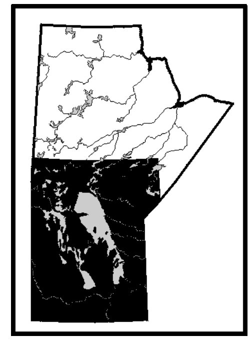
GS-32 DEVELOPMENT OF METHODS FOR 3-D GEOLOGICAL MAPPING OF SOUTHERN MANITOBA PHANEROZOIC TERRANE

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



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SUMMARY

Three-dimensional (3-D) geological mapping of the Phanerozoic succession in southern Manitoba, south of latitude 55°N and west of longitude 95°W, is being completed as a successor activity to the Prairie component of the National Geoscience Mapping Program (NATMAP). The mapping is taking advantage of current developments in computer technology and is designed to support activity related to hydrocarbon, groundwater and industrial mineral development, for example. Much of the input data is in place, including topography, bathymetry, offshore geology, soil mapping, surficial geology, Quaternary stratigraphy, bedrock surface, bedrock geology, Phanerozoic stratigraphy and sub-Phanerozoic Precambrian geology. In addition, drillhole data crucial to the completion of a 3-D model for the Quaternary, as well as a revision of the Phanerozoic succession, have been compiled. The drillhole data compilation now links to water-well data held by the Water Branch of Manitoba Conservation, the Manitoba Stratigraphic Database (MSD), the Manitoba Oil and Gas Well Information System (MOGWIS) and newly digitized records held by the Manitoba Geological Survey. The Manitoba Geological Survey and the Geological Survey of Canada are carrying out development of the required 3-D protocols on a cooperative basis. Progress is being benchmarked with that of other Canadian, American and European geological survey organizations at international workshops in Illinois in 2001 and Denver in October 2002. These workshops are being sponsored by the Geological Survey of Canada and the Illinois State Geological Survey. The key activity during 2001 and 2002 has been the selection of computer hardware and software and the refinement of model construction, verification and communication procedures.

INTRODUCTION

The National Geoscience Mapping (NATMAP) program of the 1990s was established as a collaborative effort between Canada's federal and provincial governments, industry and the academic geoscience community to promote multidisciplinary, cooperative, geological mapping. Under the Prairie NATMAP project, new surficial geological mapping and Quaternary 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 Winnipeg project began in the early 1990s with mapping of an area south of latitude 50°N and east of longitude 97°W, an area equivalent in extent to one NTS 1:250 000 map sheet. Four preliminary surficial geology maps were produced for this area at a scale of 1:100 000. In the late 1990s, the Winnipeg study area was expanded to encompass the area south of latitude 51°N and east of longitude 98°W, the 200 km wide area south of Hecla Island and east of Portage la Prairie. The expanded study area was mapped as 12 surficial geology maps at a scale of 1:100 000, including the four maps from the first phase. These maps are in the final stages of production.

The objectives of the Winnipeg-area NATMAP and associated hydrogeology, Lake Winnipeg and Red River projects were to generate new, computer-based geological maps in order to better understand the geological features of the area. To enhance our ability to carry out geological investigations, NATMAP also made commitments to establish an infrastructure for the rapid production of digital maps and to train field geologists. Applications for the mapping include facilitation of mineral exploration, support for construction and other engineering activity, support for groundwater management, a better understanding of Lake Winnipeg shoreline erosion, as well as support for environmental and land-use management.

The NATMAP mapping in the expanded Winnipeg study area was extended into the subsurface with the aid of drillhole data and geophysical surveys, to develop a 3-D 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., GS-30, this volume). This pilot 3-D model for the Winnipeg region has been 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 3-D stratigraphic model for the

[1] Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8

entire Phanerozoic terrane of southern Manitoba was launched (Matile et al., 2000, 2001). This study area encompasses most of the area south of latitude 55°N and east of longitude 102°W, a region over 400 km west to east and 600 km north to south. This paper reviews the progress in planning for and preliminary steps toward that model. First, the progress in the assembly of inputs, both data and partially processed modelling, is summarized. Then some of the issues raised by ongoing attempts to define potential protocols for final 3-D model construction, verification and communication are discussed.

