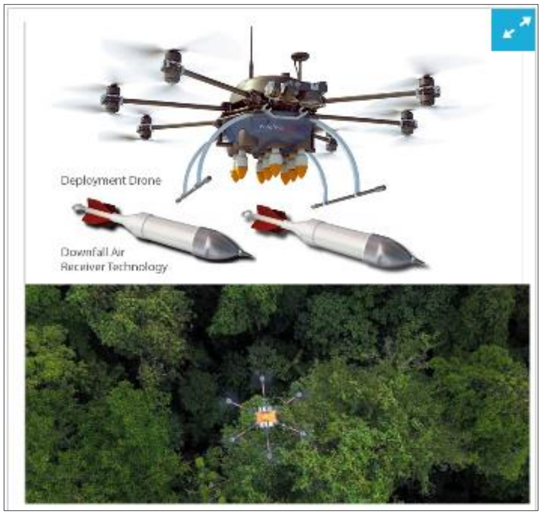

Figure 8. *Example of the drone and receiver technology currently being tested as part of the METIS project. Source: www.geoexpro.com. Disclosure: RPS designed the drones, supervised their construction, and piloted them during the METIS field trials.*

With respect to source deployment, TOTAL is developing airships to deploy conventional heli-portable seismic shot hole drills in remote locations (Figure 9). The impetus for this change is to reduce costs and ambient noise from helicopters by shifting to the use of airships for lifting and delivery of the equipment. Heli-portable drills (readily available in Canada, though at increased cost compared to conventional equipment) could be deployed in the boreal forest given existing technology, and this may be an option for achieving lower footprint source deployment. By using airships, companies would also be able to avoid noise disturbance concerns associated with helicopters.

Figure 9. *A conceptual airship being proposed for use on the TOTAL METIS project. Source: www.ep.total.com.*

Early reports of costs for the METIS technology are that it is far more expensive than traditional seismic approaches – pilot project production rates are typically very low. However, it is also being used in extremely challenging terrain and environmental conditions (hot and wet). While the environmental challenges in the boreal region of Canada are typically due to cold temperatures, the complexity of the terrain and need to address tree cover are similar to the current METIS trial. Health and safety issues have also been carefully planned and monitored throughout the METIS project. This has included the use of infrared technology on drones to facilitate equipment placement and receiver deployment.

Another example of the going airborne strategy for seismic source and receiver deployment was deployed by Apache Canada in 2002 as an experiment in Zama, AB. In this project, Apache Canada used short lengths of drill pipe dropped from helicopters to create the required source energy for the seismic survey (Figure 10) (Monk, 2002).

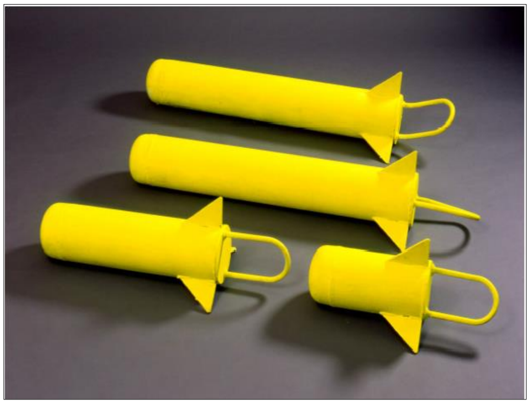

Figure 10. *Examples of drop sources used in a 'going airborne' strategy. As shown in Monk (2002).*

Despite some challenges, notably helicopter rotor noise and concerns associated with recovering the source materials, the Apache method is said to have been successfully adapted by another organization in 2004 for a project in Alaska. While still employing helicopters, the organization is said to have used a frozen mixture of water and sterilized pea gravel in paper bags as a weight source. The organization did not publish the results; however, this test was identified through the interviews completed for this report. This trial may demonstrate that creative exploration of challenges and limitations in seismic programs can lead to new ideas that were previously not considered. Considerable work would be required to scale these ideas to an operational level, but these ideas can nonetheless help support trials and experimentation with new source deployment strategies in the boreal region of Canada.

The nature of the material being dropped is not important from a seismic point of view, which simply requires it be as heavy as possible and dropped from a high enough altitude to a) reach terminal velocity and b) reduce noise derived from the aircraft to levels below that of the signal the receivers are trying to recover. From an environmental standpoint, the material must be locally benign with consideration given to aspects such as the degree of biodegradation and absence of non-native seed material. Additional operational considerations, such as health and safety requirements and cost control, could be further explored through experimental trials.

It is clear from the literature review that going airborne to deploy seismic surveys will require considerable creativity. However, airborne seismic techniques warrant more exploration and consideration by COSIA member companies and the seismic contractor community.

3. Go Underground

Of the 35 papers identified for further consideration in this report, two (~6%) involved the use of a strategy to Go Underground with seismic surveys. The low number is likely because going underground requires existing disturbance, such as well pads or other infrastructure, to deliver both receivers and sources to an underground position. This strategy, therefore, may have potential for currently developed areas and for capturing 4D seismic data. However, it is not seen as a productive or viable strategy for remote exploration or reconnaissance seismic.

