**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8969**

# 3D geological model of the Western Canadian Sedimentary Basin in Saskatchewan, Canada

K. Bédard, A. Marsh, M. Hillier, and T. Music

**2023**

**GEOLOGICAL SURVEY OF CANADA**
**OPEN FILE 8969**


# 3D geological model of the Western Canadian Sedimentary Basin in Saskatchewan, Canada

**K. Bédard[1], A. Marsh[2], M. Hillier[3], and T. Music[2]**

[1]Geological Survey of Canada, 490, rue de la Couronne, Québec, Quebec
[2]Saskatchewan Geological Survey, 201 Dewdney Avenue, Regina, Saskatchewan
[3]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario

**2023**

Publications in this series have not been edited; they are released as submitted by the author.

# Table of content

# Table of Figures

# 1 Abstract

The Western Canadian Sedimentary Basin (WCSB) covers a large part of southern Saskatchewan and hosts many resources such as critical mineral deposits (i.e. potash, helium and lithium) as well as oil and gas reservoirs and is also targeted for deep $CO_2$ storage projects. There is also growing interest in the groundwater resources, the geothermal potential and hydrogen recovery potential. These applications require knowledge of the subsurface geology such as formation thickness and depth, relationships with adjacent formations or unconformities and ultimately, distribution of physical properties within the basin. 3D geological models can provide this knowledge since they characterize the geometry of subsurface geological features. In addition, they can be used as a framework for fluid flow simulation and estimating the distribution a variety of properties.

The 3D geological model presented in this report consists of 51 geological units of which, 49 are stratigraphic units spanning from Cambrian Deadwood Formation at the base of the sequence to Upper Cretaceous Belly River Formation at the top, plus the undivided Precambrian and a preliminary Quaternary unit. The model is cut by 7 major regional unconformities, including the base of the Quaternary sediments. The regional model was constrained using oil and gas well data interpretations, provincial scale bedrock geology maps and knowledge from the previously interpreted areal extent of the Phanerozoic strata. A hybrid explicit-implicit modelling approach was employed to produce the 3D geological model of the WCSB in Saskatchewan using Gocad/SKUA$^{TM}$ geomodelling software.

## 2   Résumé

Le bassin sédimentaire de l'Ouest canadien (WCSB) couvre une grande partie du sud de la Saskatchewan et contient de nombreuses ressources telles que des gisements de minéraux critiques (ex. potasse, hélium et lithium) ainsi que des réservoirs de pétrole et de gaz, et est également ciblé pour des projets de stockage profond de $CO_2$. Les ressources en eaux souterraines, le potentiel géothermique et le potentiel de récupération de l'hydrogène suscitent également un intérêt croissant. Ces applications nécessitent une connaissance de la géologie en sous-surface, comme l'épaisseur et la profondeur des formations, les relations avec les formations adjacentes ou les discordances et, ultimement, la distribution des propriétés physiques dans le bassin. Les modèles géologiques 3D peuvent fournir ces connaissances puisqu'ils caractérisent la géométrie des éléments géologiques en profondeur. En outre, ils peuvent être utilisés comme base pour la simulation de l'écoulement des fluides et l'estimation de la distribution de propriétés variées.

Le modèle géologique 3D présenté dans ce rapport est composé de 51 unités géologiques dont 49 unités sédimentaires allant de la Formation de Deadwood au Cambrien à la base de la séquence, jusqu'à la Formation de Belly River au Crétacé supérieur au sommet, plus le socle Précambrien non divisé et une unité quaternaire préliminaire. Le modèle est découpé par 7 discordances régionales majeures, y compris la base des sédiments quaternaires. Le modèle régional a été contraint à l'aide d'interprétations de données de puits de pétrole et de gaz, de la carte géologique de surface à l'échelle provinciale et de connaissances antérieures sur l'étendue des unités phanérozoïques. Une approche de modélisation hybride explicite-implicite a été utilisée pour produire le modèle géologique 3D du WCSB en Saskatchewan à l'aide du logiciel de géomodélisation Gocad/SKUA$^{TM}$.

## 3 Introduction

The objective of this project, achieved in collaboration with the Saskatchewan Geological Survey (SGS), was to generate a volumetric model of the major Phanerozoic stratigraphic units at the provincial scale with the finest resolution possible in Saskatchewan. Structure and isopach maps of all the Phanerozoic strata that can be mapped at province-scale were previously published by Marsh and Love (2014), but a 3D volumetric model was yet to be constructed. Prior provincial-scale 3D modelling initiatives faced challenges related to the large volume of data, computational capacity and human-resource availability (Marsh and Music, 2019). This collaborative project was initiated to tackle those challenges by sharing 3D-modelling expertise and computational capacity from the Geological Survey of Canada (GSC) coupled with geological knowledge and data from the SGS. This collaboration was realised under the umbrella of the National Geological Surveys Committee (NGSC)-Canada-3D project that aims at developing a national 3D geological framework and associated knowledge base for the Canadian subsurface (Russell *et al.*, 2019; De Kemp *et al.*, 2022; Canada 3D, 2023; De Kemp, 2023).

The Phanerozoic sedimentary basin in Saskatchewan covers approximately 451,000 km$^2$ and its thickness reaches more than 3400 metres in the southern part of the province (Figure 1). The 51 modelled units comprise 49 major stratigraphic units that can be mapped regionally with sufficient thickness to be modelled in 3D, spanning from Cambrian Deadwood Formation at the base of the sequence to Upper Cretaceous Belly River Formation at the top, plus the undivided Precambrian and a preliminary Quaternary unit (Figure 2). The 3D geological model includes 7 regional unconformities that split the volume into stratigraphic blocks where units were deposited relatively continuously in between major erosional episodes.

## 4 Purpose and Scope

The main objective of this paper is to present a 3D geological model of a provincial-scale 3D stratigraphic model of the Phanerozoic basin of Saskatchewan using formation tops derived from well data. The purpose of this model and data release is to support government, industry and university for the future, where it is intended to be used by as a knowledge layer for the basin. Potential downstream applications could be 3D critical mineral prospectivity mapping for minerals, such as lithium, helium and potash, as well as assessment of geothermal and groundwater resources, in situ hydrogen extraction from hydrocarbons and evaluation of carbon capture and sequestration potential.

It should be noted that, since this is a provincial scale 3D model, it must not be used directly for local-scale projects. Moreover, the goal of this release is not to provide a complete description of all the geoscience information in the form of publication, descriptive data for rock types of the area, or an inventory of all the previous analysis performed in the basin.

Considerable technical and methodology practices were optimized during this project. We believe other projects with similar data conditions and model requirements can benefit from this experience which we have documented in the appendices (see Appendix 2 and Appendix 3).
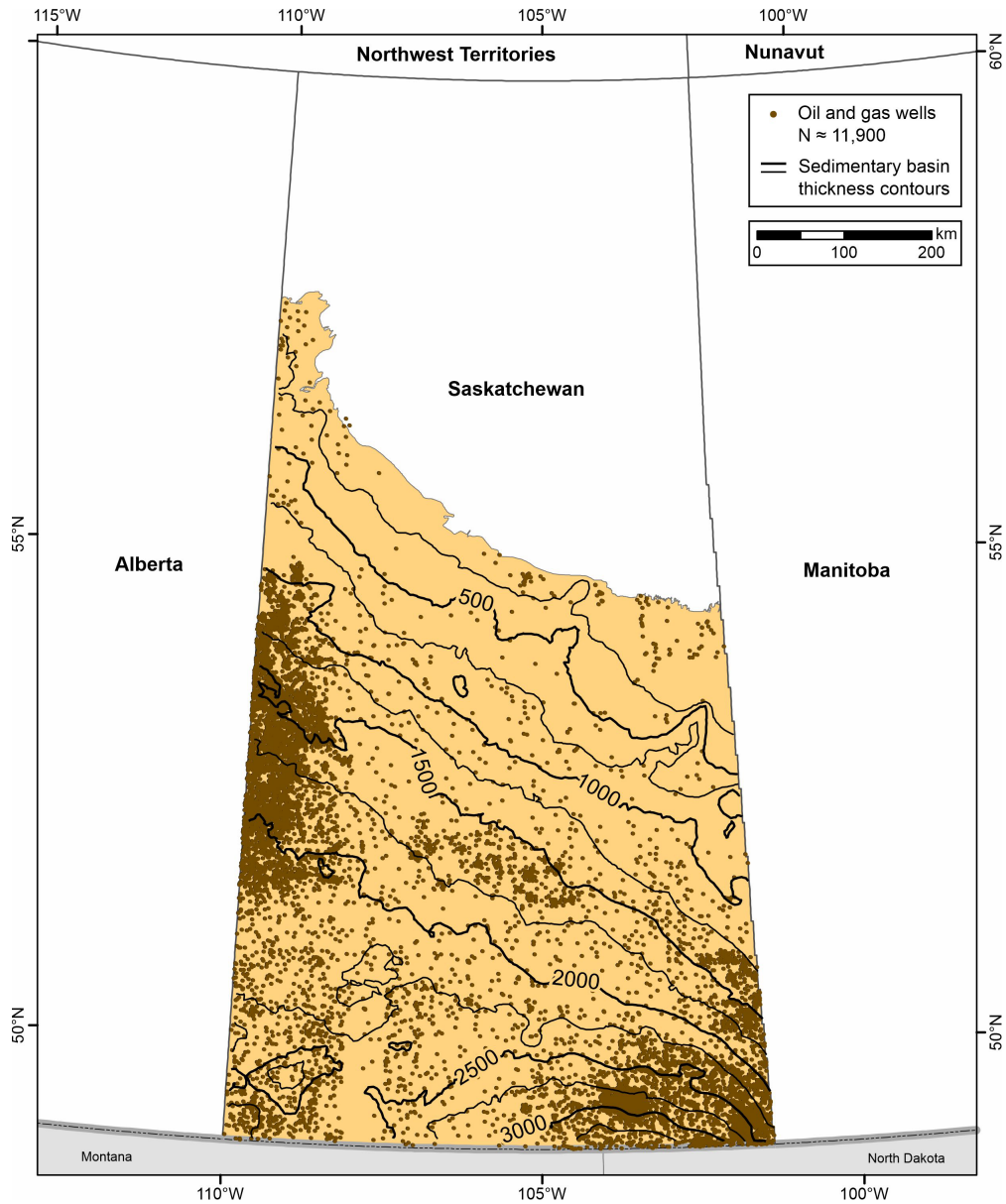


*Figure 1. Extent of the model and locations of oil and gas well data used in this project.*
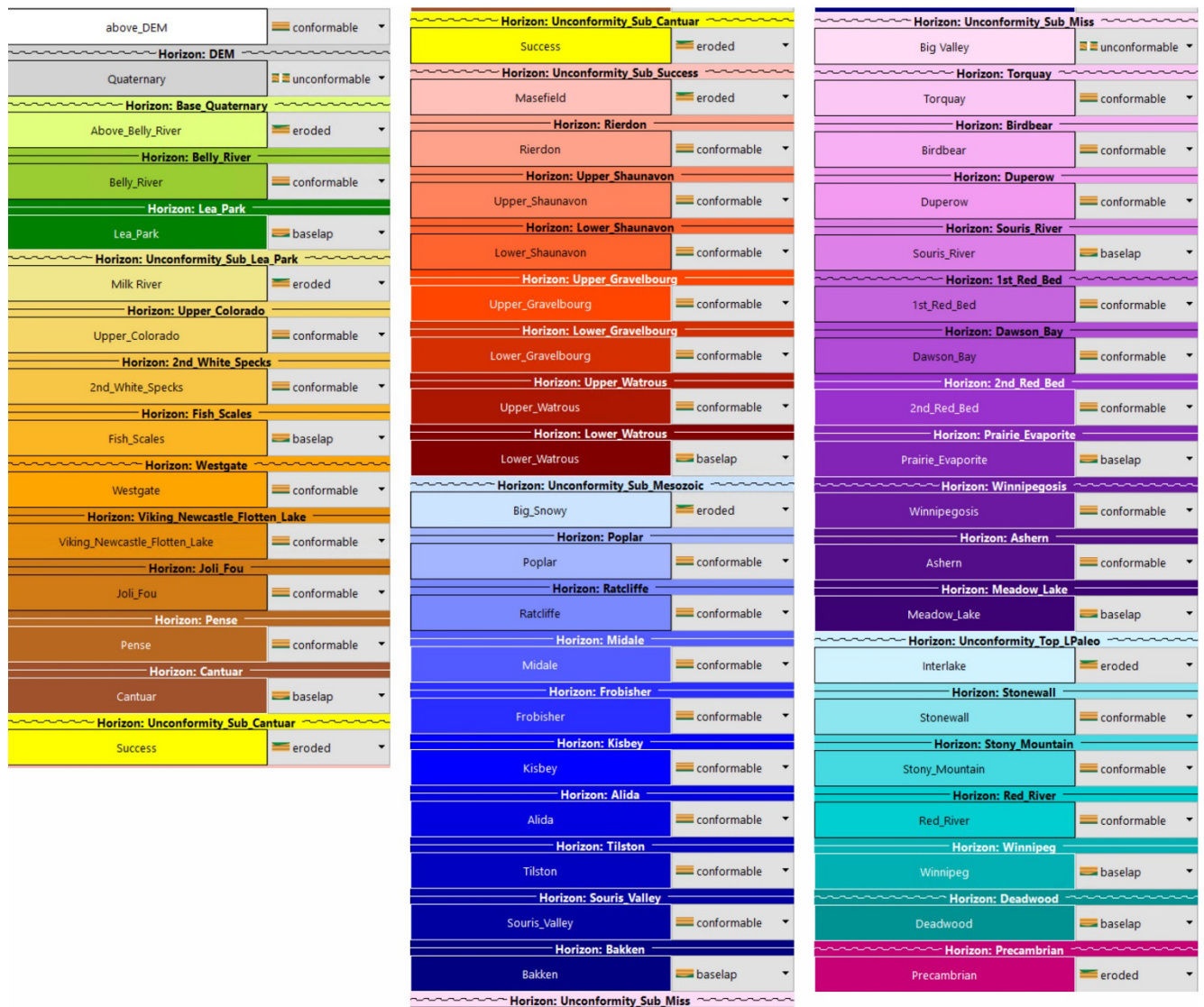
*Figure 2. Stratigraphic sequence and inter-formational relationships (conformable, unconformable, eroded, baselap) used for 3D modelling.*

