Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Innovations in Seismic Exploration for Sustainable Geothermal Development

Andrea Crook[1]*, Mostafa Naghizadeh[2] and Richard Pearcy[3]
Optiseis Solutions Ltd.[1]*
Andrea.crook@optiseis.com

Keywords: Geophysics, Seismic Exploration, Sustainability, Geothermal

INTRODUCTION

Accurately imaging the subsurface with seismic, whether for traditional energy projects or in emerging cleantech areas such as geothermal, critical mineral exploration, carbon capture and storage, or nuclear waste management, requires the acquisition of a seismic survey. Generally, this involves deploying seismic sources and sensors in various patterns optimized to avoid surface exclusions and enable operational efficiency. However, for more sustainable seismic acquisition, these surveys can also be optimized to reduce environmental impact and lower greenhouse gas emissions. This can be accomplished by incorporating ecological data into the seismic planning and utilizing new innovations such as alternative sampling methods or equipment miniaturization. When combined with advances in seismic processing algorithms, the same subsurface data quality can be achieved as that of a conventional survey, but with a significantly reduced environmental footprint (Crook, 2024; Crook et al., 2025). Through extensive collaboration between multiple disciplines (ecology, biology, geoscience, and engineering), the EcoSeis™ project has developed sustainable seismic solutions which can reduce both the surface land footprint and emissions associated with seismic acquisition by as much as 50%, all while maintaining data quality and enabling safe and efficient field operations. This case study will highlight lessons learned throughout the development, from the initial design and through field optimization, processing, interpretation, and inversion.

The development of innovative seismic acquisition geometries has become critical to addressing the dual challenge of optimizing imaging resolution while minimizing environmental footprints (Crook et al., 2025). If there were no environmental or cost constraints, the ideal sampling would be a fully sampled grid geometry where line intervals are equal to station intervals for both sources and receivers. Historically, a proper Nyquist-sampled grid geometry was not possible due to the large channel counts required. With the advent of high-density Vibroseis techniques and modern nodal receivers, grid geometries are now possible and have been shown to have significant benefits due to fully sampling the wavefield in all source and receiver spatial dimensions (Sx, Sy, Rx, and Ry) (Ourabah et al., 2015). However, in areas with limited access and various environmental constraints such as sensitive habitats and mountainous terrain as well as safety considerations (e.g. UXO avoidance), these methods are not practical or cost-effective. In these areas, the traditional approach to reducing impact (or cost) has been to acquire sparse orthogonal geometries with large station-to-line ratios. The problem with this approach is that although a decent structural image is often attained, advanced geophysical analyses that rely on accurate seismic attributes (e.g. AVO) become less reliable due to the sparse offset and azimuth sampling and low trace density at the near offsets. To address these challenges, in 2020 we began a collaborative research project to examine whether alternative geometries (such as parallel linear geometries) could provide a solution (Naghizadeh et al., 2023). This case study presents the most recent results from over 35 different geometries, all decimated from the same fully sampled grid dataset, and results from combined decimated surface 3D seismic and borehole VSP data.

1 METHODOLOGY

Geothermal energy development requires precise subsurface imaging to mitigate exploration risks, optimize reservoir management, and reduce high upfront capital costs of drilling operations. Sustainable seismic solutions, first developed for hydrocarbon exploration, show strong potential in geothermal exploration. These techniques address critical challenges in reservoir characterization, drilling optimization, and environmental sustainability. To achieve perfect sampling of the subsurface, a 3D seismic survey would need to be acquired with a continuous grid of source and receiver stations (full grid geometry) where receiver station interval = source station interval = receiver line interval = source line interval. Although ideal, this method is often cost-prohibitive or impossible due to surface constraints. The resulting interconnected, orthogonal seismic cutlines increase anthropogenic footprints, which can negatively affect sensitive species and habitats (Larson et al., 2020). Additionally, in areas with limited access and various environmental constraints such as sensitive habitats and

mountainous terrain, sparse orthogonal geometries with large station-to-line ratios have traditionally been used. Although these can be successful in obtaining an acceptable structural image, advanced geophysical analyses that rely on accurate seismic attributes become less reliable due to the sparse offset and azimuth sampling and low trace density at the near offsets (Crook et al., 2025).

Recent advances in equipment miniaturization (Crook et al., 2021) and acquisition methods (Crook, 2018, 2019) are enabling new 3D survey geometries such as alternative linear geometries to overcome these challenges. For example, parallel geometries have the potential to significantly reduce the land footprint associated with seismic acquisition with some methods, such as EcoSeis™ achieving up to a 50% reduction in seismic cut lines while maintaining subsurface data quality and enabling safe and efficient field operations (Crook, 2022; Naghizadeh et al., 2023, Goodway et al., 2025).