Despite the need to be deployed within developed areas, strategies that go underground have matured beyond an experimental/pilot stage (Figure 11). Notable from a Canadian oil sands perspective is the SeisMovie work (Lopez et al., 2015) that undertakes rapid cycle time lapse seismic imaging at a pad scale. The technique uses downhole fibre optic-based distributed acoustic sensing (DAS) technology and very small downhole vibratory sources. Very small sources need to be deployed in a dense fashion relatively near the receivers: receivers need to be deployed within a few hundred meters of the sources at most.

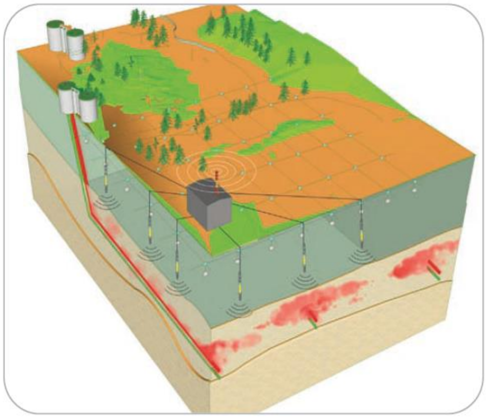

Figure 11. *A schematic of a SeisMovie installation for a SAGD heavy oil operation. Source: www.cgg.com.*

Depending on the well location relative to the target formation and the source locations, the geometry of sources and receivers would result in either a conventional seismic image (though constructed from unconventional seismic ray paths), or an estimate of the seismic wave velocity regime (model) of the subsurface. The two results theoretically contain highly similar information. In practice, energy and petroleum companies have used seismic images, though the industry is experimenting with velocity models as a type of seismic data. For example, the result of full wave inversion (FWI) is a seismic velocity model.

The clear limitation of an underground deployment strategy at present is scale. The project outlined by Lopez et al. (2015) is limited to an area of a well pad or a group of well pads (i.e., in the order of tens of hectares). The requirement to have existing wells in which to deploy both sources and receivers presents a clear limitation on both the physical dimensions and scale of seismic acquired with this general strategy, and on the application of the strategy for exploration using DAS away from existing infrastructure.

Fibre optic cables, which can be used as acoustic receivers using DAS technology, can be attached to well casing or other subsurface well elements. This system offers the potential to space sensors similarly to closely spaced "conventional" acoustic sensors. In other words, DAS allows for very high receiver densities which could reduce the required source density or enable the use of lower energy sources.

From the review of the literature, this technology may provide an interesting alternative to current 4D seismic programs which require re-entry onto existing low impact seismic lines. From an ecological perspective, this re-entry stagnates the recovery of low impact lines. By going underground within existing infrastructure, there may be opportunities to collect long-term seismic data while using existing footprints on the landscape. This approach could permit acquisition of 4D data of active operations in a less environmentally impactful way compared to continual clearing and re-use of low impact seismic lines.

4. Redefine Sampling Requirements

Another technology identified through the literature review was the concept of Redefining Sampling Requirements. The approach focuses on reducing impact by using fewer receivers that are more strategically placed compared to current practices.

To explore this option further, it's helpful to review some of the basic mathematical approaches behind seismic data processing. Conventional seismic data measurement (and conventional digital music and communications) are based on the principles of the Nyquist-Shannon Sampling Theorem. The Theorem is critical for any process that discreetly digitizes a continuous signal – such as turning a song into a digital music file, or a seismic wave into a SEGY file (i.e., a seismic version of an mp3). Importantly, Nyquist-Shannon sampling measures only the amplitude of the signal and it must do so at uniform intervals. In seismic, Nyquist-Shannon sampling principles apply to spatial sampling as well as time sampling. This means that the density of receivers on the ground has been traditionally defined by Nyquist-Shannon sampling requirements. However, if the amplitude and the gradient of the signal are measured then the requirement to sample uniformly no longer applies (Figure 12). In seismic terms, if the placement of non-uniform receivers is designed such that the gradient of the returning signal is measured adequately, it is possible to reduce the number of receivers deployed for a given survey.

Given these considerations, there are alternatives to the widely used Nyquist-Shannon technique. The application of spatial non-Nyquist sampling for seismic data recording is called compressive sensing. Compressive sensing offers the possibility of obtaining equal quality data at smaller sample rates or, the mathematical equivalent, better data at the same sample rate (compared to a notional baseline survey). According to Allegar et al. (2017), this approach can actually improve the seismic image compared to Nyquist sampling:

> *Historically surveys have been designed to acquire data with uniform temporal and spatial sampling that honored Nyquist requirements. Compressive sensing (CS) challenges this paradigm and asserts that structured signals can be recovered from sub-Nyquist sampled data by capturing the essence of this structure via random sampling. . . Challenging the rules that require seismic sampling to honor Nyquist criteria provides opportunities to improve not only acquisition efficiencies but also the seismic image itself (Allegar et.al., 2017).*