## 5 Data Description

The 3D geological model is composed of 51 geological units divided by 7 major unconformities following the stratigraphic chart shown in Figure 2. The main dataset used in this 3D geological modelling project is a compilation of well data completed by the SGS and based on various previous projects (Marsh and Love, 2014). It is based on the stratigraphic interpretation of approximately 11,900 oil and gas wells in Saskatchewan and provides the depths of the top of the stratigraphic units and unconformities along the well paths. The distribution of the oil and gas wells at the surface is shown on Figure 1 and the well paths on Figure 3. The 142,904 interpreted well markers are converted into individual pointsets for each of the units and unconformities as shown on Figure 4. The details of the well marker dataset are presented in Appendix 1.
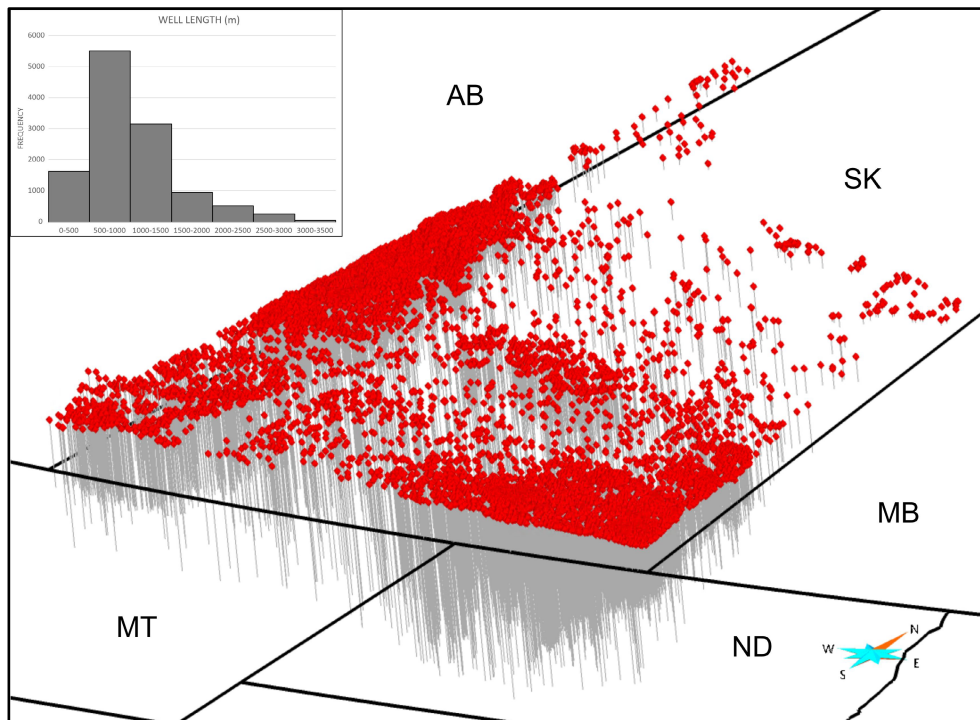
*Figure 3. 3D view of the well locations at the surface (red diamonds) and paths (gray lines) of oil and gas wells used in this project. AB: Alberta. SK: Saskatchewan. MB: Manitoba. MT: Montana. ND: North Dakota. Vertical exaggeration: 50x.*
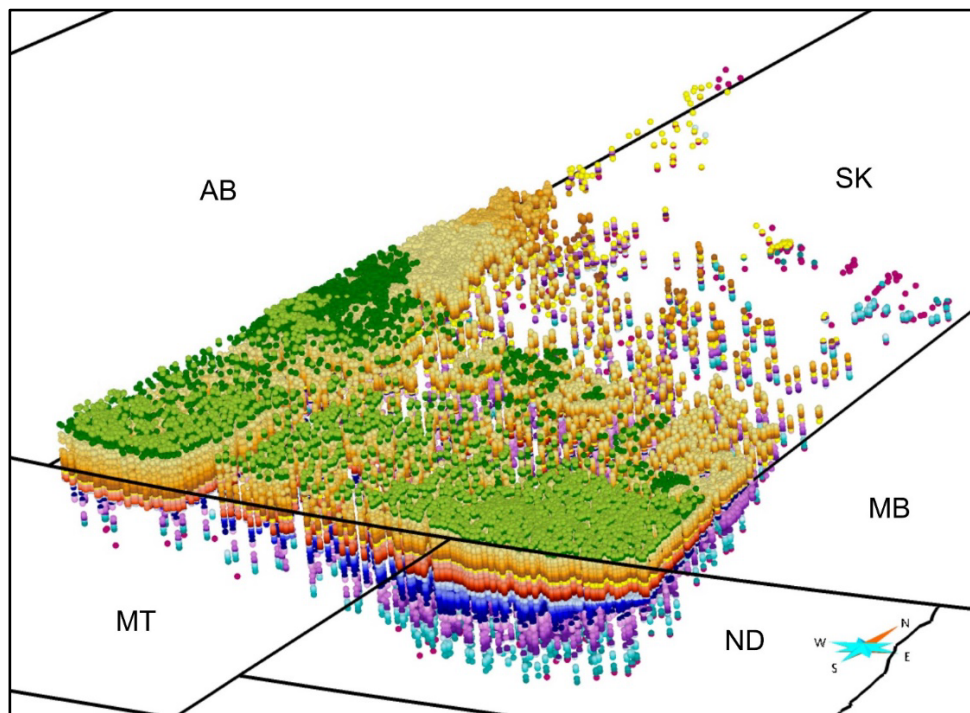


*Figure 4. 3D view of the stratigraphic unit top and unconformity markers used for 3D modelling. Colours of the points corresponds to the stratigraphic units shown in Figure 2. AB: Alberta. SK: Saskatchewan. MB: Manitoba. MT: Montana. ND: North Dakota. Vertical exaggeration: 50x.*

6

The ground elevation is derived from the Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) dataset (SRTM, 2013). The DEM, originally a raster file, was converted to a XYZ point file in ArcGIS and then imported into SKUA-Gocad™ as a point set from which a regular 2km x 2km 2D-grid was created (Figure 5).
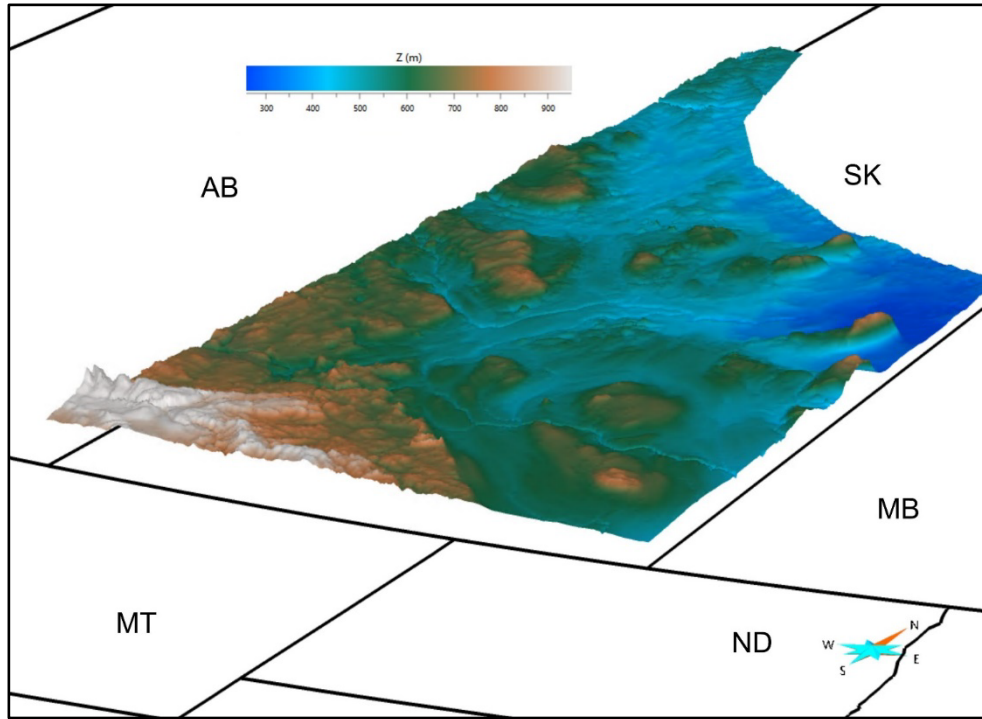


*Figure 5. DEM used in this project. Elevation of the DEM ranges from 260 m to 1380 m. AB: Alberta. SK: Saskatchewan. MB: Manitoba. MT: Montana. ND: North Dakota. Vertical exaggeration: 50x.*

The geological map (Maxeiner *et al.*, 2021) is used to identify unit top contacts and assign them as constraints for 3D modelling as they represent the top of units outcropping at the surface or below the Quaternary sediments (Figure 6A). These contacts are associated to the corresponding unit top markers and are used to model the top surface of the units (Figure 6B). The zero-edge contours of each unit (Marsh and Love, 2014) identify the underground lateral extent of each unit based on geological interpretation of seismic data as well as oil and gas well data by experts of the basin in the province (Figure 7). These contours are used for model validation to ensure modelled units generally respect the prior geological knowledge of the region.

This project uses the NAD 83, UTM zone 13N coordinate system (EPSG:26913) to integrate all the data in the same modelling environment. See Appendix 1 for detailed metadata of the 3D model.
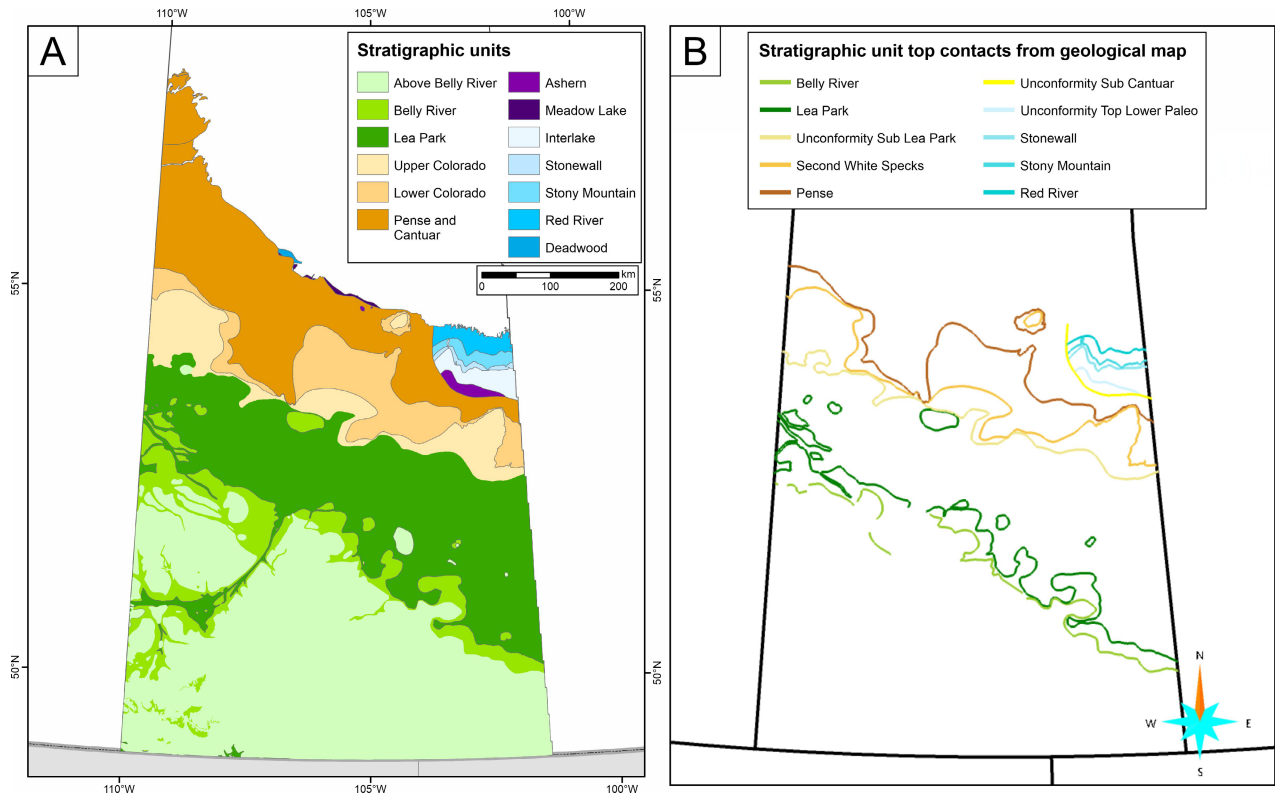
*Figure 6. A) Simplified geological map modified from Maxeiner et al. (2021). B) Stratigraphic unit top contacts derived from the map and used for 3D modelling.*
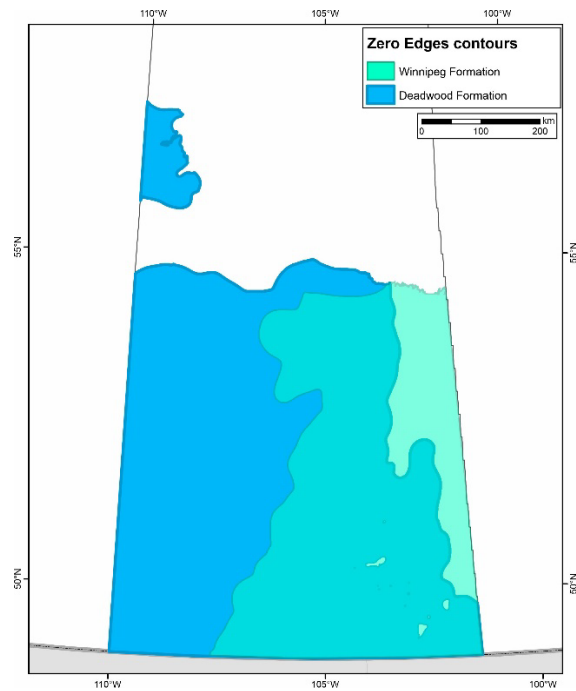


*Figure 7. Examples of zero-edges contours from Marsh and Love (2014). The coloured regions show the interpreted underground lateral extent of the formations.*

## 6   3D Modelling Methodology

There are many approaches to develop 3D geological models, and part of the difficulty in creating a regional 3D model is choosing the most suitable method for the project. In this project, the modelled region of interest is a layered slightly deformed intracratonic sedimentary basin. The available data for modelling identify geological interfaces such as major unconformities and contacts between stratigraphic units. An implicit modelling methodology that processes all the units at the same time is used to ensure units boundaries respect the stratigraphic sequence and that there is no overlap between those boundaries.

SKUA™ Structure and Stratigraphy workflow was used to implicitly model the stratigraphic horizons from the points and the stratigraphic column. However, this workflow is limited by the type and volume of data as well as the size and resolution of the output model. The software is not able to perform all the steps of the workflow to generate a final stratigraphic model with very fine resolution. For many reasons (detailed in Appendix 3), the workflow is used to generate preliminary surfaces of the unconformities and unit tops. These surfaces are then manually edited using an explicit modelling approach outside of the workflow to improve data fitting and resolution.

