CONSTRUCTION OF A HYDROSTRATIGRAPHIC MODEL FOR SOUTHERN MANITOBA

L. H. Thorleifson, Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8; Telephone 613-992-3643; Fax 613-992-0190; thorleifson@gsc.nrcan.gc.ca
G. L. D. Matile, Manitoba Geological Survey, 1395 Ellice Ave., Winnipeg MB R3G 3P2, Telephone 204-945-6530; Fax 204-945-1406; gmatile@gov.mb.ca
G. R. Keller, Manitoba Geological Survey, 1395 Ellice Ave., Winnipeg MB R3G 3P2; Telephone 204-945-6744; Fax 204-945-1406; grkeller@gov.mb.ca
D. M. Pyne, Geological Survey of Canada, 601 Booth Street, Ottawa, ON K1A 0E8; Telephone 613-943-8200; Fax 613-992-0190; thorleifson@gsc.nrcan.gc.ca

ABSTRACT
In southern Manitoba, modelling is being used to guide groundwater protection and management. New methods for the development of regional hydrostratigraphic models were developed based on a pilot model of the 200 km-wide Winnipeg area. A digital elevation model was constructed by gridding legal survey data. Large lakes were modelled using 31,607 soundings from 22 hydrographic charts. Offshore geology of Lake Winnipeg was interpreted from geophysical and coring data collected from a Coast Guard ship. Surficial geological maps were digitized and reconciled. Quaternary stratigraphy was defined at cored holes logged by geologists and geophysical surveys, and extrapolated laterally with the aid of drillhole data, soils, surficial geology, and topography. Reconciled and superimposed bedrock polygons for all Phanerozoic strata were constructed, and positioned vertically using newly digitized structure contours. A model for the remaining Phanerozoic succession of southern Manitoba is now being built, in coordination with corresponding work in neighbouring jurisdictions.

RÉSUMÉ
Dans Manitoba méridional, le modelage d'eau souterraine est utilisé pour diriger de la protection et gestion d'eau souterraine. Les nouvelles méthodes pour le développement des modèles de hydrostratigraphic régionaux exigés ont été développées basé sur un 200-km modèle de pilote à Winnipeg. Un modèle numérique d'élévation a été construit par gridding les données d'étude légales. Les grands lacs ont été modelés l'utilisation 31,607 sons de 22 graphiques de hydrographic. La géologie de Lac Winnipeg a été interprétée de géophysique et évide des données recueillies d'un bateau de Garde de Côte. Les cartes géologiques superficielles ont été digitalisées et ont été réconciliées. Quaternary stratigraphy a été défini à a évidé des trous notés par les géologues et les études géophysiques, et les données de drillhole latéralment utilisant alors extrapolé. Nouveau, réconcilié, et les polygones superposés de fondement pour toutes couches de Phanerozoic ont été construits, et a été disposé verticalement l'utilisation contours de structure récemment digitalisés. Un modèle pour la succession de Phanerozoic restant de Manitoba méridional est maintenant construit, dans la coordination avec correspondre de travail dans les juridictions avoisinantes.

1. INTRODUCTION

The National Geoscience Mapping (NATMAP) program of the 1990s was established as a collaborative effort among Canada's federal, provincial, industry, and academic geoscience community to promote multidisciplinary and cooperative geological mapping. Under the Prairie NATMAP project, new geological mapping and stratigraphic investigations were carried out in the Virden area of southwestern Manitoba and southeastern Saskatchewan (Blais-Stevens et al., 1999; Schreiner and Millard, 1995), as well as in the Winnipeg region of southeastern Manitoba.

The objectives of the Winnipeg-area geological mapping were to generate new, computer-based geological maps that would support a broad range of applications, including the requirements of associated investigations of regional hydrogeology, Lake Winnipeg shoreline erosion, and Red River flooding. A key objective of the activity was groundwater modelling (Kennedy, 2002).

