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Zero Impact Seismic in Support of Geothermal Exploration

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ABSTRACT

While the ability of high-density seismic data to improve subsurface imaging has been well understood for some time, the logistical complexity and concomitant expense of acquiring high-density seismic data has precluded most geothermal explorers from accessing the technology.

Recent advances in seismic data acquisition technology have resulted in a step change reduction in the weight, size, and cost of cableless seismic receiver nodes. Concurrently, we have made significant progress developing lightweight seismic source technology with similar reductions in size and weight. When used together, these technologies dramatically reduce cost, risk, and environmental impact of onshore seismic operations.

In late 2021, we deployed a field team to a geothermal exploration project in Northwest British Columbia, Canada to test the ability of these emerging technologies to image the subsurface in an area with complex geology.

We will review the field test conducted and the results thereof and we will compare the outcomes with seismic data acquired in the same area in 1985. We will describe how applying new nimble seismic technology in an integrated way can transform the landscape for geothermal exploration.

1. INTRODUCTION

The M'deek Geothermal Field is located about 24 kilometers south of the City of Terrace, British Columbia, Canada. It is hosted within the Kitsumkalum-Kitimat Graben situated within the Stikine Volcanic Zone in Northwestern British Columbia. The field is located within a temperate coniferous forest that is highly valued by local communities and sensitive wildlife. As such, there is a strong desire to minimize or eliminate any impact to the forest from exploration activities.

The most well-known feature of the field is the Mt. Layton (or Lakelse) Hot Springs, consisting of a series of six groups of hot springs or seeps, fed by water discharging at an estimated flow rate of approximately 600 litres per minute at temperatures of up to 87 degrees Celsius. The hot springs are well known to indigenous people in the region, who historically used them for traditional healing. Since the early 1900s, several attempts have been made to develop resorts at the site, with each successive attempt eventually failing. The most recent effort was opened in the late 1980s (Torres, Heikkinen, Eyre, Thompson, & Thompson, 2020).

A sequence of geological mapping and geophysical investigation in the area has occurred since the mid-20th century, driven by interest in tourism and recreational development, utilization of direct heat for greenhouse potential, and power generation. In 1981, a geothermal reconnaissance mapping effort by BC Hydro aimed at identifying areas with the potential for supplying geothermal power stations identified Lakelse as an 'area of interest.'

In 1985, the Geological Survey of Canada commissioned a 4.8 km seismic reflection survey consisting of three (3) cross-valley seismic lines. This survey concluded that the Lakelse Lake basin is 'blanketed by a thick layer of glaciomarine muds and clays' with 'layered valley-filling sediments extending to bedrock occurring beneath the clay sequence' (Hillman, 1985). However, the 1985 seismic data lacked sufficient resolution to reliably image the overburden-bedrock contact or predicted near-vertical faulting that would support a more robust model.

In late 2021, Explor and Borealis Geothermal acquired a 2.75 km high density 2D seismic test line to assess the ability of modern high density seismic data acquisition technologies to deliver improved subsurface images of the prospect with zero (or near-zero) environmental impact.

2. SEISMIC DATA ACQUISITION METHODS

2.1 1985 Seismic Survey Methodology (Hillman, 1985)

The 1985 survey was acquired with a twelve (12) channel seismograph called a Nimbus Instruments Model ES-1210F (Figure 1). Geophone cables were multi-cored refraction cables with twelve (12) takeouts for geophone connections. High frequency 100 Hz reflection geophones were spaced at 7.6 m intervals along the seismic lines.

Seismic source energy was generated by an 8-gauge shotgun cartridge source placed in holes drilled to a depth of approximately 1 metre. The cartridge was detonated electrically using a Nimbus Instruments HVB-1 blaster (Figure 1).

Figure 1: (Left) A photograph of a Nimbus Instruments Model ES-1210F like the one used to acquire the 1985 survey. (Credit: e-bay). (Centre) A photograph of an HVB-1 seismic trigger/timer like the one used in the 1985 survey (Photo credit: Geomatrix). (Right) A photograph of an Apple IIe like the one used to process the 1985 survey (Photo credit: Wikipedia).

The data was acquired by laying out the geophone cable in a straight line and planting geophones at equal intervals along the line. A hole was then drilled for the shotgun source and the source was detonated electrically. Recordings were made on paper and on magnetic tape.

