Delineating Buried Valleys in Southwestern Manitoba using Seismic Reflection Methods

Final Report for Field Program 2006-07
March 2007

Collaborative Research Agreement between

West Souris River Conservation District

Manitoba Water Stewardship

Geological Survey of Canada (Natural Resources Canada)

with additional funding from the National Water Supply Expansion Program through the Prairie Farm Rehabilitation Administration (Agriculture and Agri-Food Canada)

and support from the Turtle Mountain Conservation District (TMCD)

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Background:

Much of Southwestern Manitoba does not have access to high yield sources of groundwater supply from bedrock or drift aquifers. Bedrock aquifers generally have low or spatially variable yields and often have poor water quality due to high mineralization. Shallow unconfined aquifers such as the Oak Lake aquifer have higher yields and better water quality but are more vulnerable to surface contamination. The spatial extent of these aquifers is generally limited and water supplies are needed beyond these areas. Surface water is also used as a water supply in the region, but it is less secure and reliable. With increasing demand for more reliable and secure water supplies, attention is turning toward the water supply potential from sands and gravels found within buried valley features (Fig. 1). Considerable development of water from these features has already occurred in the Brandon and Waskada areas. Although the short-term yield from many of these aquifers is substantial, the long-term yield may be severely restricted by limited recharge. Thus, more information on the location and stratigraphy of these buried valley features is required in order to effectively understand and manage this groundwater resource. It was known from a short seismic reflection profile acquired in 1999 south of Brandon, Manitoba, that seismic reflection methods have the potential to map the subsurface architecture and delineate buried valleys in this area.

This report presents the results of a seismic reflection field program carried out in September 2006. The objective of this work was to determine the effectiveness of seismic methods as a tool to delineate the subsurface extent and stratigraphy of buried valleys in Southwestern Manitoba, by conducting field tests of compressional (P) and horizontally-polarized shear (SH) wave shallow seismic reflection methods using different sources and receiver layouts over well-documented buried valley locations. The target for this year was the Medora-Waskada valley (Fig. 1) along two sections where some geologic control already exists. The ultimate goal of this project is to develop and demonstrate an effective method for locating and characterizing buried valleys to aid in the management and development of groundwater resources in Southern Manitoba.

Annex 1 provides some general information on shallow seismic reflection methods as background to this report.
Workplan for 2006-07:

2. Literature review and discussions with provincial partners to determine test sites.
3. Field tests of P- and SH-wave shallow seismic reflection methods over 2 well-documented buried valley locations (2 weeks of field work in September 2006, 2 lines of 1-2 km each). Planned configurations include:
   - Compressional (P-) wave surveys
     i. geophones planted in ditch, (vertical geophone landstreamer if available)
     ii. in-hole source, Minivib source, (thumper source if funds available – not available)
   - Shear (SH-) wave surveys (horizontally-polarized shear wave)
     iii. geophones planted in ditch, horizontal geophone landstreamer,
     iv. hammer source, Minivib source.
4. *Prepare preliminary report including processed data, recommended methods, and proposed future project plans to be distributed to provincial partners for discussion and review by January 31, 2007.
5. *Final report including all data, final results and processed seismic sections, recommended methods and proposed 2007-08 workplans to be submitted to provincial partners by March 31, 2007.

*Note:* This document constitutes the reporting for 2006-07. Items 4 and 5 above were amended to:

4. Prepare draft final report including all data, final results and processed seismic sections, recommended methods and proposed 2007-08 workplans to be distributed to provincial partners by February 28, 2007. Submit the final report by March 31, 2007.
Figure 1: Estimated distribution of buried valleys of south-western Manitoba. (source: Betcher, MWS). The greens represent the higher elevations of the Manitoba Upland.
Accomplishments 2006-07:

1. Construct and test P- and SH-wave landstreamers:
Both P- and SH-wave landstreamers were constructed and tested during the summer of 2006. The SH-wave landstreamer array consists of 24 (or 48) sleds at 0.75m spacing, with 2 horizontal 8 Hz geophones per sled (Fig. 2), cross-connected as described in Pugin et al. (2002). For P-wave surveys, one vertical 40 Hz geophone was mounted on each sled and the sled spacing was increased to 3 m spacing (Fig. 2). Mating the landstreamer receiver array with the Minivib source (Fig. 3) produced excellent results in tests in the Ottawa area, and we were very interested to see the results that could be obtained with this system in the different geological setting found in southern Manitoba.

![Figure 2: Photo of the Minivib source and SH-wave landstreamer (left) and P-wave landstreamer (right) in operation in SW Manitoba, 2006.](image)

![Figure 3: Photos of the IVI Minivib minibuggy vibratory source in operation.](image)
2. Discussions with provincial partners to determine test sites

The test sites for the 2006-07 seismic field program were determined through discussions with Bob Betcher (Manitoba Water Stewardship). Seismic surveys were proposed for the Medora-Waskada valley since the narrow width of the valley would permit the comparison of multiple source-receiver configurations. This valley also had some of the highest quality borehole records in the area; boreholes drilled by the GSC in 1967-68 included the collection of sidewall samples at 10 foot intervals and downhole geophysical logs (resistivity and spontaneous potential) (Klassen and Wyder, 1970). Unfortunately, the drilling and geophysical logs from this work were not published. A digital mapping project by the GSC in the 1990’s managed to recover some of these data (Fulton et al., 2004). Photocopies of some the original logs were located; however records could not be located for several sites, including some within the Medora-Waskada valley.

