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ABSTRACT

In south-central Ontario, tunnel channels are primary targets for groundwater exploration due to their potential to contain confined, water-bearing, coarse-grained sediment fills. Despite extensive hydrogeologic and geologic exploration within these features, a comprehensive depositional model that illustrates the spatial distribution of coarse- and fine- grained sediment in tunnel-channel complexes is absent. Work in the Zephr area, north of ORM, presents new subsurface data to improve understanding of this geologic setting and to add to geologic models of these channel systems.

Findings result from combined geology, sedimentology, geophysics (seismic profiling) and sediment drilling (mud rotary and continuous core) to better our understanding the shallow channel setting north of ORM, including:

1) spatial distribution of coarse- and fine-grained sediments in tunnel-channels;
2) the architecture of tunnel-channel sequences in confluence zones.

Preferred aquifer targets aquifer units in the Zephyr area are identified in areas of channel confluence and channel bends. Channel aquifers are confined by 3.9 to 28.5 m thick deposits of rhythmically bedded silt. and clay.

BACKGROUND

The Lake Simcoe Region Conservation Authority (LSRCA), in partnership with the Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC) initiated a multiyear project to determine the potential yield of groundwater resources within tunnel-channel complexes near the community of Zephyr, Ontario (Fig. 1). Sediment packages within these systems (aquifer and aquitard complexes) were analysed through geophysical surveying and the examination of sediment-cores obtained through overburden drilling techniques to determine the location and heterogeneity of aquifer complexes within these systems.

The results of this study are intended to assist all levels of government in making informed decisions regarding Source Water Protection (SWP) policies and land-use/planning initiatives. In addition to these policies and initiatives, the identification of new aquifer complexes and a better understanding of the geologic setting within these systems (tunnel-channels), as discussed below, is multi-fold. First, the recognition of new aquifers within these systems may be used to relieve current and/or future stresses caused by urban sprawl on existing aquifer systems by municipalities (i.e. the construction of new municipal supply wells). Secondly, an improved understanding of the geologic setting within these systems will allow for improved geologic models which in turn will illustrate the heterogeneity of aquifer/aquitard complexes. It is anticipated that these models will form ‘cornerstones’ for numerous applications such as groundwater exploration programs, aquifer protection studies, identification of significant recharge areas, etc., but more importantly, these models will form the framework for groundwater flow modeling and future water budget scenarios.

INTRODUCTION

In south-central Ontario, tunnel-channels are primary targets for groundwater exploration programs due to the potential for usually confined, water-bearing, coarse-grained sediment fills located within them (Barnett 1991; Sharpe et al. 1996; Golder 2004). Despite extensive hydrogeologic and geologic exploration programs within these features, a comprehensive depositional model that illustrates the spatial distribution of coarse- and fine-grained materials in tunnel-channel complexes does not exist. For the most part, existing models of tunnel-channels illustrate extensive deposits of coarse-grained sediments (aquifer materials) near the central portion of the channel or where the channel 'thalweg' is thought to occur. This vague modeling approach is largely due to a lack of high-quality data and the scale at which the investigations are completed. However, based on the results of several sediment drilling studies (led by municipalities and private organizations) only minimal thicknesses of aquifer sediment have been observed near the central portions of many tunnel-channels. Therefore, alternative hydrogeologic exploration targets could be identified within tunnel-channel complexes.

This report documents the findings of a multiyear investigation aimed at determining the location and architecture of coarse-grained sediments within tunnel-channel complexes near the community of Zephyr, Ontario (Fig. 1). Although additional work is necessary to understand the geology of tunnel-channel complexes, it is anticipated that this study will aid future geologic and hydrogeologic investigations within these enigmatic complexes.

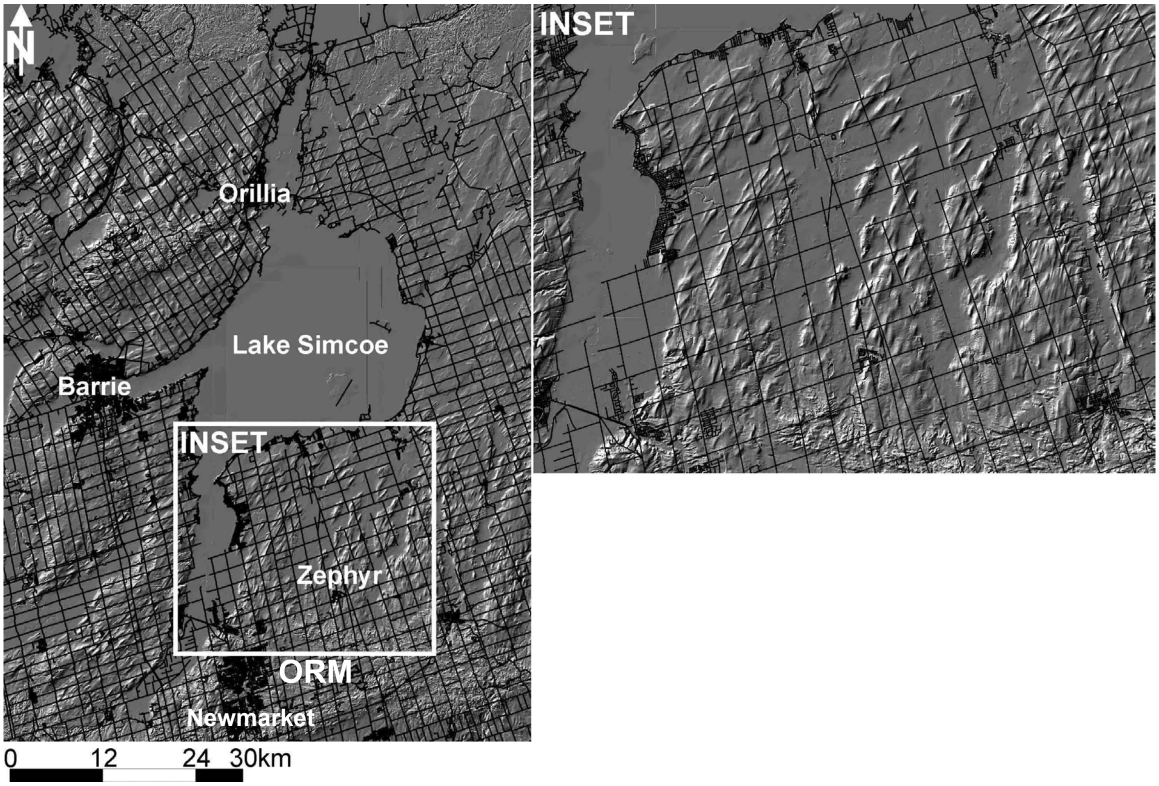

Figure 1: Location map of the study area accented by a digital elevation model with hillshade. Inset provides a more detailed view of the study area, with on the south margin representing the Oak Ridge Moraine.

PURPOSE

To understand the spatial distribution of coarse-grained sediments within tunnel-channel complexes, a detailed geologic investigation aimed at investigating confluence zones and channel bends (potential scour zones) within tunnel-channels was completed near the community of Zephyr (Fig. 1). This investigation combined sedimentology, Quaternary geology, geophysics (seismic profiling) and sediment drilling to determine the following:

1) architecture of tunnel-channel sequences (aquifer / aquitard sediment) in confluence zones;
2) spatial distribution of coarse- and fine-grained (aquifer / aquitard) sediments in tunnel-channels;
3) construct a viable depositional model of tunnel channels;
4) aid in locating additional sources of water supply for the regional municipality of Durham
5) supply all levels of government, public and scientific community with a sound depositional model of tunnel channels that will aid in groundwater exploration programs, land-use planning strategies, SWP initiatives and the Permit to Take Water process.

METHODOLOGY

A brief discussion on drilling and geophysical methods used in this study is provided below. For a detailed assessment of sediment drilling methodology and geophysical surveying techniques the reader is referred to Allen (1993) and Pugin et al. (2008).

Geophysics

A total of 11.9 km of geophysical data was obtained using a new GSC P-wave landstreamer (towed vertical geophone array) and the IVI minivib vibratory seismic source (Fig. 2). This equipment was used to acquire seismic reflection profiles along roadways oriented parallel and perpendicular to tunnel-channel complexes in the Zephyr area (Fig. 3). The unprocessed results of this survey are contained in Appendix B. For a more detailed explanation regarding this technology the reader is referred to Pugin et al. (2008). The locations of seismic reflection profiles are illustrated in Figure 3.

Figure 2: Photograph of the minivib source and SH-wave landstreamer in operation. Courtesy of Shawn Slattery.

Drilling

Mud Rotary Drilling

A total of five (5) boreholes were completed using the mud rotary drilling method where a drill bit is placed on the bottom of a string of drill rods which are rotated within a borehole. Drilling fluid is circulated into the borehole through the string of drill rods thereby transporting the drill cuttings (sediment and bedrock samples) to ground surface. Sediment samples were obtained and analysed on-site at 1.52 m intervals.

Boreholes were lined with 3-inch outside diameter polyvinyl chloride resin (PVC) pipes and 2 m lengths of 10-slot sized PVC well screens. Well screens were placed where the coarsest-grained aquifer units were intersected. A borehole location map is provided below (Fig. 3) and detailed borehole records are presented in Appendix A.

Continuous Core Drilling

One (1) borehole was completed using the continuous coring drilling method where a wire-line core barrel is attached to a string of drill rods. The drill rods and wire-line barrel are rotated and advanced through sediments and/or bedrock to obtain a continuous core sample. Water and/or drill fluid is used to cool the cutting bit and to carry cuttings to the surface. Sediment samples were retrieved and analysed on-site at 1.52 m intervals. This borehole was not completed with PVC pipes and a well screen due to flowing conditions encountered at the site. The borehole was abandoned in accordance with Ontario Regulation 903 (Ministry of the Environment 1993). The location and record of this borehole is illustrated on Figure 3 and presented in Appendix A.

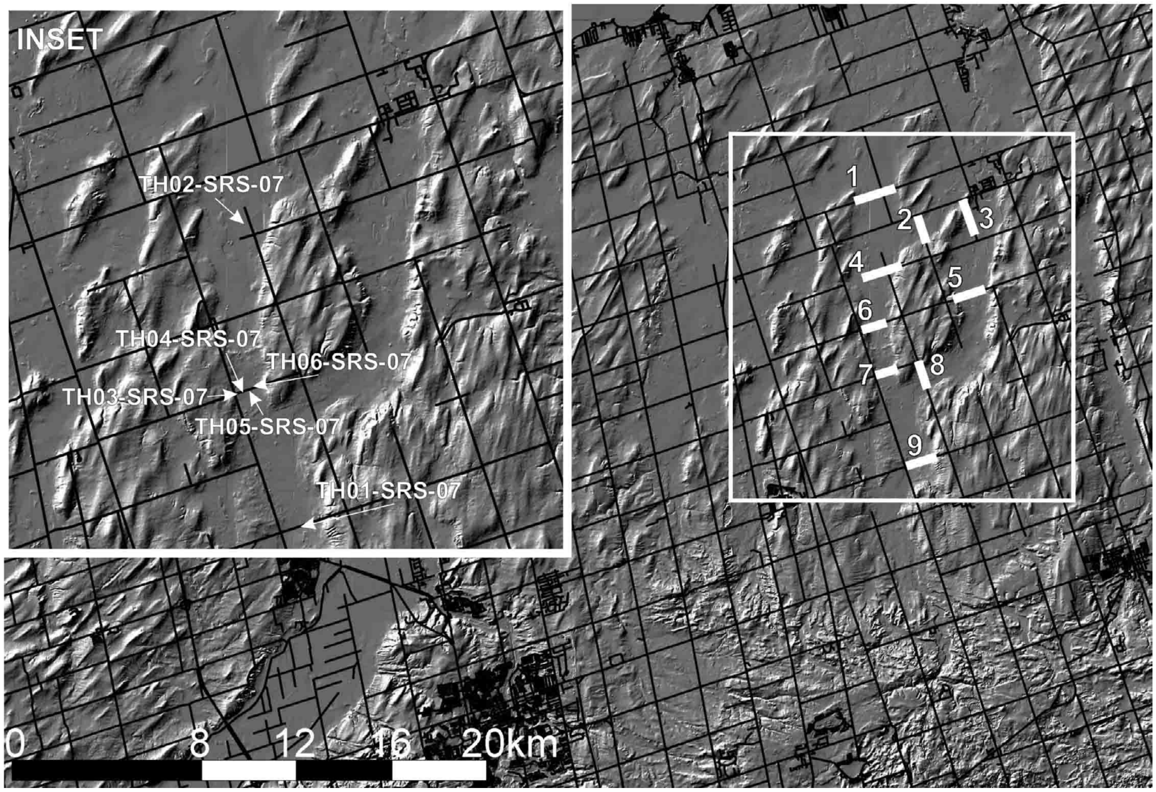

Figure 3: Digital elevation model with hillshade showing location map of geophysical profile lines completed in the study area (numbered lines located in upper right of figure). Inset refers to approximate location of boreholes.

PHYSIOGRAPHY

The study area is located within or adjacent to three (3) regional-scale physiographic regions defined by Chapman and Putnam (1984). These include the Simcoe Lowlands, the Peterborough Drumlin Field and the Schomberg Clay Plain (Fig. 4). An overview of each physiographic region is provided below.

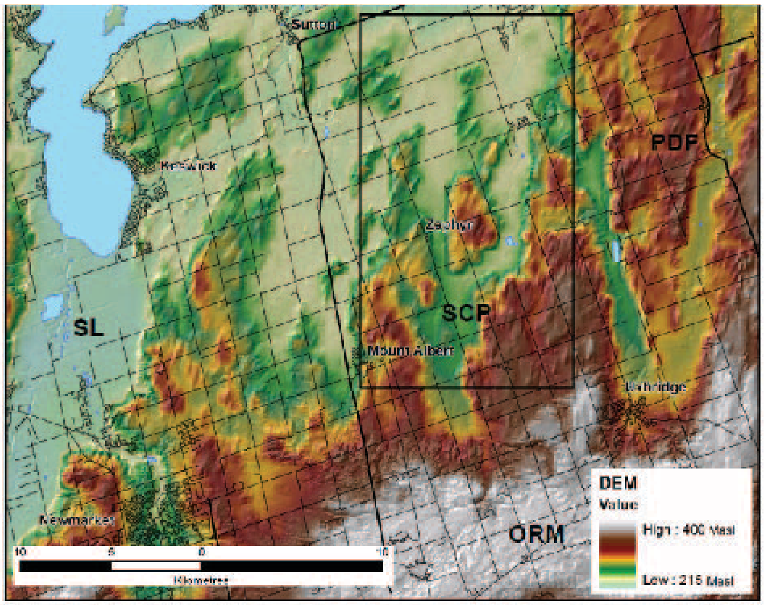

Figure 4. A coloured digital elevation model (DEM) draped over a grey-scale hill shade shows physiography of the study region. Simcoe Lowlands = SL; Peterborough Drumlin Field = PDF and Schomberg Clay Plain = SCP.

