

# **Susceptibility to Ground Motion Amplification from Seismic Waves based on Multichannel Analysis of Surface Waves in the Red Deer Area, Alberta**

AER/AGS Open File Report 2021-03

# **Susceptibility to Ground Motion Amplification from Seismic Waves based on Multichannel Analysis of Surface Waves in the Red Deer Area, Alberta**

J. Yusifbayov, C. Filewich and L.A. Atkinson

Alberta Energy Regulator  
Alberta Geological Survey

May 2021

©Her Majesty the Queen in Right of Alberta, 2021  
ISBN 978-1-4601-4935-5

The Alberta Energy Regulator / Alberta Geological Survey (AER/AGS), its employees and contractors make no warranty, guarantee or representation, express or implied, or assume any legal liability regarding the correctness, accuracy, completeness or reliability of this publication. Any references to proprietary software and/or any use of proprietary data formats do not constitute endorsement by the AER/AGS of any manufacturer's product.

If you use information from this publication in other publications or presentations, please acknowledge the AER/AGS. We recommend the following reference format:

Yusifbayov, J., Filewich, C. and Atkinson, L.A. (2021): Susceptibility to ground motion amplification from seismic waves based on multichannel analysis of surface waves in the Red Deer area, Alberta; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Open File Report 2021-03, 14 p.

Publications in this series have undergone only limited review and are released essentially as submitted by the author.

**Published May 2021 by:**

Alberta Energy Regulator  
Alberta Geological Survey  
4th Floor, Twin Atria Building  
4999 – 98th Avenue  
Edmonton, AB T6B 2X3  
Canada

Tel: 780.638.4491  
Fax: 780.422.1459  
Email: [AGS-Info@aer.ca](mailto:AGS-Info@aer.ca)  
Website: [www.ags.aer.ca](http://www.ags.aer.ca)

## Contents

Acknowledgements.....	v
Abstract.....	vi
1 Introduction.....	1
2 Ground Motion Amplification and the National Building Code of Canada Classification.....	1
3 Geological Summary of the Study Area.....	2
4 Shear-Wave Profiling.....	5
5 Shear-Wave Velocity Profiles and Amplification Susceptibility.....	5
6 Discussion.....	9
7 Conclusions.....	11
8 References.....	12
Appendix 1 – Frontier Geosciences Inc.’s <i>Multichannel Analysis of Surface Waves Survey Report, Red Deer Area, AB</i> .....	14

## Tables

Table 1. Site classification and susceptibility ratings derived from the average shear-wave velocity of the uppermost 30 m of the subsurface.....	2
Table 2. Lithologies observed in the study area and their respective interpreted shear-wave velocities.....	7

## Figures

Figure 1. Summary of geological and geophysical knowledge of the study area, including total thickness of heterogeneous sediments above bedrock and the epicentres of induced seismic events.....	3
Figure 2. Supplementary material used in this study to select the sites for the multichannel analysis of surface waves surveys.....	4
Figure 3. a) An example of a shear-wave velocity profile interpreted from a multichannel analysis of surface waves survey. b) Lithological units observed at the closest water well. c) Average shear-wave velocity as a function of depth calculated from the shear-wave velocity profile.....	6
Figure 4. Shear-wave velocities for the interbedded shale-sandstone strata, collected from multiple multichannel analysis of surface waves surveys.....	7
Figure 5. The average shear-wave velocities interpolated for the uppermost 30 m of the subsurface. These values represent the best estimate (50th percentile) from a thousand iterations.....	8
Figure 6. The average shear-wave velocities interpolated for the uppermost 30 m of the subsurface. These values represent a) the low estimate (10th percentile) and b) the high estimate (90th percentile).....	9
Figure 7. The best estimate of shear-wave velocities (50th percentile, Figure 5) organized by the National Earthquake Hazards Reduction Program’s classification. ....	10



## **Acknowledgements**

We wish to thank Shilong Mei (Alberta Geological Survey) for providing critical data needed to model the Paskapoo Formation. Additionally, we wish to thank Laurence Andriashek (Alberta Geological Survey) and Todd Shipman (Alberta Energy Regulator) whose technical commentaries and editorial review considerably improved this manuscript.

## Abstract

An increase in hydraulic fracturing–related induced seismicity near the city of Red Deer over the recent years has fueled great scientific interest in the area. Most of the research published thus far has focused on the mechanics of the recorded seismic events. The objective of this study is to map the potential susceptibility to ground motion amplification from seismic waves across the study area based on local changes in geology. To achieve this, seven locations were chosen and velocity profiles were created based on multichannel analysis of surface waves (MASW) surveys. This newly acquired geophysical data was incorporated with knowledge of the shallow geology of the Sylvan Lake sub-basin, to assign susceptibility ratings based on the National Earthquake Hazards Reduction Program’s (NEHRP) classification. This analysis demonstrates that areas with a thicker unconsolidated sediment layer above bedrock (areas exhibiting greater depth to top of bedrock) are the most susceptible to the amplification of the seismic ground motions. Conversely, areas where bedrock is at or near the surface show a much lower susceptibility to ground motion amplification. In general, the vast majority of the study area was determined to have a very low or low susceptibility to ground motion amplification (NEHRP Site classes B and C), though areas exhibiting a thicker sediment layer above bedrock were determined to be moderately susceptible (NEHRP Site Class D). As this research was conducted on a regional scale, site-specific evaluations may need to be undertaken to better assess ground motion amplification.

# 1 Introduction

In Alberta, some of the most prolific clusters of induced seismicity have occurred near the town of Rocky Mountain House (Wetmiller, 1986), the town of Fox Creek (Schultz et al., 2018), and, most recently, near the city of Red Deer (Wang et al., 2020). Following a 4.18 local magnitude ( $M_L$ ) event that occurred on March 4, 2019, near the city of Red Deer, the Alberta Energy Regulator has developed specific regulatory requirements (Subsurface Order No. 7, Alberta Energy Regulator, 2019b; Alberta Energy Regulator, 2019a) to limit the impact and potential of induced earthquakes from hydraulic fracturing activities in that area. As part of the order, operators are required to submit waveform data from passive seismic stations operating real-time in the area to improve detection thresholds (Introduction of statistical variability to the magnitude threshold calculations and the effects observed, J. Yusifbayov and R. Schultz, work in progress, 2021) and to establish spatiotemporal correlations with nearby hydraulic fracturing operations (Schultz and Wang, 2020). An increase of seismic data in this and other areas of Alberta has fueled scientific interest to better understand (Schultz et al., 2016; Galloway et al., 2018) and model (Pawley et al., 2018) regions that are susceptible to induced seismicity. Fundamentally, the nature of seismic waves at the surface depends not only on the mechanism and depth of an event, but also the path the waves travelled from the seismic source to the surface. An observed event at the surface, in terms of the duration and intensity of ground motion, is highly dependent on local site conditions. As observed in the 1985 Mexico City earthquake (Anderson et al., 1986), the characteristics of near-surface sediments can play a key role in the amplification and attenuation of the incoming seismic waves (Finn et al., 2004). Given the potential for ground motion amplification to inflict damage to infrastructure, understanding the susceptibility to ground motion amplification is key in the assessment of seismic hazard.

## 2 Ground Motion Amplification and the National Building Code of Canada Classification

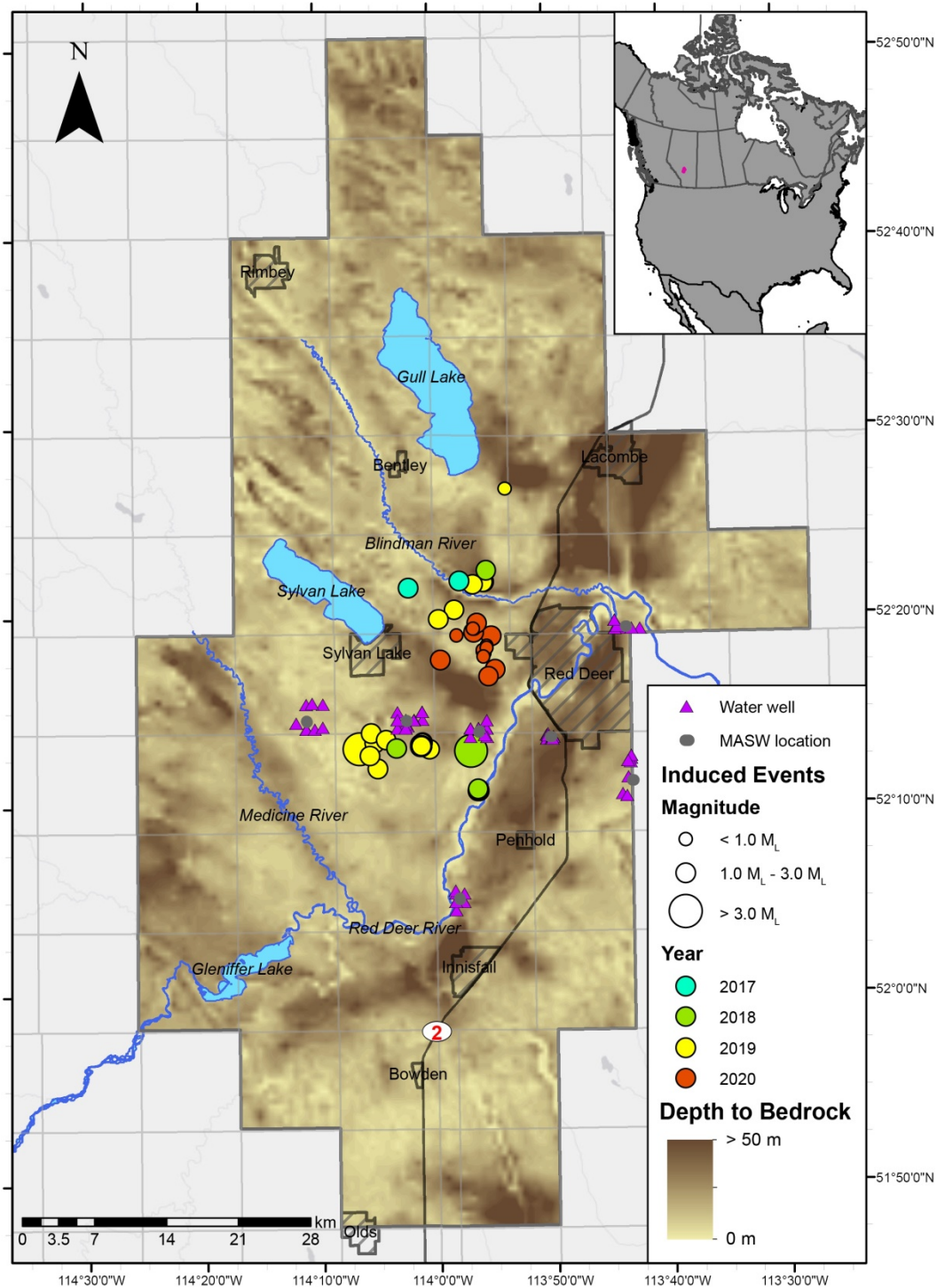
Ground motion amplification is a complex phenomenon, but the causes of it are well understood. The susceptibility for ground motion amplification is defined by the characteristics of the subsurface geology through which the waves travel as they near the surface. Amplification commonly occurs where loosely packed unconsolidated sediments overlie more tightly packed unconsolidated sediments or bedrock strata. Specifically, as shear waves travel from a denser material to a softer material, a reduction in velocity and corresponding shortening of the wavelengths causes an increase in the shear-wave amplitudes over a wide variety of the frequency bands (Shearer and Orcutt, 1987). Shear waves can be further subjected to amplification when i) a thin sediment layer above the bedrock traps and in turn amplifies seismic energy due to resonance of the waves between the surface and the sediment-bedrock interface (Kramer, 1996); ii) depressions formed at the sediment-bedrock interface focus amplification at a specific point on the surface (Bard and Bouchan, 1985); and iii) there is a superposition of the surface waves that are generated from the shear wave conversion near the edges of the depressions at the sediment-bedrock interface (Lomnitz, 1999). These effects were not directly considered as part of this study, as a three-dimensional near-surface geological model was unavailable at the scale necessary to conduct this work with confidence. Rather, this study focused strictly on modelling average shear-wave velocities in the uppermost 30 m of the subsurface, referred to herein as  $V_{S30}$  (Finn et al., 2004). Based on the  $V_{S30}$ , the National Earthquake Hazards Reduction Program (NEHRP) in the United States defined five site classes (Building Seismic Safety Council, 1994), which were later adopted by the National Research Council of Canada for the National Building Code of Canada (NBCC; Table 1; National Research Council, 2010), with the expectation that earthquakes within the same site class will experience similar amplification. Taking into account that amplification occurs when the shear-wave velocities decrease, amplification is more likely to happen at Site classes D and E, where the observed velocities are the slowest.

