# Energy Resources Conservation Board/Alberta Geological Survey Three-Dimensional Geological Modelling Workshop

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Comments from G. Hippolt-Squair improved an earlier version of this report.

# Abstract

To take advantage of recent advances in collecting airborne geophysical data and integrating them into three-dimensional geological models and hydrological studies, the Energy Resources Conservation Board/Alberta Geological Survey (ERCB/AGS) hosted a three-dimensional geological modelling workshop in Edmonton in January 2012.

ERCB/AGS staff members were joined by scientists from Alberta Environment and Sustainable Resource Development, the Geological Survey of Canada, the United States Geological Survey and the Manitoba, Illinois, and Minnesota geological surveys, as well as representatives from the private sector.

The workshop focused on developing geological frameworks for assessing the near-surface hydrology of a number of regions in North America, including Alberta, and examined two major themes. The first explored opportunities and challenges associated with the acquisition, calibration, and application of airborne geophysical surveys. The second examined the importance of developing high-quality, three-dimensional geological models and how these models can be best applied to hydrological studies.

Collectively, the expertise shared at this workshop will benefit ERCB/AGS staff members as they move forward on the Provincial Groundwater Inventory Program (www.ags.gov.ab.ca/groundwater/groundwater-inventory.html), which will provide digitally derived maps and reports to improve understanding of Alberta's groundwater resources for public, industry, and regulatory use.

# 1 Geophysical and Geological Data Collection in Central and Southern Alberta, Canada

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In response to increased urbanization and industrialization in Alberta, and the foreseeable pressures that this will have on existing water supplies, the Alberta Geological Survey has embarked on a multi-year program to determine the aerial distribution and the internal architecture of aquifer complexes in the central and southern parts of the province.

In Alberta, buried valleys have become primary targets for groundwater exploration programs due to the potential for confined, water-bearing, coarse-grained sediment fills located within them. The locations of buried valleys in many areas of Alberta are difficult to predict because they often trend obliquely to modern-day land surfaces, have little to no surface expression, and are so narrow as to fall between conventional resource evaluation borehole-drill spacing. Therefore, a combination of geophysical surveys, facilitated by high-quality borehole logging and field examination of outcrops, has been used to locate and define sediment-fill sequences within buried valleys.

The outcomes of this work are depicted as digitally derived maps and reports to be disseminated for public, industry, and government regulatory use. It is anticipated that this workflow will form the basis for future efforts on developing a more comprehensive assessment of 'shallow' sedimentary systems, which can be applied to other groundwater issues, such as urban development and other land uses, as well as providing the framework for assessing the near-surface hydrogeology of the region, including buried valleys.

## 2 Framework Mapping and Optimization Modelling for Water Resources Management

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Increasingly complex groundwater management requires more precise hydrogeological frameworks for groundwater models used in resource management. These complex issues have created the demand for innovative approaches to data collection. In complicated terrains, groundwater modellers benefit from continuous, high-resolution geological and soil maps and their related hydrogeological-parameter estimates. The U.S. Geological Survey and its partners have collaborated to use airborne-geophysical and ground-based geophysical surveys for near-continuous coverage of the North Platte River valley areas in western Nebraska.

The objective of the surveys was to map the irrigation canals and their interconnection to the aquifers and bedrock topography of the area to improve the understanding of groundwater-surface water interactions used in water management decisions. Frequency-domain helicopter electromagnetic (HEM) and ground-based capacitive-coupled-resistivity surveys were completed to collect resistivity data that can be related to lithological information to refine groundwater model inputs.

To make the geophysical data useful to multidimensional groundwater models, numerical inversion is necessary to convert the measured data into a depth-dependent subsurface resistivity model. The HEM images deep into the Earth, whereas the capacitive-coupled resistivity images the near surface (0.5 to 10 m). These inverted models, in conjunction with sensitivity analysis, geological ground-truthing (boreholes), and geological interpretations, are used to characterize hydrogeological features. The interpreted two- and three-dimensional data provide the groundwater modeller with a high-resolution hydrogeological framework and a quantitative estimate of framework uncertainty. This method of creating hydrogeological frameworks improved the understanding of the actual flow-path orientation by redefining the location of the paleochannels and associated bedrock highs. The improved models represent the actual hydrogeology at a level of accuracy not achievable using previous datasets.

