Natural Resources Canada / Ressources naturelles Canada

Helicopter time-domain electromagnetic data over the Eastern Hatfield buried-valley aquifer system, Saskatchewan

G.A. Oldenborger, D.R. Sharpe, A.J.-M. Pugin, and H.A.J. Russell

Geological Survey of Canada
Current Research 2013-13

2013

Canada

Geological Survey of Canada
Current Research 2013-13

Helicopter time-domain electromagnetic data over the Eastern Hatfield buried-valley aquifer system, Saskatchewan

G.A. Oldenborger, D.R. Sharpe, A.J.-M. Pugin, and H.A.J. Russell

2013

©Her Majesty the Queen in Right of Canada 2013

ISSN 1701-4387
Catalogue No. M44-2013/13E-PDF
ISBN 978-1-100-22214-1
doi: 10.4095/292517

A copy of this publication is also available for reference in depository libraries across Canada through access to the Depository Services Program's Web site at http://dsp-psd.pwgsc.gc.ca

This publication is available for free download through GEOSCAN http://geoscan.ess.nrcan.gc.ca

Recommended citation

Oldenborger, G.A., Sharpe, D.R., Pugin, A.J.-M., and Russell, H.A.J., 2013. Helicopter time-domain electromagnetic data over the Eastern Hatfield buried-valley aquifer system, Saskatchewan; Geological Survey of Canada, Current Research 2013-13, 15 p. doi:10.4095/292517

Critical review

P. Keating

Authors

G.A. Oldenborger ***(Greg.Oldenborger@NRCan-RNCan.gc.ca)***
D.R. Sharpe ***(David.Sharpe@NRCan-RNCan.gc.ca)***
A.J.-M. Pugin ***(Andre.Pugin@NRCan-RNCan.gc.ca)***
H.A.J. Russell ***(Hazen.Russell@NRCan-RNCan.gc.ca)***
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E9

Correction date:

All requests for permission to reproduce this work, in whole or in part, for purposes of commercial use, resale, or redistribution shall be addressed to: Earth Sciences Sector Copyright Information Officer, Room 622C, 615 Booth Street, Ottawa, Ontario K1A 0E9.
E-mail: ESSCopyright@NRCan.gc.ca

Helicopter time-domain electromagnetic data over the Eastern Hatfield buried-valley aquifer system, Saskatchewan

G.A. Oldenborger, D.R. Sharpe, A.J.-M. Pugin, and H.A.J. Russell

Oldenborger, G.A., Sharpe, D.R., Pugin, A.J.-M., and Russell, H.A.J., 2013. Helicopter time-domain electromagnetic data over the Eastern Hatfield buried-valley aquifer system, Saskatchewan; Geological Survey of Canada, Current Research 2013-13, 15 p. doi:10.4095/292517

Abstract: Buried-valley aquifers occur across the Canadian Prairies with a lack of surface expression and complicated network geometries. As part of an effort to map and characterize the Hatfield buried-valley aquifer, the Geological Survey of Canada commissioned a helicopter time-domain electromagnetic survey consisting of 2617 line-km of data over 940 km^2 near Esterhazy and Rocanville in southeastern Saskatchewan. Survey results are presented as apparent-conductivity maps and as 3D conductivity-depth models. The Hatfield and Rocanville buried valleys are clearly imaged along with several other erosional and depositional features, some of which have been previously identified at the local scale and are currently utilized as groundwater resources, but for which the extent has not been fully mapped. Other features identified in the survey represent potentially new groundwater resources and can be used to help unravel the details of valley formation, groundwater flow, and aquifer recharge.

Résumé : Des aquifères de vallées enfouies sont présents un peu partout dans les Prairies canadiennes et constituent des réseaux à géométrie complexe sans aucune expression en surface. Dans le cadre d'efforts en vue de cartographier et de caractériser l'aquifère de vallée enfouie Hatfield, la Commission géologique du Canada a commandé un levé électromagnétique dans le domaine du temps par hélicoptère au cours duquel on a recueilli des données sur une distance linéaire totale de 2 617 km dans un territoire de 940 km^2 près d'Esterhazy et de Rocanville, dans le sud-est de la Saskatchewan. Les résultats du levé sont présentés sous forme de cartes de la conductivité apparente et de modèles 3D de la relation conductivité-profondeur. On a obtenu des images claires des vallées enfouies Hatfield et Rocanville ainsi que de plusieurs autres entités érosives ou sédimentaires, certaines étant déjà connues et exploitées comme source d'eau souterraine localement, mais dont l'étendue complète n'avait jamais été cartographiée. D'autres entités identifiées au cours du levé constituent de nouvelles sources d'eau souterraine potentielles et nous permettent d'obtenir une représentation plus précise de la formation des vallées, de l'écoulement de l'eau souterraine et de la recharge des aquifères.

INTRODUCTION

Buried-valley aquifers occur across the Canadian Prairies within coarse-grained, permeable sediments that infill bedrock- and sediment-hosted valleys. Lack of surface expression and complicated network geometries make characterization of the aquifer systems difficult with sparse data (e.g. Jørgensen and Sandersen, 2009; van der Kamp and Maathuis, 2012). Tasked with better mapping and characterization of buried-valley aquifer systems, the Geological Survey of Canada and the Saskatchewan Research Council conducted a workshop with prairie partners the Saskatchewan Watershed Authority, Environment Canada, the Saskatchewan Ministry of Environment, the Saskatchewan Geological Survey, and other parties from the U.S. government, industry, consulting, and academia. The result was articulation of the objective to focus research on methods that would improve existing geological and hydrogeological frameworks for buried valleys. In particular, the intent was to build a detailed integrated understating for a portion of the Hatfield buried-valley aquifer where the value of existing data could be leveraged via integration and groundtruthing.

In the vicinity of the Hatfield buried valley, a rich geological and geophysical dataset exists from potash exploration, although much of it is proprietary and focuses on deep resource targets (Fuzesy, 1982). Geological and geophysical data have been collected in exploration for groundwater required for resource extraction and processing (B. Siguardson, Saskatchewan Ministry of the Environment, pers. comm.). However, these data are again often propriety and are not focused on the regional buried-valley aquifer system, but rather, on localized groundwater potential (Maathuis, 2002) or groundwater monitoring (MDH Engineered Solutions Corp., 2008).

As part of the Groundwater Geoscience Program, the Geological Survey of Canada (GSC) commissioned a helicopter time-domain electromagnetic (HTEM) survey over an eastern portion of the Hatfield buried-valley aquifer system near Esterhazy and Rocanville in southeastern Saskatchewan to complement existing data and as part of efforts to develop techniques of multi-scale integrated geophysical and geological aquifer characterization (e.g. Oldenborger et al., 2012). With the goal of regional characterization of the eastern Hatfield buried valley aquifer system, the GSC HTEM survey was planned with the objective of mapping the sedimentary deposits and bedrock to a depth of approximately 150 m over 940 km^2. Targets included the conductive shale-bedrock surface, erosional valleys, discrimination of the sedimentary strata and valley-fill materials and detection of previously mapped and unmapped buried valleys. Survey results are presented as apparent-conductivity maps and as three-dimensional conductivity-depth models that illustrate a variety of erosional and sedimentary features including the Hatfield and Rocanville buried valleys along with several other smaller scale valley features.

GEOLOGICAL SETTING

Poorly consolidated Cretaceous shale and minor sandstone form the main bedrock substrate of Prairie buried valleys; the bedrock surface is incised by a network of buried valleys that trend eastward and northwestward (Maathuis and Thorleifson, 2000). A glacial succession fills and buries most of these valleys and is composed predominantly of diamicton up to 300 m thick (Cummings et al., 2012). The Hatfield buried valley is a 900 km long valley that traverses Saskatchewan from the east to the northwest, eroded into Upper Cretaceous age bedrock composed of clays and silts of the Pierre Shale, Lea Park, Judith River, and Bearpaw formations (Simpson and Schreiner, 1999). The regional bedrock geology dips gently southwest toward the Rocky Mountains. The Hatfield buried valley trends generally with the structural dip of the bedrock in the east and northwest regions, but with the strike of the bedrock in the central region (Cummings et al., 2012).

The eastern Hatfield buried valley is eroded into the Pierre Shale Formation and the unconformably overlying Tertiary Bredenbury Formation (Schreiner and Maathuis, 1982). The basal valley unconformity is overlain by discontinuous beds of preglacial and glacially sourced sand, silt, and gravel of the late Tertiary and early Quaternary Empress Group that are generally less than 50 m thick (Simpson and Schreiner, 1999) but can be up to 140 m thick (Millard, 1990). The Empress Group is overlain by glacial sediments belonging to the Sutherland and Saskatoon groups of till with inter-till sands and gravel that fill and bury the bedrock valley (Simpson and Schreiner, 1999). The Sutherland tills have lower carbonate contents, higher clay and lower sand contents, higher liquid limit, and lower electrical resistance than do the overlying Saskatoon tills (Christiansen, 1992). However, analysis based on water-well records is unable to differentiate the tills. Orientation against Tertiary drainage systems combined with the interpreted fill succession leads to a general interpretation of preglacial erosion and glacial-glaciofluvial fill for the Hatfield; however, its broad/shallow morphology and apparent lack of gradient complicate this interpretation (Cummings et al., 2012).

