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3D structural geological model of the Mallik Anticline, Canadian Arctic

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Abstract

The Mallik Anticline is a geologic structure in the Mackenzie Delta in the Canadian Arctic. Tectonics throughout the Cenozoic, with compressional phases in the early Eocene to the late Miocene, formed this large, domed structure that is today an important source of hydrocarbons. Gas hydrates occur in the clastic sedimentary rocks of the Oligocene to Pleistocene Kugmallite, Mackenzie Bay, and Iperk sequences, which were essentially formed by deltaic processes. The presence of hydrocarbon gases within the permafrost zone in the Canadian Arctic has led to extensive exploration and production activities in the region since the mid-1960s, and the investigations by geologists and geophysicists have already been published in numerous scientific articles to date.

This report describes the implementation of the first field-scale 3D static geologic model of the Mallik site, which was created using data from well logs and 2D seismic reflection profiles. The dataset related to this report provides elevation depths and thickness data of the three distinct sequence boundaries Kugmallit-Richards, Mackenzie Bay-Kugmallit and Iperk-Mackenzie Bay as well as fault data from the Mallik site.

1. Model Dimensions

Spatial reference: EPSG projection 32608 – WGS 84 / UTM Zone 8N

Axis	Min	Max	Delta
X	505003.1	526216.3	21213.2
Y	7691291.9	7712505.1	21213.2

Spatial reference: geographic (latitude / longitude)

Lat	~ 69.33	~ 69.52	~ 0.19
Long	~ -134.87	~ -134.33	~ 0.54

2. Geological Overview

The Mallik Anticline is a geological structure located in the Mackenzie Delta (MD) of Canada's Northwest Territories in the Canadian Arctic (Figure 1). Today, it is an important source of hydrocarbons and has been the focus of exploration and production activities starting in the mid-1960s. The region has since then been extensively investigated by geologists and geophysicists, and the results of their studies have already been published in numerous scientific papers (e.g., Markl et al., 1970; Hollister et al., 1972; Dixon and Dietrich, 1988; Dixon et al., 1992; Collett et al., 1999; Dallimore and Collett, 1999; Li et al., 2022).

The MD was formed during the Early Cretaceous as part of a rifted continental margin basin. The geological time span represented by the deposits on the continental shelf of the MD and the adjacent Beaufort Sea ranges from the Paleozoic to the Holocene. The Palaeozoic rocks, which gradually thicken towards the west, are intersected by numerous faults and overlain by a thick post-rift basin-fill formed by deltaic processes. This sedimentary succession marks a regional unconformity at the boundary between the Upper Cretaceous and the Pre-Cretaceous rocks (Dixon et al., 1992; Collett et al., 1999).

Potential petroleum source rocks are from the Upper Devonian as well as the Boundary Creek and Smoking Hills strata from the Upper Cretaceous, overlying the aforementioned unconformity (Osadetz et al., 2005). The younger Late Cretaceous to Holocene sedimentary succession primarily consists of marine organic-rich muds and interbedded deltaic sandstones and shales derived from a series of sedimentary cycles in a foreland basin of the Laramide orogeny progressing south-west of the present coastline at that time (Dixon et al., 1992; Miller et al., 2005). The entire sequence exhibits a thickness of 12-16 km,

increasing northwards towards the coast, and reaches its maximum below sea level. Modern deltaic sediments as well as older fluvial and glacial deposits complete the sedimentary sequence at its top (Collett et al., 1999). On the basis of seismic and well-log data, eleven transgressive-regressive sequences within the Upper-Cretaceous to Cenozoic strata were identified, each terminated by a major unconformity (Dixon et al., 1992; Collett et al., 1999; Miller et al., 2005; Chen et al., 2021). In the Iviq-Mallik-Taglu area, four distinct lithostratigraphic units within the Cenozoic sequence contain gas hydrates, three of which are mentioned here and represented as layer boundaries in the 3D model.

The *Richards Sequence* of the Eocene age is mainly made up of mudstones and siltstones in finely-grained distal pro-delta and delta-slope deposits. It is unconformably covered by the coarser delta-front and delta-plain deposits of the Oligocene *Kugmallite Sequence*, which is the thickest lithostratigraphic unit in the area (Dixon et al., 1992). The Late Oligocene to Middle Miocene Mackenzie Bay Sequence consists largely of mudstones and siltstones from outer-shelf and deep-water deposits that unconformably overlie the Kugmallite Sequence and older strata. The Pliocene to Pleistocene *Iperk Sequence*, consisting of nearshore sand and gravel layers that transition to mud and silt deposits on the continental slope, has a high thickness and is relatively undisturbed. It overlies older deposits and truncates most Early to Middle Cenozoic structural features at its base (Dixon et al., 1992; Osadetz et al. 2005).

