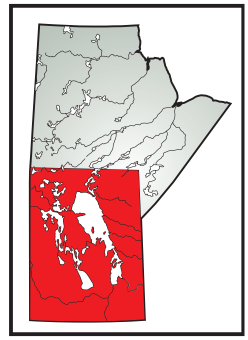
GS-21

Progress in three-dimensional geological mapping in Manitoba and the eastern Prairies

by G.R. Keller, G.L.D. Matile and L.H. Thorleifson[1]



Keller, G.R., Matile, G.L.D. and Thorleifson, L.H. 2009: Progress in three-dimensional geological mapping in Manitoba and the eastern Prairies; *in* Report of Activities 2009, Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, p. 207–213.

Summary

Completion of a three-dimensional (3-D) geological model of the Phanerozoic succession in southern Manitoba, south of latitude 55°N and west of longitude 95°W, is closer than ever. To achieve this goal, we must synthesize ongoing, recently completed and existing 3-D geological models of the area. This paper will briefly discuss these models, provide a review of the methodologies used in their construction and give an update on the status of existing and future modelling in the province.

Progress is being benchmarked against that of other Canadian, American and European geological survey organizations through international workshops sponsored by the Illinois State Geological Survey, the Minnesota Geological Survey and the Geological Survey of Canada. The Manitoba Geological Survey has attended these meetings since the inaugural workshop was held in Bloomington, Illinois in 2001. This work was also presented at the Geological Society of America workshop in Portland, Oregon in October 2009.

Introduction

Increasing demands for groundwater and hydrocarbons have been the two main drivers for 3-D mapping in Manitoba. To satisfy these demands and broaden our knowledge of the subsurface geological and hydrogeological systems, the Manitoba Geological Survey (MGS) has been working toward a provincial 3-D model by developing regional and detailed models (Figure GS-21-1). The creation of these models also includes developing protocols and methodologies for model construction.

After years of data compilation, the first of Manitoba's 3-D models was built in 2001 (Matile et al., 2001). This hydrostratigraphic model was built with funding from the National Geoscience Mapping Program (NATMAP) and covered a 200 km by 230 km area of southeastern Manitoba that included the Winnipeg region. Subsequently, a groundwater-flow model based on these 3-D data was completed by Kennedy and Woodbury (2005), proving the applicability of the 3-D data for groundwater modelling. The model has since been extended northward to include the Lake Winnipeg Basin and is currently being extended westward to include all of the Phanerozoic terrane in Manitoba south of latitude 55°N. This southwestern Manitoba 3-D model includes bedrock units derived from the recently completed Williston Basin 3-D Geological Model of the Targeted Geoscience Initiative (TGI) Williston Basin Architecture and Hydrocarbon Potential Project (Targeted Geoscience Initiative 2 Working Group, 2009). This co-operative model was created using high-quality drill data derived from more than 9000 wells in both western Manitoba and eastern Saskatchewan.

A regional-scale model was recently created using digitized structure-contour data from the Atlas of the Western Canadian Sedimentary Basin (WCSB; Mossop and Shetsen, 1994). This model covers Manitoba, Saskatchewan and Alberta.

Future plans include co-operation between MGS and both the Minnesota and North Dakota geological surveys to produce a Red River Valley 3-D geological model. This model will combine the 3-D geological model of groundwater-bearing strata in the Fargo-Moorhead region (Thorleifson et al., 2005) with Manitoba's 3-D data. The first phase of this compilation was completed in early 2009 with the production of a digital, seamless, cross-border Quaternary map covering the Red River Valley study area. The map can be viewed on the OneGeology web site at http://portal-onegeology.org by selecting View layers > Canada > Red River Valley > CAN MGS 1:250K Surficial Geology - Red River Valley.

A new project on the hydrocarbon potential of the Hudson Bay and Foxe basins has been initiated as part of the new Geological Survey of Canada Geo-mapping for Energy and Minerals (GEM) program (Nicolas and Lavoie, GS-16, this volume). One of its planned components is a 3-D model of the Hudson Bay Lowland (HBL) area of northeastern Manitoba (Table GS-21-1).

Model inputs

In the early stages of this 3-D mapping project, several years were spent building the data infrastructure and integrating the numerous disparate datasets required for the cross-section method of building the NATMAP southeastern Manitoba model. The cross-section method, described below, is the same methodology used to create the Lake Winnipeg model, a modified version of which is being used to build the southwestern Manitoba model.

