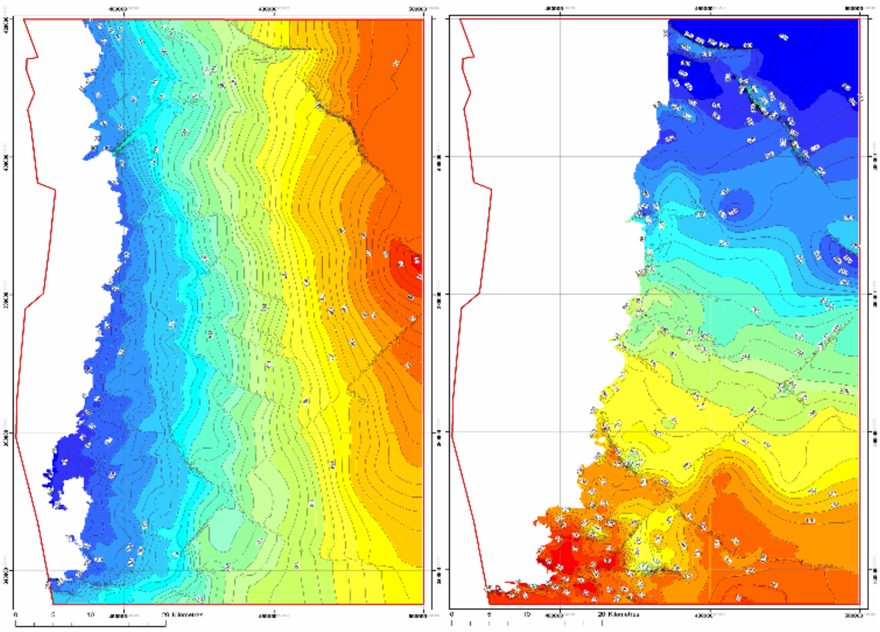
3-D Bedrock geology model of the Permo-Triassic of Yorkshire and East Midlands

Geology and Landscape Southern Britain Programme

Internal Report CR/06/091



BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPE SOUTHERN BRITAIN PROGRAMME

INTERNAL REPORT CR/06/091

3-D Bedrock geology model of the Permo-Triassic of Yorkshire and East Midlands

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Report; 3-D Model; Sherwood Sandstone Group; Mercia Mudstone Group; Sneinton Formation; Permian; Roxby Formation; Brotherton Formation; Edlington Formation; Cadeby Formation; Yellow Sands Formation; Basal Permian Breccia; Aquifer;.

Front cover

Model output showing faulted elevation grid for the base Sherwood Sandstone Group and the thickness of the Sherwood Sandstone Group

Bibliographical reference

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Contents

1 Overview

A series of 3D surfaces and isopach maps representing key bedrock horizons in the area between Doncaster and Nottingham were created using the GoCAD modelling application. This series of surfaces is henceforth referred to as the bedrock geology model. This model integrates rockhead elevation data, surface geological linework, interpreted downhole geological borehole data, and structural information derived from seismic data and geomorphological analysis of digital elevation data. Additional resources were incorporated, including published information concerning the regional geological framework. An account of the bedrock geology model and a synthesis of the geological information are presented here.

2 Source Data and 3D Modelling Information

2.1 PROJECT EXTENT

The extent of the bedrock geology model is shown as the red boundary in Figure 1. This area extends from northing 420000 to northing 335000, and from easting 500000 to approximately easting 445500, corresponding with the westernmost outcrop of the Permo-Triassic succession.

2.2 BOREHOLE DATA

A total of 607 borehole records were selected from within and directly adjacent to the model area. Each of these records was classified with respect to the EA-specific model requirements in terms of lithology and lithostratigraphy. The resulting digital database contained approximately 3650 data points, each representing a spatially attributed intersection of a key geological horizon. Appropriate data validation was carried out at each stage of the procedure to ensure internal consistency and agreement with surface geological linework. This was achieved by the application of SQL database queries to inspect internal consistency, and 3-D visualisation using ArcScene to determine spatial integrity.

Initial borehole selection was based on record quality, borehole depth and increased data density in areas of structural complexity and within the Sherwood Sandstone and Cadeby Formation outcrop zones. Several borehole records were specified for inclusion by the Environment Agency.

Figure 1 represents the distribution and density of borehole data used in this study. A regular grid is colour coded according to the number of boreholes located within each 1 km square. This approach is intended to protect the exact location of individual boreholes, including a significant proportion that are held in confidence by the BGS.

2.3 BEDROCK GEOLOGICAL LINEWORK

The extent of each unit is constrained in the west by existing geological mapping, as represented by DiGMapGB-50. This 1:50,000-scale dataset provides a 2D representation of the bedrock geology (Formations, Groups and faulting) beneath any superficial deposits. An overview of the regional geology (based on 1:625,000-scale data) is shown in Figure 3.

For modelling purposes, it was necessary to decimate the dataset to a 200 m node spacing, and ascribe elevation values from the published rockhead elevation model (i.e. the base of superficial deposits).

The published rockhead elevation model is based on a prior study of borehole data and other geological information, and is derived from a NextMap DTM with a reduced horizontal resolution of 50 m, and a sub-metre vertical resolution.

2.4 SEISMIC DATA

The existing geological mapping for the project area provides an uneven coverage of fault information. Consequently, seismic interpretation has been used in selected parts of the model to provide additional information on the position and nature of faulting within the Permo-Triassic succession.

500 km line length of hydrocarbon industry reflection seismic data licensed from the UK Onshore Geophysical Library were interpreted using the GeoGraphix digital seismic workstation.

A widely spaced net of lines of predominantly N-S (strike) orientation was selected to provide horizon control in areas with poor borehole coverage and known post-Permian faulting (Figure 2). Lines were chosen to provide additional structural control in areas of poor borehole coverage and to maximise the use of high-precision seismic imaging that is available in the central part of the project area. Horizon picks from the licensed seismic data were supplemented by information derived from ongoing BGS regional sub-surface mapping projects. The following key horizons were interpreted:

- SSG Top Sherwood Sandstone Group (i.e. base Mercia Mudstone Group)
- ROX Top Roxby Formation (i.e. base Sherwood Sandstone Group)
- BTH Top Brotherton Formation (i.e. base Roxby Formation)
- UVAR Variscan Unconformity (i.e. base Permian, largely equivalent to base Cadeby Formation)
-

A grid spacing of 250 m was selected for each horizon. Depth conversion was carried out with an option rejecting faults as line-of-sight barriers, to minimise 'spiking' of the depth grids. The depth grids were then exported from the SeisVision module into the GeoAtlas module, before export of files in ASCII .xyz format. Fault polygons were exported directly from SeisVision as non-depth converted ASCII location files.

Fault and depth information from seismic interpretation was appraised in conjunction with borehole data, existing geological mapping and topographic lineament analysis to compile a combined fault pattern for the project area, as discussed below.

2.5 EXISTING 3-D MODELLING

Existing 3-D geological modelling work from the south-western part of the project area (Bridge et al., 1999) was considered in the early stages of construction of the current bedrock geology model. The current model is intended to be largely compatible with, but supersede the Permo-Triassic content of the existing 3-D model. However, the inclusion of faulting in the current model has necessarily resulted in inconsistencies with respect to the work of Bridge et al. (1999) that did not include faults in the model.

2.6 PUBLISHED SOURCES OF DATA

A range of additional geological information was consulted during the construction of this model and associated figures. A corresponding list of references is presented at the end of this section.

Information on subsurface structure including faulting was obtained from Edwards (1951), Edwards, (1967) and Gaunt at al. (1994). Thickness and sedimentology-related information for the Permian succession was obtained from Smith (1989). This information was scanned and georectified to provide a backdrop for the subsequent modelling work.

2.7 GOCAD MODELLING WORKFLOW

The bedrock geology model was constructed using GoCAD 3-D modelling software. This application facilitates the construction of digital faulted surfaces based on a combination of the datasets described above. The workflow used in the construction of the bedrock geology model is detailed below. This workflow represents the conventional BGS approach to 3-D geological modelling of bedrock. GoCAD permits the manual enhancement of interpolated surfaces, allowing geological understanding of the local geology to be captured during the modelling work.

- Import and collate 3-D baseline data: quality assured borehole information, regional rockhead elevation model (50 m horizontal resolution, sub-metre vertical resolution), and seismic grids.
- Import and collate 2-D baseline data: project extent, bedrock linework (DiGMap50) for selected bedrock horizons.
- Decimation of 2-D baseline data using 200 m minimum vertex spacing.
- Apply 3-D control to 2-D baseline data: apply elevation from regional rockhead model to bedrock linework.
- Import fault pattern information, and construct appropriate fault geometries.
- Prepare data resources for inclusion in the GoCAD Structural Modelling Workflow (SMW).
- Application of the GoCAD SMW, comprising:
    - Data Management
    - Volume of Interest definition

    - Fault Modelling
    - Horizon Modelling
    - Fault Contact Modelling
    - Horizon-Fault Contact Modelling
    - Horizon Well Marker Fitting
    - Remove Crossovers
- Post-SMW enhancement, comprising multiple manual iterations of:
    - Identify irregularities: visual inspection and derivation of thickness models to highlight areas where surfaces differ from the conceptual geological model.
    - Obtain additional geological information including borehole information to better constrain the model in these areas.
    - Manipulate the model geometry to honour the additional geological control.
- Export model as a series of surfaces defined by 3-D nodes and bounding curves for subsequent work, including the derivation of isopach and contour maps using GIS.

An initial set of draft surfaces were provided to the client for inspection. Corresponding feedback, including the incorporation of additional borehole control in selected areas was carried out during the post-SMW phase of this workflow.

2.8 DERIVATION OF ELECTRONIC OUTPUTS

The structure contour maps and isopach maps presented in Figures 5 to 23 are based on surfaces derived from the GoCAD node and boundary data using the nearest-neighbour interpolation algorithm of the 3-D Analyst extension of ArcMap. A 200 m cell-size was specified for all grid operations. Contour plots using intervals ranging from 2.5 m to 25 m have been derived from each of the grids using the contour functionality of the Surface Analysis component of 3-D Analyst.

3 Geology of the Bedrock Units

A schematic cross-section of the Permo-Trias bedrock succession of the project area is presented in Figure 4. This figure summarises facies changes, thickness variation, and boundary conditions for the main units considered in this study. Thickness values presented in Figure 4 are based on combination of existing published sources and results from the current model. A comprehensive breakdown of the stratigraphic nomenclature is given, including reference to alternative and obsolete terms. Overlying Jurassic units and underlying Carboniferous strata are not shown.

3.1 MERCIA MUDSTONE GROUP

The Mercia Mudstone Group is characterised by red mudstones, siltstones, thin beds of green-grey dolomitic siltstone, and subordinate sandstones. Much of the group is gypsiferous, particularly the upper c. 50 m, which contains gypsum beds.

In the south of the project area, the Mercia Mudstone Group is subdivided into 6 formations (Figure 4), ranging from the Sneinton Formation (or “Waterstones”) at the base of the group, to the Blue Anchor Formation (or “Tea Green Marl”) at the top.

The Mercia Mudstone Group conformably overlies the Sherwood Sandstone Group, and is conformably overlain by the Penarth Group. The lower boundary with the Sherwood Sandstone Group is typically gradational.

For the purpose of this work, the Mercia Mudstone Group is represented by 2 surfaces: base Mercia Mudstone Group and Top Sneinton Formation (restricted to the south of the project area).

The base Mercia Mudstone surface is comparatively well-constrained, being proven at depth by over 253 boreholes in the model (Figure 5). This surface ranges in elevation from rockhead in the west to a minimum of approximately -510 m in the east of the project area.

The Sneinton Formation is characterised by siltstones and fine-grained sandstones with subordinate mudstones. This formation is proven at depth by a comparatively low number of boreholes (approximately 68) in the bedrock geology model. Consequently, an appropriate modelling procedure was required to achieve a representative surface. Whereas surfaces for other units use borehole data directly, the top Sneinton surface is largely derived from a combination of the well-constrained base Mercia Mudstone surface and a thickness distribution model for the Sneinton Formation, as defined by the sparse borehole data.

The Sneinton Formation ranges in thickness from 0 m to over 75 m, the top of the formation ranging in elevation from rockhead in the west to approximately –480 m in the east of the project area (Figures 6 and 7). Borehole evidence suggests that the thickness is highly variable, perhaps in response to local facies variation. The thickest sequences of the Sneinton Formation mainly occur in the south of the project area. Borehole evidence indicates a pronounced north-south aligned embayment of comparatively thin Sneinton Formation close to the northern limit of this formation.

3.2 SHERWOOD SANDSTONE GROUP

The Sherwood Sandstone Group is represented in the bedrock geology model as a single unit, characterised by red sandstone with locally abundant pebbly sandstone and pebble-beds. Subordinate red mudstone and siltstone is common in the upper and lower parts of the group where the sandstone-dominated succession passes gradationally into mudstones of the Mercia Mudstone Group and Roxby Formation respectively. In the far south of the project area the Sherwood Sandstone Group rests with a sharp unconformity on Carboniferous strata. The group shows a decrease in grain size northwards, gradually becoming less pebbly.

In the south of the project area, existing mapping at 1:50,000-scale subdivides the Sherwood Sandstone Group into the upper Nottingham Castle Formation and the lower Lenton Formation. As shown in Figure 4, the locally developed Calverton Breccia underlies parts of this succession.

The Sherwood Sandstone Group ranges in thickness across the project area from a minimum of approximately 60 m in the south-west to over 370 m in the north-east (Figure 9). On a regional scale, the thickness variation is comparatively regular, increasing by approximately 3.5 m per km towards the north. As discussed below, modelling suggests that sedimentation of the Sherwood Sandstone Group may have been affected by syn-sedimentary faulting, resulting in thickness changes across faults.

The base of the Sherwood Sandstone Group ranges in elevation from rockhead in the west to minimum of approximately -750 m in the east of the project area (Figure 8). This is a well-constrained surface, intersected by over 330 boreholes in the bedrock geology model.