Tectonics throughout the Cenozoic, beginning with periods of extension during Mesozoic rifting owing to the opening of the Canada Basin, and periods of compression during the early Eocene to late Miocene, have deformed the basin fill in the MD. The strata has undergone normal, thrust and strike-slip faulting, as well as folding in predominantly northwest direction, leading to the formation of various large-amplitude anticlinal systems, including the Mallik Anticline, located in the central MD. Gas hydrates are rich in natural gases that likely migrated upward from deep conventional hydrocarbon source rocks via evolved fault systems into the Cenozoic sediments of the continental shelf and onshore. At appropriately high gas concentrations, the gas hydrates form here under high pressure and low temperatures and accumulate in the anticlines as they provide efficient structural traps (Dixon et al., 1992; Brent et al., 2005). Approximately one-third of gas hydrate reserves in the MD are located onshore, while the bulk of reserves lie beneath the Beaufort Sea (Dallimore and Collett, 1999; Osadetz et al., 2005).

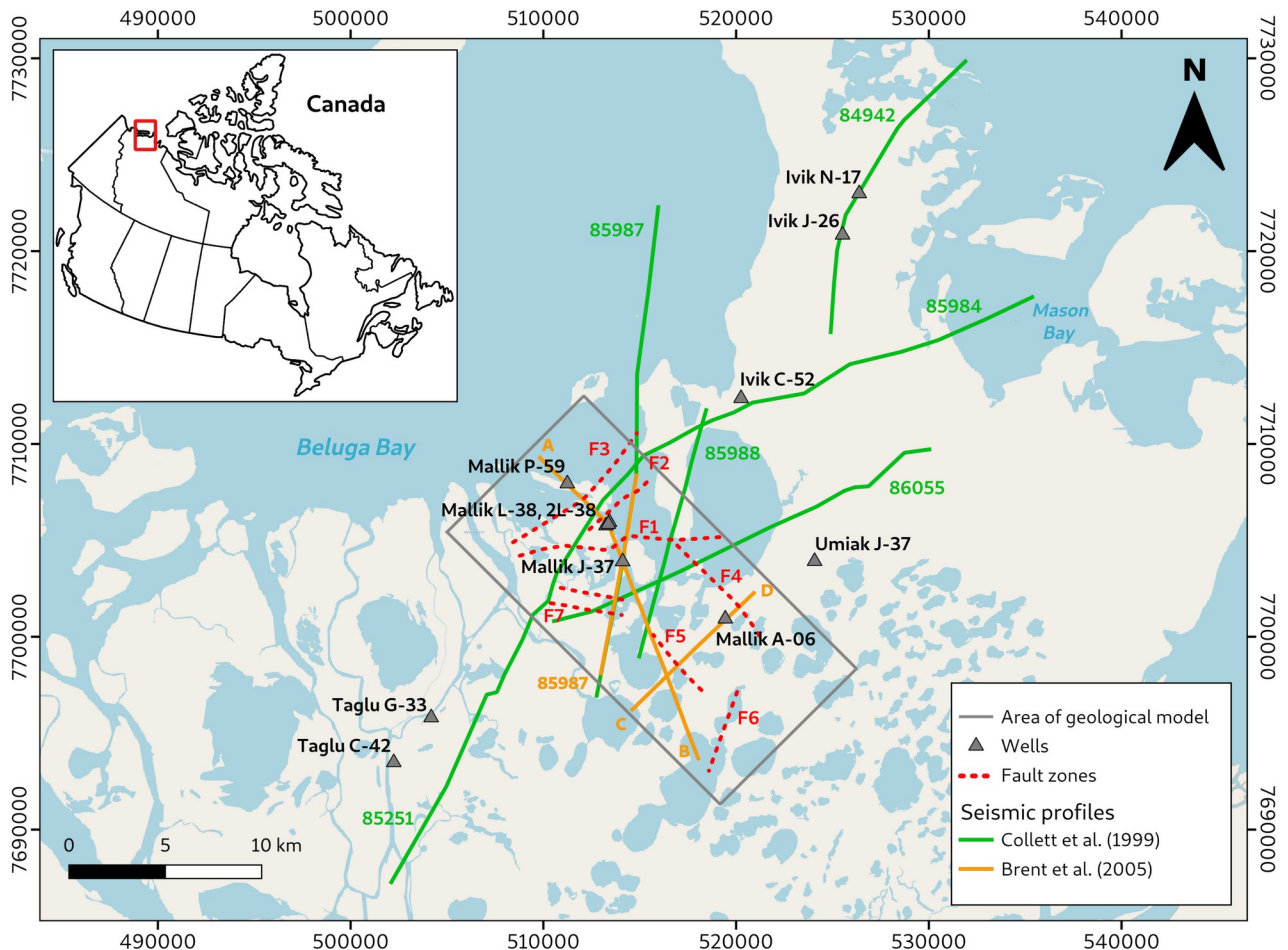


Figure 1. Overview map of the 3D geological model area with underlying seismic reflection profiles and wells, including the trend of the regional fault zones. Basemap: © OpenStreet Map contributors (obtained through QGIS). Spatial reference: – WGS 84 / UTM Zone 8N.