INPUTS TO THE MODEL

Assembly of the data and partially processed portions of the model that will be required for the southern Manitoba Phanerozoic model is nearing completion. These inputs include the following:

Topography

A 100 m grid cell digital elevation model (DEM) is being used as a datum for all data input to the model, including vertically positioning 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 DEMs from neighbouring jurisdictions. Horizontal grid resolution for the DEM is 100 m and absolute vertical accuracy, is approximately $\pm$3 m, based on an audit using primary vertical control. In September 2002, a version of the model, upgraded with new detailed data, was completed and prepared in grid format and high-resolution graphic files for web access (http://www.gov.mb.ca/itm/mrd/geo/demsm/introduction.html).

Bathymetry

To incorporate large lakes, including Lake Winnipeg, Lake Manitoba, Lake Winnipegosis, Playgreen Lake and Lake of the Woods in the 3-D model, 31 607 soundings on 22 Canadian Hydrographic Survey (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.

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 seismostratigraphy data was interpreted for the Quaternary sediments mapping and Paleozoic bedrock was differentiated from Precambrian on the basis of geometry and elevation. Where seismic velocities could be inferred, it was sometimes possible to distinguish till from Paleozoic bedrock. The offshore Quaternary and Paleozoic geology is now being 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.

Soil Mapping

Digital soil maps, produced by agricultural agencies, provide information on the texture and composition of sediment in the uppermost 0.5 m of the Quaternary sequence. Procedures to incorporate these data into the model are being assessed, such as the inclusion of an upper stratum that is much more detailed than the strata below.

Surficial Geology

A digital version of the surficial geology maps of southern Manitoba is being compiled at a scale of 1:250 000. 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 corrected. The map legend will define map units on the basis of factors such as texture, mineralogy, morphology and genesis of the sediments at depths between approximately 0.5 to 1.5 m. These maps guide the 3-D modelling, although at present the surficial mapping is more detailed than the resolution that can be achieved in the 3-D subsurface model. Consequently, the two models are not fully integrated, and as a result subsurface Quaternary strata outcrop as polygons that are generalized relative to the 1:250 000 mapping.

Quaternary Stratigraphy

The 3-D stratigraphic model of the Quaternary sediments in the Winnipeg pilot area was guided by an existing lithostratigraphic model based on previous research by Teller and Fenton (1980) and NATMAP project coring by Thorleifson and Matile (1993). The stratigraphic correlations, available from drillholes logged in detail, were extrapolated laterally with the aid of geophysical surveys, other drillhole data, topography and surficial geology mapping. A key source of data was the 80 000 site water-well database (GWDrill) which is maintained by the Manitoba Conservation Water Branch. 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 locate the water wells in the database. For the NATMAP pilot, the 200 by 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 elevations. 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, it did guide the interpolation between already correlated units and allowed the recognition of stark lithological breaks such as large sand lenses. To facilitate groundwater modelling, for example, it was necessary to predict the types of sediments present in areas of no data. 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. 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. It is anticipated that the same methods will be used for the current 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.

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. As a result, the bedrock units need to be updated to accommodate the new bedrock surface model, while, at the same time, preserving the expert opinion incorporated into previously published bedrock maps.

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 conflicting versions of the 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 is currently being assessed, as is revision of this mapping based on the drillhole compilation completed for the project. This compilation includes all available drillhole 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.

Phanerozoic Stratigraphy

Stratigraphic maps with structure contours and isopachs of the Phanerozoic strata were previously compiled by the 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 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. The current version of the pre-Quaternary model is being prepared for web release (http://www.gov.mb.ca/itm/mrd/geo/index.html). The site will permit users to query the model through a cross-section-based interface (Fig. GS-32-1), and display the full extent of the corresponding stratigraphic unit in map view. Users will also be able to rotate a 3-D block diagram for the Winnipeg NATMAP area and browse the geological model by progressively removing strata from a graphic model.