# 3 Beyond the 'Best' Model: Data Calibration and Model Assessment Tools for Airborne EM

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An important aspect of interpreting airborne-electromagnetic data in a hydrogeological context involves quantifying uncertainty and understanding the constraints on subsurface properties provided by the measured geophysical data. To achieve this, we present a trans-dimensional Bayesian Markov chain Monte Carlo (MCMC) algorithm that samples the distribution of models consistent with the measured data. Assessing the distribution of plausible models, rather than a single 'best-fit' model, provides valuable details about parameter uncertainty and non-uniqueness that leads to a more robust interpretation.

To achieve a meaningful assessment of model uncertainty, systematic data errors caused by imperfect instrument calibration must be accounted for. Factory and in-flight internal system calibrations have helped to reduce, although not always eliminate, calibration errors in modern frequency domain electromagnetic methods (FDEM). A number of methods have been developed to calibrate data after they have been acquired, but these are primarily based on having auxiliary information about subsurface properties from well logs or ground-based geophysical surveys, which are not always available and may have inaccuracies of their own.

We propose a new strategy for calibrating FDEM data that does not rely on prior knowledge of the subsurface structure. This calibration procedure involves acquiring multiple datasets along a single calibration line at several different survey elevations at the beginning of a survey. Calibration parameters, consisting of gain, phase, and bias correction factors for each frequency, are derived by requiring that data from the multiple survey elevations must be consistent with the same Earth model at each location along the line. This is accomplished by simultaneously inverting the multi-elevation data for an Earth model at each location along the profile along with a single set of calibration parameters. This joint inversion strategy recovers the combination of Earth models and calibration parameters that are optimally consistent with the multi-elevation data. The derived calibration parameters are then applied to the survey data, and the calibration procedure can be repeated as necessary to correct for system drift.

# 4 Results of Recent VTEM Helicopter System Development Testing Over the Spiritwood Valley Aquifer, Manitoba

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Early-time or high-frequency airborne-electromagnetic data (AEM) are desirable for shallow sounding or mapping of resistive areas. Yet many time-domain AEM systems have problems obtaining quantitative early-time data due to a variety of issues, such as system bandwidth, system calibration, and parasitic loop capacitance.

Part of an ongoing system-design strategy aimed at improving the early-channel VTEM data collected in late 2010 with a dedicated early-time receiver system. By late 2011, this strategy resulted in further advancements in hardware and new digital signal-processing techniques. These advancements appear to have achieved fully calibrated, quantitative measurements closer to the transmitter current turn off, while maintaining reasonably optimal deep-penetration characteristics of the VTEM system.

The most recent VTEM system development is designed to improve the accuracy of time-domain electromagnetic (EM) decays for better near-surface mapping than was possible with previous VTEM systems. The new design, known as the *full-waveform VTEM system* uses the streamed half-cycle recording of transmitter and receiver waveforms to obtain a complete system-response calibration throughout the entire survey flight. This helps to precisely eliminate the effect of the data-acquisition system response on the recorded signals. The full-waveform technology can be added to either the standard VTEM or VTEM early-time systems.

In addition to improving the system bandwidth and the complete system response calibration, newly developed digital signal-processing techniques have been applied that reduce the effect of the input transmitter waveform and time-varying injected current using both a parasitic loop-capacitance correction and a transmitter-drift correction, as well as ideal waveform deconvolution. These implementations have improved the accuracy of the measured Earth response, particularly in the earliest portions of the off-time EM decay.

Results of the full-waveform VTEM helicopter system implementation over the Spiritwood Valley aquifer in southern Manitoba have shown a significant improvement in quantitative VTEM data at earlier times than previously achieved (as early as 20µs after the current turn off). This has resulted in improvements in the model space that include better definition of the near-surface heterogeneity and a more compact resistive anomaly associated with the buried-valley aquifer that is in good agreement with previous seismic and resistivity results.