3. Data Sources and Processing as well as Model Implementation

Nine 2D seismic reflection profiles and petrophysical log data from eleven wells were used to identify lithologic contacts and fault zones, and to develop the 3D geologic structural model of the Mallik Anticline. Six high-resolution 2D seismic reflection profiles (84942, 85251, 85984, 85987, 85988, 86055) were derived from Collett et al. (1999; Figure 1). The authors reprocessed profiles previously commissioned by Imperial Oil Ltd. in 1984 for a seismic survey in the Ivik–Mallik–Taglu area. Furthermore, three 2D seismic reflection profiles (A-B, C-D, 85987) were taken from Brent et al. (2005), who reprocessed the Mallik 3D seismic data acquired by Veritas DGC Land, previously processed by Veritas Geoservices in 2002 (Figure 1).

All reflection profiles were first georeferenced to the UTM grid system (Spatial reference: EPSG Projection 32608 – WGS 84 / UTM zone 8N). The Petrel™ software package (Schlumberger, 2012) was used to digitise two-way travel times of the individual sequence boundaries from the seismic reflection profiles (Figure 2). Two-way travel time-to-depth conversion was undertaken based on average checkshot- and VSP-derived velocities in the Mallik area between 2.25 km/s and 3.0 km/s obtained from industry downhole velocity surveys provided by the National Energy Board of Canada (Brent et al., 2005). The seismic profiles were further used to determine the vertical fault lines of seven major regional fault zones. Fault strikes were adopted from the two-way travel time structure map from Brent et al. (2005; F1-F6). Seismic profiles from Collett et al. (1999) indicate the presence of two additional fault zones at the top of the Mallik Anticline, interpreted as F7-1 and F7-2.

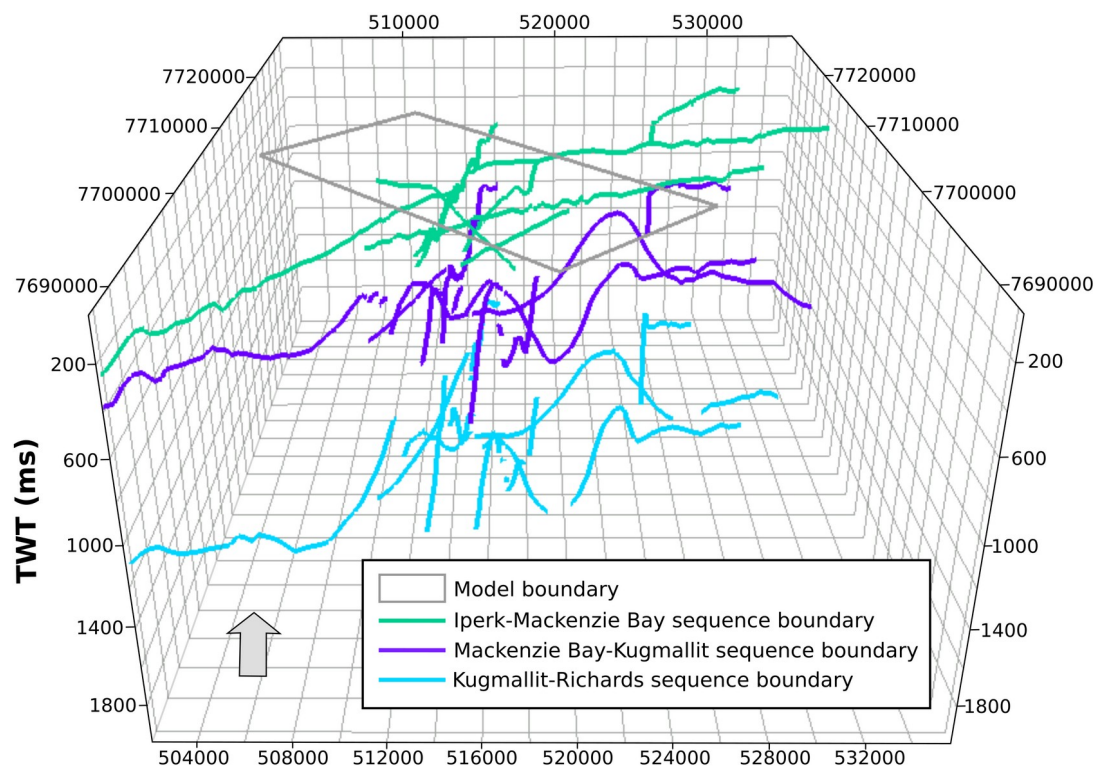


Figure 2. Two-way travel time of the three sequence boundaries derived from the seismic reflection profiles from Collett et al. (1999) and Brent et al. (2005). Vertical exaggeration is 7.5 times. Spatial reference: – WGS 84 / UTM Zone 8N.

On the basis of the derived set of polylines, the depths of the surfaces and fault zones were calculated by convergent interpolation. This algorithm is suited for dense and sparse data sets through converging iterations at successively finer grid resolutions, and minimises edge effects while also honouring the original data points. The extrapolation of data trends was accomplished using a basic

gridder based on a Taylor series projection as well as the Briggs biharmonic and the minimum curvature methods for grid smoothing (Schlumberger, 2012). Collett et al. (1999) further provided log data from wells drilled by Imperial Oil Ltd. in the Ivik-Mallik-Taglu area in the early 1970s, which was used to adjust the depths of the relevant sequence boundaries in the processed surfaces (Figure 3).