Figure 4 shows the initially proposed transects of the Medora-Waskada Valley, along with an indication of the borehole control available. Surveys were planned along two to four cross-sections of the valley. During the field program it was determined that the proposed transect immediately south of Waskada would be difficult to survey because of the traffic volume, so instead a profile just north of Waskada was obtained (Fig. 5). As well, the proposed transects between Waskada and Medora were moved to test more of the known valley extent.

![BURIED VALLEY AQUIFERS 2006 REFLECTION SEISMIC POSSIBLE DETAILED STUDY LOCATIONS](image)

Figure 4: Proposed and actual study locations for 2006-07 geophysical surveys.
3. Field tests of P- and SH-wave shallow seismic reflection methods

The seismic field program in SW Manitoba was carried out in late September 2006 (data collected between September 19-27, 2006). The crew from the Geological Survey of Canada consisted of André Pugin, Tim Cartwright, Marten Douma and Ron Good, with some help on start-up provided by Marc Hinton (Geological Survey of Canada) and Bob Betcher (Manitoba Water Stewardship).

Data were collected along four lines (Sections A-D in Figure 5), as outlined in Table 1. In all cases the recording instrument was the Geometrics Stratavisor (48-channel). Most of the tests of different source-receiver configurations were carried out on Section B, and included:

- **Compressional (P-)** wave surveys
  - geophones planted in ditch, in-hole shotgun source
  - P-wave landstreamer, Minivib source (vertical mode)

- **Shear (SH-)** wave surveys
  - horizontal geophone landstreamer, hammer on roller source
  - horizontal geophone landstreamer source, Minivib source (shear mode)

Both P- and SH-wave data were also collected along Section A, and additional profiles (SH-wave only) were acquired along two lines to the north (Sections C and D). In total, 10.6 line-km of data were acquired during the field program.

<table>
<thead>
<tr>
<th>Location</th>
<th>Source (Source spacing)</th>
<th>Source parameters</th>
<th>Receivers (#receivers @ receiver spacing)</th>
<th>Source-nearest receiver offset</th>
<th>Record length</th>
<th>#Samples per trace (sample rate)</th>
<th>Line length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section A (see Fig. 7)</td>
<td>Minivib (P) (3 m)</td>
<td>45 – 300 Hz sweep</td>
<td>P-wave landstreamer (47@3 m)</td>
<td>3 m</td>
<td>1.5 s</td>
<td>3000 (0.5 ms)</td>
<td>1550 m</td>
</tr>
<tr>
<td>Section A (see Fig. 7)</td>
<td>Minivib (SH) (1.5 m)</td>
<td>10 – 100 Hz sweep</td>
<td>SH-wave landstreamer (47@0.75 m)</td>
<td>3 m</td>
<td>1.5 s</td>
<td>1500 (1 ms)</td>
<td>1600 m</td>
</tr>
<tr>
<td>Section B (see Fig. 4 in Annex 2)</td>
<td>In-hole gunshot source (3 m)</td>
<td>1 shot per station</td>
<td>50 Hz vertical geophones planted in ditch (48@3 m)</td>
<td>1.5 m</td>
<td>0.5 s</td>
<td>4000 (0.125 ms)</td>
<td>650 m</td>
</tr>
<tr>
<td>Section B (see Fig. 8)</td>
<td>Minivib (P) (3 m)</td>
<td>45 – 300 Hz sweep</td>
<td>P-wave landstreamer (47@3 m)</td>
<td>3 m</td>
<td>1.5 s</td>
<td>3000 (0.5 ms)</td>
<td>900 m</td>
</tr>
<tr>
<td>Section B (see Fig. 8)</td>
<td>Hammer on roller (1.5 m)</td>
<td>1 hit per station</td>
<td>SH-wave landstreamer (24@0.75 m)</td>
<td>1.5 m</td>
<td>1.5 s</td>
<td>3000 (0.5 ms)</td>
<td>1550 m</td>
</tr>
<tr>
<td>Section B (see Fig. 8)</td>
<td>Minivib (SH) (1.5 m)</td>
<td>10 – 100 Hz sweep</td>
<td>SH-wave landstreamer (47@0.75 m)</td>
<td>3 m</td>
<td>1.5 s</td>
<td>1500 (1 ms)</td>
<td>750 m</td>
</tr>
<tr>
<td>Section C (see Fig. 9)</td>
<td>Minivib (SH) (1.5 m)</td>
<td>10 – 100 Hz sweep</td>
<td>SH-wave landstreamer (47@0.75 m)</td>
<td>3 m</td>
<td>1.5 s</td>
<td>1500 (1 ms)</td>
<td>1400 m</td>
</tr>
<tr>
<td>Section D (see Fig. 10)</td>
<td>Minivib (SH) (1.5 m)</td>
<td>10 – 100 Hz sweep</td>
<td>SH-wave landstreamer (47@0.75 m)</td>
<td>3 m</td>
<td>1.5 s</td>
<td>1500 (1 ms)</td>
<td>2200 m</td>
</tr>
</tbody>
</table>

**Table 1:** Recording parameters for seismic reflection profiles, SW Manitoba, 2006.
**Figure 5:** Map showing location of seismic profiles obtained near Waskada, SW Manitoba, in 2006.

**Figure 6:** Left: Augering shotholes and planting geophones for P-wave survey using in-hole shotgun source. Right: Hammer on roller source in operation.
Results:

Results from Sections A-D are presented in this paper. Details on the processing of the seismic sections and on some of the source comparisons are documented in a conference proceedings paper that is included as Annex 2 (Pugin et al., 2007).