This case study began with the examination of a fully sampled grid geometry that was decimated in both conventional and novel linear-type geometries (Crook et al., 2023; Cova et al., 2023). Conventional (orthogonal) and lower impact geometries were generated from a well-sampled grid seismic dataset via decimation. Lower impact linear geometries were perturbed by varying the shape, amplitude and frequency of line deviations. Each design was measured based on their trace density and linear and areal cut-line disturbances to compare subsurface coverage and surface impact. The full grid and decimated datasets were processed through AVO compliant pre-stack time migration. Interpolation algorithms assist in reconstructing data that fell outside of Nyquist sampling. An independent interpretation of each geometry provided target level horizons and attributes. Attributes from each geometry were compared mathematically via NRMS calculations (Detomo, 2012) to quantify the imaging differences between low impact and orthogonal geometries. To avoid bias, rather than comparing these datasets to standard orthogonal geometries, all datasets (orthogonal, linear, and alternative) were compared back to the fully sampled grid dataset. To date, thirty-five geometries have been evaluated through an identical 5D interpolation, pre-stack time migration (PSTM), and advanced processing workflows to assess their imaging performance.

Vertical Seismic Profiling (VSP), another technique adapted from the oil and gas sector, provides direct, high-resolution borehole seismic data. VSP facilitates precise calibration of surface seismic interpretations and detailed imaging of geological features, significantly enhancing subsurface model accuracy. This precision informs strategic drilling decisions and reduces exploration risks by providing a better understanding of geothermal reservoir geometry, depth, thickness, and volumetrics.

VSPs have been widely studied as part of a Geothermal imaging process. The geometry of a VSP survey can allow for undershooting of structures for imaging of high angle structures in complex geologies. In addition to imaging, VSPs can be designed to analysis azimuthal in-situ velocity changes that are dependent on fracture networks around a wellbore. An excellent example of one of these studies is 2018 Fabienne Reiser's Doctorate thesis showing synthetic design studies to evaluate the use of VSP data in imaging fracture zones within a crystalline basement, as well as some analysis of data collected as a part of the Krafla, Iceland geothermal area (Reiser, 2018). Some lessons learned from this thesis are helpful in planning any future VSP surveys as a part of a planned geothermal program. In the case of the data collected and analyzed in Iceland and Switzerland which was part of the thesis it was observed that the limited data collected for these complex geologic conditions resulted in an inability to properly evaluate and image the results. Both the synthetic and real data analysis showed that improvements in the acquisition design can have better results for VSP imaging and data analysis in these complex high-angle structured, fractured zones that are a part of geothermal projects. Pre-survey modeling using a complete 3D structural model can ensure proper placement of the sources for VSP imaging and data analysis is highly recommended.

2 RESULTS

The intersecting lines of conventional orthogonal surveys result in habitat fragmentation, which is particularly problematic in forested areas with sensitive species that rely on continuous, undisturbed habitat. Linear and alternative irregular geometries help reduce both the total linear km of seismic as well as the habitat fragmentation associated with orthogonal surveys. However, traditional linear geometries (Goodway & Ragan, 1996), can suffer from poor crossline interpolation due to the continuous gaps created in crossline subsurface bin sampling. Therefore, alternative linear geometries were developed. Figure 1 highlights some of the geometry comparisons from the testing. The plots a), c), and e) represent higher resolution designs with orthogonal, straight line linear, and zigzag respectively, all with the same line interval and equal trace density (same number of sources and receivers), but with c) and e) having ~50% fewer linear km than a). The plots b), d), and f) represent end member testing for the same types of geometries, but with lower trace density due to the larger line interval.

Results from field seismic data acquisition testing, which included both 3D and 4D timelapse comparisons, show that alternative timelapse survey designs such as those with sparser monitor surveys with different geometry from the baseline are possible. (Naghizadeh et al., 2024) This has led to new options for CCS monitoring where combinations of sparse surface seismic with borehole (VSP) measurements may enable more accurate, yet cost-effective monitoring. Preliminary testing to evaluate the VSP response of various alternative seismic sources was conducted in late 2024 and further testing of combined alternative 3D seismic geometries with VSPs is planned is planned for late 2025 / early 2026.