Sub-Phanerozoic Precambrian Geology

A preliminary sub-Phanerozoic Precambrian geology map for all of southern Manitoba was prepared in order to complete the model down to the deformed basement rocks. This map was compiled from aeromagnetic maps, compilation maps, drillhole and seismic data from Project Cormorant and subsurface correlation of drilled Precambrian intervals. A revision of the map is in progress.

WORKSHOPS

Implementation of the 3-D program has required choices to be made regarding hardware, software and protocols for construction, verification and communication of the 3-D model. In order to share ideas and benefit from experience recently gained by other agencies, the authors have participated in regular meetings sponsored by the Central Great Lakes Geological Mapping Coalition. After presenting posters and learning from the experience of others at Coalition-sponsored sessions in Illinois (Matile et al., 1999a) and Denver (Thorleifson et al., 1999), the authors collaborated with the Illinois State Geological Survey to sponsor two workshops on 3-D mapping and model development, one in Illinois in 2001 (Berg and Thorleifson, 2001) and the other in Denver in October 2002. Organization of and participation in the workshops have guided selection of options, and has indicated that, although approaches differ, the work being done in southern Manitoba is at a stage of development at least similar to corresponding activity elsewhere in North America and Europe.

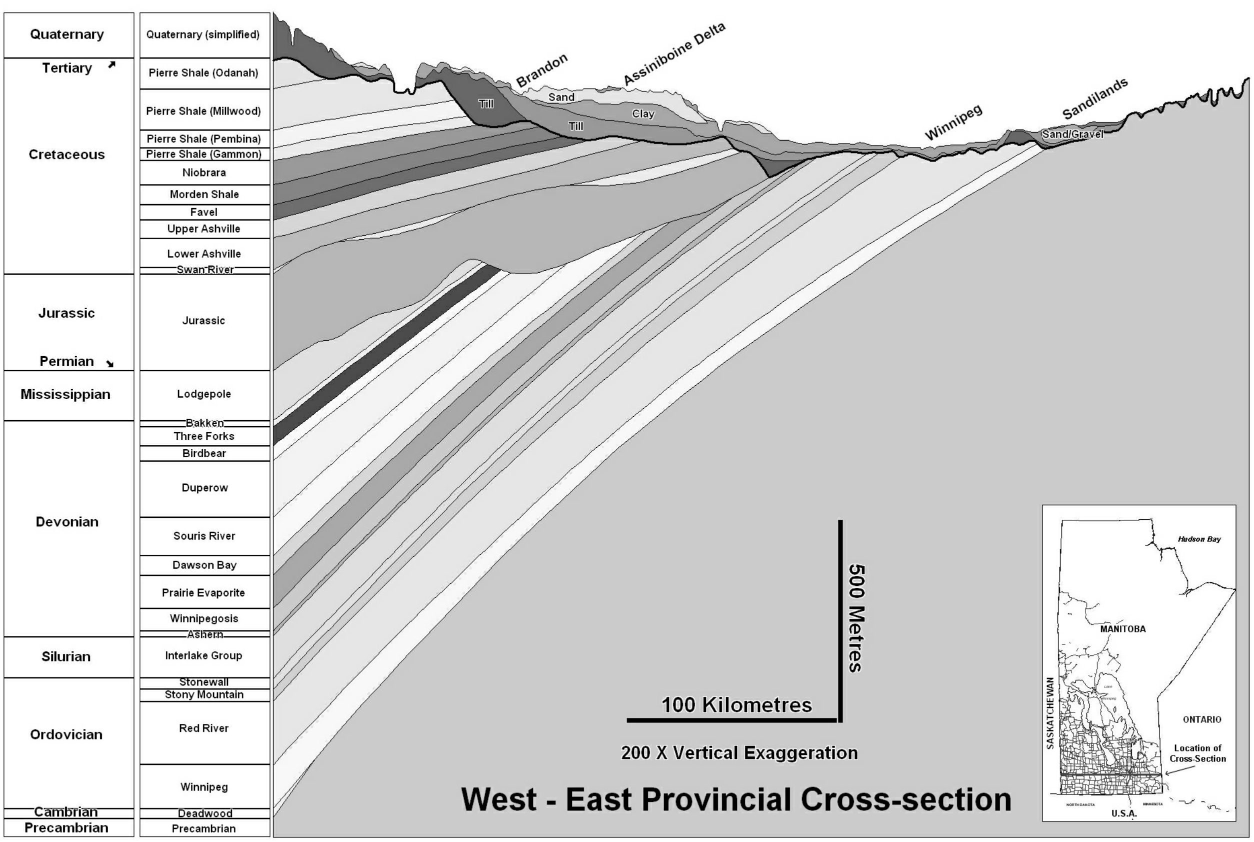

Figure GS-32-1: West-east provincial cross-section through Winnipeg and Brandon depicting modelled Phanerozoic stratigraphy. Quaternary units have been simplified due to the limits of the vertical exaggeration.

MODELLING METHODS

