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Alberta Energy and Utilities Board

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Cristina Pana

Alberta Energy and Utilities Board
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Alberta Energy and Utilities Board
Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, Alberta
T6B 2X3
Canada

Tel: (780) 422-1927
Fax: (780) 422-1918
E-mail: EUB.AGS-Infosales@gov.ab.ca
Website: www.ags.gov.ab.ca

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# Abstract

Two major aspects of economic and environmental interest in Alberta—coalbed methane (CBM) exploration and development and $CO_2$ injection in coal strata to increase the enhanced CBM recovery ($CO_2$-ECBM)—motivated the present study. The economic importance of CBM in the Ardley Coal Zone, associated with the emerging issue of potential $CO_2$ storage in coals have led the Alberta Geological Survey to undertake this project to better understand the geological reservoir conditions within the Edson CBM exploration block.

The present study focuses on the following:

**a.** development of a sequence stratigraphic model, which allows a more realistic coal correlation in the Edson CBM exploration block;

**b** Ardley Coal Zone reservoir characterization, and

**c** geometry of the adjacent sandstone channels and their connectivity with the coal reservoirs units.

The report is structured in three parts: the first part presents an overview based on new data, of the Battle-Scollard-Paskapoo succession in the Edson CBM exploration block; the second part focuses on the Ardley Coal Zone reservoir characterization, where new lithologic and stratigraphic data were associated with coal zone internal structure, hydrogeology and fracture pattern; and the third part defines the fluvial channels within Scollard-basal Paskapoo succession and the coal-channels architecture in the Edson block, emphasizing the potential pathways of geo-fluid migration.

There are five fluvial sequences defined and described in the Edson block, interpreted as dynamic responses to cyclic slow-thrusting tectonic stages followed by isostatic rebounding, similar to the model presented for the Pembina coal sub-basin (Pana, 2007). The depositional environments favourable to coal accumulation migrated from the east-central part of the Edson coal sub-basin at the beginning of coal deposition time ('N' coal subzone) to the west-central ('Ml' and 'Mu' coal subzones) and strongly to the southwest at the end of the Ardley deposition time ('S' coal subzone). The coal subzones ('N,' 'Ml,' 'Mu' and 'S') can be considered individual reservoirs due to their particular geometry and sealing characteristics. The examined drillcores have shown that the 'banded coal' category is the dominant type of coal in the Edson block. Coal-cleats are predominantly unmineralized. Vitrinite reflectance is 0.52–0.63% within the onset of hydrocarbon generation. Interpretation of the fracture system suggests two areas of potential 'two-face-cleats systems' northwest and southeast of the Athabasca River. Differential compaction of the underlying sediments locally amplified existing cleats and possibly generated additional coal small-scale fractures at the contact of the coal seams with the sandstone channels.

The vertical connectivity of the reservoir units is amplified in the Edson CBM exploration block by post-Scollard structural re-adjustments. The post-Scollard structural re-adjustments are interpreted based on a set of three successive structural maps generated at the top of the Battle Formation, the top of the non-coal-bearing part of the Scollard Formation and at the top of the Scollard Formation. All three structural maps reveal a consistent northwest-southeast trend of a narrow zone of structural low flanked by two areas of structural high. In contrast, the isopach map of the Scollard Formation shows a gradual but substantial increase in thickness towards the southwest. This consistent thickening clastic prism suggests that the elongated structural low formed after the deposition of the Scollard Formation. The analysis of structural maps corroborated with outcrop and core observations suggests strong vertical hydraulic connectivity among the reservoirs in the Edson block. Therefore, in the Edson block, the suitability

for $CO_2$ sequestration in the Ardley Coal might be limited by the increased vertical connectivity of the reservoir units due to post-depositional structural re-adjustments.

# 1 Introduction

During the last decade coalbed methane (CBM) resources in Alberta have become an important exploration target. Among the sustained interests in unconventional sources of hydrocarbon (CBM) in the province, the early Tertiary coals referred to as the Ardley Coal Zone, represents one of the main CBM exploration objectives (Figure 1). The shallowest coal zone in Alberta contains important coal and CBM resources (Dawson et al., 1994). A CBM resource of approximately 53 Tcf of methane has recently been estimated for the Ardley Coal Zone (Beaton et al., 2002; Beaton, 2003).

Regionally, the Ardley Coal Zone occurs mainly in two coal sub-basins known as the Pembina and Edson CBM exploration blocks, both located north of township 42. The present study concentrates on deciphering the coal strata geometry and reservoir characteristics of the northern coal sub-basin, the Edson CBM exploration block, following the methodology of the previously published report: "Ardley Coal Zone regional characterization and coal-channels architecture in Pembina block" (Pana, 2007).

The modern view of the Ardley Coal Zone as a source and reservoir rock for hydrocarbons integrates the coal formation processes, coal quality and reservoir considerations, leading to a more complete description of the Ardley Coal Zone as a unique coal system. The concept of "coal system" (Warwick, 2006) considers coal as unconventional type of reservoir defined as an anisotropic, non-homogenous organic rock with respect to physical structure and chemical content. The unique characteristic of coal is the dual role of source and reservoir of hydrocarbons. The amount of gas generated, stored and expelled can be estimated from geological models. Lateral migration of gas is limited by the general low and very low permeability matrix (if lack of fractures). Vertical gas migration outside of the coal reservoir entity can be limited by encasing or sealing layers of rocks such as shale and mudstone, predictable from depositional sequences. Updip gas migration into adjacent reservoirs (i.e. sandstones) can be favoured by local erosion or non-deposition of layers with sealing properties. Nevertheless considerable amount of gas has retained in the coal strata. This property maintains the core strata within the reservoir definition.