As random parts of the data are automatically ignored in the workflow (see Appendix 3), manual editing of the surfaces is used to ensure that all the data are used to constrain the surfaces. The surfaces are therefore manually interpolated with all the available data set as constraints. Then input data that are too far from each surface (40 meters distance was used as suggested by the workflow based on the data distribution) are considered as misinterpreted and are discarded from the input dataset. The next modelling iterations only use the remaining data. The resolution of each surface can also be adapted according to the data density. These steps better respect all of the input data but generates inconsistencies in between the surfaces as each surface is edited independently without stratigraphic relationships (conformable, eroded, baselap) with its neighbours. There is then a back-and-forth modelling process between the adjacent surfaces to ensure that the stratigraphic relationships are indeed respected. This process is tedious, and the results vary depending on the 3D modeller. This is however the only way that is possible, with the actual available computer and software resources, to generate a complete model with a very large dataset and a large area of interest with a fine resolution.

Finally, a volumetric model is generated from the modelled unconformities and surface tops. This model consists of a voxet (regular 3D grid) with a 2 km x 2 km x 10 m resolution. Every cell of the voxet is assigned to a stratigraphic unit based on the regions limited by the previously modelled surfaces.

Appendix 3 presents the parameters used in each step of the SKUA™ Structure and Stratigraphy workflow and a summary of the subsequent manual editing steps.

# 7    3D Model

The resulting 3D model consist of 51 surfaces representing the DEM, unit tops and unconformities and a volumetric model where each cell is assigned to a geological unit. The unconformities encompass "unconformity blocks" in which stratigraphic units are confined. The base of the Quaternary sediments is a preliminary surface approximately based the DEM geometry with some translations to adjust to the well markers. It is a working surface and should not be considered for future studies on the shallow geology of the region. Figure 8 illustrates the modelled unconformity surfaces and the "unconformity blocks" that they define. Figure 9 shows a 3D print of the model where each colour is a distinct "unconformity block".
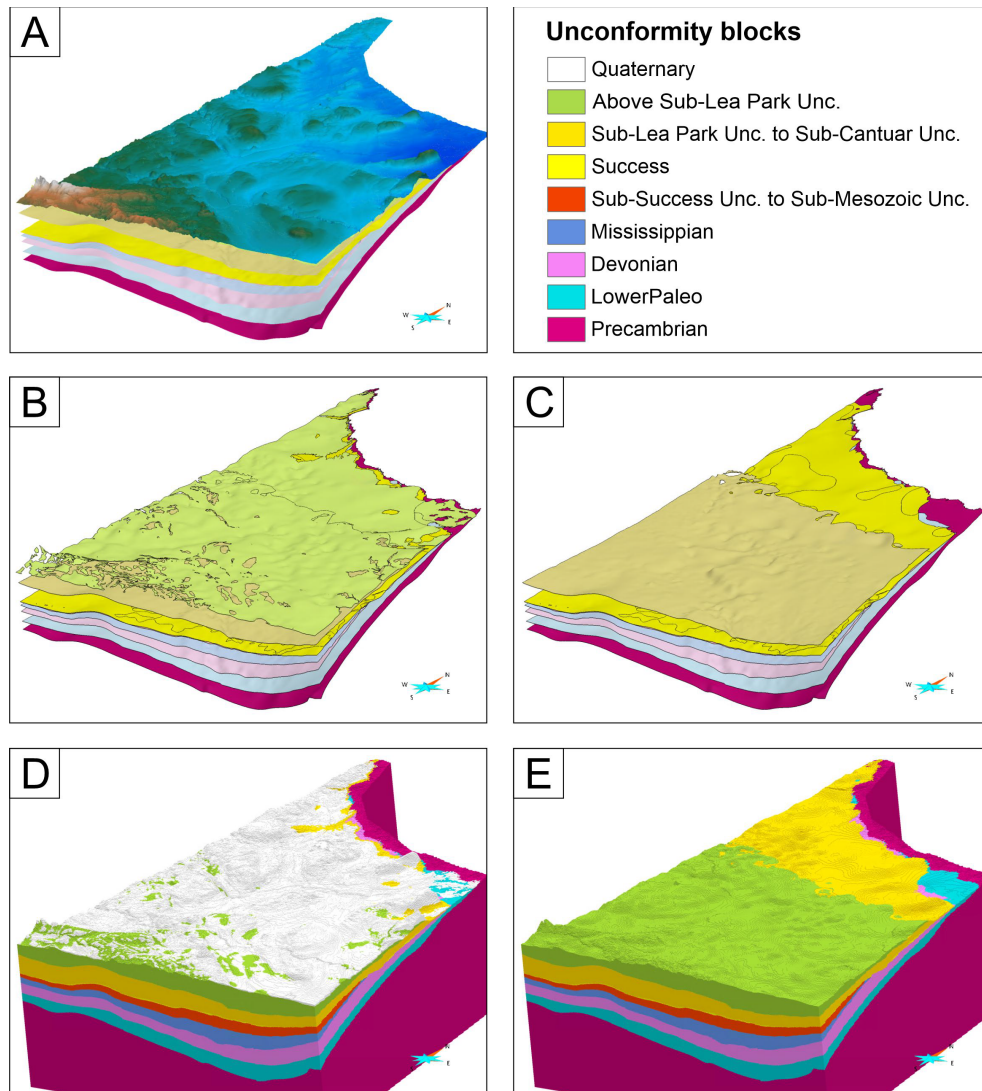


*Figure 8. 3D model of the "unconformity blocks" and associated unconformity surfaces. A) All unconformity surfaces, including DEM. B) Unconformity surfaces without the DEM. C) Unconformity surfaces without the DEM and the base of the Quaternary. D) Volumetric model of all the "unconformity blocks". E) Volumetric model of the unconformity blocks without the Quaternary. Vertical exaggeration: 50x.*
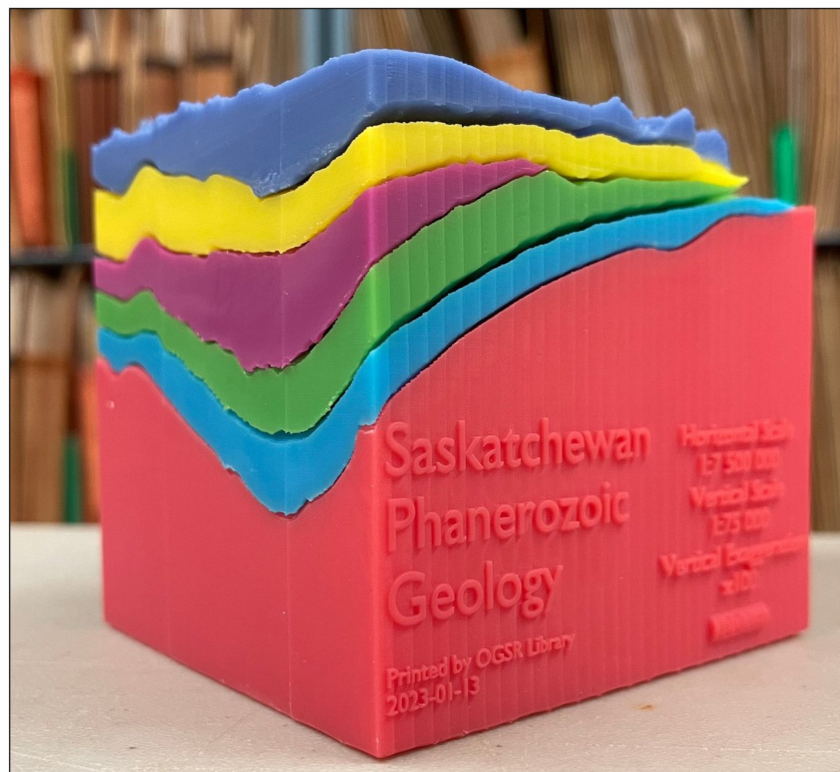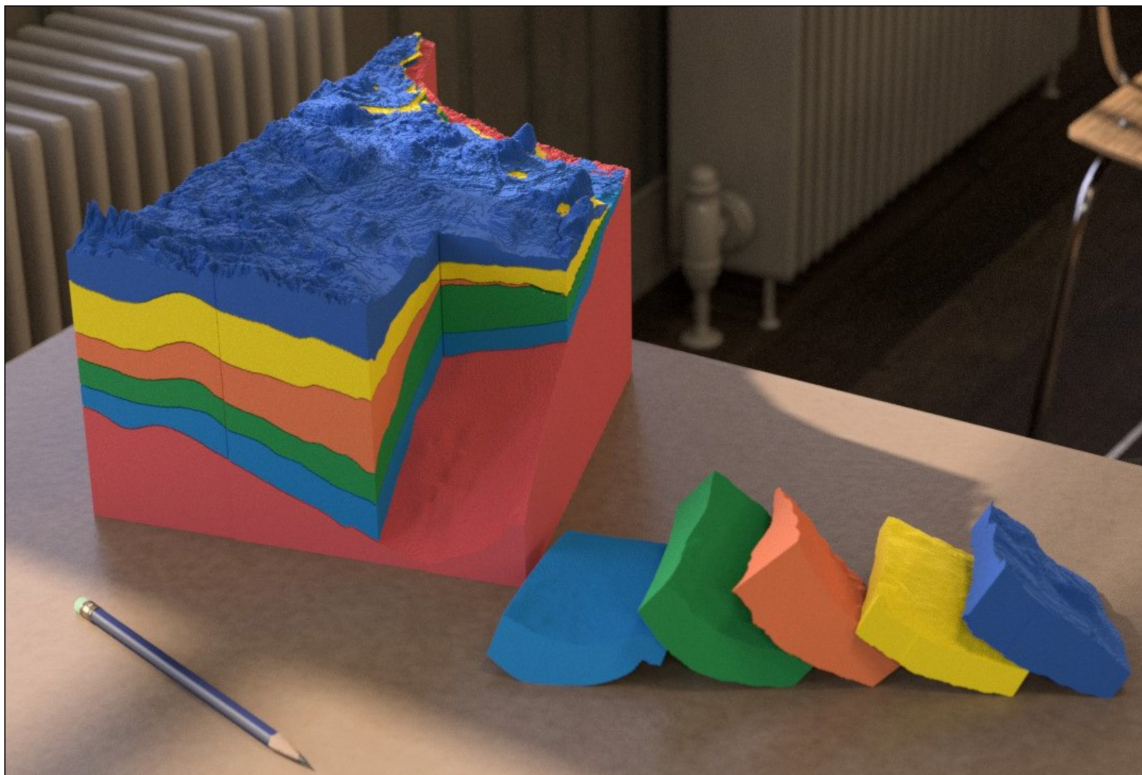
*Figure 9. 3D prints of the "unconformity blocks" of the 3D model. Photographs by J. Clark, courtesy of the Oil, Gas and Salt Resources Library.*

Figure 10 shows all the modelled surfaces (unit tops and unconformities) and the associated 51 volumetric units. Figure 11, shows the units of each of the unconformity blocks and allows a better understanding of the areal distribution of the units in the basin. Figure 12 allows for the visualization of the structure of the basin with the help of cross-sections cutting the volumetric model. It shows how the units are eroded by unconformities and how some units are baselapping on unconformities or other units.
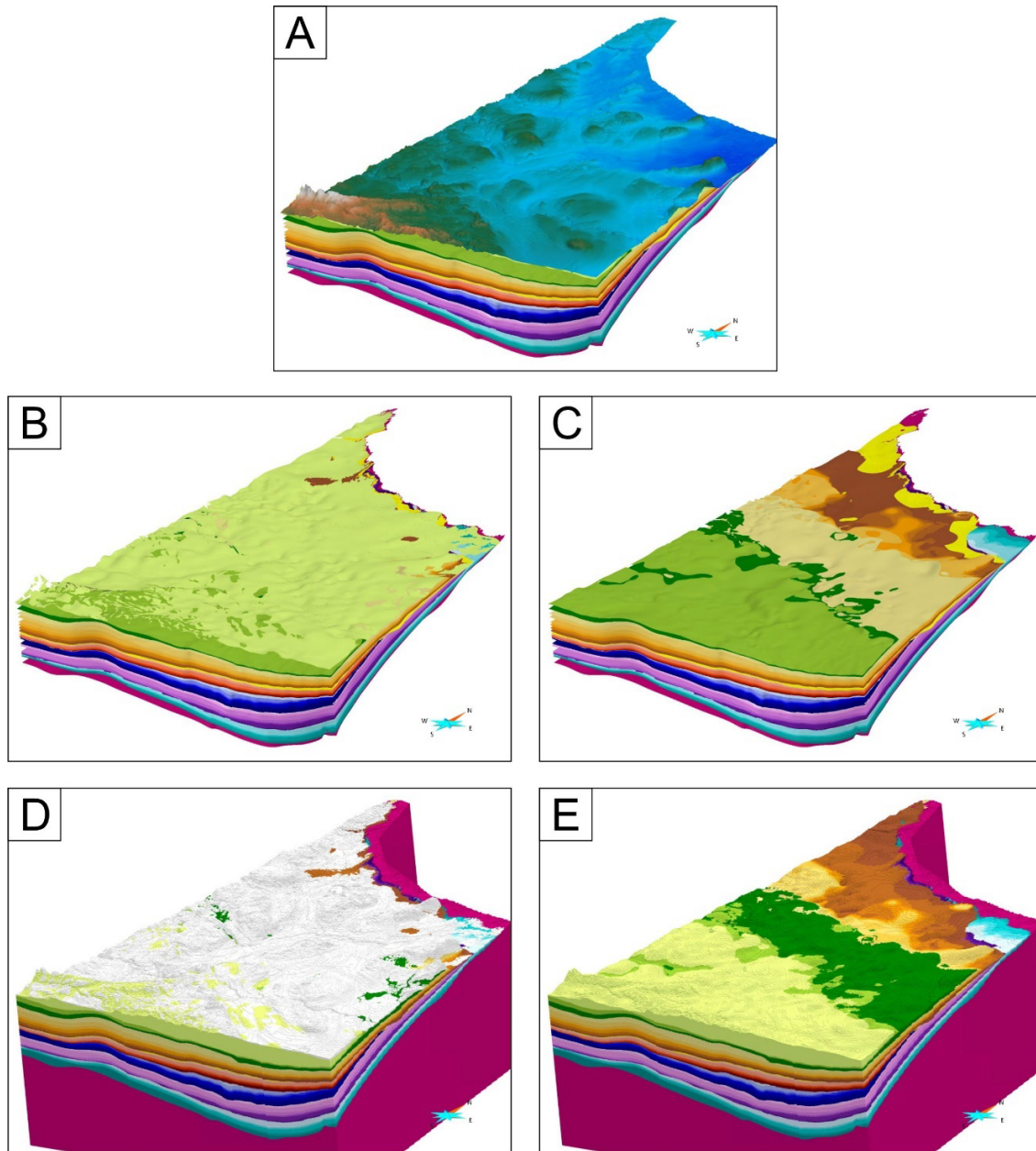