**Table 1. Site classification and susceptibility ratings derived from the average shear-wave velocity of the uppermost 30 m of the subsurface (National Research Council, 2010).**

Site Class	General Description	Velocity Range (m/s)	Susceptibility Rating
A	Hard rock	$1500 < V_{S30}$	None
B	Rock	$760 < V_{S30} < 1500$	Very low
C	Soft rock and dense soils	$360 < V_{S30} < 760$	Low
D	Stiff soils	$180 < V_{S30} < 360$	Moderate
E	Soft soils	$V_{S30} < 180$	High

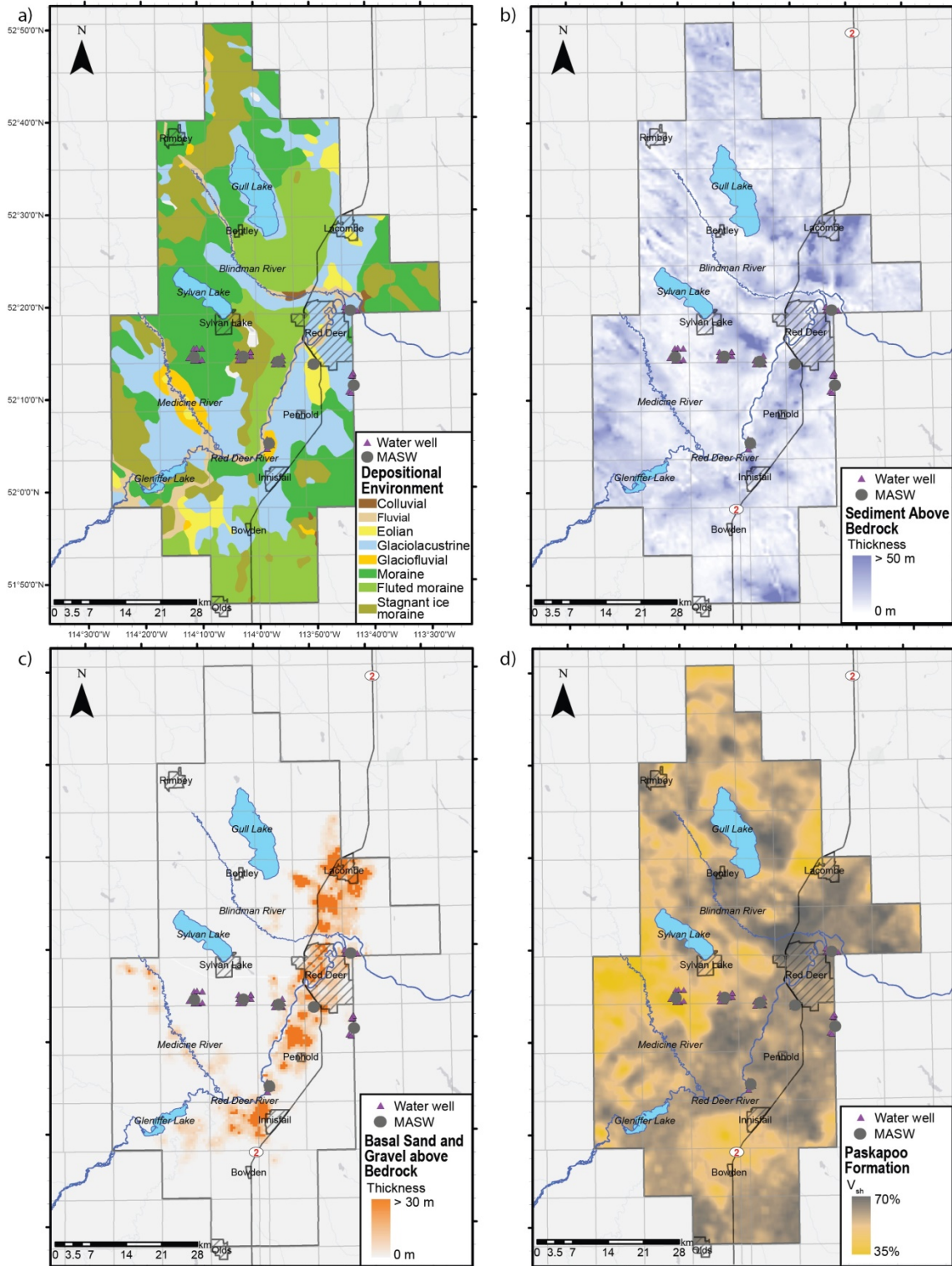
### 3 Geological Summary of the Study Area

The study area is located in central Alberta, near the city of Red Deer and includes NTS map areas 82O, P, 83A, and B. This area was specifically chosen to encompass seismic events from anthropogenic activity starting in mid-2017 (Figure 1; Schultz and Wang, 2020; Wang et al., 2020). It lies within the area of the newly established Subsurface Order No. 7 (Alberta Energy Regulator, 2019b), and it encompasses geological conditions that differ significantly across the study area; principally, the uppermost unconsolidated layer of heterogeneous sediments deposited during the Neogene–Quaternary periods, which overlie consolidated bedrock (Figure 2a; Riddell et al., 2009; Fenton et al., 2013). The above-bedrock Neogene–Quaternary sedimentary succession consists of four main units divided as part of the Sylvan Lake hydrostratigraphic model by Atkinson and Glombick (2015). The most important component of the model for this study is the preglacial fluvial and lacustrine deposits, mainly sand and gravel resting on bedrock and constrained to the Red Deer paleovalley (informally referred to as HSU S1 in Atkinson and Glombick, 2015). Deposits overlying the preglacial deposits in the Red Deer paleovalley and resting on bedrock outside of the Red Deer paleovalley are discontinuous sediments of glaciolacustrine and glaciofluvial origin, as well as moraine (till) and postglacial sediments (collectively referred to herein as undifferentiated sediments above bedrock). These deposits range in thickness significantly, from 0 m to as much as 45 m in places (Figure 2b; Atkinson and Glombick, 2015). The sediment on the floor of the Red Deer paleovalley mainly consists of preglacial sand and gravel, which reaches a thickness of more than 30 m and trends through the city of Red Deer in a northeast direction (Figure 2c; Atkinson and Glombick, 2015). As the thickness considered in this study only includes the uppermost 30 m of the subsurface, most of the studied interval is dominated by the combined thickness of undifferentiated sediments above bedrock and a basal sand and gravel above bedrock unit in the Red Deer paleovalley (Figure 1). The basal sand and gravel unit was differentiated from the rest of the sediments above bedrock primarily because the depositional nature of the deposits makes it easier to map, but also because it was expected to exhibit much higher shear-wave velocities than the undifferentiated sediments above it. In areas where the combined thickness of these sediment units is less than 30 m, the investigation included the topmost part of the underlying bedrock. In the study area, the Paskapoo Formation constitutes the top of the bedrock and consists of an eastward-thinning succession of Paleogene nonmarine clastic sedimentary rocks (Figure 2d; Lyster and Andriashek, 2012; Atkinson and Glombick, 2015; Mei, 2019).



**Figure 1. Summary of geological and geophysical knowledge of the study area (Red Deer area, Alberta), including total thickness of heterogeneous sediments above bedrock (Atkinson et al., 2020) and the epicentres of induced seismic events. Seismic events are indicated as circles sized and colour-coded based on the magnitude and year of the event, respectively. Locations of the multichannel analysis of surface waves (MASW) surveys are indicated in grey and selected water wells surrounding the surveyed areas are shown as purple triangles. The earthquake data was retrieved from the Alberta Geological Survey Earthquake Dashboard ([https://ags-aer.shinyapps.io/Seismicity\\_waveform\\_app](https://ags-aer.shinyapps.io/Seismicity_waveform_app)). Abbreviation:  $M_L$ , local magnitude.**





**Figure 2. Supplementary material used in this study to select the sites for the multichannel analysis of surface waves (MASW) surveys (Red Deer area, Alberta). Criteria considered were a) surficial geology (Fenton et al., 2013), b) thickness of the undifferentiated sediments above bedrock unit (Atkinson and Glombick, 2015), c) thickness of the basal sand and gravel above bedrock unit (Atkinson and Glombick, 2015), and d) volume of shale ( $V_{sh}$ ) for the topmost 30 m of the Paskapoo Formation (Mei, 2019).**

## 4 Shear-Wave Profiling

There are various techniques developed to investigate local site conditions and susceptibility for ground motion amplification. Most can be divided into intrusive seismic techniques, such as sonic logging, seismic cone penetration testing (SCPT), and borehole logging techniques. Others can be classified as nonintrusive methods and include shear-wave refraction techniques, spectral analysis of surface waves (SASW), and multichannel analysis of surface waves (MASW). Readers interested in these techniques are referred to Hunter and Crow (2012) for an in-depth review. In summary, most of the intrusive methods are more difficult to implement in the field, as they require costly drilling and/or prolonged collection campaigns, but typically the results are less subject to interpretation, as measurements are more direct and of higher resolution. Conversely, nonintrusive methods measure seismic surface and body waves, which are less costly to acquire but require more rigorous interpretation.

This study used a MASW technique, first proposed in Park et al. (1999), to indirectly measure shear-wave velocities as a function of depth. This technique uses a spread of 48 geophones with a spacing of 2.5 m between each geophone to measure the velocities of the Rayleigh waves along an approximately 100 m spread to a depth of 30 m. The surface waves are produced by a sledgehammer striking a steel plate placed between every other geophone. Produced waves propagate cylindrically from the source near the surface and are reliably detected by the geophones. This method allows for redundant stacking of the phase arrivals and can be checked in the field to ensure the best quality of data collected. Later, the dispersion curves are generated from the combined waveform data collected from the individual geophones and inverse modelled to create a high-quality shear-wave velocity profile of the surveyed area. This approach was conducted by the Alberta Geological Survey with the assistance of Frontier Geosciences Inc. A detailed report on the field campaign, interpretive procedure, and the results can be found in Appendix 1.

A key criterion in acquiring accurate velocity profiles is in the selection of appropriate sites for the survey. As such, seven locations (Figure 1) were carefully chosen to best leverage knowledge of the surficial and near-surface geology. As mentioned in the previous section, the geology of the study area is quite varied, in both thickness of mappable units and their composition. This can play a significant role in the recorded shear-wave velocities as greater compaction of a material due to greater depth of burial can increase the velocity within a unit. Porosity, permeability, and weathering can also further increase velocity variability and impact the strata's ability to transfer seismic energy. Overall, capturing and understanding the variability between different and similar formations can yield a more accurate velocity profile of the surveyed area. Lithological descriptions from boreholes proximal to the survey sites and across the study area were used to capture and map this variability of the geological units, offering a form of ground-truthing of the interpretations derived from the MASW surveys. This integration of geological and seismological data can yield an accurate assessment of the  $V_{S30}$  profiles used to map the susceptibility to ground motion amplification.

## 5 Shear-Wave Velocity Profiles and Amplification Susceptibility

The NBCC and the NEHRP classifications are based on the  $V_{S30}$  profiles and can be calculated using the following equation:

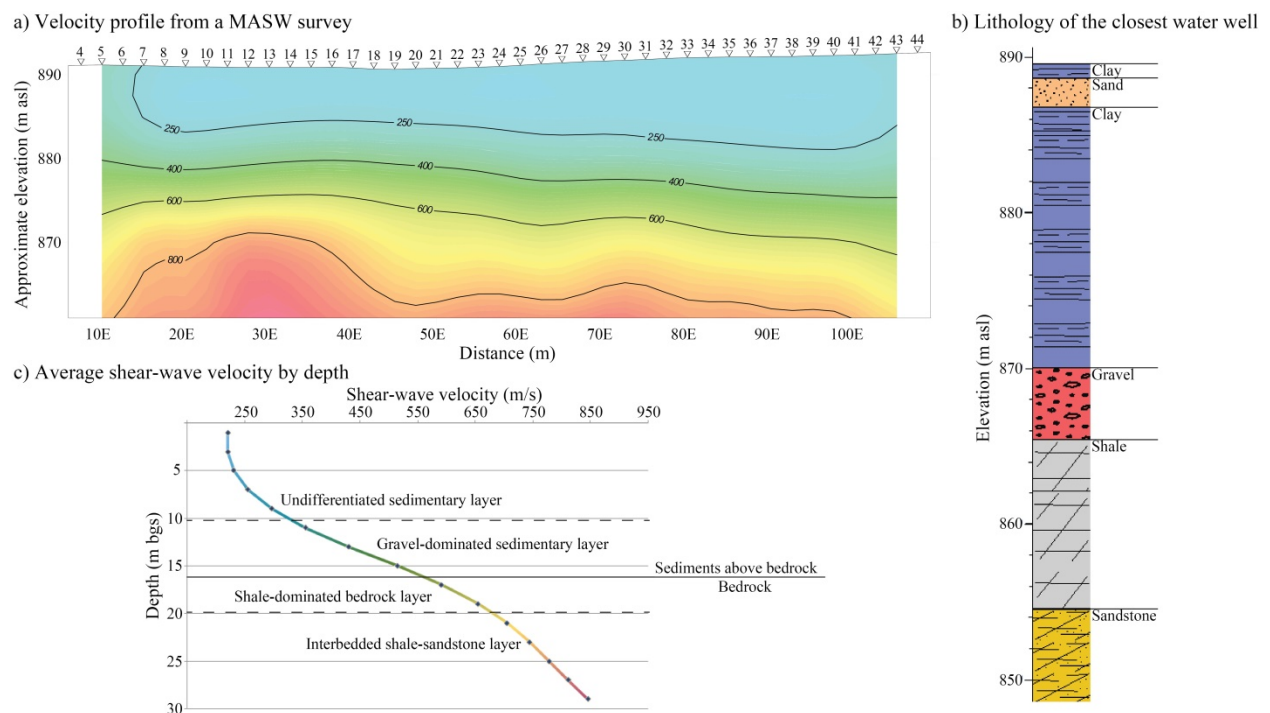
$$V_{S30} = \frac{h}{\Sigma t} \quad (1)$$

where  $h$  is the thickness of the medium and  $\Sigma t$  is the time it takes for a shear wave to travel through that medium. The numerator of the equation is simple and remains constant at 30 m for this study. However, the denominator is trickier to define, as the wave travel time is dependent on the thickness and the strata below the surface, but it can be calculated using the following equation:

$$t_{strata} = \frac{H_{strata}}{V_{strata}} \quad (2)$$

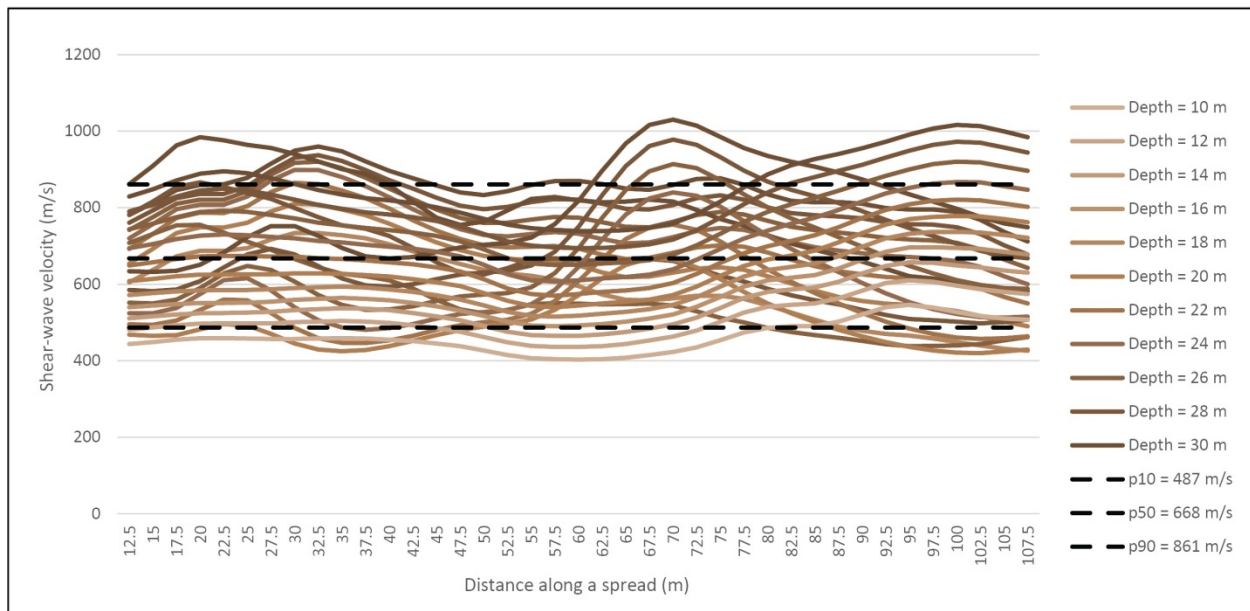
As such, it is important to determine the velocities at which waveforms propagate through different geological units ( $V_{strata}$ ) in the study area. This is achieved by comparing the velocity profiles collected from the field with the lithology observed at the nearest boreholes. To start, three major units were considered in this study: an undifferentiated sediments above bedrock unit, a basal sand and gravel above bedrock unit, and a bedrock unit. The bedrock unit, composed of the Paskapoo Formation, was then divided into three lithostratigraphic subdivisions (following Demchuk and Hills, 1991) based on the volume of shale ( $V_{sh}$ ; Mei, 2019). With this approach, areas with  $V_{sh}$  less than 45% were categorized as sandstone rich, volumes over 60% were categorized as shale rich, and volumes in-between were categorized as interbedded shale-sandstone. These cutoffs were chosen as they best correlate with the lithology observed in the water well logs and the velocity profiles collected from the MASW surveys. These five stratigraphic units were used in this study.

As shown in Figure 3, the thickness and the velocity for individual strata can be extrapolated from a velocity profile collected from the MASW surveys, where a sudden change in velocity usually indicates a phase change (Appendix 1, Figure 9). Contrary to that, a gradual change in velocity can be observed with depth, where compaction due to gravity increases density of a formation (Appendix 1, Figure 3). Similarly, a gradational change in velocity develops where thinly interbedded lithologies, such as those within the Paskapoo Formation, have a tendency to mute the seismic response. As such, exact velocities per strata were substituted with a bell curve of possible values (Figure 4) resulting in an interpreted velocity for the 10th (p10), 50th (p50), and 90th (p90) percentile of the velocities for each lithology (Table 2).



**Figure 3. a) An example of a shear-wave velocity profile interpreted from a multichannel analysis of surface waves (MASW) survey. b) Lithological units observed at the closest water well. c) Average shear-wave velocity as a function of depth calculated from the shear-wave velocity profile. Solid and dashed black lines represent the interpreted unit boundaries, generalized for that survey's point location. All three components were needed to determine the average shear-wave velocity in the uppermost 30 m of the subsurface ( $V_{S30}$ ). Abbreviations: bgs, below ground surface; E, to the east.**



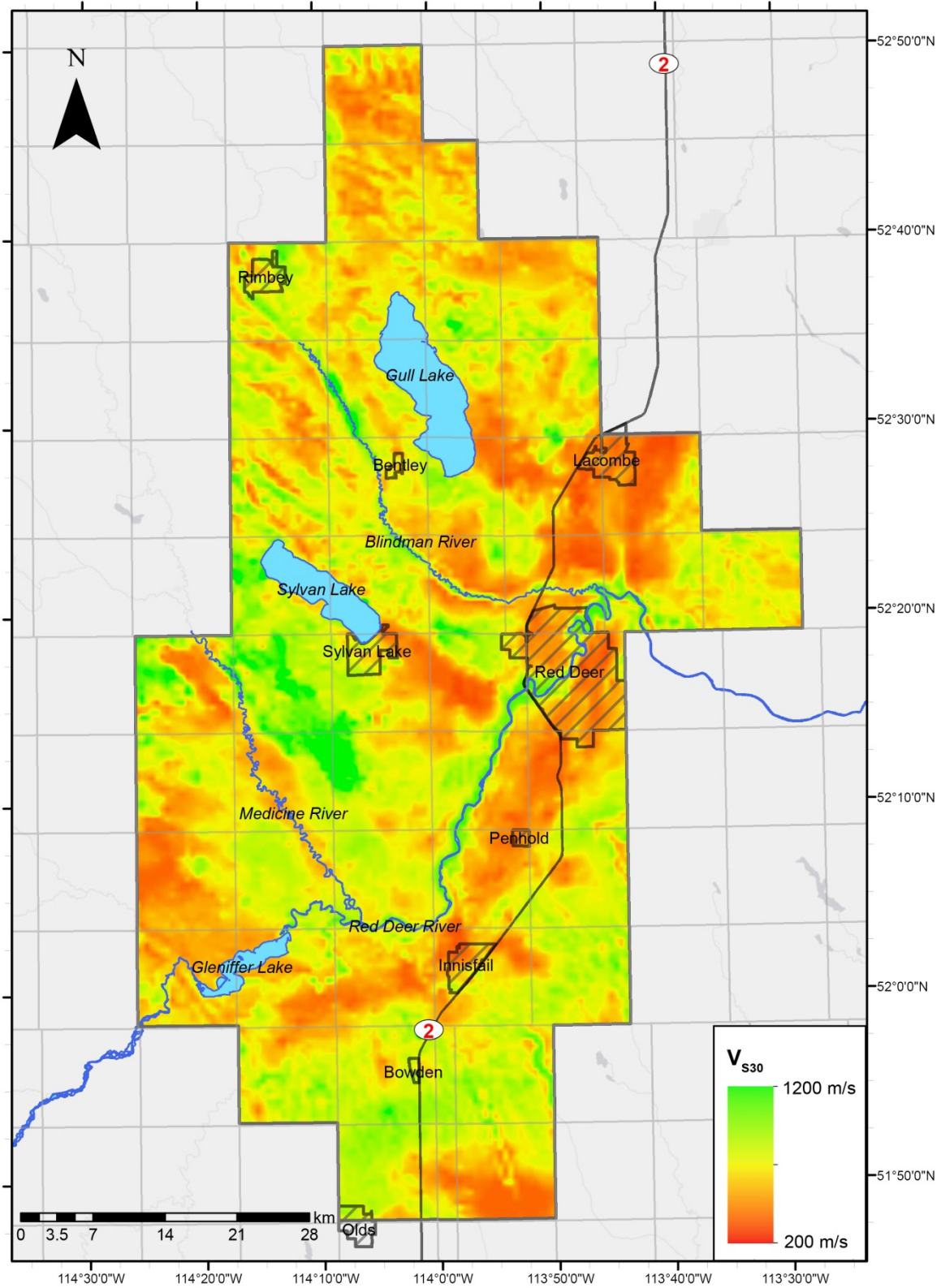


**Figure 4. Shear-wave velocities for the interbedded shale-sandstone strata, collected from multiple multichannel analysis of surface waves (MASW) surveys, Red Deer area, Alberta. Common trait exhibited is an increase of the velocities with depth, however, variation was also observed within the same depth at a single survey site. As such, a bell curve of possible velocities is generated and used for five stratigraphic units used in this study. Abbreviation: p, percentile.**

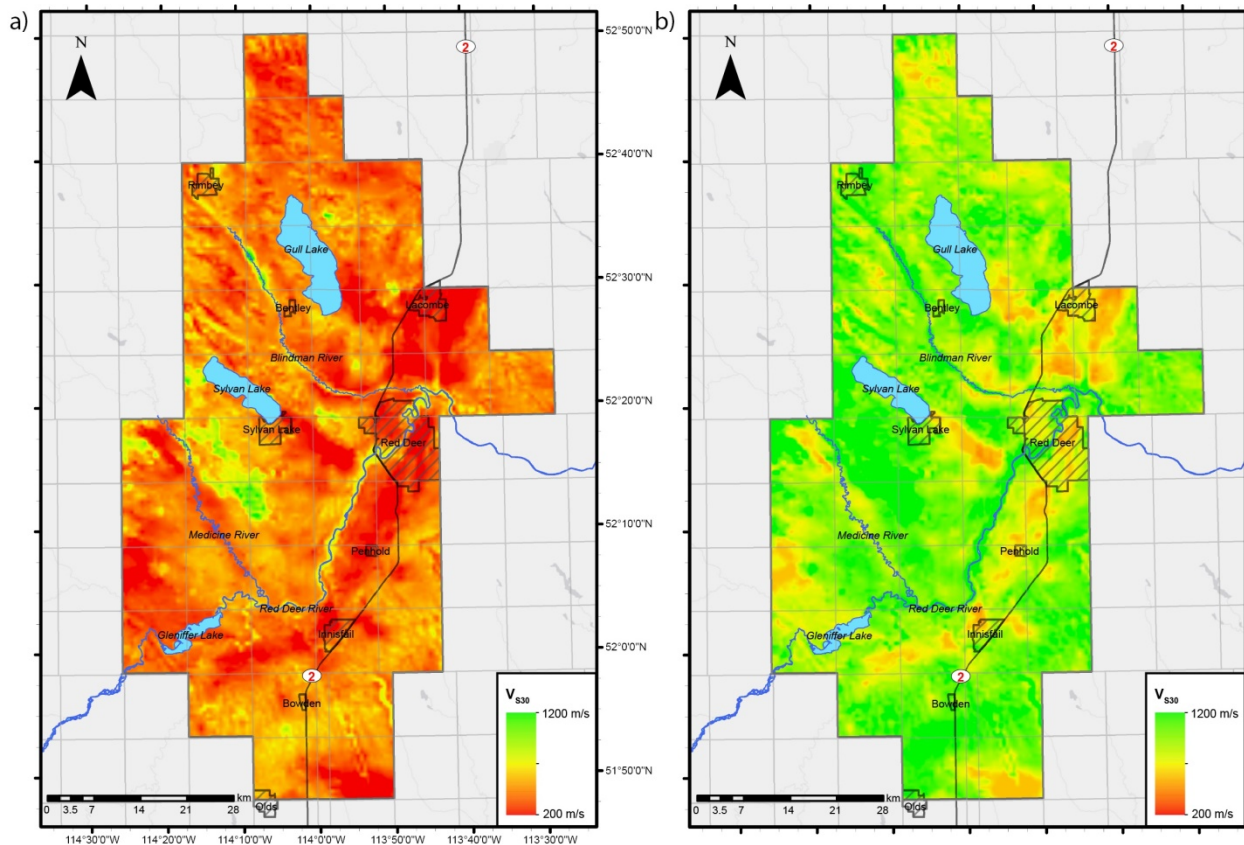
**Table 2. Lithologies observed in the study area (Red Deer area, Alberta) and their respective interpreted shear-wave velocities. Abbreviation: p, percentile.**

Lithology	p10 (m/s)	p50 (m/s)	p90 (m/s)
Sediments above bedrock, undifferentiated	224	327	397
Sediments above bedrock, basal sand and gravel	347	501	732
Bedrock, shale	391	476	589
Bedrock, interbedded shale-sandstone	487	668	861
Bedrock, sandstone	898	1143	1382

Cognizant of the  $V_{strata}$ , location-dependent  $t_{strata}$  is easy to calculate. To do this, a digital stratigraphic model was reconstructed, with a cell density of 0.5 by 0.5 km, of the five units: undifferentiated sediments above bedrock, basal sand and gravel above bedrock (both units from an updated version of the Sylvan Lake sub-basin hydrostratigraphic model; Atkinson and Glombick, 2015), and the three subdivisions of the Paskapoo Formation (from a three-dimensional  $V_{sh}$  property model; Mei, 2019). Every cell was evaluated to ensure that the 30 m depth was maintained and the timing of the waveform going through each formation was calculated using Equation 2. The total time per cell is then used in Equation 1, to calculate a shear-wave velocity for the uppermost 30 m of the succession. To account for the variability in  $V_{strata}$ , a random velocity percentile per strata was assigned and calculated for individual formations, and the final result was averaged from a thousand iterations (Figure 5). This method captures an amplification that is dependent on the strata and the velocity at which shear waves propagate through it. This approach was later modified, and a constant value for the  $V_{strata}$  was used to find the amplification caused by the likely lowest (p10; Figure 6a) and highest (p90; Figure 6b) theoretical velocities. The information shown in Figure 5 was recompiled with the NBCC site classification to best illustrate areas that have the highest susceptibility to ground motion amplification (Figure 7).