[1] University of Minnesota, Minnesota Geological Survey, 2642 University Avenue West, St. Paul, Minnesota 55114-1057

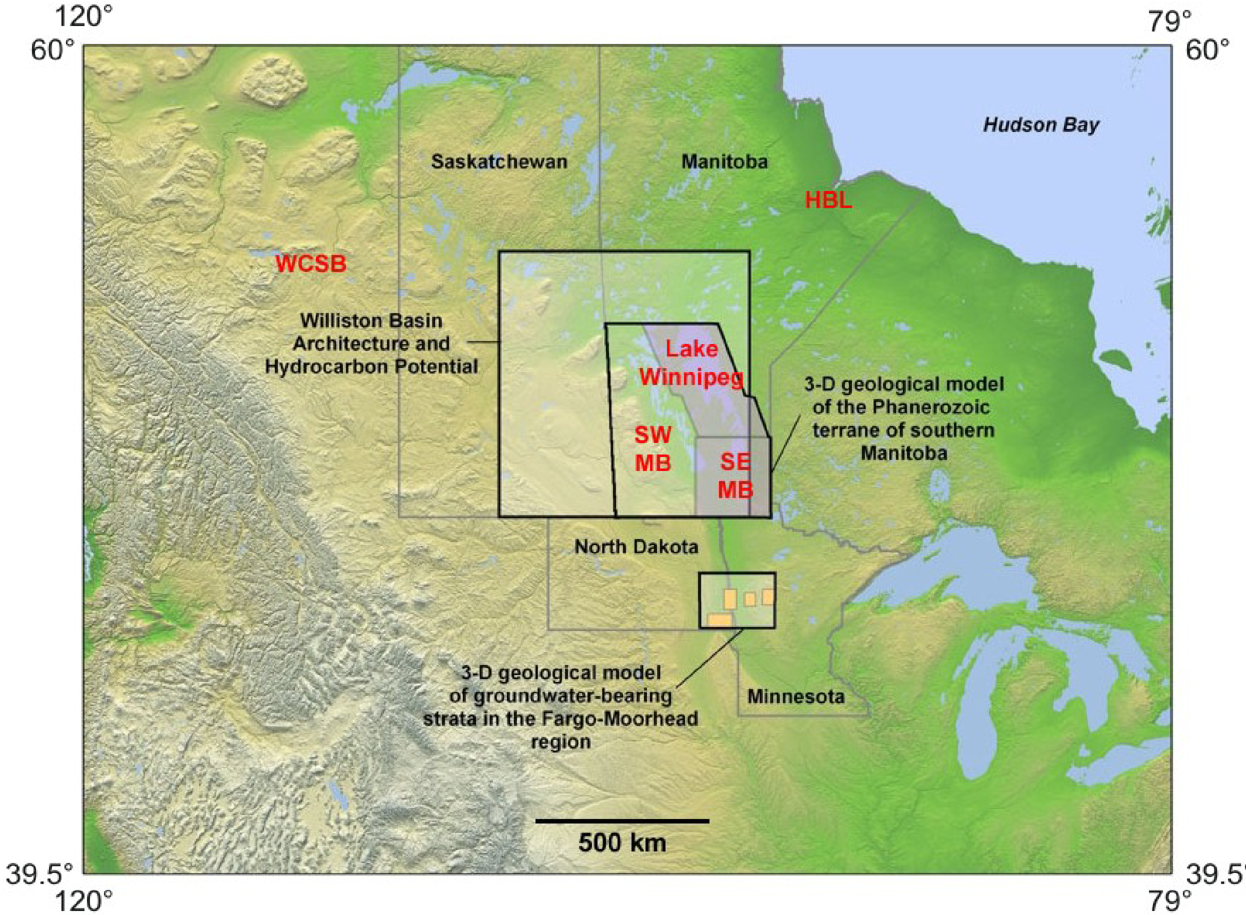


Figure GS-21-1: *Index map outlining the location of the various three-dimensional geological models completed or in progress in southern Manitoba and nearby areas. Yellow blocks indicate areas of higher detail within the Fargo-Moorhead model.*

Table GS-21-1: Three-dimensional geological models in Manitoba: areal extent, details and number of units mapped (Figure GS-21-1).

Model	Latitude Range	Longitude Range	Area	Units
Southeastern Manitoba	49° to 51°N	98° to 95°W	45 000 km^2 (17,500 sq. mi.)	14 bedrock units, 17 Quaternary units
Lake Winnipeg	51° to 54°N	100.3° to 95.3°W	78 000 km^2 (30,000 sq. mi.)	8 bedrock units, 24 Quaternary units
TGI Williston Basin	49° to 55.5°N	106° to 96°W	494 000 km^2 (190,700 sq. mi.)	42 bedrock units
WCSB	Manitoba, Saskatchewan and Alberta		2 920 940 km^2 (1,127,780 sq. mi.)	10 bedrock units (chronostratigraphic)
Southwestern Manitoba	49° to 55°N	101.5° to 98°W	176 225 km^2 (68,041 sq. mi.)	Yet to be determined
Red River Valley	45.5° to 51°N	98° to 95°W	136 100 km^2 (52,550 sq. mi.)	Yet to be determined
Hudson Bay Lowland	~54° to ~59°N	~97.5° to ~89°W	190 060 km^2 (73,400 sq. mi.)	Yet to be determined