*Figure 10. 3D model of the stratigraphic unit and unconformity surfaces. A) All surfaces, including DEM. B) All surfaces without the DEM. C) All surfaces without the DEM and the base of the Quaternary. D) Volumetric model of all the units. E) Volumetric model of all the units without the Quaternary. Colours of the surfaces and regions correspond to the units shown in Figure 2. Vertical exaggeration: 50x.*
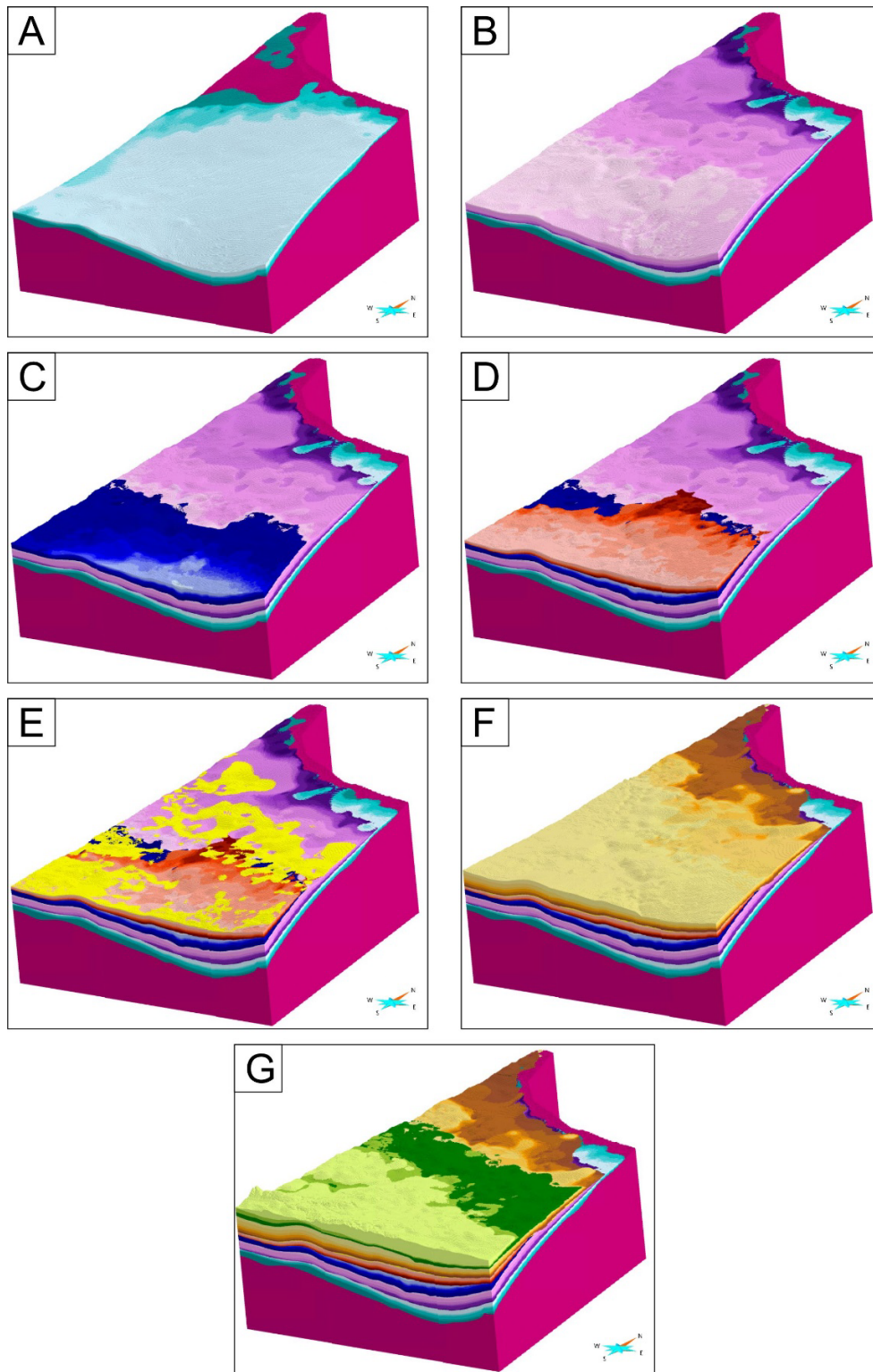
*Figure 11. Areal distribution of the stratigraphic units in the basin. A) Lower Paleozoic units. B) Devonian units. C) Mississippian units. D) Units from Sub-Success Unc. to Sub-Mesozoic Unc. E) Success unit. F) Units from Sub-Lea Park Unc. to Sub-Cantuar Unc. G) Units above Sub-Lea Park Unc. Colours of the surfaces and regions correspond to the units shown in Figure 2. Vertical exaggeration: 50x.*

13
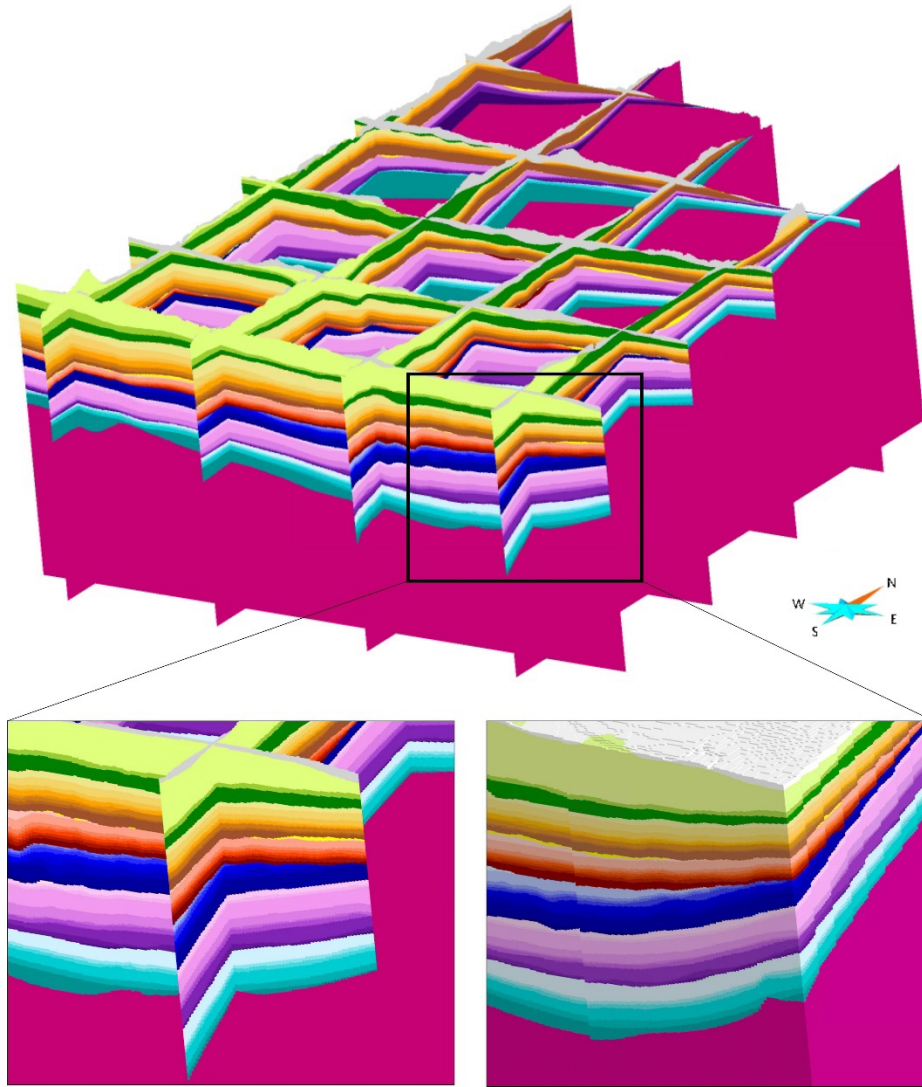
*Figure 12. Cross-section view of the volumetric model. Colours of the surfaces and regions correspond to the units shown in Figure 2. Vertical exaggeration: 50x.*

## 8   Conclusions

This 3D data and model release represents a significant advance in amalgamation of our best public 3D information representing the sub-surface geology of the WCSB in southern Saskatchewan. It brings together well data interpretation, geological map contacts and previously interpreted subsurface lateral extent of the unit in a harmonized lithostratigraphic scheme and places these in a common 3D reference frame, with stratigraphic constraints. The 3D model consists of surfaces of the unconformities and the top of the units as well as the associated volumetric model. This model could be used as a framework for future application such as fluid flow simulation, structurally constrained interpolation of property data within the basin or 3D geothermal and critical mineral prospectivity.

This report also presents a detailed description of the methodology used to generate the 3D model with SKUA-GOCAD™ using a stratigraphic framework and this contribution that could be used as a basis for future 3D modelling of sedimentary basins of similar extent and with large constraint datasets, primarily from well information.

## 9   Acknowledgements

## 10 References

Canada 3D. 2023 *Canada-3D* [online]. https://canada3d.geosciences.ca/. Accessed: 2013-03-14.

De Kemp, E. (2023) *Canada in 3D - National Geological Surveys Committee update report*. Geological Survey of Canada. Scientific Presentation 153. 134 pages. https://doi.org/10.4095/331340.

De Kemp, E., Russell, H.A.J., Brodaric, B., Snyder, D.B., Hillier, M., St-Onge, M., Harrisson, C., Paul, D., Vaillancourt, A., Bédard, K., Mort, A., Schetselaar, E., White, D., Logan, C. and Ashoori Pareshkoohi, A. (2022) *Initiating transformative geoscience practice at the Geological Survey of Canada: Canada in 3D*. Geological Survey of Canada. Scientific Presentation 141. 23 pages. https://doi.org/10.4095/331097.

Marsh, A. and Love, M. (2014) *Regional stratigraphic framework of the Phanerozoic in Saskatchewan: Saskatchewan Phanerozoic Fluids and Petroleum Systems Project*. Saskatchewan Ministry of Economy, Saskatchewan Geological Survey. Open File 2014-1. 156 maps.

Marsh, A. and Music, T. (2019) Saskatchewan 3D Phanerozoic stratigraphic framework; Chapter 22. *In: 2019 Synopsis of Current Three-Dimensional Geological Mapping and Modelling in Geological Survey Organizations.* Alberta Energy Regulator / Alberta Geological Survey. AER/AGS Special Report 112. pp. 239-242.

Maxeiner, R., Ashton, K.E., Bosman, S., Card, C., Kohlruss, D., Love, M., Love, T., Marsh, A., Morelli, R. and Slimmon, W.L. (2021) *Geological Map of Saskatchewan, 1:1 000 000 Scale*. Saskatchewan Geological Survey, Saskatchewan Energy and Resources. http://dx.doi.org/10.13140/RG.2.2.27014.09283.

Russell, H., Brodaric, B., De Kemp, E., Hillier, M., Schetselaar, E., Snyder, D.B. and St-Onge, M. (2019) Chapter 8. Geological Survey of Canada: Geological mapping in three-dimensions. *In:* MacCormack, K.E., R.C. Berg, H. Kessler, H.A.J. Russell et L.H. Thorleifson [eds] *2019 synopsis of current three-dimensional geological mapping and modelling in geological survey organization.* Alberta Energy Regulator / Alberta Geological Survey. AER/AGS Special Report 112. pp. 62-75.

SRTM. 2013 *Shuttle Radar Topography Mission (SRTM) Global. Distributed by OpenTopography* [online]. https://doi.org/10.5069/G9445JDF. Accessed: 2014-02-26.

**Appendix 1**        **3D Model Metadata**

| | |
|---|---|
| Title | 3D Geological Model of the Western Canadian Sedimentary Basin in Saskatchewan, Canada |
| Organisation | Government of Canada; Natural Resources Canada; Geological Survey of Canada |
| Dataset creation date | 2023 |
| Dataset publication date | 2023 |
| Presentation form | Digital model |
| Dataset status - Update frequency | Completed - Not planned |
| Dataset language | English |

**License**

Open Government Licence - Canada ([http://open.canada.ca/en/open-government-licence-canada](http://open.canada.ca/en/open-government-licence-canada))

**Constraints**

The downloaded data must be identified in any re-use of the materials, and the materials must not be misused or misrepresented in any way. The materials in this Open File, including data and other information provided, are made available under Crown copyright, such that ownership is retained by the original source.

**Keyword(s)**

3D Model, Saskatchewan, Western Canadian Sedimentary Basin

**Spatial reference**

| | |
|---|---|
| Extent | Southern Saskatchewan |
| Spatial extent (Lat/Long) | X Min: -110.0      X Max: -102.6<br>Y Min: 49      Y Max: 57.7 |
| Reference system code | EPSG:26913 |
| Reference system name | UTM NAD 83 Zone 13 |

**Lineage**

- 3D model creation

    1) Data cleaning, preparation and integration in SKUA-Gocad™

    2) Stratigraphic column definition

    3) Surface creation

        a. Implicit modelling of all the surfaces
        b. Manual edits of the unconformities
        c. Manual edits of the other surfaces
        d. Cutting surfaces to respect stratigraphic relationships (conformable, eroded, baselap)

    4) Volumetric model creation

- Data source

    o Stratigraphic interpretations of oil and gas wells
    o Surficial geological map
    o Zero-edge contours
    o Digital elevation model (DEM)

**Dataset formats**

- Gocad model
- Individual objects format
    o Gocad format
    o DXF
    o VTK
    o TXT

**Dataset contacts**

| | |
|---|---|
| **Principal investigator** | Arden Marsh<br>Government of Saskatchewan; Ministry of Energy and Resources; Saskatchewan Geological Survey,<br>201, Dewdney Avenue, Regina, Saskatchewan, Canada |
| **Originator** | Karine Bédard<br>Government of Canada; Natural Resources Canada; Geological Survey of Canada - GSC Quebec<br>490, rue de la Couronne, Québec, Québec, Canada |

## Appendix 2    Stratigraphic Well Constraint Data

Number of interpreted well markers for each of the horizon used in the construction of the 3D model.

| | |
|---|---|
| Base_Quaternary | 1063 |
| Belly_River | 2674 |
| Lea_Park | 4615 |

| | |
|---|---|
| Sub_LeaPark_Unconformity | 7930 |
| Upper_Colorado | 7683 |
| 2nd_White_Specks | 8615 |
| Fish_Scales | 7119 |
| Westgate | 7329 |
| Viking_Newcastle_Flotten_Lake | 8469 |
| Joli_Fou | 8906 |
| Pense | 8752 |
| Cantuar | 8573 |

| | |
|---|---|
| Sub_Cantuar_Unconformity | 7132 |

| | |
|---|---|
| Sub_Success_Unconformity | 2023 |
| Rierdon | 1166 |
| Upper_Shaunavon | 2552 |
| Lower_Shaunavon | 2682 |
| Upper_Gravelbourg | 2687 |
| Lower_Gravelbourg | 2705 |
| Upper_Watrous | 2195 |
| Lower_Watrous | 2302 |

| | |
|---|---|
| Sub_Mesozoic_Unconformity | 4743 |
| Poplar | 30 |
| Ratcliffe | 642 |
| Midale | 1084 |
| Frobisher | 1311 |
| Kisbey | 1166 |
| Alida | 1196 |
| Tilston | 1163 |
| Souris_Valley | 1264 |
| Bakken | 2219 |

| | |
|---|---|
| Sub_Mississippian_Unconformity | 2327 |
| Torquay | 1183 |
| Birdbear | 2096 |
| Duperow | 1772 |
| Souris_River | 1618 |
| 1st_Red_Bed | 1624 |
| Dawson_Bay | 1636 |
| 2nd_Red_Bed | 1409 |
| Prairie_Evaporite | 1172 |
| Winnipegosis | 1081 |
| Ashern | 962 |
| Meadow_Lake | 62 |

| | |
|---|---|
| Top_LowerPaleo_Unconformity | 906 |
| Stonewall | 608 |
| Stony_Mountain | 633 |
| Red_River | 635 |
| Winnipeg | 463 |
| Deadwood | 351 |

| | |
|---|---|
| Precambrian | 376 |

| | |
|---|---|
| TOTAL | 142,904 |

## Appendix 3        3D Model Construction Methodology

This appendix presents the steps and parameters used in SKUA-Gocad™ to model construct the 3D model.