There is little reported data on the water chemistry from the bedrock beneath the Hatfield valley. In the Esterhazy area, Pierre Shale waters could be expected to be in excess of 10000 mg/L (MDH Engineered Solutions Corp., 2009). Within the Empress Group in the Lanigan and Fort Qu'Appelle area, groundwater chemistry is commonly of the sodium-sulphate type with concentrations ranging from approximately 1950–3000 mg/L (Maathuis, 1980). Potash mine site studies near Jansen yield TDS values for inter-till aquifers within the glacial stratigraphy of 681–2260 mg/L (Rescan Environmental Services Ltd., 2008) indicating relatively strong recharge with fresh surface waters. Within the upper Saskatoon Group tills, sulphate concentrations can be as high as 24 700 mg/L due to oxidation of pyrite; and within the Sutherland Group sands and gravels, chloride concentrations can range from

12 mg/L to over 30 000 mg/L; such locally elevated chloride levels indicate impact from mine activity (MDH Engineered Solutions Corp., 2009).

HTEM SURVEY

Data Acquisition

The Esterhazy-Rocanville HTEM survey was flown by Fugro Airborne Surveys from March 6 to 24, 2011 utilizing a HeliTEM system (Hefford et al., 2012a–f). The survey was flown in three blocks and consists of 2617 line-km of data over 940 km^2 (Fig. 1). Block co-ordinates are given in Table 1 with the flight-line specifications given in Table 2. The helicopter was flown at approximately 82 m altitude towing the transmitting system with a mean terrain clearance of 35 m. Flight-line navigation was maintained using dual frequency GPS; deviations from the planned flight path were made at the sole discretion of the pilot as per Transport Canada regulations.

The HeliTEM system is designed for exploration for deep conductive mineralization targets (e.g. Mulè et al., 2012). System specifications are given in Table 3 and a schematic is shown in Figure 2. The transmitter waveform is a half-sinusoid. The three-component EM receiver measures the three orthogonal components of the change in magnetic field with respect to time (d**B**/d*t*) in both the on and off time. The off-time halfspace nomogram for the HeliTEM system is shown in Figure 3. The resistive, relatively shallow target objectives of the Esterhazy-Rocanville survey were addressed through a 90 Hz base frequency, a 2 ms on-time duration, and modification of the HeliTEM transmitter to include only two turns in the 708 m^2 transmitting loop for a dipole moment of approximately 1000 kAm^2. The reduction in the number of turns reduces the system power and self-induction, which allows better measurement of early-time gates with the earliest off-time gate (gate 5) being centred at 60 µs after turn off. Nevertheless, peak response for the HeliTEM system occurs at conductivities well above those for typical glacial sediments (Fig. 3).

Data acquisition, quality control, and processing were carried out by Fugro with GSC oversight. Additional processing, gridding, and mapping were carried out by the GSC. Processing flow for the TEM data was as follows: differential GPS correction and editing of elevation, altitude despiking, stacking and gating, spheric removal, coil pitch correction, noise (smoothing) filter, drift correction based on pre- and post-flight checks at high altitude, and line-based levelling. The final result is a three-component decay curve or 'sounding' approximately every 3 m along each flight line.

The resulting *z*-component decay curves were used to derive the electrical conductivity using Fugro's in-house procedure: 1) For the *i*th sounding and the *j*th time gate, the

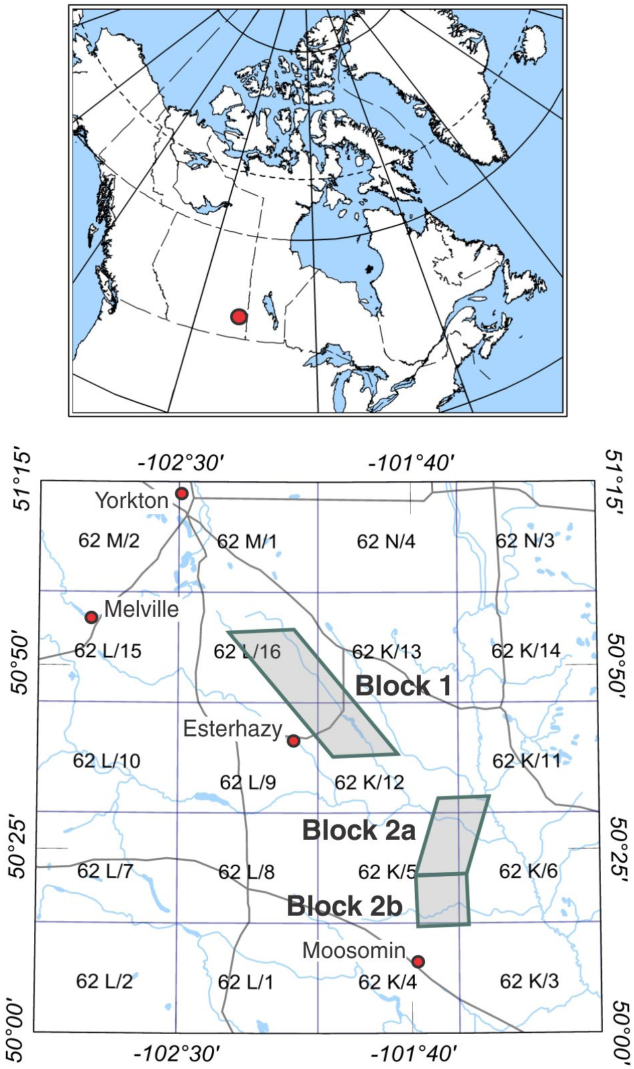


Figure 1. Map of the survey area illustrating Block 1 (Esterhazy) and Blocks 2a and 2b (Rocanville). Canada map shows survey location.

Table 1. Survey block corner co-ordinates, UTM NAD83 Zone 13N.

Block 1		Block 2a		Block 2b	
Esterhazy		Rocanville			
Easting (m)	Northing (m)	Easting (m)	Northing (m)	Easting (m)	Northing (m)
291600	5612600	311243	5581800	324143	5569000
266600	5645000	316400	5597000	311343	5569000
283100	5645000	329300	5597000	311343	5581800
308100	5612600	324143	5581800	324143	5581800

Table 2. Survey specifications.

	Block 1	Block 2a	Block 2b
Traverse-line azimuth	90°	90°	0°
Traverse-line spacing	400 m	400 m	400 m
Tie-line azimuth	142°	19°	90°
Tie-line spacing	5000 m	5000 m	5000 m
Area	535 km^2	245 km^2	164 km^2

Table 3. HeliTEM system specifications.

Data rate (Hz)	Survey speed (m/s)	Base frequency (Hz)	Pulse width (ms)	Off Time (ms)	MTC* (m)	Loop area (m^2)	Peak current (A)	Dipole moment (kAm^2)
10	30	90	2	3.5	35	708	706	1000

*Mean terrain clearance of transmitter

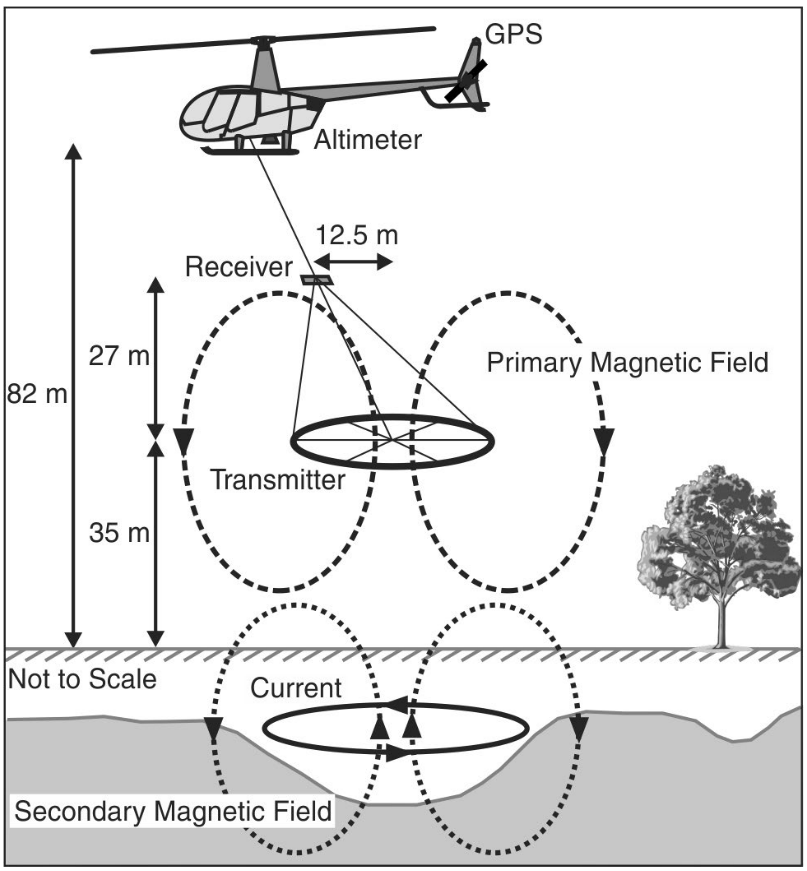


Figure 2. Schematic diagram of the HeliTEM system showing system components and geometry.