The application of the principles of sequence stratigraphy to non-marine fluvial deposits has enabled a reconstruction model of the fluvial channels geometry within the Scollard-basal Paskapoo succession. This has led to a more realistic coal strata correlation and a better definition of the Ardley coal reservoir geometry. Limited coal analysis, including quantitative data of proximate and ultimate analysis and coal petrographic analysis for the Ardley Coal Zone, are available in the public domain. The new stratigraphic data defined in this report represent the interpretation of geophysical logs calibrated by the examined drillcores from the study area. Results of the stratigraphic analysis provided the following: 1. information regarding the nature and the timing of the sedimentary fill, mechanisms and geometry; 2. some key sequence stratigraphic surfaces, which aimed at deciphering the sequence stratigraphic model; 3. tectonic and climatic allogenic control factors as complex response characters of fluvial systems; 4. a preliminary correlative model for the fluvial sequences of the Scollard succession at the basin scale.

Coal reservoir characteristics, including hydrogeology and fracture pattern, are presented briefly in the report. Very limited information exists in the public domain for other parameters needed to define the Ardley reservoirs in the Edson block, such as formation-temperature measurements, permeability and water chemistry analysis. However, the few data accessible were interpreted based on the new Edson sequence stratigraphic model.

Displays of the sandstone channels architecture, and their proximity to the adjacent coal seams, indicate areas of the potential hydraulic connectivity throughout the geological time, and allow for an assessment of the open system character of the Ardley Coal Zone as a part of Scollard-Paskapoo aquifer system.

Locally, variable-scale fractures associated with the end of the Laramide Orogeny increase the vertical connectivity among the aquifers within the Scollard-Paskapoo succession.

This new interpretation of the Ardley Coal Zone in the Edson CBM exploration block represents a contribution to the general stratigraphy of uppermost Cretaceous-early Tertiary in the basin and provides a solid stratigraphic framework of the Scollard-Paskapoo clastic succession. As the result, the detailed interpretation of the Edson exploration block indicates areas with high CBM potential (coal thickness and continuity, coal quality, optimum depth, fracture pattern, etc.) and implications for $CO_2$ storage in the Ardley coal strata. The dataset used to produce this new stratigraphic framework is appended to the report.

## 2 Edson CBM Exploration Block

### *Study Area*

The Edson CBM exploration block encompasses an area between Townships 52–61, Ranges 14–24 West of the 5th Meridian, representing approximately 1000 km $^2$. The study area includes the town of Edson to the south and the town of Whitecourt to the northeast. The topographic elevation in the area varies from 1600 m between the Athabasca and McLeod rivers in the southwest, to about 700 m easterly towards the Athabasca-McLeod confluent basin (Figure 1). An area of medium-high topography occurs in the north-west part of the study area. The uppermost Cretaceous-early Tertiary succession consists of the clastic succession of the Wapiti Group, Battle Formation, Scollard Formation and the Paskapoo Formation (Figure 2).

### 2.1 Geological Setting

The study area is located in the northern part of the Scollard sedimentary basin, west-central Alberta and encompasses the main part of the Edson coal sub-basin (Figure 3).

Regionally, the Scollard basin represents the Uppermost Maastrichtian-early Tertiary clastic infill succession, now deepening to the west toward the thrust and fold belt. The basin was fed from the Cordilleran Orogen during the uplift stages. The top of the succession corresponds to the disconformable contact with the overlying Paskapoo Formation. The base of the Scollard Formation coincides with the top of the Battle Formation (Figure 2).

The stratigraphic succession within the Edson block, as a part of the Scollard Formation basin, represents entirely a fluvial succession with no marine influence (Figure 2).

North of the township 52, in the Edson block, the Scollard Formation thickness ranges between less than 65 m to more than 290 m (Figure 4). The isopachs of the Scollard Formation in the Edson block show a gradual increase in thickness from the northwest to the southeast, paralleling the deformation belt. The area with a thickness of more than 200 m covers the southwest part of the study area. The maximum thickness of more than 290 m is found in the extreme south-central part of the study area.

Informally, the Scollard Formation is divided into two members based on the coal distribution: the lower member is coal-barren in contrast to the upper member, which is coal-bearing and thus referred to as Ardley Coal Zone.

The isopachs of the lower member of the Scollard Formation show a thickness between less than 50 m to more than 130 m (Figure 5). A particular characteristic of the lower member is the location of the thickest area of more than 170 m in the central-west part of the study area. The upper member or the Ardley Coal Zone represents the primary stratigraphic focus of the study and will be discussed in the next section.

The Battle Formation is a consistently distributed stratigraphic unit with a thickness between 3.6 m and 24 m, in the study area. The isopachs of the Battle Formation show an increased thickness along a northwest-southeast structure (Figure 6).

The comparison of the set of three maps representing the depth from surface to the top of the upper member of the Scollard Formation, the top of the lower member and to the top of the Battle Formation shows a similar depth pattern resulting from the present-day surface topography (Figures 7, 8, 9).

The comparison of the structural contours at the top of the same three selected surfaces: top of the upper member of the Scollard Formation, top of the lower member and top of the Battle Formation, reveals a similar northwest-southeast trend of structural-low (Figure 10, 11, 12).

## 2.2 Upper Member of the Scollard Formation (Ardley Coal Zone)

The Ardley Coal Zone, defined as the informal upper member of the Scollard Formation, represents the stratigraphic interval arbitrarily considered between the uppermost and the lowermost coal seam identified in any location.