First, the Structure and Stratigraphy workflow is used to implicitly model the all the horizons simultaneously and ensures that the relationships between the units are respected as well as prohibiting horizon cross overs. Manual editing of the surfaces is then required, using explicit modelling techniques, to improve the surface resolution and fitting to the data. Finally, a volumetric model is generated from the modelled unconformities and surface tops.

### 1.   Limits and considerations on the SKUA™ Structure and Stratigraphy Workflow

The workflow performances are restricted by the type and volume of data and the size and resolution of the output model. It is designed to use wells with well markers defining units along the well paths as input data. The use of well data is interesting as it takes the stratigraphic relationships in the well into account in the modelling processes. For example, if a marker is not present in a well, it can be defined as not interpreted, eroded, baselap or with an unknown status. This helps modelling the lateral continuity/discontinuity of units as the well paths act as constraints in addition to well markers. However, SKUA-Gocad™ struggles at handling large datasets composed of well data. In this project, loading and showing the wells in the software takes several minutes/hours. It was impossible to get the workflow to generate horizons from the well data; it took several days of computing only to validate the input data. Thus, it was not realistic in terms of modelling time to work with well data directly in the software.

An alternate solution is to use points derived from well markers as input data instead of the whole well dataset. Points are better handled by SKUA-Gocad™ and their loading and presentation is almost instantaneous in the software. The workflow can use the large point dataset to generate surfaces in a few hours. However, the stratigraphic relationships contained in the well dataset, such as if a unit is eroded or not present along a well path, are lost.

However, even with the use of points instead of wells, the software is not able to perform all the steps of the workflow to generate a final stratigraphic model with good resolution. Critical errors are generated during the volume construction, which may be because not enough data are selected to constrain very thin units over the area of interest. As discussed in the 3D modelling methodology section, a data reduction of the large dataset is made in the background without any control on the user side and it is possible that this process could be the cause of the errors preventing volume creation. This random data reduction also affects the reproducibility of the workflow as, every time the workflow is run, a different random sample of the data is used to generate the horizons.

Moreover, as the area of interest of the model is large and the expected resolution is fine, every step of the workflow is in the order of many hours to days. This is not sustainable when building a model and wanting to test the effect of using different parameters on the modelling results. For

these reasons, the workflow is used to generate preliminary surfaces of the unconformities and unit tops. These surfaces are then manually edited outside of the workflow to improve data fitting and resolution.

Another consideration to consider is that the SKUA™ Structure and Stratigraphy Workflow forces younger unconformities to always cut the older horizons and unconformities, and there is no way to indicate the cutting sequences between unconformities. In this case, this means that the syn-sedimentary unconformities would cut the Precambrian surface while it should be continuous across the model. The solution to get around this problem was to conduct the modelling in two phases. The first one where the Precambrian surface is built independently, and a second phase where the modeled surface is used as input data.

## 2.   Implicit modelling with the SKUA™ Structure and Stratigraphy workflow

### 2.1.      Create Stratigraphic Column

The stratigraphic column defining the relationships between the units and horizons in this model is showed in Figure 2.

### 2.2.      Precambrian surface modelling

### 2.2.1.   Selecting Data: Horizons

The role for every input dataset is set to "Picks".
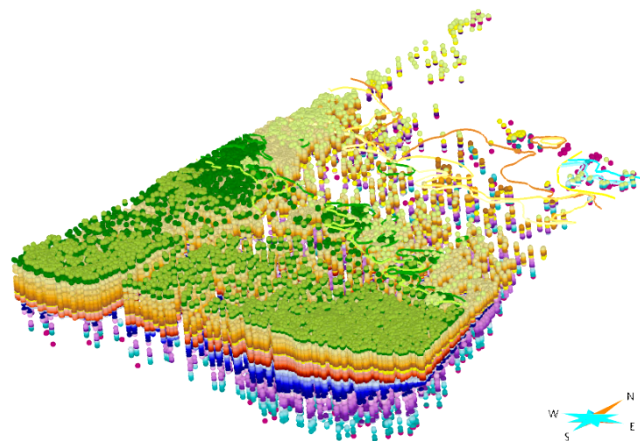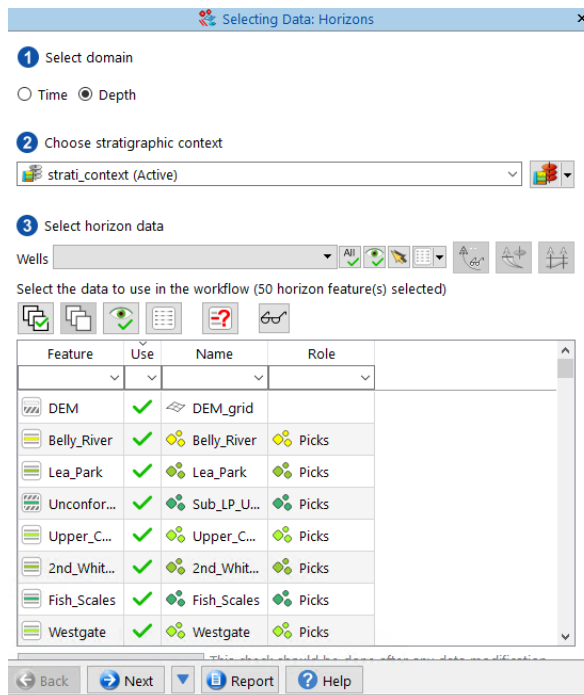
### 2.2.2. Defining the Volume of Interest (VOI)

The VOI is defined with a closed boundary curve, a flat top above the highest point of the DEM and a base following the general shape of the Precambrian points distribution.
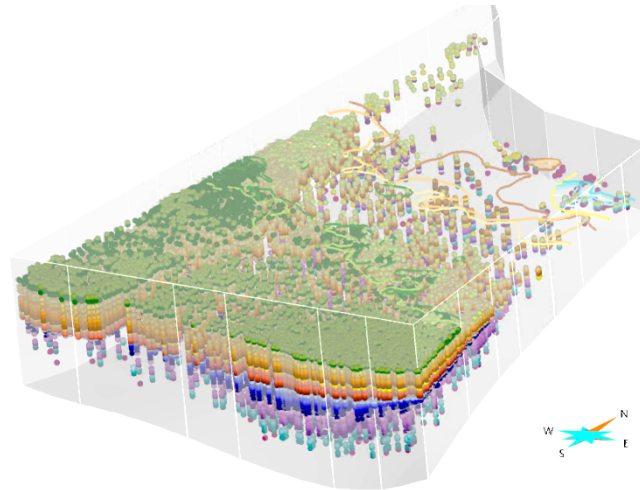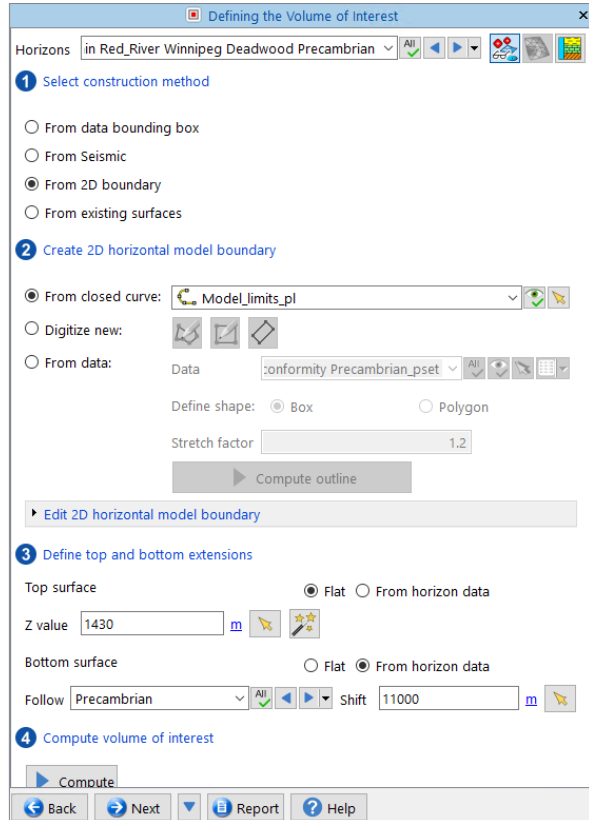
### 2.2.3. Modelling Horizon

In this step, only the Precambrian horizon is modeled. After building the horizon, the data is cleaned to remove points that are located more than 40 metres from the modeled horizon. This allows for the removal of outliers and points that were misinterpreted or misplaced in depth. The horizon is then built a second time with the cleaned dataset, which improves the smoothness of the surface without decreasing the fit to the input points.
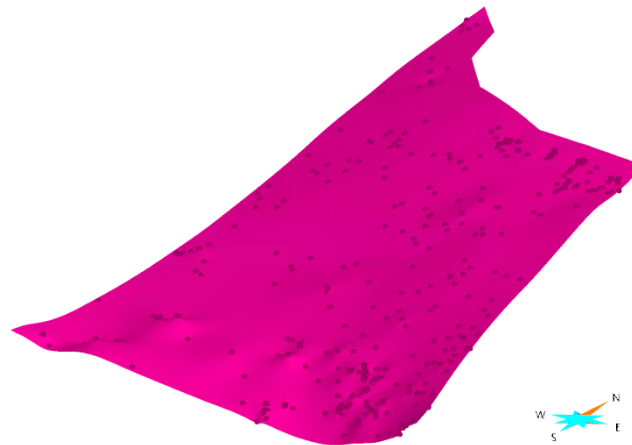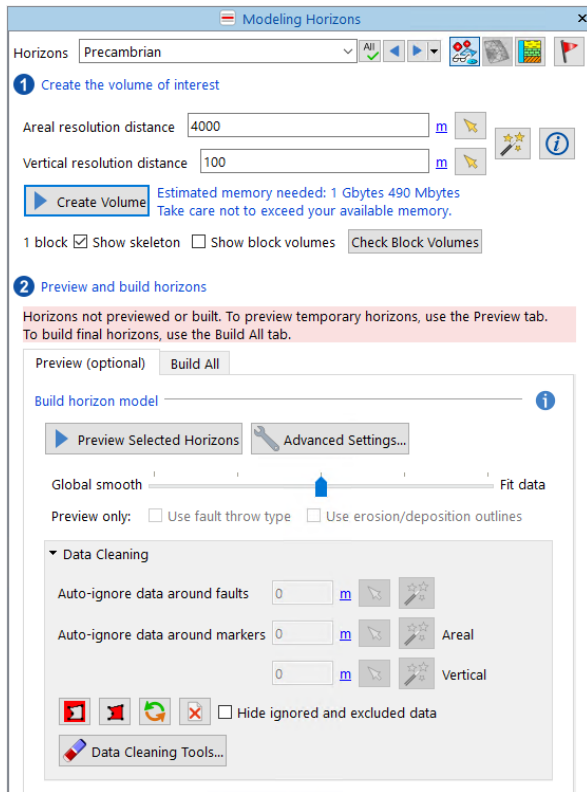


The Precambrian surface is then extracted from the workflow horizons as an independent surface.

Surface → New → from SKUA model → Horizons → Horizons with Resampling

Resampling resolution can be specified if needed. The extracted surfaces can continue beyond unconformities and baselaps (uncheck last box), or be extracted and seen as the result of the workflow (check last box). In that case, as the horizon is not cut by any other horizon, the check box does not have an impact on the extracted surface.
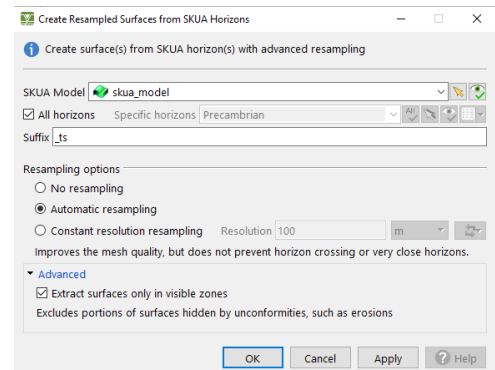
## 2.3. Construction of all stratigraphic surfaces

Precambrian surface is added as input data for this horizon in the SKUA™ Structure and Stratigraphy workflow. This was found to give better results. The previously completed workflow steps must be repeated to build the remaining horizons.

### 2.3.1. Selecting Data: Horizons

The role for every input data is set to "Picks", including the Precambrian surface.
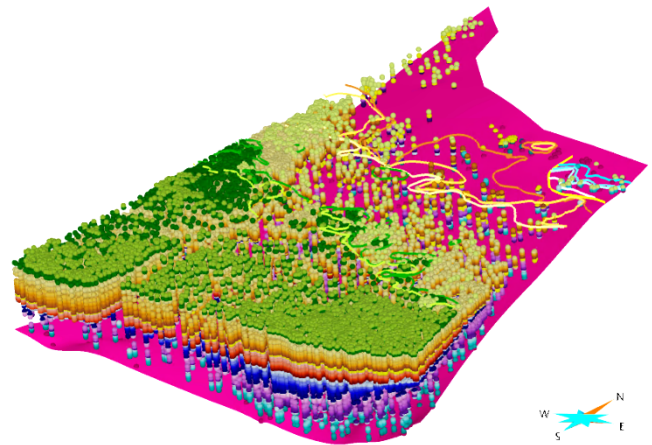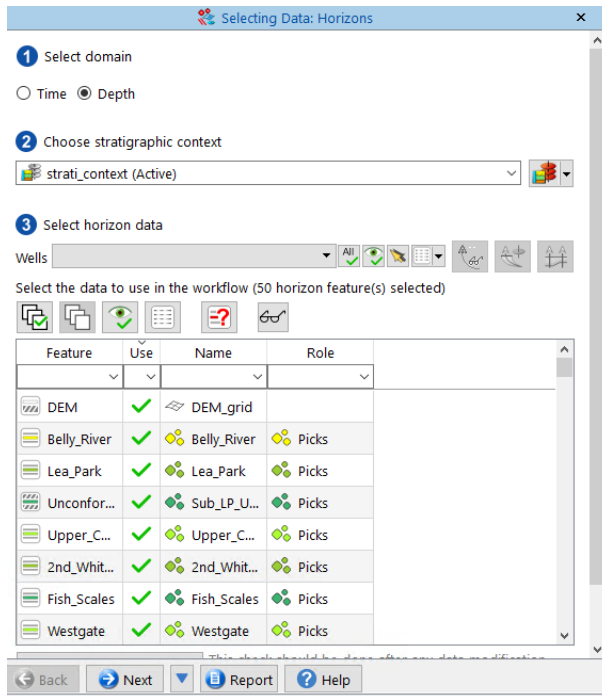


### 2.3.2. Defining the Volume of Interest (VOI)

The VOI is defined as previously.