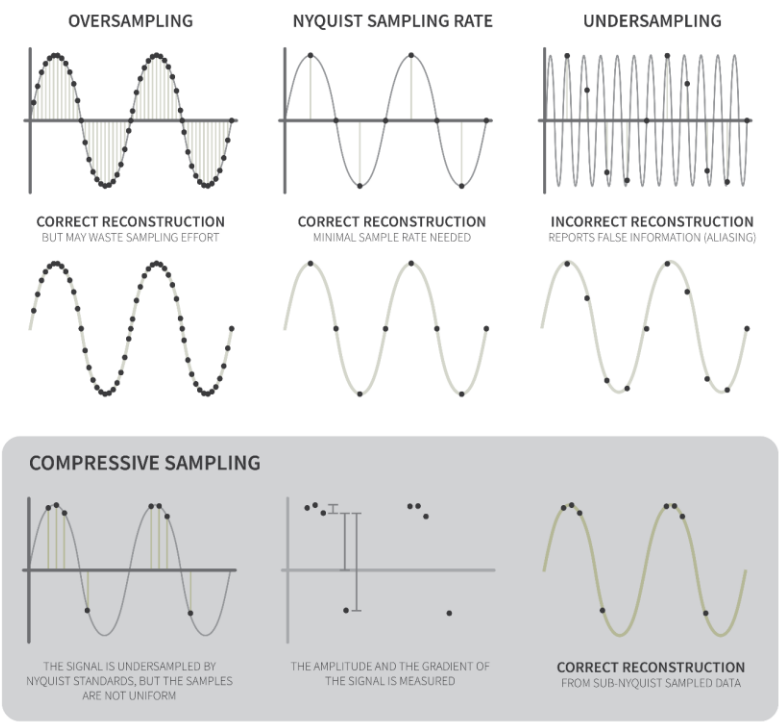

Figure 12. *Example of sampling approaches required for Nyquist sampling and compressive sampling.*

Compressive sensing is at a commercial stage of development and was the subject of a full Special Section in the SEG's publication The Leading Edge in 2016 (Allegar et al., 2017). It is viewed here as a promising technology in terms of reducing seismic impact in the boreal region of Canada. However, its direct impact on footprint is likely only incremental. Compressive sensing cannot eliminate either receiver or source placements, but it can reduce them. Non-uniform sampling may offer the ability to group receivers strategically in areas that are easier to access. Likewise, the approach could be used to avoid areas that are sensitive to even minor disturbances. In this case, compressive sensing could help capture seismic data in highly sensitive habitats throughout a seismic program.

Careful pre-planning and modeling of the expected seismic response would be required to take advantage of the impact-reducing aspects of compressive sensing while at the same time preserving data quality. Therefore, the method offers incremental improvement and would need to be paired with a Modify and Miniaturize strategy to realize its potential as a near zero footprint seismic approach. Nonetheless, it is a viable technology that could be utilized, in combination with other strategies, to reduce seismic data acquisition impact and maximize the data value for any given location.

5. Redefine "Data" – Full Waveform Inversion

Conventional reflection seismic data seeks to build a representation of the subsurface geology that is effectively a series of layers. The boundaries of these layers are defined by an acoustic (compressional) seismic pulse reflected by contrasts in the acoustic properties of different rock layers. To build a model based on these data, specialist seismic data processors examine the seismic shot records and will generally discard all data that does not behave like a reflection. Since the bulk of a given recording is not reflection energy, most of a seismic shot record is discarded. However, there are different techniques available which aim to use all the information recorded in a seismic shot record. By leveraging this additional data, these techniques offer some promise that fewer shot records will be required and a lower footprint could potentially be realized.

An alternative approach to building a model of the subsurface geology using seismic data has been under development for some time. The method is called full waveform inversion. This approach seeks to build a finely layered "velocity model" of the subsurface. In the case of full waveform inversion, "velocity" means the speed at which sound travels through a particular piece of rock. Different rock types have different velocities: for example, carbonates are typically "faster" than clastics.

Full waveform inversion looks at everything in the shot record, assuming that any energy recorded by the receiver (so long as it actually came from the source) can be used to "back calculate" the answer to the question: what rock types or substrates must be present to have produced the observed recording?

The image below shows an old 2D seismic shot record for simplicity (Figure 13). Reflections, refractions and direct arrivals are indicated. Traditional seismic processing would use the refraction events to work out near-surface velocities in a simple one- or two-layer model. It would seek to extract the reflection energy and would not use the rest of the data. The two yellow ovals show areas of coherent non-reflection energy (too flat or too steep to be reflections) that would be discarded for this type of imaging. In contrast, full waveform inversion methods would try to work out what velocity structure gave rise to the refraction events and all of the other identified features. It must be stated that the 2D profile, provided as an example of the type of signals present in shot records, does not include any far offset traces (seismic traces recorded by a receiver a long distance from the shot). Far offset traces are required for full waveform inversion imaging because some diagnostic waveforms appear only at far offsets (e.g., critical angle reflections). Old 2D data almost never includes truly far offset recording.