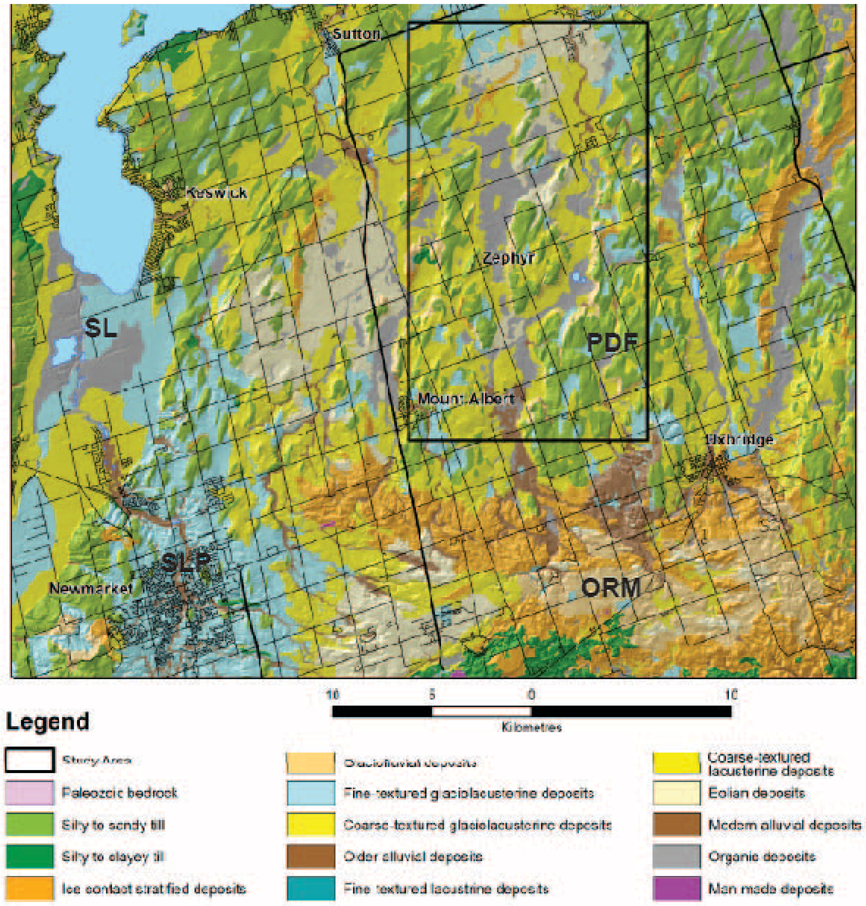

Figure 5: Surficial geology map draped over a hill shade covering the study region. Source: OGS 2003. Simcoe Lowlands = SL; Peterborough Drumlin Field = PDF and Schomberg Clay Plain = SCP; ORM=Oak Ridges Moraine

Simcoe Lowlands

The Simcoe Lowlands extend from near Orillia, south along the western edge of Lake Simcoe continuing south of the study area (Fig. 1). A small portion of this region is located east of Lake Simcoe and north of drumlin uplands. This region is characterized by flat, low-lying plains composed of silts, clays and fine- to medium-grained sands deposited within glacial Lake Algonquin (~12 500 years B.P.; Karrow 1989), south of Keswick (Fig. 5). Evidence of glacial Lake Algonquin is provided by shorelines, wave-cut notches, terraces and beach ridges located throughout the study area.

Peterborough Drumlin Field

A small portion of the Peterborough drumlin field region occurs southeast of Lake Simcoe across most of the study area (Fig. 4). This region comprises an undulating to rolling drumlinized till plain. Drumlins that occur between the Oak Ridges Moraine (immediately south of the study area) and the Lake Simcoe shoreline (northwest of the study area) are oriented ~60^0 west of south or 240^0 azimuth. On average, drumlins are 20-75 m in width and 100-450 m in length. Many of the drumlins resemble classic "whale-back" features described by many researchers (e.g., Hall 1812; Cox 1979; Hambrey 1994), however, spindle- and fishhook-shaped forms are also evident (Shaw and Kvil 1984; Shaw and Sharpe 1987). Internally, drumlins are composed of a stone-rich, slightly silty to silty fine- to medium-grained sandy diamicton (Fig. 6). Texturally, the percentage of silt increases in a southerly direction, more specifically drumlins immediately south of Lake Simcoe are composed of a stone-rich, slightly silty, fine to medium grained till whereas those immediately north of the Oak Ridges moraine are composed of a stone rich, fine- to medium-grained sandy, silty diamicton.

Figure 6: Cross-section (~ 5 m high) through a drumlin in the Peterborough Drumlin Field physiographic region. Courtesy of Shawn Slattery.

Schomberg Clay Plain

Low relief basins located north of the Oak Ridges moraine (Fig. 4) are collectively referred to as the Schomberg clay plain (Barnett et al. 1998). These areas are characterised by thick deposits of fine-grained sediments that occur approximately 30 m above the highest lake level of glacial Lake Algonquin (Fig. 5). These fine-grained sediments commonly drape over an irregular till plain and are typically 15 m in thickness. The extent of the lake is poorly defined due to likely ice contact support. Some researchers believe that glacial Lake Schomberg may have been confluent with the

Early Phase of glacial Lake Algonquin and have tentatively dated it at ca. 12 500 years B.P. (Karrow 1989).

MORPHOLOGICAL ELEMENTS

Based on the analysis of digital elevation models (DEM), LandSAT imagery, the interpretation of aerial photographs viewed in stereo, and previous morphological studies (e,g., Chapman and Putnam 1984) the study area can be simplified into two main landscape elements. These elements include upland and tunnel-channel complexes (Fig. 7). Physiographic regions identified in the section above (ie. Simcoe Lowlands) are interpreted as components contained within these elements. For example, the Peterborough Drumlin Field forms the upland complex element whereas the Simcoe Lowland and Schomberg Clay Plain regions physiographic regions collectively form the tunnel-channel element. The details of these elements are discussed further below.

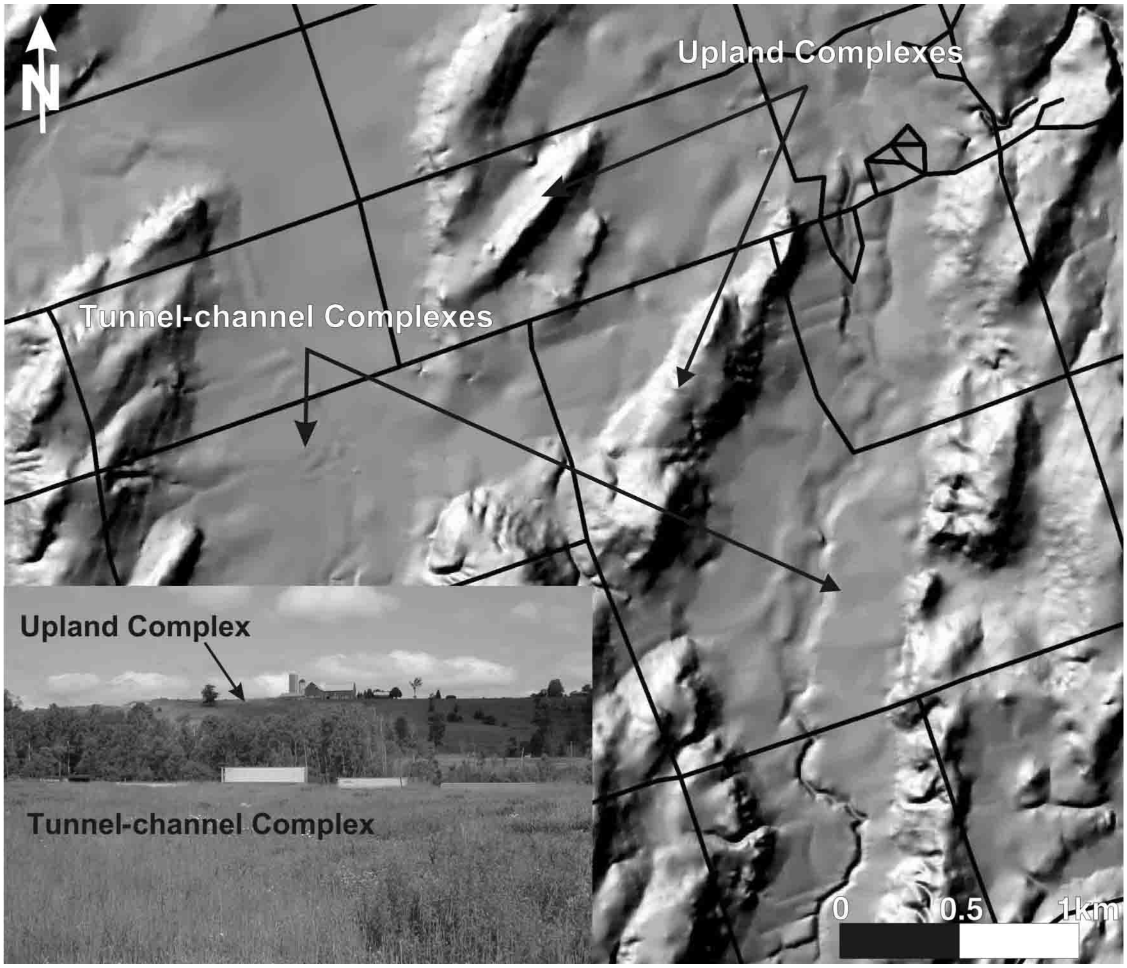

Figure 7: Digital elevation model of landscape elements located in the study area. Photograph of upland and tunnel-channel complexes northwest of the study area illustrates topographic variation amongst elements. Note train travelling through low-lying tunnel-channel complex in photograph. Courtesy of Shawn Slattery.

Upland Complexes

The first element, referred to as upland complexes, is defined by a series of step-sided knolls that are capped by drumlinised till. Typically, upland complexes exceed 50 m in height and can extend laterally for several kilometers. The morphology of these complexes often mirrors the morphology of drumlins that form the overlying till. In plan view these complexes, and the drumlins on them, are defined by a variety of drumlinoid forms that range from tear-drop to spindle-like in shape.

In some cases, the overall morphology of uplands is similar to the morphology of fluvial bar complexes described by Bluck (1979), Ashmore (1982, 1991), Allen (1983) and Church and Jones (1982). These uplands are characterized by sculpted, blunt stoss-side (up-stream) heads and tapered lee-side (down-stream) tails (Fig. 8). The morphology of one upland complex is of particular interest as it displays a horseshoe- to fish-hook shaped morphology similar to those constructed experimentally in laboratory flumes by Allen (1971, 1985; Fig. 8). More recently, the genesis of similar landforms identified in northern Alberta has been attributed to erosion by the rapid release of ponded subglacial meltwater by Shaw and Kvill (1984). The origin of upland complexes and enigmatic drumlinoid forms is discussed below.

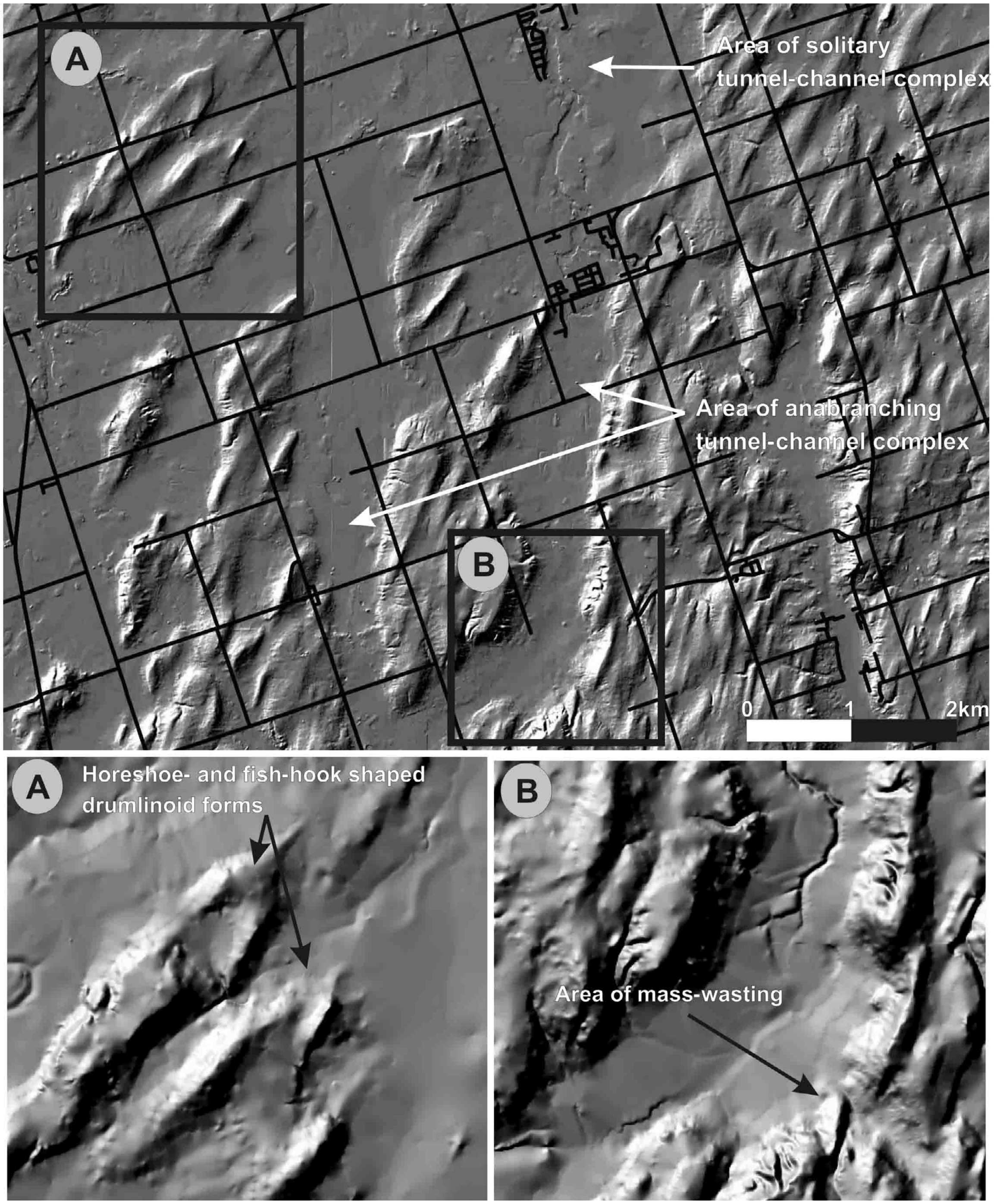

Figure 8: Digital elevation model accented with hill-shaded relief illustrating the morphology of the Zephyr tunnel-channel complex. In the northern portion of the study area the complex is represented by a single channel system that evolves southward into an anabranching complex. Inset with circled letter A depicts horseshoe and fish-hook shaped drumlins potentially formed due subglacial meltwater sheet-flow (e.g., Shaw and Sharpe 1987). Inset with circled letter B illustrates an area of mass-wasting near the toe of an upland complex. Mass-wasting is attributed to undercutting of the bank (upland complex) by the adjacent tunnel-channel during meltwater flow.

Tunnel-Channel Complexes

The second morphological element identified, tunnel-channel complexes, are defined by a series of low-lying, flat-floored, steep-walled valleys. Valleys are interpreted to represent the remnants of former subglacial meltwater channels (R-channels) and are herein referred to as tunnel-channels (e.g., Brennand et al. 2006). Based on the analysis of a 10 m DEM accented with hill-shaded relief, the tunnel-channel complex initiates north of the study area and is defined by a single, 12 km wide, north-south trending trunk or main channel (Fig. 8). Moving southward, several northeast-southwest and northwest-southeast trending chute-like channels intersect the north-south trending trunk channel forming an anabranching complex of channels (Fig. 8). Overall channel width decreases in a southward direction and channels that coalesce to form the anabranching complex reach a maximum width of 800 m (Fig. 8).