P-wave reflection methods

Two source-receiver configurations using P-wave techniques were tested: (i) an in-hole shotgun source and planted marsh geophones (Fig. 6), and (ii) Minivib source in vertical mode coupled to a 47-channel landstreamer mounted with single 40 Hz vertical geophones at 3 metre spacing (Fig. 2). Example field records show that both systems recorded very good reflection data, and that even under windy conditions, the landstreamer data displayed useable reflection energy (see Fig. 3 in Annex 2). The landstreamer data showed less interference from surface waves and reflections from depths well below the bedrock surface were clearly visible when the signal-to-noise ratio of the data was high. The stacked sections show that a higher signal/noise ratio is achieved with the Minivib data (see Fig. 4 in Annex 2).

While the final data quality of the processed sections is similar between the conventional and the Minivib/landstreamer acquisition modes, the acquisition rate is very different. The 650 m of line acquired with the shotgun source and geophones planted in the ditches took 1 day with a crew of 6 men. In contrast, a data acquisition rate of 3 km/day was achieved with a 4-man crew using the Minivib/landstreamer.

SH-wave reflection methods

Two source-receiver configurations using SH-wave techniques were tested: (i) the hammer-roller source and a 24-channel SH-wave landstreamer (Fig. 6), and (ii) Minivib source in shear mode coupled to a 47-channel landstreamer (Fig. 2). Example field records show that the hammer-roller system produced very little reflection signal from the depths of interest in this survey area, but the Minivib system produced excellent quality records (even under rainy and windy conditions) after an FK filter (spatial bandpass filter used to attenuate or enhance signals based on apparent velocity) was applied to remove strong surface waves (see Fig. 3 in Annex 2).

The SH-wave sections acquired with the Minivib have the advantages of the improved data acquisition rates described above for the P-wave system, and require less processing time as sophisticated static corrections are not required. However, migration of the sections may be a more critical processing step for the SH-wave sections.

Comparison of P- and SH-wave reflection methods

The P- and SH-wave stacked sections (plotted in elevation) acquired with the Minivib/landstreamer along Section A are shown in Figure 7 (see also time section shown in Fig. 6 in Annex 2), and those acquired along Section B are shown in Figure 8 (see also time section shown in Fig. 5 in Annex 2). The SH-wave stacked sections exhibit higher near-surface resolution, but lesser signal penetration than the P-wave sections. It is suspected (based on previous experience) that the lack of penetration of SH-waves may be related to the presence of coarse gravel, though this has yet to be confirmed by borehole data.

Section A (Figure 7; see also Figure 6 in Annex 2)

The P- and SH-wave profiles acquired with the Minivib source along Section A are shown in Figure 7. Both clearly show the presence of the buried valley with a sharp western edge and steep western slope. The base of the channel is not clearly seen as a reflection in the SH-wave profile. At the east end of the line the P-wave profile shows a dome-shape feature filled with high-reflectivity reflectors (CMP’s 800-1000). Bedrock appears to shallow here, but may be overlain by 40-50 m of coarse-grained deposits, and the P-wave section suggests that the channel may extend further to the east. Signal penetration into the
shale bedrock is also very limited for the SH-wave data; the P-wave reflection present at ~300 masl (within bedrock) does not appear in the SH-wave section. The borehole logs indicate the presence of coarser sediment (interlayered sand (mostly described as shaly), gravel and clay) in the middle R2-85 (well) and the lower sections (Pipeline well) of the valley, and this is labelled as “gravel” in the interpreted sections (Figure 7). The coarser sediment correlates in a general sense with larger amplitude reflection signals on the P-wave section. The SH-wave section also shows some high-amplitude layered reflectors at depth in the vicinity of borehole R2-85; these sediments are reported as interbedded shaly sand and clay.

Section B (Figure 8; see also Figure 5 in Annex 2)

The P- and SH-wave profiles acquired with the Minivib source along Section B are shown in Figure 8. Only the western portion of the buried valley is imaged by these sections. The eastern side of the valley shown in the upper section is inferred from the longer profile obtained with hammer-roller source (poor data), which suggests that the valley >1 km wide at this location (similar to Section A). Again the valley shows an abrupt edge and steep valley wall on the west, and reaches a depth of ~100m below the surrounding bedrock surface. The borehole log reported for the “loading station well” mentions the presence of gravel in the lower part of the glacial sedimentary sequence; this corresponds to the high-amplitudes reflection observed in the SH-wave section.

Section C (Figure 9)

The SH-wave profile acquired with the Minivib source along Section C is shown in Figure 9. This section was chosen to further test the SH-wave seismic technique for its ability to image this deep channel. At this location the seismic section shows a thicker sequence of overlying tills. Beneath that, there is little in the way of coherent stratified reflections which may be an indication of the presence of gravel as suggested above; however, the borehole control reports mostly the presence of diamicton; some gravel has been observed in the TH3A hole but the pump test showed a rapid drawdown indicating that this gravel layer has a very limited extent (Manitoba Water Stewardship). The channel fill can be subdivided into two seismic units (or sequences) separated by a reflector highlighted in orange.

Section D (Figure 10)

The SH-wave profile acquired with the Minivib source along Section D is shown in Figure 10. This section investigates the buried valley structure just south of Medora, ~10 km north of Section C (Fig. 5), and was chosen because of the subsurface information available from a series of boreholes (Klassen and Wyder, 1970). The seismic section shows the valley to have a similar lateral extent (>1 km wide) but at this location, the eastern slope is gentle and extends another ~1 km. As with Section C, there is little stratification observed below the surface tills. The borehole resistivity logs show that diamicton mostly fills the valley with a few sand layers. High reflection amplitudes may possibly indicate the presence of coarser sand or gravel to the eastern side of the profile, this would have to be confirmed with borehole data. As with Section C, the channel fill can be divided into two units based on the character of the seismic reflection data.