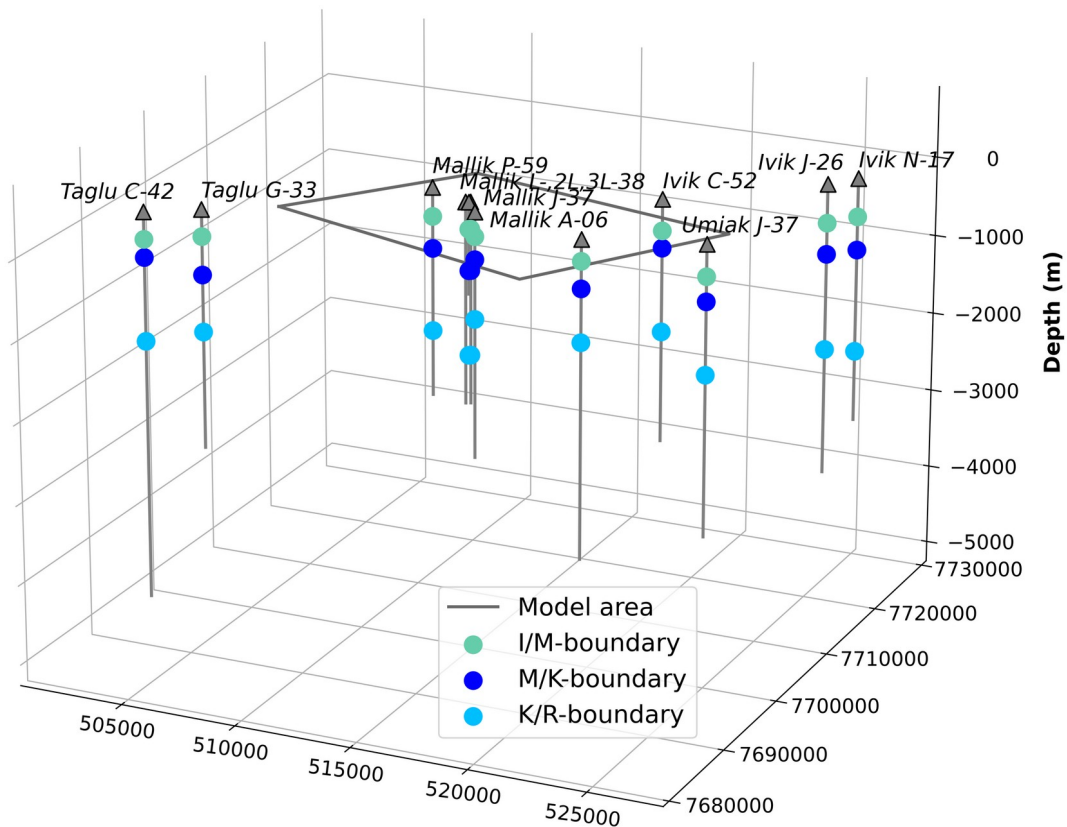


Figure 3. Well data in the Mallik-Ivik-Taglu area with tops of the Iperk-Mackenzie Bay, Mackenzie Bay-Kugmallit and Kugmallit-Richards sequence boundaries used for model implementation and derived from Collett et al. (1999). Depth in meters below sea level. Spatial reference: – WGS 84 / UTM Zone 8N.

Reflection profiles and wells beyond the boundaries of the model area were also considered to accurately incorporate stratigraphic inclination trends. The dip of the faults is digitised from the vertical 2D seismic profiles. The set of the resulting vertical lines along the fault strike defining dip and shape of each of the faults was then used to create each fault surface. In the presence of only one vertical fault line along the fault strike this dip was assumed to be invariant along the entire length of the fault, unless other defining criteria were present.

The final step was to merge the gridded depth surfaces into a 3D model. The faults displace the geologic units by several tens up to hundred meters in maximum. However, the layer boundaries are modelled as continuous surfaces.

The topography in the study area is obtained from the Canadian Digital Elevation Model at a resolution of 90 m (Figure 4; Government of Canada, 2013).