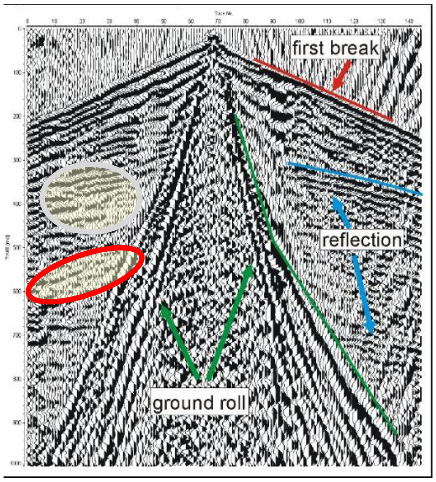

Figure 13. *An example of an old 2D seismic shot record showing some of the waveforms used for full waveform inversion processing. The shaded ovals outline body wave that would be used in full waveform inversion imaging but discarded in reflection imaging. Source: Aminzadeh and Dasgupta (2013).*

The challenges identified here fall within a technical class of problems called inversion problems. Inversion problems are underdefined: theoretically there are an infinite number of velocity models that could give rise to a single recorded shot record. The trick is to eliminate from consideration any improbable ones.

Full waveform inversion methods have very high computational demands. While the full waveform inversion method has been proposed for several decades, only recent advances in computer technology (including vast amounts of cloud storage) have enabled practical tests of the method. With these advances in technology, full waveform inversion is seeing increased attention in the literature. In fact, full waveform inversion was the topic of a recent Special Section of the SEG's publication of The Leading Edge (March 2019). Charles et al. (2019) published a paper in the January 2019 issue of The Leading Edge in which a promising example of full waveform inversion imaging in the Canadian in situ heavy oil fields was outlined. They included a full waveform inversion test as part of a project that featured high resolution 3D seismic and a 3D vertical seismic profile. The authors observed that full waveform inversion was theoretically capable of handling local subsurface conditions (i.e., subsurface velocity distributions) more effectively than traditional common image point reflection methods. They undertook a full waveform inversion test and concluded that "Full Waveform Inversion works reasonably well in the project area and adds value." They further state that the "3D Full Waveform Inversion test has shown promising results," though "more work is required." Full waveform inversion was also recently used by BP to discover a previously unidentified oil deposit within the Gulf of Mexico.

Full waveform inversion is at a commercial stage of development. Like compressive sensing, described above (4. Redefine Sampling Requirements), full waveform inversion is a promising technology in terms of reducing seismic impact in the Canadian boreal forest, but only in an incremental sense. Full waveform inversion cannot eliminate either receiver or source placement, but it can reduce the density of the required placements. Careful pre-planning and modeling of the expected seismic response would be required to take advantage of the impact-reducing aspects of full waveform inversion imaging while at the same time preserving data quality.

To be effective, full waveform inversion requires some measurements that involve longer source to receiver offsets than conventional seismic reflections. This requirement has the natural effect of slightly increasing footprint. Recovering a high-resolution velocity model using full waveform inversion methods will require some, at present undefined, minimum density of receivers. It may be possible to optimize footprint by using sparse full waveform inversion to recover the low frequency/low resolution part of the subsurface velocity model and combining that with reflection seismic obtained using very small sources (which may be deficient in low frequency content). Research and pilot studies are required.

Regardless of ultimate end user suitability, the full waveform inversion method offers, at best, incremental improvement and would require subsequent advances in the Modify and Miniaturize category to lead to zero footprint seismic. Nonetheless, full waveform inversion is a viable technology that could be exploited, in combination with other strategies, to reduce seismic data acquisition impact.

Results from the COSIA Exploration Tools Workshop

Participants at the COSIA Exploration Tools Workshop had the opportunity to brainstorm near-term, long-term and more theoretical ideas related to achieving near zero footprint seismic exploration. Participants were then asked to identify their one big idea and one next step. These ideas were then voted on and ranked by colleagues at the workshop. The result was a broad list of potential ideas for pursuing near zero footprint seismic exploration. The ranking assisted in identifying specific ideas that warranted further discussion by workshop participants and was not intended to imply endorsement or company support for the technology area.

Based on the voting from the 25/10 exercise, the following four ideas were selected for further discussion:

1. Using Robotics for Remote Operated Vehicles and Drones
2. Airborne Seismic
3. Go VERY Small – Small Receiver-nodes, Tiny Charges and Tiny Drills
4. Determine Feasibility of Other Methods

Participants selected the topic they were most interested in. To foster creativity and allow for free-flowing discussions, no specific structure was imposed on these conversations. However, participants were encouraged to work through a series of provided questions about the technology (Table 3).

Table 3. *Summary of key discussion points from small group discussions about the top four ideas which emerged from the 25/10 ranking exercise at the COSIA exploration tools workshop. NOTE: Discussion notes do not represent consensus views. Rather, the notes represent the results of open and creative discussion among COSIA member companies.*