The southern Manitoba Phanerozoic 3-D 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 3-D modelling can proceed. Hence achievement of the objectives described here not only require selection of appropriate methods with reference to the software market and previous research (e.g., Shetsen and Mossop, 1994; Houlding, 1994), but also a more comprehensive definition of strata will be required. An adequate definition of a stratum will require the extent of the uneroded portion, elevation of its top, extent of its edge and elevation of its edge (Fig. GS-32-2).

A significant topic that is the subject of discussion and experimentation is the handling of contacts that together form map polygons. Contacts can either be input to the model or output from the model. In the case of the input approach, contacts on the Manitoba Geological Survey 1:1 000 000 and 1:250 000 geological maps are digitized as lines. The contacts would then be audited in plan view relative to recently obtained data, and would be revised. Wherever possible, the trend of these contacts would be maintained based on the assumption that the author would have drawn the contact as an expert prediction based on various considerations such as regional structure and lithology. In the case of bedrock contacts, it then would be necessary to have a complete model for the topography of the bedrock surface, so that the contacts could be converted from lines to points, and the model queried for elevation values for each point. Alternatively, the projection of the top of the stratum could be queried to obtain elevations for the upper contact, where the eroded edge meets the overlying stratum, and the lower contact could be positioned using the top of the underlying stratum. The lower contact is, of course, the upper contact of the underlying unit. Having audited and revised the contacts laterally, and having assigned them elevations, these lines would then be considered ‘hard’ inputs that have to be honoured by the model. Overlying and underlying surfaces would be forced to conform to these constraining lines.

The alternative to this approach is to allow the modelling procedure to generate new contacts based on a full 3-D analysis of all currently available data, including in some approaches, the previous geological models to guide the