The upper member of the Scollard Formation is present within the entire study area. The thickness ranges between less than 30 m in the northeast to more than 120 m to the southwest (Figure 13). A wide plateau of about 100 m in thickness is distributed in the central part of the study area. The maximum thickness of more than 137 m is recorded in the extreme south-central part of the considered area. Particularly low values of 8 to 21 m are shown in isolated locations to the east and in the extreme northeast part of the Edson block. The unsystematic pattern of small thickness values can be explained in some instances by fewer Ardley coal seams recorded in the considered locations. In the areas where the Ardley Coal Zone thickness reaches more than 100 m, the upper succession represents approximately half of the Scollard thickness as it is illustrated in the southern part of each of the following north-south stratigraphic cross-sections: A-A,' I-I' and F-F' (Figures 15, 16, 17). The most easterly part of the north-south G-G' stratigraphic cross-section (Figure 18) displays an irregular distribution of the Ardley Coal Zone subunits. Where the thickness of the Ardley Coal Zone is less than 100 m, to the north, (Figures 16, 17) and to the east (Figures 19, 20, 21, 22), the Ardley Coal Zone represents only a quarter or a third of the total Scollard Formation thickness. In the extreme southern part of the study area (Figure 22), the thickness of the Ardley Coal Zone represents approximately half of the Scollard interval.

The gradual increase of the Ardley Coal Zone thickness in the central part of the basin, from 30 m to 90 m then abruptly to 120 m in the extreme southern part of the study area, led to the interpretation that the most accentuated subsidence recorded during lower Paleocene took place further to the southwest. This aspect is well illustrated by the north-south stratigraphic cross-sections (Figures 15,16, 17) and by the most southern west-east cross-section (Figure 22).

The Ardley Coal Zone in the Edson CBM exploration block consists of a variable number (1–4) of discontinuous coal subunits that are considerably more difficult to correlate than the coal subzones in the Pembina sub-basin (Figure 23). The four coal subunits are named in this report as following, from top to bottom: 'S,' 'Mu,' 'Ml' and 'N.' Locally, the Ardley sandstone channels generated superficial erosion at the top of the underlying coal seams**.** Deeper erosion of the upper part of the Ardley Coal Zone is recorded in the northeast half of the study area (Figure 13), at the base of the Paskapoo channels as it is shown by the A-A,' I-I,' F-F' and G-G' stratigraphic cross-sections (Figures 15, 16, 17, 18). To the northeast, the erosion due to the basal Paskapoo channels led to the total disappearance of the uppermost coal seams (Figures 15, 16, 17, 18). In the central part of the study area and to the east, Paskapoo erosion cut down to the top of the middle coal subzones. The E-E' and K-K' west-east stratigraphic cross-sections (Figures 20 and 21) illustrate the deeper Paskapoo erosion. To the east, locally, Paskapoo channels eroded deeper to the top of the lower coal subzone as shown by the southern segment of the west-east N-N' cross-section (Figure 22).

The coal cumulative thickness map shows the location of the major coal accumulation in the central part of the study area where the total coal thickness can reach 15–18 m, representing approximately 20% of the Ardley succession (Figure 24). The thickest coal accumulation of the Ardley Coal Zone corresponds to the major increase of the number of coal seams to 21 (Figure 25).

## 2.3 Post-Scollard Formation Structural Readjustments

The Edson block has similar lithological components to the uppermost Maastrichtian-lower Paleocene succession within the Pembina block, but structurally, in the Edson block, the Scollard clastic interval shows a consistent axial area of structural low oriented northwest-southeast and flanked laterally by two areas of structural high. In order to define the character of the structural low, a set of three structural maps have been generated. They include both the Edson and Pembina study areas (Figure 26, 27, 28).

The structural contours at the top of the Battle Formation (Figure 26) depict a general southwest-northeast trend from a low of +240 m recorded in the southwest of the Pembina area to +700 m in the northeast of the Edson block. In the Pembina block, the structural contours show a gradational change from low to high values. In the Edson block, an axial area of a structural low oriented northwest-southeast is bounded laterally by two areas of structural high. Nevertheless, structurally, the top of Battle Formation in the Edson block is higher, with an average of 40 m, than in the Pembina area.

The structural contours of the top of the lower member of the Scollard Formation (Figure 27) ranges from + 340 m southwest of the Pembina block to +740 m in the northeast of the Edson block. Some small inconsistencies shown by the structural contours are the result of the infrequent distribution of the lowermost coal seams of the overlying member or Ardley Coal Zone, arbitrarily considered the top of the lower Scollard member. In the Edson block, the structural contours of the top of the lower member of the Scollard Formation (Ardley Coal Zone) shows an area of structural low of +500 m oriented northwest-southeast and laterally delimited by two areas of structural high of +720 m in the northwest and +560 m in the southeast, respectively.

The regional structural map of the top of the upper member of the Scollard Formation (Ardley Coal Zone) (Figure 28) shows the lowest structural area located in the southwest of the Pembina study area of +420 m and the highest of +760 m in the northeast part of the Edson block. The structural high flanking to the southwest the structural axial low within the Edson block, records values of +660 m. In between the two higher structural areas there is a zone of lower structural values of about +600 m. The axial low area appears to be wider at the end of the Scollard deposition time, and it seems to be a well-defined extension of the structural low depicted within the southwest part of the Pembina block.

Analysing the set of the three structural maps presenting different geological intervals of the uppermost Maastrichtian-lower Paleocene deposition time, the consistency of the axial structural low within the Edson study area is noticeable. The comparison of the structural maps with the isopach map of the Scollard Formation (Figure 29) shows almost no relationship because the Scollard Formation thickness presents a gradual but substantial increase in thickness towards the southwest as a consistent thickening clastic prism. This observation has led to the conclusion that the process that generated the axial low in the Edson block, took place post-lower Paleocene time or post-Scollard Formation deposition time. A different set of structural factors governed the Battle and Scollard formations synsedimentary processes.