What is the idea?	Why might it work?	Key Considerations
Using Robotics Autonomous vehicle that can navigate through forest, plant geophones, drill source holes, pick up receivers. Line viewer and data harvest with drones.	• Eliminates health and safety concerns • Eliminates or reduces need to cut trees • Militaries are developing, can leverage their learnings • 24/7 operations • Carry big loads	• Volume – amount of autonomous vehicles • Runtime/recharge • Survey? Will it eliminate • Will need to retrieve if it gets stuck • Can it start a fire? • Sensory disturbance to wildlife/stakeholders • Today feels like a very high cost • Emergent technology – will it go lower, and how fast?
Airborne Seismic Airship to drop sources and receivers with random survey approach.	• Easily <u>scalable</u> • More <u>productive</u> (air power + multiple seasons) • Same amount of data quality for less <u>data footprint</u> + <u>land footprint</u>; "perfect random survey" • More reliable than ground-based robots	• Accurate timing of source • Forest canopy preventing ground connection • Collection • Ground retrieval of nodes • Concerns about dropping on people/animals • Research and development initial investment • Node recovery
Going Very Small/Small Source with Hand cut Receiver Develop equipment to reduce line size - mulchers, drills, people transport. Smaller charge sizes, different receiver types, different configurations and alternative air support (drones) for crews.	• Making smaller lines is possible if regulatory drivers appear • Building smaller machinery is possible – development is cost constrained • Some options exist, but need to be tested, or they are not fully developed (i.e., data quality)	• Labour (cutters) – limited source • Difficult terrain • Difficult weather • Small lines/no lines – how do you evacuate effectively? (onerous) • Weather restrictions • Productivity and cost to do higher effort work (hand drill, hand cut, helicopters) • Limited incentive to make investment to add new equipment
Evaluating Other Methods Calibrate other techniques against known seismic data	• It has worked in mining and other sectors • Cheaper • Decreased health, safety and environment exposure • Widely scalable	• Use all 12 months • Any area, anytime • Safe to fly • Feb 15 caribou deadline not an issue • Fewer human exposure hours • Airplane risk • Could use drone • Cheap = office + airplane needed • No dynamite • Not wide expertise • Existing infrastructure could be a data contaminant.

6. Evaluation of Limitations and Benefits of Technologies Identified in the Literature Review

The next step in the project was to evaluate the limitations and benefits of the 15 priority papers and technologies identified in the literature review. The goal was to help COSIA member companies identify the most likely strategic avenue for successfully reducing seismic impact in the boreal forest. Each of the 15 priority papers was assigned ranks for six different categories on a scale from 1–10 (Table 4). Aggregate scoring, therefore, was on a 0 to 60 scale (Table 5).

To test the subjectivity of the evaluation process, a sub-test was completed where two teams reviewed the same paper and compared rankings. In the test case, the aggregate scoring proved to be identical, although there was some variation in how individual elements were scored. Regardless, the sub-test suggests that the criteria were robust and should not be heavily influenced by individual subjectivity.

Table 4. *Ranking criteria used to evaluate the 15 priority papers identified as part of the literature review for this project.*

Category	Scoring Criteria
Technical Viability	10 = commercially available at a post-pilot level of commerciality
Commercial Viability	10 = established commercial practice available with multiple bidders in a competitive bid process
Effect on Footprint/Impact	10 = a reasonable expectation of absolutely zero footprint operations
Data Quality	10 = an expectation of seismic data quality equal to high density modern vibroseis data
Safety	10 = a reasonable expectation of a reduction in reportable lost time incident rates compared to current practices (highly subjective)
Cost	10 = an expectation that zero footprint seismic data could be acquired at per unit are costs equal to current low impact seismic practice

Table 5. *Results of the ranking exercise for the 15 priority papers identified as part of the literature review for this project. Total scores are rounded up to the nearest whole number.*

Title	Authors	Year	Target Strategy	Technical Viability	Commercial Viability	Effect on Footprint	Data Quality	Safety	Cost	Total Score
A New Seismic Technology for High Density Acquisition With Near Zero Environmental Footprint	Chatenay & Thacker	2019	Modify and Miniaturize	9	8.5	8.5	7.5	6.5	7	**47**
Experiments in low impact seismic acquisition for oil shale	Costello et al.	2011	Modify and Miniaturize	8.5	7	8.5	4	6.5	7	**42**
Near Surface Imaging using ambient noise body waves	Edme & Halliday	2016	Modify and Miniaturize	6.5	5	7.5	4	8	7	**38**
Ambient seismic noise interferometry for exploration and surveillance	Verdel et al.	2009	Modify and Miniaturize	6.5	4	7.5	4	8	7	**37**
Simultaneous Mini Sources for Simultaneous Infill	Berron et al.	2014	Modify and Miniaturize	5	5	7	7	8	4	**36**
Broadband imaging via direct inversion of blended dispersed source array data	Caporal et al.	2017	Modify and Miniaturize	9	3	4	6	5	4.5	**34**
Reservoir monitoring using permanent sources and vertical receiver antennae	Meunier et al.	2001	Go Underground	6.3	7.3	7.3	5.3	8	7	**41**
Real-Time Seismic Surveillance of Thermal EOR at Peace River	Lopez et al.	2015	Go Underground	6	8	6	5.5	6	4.5	**36**
Canadian Seismic with a Thump	Monk	2002	Go Airborne	8	7	9.5	7.5	2.5	5	**40**
METIS, a disruptive R&D project to revolutionize land seismic acquisition	Lys, Elder & Archer	2018	Go Airborne	9	8	6	8	5	2	**38**
Measuring seismic signals with airborne stereo cameras	Rapstine & Sava	2017	Go Airborne	3	3	5	5	5	5	**27**
Special Section: Impact of compressive sensing on seismic data acquisition and processing	Allegar et al.	2017	Redefine Sampling	8	8.5	3	8.5	5	6.5	**40**
A five-component land seismic sensor for measuring lateral gradient of the wavefield	Muyzert et al.	2018	Redefine Sampling	4	3	5	8	8	3	**33**
Special Section: Full-waveform inversion (The Leading Edge: March 2019, Vol 38)	Zimmer	2019	Redefine Data	7	7	5	8	5	5	**37**
A high-density, high-resolution joint 3D VSP-3D surface seismic case study in the Canadian oil sands	Charles et al.	2019	Redefine Data	8	8	3	8	5	4	**36**