To support regional groundwater modelling, mapping in the Winnipeg study area was extended into the subsurface with the aid of drillhole data and geophysical surveys, to develop a 3D lithostratigraphic model for the Quaternary sediments (Matile et. al, 1999b). Extension of the model to encompass the entire Phanerozoic succession was completed collaboratively with other programs of the Manitoba Geological Survey, including Phanerozoic stratigraphic investigations and the Capital Region study (Bezys et al., 2002). This pilot 3D model for the Winnipeg region was successfully used to model groundwater flow across the region and to assess climate change scenarios with respect to impacts on groundwater systems (Kennedy, 2002).

Following completion of the Winnipeg area pilot model, a project to develop a 3D stratigraphic model for the entire Phanerozoic terrane of southern Manitoba was launched (Matile et. al, 2000; 2001). This study area encompasses most of the area south of 55°N and east of 102°W, a region over 400 km west to east and 600 km north to south. This paper reviews the methods developed to construct this model.

2. INPUTS TO THE MODEL

In anticipation of the completion of a model for all of southern Manitoba, and to facilitate development of database protocols, work toward the Winnipeg pilot in many cases included preparation of inputs for the province-wide model. The methods and status of the activity with respect to the various required inputs is here summarized.

2.1 Topography

A 100-m grid cell digital elevation model (DEM) was used as a datum for all inputs to the model, including vertically positioning of drillholes and the upper surface of the model. It has also been used for landform analysis, and has drawn attention to previously unrecognized geological features. Data input for development of this model included rectification data for provincial digital orthophotography, federal 1:50,000 and 1:250,000 topographic maps, and DEM's from neighbouring jurisdictions. Horizontal grid resolution for the DEM is 100 m, and absolute vertical accuracy, based on an audit using primary vertical control, is about $\pm$ 3 m.

2.2 Bathymetry

To incorporate large lakes, including Lake Winnipeg, Lake Manitoba, Lake Winnipegosis, Playgreen Lake, and Lake of the Woods into the 3D model, 31,607 soundings on 22 Canadian Hydrographic Service (CHS) charts were digitized and their locations were corrected relative to shorelines as depicted on NTS 1: 250 000 topographic maps. The data were modelled at 100 m resolution after adjustment of the soundings from the varying CHS low-water datum to a consistent value for long term mean lake level, and following addition of shorelines and shoals to the database.

2.3 Offshore geology

During two cruises of the Canadian Coast Guard Ship *Namao* in 1994 and 1996 (Todd et al., 1998), low frequency and high frequency seismic data were acquired for over 1000 km of survey lines. The seismo-stratigraphy was interpreted for the Quaternary sediments, and Paleozoic bedrock was differentiated from Precambrian on the basis of geometry and elevation. Till in some cases was distinguished from Paleozoic bedrock where seismic velocities could be inferred. The offshore Quaternary and Paleozoic geology was then modelled, guided by geology on land, bathymetry, and seismic data digitized in the form of line-traces captured as profiles at intervals of five seconds of ship travel time.

2.4 Soil mapping

Digital soil maps produced by agricultural agencies provide information on the texture and composition of sediment in the uppermost metre of the Quaternary sequence. Procedures to incorporate these data into the model are being assessed, such as inclusion of an upper stratum much more detailed than those below.

2.5 Surficial geology

A digital compilation at 1: 250,000 of the surficial geology of southern Manitoba is being completed. A large part of this task is the conversion of data from paper maps to digital vector coverages. Map legends are being standardized and map polygon boundary discrepancies are being reconciled with adjacent mapsheets. The map legend will define map units on the basis of factors such as texture, mineralogy, morphology, and genesis of the sediments at depths of about one metre. These maps guided the 3D modelling, although at present the surficial mapping is more detailed than the resolution that can be achieved in the 3D subsurface model. Consequently, the two models are not fully integrated, so subsurface Quaternary strata outcrop as polygons that are generalized relative to the 1: 250, 000 mapping.

2.6 Quaternary stratigraphy

The 3D stratigraphic model of the Quaternary sediments was completed for the Winnipeg area by first updating the lithostratigraphic model for the region based on previous research (Teller and Fenton, 1980) and NATMAP project coring (Thorleifson and Matile, 1993). The stratigraphic correlations available at drillholes logged in detail were extrapolated laterally with the aid of geophysical surveys, other drillhole data, topography, and surficial geology.