The two sets of structural cross-sections oriented north-south and west-east represent the structural equivalent of the stratigraphic cross-sections described earlier. The structural cross-sections reveal a less uniform structural change in the present-day geometry of the upper Cretaceous-lower Tertiary succession in the Edson block than the simple linear position of the equivalent strata shown by the structural cross-sections in the Pembina block (Pana, 2007). The change observed on both sets of north-south and west-east structural cross-sections in the Edson block, occurs in the central and southwest parts of the sub-basin, south of township 59, range 20 West of the 5th Meridian (Figures 30–38).

The schematic chart presented in Figure 39 represents the resulting interpretation of four main stages of sedimentary infill in the Edson sub-basin based on the reconstructed geometry of the subunits presented in this report. At the end of **stage 1,** corresponding to the end of the Battle Formation deposition time, it is assumed that the top of the Battle Formation represented a quasi-horizontal surface. During **stage 2,** representing the lower member of the Scollard Formation deposition time, successive episodes of subsidence generated thicker clastic succession to the southwest part of the Edson study area. Similar structural mechanisms took place cyclically during **stage 3,** but different sedimentary conditions favoured coal accumulation at the end of each of the last four clastic cycles consistently thicker to the southwest. Later, post-Scollard deposition time, possibly during upper Paleocene, **stage 4**, the axial northwest-southeast structural event took place.

The reconstruction model of the structural re-adjustments in the Edson block offers a better understanding of the process itself associated with increased permeability characteristics of the succession:

- timing of structural re-adjustments;
- increased permeability of the coal reservoirs due to amplification of the existing coal cleats and possible generation of additional coal cleats;
- increased vertical connectivity of the reservoirs, at a larger scale due to associated tectonic fractures affecting the coal strata and the adjacent sandstone reservoirs.

## 2.4 Lithological Description and Facies Association

The interpretation of the coal stratigraphy and sedimentology in the Edson CBM exploration block is based on 54 oil and gas exploration wells (Figure 30). The considered wells have a nonuniform distribution which represents generally a frequency of one well per township. The selected wells are located mainly along the cross-sections constructed for the present study (Figure 30). Locally, the well distribution increases with additional wells considered necessary for stratigraphic clarifications. In the northeast part of the study area, it is difficult to find geophysical logs meeting the criteria of required depth and ideal association of log traces. The new descriptive data set interpreted in this report consists of stratigraphic, lithological and detailed coal picks. The coal database reflects the architecture of the Scollard Formation sequence stratigraphic model deciphered in the Edson coal sub-basin, that represents the extension of the model defined in the Pembina block (Pana, 2007).

In addition to the log interpretation, four drillcores had been examined (Figure 40) within the study area and vicinity:

- 00/11-01-056-19W5 (513–633 m)
- 02/11-06-056-19W5 (704–789 m)
- 00/10-27-061-20W5 (254–282 m)
- 00/10-19-050-19W5 (546–609 m).

### 2.4.1 Lithofacies Description

In essence, the vertical lithological profile of the Ardley Coal Zone as shown by the cross-sections in the Edson CBM exploration block shows a succession of sandstones, siltstone-mudstone, coal and tonstein as the main lithological components (Figures 14-22). Selective core photographs are presented in the report to illustrate the considered important aspects of the lithological components in the Edson study area (Plates 1-12).

### 2.4.2 Sandstones

In the examined drillcores, the sandstone is lithic with 'salt-and-pepper' aspect, medium to fine-grained, poorly sorted and poorly to well-cemented, containing sub-angular lithic fragments (Plate 1, Figures A and B). The occurrence and characteristics of the sandstone units attest to the higher energy stage of each fluvial sequence within the Scollard-basal Paskapoo succession.

Similar to the Pembina exploration block, the thick sandstone channels in the Edson block represent an amalgamation of individual depositional units that produced stacked, widespread sand units of almost uniform composition (Plate 2, Figures A and B). In stacked sandstone units, several thin fining-upward units alternating with coarsening-upward units may occur. The sandstone overall has a massive texture (Plate 1, Figure A). Simple sets of sedimentary structures dominated by planar stratification or low-angle (Plate 2, Figure A, to the top) tabular cross-stratification are rarely observed. Coarser sediments such as coarse sandstones or fine conglomerates appear to be more frequent in the Edson block than in the Pembina area (Pana, 2007), but they represent thin intervals at the centimetre scale (Plate 1, Figures G and H). Locally, small-scale scour surfaces or cutbank planes (Plate 1, Figure K) are recorded. The sandstone matrix is represented by clay. Frequently, grouped or dispersed variably sized fragments of carbonized vegetal matter are observed in the sandstone units (Plate 1, Figures C–J).

Occasionally, in the examined drillcores, a few fractures have been observed in very fine sandstone units. Each of the rock sides along the fractures shows very fine layers of calcite deposits developed individually as stepped 'fish-scales' texture (Plate 5, Figures A-C).

### 2.4.3 Mudstone and Siltstone

Similar to the mudstone-siltstone units described in the Pembina block, the two lithological components within the Edson block are usually medium to dark brownish-grey, frequent slickensides, abundant carbonized vegetal debris and root traces. The observed soil structures and root traces lead to the interpretation of particular mudstone-siltstone intervals as paleosols.

Generally, two or three thin paleosol units of an approximately 1–2 m individual thickness have been recognized in every cycle. Every recognizable unit can be associated to a stage of pedogenesis (Plate 3, Figure B). The lower unit is usually massive, structureless, light to medium grey or brownish-grey with no root traces or vegetal debris and is interpreted as an incipient stage of pedogenesis; the middle unit contains rare root traces, is medium to dark brownish-grey in colour (Plate 3, Figure A), and occasionally contains carbonized vegetal debris and slickensides. The top-unit is considered the mature paleosol unit. Commonly, the upper unit has a darker brownish-grey colour, multiple root-traces, frequent slickensides, and is commonly overlaid by coal strata (Plate 3, Figure C). The recognizable paleosol profile in each of the examined drillcores proves the lateral distribution of the paleosol series within the Scollard sequences described now in the Edson block and recently in the Pembina coal sub-basin (Pana, 2007).