Channel complexes have sediment fill that fines upward from coarse grained (sand and gravel) to fine grained (silt, clay) sediment (Fig. 9). Gravel and sand occur up to ~25 m thick on a scoured channel floor of eroded Newmarket Till. Coarse sediment fines upward to silty sand and silty clay, a sequence up to ~25 m thick. A capping sequence, ~5-10 m consists of interbedded gravel, sand and silt of post-glacial lake origin,

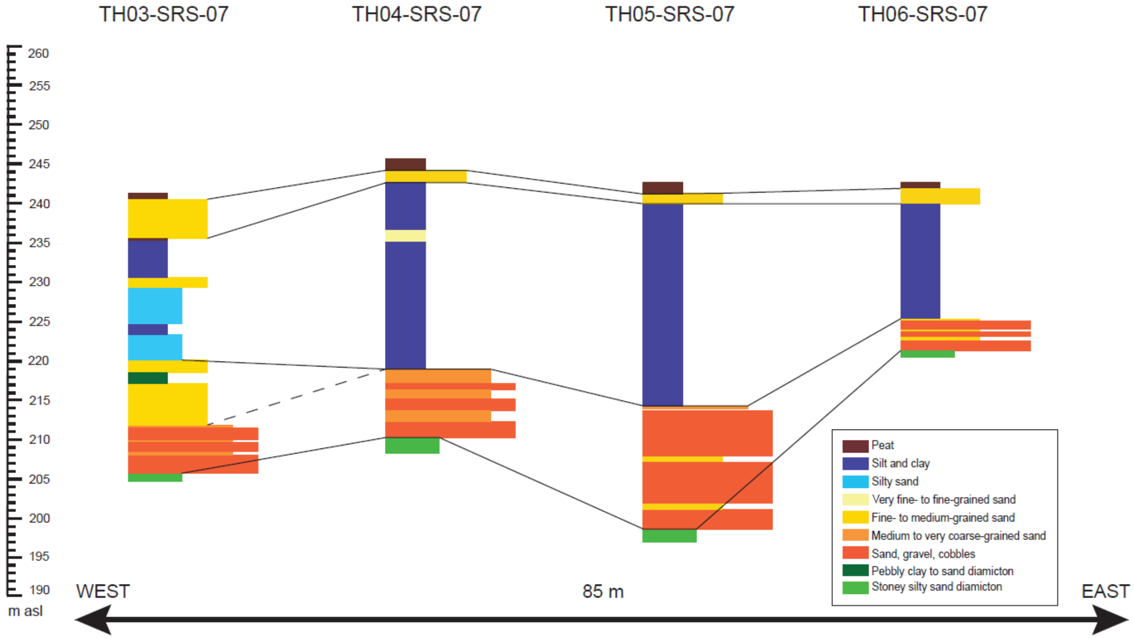

Figure 9: Sediment logs from Meyers Road mud rotary boreholes. This sediment section reveals the scoured channel bottom with a truncated diamicton surface and gravel partially infilling scours. See Appendix A for the complete drill core logs. Revised after Abigail Burt (personal communication).

Evidence of slope failure or mass-wasting is common along the flanks of upland complexes adjacent to channel bends or in areas where helical flow occurred along the margins of channel complexes (Fig. 8). Mass-wasting likely occurred when the tunnel-channel complex was in flood stage as remnants of the former bank (upland complex) are not evident at the base of the upland complex, nor within the adjacent tunnel-channel reaches.

EVENT SEQUENCE OF THE ZEPHYR AREA

Background

Based on the information obtained through sediment drilling, geophysical surveying (seismic) field-based sedimentological investigations, and work completed by others (Shaw and Gilbert 1990; Barnett 1991; Sharpe et al. 1996, 2004) the timing of geological events that occurred within the study area can be determined. By doing so, event sequence or a paleoreconstruction can be completed to gain an understanding of the physical environment (local geology and hydrogeology), its relationship with regional scale events, and the possible ramifications that new data will have on accepted interpretations and existing geologic models.

The physiography of the study area is largely a result of advance and retreat of the Laurentide Ice Sheet during the Late Wisconsinan and a regional-scale, subglacial flood event that occurred late glacial time, ~13-14 ka (e.g., Shaw and Gilbert 1990; Sharpe et al. 2004). According to Sharpe et al. (2004) the flood event is defined by an unconformity which is marked by a series of boulder-rich lag deposits and several landforms including drumlins and tunnel-channels. Despite a plethora of field evidence (Barnett 1991; Shaw and Gilbert 1990; Brennand et al. 1996; Sharpe et al. 1996, 2004) the occurrence and mechanism(s) responsible such events remain controversial among researchers (cf. Clarke et al. 2004; Sharpe 2005). Regardless of the mechanism(s) responsible for subglacial meltwater release, the incision and subsequent erosion of preexisting sediments from the flood event was instrumental in forming the present-day morphology.

According to Shoemaker (1992) incipient flood stages during the event formed as unconfined subglacial sheet-flow. In the Zephyr area, this unconfined sheet-flow formed erosional-type drumlinoid forms that ornament the upland complex morphological element (refer to Fig. 8). Additional evidence to support an unconfined sheet-flow exists in the northern portion of the study area (Barnett and Mate 1998) where a single, broad, flat-floored, scour-like channel system defines the tunnel-channel complex. This portion of the landscape is defined by a barren, pseudo-sediment-free landscape that contains numerous outliers of sculpted bedrock. These observations suggest that subglacial meltwater flow behaved as a highly erosive unconfined sheet-flow. It is plausible to assume that during this stage of the flood event upper-stage flow conditions predominated thereby creating an erosional regime that impeded sediment deposition. As flow rates subsided from upper- to lower-stage conditions, a breakdown of the unconfined sheet flow occurred and an anabranching complex of tunnel-channels formed throughout the area (Barnett and Mate, 1998; Sharpe et al. 2004). Present-day fluvial valleys and wetland areas now occupy the remnants of this tunnel-channel complex.

Tunnel-Channel Evolution

Although the genesis of tunnel-channel complexes is not an objective of this investigation, it is imperative that the reader is provided with an overview of current research pertaining to tunnel-channel genesis so that a general understanding of these complex systems is be gained. A brief summary of recent research contributions pertaining to tunnel-channel genesis is presented below.

The genesis of tunnel-channel complexes has been investigated by several researchers (Wright 1973; Shaw and Gilbert 1990; Shoemaker 1992; Booth and Hallet 1993; Piotrowski 1994; Sjogren and Rains 1995; ‘O Cofaigh 1996; Trisko 1996; Beaney and Shaw 2000; Sharpe et al. 2004). Despite this research our understanding of sediment architecture and geometry within these complexes remains poor as very few detailed investigations have been completed (cf. Brennand and Shaw 1993; Russell and Arnott 2003).

Tunnel channels are defined as elongate depressions with overdeepened areas along their floors cut into bedrock or unconsolidated sediment (‘O Cofaigh 1996). They commonly form sinuous and/or anastomosing complexes, as evident in the Zephyr area, although they may also exist as independent, straight valleys. Their sedimentary infill is variable but is characteristically dominated by sediment gravity flows (Brennand and Shaw 1993; Russell and Arnott 2003) and thick units of glaciofluvial sands that are capped by fine-grained glaciofluvial and glaciolacustrine sediments where sedimentation occurred in subaqueous fans. Three main theories of tunnel channel formation exist at present. The first ascribes the formation of tunnel valleys cut into unconsolidated sediment to the creep of deformable subglacial sediment into a subglacial conduit from the sides and below (piping), followed by removal of this material through the conduit by steady meltwater flow (Benn and Evans 1998). Tunnel channels are thus created by lowering of the sediment surface on either side of the conduit (Benn and Evans 1998). The second theory argues that tunnel channels form during deglaciation, at or close to the ice margin, by subglacial meltwater erosion and that the valleys are time transgressive (Mäkinen 2003). The third theory also argues for an origin by subglacial meltwater erosion but claims that the discharges involved took the form of catastrophic channelized floods and that the tunnel valleys within anastomosing networks formed synchronously (Shaw 2002).

The genesis of the Zephyr tunnel-channel complex is enigmatic at best. In the northern portion of the study area, the tunnel-channel complex is defined by a single, broad, ~7 km wide, scour-like feature (Fig. 8). Geophysical data obtained from Old Shiloh Road (Fig. B.6; Appendix B), the northern most section completed in the tunnel-channel complex, is characterized by a 30 m thick stacked sequence of low-angle to flat-lying, continuous to semi-continuous reflectors. Low-angle reflectors are interpreted as bounding discontinuities or bedding planes associated with a multi-storey sheet-flow deposit. Similar geometries have been interpreted as sheet-flow deposits by several authors (Pugin et al. 1999 and Fischer et al. 2007). Approximately 6 km south in the same channel, geophysical data oriented perpendicular to the direction of former paleoflow in the channel-complex acquired from Meyers Road (Fig. B.5; Appendix B), illustrates a sediment thickness of approximately 70 m near the central-axis of the channel-complex. As demonstrated from Figures B.1, B.2, B.5 and B.6 (Appendix B) dark-coloured semi-continuous, concave-up reflectors illustrate a U-shaped geometry associated with confined, lower-stage (non-flood) flow regimes (Allen 1985; Miall 1985).

Tunnel-channel infill thickness, or lack thereof, in the northern portion of the channel-system is attributed to minimal sediment thickness prior to tunnel-channel formation. If sediment thickness was minimal, then the amount of sediment eroded and subsequently deposited within the channel system would also be minimal. Therefore, the solitary, scour-like channel-system in the northern portion of the study area likely reflects a sediment-starved system formed under upper-flow regime, erosional conditions. In addition, the absence of sediment in this area prior to tunnel-channel formation would also support the existence of a broad, unconfined sheet-flow. If sediment-outcrops were present they would have likely acted as obstacles, thereby impeding flow in the sheet-flow system, causing a reduction in meltwater flow rates, a possible breakdown of the sheet-flow and the subsequent formation of confined steep-walled channels rather than the remnants of broad, shallow systems that occupy the area. Initial breakdown of the subglacial sheet-flow and the onset of anabranching channel-complexes likely occurred in the northern portion of the study area where the remnants of well-defined, steep-walled channels are abundant. It is difficult to determine the exact geographic position of where subglacial meltwater transformation from upper stage sheet-flow to lower-stage (sheet-flow to channelized-flow) flow occurred, but thickness of channel infill sediment and the presence of well-defined upland and tunnel-channel complexes may be used as a tentative guide (Fig. 7).

Architecture of Tunnel-Channel Complexes: Channel Confluences and Bends

The location of scour zones (flow separation and reattachment zones) within tunnel-channel confluences and bends in relation to upland complexes is important in understanding past patterns of preferential erosion. A better understanding of upland complex erosion from tunnel-channel systems will allow for informed predictions concerning the location of scour zones and coarse-grained scour-fill sediments. In turn, the location of these coarse-grained sediment zones (potential aquifer units) will aid in identifying additional sources of potable groundwater, and more importantly, assist in Source Water Protection (SWP) policies and land-use/planning initiatives.

Channel Confluences

In modern-day fluvial settings, channel confluences are defined as areas of amalgamation amongst upstream channels where significant changes in downstream hydraulics occur (Ashmore 1982, 1991; Ashmore and Parker 1983). In these areas obstacles located within the fluvial system (i.e. medial bar forms) may impede and redirect water flow around their stoss or upstream sides creating zones of flow separation. These areas are characterized morphologically by blunt or rounded stoss sides (also referred to as bar heads; cf. Allen 1985; Miall 1985). Flow reattachment within the fluvial system occurs downstream (leeside) near the terminus of the obstacle creating a tapered or streamlined tail. Although direct observations have not been completed in subglacial fluvial settings for obvious logistical reasons, it is plausible to assume that areas of vigorous and complex flow patterns (zones of flow separation and reattachment) existed at the confluences of tunnel-channel complexes. In these areas, upland complexes likely acted as obstacles within the channel-system, impeding and redirecting subglacial meltwater flow around upland complexes (Fig. 8).

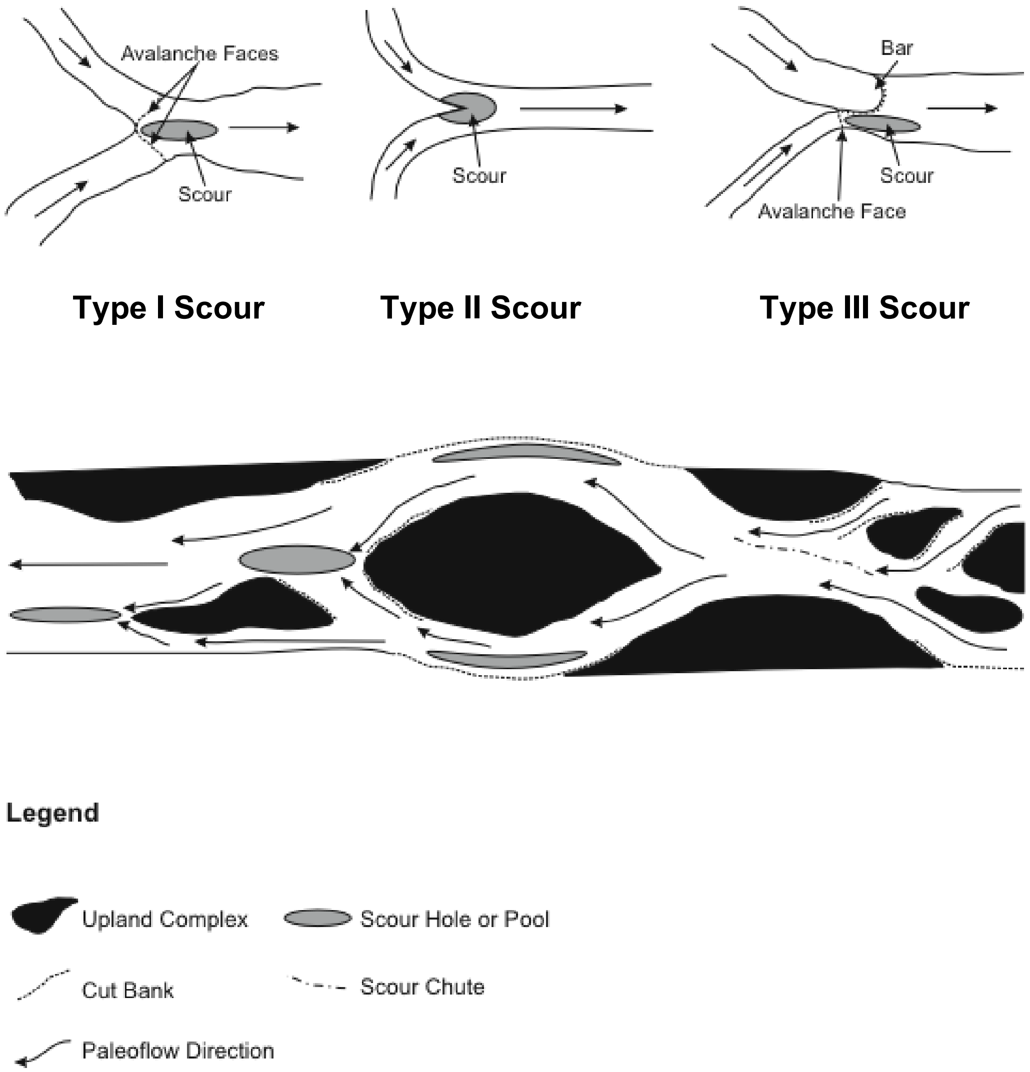

Figure 10: Upper portion of figure depicts three hypothetical scour-bed formations (Type I, Type II and Type III). Type I is defined by a lens-shaped scour at the confluence of two upstream anabranches of equal flow ratios. Type II is the result of back-to-back bending anabranches of equal flow ratios and low angles of incidence. Type III scour-bed formation is based on unstable and variable flow ratios within upstream anabranches. The lower portion of the figure illustrates where areas of scour-bed formation would likely occur in relation to upland complexes in the study area. Figure is modified from Ashmore (1991).