A key source of data was the 80,000-site water well database of the Manitoba Conservation

Water Branch (GWDrill). Much effort was required to parse the 75 000 unique lithological descriptions in this database into geologically meaningful terms suitable for database operations. Additionally, it was necessary to assign locations at quarter section or river lot centroids, as well as elevations from the DEM, to the sites.

For the NATMAP pilot, the 200 km x 230 km area was divided into 46 transects each 5 km wide, and a large colour cross-section chart was printed for each transect, showing all drillhole data, surficial geology, and surface elevation. The drillhole data, colour-coded for lithology, were interpreted as a series of vertical maps using established techniques for lithostratigraphic correlation (e.g. Miall, 2000), although the water well data is variable in resolution and reliability, and rarely permitted the distinction of the units recognized at the stratigraphic reference sites. At best, it can be said that the water well data guided interpolation between already-correlated units, and allowed recognition of stark lithological breaks such as large sand lenses.

To facilitate groundwater modelling, for example, it was necessary to include in the model predictions for the sediments likely present in areas for which no data was available. The hand-drawn section approach, in which correlations were not linked to specific drillhole intersections, permitted the geologist to apply judgement by occasionally ignoring data based on suspect lithological descriptions or locations apparently in error. The resulting west-east cross sections were hand drawn as an overlay on the drillhole data, and the interpretation was captured as predicted stratigraphy points at 5-km intervals. It is anticipated that the same methods will be used for the expanded study area, although plans are in place to experiment with an alternative approach in which the polygons drawn on the sections are digitized and linked to their lateral equivalents.

2.7 Bedrock surface

Because the bedrock surface is being interpreted on all transects, a new bedrock elevation model will be produced as the new Quaternary model is compiled.

2.8 Bedrock geology

Model construction to date has been guided by Manitoba Geological Survey 1:1,000,000 bedrock geology map polygons, following linkage and reconciliation of polygons depicting outcrop and subcrop. A major effort was required to produce stacked polygons, in which each stratum is not truncated at the limits of overlying strata. Conversion of the model to reliance on 1:250,000 polygons presently is being assessed, as is revision of this mapping based on the drillhole compilation completed for the project. This compilation includes all available drill hole data, including Manitoba Stratigraphic Database (MSD), Manitoba Oil and Gas Well Information System (MOGWIS), Western Canada Sedimentary Basin Atlas database (WCSB), as well as newly digitized data previously stored on historical index cards.

2.9 Phanerozoic stratigraphy

Stratigraphic maps with structure contours and isopachs of the Phanerozoic strata were previously compiled by Manitoba Geological Survey (Bezys and Conley, 1999). The digital versions of these stratigraphic maps were obtained, and supplemented where necessary with information from the Western Canada Sedimentary Basin Atlas (Mossop and Shetsen, 1994).

A point dataset derived from the structural contours for each unit was gridded and trimmed to their extent as defined by the 1:1,000,000 mapping. The model has more units than were depicted in the Atlas, although less than are recognized in the Manitoba Geological Survey Stratigraphic Database, which includes many units that are only recognizable in limited areas.

Modifications were required for pairs of previously modelled surfaces for which interpolations in data-poor areas were found to intersect. Whereas the current Phanerozoic model was derived directly from previously published stratigraphic maps, construction of a revised model is being contemplated, based on the drillhole compilation previously described. The water well database also provides lithological data that can constrain the mapping. The drillhole data are now being plotted using methods similar to those previously described for the Quaternary.

2.10 Sub-Phanerozoic Precambrian geology

A sub-Phanerozoic Precambrian geology map for all of southern Manitoba Phanerozoic terrane was prepared in order to complete the model down to the deformed basement rocks. This map was compiled from aeromagnetic maps, compilation maps, and subsurface correlation of drilled Precambrian intervals.

3. MODELLING METHODS.

The southern Manitoba Phanerozoic 3D model envisaged here is intended to eventually supersede paper maps and their digital equivalents, so the methods that are being adopted are meant to conform to this objective.