Summary:

The primary objective of the 2006-07 work was to determine whether seismic reflection methods could be used effectively to detect the Medora-Waskada valley at locations where it is known to exist from drill logs. It is clear from the results presented here that seismic reflection data acquisition using the Minivib/landstreamer technology can be used very effectively to image buried-channels in this geological environment. It should be stressed that this geophysical technique responds to changes in seismic velocity and/or density only, and cannot directly detect whether subsurface materials are water-bearing.

The sections show as well that in general the higher amplitudes clearly seen in the SH-wave profiles are related with coarser stratified sediments. These high amplitudes are likely more present in the southern
part of the channel, in the sections A and B as the sections C and D display more chaotic seismic facies which can be associated with diamictons based on the borehole data available on these sections.

Tests were carried out using both P- and SH-wave methods and with different source-receiver systems, in order to evaluate the most effective and efficient method(s) for delineating the buried valley and its fill. It has been determined that the Minivib/landstreamer system is the optimum method. The P-wave mode with a longer shot spacing interval is more efficient to cover long distances for regional studies. The SH-wave mode presents the advantage of producing higher resolution in the very shallow section, but with somewhat lesser signal penetration especially for imaging deeper coarse gravel sediments or reflectors below the bedrock surface. However, acquiring both P- and SH-wave data along the same section may provide data that could be used to locate, delineate and identify sediment architectures and possibly also information on lithologies within buried channels which would be targets for hydrogeological investigations. The lower acquisition costs using the Minivib/landstreamer technology (this work has shown acquisition rates can be up to ~5 times faster than with conventional techniques) means that even acquiring both P- and SH-wave data along each line could be cost-effective. One effective approach would be to use P-wave surveys to locate the buried valleys, with follow-up SH-wave surveys over selected target areas.

Detailed interpretation of the observed seismic facies (for both P- and SH-wave data) depends on the quality of the borehole control available. While there are several boreholes along the lines that were surveyed before this seismic data acquisition, the logs were compiled from cuttings only (with the exception of section D where cored samples were obtained). In several cases, the extent of the channel as determined from the seismic data was wider than what had been inferred from the boreholes. This could be explained by the difficulty in recognizing the differences between bedrock shales and shaly tills or compacted sands, or simply identifying shale boulders as bedrock due to the drilling and sampling methods. Our ability to interpret the seismic responses in terms of the sedimentary units filling the valley will improve as we acquire more data and compare it to available ground truth like geophysical well logs.
Proposed Workplan for 2007-08:

1. Consult with partners to determine hydrogeological priorities for buried valley/sediment mapping and delineation using seismic techniques and for boreholes where it would be possible to acquire a full suite of geophysical logs.
2. Seismic field program to acquire P- and SH-wave profiles using the Minivib/landstreamer system along prioritized transects (2 weeks of field work in late summer or fall 2007, total line-km estimated to be 20 km = 10 km of P-wave profiles and 10 km of SH-wave profiles).
3. Expand the field program to include geophysical logging in boreholes along seismic sections.
4. Prepare a draft final report including all data, final results and processed seismic sections to be distributed to provincial partners by February 28, 2008. Submit the final report by March 31, 2008.
5. Report of methodology development and potential use of seismic methods through conference presentation(s) and/or presentations to local/provincial groups.
6. With partners, start preparation of technical report/journal paper on results of this collaborative project. Report/paper to be completed and submitted in 2008-09.

Estimated Costs (2007-08):

Seismic reflection production program (P- and SH-wave):
- Instrumentation/equipment usage/maintenance .......................................................... $ 5,000
- Minivib mob .................................................................................................................. $ 500
- Field expenses (4-man crew, 12 working days, 6 days travel)
  - Van rental + gas ........................................................................................................ $ 3,500
  - Minivib + truck + gas ................................................................................................ $ 1,500
  - Accommodation/meals ............................................................................................... $ 12,000
  - Airfare (x2) ................................................................................................................ $ 2,000
  - Expendables ................................................................................................................ $ 1,500
- Technician (casual salary)* ....................................................................................... $ 8,500
- Overtime (O&M)** ...................................................................................................... $ 11,000
- Data analysis and report preparation
  - Computer support ..................................................................................................... $ 3,000
  - Software maintenance .............................................................................................. $ 1,500
- Travel for consultations/presentation to partners etc .............................................. $ 5,000

Geophysical borehole logging program:
- Expand crew/equipment to allow logging of 2 x 100 m boreholes ........................... $ 5,000

Total estimated required funds: .................................................................................. $ 60,000

Notes:  * need to hire casual technician support (recently retired personnel)
  ** 10 hour working days require overtime to be paid to technical staff

GSC contribution:
- Salary (technical and scientific expertise) ................................................................. ~$ 60,000
- Minivib+truck (rental equivalent) ............................................................................ ~$ 15,000
- Instrumentation/equipment/software
  - (Seismograph, landstreamers etc) .......................................................................... ~$ 10,000

Total GSC contribution: .............................................................................................. ~$ 85,000
References:


(see Annex 2)
Figure 7: Interpreted SH- and P-wave reflection profiles acquired with Minvib source along Section A. The yellow circles indicate where “shale boulder gravel” was noted in the borehole logs. The indication of “stratified sediments” (implying layered sand/coarse-grained sediments) is based on the seismic reflection character and supported by the borehole logs. The “?” indicates a dome-shaped feature (P-wave section) which could be coarse-grained deposits. The buried valley may extend to the east of this feature.
Figure 8: Interpreted SH- and P-wave reflection profiles acquired with Minivib source along Section B. The yellow circle indicates where “shale boulder gravel” was noted in the borehole log. The indication of “stratified sediments” (implying layered sand/coarse-grained sediments) is based on the seismic reflection character.
Figure 9: Interpreted SH-wave reflection profile acquired with Minivib source along Section C. The yellow circle indicates where “shale boulder gravel” was noted in the borehole logs. Otherwise the borehole logs suggest thick diamicton to the bedrock surface. There is no indication on the seismic section of stratified sediments that may be more conducive to the storage or movement of groundwater.
Figure 10: Interpreted SH-wave reflection profile acquired with Minivib source along Section D. As in Section C, the borehole logs suggest thick diamicton to the bedrock surface, and again there is little indication on the seismic section of stratified sediments that may be more conducive to the storage or movement of groundwater. The possible exception is the area on the eastern side of the profile, outlined by the yellow circle, where higher-amplitude reflections may possibly indicate the presence of coarser stratified sediments. Resistivity logs from the two boreholes are plotted on the sections to show qualitatively the variation in resistivity with depth. Resistivities are generally low (~30 ohm-m) with maximum values of 40-50 ohm-m.
Annex 1

Methodology

Shallow Seismic Reflection Methods

Land-based seismic methods are geophysical techniques which use measurements of the time taken for acoustic energy to travel from a source on the surface through the subsurface and back to a series of receivers on the ground. Energy is refracted or reflected at boundaries where there is a change in acoustic impedance (the product of material density and seismic velocity). Because contrasts in acoustic impedance are generally associated with lithological boundaries, seismic techniques can be used to obtain subsurface structural information. This section briefly outlines the application of shallow seismic reflection methods to delineating the structure of unconsolidated sediments and the underlying bedrock surface.

Seismic reflection methods have been the primary geophysical tool used in oil and gas exploration for over 60 years. Because of the tremendous commercial importance of oil, much industrial research and development has been invested in this branch of geophysics. By the 1960s, specialized field procedures, digital magnetic tape recording, and computer processing of the data had become standard in the industry. Conventional seismic reflection techniques are highly sophisticated, but require considerable investment in both data acquisition and processing.

In the early 1980s, the development of digital enhancement engineering seismographs with high-pass filtering capabilities and the proliferation of increasingly powerful microcomputers, began to make the application of seismic reflection methods to “shallow” problems a viable alternative. Over the last 20-25 years, much experience and expertise in the application of shallow high-resolution reflection techniques have been gained, and today these methods are accepted and proven shallow geophysical tools. Seismic reflection techniques can be applied using compressional (P-wave) or shear (S-wave) energy. Compressional waves are those in which the particle motion and direction of wave propagation are the same, whereas shear waves are those in which the particle motion is normal to the direction of wave propagation (Fig. A1-1).

![Diagram of Compressional or P wave and Shear or S wave](image)

**Figure A1-1:** Schematic diagram showing the particle motions for compressional or P waves (upper panel) and shear or S waves (lower panel).
Seismic reflection methods involve measurement of the time taken for seismic energy to travel from the source at or near the surface, down into the ground to an acoustical discontinuity, and back up to a receiver or series of receivers on the ground surface (Fig. A1-2a). Data are usually acquired continuously along a survey line, and processed to produce a seismic section which is a two-way travel time cross-section of the subsurface (Fig. A1-2b). Velocity-depth functions calculated from the data, or seismic logging of a nearby borehole(s) are used to translate the two-way travel time into depth.

![Diagram](image)

**Figure A1-2:** Basic premise of seismic reflection methods. a) Seismic energy produced on the ground surface travels from the source down to an acoustic impedance (product of density and velocity) boundary, where it is partially transmitted and partially reflected back towards the surface. b) Data are usually acquired continuously along a survey line and the record of ground motion as a function of time is related to the subsurface structure.
Today, virtually all shallow seismic data are collected and processed based on the common midpoint (CMP) method (often also referred to as the common-depth-point, or CDP, method) which is an adaptation of the methods used by the petroleum industry. In CMP surveys, multi- (12, 24, or more) channel data are recorded for each shotpoint. During processing, the data are sorted according to their common midpoints or common depth points (Fig. A1-3). Each trace is corrected for offset according to a velocity-depth function determined from the data (normal moveout, or NMO, corrections). A standard sequence of CMP data processing steps includes trace editing, static corrections, bandpass filtering, gain scaling, velocity analyses, normal moveout corrections and finally, stacking of the NMO-corrected traces in each CMP gather to create a single trace on the final section. This stacking procedure is the essence of the CMP technique, and allows a potential improvement in the signal-to-noise ratio of the data according to the square root of the fold (number of traces summed to produce the final processed trace at a given point along the seismic profile).

![Common shot gather (Field record)](image1)

![Common midpoint (CMP) gather](image2)

Figure A1-3: Schematic diagram showing a) the subsurface travel paths of reflections from a field record and b) a common midpoint gather. The traces in the CMP gather will be processed and stacked together to form a single trace on the final CMP section (6-fold).