Thirteen (13) shots were recorded for each geophone spread starting with the source positioned 38 metres off the end of the spread with all twelve (12) channels of data recorded for that shot. This data, referred to in the report (Hillman, 1985) as "Expanding Spread" data was used for velocity analysis. Twelve (12) shots were then fired sequentially such that each shot was 60 metres away from the geophone spread that was recording the shot. A composite record (called a Common Offset record) was derived from these twelve (12) single shots into a single geophone 60 metres away. The Common Offset records were then amalgamated to produce the 'pseudo-sections' for the 2D seismic lines.

Data was processed with an Apple IIe computer system (Figure 1). The processing flow consisted of picking first breaks and the water table, which generated near-surface statics corrections. These statics were applied to the data, after which automatic gain control, gain tapers, and additional filters were applied. Filtered Common-Offset records were plotted sequentially on an Epson FX-100 printer to produce the final seismic 'pseudo-sections'. Velocity analysis conducted on the "Expanding Spread" data was used to calculate the depth scales. In this manner, a pseudo-section with approximate depths was produced.

2.2 2021 Seismic Survey Methodology

In late 2021, a 2.7 km long 2D test was acquired by a field team comprised of five (5) individuals, with four (4) Kitselas Geothermal representatives being trained on site. Acquisition design, comprised of STRYDE receiver nodes and the portable PinPoint® seismic source system, enabled efficient deployment by hand, whilst also enabling efficient movement through the forest when needed, thus eliminating any need for line clearing, such as cutting trees. The line was acquired along the side of an existing roadway, but several segments of the line passed through forested areas with no cleared pathway.

A total of 451 STRYDE receiver nodes were deployed along the line. 401 STRYDE nodes were placed 5 metres apart in 3.8 cm (1½") diameter holes drilled approximately 13 cm (5") deep into the ground over a 2 km segment of the line. An additional 50 nodes were deployed at the SW end of the line at 15 metre intervals to extend the line a further 700 metres, albeit with sparser receiver sampling.

Source points were acquired with the PinPoint® source system (Figure 2) using a 12-gauge cartridge loaded with propellant. The system is integrated with an RTK GNSS receiver such that a precise position and time is recorded for each shot. Initially, 401 shots were planned at a 5-metre interval on the half-station, but only 373 recordable shots were taken as the project was waylaid by very heavy snow and the team encountered equipment failure towards the end of the allotted time for the source acquisition operation, by which point adequate data had been acquired to deliver a robust test outcome.

Figure 2: The innovation sequence of PinPoint®, the nimble seismic source used on the M'deek test in 2021. The 2020 version of the tool was the version used. The version on the far right is the latest version, set for commercial release in 2023.

All nodes were deployed prior to the first shot, and the line was recorded such that all receivers recorded every source point, referred to as a full live spread, eliminating the need to redeploy geophones as the source progressed across the line. This method of deployment and design provided benefit in both acquisition operations and the recorded data quality, resulting in a total of 168,223 recorded seismic traces over the 2.75 km long line (61,172 traces/km).

Receiver deployment was completed by three (3) people over a total of 6h 30m of field time (~51 seconds per deployed node). Source acquisition took a team of four (4) people a total of 6h 15m of field time (~60 seconds per shot point). Primary node retrieval took five (5) people just 2h 35 min (~20 seconds per node), but with the heavy snowfall (Figure 3) a secondary effort was required to retrieve the nodes. Thus, the total acquisition effort took just 72 person-hours, producing a trace acquisition efficiency of ~2,336 seismic traces per person-hour.

Figure 3: Explor President Allan Châtenay stands beside the RTK GNSS base station covered in heavy snow at the NW end of the 2021 high-density 2D seismic line. (Photo credit: Explor, 2021)

3. SEISMIC DATA RESULTS

3.1 1985 Seismic Data Results

Line 2 of the 1985 seismic survey (Hillman, 1985) was acquired directly through the main Lakelse Hot Springs area. It was 1,368 metres long and was acquired with fifteen (15) geophone spreads that each consisted of twelve (12) geophones with a single shot into each geophone on the spread for a total of 180 shots. Fifteen (15) additional shots were taken into the twelve (12) geophone spread for the purposes of velocity analysis. The result is the 180-trace pseudo-section with depth shown on the y-axis as shown in Figure 4 below.