3.3 ROXBY FORMATION

Throughout most of the area, the Roxby Formation comprises a sequence of red-brown calcareous and gypsiferous mudstones. This formation ranges in thickness from 0 m in the south of the project area to over 80 m in the north (Figure 11). The Roxby Formation is subject to considerable facies variation across the project area (Figure 12). In the south, the formation is locally silty and sandy with sparse evaporitic mineral content. In the north and north-east, gypsum (passing into anhydrite with depth) becomes significant within the sequence. The evaporites occur as two units, the Billingham Anhydrite at the base of the sequence and the Sherburn Anhydrite in the upper part; halite beds may also occur at the north-eastern limit of the project area.

At and near outcrop, the majority of the evaporitic rocks are dissolved away and in the north of the district the overlying sequence near outcrop may have suffered from slight foundering and slight brecciation (this process also affects the underlying sequence - see below). Near outcrop, the gypsum may be a very minor karstic aquifer on top of the underlying Brotherton Formation; it may also contribute sulphate-rich water (Cooper, 1988, 1998).

The base of the Roxby Formation ranges in elevation from rockhead in the west to less than –860 m in the east (Figure 10). This surface is reasonably well-constrained by over 175 boreholes over it’s comparatively limited extent in the bedrock geology model.

The Roxby Formation is overlapped by the Sherwood Sandstone Group in the south-centre of the project area. The corresponding subcrop is presented in Figure 12.

3.4 BROTHERTON FORMATION

The Brotherton Formation is composed mainly of dolomite and dolomitic limestone that occurs as thin to medium even beds with partings of bituminous mudstone; the rock is generally well-jointed. The formation thickens fairly evenly from 0 m in the south of the project area to over 45 m in the north-east (Figure 14). The rock contains vughs and small cavities that are filled with gypsum or anhydrite at depth, but towards outcrop these minerals are dissolved leaving open vughs and a more porous rock texture. The Brotherton Formation is a minor aquifer in the sequence.

The base of the Brotherton Formation ranges in elevation from rockhead in the west to less than -890 m in the east of the project area (Figure 13). This surface is reasonably well-constrained by over 195 boreholes over it's comparatively limited extent in the bedrock geology model.

The Brotherton Formation is overlapped by the Sherwood Sandstone Group in the south-centre of the project area. The subcrop for this unit corresponds with that of the Roxby formation, as shown in Figure 12.

3.5 EDLINGTON FORMATION

The Edlington Formation varies considerably in terms of thickness and lithology across the area. The formation ranges from 0 m in the south to over 70 m in the north (Figure 16). In the south, the Edlington formation is coarse-grained, sandy and gravelly indicating an influx of terrigenous material form the south (Figure 17). Northwards the formation becomes fine-grained and passes into red-brown calcareous siltstone and mudstone, with the proportion of evaporitic minerals increasing to the north and north-east as the formation thickens.

Significant thicknesses of gypsum (passing into anhydrite with depth) occur in the north-east of the area and some salt may also be present at depth. In the north-west, towards the outcrop, the anhydrite passes into gypsum and this in turn can be largely removed by dissolution. The dissolution of the gypsum can lead to voids (caves) and the collapse of the overlying sequence. This process only occurs down to a depth of 100 m or so and may cause foundering and brecciation of the overlying sequence, especially the Brotherton Formation. Near outcrop, the gypsum may be a minor karstic aquifer on top of the underlying Cadeby Formation; it may also contribute sulphate-rich water (Cooper, 1988, 1998).

The base of the Edlington Formation ranges from rockhead in the west to less than -950 m in the east of the project area (Figure 15). This surface is well-constrained by over 350 boreholes in the bedrock geology model.

The Edlington Formation is overlapped by the Sherwood Sandstone Group in the south of the project area. The corresponding subcrop is presented in Figure 17.

The combined thickness of intervening strata between the base of the Sherwood Sandstone Group and the top of the Cadeby Formation ranges from 0 m in the south of the project area to over 180 m in the north (Figure 18).

3.6 CADEBY FORMATION

The Cadeby Formation varies in lithology and thickness across the project area.

Thickness ranges from 0 m in the south to over 130 m in the north (Figure 20), varying in response to irregularities in the underlying surface; for example, the formation thins over local palaeo-topographic highs of the basal Permian unconformity and dune features associated with the Yellow Sands Formation. Modelling suggests that sedimentation of the Cadeby Formation may have been affected by syn-sedimentary faulting, resulting in thickness changes across faults.

The formation ranges from a thin dolomitic breccia and sandstone in the south passing northwards into a calcareous mudstone facies. This calcareous mudstone facies is mainly in the lower part of the formation and was formerly referred to as the Lower Permian Marl. The marl facies is overlain by the main dolomite facies of the Cadeby

Formation. The rock is mainly dolomite with subordinate dolomitic mudstone and mudstone. The principal facies variation of the Cadeby Formation is represented in Figure 21.

The dolomite of the Cadeby Formation commonly has significant vughs, but below a depth of about 100 to 120 m these are usually filled or cemented with gypsum or anhydrite. The Cadeby Formation is a significant aquifer, but only where the evaporites have already been dissolved from within the rock.
The base Cadeby Formation ranges in elevation from rockhead in the west to less than -1060 m in the east (Figure 19). This surface is well-constrained by over 460 boreholes in the bedrock geology model.

The Cadeby Formation is overlapped by the Sherwood Sandstone Group in the south of the project area. The corresponding subcrop is represented in Figure 21.

3.7 MARL SLATE FORMATION

The Marl Slate Formation is a very thin sequence of dark grey mudstone that generally ranges from 0 to 2 m in thickness. It is restricted to the deeper parts of the sedimentary basin in the north-east, largely outside the project area.

3.8 YELLOW SANDS FORMATION / BASAL PERMIAN BRECCIA

The base Permian is locally represented by a thin and discontinuous spread of continental sandstones and breccias, the Yellow Sands Formation and Basal Permian Breccia.

The Yellow Sands Formation comprises mainly aeolian sand that ranges from 0 m up to around 20 m thick, rarely reaching over 50 m. This formation generally takes the form of relict dunes resting on the underlying Carboniferous surface or the Permian Basal Breccias. The sands are characterized by rounded wind-worn grains and at depth are bluish-grey in colour. Towards outcrop where the rock has been oxidised, the sandstone is yellow in colour.

The Basal Permian Breccia is generally restricted to the south of the project area, ranging from 0 to 5 m in thickness. This unit directly underlies the Cadeby Formation, or more rarely the Yellow Sands Formation. The Permian Basal Breccia mainly comprises locally eroded bedrock, and commonly fills slight depressions in the underlying Carboniferous bedrock surface.

For the purpose of this model, the Yellow Sands Formation and Basal Permian Breccia are considered as a single unit, its base ranging in elevation from rockhead in the west to less than –1080 m in the east (Figure 22). This surface is comparatively well-constrained by over 320 borehole intersections in the bedrock geology model. Due to the laterally impersistant nature of the Yellow Sands Formation and Basal Permian Breccia, the approach to modelling this surface is equivalent to that used in modelling the top of the Sneinton Formation.

3.9 STRUCTURE

Regionally, the Permo-Triassic succession dips gently to the east by an average of 1.25 degrees. Existing field mapping suggests that steeper dips, and local changes in dip direction may occur in association with major structures. The bedrock geology model represents corresponding structural variations where scale permits.

Figure 23 shows the fault pattern used in the construction of the model. For the purpose of this work, faults with an estimated throw in excess of 25 m were used. The fault information was derived from a range of sources: existing geological maps (1:50,000 scale), published material (Aitkenhead et al. 2002, Edwards 1951 and 1967), lineament analysis of high-resolution digital elevation data (NextMap), an appraisal of borehole information, and the interpretation of over 500 line-km of seismic data.

A northwest-southeast trending fault pattern dominates, crosscut by a limited number of southwest-northeast structures. Fault displacement is typically normal (assuming a dip of 65 degrees), with throws reaching in excess of 100 m. The structural complexity increases in the south of the project area, where several regionally significant structures are known to affect the modelled succession. Figure 23 includes a thematic representation of the throws associated with the modelled faults.

Modelling suggests that many of the faults have directly affected sedimentation. Notwithstanding the uncertainties associated with modelling faulted strata, this work indicates that sediment thickness for many of the units considered here increases from north to south across many of the structures, accounting for much of the regional thickness variation. Consequently, many of the structures show an increasing throw with depth.

Faulting that juxtaposes the Sherwood Sandstone Group with the Cadeby Formation is largely restricted to the south of the project area where the intervening strata are comparatively thin. In the north of the project area, the greater thickness of intervening strata reduces the likelihood of a direct offset between these two units. However, two structures are recognised as potentially resulting in direct connectivity between. Figure 23 highlights those faults that are interpreted to juxtapose the Sherwood Sandstone Group and the Cadeby Formation.

4 Resolution and Limitations and of the Bedrock Geology Model

The bedrock geology modelling process integrates a range of 2-D and 3-D geological information to produce an interpretation of the subsurface geology of the project area. Every effort has been made to ensure that the model is consistent with this information and the conceptual geological model for the project area. However, this model represents one interpretation of the available data; it is important to recognise that other equally valid interpretations may be possible. Known and potential limitations to the model are described below.

As per the project specification, the 3D surfaces have been created using a regular cell-size of 200 m. As discussed above, this has been achieved by applying a nearest-neighbour gridding algorithm to the spatial output from GoCAD. Over the majority of the project area, these grids accurately reproduce the GoCAD model. However, the interpolation process necessarily introduces a slight generalisation to the grids that can result in a poor representation of faulting, introducing ‘spikes’ and limited ‘cross-overs’ between adjacent surfaces along fault planes.

The bedrock geology model uses over 607 selected boreholes. The borehole selection was carried out to provide coverage, depth, and a good representation of the subsurface geology. Additional un-used borehole records are available in the project area. Whilst the current interpolated surfaces provide an accurate representation of the data used, it is likely that a slight difference will exist with respect to the information provided in these additional records.

In general, model uncertainty is greatest in areas where faulting is coincident with limited borehole control. Where possible, supplementary data including seismic grids and existing published material have been used to improve model confidence. However, the limitations of data availability mean that bedrock geology model in areas of closely spaced faulting, such as the south-west of the project area, is based largely on manual interpretation. The corresponding level of confidence in this area is comparatively low with respect the central and northern parts of the model.

The deeper parts of the model (>500 m depth) are typically proven by comparatively few boreholes. Although the results from seismic interpretation provides an additional constraint in this part of the model, the level of uncertainty is generally higher than in the shallow parts (<500 m depth), where both seismic and borehole information is available and surface geological linework has a greater influence. The deeper parts of the north-east of the model are affected by this lower level of confidence.

Project resources have focused on ensuring the quality of the key surfaces (top Sneinton Formation, base Mercia Mudstone Group, base Sherwood Sandstone Group, top and base Cadeby Formation, and base Permian) Additional surface grids, maps and isopach maps for each of the intervening units between the Cadeby Formation and Sherwood Sandstone Group (Roxby Formation, Brotherton Formation, and Edlington Formation) have been subject to less intensive validation and represent lower-confidence surfaces with respect to the key surfaces defined above.

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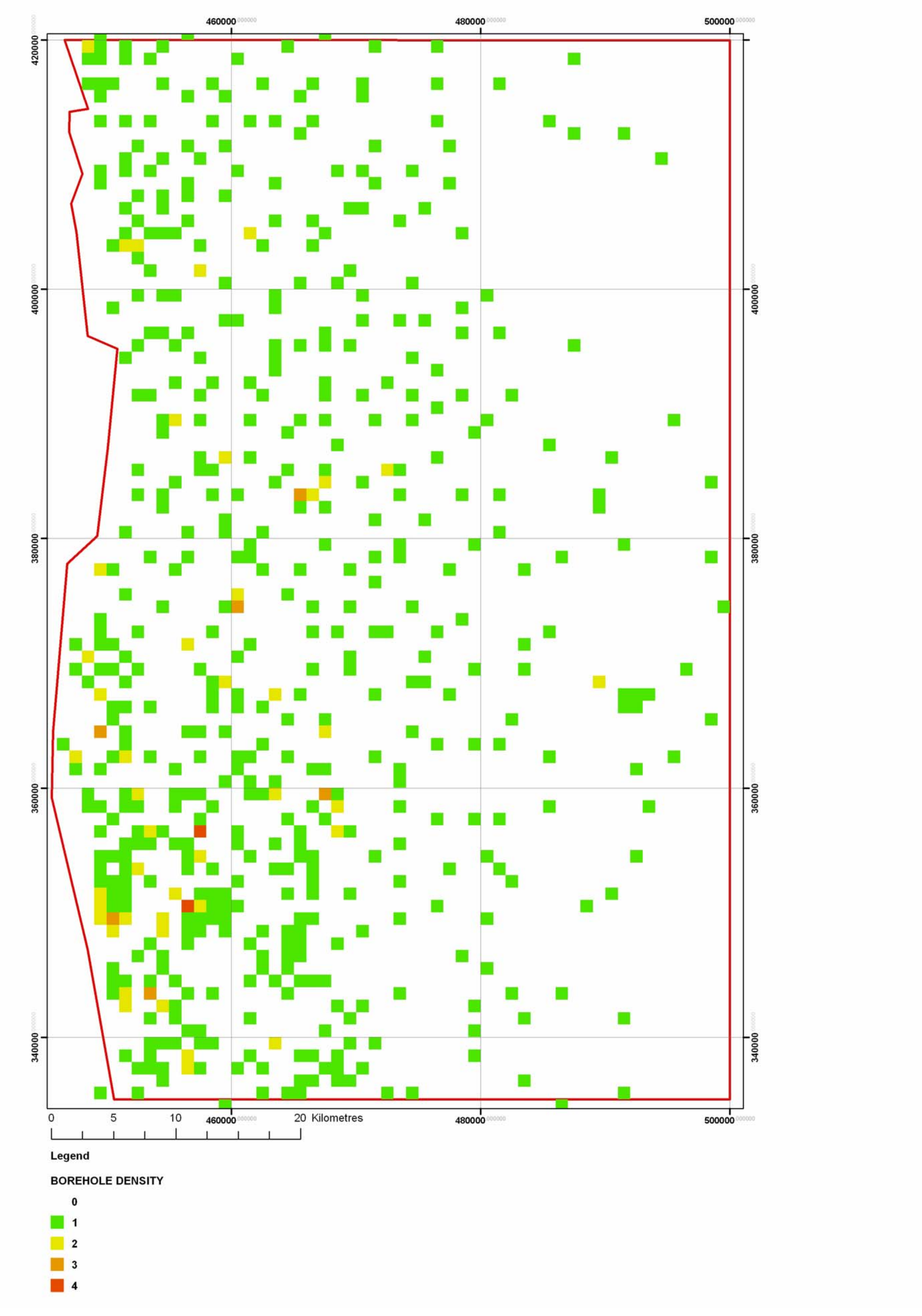