Traditionally, geological maps depict the extent of the uppermost stratum in the range of strata being mapped, while the legend, structural symbols, and cross sections convey superposition. Structural maps have shown the geometry of multiple strata by providing structure contours for the top of each stratum, which can be expressed as an isopach when one is subtracted from another. Structural charts typically have not, however, shown the elevation of the eroded edge of a stratum, the outcrop and subcrop, as this elevation is not relevant to interpreting the structural geology of the unit.

This lack of elevation information for the eroded portion of a stratum is a limitation that requires correction before full 3D modelling can proceed. Hence achievement of the objectives described here not only require selection of appropriate methods with reference to available software and previous research (e.g. Shetsen and Mossop, 1994; Houlding, 1994), a specification of strata more comprehensive than previously attempted is required. An adequate definition of a stratum will require full extent, elevation of its top, extent of its edge, and elevation of its edge.

Modelling of the top elevation of each stratigraphic unit is being completed using an appropriate interpolation procedure, typically triangular irregular network (TIN) methods. A principal challenge is to avoid intersection of surfaces in data-poor areas. Methods for achieving this objective that are being tested include computer-based multiple-surface modelling procedures, database approaches to force the surfaces into order, and/or arithmetic approaches to remove intersections and impose a minimum thickness. Another issue in modelling surfaces is choice of an appropriate compromise between strictly honouring data points, and obtaining a slightly smoothed model that will aesthetically appear reasonable.

In the case of the Winnipeg pilot (Figure 1), the 3D model was conveyed as a series of surfaces modelled as TINs. There are advantages, however, in converting the intervals between the surfaces to solids, either hollow or filled. Advantages include greater ability to interactively produce cross sections with a pattern or colour filling each stratum, as well as an ability to assign properties to each solid, and to analyze it from the point of view of volume. It has been found, however, that constructing solids that do not 'leak' is a nontrivial exercise that requires selection among many options, as well as acceptance of unanticipated compromises such as simplification. Experiments completed for the project to date include hollow solids that produce linework cross-sections, as well as solids built as a matrix of tetrahedra that have some advantages but are very large to store and slow to manipulate and give cross sections with a corrugated effect. The currently favoured approach is construction of a grid of vertical rectangular solids of varying thickness. The resulting solid is slow to manipulate in interactive applications using current computer technology.

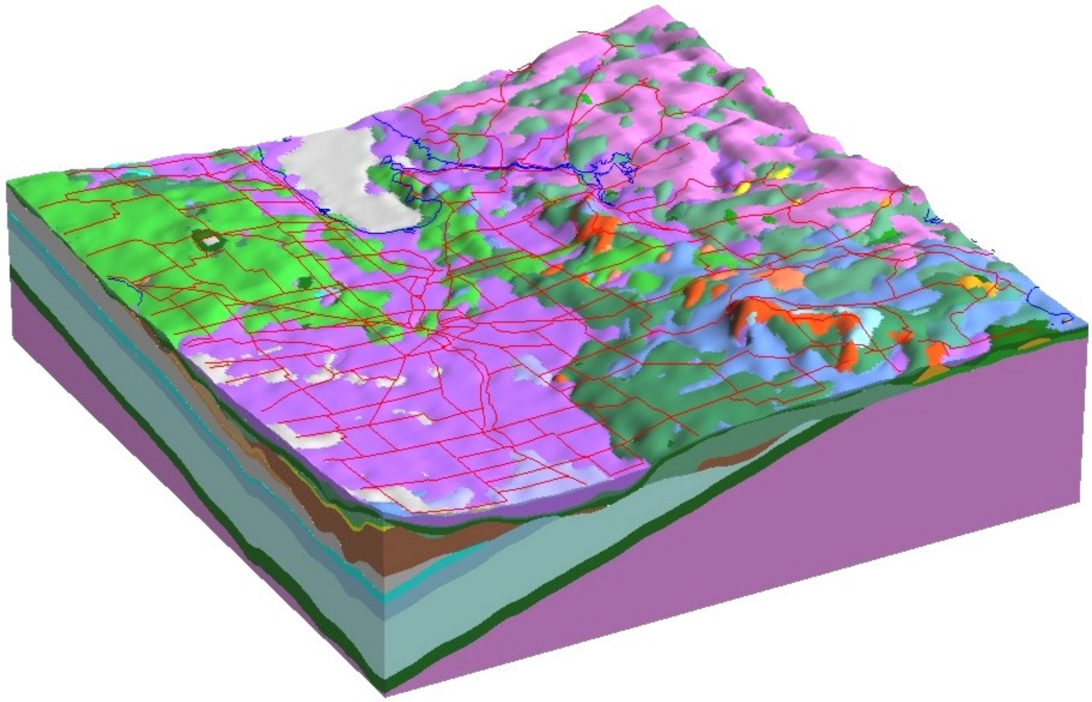
Current procedures now allow a discontinuous stratum to be stored in the model as one unit with varying thickness. Where absent, however, the stratum must be specified as being present, but with a thickness of zero. This requirement has presented challenges. For example, a thickness of zero has to be specified for every Phanerozoic stratum at a Precambrian outcrop in eastern Manitoba. Because some smoothing and therefore slight deviation from data points are required for the surfaces to be aesthetically acceptable, successive zero thickness strata may not exactly coincide beyond the extent of the actual stratum where it has a non-zero thickness. This would lead to a patchwork of fictitious thin outliers, some with negative thickness.