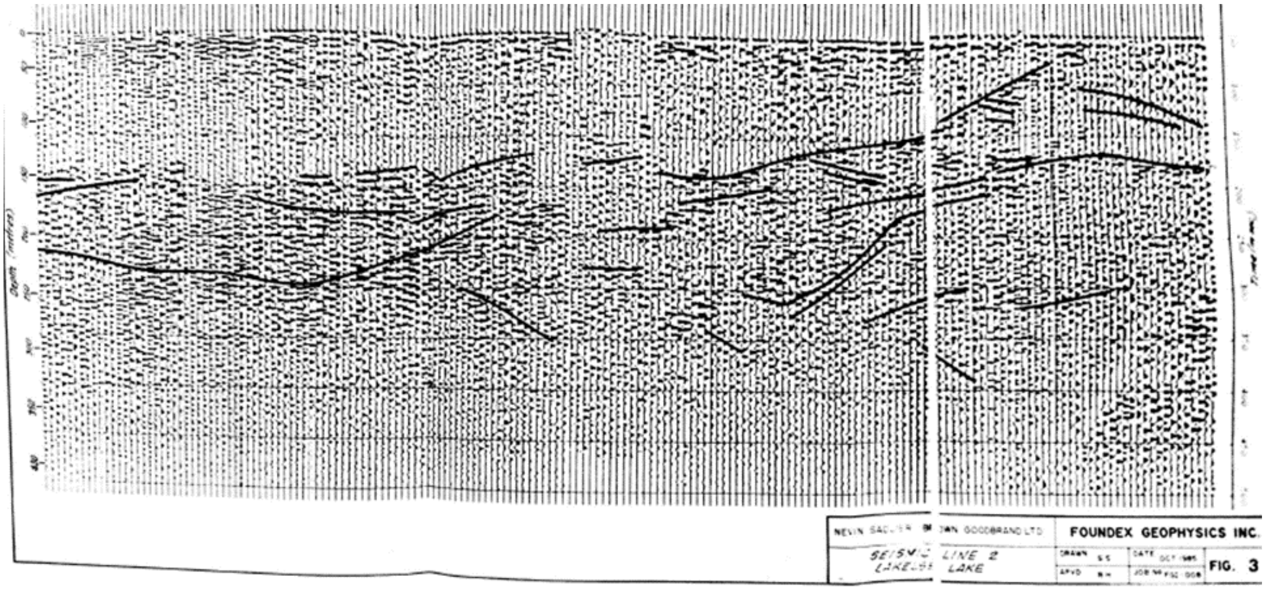


Figure 4: Seismic (depth) section for Seismic Line 2 from the 1985 Lakelse seismic survey by the Geological Survey of Canada. This line goes through the Lakelse Hot Springs area, parallel and approximately 1 km to NE of the 2021 high density 2D line. (Hillman, 1985))

The spacing of geophones in the 1985 survey was quite dense at 7.6 metre intervals. However, the very short (83.6 m) length of each spread, the short distance (60 m) of the offset between the source and the receiver in each case, and the fact that the data was single-fold all limited the ability of the 1985 effort to deliver a high quality image of the subsurface. The discontinuity of reflectors made reliable interpretations difficult. However, enough reflection data was evident to permit a rudimentary, discontinuous interpretation of the data. Building a reliable detailed subsurface model based on this data is difficult.

The method used, and subsequent data quality, from the 1985 survey was driven by the relatively limited capabilities of the system deployed. It is worth noting that even in the mid 1980s systems such as Texas Instruments' DFS-V recording system were capable of recording 120 channels of data onto 9-track tapes. During that era, the DFS-V was the dominant recording system in North America, however it would have cost considerably more to deploy and operate than the small system used by the 1985 team. 1985 was also the year that Sercel released the Sercel 368, a system capable of recording 1,200 channels, a 10-fold increase in capability over the DFS-V. As is often the case with geothermal exploration, funding is limited, and this was perhaps the case with the Geological Survey of Canada's budget for the 1985 exploration effort.

3.2 2021 Seismic Data Results

The primary driver of seismic data quality is trace density (Ourabah, et al., 2014), (Ourabah, Keggin, Brooks, Ellis, & Etgen, 2015). Figure 5 shows the progression of seismic trace density over time, which follows a logarithmic trend somewhat approximating Moore's Law (Manning, Ablyazina, & Quigley, 2019).