As previously discussed, many upland complexes are defined morphologically by blunt stoss-side heads and tapered lee-side tails. Although additional work may be required to validate the following hypothesis, preferential erosion of upland complexes by subglacial meltwater is likely related to the internal architecture or stratigraphic assemblage of sediments that constitute upland complexes. In many of the upland complexes in the Zephyr area and north of Barrie, the heads of upland complexes are composed of Newmarket till, a silty, sand-rich, stoney diamicton, that unconformably overly deposits of matrix-supported boulder gravels interpreted as the apexes of subaquatic fans (Slattery 2003). The tails or lee-sides of upland complexes are typically composed of deposits of Newmarket till that unconformably overly silty, fine- to medium-grained sands related to mid- to distal-facies of the underlying fan complex. Based on these observations, it is plausible to assume that erosive, subglacial meltwater flow was redirected laterally around the stoss-sides of upland complexes by underlying deposits of boulder-gravels toward finer-grained sediments that composed the lateral facies of the fan. These finer-grained sediments, being more susceptible to erosion, were incised and subsequently eroded by the tunnel-channel complex. In many subaquatic fans, fine-grained sediments (fine sands, silts and clays) are located laterally adjacent to coarse-grained sediments that form the apex or core of the subaquatic fan (Russell and Arnott 2003). This hypothesis may aid in explaining the blunt-head and tapered-tail morphology of upland-complexes located throughout the study area. In addition, erosion against an obstacle occurs due to turbulent scour against a 'bluff' (Allen 1985).

Similar to modern-day fluvial systems, distinct scour-bed morphologies would have likely occurred at the lee-ends (down-stream) of upland complexes. Field- and laboratory-based observations completed by Mosley (1976, 1982a, 1982b), Best (1986, 1987, 1988, 2006) and Parker and Ashmore (1983) in modern-day fluvial settings have determined that scour-bed morphology is largely dependent on the junction angle (angle of incidence), and the ratio of discharge within upstream confluent channels. Additional factors that contribute to scour-bed morphology include total sediment load within confluent channels and the cohesiveness of channel bed substrate (Mosley 1976; Ashmore and Parker 1983). Although some of these factors are not fully accepted by some authors (Best 1988) it is generally accepted that the greatest factor controlling relative scour depth is the angle of incidence of upstream confluences (Mosley 1976; Best 1986, 1987,1988 and Ashmore and Parker 1983; Fig. 7).

Based on the information above, possible similarities between subaerial and subglacial fluvial systems can be formulated. As in modern-day systems, it is plausible to assume that incidence angles of upstream tunnel-channel anabranches and discharge ratios within these anabranches would have likely governed scour-bed morphology during the operation of the tunnel-channel complex. Therefore, the deepest scour zones are likely located directly downstream from tunnel-channel anabranches with the greatest angles of incidence. Although this hypothesis assumes equal meltwater flow ratios in both upstream tunnel-channel anabranches, if valid, anabranches that are separated by large incidence angles should mark the location of the largest confluence zones, the deepest scour formations and possibly the thickest deposits of coarse-grained sediments. In the channel-confluence zone three (3) possible scour-bed morphologies have been formulated. These morphologies, herein referred to as Type I, Type II and Type III scour-beds are illustrated on Figure 10 and are described briefly below.

Type I: Type I scour-bed formation results in the formation of a lens-shaped scour at the confluence of two upstream anabranches of equal flow ratios (Fig. 10). Variations of this scour-bed morphology are likely due to fluctuating flow ratios.

Type II: Type II scour-bed formation is the result of back-to-back bending anabranches of equal flow ratios and low angles of incidence. In this setting a lens- to oblate-shaped scour-bed would form, extending upstream form the confluence zone to the anabranches (Fig. 10).

Type III: Type III scour-bed formation is based on unstable and variable flow ratios within upstream anabranches. In these areas, an elongated scour would form immediately downstream of the confluence with the greatest flow strength. At the mouth of the confluence with lesser flow strength an aggrading bar complex may form (Fig. 10). In some cases, it is likely that this bar complex would prograde into the scour forming a multi-storey sequence of coarse-grained sediments.

To validate this hypothesis, angles of incidence between tunnel-channel anabranches were measured in the study area to estimate the location, depth of scour formations and thickness of scour-bed infill sediments. Where anabranch width was similar it was assumed that flow ratios were of equal strength. Prior to geophysical surveying a potential Type I scour was identified adjacent to Brewster Road based on an angle of incidence of ~39^0 between upstream anabranches (Fig. 11). Unprocessed geophysical data completed over Brewster Road indicates an estimated 20 m thick sequence of coarse-grained sediments (gravels? refer to Fig. B.2; Appendix B). To verify the geophysical data, a borehole was advanced near the periphery of the potential scour-bed formation. A total of 16.4 m (52.7 feet) of medium- to very-coarse grained, pebbly sands and boulder-grade gravels were identified at the site (refer to borehole record TH02-SRS-07; Fig. A.2; Appendix A). Unfortunately, a borehole could not be advanced near the proposed centre of the scour-bed formation due to logistical reasons (land access). However, based on the geophysical data an estimated 20 m of coarse-grained sediments are located in this area (refer to Fig. B.2; Appendix B). Although additional data are required to further validate the geometry of this scour-bed formation the Brewster Road borehole, as predicted, yielded the thickest deposit of coarse-grained sediments in the study area.

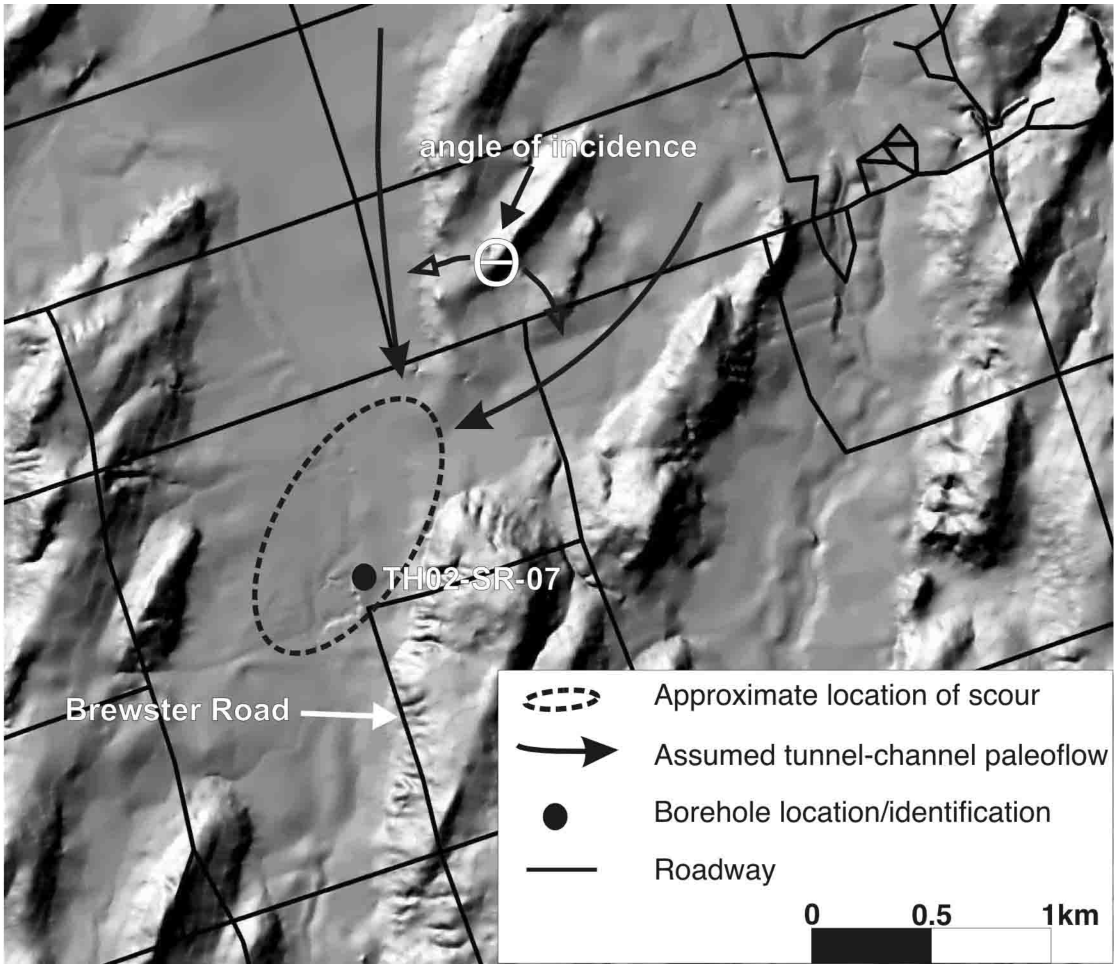

Figure 11: Digital elevation model accented with hill-shade of the Brewster Road area. Figure depicts estimated location and morphology (dashed line in figure) of a Type I scour formation. Courtesy of Shawn Slattery.

Channel Bends: Helical Flow

The dynamics of subaerial fluvial systems is predominantly governed by friction, channel topography and channel morphology (cf. Allen 1985). In areas where channel bends occur, such as meander bends, a secondary flow phenomenon know as helical flow occurs (Allen 1985; Ashmore 1991). Although this type of flow does not have any strong influence on the general flow pattern in rivers with large width to depth ratios, it has significant influence on the direction of sediment transport and hence the distribution of coarse-grained sediments within the fluvial system (Miall 1987, 1977). Like the identification of scour-bed zones in subglacial settings, detailed assessments concerning the location of helical flow zones and the distribution of coarse-grained sediments in channel bends have not been studied for obvious logistical reasons. In this study, a comparative approach between channel-bend architecture of modern-day and subglacial fluvial systems was completed to determine if similarities in grain-size distribution (the location of fine- and coarse-grained sediments) exist. If similar sedimentary architectures occur (i.e. the location of point bars) this approach may aid in locating coarse-grained deposits or potential aquifer units.

In meandering channel-systems, channel-bends reflect the areas of highest flow velocities within the system. In these areas, water is driven to the outside of a meander by helical flow (refer to number 1 in Fig. 12) and on the outside of the meander, the surface of the water is slightly higher or super-elevated because it has gained momentum and acceleration due to centrifugal forces (Allen 1985). Water flow is forced down the outer bank resulting in a steeper velocity gradient and greater bed shear stresses. Eventually water flow returns to the surface toward the inside of the meander where flow is less turbulent (refer to number 2 in Fig. 12) due to helicoidal flow (refer to number 3 in Fig. 12). When stream flow reaches the outer bank of a channel-bend increased water acceleration undercuts or erodes the bank creating a toe scour (refer to steep bank in Fig. 12) that may lead to collapse or mass-wasting of the bank. In the study area, evidence of mass-wasting attributed to undercutting of the upland complexes, the former bank, by subglacial meltwater is evident in two localities adjacent to channel bends (Fig. 12). In these areas, sediment is deposited at the slower moving inside bend (refer to number 5 in Fig. 12) resulting in the incipient stages of point bar formation. As water flows away from the outer bank and rises up the slope of the inner bank, or point bar, momentum is lost, and sediments eroded from the outer bank are deposited.

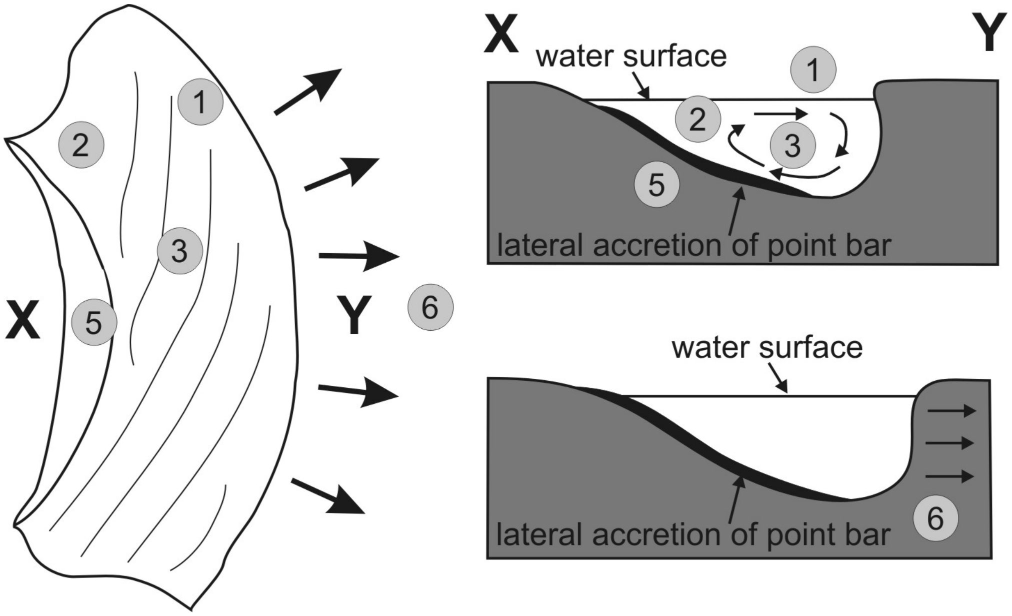

Figure 12: Plan view and cross-sectional view of flow dynamics within a channel bend. In these areas water is driven to the outside of a meander by helical flow (circled number 1). Flow is directed toward the outer bank resulting in a steeper velocity gradient and greater bed shear stresses. Eventually water flow returns to the surface toward the inside of the meander where flow is less turbulent (circled number 2) due to helicoidal flow (circled number 3). When flow reaches the outer bank, increased water acceleration undercuts the bank creating a toe scour (see step bank wall) that

may lead to bank collapse. In these areas, sediment is deposited at the slower moving inside bend (circled number 5) resulting in the formation of a point bar. As water flows away from the outer bank and rises up the slope of the point bar momentum is lost, and sediments eroded from the outer bank are deposited (circled number 6).

Typically, coarse-grained sediments are deposited near the base of the point bar and fine-grained sediments are deposited toward the top of the bar forming a wedge-shaped, fining upwards succession (Fig. 13). As a result of decreasing flow velocities, trough cross-bedded sands and gravels are typically located at the base of the point bar whereas planar-bedded deposits of silts and clays and drape-like sequences of climbing ripples are located near the top of the bar (Fig. 13). Depending on the dynamics of the fluvial system, a point bar will continue to aggrade laterally until channel avulsion occurs (where the channel abruptly changes course). If avulsion occurs, secondary chute-channels commonly incise the top of the bar forming a series of concave-up scours. These scours are commonly infilled with coarse-grained lag-deposits during the later stages of waning flow.