**Figure 5. The average shear-wave velocities interpolated for the uppermost 30 m of the subsurface ( $V_{s30}$ ), Red Deer area, Alberta. These values represent the best estimate (50th percentile) from a thousand iterations, where shear-wave velocity per unit was randomly assigned from a bell curve of possibilities.**



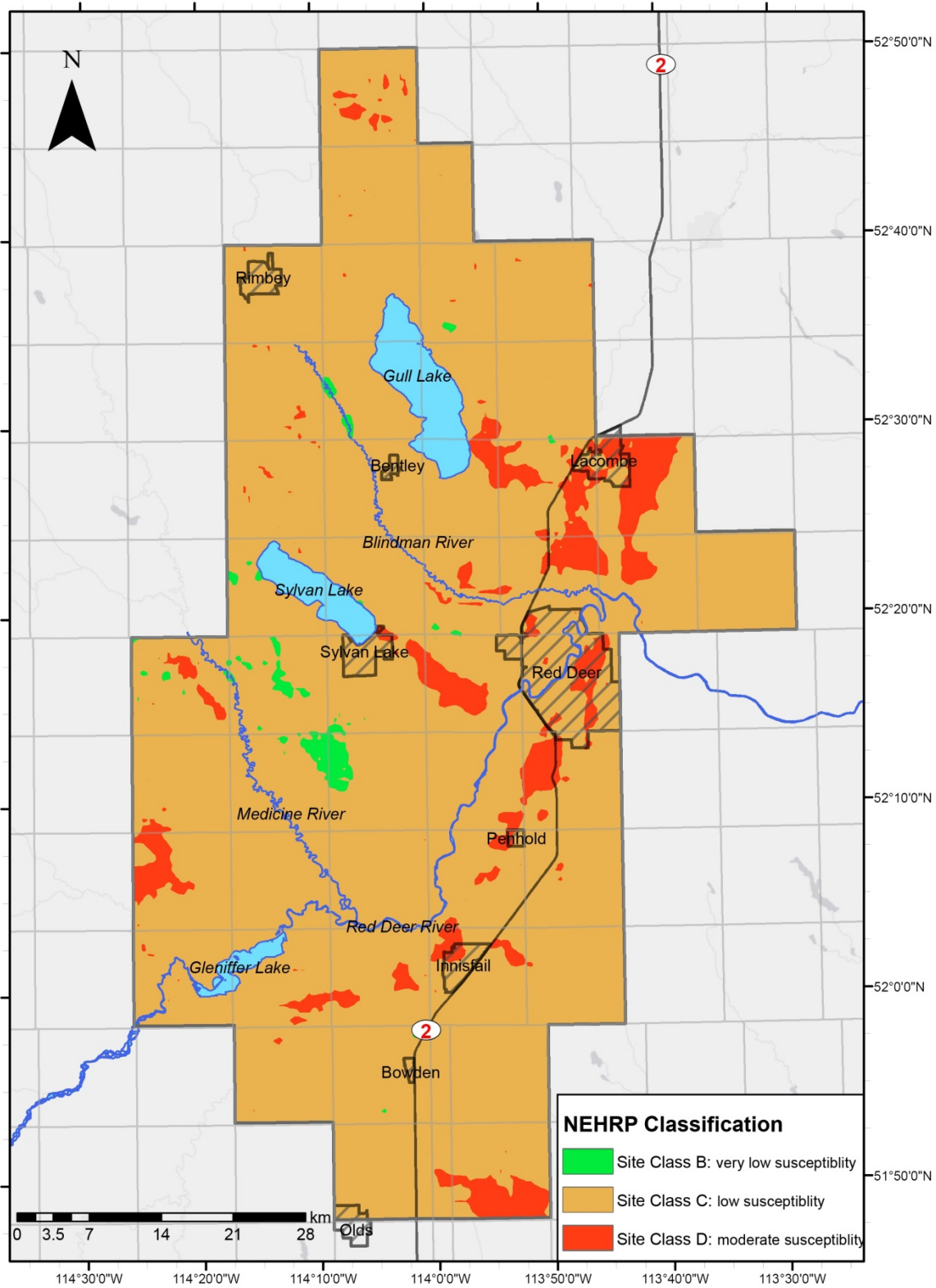
**Figure 6. The average shear-wave velocities interpolated for the uppermost 30 m of the subsurface ( $V_{s30}$ ), Red Deer area, Alberta. These values represent a) the low estimate (10th percentile) and b) the high estimate (90th percentile).**

## 6 Discussion

The data collected, and subsequent interpretations made from the MASW surveys, support previously expected outcomes, i.e., stiffer soils have the highest propagating velocities. In this study area, the stiffest soils were encountered where the sandstone-rich areas of the Paskapoo Formation are at or near the surface, east of the town of Sylvan Lake (Figure 2d). The shale and the interbedded shale-sandstone encountered in other parts of the Paskapoo Formation have progressively lower velocities. The basal sand and gravel above bedrock unit of the Red Deer paleovalley and the undifferentiated sediments above bedrock unit have distinctly lower velocities than the bedrock.

Overall, amplification susceptibility in the study area is deemed to be low, with most of the area classified in Site Class C according to the NEHRP and NBCC classifications, with few areas in Site Class D, and even less in Site Class B. The findings of this study show that a key factor in the susceptibility to amplification of seismic ground motions is the presence of an over-thickened sediment unit above the bedrock. However, other factors such as the paleotopography at the bedrock unconformity can further affect ground motion by focusing incoming seismic waves. Areas with a thinner sediment unit above bedrock could also experience some amplification due to resonance, if the site period matches that of the short period ground motion. As such, findings presented in this research should only be used as a broad assessment of the regional susceptibility. Site-specific evaluations, including site-specific seismic surveys and lithological interpretations, and consideration of the potential for natural and induced seismic activity should be used to inform site-specific hazard assessments.





**Figure 7. The best estimate of shear-wave velocities (50th percentile, Figure 5) organized by the National Earthquake Hazards Reduction Program's (NEHRP) classification (Building Seismic Safety Council, 1994). Based on these findings, the susceptibility of amplification in the study area is directly related to the thickness of the unconsolidated sediments above the bedrock.**

## 7 Conclusions

This study focused on the regional susceptibility to the ground motion amplification from seismic waves near Red Deer. Such analysis is useful in the planning phases of major infrastructure projects, as it can identify areas where more detailed site-specific studies should be considered to evaluate the seismic hazard. In the study area, estimated susceptibility is generally low, but increases in areas with an increasing thickness of the sediment layer above bedrock. This research was conducted on a regional scale and therefore should not be used to assess site-specific susceptibility to ground motion amplification. Instead, it highlights areas where site-specific evaluations may need to be undertaken to better identify and mitigate potential risks from ground motion amplification.

## 8 References

- Alberta Energy Regulator (2019a): Recommendations around hydraulic fracturing in the Red Deer area; Alberta Energy Regulator, AER Bulletin 2019-07, 2 p., URL <<https://www.aer.ca/documents/bulletins/Bulletin-2019-07.pdf>>.
- Alberta Energy Regulator (2019b): Subsurface Order No. 7; Alberta Energy Regulator, 4 p., URL <<https://static.aer.ca/prd/documents/orders/subsurface-orders/SO7.pdf>>.
- Anderson, J.G., Bodin, P., Brune, J.N., Prince, J., Singh, S.K., Quass, R. and Onate, M. (1986): Strong motion from the Michoacan, Mexico, earthquake; *Science*, v. 233, p. 1043–1049.
- Atkinson, L.A. and Glombick, P.M. (2015): Three-dimensional hydrostratigraphic modelling of the Sylvan Lake sub-basin in the Edmonton-Calgary Corridor, central Alberta; Alberta Energy Regulator, AER/AGS Open File Report 2014-10, 58 p., URL <[https://static.ags.aer.ca/files/document/OFR/OFR\\_2014\\_10.pdf](https://static.ags.aer.ca/files/document/OFR/OFR_2014_10.pdf)>.
- Atkinson, L.A., Pawley, S.M., Andriashek, L.D., Hartman, G.M.D., Utting, D.J. and Atkinson, N. (2020): Sediment thickness of Alberta, version 2; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Map 611, URL <[https://static.ags.aer.ca/files/2020-10/MAP\\_611.pdf](https://static.ags.aer.ca/files/2020-10/MAP_611.pdf)>.
- Bard, P. Y. and Bouchon, M. (1985): The two-dimensional resonance of sediment-filled valleys; *Bulletin of the Seismological Society of America*, v. 75, p. 519–541.
- Building Seismic Safety Council (1994): NEHRP recommended provisions for seismic regulations of new buildings: part 1, provisions; Publication FEMA 222A, prepared for Federal Emergency Management Agency, 290 p.
- Demchuk, T.D. and Hills, L. (1991): A re-examination of the Paskapoo Formation in the central Alberta Plains: the designation of three new members; *Canadian Society of Petroleum Geologists Bulletin*, v. 39, no. 3, p. 270–282.
- Fenton, M.M., Waters, E.J., Pawley, S.M., Atkinson, N., Utting, D.J. and McKay, K. (2013): Surficial geology of Alberta; Alberta Energy Regulator, AER/AGS Map 601, URL <[https://static.ags.aer.ca/files/document/MAP/Map\\_601.pdf](https://static.ags.aer.ca/files/document/MAP/Map_601.pdf)>.
- Finn, W.D.L., Onur, T. and Ventura, C.E. (2004): Microzonation: developments and applications; Chapter 1 *in* *Recent Advances in Earthquake Geotechnical Engineering and Microzonation*, A. Ansal (ed.), Kluwer Academic Publishers, Dordrecht, Boston and London, p. 3–26.
- Galloway, E., Hauck, T., Corlett, H., Paná, D. and Schultz, R. (2018): Faults and associated karst collapse suggest conduits for fluid flow that influence hydraulic fracturing-induced seismicity; *Proceedings of the National Academy of Sciences*, v. 115, no. 43, p. E10003–E10012, [doi:10.1073/pnas.1807549115](https://doi.org/10.1073/pnas.1807549115)
- Hunter, J.A. and Crow, H.L., ed. (2012): Shear wave velocity measurement guidelines for Canadian seismic site characterization in soil and rock; Geological Survey of Canada, Open File 7078, 226 p., [doi:10.4095/291767](https://doi.org/10.4095/291767)
- Kramer, S.L. (1996): *Geotechnical Earthquake Engineering*; Prentice Hall, 653 p.
- Lomnitz, C. (1999): The end of earthquake hazard; *Seismological Research Letters*, v. 70, p. 387–388.
- Lyster, S. and Andriashek, L.D. (2012): Geostatistical rendering of the architecture of hydrostratigraphic units within the Paskapoo Formation, central Alberta; Energy Resources Conservation Board, ERCB/AGS Bulletin 66, 103 p., URL <[https://www.ags.aer.ca/document/BUL/BUL\\_066.pdf](https://www.ags.aer.ca/document/BUL/BUL_066.pdf)>.

- Mei, S. (2019): Three-dimensional property modelling of the Scollard, Paskapoo and Porcupine Hills formations in southwest Alberta; Alberta Energy Regulator / Alberta Geological Survey, AER/AGS Open File Report 2019-05, 42 p., URL <[https://www.ags.aer.ca/document/OFR/OFR\\_2019\\_05.pdf](https://www.ags.aer.ca/document/OFR/OFR_2019_05.pdf)>.
- National Research Council (2010): National Building Code of Canada 2010; National Research Council, Volume 2, Division B, Part 4.
- Park, C.B., Miller, R.D. and Xia, J. (1999): Multichannel analysis of surface waves (MASW); Geophysics, v. 64, p. 800–808.
- Pawley, S., Schultz, R., Playter, T., Corlett, H., Shipman, T., Lyster, S. and Hauck, T. (2018): The geological susceptibility of induced earthquakes in the Duvernay play; Geophysical Research Letters, v. 45, issue 4, p. 1786–1793, [doi:10.1002/2017GL076100](https://doi.org/10.1002/2017GL076100)
- Riddell, J.T.F., Andriashek, L.D., Jean, G. and Slattery, S. (2009): Preliminary results of sediment coring in the Edmonton-Calgary Corridor, central Alberta; Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-17, 81 p., URL <[https://static.ags.aer.ca/files/document/OFR/OFR\\_2009\\_17.pdf](https://static.ags.aer.ca/files/document/OFR/OFR_2009_17.pdf)>.
- Schultz, R. and Wang, R. (2020): Newly emerging cases of hydraulic fracturing induced seismicity in the Duvernay East Shale Basin; Tectonophysics, v. 779, art. 228393, [doi:10.1016/j.tecto.2020.228393](https://doi.org/10.1016/j.tecto.2020.228393)
- Schultz, R., Corlett, H., Haug, K., Kocon, K., MacCormack, K., Stern, V. and Shipman, T. (2016): Linking fossil reefs with earthquakes: geologic insight to where induced seismicity occurs in Alberta; Geophysical Research Letters, v. 43, issue 6, p. 2534–2542, [doi:10.1002/2015GL067514](https://doi.org/10.1002/2015GL067514)
- Schultz, R., Atkinson, G., Eaton, D.W., Gu, Y.J. and Kao, H. (2018): Hydraulic fracturing volume is associated with induced earthquake productivity in the Duvernay play; Science, v. 359, issue 6373, p. 304–308, [doi:10.1126/science.aao0159](https://doi.org/10.1126/science.aao0159)
- Shearer, P.M. and Orcutt, J.A. (1987): Surface and near-surface effects on seismic waves - theory and borehole seismometer results; Bulletin of the Seismological Society of America, v. 77, p. 1168–1196.
- Wang, J., Li, T., Gu, Y.J., Schultz, R., Yusifbayov, J. and Zhang, M. (2020): Sequential fault reactivation and secondary triggering in the March 2019 Red Deer induced earthquake swarm; Geophysical Research Letters, v. 47, [doi:10.1029/2020GL090219](https://doi.org/10.1029/2020GL090219)
- Wetmiller, R.J. (1986): Earthquakes near Rocky Mountain House, Alberta, and their relationship to gas production facilities; Canadian Journal of Earth Sciences, v. 23, no. 2, p. 172–181, [doi:10.1139/e86-020](https://doi.org/10.1139/e86-020)

**Appendix 1 – Frontier Geosciences Inc.’s *Multichannel Analysis of Surface Waves Survey Report, Red Deer Area, AB***



# FRONTIER GEOSCIENCES INC.

## MULTICHANNEL ANALYSIS OF SURFACE WAVES SURVEY REPORT RED DEER AREA, AB

Submitted to:  
**Alberta Energy Regulator**  
November 8, 2019

Authors:  
Owen Jones, GIT  
Beth Galambos, P.Geo.

