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Delineating Buried Valleys in Southwest Manitoba using Seismic Reflection Methods: Cross-Sections over the Medora-Waskada, Pierson and Killarney valleys (2006-07)

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Summary

This open file report presents the results from field programs conducted in 2006 and 2007 to test and apply shallow seismic reflection techniques as a means of identifying and imaging buried valleys or channels in southwest Manitoba. The work was conducted collaboratively with Manitoba Water Stewardship (MWS) and with the assistance of local Conservation Districts, and with funding from the Prairie Farm Rehabilitation Administration (PFRA). Data were acquired across three buried valleys: the Medora-Waskada valley, the Pierson valley, and the Spiritwood valley (near Killarney). Results clearly show that seismic reflection data acquisition using the Minivib/landstreamer technology can be used very effectively to image buried-channels in this geological environment, and provides subsurface architectural information that is critical to the identification of buried valleys and a preliminary assessment of the sediment infill characteristics.

Overview

Much of southwest Manitoba does not have access to high yield sources of groundwater supply from traditional bedrock or sediment aquifers. With increasing demand for groundwater in this area, attention is returning toward evaluating the water supply potential from sands and gravels found within buried valley features (see Figure 1).

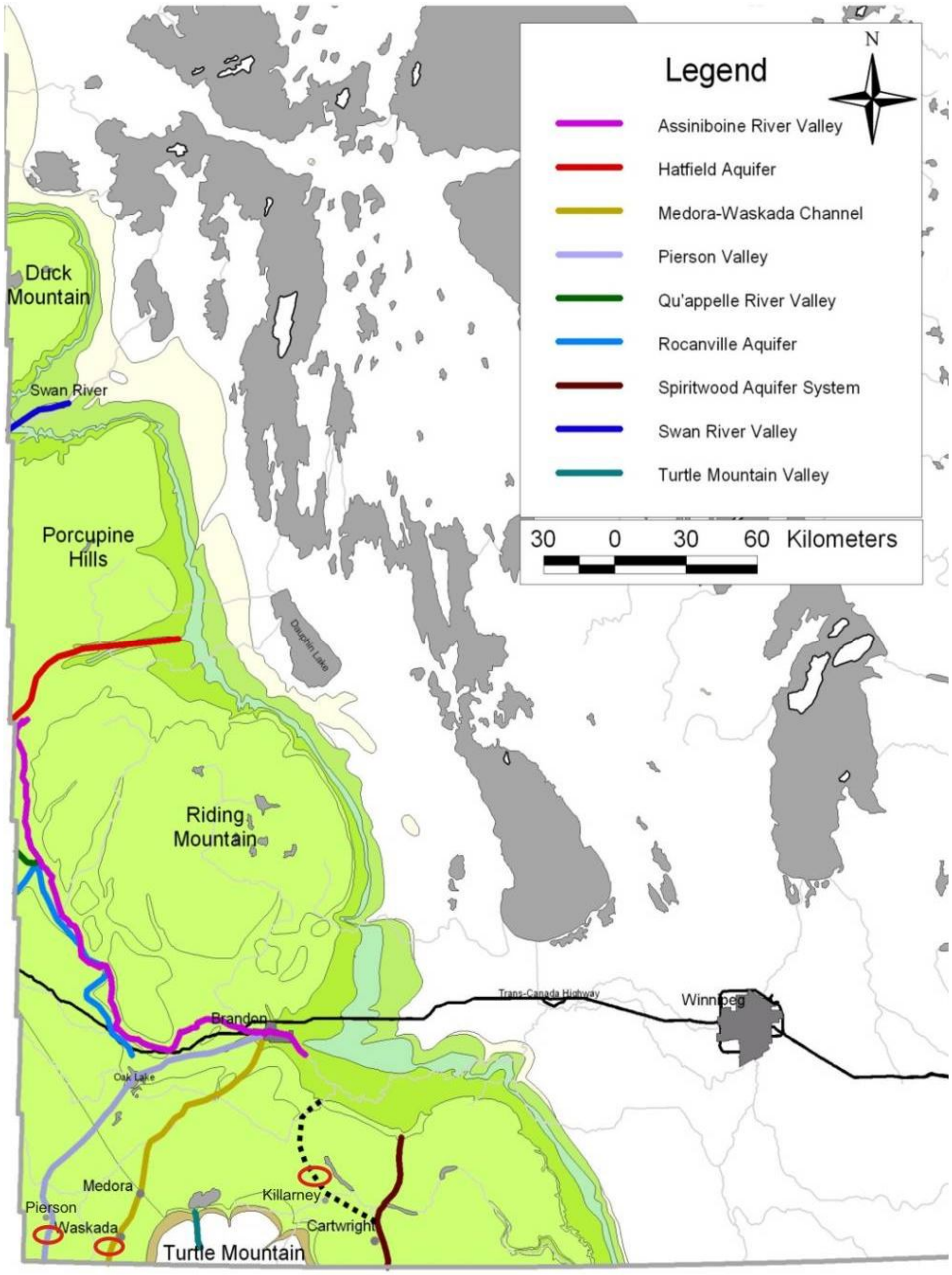


Figure 1: Estimated distribution of buried valleys of south-western Manitoba (modified from Betcher et al., 2005). An alternate northward extension of the Spiritwood Valley is shown as a dashed black line. The three areas where seismic reflection surveys were carried out in 2007 (Pierson, Waskada and Killarney) are outlined in red.

In 2006-07 and 2007-08, funding was obtained from the National Water Supply Expansion Program of the Prairie Farm Rehabilitation Administration (Agriculture and Agri-Food Canada) to determine the effectiveness of seismic reflection methods as a tool for delineating the subsurface extent and stratigraphy of buried valley aquifers in southwest Manitoba. Work in 2006 focused on the Medora-Waskada buried valley which, at its southern defined extent, is the source of water supply for two loading stations, a pipeline bringing water to regional areas, and the village of Waskada. 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, and to assess the best source/receiver parameters to be used in production data acquisition.

In the following year (2007-08), we used the P-wave minivib/landstreamer system (determined from the 2006 results to be the most effective subsurface mapping technique) to acquire cross sections across three known or suspected buried valleys in southwest Manitoba. In a two-week field program in October 2007, we collected 38 line-km of P-wave shallow seismic reflection profiles in these three areas. The goals of this work were to help delineate and characterize these buried valleys and to improve our understanding of buried valley systems in the region. Ultimately, the goal is to provide information and techniques that will assist in the long-term assessment, development and management of groundwater resources in southern Manitoba.

The field programs were planned cooperatively by the Geological Survey of Canada (GSC) and Manitoba Water Stewardship (MWS), in consultation with the West Souris River Conservation District (WSRCD). Seismic cross-sections have been collected in the WSRCD, the Turtle Mountain Conservation District (TMCD) and the Tiger Hills Conservation District (THCD).

This report presents the results from the 2006 and 2007 field programs, and includes all seismic sections and preliminary interpretations. Interpretations may evolve with further input from geologists and hydrogeologists familiar with the area, and as additional ground-truth data are acquired.

Buried Valleys in Southwest Manitoba

Buried valleys in the Prairies have been attributed to preglacial erosion of Cretaceous bedrock followed by infilling with Tertiary and Quaternary deposits (e.g. Maathuis and Thorleifson, 2000), or to pro- or sub-glacial erosion and deposition (e.g. Andriashek, 2001). The sequence of erosional and depositional events may be complex; glacial erosion may have occurred within or beyond preglacial valleys with partial or complete erosion of sediment followed by subsequent deposition (e.g. Bluemle, 1985). Therefore, bedrock valley geometry and sediment stratigraphy may be highly variable along valleys and may differ among valleys (Cummings et al., 2012a, b).

Development of water supplies from these features has already occurred in the Brandon and Waskada areas. However, the short-term yields from these aquifers are variable and the long-term yields may be severely restricted by limited recharge. Thus, more information on the location, extent, stratigraphy and architecture of these buried valley features is required in order to effectively understand and manage their groundwater resources (e.g. Cummings et al., 2012b).

These buried valleys have little or no surface expression and the sedimentary architecture is poorly known and only partially delineated by boreholes (e.g. Klassen and Wyder, 1970). The limited information available is based predominantly on records from mud rotary boreholes and a few borehole geophysical logs (spontaneous potential and resistivity). Although these records have provided useful information on the locations of bedrock valleys and the general stratigraphy, they have provided only limited information on valley shape, sediment architecture, heterogeneity, and geological history.

The buried valleys investigated by this survey (Fig. 1), differ markedly in size and shape; the Medora-Waskada Valley is narrow (~1.3–2 km wide) with steep sides (see Annex 2, this report; Pugin et al., 2007), whereas the Pierson Valley is wider (4-5 km) and more deeply buried under glacial tills, and the Spiritwood Valley may exceed 8 km in width (15 km in North Dakota). Well yields are estimated from 2-

110 IGPM (Imperial gallons/minute) in the Pierson Valley (Watermark Consulting, 2004), whereas yields can exceed 1000 IGPM in the Spiritwood Valley in North Dakota just south of the Canadian border.

Shallow Seismic Reflection Data Acquisition and Processing

Annex 1 provides some general information on shallow seismic reflection methods as background information to this report.

In 2006, we conducted tests of both P- (compressional wave) and SH-(shear) wave methods and different source-receiver systems over the Medora-Waskada valley (Fig. 1). Annex 2 presents a detailed account of the tests conducted and the results obtained. These tests demonstrated that data acquired in this geological environment with the Minivib/landstreamer system were comparable to data collected with planted geophones and an in-hole shotgun source, but could be acquired at much higher rates (Hinton et al., 2007; Pugin et al., 2007; Pullan et al., 2008). The P-wave mode was more efficient at covering long distances for regional studies, and was the chosen method for the production surveys conducted the following year.

In 2007, we carried out an expanded P-wave Minivib/landstreamer survey over three different buried valley systems: Medora-Waskada, Pierson and Spiritwood valleys (Fig. 1; Pugin et al., 2009). The field plan of proposed seismic transects (along with alternate lines) was developed cooperatively by the Geological Survey of Canada (GSC) and Manitoba Water Stewardship (MWS), in consultation with the West Souris River Conservation District (WSRCD). The goal was to acquire seismic sections across three different known or suspected buried valleys in southwest Manitoba along transects where some borehole ground-truth data were available.

Over a period of 9 operational days (October 11-19, 2007), we acquired a total of 38 line-km of P-wave reflection data. In all three survey areas, we were able to acquire significantly more data than planned, both in number and length of lines. This was due to:

- continued improvements in efficiency of data collection with the minivib/landstreamer system;
- very quiet road conditions (little or no traffic);
- zero down time related to weather (despite some windy conditions encountered in the Waskada and Killarney areas);
- zero down time due to equipment problems or malfunctions.

Details on the recording parameters for each line are given in Table 1. The same landstreamer set-up was used for all lines, consisting of 47 sleds at 1.5 m spacing, each equipped with a single 50 Hz vertical geophone. The Minivib was operated in vertical mode with a 7 second sweep. The frequency range was varied slightly (45-250 Hz to 45-350 Hz) depending on the results of tests conducted at the start of each line. Photos of the system in operation are presented in Figure 2. An example field record from the Pierson area is shown in Figure 3.

Line	**Source *(Source spacing)***	**Source parameters**	**Receivers *(#receivers @ receiver spacing)***	**Source-nearest receiver offset**	**Record length**	**Sample rate**	**Line length**
Wask 07-A **(Fig. 7a)**	Minivib (P) *(3 m)*	45 – 350 Hz linear sweep	P-wave landstreamer on gravel road *(47@1.5 m)*	3 m	7.2 s	0.25 ms	2 km
Wask 07-E **(Fig. 7b)**	Minivib (P) *(3 m)*	45 – 300 Hz linear sweep	P-wave landstreamer on gravel road *(47@1.5 m)*	3 m	7.2 s	0.5 ms	3 km
Wask 07-F **(Fig. 7c)**	Minivib (P) *(3 m)*	45 – 300 Hz linear sweep	P-wave landstreamer on gravel road *(47@1.5 m)*	3 m	7.2 s	0.5 ms	3 km
Pier 07-A **(Fig. 9a)**	Minivib (P) *(4.5 m)*	45 – 350 Hz linear sweep	P-wave landstreamer on gravel road *(47@1.5 m)*	3 m	7.2 s	0.5 ms	2 km
Pier 07-B **(Fig. 9c)**	Minivib (P) *(4.5 m)*	45 – 350 Hz linear sweep	P-wave landstreamer on gravel road *(47@1.5 m)*	3 m	7.2 s	0.5 ms	5 km
Pier 07-C **(Fig. 9b)**	Minivib (P) *(6 m)*	45 – 350 Hz linear sweep	P-wave landstreamer on gravel road *(47@1.5 m)*	3 m	7.2 s	0.5 ms	5 km
Killar 07-E **(Fig. 11a)**	Minivib (P) *(4.5 m)*	45 – 300 Hz linear sweep	P-wave landstreamer on gravel road *(47@1.5 m)*	3 m	7.2 s	0.5 ms	9 km
Killar 07-F **(Fig. 11c)**	Minivib (P) *(6 m)*	45 – 300 Hz linear sweep	P-wave landstreamer on gravel road *(47@1.5 m)*	3 m	7.2 s	0.5 ms	6 km
Killar 07-G **(Fig. 11b)**	Minivib (P) *(6 m)*	45 – 250 Hz linear sweep	P-wave landstreamer on gravel road *(47@1.5 m)*	3 m	7.2 s	0.5 ms	3 km

Table 1: Recording parameters for P-wave seismic reflection profiles, southwest Manitoba, 2007. All data were recorded uncorrelated. Final sections are shown in the figures indicated below the line name.

Figure 2: Photos of the Minivib source and P-wave landstreamer in operation in southwest Manitoba, October 2007: a) and b) Killarney area, c) south of Waskada, d) waiting for the herd to pass, Pierson area.

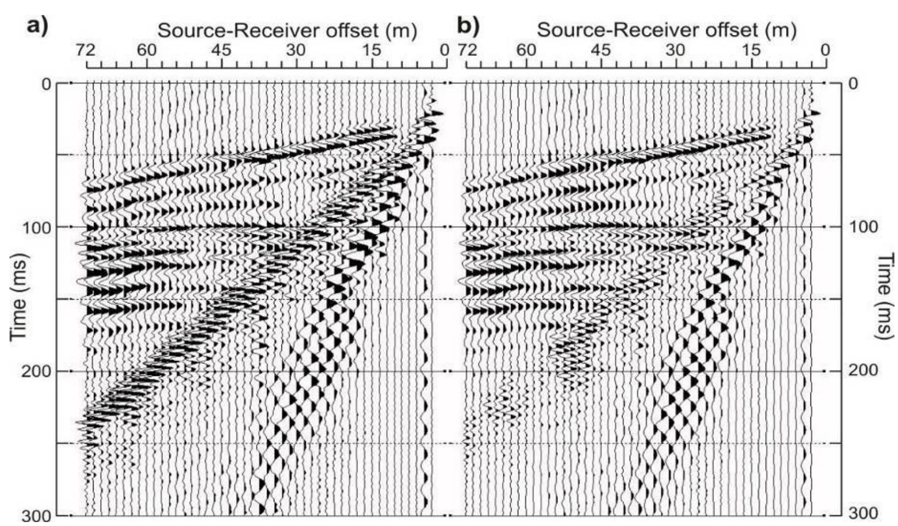


Figure 3: Example field shot gather obtained during the P-wave reflection survey near Pierson, Manitoba, using the minivib source and 50 Hz vertical geophones at 1.5 m spacing mounted on a landstreamer. Uncorrelated data are recorded in order to allow careful choice of the correlating function. a) raw record, after correlation, b) correlated record after FK and high-pass filtering. Increasing time corresponds to increasing depth.

Data were processed using WinSeis™ (Kansas Geological Survey) seismic processing software, in combination with Seismic Unix and in-house seismic processing software. The main processing steps are outlined in Table 2. For P-wave data, static corrections are a critical part of the processing sequence, and have a strong effect of the quality and resolution of the final processed section (Figure 4). Lateral variations in near-surface velocity, largely due to variable water saturation of the near-surface sediments, can generate very significant statics. Time shifts of up to 10 to 20 ms can be observed between receivers, even with receiver spacings of only 1-3 m. We have found that the optimum static correction method is based on refraction modeling of the near-surface and statistical analysis of shot and receiver statics using first break picks (modified from Pugin and Pullan, 2000).

Format conversion, SEG2 to KGS SEGY
Spectral whitening
Cross correlation
Editing of the geometry
Refraction analysis for statics calculation
Frequency filter
Scaling (trace normalization)
Bottom mute of remaining surface-wave energy
Static corrections
Velocity analysis
NMO Corrections
Top mute
Stack, nominal fold: 24
Correction for ground-surface topography
Conversion to elevation (using velocity analysis results)

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

Source Spacing Test (Waskada 07-E)

A portion of the east-west cross-section (Wask 07-E) is shown in Figure 4. These data were recorded early in the southwest Manitoba survey and a number of tests were conducted to determine the source spacing that would optimize the data quality and acquisition rate. This figure presents the results of processing the data over the buried valley using either 3 m or 6 m as a source spacing. The upper panels (Fig. 4a, b) are the preliminary stacked sections (before and after static corrections respectively), using a source spacing of 3 m and a bin size (i.e. trace spacing on the final section) of 1.5 m. In Figure 4c, the section produced using a source spacing of 6 m and increasing the bin size to 3 m. This section is smoothed laterally compared to Fig. 4b, but with little or no deterioration in data quality. As a result of these tests, the source spacing was increased to 4.5 or 6 m for the data acquired in Pierson and Killarney, allowing an increase in data production.

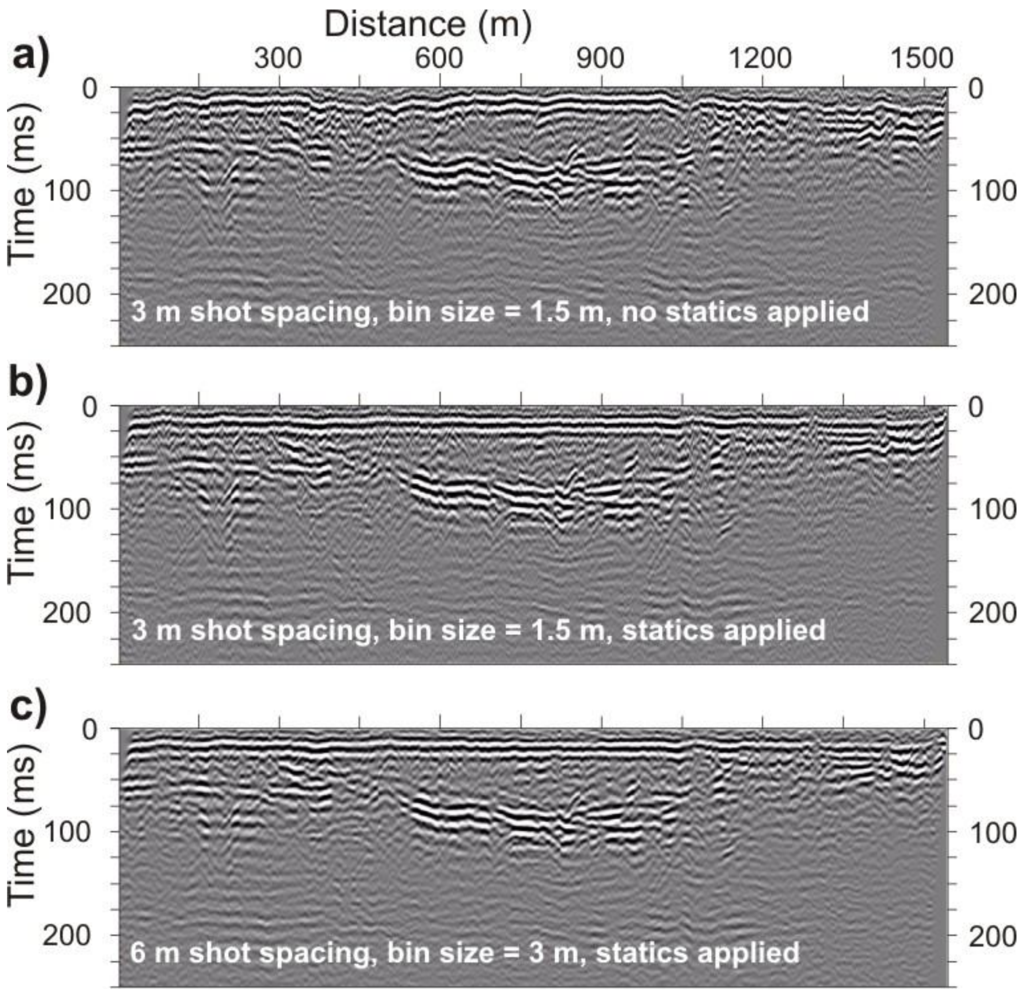


Figure 4: Preliminary P-wave seismic section (in two-way travel-time) over the Medora-Waskada buried valley demonstrating the importance of static corrections to the quality of the final stack, and showing the effect of increasing the source spacing on the quality of the final stacked section. These data are the western 1.5 km of Line Wask 07-E. A 3 m source spacing was used to collect the data along this line: a) Stacked section using 3 m source spacing before static corrections have been applied (24-fold); b) same section after static corrections have been made; c) effect of increasing the source spacing to 6 m and the bin size to 3 m (24-fold).