The successful application of any shallow reflection survey depends on the detection of high-frequency energy reflected from velocity discontinuities within the subsurface. However, earth materials, and especially unconsolidated overburden materials, are strong attenuators of high-frequency energy. Thus, compressional (P) seismic waves in the 10-90 Hz range commonly used in petroleum exploration may be reflected from depths of thousands of metres, but energy with frequencies above 100 Hz normally only have travel paths on the order of tens or hundreds of metres. The ability of a particular site to transmit high-frequency energy is a major factor in determining the quality and the ultimate resolution of a shallow reflection survey.

The optimum conditions for shallow reflection surveys (P-wave) are usually when the surface materials are fine-grained and water-saturated; reflections with dominant frequencies of 300-500 Hz can be obtained in such field situations. These frequencies correspond to seismic wavelengths in unconsolidated overburden materials on the order of 3-5 m, with a potential subsurface structural resolution of approximately 1 m. Experience has shown that excellent high-resolution, P-wave, seismic reflection data can be obtained where water-saturated, fine-grained sediment is exposed at the surface (Fig. A1-4).
Figure A1-4: Example field shot gather obtained during a P-wave reflection survey using a 12-gauge shotgun source and 50 Hz vertical geophones at 3 m spacing: a) raw record, b) same record after high-pass filtering. These records show excellent reflection energy (hyperbolic events).

Shear wave reflections are commonly much lower in frequency (10-100 Hz) than shallow P-wave reflections. However, resolution of the seismic signals depends on the signal wavelength (higher resolution associated with shorter wavelengths). As the velocity of shear waves in unconsolidated materials can be an order of magnitude lower than the P-wave velocity of the same sediments (particularly if those sediments are water-saturated), the resolution of shear wave data can exceed that obtainable with P-wave data.

Seismic profiles are sections in two-way travel time (not depth). Velocity functions are estimated from the seismic data at intervals along the line during the processing sequence, in order to calculate the normal moveout corrections applied to the data before the stacking procedure, and these velocities can also be used to convert the two-way travel time section to a depth section. However, velocities determined from reflection data can be subject to large uncertainties, depending on the moveout of reflection events. Whenever possible, accurate downhole velocity data from borehole measurements should be obtained in support of the seismic reflection survey (Hunter et al., 1998).

Further discussion on the application of seismic methods to geomorphic and environmental problems can be found in Pullan and Hunter (1999). Steeples (1998) provides an overview of the development of shallow seismic reflection techniques, and the suite of papers in that special issue of Geophysics provides a summary of the state-of-the-art of shallow seismic reflection at that time.
Seismic Landstreamer/Minivib System

Shallow seismic reflection surveys are a powerful tool for mapping detailed subsurface structure, with applications in a wide variety of groundwater, hazard, engineering and environmental investigations. More widespread use of this technique has been limited partly by the time and cost involved in acquiring and processing the data. The efficiency of data collection is largely dependent on the time required to individually plant every receiver (geophone) and to move and reconnect seismic cables as the survey proceeds along a seismic line. As well, the ability to produce and record high-frequency energy for shallow seismic reflection surveys depends on the ground conditions, the effectiveness of ground coupling for both the receivers and the source, the frequency and energy of the seismic source, and the source and receiver spacings (which define the fold – see Fig. A1-3).

The Geological Survey of Canada has recently been successful in mating the IVI (Industrial Vehicles International, Inc) minibuggy Minivib source (http://www.indvehicles.com) and landstreamer receiver arrays (both P-wave and horizontally-polarized shear (SH-) wave). The seismic landstreamer/Minivib system is one way of addressing both the efficiency of data collection and data quality (improvement of signal-noise ratio by decreased source and receiver spacings).

Landstreamers consist of towed arrays of geophones fixed on sleds and have been demonstrated to be an efficient means of recording shear-wave reflection data (e.g. Inazaki, 2004, Pugin et al., 2004). The Geological Survey of Canada has built an SH-wave landstreamer array (24-48 channels) consisting of small metal sleds with 2 horizontal 8 Hz geophones per sled (Fig. A1-5), cross-connected as described in Pugin et al. (2002). Typically, receiver spacings of 0.75 m are used, though the spacing can be adjusted according to the survey targets. The short spacing of the sleds avoids spatial aliasing of the surface waves for optimum results when FK spatial filters are applied. For P-wave surveys, one vertical 40 Hz geophone is mounted on each sled and the sled spacing is typically 1.5-3 m. These landstreamers are designed for use along paved or gravel roads.

The minibuggy Minivib source (Fig. A1-6) provides a low-impact, vibrating seismic source which can be operated in both P- (vertical) and SH- (horizontal) mode. The vibrating sweeps are programmable in length (seconds) and frequency range (10-550 Hz). The Minivib is used to tow the landstreamer, and fitted with a distance-measuring wheel which allows the operator to move and set the source at a pre-determined source spacing. Small source spacings (typically 1.5-3 m), coupled with the small receiver spacings that are possible (and practical) with the landstreamer, allow high-fold data to be acquired. Using the landstreamer-Minivib system with the typical source and receiver spacings outlined above, a 3-4 person crew can acquire 1-2 km of line a day. This is an improvement in data acquisition rates of 2-5 times over that possible with the traditional method of planted geophones.
**Figure A1-5:** Photo of the Minivib source and SH-wave landstreamer in operation, 2006.