Slickensides represent the distinctive type of structure for mature paleosol units. The slickensides were recognized and initially described in the Scollard succession in the examined drillcores in the Pembina CBM exploration block (Pana, 2007). Easy to recognize, they originated in soil peds formed initially by the disruption (swelling and shrinking associated with wetting and drying) of relict laminar clay bedding on top of an impermeable layer of soil. The disruption can be caused in some instances by the presence of kaolin aggregates, which absorb less water and thus have lower plasticity index, lower liquid limits and less shrinkage when drying from a wet state than the surrounding smectite-rich layers (Wright, 1992). The resulting “lentil peds” are thus separated by slickensides (Krishna and Perumal, 1948, *in* Wright, 1992). Based on the presence of the slickensides within the top paleosol units in the Edson block, the original soil units are assumed rich in smectite (Plate 4, Figures A1, A2 and B). The paleosol slickensides present the characteristic 'soapy' lustre (Plate 4, Figure A2).

Grey to dark brownish-grey paleosol colour indicates reducing and wet soil units, which correspond to waterlogged conditions favourable to the peat-forming environments (Plate 3, Figures B–C and Plate 4, Figure A).

Paleosol units in the Edson block represent thicker strata (~3m) than in the Pembina block; however, they are too thin and difficult to recognize on the geophysical log record without core examination.

The coal-mudstone contact, when mudstone is present in small lenses or very thin beds, <1–2 cm, usually presents dense calcite infillings into the adjacent coal. In most of the cases, the infilling interval is lenticular in shape with a “spider-web” fine network aspect. The fine network of calcite infillings extends maximum 5 cm into the coal and shows a different pattern of coal fractures from the general vertical orthogonal coal-cleat system within the same coal core interval. This different aspect suggests an infilling process prior to the cleats genesis and it may be contemporaneous to the early sediment compaction process (Plate 11, Figure F).

### 2.4.4 Coal

Lateral and vertical distributions of the coal lithotypes in the Edson CBM exploration block reflect the original peat plant association and the record of the physical and chemical conditions during peat development.

In this report, the coal strata are macroscopically described based on drillcore examination and on geophysical log interpretation.

The coal core description followed the Australian coal lithotypes divisions (Table 1). The Ardley coals in the Edson block are in the range of 'bright' to 'dull coal' lithotypes (Plate 6–10). In the Edson block, the dominant category is 'banded coal' (Plates 6 and 7) followed by 'banded bright' coal (Plate 8 and 10) and 'banded dull' coal (Plate 6, Figures C and D). In the examined drillcores the coal subcategories, such as 'coaly shale' or 'shaly coal' (Plate 12, Figures A, B and D), do not represent a frequent component of the organic-rich strata. 'Coaly shale' and 'shaly coal' categories commonly occur as thin and discontinuous intervals (0.10–0.20 m) within the coal seams or at the top or base of the coal seams, usually too thin to be recorded by the geophysical logs.

**Table 1. Lithotype correlation table (summarized after Bustin et al., 1983).**

| Divisions after Stopes | Divisions used in Australia | Macroscopic description |
|---|---|---|
| Vitrain | Bright coal | <10% dull |
|  | Banded bright coal | 10–40% dull |
| Clarain | Banded coal | 40–60% dull |
|  | Banded dull coal | 10–40% bright |
| Durain | Dull coal | <10% bright |
| Fusain | Fibrous coal |  |

Another important criterion in coal description is the presence and the particularities of the coal cleat systems. The natural system of vertical extensional fractures consisting of two orthogonal sets, both normal to bedding, depends upon the coal rank, lithotypes, bed thickness and stress regime. The dominant fracture set makes the 'face-cleat' and it is characterized by continuity and by the approximately perpendicular orientation to the deformation front.

The examined coal core intervals show the dominance of the banded coal with vertical changes (in range of centimetres) to bright or dull coal (Plates 6–10). In the coal lithotypes with reduced ash content such as 'banded bright' coal or 'banded coal' strata (Plate 6, Figure E, Plate 7, Figures A, D and E, Plate 11, Figures A–E and G–I), the fracture system is well developed (~1cm spacing or less). Dull coal and banded dull coal strata have a less developed face-cleat system and the space between the consecutive cleats represents more than 1 centimetre (Plate 11, Figures G and H). Most of the examined coal intervals present a strong face cleat set that generates the overall aspect of sliced coal along an approximate vertical plan (Plates 6–10).

Locally, the cleat apertures are obstructed by calcitic infillings. In the Edson block, the examined cores show calcite infillings along the cleats systems as local and/or discontinuous (Plate 11, Figures B, C–F). The majority of coal seams is free of calcitic infillings at the macroscopic scale (Plate 6–10 and Plate 11 Figures A, D and G–I).

In some intervals of the examined cores, the coal strata have preserved parts of the original wood structure (Plate 7, Figure E, Plate 8, Figures A–C, Plate 9, Figure D, Plate 10, Figures A and B). Rarely, granules of amber are also observed attesting to the contribution of conifers based on the resin component in the decomposed vegetal mass (Plate 6, Figure E and Plate 10, Figure C).

The coal lithotype description using the geophysical log signature has been added to the database. The complementary gamma-ray, neutron and density log records are sensitive to major fluctuations in coal mineral matter content. The resolution of the geophysical log interpretation is generic, but allowed separation into layers thicker than 0.33 m of low and high ash content within the organic components. The generic coal sub-categories identified on the geophysical log are:

- clean coal (60%–80% organic matter as bright, banded, dull and fibrous coal).
- shaly coal (~60% organic matter as considerable coal debris or individual thin bands in clay or silt)
- coaly shale (~40% organic matter finely dispersed or agglomerated in bands).