Figure 1 – Thematic borehole distribution map; project extent represented by red boundary

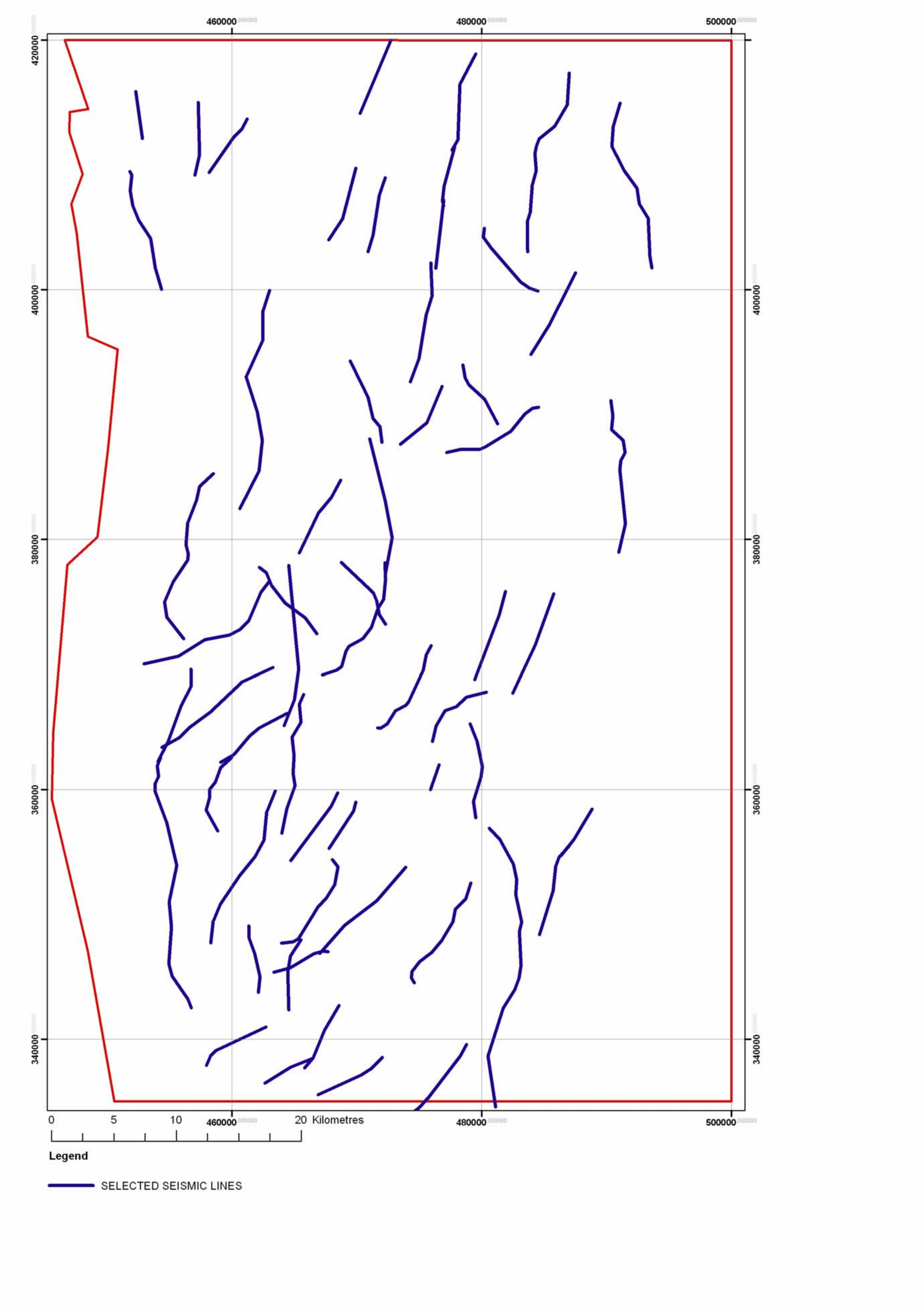

Figure 2 – Distribution of selected seismic lines

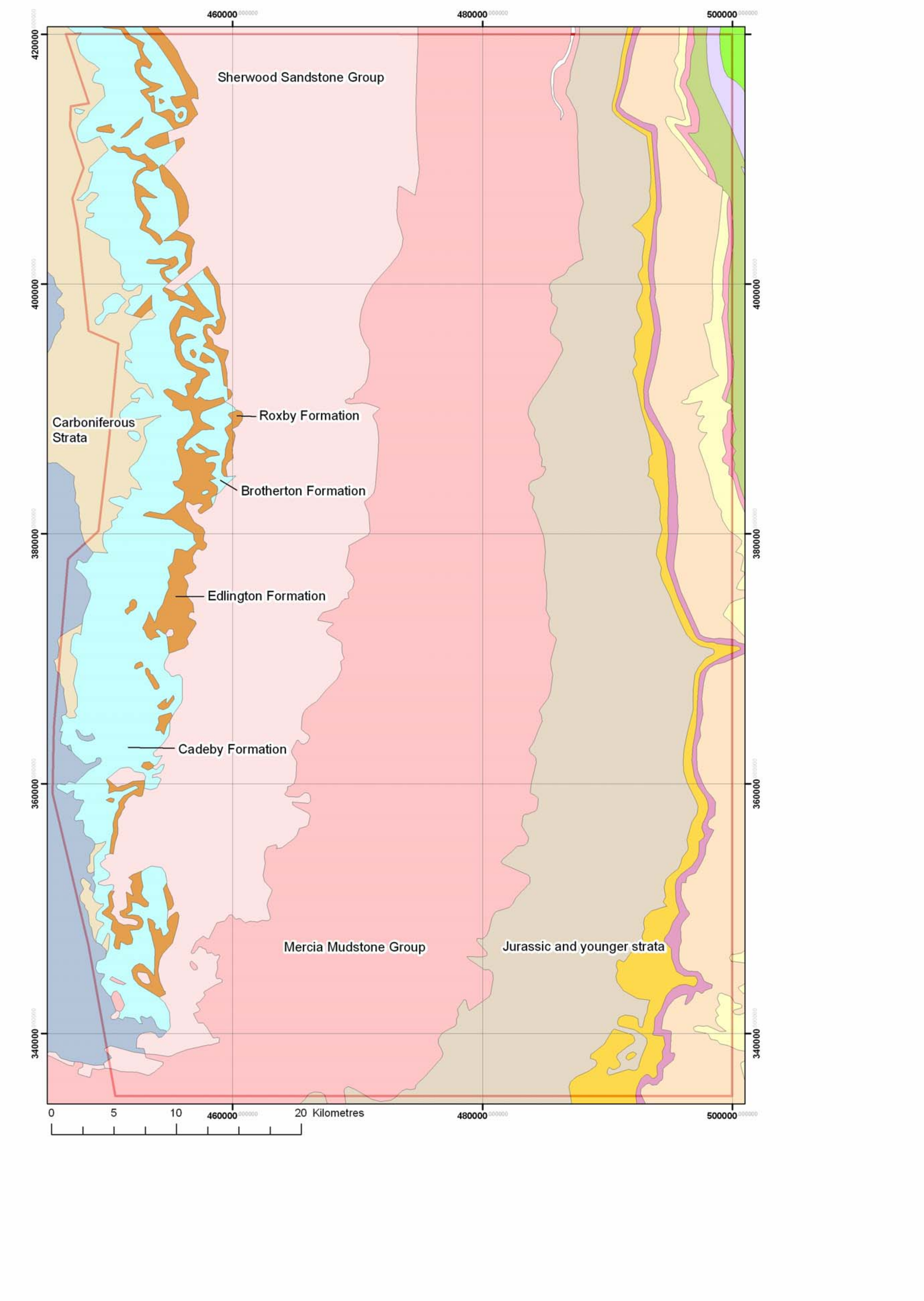

Figure 3 – Geological overview map

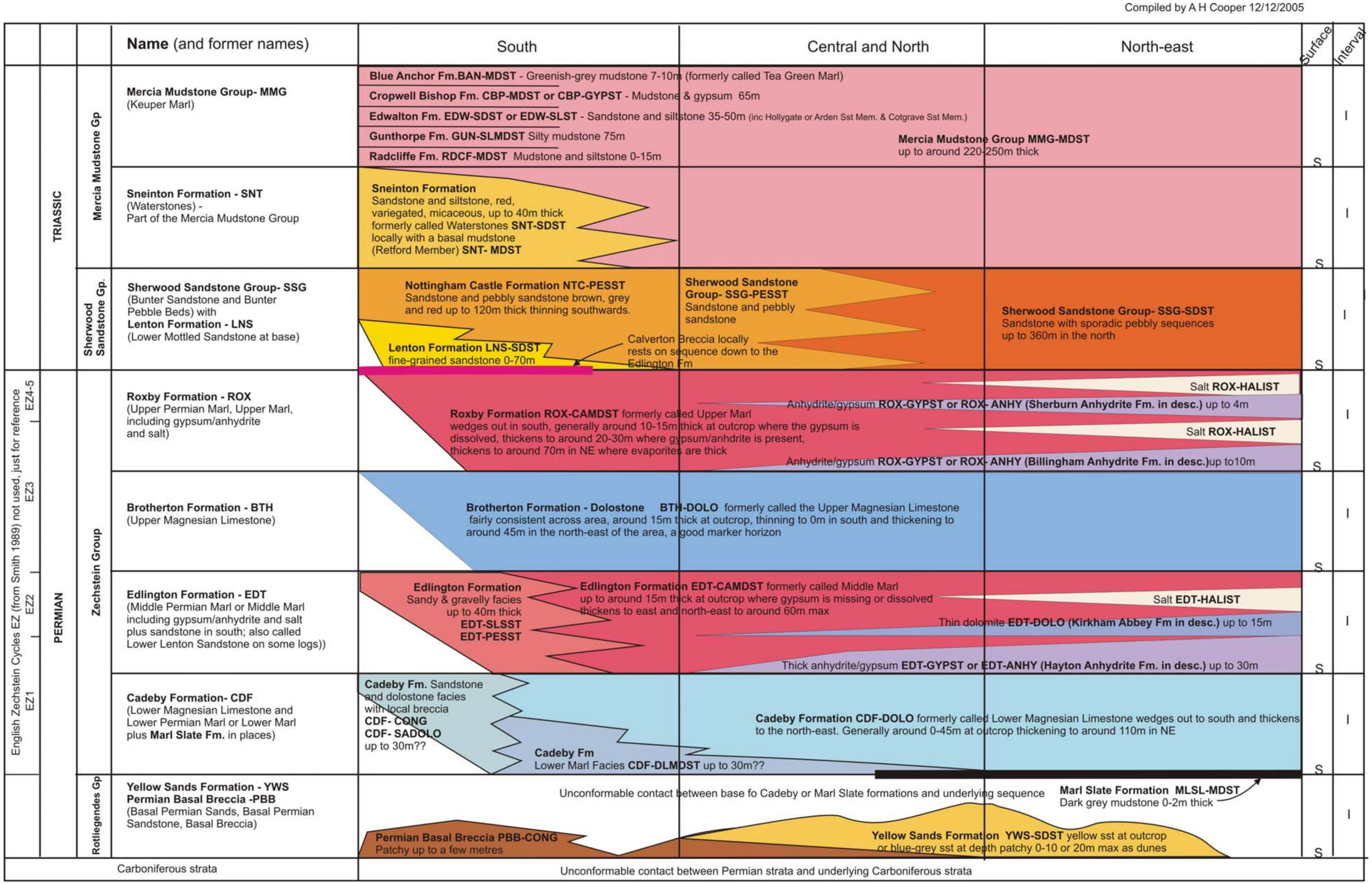

Figure 4 – Schematic cross-section and stratigraphic column