A final evaluation was completed for each of the target strategies based on life cycle costs and considerations, to reflect that different approaches may have disproportionate effects on construction and reclamation costs. Table 6 summarizes key life cycle considerations for each target strategy.

Table 6. *Review of the life cycle costs and considerations for each of the target strategies identified as part of the literature review for this project.*

Target Strategy	Title	Authors	Year	Life Cycle Costs and Considerations
Modify and Miniaturize	A New Seismic Technology for High Density Acquisition With Near Zero Environmental Footprint	Chatenay & Thacker	2019	- Requires more up-front costs due to development and testing of new technologies - Reduced or nonexistent reclamation liabilities over the long-term - Possible to increase randomization of both source and receiver points to potentially improve data quality - Requires more people on the ground due to reduced equipment usage, which creates potential for increased local employment - Requires a more technically savvy and better trained workforce than traditional seismic programs - Requires a pilot project for source energy deployment - By eliminating the use of heavy equipment, the seismic season can be extended (i.e., into non-winter months)
Modify and Miniaturize	Experiments in low impact seismic acquisition for oil shale	Costello et al.	2011	
Modify and Miniaturize	Ambient seismic noise interferometry for exploration and surveillance	Verdel et al.	2009	
Modify and Miniaturize	Near Surface Imaging using ambient noise body waves	Edme & Halliday	2016	
Modify and Miniaturize	Broadband imaging via direct inversion of blended dispersed source array data	Caporal et al.	2017	
Modify and Miniaturize	Simultaneous Mini Sources for Simultaneous Infill	Berron et al.	2014	
Go Airborne	Canadian Seismic with a Thump	Monk	2002	- Airborne sources are likely to be expensive - Footprint may exist from residual materials (e.g., frozen pea gravel) - Higher safety risks for both people and wildlife - Requires creative solutions for source deployment - Requires no line cutting, depending on solutions for receiver deployment
Go Airborne	METIS, a disruptive R&D project to revolutionize land seismic acquisition	Lys, Elder & Archer	2018	
Go Airborne	Measuring seismic signals with airborne stereo cameras	Rapstine & Sava	2017	
Go Underground	Reservoir monitoring using permanent sources and vertical receiver antennae	Meunier et al.	2001	- Requires existing infrastructure for deployment (i.e., well pads, exploration pads) - Suitable for 4D seismic programs – where the spatial geography of the infrastructure (i.e., well pads, explorations pads) is suitable - Could eliminate the need to re-occupy low impact seismic lines for 4D, enabling recovery of existing seismic lines - Cost implications currently uncertain - Requires operational alignment between seismic and well engineering departments
Go Underground	Real-Time Seismic Surveillance of Thermal EOR at Peace River	Lopez et al.	2015	

Target Strategy	Title	Authors	Year	Life Cycle Costs and Considerations
Redefine Sampling Requirements	Special Section: Impact of compressive sensing on seismic data acquisition and processing (The Leading Edge: Vol36)	Herrmann & Mosher	2017	- Strategy offers incremental improvement, unless paired with a modify and miniaturize strategy - Sensors and data processing are more experimental/expensive - Potential to make better use of seismic data
Redefine Sampling Requirements	A five-component land seismic sensor for measuring lateral gradient of the wavefield	Muyzert et al.	2018	
Redefine Data	A high-density, high-resolution joint 3D VSP-3D surface seismic case study in the Canadian oil sands	Charles et al.	2019	- Strategy offers incremental improvement, unless paired with a modify and miniaturize strategy - Data processing is more experimental/expensive - Potential to make better use of seismic data
Redefine Data	Special Section: Full-waveform inversion (The Leading Edge: March 2019, Vol38)	Zimmer	2019	

7. Discussion

Through this study it was determined there is widespread interest to explore the topic of near zero footprint seismic exploration in the seismic community. The workshop and the literature review also indicated the goal is technically feasible using technologies and techniques that are in development. While it is important to temper expectations about the commercial readiness of some of these techniques, the foundations for operational trials and exploratory research and development for new and emerging approaches to seismic exploration appear to exist. Challenges related to health and safety, cost, and scale of implementation remain; however, few of the participants in this project saw these challenges as barriers to continuing to innovate in the area of near zero footprint seismic exploration.

The results of the workshop and literature review outlined various potential innovations and there was a high degree of overlap among the opportunities identified (Table 7). A draft of the literature review was presented to COSIA member companies ahead of the workshop, which may have contributed to this alignment between opportunities identified in the workshop and the literature review.