Project: FGI-1637

Table of Contents

1. Introduction	1
2. Seismic Refraction and Multichannel Analysis of Surface Waves (MASW)	2
2.1 Survey Equipment	2
2.2 Survey Procedure	2
2.3 MASW Interpretive Method	3
4. Geophysical Results	4
4.1 General	4
4.2 Discussion	4
5. Limitations	7

Illustrations

	Location
Figure 1 Survey Location Plan	Appendix
Figure 2 SL19-1 Site Plan	Appendix
Figure 3 Interpreted MASW Section SL19-1	Appendix
Figure 4 SL19-2 Site Plan	Appendix
Figure 5 Interpreted MASW Section SL19-2	Appendix
Figure 6 SL19-3 Site Plan	Appendix
Figure 7 Interpreted MASW Section SL19-3	Appendix
Figure 8 SL19-4 Site Plan	Appendix
Figure 9 Interpreted MASW Section SL19-4	Appendix
Figure 10 SL19-5 Site Plan	Appendix
Figure 11 Interpreted MASW Section SL19-5	Appendix
Figure 12 SL19-6 Site Plan	Appendix
Figure 13 Interpreted MASW Section SL19-6	Appendix
Figure 14 SL19-7 Site Plan	Appendix
Figure 15 Interpreted MASW Section SL19-7	Appendix

**1. Introduction**

During the period of September 10 and September 11, 2019, Frontier Geosciences Inc. carried out a multichannel analysis of surface waves (MASW) investigation for Alberta Energy Regulator in Red Deer, AB. A Survey Location Plan of the area is shown at a scale of 1:300,000 in Figure 1.

The purpose of the geophysical survey was to determine shear wave velocity information of subsurface materials across multiple sites in the Red Deer Area. Approximately 820 metres of detailed seismic MASW data was collected along seven lines, at seven separate locations. Site Plans of individual sites showing the line locations are presented at a scale of 1:1,500 in Figures 2, 4, 6, 8, 10, 12 and 14 in the Appendix.

## **2. Seismic Refraction and Multichannel Analysis of Surface Waves (MASW)**

### **2.1 Survey Equipment**

The MASW investigation was carried out using two Geometric Geode, 24 channel, signal enhancement seismographs and Oyo Geospace 10 Hz geophones. Geophone intervals along the multicored seismic cable were maintained at 2.5 metres in order to ensure high resolution data on subsurface layering. Seismic energy was provided from a sledgehammer striking a steel plate, with shot initiation or zero time was established by metal to metal contact of the hammer striking the plate.

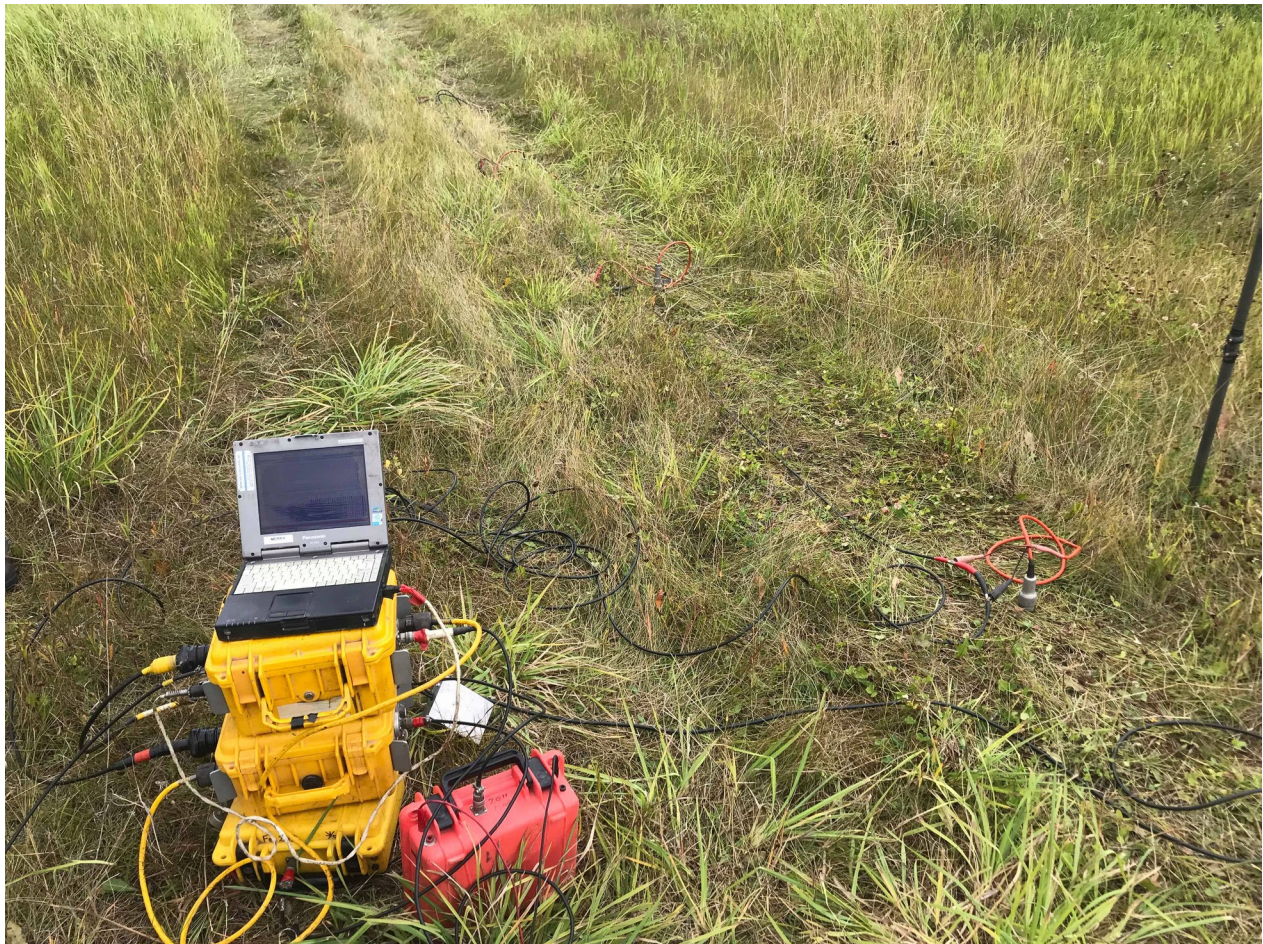
### **2.2 Survey Procedure**

Field procedure entailed setting out two 24 channel geophone cables in a straight line and implanting the geophones. The line was traversed with the sledgehammer source, moving progressively down the array of geophones. The seismic source was operated at each individual shotpoint and up to 48 channels of data were recorded digitally with the seismograph. The record lengths were planned to be sufficiently long to capture the full surface wave train. For quality assurance, field inspection of raw data after each shot was carried out, with additional shots recorded if first arrivals were unclear. Data recorded during field surveying operations was generally of good to excellent quality.

Throughout the survey, notes were recorded regarding seismic line positions in relation to topographic and geological features. Relative elevations along the seismic lines were recorded by chain and inclinometer.

### **2.3 MASW Interpretive Method**

Interpretation of the MASW data involves a wavefield transformation of the seismogram record. This converts the seismogram from a multichannel shot gather to a dispersion curve that shows the phase velocity of the signal as a function of frequency. The fundamental event is picked on the dispersion curve and this data is inputted into the ParkSeis modelling program for inversion. The resulting model reveals the shear wave layer velocity structure, and is plotted at the centre of picked geophone array. The individual models produced are then gridded together to produce a shear wave velocity depth section along the survey lines.



*Survey Set Up at SL-5*



## **4. Geophysical Results**

### **4.1 General**

The interpreted results of the MASW lines SL19-1 to SL19-7 are illustrated in Figures 3, 5, 7, 9, 11, 13, and 15 at a scale of 1:500, in the Appendix. Corresponding individual site plans for each location are displayed at a scale of 1:1,500 in Figures 2, 4, 6, 8, 10, 12, and 14. The shear wave velocity data are displayed as colour contours on the profile, with cool colours indicating lower values and warm colours indicating higher values.

### **4.2 Discussion**

Line SL19-1 is located just northeast of Red Deer. The line runs west to east on the western side Range Road 265, 500 metres north of Township Road 390. The interpreted MASW results for line SL19-1 is presented in Figure 3. The shear wave velocities gradually increase with depth, displaying a range from 200 m/s at surface to 600 m/s at approximately 30 metres depth. The interpreted MASW profile displays the 400 m/s shear wave velocity contour occurring a depth of approximately 15 metres. These velocities are indicative of soft to stiff clays, sands and gravels, with higher velocities at depth likely corresponding to an increase in stiffness and/or compaction.

Figure 5 displays the interpreted results of the MASW data along SL19-2. Line SL19-2 is located in south Red Deer, running west to east parallel to Wedgewood Lane. The shear wave velocities continuously increase with depth from approximately 220 m/s at surface, to reaching a maximum velocity of 950 m/s at 30 m depth near STN 30E. Shear wave velocities in the range of approximately 220 m/s to 600 m/s correspond to clays, silts, sands, sands & gravels.. Higher shear wave velocities over 800 m/s are encountered at around 25 metres depth, indicating possible clay till or the onset of shale or sandstone bedrock.

Line SL19-3 is located approximately eight kilometres north of Innisfail, running south to north at the western end of Range Road 362. Figure 7 displays the interpreted results of the MASW data along SL19-3. The shear wave velocity profile shows the most gradual increase of all the profiles, with interpreted shear wave velocities of 250 m/s at surface to the 400 m/s contour at an average depth of 20 metres. These velocities are indicative sandy clays, sands, and sandy clay encountered in nearby water wells. Beneath this contour, velocities are increase to above 700 m/s, consistent with a general increase in compaction and/or density of soils.

Line SL19-4 is located at Gablehouse Farm & Gardens, approximately 13 kilometres southwest of Sylvan Lake. The line runs south to north on the eastern side of the clearing east of the house. Figure 9 displays the interpreted results of the MASW data along SL19-4. The shear wave velocity profile displays a wide range of values from 350 m/s at surface to 1250 m/s at 30 metres below surface. Velocities increase from around 350 m/s at surface to the 600 m/s contour at a depth of approximately 10 metres. Below this velocities increase, much more significantly in the north of the sections, with the transition into 1000 m/s shear velocity occurring at a depth of 29 metres at STN 10N, rising to a depth of 8 metres at STN 100N.

Figure 11 shows the interpreted results of the MASW data along SL19-5. Line SL19-5 is located approximately 10 kilometres southeast of Sylvan Lake. The line runs south to north, south of the property at the corner of Highway 596 and Range Road 12. The results illustrate a thick surficial layer with very homogeneous shear wave velocities averaging approximately 350 m/s. This layer extends to an average depth of 20 m and is consistent with stiff soils, such as clay or clay till. Beneath this layer velocities increase quickly, reaching close to 1000 m/s at the south end of the line.

Figure 13 displays the interpreted results of the MASW data along SL19-6. Line SL19-6 is located approximately 17 kilometres west of Red Deer. The line runs south to north, 300 metres east of the intersection at Township Road 380 and Range Road 283. Similar to line SL19-5, the results illustrate a thick surficial layer with velocities averaging approximately 400 m/s. This layer extends to an average depth of 25 m and is consistent with stiff to dense soils, such as clay. A minor velocity inversion is observed over the southwestern half of the profile at approximately 15 m depth. This inversion may be due to a geological thin layer change. A shear wave velocity high is present at depth at STN 65NE, with velocities increasing to over 1000 m/s this may correspond to the top of sedimentary bedrock in the area.

Line SL19-7 is located just southeast of Red Deer. The line runs west to east on the eastern edge of Range Road 270, halfway between Township Road 374 and 372. Figure 15 shows the interpreted results of the MASW data along SL19-7. The shear wave velocities increase consistently with depth, ranging from 250 m/s at surface to 1000 m/s at 30 metres depth. Velocities within this zone are consistent with stiff to hard clay, with higher velocities indicating possible clay till, or sedimentary bedrock. The velocity layers displayed are closely parallel to surface, with a small depression in contours observed at STN 60E. Velocities change at a relatively uniform rate with depth. The gradual change suggests a more homogeneous lithology with an increase in compaction, rather than a distinct compositional change.



**5. Limitations**

The multichannel analysis of surface waves (MASW) method is carried out in the Active or Passive mode with the Active mode generally the most accurate for evaluation of shallow, shear wave velocities. For this survey the Active mode was utilized. Limitations include reflection and scattering of surface and body waves due to extreme surface topography and in-homogeneous conditions in the subsurface such as boulder concentrations or isolated soil lenses with contrasting properties. The method is generally accepted as an effective means of determining shear wave velocities of geological units.

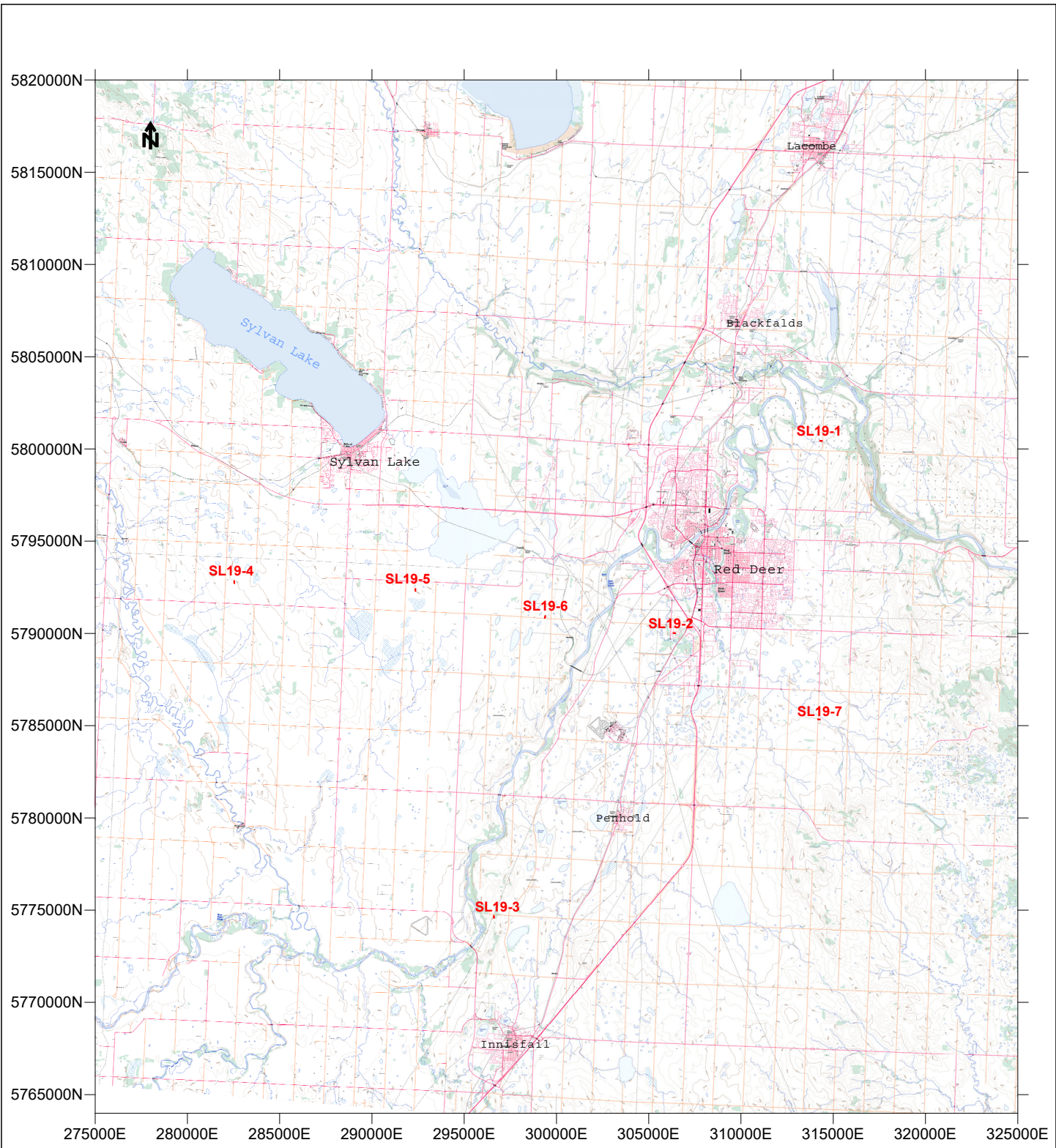
The information in this report is based upon geophysical measurements and field procedures and our interpretation of the data. The results are interpretive in nature and are considered to be a reasonably accurate representation of existing subsurface conditions within the limitations of the seismic refraction and MASW methods.