Some of the macroscopically visible layers of mineral matter that originated in airfall tuffs display a relative lateral continuity in the Edson block. Where they are present, they become an integral part of the vertical lithological profile of each coal subzone (Plate 12, Figures A–F). The tonstein thin lenses, or strata, represent the local seals of the coal subzones and the markers used for the regional stratigraphic correlation.

Vertical and lateral variability of the coal seam characteristics of each of the Ardley coal subzones on the geophysical logs makes it difficult to find a typical “coal vertical profile” for the Edson sub-basin.

### 2.4.5 Tonstein

In the Edson CBM exploration block, tonstein occurs as thin layers associated mainly with the coal seams (Plate 12, Figures A–F). Bohor and Triplehorn (1993) have shown that tonstein represents an alteration product of volcanic ash that has fallen into an acidic environment, such as a coal swamp or inland waterlogged area. Similar to the Pembina block, the thin tonstein beds in the Edson study area occasionally contain detrital and carbonaceous material (Plate 12, Figure F). They occur predominately in intimate relationship with the coal seams (at the top, at the base or between coal layers). Under advanced diagenesis, the tonstein beds contain predominately kaolinite. The colour is generally white, occasionally with very light nuances of yellow, pink, blue or green (Plate 12, Figures A, D and F).

Some of the tonstein beds are interbedded with mudstone and siltstone and generated thicker paleosol units. On the geophysical logs, the layers of tonstein are recorded by abrupt deflection to the right (high API values, usually off-scale) of gamma ray response simultaneously with an abrupt low induction signature.

## 2.5 Edson Coal Sub-Basin Sequence Stratigraphic Model

A better prediction of the CBM production and reservoir characteristics in the Edson coal sub-basin begins in essence, with deciphering the fluvial architecture as coal genetic sequences. Usually, the most realistic reservoir models are the result of the deciphered depositional architecture because they create the stratigraphic framework for quantitative estimates of reservoir parameters.

The stratigraphic model considered in this study to assist in the Edson CBM exploration block characterization is similar to the model documented in the Pembina coal sub-basin (Figure 41) (Pana, 2007). The Pembina sequence stratigraphic model was compared with the Edson sedimentological characteristics and then incorporated to define sequences within the northern coal sub-basin (Figure 41).

The regional sequence stratigraphic model of the Scollard Formation proposed in the Pembina block (Pana, 2007) was defined by the geometry of the sandstone channels, subaerial unconformities and lateral continuity of the correlatable markers (Figure 41). Coal strata occupy specific positions within the genetic sequences of the Scollard Formation and represent reference horizons for the uppermost Cretaceous-Tertiary sequence analysis in the Alberta foreland basin.

In the Edson coal sub-basin, similar to the major lithological components described in the Pembina sub-basin, the lithological succession is made up of sandstone, mudstone-siltstone, coal and tonstein. Also, the relative stratigraphic position of the successive lithological units shows a distinctive cyclic succession from sandstone (fluvial channels) to mudstone-siltstone (paleosols units) to coals (swamps), which represents comparable sedimentological response to similar tectonic and climatic factors as allogenic controls. The regional correlation framework has used the correlatable tonstein markers located at the top and base of the Edson coal subzones as selected time lines.

During the late Maastrichtian-early Paleocene, weak cycles of subsidence and uplift superimposed on a long-term humid climatic background led to the development of fluvial cyclicity in the Scollard Formation deposits. Five major cycles (C1–C5) had been recognized in the Pembina and Edson coal sub-basins, consisting of repetitive successions of fluvial sequences separated by subaerial intra-formational unconformities (Figure 41). In the Edson block, the subaerial unconformities are marked locally by fluvial incisions, sediment bypass, and by extensive paleosol units associated with coal strata. The subaerial unconformities can thus be traced at the top of the paleosol horizons or coal strata where they are present, and considered in both coal sub-basins as sequence boundaries (Figure 41).

Generally, the deposition of the Scollard clastic succession was mainly controlled by the foreland drainage systems. Each stratigraphic sequence represents the response to a first stage of thrusting in the adjacent orogen accompanied by flexural subsidence in the foredeep. The next stage was associated with isostatic rebound, and generated sequence boundaries related to the timing of fluvial aggradation. The intensity of the tectonic pulses was different from one cycle to another. Source area tectonism controlled the topographic gradients of the fluvial landscape during uplift. The differential subsidence controlled the sedimentary processes during the orogenic unloading stages. The fining-upward profile displayed by each of Scollard foreland fluvial sequences reflects the change in fluvial pattern from high to low energy.

The upper four cycles of the Scollard succession are capped by coals. Coal deposition was thus closely tied to the tectonic, structural and depositional settings, because peat accumulation and preservation as coal require a delicate balance of vegetal mass accumulation, subsidence rate and optimum level of water-table with minimal clastic sediment influx (Reinhardt and Sigleo, 1988).

Following the relative tectonic stability in the source area during coal deposition, the last stage of renewed tectonism (thrusting) during middle and upper Paleocene resulted in the high-energy, thick clastic deposits of the Paskapoo Formation.

Climate and tectonic changes modified the loading index of the river systems. The excess of sediment load during massive rainfalls combined with the uplifting of the source area, led to a considerable increase of cyclic discharge. Climate interpretation in the Scollard sedimentary succession was mainly based on vegetation, paleosols and syn-diagenetic minerals. Rainfall and temperature together controlled the amount and type of vegetation.

Different settings of the humid climate during little or no sediment influx were also responsible for the high growth rate of plants. The Upper Scollard coal strata are the result of the abundance of botanical colonies characterized by gymnosperms in decline, ascending angiosperms, deciduous trees and shrubs (Demchuck and Hills, 1991).