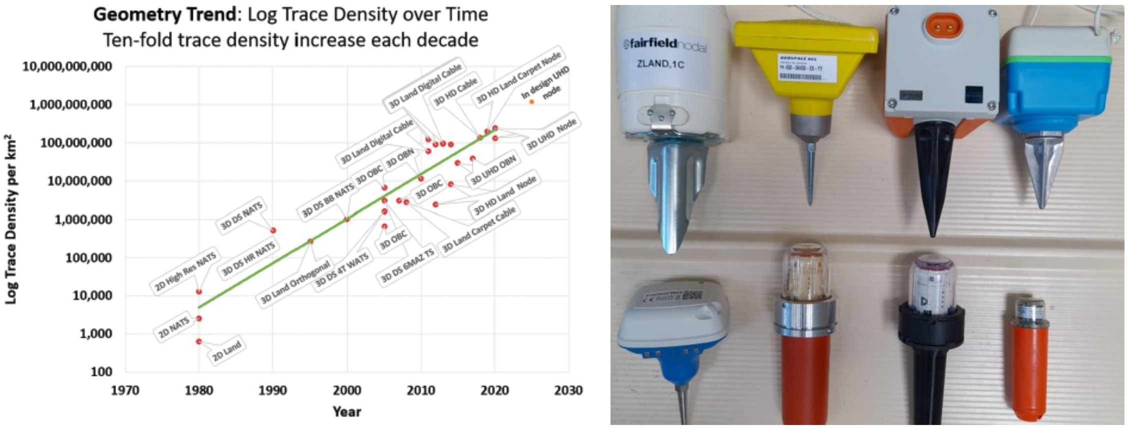


Figure 5: (Left) Graph from (Manning, Ablyazina, & Quigley, 2019) showing the logarithmic increase in seismic trace density every decade since 1980. (Right) Photo comparing the latest generation of nodes from a variety of manufacturers, with the STRYDE node used on the 2021 test shown in the bottom right (STRYDE, 2023).

Increases in seismic trace density have been driven by improvements in technology. On the receiver side, the advent of progressively lighter, smaller autonomous nodes that have eliminated the need for cables have delivered a step change over recent years. With the commercial release of the STRYDE node in 2020, a new step change was delivered. Whereas previous autonomous node designs released in the period from 2017 to 2020 allowed for a single person to carry between 6-10 nodes, a single person can safely carry up to 90 STRYDE nodes. Capital cost of an individual node was reduced from a range of USD$300 - USD$1,500 down to USD$75. Thus, a ten-fold increase in deployment efficiency is possible, with a concomitant reduction in the cost per deployed node driven both by reductions in capital and operating costs. The fact that autonomous nodes also permit nodal self positioning further reduces cost by eliminating the need for a separate survey/positioning operation (Châtenay, 2016).

On the source side, high efficiency vibroseis operations have been developed for large commercial-scale operations the world over. However, these vibroseis operations require heavy vibrators that in turn require paths or lines to be cleared from 3 m to 6 m wide through the forest. These are not well suited to early-stage, small scale operations in the forest. Similarly, the use of explosives requires drilling equipment that is often just as wide as vibrators. Hand drilling shot holes to accommodate explosives is possible, but is quite expensive. Many tests of smaller scale sources have been conducted over the decades (Miller, Pullan, Waldner, & Haeni, 1986) (Brom, 2015). However, the use of small, low-energy seismic sources has typically been confined to academia and near-surface engineering work. Historically, there has not been a high-efficiency, low-energy seismic source option available.

The advent of autonomous nodes, that use GPS time to synchronize, unlocked the potential for the use of independent simultaneous source with nodes (or ISSN^{TM}) methodologies (Howe, Foster, Allen, Taylor, & Jack, 2008) (Bouska, 2009) (Ourabah, et al., 2014) (Ourabah, Keggin, Brooks, Ellis, & Etgen, 2015) (Howe et. al., 2008; Bouska, 2009; Ourabah et. al., 2015). This also permitted the invention of the PinPoint® seismic source system, which integrates concepts published by Varsek and Lawton (Varsek & Lawton, The Seisgun-Part I: Field Tests., 1985) (Varsek & Lawton, The Seisgun-Part II: Data acquisition from a study of stacked sections., 1985) and Miller et. al. (Miller, Pullan, Waldner, & Haeni, 1986) with GNSS positioning and timing. Additional engineering has driven increases in efficiency that were not possible with previous single-person portable seismic source systems (Châtenay & Thacker, 2017), (Châtenay & Thacker, 2018), (Châtenay & Thacker, 2019), (Ourabah & Châtenay, 2022), (Châtenay, 2022)). The 2021 M'deek test assessed the suitability of combining the lightest, most efficient seismic receiver node on the market with the lightest and most efficient impulsive seismic source available to support goethermal exploration at the M'deek Geothermal Field.