Current modelling efforts in southwestern Manitoba employ the same cross-section methodology used in the original southeastern Manitoba model. In order to interpret the cross-sections, which contain all available subsurface information from the area, various forms of surficial data, which provide context, are readily available in an ArcMap® project file. The addition of subsurface data from neighbouring jurisdictions allows for correlation beyond the project area.

Cross-sections

Cross-sections are plotted on 107 by 137 cm (42 by 54 inch) paper. They represent east-west transects drawn every 5 km and include all available data within 2.5 km of the cross-section trace; a sample of a cross-section is shown in Figure GS-21-2. For reference, each cross-section includes two map windows across the top containing bedrock mapped extents and surficial-geology polygons. A shaded-relief digital-elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) and drillhole locations for the area of the cross-section are also displayed. The cross-section itself comprises an SRTM DEM surface profile and drillhole plots from

- the Manitoba water-well database (GW drill, 107 000 drillholes; Manitoba Water Stewardship, 2007),
- the Manitoba Oil and Gas Well Information System database (MOGWIS; 4400 oil and gas wells),
- the Manitoba Stratigraphic Database (4800 drillholes),
- the TGI Williston Basin formation tops database (9012 drillholes; Targeted Geoscience Initiative 2 Working Group, 2009),
- the Western Canada Sedimentary Basin database (750 drillholes), and
- the 27 rotosonic drillholes that were drilled with the support of the Canadian NATMAP program in the early 1990s.

The drillholes are colour coded based on lithology for Quaternary glacial sediments, and by formation for sedimentary bedrock. The cross-sections are correlated by hand, and the stratigraphy is captured every 5 km. The resultant 5 km grid of predicted stratigraphy points is then imported into the GOCAD® software and compiled into a 3-D model. The glacial stratigraphy is then correlated with the prominent published stratigraphic model in the region; Teller and Fenton (1980) was used for southeastern Manitoba and Klassen (1979) was used for southwestern Manitoba.

ArcMap® project file

During the interpretation of the cross-sections, an ArcMap® project was created by compiling additional map data, representing various aspects of published paleogeographic reconstructions for the area (e.g., Elson, 1956; Christiansen, 1979; Klassen, 1979). For example,