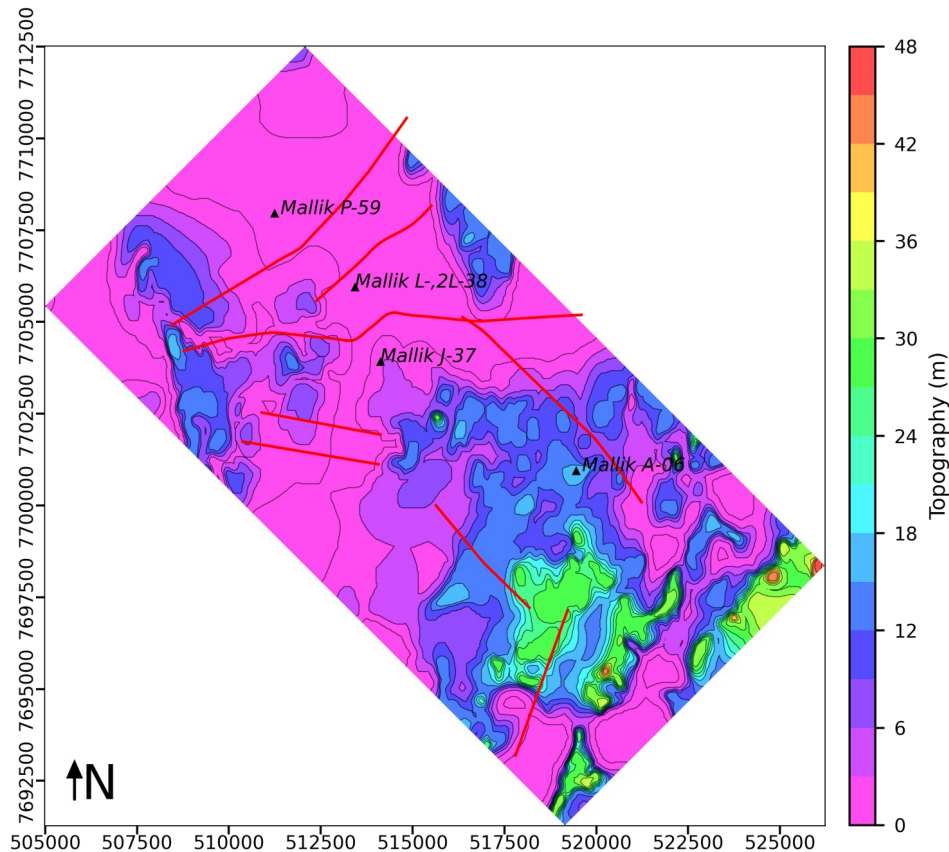


Figure 4. Topography in the study area. Traces of regional fault zones are shown in red. Contains information licensed under the Open Government Licence – Canada. Government of Canada (2013). Spatial reference: – WGS 84 / UTM Zone 8N.

The final 3D structural geological model covers the central anticline structure of the Mallik site in the Mackenzie Delta with an areal extent of 10 km x 20 km. It is implemented with a horizontal grid spacing of 50 m, and a vertical resolution corresponding to the number of integrated layers. The grid dimensions are X_{\min} 505003.1, X_{\max} 526216.3, Y_{\min} 7691291.9, Y_{\max} 7712505.1.

In total, the 3D model includes eight fault surfaces, the topography in the study area and the elevation depth of three surfaces: (1) Iperk-Mackenzie Bay sequence boundary (2) Mackenzie Bay-Kugmallit sequence boundary (3) Kugmallit-Richards sequence boundary (Figure 5-8).

The geospatial data sets in comma-delimited ASCII format (.csv) contain isoline points stored in an array of (X, Y, Z) values. The first two column entries X and

X and Y are the geographical coordinates measured in metres (X = Easting value, Y = Northing value). Depending on the data set, the Z-value (last column entry; in m) corresponds to either the depth below ground surface to the respective sequence boundary or the thickness at the respective coordinate. The finite number of data points is derived from the contour lines generated for each surface and varies depending on the vertical extent of the surface and the chosen interval (10 m – 50 m). The vertical datum to which the depth refers is the mean sea level (MSL). Thickness values of layers are true vertical thicknesses (TVT). In order to capture the full extent of the fault surfaces and ensure accurate reconstruction, points along their top and bottom surfaces, as well as points regularly distributed over their surface with a mean spacing of 50 m in vertical and 200 m in both horizontal directions, were extracted and stored in an array of (X, Y, Z) values.

Data sets from the 3D Mallik Anticline structural geological model are arranged in chronological order of strata from young to old (from top to bottom in the model):

Elevation depth data

Directory: 2023_001_Chabab-Kempka_MallikAnticline_Elevation_depth_data

0_topography.csv

1_iperk_mackenzie-bay_sequence_boundary.csv

2_mackenzie-bay_kugmallit_sequence_boundary.csv

3_kugmallit_richards_sequence_boundary.csv

Thickness data

Directory: 2023_001_Chabab-Kempka_MallikAnticline_Thickness_data

1_thickness_mackenzie-bay.csv

2_thickness_kugmallit.csv

Fault data

Directory: 2023_001_Chabab-Kempka_MallikAnticline_Fault_data

F1.csv; F2.csv; F3.csv; F4.csv; F5.csv; F6.csv; F7-1.csv; F7-2.csv

The 3D geological structural model of the Mallik Anticline presented here was first applied in Li et al. (2023) to investigate the mechanism of gas hydrate formation in Arctic sub-permafrost.