### 2.3.3. Modelling Horizons

In this step all the horizons are modeled at once. For this reason, the vertical resolution of the volume of interest must be finer than when modelling the Precambrian to help model thin units. The areal and vertical resolution are set as fine as possible while still being manageable by the computer memory. The modelling process respects a fitting factor between the input data and the modeled horizons. The more the data are fitted, the more the horizons are rough, and processes take more time. On the other hand, if the fitting is too low, the horizons are too smooth, and they don't respect the input points. For this model, the fitting factor is balanced between smooth and fit for all horizons except for the DEM where the fitting factor is set to maximum to respect the more reliable and continuous DEM data.
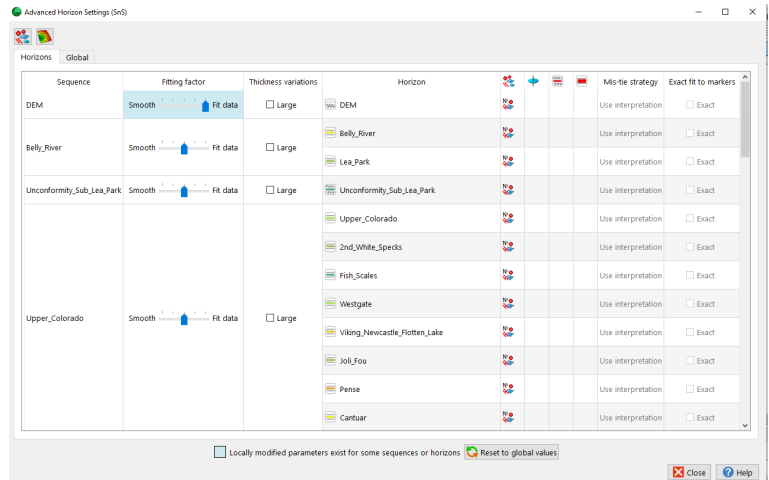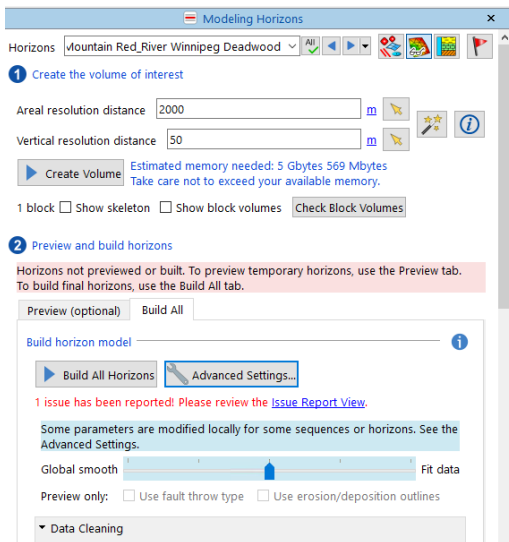
After building the horizons, the dataset is cleaned to ignore points that are located more than 40 metres from the modeled horizons. This allows to remove outliers and points that were misinterpreted or misplaced in depth. The horizons are then rebuilt a second time with the cleaned dataset.

A second cleaning step is performed to ignore points that are located more than 40 metres from the rebuilt horizons. The horizon is then built a third time without the ignored points from the two cleaning passes, which improves the smoothness of the surfaces without decreasing the fit to the input points.
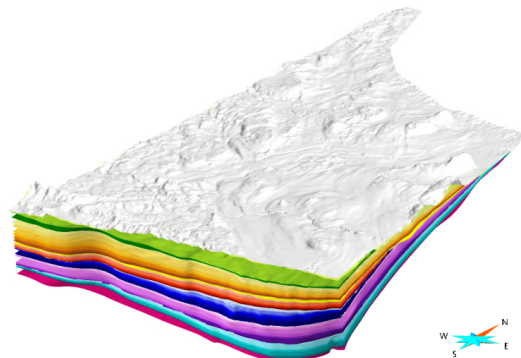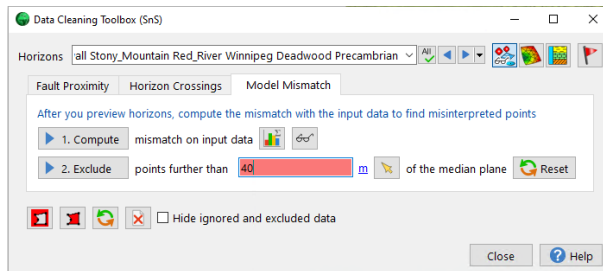


All the surfaces are then extracted from the workflow horizons as independent surfaces.

Surface → New → from SKUA model → Horizons → Horizons with Resampling

In that case, the resampling was automatic, and the extracted surfaces continue beyond unconformities and baselaps (uncheck last box). Using continuous surfaces makes it easier for next manual editing steps.
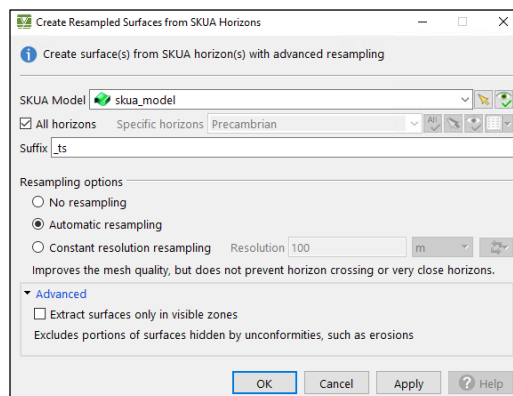
## 3. Stratigraphic surfaces construction

Manual editing of the surfaces is done to ensure that all the data are used in the modelling process as random parts of the datasets are ignored in the workflow. If these manual edits allow for a better respect of the data, it generate inconsistencies in between the surfaces as each surface is edited without stratigraphic relationships (conformable, eroded, baselap) with its neighbours. There is then a back-and-forth modelling process between the neighbour surfaces to ensure that the stratigraphic relationships are respected and that crossovers between surfaces are as limited as possible. This process is tedious, and the results vary depending on the 3D modeller. This is however the only way, with the actual available computer and software resources, to generate a complete model with a very large dataset and a large area of interest with a fine resolution. The image below shows the initial surfaces extracted from the workflow and the final surfaces as edited by the modeller.

| Uncut surfaces extracted from workflow | Final surfaces |
| --- | --- |
|  |  |
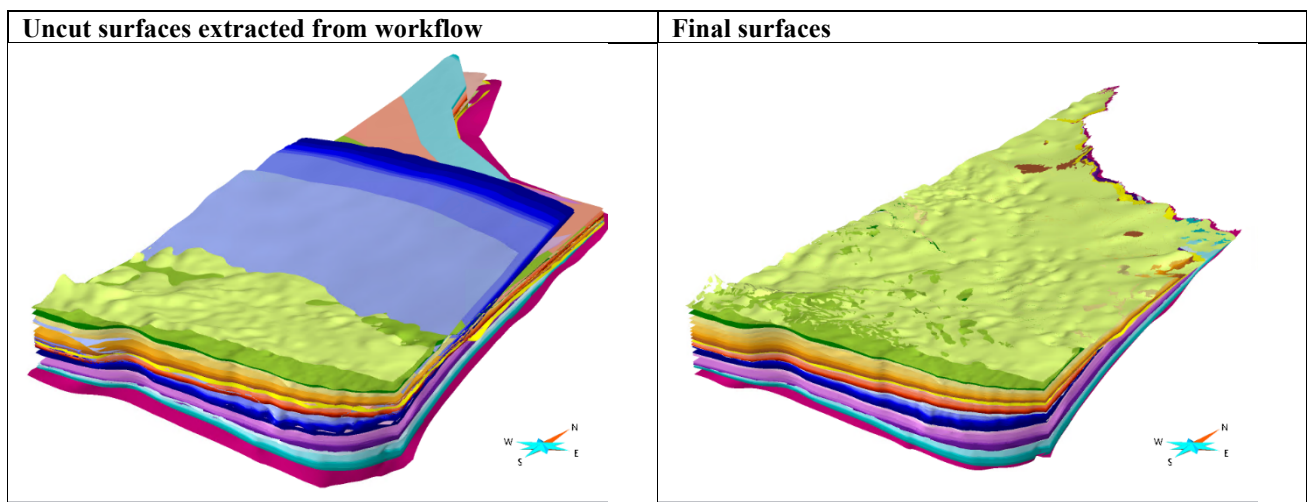
The manual editing of each surface starts with a first interpolation with the surface top markers and geological map contacts. Following that interpolation, input data that are too far from the surface (more than 40 m) are considered as misinterpreted and are discarded from the input dataset. The next modelling iterations only use the remaining data. The manual editing may also consist of adding control points in a region where no data is available, to ensure a modeled surface goes above or below control points of other horizons, as required to respect the available geological knowledge. The resolution of each surface mesh can also be adapted according to the data density. The unconformity surfaces are modelled first to ensure that the horizon surfaces are contained in the corresponding "unconformity blocks". The horizon surfaces are then interpolated individually before being compared to each other to identify stratigraphic inconsistencies like crossovers between surfaces. Removing the crossovers between surfaces is realised in an iterative way. Usually, the surface with the most control points is considered as best modelled, and its neighbours are edited according to its geometry and position. Surfaces considered to be as accurate as possible by the modeller are cut by the unconformities and by any other cutting surfaces, such as older surfaces on which a surface baselaps. The cutting steps that are used to get the final surfaces are detailed below.

26

| Step | Surface(s) being cut | Surface(s) used to cut | Comments |
|------|----------------------|------------------------|----------|
| 1 | All surfaces except DEM | DEM | Delete everything **above** DEM |
| 2 | All surfaces except DEM and Precambrian | Precambrian | Delete everything **below** Precambrian |
| 3 | Unconformity Sub Cantuar | Unconformity Sub Lea Park | Delete everything **above** the unconformity |
| 4 | Unconformity Sub Success | Unconformity Sub Cantuar<br>Unconformity Sub Lea Park | Delete everything **above** the unconformities |
| 5 | Unconformity Sub Mesozoic | Unconformity Sub Success<br>Unconformity Sub Cantuar<br>Unconformity Sub Lea Park | Delete everything **above** the unconformities |
| 6 | Unconformity Sub Mississippian | Unconformity Sub Mesozoic<br>Unconformity Sub Success<br>Unconformity Sub Cantuar<br>Unconformity Sub Lea Park | Delete everything **above** the unconformities |
| 7 | Unconformity Top Lower Paleozoic | Unconformity Sub Mississippian<br>Unconformity Sub Mesozoic<br>Unconformity Sub Success<br>Unconformity Sub Cantuar<br>Unconformity Sub Lea Park | Delete everything **above** the unconformities |
| 8 | Stonewall<br>Stony Mountain<br>Red River<br>Winnipeg<br>Deadwood | Unconformity Sub Mississippian<br>Unconformity Sub Mesozoic<br>Unconformity Sub Success<br>Unconformity Sub Cantuar<br>Unconformity Sub Lea Park<br>Unconformity Top Lower Paleozoic | Delete everything **above** the unconformities |
| 9 | Winnipeg | Deadwood | Delete everything **below** Deadwood to respect **baselap** |
| 10 | Torquay<br>Birdbear<br>Duperow<br>Souris River<br>1$^{st}$ Red Bed<br>Dawson Bay<br>2$^{nd}$ Red Bed<br>Prairie Evaporite<br>Winnipegosis<br>Ashern<br>Meadow Lake | Unconformity Sub Mississippian<br>Unconformity Sub Mesozoic<br>Unconformity Sub Success<br>Unconformity Sub Cantuar<br>Unconformity Sub Lea Park | Delete everything above the unconformities |
| | | Unconformity Top Lower Paleozoic | Delete everything **below** the unconformity |
| 11 | 2$^{nd}$ Red Bed<br>Prairie Evaporite | Winnipegosis | Delete everything **below** Winnipegosis to respect **baselap** |
| 12 | Poplar<br>Ratcliffe<br>Midale<br>Frobisher<br>Kisbey | Unconformity Sub Mesozoic<br>Unconformity Sub Success<br>Unconformity Sub Cantuar<br>Unconformity Sub Lea Park | Delete everything **above** the unconformities |
| | Alida<br>Tilston<br>Souris Valley<br>Bakken | Unconformity Top Lower Paleozoic<br>Unconformity Sub Mississippian | Delete everything **below** the unconformities |

| Step | Surface(s) being cut | Surface(s) used to cut | Comments |
|---|---|---|---|
| 13 | Rierdon<br>Upper Shaunavon<br>Lower Shaunavon<br>Upper Gravelbourg<br>Lower Gravelbourg<br>Upper Watrous<br>Lower Watrous | Unconformity Sub Success<br>Unconformity Sub Cantuar<br>Unconformity Sub Lea Park | Delete everything above the unconformities |
| | | Unconformity Top Lower Paleozoic<br>Unconformity Sub Mississippian<br>Unconformity Sub Mesozoic | Delete everything **below** the unconformities |
| 14 | Upper Colorado<br>$2^{nd}$ White Specks<br>Fish Scales<br>Westgate<br>Viking/Newcastle/Flotten Lake<br>Joli Fou<br>Pense<br>Cantuar | Unconformity Sub Lea Park | Delete everything **above** the unconformity |
| | | Unconformity Top Lower Paleozoic<br>Unconformity Sub Mississippian<br>Unconformity Sub Mesozoic<br>Unconformity Sub Success<br>Unconformity Sub Cantuar | Delete everything **below** the unconformities |
| 15 | $2^{nd}$ White Specks<br>Fish Scales | Westgate | Delete everything **below** Westgate to respect **baselap** |
| 16 | Belly River<br>Lea Park | Unconformity Top Lower Paleozoic<br>Unconformity Sub Mississippian<br>Unconformity Sub Mesozoic<br>Unconformity Sub Success<br>Unconformity Sub Cantuar<br>Unconformity Sub Lea Park | Delete everything **below** the unconformities |

## 4.  Volumetric stratigraphic model

When all the surfaces are considered to have been modelled satisfactorily, a volumetric model is generated from the modelled unconformities and unit tops. This model consists of a voxet (regular 3D grid) with a 2 km x 2 km x 10 m resolution. Every cell of the voxet is assigned to a stratigraphic unit based on the regions limited by the previously modelled surfaces.