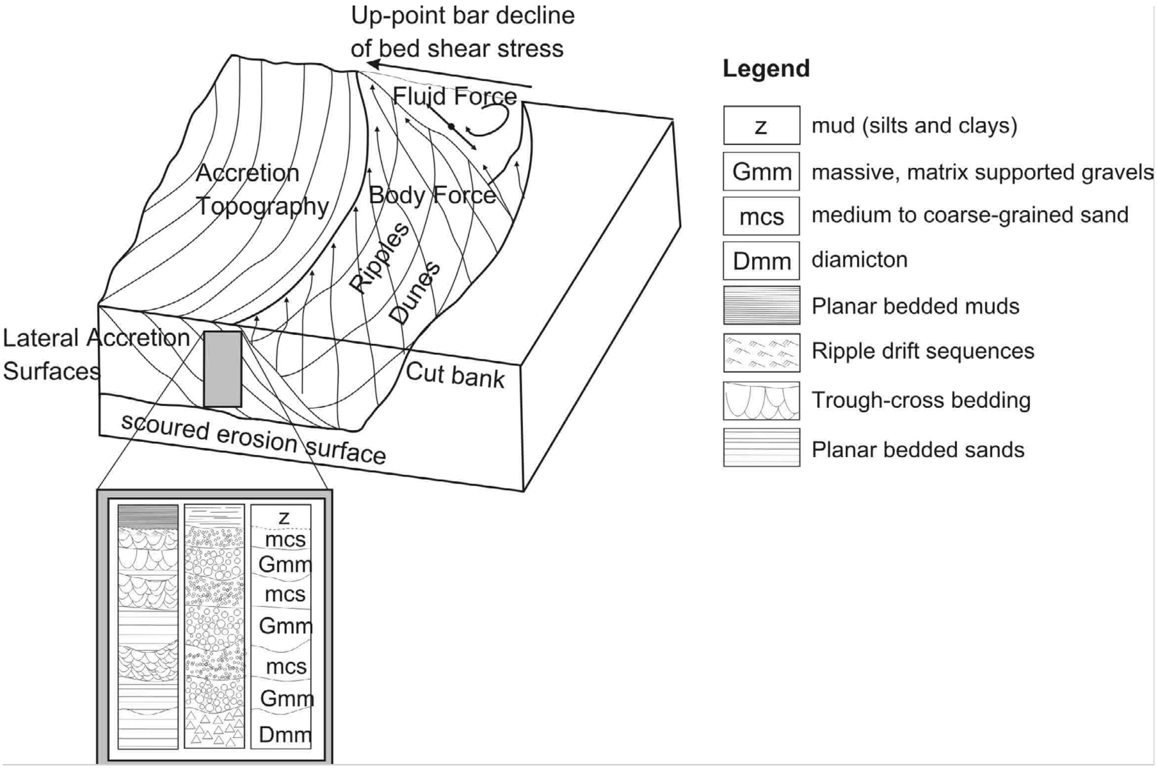

Figure 13: Cross-section of a point bar complex. Inset depicts common sedimentary structures and grain-size fluctuations within a point bar complex. Modified from Allen (1985).

To validate possible commonalities between channel-bends in modern-day and subglacial fluvial systems, geophysical data was acquired perpendicular to the former north-south direction of paleoflow adjacent to a tunnel-channel bend on Meyers Road (Figs. 3 and 14). Prior to geophysical surveying, evidence of mass-wasting was noted adjacent to the inside of the channel-bend through the interpretation of a 10 m DEM accented by hill-shaded relief. The results of initial unprocessed geophysical profiling illustrate a series of dark-coloured, semi-continuous reflectors that collectively form a wedge-shaped feature (Fig. B.5; Appendix B). This wedge-like feature is incised by two (2), step-sided, semi-continuous, concave-up reflectors (Fig. B.5; Appendix B). To verify the geophysical data, a series of four (4) boreholes, spaced approximately 50 m apart, were advanced through the wedge-like feature (Figs. A.3 to A.6; Appendix A).

Traversing east to west across the channel-bend the uppermost elevation of coarse-grained sediments increases from 24.1 mbgs to 17.4 mbgs (Figs. A.3 to A.6; Appendix A) verifying the wedge-shaped geometry and dark-coloured semi-continuous reflector that marks the top of coarse-grained sediments in the unprocessed geophysical results (Fig. B.5; Appendix B). In borehole TH03-SRS-07 (Fig. A.3; Appendix A), completed closest to the inner-bend of the channel, a silty, clayey, fine to medium sandy diamicton was observed at 22.9 mbgs to 24.1 mbgs. Based on the proximity to the former bank (the adjacent upland complex) this sequence is interpreted as a debris flow unit derived from the undermining of the adjacent bank. Although supplementary data (i.e. additional boreholes) are required to support the following interpretation, the wedge-shaped feature identified below Meyers Road is interpreted as point-bar complex deposited through secondary helical flow during the lower-stage flow regimes within the tunnel-channel complex. Step-sided, semi-continuous reflectors that incise the upper portion of the bar complex are likely chute-channels formed during the onset of channel avulsion or lateral aggradation of the bar complex (Fig. B.6; Appendix B).

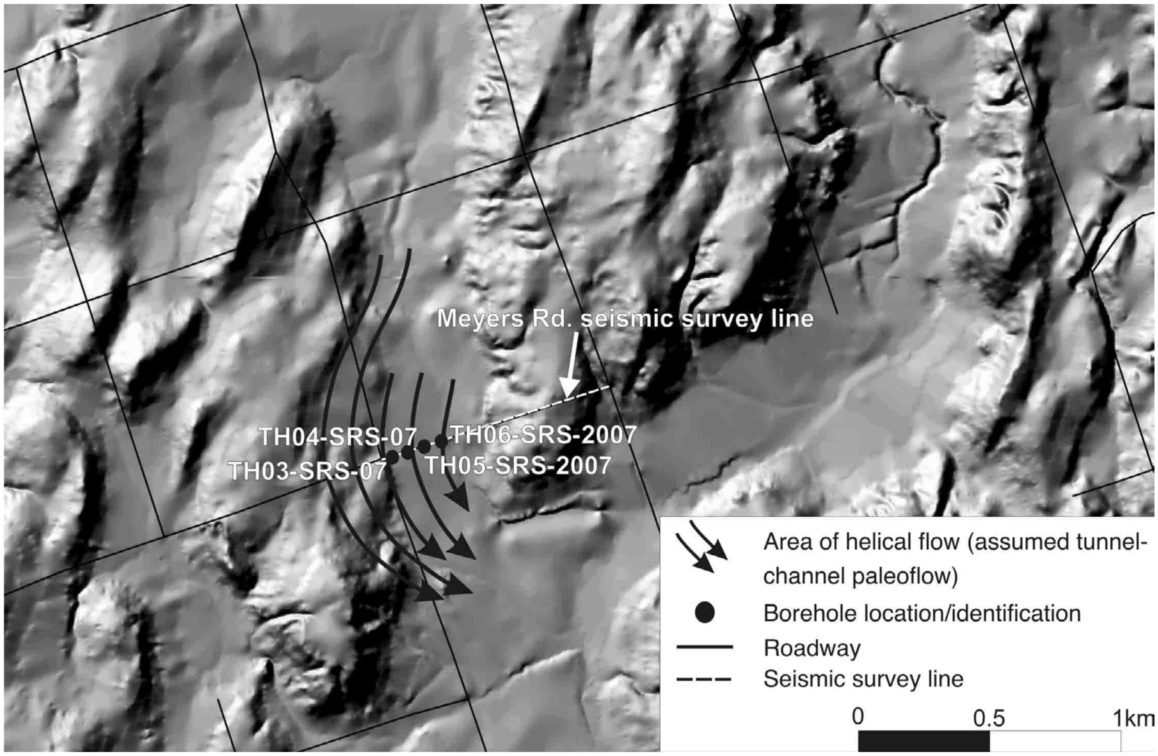

Figure 14: Location map of proposed helical flow in the Meyers Road area. Proposed helical flow patterns, seismic survey location and borehole locations are illustrated in figure. Courtesy of Shawn Slattery.

POTENTIAL AQUIFER EXPLORATION TARGETS

Of particular interest to municipalities and private sector organisations exploring for additional sources of potable groundwater is the location of suitable aquifer materials. To deem aquifer media as being suitable targets for groundwater exploration, several criteria must be present prior to aquifer performance testing (i.e. constant rate pumping tests, step-tests, etc.). Some of these criteria include the following: aquifer media must be blanketed by a confining layer of suitable thickness; sediments that constitute aquifer materials must be of adequate thickness and grain size, and theoretical estimates of aquifer transmissivity (the measure of an aquifer to transmit water) must be positive.

From this study, two (2) potential aquifer exploration targets have been identified within tunnel-channel complexes that satisfy the above criteria. These targets include areas where channel-bends and channel confluence zones occur within tunnel-channel complexes. In all boreholes completed, rhythmically bedded deposits of silts and clays (aquitard units) were encountered above coarse-grained aquifer sediment associated with the tunnel-channel complex. This gravel-sand mud sequence indicates sedimentation in a ponded water setting. The thickness of the aquitard unit varied from a minimum thickness of 3.9 to a maximum thickness of 28.5 m (refer to Appendix A). Therefore, based on the data tunnel-channel aquifer units are confined systems.

Channel Confluences

Based on data obtained from sediment drilling and geophysical surveying, accumulations of coarse-grained sediments (aquifer sediment) are likely concentrated directly downstream of tunnel-channel complexes where high angles of incidence occur between upstream tunnel-channel anabranches (Fig. 8). Although this hypothesis assumes several variables (i.e. equal meltwater flow rates in upstream tunnel-channel anabranches), if valid, areas immediately downstream of high angle tunnel-channel anabranches likely mark the location of thick deposits of coarse-grained sediments. However, additional data are required to further support the findings of this study; nevertheless, based on the data obtained in this study, these areas yielded the thickest deposits of coarse-grained sediments.

Channel Bends

As demonstrated through morphological data (Fig. 12), geophysical data (Figs. A.3 to A.5; Appendix B) and sediment drilling data (Appendix A), the distribution and architecture of coarse-grained sediments in tunnel-channel bends is similar to present-day fluvial systems where helical flow occurs. Although additional data are required to validate this conclusion, point bar formation in channel-bends may yield thick deposits of coarse-grained sediments. These should be investigated further to determine the lateral extent, heterogeneity and aquifer potential of bar complexes (point bars) within these areas.

Aquifer Transmissivity

Aquifer performance testing has not been completed on any of the aquifer units identified in the study area, however, aquifer transmissivity, a measure of the ability of an aquifer to transmit water can be estimated through the following equation:

$$T=KB$$

Where,
T= Transmissivity (m^2/sec)
K= Hydraulic Conductivity (m/sec)
B= Saturated Thickness (m)

Data obtained from each borehole (i.e. aquifer thickness, etc.) and the results of transmissivity calculations are illustrated in the table below. Maximum and minimum estimates of hydraulic conductivity (K) for gravel were obtained from Singer et al. (2003) to provide a range of transmissivity for the given aquifer unit.

Borehole ID	Water Table (mbgs)	K (m/sec) Max.	K (m/sec) Min.	B (m)	T (m^2/sec)
TH01-SRS-07	0.86	3 x 10^{-4}	3 x 10^{-2}	6.5	3.27 x 10^{-3} – 3.27 x 10^{-1}
TH02-SRS-07	1.45	3 x 10^{-4}	3 x 10^{-2}	16.5	4.95 x 10^{-3} - 4.95 x 10^{-1}
TH03-SRS-07	1.21	3 x 10^{-4}	3 x 10^{-2}	11.6	3.48 x 10^{-3} – 3.48 x 10^{-1}
TH04-SRS-07	1.23	3 x 10^{-4}	3 x 10^{-2}	8.6	2.58 x 10^{-3} – 2.58 x 10^{-1}
TH05-SRS-07	1.22	3 x 10^{-4}	3 x 10^{-2}	15.5	4.65 x 10^{-3} - 4.65 x 10^{-1}
TH06-SRS-07	1.22	3 x 10^{-4}	3 x 10^{-2}	4.2	1.26 x 10^{-3} – 1.26 x 10^{-1}

Based on the above calculations, tunnel-channel aquifers in the Zephyr area have an estimated theoretical transmissivity of 1.26 x 10^{-3} m/sec to 4.95 x 10^{-1} m/sec. Although these values are deemed as being favorable, it is recommended that aquifer performance testing and water quality testing is completed to determine the specific yield of aquifer units and determine if groundwater is potable.

CONCLUSIONS AND RECOMMENDATIONS

Based on data obtained from the above investigation the following conclusions are made:

1) Geophysical surveying facilitated by sediment drilling and field-based sedimentological investigations have proven to be an effective means in determining the location and architecture of aquifer and aquitard complexes.

2) Channel bends (areas of helical flow) and channel-confluence zones (areas where tunnel-channels amalgamate) may yield the thickest deposits of coarse-grained sediments (aquifer sediment). However, additional drilling and geophysical investigations are required to accurately define the architecture of tunnel-channel complexes.

3) Areas of channel-wall mass-wasting may be an indication of where helical flow occurred within the tunnel-channel complex. These areas may provide an additional means in locating coarse-grained sediment. However, additional investigations are needed to confirm this hypothesis.

4) Aquifer units in the Zephyr area are confined by 3.9 to 28.5 m thick deposits of rhythmically bedded silts and clays.

5) Tunnel-channel aquifers in the Zephyr area likely have enhance transmissivity for up to kms along the channel reach.

6) Artesian or flowing conditions were encountered at borehole TH01-SRS-07. An estimated flow rate of 29 IGM (imperial gallons per minute) and an above ground head measurement of 21m were calculated shortly after flowing conditions were encountered. Flowing conditions occurred shortly after penetrating a brown to olive coloured, stone-

rich, silty, fine- to medium- grained diamicton approximately 42 mbgl (metres below ground level).

ACKNOWLEDGMENTS

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APPENDIX A

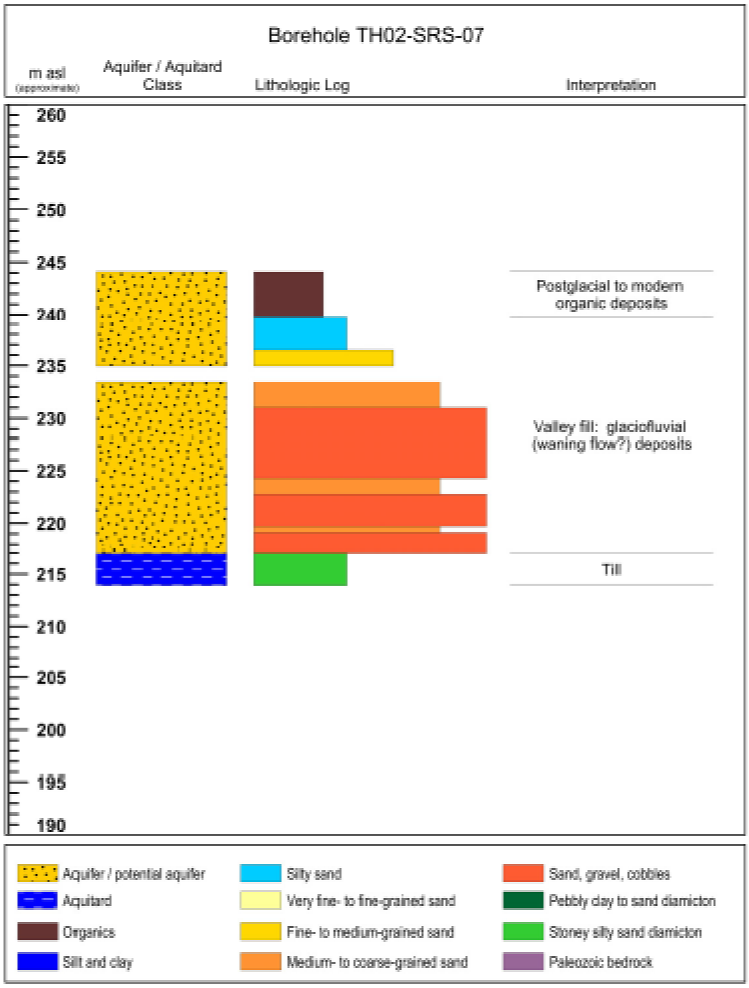
Borehole Records
(From Abigail Burt, personal communication).