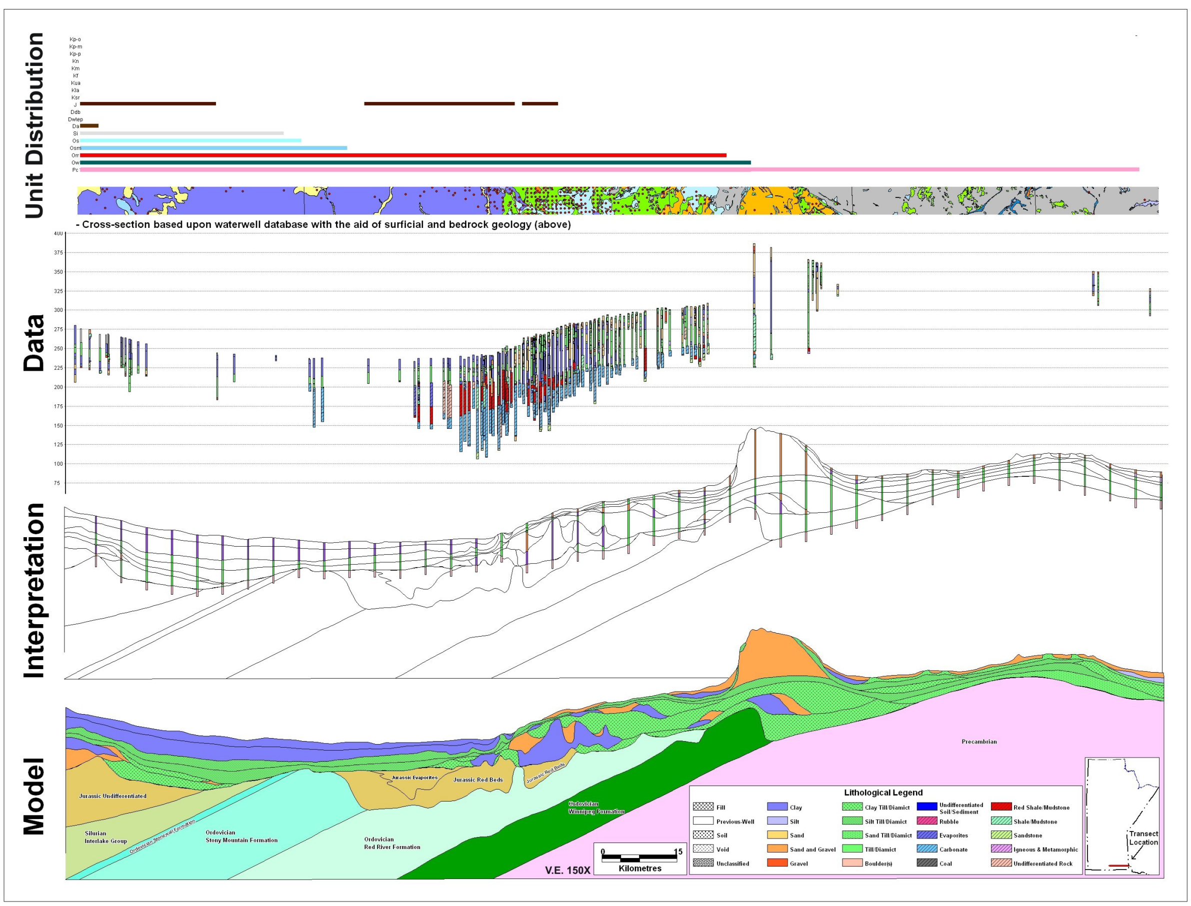


Figure GS-21-2: *Overview of the cross-section methodology of 3-D modelling, showing a typical 5 km east-west transect from southeast Manitoba. Shown at the top are bedrock extent and surficial geology. Below are various iterations of the cross-section and the hand-drawn geological interpretation. Note that the figure is intended to be conceptual, so small text labels within the figure are not intended to be legible.*

the understanding of both glacial processes and glacial Lake Agassiz factor strongly into the interpretation of the cross-sections, and these and other concepts need to be readily available for reference. The map base for the ArcMap project is the surficial geology by Matile and Keller (2007) with shaded relief from the United States Geological Survey (2002). Layers draped on the surficial geology include

- glacial ice margins modified from Thorleifson (1996), Elson (1956) and Christiansen (1979);
- Lake Agassiz shorelines, levels and isobases modified from Thorleifson (1996);
- preglacial drainage from Elson (1956); and
- the locations of various datasets that assist in subsurface correlation, such as river sections from Klassen (1979) and bedrock outcrops.

Correlation with adjacent regions

In order to correlate with previously completed 3-D mapping from eastern Manitoba, cross-sections from western Manitoba are directly compared to cross-sections from eastern Manitoba (southeastern Manitoba and Lake Winnipeg phases). To correlate Manitoba's 3-D mapping with the Saskatchewan subsurface geology along the Manitoba-Saskatchewan border, published cross-sections and depth to bedrock and bedrock geology maps are from the Saskatchewan Watershed Authority (2009).

Model construction

To date, three different approaches to 3-D mapping have been used, based on the nature of the project and data availability. The southeastern Manitoba model was the first attempt at 3-D mapping in Manitoba (Matile et al., 2001). Manually interpreted cross-sections were used to filter datasets with variable data quality. The Lake Winnipeg model used the same approach; the added information derived from high-quality seismic data from the bottom of Lake Winnipeg complemented and enhanced the model's quality and accuracy beyond what was possible with the conventional methods previously used. A different approach was chosen for the TGI Williston Basin Project because of the high-quality project data, which were used directly for 3-D modelling. The biggest issue with the TGI Williston Basin Project was limited drillhole data in the fringe areas, leading to greater uncertainties along the map edges and locally flattened escarpments. A third approach was used in the creation of the WCSB model, converting a published 2-D version of a 3-D geological model into a fully 3-D digital model. This was achieved by scanning and geo-rectifying unit structure contours and edges, and transforming them into 3-D point sets. Current modelling efforts in southwestern Manitoba take advantage of the cross-section methodology and incorporate a modified version of the TGI bedrock dataset. All three approaches are further explained below.

Southeastern Manitoba model

The southeastern Manitoba 3-D geological model (Figure GS-21-3) is based on a 5 km grid of predicted stratigraphy points modelled in GOCAD®. The individual units were modelled from the bottom up, starting with the Precambrian surface. In this methodology, each predicted stratigraphic data point (location) contains a measurement for every possible unit in the model. Where there are no data for a unit, it is given a zero thickness value. The result is a 5 km grid of tops for each mapped unit, which in turn was used to create a surface for that unit. Unit edges were controlled by pressing the modelled surface (upper unit) below the underlying unit where the upper unit doesn't exist (zero thickness value) and then clipping that upper surface with the underlying surface. This methodology allows control over the unit morphology and the nature of the edge. A surface and an 'Sgrid' (GOCAD® stratigraphic grid–solid block model) were created for each of the units in the model.