## 5 The Utility of Airborne Electromagnetic Surveying in the Characterization of Aquifers

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The use of electromagnetic surveying methods, particularly airborne EM, has seen rapid growth during the last 10 years. This is in large part due to the introduction of helicopter-borne, time-domain electromagnetic (HTEM) systems by Aeroquest in 1998. The maturation of the HTEM method has come to the point that these systems are now capable of addressing a wide variety of non-mining applications. In these applications, the geological challenge often requires a high degree of clarity and transparency in the defining, monitoring, and characterizing of the attributes of the final data.

Quantitative interpretation methods, such as the inversion routines that are now widely available, require a high degree of rigour but output valuable information. The AeroTEM system produces a transparent output accompanied by co-located GPS, orientation, and altimetry datasets. Calibration of the EM data, together with constant monitoring of the waveform, provides confidence in the accuracy and consistency of the results.

We demonstrated the system by 3-D inversion of a demonstration survey in the oil sands mining area of northeastern Alberta. The 3-D geology is well served by the 3-D inversion, and these results provided an accurate model in a relatively complex area.

# 6 Buried Valleys in Southern Ontario, Canada

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The glacial landscape of southern Ontario hosts buried valleys in bedrock and in sediment. The form and infill sequences of bedrock valleys, such as the Laurentian Valley, are poorly defined and are based on archival well records and sparse high-quality data. Bedrock valleys may reflect a structural control from the Precambrian basement and have a glacial overprint, although most are thought to have originated as part of a Tertiary[1] drainage system that, in part, led to the formation of the Great Lakes.

Buried valleys hosted in sediment have been identified using digital elevation models and detailed geological mapping, and an increase in the use of high-resolution, shallow-reflection seismic and continuous borehole data that permit definition of length (tens of km), width (km), and depth (<200 m). High-quality subsurface data are conditioned with outcrop data that enable the development of key conceptual and sedimentary process models. Sediment valley-fills are dominated by sequences of coarse-grained, high-energy sediments that are transitional to fine-grained, low-energy sediments. Process models are considered to relate to regional proglacial and mainly subglacial landscapes that are used to explain the origin of regional unconformities and the formation of subglacial (tunnel) valleys. Depositional process models, such as the jet-efflux model, help interpret common sedimentary facies and evidence for hydraulic jumps where rapid flow meets standing bodies of water.

Sediment-hosted buried valleys were mainly formed during late glacial (late Wisconsinan) events; however, the regional glacial stratigraphy of older inter-valley sediments (seismic profiles) show a number of earlier valley signatures. Sediment-hosted buried valleys are predominantly filled with glaciofluvial and glaciolacustrine sediments.

Southern Ontario buried valleys form significant freshwater aquifers, and the Oak Ridges Moraine area tunnel valleys are being studied as reservoir analogues for Middle Eastern and North African tunnel valleys in Ordovician glaciogenic deposits.

[1] 'Tertiary' is an historical term. The International Commission on Stratigraphy recommends using 'Paleogene' (comprising the Paleocene to Oligocene epochs) and 'Neogene' (comprising the Miocene and Pliocene epochs).

# 7 Integration of Geophysical Data in 3-D Geological Models of Northeastern Illinois


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Currently, 3-D geological modelling and mapping is occurring in Illinois for Lake and McHenry counties in metropolitan Chicago and in a multi-county area across the Mahomet Bedrock Valley in east-central Illinois (Figure 1). This mapping is being undertaken to assist county and municipal governments and a private water company to determine available water supplies and improve models of groundwater flow in glacial aquifers. The 3-D geological models are being compiled from available subsurface data archived at the Illinois State Geological Survey (ISGS) and Illinois State Water Survey (ISWS).