Results

The results of the 2007 southwest Manitoba surveys are presented in Figures 5-11. Figures 5, 8 and 10 are detailed maps of the survey areas with CMP (common midpoint) numbers indicated along each of the seismic lines for the Waskada, Pierson and Killarney (Spiritwood) surveys respectively. The accompanying figures (Figs. 6, 7, 9 and 11, and Plates 1-3) present the P-wave stacked sections converted to depth and displayed as a function of elevation (metres above sea level). At the top of each section are two scales: the upper scale indicates the CMP number (as shown on the detailed maps) and the lower scale gives the distance in metres along the seismic line. The processed section is displayed with a preliminary interpretation indicated by coloured lines. These interpretations are based on the observed seismic facies and available waterwell data. These interpretations may evolve with input for geologists and hydrogeologists who are familiar with the area, and as additional ground-truth data are acquired (e.g. MWS drilling).

Waskada area (Figures 5-7, Plate 1)
Three sections were obtained south of Waskada (Figs. 1, 5) to further our understanding of the Medora-Waskada Valley in this area (see Annex 2). The first section (Wask 07-A) was obtained to complete the section acquired in 2006 (Fig. 6) which suggested that the valley may have extended further to the east. Sections Wask 07-E and Wask 07-F were acquired 1 and 2 miles to the south respectively.

Waskada 07-A (Figure 7a)
This line extended Section A (acquired in 2006 – see Annex 2; Fig. 6) eastward by an additional 1300 m in order to confirm the width and character of the buried valley at this location. The section (Fig. 7a) shows that the Waskada buried valley is ~1.9 km wide in this cross-section and that in the centre of the valley there is a bedrock ridge overlain by a highly reflective mound-like deposit. The nature of this mound is not well understood. It may be predominantly bedrock overlain by till remnants, or it may also contain coarse-grained stratified sediments. The unit extends to within 20 m of ground surface at CMP 530 and may limit the hydraulic connectivity between the two portions of the valley. This mound also appears to separate portions of the buried valley with different fill characteristics. The western portion of the channel fill is characterized by a high amplitude reflection package above bedrock (see Fig. 6) overlain by a sequence showing little coherent structure. In contrast, the eastern portion of the valley (CMPs 550-1050) is characterized by a coherent flat-lying reflection in the centre of the section (~430 masl) and less energy above the bedrock surface. The eastern portion of the valley is also slightly shallower than the western portion (elevation of 380 masl and 365 masl respectively). These characteristics suggest that there may have been different periods of channel cutting and infill. Along the entire section the surface sediment is a till unit interpreted to be ~20 m thick, and indicated in the borehole log (R-2-85 Waskada) to be a stony till.

Waskada 07-E (Figure 7b)
Waskada 07-E was acquired 1 mile south of Section A (Fig. 5) and again outlines a buried valley separated into two sections by a bedrock high. In this case, the western portion of the valley is slightly shallower (375 masl), but again shows the high amplitude reflection package above the bedrock surface (CMPs 1400-1750, 380-400 masl). The central bedrock mound is broader than observed on Waskada 07-A (~500 m wide) and does not show the same mound-like deposits on its surface. Again the eastern portion of the valley (CMPs 600-1000) is characterized by coherent flat-lying reflections above 405 masl and a low-amplitude facies above the bedrock surface. The separation between the two valley fills appears to correlate with a westward-sloping reflector observed at CMP 1250-1300. This perhaps correlates with the westward dipping face of the mound-like structure observed on Waskada 07-A, which suggests that the western portion of the buried valley was cut after the eastern portion.

However, boreholes drilled for Water Resources Branch (WRB; now Manitoba Water Stewardship) along this section in 1993 indicate shale at shallow depth (12 m in WRB #7-93; 18 m in WRB #8-93; 25 m in WRB #9-93). Additional drilling is required to decide whether the valley features observed in the seismic sections are Quaternary or within the bedrock sequence.

Waskada 07-F (Figure 7c)
Figure 7c shows the section (Waskada 07-F) obtained 1 mile south of Waskada 07-E. It is apparent that the buried valley, which has been traced in the seismic sections acquired from south of Medora (see Annex 2), is not observed on this line or has become significantly shallower and broader. In four WRB boreholes along this line, bedrock is estimated to be 15-25 m beneath the ground surface. The bedrock surface is interpreted here as the near-surface high-amplitude reflection observed along the entire line.

There is another interesting feature on this section – and that is a low velocity zone (CMPs 1500-1650) that indicates some sort of disruption in the surface tills. Low velocity can indicate a change in lithology to softer materials, a reduction in water content, or an increase in gas or air within the sediments (e.g. peat). It is not known at this time what causes this feature or whether it is related in any way to the buried valley to the north.

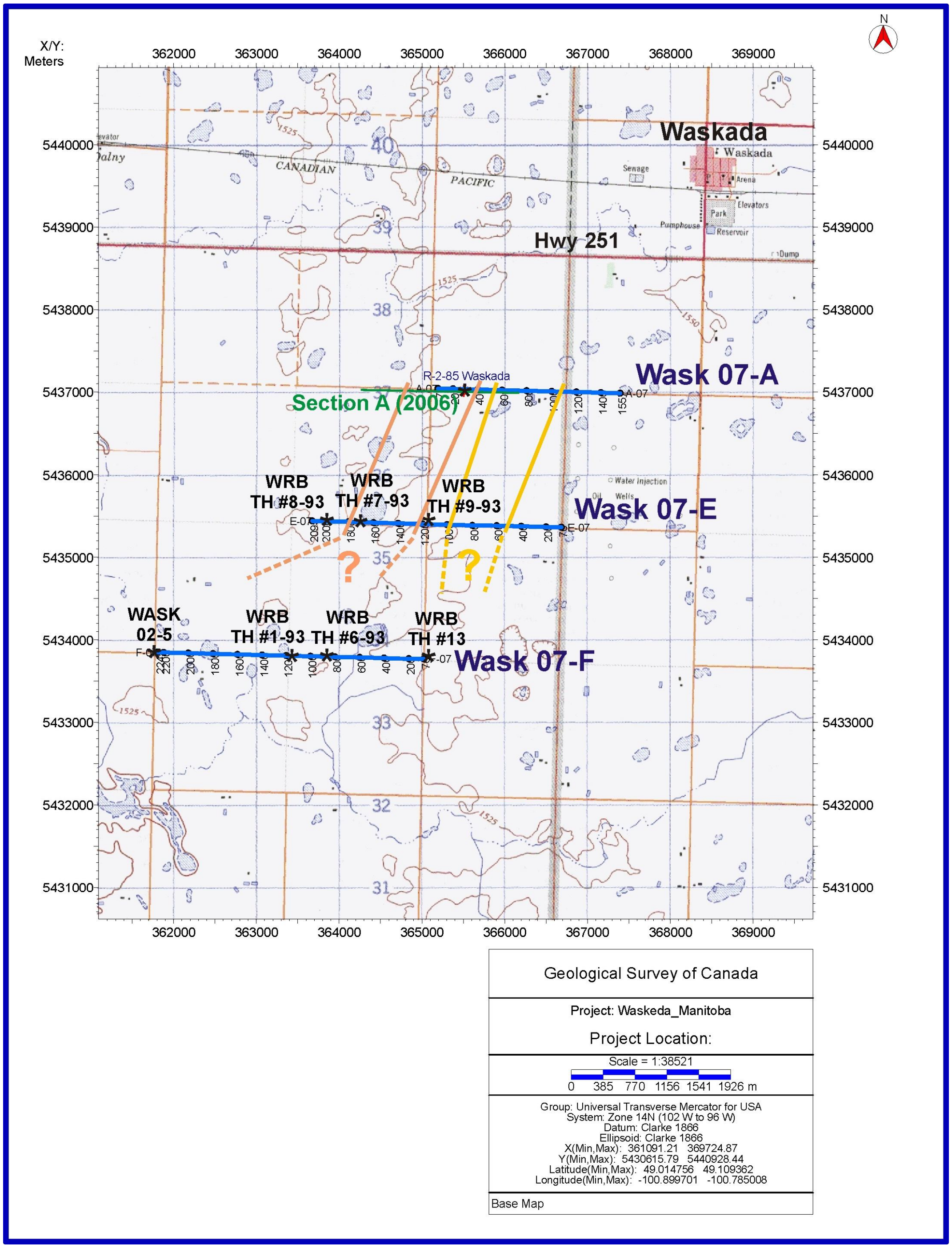


Figure 5: Detailed map showing the three seismic lines completed in the Waskada area in 2007. The small numbers along each seismic transect are the CMP numbers which indicate the trace numbers along each line (see Fig. 7). The east and west portions of the buried valley that were observed in seismic sections WASK 07-A and E are indicated by the yellow and tan coloured lines respectively. Datum: NAD27.

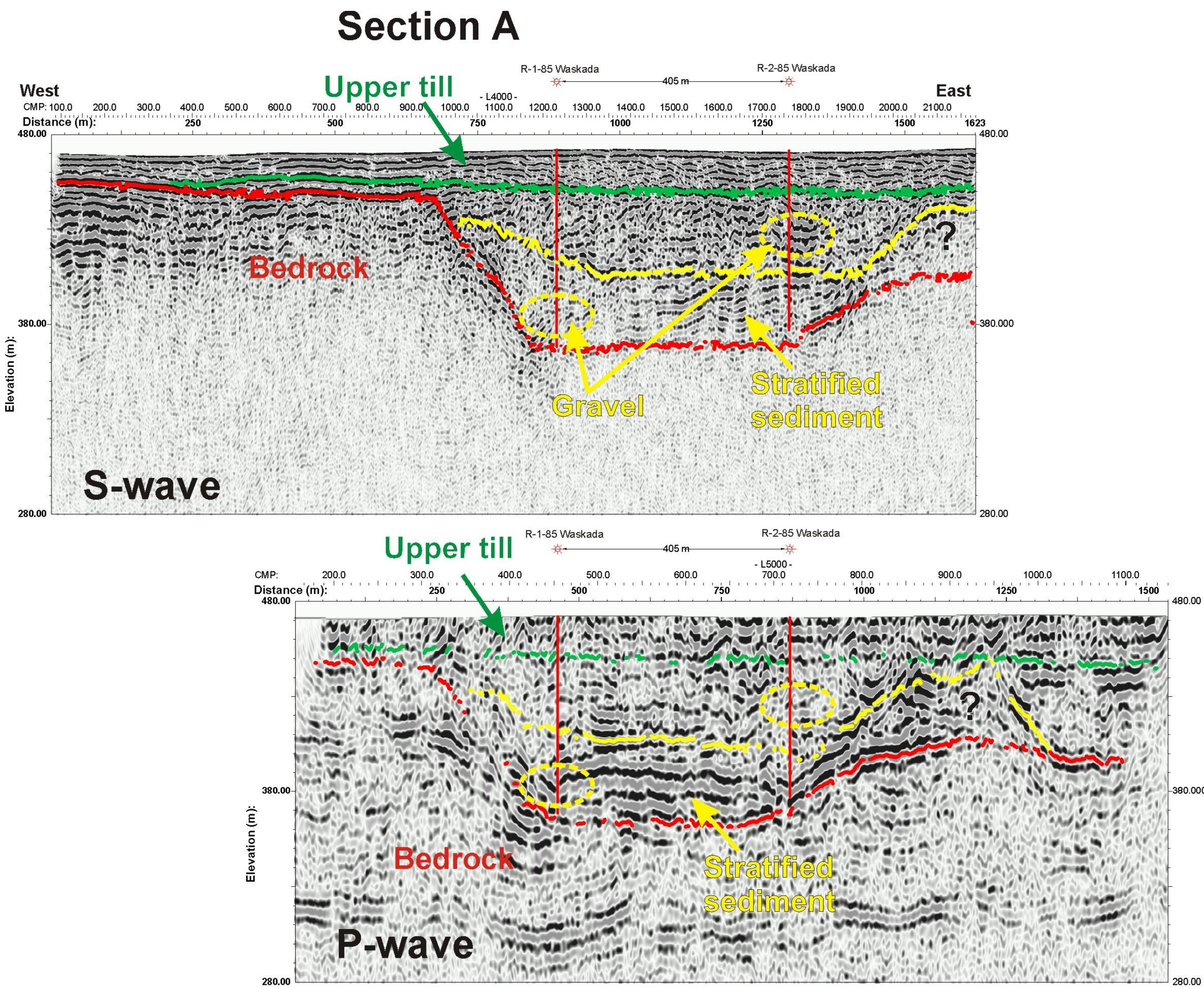
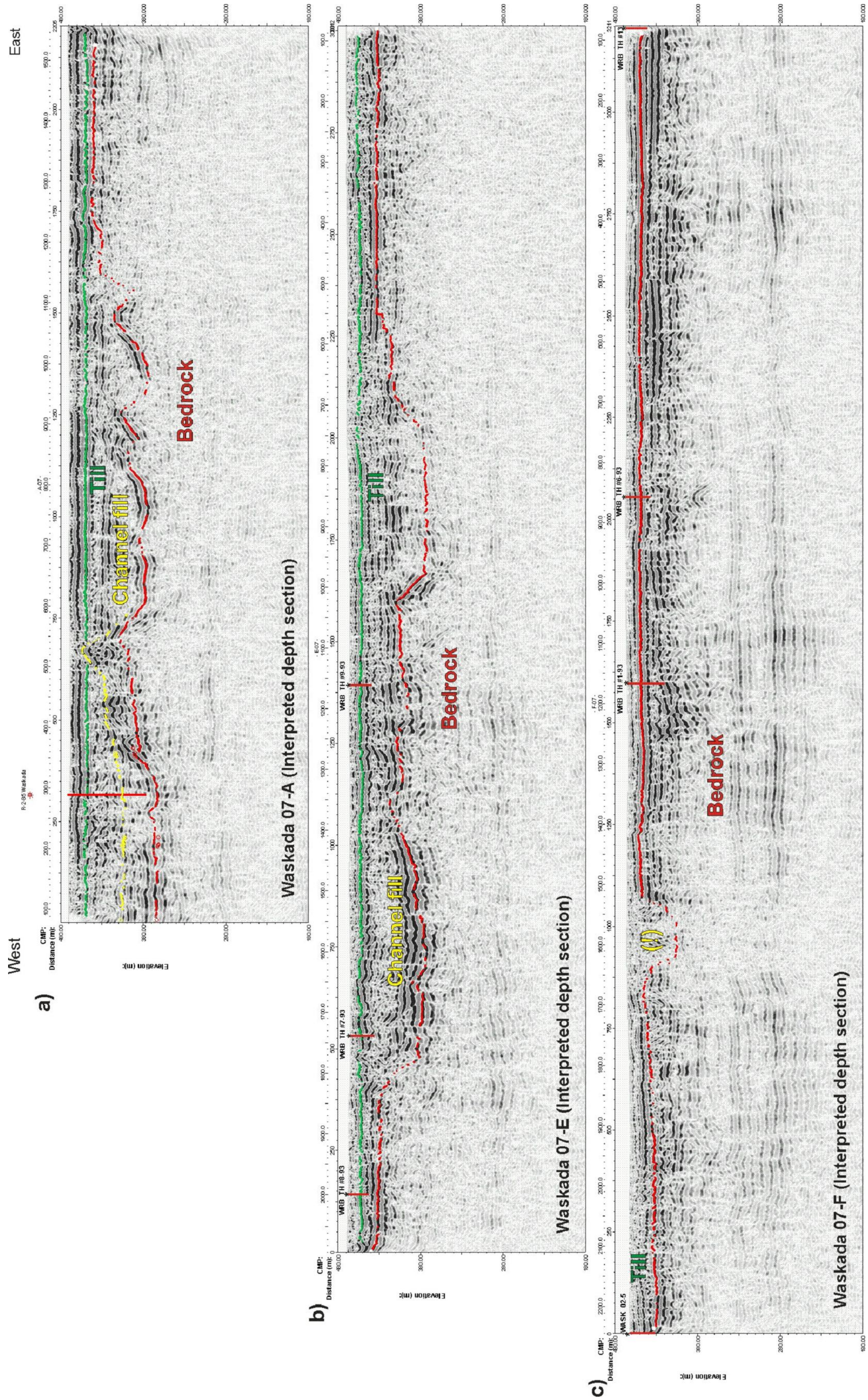


Figure 6: Interpreted SH- and P-wave reflection profiles (upper and lower panels respectively) acquired with Minivib source along Section A south of Waskada in 2006 (see Fig. 5 for location; also shown in Annex 2 as Fig. A2-10b). The yellow circles indicate where "shale boulder gravel" was noted in the borehole logs (borehole locations and depths are shown as vertical red lines). 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 7 (following page – see also Plate 1): Three seismic sections (converted to depth and plotted as elevation sections) obtained in the Waskada area (see Fig. 5 for line location). For each line, the processed section is displayed with interpretation indicated by coloured lines. At the top of each section are two scales: the upper scale indicates the CMP number (as shown on the detailed maps) and the lower scale gives the distance in metres along the seismic line.

a) Waskada 07-A (northernmost line; Fig. 5) note that the western 900 m of this line overlaps with the eastern half of the P-wave line acquired along Section A in 2006 (see Fig. 6, lower panel)
b) Waskada 07-E (central line; Fig. 5)
c) Waskada 07-F (southernmost line; Fig. 5)



a)
West
East
Waskada 07-A (Interpreted depth section)
Till
Channel fill
Bedrock
b)
Waskada 07-E (Interpreted depth section)
Till
Channel fill
Bedrock
c)
Waskada 07-F (Interpreted depth section)
Till
Bedrock

Pierson area (Figures 8 and 9, Plate 2)
Three cross-sections of the Pierson buried valley were obtained south of Pierson, 5-8 miles north of the Canada-US border (Figs. 1, 8). We were unable to continue Section Pier 07-A eastwards to the boreholes TH-101 and TH-102 because the road became a grassy track which was not amenable to the minivib/landstreamer system.

These lines yielded the highest resolution data obtained during the southwest Manitoba survey, and have produced excellent images of the buried valley (Figure 9). The high data quality is likely related to the fine-grained near-surface tills in this area, which are slightly lower in velocity (finer-grained or less compacted?) than the surface tills in the Waskada and Killarney areas.