Borehole ID: TH02-SRS-07
Location: 639773E 4898362N
Elevation: 244 m asl (+/- 5m)
Type: Mud Rotary

Well Tag: A044224

Construction Record: Casing
Inside Diameter: 7.5 cm
Material: PVC
Wall Thickness: Schedule 40
Depth: 0 - 14.4, 17.4 - 30.2 mbgl

Construction Record: Screen
Outside Diameter: 7.5 cm
Material: PVC
Slot No.: 0.10
Depth: 14.4 - 17.4 mbgl



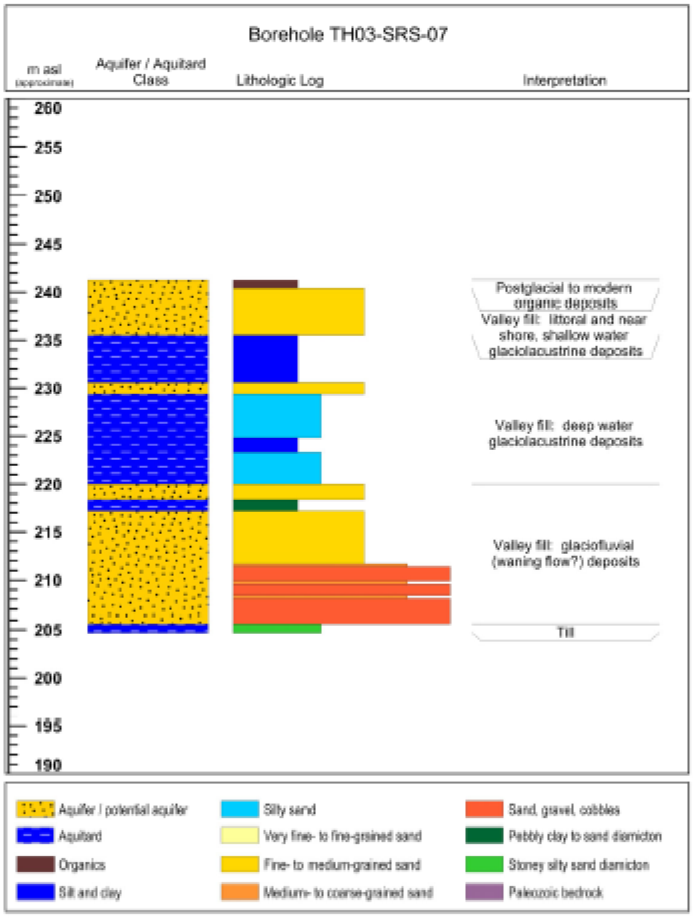
Depth (m)		Colour	Lithology	Additional Notes
0.00	4.30	black	muck and peat	
4.30	5.20	brown/grey	silty fine-grained sand	
5.20	7.62	brown/grey	rhythmically bedded silty fine-grained sand and silts	
7.62	9.14	grey	fine- to medium-grained sand	
10.67	12.19	brown	medium- to coarse-grained sand	
12.19	13.11	light brown	coarse- to very coarse-grained sand with pebbles	
13.11	19.81	brown	boulder gravel	mud loss (~40 - 50 IGPM)
19.81	21.34	brown	medium- to coarse-grained sand	mud loss (~70 IGPM)
21.34	24.38	brown	boulder gravel	
24.38	24.99	brown	medium- to coarse-grained sand	
24.99	27.13	brown	boulder gravel	mud loss (~70 IGPM)
27.13	30.20	brown	stoney silty sand till	

Borehole ID: TH03-SRS-07
Location: 639524E 4893782N
Elevation: 241 m asl (+/- 5m)
Type: Mud Rotary

Well Tag: A044228

Construction Record: Casing
Inside Diameter: 7.5 cm
Material: PVC
Wall Thickness: Schedule 40
Depth: 0 – 26.5 mbgl

Construction Record: Screen
Outside Diameter: 7.5 cm
Material: PVC
Slot No.: 0.10
Depth: 26.5 – 29.5 mbgl



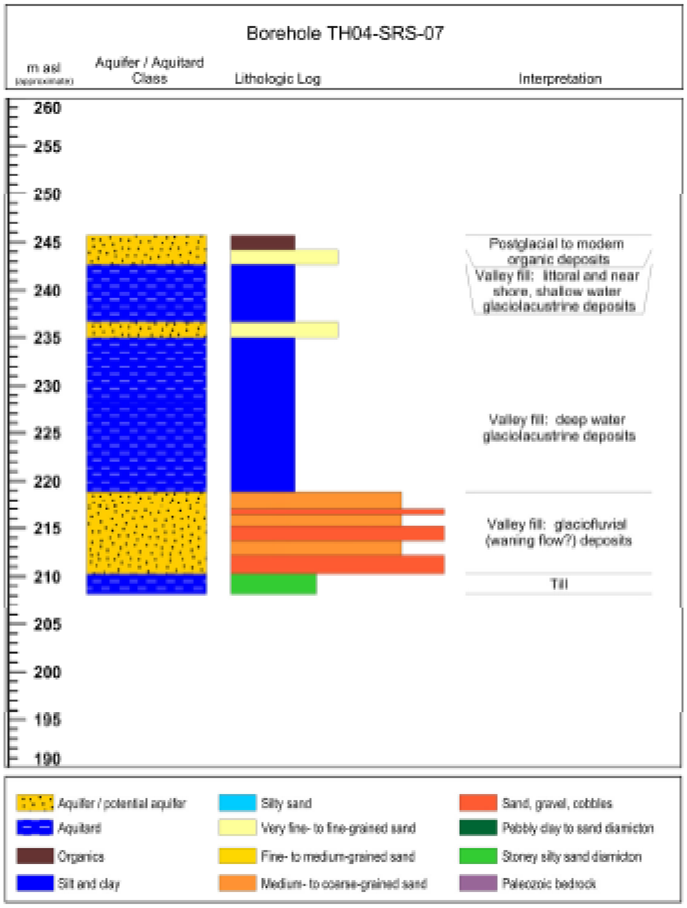
Depth (m)		Colour	Lithology	Additional Notes
0.00	0.91	black	muck and peat	
0.91	5.79	dark brown	fine- to medium-grained sand	
5.79	10.67	grey	rhythmically bedded silt and clay	
10.67	11.89	light brown	fine- to medium-grained sand	
11.89	16.46	light brown	silty fine- to medium-grained sand	
16.46	17.98	light grey	rhythmically bedded silt and clay	
17.98	21.03	light grey	silty fine- to medium-grained sand	
21.03	21.34	light brown	silty fine- to medium-grained sand	
21.34	22.86	light brown	fine- to medium-grained sand	
22.86	24.08	light brown	pebbly, silty, clayey sand diamicton	possible debris flow
24.08	29.57	light brown	fine- to medium-grained sand	
29.57	29.87	brown	medium-grained sand	
29.87	31.39	grey	cobble gravel (matrix - very coarse sand)	
31.39	31.70	brown	medium- to coarse-grained sand	
31.70	32.92	grey	cobble gravel (matrix - very coarse sand)	
32.92	33.22	brown	medium- to coarse-grained sand	
33.22	35.66	grey	cobble gravel (matrix - very coarse-grained sand)	
35.66	36.60	brown	stoney silty sand till	

Borehole ID: TH04-SRS-07
Location: 639443E 4893753N
Elevation: 246 m asl (+/- 5m)
Type: Mud Rotary

Well Tag: A044229

Construction Record: Casing
Inside Diameter: 7.5 cm
Material: PVC
Wall Thickness: Schedule 40
Depth: 0 – 33.6 mbgl

Construction Record: Screen
Outside Diameter: 7.5 cm
Material: PVC
Slot No.: 0.10
Depth: 33.6 – 36.6 mbgl



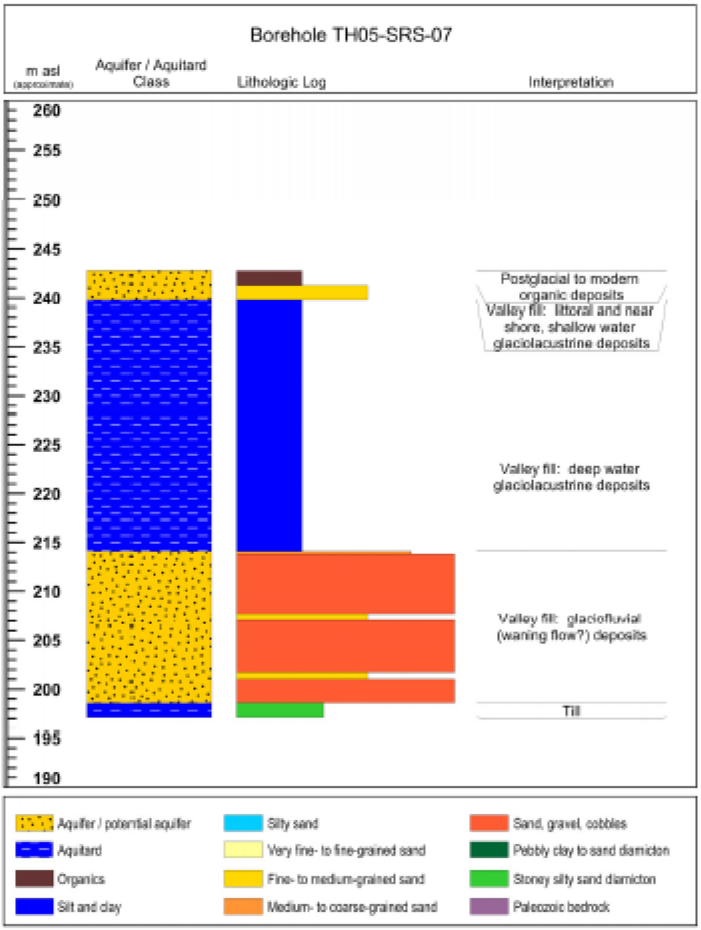
Depth (m)		Colour	Lithology	Additional Notes
0.00	1.52	brown/black	muck and peat	
1.52	3.05	brown	very fine- to fine-grained sand	
3.05	9.14	grey	rhythmically bedded silt and clay	
9.14	10.67	brown	very fine- to fine-grained sand	
10.67	21.34	grey	rhythmically bedded silt and clay	
21.34	26.80	light grey	rhythmically bedded silt and clay	
26.80	28.65	light brown	pebbly medium-grained sand	
28.65	29.26	light brown	cobble gravel (matrix - very coarse-grained sand)	
29.26	30.48	light brown	pebbly medium- to very coarse-grained sand	
30.48	32.00	light brown	cobble gravel (matrix - very coarse-grained sand)	mud loss (~40 IGM)
32.00	33.53	light brown	pebbly medium- to very coarse-grained sand	
33.53	35.40	light brown	cobble gravel (matrix - very coarse-grained sand)	
35.40	37.50	brown	stoney silty sand till	

Borehole ID: TH05-SRS-07
Location: 639464E 4893759N
Elevation: 243 m asl (+/- 5m)
Type: Mud Rotary

Well Tag: A044225

Construction Record: Casing
Inside Diameter: 7.5 cm
Material: PVC
Wall Thickness: Schedule 40
Depth: 0 – 33.6, 36.6 – 45.5 mbgl

Construction Record: Screen
Outside Diameter: 7.5 cm
Material: PVC
Slot No.: 0.10
Depth: 33.6 – 36.6 mbgl



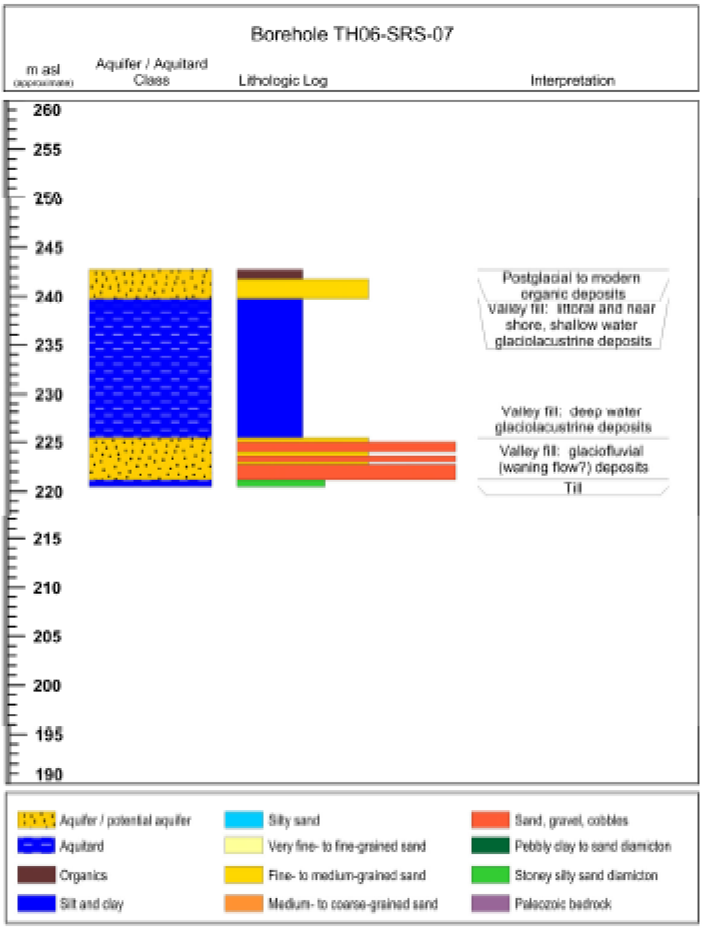
Depth (m)		Colour	Lithology	Additional Notes
0.00	1.52	black	muck and peat	
1.52	3.05	brown	fine- to medium-grained sand	
3.05	5.49	brown	rhythmically bedded silt and clay	
5.49	18.29	grey	rhythmically bedded silt and clay	
18.29	24.38	light grey	rhythmically bedded silt and clay	
24.38	24.99	light brown	rhythmically bedded silt and clay	
24.99	28.65	light grey	rhythmically bedded silt and clay	
28.65	28.96	grey	pebbly medium-grained sand	
28.96	35.05	grey	cobble gravel (matrix - very coarse-grained sand)	
35.05	35.66	grey	fine- to medium-grained sand	
35.66	41.15	grey	cobble gravel (matrix - very coarse-grained sand)	mud loss (~50 IGPM)
41.15	41.76	grey	fine- to medium-grained sand	
41.76	44.20	grey	cobble gravel (matrix - very coarse-grained sand)	mud loss (~50 IGPM)
44.20	45.72	brown	stoney silty sand till	

Borehole ID: TH06-SRS-07
Location: 639491E 4893766N
Elevation: 243 m asl (+/- 5m)
Type: Mud Rotary