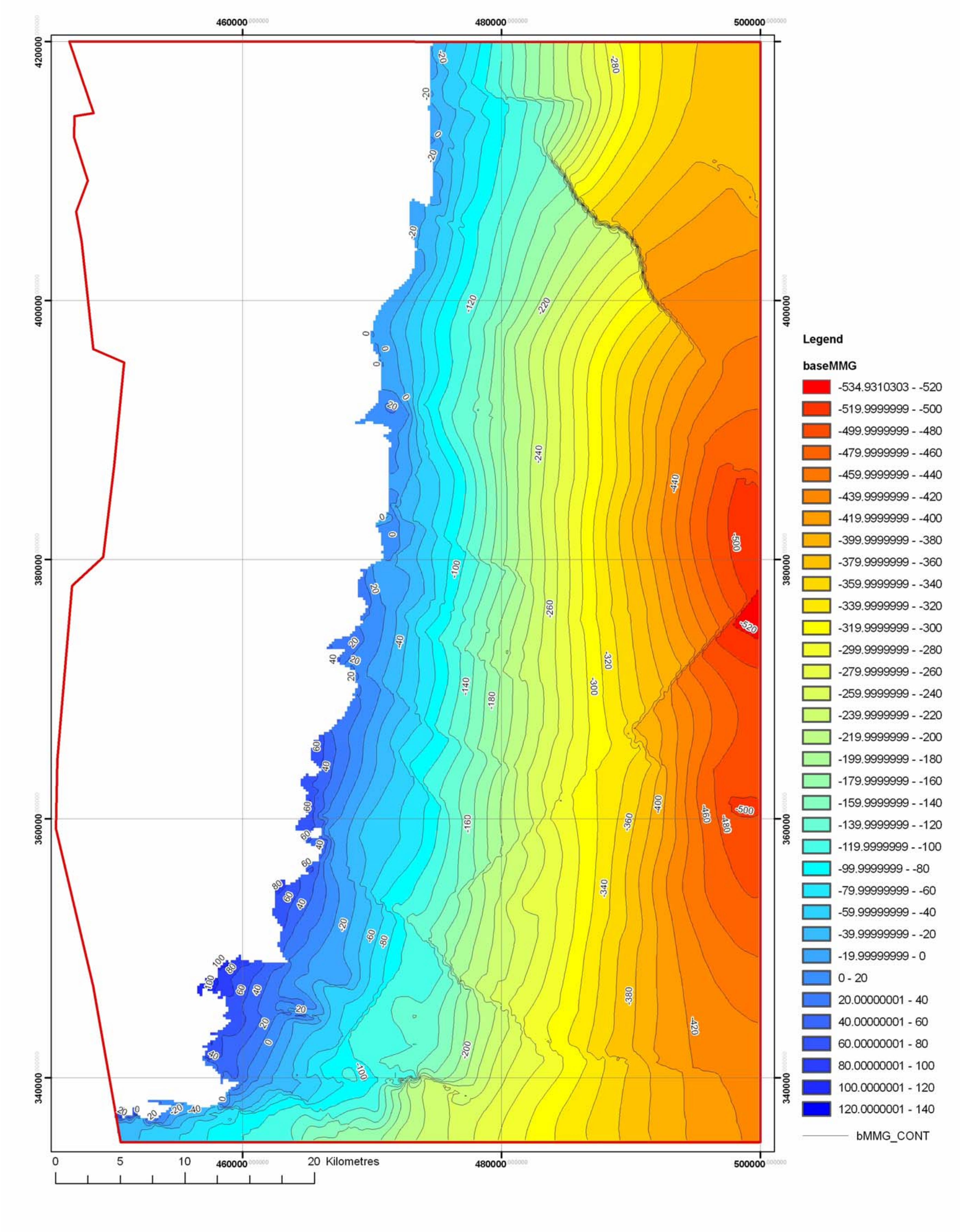

Figure 5 – Base Mercia Mudstone Group surface elevation map

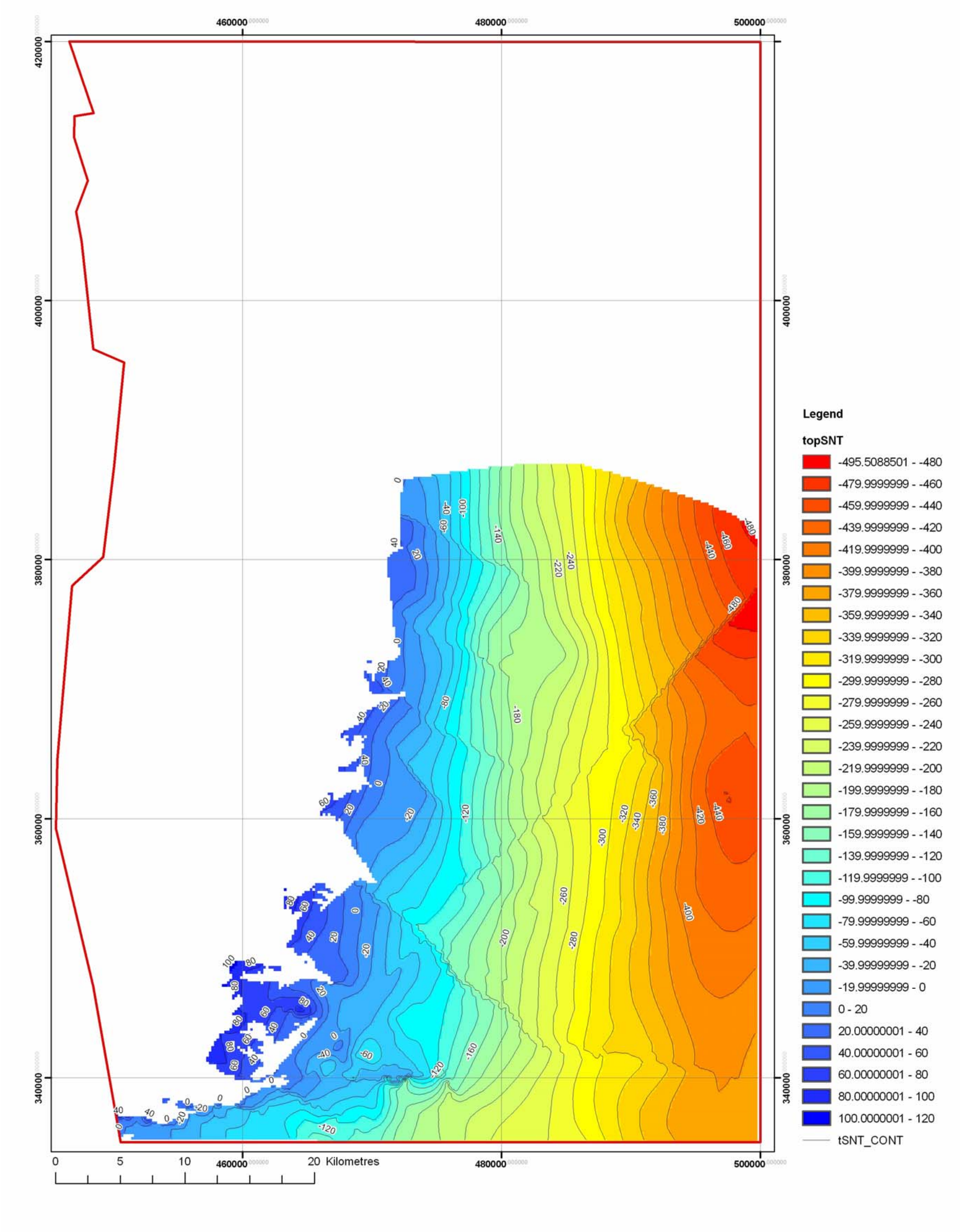

Figure 6 – Top Sneinton Formation surface elevation map

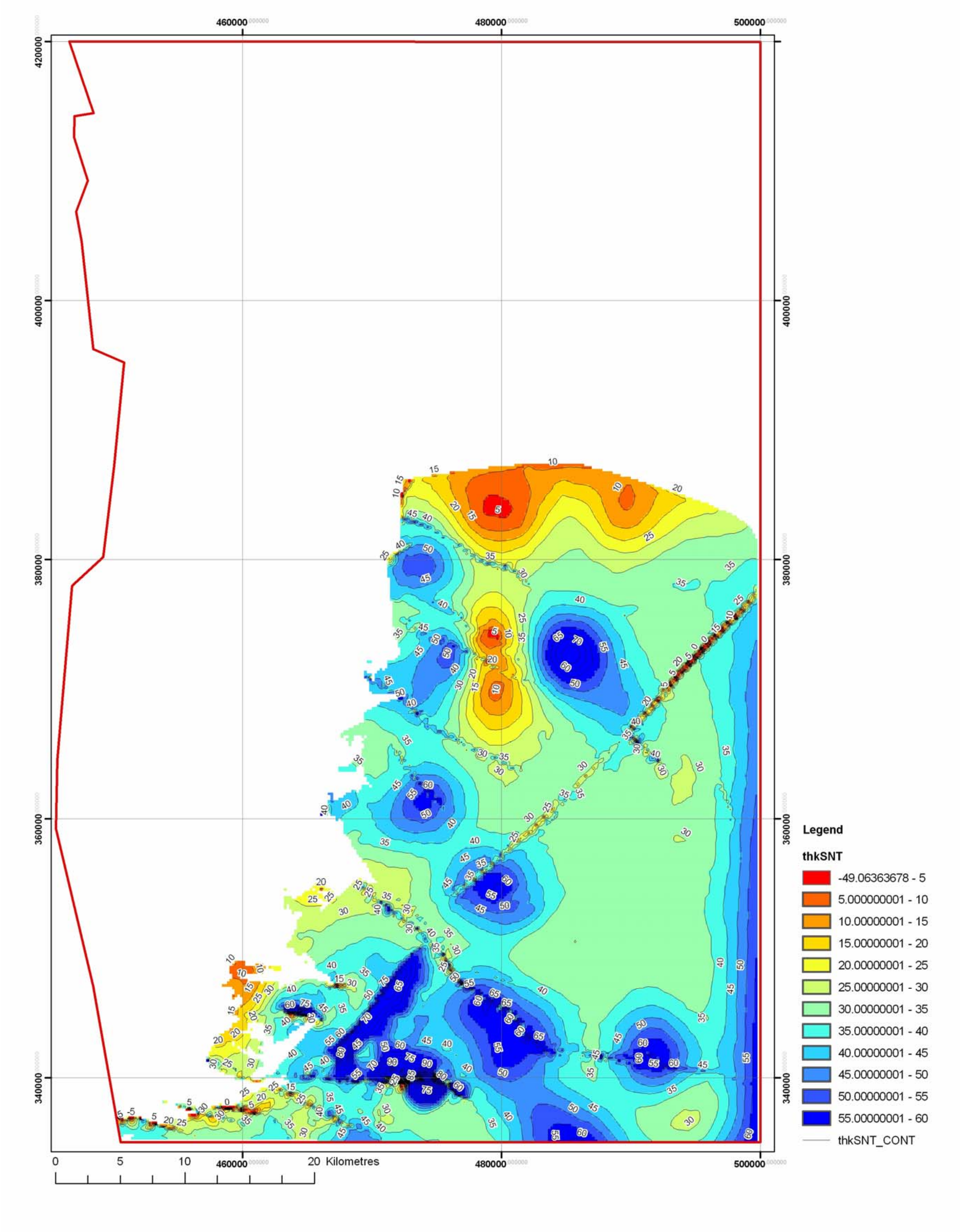

Figure 7 – Sneinton Formation thickness map

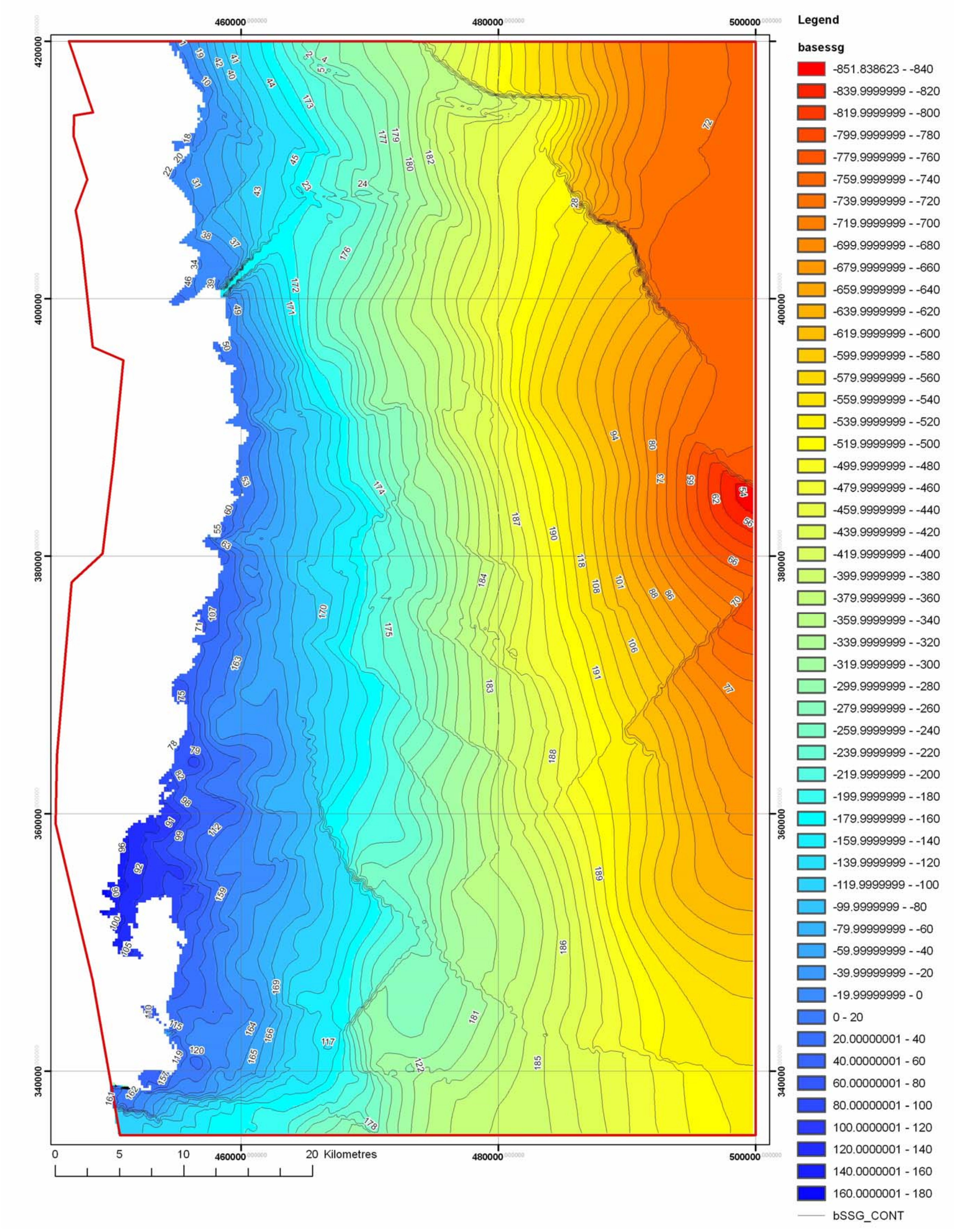