TGI model

Compared to the highly variable quality of drillhole data in southeastern Manitoba (as described above), drillhole data for the TGI Williston Basin Project were screened at a much higher level of consistency by selecting five to eight deep, stratigraphically significant drillholes per township (10 km by 10 km). This resulting dataset of formation tops, plus a dataset of formation edges, form the basis of the TGI Williston Basin model (Figure GS-21-4). The 3-D surfaces were constructed using these selected formation tops from a total of 9012 wells, including 5046 from Saskatchewan, 2606 from Manitoba, 771 from North Dakota and 589 from Montana. The North Dakota and Montana wells were included to reduce edge effects and to facilitate correlation with the American portion of the Red River Valley 3-D model to be built in the near future. Although data for 60 formation tops are available in the TGI Williston Basin Project, only 42 were selected for modelling. This model is based entirely on the formation-tops dataset, and formation edges that were defined by forcing the surfaces to conform to the predefined TGI formation edges. Due to commonly low data density in fringe areas, especially those areas close to formation edges, the shape of the unit edge, especially along escarpments, tends to be less accurate. The completed model consists of a set of 3-D surfaces; no solid model (block model) was created.

WCSB model

The WCSB 3-D model (Figure GS-21-5) is based entirely on the published structure contours contained in the WCSB Atlas of Mossop and Shetsen (1994). Structure

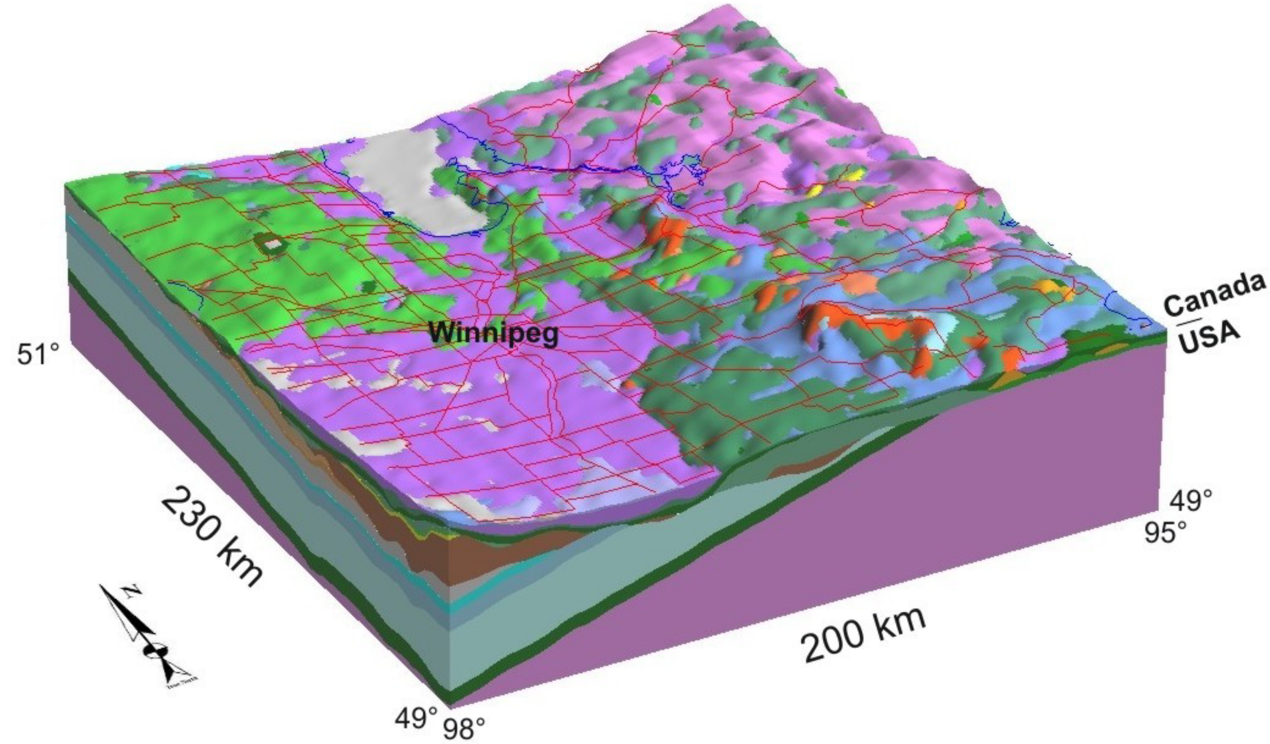


Figure GS-21-3: *Three-dimensional geological model of southeastern Manitoba, including the Winnipeg region.*