This has been overcome by cutting out the area beyond the extent of a stratum from the next underlying continuous stratum, and stitching that surface to the less continuous stratum. For example, the top of the Precambrian east of the extent of the Winnipeg Formation has been spliced to the top of the Winnipeg Formation where it is present, so the top of zero-thickness Winnipeg Formation east of its extent is exactly coincident with the top of Precambrian. A good 'seal' between the two surfaces is ensured if the top of the stratum beyond its extent is lowered in elevation prior to modelling. The extent to which the zero thickness stratum needs to be pushed down in the area beyond its extent requires an iterative approach to achieve the desired result. Failure to seal individual surfaces results in thin tongues projecting beyond the actual extent of the stratum.

4. CONCLUDING REMARKS

The assembly of inputs, both data and interim models, was completed concurrently with iterative selection of modelling procedures. The model then will serve as the basis for identifying priorities areas for upgrade. Areas requiring upgrading will be identified using a confidence level based predominantly on data density and geological complexity and a priority level based on social and economic issues. The model then would be upgraded in increments indefinitely, with protocols in place for version identity and

Figure 1. Pilot hydrostratigraphic model for the 200 by 230-km Winnipeg region, extending from Lake Winnipeg at upper center to Lake of the Woods at lower right, which facilitated successful regional groundwater modeling (Kennedy, 2002), and which permitted the development of new methods for regional hydrostratigraphic modeling that are now being applied to all of southern Manitoba.



documentation. Concurrently with refinement of models that define the outline geometry of units, progress will be required in defining the properties of the strata and their variability (e.g. Fraser and Davis, 1998).

Finally, a major issue that is progressively being dealt with is the requirement to reconcile the model with corresponding activity in Saskatchewan, North Dakota, Minnesota, and Ontario. Applications such as hydrocarbon and groundwater analyses in cross-border settings will fail if the respective models are not compatible. Achieving compatibility will require consultations, data sharing, and compromise. When complete, the model will have many applications such as groundwater modelling, oil and gas assessments, and industrial mineral management.

REFERENCES

Berg, R.C. and Thorleifson, L.H. 2001. Geological Models for Groundwater Flow Modeling. Geological Society of America North-Central Section, Workshop Extended Abstracts. Illinois State Geological Survey Open File Series 2001-1, 62 pp.

Bezys, R.K. and Conley, G.G. 1999. Manitoba Stratigraphic Database and the Manitoba Stratigraphic Map Series. Manitoba Energy and Mines, Geological Services, Open File Report OF98-7, one CD.

Bezys, R.K., Bamburak, J.D. and Conley, G.G. 2002. Capital Region Study (Winnipeg and Surrounding Areas) Update and Stratigraphic Drilling 2002, Manitoba. Report of Activities 2002, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, pp. 266-272.