Figure 8 – Base Sherwood Sandstone Group surface elevation map

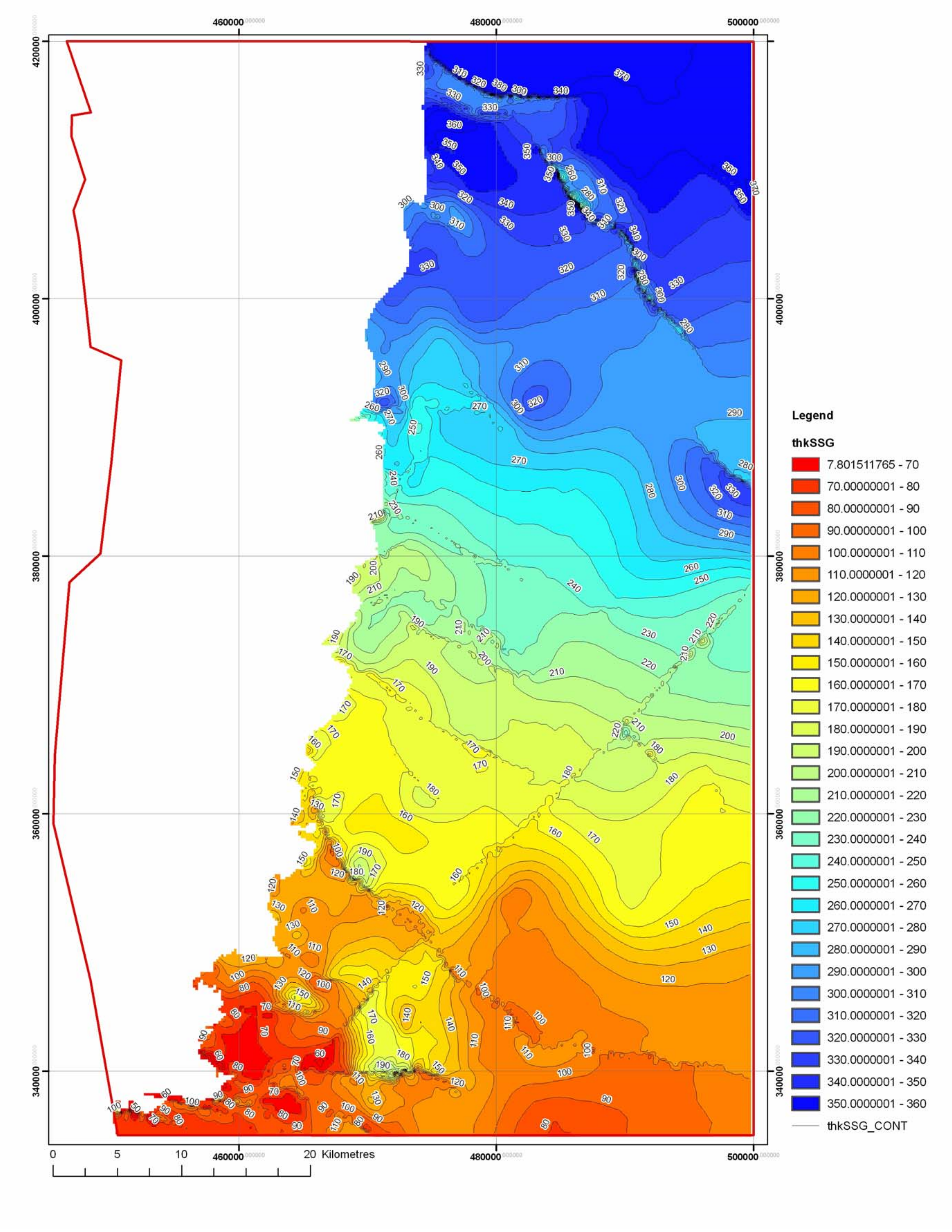

Figure 9 – Sherwood Sandstone Group thickness map

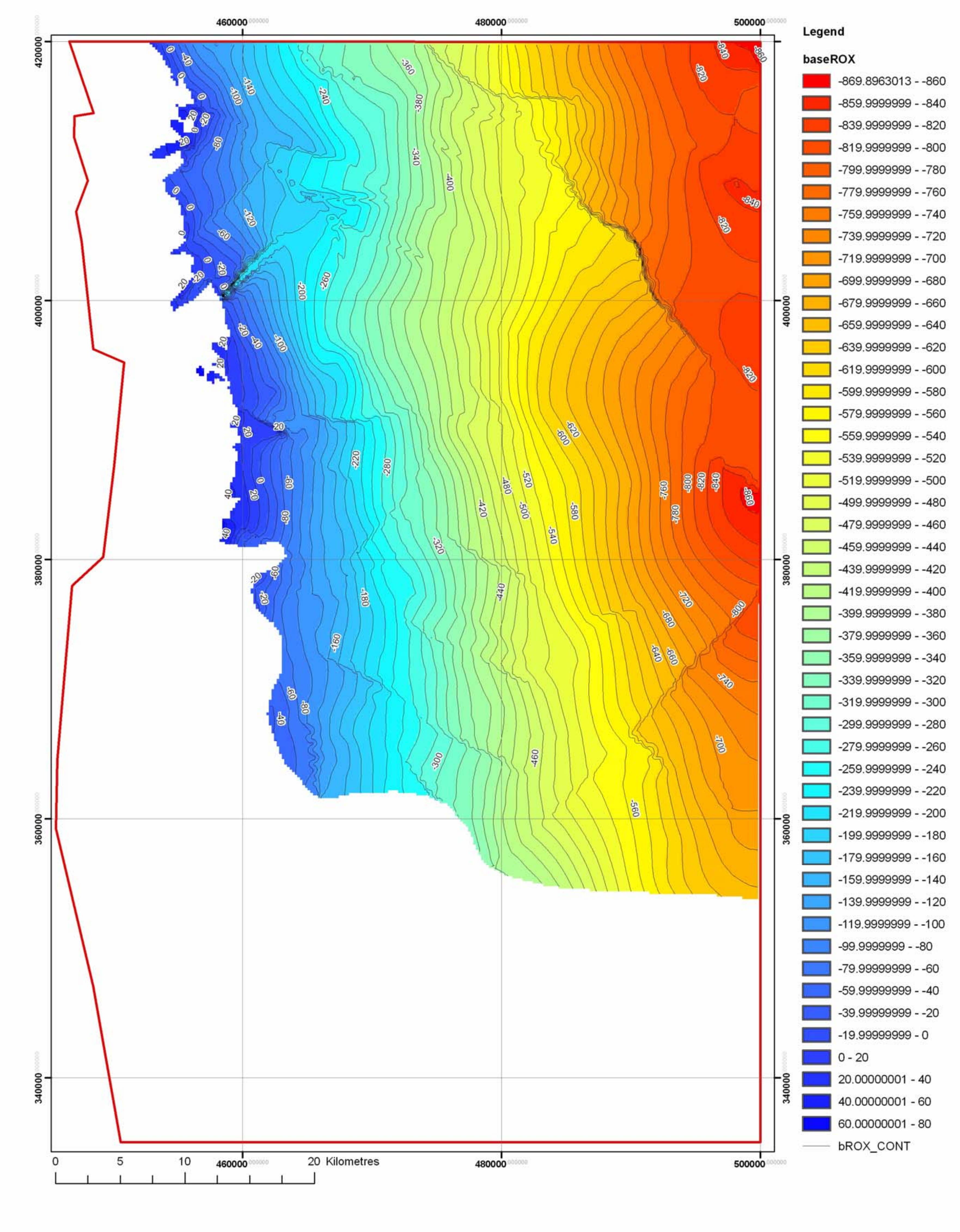

Figure 10 – Base Roxby Formation surface elevation map

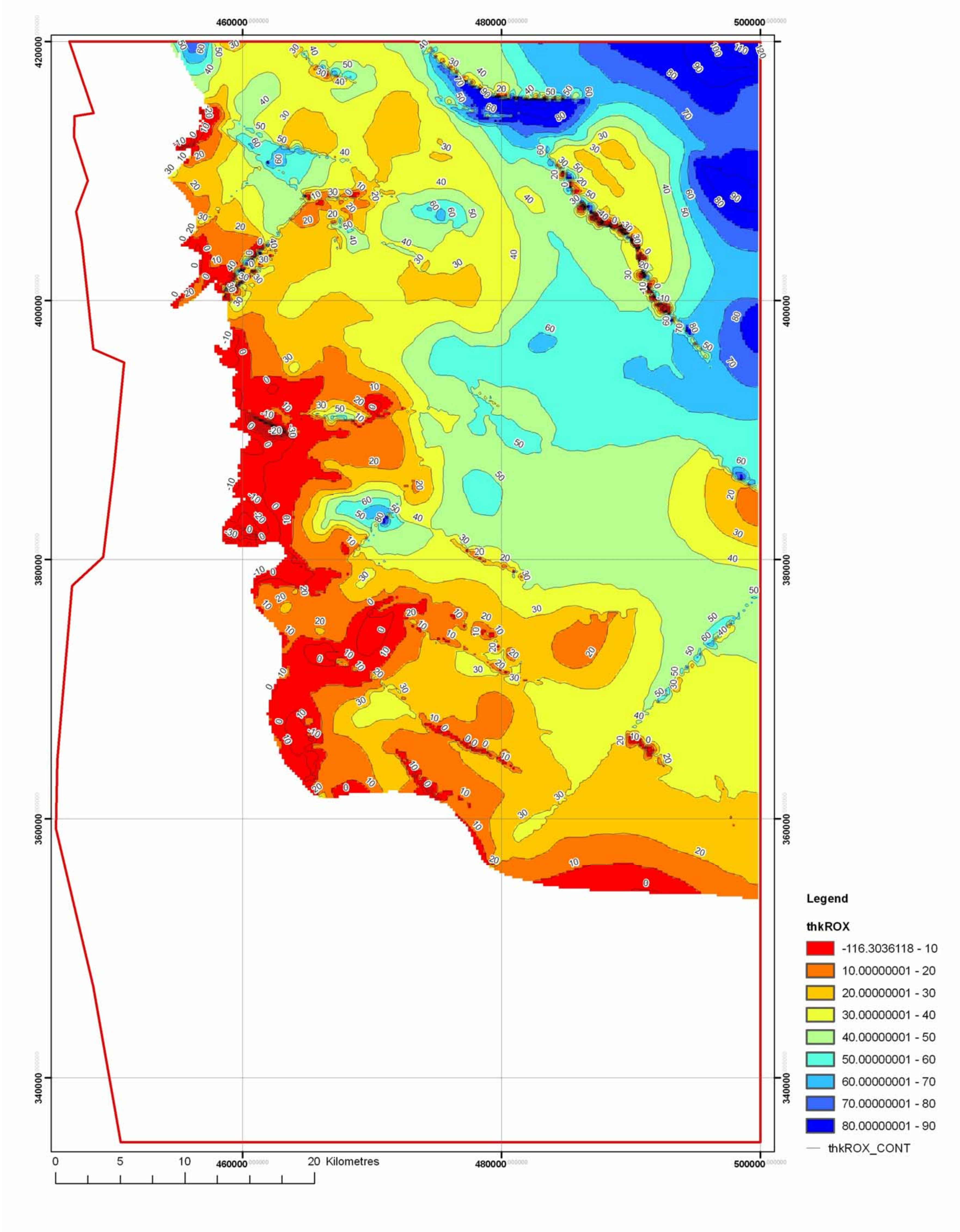

Figure 11 – Roxby Formation thickness map