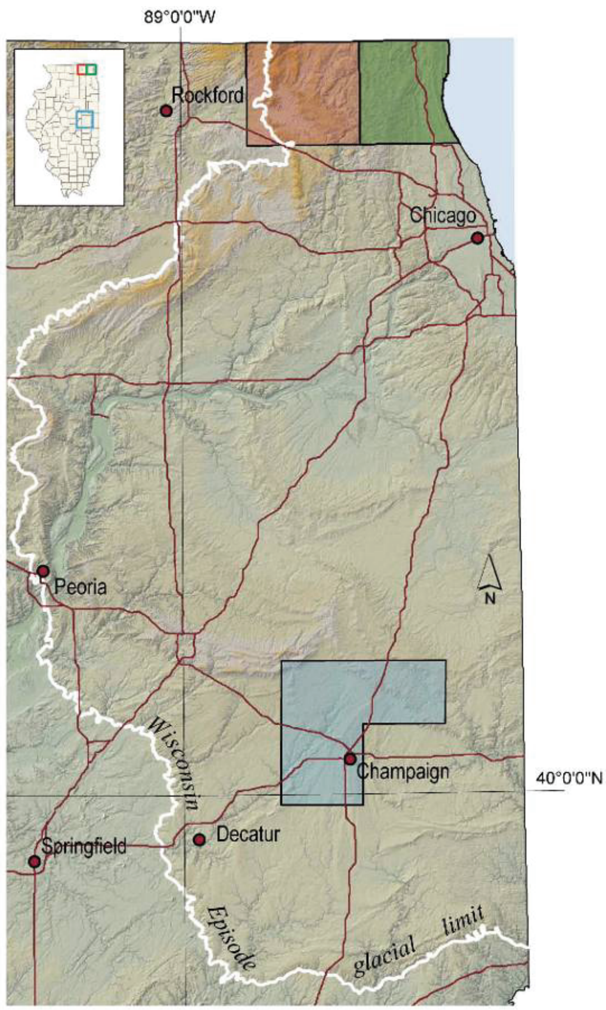


**Figure 1. Geological mapping and modelling in Illinois; McHenry County (red), Lake County (green), and across the Mahomet Bedrock Valley (blue).**

These data include information collected from continuous cores acquired by the ISGS, near-surface and borehole geophysical surveys conducted by the ISGS, geological logs recorded by drillers when constructing water-supply wells, reports, logs, and data recorded for engineering sites and coal and petroleum exploration, and water-level measurements recorded in groundwater monitoring wells by the ISWS.

An important component in constructing the 3-D geological models was acquiring the geophysical data of the land surface and in the boreholes, as well as interpreting these data to identify different geological mapping units. Seismic reflection and electrical Earth resistivity surveys were conducted in the project areas to identify prominent reflectors in the subsurface, commonly representing the contact between different geological materials.

Data collected in boreholes were acquired using several different probes or sensors (e.g., natural gamma radiation, single-point resistance, electro-magnetic induction, fluid temperature, seismic velocity, and sonic logging) that measure different properties.

Various database, GIS, and modelling software were used to develop the 3-D geological models. The subsurface borehole data from all three areas were initially compiled and standardized using Microsoft Access®. These standardized data were then analyzed in two and three dimensions in ArcGIS Desktop with the geophysical data to assign the geological mapping units.

Customized tools developed for ArcMap and ArcScene by the ISGS were instrumental in creating 3-D shapes (multi-patch shapefile format) that represented the borehole data. The 3-D borehole shapes provided the capability for visualization in ArcScene and other applications that can import the 3-D shape file format.

Various methodologies have been used for these projects to interpolate/model the surfaces of geological mapping units. In McHenry County (Figure 1), the surfaces for each unit were constructed from a series of cross-sections compiled using GSI$^{3D}$ (Geological Surveying and Investigation in Three Dimensions). In Lake County, a combination of hand and computer contouring was done to make the surfaces from the coded data. For the project over the Mahomet Bedrock Valley, a geological model was developed from surfaces of mapping units constructed in ArcMap and Gocad (Geological Object Computer-Aided Design). The Gocad software interpolated the top and bottom surfaces of mapping units above the bedrock surface.

## 8 Status of 3-D Geological Mapping in Minnesota

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In Minnesota, 3-D county geological atlases showing Quaternary, Phanerozoic, and Precambrian geology provide information essential to sustainable management of groundwater resources for monitoring, water allocation, permitting, remediation, and well construction. They define aquifer properties and boundaries, as well as the connection of aquifers to the land surface and to surface-water resources. They also provide a broad range of information on county geology, mineral resources, and natural history.

A complete atlas consists of a Part A and Part B. Part A, prepared by the Minnesota Geological Survey (MGS), includes a water-well database and 1:100 000 scale geological maps showing properties and distribution of sediments and rocks in the subsurface. Part B, constructed by the Department of Natural Resources (DNR) Division of Waters, includes maps of water levels in aquifers, direction of groundwater flow, water chemistry, and sensitivity to pollution. Atlases are usually initiated by a request from a county with an offer to co-fund or provide in-kind service. The MGS is committed to the expeditious completion and periodic updating of atlases statewide (Figure 2).