3 CONCLUSIONS

Recent innovations in seismic acquisition, such as alternative survey geometries, miniaturized equipment, and autonomous nodal sensors, enable high-density data acquisition while reducing environmental impact and improving operational efficiency. These advancements allow denser receiver layouts across varied and sensitive terrains. In some cases, surface disturbance has been reduced by up to 50% compared to conventional methods—particularly valuable in ecologically sensitive or logistically challenging geothermal sites. These methods reduce operational costs while maintaining high-resolution imaging needed to characterize key subsurface features such as faults, fractures, and permeability pathways critical to geothermal fluid flow.

To fully evaluate a new seismic acquisition method, the data must be examined through processing, interpretation, and inversion. Here we present the results from decimation tests of 35 different conventional and alternative geometries as well as more recent results from several successful field trials, which have shown that alternative geometries that minimize the total linear km of seismic can reduce both the environmental impact of clearing seismic lines or disturbing sensitive habitat, and potentially reduce the cost of acquiring the data. Observations from processing and interpretation indicate that in addition to generating comparable 3D subsurface images, the new methods are compatible with time-lapse (4D) over legacy surveys providing a new, cost-effective way of monitoring. However, one must be careful to ensure the trace density of these alternative geometries remains sufficient for accurate target resolution. If carefully implemented, these new methods can provide optimal subsurface imaging that will support sound economic decisions while reducing the overall environmental impact of acquiring land seismic datasets.

Integrating innovations in alternative 3D surface seismic designs and VSP methods improves the accuracy of geothermal reservoir mapping, reduces uncertainty in drilling, and supports informed decision-making throughout the development process. By utilizing advanced seismic technologies, geothermal exploration can achieve more sustainable operations while accelerating the development of clean, reliable energy resources worldwide.