Despite PinPoint® being a very low energy source, it delivered robust raw data, where reflection data is visible on the single-fold gathers as shown below in Figure 6. Recent experience with high density data acquisition with low energy sources, when paired with a substantial increase in trace density, has shown an increased tolerance to noisier raw field data. The abundant sampling and full fold distribution across the M'deek survey allowed for easier removal of random noise (present in the receiver example shown in Figure 6), resulting in high-quality imaging and deliverables..

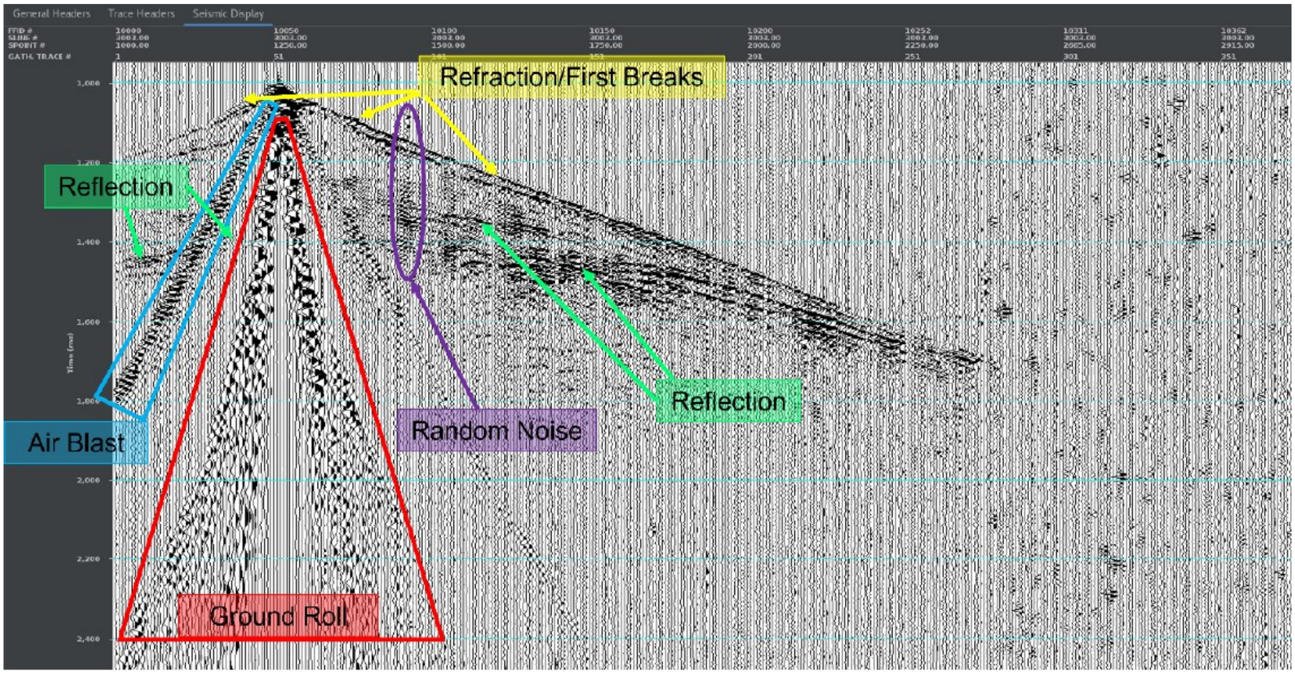
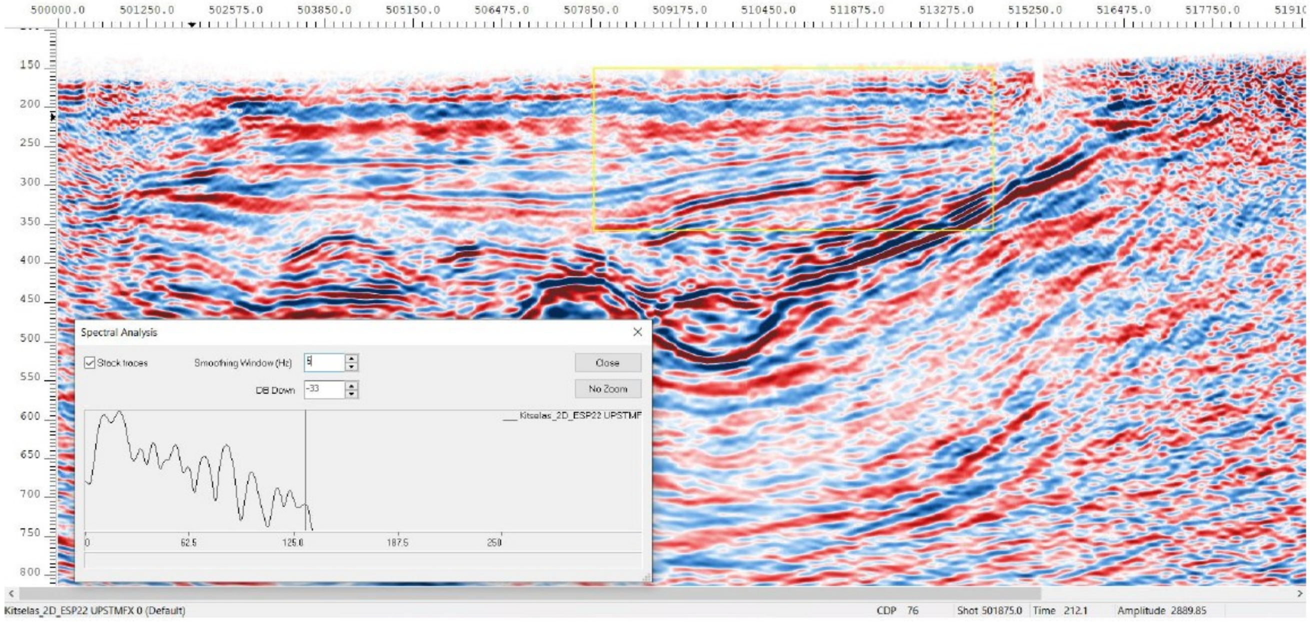