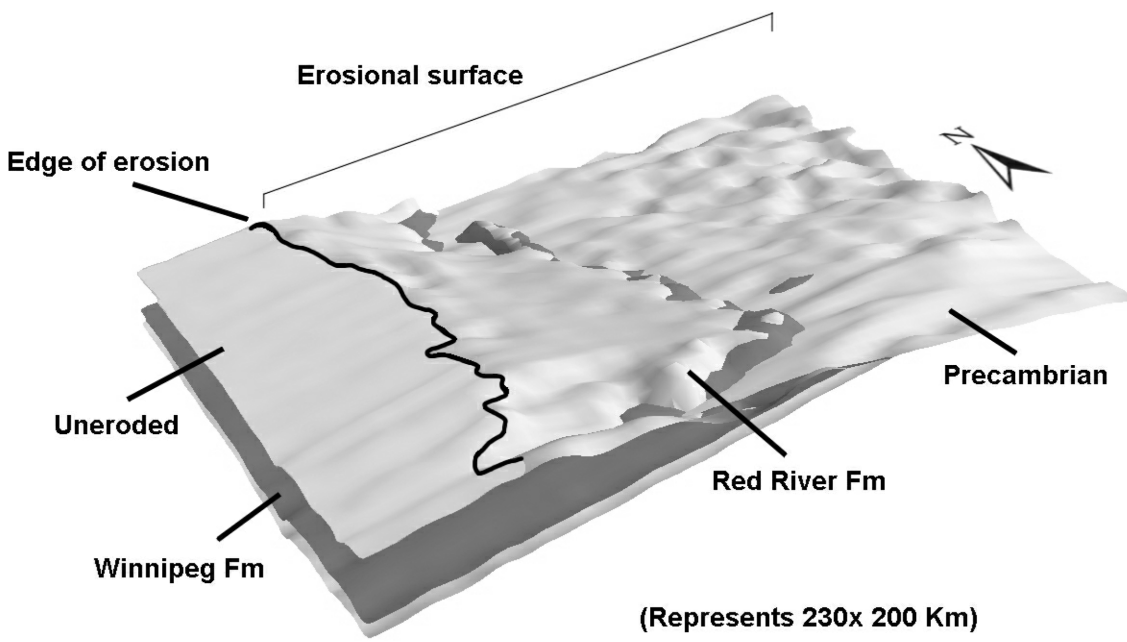

Figure GS-32-2: Each stratum is being defined by its full extent, the elevation of its uneroded top, as well as the extent and elevation of the edge that has been subject to erosion. The digital version also requires a surface defining the area of zero thickness that must coincide with the next lower surface that is present. In this example, the thickness of the Ordovician Winnipeg Formation in the area of exposed Precambrian is zero, so the top of the Ordovician Winnipeg Formation must equal the top of the Precambrian in this area.

interpretation. The advantage of this approach is that it honours more thoroughly, drillhole data obtained during the years since the maps were drawn, although there is a risk with this method that the expert opinion of the mapper may be lost if new interpolations are made. Having generated new upper and lower contacts for each unit, a new map polygon is created. It remains to be seen whether these new polygons would be accepted. Approaches will differ between Quaternary and pre-Quaternary due to the tendency of Quaternary units to feather out while many pre-Quaternary units terminate as escarpments. Furthermore, although the polygons guide 3-D model construction, the surficial geology map polygons are too detailed to be directly linked to the 3-D model, whereas all bedrock polygons will be linked to the 3-D units except for contacts that can only be mapped locally.

Modelling of the top elevation of each stratigraphic unit is being completed using an appropriate interpolation procedure, typically triangular irregular networks (TIN) base 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 the choice of an appropriate compromise between strictly honouring data points and obtaining a slightly smoothed model that will aesthetically appear reasonable. Software has been found to vary significantly with respect to ease of interactively editing the grids that represent surfaces. Handling of discontinuous strata has also presented challenges, as some software options require that a new stratum be declared for each outlier. Over the past year, the 3-D software platform for the project has been converted to one capable of handling surfaces that represent the top of discontinuous strata.

In the case of the Winnipeg pilot, the 3-D 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, so the required computer infrastructure to do so is being implemented. 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. The matrix approach has some advantages but the tetrahedra solids are very large to store and slow to manipulate and give cross-sections with a corrugated effect. The currently favoured approach is the construction of a grid of vertical rectangular solids of varying thickness. The resulting solid is slow to manipulate in interactive applications but the computer technology to more readily handle the resulting solid model is likely to become readily available in forthcoming years.

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 (Fig. GS-32-3). 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 (Fig. GS-32-4). 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 (Fig. GS-32-5). 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.