The sections show that, in this region, the Pierson Valley is buried beneath thick tills (60-70 m). Based on the seismic data, the till sequence can be divided into upper and lower units, separated by a strong flat-lying reflection at ~30 ms two-way travel time (10-20 m depth). This interface is observed at the same depth on all sections acquired in this area and so appears to be regionally extensive. This interface is not generally noted on borehole logs. The upper unit may represent the surface oxidized layer, or a slightly sandier surface till unit (as noted in the log for BH GSC 68-22). Both till units are characterized by low internal reflectivity and are interpreted to be fairly massive and relatively fine-grained (i.e. clay-silt to fine-sandy tills). In borehole TH-103 (see Fig. 8; Watermark Consulting Ltd, 2004), the till is interpreted to consist of a surface silty clay till, underlain at an elevation of ~420-430 masl by a sandy till. This interface is based on a slight change in resistivity at this depth, but is not observed on any of these seismic sections.

All three seismic sections are characterized by an approximately-planar, high-amplitude reflector or reflector package at an elevation of ~390-400 masl. This is interpreted as the till/bedrock interface, or the top of the channel fill sequence. The sections show that the Pierson Valley is a broad (~3 km wide) and relatively shallow feature cut into the bedrock beneath this elevation. The morphology of the bedrock surface and the characteristics of the channel fill vary along these three sections and will be discussed below for each individual line.

Pierson 07-A (Figure 9a)
The northernmost cross-section (Pier 07-A) is shown in Figure 9a. In the western part of the line (west of Highway 256), the strong event at 390-400 masl is interpreted as the reflection from the bedrock surface. This is supported by the log for WRB Pierson Test hole #20-65 (further to the west) which encountered shale bedrock at a depth of ~68 m. However, ~200 m east of Highway 256, the edge of the bedrock valley is imaged in the seismic section. The section indicates that the valley bottom exhibits an undulating topography, with a western portion of the channel (~600 m wide and up to 35 m deep) separated from an eastern portion by a rise in bedrock elevation just to the east of BH TH-103. The two portions of the valley may not be hydraulically connected in this area. The western section of the valley (CMPs 400-650) is characterized by low reflectivity contrast with the overlying till, mounded and channel structures within the valley and a relatively strong basal reflection (interpreted as bedrock surface). The nature of the channel fill also varies in this section of the valley, with lower reflection amplitudes in the west (CMPs 550-700) and higher amplitude internal reflections towards the borehole location (CMPs 400-550).

Borehole TH-103 sampled the eastern edge of this portion of the valley, and encountered a 24 m thick sequence of sand, gravel and fine-grained layers below a depth of 65 m (Watermark Consulting Ltd, 2004). On the basis of the seismic section, the deepest portion of this section of the valley would be 100-200 m west of the borehole location where bedrock would be expected to be ~10 m deeper and overlain by a greater thickness of coarse-grained material.

The eastern section of the valley (CMPs 50-350) appears to be broader and somewhat shallower, and is characterized by a very strong reflection at the interface with the overlying till. Based on the seismic sections further south, the Pierson Valley is expected to extend perhaps another 1-2 km to the east.

Pierson 07-C (Figure 9b)

Figure 9b shows the section (Pier 07-C) obtained 1 mile south of the Pier 07-A (Fig. 9a). The section shows the Pierson Valley to be a broad complex valley on the order of 2.5 km in width (CMPs 250-1300), and perhaps also extends further to the west. Along this line, we again observe two major sections of the valley, similar in some respects to Pier 07-A (Fig. 9a). The two sections may be separated by a bedrock ridge within the valley (CMPs 700-760). The deepest part of the bedrock valley observed on all sections acquired in the Pierson area is at ~CMP 650 along this line (40 m deep). The infill of this deeper portion of the valley is characterized by very low reflectivity, which suggests that it may be massive sand (or a fine-grained massive till?). West of what we infer to be the main portion of the valley (CMPs 0-200) WRB Test Hole #M-22 encountered 6 m of gravel and sand at 65 m depth underlain by 27 m of "slightly gravely till". This suggests that there may be a westward extension of the valley system, but the seismic section suggests that this is shallower than the main part of the valley described above. East of the bedrock high in the centre of the valley, bedrock is observed to rise gently towards the east, but the overlying deposits show two different seismic facies. From CMPs 800-1100 we observe some moderate-amplitude mound/channel reflections which could possibly represent coarse-grained channel fill deposits. Further to the east (CMPs 1100-1300), the reflection at ~395 masl (top of channel fill) is again extremely planar and high in strength, with no significant structure observed below that above the bedrock surface. These abruptly changing seismic reflection characteristics suggest that there may have been a number of channel cutting and infilling events.

Pierson 07-B (Figure 9c)

The southernmost cross-section (Pier 07-B) is shown in Figure 9c. We believe that this section transects the entire buried valley, though the valley extends close to the eastern end of the line (CMP 2100). In this case, the valley is not clearly divided into two sections by a bedrock ridge, though a slight shallowing of the bedrock surface is interpreted at CMPs 1300-1600. In the western half of the valley, bedrock slopes very gently downwards (CMPs 200-900) – in contrast to the relatively steeper western valley edges observed in the two northern seismic sections. In the deeper parts of the valley (CMPs 900-1900) the section is characterized by a series of higher-amplitude mound-like reflections (e.g. ~CMP 900, 1200, 1700). These are interpreted to be the most likely indicators of coarse-grained channel deposits (e.g. sands and gravels). GSC 68-22 encountered 27.5 m of sand, gravel and till (channel fill deposits).

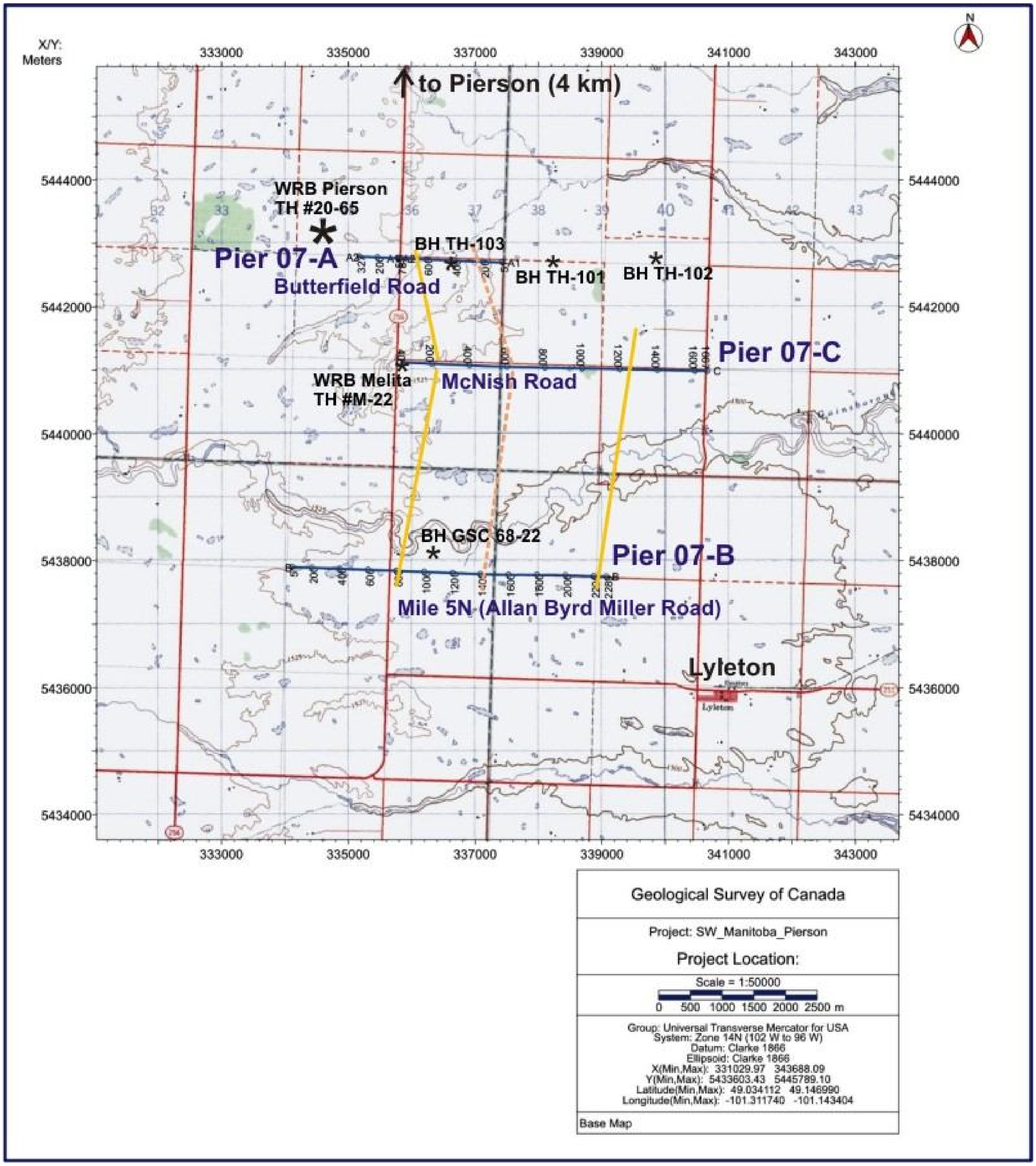
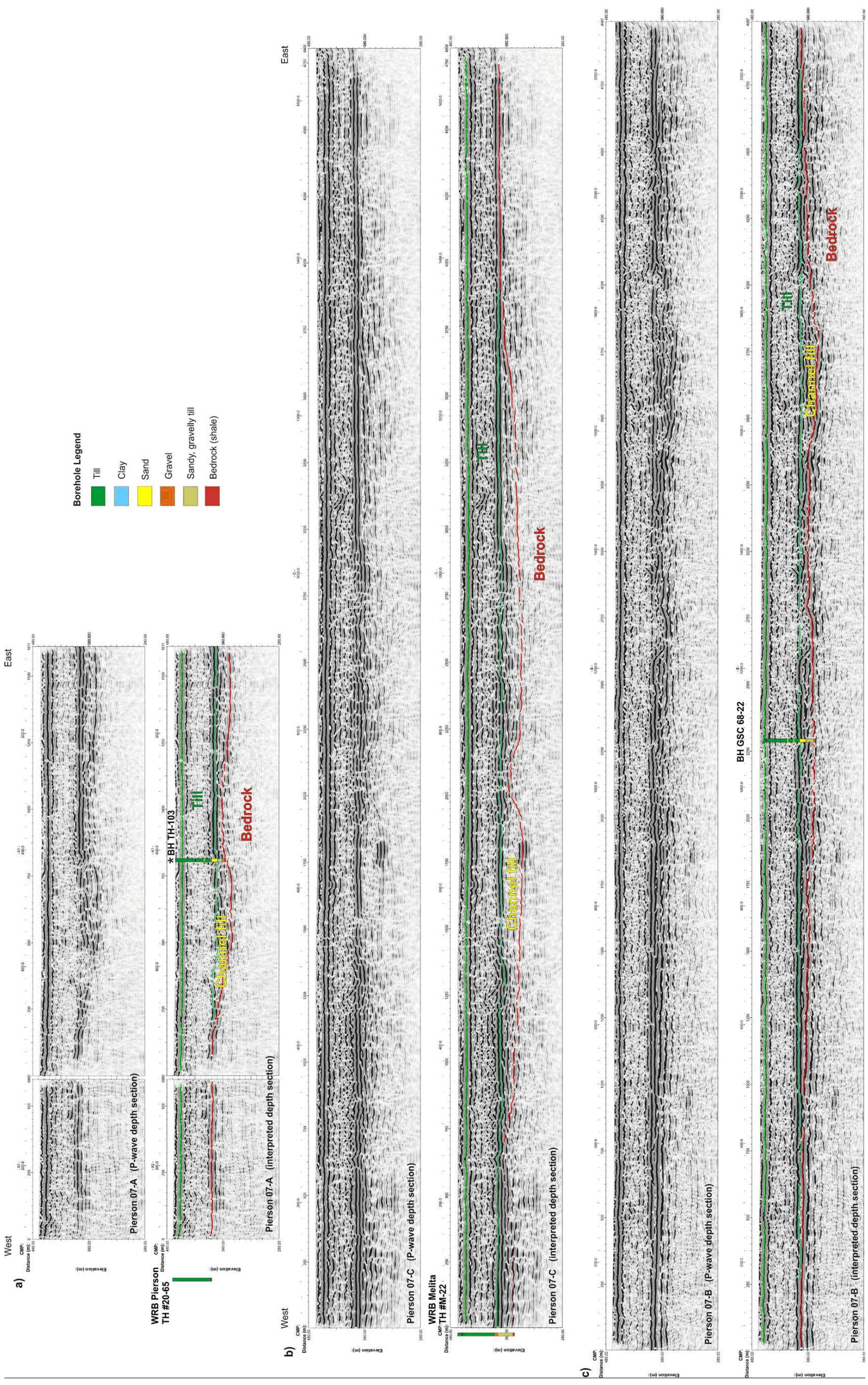


Figure 8: Detailed map showing the three seismic lines completed in the Pierson area in 2007, and the location of some boreholes in the area. The small numbers along each seismic transect are the CMP numbers which indicate the trace numbers along each line (see Fig. 9). The boreholes indicated by the large asterisks are only located to within the quarter section. The approximate edges of the buried channel as determined from the seismic sections are indicated as yellow lines; the location of the slight bedrock high within the valley is shown as a dashed tan-coloured line. Datum: NAD27.

Figure 9 (following page – see also Plate 2): Three seismic sections (converted to depth and plotted as elevation sections) obtained in the Pierson area (see Fig. 8 for line locations). For each line, the processed section is displayed above a copy of the section with interpretation indicated by coloured lines. At the top of each section are two scales: the upper scale indicates the CMP number (as shown on the detailed maps) and the lower scale gives the distance in metres along the seismic line.

a) Pierson 07-A (northernmost line; Fig. 8)
b) Pierson 07-C (central line; Fig. 8)
c) Pierson 07-B (southernmost line; Fig. 8)



a)
West
East
Pierson 07-A (P-wave depth section)
WRB Pierson
TH #20-65
* BH TH-103
Till
Channel fill
Bedrock
Pierson 07-A (interpreted depth section)
Borehole Legend
Till
Clay
Sand
Gravel
Sandy, gravelly till
Bedrock (shale)
b)
West
East
Pierson 07-C (P-wave depth section)
WRB Melita
TH #M-22
Till
Channel fill
Bedrock
Pierson 07-C (interpreted depth section)
c)
Pierson 07-B (P-wave depth section)
BH GSC 68-22
Till
Channel fill
Bedrock
Pierson 07-B (interpreted depth section)
CMP:
Distance (m):
Elevation (m):

Killarney area (Figures 10 and 11, Plate 3)

Three sections were obtained over the western arm of the Spiritwood Valley north of Killarney (Figs. 1, 10) in order to obtain a first look at the subsurface structure in this area. Based on water well records, the valley is estimated to be 10-15 km wide. These seismic transects were located to try to image the east side of this valley. A long east-west line (Killar 07-E) and two north-south sections (Killar 07-F and Killar 07-G) were surveyed (Fig. 10).

Killarney 07-E (Figure 11a)

Killarney 07-E (Fig. 11a) is 8.5 km long and represents a cross-section of the eastern portion of the Spiritwood Valley in this area. A WRB monitoring well (Kilcart #8, G05OA009), located in the centre of this line, provides some ground-truth. In many places along the line it is difficult to confidently interpret the bedrock surface because of the low acoustic contrast between "bedrock" and the overlying tills or coarse-grained sediments. This low acoustic contrast allows considerable reflection energy to penetrate into bedrock and reflections from several hundreds of metres within the bedrock sequence can be seen on these data (e.g. strong reflection at 330-340 masl on the eastern portion of this section – deeper reflections are not displayed in this presentation but are clearly visible on all the Killarney sections).

The bedrock surface is interpreted to be within 20 m of the ground surface on the eastern portion of this section (CMPs 1400-2100) and this is corroborated by local water well records. The eastern edge of the buried valley has a gently dipping slope which starts approximately 1.5 km west of the end of the line. The deepest part of the valley imaged on this section is located ~1 km west of the WRB production well. In this area, there appears to be an incised valley (~800 m wide and 20 m deep; CMPs 1550-1900). Within and overfilling this portion of the valley, there is a thick sequence of high-amplitude, coherent reflections which are interpreted as stratified deposits and likely correlated with the 15 m of sand and gravel encountered above the bedrock in the monitoring well. In the deepest part of the valley, these units are estimated to be ~40 m thick, and are a potential drilling target for a high-yield well. The location of this incised portion of the valley is shown in Figure 10 as yellow lines.

The western portion of this line is characterized by a more complex channel fill sequence which includes mounded and potential deformation (thrust?) structures (e.g. CMPs 200-600). These deposits may be predominantly till although cored drilling would be required to confirm this interpretation.

Killarney 07-G (Figure 11b)

Figure 11b shows the 3 km long north-south section which intersects Killarney 07-E at the blue line shown in the section (just east of the WRB monitoring well). The interpreted bedrock surface is ~50-55 m below ground surface along most of this line, though bedrock is starting to dip to the south at the south end of the line (CMPs 0-300), which is interpreted to be the southern extension of the deeper incision of the valley observed on Killarney 07-E (see Fig. 10).

Killarney 07-F (Figure 11c)

Killarney 07-F (Fig. 11c) is a 6.4 km long north-south section that extends southwards from close to the eastern edge of the buried valley (Fig. 10). Bedrock is observed to slope gently to the south along the entire section, reaching its deepest point at the south end of the line (~110 m below ground surface). The channel fill sequence varies considerably along the line from high-amplitude mounded reflections (till? or stratified deposits?; see e.g. CMPs 100-850), to low amplitude facies beneath high amplitude near-surface reflections (fine-grained deposits beneath near-surface tills?; see e.g. CMPs 900-1000, 1300-1500), to thick, layered reflection packages (tills, sands and gravels?; see e.g. CMPs 1700-2200). Again, high-quality borehole control is needed to confidently interpret the observed seismic facies and better estimate their groundwater potential.