Figure 6: A raw receiver gather showing all 373 source points recorded by a single STRYDE receiver node annotated to show the primary data elements visible in the gather. The NW end near Lakelse Lake shown on the left and the SE to the right. Note the abrupt end to visible first breaks and reflection data at the SE end of line.

Figure 7 shows a spectral analysis of the pre-stack time migrated seismic section, revealing broadband data from <10 Hz to over 130 Hz in a key area of interest. Reflections are visible from the surface to the granitic bedrock, with the overburden-bedrock contact being well imaged.



☑ Stack traces

Smoothing Window (Hz) 5

DB Down -33

Kitselas_2D_ESP22 UPSTMFX 0 (Default) CDP 76 Shot 501875.0 Time 212.1 Amplitude 2889.85

Figure 7: Original unfiltered AVO-compliant pre-stack time migration section with spectral analysis window.

In Figure 8 we show the initial interpretations of key horizons. A considerably more robust and precise interpretation is possible with this high density 2D data. Significant detail is imaged, such that the glaciolacustrine clay layering is visible in the data. This may have important implications for building a detailed understanding of subsurface fluid flow.

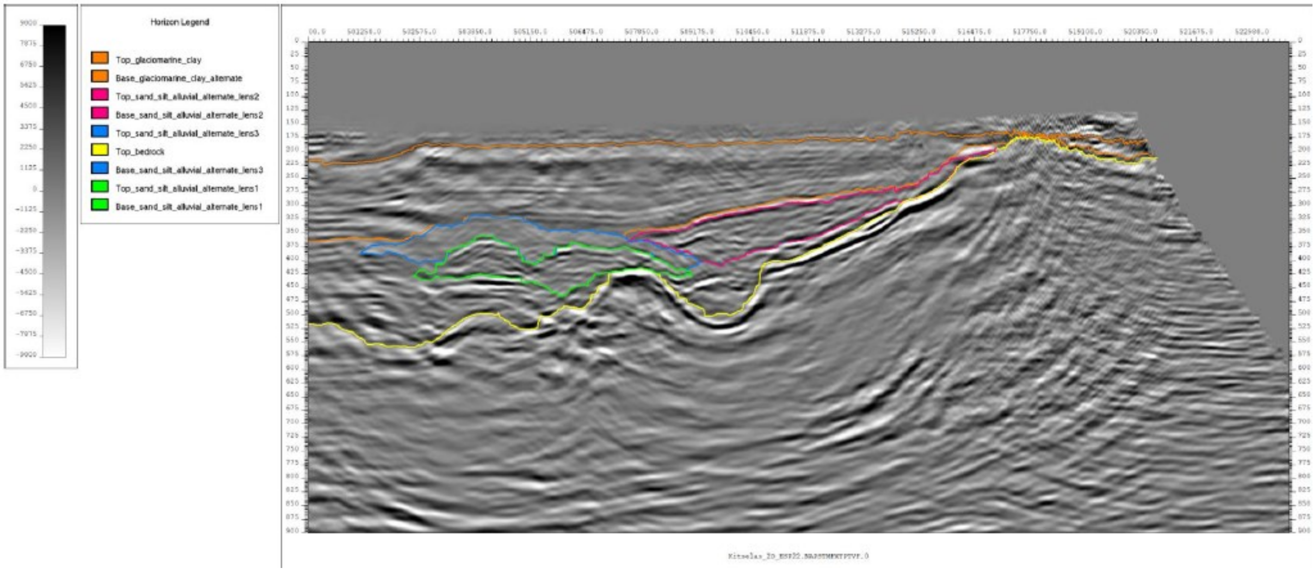


Figure 8: Preliminary pre-stack time migrated seismic section with initial interpretations of key horizons.

We note that the SE portion of the section (the right side of the sections shown in Figure 8 above) lacks strong reflections. This is almost certainly because of granitic bedrock outcropping at that location. We can see the bedrock feature rising to surface, which aligns well with the surface expression of bedrock outcrops visible on Light Detection and Ranging (LiDAR) data.