Well Tag: A044226

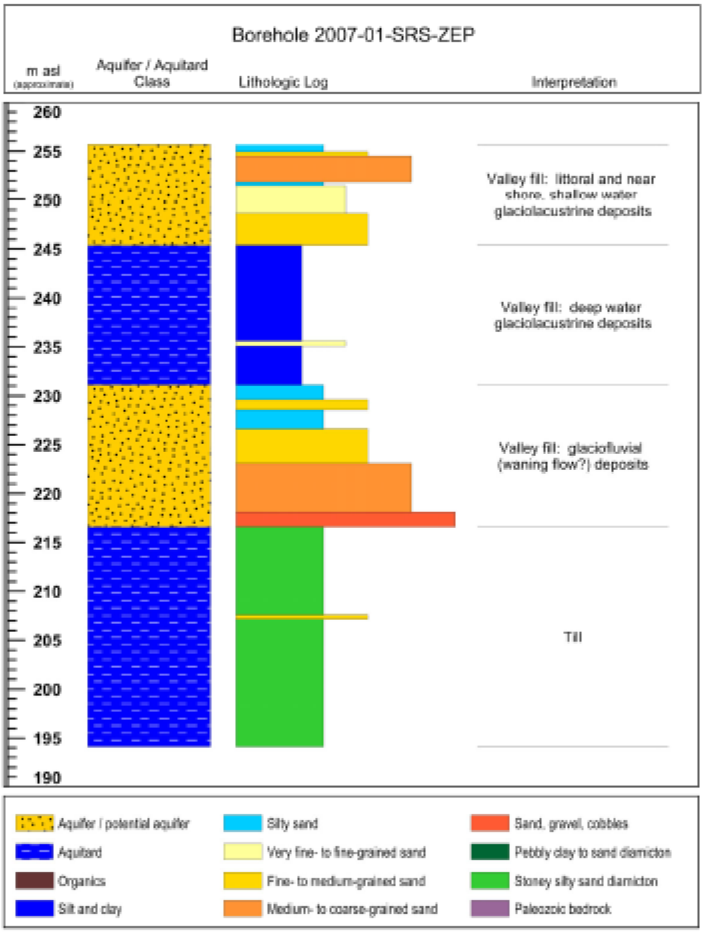
Construction Record: Casing
Inside Diameter: 7.5 cm
Material: PVC
Wall Thickness: Schedule 40
Depth: 0 – 18.3 mbgl

Construction Record: Screen
Outside Diameter: 7.5 cm
Material: PVC
Slot No.: 0.10
Depth: 18.3 – 19.8 mbgl



Depth (m)		Colour	Lithology
0.00	1.01	black	muck and peat
1.01	3.05	brown	fine- to medium-grained sand
3.05	5.49	brown	rhythmically bedded silt and clay
5.49	6.23	grey	rhythmically bedded silt and clay
6.23	17.40	light grey/white	rhythmically bedded silt and clay
17.40	17.80	brown	fine- to medium-grained sand
17.80	18.80	brown	cobble gravel (matrix - very coarse-grained sand)
18.80	19.20	brown	fine- to medium-grained sand
19.20	19.80	brown	cobble gravel (matrix - very coarse-grained sand)
19.80	20.10	light brown	fine- to medium-grained sand
20.10	21.60	light grey	cobble gravel (matrix - very coarse-grained sand)
21.60	22.30	brown	stoney silty sand till

Borehole ID: 2007-01-SRS-ZEP
Location: Ashworth Road
Elevation: 256 m asl (+/- 5m)
Type: Continuously cored



Depth (m)		Colour	Lithology
0.000	0.732	dark brown	silty sand
0.732	1.189	light brown/yellow	fine- to medium-grained sand
1.189	3.840	light brown	medium-grained sand
3.840	4.191	brown	silty fine- to medium-grained sand
4.191	7.041	light brown	fine-grained sand
7.041	10.287	light brown	fine- to medium-grained sand
10.287	20.090	light to dark grey	rhythmically bedded silt and clay
20.090	20.590	light brown	fine-grained sand
20.590	24.590	light to dark grey	rhythmically bedded silt and clay
24.590	26.090	dark brown	silty fine- to medium-grained sand
26.090	27.090	light to dark brown	fine- to medium-grained sand
27.090	29.090	dark brown	silty fine- to medium-grained sand
29.090	32.590	dark brown	fine- to medium-grained sand (rare pebbles)
32.590	37.590	light to dark yellow/brown	coarse pebbly sand
37.590	39.090	light yellow	cobble gravel (matrix - very coarse-grained sand)
39.090	48.070	light to dark brown	overconsolidated silty sand, stone rich till
48.070	48.530	light brown	fine- to medium-grained sand
48.530	61.580	light to dark brown	overconsolidated silty sand, stone rich till

Appendix B

Unprocessed Geophysical Results (Ground Seismic)

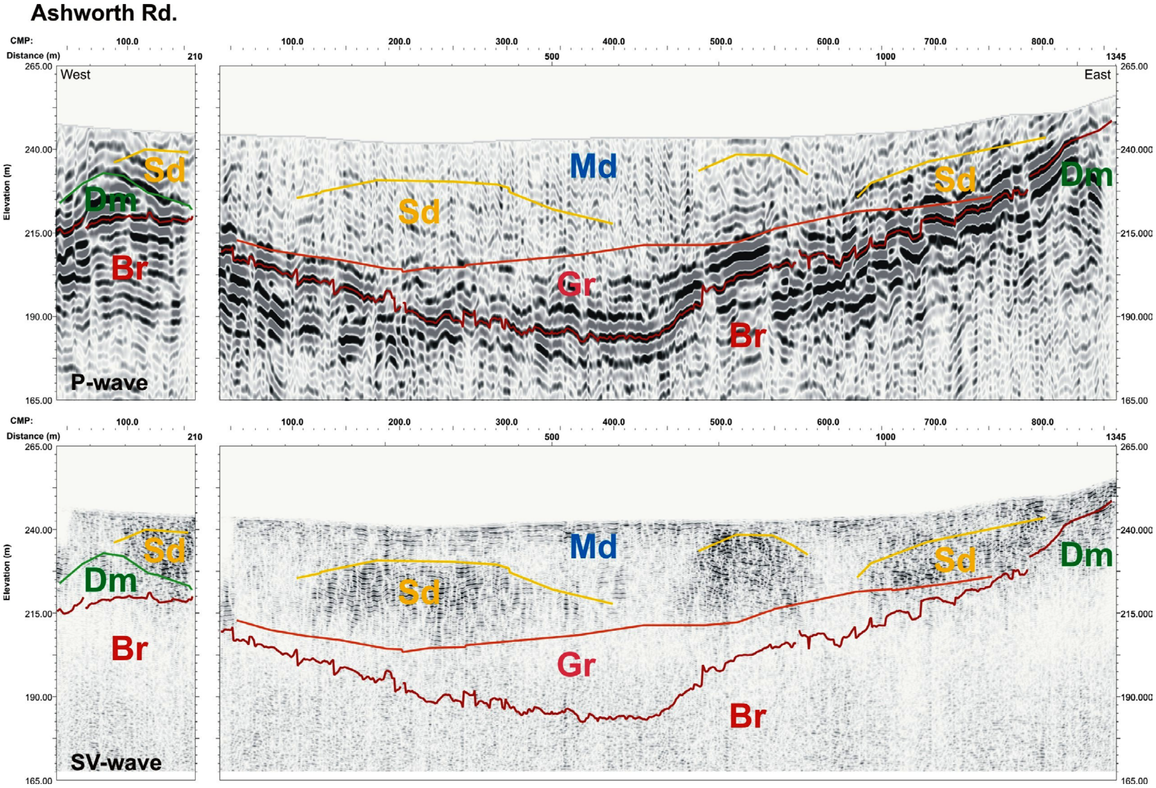


Figure B.1. Ashworth Road unprocessed seismic profile with preliminary interpretations. Letter code Md indicates mud, Sd indicates sand, Dm indicates till and Br indicates bedrock.

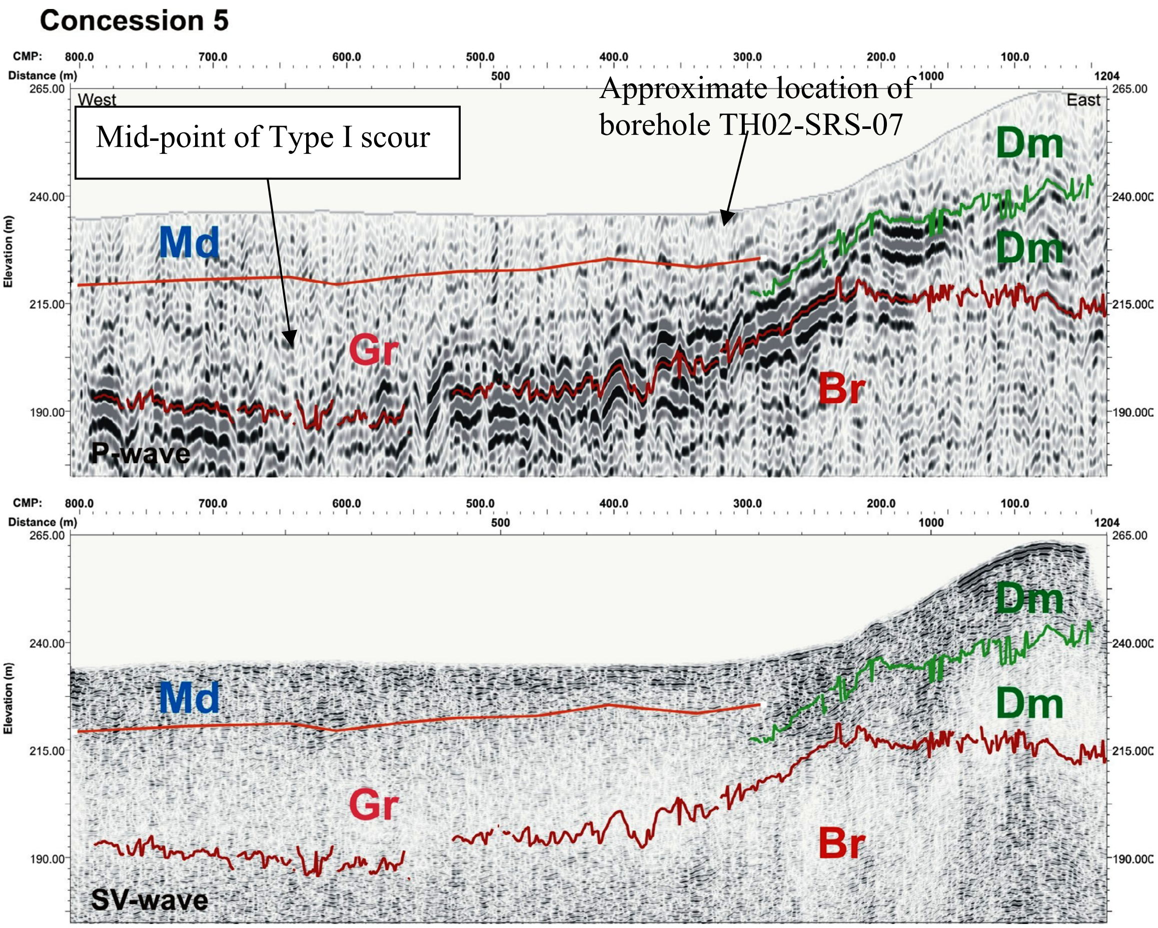


Figure B.2. Brewster Road/Concession 5 unprocessed seismic profile with preliminary interpretations. Letter code Md indicates mud, Dm indicates till and Br indicates bedrock.

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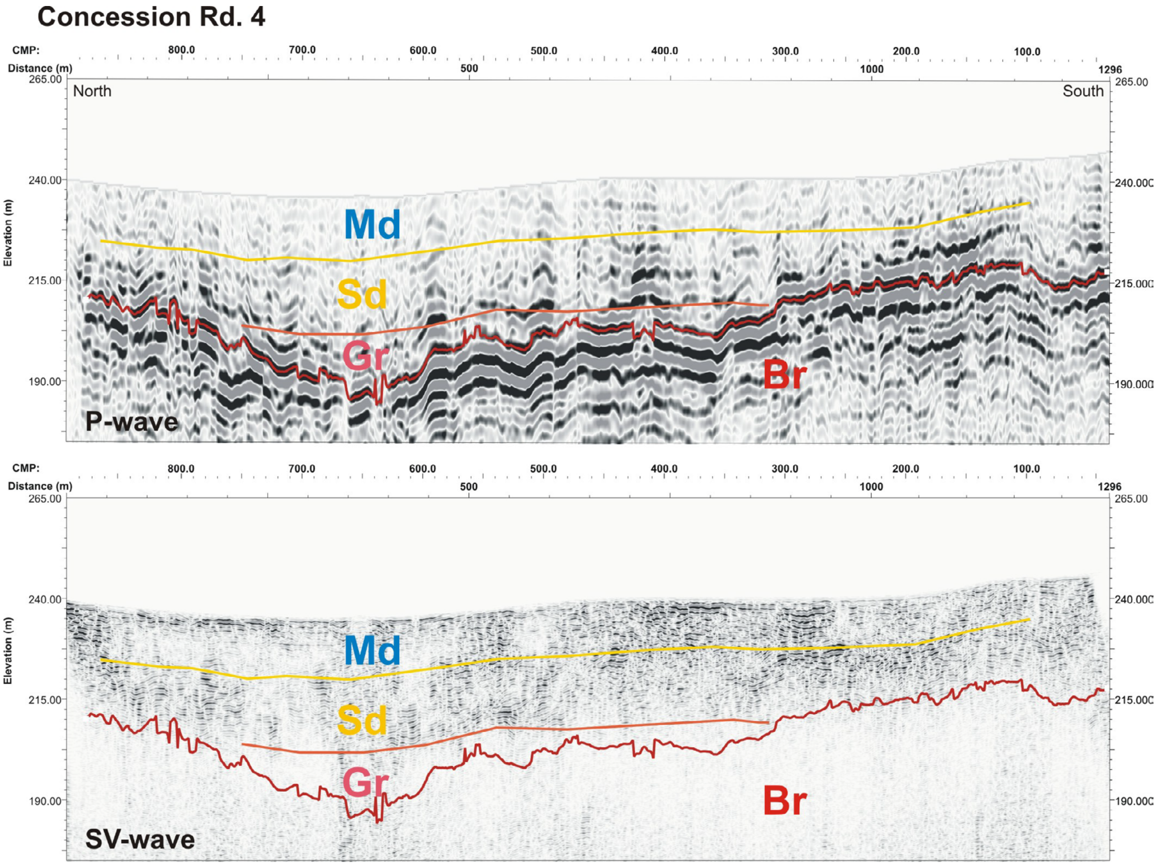

Figure B.3. Concession 4 unprocessed seismic profile with preliminary interpretations. Letter code Md indicates mud, Sd indicates sand, Gr indicates gravel and Br indicates bedrock.