### 4.1.    Voxet creation

The volumetric model is contained in a voxet that has the following parameters with an areal resolution of 2 km x 2 km and a vertical resolution of 10 metres, with a total of nearly 123 million cell.

| Sizes | |
|---|---|
| Number of nodes/cells along U: | 699 |
| Number of nodes/cells along V: | 335 |
| Number of nodes/cells along W: | 525 |
| Total number of nodes/cells: | 122936625 |

| Location | |
|---|---|
| Domain: | Depth |
| Origin: | 119000 5406000 -4500 |
| U extremity: | 119000 5406000 2480 |
| V extremity: | 787000 5406000 -4500 |
| W extremity: | 119000 6454000 -4500 |
| U step: | 0 0 10 |
| V step: | 2000 0 0 |
| W step: | 0 2000 0 |
| Data spacing (U V W): | 10m 2000m 2000m |

### 4.2.    Volumetric stratigraphic unit creation

The volumetric stratigraphic units were computed from multiple operations on voxet regions based on their location (above or below) the previous cut and uncut stratigraphic surfaces. This process allows assigning every cell of the model to a region that corresponds to a specific stratigraphic unit. The extent of the regions is limited by an irregular border that is based on the workflow region of interest. Step by step methodology for the region creation is detailed below.

### 4.2.1. *Unconformity blocks construction*

Region creation steps are detailed below.

| Step | Created region | Voxet region creation method | Object used to create region |
|------|----------------|------------------------------|------------------------------|
| 1 | Model_inside | Create region from closed polyline | Polyline of the border of the model |
| 2 | Above_DEM | Region from horizon – Above | DEM surface |
| 3 | Below_DEM | Region from horizon – Below | DEM surface |
| 4 | 00_01_Quaternary | Region from horizon – Above | Base_Quaternary |
| 5 | 00_02_Above_SubLP_Unc | Region from horizon – Above | Unconformity_Sub_Lea_Park |
| 6 | 00_03_SubLP_SubCantuar | Region from horizon – Above | Unconformity_Sub_Cantuar |
| 7 | 00_04_Success | Region from horizon – Above | Unconformity_Sub_Success |
| 8 | 00_05_SubSuccess_SubMesozoic | Region from horizon – Above | Unconformity_Sub_Mississipian |
| 9 | 00_06_Mississippian | Region from horizon – Above | Unconformity_Sub_Mesozoic |
| 10 | 00_07_Devonian | Region from horizon – Above | Unconformity_Top_LPaleo |
| 11 | 00_08_LowerPaleo | Region from horizon – Above | Precambrian uncut surface |
| 12 | 00_09_Precambrian | Region from horizon – Below | Precambrian uncut surface |

Region editing steps are detailed below. It is important to assess the quality of the resulting region(s) after each step, as the result can impact following steps. This consists of a visual check of the region and, if needed, some specific edits to remove outliers or any inconsistencies.

| Step | Edited region(s) (bold: final region) | | Region(s) subtracted from edited region |
|------|---------------------------------------|--|------------------------------------------|
| 1 | Above_DEM<br>Below_DEM<br>00_01_Quaternary<br>00_02_Above_SubLP_Unc<br>00_03_SubLP_SubCantuar<br>00_04_Success | 00_05_SubSuccess_SubMesozoic<br>00_06_Mississippian<br>00_07_Devonian<br>00_08_LowerPaleo<br>00_09_Precambrian | Model_outside |
| 2 | 00_01_Quaternary<br>00_02_Above_SubLP_Unc<br>00_03_SubLP_SubCantuar<br>00_04_Success | 00_05_SubSuccess_SubMesozoic<br>00_06_Mississippian<br>00_07_Devonian<br>00_08_LowerPaleo<br>**00_09_Precambrian** | Above_DEM |
| 3 | **00_01_Quaternary**<br>00_02_Above_SubLP_Unc<br>00_03_SubLP_SubCantuar<br>00_04_Success | 00_05_SubSuccess_SubMesozoic<br>00_06_Mississippian<br>00_07_Devonian<br>00_08_LowerPaleo | 00_09_Precambrian |
| 4 | **00_08_LowerPaleo** | | 00_01_Quaternary<br>00_02_Above_SubLP_Unc<br>00_03_SubLP_SubCantuar<br>00_04_Success<br>00_05_SubSuccess_SubMesozoic<br>00_06_Mississippian<br>00_07_Devonian |

| Step | Edited region(s) (bold: final region) | Region(s) subtracted from edited region |
|---|---|---|
| 5 | **00_07_Devonian** | 00_01_Quaternary<br>00_02_Above_SubLP_Unc<br>00_03_SubLP_SubCantuar<br>00_04_Success<br>00_05_SubSuccess_SubMesozoic<br>00_06_Mississippian |
| 6 | **00_06_Mississippian** | 00_01_Quaternary<br>00_02_Above_SubLP_Unc<br>00_03_SubLP_SubCantuar<br>00_04_Success<br>00_05_SubSuccess_SubMesozoic |
| 7 | **00_05_SubSuccess_SubMesozoic** | 00_01_Quaternary<br>00_02_Above_SubLP_Unc<br>00_03_SubLP_SubCantuar<br>00_04_Success |
| 8 | **00_04_Success** | 00_01_Quaternary<br>00_02_Above_SubLP_Unc<br>00_03_SubLP_SubCantuar |
| 9 | **00_03_SubLP_SubCantuar** | 00_01_Quaternary<br>00_02_Above_SubLP_Unc |
| 10 | **00_02_Above_SubLP_Unc** | 00_01_Quaternary |
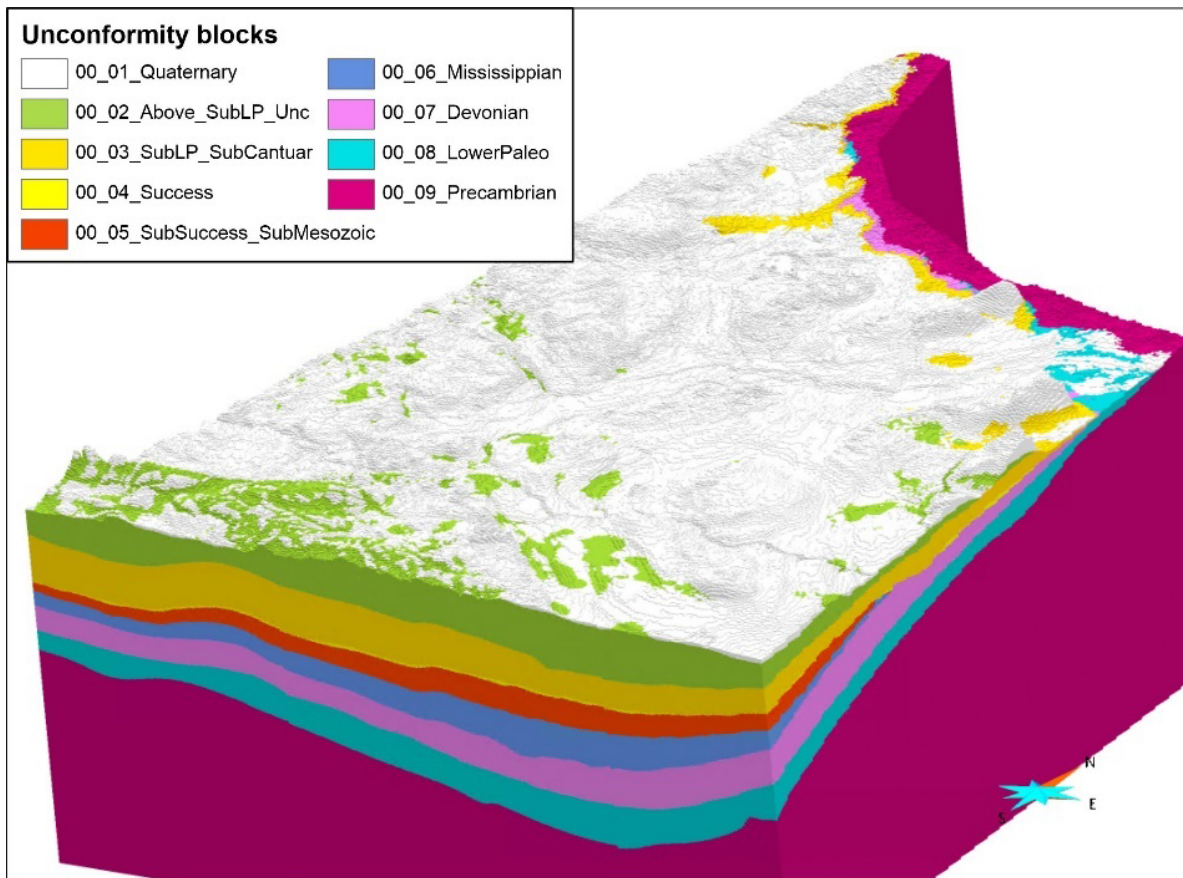
### 4.2.2. Unit regions construction

Region creation steps are detailed below.

| Step | Created region(s) (bold: final region) | Voxet region creation method | Object used to create region |
|---|---|---|---|
| 1 | **01_Quaternary** | Copy region | 00_01_Quaternary |
| 2 | 02_Above_Belly_River<br>03_Belly_River<br>04_Lea_Park | Copy region | 00_02_Above_SubLP_Unc |
| 3 | 05_Milk_River<br>06_Upper_Colorado<br>07_2nd_White_Specks<br>08_Fish_Scales<br>09_Westgate<br>10_Viking_Newcastle_Flotten_Lake<br>11_Joli_Fou<br>12_Pense<br>13_Cantuar | Copy region | 00_03_SubLP_SubCantuar |
| 4 | **14_Success** | Copy region | 00_04_Success |
| 5 | 15_Masefield<br>16_Rierdon<br>17_Upper_Shaunavon<br>18_Lower_Shaunavon<br>19_Upper_Gravelbourg<br>20_Lower_Gravelbourg<br>21_Upper_Watrous<br>22_Lower_Watrous | Copy region | 00_05_SubSuccess_SubMesozoic |
| 6 | 23_Big_Snowy<br>24_Poplar<br>25_Ratcliffe<br>26_Midale<br>27_Frobisher<br>28_Kisbey<br>29_Alida<br>30_Tilston<br>31_Souris_Valley<br>32_Bakken | Copy region | 00_06_Mississippian |
| 7 | 33_Big_Valley<br>34_Torquay<br>35_Birdbear<br>36_Duperow<br>37_Souris_River<br>38_1st_Red_Bed<br>39_Dawson_Bay<br>40_2nd_Red_Bed<br>41_Prairie_Evaporite<br>42_Winnipegosis<br>43_Ashern<br>44_Meadow_Lake | Copy region | 00_07_Devonian |

| Step | Created region(s) (bold: final region) | Voxet region creation method | Object used to create region |
|---|---|---|---|
| 8 | 45_Interlake<br>46_Stonewall<br>47_Stony_Mountain<br>48_Red_River<br>49_Winnipeg<br>50_Deadwood | Copy region | 00_08_LowerPaleo |
| 9 | **51_Precambrian** | Copy region | 00_09_Precambrian |
| 10 | Belly_River<br>Lea_Park<br>Upper_Colorado<br>2nd_White_Specks<br>Fish_Scales<br>Westgate<br>Viking_Newcastle_Flotten_Lake<br>Joli_Fou<br>Pense<br>Cantuar<br>Rierdon<br>Upper_Shaunavon<br>Lower_Shaunavon<br>Upper_Gravelbourg<br>Lower_Gravelbourg<br>Upper_Watrous<br>Lower_Watrous<br>Poplar<br>Ratcliffe<br>Midale<br>Frobisher<br>Kisbey<br>Alida<br>Tilston<br>Souris_Valley<br>Bakken<br>Torquay<br>Birdbear<br>Duperow<br>Souris_River<br>1st_Red_Bed<br>Dawson_Bay<br>2nd_Red_Bed<br>Prairie_Evaporite<br>Winnipegosis<br>Ashern<br>Meadow_Lake<br>Stonewall<br>Stony_Mountain<br>Red_River<br>Winnipeg<br>Deadwood | Region from horizon – Below | Uncut surface of each horizon |

As for the unconformities, region editing steps are detailed below. It is important to assess the quality of the resulting region(s) after each step, as the result can impact following steps. This consists of a visual check of the region and, if needed, some specific edits to remove outliers or any inconsistencies.

| Step | Edited region(s) (bold: final region) | | Region(s) subtracted from edited region |
|---|---|---|---|
| 1 | Above_Belly_River | Frobisher | |
| | Belly_River | Kisbey | |
| | Lea_Park | Alida | |
| | Milk_River | Tilston | |
| | Upper_Colorado | Souris_Valley | |
| | 2nd_White_Specks | Bakken | |
| | Fish_Scales | Big_Valley | |
| | Westgate | Torquay | |
| | Viking_Newcastle_Flotten_Lake | Birdbear | |
| | Joli_Fou | Duperow | |
| | Pense | Souris_River | |
| | Cantuar | 1st_Red_Bed | Model_outside |
| | Success | Dawson_Bay | Above_DEM |
| | Masefield | 2nd_Red_Bed | 09_Precambrian |
| | Rierdon | Prairie_Evaporite | |
| | Upper_Shaunavon | Winnipegosis | |
| | Lower_Shaunavon | Ashern | |
| | Upper_Gravelbourg | Meadow_Lake | |
| | Lower_Gravelbourg | Interlake | |
| | Upper_Watrous | Stonewall | |
| | Lower_Watrous | Stony_Mountain | |
| | Big_Snowy | Red_River | |
| | Poplar | Winnipeg | |
| | Ratcliffe | Deadwood | |
| | Midale | | |
| 2 | **02_Above_Belly_River** | | Belly_River |
| 3 | 03_Belly_River | 04_Lea_Park | 02_Above_Belly_River |
| 4 | **03_Belly_River** | | Lea_Park |
| 5 | **04_Lea_Park** | | 03_Belly_River |
| 6 | **05_Milk_River** | | Upper_Colorado |
| 7 | 06_Upper_Colorado | 10_Viking_Newcastle_Flotten_Lake | |
| | 07_2nd_White_Specks | 11_Joli_Fou | |
| | 08_Fish_Scales | 12_Pense | 05_Milk_River |
| | 09_Westgate | 13_Cantuar | |
| 8 | **06_Upper_Colorado** | | 2nd_White_Specks |
| 9 | 07_2nd_White_Specks | 10_Viking_Newcastle_Flotten_Lake | |
| | 08_Fish_Scales | 11_Joli_Fou | |
| | 09_Westgate | 12_Pense | 06_Upper_Colorado |
| | | 13_Cantuar | |
| 10 | **07_2nd_White_Specks** | | Fish_Scales |
| | | | Westgate |
| 11 | 08_Fish_Scales | 11_Joli_Fou | |
| | 09_Westgate | 12_Pense | 07_2nd_White_Specks |
| | 10_Viking_Newcastle_Flotten_Lake | 13_Cantuar | |
| 12 | **08_Fish_Scales** | | Westgate |