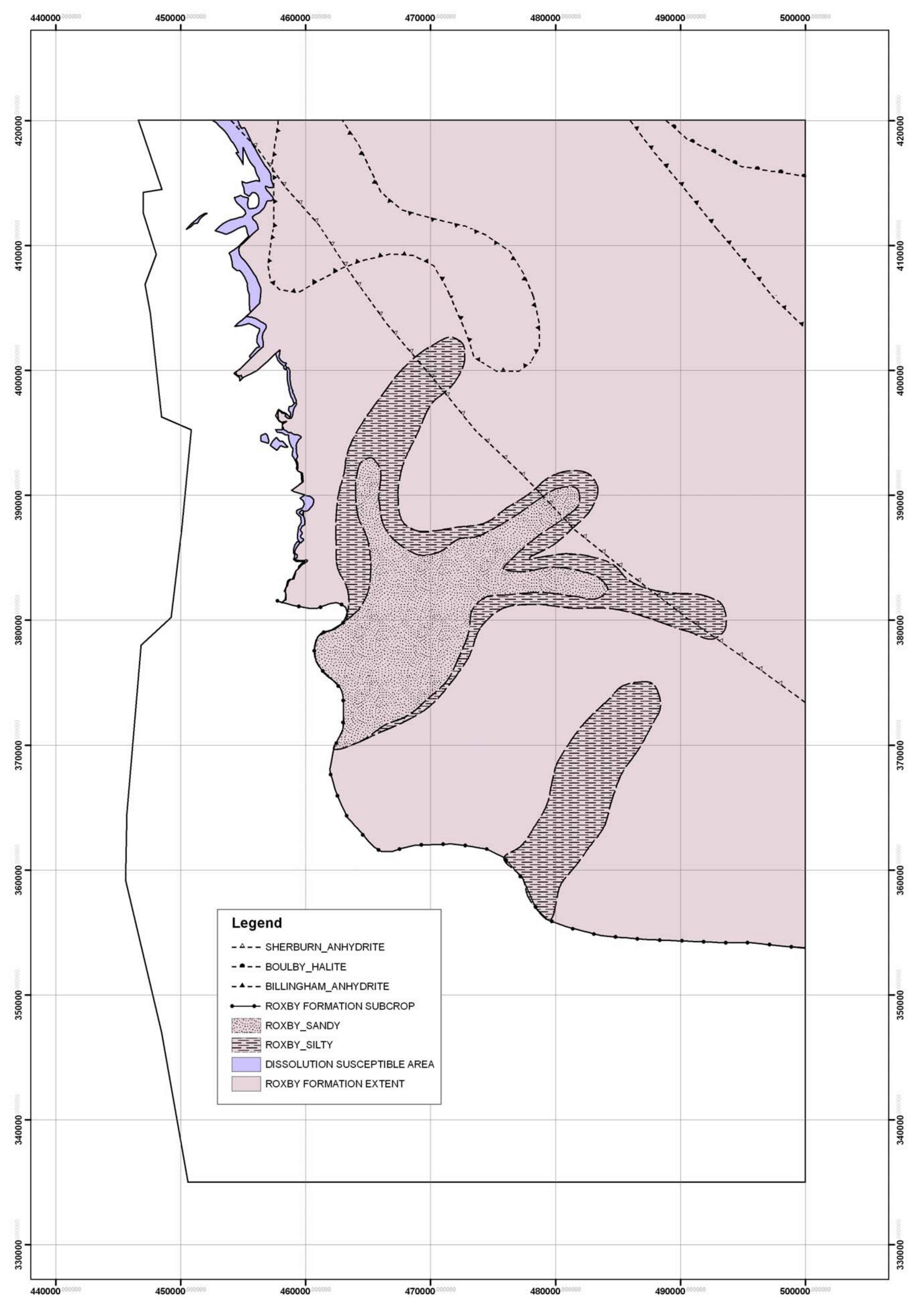

Figure 12 – Roxby Formation facies map

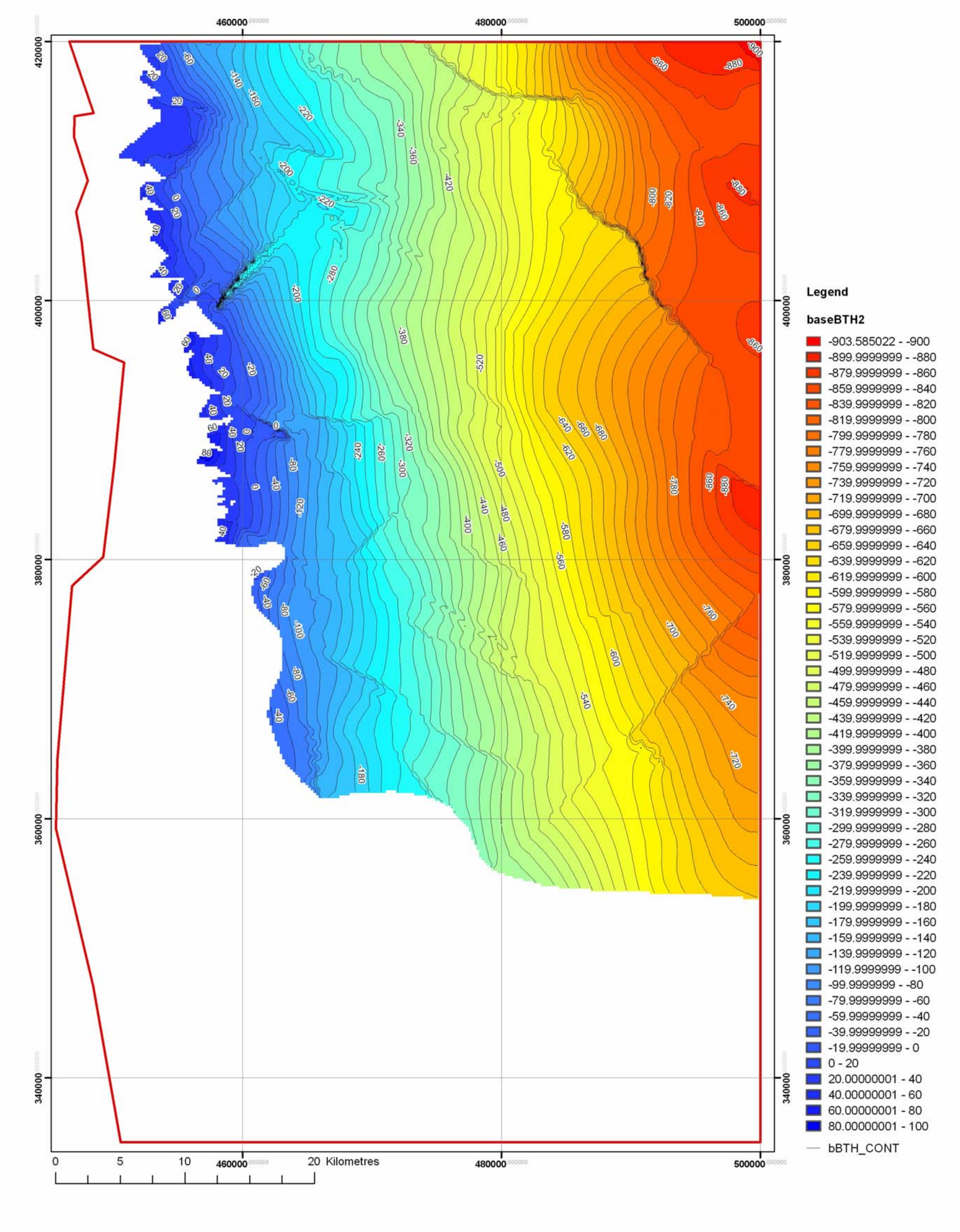

Figure 13 – Base Brotherton Formation surface elevation map

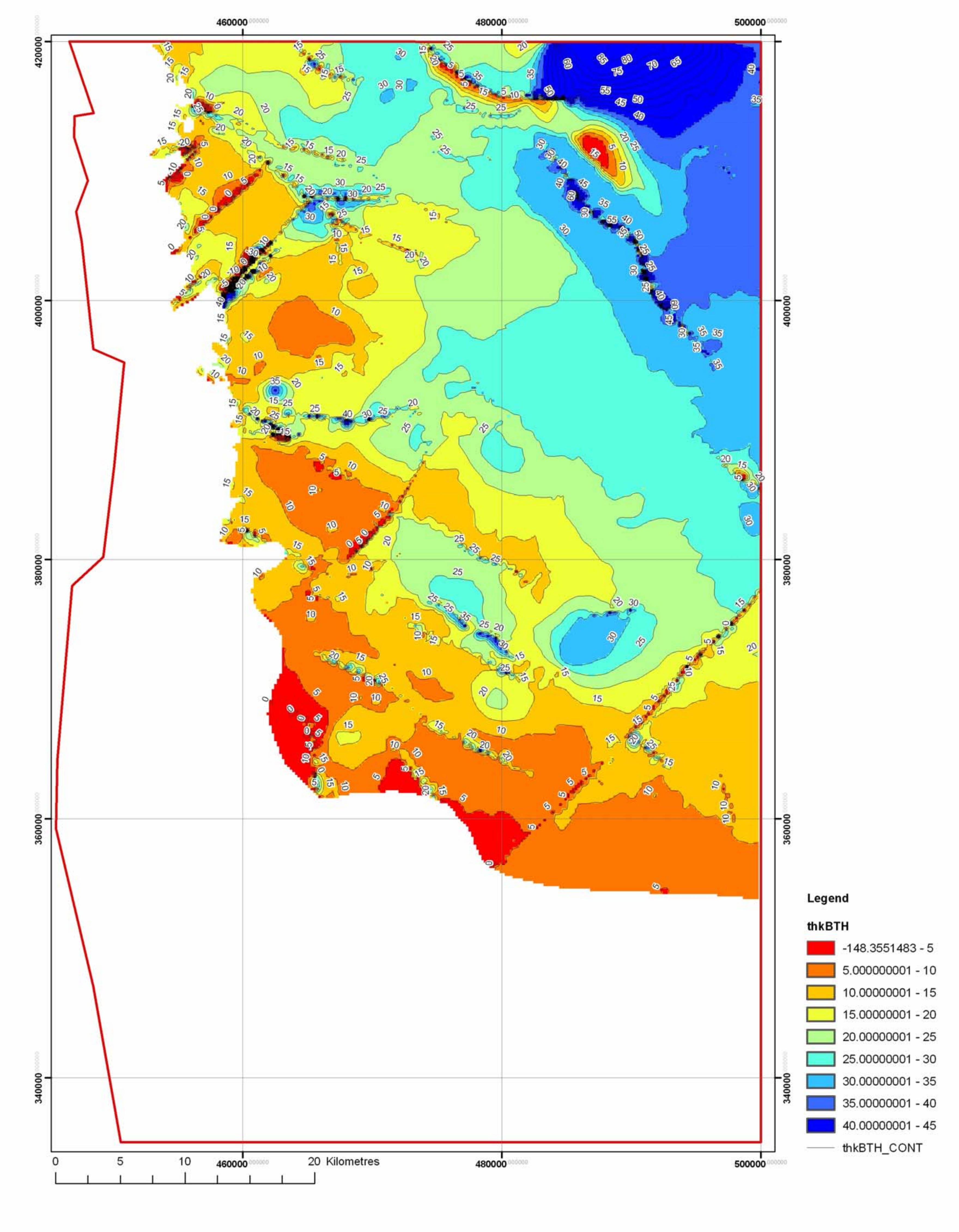

Figure 14 – Brotherton Formation thickness map

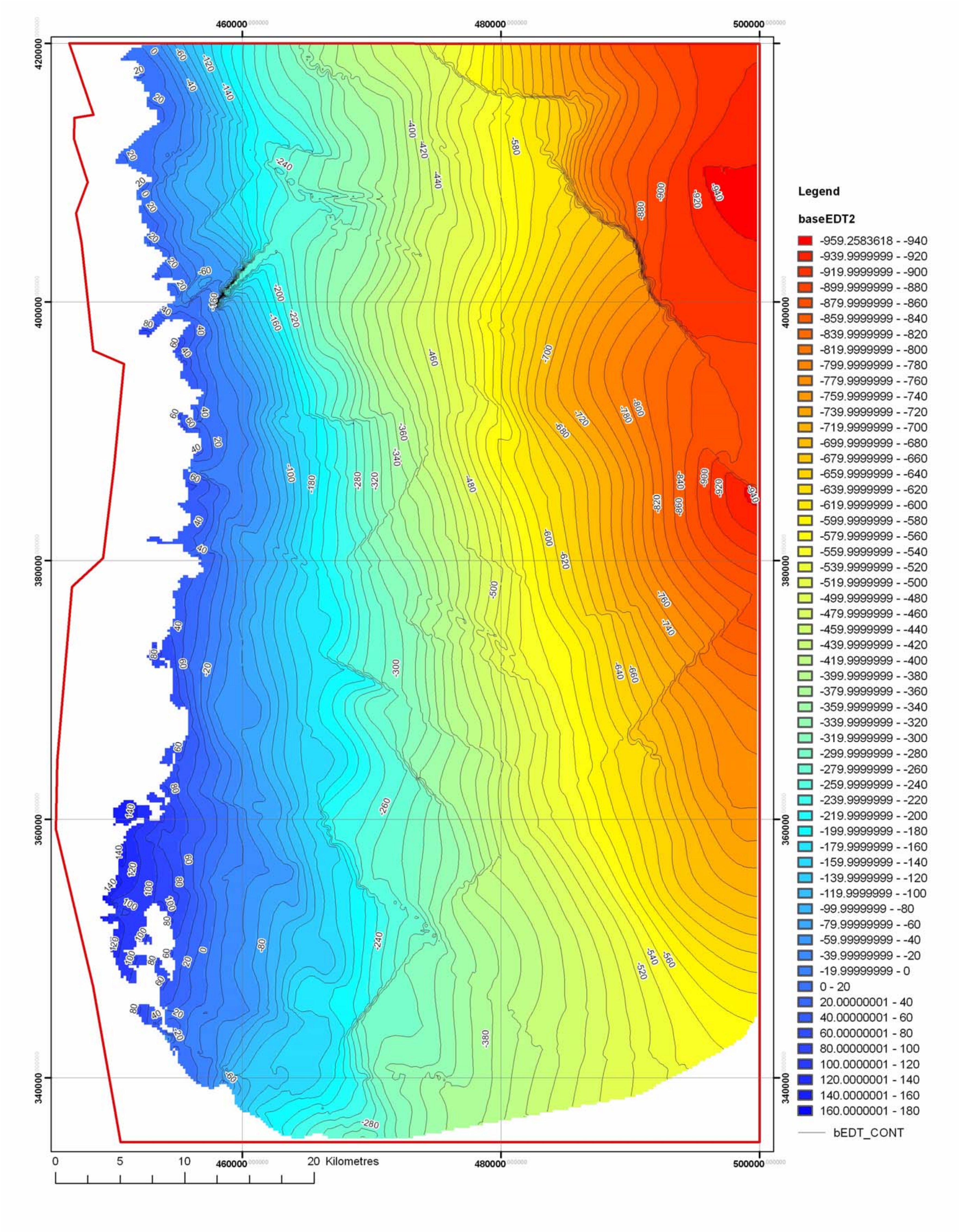

Figure 15 – Base Edlington Formation surface elevation map