Atlases begin with the compilation of a database of the subsurface information. The most abundant data source is the construction records of water wells. With the cooperation of the county, accurate digital locations are established for these wells to support their use in mapping. Concurrently, geologists visit the project area to describe and sample landforms and exposures of rock or sediment. An initial assessment of the geological data is then completed to focus additional data gathering, which includes shallow- and deep-drilling programs. Analysis of the complete dataset is then completed, and maps and associated databases are prepared for use in GIS and distribution via DVD and the Web. Most of the products are also printed for the benefit of users who prefer this format.

In 2011, the Minnesota Water Sustainability Framework, a report resulting from broad consultation and delivered to the legislature, specified that county geological atlases are one of the essential elements for implementation of the framework. The report noted that the MGS has completed, or is in process of completing, 25 of the 87 atlases, and that at the current rate of investment, they will not be completed statewide for another 24 years. The atlases were cited as a critical component for long-term planning, and it was recommended that the completion of the county geological atlases by the MGS and DNR should be accelerated. It was stated that at a minimum, the current investment should be doubled to allow for completion in about 10–12 years, along with concurrent updating. Finally, the rate of completion of atlases and aquifer characterization was identified as a key benchmark for assessing progress on the strategy as a whole, with the goal being atlases and aquifer mapping completed for 80% of the state, including all priority areas, within 12 years. As a result of this and preceding recommendations, the MGS budget has increased by 50% in the past four years.