best-fit halfspace conductivity σ_{ij} is determined for the given system geometry and the measured $[dB_z/dt]_{ij}$. This is repeated for each sounding and every time gate. 2) For the jth time gate, the effective depth is computed using the skin depth (e.g. West and Macnae, 1991; Meju, 1998) as

$$\delta_{ij} = \sqrt{2 / \sigma_{ij}\mu\omega} \approx \sqrt{t_j / \sigma_{ij}\mu\pi}$$

where ω is the angular frequency and μ is the permeability of free space. Whereas the time gates are constant for all soundings, effective depth is not, due to its dependence on conductivity. 3) For each sounding, the apparent conductivity σ_a is computed as the average conductivity weighted by effective depth. The apparent conductivities for all soundings are gridded to 100 m × 100 m and result in a single mapped parameter over the survey area (e.g. Hefford et al., 2012a–f). The conductivity-depth information is converted to a series of conductivity-depth images (CDI) by interpolating σ_{ij} to regular 10 m depth intervals and then gridding in the horizontal direction to 100 m × 100 m. The images are combined to yield a 3D CDI model.

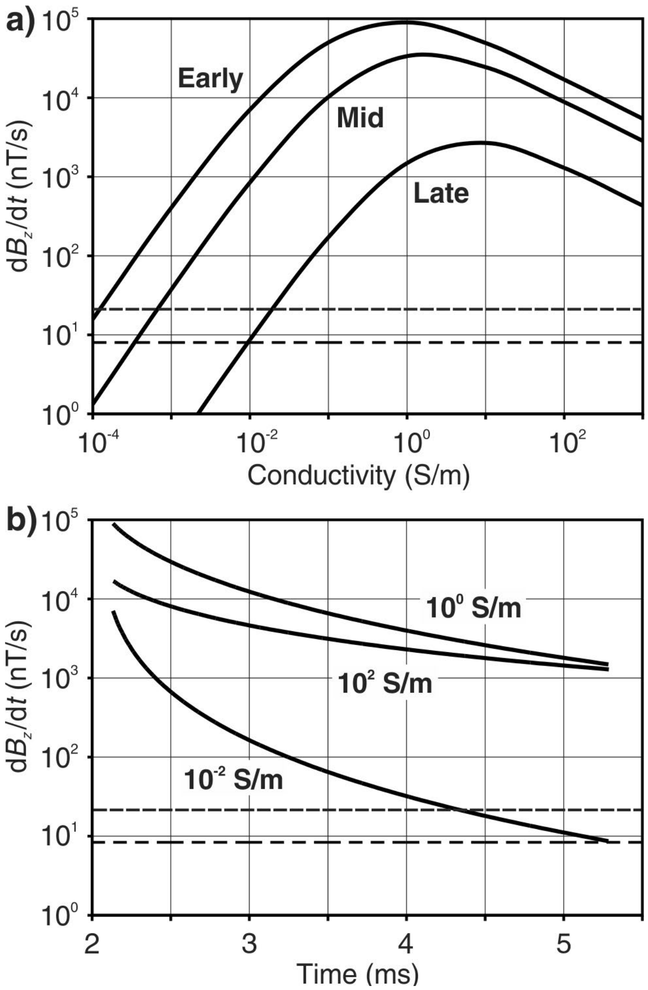


Figure 3. System response over a halfspace for the HeliTEM system with a 30 m diameter, 2-turn transmitter loop at 35 m height; the waveform is a 2 ms half-sinusoid with a peak current of 734 A. The response is computed using the method of Farquharson and Oldenburg (1993). **a)** Halfspace nomogram illustrating early-, mid- and late-time response at gate centres 5, 17, and 30 (60 µs, 370 µs, and 3212 µs after turn off). Gate 5 is the first off-time gate. **b)** Decay curves as a function of halfspace conductivity. The dashed lines represent the nominal (lower) noise level for the system and the practical (higher) noise level as determined from reference flights.

RESULTS

Apparent-conductivity maps for Blocks 1 (Esterhazy) and Blocks 2a and 2b (Rocanville) are shown in Figures 4 and 5. The approximate surface-elevation measurements obtained in-flight are shown as Figure 6. The EM response may include both natural and cultural contributions. The data have not been edited for cultural contributions before conversion to apparent conductivity, and the most obvious cultural response originates from the tailings management areas (TMA) associated with potash mining at Mosaic Potash Esterhazy's K1 and K2 mine sites (Fig 4) and PotashCorp's Rocanville mine site (Fig. 5). Other cultural response arises from coupling with road-based infrastructure and railways. Based on generic material conductivities (e.g. Palacky, 1988) and the descriptions by Christiansen (1992) we expect the geological response to be characterized by conductive shale bedrock, moderately conductive glacial till sequences, and less-conductive (resistive) sands and/or gravels.

Interpretation

Based on the apparent-conductivity maps (Fig. 4, 5) features evident in the eastern Hatfield HTEM dataset can be grouped into four general categories: 1) small-scale cultural effects, 2) significant cultural anomalies, 3) modern day fluvial systems, and 4) the near-surface geology to approximately 150 m depth. Firstly, small-scale cultural effects are visible mainly due to roads, railways, power lines, and other small-scale infrastructure. These features are typically linear, but may appear broken or 'boudinaged' due to flight-line aliasing and gridding artifacts, or they may appear as isolated conductive features due to variable system response. These features are most accurately identified using overlays of the EM response on cultural maps, or by examining the powerline monitor and flight video. In general, these features do not significantly affect the mapped apparent conductivity, but they are evident in the later-time data (and in the CDI at depth) and will likely be of concern for any attempt to invert the data. In contrast to small-scale cultural effects, significant cultural anomalies arise primarily due to the TMA associated with potash mining activity in the area. The TMA consist of salt piles and brine ponds that represent strong, large-scale conductors that dominate the apparent-conductivity maps with calculated conductivities of over 1700 mS/m that are off the scales of Figures 4 and 5.

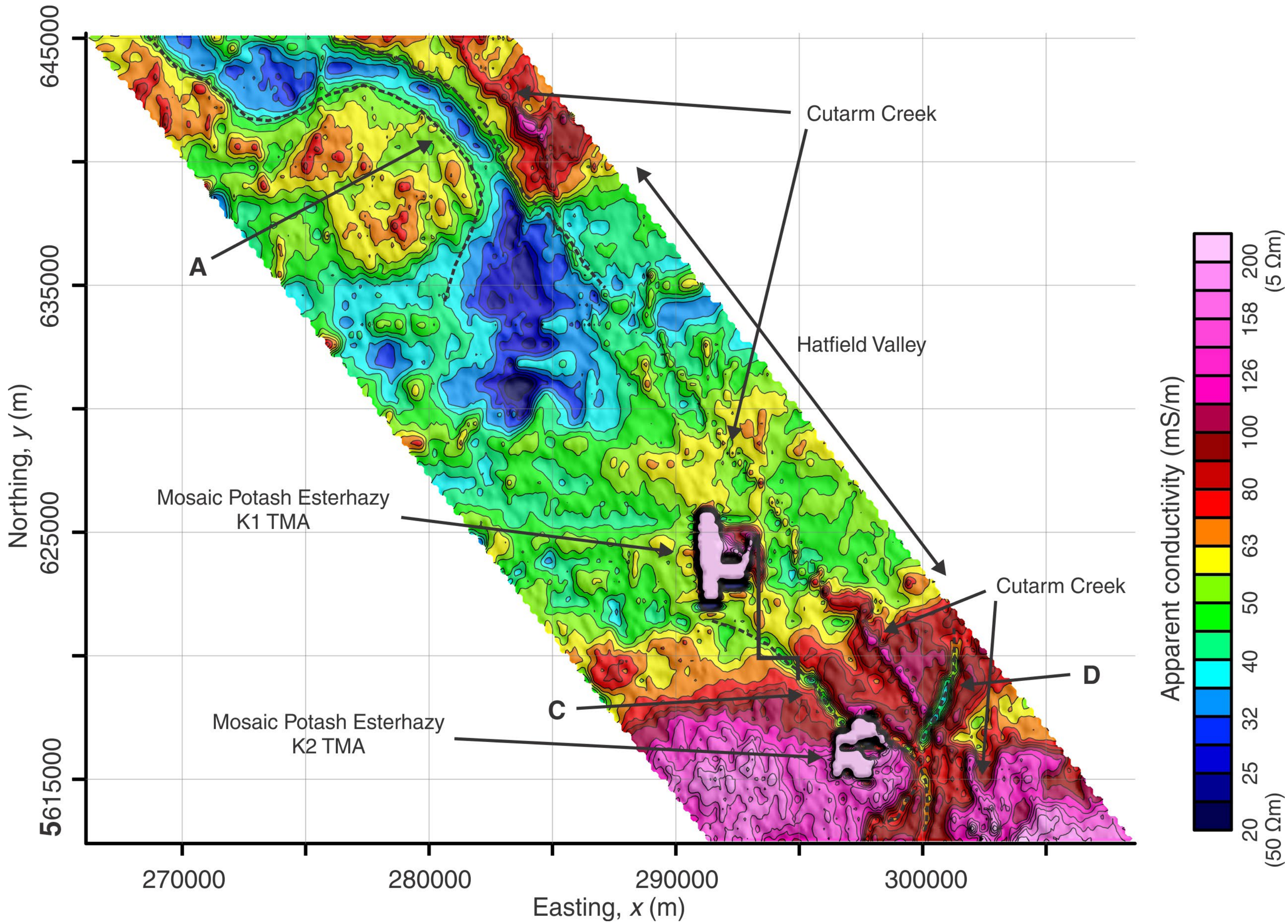


Figure 4. Apparent conductivity map for Block 1, Esterhazy. Solid black line indicates location of seismic section. Features A, C and D are discussed in the text.