For: Frontier Geosciences Inc.

Owen Jones, GIT

Beth Galambos, P.Geo.

**APPENDIX**



KILOMETRES

ALBERTA ENERGY REGULATOR  
RED DEER AREA, AB

MASW SURVEY

SURVEY LOCATION PLAN

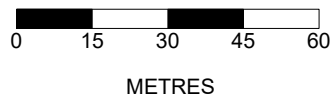
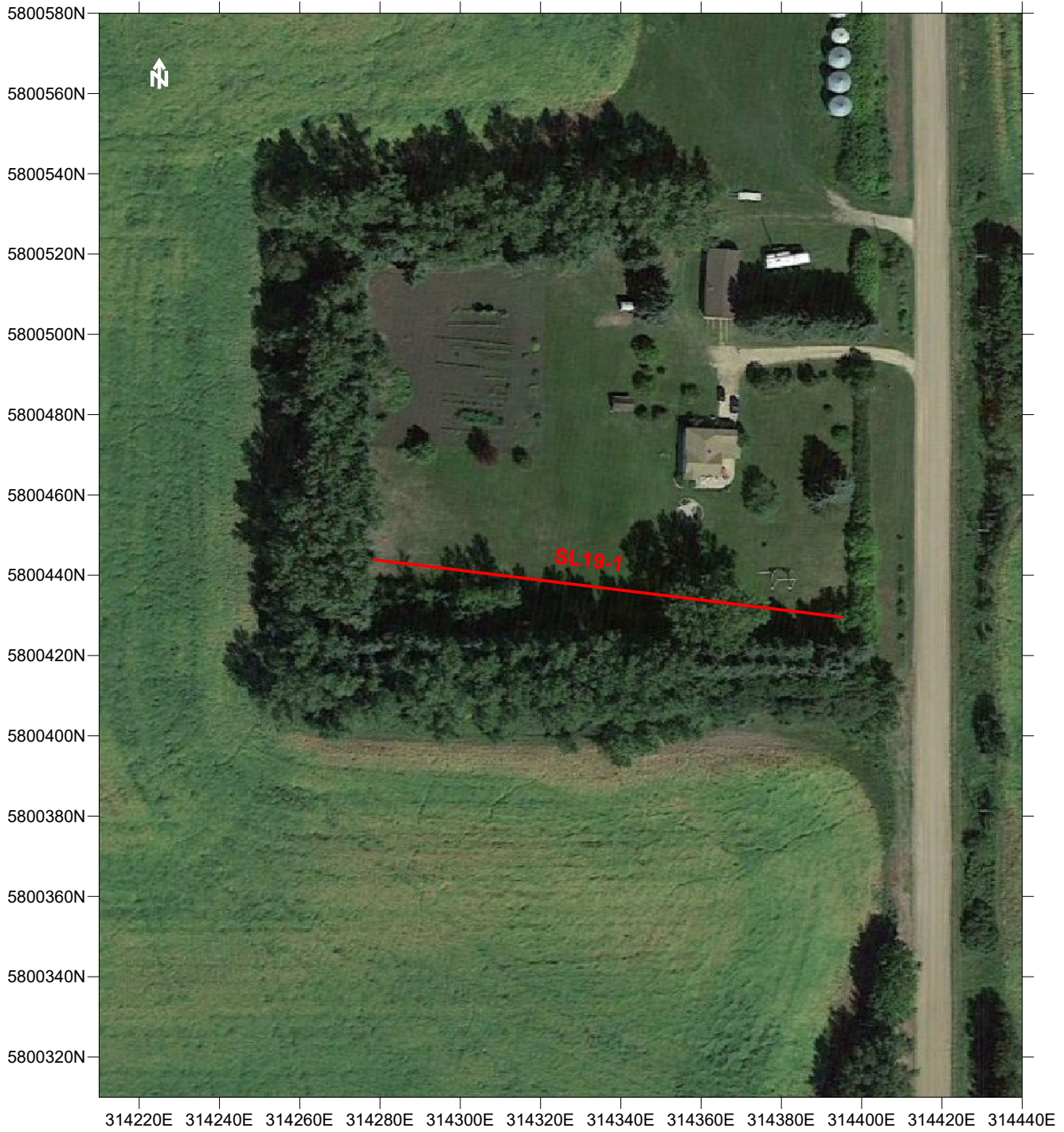
**FRONTIER GEOSCIENCES INC.**

DATE: SEPT. 2019

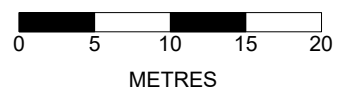
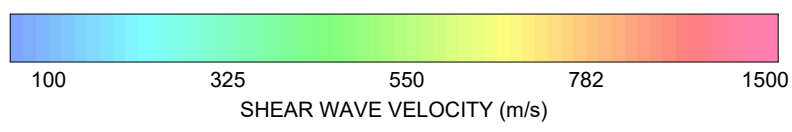
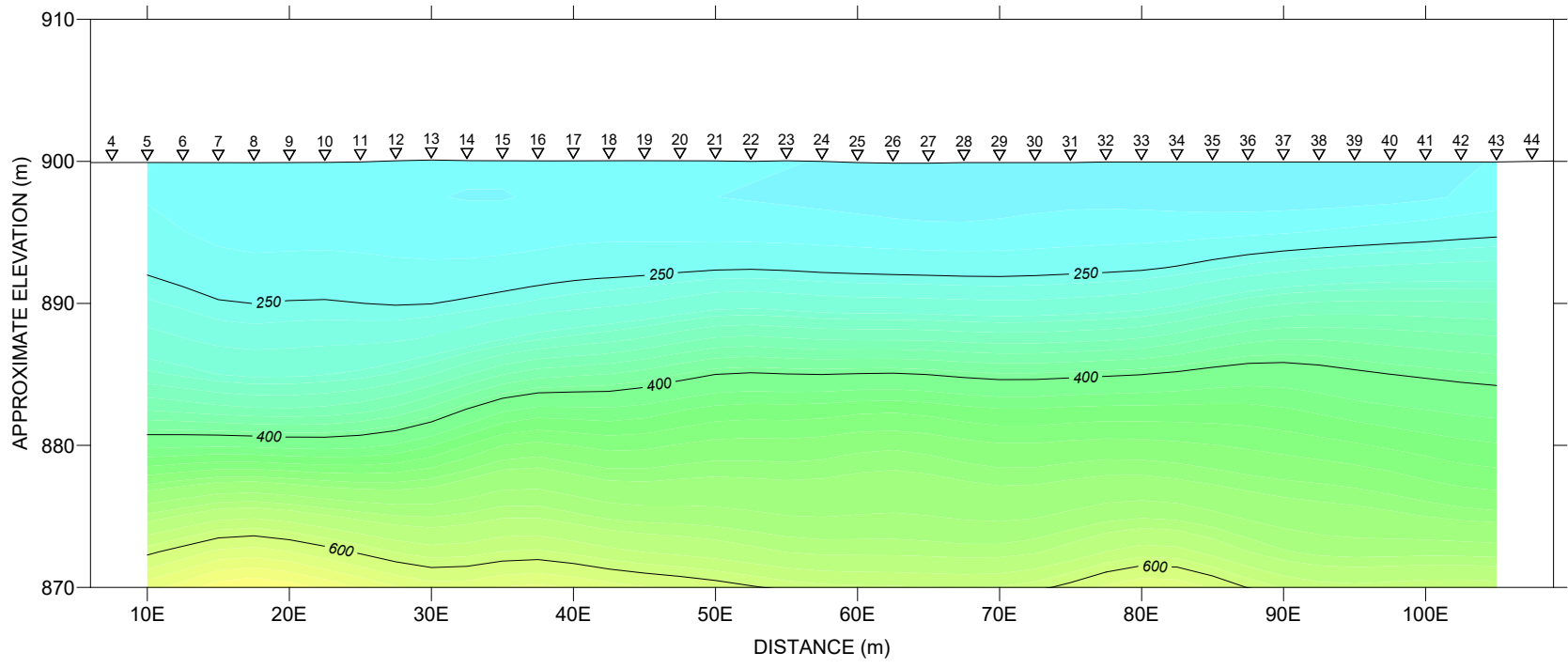
SCALE 1:300,000

FIG. 1

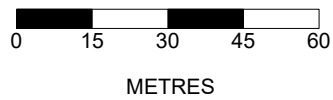




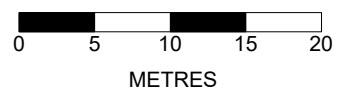
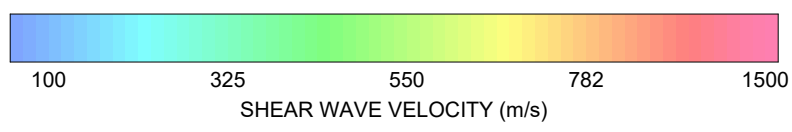
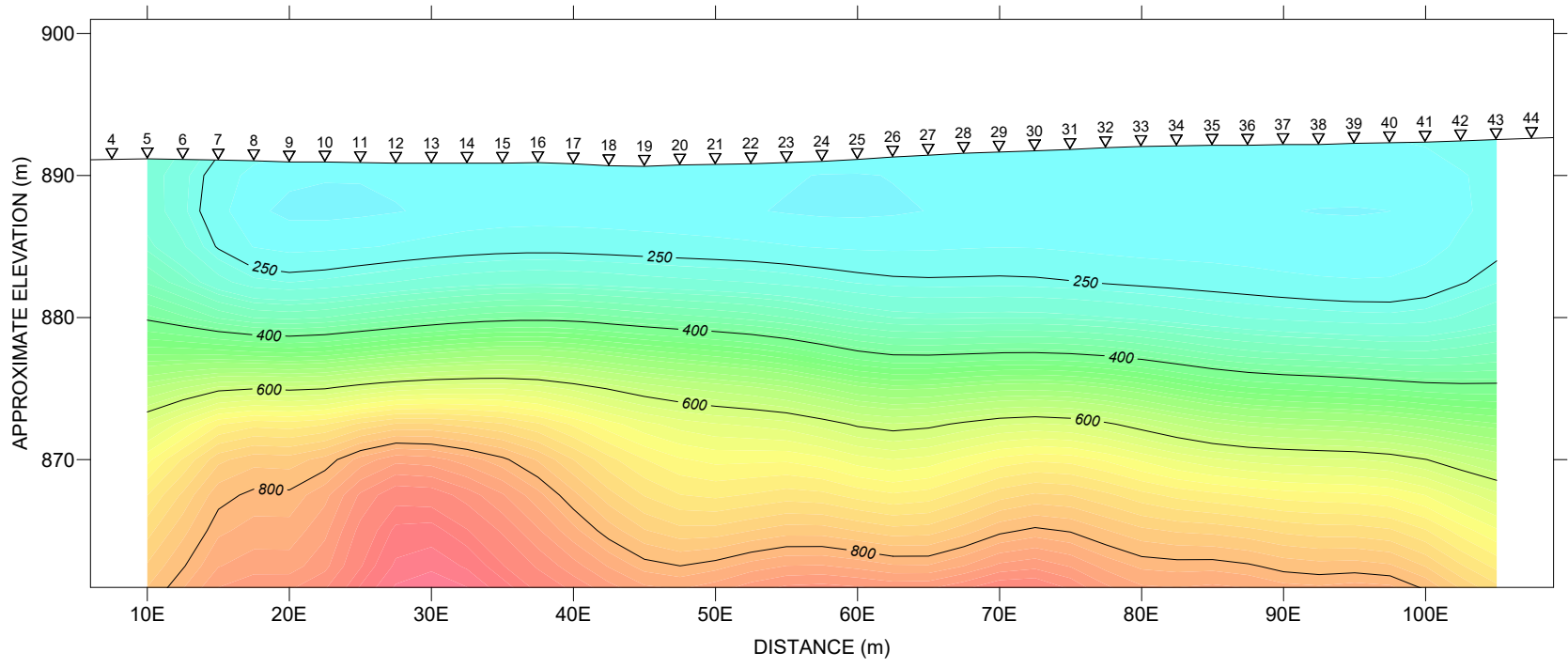
ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
SL19-1 SITE PLAN		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:1,500	FIG. 2



ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
INTERPRETED MASW SECTION SL19-1		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:500	FIG. 3