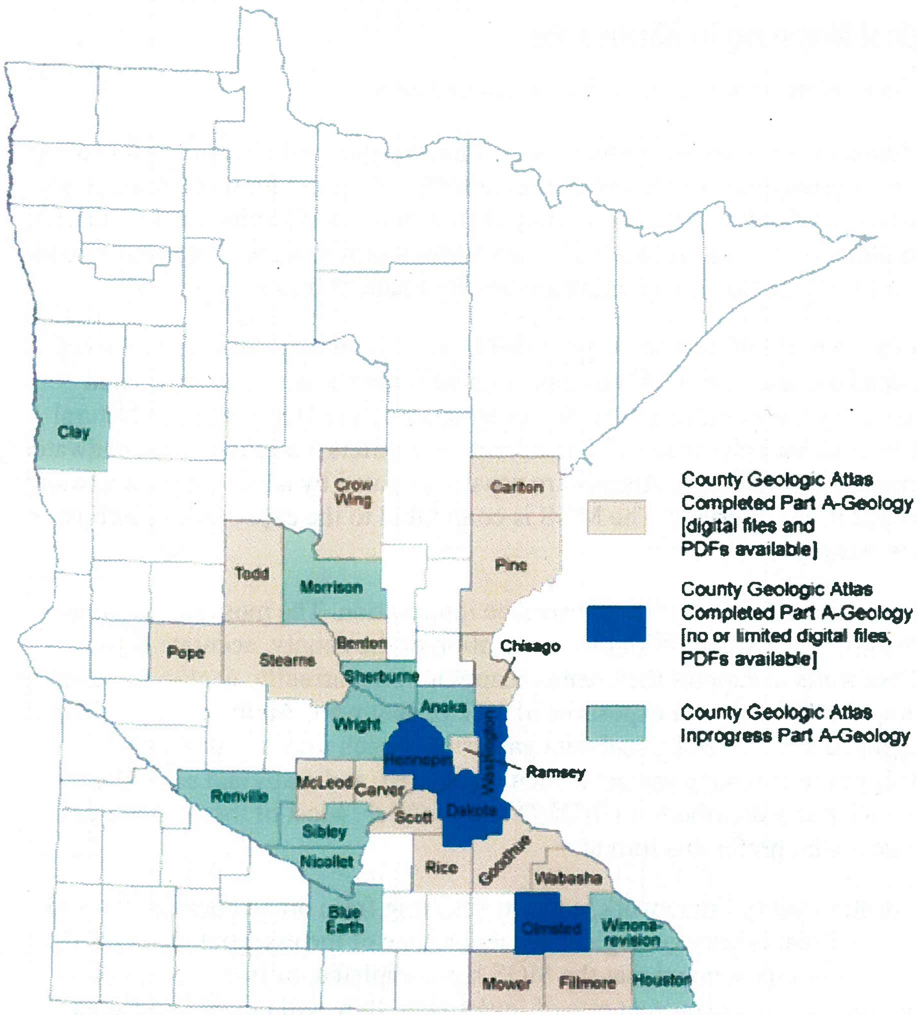


**Figure 2. The status of geological atlases in Minnesota.**

## 9 Three-Dimensional Geological Mapping in Manitoba: Overview and Products

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Increasing demand for groundwater and hydrocarbons has been the main driver for 3-D mapping in Manitoba. To help meet these demands, and to broaden knowledge of the subsurface, the Manitoba Geological Survey (MGS) is developing a 3-D geological model of the Phanerozoic succession in southern Manitoba, south of latitude 55°N (Figure 3). The MGS has developed a workable infrastructure for data collection, integration, and output as it relates to 3-D modelling. A cross-section methodology was used to create the National Geoscience Mapping Program (NATMAP) southeast Manitoba (SE MB) model and the Lake Winnipeg model. On the other hand, the Targeted Geoscience Initiative (TGI) Williston Basin model was modelled directly from high-quality drillhole data. A modified version of the cross-section methodology was used to model all of Manitoba's Phanerozoic terrane south of 55°N.