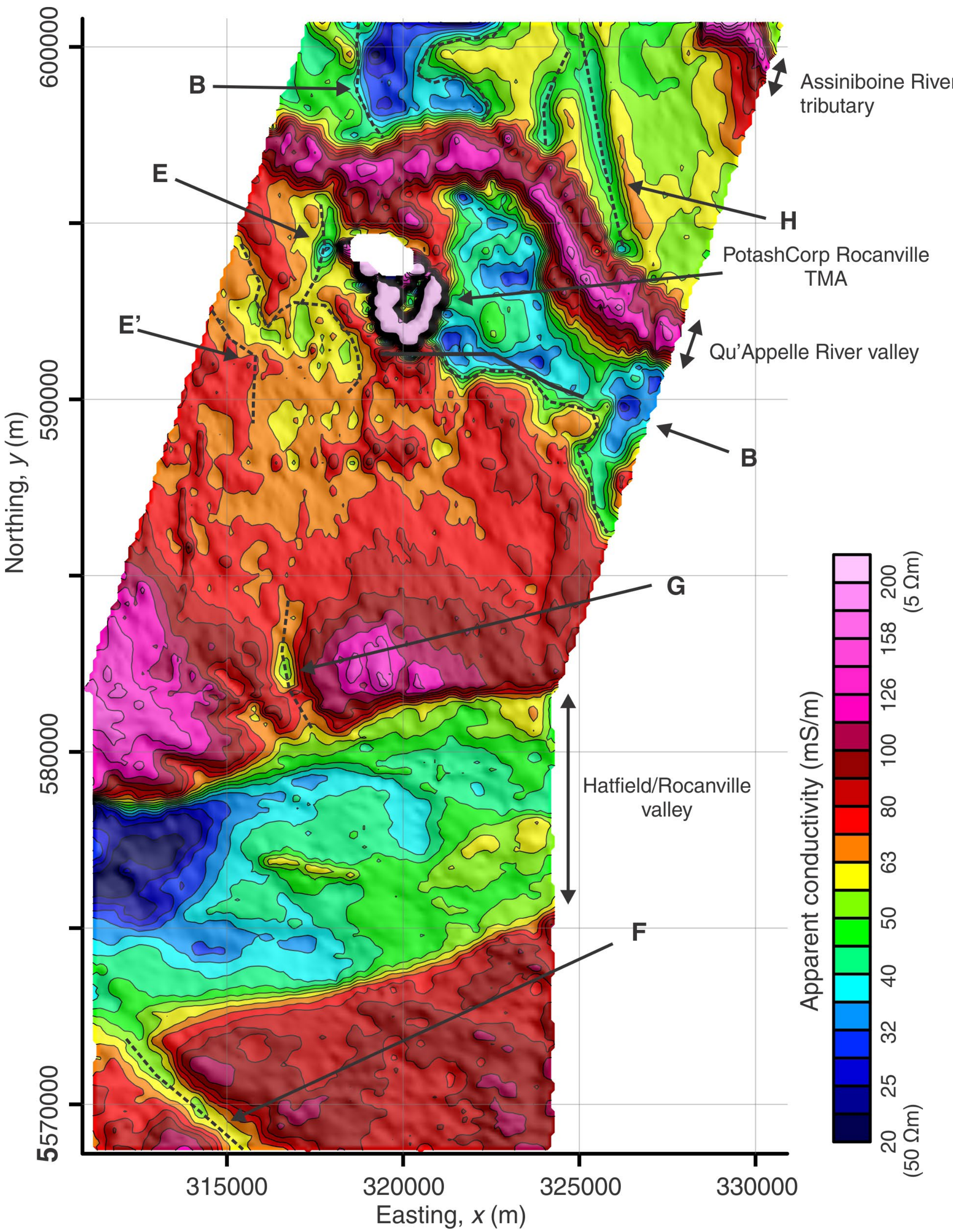


Figure 5. Apparent conductivity map for Blocks 2a and 2b, Rocanville. Solid black line indicates location of seismic section. Features B, E, E', F, G, and H are discussed in the text.

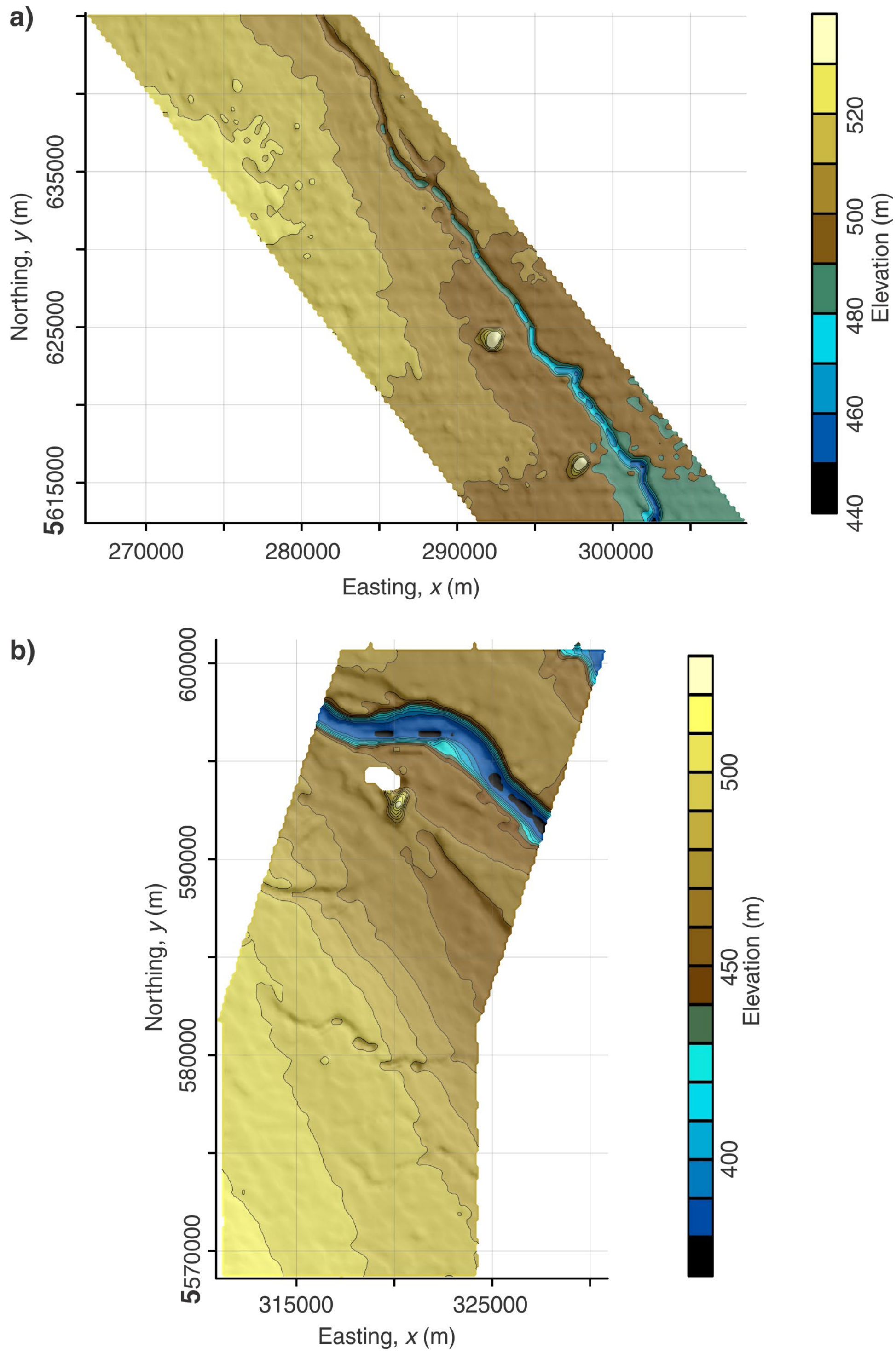


Figure 6. Approximate in-flight surface elevations for **a)** Block 1 and **b)** Blocks 2a and 2b.