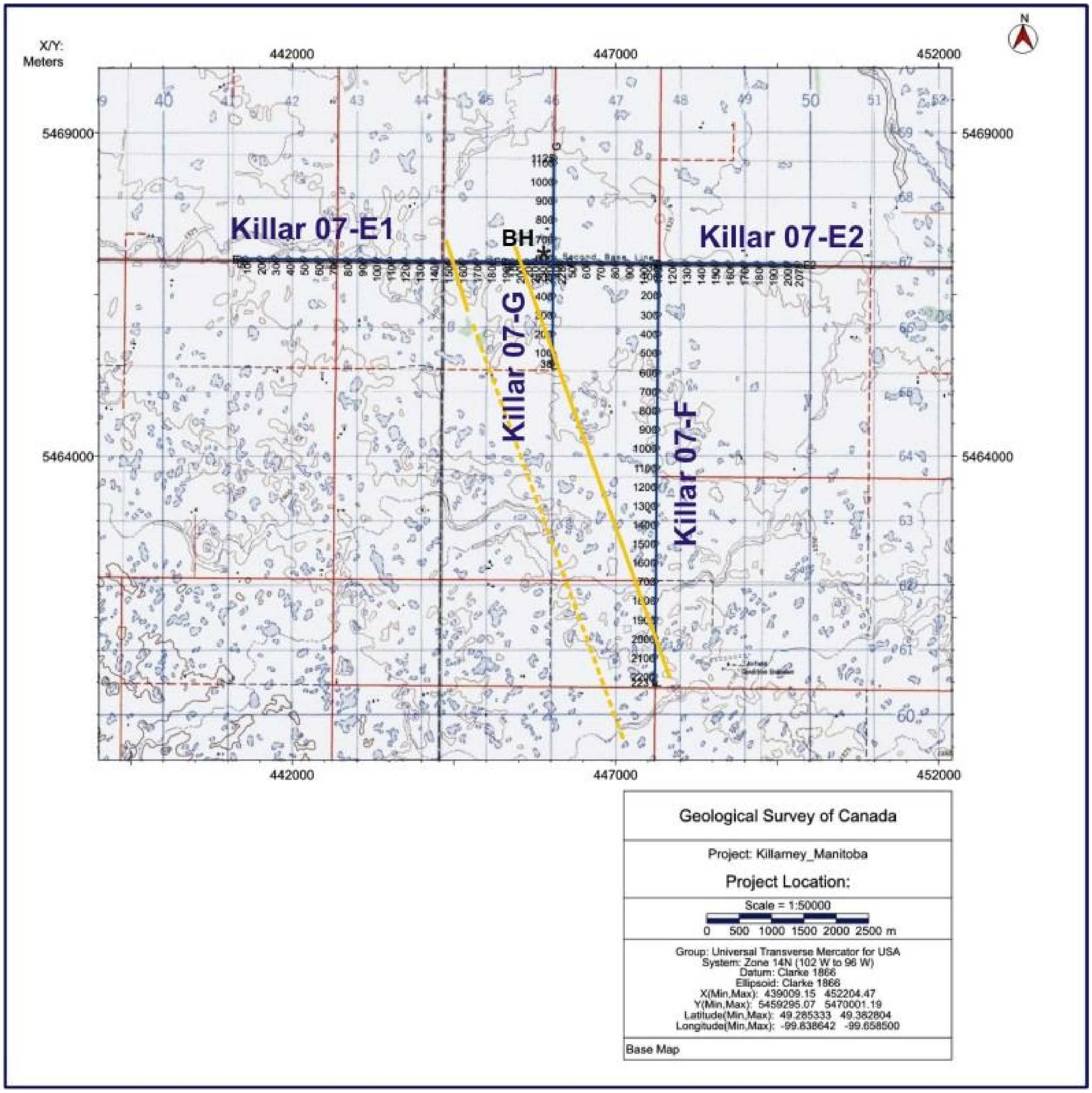


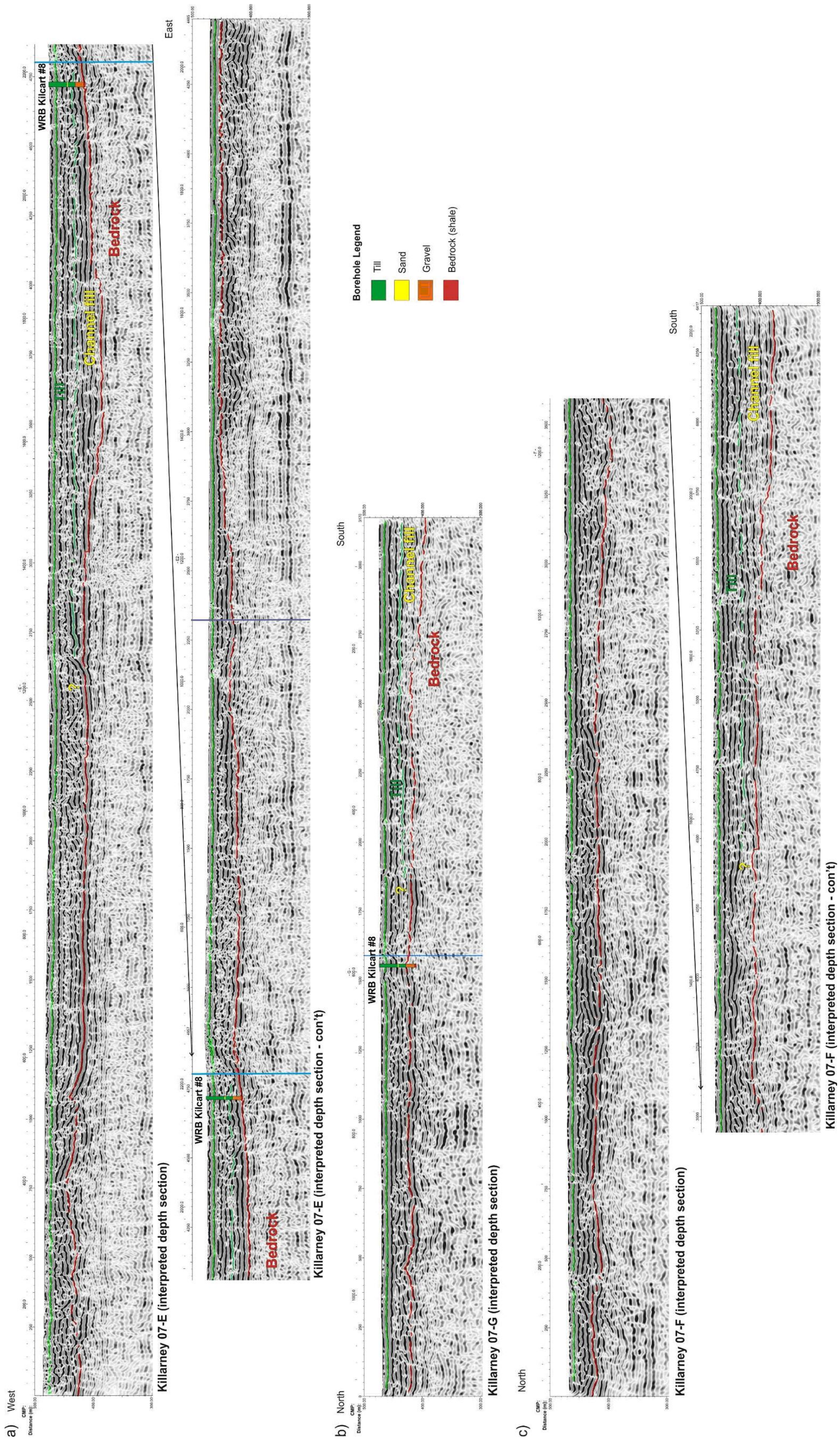
Figure 10: Detailed map showing the three seismic lines completed in the Klilarney area in 2007. The small numbers along each seismic transect are the CMP numbers which indicate the trace numbers along each line (see Fig. 11). The edges of the deepest part of the buried valley as determined from the seismic sections are shown as yellow lines. Datum: NAD27.

Figure 11 (following page – see also Plate 3): Three seismic sections (converted to depth and plotted as elevation sections) obtained in the Killarney area (see Fig. 10 for line locations). For each line, the processed section is displayed with interpretation indicated by coloured lines. At the top of each section are two scales: the upper scale indicates the CMP number (as shown on the detailed maps) and the lower scale gives the distance in metres along the seismic line.

a) Killarney 07-E (west-east line; Fig. 10) - note that due to the length of the line it is presented in two sections (with some overlap); an arrow shows the point on the lower section that corresponds to the end of the upper section. The blue line represents the intersection with Killarney 07-G. The purple line represents the intersection with Killarney 07-F.

b) Killarney 07-G (north-south line that crosses the central portion of Killarney 07-E; Fig. 10).

c) Killarney 07-F (north-south line that extends southward from Killarney 07-E; Fig. 10) - note that due to the length of the line it is presented in two sections (with some overlap); an arrow shows the point on the lower section that corresponds to the end of the upper section.



a) West
East
WRB Kilcart #8
Till
Channel fill
Bedrock
?
Killarney 07-E (interpreted depth section)
Killarney 07-E (interpreted depth section - con't)
Borehole Legend
Till
Sand
Gravel
Bedrock (shale)
b) North
South
Killarney 07-G (interpreted depth section)
c) North
South
Killarney 07-F (interpreted depth section)
Killarney 07-F (interpreted depth section - con't)

Discussion

The three case studies completed in 2007 clearly demonstrate that seismic reflection data acquisition using the vibratory source/landstreamer technology can be used very effectively to image buried valleys in this geological environment where thick (~100m) glacial deposits overly Cretaceous (shale) bedrock. Understanding of three buried valley systems in southwest Manitoba has been substantially improved based on the subsurface images that have been produced.

These results show that the three valleys differ markedly in depth, size and type of valley fill. The Medora-Waskada buried valley is a narrow (1-2 km) feature, up to ~100 m deep with relatively steep sides, and buried beneath only a few 10s metres of surficial glacial deposits (till). South of Waskada, the results reveal that the buried valley was not observed where it had been previously "mapped" based on limited borehole information midway between Waskada and the US border and furthermore is divided into two valleys, each with distinct seismic facies (Figs. 12).

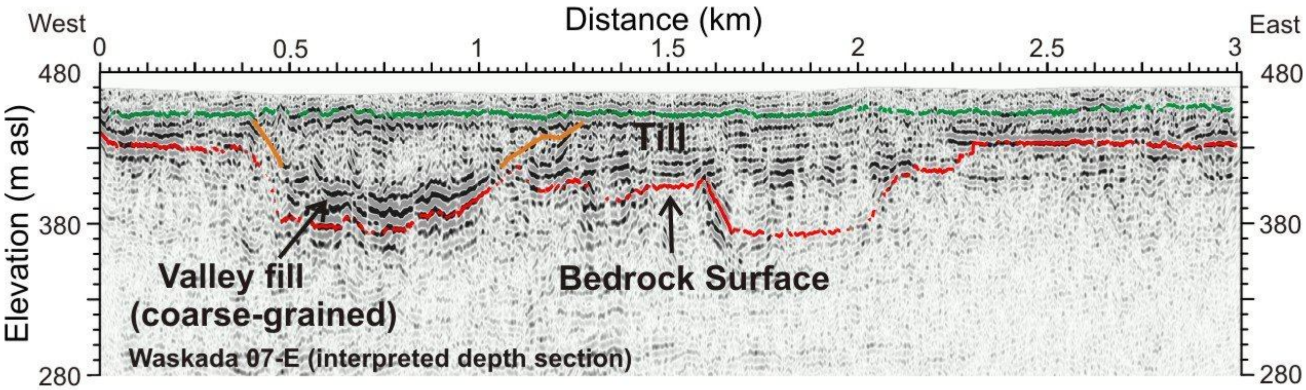


Figure 12: Interpreted east-west seismic section (3 km in length) from south of Waskada showing the two buried valleys observed in this area. Vertical exaggeration is ~ 4.3.

The current geological understanding of the Medora-Waskada valley and its fill is limited and somewhat contradictory. Klassen and Wyder (1970) indicate that the valley and its fill are of Pleistocene age and that the "lowest elevations are not necessarily coincident with the courses of preglacial river systems". Fulton et al. (2004) identified the stratified sediment drilled by Klassen and Wyder (1970) near Waskada to belong to the Empress Group. In the Saskatoon area, Christiansen (1992) identified the Empress Group as Late Tertiary pre-glacial valley fills (mountain-derived sediment) and early pro-glacial deposition (Shield-derived sediment). To our knowledge, there have been no additional interpretations regarding the geological origin of the valley and its fill. Without an improved geological understanding from high-resolution data, there is little capability to predict the distribution of sediment within the valley beyond what has been observed.

The nature of the Medora-Waskada valley fill appears to change significantly in the 3.5 km distance between sections B and C (midway between Medora and Waskada – see Annex 2). Towards Medora, most boreholes describe the sediment filling the valley to be "till". Seismic facies in this area differ from those in sections close to Waskada and do not show some of the high amplitude reflectors along the base of the valley which are interpreted as coarser-grained sediments with aquifer potential. This transition is both geologically and hydrogeologically significant since it seems to represent a bounding surface in the sedimentary sequence and since it also likely forms a hydrogeological boundary. Where high amplitude reflectors occur in sections C and D, they are not as extensive suggesting that potential aquifers would be of limited lateral extent and hydraulic boundaries would be encountered much sooner than in the southern extent of the valley (Hinton et al., 2007).

The transition from minimal to no stratified sediment near Medora to ~85 m of stratified sediment filling the bedrock valley near Waskada suggests a more complex history than fluvial or proglacial deposition of the aquifer in a pre-existing valley with subsequent burial by till. Such large changes in deposition or erosion over such short distances do not seem likely in a subaerial environment and portions of the valley history may have occurred in a subglacial enviroment where very high hydraulic gradients may lead to abrupt depositional and erosional events (Alley et al., 1997). Conceptual geological models of buried-valley aquifers for the area need to be re-assessed.

The Pierson Valley is a broad (~2.5 km wide), relatively shallow feature (<40 m deep), buried beneath thick (60-70 m) regional tills, and exhibits a variable bedrock surface which could be indicative of several episodes of valley formation. Recharge rates to the channel fill deposits beneath the thick surficial tills are likely to be extremely low, which may limit the long-term sustainability of groundwater extraction from this feature.

Figure 13 shows that, in this area, the western edge of the valley is characterized by a very gentle slope to the east (0.5-2 km). A GSC borehole drilled in 1968 encountered 27.5 m of sand, gravel and till above the bedrock surface, and these are the materials which are assumed to make up the valley fill deposits observed on the seismic sections. These deposits are characterized by a high-to-moderate amplitude reflection package. The section indicates that the valley bottom exhibits an undulating topography, with a bedrock rise observed east of the borehole that separates the valley into two channels. The channel to the east is also characterized by moderate-to-high amplitude facies interpreted as stratified deposits, and is slightly deeper (30-35 m) than observed at GSC 68-22. Thus the eastern channel would be an area to investigate further for groundwater potential.

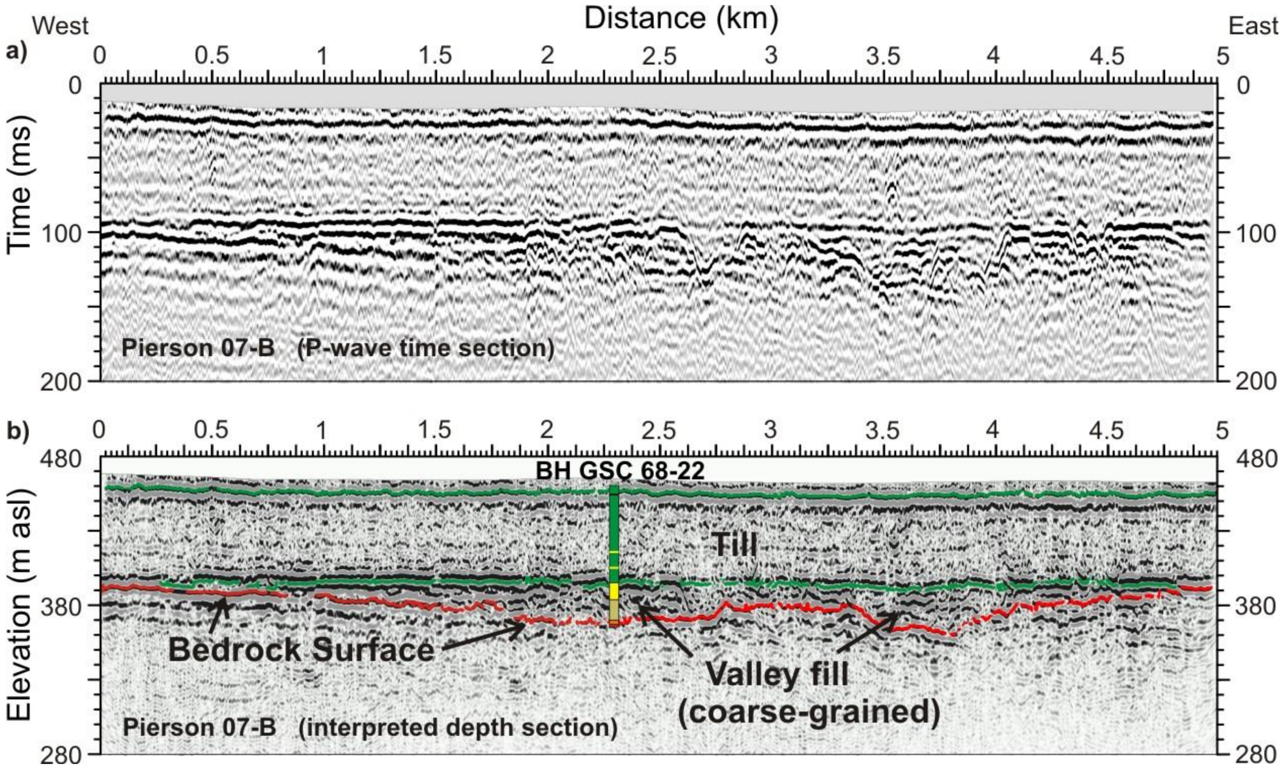


Figure 13: East-west seismic section (5 km in length) across the Pierson buried valley. Vertical exaggeration is ~7. a) processed time section (after topographic corrections); b) interpreted depth section (plotted in elevation).

The Spiritwood buried valley in the Killarney area is a very broad (~ 15 km) feature that reaches depths of >100m in some areas. The seismic results indicate the presence of a smaller incised valley within the Spiritwood Valley (Fig. 14). The current monitoring well is located on the shoulder of this incised valley. The deepest part of this incised valley appears to be infilled with stratified deposits and is interpreted to be a promising target for groundwater production wells.

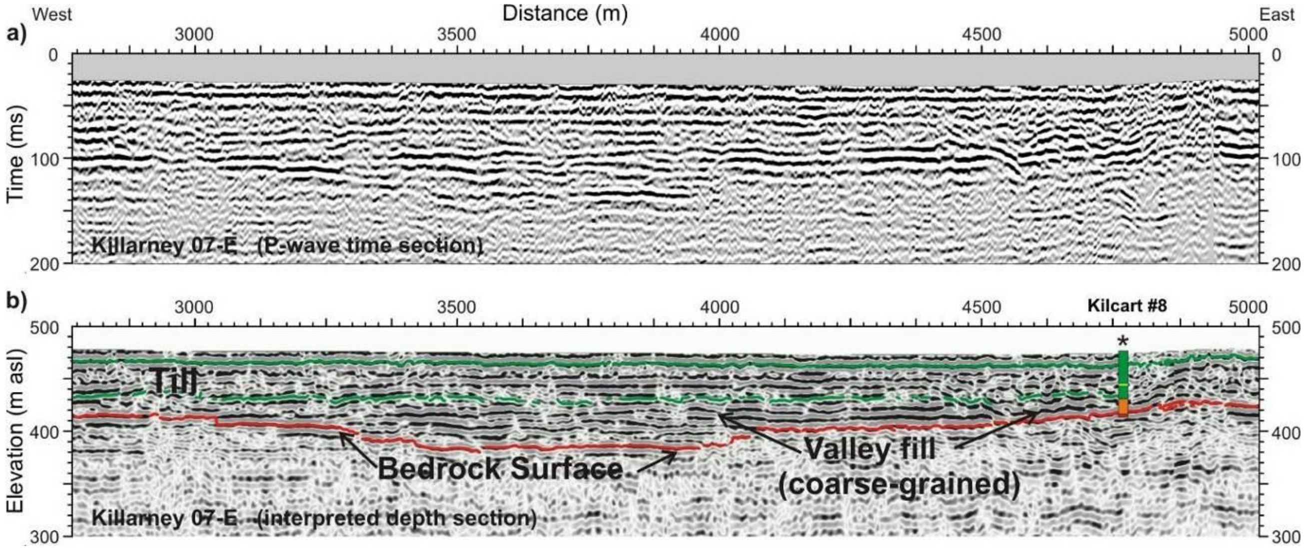


Figure 14: P-wave seismic reflection section acquired north of Killarney, Manitoba, across part of the buried Spiritwood Valley. Vertical exaggeration is ~2x. a) processed time section after topographic corrections; b) interpreted depth section (plotted in elevation).

These examples demonstrate how seismic reflection data provide an assessment of the subsurface architecture, and of the thickness and properties (e.g. uniformity or lateral variability, layering, lithology, evidence of channels) within both the channel fill and the overlying sediments. Such information is critical to hydrogeological assessment and modelling of groundwater resources, recharge potential, and aquifer vulnerability, and is often difficult or impractical to obtain by other means (e.g. drilling). Ultimately, these data will allow improved long-term aquifer management practices to be developed.