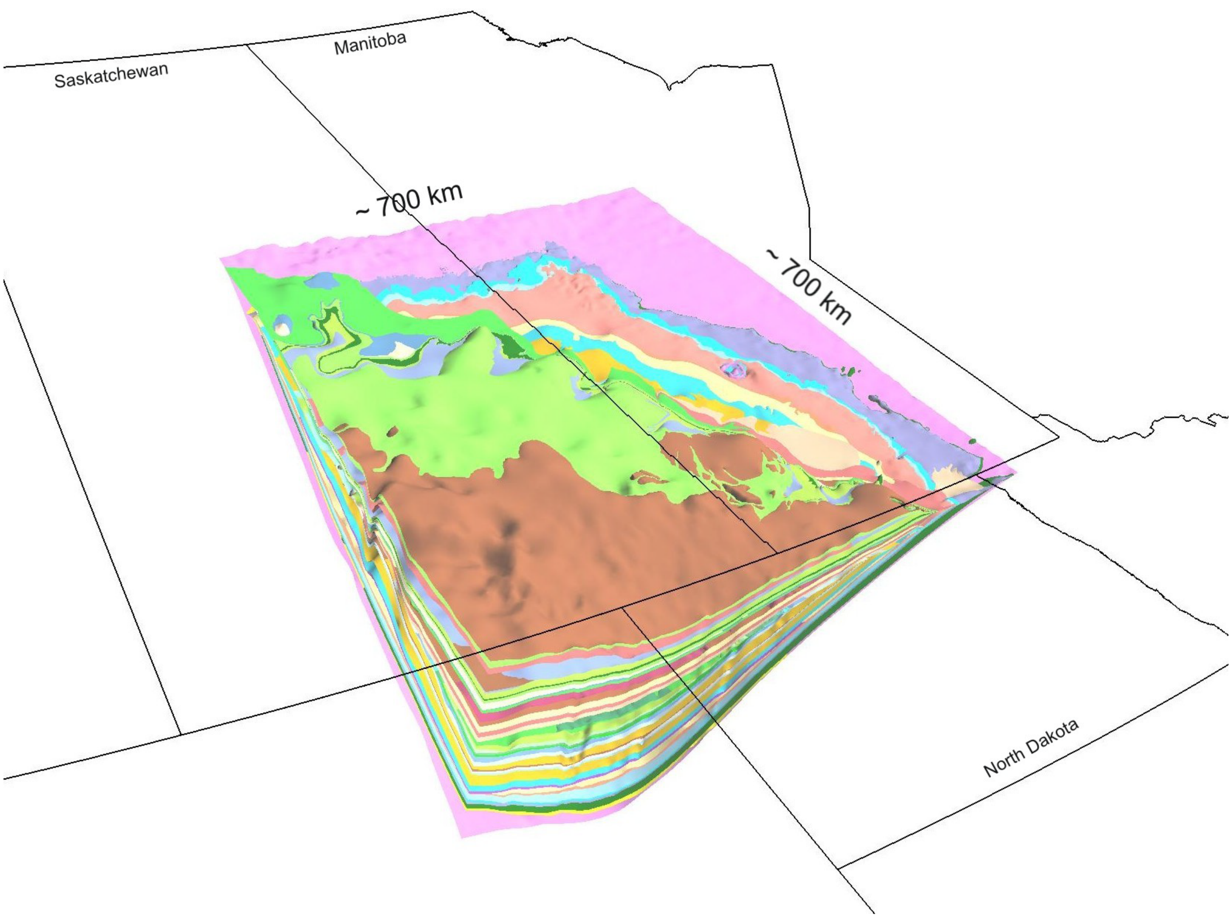


Figure GS-21-4: *Three-dimensional geological model of the TGI Williston Basin Project area.*