Anomalies associated with the TMA are generally confined to the mapped extents (e.g. MDH Engineered Solutions Corp., 2008; 2009; Hefford et al., 2012a–f). In the case of the K2 TMA (Fig. 4), we may be observing the affect of documented elevated groundwater chloride concentrations just northeast of the TMA (MDH Engineered Solutions Corp., 2009) although differentiation of this signal from that of the conductive bedrock and the TMA itself is difficult. For Block 2a (Fig. 5), we observe a high conductivity anomaly extending northward from the Rocanville TMA. This conductivity anomaly is also consistent with the occurrence of known elevated groundwater chloride concentrations (MDH Engineered Solutions Corp., 2008).

The modern-day fluvial systems in the region (Fig. 6) also show up as strongly conductive features in the apparent-conductivity maps. In Block 1, Cutarm Creek runs from northwest to southeast and has an elevated conductivity signature that increases to the south (Fig. 5). In Block 2a, the Qu'Appelle and Assiniboine River valleys are clearly manifest as high conductivity anomalies (Fig. 6). The Qu'Appelle River valley is 75 to 90 m deep when hosted in sediment and up to 145 m deep in bedrock where it meets the Assinboine River; in the vicinity of the study area, it is inferred to be filled with up to 50 m of silt and clay or 50 m of sand and gravel (Klassen, 1975). In general, sand and gravel saturated with fresh water would have a conductivity of approximately 1 mS/m, or up to 40 mS/m for shale-derived sands and gravels (Palacky, 1988; Oldenborger et al., 2012). Water-quality reports for the Qu'Appelle and Assiniboine Rivers indicate relatively fresh waters (approximate 32-year median 975 mg/L TDS, J.-M. Davies, Saskatchewan Water Security Agency, pers. comm.) such that elevated river-water conductivity is not a likely explanation for the observed apparent conductivity of greater than 100 mS/m, and there must be other contributing factors such as the influence of conductive bedrock.

The near-surface geology can be broadly characterized in terms of the distribution of conductive shale bedrock, and a buried valley system of three general scales. We observe the Hatfield and Rocanville valleys (labelled in Fig. 4, 5) as large-scale moderately conductive features set within the conductive shale interfluves. These valleys appear to have either variable valley fill, or valley floor topography. Also apparent are medium-scale resistive valley features in the northern half of Block 1 (feature A on Fig. 4) and the northeast portion of Block 2a (feature B on Fig. 5). From the apparent conductivity maps, feature A crosses bedrock and the Hatfield valley fill. Feature B is crossed by the Qu'Appelle River valley. The smaller scale features appear to be moderately resistive channels crossing bedrock such as features C and D in Block 1 (Fig. 4) and features E, F, and G in Blocks 2a and 2b (Fig. 5) or crossing valley fill such as H in Block 2a (Fig. 5). Feature B (Fig. 5) is interpreted to be the expression of the 'Welby Channel aquifer' (MDH Engineered Solutions Corp., 2008). Feature C (and perhaps D, Fig. 4) is interpreted to be the expression of the Yarbo Channel and the extension of the 'K2 aquifer' (MDH Engineered Solutions Corp., 2009). Features E and E' (Fig. 5) are interpreted to be the expression of the 'West Channel aquifer' and the 'Unnamed Sutherland Group aquifer', respectively (MDH Engineered Solutions Corp., 2008). More insight into the geology of the region including depth relationships can be obtained from the CDI models.

Block 1

The 3D CDI model for Block 1 is shown in Figure 7 as a series of constant-elevation slices of the electrical conductivity. The CDI conductivity represents a time-variable best-fit halfspace conductivity that is depth-transformed based on a skin-depth approximation. The CDI algorithm is inherently flawed for 2D and 3D features and particularly features with high conductivity and limited extent in depth. Such features may appear significantly extended in the vertical direction (Huang and Rudd, 2008) due in part to their strong slowly decaying response that is present over all time gates, but that cannot be correctly represented with a halfspace model. Any conductive feature with limited horizontal extent will also appear extended laterally due to the finite footprint of the EM system (Fig. 2). Resistive features will also appear extended vertically (Huang and Rudd, 2008). However, due to lack of sensitivity to resistive material, thin resistive layers tend to go undetected and the horizontal footprint of the EM system is reduced. Despite limitations of the CDI procedure, it provides a 3D image of the subsurface that has been shown to be in general agreement with other geophysical datasets (Oldenborger et al., 2012).

For Block 1, we see that feature A (Fig. 4) is a near-surface feature present from the surface to over 50 m depth. Feature A occupies a valley eroded into the northern bedrock interfluve. The resistive signature associated with feature A extends into the Hatfield valley, where its lateral dimension increases. Feature A represents the most resistive material in the survey block, consistent with an interpretation of more coarse and sorted sediment (although the conductivity is high enough to suggest a shale clast provenance). Conversely, the interfluves are strongly conductive. The Hatfield valley is apparent in the Block 1 CDI model from approximately 480 m elevation; we are unable to image conductive bedrock beneath the Hatfield valley and the valley bottom remains undetected below 410 m elevation. We are able to discern a distinction between the northern half of the valley and the southern half for which the valley bottom may be shallower and against which feature A appears to terminate. Furthermore, the southern interfluve appears more conductive and at shallower depth; bedrock is observed at 10 to 20 m below surface just west of the K2 TMA (MDH Engineered Solutions Corp, 2009). Note that the CDI model is undefined at depth in this most conductive material due to reduced skin depth; signal penetration is less in conductive material and the latest time gate

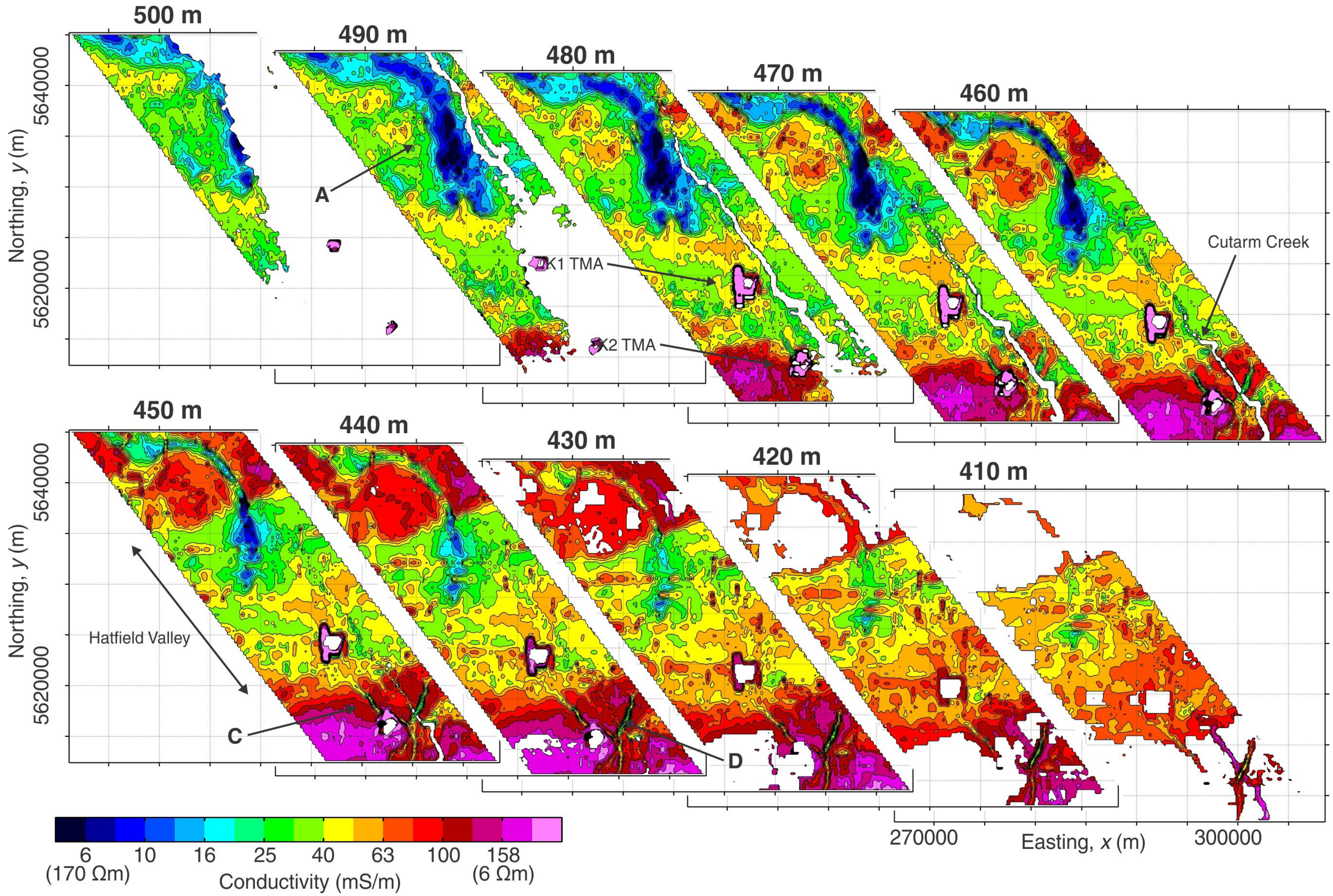
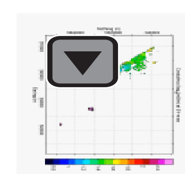


Figure 7. CDI model for Block 1 at 10 m elevation intervals (a.s.l.) Features C and D are discussed in the text. K1 TMA and K2 TMA are the Mosaic Potash Esterhazy K1 and K2 tailings management areas. An animated version of this figure can be viewed by clicking the video icon in the bottom right-hand corner of this page.



corresponds to a shallower maximum model depth. These regions should not be confused with areas of low topography, such as Cutarm Creek, that can be identified from Figure 6.