The pedogenesis associated with the peat-forming conditions were dependent upon a humid environment with pH slightly acidic (Wright, 1992). The paleosol sequences and the adjacent coal strata document the stratigraphic breaks in fluvial associated facies. The association of paleosols with unconformities requires long term landscape stability in a sedimentary regime, characterized by almost non-deposition and non-erosion, which allow the parental material to go through the pedogenesis processes (Wright, 1992). The final stage of each of the upper Scollard cycles is marked by coal accumulation, which indicates a more mature stage of pedogenesis when the paleosols are populated by plant ecosystems.

The sequence stratigraphic model described in the Pembina block (Figure 41, left) consists of four fluvial cycles caped by coal strata. Their names Mynheer, Silkstone, Arbour and Val D'Or represent names borrowed from the foothills informal nomenclature (Dawson et al., 2000). In the Edson block, the four coal subzone names used are 'N,' 'Ml,' 'Mu' and 'S'. The names represent arbitrary codes with no stratigraphic implications (Langenberg et al., 2006). Identical codes for the coal seams were also used in coal data record.

Correlative table of the major coal subunits within the Ardley Coal Zone

| | ***Pembina sub-basin*** | | ***Edson sub-basin*** |
|---|---|---|---|
| • | 'Mynheer' coal subzone | — | 'N' coal subzone |
| • | 'Silkstone' coal subzone | — | 'ML' coal subzone |
| • | 'Arbour' coal subzone | — | 'MU' coal subzone |
| • | 'Val D'Or' coal subzone | — | 'S' coal subzone |

In the Edson block, the succession of lithological components in every cycle shows an initial stage characterized by higher energy at the base, marked by channel sandstones, followed by a change in the energy level recorded as finer or fining-upward units accompanied by pedogenesis sequences which are finally capped by coal strata. The intensity of the fluvial drainage processes varies in the two coal sub-basins (Figure 41). For instance, cycles 3 and 5 are weaker than cycles C1, C2 and C4 in the Pembina block. In the Edson sub-basin, all five cycles have a strong signature of the drainage systems. Overall, all the Scollard cycles are weaker than the basal clastic cycle (Haynes Member) of the Paskapoo Formation. Miall (1985) demonstrated the direct relationship between the higher level of energy and the greater thickness, grain size and the areal extent of the sandstone channels. Distally, the Ardley fluvial cycles become thinner and can be exclusively characterized by paleosol units capped by coals.

Cycle C1, represented by the basal sandstone channels of the Scollard Formation in the Edson block, is capped at the top by a thin layer of tonstein defined in the sequence stratigraphic model as 'lower Scollard marker' (Figure 41). The marker is well preserved in some locations, especially in the northern and in the western parts of the Edson block as captured in the associated database. Locally, at the base of the sequence C1, thin and isolated coal seams are observed mainly in the southwest part of the study area (Figure 15, well 00/15-28-059-22W5/0 and Figure 22, well 00/02-22-052-22W5/0). They are not part of the Ardley Coal Zone and have no economic importance.

Each of the last four major fluvial cycles or fluvial genetic units, regionally recognizable within the upper part of the Scollard Formation in the Pembina and Edson coal sub-basins, is capped by coal strata and considered in this report as equivalent to cycles C2, C3, C4, and C5.

Cycle C2 represents the facies association that generated the 'N' coal subzone. This sequence has a better distribution south of township 59 (Figures 20–22). The 'N' coal subzone represents only 2–3 thin and discontinuous coal seams.

Cycle C3 is related to the 'Ml' coal subzone and can be easier identified where the underlying 'N' coal subzone is present (Figures 16 and 19–21). It represents a succession of stacked channels, paleosol units and coal seams at the top.

The C4 cycle represents the response to the genetic conditions that generated the 'Mu' coal subzone in the Edson block. The cycle is well represented in the central and the northern part of the sub-basin (Figures 16–17 and 19–21) by stacked channels, paleosol units and coal seams.

The uppermost cycle, C5, represents the final stage of coal deposition in the lower Paleocene and it is genetically associated with the 'S' coal subzone in the Edson block. Only three of the stratigraphic cross-sections A-A,' K-K' and N-N' (Figures 15, 21 and 22) show the complete presence of the cycle C5. The unit is partially removed from the northeast half of the basin due to post-sedimentary erosion. The present-day geometry, strongly affected by the post-Scollard erosion, was induced by the structural re-adjustments. Cycle 5 has a very weak signature of the drainage processes in the Pembina block, (except in the proximal area to the foothills where the sandstone channels are present) and a much stronger energy in the Edson block. The preserved 'S' clastic succession can be interpreted as an alluvial fan system (Figure 22). The 'S' sequence consists mainly of sandstone sheets and coal seams.

The Edson block presents the main set of five sequences defined in the Pembina block. Difficulties in interpreting the sequences can occur if the wells are considered independently neglecting the regional correlation framework especially due to the erosional or no-deposition aspects combined with post-Scollard structural re-arrangements.

A comparison of the stratigraphic sequences in both coal sub-basins leads to the observation that within the Scollard Formation there are regionally mappable units bounded by extensive intra-formational unconformities corresponding to five fluvial depositional cycles. The unconformities correspond to five short quiescence tectonic stages of no thrusting in the adjacent orogene. Every cycle reflects a stage of tectonic uplift followed by a time interval of tectonic quiescence, accompanied by isostatic rebound in the foredeep. Emphasizing the complexity and variability of the Scollard fluvial succession and the difficulties in predicting fluvial architecture in the subsurface, this study presents a conceptual approach to the understanding of fluvial systems in nonmarine environments in developing realistic solutions for coal reservoir geometry in the Edson area.