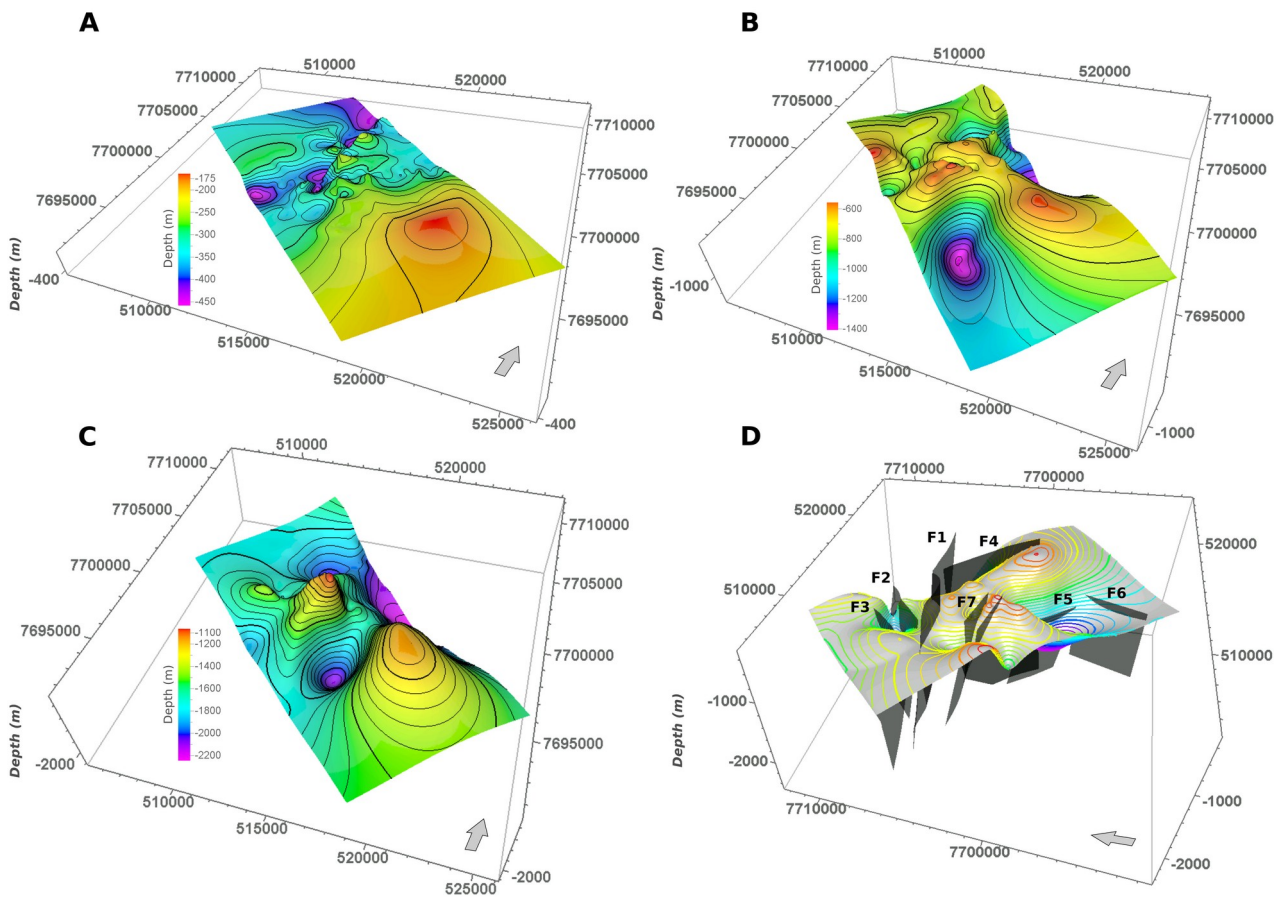


Figure 5. 3D view on the three implemented surfaces of the **A** Iperk-Mackenzie Bay **B** Mackenzie Bay-Kugmallit and **C** Kugmallit-Richards sequence boundaries as well as **D** the seven fault zones. Vertical exaggeration is 5 times. Depth in meters below sea level. Spatial reference: – WGS 84 / UTM Zone 8N.