Shallow seismic reflection methods are now well-developed and becoming increasingly cost-effective and efficient. The advent of vibratory source/landstreamer systems has greatly enhanced both the speed of data acquisition and the range of environments and types of interference that can be tolerated during data acquisition. It is our contention that these techniques have now moved from the realm of being an expensive option for detailed site-specific surveys, to being a viable reconnaissance or regional mapping tool. In fact where water resource pressures are intense, it is too expensive to guess where a valley aquifer occurs with boreholes, as illustrated by the seismic lines south of Waskada. As groundwater and its protection becomes increasingly valued in our society, it is expected that seismic reflection methods will become as essential a component of hydrogeological characterization as they have long been in hydrocarbon exploration.

Summary

In October 2007, 9 seismic reflection transects totalling 38 line km were obtained using the P-wave minivib/landstreamer system across three known or suspected buried valleys in southwest Manitoba: the Medora-Waskada, Pierson and Spiritwood Valleys. The processed sections are presented in this report, along with preliminary interpretations. The results of the seismic surveys can be briefly summarized as follows:

- P-wave minivib/landstreamer system produced good-excellent data in all three locations;
- the highest quality (highest frequency and resolution) data were acquired in the Pierson area (this is attributed to thick (>50m), fine-grained near-surface materials in this region), though good data were obtained at all sites.
- Medora-Waskada valley has been determined to consists of two channel features south of Waskada. The seismic sections suggest that these are related to two episodes of channel-cutting. These channels may diverge to the south.
- Medora-Waskada valley was not clearly observed where it has been previously mapped midway between Waskada and the US border. It either shallows/disappears in this area, or one or both portions of the valley change directions to the west and/or east.
- Pierson valley is a broad (~2.5 km wide), relatively shallow feature buried beneath thick regional tills, and exhibits a complex and variable fill sequence which could be indicative of several episodes of channel formation.
- maximum observed depth of the Pierson valley was ~40 m below the bedrock surface in the surrounding area.
- surficial tills in the Pierson area are 60-70 m thick, and based on their low reflectivity and lack of internal structure, are interpreted to be fairly massive and relatively fine-grained. This suggests that recharge to the underlying channel fill deposits would be extremely low.
- seismic sections have delineated the presence of a broad (>>6 km wide) buried valley north of Killarney (northwestern arm of the Spiritwood Valley).
- within the broad valley, a smaller incised valley has been identified (1-1.5 km wide) which appears to be infilled with stratified sediments and represents a potential groundwater target.
- bedrock slopes gently to the west and south on the surveyed lines and reaches a depth of >100 m below ground surface in parts of this valley.
- deepest part of the valley appears to be infilled with stratified deposits and is interpreted as a the most promising target for groundwater wells.
- reflections from several hundred metres within the bedrock sequence are visible on the Killarney sections, making this data set of potential use for bedrock mapping in the area.
- infilling sediments are observed to have highly variable seismic reflection characteristics.
- additional borehole control is needed to better interpret the lithological and groundwater potential on the channel fill deposits.

The seismic surveys have provided images of three buried valley systems in southwest Manitoba and show that the three valleys differ markedly in depth, size and type of infill. Data such as these can be used to help locate groundwater wells in the deeper parts of the valley or where the highest yields might be expected on the basis of seismic facies analysis, assess the recharge potential of different geological settings, and assist in understanding the results of pumping tests and possible interwell connections by providing details on the subsurface architecture and stratigraphy.

Potential drilling targets

Potential drilling targets include both possible aquifers and areas where there is a need to confirm the geology of layers identified in the seismic surveys.

Near Waskada, the nature of the sediments in the mound at CMP 530 along Wask 07-A are not known. Depending on its permeability, it could either provide hydraulic connection both vertically and horizontally between the two channels within the valley or it could be a hydraulic barrier between the channels. Drilling this mound would provide some insight into the nature of the sediment separating the two channels. Another possible target occurs along Wask 07-E where the channel on the seismic section contradicts the existing well logs (WASKADA TH #7-93 in particular). Drilling is needed to determine the geological materials and stratigraphy within the apparent channel.

Near Killarney, the incised channel within the broad regional valley appears to be a possible aquifer. The incised channels seems to be oriented approximately NNW-SSE. The pattern of wells yielding more than 50 IGPM appears to follow a similar trend in the valley. The primary target would be the incised zone of the channel (e.g. CMP 1600-1840 along Killar 07-E) although it appears that a thinner layer of coarse materials may extend beyond the incised channel as is observed at the WRB Killcart #8 well.

Near Pierson, there is less apparent need for drilling to confirm the geophysical results and the nature of the sediment fill since the existing logs are consistent with the drilling results. Any further drilling in this area could be used to better characterize the hydraulic properties of the aquifers and to test for hydraulic connectivity between the two portions of the valley.

Acknowledgments

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References

Alley, R.B., Cuffey, K.M., Evenson, E.B., Strasser, J.C., Lawson, D.E., and Larson, G.J. 1997. How glaciers entrain and transport basal sediment: Physical constraints. Quaternary Science Reviews, 16, 1017-1038.

Andriashek, L.D. 2001. Quaternary stratigraphy of the buried Birch and Willow bedrock channels, NE Alberta, Alberta Energy Utilities Board Earth Sciences Report 2000-15.

Betcher, R. N., Matile, G., and Keller, G. 2005. Yes Virginia, there are buried valley aquifers in Manitoba. In: Proceedings of the 58th Canadian Geotechnical Conference and 6th Joint CGS and IAH-CNC Groundwater Specialty Conference, September 18-21, 2005, Saskatoon, Saskatchewan, Canada.

Bluemle, J. P. 1985. Geology of Bottineau County, North Dakota. Bulletin 78-Part I, North Dakota Geological Survey.

Christiansen, E.A. 1992. Pleistocene stratigraphy of the Saskatoon area, Saskatchewan, Canada: an update. Canadian Journal of Earth Sciences, 29: 1767-1778.

Cummings, D.I., Russell, H.A.J., and Sharpe, D.R. 2012a. Buried valleys and till in the Canadian Prairies: geology, hydrogeology, and origin. Geological Survey of Canada, Current Research 2012-4, 26 p.

Cummings, D.I., Russell, H.A.J., and Sharpe, D.R. 2012b. Buried-valley aquifers in the Canadian Prairies: geology, hydrogeology, and origin. Canadian Journal of Earth Sciences, 49, 987-1004.

Fulton, R.J., Blais-Stevens, A., Sun, C., Eilers, R.G., Betcher, R., Elson, J.A., Veldhuis, H., and Fraser, W.R., 2004, Surficial materials of the Virden area, Manitoba and Saskatchewan. Geological Survey of Canada, Bulletin , no. 546, 2004; 104 p.

Hinton, M.J., Pugin, A.J.-M., Pullan, S.E., and Betcher, R.N. 2007. Insights into the Medora-Waskada buried-valley aquifer from geophysical surveys, southwest Manitoba. In: Proceedings of the 60th Canadian Geotechnical Society Conference and 8th Joint IAH-CNC and CGS Groundwater Specialty Conference. Ottawa, Ontario, October 21-24, 2007. p. 515-522.

Klassen, R.W. and Wyder, J.E. 1970. Bedrock topography, buried valleys and nature of the drift, Virden map-area, Manitoba. Geological Survey of Canada, Paper 70-56, 11p.

Maathuis, H., and Thorleison, L.H. 2000. Potential impact of climate change on prairie groundwater supplies: review of current knowledge. Saskatchewan Reseearch Council Publication No. 11304-2E00.

Pugin, A.J.-M. and Pullan, S.E. 2000. First-arrival alignment static corrections applied to shallow seismic reflection data. J. Environmental and Engineering Geophysics, 5, 7-15.

Pugin, A.J.-M., Hunter, J.A., Pullan, S.E., Cartwright, T., Douma, M., Good, R.L., and Burns, R.A. 2007. Buried-channel imaging using P- and SH-wave shallow seismic reflection techniques, examples from Manitoba, Canada. In Proceedings, SAGEEP'07 (Symposium on the Application of Geophysics to Engineering and Environmental Problems), Denver, CO, April 1-5, 2007, p. 1330-1338.

Pugin, A.J.-M., Pullan, S.E., Hinton, M.J., Cartwright, T., Douma, M. and Burns, R.A 2009. Mapping buried valley aquifers in SW Manitoba using a vibrating source/landstreamer seismic reflection system. In Proceedings, SAGEEP'09 (Symposium on the Application of Geophysics to Engineering and Environmental Problems), Fort Worth, TX, March 29-April 1, 2009, p. 586-595.

Pullan, S.E., Pugin, A.J-M., Hunter, J.A., Cartwright, T., and Douma, M., 2008. Application of P-wave seismic reflection methods using the landstreamer/minivib system to near-surface investigations. In Proceedings, SAGEEP'08 (Symposium on the Application of Geophysics to Engineering and Environmental Problems), Philadelphia, PA. April 4-10, 2008. 12 pp.

Randich, P. G. and Kuzniar, R. L. 1984. Ground-water Resources of Bottineau and Roulette Counties. North Dakota State Water Commission, County Ground-water Studies 35 – Part III; North Dakota Geological Survey, Bulletin 78 – Part III. 41 p.

Watermark Consulting Ltd. 2004. Groundwater investigations, Southwestern Manitoba, Pierson, Tilston, Broomhill and Willen areas. WM124. Report to AAFC-Prairie Farm Rehabilitation Administration. Regina, Saskatchewan. 31 January 2004.

Wanek, A. 1994. Investigation to Identify a Water Supply for the City of Westhope, Bottineau County, North Dakota, North Dakota Ground Water Study No. 103, North Dakota State Water Commission and the City of Westhope, 139 pp.

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).

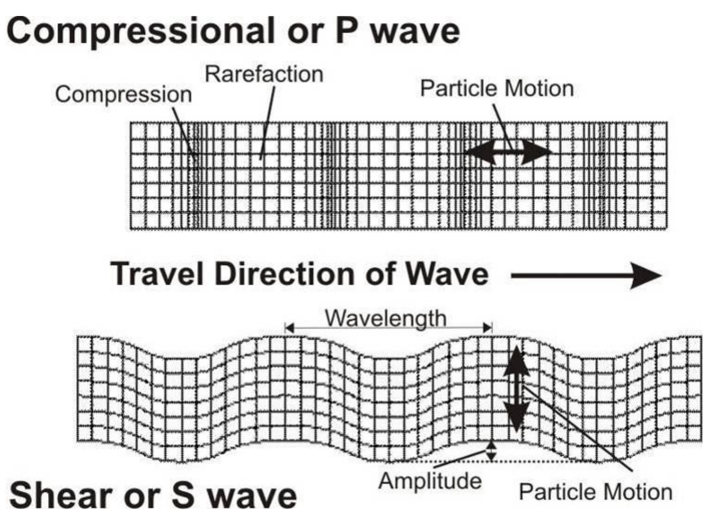

Figure A1-1: Schematic diagram showing the particle motions for compressional or P waves (upper panel) and shear or S waves (lower panel).

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.

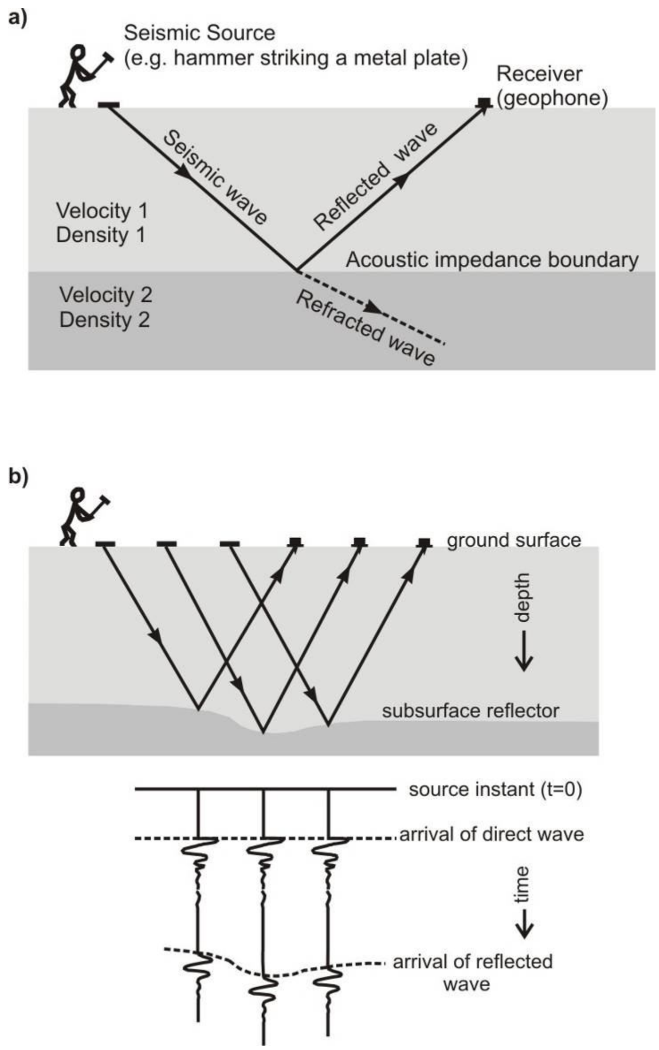

Figure A1-2: Basic premise of seismic reflection methods. a) Seismic energy produced on the ground surface travels from the source down to an acoustic impedance (product of density and velocity) boundary, where it is partially transmitted and partially reflected back towards the surface. b) Data are 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).

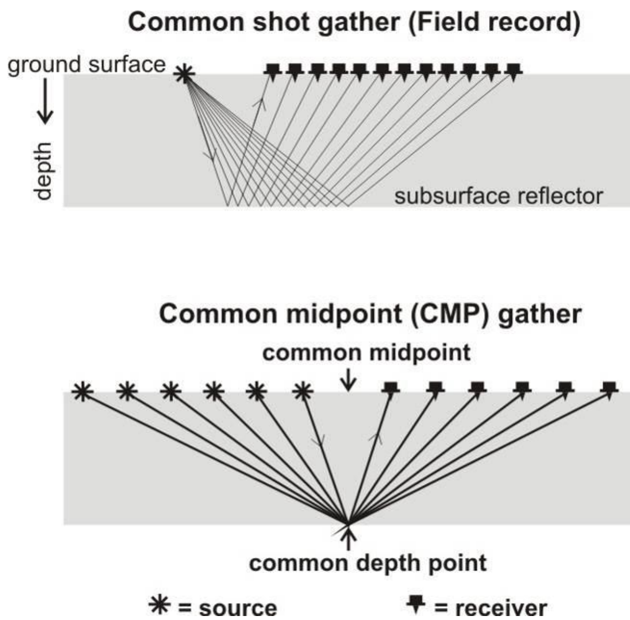

Figure A1-3: Schematic diagram showing a) the subsurface travel paths of reflections from a field record and b) a common midpoint gather. The traces in the CMP gather will be processed and stacked together to form a single trace on the final CMP section (6-fold).

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).

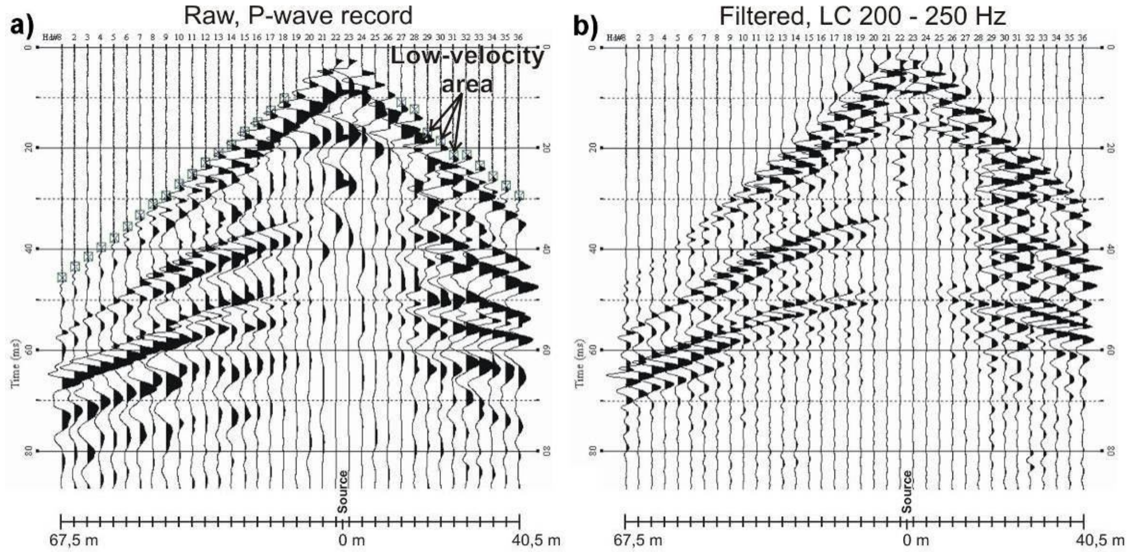

Figure A1-4: Example field shot gather obtained during a P-wave reflection survey using a 12-gauge shotgun source and 50 Hz vertical geophones at 3 m spacing: a) raw record, b) same record after high-pass filtering. These records show excellent reflection energy (hyperbolic events).

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.

Figure A1-5: Photo of the Minivib source and SH-wave landstreamer in operation, 2006.

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 A1-6: **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

Hunter, J.A., Pullan, S.E., Burns, R.A., Good, R.L., Harris, J.B., Pugin, A., Skvortsov, A., and Goriainov, N.N., 1998, Downhole seismic logging for high-resolution reflection surveying in unconsolidated overburden; Geophysics, **63**, p. 1371-1384.

Inazaki, T., 2004. High resolution reflection surveying at paved areas using S-wave type land streamer. Exploration Geophysics, **35**, 1-6

Pugin, A., Larson, T. and Phillips, A., 2002. Shallow high-resolution shear-wave seismic reflection acquisition using a land-streamer in the Mississippi River floodplain: potential for engineering and hydrogeologic applications. In Proceedings, SAGEEP'02 (Symposium on the Application of Geophysics to Engineering and Environmental Problems), February 10-14 Las Vegas, Nevada. CD-ROM edition, 7p.

Pugin, A.J.M., Larson, T.H., Sargent, S.L., McBride, J.H. and Bexfield, C.E., 2004. Near-surface mapping using SH-wave and P-wave seismic land-streamer data acquisition in Illinois, U.S. *Leading Edge (Tulsa, OK),* **23**(7), p. 677-682.

Pullan, S.E. and Hunter, J.A., 1999, Land-based shallow seismic methods, Chapter 3 in A handbook of geophysical techniques for geomorphic and environmental research; by Gilbert, R; Geological Survey of Canada, Open File 3731, 1999; p. 31-55.

Steeples, D.W., 1998, Special issue: Shallow seismic reflection section - Introduction; Geophysics, **63**, p. 1210-1212.

Annex 2

Medora-Waskada Seismic Reflection Testing Program (2006)

Medora-Waskada Buried Valley

The Medora-Waskada buried valley is a north-northeast trending feature, about 1-2 km wide and up to 110 m deep, eroded into the Pierre Shale. Adjacent to the valley, shale bedrock is typically found at a depth of 15-20 m. There is little surface expression which would indicate the feature's presence.

Initial test drilling occurred in 1964 as part of water supply investigations for Waskada. However, this test drilling did not penetrate the full depth of the feature and did not lead to development of a groundwater supply. In 1968, test drilling was carried out by the Geological Survey of Canada (GSC) across the width of the valley south of Medora, southwest of Waskada and midway between the two villages (Klassen and Wyder 1970). The GSC drilling penetrated the full valley depth and found that infill material south of Medora was almost entirely glacial till while the deeper sediment in the valley southwest of Waskada consisted of interbedded clay, sand, and gravel (Klassen and Wyder 1970; Fulton et al. 2004, and unpublished data). 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.