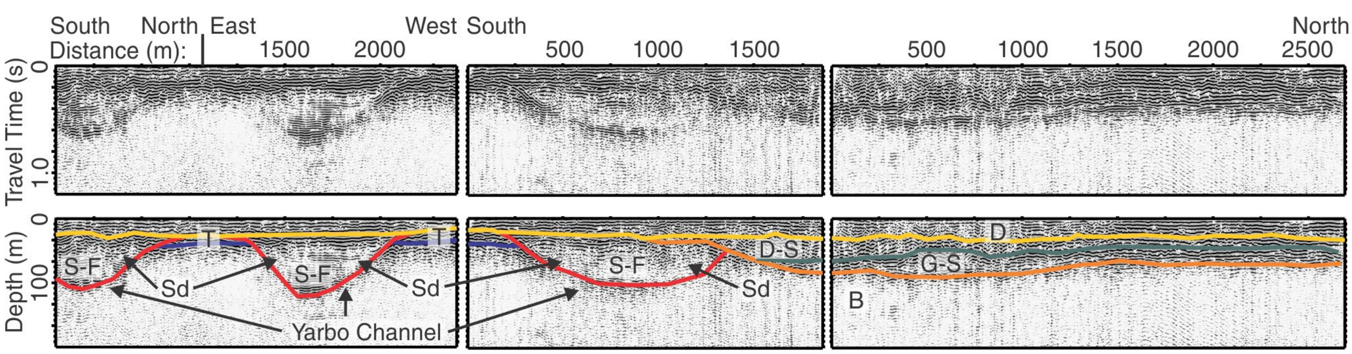
Features C and D also extend to depth in the CDI model with a moderately resistive signature (Fig. 7). Feature C (the Yarbo Channel) appears to deepen toward and extend to the Hatfield valley. We do not detect the bottom of either feature C or D, but feature D appears to be over-deepened in places. From 440–460 m elevation, features C and D appear to be connected, but a genetic or age relationship is difficult to distinguish from the CDI model.

A GSC seismic section presented in Figure 8 was collected across the Yarbo Channel using a pulled array and a vibratory source (Pugin et al., 2009a; 2009b). The section crosses the Yarbo Channel three times in different directions (Fig. 4). High-amplitude reflections are interpreted as erosional surfaces (unconformities) that indicate depth of the Yarbo Channel to be approximately 120 m. Within the Hatfield valley fill to the north, a broader shallower valley is also interpreted from the seismic data. Between the erosional surfaces, seismic facies are used to interpret material type that can be correlated with the CDI model. The gravel and sand interpreted to fill the bottom of the northern valley (Fig. 8) can be identified in the CDI model as a resistive anomaly just east of the K1 TMA site from 420 to 450 m elevation (Fig. 7). This feature may be the expression of part of the 'Hatfield valley aquifer system' (MDH Engineered Solutions Corp, 2009). Based on the interpreted erosional surfaces from the seismic data, it appears that the shallower northern valley crosscuts, and is therefore younger than, the Yarbo Channel. However, the CDI model does not reveal any clear overlap of the conductivity signatures associated with the Hatfield buried-valley aquifer system and the Yarbo Channel. Further, the Yarbo Channel anomaly appears to extend into the Hatfield buried valley, an observation that implies that the fill in the Yarbo Channel is younger than the Hatfield valley. The result is a complicated age relationship that may be explained by multiple erosion phases of the Hatfield valley, but requires further investigation.

Blocks 2a and 2b

The 3D CDI model shown in Figure 9 for Blocks 2a and 2b clearly depicts the Rocanville arm of the Hatfield valley. The Rocanville valley is persistent with depth from the surface to beyond the bottom of the CDI model at 380 m elevation. Feature F (Fig. 5) represents moderately conductive material that appears to occupy a relatively shallow bedrock valley (compared to the Rocanville). Feature G is also relatively shallow and has a broad near-surface expression associated with a saddle-type bedrock topography. Neither of these features seems to be related to the strongly resistive anomaly within the Rocanville valley at the west edge of Block 2b and extending eastwards at depth. This feature is interpreted to be a wedge of coarse clastic material and it may represent an import zone of recharge.

The topography of the Qu'Appelle River valley is such that maximum skin depth is reached for most of the model at elevations greater than that of the river level. Figure 9b shows the CDI model at elevations below the river level. The shallow river bed exhibits moderate conductivities consistent with water quality reports for the Qu'Appelle



LEGEND

Symbol	Description	Reflection Facies
B	Bedrock (Pierre Shale)	Low amplitude, weak penetration
T	Dense till	High amplitude, semi-continuous
S-F	Stratified sand to silt fining upwards (Yarbo Channel)	Medium to low amplitude, flat, continuous
Sd	Slumped sediments (Yarbo Channel)	Chaotic to transparent
G-S	Gravel and sand	Medium to high amplitude, semi-discontinuos, dome-shaped
D-S	Diamicton with sand layers	Medium to low amplitude, chaotic
D	Sandy silty diamicton	Medium to low amplitude, continuous to semi-continuous

Figure 8. Seismic section across the Yarbo Channel; location is given in Figure 4. Top: shear-wave seismic data. Bottom: interpreted section showing approximate depth and erosional surfaces from oldest to youngest: blue, red, orange, green, yellow.

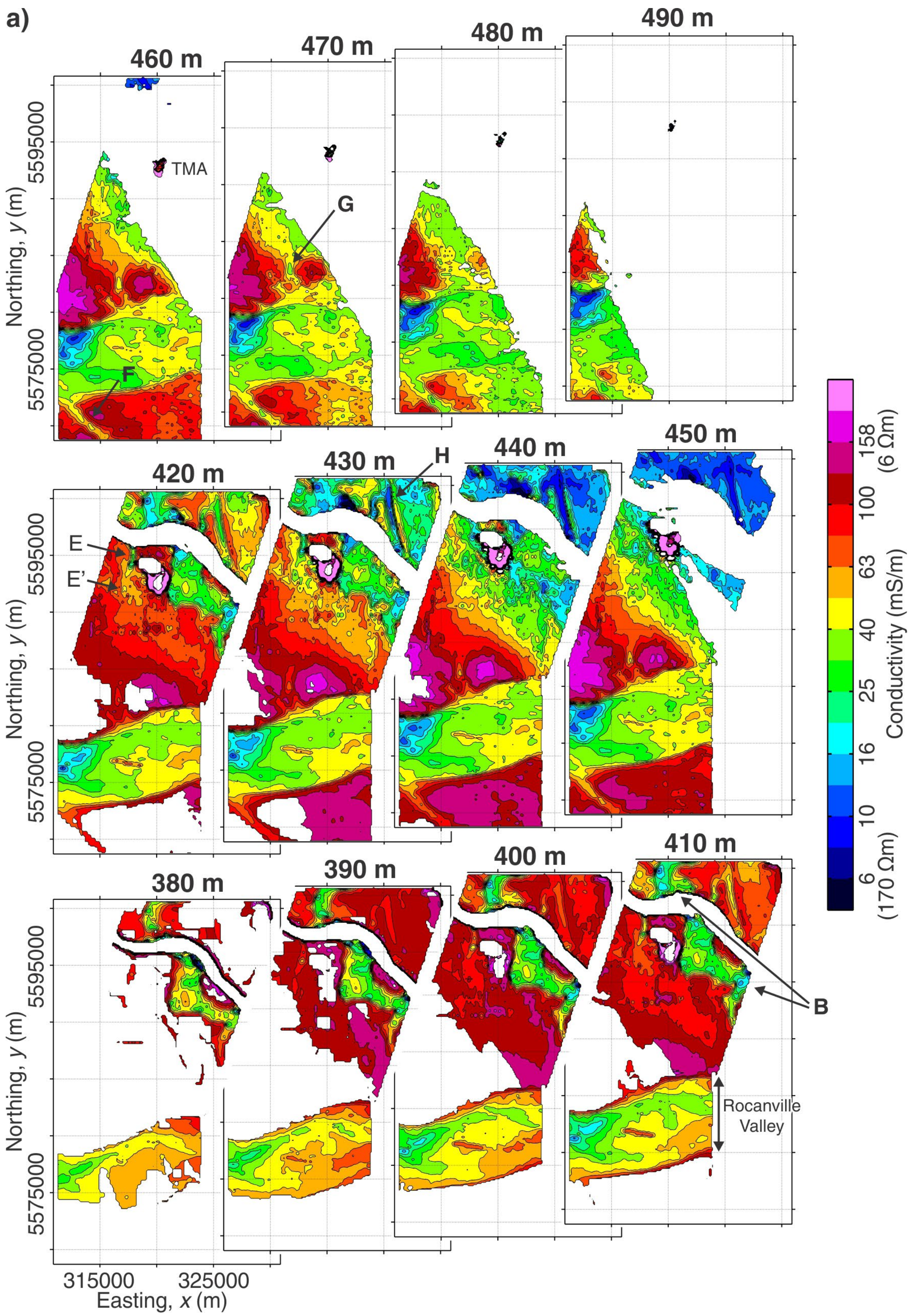
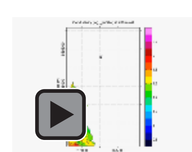