**Figure A1-6:** Photos of the IVI minibuggy vibratory source in operation. In the photo on the left, the Minivib is being operated in SH-mode (note weight above plate in mounted horizontally.)
References


Annex 2

Preprint of conference proceedings paper (in press)

BURIED-CHANNEL IMAGING USING P- AND SH-WAVE SHALLOW SEISMIC REFLECTION TECHNIQUES, EXAMPLES FROM MANITOBA, CANADA

BURIED-CHANNEL IMAGING USING P- AND SH-WAVE SHALLOW SEISMIC REFLECTION TECHNIQUES, EXAMPLES FROM MANITOBA, CANADA

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Abstract

Buried channels are erosive sedimentary features that can possibly be formed by sub-glacial melt-water circulation. The size of these channels is very variable with widths up to several kilometres and depths from few metres up to several hundreds of metres. Their coarse-gravelly, sandy sediment fills act as reservoirs which can be important sources of water or occasionally gas. In the fall of 2006, comparative seismic reflection tests were conducted in south-western Manitoba over a buried channel aquifers that is capped by glacial till. Tests included an in-hole shotgun source with planted geophones, landstreamers with vibroseis technology (Minivib) in P-wave and SH-wave mode and an impulsive sledge-hammer source. The highest quality results were obtained using a Minivib. Uncorrelated data recording has allowed major signal spectral improvements. The best resolution and signal/noise ratio have been obtained using a SH vibroseis signal with a 48 channel landstreamer (a geophone spacing at 0.75 m and shot-spacing at 1.5 m) and the fastest acquisition is realized using a P-wave landstreamer. A rate of 2-D profiling of up to 2.2 km/day has been achieved using a SH-landstreamer and up to 3 km/day using a P-wave landstreamer.

Introduction

Ground-water resources exploration and management strongly depends on the spatial distribution of aquifers and aquitards; consequently flow models can often benefit from geophysical observations which provide spatial information on the subsurface. This paper reports results obtained using shallow seismic reflection techniques in south-western Manitoba to image buried-channel features which are significant ground water reservoirs in the area (see also Pugin et al. 1999). By being possibly formed by sub-glacial water circulation the buried-channels are difficult to delineate from the surface. To date, borehole information has been used to locate these subsurface features with moderate success (Klassen and Wyder, 1970, Betcher et al., 2005). Because most of these boreholes were logged using cuttings extracted from the drilling mud, the information they provide on the buried channel fill is not completely reliable. A complicating factor in the interpretation of borehole cuttings is that the buried channels in the shale bedrock are filled with shale boulders and shaly gravel sand and till.

In collaboration with the West Souris River Conservation District and the Manitoba Water Stewardship Department, the Geological Survey of Canada has conducted a survey over the Medora-Waskada buried-channel (Figure 1). We have used conventional seismic reflection techniques with a shotgun and planted geophones (Pullan and MacAulay, 1987) as well as a vibrating source towing landstreamers recording in P-wave and SH-wave modes (Figure 2).

Landstreamers have demonstrated their efficiency at acquiring data over sediments with low compaction (Pugin et al., 2002); however the entire south-western part of Manitoba is covered with high-velocity till (P-wave: ~1900 m/s, SH-wave: ~400 m/s), with the potential of generating significant trends of surface waves. Thus, some uncertainties about the best and most efficient method to image the near-surface remained. Tests have been conducted to determine the most appropriate technique to locate and observe the fill within the ~100 m deep channels in south-western Manitoba. The aim of the survey was to answer two questions: a) what is the fastest method of acquisition; b) what is the best resolution that can be achieved to observe the sedimentary architecture present within the channel.

![Figure 1: Location of the seismic section imaging the Medora-Waskada buried-channel, southwest Manitoba, Canada. Surficial geology of southern Manitoba (south of 53°), scale 500’000 by G.L.D. Matile and G.R. Keller; http://www.gov.mb.ca/iedm/mrd/info/libmin/SG-SMB.pdf](image)

**P-wave reflection methods, acquisition and processing**

Two source-receiver configurations using P-wave techniques have been tested. A 650-m line was acquired using an in-hole shotgun and planted marsh geophones with the following parameters: 48-channel receiver array of single 50 Hz geophones at 3 m spacing planted in the ditch alongside the road and a 12-gauge in-hole shotgun source at 3 m spacing. Along the same line, a P-wave vibro-seismic survey was conducted with an IVI minivib source (6 seconds sweep from 45 Hz to 250 Hz), coupled to a 47-channel landstreamer mounted with single 40 Hz vertical geophones at 3 metre spacing. The record lengths were 0.5 second for the shotgun data and 7 seconds for the P-wave uncorrelated minivib data with a sampling rate of 500 µs.
Shot gathers using an in-hole shotgun (Figure 3A) show a strong packet of near-surface reflections with a frequency band centered at 150 Hz. At near-offsets the records are dominated by surface waves. The correlated minivib record (Figure 3B) shows the same frequency content for the reflection package, but without the surface wave interference. This can be explained by the fact that the vibrating sequence starts at 45 Hz, above the dominant frequency of the surface waves. Consequently deeper reflections are clearly visible in the near-offset at times greater than 300 ms. This type of high signal/noise ratio record was recorded in low wind conditions. Figure 3C shows a vibroseis record that was acquired with wind conditions of above 30 km/h; in this case, shallow reflections can still be seen but the deeper reflections are hidden under the background noise.

The stacked sections (Figure 4) show that a higher signal/noise ratio is achieved with the minivib data, along the signal penetration through the entire Mesozoic and Paleozoic rocks down to the top of the Canadian bedrock shield at a depth close to 1.7 km (processing parameters in Table 1). Comparing both minivib and shotgun sections in Figure 4, there is a good match of the internal reflectors situated within the buried-channel with less noise in the minivib/landstreamer section.