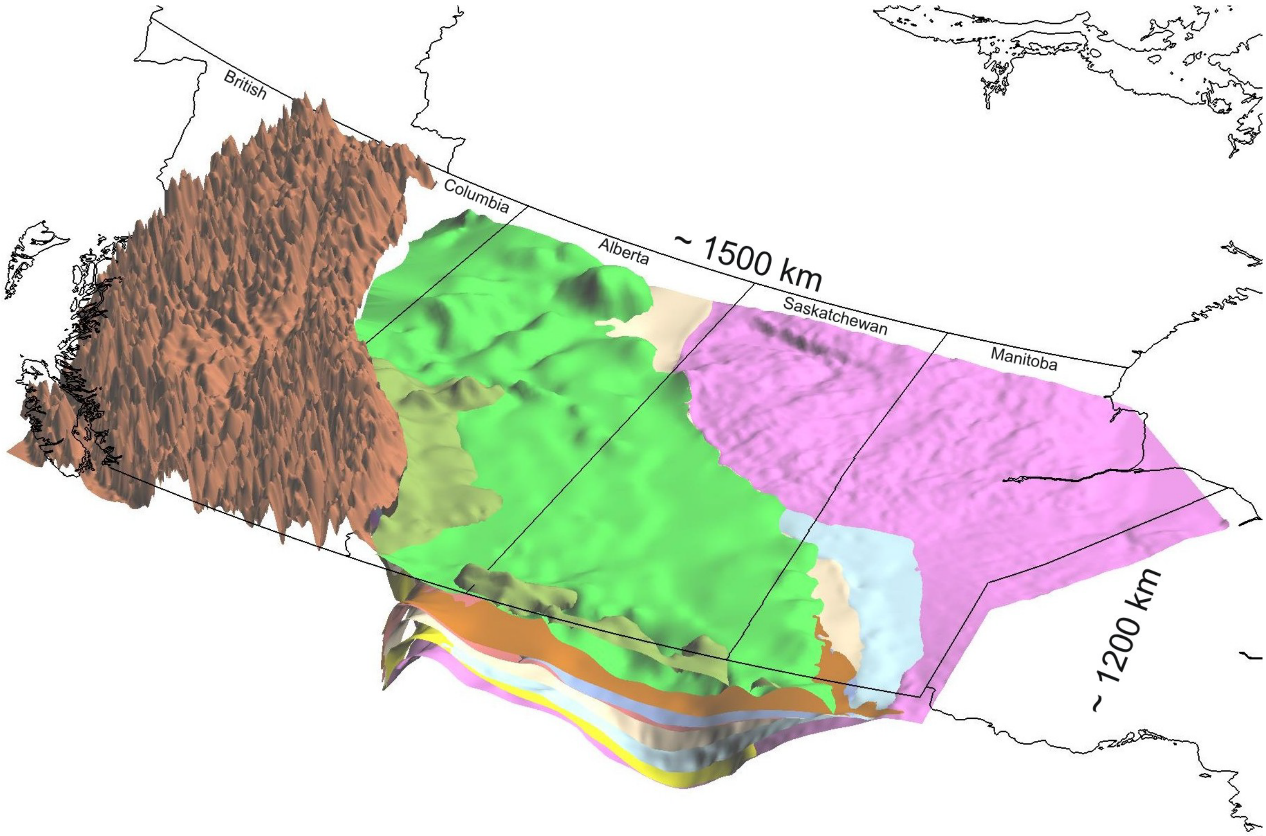


***Figure GS-21-5:** Three-dimensional geological model of the Western Canada Sedimentary Basin, spanning Manitoba, Saskatchewan and Alberta. Model is approximately 1500 km x 1200 km.*

contours for each geological time period were scanned, digitized and geo-rectified. The structure contours were then broken into points and given x-y-z co-ordinates. The same was done with the published edges for each time period, although the edges were pressed onto the next older unit to obtain an elevation. This point dataset, derived from the contours and the unit edges, was then brought into GOCAD® to create a unit surface, which was trimmed at the edge of the model. The completed model consists of a set of 3-D surfaces; no solid model (block model) was created.

Issues

In data-rich areas, a 5 km width of drillholes merged onto a single cross-section trace yields a large dataset that may prove difficult to interpret and manage. In data-poor areas, however, this method generates data that aid interpolation. In data-poor areas, modelled surfaces tend to have ridges parallel to the cross-sections due to slight variations in the interpreted unit tops, an issue that can be eliminated by using strict tops-picking guidelines in drillholes. Having all available data visible on the cross-section, however, ties all available geological data together, even in data-poor areas, and especially in areas of high local relief, whether that relief is at the ground or rock-surface level. Drawing unit edges in plan view and then transposing them into 3-D (as was done in the TGI model) vertically distorts the edges, leading to flattened bedrock escarpments. The southwestern Manitoba model has the benefit of the high-quality TGI dataset. The cross-section method supplements the TGI dataset with predicted stratigraphy points based on extrapolated rock trends onto the interpreted bedrock surface, which may or may not correspond to the ground (SRTM) surface. This provides the ability to alter the TGI rock surfaces and integrate them with the glacial-sediment data.

Another potential issue is the buried valleys in southern Manitoba. A network of preglacial/Tertiary buried-valley aquifers has been cut into the bedrock surface but has not been systematically mapped in detail. As a consequence, some of these channels, which are locally important water sources, may not have been recognized in some of the cross-sections, particularly where the channel intersects the cross-section at a low angle.