FUTURE PLANS

The assembly of inputs, both data and interim models, will be completed concurrently with iterative selection of modelling procedures. It is anticipated that this process will take several months and then a first version of the model can be released. The model will then serve as the basis for identifying priority areas for new data collection. 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 documentation. Concurrently with the refinement of models that define the outline geometry of units, progress will be required in defining the properties of the strata and

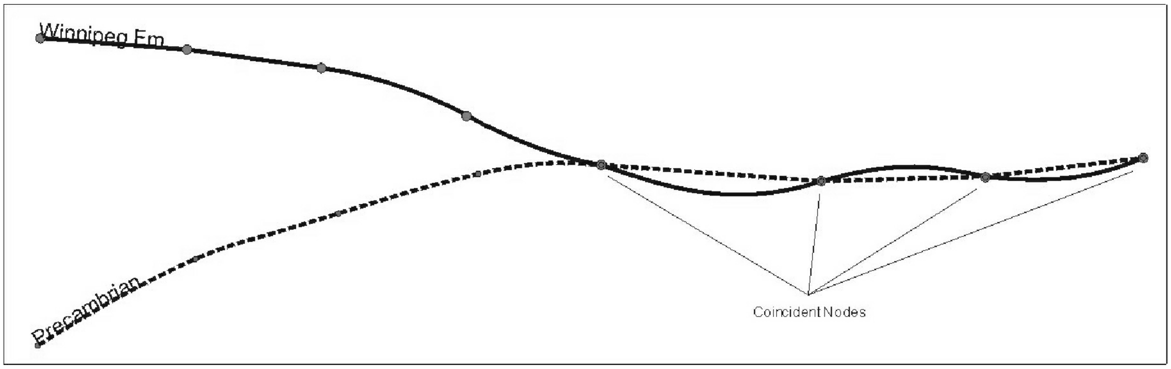

Figure GS-32-3: Example of how two modelled surfaces of vertically adjacent units can deviate from one another even though they have coincident points beyond the extent of the upper unit.

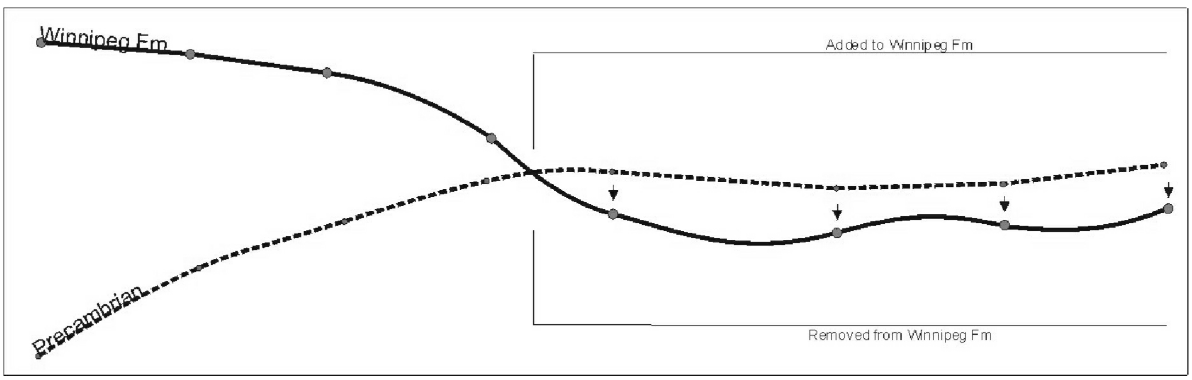

Figure GS-32-4: Lowering the elevation of a stratum beyond its actual extent produces a surface that will seal against the underlying stratum, and also more realistically produces a limit that appropriately falls short of the first zero-thickness point.