**Figure 2:** IVI minivib buggy towing the 47-channel 0.75 m spaced SH-wave landstreamer array.

**Figure 3:** Shot gather records. A: In-hole shotgun P-wave record. B: Minivib/landstreamer P-wave record. C: same as B but data acquired under windy conditions. D: Sledge-hammer/roller SH-wave records. E: Minivib/landstreamer SH-wave record. F: same record as E, FK-filter applied.
Figure 4: Comparison of stacked P-wave section. Minivib/landstreamer on the left, in-hole shotgun/planted phones on the right. Further explanations in the text. Location shown in Figure 1.
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*Shotgun data only
**Vibroseis data only

**Table 1:** Processing flow chart for P-wave seismic reflection data

While the final data quality of the processed sections is similar between the conventional and the minivib/landstreamer acquisition modes, the acquisition rate is very different. The 650 m of line acquired with the shotgun source and geophones planted in the ditches took 1 day with a crew of 6 men. In contrast, a data acquisition rate of 3 km/day was achieved with a 4-man crew using the minivib/landstreamer. The use of the minivib/landstreamer P-wave reflection technique considerably lowers the acquisition cost for an acquisition rate ~5 times faster than for the conventional techniques.

**SH-wave reflection methods, acquisition and processing**

The hammer-roller source and the minivib in shear mode were used to generate SH-wave motion energy in conjunction with landstreamers as receiver arrays. It has been shown that landstreamers are very efficient instruments for recording shear-wave reflection data (e.g. Inazaki, 2004, Pugin et al., 2004). Shot record gathers from the 2006 Manitoba survey are displayed in Figure 3. The small sledge hammer/roller source (Figure 3D) did not produce enough reflection energy to overcome the background and surface noise, and data from this source only produced a very blurred image of the buried-channel (not shown in this paper). The minivib (7 seconds sweep, 10 Hz to 100 Hz) produced excellent quality records even with rainy and windy conditions (Figure 3E), though with the presence of strong surface waves likely related with the high-velocity of the near surface sediments (~400 m/s). An FK-filter had to be applied to remove this unwanted energy (Figure 3F). The landstreamer array consisted of 47 sleds at 0.75m spacing, with 2 horizontal geophones per sled, cross-connected as described in Pugin et al. (2002). A source spacing of 1.5 m was used, resulting in a bin size CDP spacing of 0.75 m with 24 nominal stack fold. The short spacing of the sleds is chosen to avoid spatial aliasing of the surface waves for optimum results when FK-spatial filters are applied.
Figure 5: Comparison of P-wave and SH-wave seismic minivib section over a buried-channel. Location shown in Figure 1.
Figure 6: Comparison of P-wave and SH-wave seismic minivib section over a buried-channel. Location shown in Figure 1.

The processing is rather minimal (Table 2) as sophisticated static corrections are not required. Based on our experience, the near surface lateral velocity change for the SH-wave is less important than for the P-wave.
Format conversion, SEG2 to KGS SEGY
Spectral whitening
Cross correlation
FK-filtering
Edition of the geometry
Frequency filter
Scaling (trace normalization)
Velocity analysis
NMO Corrections
Top mute
Stack, nominal fold: 24
Topography-datum static shift*
Phase-shift migration

* For the section displayed in the Figure 7 only

Table 2: Processing flow chart for SH-wave seismic reflection data

Figures 5 and 6 (location shown in Figure 1), show a comparison of stacked sections acquired with the minivib/landstreamer in P-wave and SH-wave mode. The SH-wave stacked sections clearly show a higher near-surface resolution but lesser signal penetration than the P-wave sections. Previous experience (Pugin et al. 2006) suggests that the SH-wave has little or no penetration into coarse gravel, so even without borehole data available from the base of the channel observed in Figure 6, we suspect that gravel is present. No reflection are seen in SH-wave mode but the base of the channel displays a dome-shape feature filled with high-reflectivity reflectors in the P-wave section (CMP’s 800-1000). The penetration into the shale bedrock is also very limited for the SH-wave: the P-wave reflection present at a time of 180 ms (within bedrock) does not appear in the SH-wave section. Due to the lower velocity of the SH-wave, waves ray-paths can be more complex; for example a feature that appears as a trough in the P-wave domain (Figure 5, P-wave section, ~CMP 425) show up as bow-tie structure in the SH-wave domain before migration (Figure 5, SH-wave section, ~CMP 450). Consequently, migration is a more critical processing step for SH-wave data.

In several cases using seismic reflection, it has been found that the extent of the channel was wider than what could be inferred using borehole data. This could be explained by the fact that it is very difficult to recognize the differences between bedrock shales and shaly tills due to the drilling and sampling methods.

Conclusions

Our experiments in south-western Manitoba have shown that seismic reflection data acquisition using the minivib vibroseis technology can be an extremely efficient tool to image buried-channels. The P-wave mode with a longer shot spacing interval is more efficient to cover long distances for regional studies (Vangkilde-Pedersen et al. 2006). The SH-wave mode presents the advantage of producing higher resolution in the very shallow section, but with somewhat lesser signal penetration especially for imaging coarse gravel sediment or below the bedrock surface. This last limitation is a major disadvantage for hydrological investigations but when P-wave and SH-wave seismic reflection are used together, these methods can be used to locate, delineate and identify sediment architectures within
buried channels and therefore constitute a very effective and economical approach for hydrological investigations

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References