In the late 1970's the channel was investigated as a potential source of water supply for Waskada. Test drilling south of the village encountered a similar geologic sequence to that reported by the GSC. A municipal well was installed by screening a portion of a gravel layer from 60-66 m. Further test drilling a few kilometres both north and south of this site found a similar geologic sequence. Two wells to supply loading stations and a well supplying a rural water pipeline were installed in the mid to late 1980's. Two of these wells were screened in sand/gravel units near the base of the channel while a third was completed in a shallower sand/gravel at a depth of about 45 m.

The Medora-Waskada buried valley was chosen for the 2006 seismic testing program because of the high quality borehole records in the area and because the narrow width of the valley would permit the comparison of multiple source-receiver configurations in a limited testing program.

Field Survey Parameters:

Test sites for the 2006 seismic field program were determined through discussions with Bob Betcher (Manitoba Water Stewardship). Figure A2-1 shows the proposed and final transects of the Medora-Waskada Valley, along with an indication of the borehole control available. Adjustments of the survey lines were made during the field program to avoid the proposed transect immediately south of Waskada because of the traffic volume, and to test more of the known valley extent.

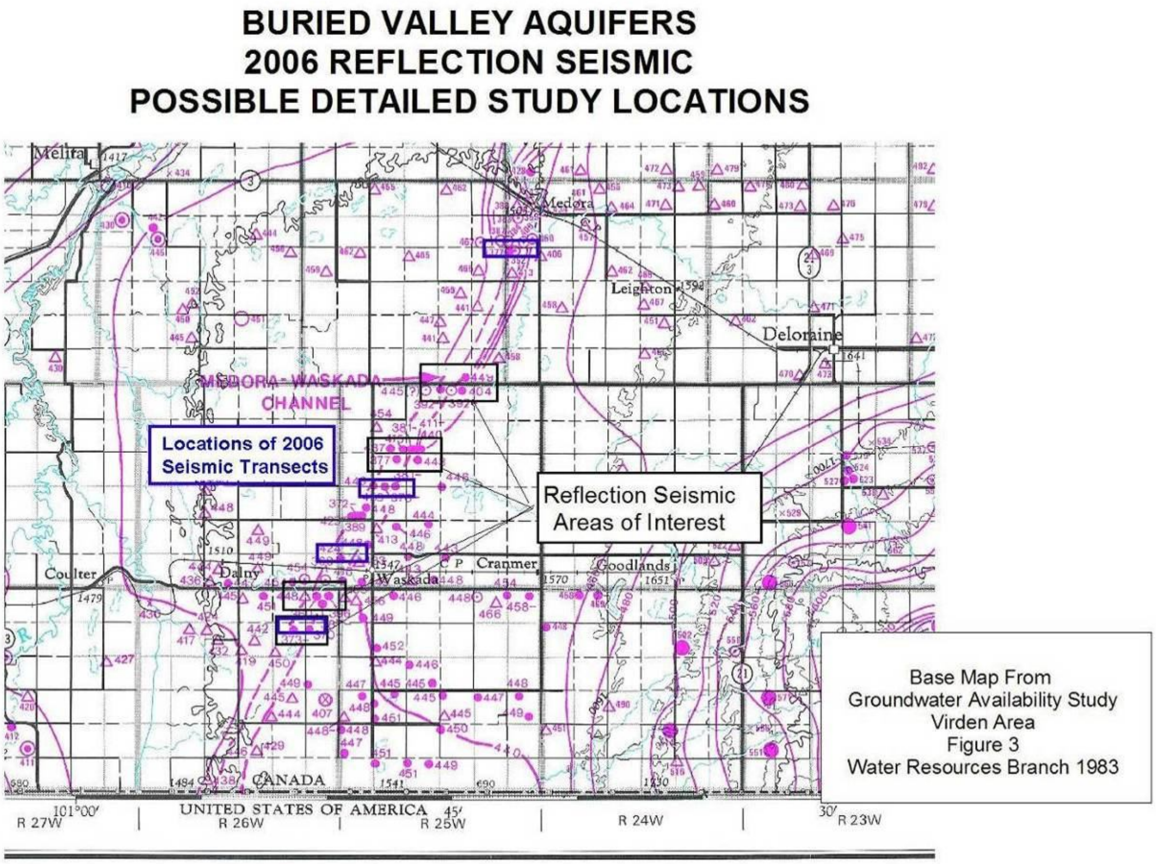

Figure A2-1: Proposed and actual study locations for 2006-07 geophysical surveys.

The Medora-Waskada seismic field program was carried out from September 19-26, 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 A2-2), as outlined in Table A2-1. 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 (Fig. A2-3a)
- P-wave landstreamer (Fig. A2-4a), Minivib source (vertical mode)

Shear (SH-) wave surveys

- horizontal geophone landstreamer, hammer on roller source (Fig. A2-3b)
- horizontal geophone landstreamer source (Fig. A2-4b), 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.

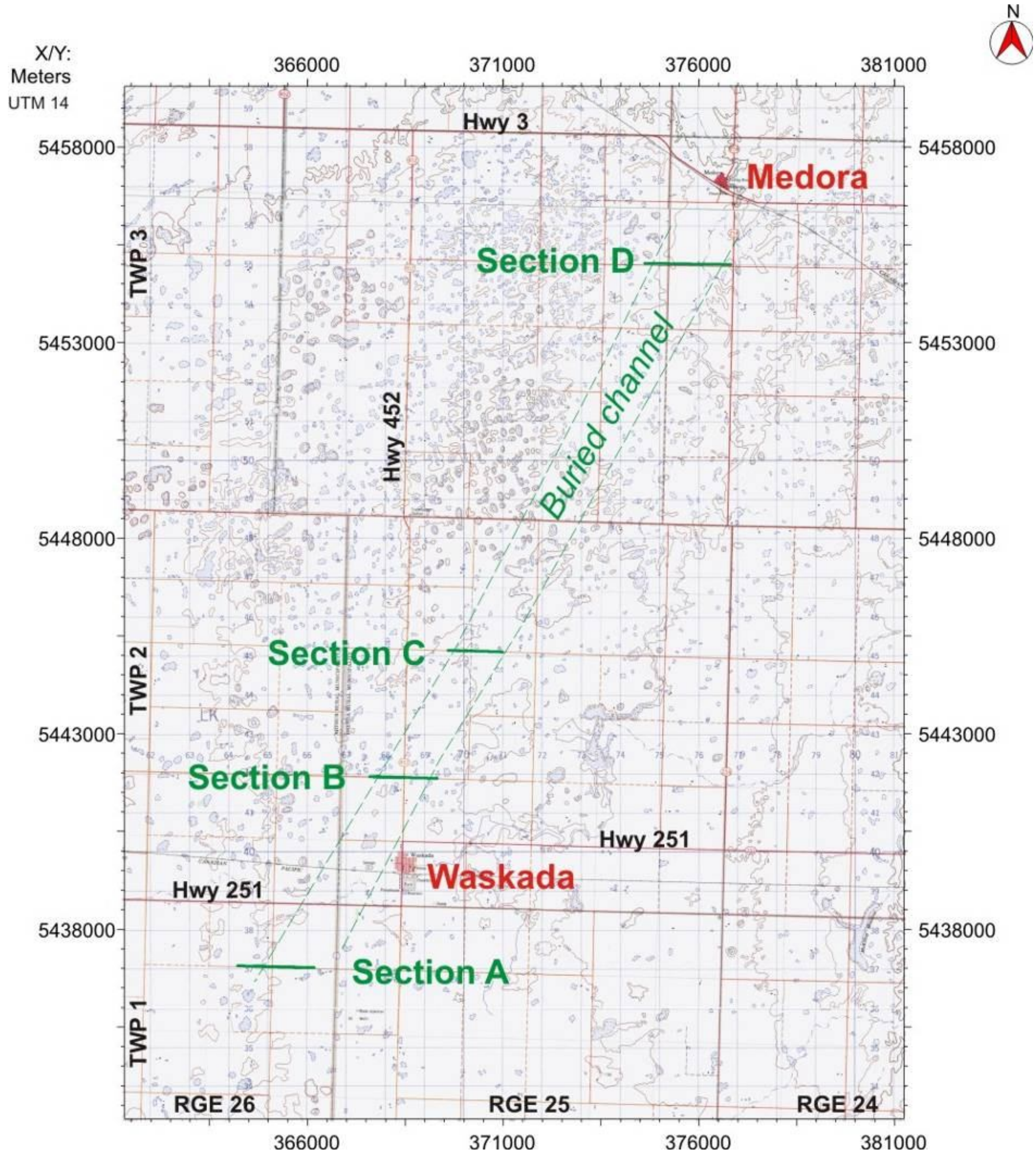

Figure A2-2: Map showing location of 2006 seismic profiles obtained near Waskada, SW Manitoba.

Location	**Source *(Source spacing)***	**Source para-meters**	**Receivers *(#receivers @ receiver spacing)***	**Source-nearest receiver offset**	**Record length**	**#Samples per trace *(sample rate)***	**Line length**
Section A **(Fig. A2-9, 10)**	Minivib (P) *(3 m)*	45 – 300 Hz sweep	P-wave landstreamer *(47@3 m)*	3 m	1.5 s	3000 *(0.5 ms)*	1550 m
Section A **(Fig. A2-9, 10)**	Minivib (SH) *(1.5 m)*	10 – 100 Hz sweep	SH-wave landstreamer *(47@0.75 m)*	3 m	1.5 s	1500 *(1 ms)*	1600 m
Section B **(Fig. A2-6)**	In-hole shotgun source *(3 m)*	1 shot per station	50 Hz vertical geophones planted in ditch *(48@3 m)*	1.5 m	0.5 s	4000 *(0.125 ms)*	650 m
Section B **(Fig. A2-6, 8, 11)**	Minivib (P) *(3 m)*	45 – 300 Hz sweep	P-wave landstreamer *(47@3 m)*	3 m	1.5 s	3000 *(0.5 ms)*	900 m
Section B **(poor data, not shown)**	Hammer on roller *(1.5 m)*	1 hit per station	SH-wave landstreamer *(24@0.75 m)*	1.5 m	1.5 s	3000 *(0.5 ms)*	1550 m
Section B **(Fig. A2-8, 11)**	Minivib (SH) *(1.5 m)*	10 – 100 Hz sweep	SH-wave landstreamer *(47@0.75 m)*	3 m	1.5 s	1500 *(1 ms)*	750 m
Section C **(Fig. A2-12)**	Minivib (SH) *(1.5 m)*	10 – 100 Hz sweep	SH-wave landstreamer *(47@0.75 m)*	3 m	1.5 s	1500 *(1 ms)*	1400 m
Section D **(Fig. A2-13)**	Minivib (SH) *(1.5 m)*	10 – 100 Hz sweep	SH-wave landstreamer *(47@0.75 m)*	3 m	1.5 s	1500 *(1 ms)*	2200 m

Table A2-1: Recording parameters for seismic reflection profiles, Medora-Waskada buried valley, SW Manitoba, 2006.

Figure A2-3: **a) Augering shotholes and planting geophones for P-wave survey using in-hole shotgun source. b) Hammer on roller source in operation (SH-wave survey).**

Figure A2-4: **Photo of the a) Minivib source and P-wave landstreamer (vertical geophones) and b) SH-wave landstreamer (horizontal geophones) in operation in SW Manitoba, 2006.**

Results:

P-wave testing- Section B
Two source-receiver configurations using P-wave techniques were tested along Section B. 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 (Fig. A2-3a). 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 meter spacing (Fig. A2-4a). 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 source (Fig. A2-5a) 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 (Fig. A2-5b) 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 high signal/noise ratio record was recorded in low wind conditions. Figure A2-5c shows a vibroseis record that was acquired under windy conditions (wind speeds of above 30 km/h); in this case, shallow reflections can still be seen but the deeper reflections are hidden under the background noise.

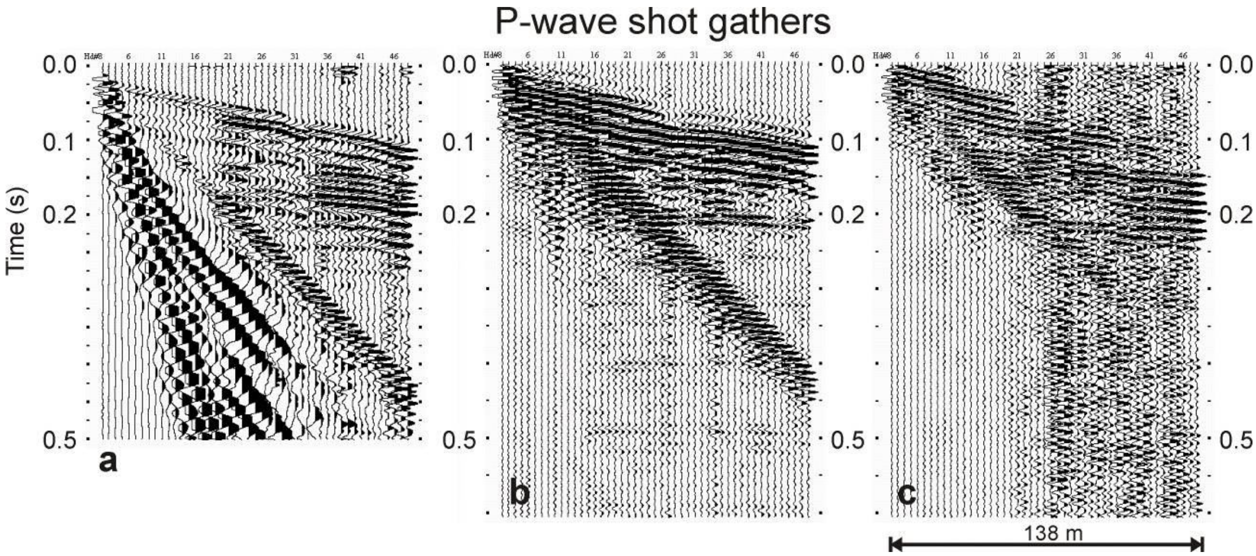

Figure A2-5: Shot gather records. a: In-hole shotgun P-wave record. b: Minivib/landstreamer P-wave record. c: same as B but data acquired under windy conditions.

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Cross correlation**
Edition of the geometry
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Phase-shift migration
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Table A2-2: Processing flow chart for P-wave seismic reflection data

Stacked P-wave seismic sections were produced using the processing steps outlined in Table A2-2. The stacked sections (Fig. A2-6) show that a higher signal/noise ratio is achieved with the minivib data, along with signal penetration through the entire Mesozoic and Paleozoic sequence to depths of greater than 1 km. Comparing both minivib and shotgun sections in Figure A2-6, there is a good match of the internal reflectors situated within the buried-channel with less noise in the minivib/landstreamer section.

While the final data quality of the two processed sections is similar in the depth range of interest for buried valley mapping, 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 system.

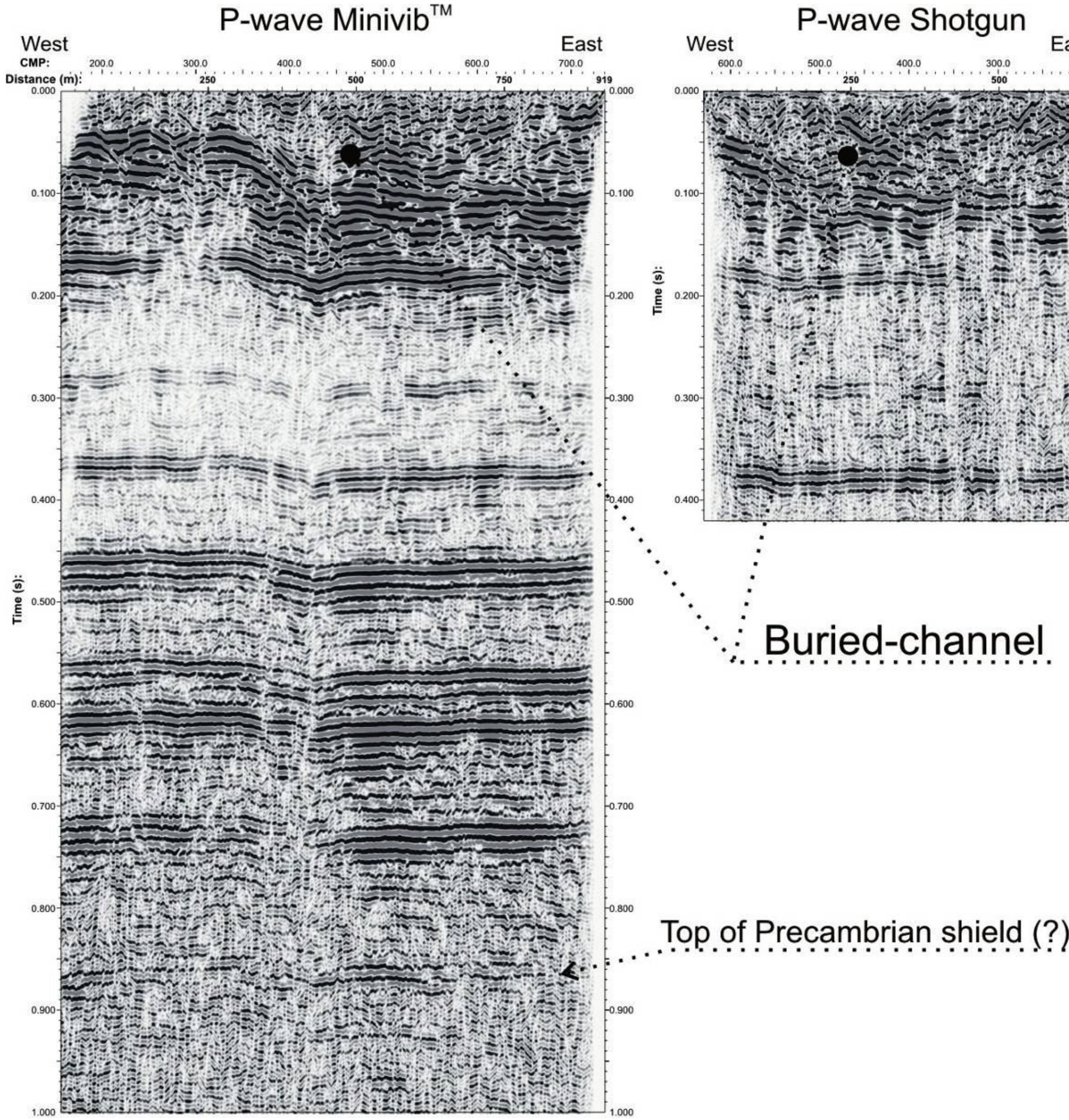

Figure A2-6: Comparison of stacked P-wave sections. Left: Data acquired using the Minivib/landstreamer system. Right: Data acquired using the in-hole shotgun source and planted geophones.

SH-wave testing- Section B

Two source-receiver configurations using SH-wave techniques were also tested along Section B: (i) the hammer-roller source and a 24-channel SH-wave landstreamer (Fig. A2-3b), and (ii) Minivib source in shear mode coupled to a 47-channel landstreamer (Fig. A2-4b). Details on the recording parameters are given in Table A2-1. Example field records show that the hammer-roller system produced very little reflection signal from the depths of interest in this survey area (Fig. A2-7a), 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 wave interference (Fig. A2-7b,c).