| Step | Edited region(s) (bold: final region) | | Region(s) subtracted from edited region |
|------|----------------------------------------|--|------------------------------------------|
| 13 | 09_Westgate<br>10_Viking_Newcastle_Flotten_Lake<br>11_Joli_Fou | 12_Pense<br>13_Cantuar | 08_Fish_Scales |
| 14 | **09_Westgate** | | Viking_Newcastle_Flotten_Lake |
| 15 | 10_Viking_Newcastle_Flotten_Lake<br>11_Joli_Fou | 12_Pense<br>13_Cantuar | 09_Westgate |
| 16 | **10_Viking_Newcastle_Flotten_Lake** | | Joli_Fou |
| 17 | 11_Joli_Fou<br>12_Pense | 13_Cantuar | 10_Viking_Newcastle_Flotten_Lake |
| 18 | **11_Joli_Fou** | | Pense |
| 19 | 12_Pense | 13_Cantuar | 11_Joli_Fou |
| 20 | **12_Pense** | | Cantuar |
| 21 | **13_Cantuar** | | 12_Pense |
| 22 | **15_Masefield** | | Rierdon |
| 23 | 16_Rierdon<br>17_Upper_Shaunavon<br>18_Lower_Shaunavon<br>19_Upper_Gravelbourg | 20_Lower_Gravelbourg<br>21_Upper_Watrous<br>22_Lower_Watrous | 15_Masefield |
| 24 | **16_Rierdon** | | Upper_Shaunavon |
| 25 | 17_Upper_Shaunavon<br>18_Lower_Shaunavon<br>19_Upper_Gravelbourg | 20_Lower_Gravelbourg<br>21_Upper_Watrous<br>22_Lower_Watrous | 16_Rierdon |
| 26 | **17_Upper_Shaunavon** | | Lower_Shaunavon |
| 27 | 18_Lower_Shaunavon<br>19_Upper_Gravelbourg<br>20_Lower_Gravelbourg | 21_Upper_Watrous<br>22_Lower_Watrous | 17_Upper_Shaunavon |
| 28 | **18_Lower_Shaunavon** | | Upper_Gravelbourg |
| 29 | 19_Upper_Gravelbourg<br>20_Lower_Gravelbourg | 21_Upper_Watrous<br>22_Lower_Watrous | 18_Lower_Shaunavon |
| 30 | **19_Upper_Gravelbourg** | | Lower_Gravelbourg |
| 31 | 20_Lower_Gravelbourg<br>21_Upper_Watrous | 22_Lower_Watrous | 19_Upper_Gravelbourg |
| 32 | **20_Lower_Gravelbourg** | | Upper_Watrous |
| 33 | 21_Upper_Watrous | 22_Lower_Watrous | 20_Lower_Gravelbourg |
| 34 | **21_Upper_Watrous** | | Lower_Watrous |
| 35 | **22_Lower_Watrous** | | 21_Upper_Watrous |
| 36 | **23_Big_Snowy** | | Poplar |
| 37 | 24_Poplar<br>25_Ratcliffe<br>26_Midale<br>27_Frobisher<br>28_Kisbey | 29_Alida<br>30_Tilston<br>31_Souris_Valley<br>32_Bakken | 23_Big_Snowy |

| Step | Edited region(s) (bold: final region) | | Region(s) subtracted from edited region |
|------|-----|-----|-----|
| 38 | **24_Poplar** | | Ratcliffe |
| 39 | 25_Ratcliffe<br>26_Midale<br>27_Frobisher<br>28_Kisbey | 29_Alida<br>30_Tilston<br>31_Souris_Valley<br>32_Bakken | 24_Poplar |
| 40 | **25_Ratcliffe** | | Midale |
| 41 | 26_Midale<br>27_Frobisher<br>28_Kisbey<br>29_Alida | 30_Tilston<br>31_Souris_Valley<br>32_Bakken | 25_Ratcliffe |
| 42 | **26_Midale** | | Frobisher |
| 43 | 27_Frobisher<br>28_Kisbey<br>29_Alida | 30_Tilston<br>31_Souris_Valley<br>32_Bakken | 26_Midale |
| 44 | **27_Frobisher** | | Kisbey |
| 45 | 28_Kisbey<br>29_Alida<br>30_Tilston | 31_Souris_Valley<br>32_Bakken | 27_Frobisher |
| 46 | **28_Kisbey** | | Alida |
| 47 | 29_Alida<br>30_Tilston | 31_Souris_Valley<br>32_Bakken | 28_Kisbey |
| 48 | **29_Alida** | | Tilston |
| 49 | 30_Tilston<br>31_Souris_Valley | 32_Bakken | 29_Alida |
| 50 | **30_Tilston** | | Souris_Valley |
| 51 | 31_Souris_Valley | 32_Bakken | 30_Tilston |
| 52 | **31_Souris_Valley** | | Bakken |
| 53 | **32_Bakken** | | 31_Souris_Valley |
| 54 | **33_Big_Valley** | | Torquay |
| 55 | 34_Torquay<br>35_Birdbear<br>36_Duperow<br>37_Souris_River<br>38_1st_Red_Bed<br>39_Dawson_Bay | 40_2nd_Red_Bed<br>41_Prairie_Evaporite<br>42_Winnipegosis<br>43_Ashern<br>44_Meadow_Lake | 33_Big_Valley |
| 56 | **34_Torquay** | | Birdbear |
| 57 | 35_Birdbear<br>36_Duperow<br>37_Souris_River<br>38_1st_Red_Bed<br>39_Dawson_Bay | 40_2nd_Red_Bed<br>41_Prairie_Evaporite<br>42_Winnipegosis<br>43_Ashern<br>44_Meadow_Lake | 34_Torquay |
| 58 | **35_Birdbear** | | Duperow |

| Step | Edited region(s) (bold: final region) | | Region(s) subtracted from edited region |
|---|---|---|---|
| 59 | 36_Duperow<br>37_Souris_River<br>38_1st_Red_Bed<br>39_Dawson_Bay<br>40_2nd_Red_Bed | 41_Prairie_Evaporite<br>42_Winnipegosis<br>43_Ashern<br>44_Meadow_Lake | 35_Birdbear |
| 60 | **36_Duperow** | | Souris_River |
| 61 | 37_Souris_River<br>38_1st_Red_Bed<br>39_Dawson_Bay<br>40_2nd_Red_Bed | 41_Prairie_Evaporite<br>42_Winnipegosis<br>43_Ashern<br>44_Meadow_Lake | 36_Duperow |
| 62 | **37_Souris_River** | | 1st_Red_Bed |
| 63 | 38_1st_Red_Bed<br>39_Dawson_Bay<br>40_2nd_Red_Bed<br>41_Prairie_Evaporite | 42_Winnipegosis<br>43_Ashern<br>44_Meadow_Lake | 37_Souris_River |
| 64 | **38_1st_Red_Bed** | | Dawson_Bay |
| 65 | 39_Dawson_Bay<br>40_2nd_Red_Bed<br>41_Prairie_Evaporite | 42_Winnipegosis<br>43_Ashern<br>44_Meadow_Lake | 38_1st_Red_Bed |
| 66 | **39_Dawson_Bay** | | 2nd_Red_Bed |
| 67 | 40_2nd_Red_Bed<br>41_Prairie_Evaporite<br>42_Winnipegosis | 43_Ashern<br>44_Meadow_Lake | 39_Dawson_Bay |
| 68 | **40_2nd_Red_Bed** | | Prairie_Evaporite<br>Winnipegosis |
| 69 | 41_Prairie_Evaporite<br>42_Winnipegosis | 43_Ashern<br>44_Meadow_Lake | 40_2nd_Red_Bed |
| 70 | **41_Prairie_Evaporite** | | Winnipegosis |
| 71 | 42_Winnipegosis<br>43_Ashern | 44_Meadow_Lake | 41_Prairie_Evaporite |
| 72 | **42_Winnipegosis** | | Ashern |
| 73 | 43_Ashern | 44_Meadow_Lake | 42_Winnipegosis |
| 74 | **43_Ashern** | | Meadow_Lake |
| 75 | **44_Meadow_Lake** | | 43_Ashern |
| 76 | **45_Interlake** | | Stonewall |
| 77 | 46_Stonewall<br>47_Stony_Mountain<br>48_Red_River | 49_Winnipeg<br>50_Deadwood | 45_Interlake |
| 78 | **46_Stonewall** | | Stony_Mountain |
| 79 | 47_Stony_Mountain<br>48_Red_River | 49_Winnipeg<br>50_Deadwood | 46_Stonewall |
| 80 | **47_Stony_Mountain** | | Red_River |
| 81 | 48_Red_River<br>49_Winnipeg | 50_Deadwood | 47_Stony_Mountain |

| Step | Edited region(s) (bold: final region) | Region(s) subtracted from edited region |
|---|---|---|
| 82 | **48_Red_River** | Winnipeg<br>Deadwood |
| 83 | 49_Winnipeg         50_Deadwood | 48_Red_River |
| 84 | **49_Winnipeg** | Deadwood |
| 85 | **50_Deadwood** | 49_Winnipeg |

## 5. Stratigraphic property assignation

Every object in the project is assigned a numerical property "Strat_code" which allows to relate the objects to a specific unit/horizon. The correlation between the "Strat_code" values and the stratigraphic column is presented in the table below.

| Strat_code | Horizon | Unit |
|---|---|---|
| 1 | DEM | Quaternary |
| 2 | Base_Quaternary | Above_Belly_River |
| 3 | Belly_River | Belly_River |
| 4 | Lea_Park | Lea_Park |
| 5 | Unconformity_Sub_Lea_Park | Milk_River |
| 6 | Upper_Colorado | Upper_Colorado |
| 7 | 2nd_White_Specks | 2nd_White_Specks |
| 8 | Fish_Scales | Fish_Scales |
| 9 | Westgate | Westgate |
| 10 | Viking_Newcastle_Flotten_Lake | Viking_Newcastle_Flotten_Lake |
| 11 | Joli_Fou | Joli_Fou |
| 12 | Pense | Pense |
| 13 | Cantuar | Cantuar |
| 14 | Unconformity_Sub_Cantuar | Success |
| 15 | Unconformity_Sub_Success | Masefield |
| 16 | Rierdon | Rierdon |
| 17 | Upper_Shaunavon | Upper_Shaunavon |
| 18 | Lower_Shaunavon | Lower_Shaunavon |
| 19 | Upper_Gravelbourg | Upper_Gravelbourg |
| 20 | Lower_Gravelbourg | Lower_Gravelbourg |
| 21 | Upper_Watrous | Upper_Watrous |
| 22 | Lower_Watrous | Lower_Watrous |
| 23 | Unconformity_Sub_Mesozoic | Big_Snowy |
| 24 | Poplar | Poplar |
| 25 | Ratcliffe | Ratcliffe |
| 26 | Midale | Midale |
| 27 | Frobisher | Frobisher |
| 28 | Kisbey | Kisbey |
| 29 | Alida | Alida |

| Strat_code | Horizon | Unit |
|---|---|---|
| 30 | Tilston | Tilston |
| 31 | Souris_Valley | Souris_Valley |
| 32 | Bakken | Bakken |
| 33 | Unconformity_Sub_Miss | Big_Valley |
| 34 | Torquay | Torquay |
| 35 | Birdbear | Birdbear |
| 36 | Duperow | Duperow |
| 37 | Souris_River | Souris_River |
| 38 | 1st_Red_Bed | 1st_Red_Bed |
| 39 | Dawson_Bay | Dawson_Bay |
| 40 | 2nd_Red_Bed | 2nd_Red_Bed |
| 41 | Prairie_Evaporite | Prairie_Evaporite |
| 42 | Winnipegosis | Winnipegosis |
| 43 | Ashern | Ashern |
| 44 | Meadow_Lake | Meadow_Lake |
| 45 | Unconformity_Top_LPaleo | Interlake |
| 46 | Stonewall | Stonewall |
| 47 | Stony_Mountain | Stony_Mountain |
| 48 | Red_River | Red_River |
| 49 | Winnipeg | Winnipeg |
| 50 | Deadwood | Deadwood |
| 51 | Precambrian | Precambrian |

## Appendix 4          Geoinformation Table of Contents

of_8969.zip

```
of_8969.pdf                    (report)
of_8969_readme.rtf             (Publication information file)


\3D
   2023_SK_WCSB_3D_Model.pdf                          3D Acrobat™ PDF
   of_8969_2023_SK_WCSB_3D_Model_Metadata.html        Metadata file

   \Gocad_Project              Model in SKUA-Gocad™ format (version 19p4)

   \Objects                    Individual object exports from 3D model

      \DXF                     Objects in DXF format
         \Points_Curves
            \*_contact.dxf      Input geological map contacts
            \*_pset.dxf         Input well markers
         \Surfaces
            \*_cut.dxf          Final triangulated surfaces
            \*_uncut.dxf        Surfaces extracted from SKUA before manual edits
         \Voxet
            \SK_vo_pset.dxf     Points extracted from the voxet, 1point/cell

      \Gocad                              Objects in Gocad format
         WCSB_SK_colormap.xcmap           File defining the stratigraphic column
         WCSB_SK_Stratigraphic_Column.xml File defining colour scale for stratigraphic column

            \Points_Curves
               \Geological_map_contacts.pl   Input geological map contacts
               \Model_limits_pl.pl           Areal extent of the model
               \SK_province.pl               Saskatchewan borders
               \well_markers.vs              Input well markers
            \Surfaces
               \DEM_surf.ts                  DEM triangulated surface
               \Model_limits_surf.ts         3D model limits
               \Final*.ts                    Final triangulated surfaces
               \Uncut*.ts                    Surfaces extracted from workflow before manual edits
            \Voxet
               \SK_2km_10m_2022.vo           Final voxet with regions
               \*@@                          Voxet properties
               \SK_vo_pset.vs                Points extracted from the voxet, 1point/cell

      \TXT                                  Objects in delimited (;) text format
         \Points_Curves
            \geological_map_contacts_XYZ.txt  Input geological map contact points
            \well_markers_XYZ.txt             Input well markers
         \Surfaces
            \DEM_surf_XYZ.txt                 DEM triangulated surface points
            \Final_surfaces_XYZ.txt           Final triangulated surfaces points
```

| | |
|---|---|
| \Uncut_surfaces_XYZ.txt | Surfaces extracted from workflow before manual edits |
| \Voxet | |
| \SK_vo_pset.txt | Points extracted from the voxet, 1point/cell |
| | |
| \VTK | Objects in VTK format |
| \Points_Curves | |
| \*_contact.vtp | Input geological map contacts |
| \*_pset.vtp | Input well markers |
| \Surfaces | |
| \DEM_surf.vtp | DEM triangulated surface |
| \Model_limits_surf.vtp | 3D model limits |
| \*_cut.vtp | Final triangulated surfaces |
| \*_uncut.vtp | Surfaces extracted from SKUA before manual edits |
| \Voxet | |
| \SK_vo_2km_10m_2022.vts | Voxet |