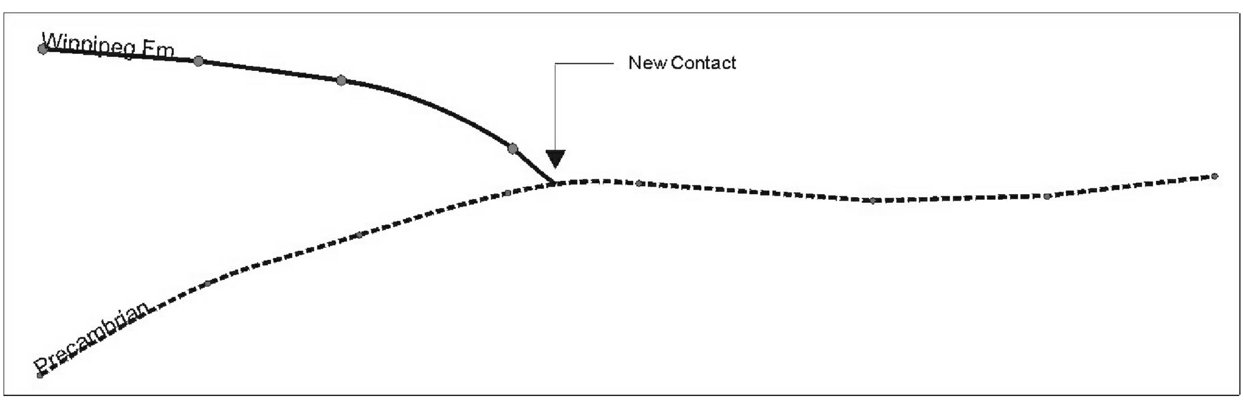

Figure GS-32-5: The surface beyond the extent or surface intersection is removed and the surface of the next underlying stratum is spliced on, so the two are coincident where the thickness of the upper unit is zero.

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 (Fig. GS-32-6).

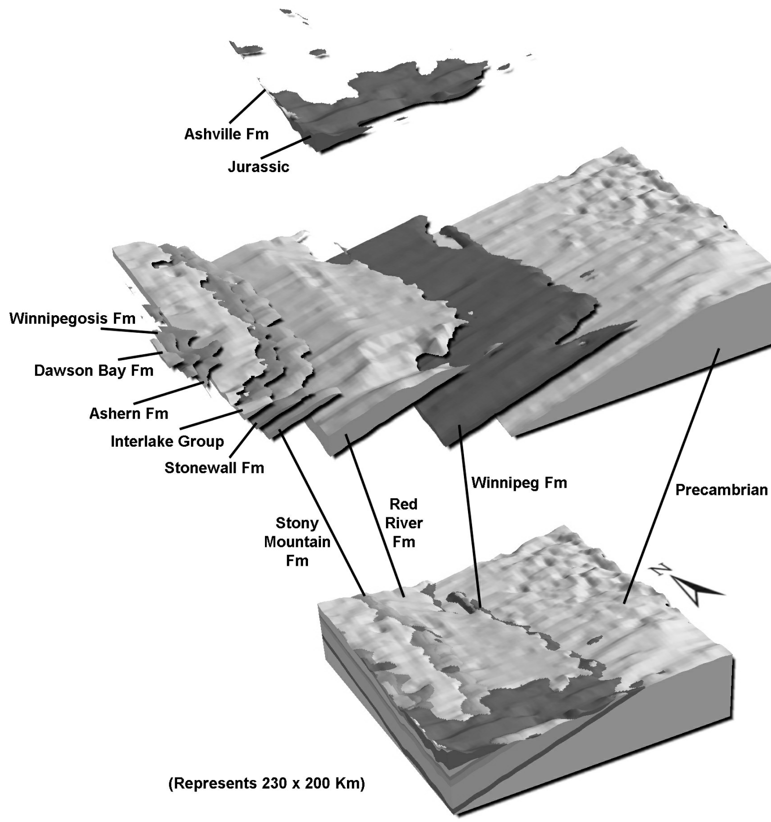

Figure GS-32-6: The 3-D model for the Phanerozoic geology of southern Manitoba will facilitate interactive viewing, as well as applications for groundwater modelling, oil and gas assessments and industrial mineral management.

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