Figure 9. a) CDI model for Blocks 2a and 2b at 10 m elevation intervals (a.s.l.). Features B, E, F, G, and H are discussed in the text. TMA is the PotashCorp Rocanville tailings management area. An animated version of this figure can be viewed by clicking the video icon in the bottom right-hand corner of this page



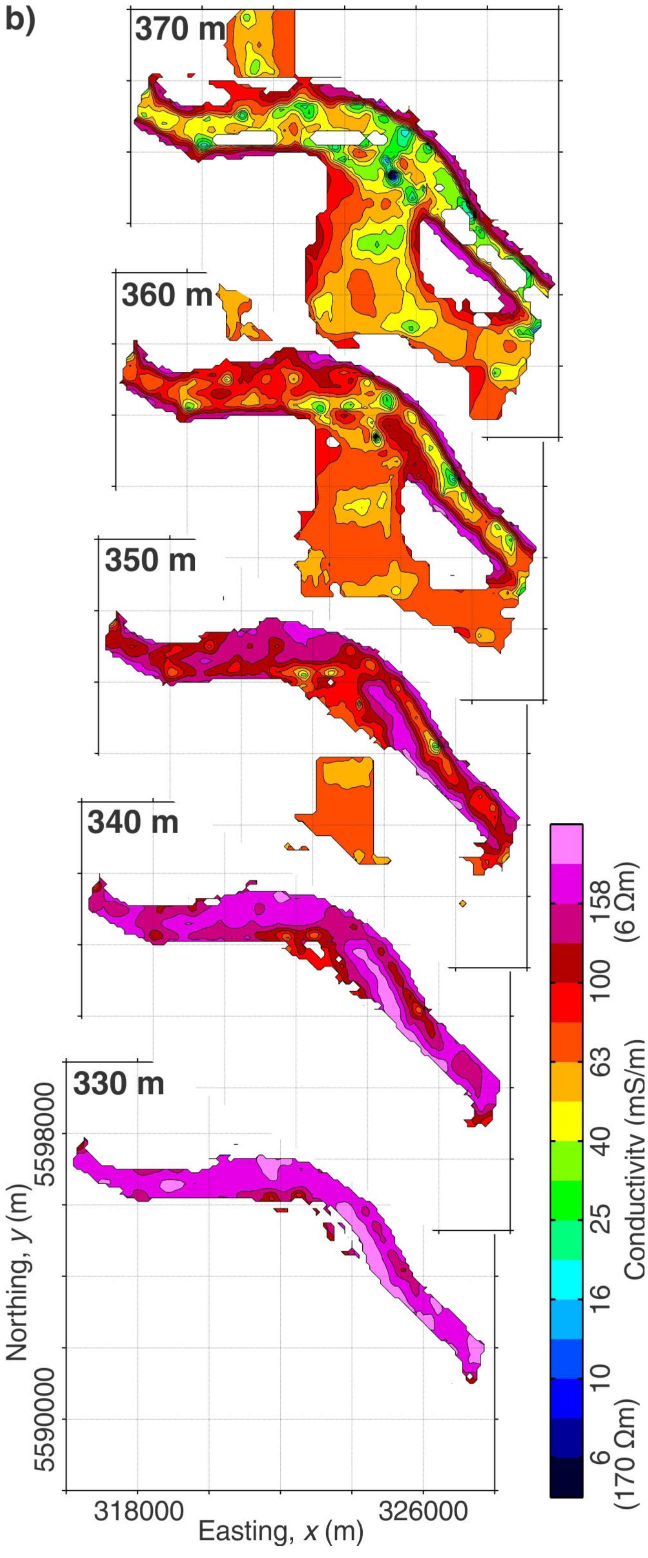


Figure 9. b) CDI model for the Qu'Appelle River valley in Block 2a at 10 m elevation intervals (a.s.l.).

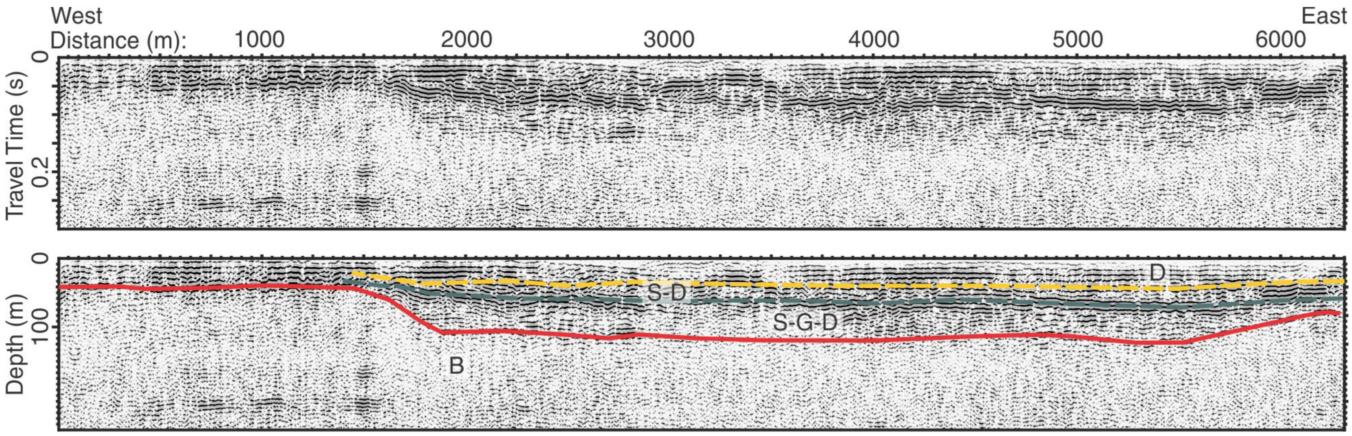
(approximately 700 mg/L TDS) and the river valley is interpreted to be filled with saturated sediments to approximately 350 m elevation consistent with valley fill estimates of less than 40 m thickness (Klassen, 1975). However, below 350 m elevation, we observe a strong conductive anomaly. We attribute this anomaly to the shale bedrock beneath the alluvial cover. Such a scenario would result in relatively high apparent conductivity for the Qu'Appelle River as observed in Figure 5 and the same rationale applies to the conductive anomaly observed for Cutarm Creek in Block 1 (Fig. 4). This example demonstrates the value of the CDI model in comparison to the apparent conductivity.

At the northern end of survey Block 2a, we see near-surface resistive material north of the Qu'Appelle River. The resistive nature of this material is not evident from the apparent conductivity map (Fig. 5) and neither is the strongly resistive signature of feature H which is interpreted to be a narrow shallow valley with coarse sediment fill cut into other coarse sedimentary material. Conversely, feature B is only moderately resistive in the CDI model (note that in the apparent conductivity map, feature B shows up as one of the most resistive features as a result of depth-averaging). Feature B occurs lower in the sedimentary succession and extends at least as deep as the Rocanville valley to 380 m elevation. The valley fill for feature B is interpreted to be different from that of the Hatfield or Rocanville valleys. Drilling logs confirm the presence of coarse sediment (sand and gravel) along feature B to thicknesses in excess of 45 m as part of the Welby Channel aquifer that outcrops in the Qu'Appelle river valley, but for which the southern extent was previously unknown (MDH Engineered Solutions Corp., 2008). The CDI model allows for extension of the mapped limits of this local aquifer. A GSC seismic section collected across the Welby Channel is shown in Figure 10. The data are such that we cannot distinguish erosional (unconformable) surfaces, except for the shale bedrock which occurs at a depth of over 100 m at the bottom of the Welby Channel. Above bedrock, seismic facies can be used to interpret variable lithology that illustrates the valley morphology.

The West Channel and Sutherland Group aquifers (E and E', Fig. 5) are not as easily identified in the CDI model as the Welby Channel. The West Channel aquifer appears to be a relatively shallow resistive valley feature (above 420 m elevation) that may be connected to a more depth-limited moderately-resistive expression of the Sutherland Group aquifer, although Engineered Solutions Corp, M.D.H. (2008) reports that the West Channel and Sutherland Group aquifer are not hydraulically connected.