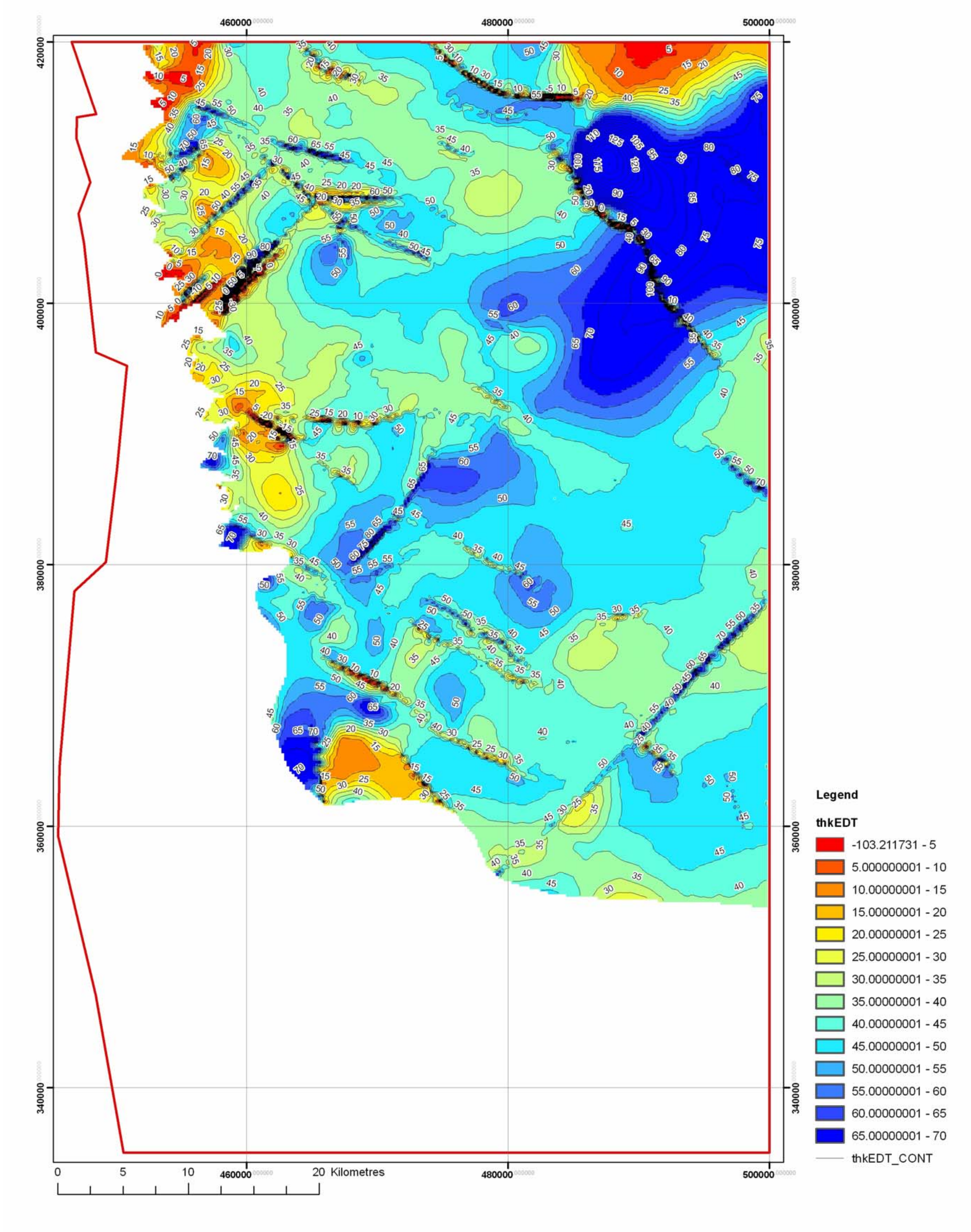

Figure 16 – Edlington Formation thickness map

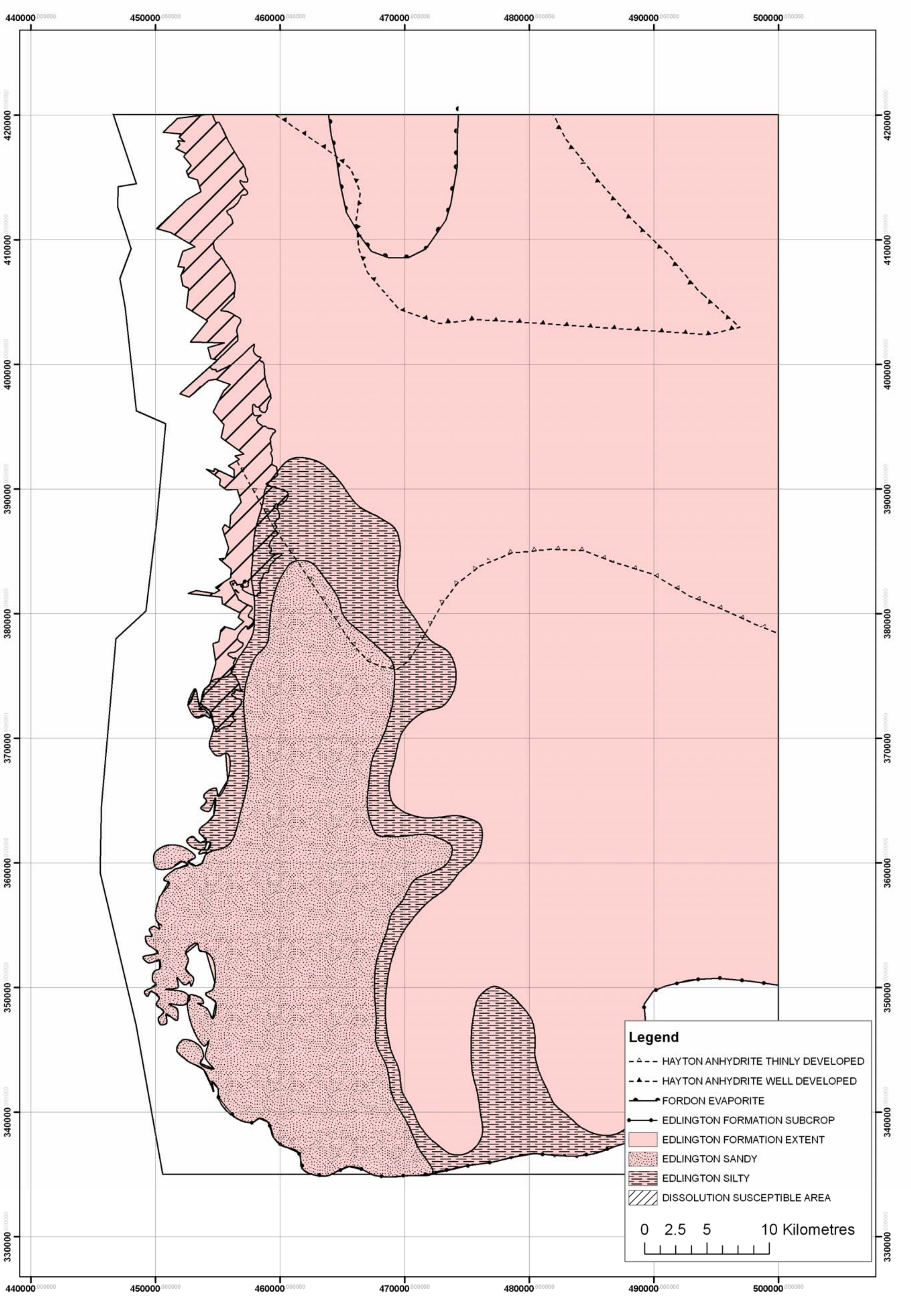

Figure 17 – Edlington Formation facies map

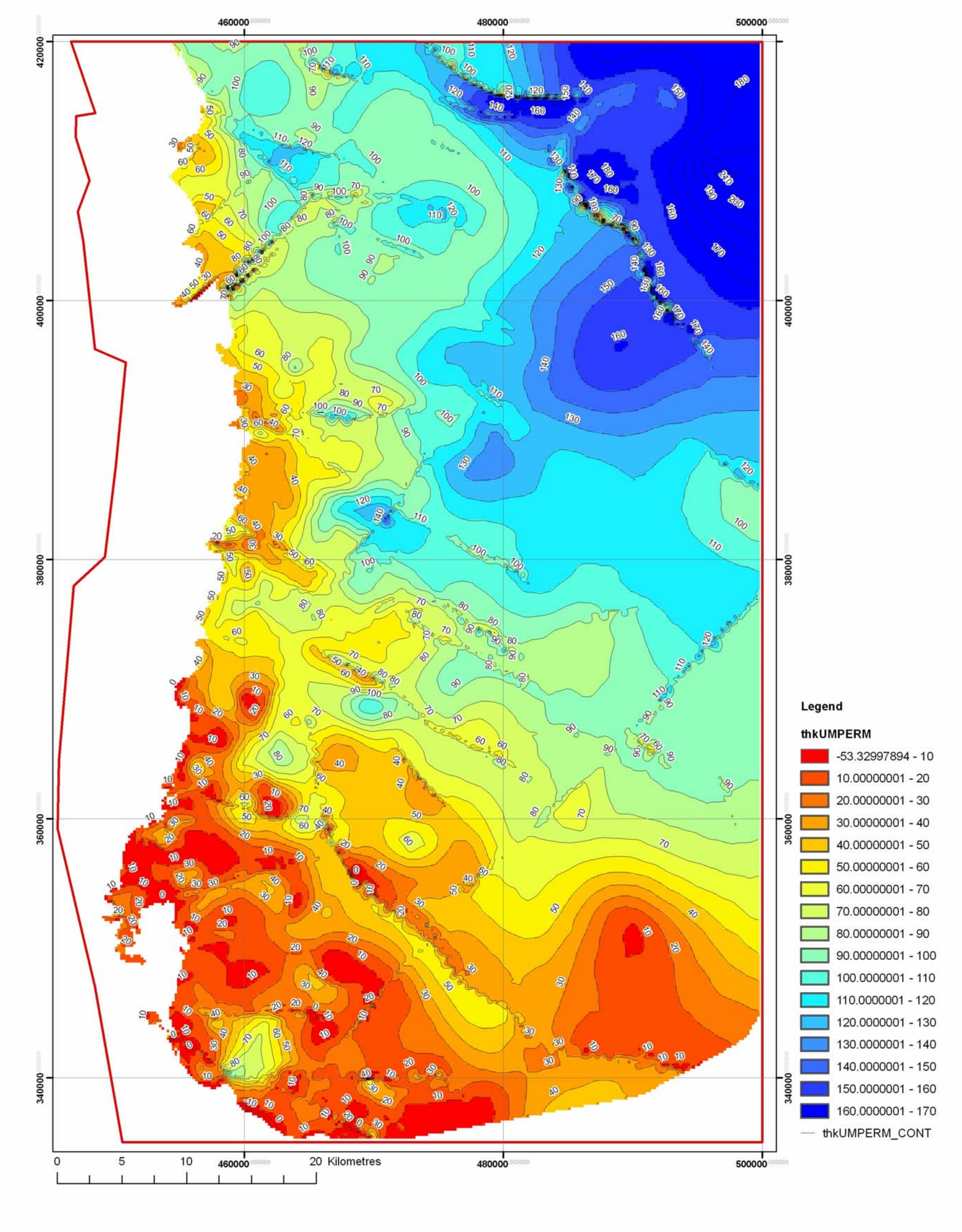

Figure 18 – Intervening Strata between Cadeby Formation and Sherwood Sandstone Group thickness map