Blais-Stevens, A., Sun, C. and Fulton, R.J. 1999. Surficial geology, Virden, Manitoba-Saskatchewan. Geological Survey of Canada; A-Series Map 1922A, Scale 1:125 000.

Fraser, G.S. and Davis, J.M. 1998. Hydrogeologic models of sedimentary aquifers. SEPM Concepts in Hydrogeology and Environmental Geology No. 2, 188 pp.

Houlding, S.W. 1994. 3D Geoscience Modeling. Springer-Verlag, New York, 309 pp.

Kennedy, P.L. 2002. Groundwater flow and transport model of the Red River/Interlake area in southern Manitoba. University of Manitoba Ph.D. thesis, 273 pp.

Matile, G.L.D., Bamburak, J.D., Bezys, R.K., Conley, G.G., Burt, A.K., Grant, N.M., Mann, J.D., McDougall, W.J., Hughes, J.D., Thorleifson, L.H. 1999a. New 3D geological mapping, Winnipeg region, Manitoba, Canada. Geological Society of America, North-Central Section, Champaign, Illinois, Abstracts with Programs v. 31, no. 5, p. A-58.

Matile, G.L.D., Thorleifson, L.H., Grant, N., Burt, A., and Mann, J. 1999b. Geology of the Winnipeg Region NATMAP Project (NTS 62H/W, 62I and 52L/W). in Report of Activities 1999, Manitoba Industry, Trade and Mines, Geological Services, pp. 114-115.

Matile, G.L.D., Thorleifson, L.H., Bamburak, J., Bezys, R., Burt, A., Conley, G., Grant, N., Keller, G., Mann, J., McGregor, C., and Pyne, M. 2000. Geology of the Winnipeg Region NATMAP Project: 1999-2000 Progress (NTS 62H/W, 62I and 52L/W). in Report of Activities 2000, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, pp. 189-193.

Matile, G.L.D., L.H. Thorleifson, J.D. Bamburak, R.K. Bezys, M.P.B. Nicolas, G.G. Conley, G.R. Keller, and M. Pyne 2001. Construction of a 3D geological model for the southern Manitoba Phanerozoic terrane. in Report of Activities 2001, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, pp. 152-155.

Miall, A.D. 2000. Principles of Sedimentary Basin Analysis. Springer-Verlag, New York, 616 pp.

Mossop, G.D. and Shetsen, I. (compilers) 1994. Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists (Calgary) and Alberta Research Council, 510 pp.

Shetsen, I. and Mossop, G.D. 1994. in Mossop, G. D. and Shetsen, I. (compilers), Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists (Calgary) and Alberta Research Council, pp. 503-507.

Schreiner, B.T. and Millard, M.J., 1995. Quaternary stratigraphic framework for the Virden area (62F). Saskatchewan Research Council Publication R-1210-8-E-95 18 pp.

Teller, J.T. and Fenton, M.M. 1980. Late Wisconsinan glacial stratigraphy and history of southeastern Manitoba. Canadian Journal of Earth Sciences, 17, pp. 19-35.

Thorleifson, L.H. and Berg, R.C. 2002. Three-dimensional geological mapping for groundwater applications: workshop extended abstracts. Geological Survey of Canada Open File 1449, 87 pp.

Thorleifson, L.H. and Matile, G.L.D. 1993. Till geochemical and indicator mineral reconnaissance of southeastern Manitoba. Geological Survey of Canada Open File 2750, 1 diskette.

Thorleifson, L.H., Matile, G.L.D., Bamburak, J.D., Bezys, R.K., Conley, G.G., McDougall, W.J., Hughes, J.D., Burt, A.K., Grant, N.M., Mann, J.D., 1999. New 3D geological mapping, Winnipeg region, Manitoba, Canada. Geological Society of America Annual Meeting, Denver, Abstracts with Programs v. 31, no. 7, p. A-81.

Todd, B.J., Lewis, C.F.M., Nielsen, E., Thorleifson, L.H., Bezys, R.K., and Weber, W. 1998. Lake Winnipeg: geological setting and sediment seismostratigraphy. Journal of Paleolimnology, v. 19, pp. 215-244