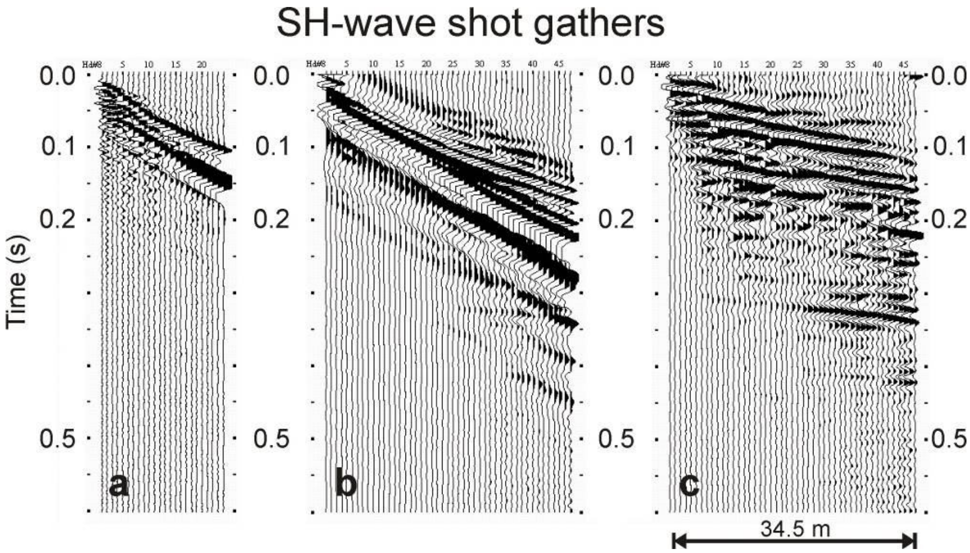

Figure A2-7: Shot gather records. a. Sledge-hammer/roller SH-wave records. b: Minivib/landstreamer SH-wave record. c: same record as b, FK-filter applied.

Stacked SH-wave seismic sections were produced using the processing steps outlined in Table A2-3. 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. SH-wave processing does not require sophisticated static corrections, as based on our experience, accounting for near surface lateral velocity changes in SH-wave data is less important than for P-wave surveys.

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
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Phase-shift migration
* For the section displayed in the Figure A2-10 only

Table A2-3: Processing flow chart for SH-wave seismic reflection data.

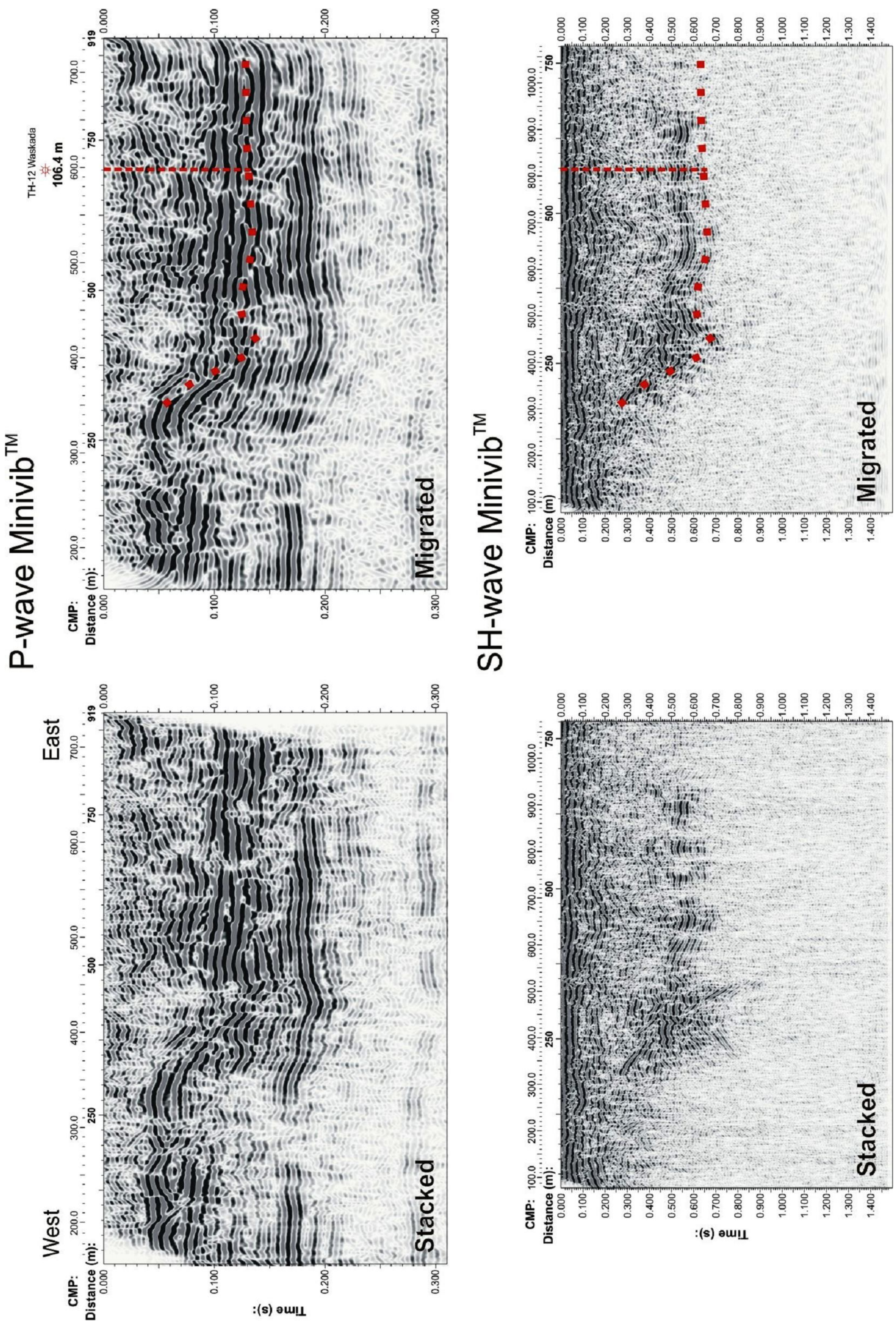

Figure A2-8: Comparison of P-wave and SH-wave seismic sections (in two-way travel time) over the Medora-Waskada buried-channel along Section B (Fig. A2-2). Phase-shift migration has been applied to the sections shown on the right side (see Tables A2-2,3). The red dots indicate the interpreted bedrock surface.

Comparison of P- and SH-wave reflection profiles – Sections A and B

Figures A2-8 and A2-9 show a comparison of stacked sections acquired with the minivib/landstreamer in P-wave and SH-wave mode along Sections B and A respectively (Fig. A2-2). 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 A2-9, we suspect that gravel is present. No reflection is observed in the SH-wave data, 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).

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 A2-8, P-wave section, ~CMP 425) show up as bow-tie structure in the SH-wave domain before migration (Figure A2-8, SH-wave section, ~CMP 450). Consequently, migration is a more critical processing step for SH-wave data.

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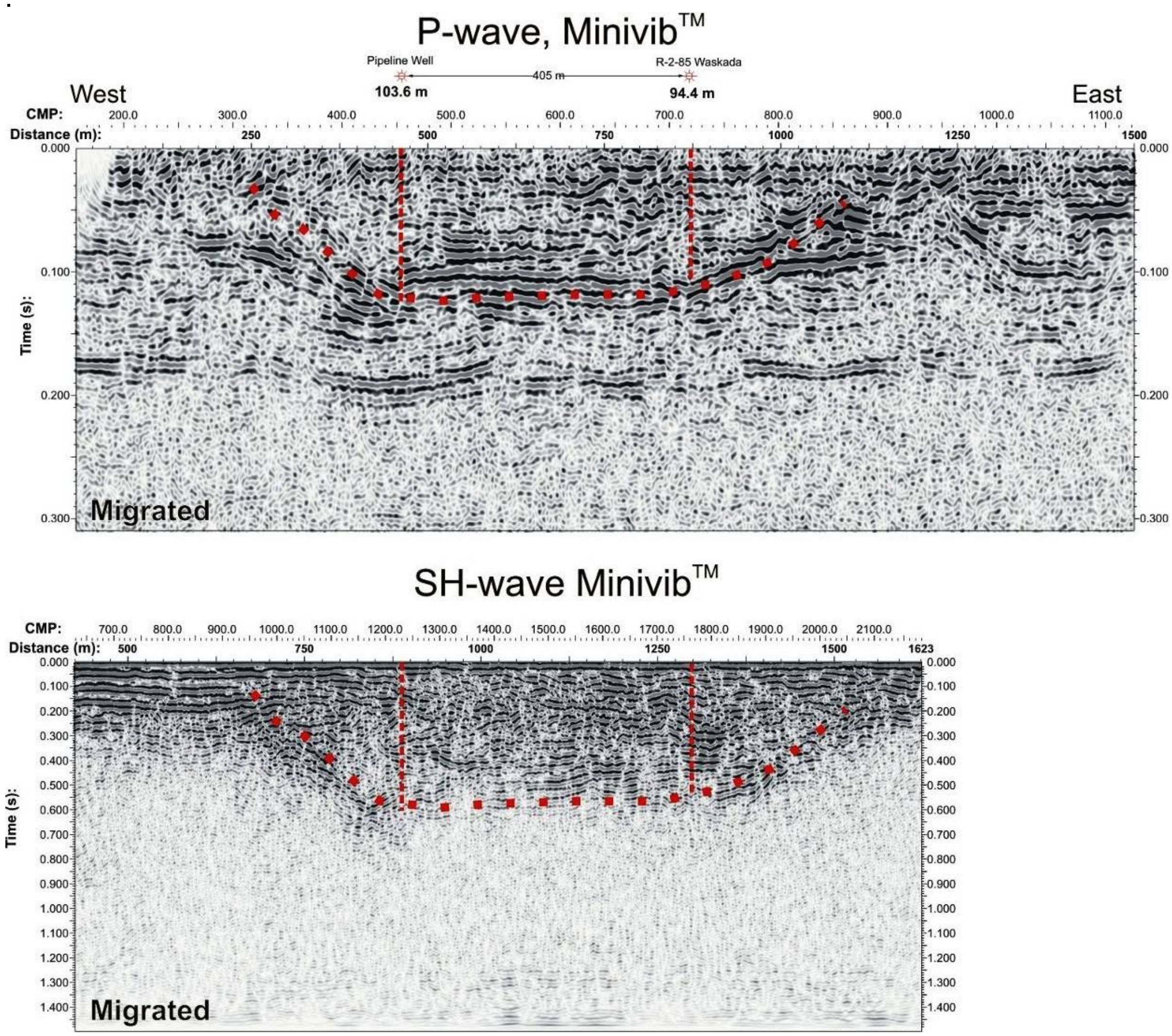

Figure A2-9: Comparison of migrated P-wave and SH-wave seismic sections (in two-way travel time) over the Medora-Waskada buried-channel along Section A (Fig. A2-2). The red dots indicate the interpreted bedrock surface.

Section A – Interpreted profiles (Figure A2-10)

The P- and SH-wave profiles acquired with the Minivib source along Section A (Fig. A2-10a) are shown in Figure A2-10b. 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 shaly sand, gravel and clay) in the middle (R-2-85 Waskada well) and the lower sections (R-1-85 Waskada well) of the valley, and this is labelled as "gravel" in the interpreted sections (Fig. A2-10b). 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 R-2-85; these sediments are reported as interbedded shaly sand and clay.

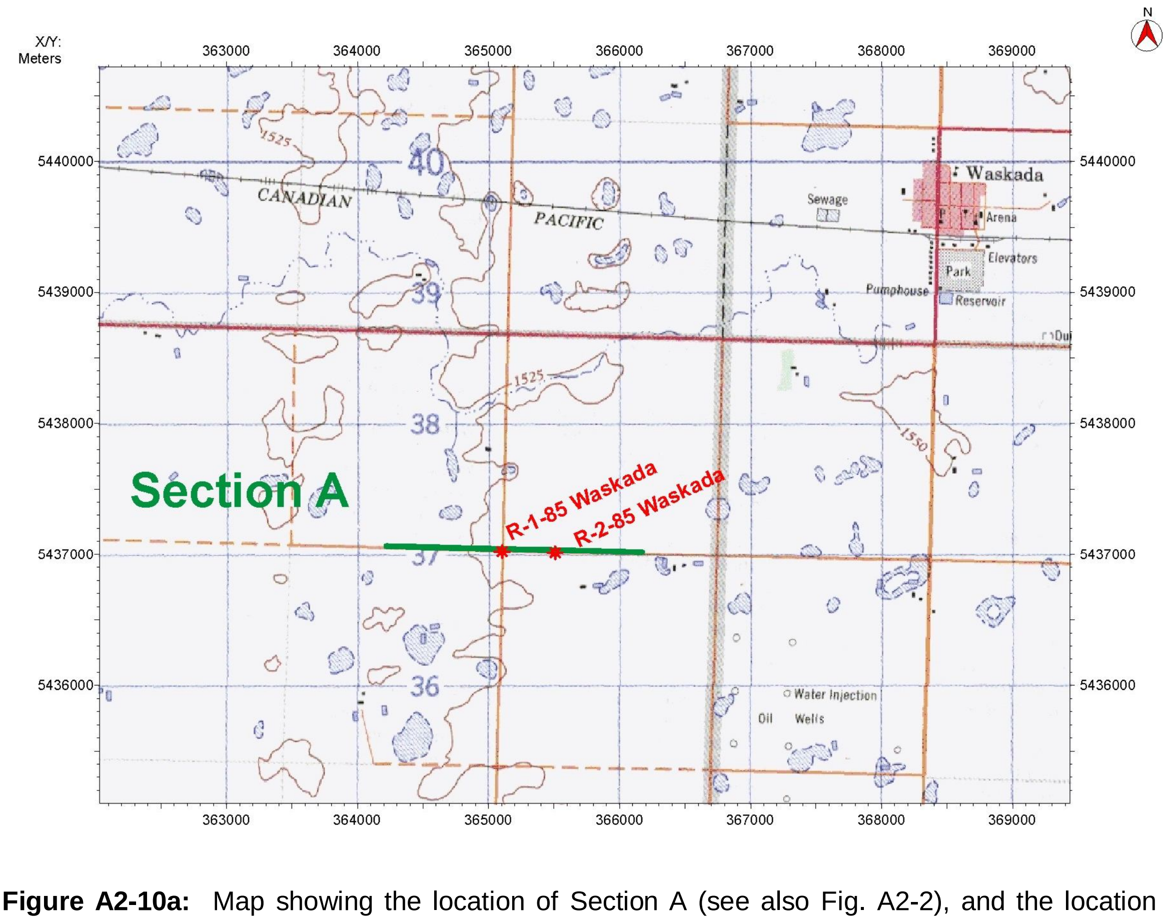

Figure A2-10a: Map showing the location of Section A (see also Fig. A2-2), and the location of two boreholes used in the data interpretation.

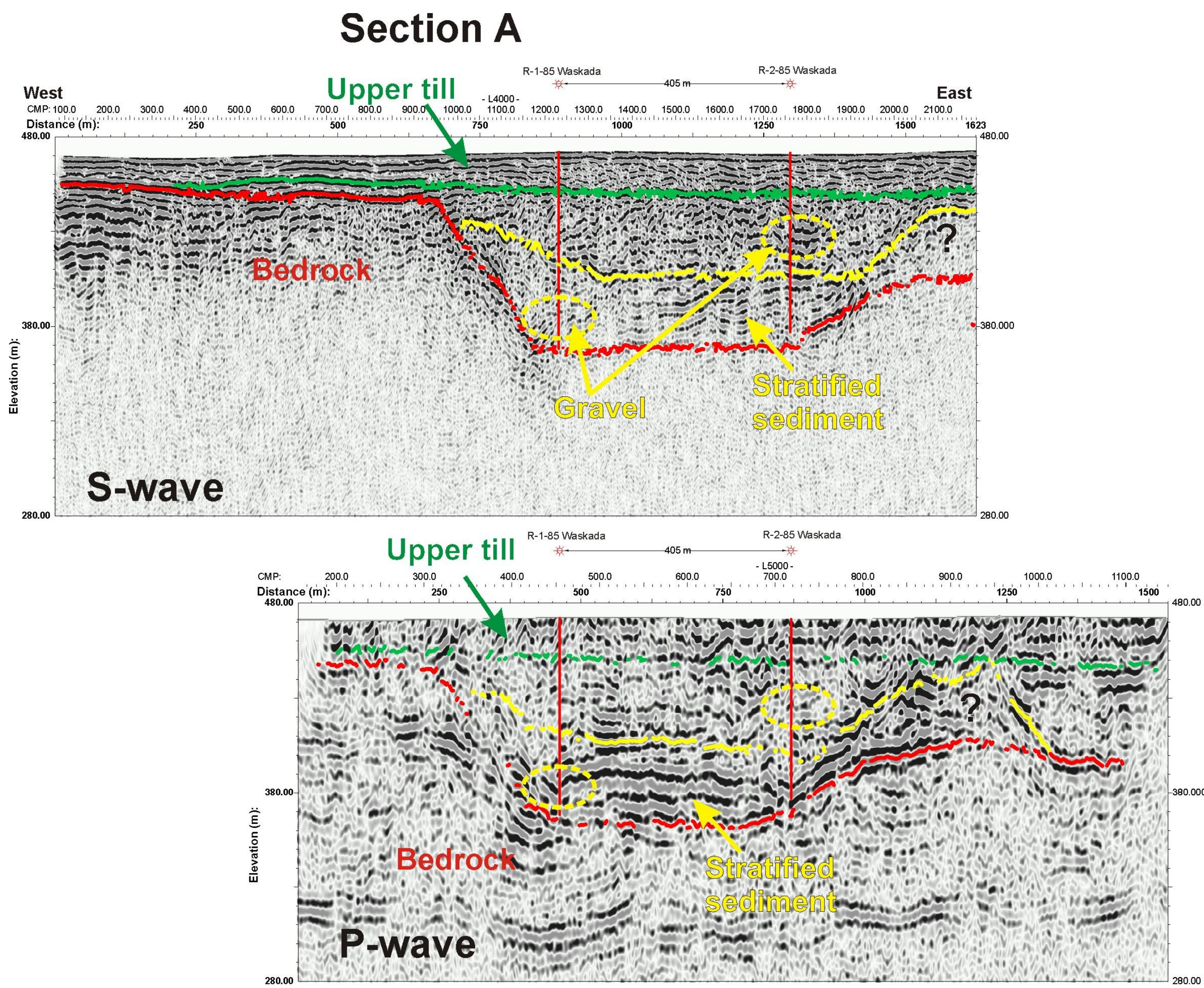

Figure A2-10b: Interpreted SH- and P-wave reflection profiles acquired with Minivib source along Section A. The yellow circles indicate where “shale boulder gravel” was noted in the borehole logs. The indication of “stratified sediments” (implying layered sand/coarse-grained sediments) is based on the 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.

Section B – Interpreted profiles (Figure A2-11)

The P- and SH-wave profiles acquired with the Minivib source along Section B (Fig. A2-11a) are shown in Figure A2-11b. 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 is >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.