CONCLUSION

Buried-valley aquifers such as the Hatfield buried-valley aquifer system occur across the Canadian Prairies with a lack of surface expression and complicated network geometries. As such, we require spatially extensive subsurface imaging



LEGEND

Symbol	Description	Reflection Facies
B	Bedrock (Pierre Shale)	Low amplitude, weak penetration
S-G-D	Sand, gravel and discontinuous diamicton	Medium to low amplitude, semi-continous, transparent
S-D	Sand and diamicton	Medium amplitude, continuous, cross-bedded, dome-shaped
D	Diamicton	Variable amplitude, continuous to semi-continuous

Figure 10. Seismic section across the Welby Channel; location is given in Figure 5. Top: compressional-wave seismic data. Bottom: interpreted section showing approximate depth, discrimination of seismic facies, and the erosional surface marking the top of the shale bedrock (red).

techniques for aquifer mapping and characterization. In the case of the Hatfield, HTEM data and derived maps and 3D models reveal the Hatfield and Rocanville buried valleys in addition to a more complicated network of smaller buried valleys, erosional features, and sedimentary deposits.

Valley depths, valley fill, and age relationships can be interpreted from the airborne data and corroborated by seismic data where available. A full stratigraphic analysis or correlation with existing stratigraphy data are beyond the current scope, but we have been able to correlate features observed in the HTEM data and CDI models with known valleys and aquifers in addition to mapping the extent of these known features and identifying new features potentially important for groundwater resources, groundwater flow, and aquifer recharge.

ACKNOWLEDGMENTS

This work was conducted as part of the Groundwater Geoscience Program of the Geological Survey of Canada. Contracting and technical inspection of the Esterhazy-Rocanville HeliTEM survey were carried out by S. Hefford. Quality control and in-house processing were conducted by F. Kiss and W. Miles. The Saskatchewan Watershed Authority helped advance the survey objectives and provided outreach and public notification. We thank G. Bechard, D. Kirkwood, and D. Boerner for support in obtaining funding for this survey. We thank B. Schreiner of the Saskatchewan Research Council and G. Delaney of the Saskatchewan Geological Survey for collaborative discussion.

REFERENCES

Christiansen, E.A., 1992. Pleistocene stratigraphy of the Saskatoon area, Saskatchewan, Canada: and update; Canadian Journal of Earth Sciences, v. 29, p. 1767–1778. doi:10.1139/e92-139

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

Farquharson, C.G. and Oldenburg, D.W., 1993. Inversion of time-domain electromagnetic data for a horizontally layered Earth; Geophysical Journal International, v. 114, p. 433–442. doi:10.1111/j.1365-246X.1993.tb06977.x

Fuzesy A. 1982. Potash in Saskatchewan; Saskatchewan Energy and Mines, Report 181.

Hefford, S.W., Miles, W.F., Oldenborger, G.A., and Pugin, A.J.-M., 2012a. HeliTEM Survey of Esterhazy, NTS Parts of 62 K/12, 62 K/13, 62 L/9, and 62 L/16, Saskatchewan, residual total magnetic field; Geological Survey of Canada, Open File 6970, scale 1:150 000. doi:10.4096/291510

Hefford, S.W., Miles, W.F., Oldenborger, G.A., and Pugin, A.J.-M., 2012b. HeliTEM Survey of Esterhazy, NTS Parts of 62 K/12, 62 K/13, 62 L/9, and 62 L/16, Saskatchewan, time decay constant (TAU-Z); Geological Survey of Canada, Open File 6971, scale 1:150 000. doi:10.4096/291511

Hefford, S.W., Miles, W.F., Oldenborger, G.A., and Pugin, A.J.-M., 2012c. HeliTEM Survey of Esterhazy, NTS Parts of 62 K/12, 62 K/13, 62 L/9, and 62 L/16, Saskatchewan, apparent conductivity; Geological Survey of Canada, Open File 6972, scale 1:150 000. doi:10.4096/291512

Hefford, S.W., Miles, W.F., Oldenborger, G.A., and Pugin, A.J.-M., 2012d. HeliTEM Survey of Esterhazy, NTS parts of 62 K/3, 62 K/4, 62 K/5, 62 K/6, 62 K/11, and 62 K/12, Saskatchewan, residual total field; Geological Survey of Canada, Open File 6973, scale 1:50 000. doi:10.4095/291513

Hefford, S.W., Miles, W.F., Oldenborger, G.A., and Pugin, A.J.-M., 2012e. HeliTEM Survey of Esterhazy, NTS parts of 62 K/3, 62 K/4, 62 K/5, 62 K/6, 62 K/11, and 62 K/12, Saskatchewan, time decay constant (TAU-Z); Geological Survey of Canada, Open File 6974, scale 1:50 000. doi:10.4095/291514

Hefford, S.W., Miles, W.F., Oldenborger, G.A., and Pugin, A.J.-M., 2012f. HeliTEM Survey of Esterhazy, NTS parts of 62 K/3, 62 K/4, 62 K/5, 62 K/6, 62 K/11, and 62 K/12, Saskatchewan, apparent conductivity; Geological Survey of Canada, Open File 6975, scale 1:50 000. doi:10.4095/291515

Huang, H. and Rudd, J., 2008. Conductivity-depth imaging of helicopter-borne TEM data based on a pseudolayer half-space model; Geophysics, v. 73, p. F115–F120.

Jørgensen, F. and Sandersen, P.B.E., 2009. Buried valley mapping in Denmark: evaluating mapping method constraints and the importance of data density; Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, v. 160, p. 211–223. doi:10.1127/1860-1804/2009/0160-0211

Klassen, R.W., 1975. Quaternary geology and geomorphology of Assiniboine and Qu'appelle Valleys of Manitoba and Saskatchewan. Geological Survey of Canada, Bulletin 228, 61 p.

Maathuis H. 1980. Hatfield valley project – Phase 1. Preliminary study of the Hatfield valley aquifer system in the Lanigan–Fort Qu'Appelle area. Saskatchewan Research Council, Publication No.G-1047–1-E-80, 43 p.

Maathuis, H., 2002. Groundwater, a key to economic development in Saskatchewan. Saskatchewan Business Magazine, v. 23, 7 p.

Maathuis H. and Thorleifson J.H. 2000. Potential impact of climate change on Prairie groundwater supplies: review of current knowledge. Saskatchewan Research Council, Publication No. 11304–2E00, 93 p.

MDH Engineered Solutions Corp., 2008. PotashCorp Rocanville Rocanville West Expansion, Environmental Impact Statement, PotashCorp Rocanville.

MDH Engineered Solutions Corp., 2009. Mosaic Potash Esterhazy K2 Phase V TMA and Mill Expansion, Environmental Impact Statement, Mosaic Potash Esterhazy.

Meju, M.A., 1998. A simple method of transient electromagnetic data analysis; Geophysics, v. 63, p. 405–410. doi:10.1190/1.1444340

Millard, M.J., 1990. Geology and Groundwater Resources of the Melfort area (73A), Saskatchewan. Saskatchewan Research Council, Publication R-1210–6-E-90, 114 p.

Mulè, S., Carter, S., and Wolfgram, P., 2012. Advances in helicopter airborne electromagnetics. ASEG Extended Abstracts, V. 20012(1), p. 3.

Oldenborger, G.A., Pugin, A.J.-M., and Pullan, S.E., 2012. Airborne time-domain electromagnetics, electrical resistivity and seismic reflection for regional three-dimensional mapping and characterization of the Spiritwood Valley Aquifer, Manitoba, Canada; Near Surface Geophysics, v. 11, p. 63–74

Palacky, G.J., 1988. Resistivity characteristics of geologic targets; *in* Electromagnetic Methods in Applied Geophysics, (ed.) M.N. Nabighian; Society of Exploration Geophysicists, v. 1, p. 53–129.

Pugin, A.J.-M., Pullan, S.E., and Hunter, J.A., 2009a. Multicomponent high resolution seismic reflection profiling; Leading Edge (Tulsa, Okla.), v. 28, p. 1248–1261. doi:10.1190/1.3249782

Pugin A.J.-M., Pullan S.E., Hunter J.A. and Oldenborger G.A. 2009b. Hydrogeological prospecting using P- and S-wave landstreamer seismic reflection methods; Near Surface Geophysics, v. 7, p. 315–327.

Rescan Environmental Services Ltd, 2008. Jansen Project, Environmental Impact Statement, BHP Billiton Canada Inc.

Schreiner, B.T. and Maathuis, H., 1982. Hatfield valley aquifer system in the Melville region, Saskatchewan. Saskatchewan Research Council, Publication G-743–3-B-82, 77 p.

Simpson, M.A. and Schreiner, B.T., 1999. Geology and hydrostratigraphy of the Melville region (62L,K), Saskatchewan. Saskatchewan Research Council, Publication 10416–1C99, 149 p.

van der Kamp, G. and Maathuis, H., 2012. The Unusual and large drawdown response of buried-valley aquifers to pumping; Ground Water, v. 50, p. 207–215. doi:10.1111/j.1745-6584.2011.00833.x

West, G.F. and Macnae, J.C., 1991. Physics of the electromagnetic induction exploration method; *in* Electromagnetic Methods in Applied Geophysics, (ed.) M.N. Nabighian; Society of Exploration Geophysicists, v. 2, p. 5–45.

Geological Survey of Canada Project AM 1002