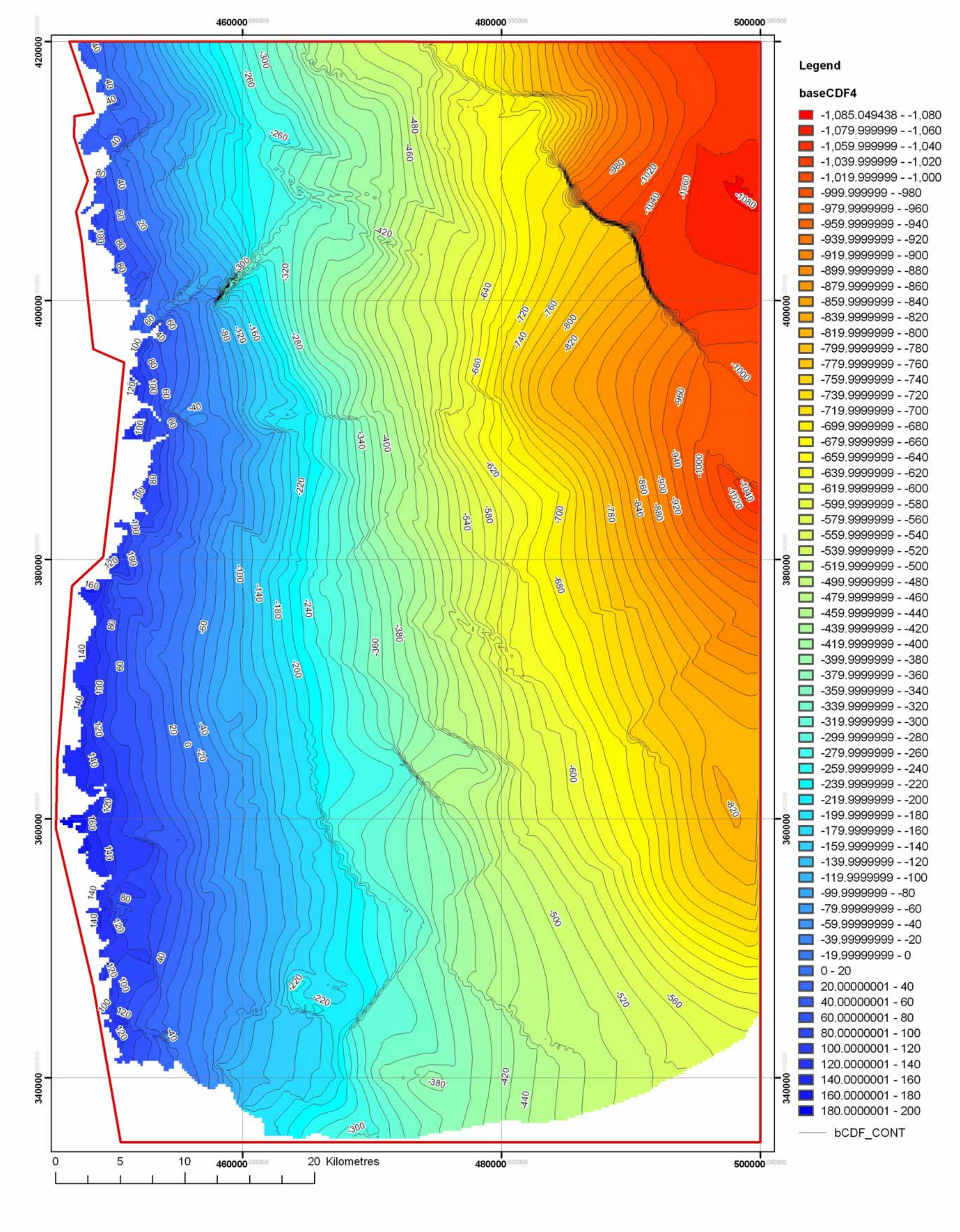

Figure 19 – Base Cadeby Formation surface elevation map

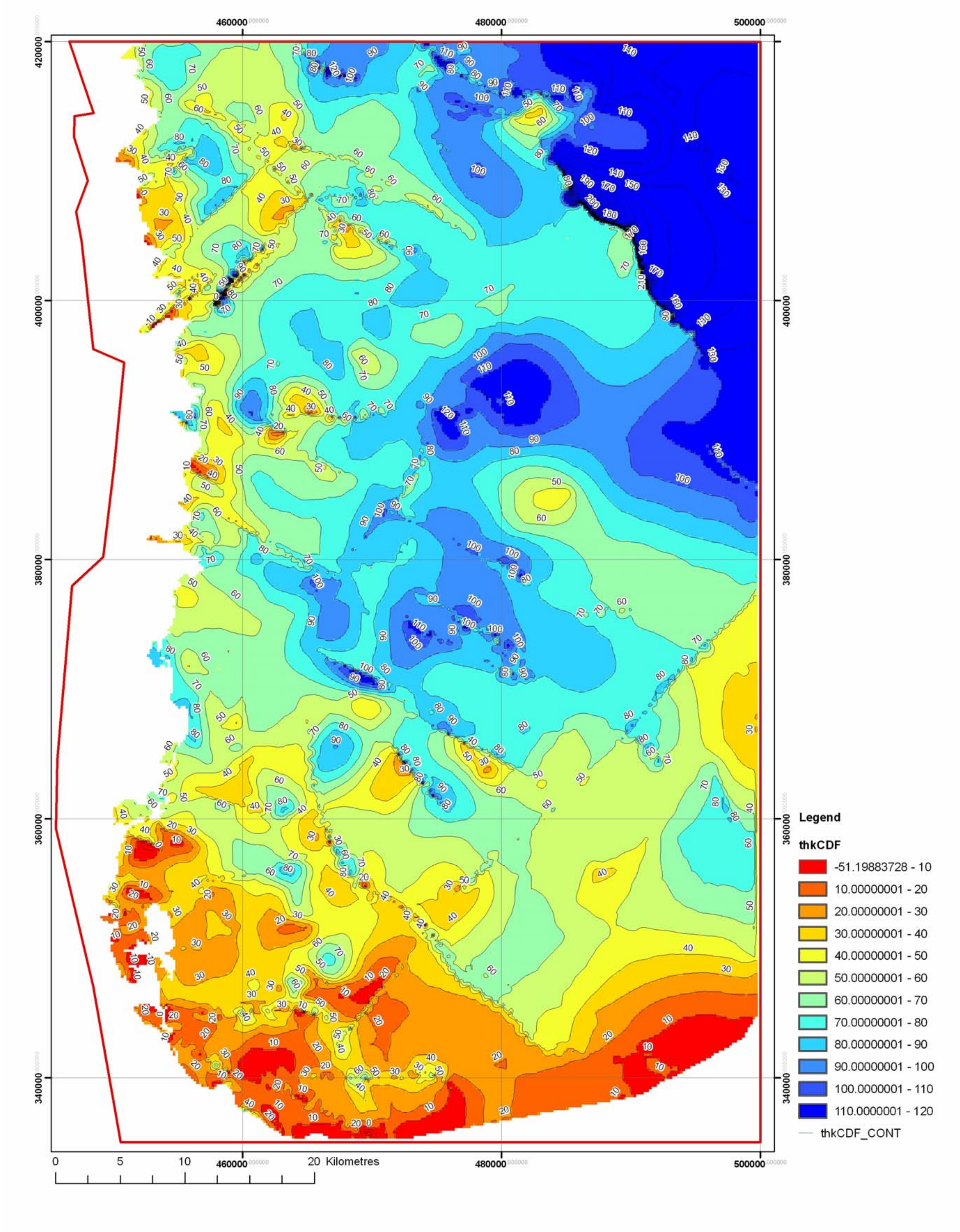

Figure 20 – Cadeby Formation thickness map

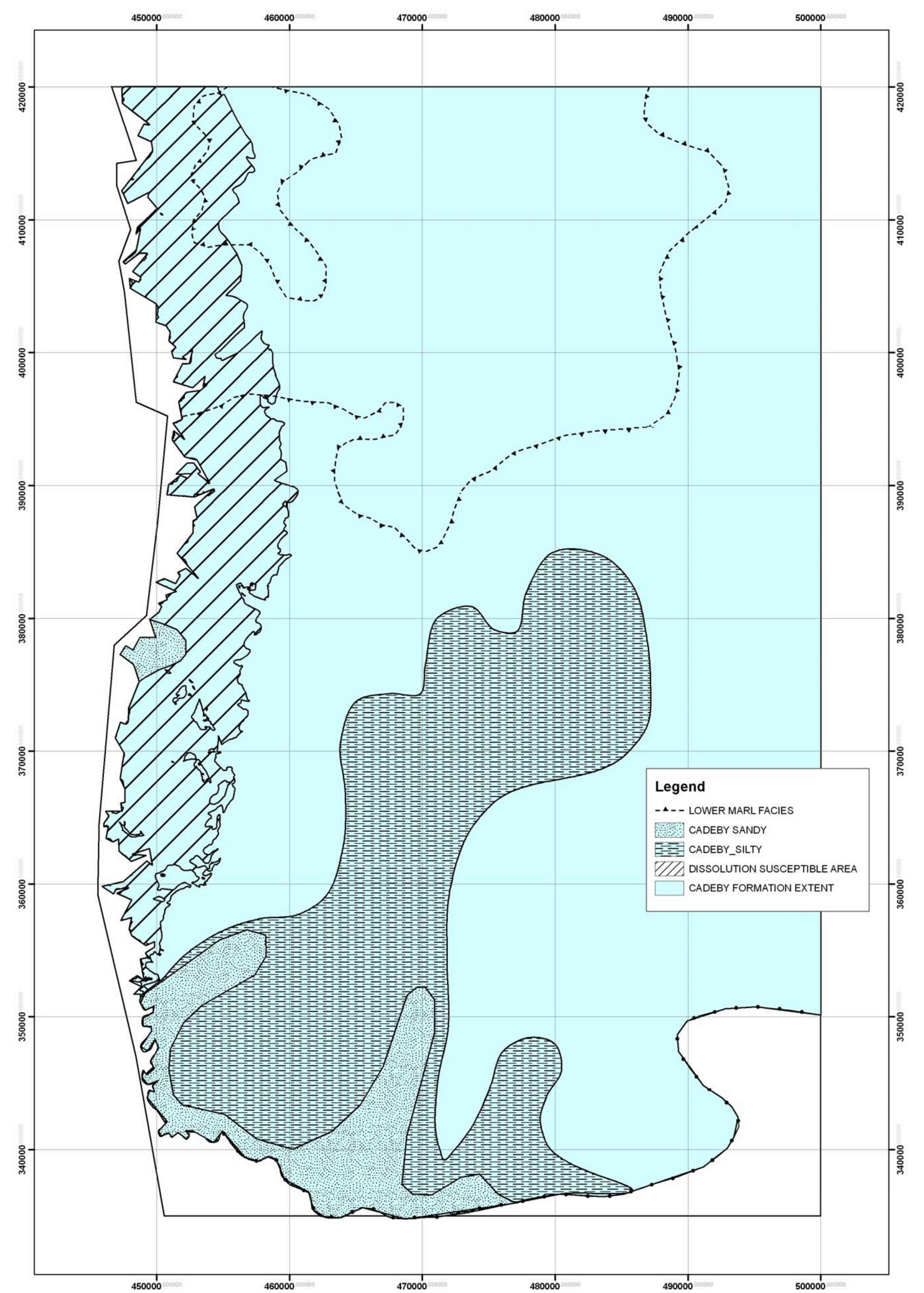

Figure 21 – Cadeby Formation facies map

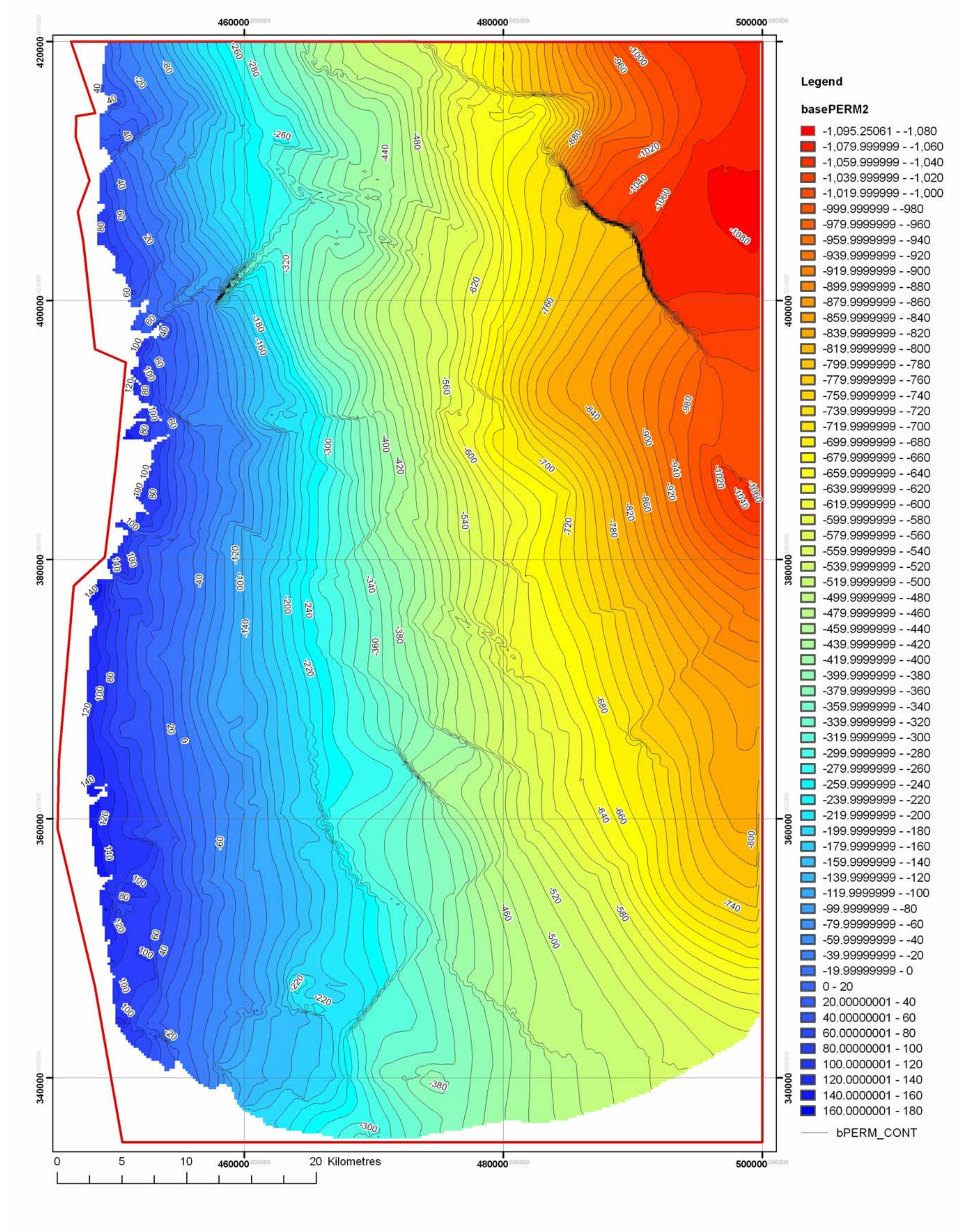

Figure 22 – Base Permian Formation surface elevation map

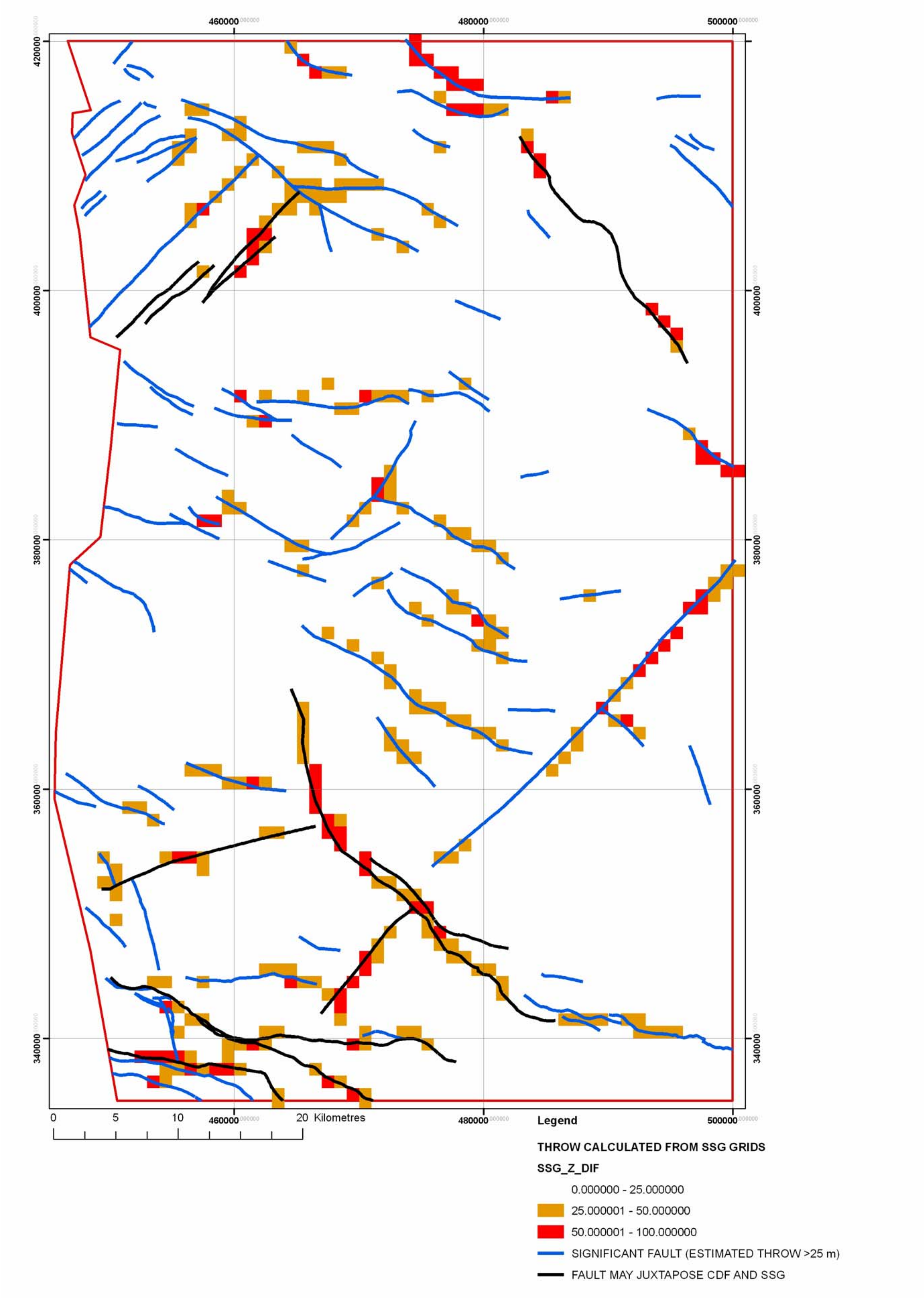

Figure 23 – Fault pattern map