Iperk-Mackenzie Bay sequence boundary

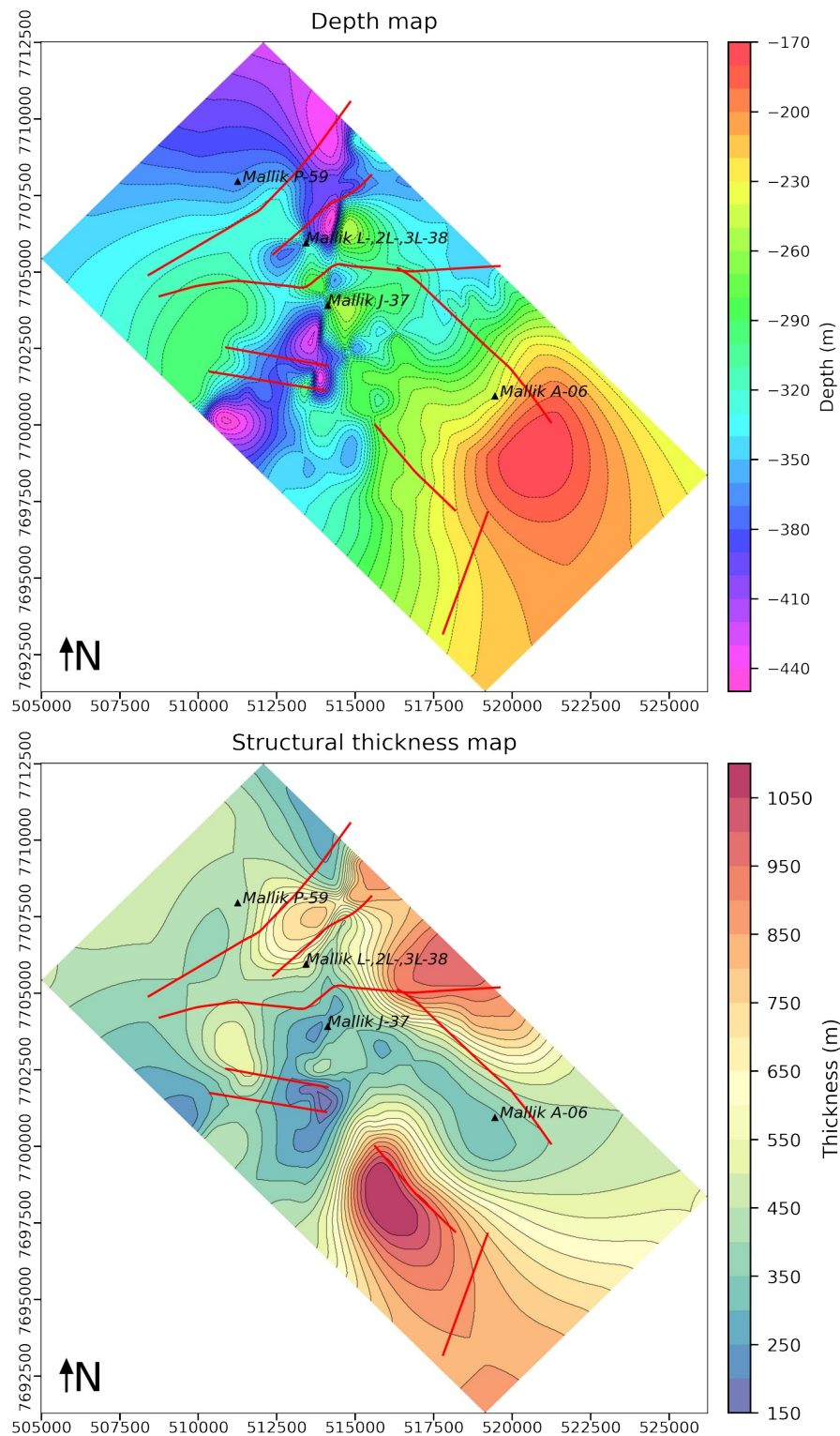


Figure 6. Layer 1 – Depth map (data file: 1_iperk_mackenzie-bay_sequence_boundary.csv) of the Iperk-Mackenzie Bay sequence boundary and thickness map (data file: 1_thickness_mackenzie-bay.csv) of the Mackenzie Bay sequence. Traces of regional fault zones are shown in red. Depth in meters below sea level. Spatial reference: – WGS 84 / UTM Zone 8N.