We also note the presence of bright spots in the seismic data, an indicator of acoustic impedance contrasts that can result from the presence of different fluids in the subsurface. This points to the ability of the data to support seismic attribute analysis to deliver an enhanced understanding of the subsurface.

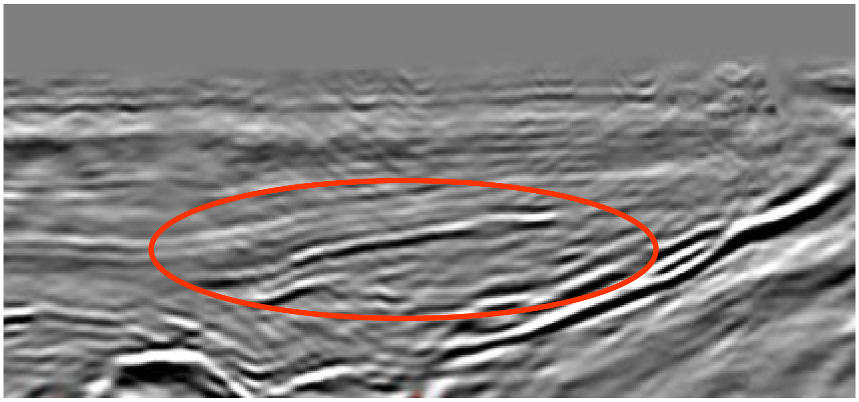


Figure 9: Circle showing a bright spot within the sediments overlying the NW dipping overburden-bedrock contact..

4. CONCLUSIONS

The 2021 M'deek geothermal exploration survey produced much higher quality 2D seismic data than the previous 1985 survey. With a near-zero environmental footprint and exceptional trace density, the cost to deploy this survey was 3-10 times lower than acquiring the survey with conventional vibroseis or dynamite sources.

This project demonstrates the ability of the latest generation of nimble receiver nodes and low-energy, single person portable seismic source technology to deliver excellent outcomes in support of geothermal exploration and development.

The highly structured geology of the project area is susceptible to out-of-plane energy dispersion and complex data resolution, which is often a challenge when seismic design and acquisition is limited to 2D data. Further exploration should consider the use of high-density 3D data using the same nimble source and receiver technology.

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