Table 7. *Opportunities in near zero footprint seismic identified though a COSIA workshop and a global review of the literature and currently available technologies.*

Literature Review Opportunities	Workshop Opportunities
Modify and miniaturize existing methods	Using robotics for remote operated vehicles and drones
Leave the ground entirely by going airborne	Airborne seismic
Go underground by using existing footprints and well bores	Go very small. Small R-nodes, tiny charges and tiny drills
Use alternative seismic sampling theory	Determine feasibility of other methods
Accept a different definition of seismic data	

However, the themes which emerged are also in line with technologies and techniques under exploration by other organizations. For example, the METIS program has advanced to a second pilot project for aerial and autonomous seismic programs. BP has announced the successful use of full waveform inversion in delineating a major oil deposit which had previously been overlooked in the Gulf of Mexico. SeisMovie has been piloted within the oil sands region of Alberta to evaluate its ability to provide 4D seismic technologies. It is therefore clear there are opportunities for COSIA member companies to advance technologies and techniques that could move seismic exploration programs towards near zero footprint practices.

The technological and commercial readiness of different approaches identified in this report varies widely for each specific technology. While many technologies and techniques in this report are at a stage where pilot projects could be successfully delivered, others are more theoretical and will require a longer developmental runway to realize their potential. Timelines are, therefore, important to consider when evaluating potential opportunities to apply these technologies at a commercial scale.

It is helpful to group technologies and techniques in the context of near-term and longer-term opportunities. In the near term, there is significant potential for advancing Modify and Miniaturize approaches. Modify and Miniaturize approaches would provide the most direct benefit to reducing seismic exploration footprints and were identified in the literature review as a necessary component for technologies like full waveform inversion to realize near zero footprint exploration. A Modify and Miniaturize approach would use smaller scale cableless receivers in exploration programs and more strategic placement of source charges. This may involve miniaturizing source charges and applying smaller charges at a higher density.

The potential for creative discussions in the Modify and Miniaturize space is seen as significant. Basic modelling completed by the authors helps visualize the potential impacts on seismic footprint of reducing source and receiver widths or eliminating clearings entirely (Figure 14).

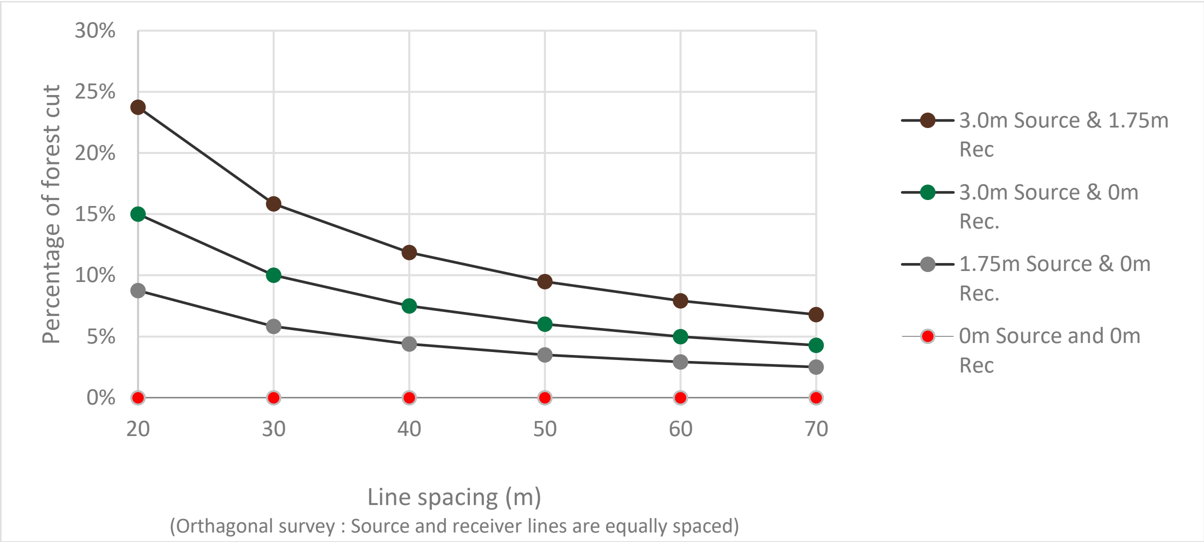

Figure 14. *Graphical representation of the amount of forest cut considering various line width and line density spacings.*

Similarly, by adopting techniques and technologies which could make use of more data from individual seismic programs, it is possible to envision scenarios where seismic densities could be modified. While considerable analyses would need to be done to advance these ideas to ensure sufficient data quality for delineating resource deposits and modelling of cap rock integrity to meet regulatory requirements, changing seismic densities could also incrementally assist in reducing the cumulative footprint of exploration programs (Figure 15).