Mackenzie Bay-Kugmallit sequence boundary

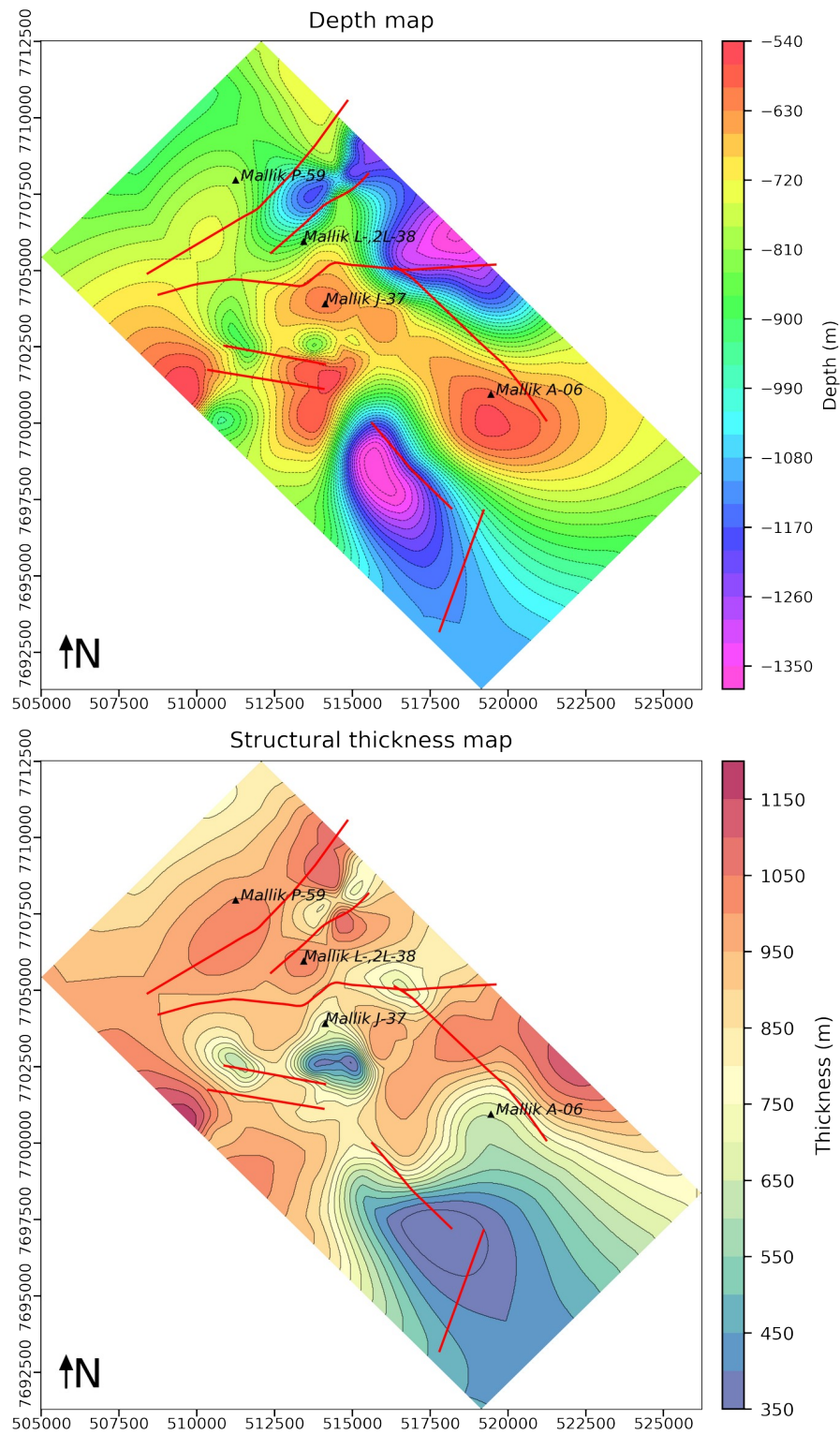


Figure 7. Layer 2 – Depth map (data file: 2_mackenzie-bay_kugmallit_sequence_boundary.csv) of the Mackenzie Bay-Kugmallit sequence boundary and thickness map (data file: 2_thickness_kugmallit.csv) of the Kugmallit sequence. Traces of regional fault zones are shown in red. Depth in meters below sea level. Spatial reference: – WGS 84 / UTM Zone 8N.

Kugmallit-Richards sequence boundary

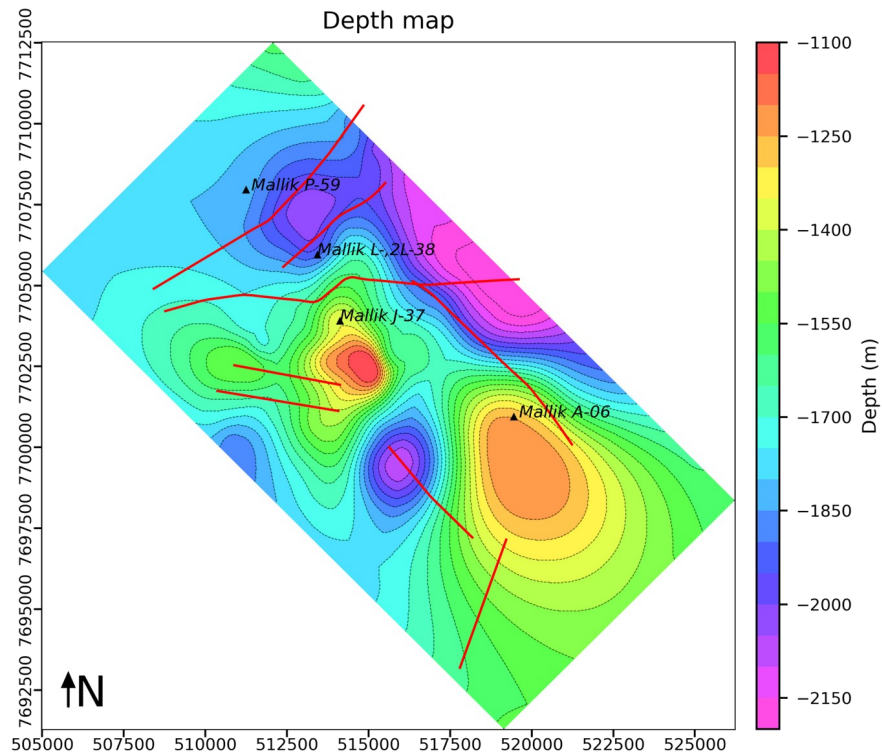


Figure 8. Layer 3 – Depth map (data file: 3_kugmallit_richards_sequence_boundary.csv) of the Kugmallit-Richards sequence boundary. Traces of regional fault zones are shown in red. Depth in meters below sea level. Spatial reference: – WGS 84 / UTM Zone 8N.

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