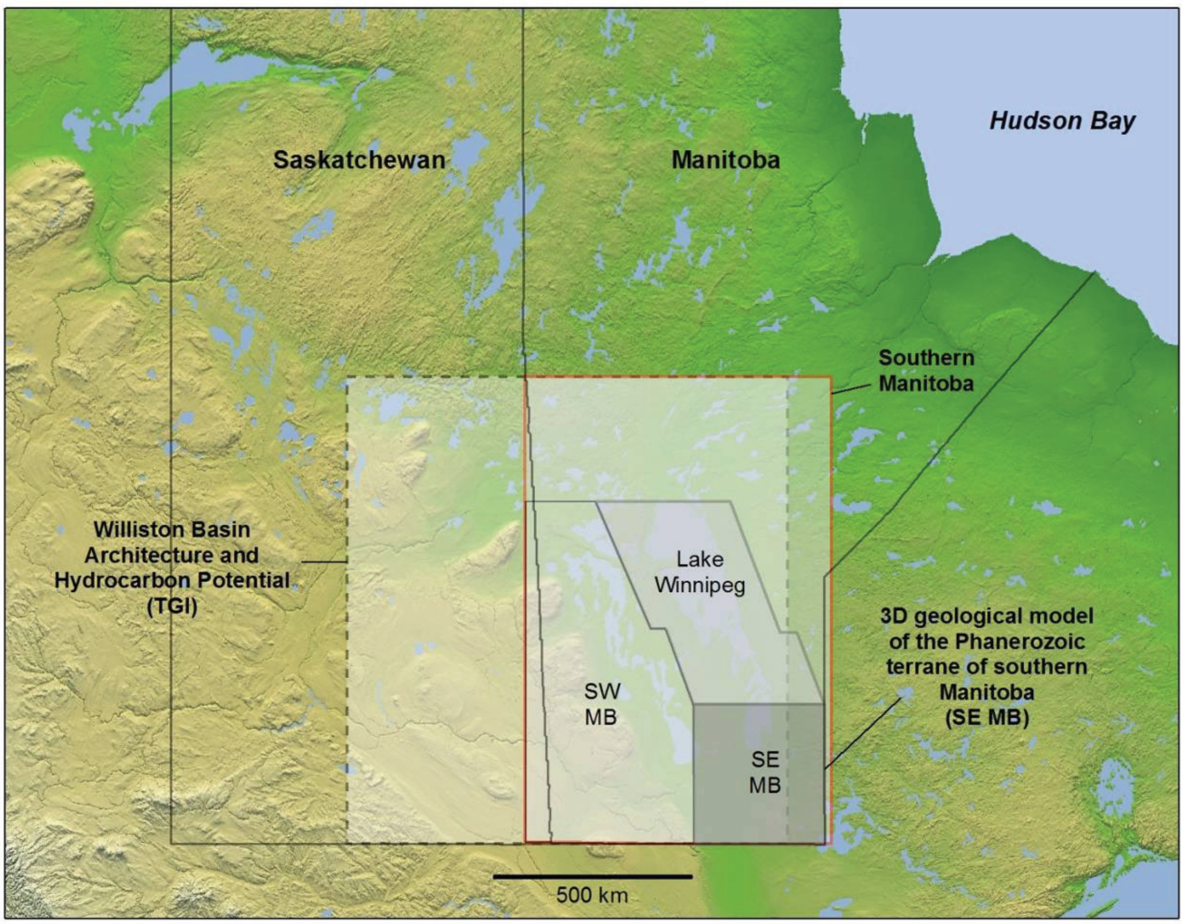


**Figure 3. Index map showing the model areas in Manitoba and the adjacent areas in Saskatchewan.**

Several datasets directly and indirectly related to the geological interpretation are used during the initial stages of the modelling process. Geological maps and reports from various geologists, including published and unpublished subsurface and surficial information, are considered. Data representing various aspects of paleogeography for the area are also included. This creates a greater understanding of regional deglaciation and spatial and temporal distribution of glacial Lake Agassiz, which factors strongly in the interpretation. Overall, the goal is to integrate all available information from every potential source into the cross-sections.

The geological interpretation for the southern portion of Manitoba, south of 55°N, has recently been completed. The southwest Manitoba area (SW MB) was not modelled separately, as was done in previous projects. Instead, all of the previous models were combined into one large southern Manitoba model. This method was selected to resolve two issues:

1) subtle nomenclature differences from area to area

2) TGI modelling issues resulting from projected bedrock formation edges not matching the trend of outcrops mapped along escarpments

To accomplish this, geological transects representing a 5 km wide east-west swath containing all available geological data for that area, along with hand-drawn rock and Quaternary (sediment) units from previously completed regions, were combined into 134 province-wide, georeferenced vertical maps. Hand-drawn transects from Phase 1 (southeast Manitoba NATMAP), Phase 2 (Lake Winnipeg), and Phase 3 (southwest Manitoba) were scanned, georeferenced and combined in ArcGIS with computer-generated transects containing predicted stratigraphy points or virtual drillholes from the TGI Williston Basin project. All 134 province-wide transects have been digitized and depict up to 41 rock formations and 35 Quaternary units. These completed vertical maps are currently being imported into the 3-D modelling software. Once this has been completed, construction of the 3-D surfaces and voxel model will begin.

## 10 Buried-Valley Aquifers and Till Aquitards in the Canadian Prairies: Geology, Hydrogeology, and Origin

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We reviewed more than 100 years of literature to better understand the geology, hydrogeology, and origin of buried valleys (aquifers) and till (aquitards) in the Canadian Prairies and North Dakota (Figure 4). Buried-valley aquifers in the Prairies have distinct geologies and a distinct stratigraphic setting, which imparts distinct hydrogeological properties and provides indications as to how they formed and filled. They are commonly encased in low-permeability strata: Cretaceous shale tends to underlie them and thick (10–300 m), low-permeability Quaternary till tends to overlie them. This reduces recharge, in rare cases nearly completely, while protecting groundwater resources from contamination and drought. It also tends to lead to highly mineralized groundwater chemistries. The stratigraphic position of Prairie buried valleys also speaks to their origin: those that subtend ('hang') from the bedrock unconformity were likely eroded by preglacial fluvial systems during late Tertiary[2] uplift of the Rocky Mountains, whereas those that subtend from surfaces within the till package are likely glaciofluvial valleys eroded in proglacial spillways or tunnel valleys.

Another key trait of Prairie buried valleys is that their fills tend to be heterogeneous and architecturally complex. Sand, gravel, mud, and diamicton are common; any one can dominate the fill at a given location. This heterogeneity, in conjunction with irregularity common to buried-valley bedrock floors, commonly causes aquifer compartmentalization and makes prediction of aquifer potential difficult prior to drilling. It also suggests that most Prairie buried valleys filled over time, and possibly over multiple glaciations, in multiple depositional environments.

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[2] Ibid.