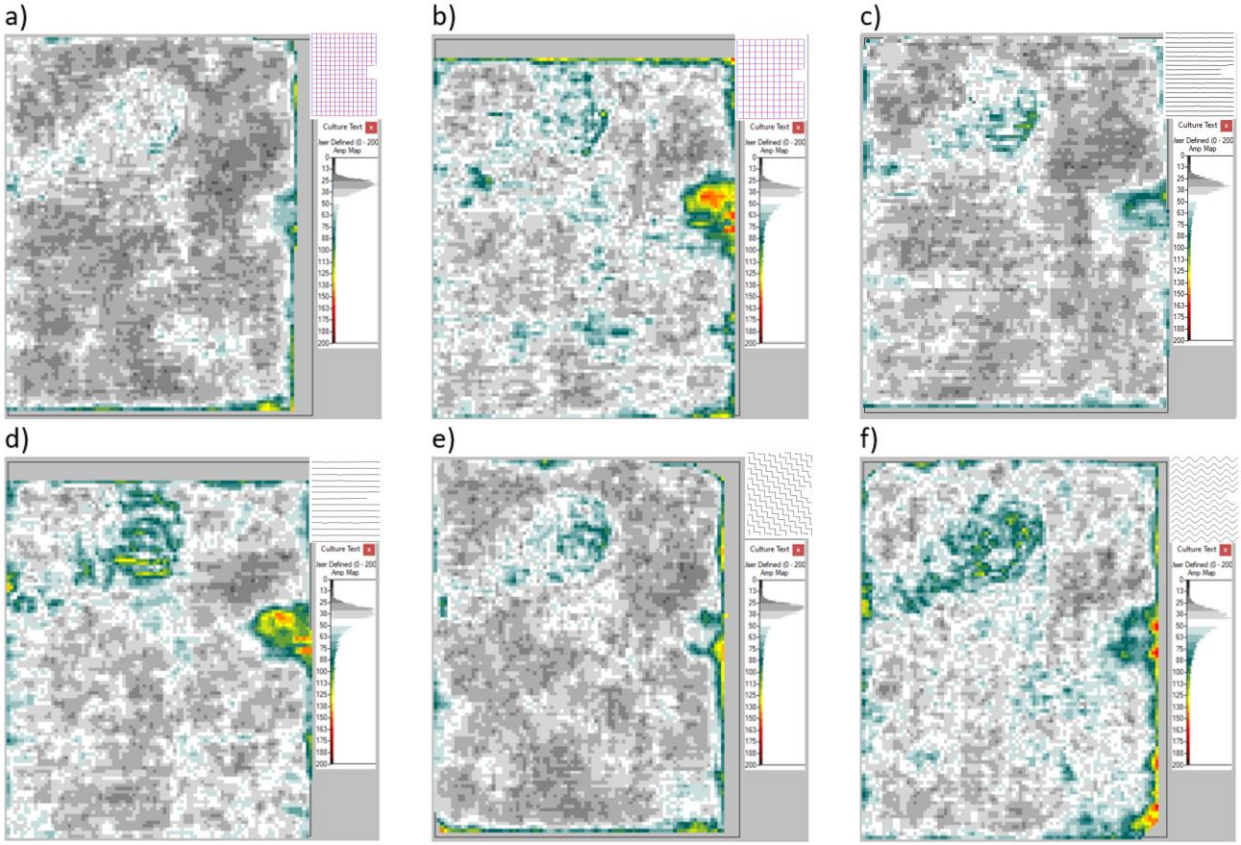


Figure 1. NRMS plots comparing each decimation to the fully sampled grid. Greys, whites, and light greens represent a good fit with the fully sampled dataset, whereas dark greens, yellows, and reds represent areas where the decimated geometry results in deviations from the fully sampled data.

Acknowledgements

The authors would like to acknowledge Cenovus Energy Inc. for use of the seismic dataset as well as other project collaborators for research-funding contributions.

REFERENCES

Crook, A. [2018]. Seismic Acquisition Innovations Applied in Canada. CSEG Recorder, 43(5), 22-29.

Crook, A., McGrory, R., Baker, N., and Westlake, A. [2019]. Transitioning to High Density Vibroseis Seismic Acquisition: A Case Study. GeoConvention conference abstracts.

Crook, A., Bossaer, S., Boutin, M., Contenti, S., Crook, C., Nwafor, K., and Sun, F. [2021]. Case study: The use of miniaturized seismic sources for reduced environmental impact. 82nd EAGE Annual Conference & Exhibition Extended Abstracts, 1–5.

Crook, A. [2022]. Evaluating seismic acquisition techniques for reduced environmental impact. Second EAGE Workshop on Near-Surface and Mineral Exploration in Latin America, Bogotá, Colombia (Abstract).

Crook, A., Cova, R., Rodriguez, M., Goodway, B., Vermeulen, P., and Pardasie, W. [2023]. Sustainable subsurface imaging technology Part 1: Design, Processing, and Interpretation. Recent Discoveries, Exploration Opportunities, and Sustainable Development Strategies in Caribbean Basins, AAPG Workshop Abstracts.

Crook, A. [2024]. Sustainability and Innovation in Seismic Data Acquisition. Canadian Society of Exploration Geophysicists Distinguished Lecture Tour 2024/2025 Abstract.

Cova, R., Rodriguez, M., Goodway, B., Vermeulen, P., Crook, A., and Pardasie, W. [2023]. Sustainable subsurface imaging technology part 2: Using AVO seismic inversion as a tool to assess seismic survey designs. Recent Discoveries, Exploration Opportunities, and Sustainable Development Strategies in Caribbean Basins, AAPG Workshop Abstracts.Crook, A. [2024]. Sustainability and Innovation in Seismic Data Acquisition. Canadian Society of Exploration Geophysicists Distinguished Lecture Tour 2024/2025 Abstract.

Crook, A., Naghizadeh, M., and Pearcy, R. [2025]. Sustainable Solutions for Seismic Imaging. 86th EAGE Annual Conference & Exhibition Extended Abstracts.

Detomo, R. [2012] 4D Time-laps seismic reservoir monitoring of African reservoirs. SEG on Demand, Honorary Lecture recordings.

Goodway, W. & Ragan, B., inventors, PanCanadian Petroleum Limited, owner, Canada Patent 2176058, 1996.

Goodway, B., Crook, A., Cova, R., Naghizadeh, M., Hons, M., Rodriguez, M., Crook, C., and Pardasie, W. [2025]. Land 3D Acquisition Design: Theory of wavefield sampling. Part 2: Present 3D design tests for environmentally sustainable sparse perturbed parallel geometries. First Break, 43(1), 89–100.

Larson, A. [2020]. A review of exploration tools and techniques to support the COSIA Land Challenge: Near Zero Footprint Seismic Exploration.

Naghizadeh, M., Vermeulen, P., Crook, A., Birce, A., Ross, S., Stanton, A., Rodriguez, M., and Cookson, W. [2023]. EcoSeis: A novel acquisition method for optimizing seismic resolution while minimizing environmental footprint. The Leading Edge, 42(1), 61–68.

Ourabah, A., Bradley, J., Hance, T., Kowalczyk-Kedzierska, M., Grimshaw, M., and Murray, E. [2015]. Impact of acquisition geometry on AVO/AVOA attributes quality - A decimation study onshore Jordan. Proceedings of the 77th EAGE Conference & Exhibition, Extended Abstracts.

Reiser, Fabienne [2018] Imaging geothermal reservoirs using vertical seismic profiling, Ph.D. Thesis, Doctor of Sciences of ETH Zurich.