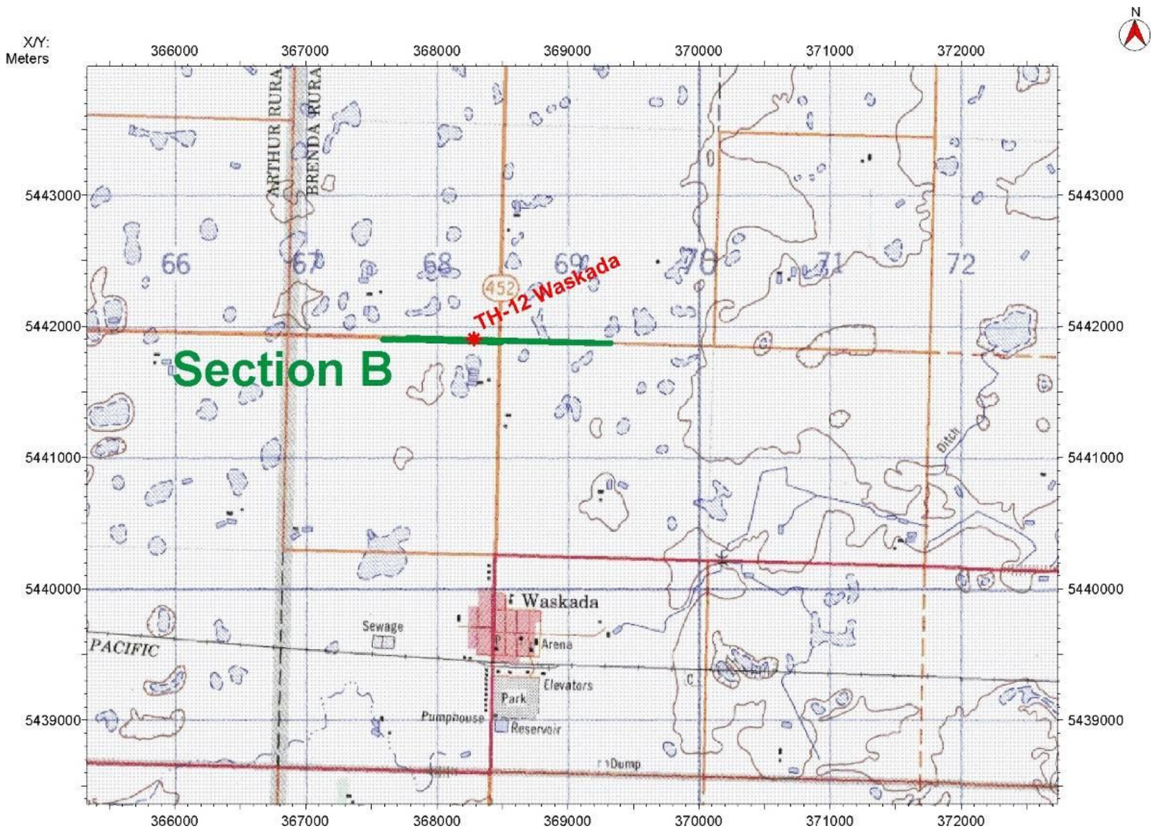

Figure A2-11a: Map showing the location of Section B (see also Fig. A2-2) and the location of a borehole used in the data interpretation.

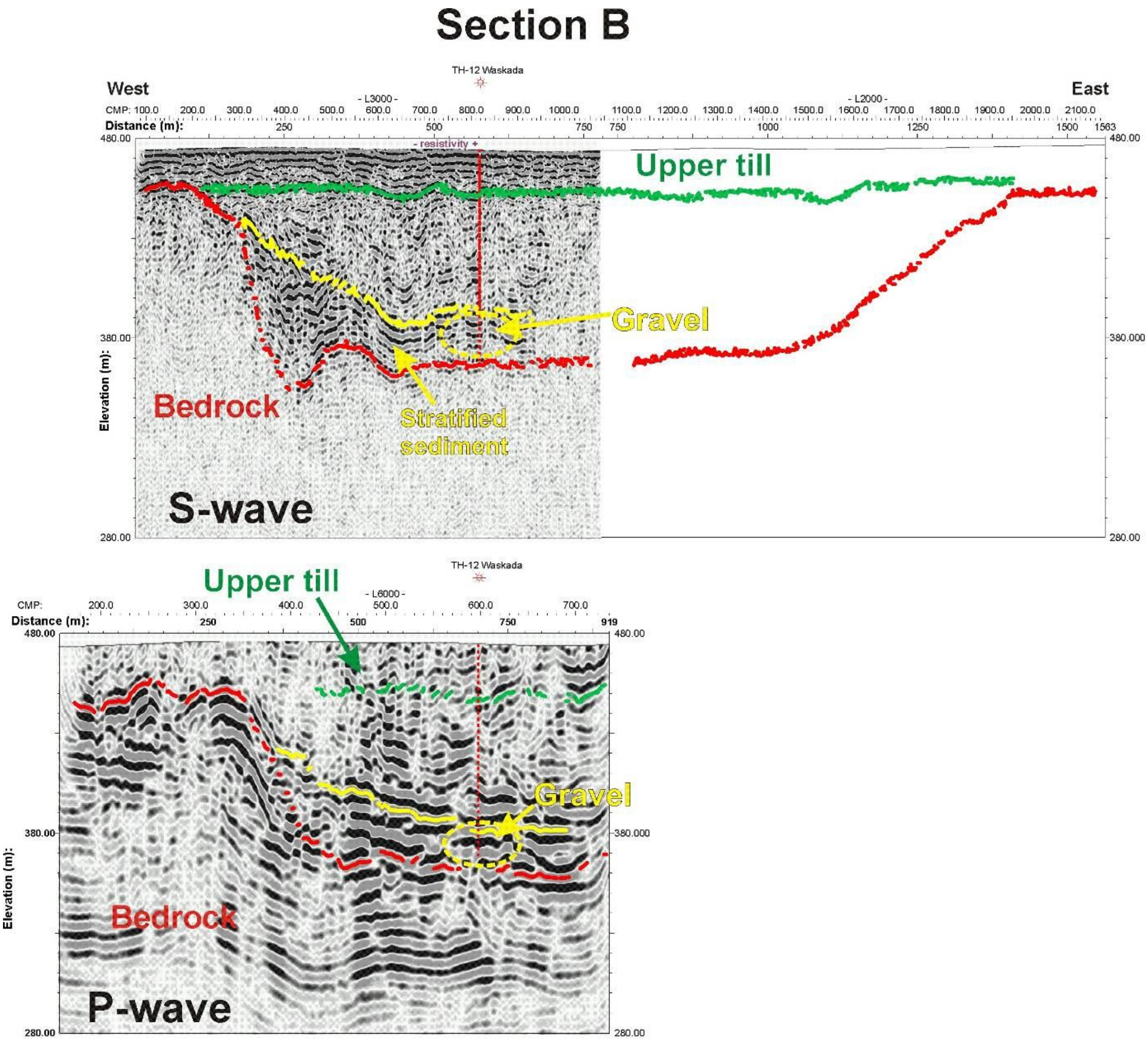

Figure A2-11b: Interpreted SH- and P-wave reflection profiles acquired with Minivib source along Section B. The yellow circle indicates where "shale boulder gravel" was noted in the borehole log. The indication of "stratified sediments" (implying layered sand/coarse-grained sediments) is based on the seismic reflection character.

Section C – Interpreted profiles (Figure A2-12)

The SH-wave profile acquired with the Minivib source along Section C (Fig. A2-12a) is shown in Figure A2-12b. 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. Most of the borehole logs indicate diamicton, though some gravel was noted in the TH3A hole. However, pump tests there resulted in a rapid drawdown suggesting that this gravel layer may be very limited extent in extent (Manitoba Water Stewardship). The channel fill can be subdivided into two seismic units (or sequences) separated by a reflector highlighted in orange.

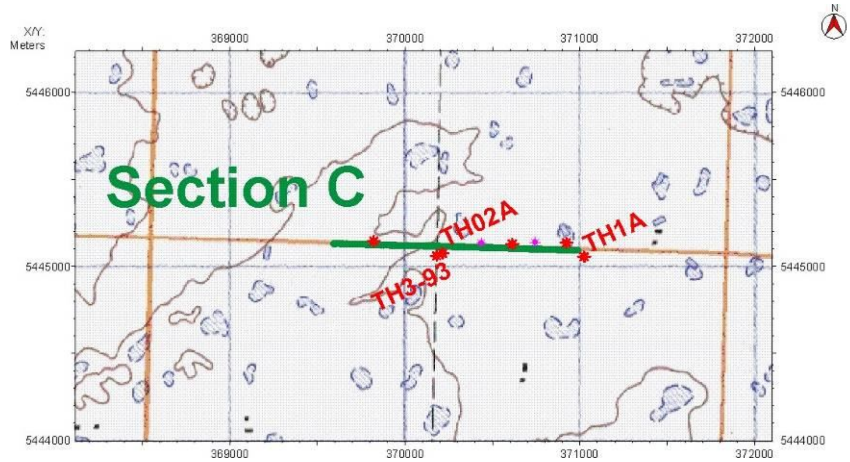

Figure A2-12a: Map showing the location of Section C (see also Fig. A2-2) and the location of the boreholes used in the data interpretation.

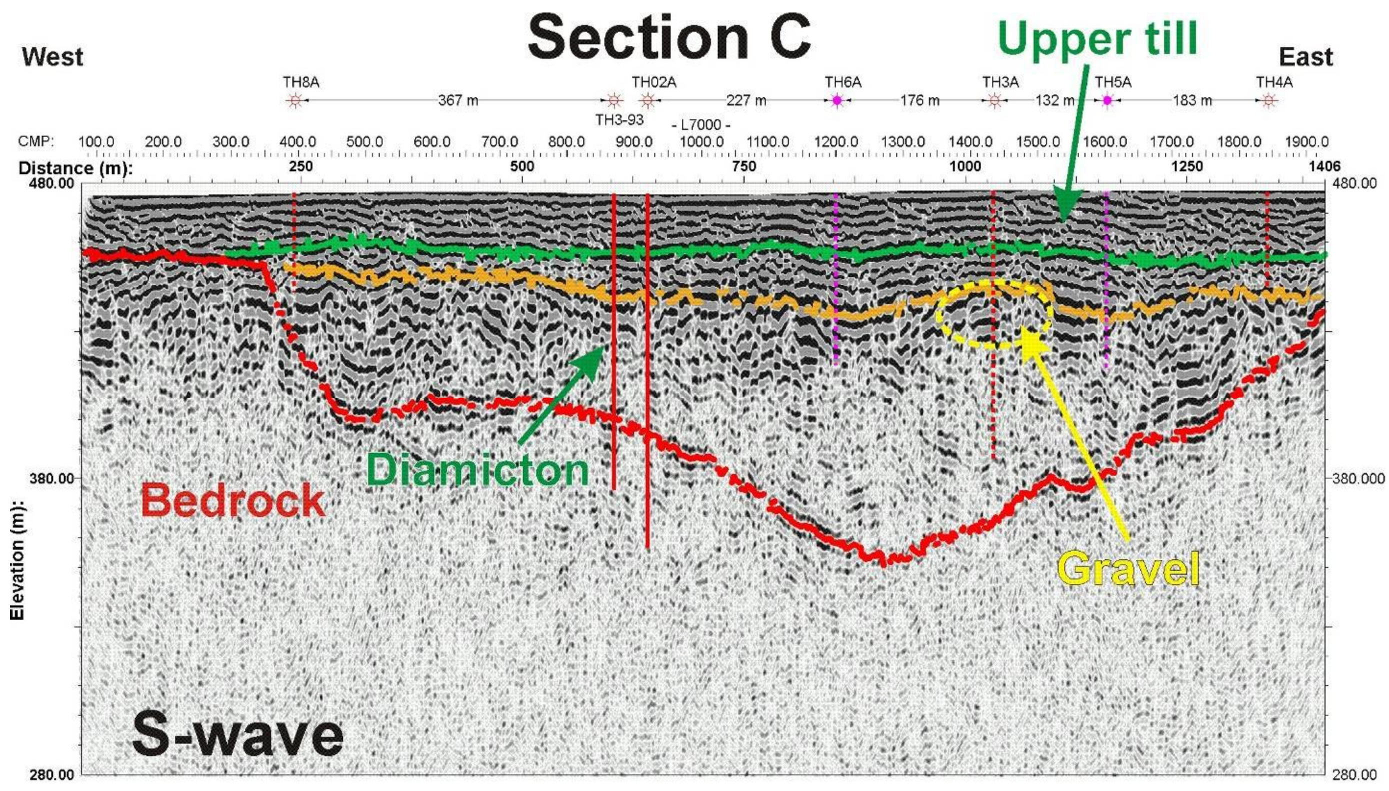

Figure A2-12b: Interpreted SH-wave reflection profile acquired with Minivib source along Section C. The yellow circle indicates where "shale boulder gravel" was noted in the borehole logs. Otherwise the borehole logs suggest thick diamicton to the bedrock surface. There is no indication on the seismic section of stratified sediments that may be more conducive to the storage or movement of groundwater.

Section D – Interpreted profiles (Figure A2-13)

The SH-wave profile acquired with the Minivib source along Section D (Fig. A2-13a) is shown in Figure A2-13b. This section investigates the buried valley structure just south of Medora, ~10 km north of Section C (Fig. A2-12), and was chosen because of the subsurface geological and geophysical (resistivity and spontaneous potential borehole logs) information available from a series of boreholes (Klassen and Wyder, 1970, and unpublished data). The seismic section shows the valley to have a depth of ~110 m and a similar lateral extent (>1 km wide) to other sections, but at this location, the eastern slope is gentle and extends another ~1 km.

Three seismic units are present in the cross-section. As with Section C, there is little stratification observed below the surface tills. The lowermost unit (**I**) in the centre of the buried valley generally has weak and discontinuous reflectors although there appears to be loss of signal strength in the base of the bedrock valley as in section A. This unit is identified as till in boreholes 11-68 and 12-68, though near the base of 12-68 there is a layer of sand and the identification of the unit as a till (rich in shale pebbles) is questioned in the original borehole log. High reflection amplitudes may possibly indicate the presence of sand or gravel to the eastern side of the profile; this would have to be confirmed with additional borehole data. Unit **I** and **II** are separated by a continuous reflector identified as a sand-silt till in borehole 11-68 and associated with a small increase in resistivity. The overlying units (**II** and **III** "Upper Till") are also identified as till in the boreholes but are separated on the basis of the continuity of reflectors. The Upper Till (**III**) has more continuous reflectors whereas unit **II** reflectors are more discontinuous.

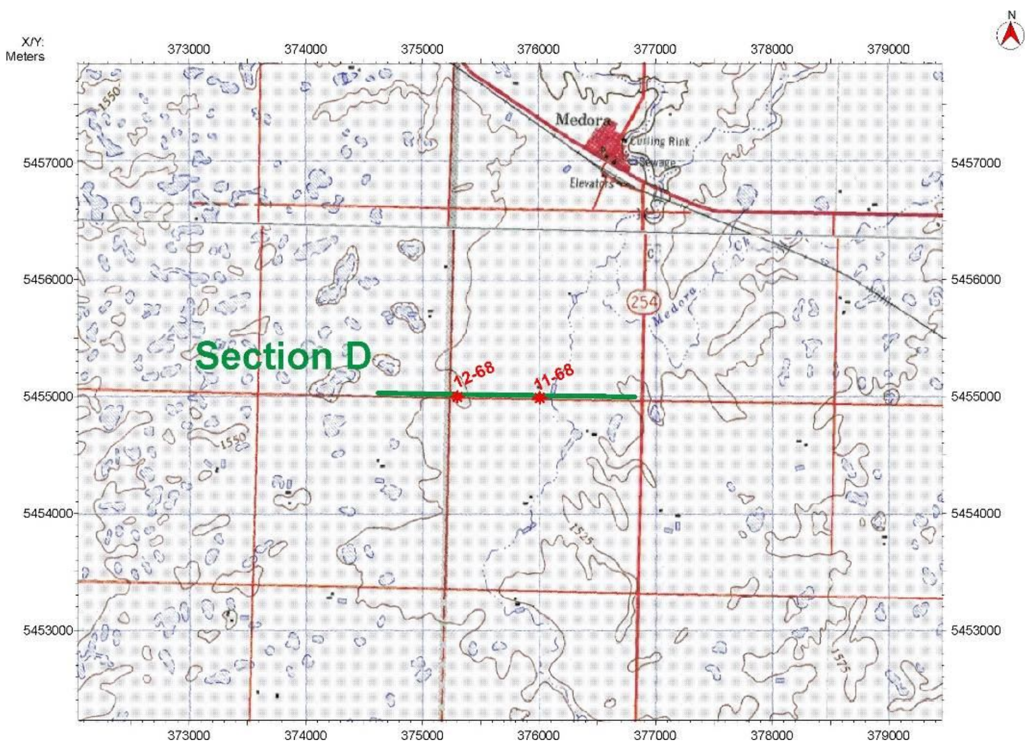

Figure A2-13a: Map showing the location of Section D (see also Fig. A2-2) and the location of the boreholes used in the data interpretation.

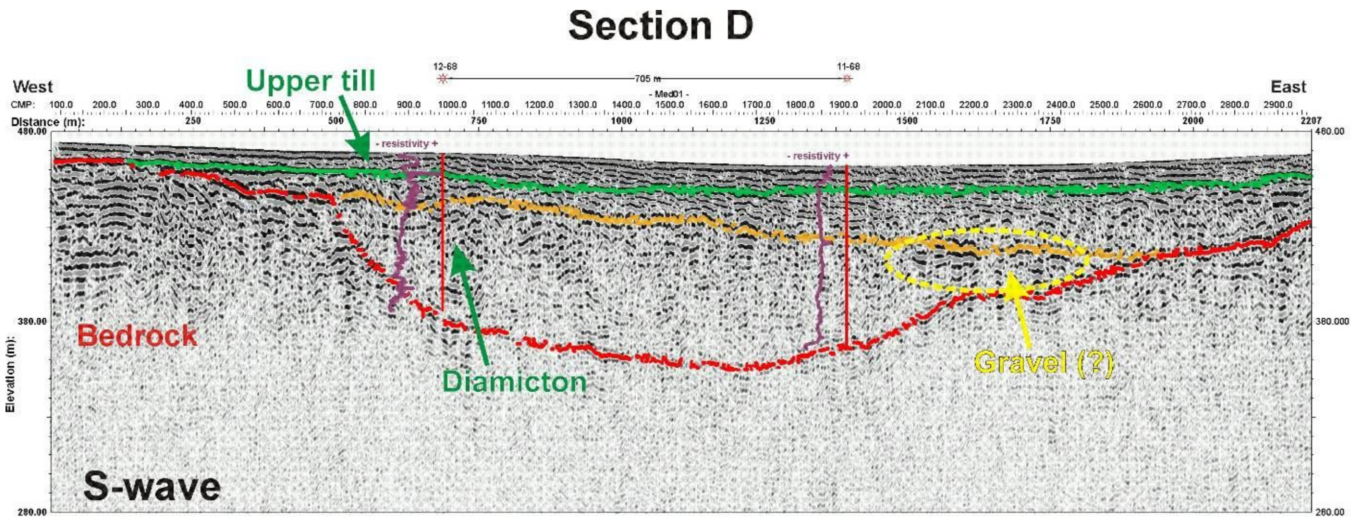

Figure A2-13b: Interpreted SH-wave reflection profile acquired with Minivib source along Section D. As in Section C, the borehole logs suggest thick diamicton to the bedrock surface, and again there is little indication on the seismic section of stratified sediments that may be more conducive to the 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 resisitivity with depth. Resistivities are generally low (~30 ohm-m) with maximum values of 40-50 ohm-m.

Summary:

The primary objective of the 2006-07 work was to determine whether seismic reflection methods could be effective in detecting 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 could be productive aquifers.

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

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 would be more efficient to cover the long distances need for regional studies. The SH-wave mode data has the advantage of producing higher resolution in the very shallow section, but with lesser signal penetration making it difficult to image 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.

References:

Fulton, R.J., Blais-Stevens, A., Sun, C., Eilers, R.G., Betcher, R., Elson, J.A., Veldhuis, H., and Fraser, W.R., 2004, Surficial materials of the Virden area, Manitoba and Saskatchewan. Geological Survey of Canada, Bulletin , no. 546, 2004; 104 p.

Klassen, R.W. and Wyder, J.E., 1970. Bedrock topography, buried valleys and nature of the drift, Virden map-area, Manitoba. Geological Survey of Canada, Paper 70-56.

Pugin, A.J.M., Sargent, S.L., Hunt, L. 2006. SH- and P-wave seismic reflection using landstreamers to map shallow features and porosity characteristics in Illinois. SAGEEP 2006, April 2-6, Seattle, Washington, p. 1094-1109.

Pugin, A.J.-M., Hunter, J.A., Pullan, S.E., Cartwright, T., Douma, M., Good, R.L., and Burns, R.A., 2007. Buried-channel imaging using P- and SH-wave shallow seismic reflection techniques, examples from Manitoba, Canada. In Proceedings, SAGEEP'07 (Symposium on the Application of Geophysics to Engineering and Environmental Problems), Denver, CO, April 1-5, 2007, 9 p.