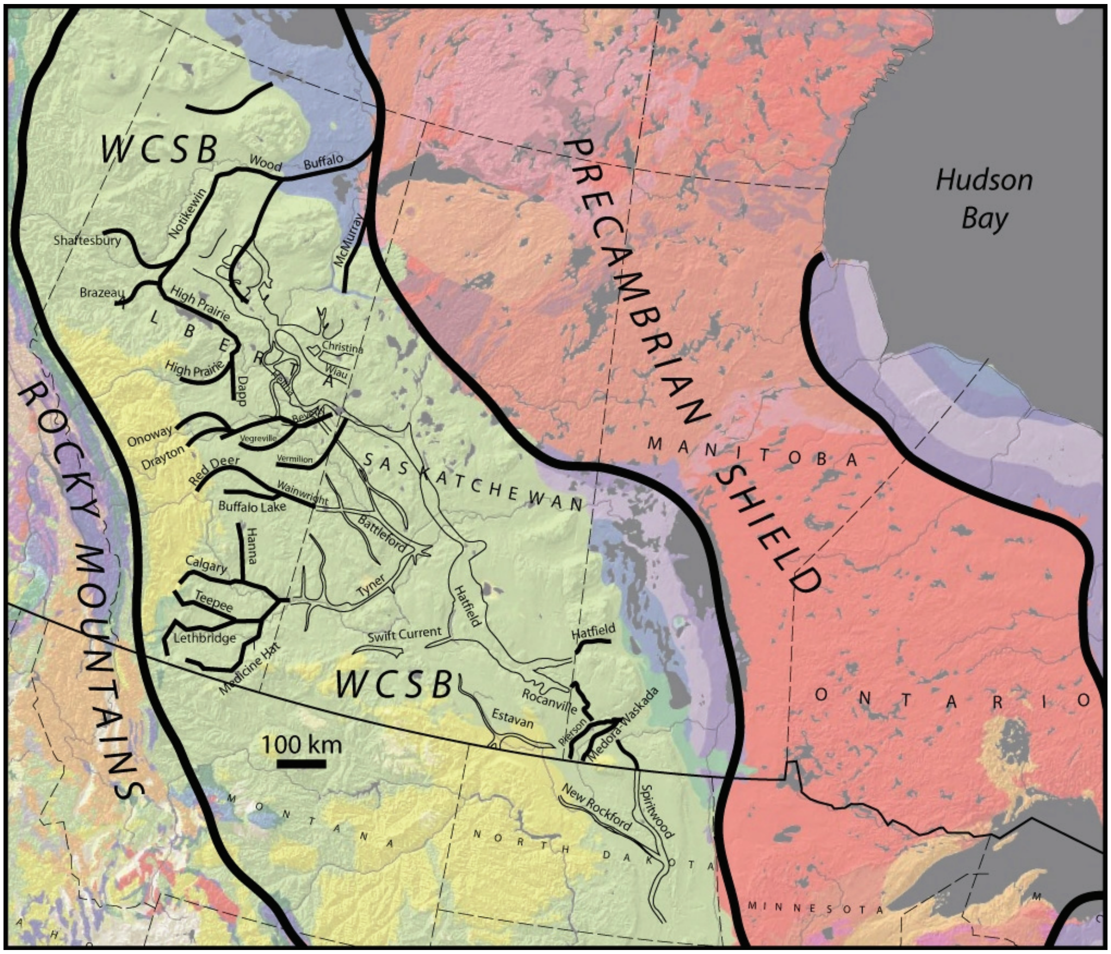


**Figure 4. Buried valleys in the Canadian Prairies and North Dakota. Thick black lines roughly define buried valley extents, whereas thin black lines correspond to buried-valley talwegs. WCSB: Western Canadian Sedimentary Basin; red: Precambrian Shield rocks; blue and purple: Paleozoic carbonate rocks; green: Mesozoic sedimentary rock (primarily shale); yellow: Tertiary[3] sedimentary rock. Compiled from Stalker (1961), Whitaker and Christiansen (1972), Kehew and Boettger (1986), Maathuis and Thorleifson (2000), Andriashek et al. (2001), Hinton et al. (2007) and Oldenborger et al. (2010).**

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[3] Ibid.

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