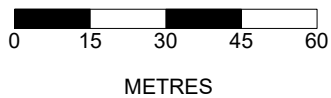


ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
SL19-2 SITE PLAN		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:1,500	FIG. 4



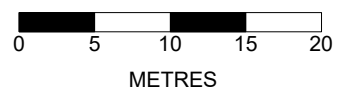
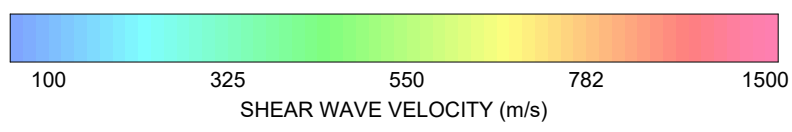
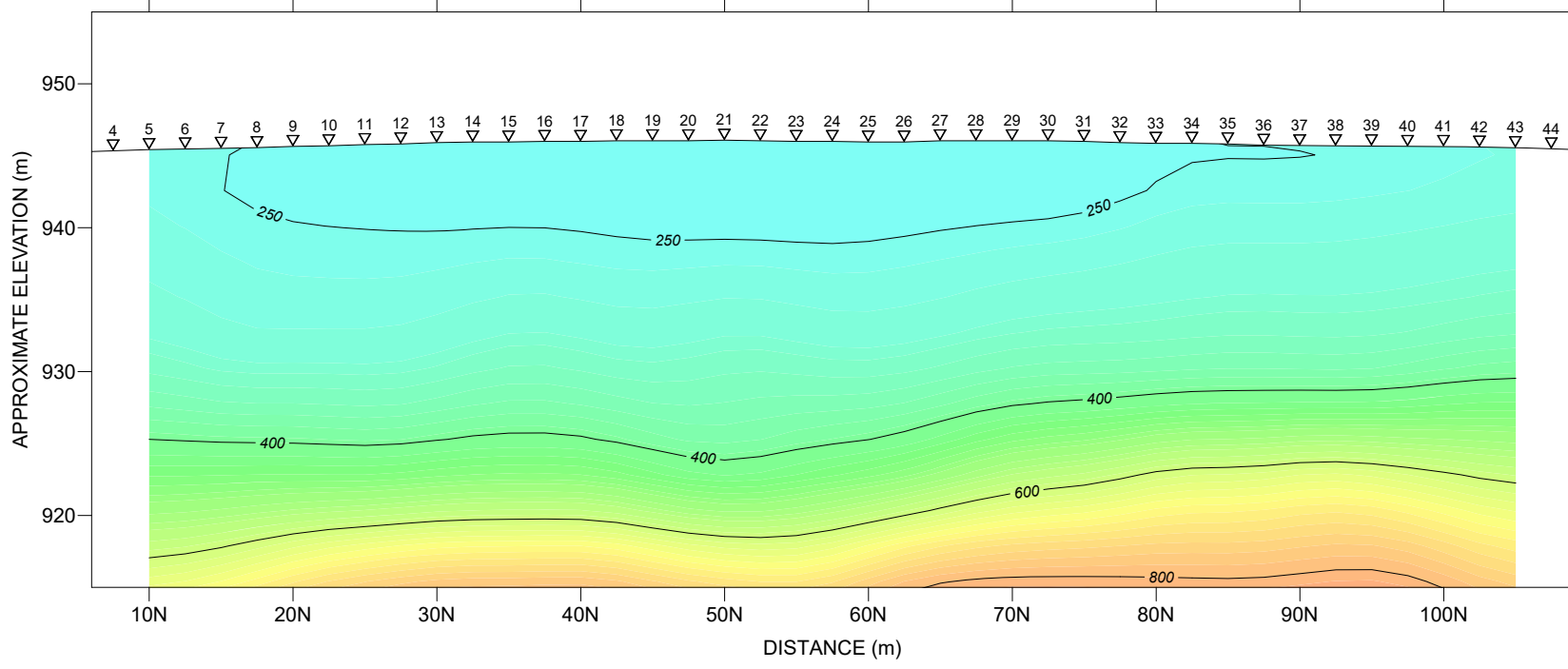
ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
INTERPRETED MASW SECTION SL19-2		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:500	FIG. 5



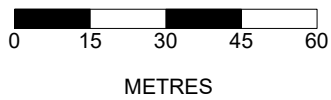
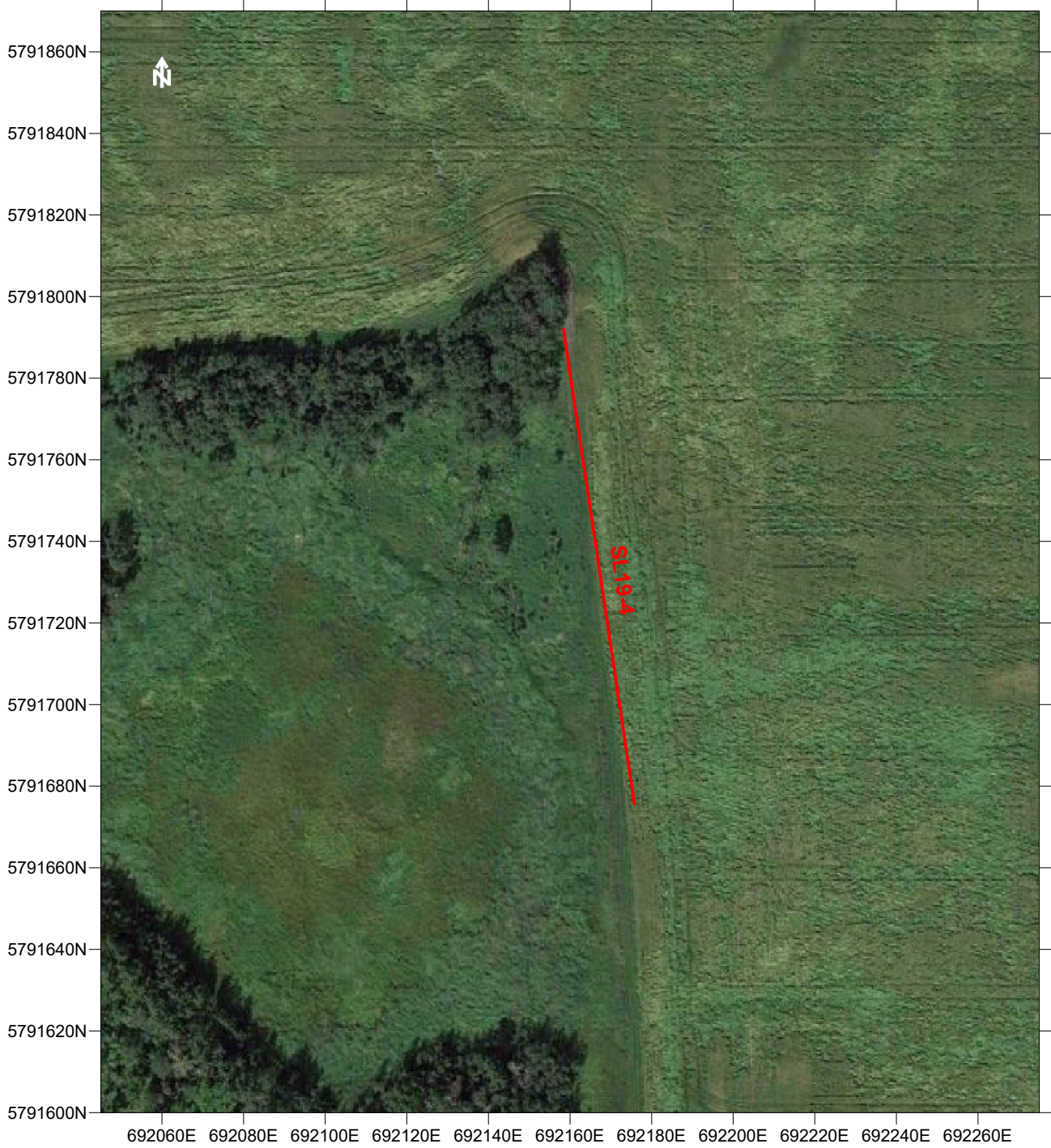


ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
SL19-3 SITE PLAN		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:1,500	FIG. 6

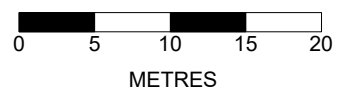
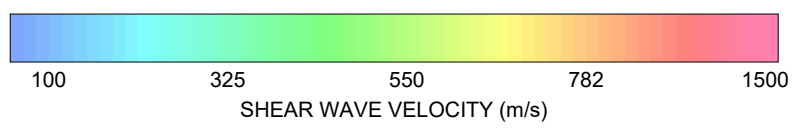
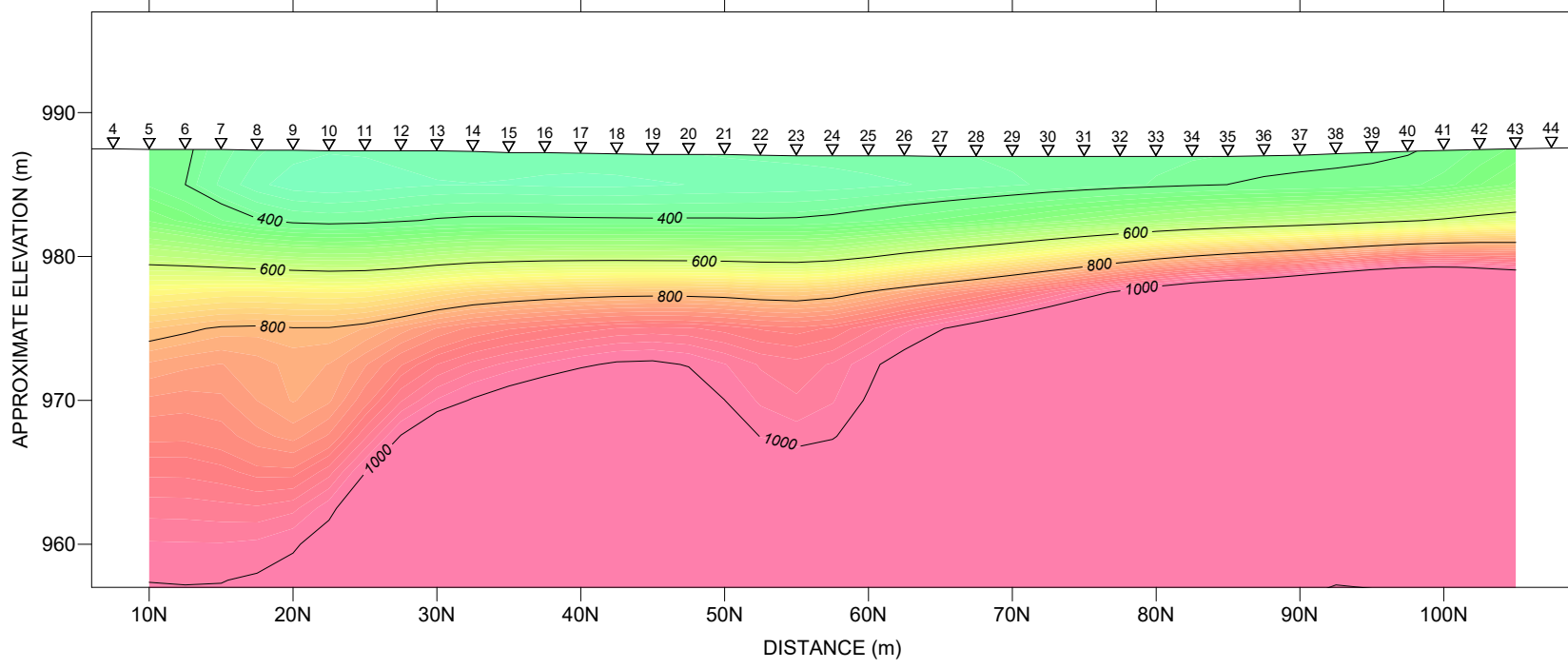




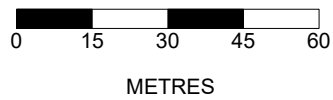
ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
INTERPRETED MASW SECTION SL19-3		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:500	FIG. 7



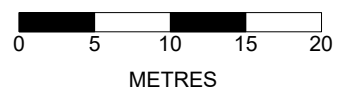
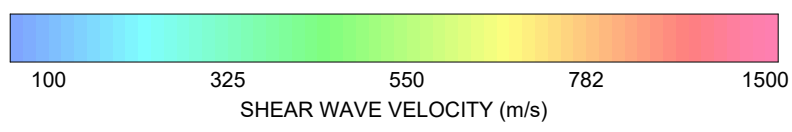
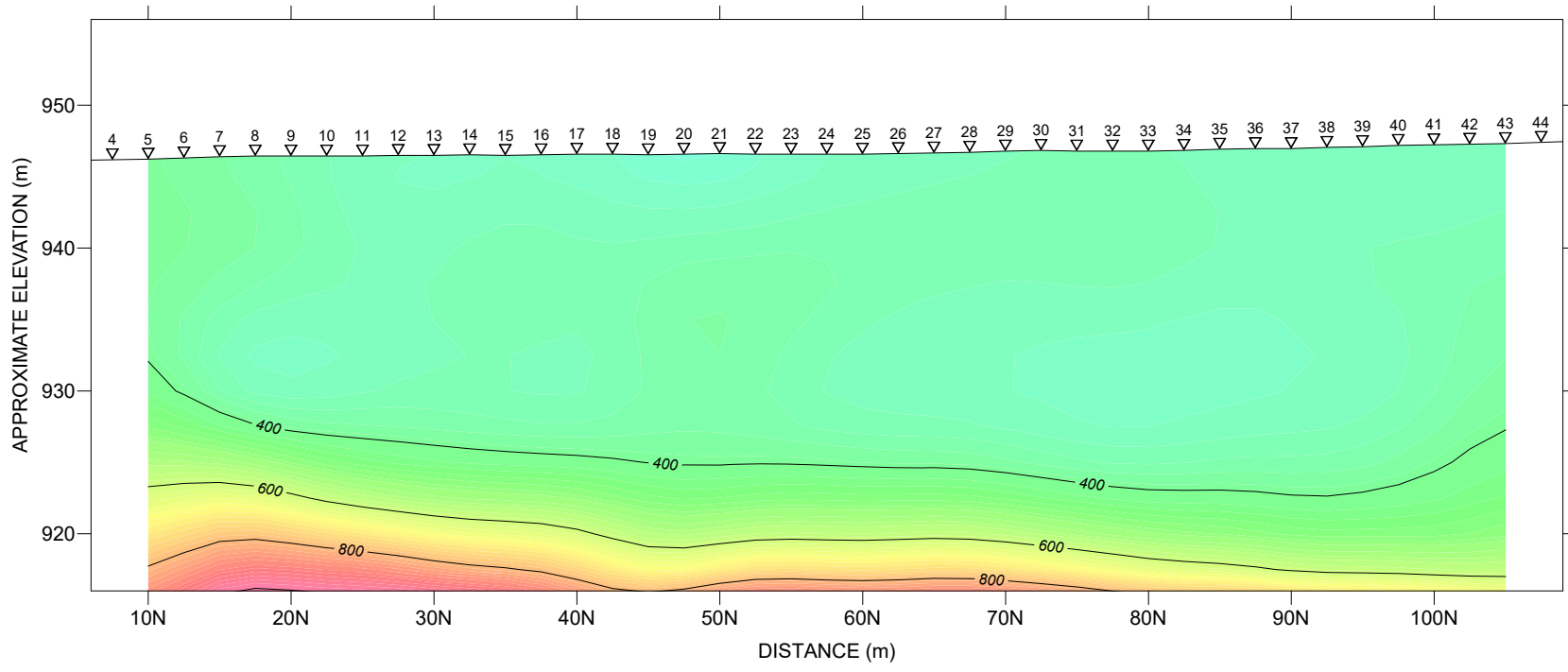
ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
SL19-4 SITE PLAN		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:1,500	FIG. 8



ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
INTERPRETED MASW SECTION SL19-4		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:500	FIG. 9

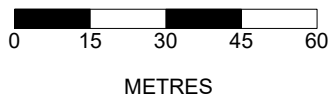
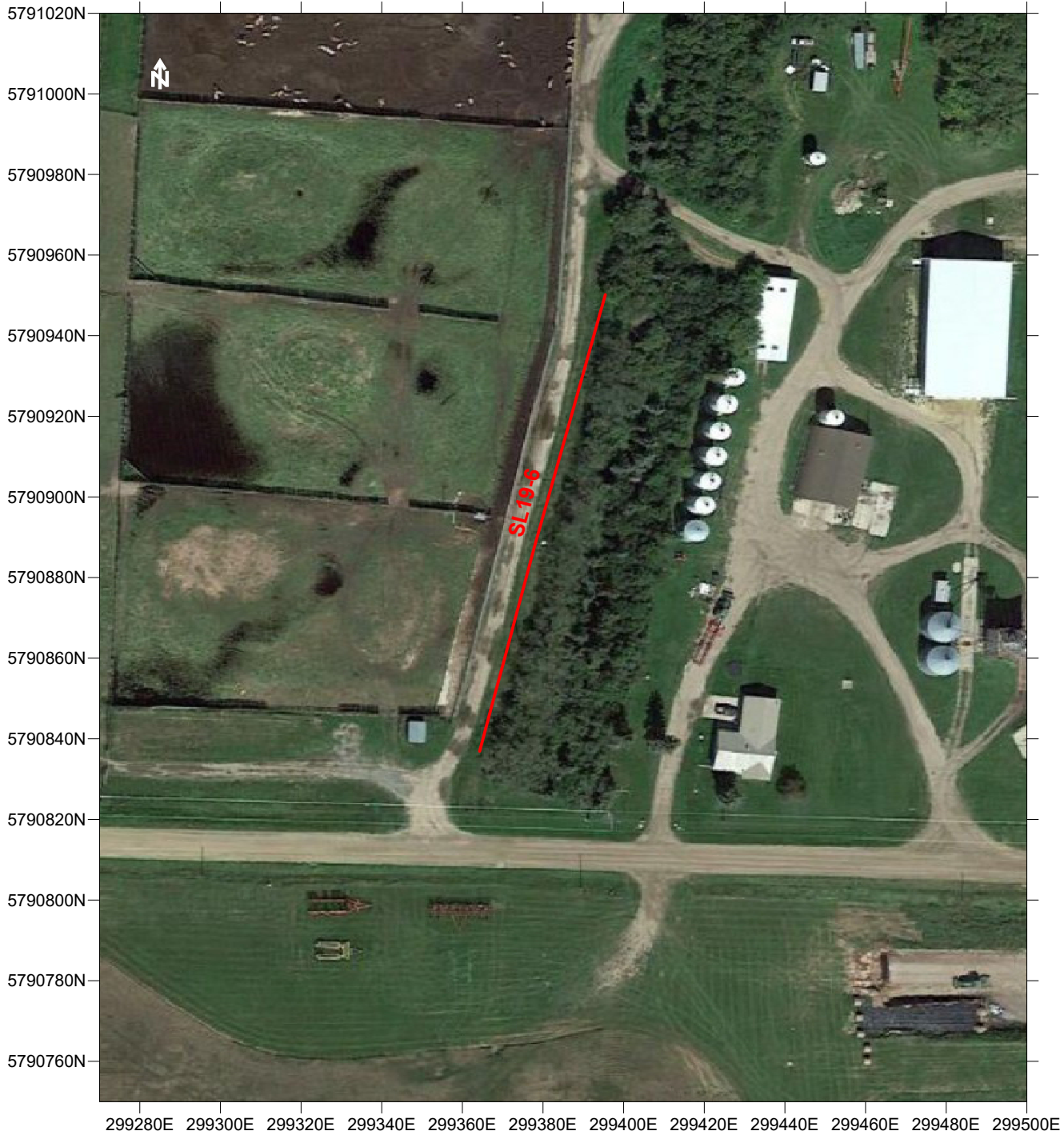


ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
SL19-5 SITE PLAN		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:1,500	FIG. 10

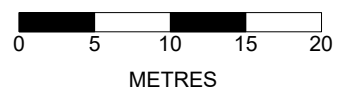
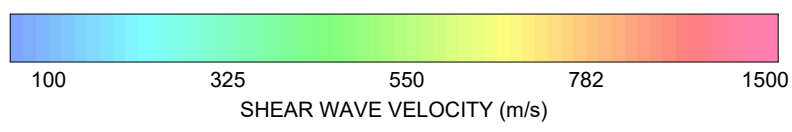
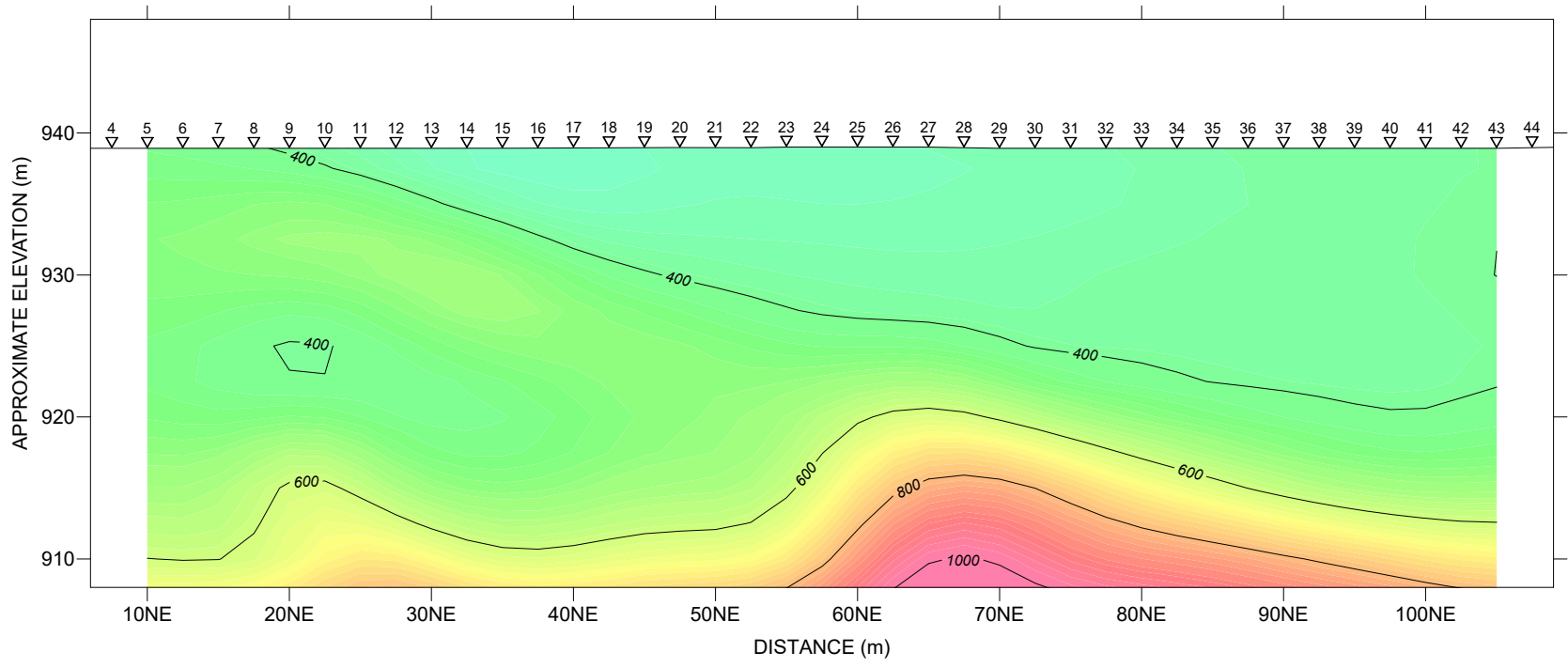


ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
INTERPRETED MASW SECTION SL19-5		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:500	FIG. 11

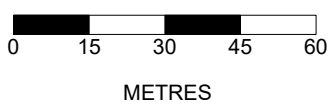




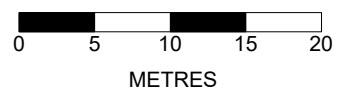
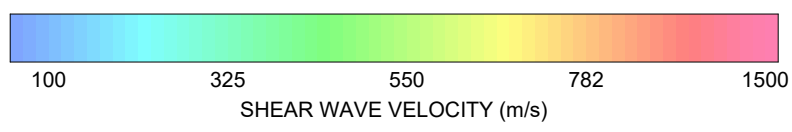
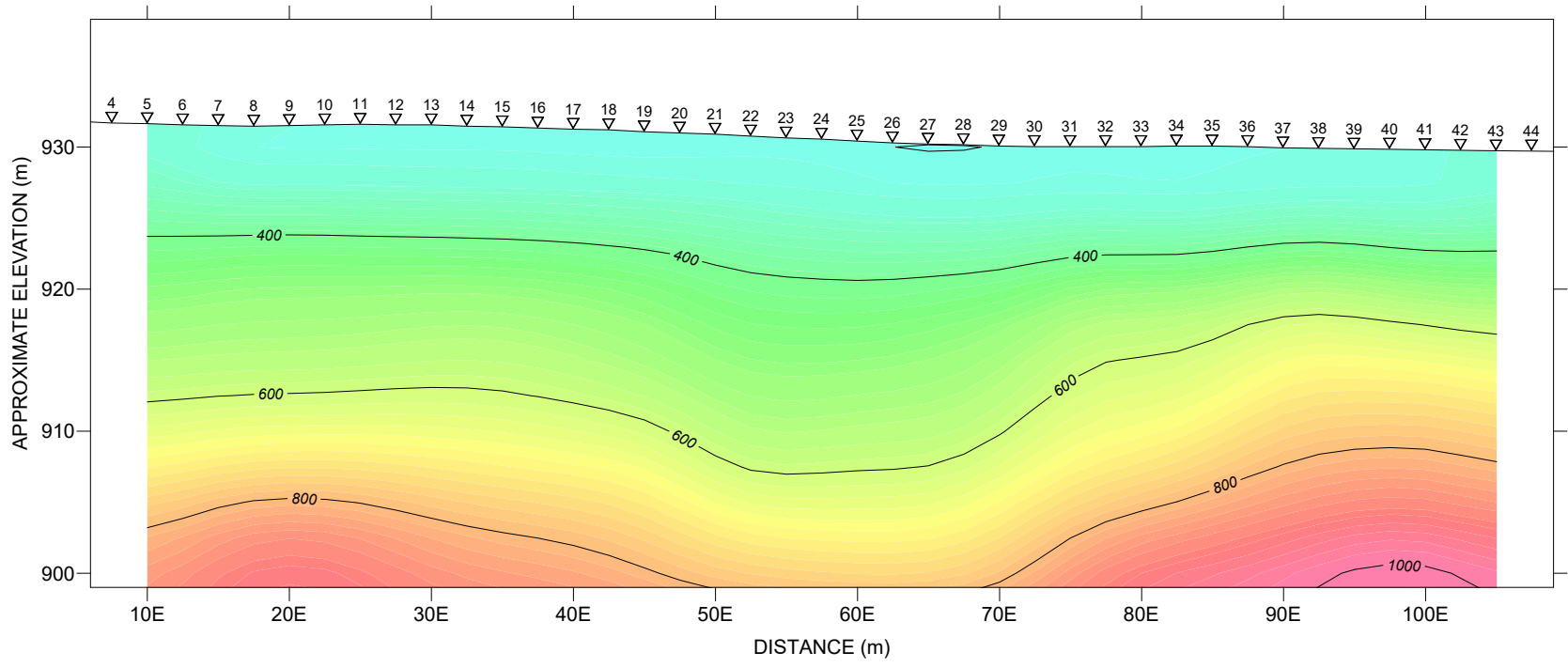
ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
SL19-6 SITE PLAN		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:1,500	FIG. 12



ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
INTERPRETED MASW SECTION SL19-6		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:500	FIG. 13



ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
SL19-7 SITE PLAN		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:1,500	FIG. 14



ALBERTA ENERGY REGULATOR RED DEER AREA, AB		
MASW SURVEY		
INTERPRETED MASW SECTION SL19-7		
FRONTIER GEOSCIENCES INC.		
DATE: SEPT. 2019	SCALE 1:500	FIG. 15