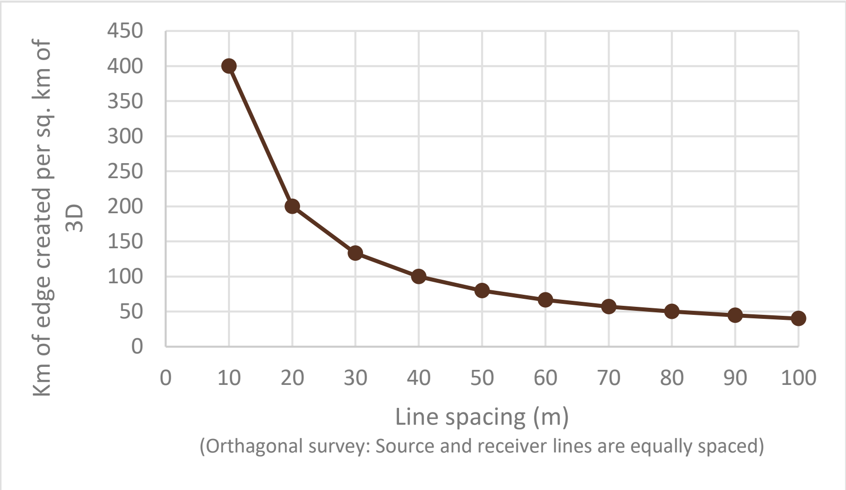

Figure 15. *Graphical representation of the amount of edge created for low impact 3D seismic programs with various line spacing.*

Another series of technologies which may be considered in the near term is the use of robotics for autonomous operations or the use of drones to deploy seismic programs aerially ("Go Airborne"). These technologies were both identified in the COSIA workshop and through the literature search. While none of these technologies could be commercially deployable tomorrow, they are at a technology readiness level in which pilot programs could be delivered within the oil sands region. In the case of aerially delivered programs such as METIS, these approaches capitalize on real time drone-carried infrared technology and visual inspections to provide a safe environment for dropping sources and receivers from the air. It is possible that similar approaches could be leveraged and applied in the boreal region of Canada. In fact, multiple studies were identified that tested creative approaches to dropping source charges from the air, including dropping modified drill pipe or large bags of sterilized frozen pea gravel as sources. While there are logistical challenges related to safety and waste clean-up, there is still significant room for creativity in this space. Initial observations from COSIA member companies at the workshop also suggested that the use of robotics, could be available for testing and experimentation in the oil sands region to place and retrieve receivers autonomously.

Longer-term or earlier stage technologies that could be explored by COSIA member companies include Going Underground by inserting seismic receivers and sources within exploration wells or other capped wells to capture seismic imagery. This approach is more applicable for 4D monitoring of developed areas than new exploration of remote areas. It has potential to reduce the ecological footprint of seismic programs by removing the need to continually clear seismic lines throughout a developed area.

Other options include using full waveform inversion to make more full use of seismic data, and testing ideas related to non-Nyquist sampling approaches that may permit changes in the density of seismic locations while still producing accurate mapping data ("Redefine Sampling Requirements"). A highlight from the interviews is that seismic data collection has become synonymous with creating linear lines. While these linear features are currently critical for delivering predictable costs for programs and ensuring safe operations, the advent of cableless receivers means there is no technical limitation to the pattern required for seismic data. More strategic placement of receivers and new methods that can utilize a higher proportion of the data collected through seismic exploration programs may be significant opportunities for COSIA member companies.

More theoretical or longer-term opportunities included the potential to utilize ambient noise as a seismic source, collecting seismic data over long periods of time to create robust seismic images ("Redefine 'Data'"). This technology has limitations in that it may only be applicable within areas with sufficient ambient noise sources.

Next Steps

There are many creative opportunities that could be developed and commercialised to realise the COSIA Land Environmental Priority Area goal of near zero footprint seismic exploration.

However, there are significant challenges that need to be considered in any discussions about future innovations for achieving near zero footprint seismic operations. For example, linear seismic lines used in current low impact seismic programs are currently critical to delivering safe and efficient seismic exploration programs. Linear low impact seismic lines provide a predictability to seismic acquisition programs that leads to more predictable and efficient cost structures for programs. Linear features also provide critical, and predictable, transportation corridors in the event of an injury or medical emergency. For new technologies to be delivered at the scale of current seismic acquisition programs, it will be important to identify ways in which programs can be delivered efficiently and in a way that achieves robust health and safety objectives for crews delivering programs.

A detailed analysis of health and safety risks, costs and scalability potential, was not included in this project. Therefore, new technology development will require a thorough evaluation of risks, effectiveness of mitigation measures and reward in order to support business leaders in making investment decisions. Establishing innovation funds, or budget line items, could also be a mechanism for facilitating continued innovation and analysis of the health and safety implications of technologies that are nearing market readiness. Future work could also be accelerated by looking at opportunities for data sharing across COSIA member companies to facilitate more rapid learning and evaluation of potential for implementation.

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Appendix 1: Interview Questions

1. In your opinion is zero impact seismic technically achievable?
2. What do you see as the primary obstacles?
3. If you think it is not achievable, how close to zero is possible?
4. What data quality, or data quality compromise, would you expect from a lower footprint program and what would be the key to maximizing quality?
5. What are the safety implications of very low, or zero impact seismic acquisition?
6. What technologies should be considered in decreasing boreal forest seismic footprint? (e.g., source, receiver, line clearing, UAVs, decomposable gear)?