Economic considerations

Manitoba plays an active and leading role as a contributor to local, national and international 3-D modelling projects. The 3-D models, which unite disparate datasets and put them into a single standardized nomenclature, significantly contribute to a variety of geoscience knowledge bases relevant to Phanerozoic stratigraphy, hydrocarbon, groundwater and industrial-mineral resource development, and geological education.

An increasing number of applications for emerging 3-D models reflect the value of 3-D geological mapping. For example, the 3-D model for the Winnipeg-area NATMAP has been successfully used to model groundwater flow across the Winnipeg region and to assess climate-change scenarios with respect to impacts on groundwater (Kennedy and Woodbury, 2002). New and ongoing modelling (TGI, WCSB, southwestern Manitoba) is significantly contributing to our understanding of the Assiniboine Delta Aquifer (ADA), which is of high economic importance to the province. The ADA is centred on the community of Carberry, which hosts a large and growing potato industry. This local example of a relatively new industry owes its existence to the sandy soils of the ADA, required for potato growth, and to the availability of abundant groundwater resources needed for irrigation and food processing. Programs such as the cross-border 3-D geological mapping of the Red River Valley, in comparison, assist in groundwater management at far larger scales on both sides of the Canada–United States border.

References

Christiansen, E.A. 1979: The Wisconsin deglaciation of southern Saskatchewan and adjacent areas; Canadian Journal of Earth Sciences, v. 16, p. 913–938.

Elson, J.A. 1956: Surficial geology of the Tiger Hills region, Manitoba; Ph.D. thesis, Yale University, New Haven, Connecticut, 316 p.

Kennedy, P.L. and Woodbury, A.D. 2002: Geostatistics and Bayesian updating for transmissivity estimation in a multiaquifer system in Manitoba, Canada; Ground Water, v. 40, p. 273–283.

Kennedy, P.A. and Woodbury, A.D. 2005: Sustainability of the bedrock aquifer systems in south-central Manitoba: implications for large-scale modeling; Canadian Water Resources Journal, v. 30, no. 4, p. 281–296.

Klassen, R.W. 1979: Pleistocene geology and geomorphology of the Riding Mountain and Duck Mountain area, Manitoba-Saskatchewan; Geological Survey of Canada, Memoir 396, 52 p.

Manitoba Water Stewardship 2007: GWDrill: a data base of water well logs and groundwater chemistry for the province of Manitoba; Manitoba Water Stewardship, Groundwater Management Section, Winnipeg, Manitoba.

Matile, G.L.D. and Keller, G.R. 2007: Surficial geology of Manitoba; Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Surficial Geology Compilation Map Series, SG-MB, scale 1:1 000 000.

Matile, G.L.D., Thorleifson, L.H., Bamburak, J.D., Bezys, R.K., Nicolas, M.P.B., Conley, G.G., Keller, G.R. and Pyne, M. 2001: Construction of a three-dimensional geological model for the southern Manitoba Phanerozoic terrane; *in* Report of Activities 2001, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 152–155.

Mossop, G.D., and Shetsen, I., compilers 1994: Geological Atlas of the Western Canada Sedimentary Basin; Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report 4, 509 p.

Saskatchewan Watershed Authority 2009: Geology and groundwater resources of southern Saskatchewan; Saskatchewan Watershed Authority, URL <http://www.swa.ca/WaterManagement/Groundwater.asp?type=Mapping> [October 2009].

Teller, J.T. and Fenton, M.M. 1980: Late Wisconsinan glacial stratigraphy and history of southeastern Manitoba; Canadian Journal of Earth Sciences, v. 17, p. 19–35.

Targeted Geoscience Initiative 2 Working Group 2009: Williston Basin TGI; Manitoba Geological Survey and Saskatchewan Geological Survey, URL <http://www.willistontgi.com> [September 2009].

Thorleifson, L.H. 1996: Review of Lake Agassiz history: sedimentology, geomorphology and history of the central Lake Agassiz basin; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Winnipeg, Manitoba, May 27–29, 1996, Field Trip Guidebook B2, p. 56–79.

Thorleifson, L.H., Harris, K., Berg, J., Tipping, R., Malolepszy, Z., Lusardi, B., Setterholm, D. and Anderson, F. 2005: Geological mapping and 3D model of deposits that host ground-water systems in the Fargo-Moorhead region, Minnesota and North Dakota; Minnesota Geological Survey, 155 p.

United States Geological Survey 2002: Shuttle Radar Topography Mission, digital elevation model, Manitoba; United States Geological Survey, URL <ftp://edcsgs9.cr.usgs.gov/pub/data/srtm/>, portions of files N48W88W.hgt.zip through N60W102.hgt.zip, 1.5 Mb (variable), 90 m cell, zipped hgt format [March 2003].