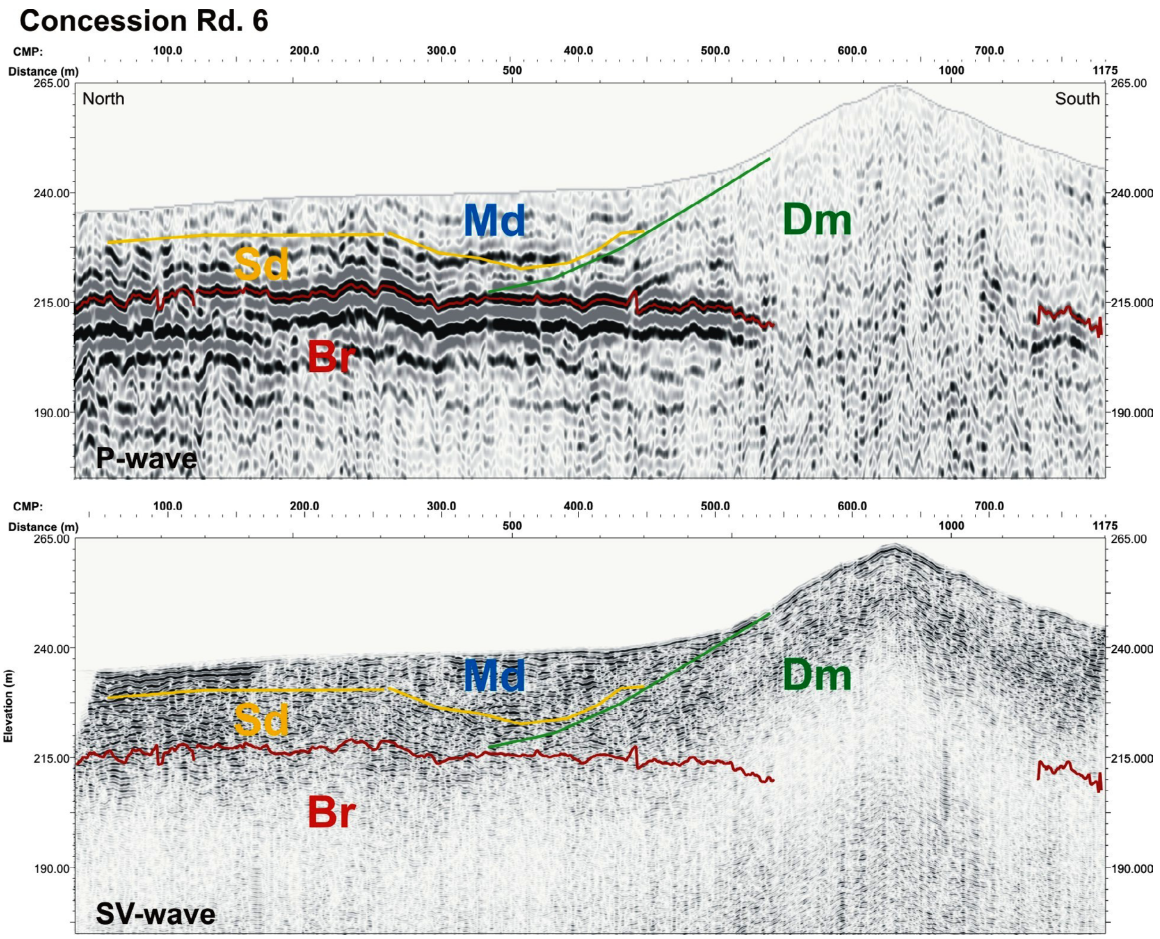

Figure B.4. Concession 6 unprocessed seismic profile with preliminary interpretations. Letter code Md indicates mud, Sd indicates sand, Dm indicates till and Br indicates bedrock.

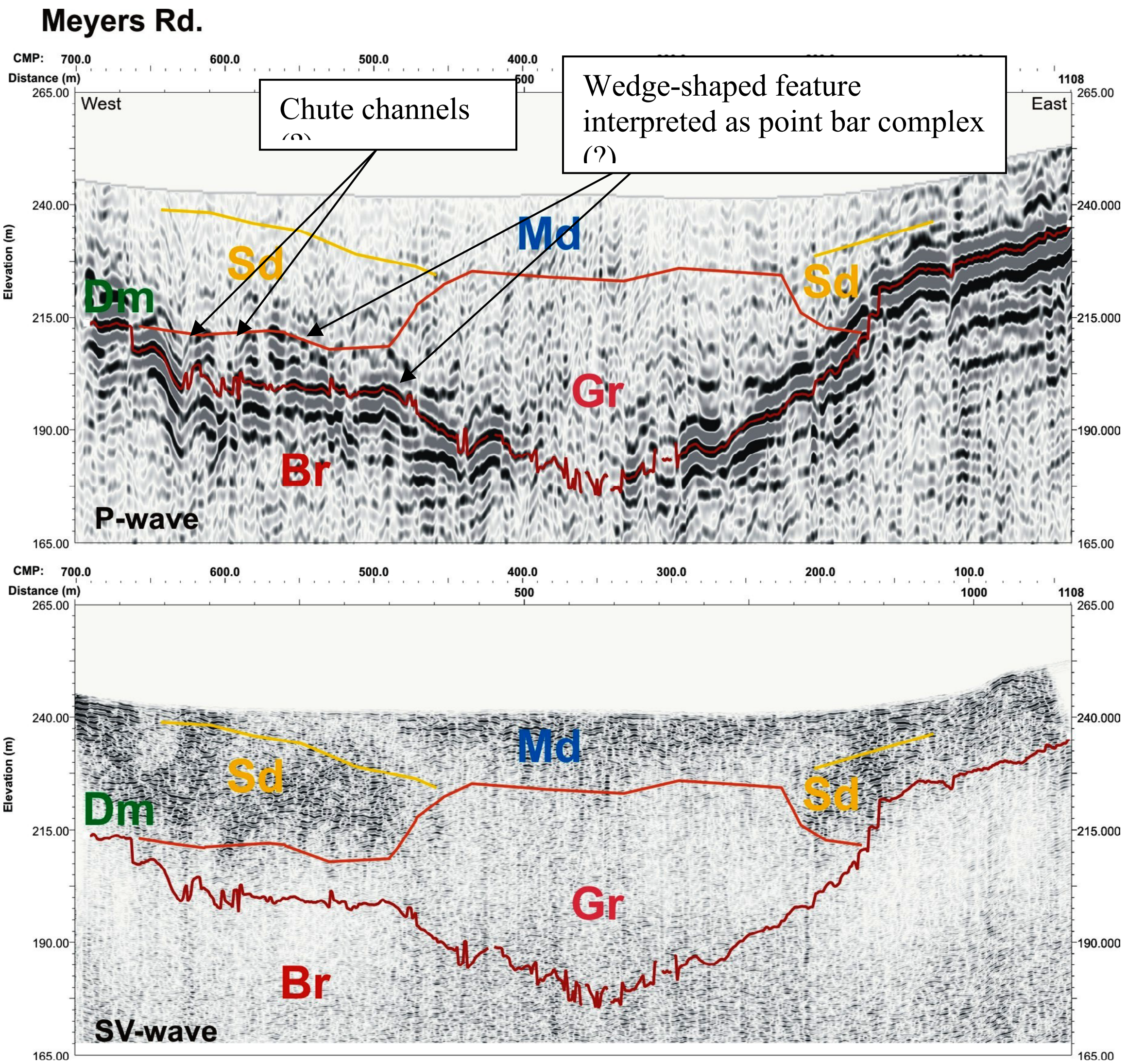

Figure B.5. Meyers Road unprocessed seismic profile with preliminary interpretations. Letter code Md indicates mud, Sd indicates sand, Gr indicates gravel and Dm indicates till and Br indicates bedrock. Step-sided semi-continuous reflectors interpreted as chute-channels that appear to incise top of wedge-shaped feature interpreted as point bar complex (?).

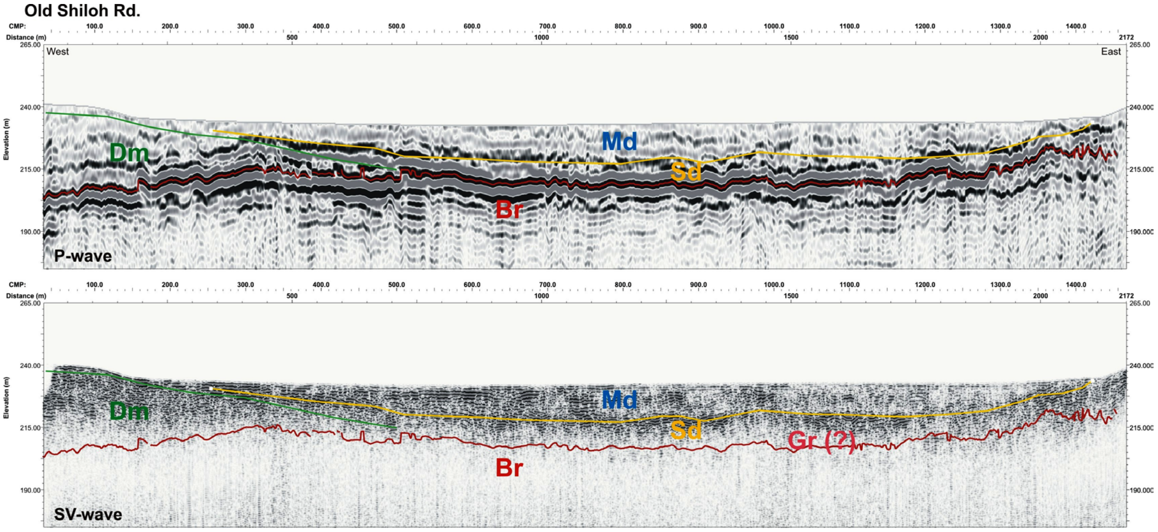

Figure B.6. Old Shiloh Road unprocessed seismic profile with preliminary interpretations. Letter code Md indicates mud, Sd indicates sand, Gr indicates gravel and Dm indicates till and Br indicates bedrock.

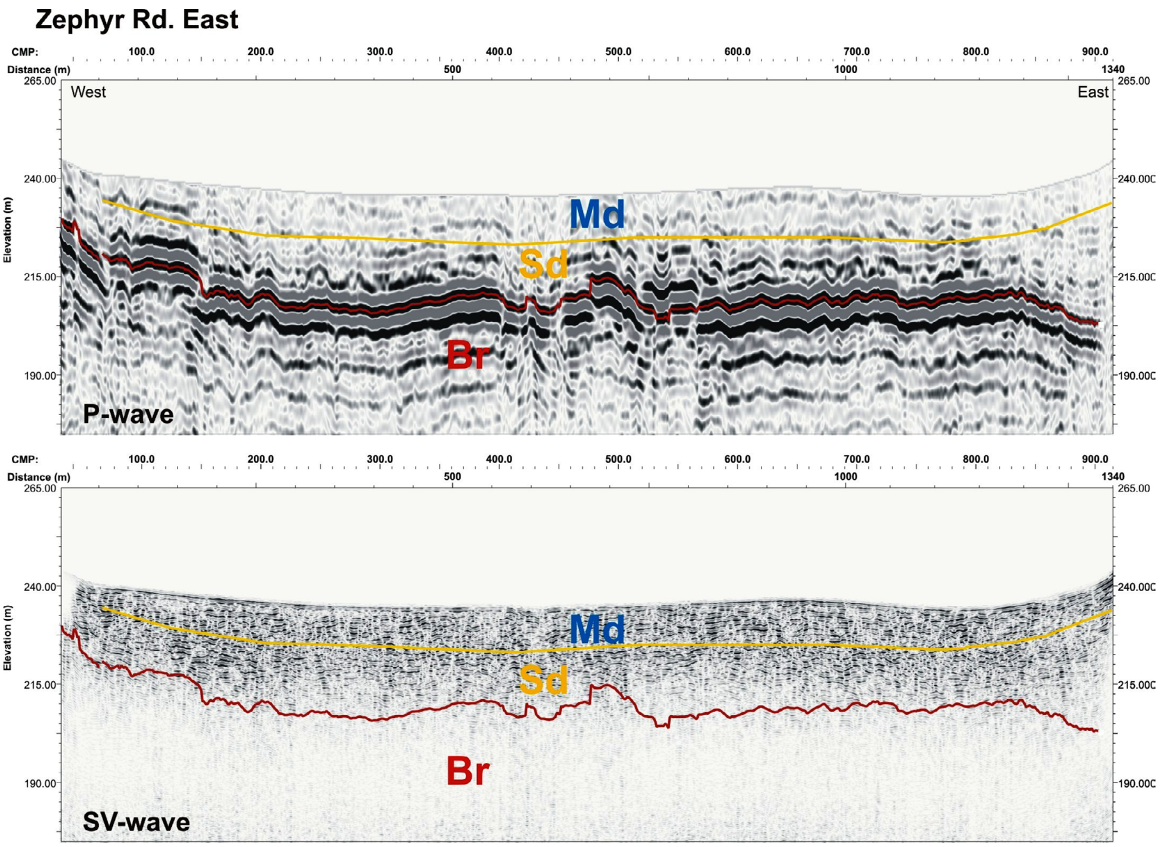

Figure B.7. Zephyr Road East unprocessed seismic profile with preliminary interpretations. Letter code Md indicates mud, Sd indicates sand, Dm indicates till and Br indicates bedrock.

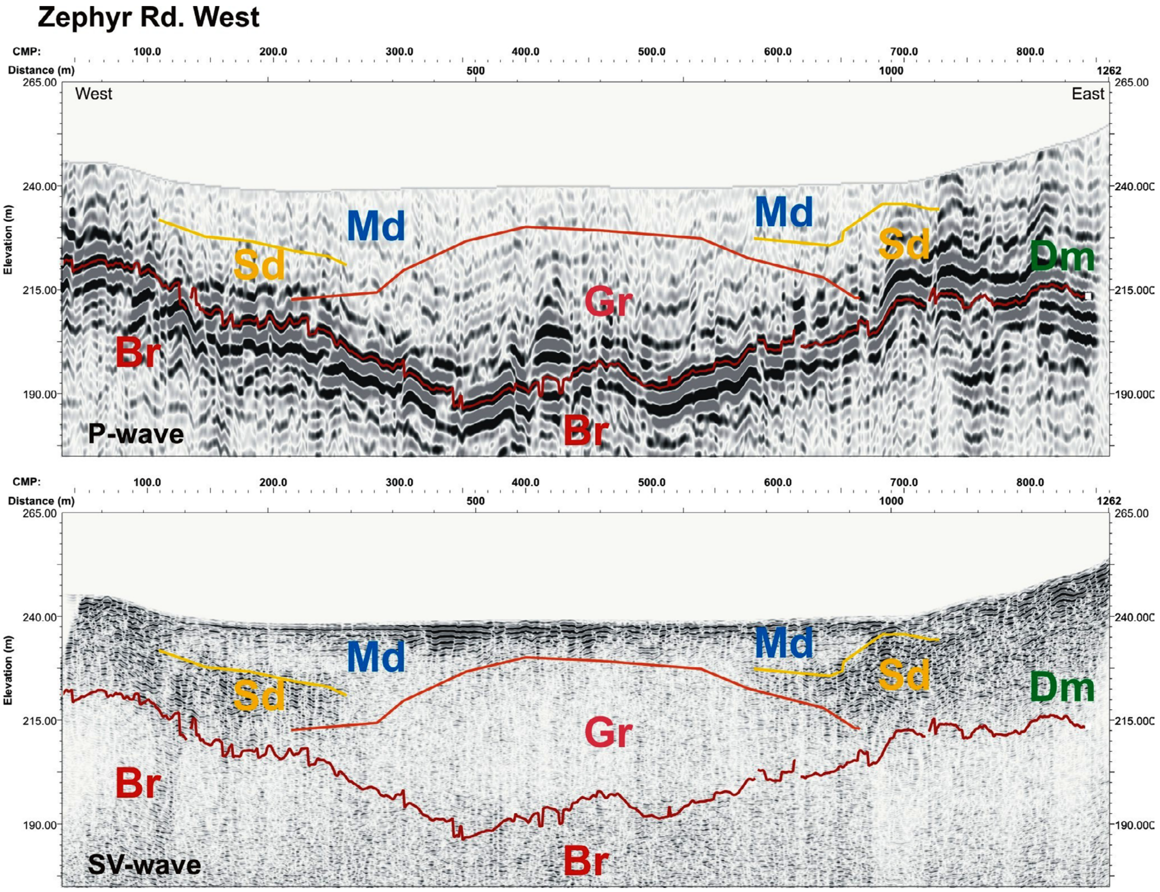

Figure B.8. Zephyr Road West unprocessed seismic profile with preliminary interpretations. Letter code Md indicates mud, Sd indicates sand, Gr indicates gravel, Dm indicates till and Br indicates bedr