## 2.6 Coal Depositional Model in the Edson Sub-Basin

The lateral continuity of the Ardley coal seams in the Edson block over an area of approximately 1000 km$^2$ is remarkably. The relative stratigraphic position of the successive lithological units shows a distinctive cyclic succession from sandstones to mudstone-siltstone (paleosols) and coal strata (Figure 41). No sandstone channels contemporaneous to the coal units are identified in the study area (Figure 42).

In the Edson block, the prime factor influencing the extensive distribution of the coal peat-forming environments was the topographic surface and the nature of the substrate on which it evolved. Similar to the Pembina coal sub-basin, the topographic surface on which the peat environment was favoured in the Edson block was almost flat and quasi-horizontal over a wide area allowing a consistent distribution of the peat development each time. The nature of the substrate imposed the relocation of the depocentre of the swamp mainly due to the differential compaction of the underlying sediments. A higher rate of compaction was found in clay-rich substrate (including peat-swamp sediments) than in the sandy substrate.

The preliminary paleo-reconstruction model in the Edson area suggests that the favourable conditions for peat-development had been met four times in the depositional record of the northern Ardley coal sub-basin. A synergic effect of low-topographic gradient, water-saturated mudstone and regular rain-falls seems to lead cyclically to peat-swamp environmental conditions within the upper part of the Scollard Formation. Consistent flat substrate surface and low topographic gradient are inferred from the absence of any relict drainage systems contemporaneous to the coal strata in the study area. In addition, during the peat forming time the sediment influx was low or absent due to the tectonic quiescence during the flexural rebounding stage. The water level was maintained by the underlying water-saturated paleosol mudstone-siltstone units. The vegetal growth was stimulated by the humid climate and possibly by volcanic thin layers considered as fertile soils. The source of water is considered to be rainfall in the absence of any indication of contemporaneous fluvial channels to the peat environments in the study area. The water table in the peat area remained at or near the ground surface, with no pronounced seasonal lowering. A low pH close to 5 of the peat-swamp waters was critical, because total degradation of the vegetal matter results at higher pH values (Retallack, 1990). Sequentially renewed tectonic uplift in the sediment source area on a humid climatic background imposed changes in the paleoenvironment energy from low energy during the peat stage—interpreted as the last stage of the previous sequence or cycle—to high energy associated with the fluvial channels, which represent the first stage of the next cycle or sequence. The channels eroded parts of the previous coal-peat deposits. The vertical association of channel deposits, resulting thick successions of stacked channels, are difficult to separate as it is shown in the wells 00/05-01-52-24W5, 00/02-22-052-22W, 00/01-25-052-14W5 (N-N' cross-section, Figure 22), 00/08-19-061-22W5, 00/11-32-061-14W5( B-B' cross-section, Figure 19) and 00/15-28-059-22W5), (E-E' cross-section, Figure 22).

The set of four west-east stratigraphic cross-sections B-B,' E-E,' K-K' and N-N' (Figures 19, 20, 21. 22) with the top of the Battle Formation as Datum shows a severe change in thickness and in coal distribution from north to south. The B-B' cross-section (Figure 19) presents almost a parallel distribution of the coal subzones of 'N,' 'Ml' and 'Mu' and of the inter-coal subzones channels. The 'Ml' and 'N' coal subzones are separated by a small inter-coal interval to the west that gradually increases in thickness to 50 m easterly. The 'S' coal subzone is absent in the extreme north part of the cross-section.

The E-E' stratigraphic cross-section (Figure 20) through the central Edson block succession shows the presence of all four coal subzones: 'S,' 'Mu,' 'Ml' and 'N.' The general distribution depicts a gradual thinning of the entire succession to the east from more than 200 m to less than 40 m. The 'S' coal subzone pinches out between range 22 and 21, west of the 5th Meridian, township 59. A thin but wide 'Mu-Ml' channel assemblage is illustrated in the central part of the cross-section. A thicker part of the 'Ml-N' channel separates the two successive coal subzones 'Ml" and 'N' respectively, but it pinches out easterly within township 59, range 15 west of the 5th Meridian, enabling the 'Ml' and 'N' coal subzones to merge.

The K-K' stratigraphic cross-section (Figure 21) depicts a significant change in the Scollard Formation thickness along approximately 100 km distance, from about 250 m in the west to less than 100 m to the east**.** All four coal subzones are present but a wide variability in coal subzone thickness is illustrated. Also, the recorded number of coal seams in each of the coal subzone is variable. The Ardley inter-coal subzone channels vary in thickness and distribution. West of township 55, range 22 west of the 5th Meridian, all four coal subzones are present, but very thin (1-3 m including the inter-coal seams partitions). East of township 55, range 22, west of the 5th Meridian, the 'Mu' coal subzone becomes the thickest coal subzone with multiple coal seams, which further east of township 56, range 15, west of the 5th Meridian thin before pinching out. Overall, the coal subzones thickness migrates from east to west. The inter-coal subzones channels depict a similar east-west migration.

The most southerly west-east stratigraphic cross-section, N-N,' (Figure 22) shows an increase in Scollard succession thickness in the central part. In addition, it shows that the basal Paskapoo channels eroded deeply into the Ardley Coal Zone to the east. The erosion affects the 'S' coal subzone to the total absence, east of township 52, range 15 west of the 5th Meridian. The 'Mu' coal subzone pinches out also to the east due to the 'S-Mu' channels erosion, and it is preserved only in the central part. The 'N' coal subzone becomes thin and discontinuous whereas the 'Ml' coal subzone records multiple splits. The channels migration is well shown by this stratigraphic cross-section. For instance, the 'S-Mu' fan assemblage is thicker to the west and the 'Mu-Ml' channels cover only the central area, whereas the 'Ml-N' channels extend to the east.

The next set of four analyzed north-south stratigraphic cross-sections A-A,' G-G,' F-F' and I-I' intersect at key points the west-east cross-sections described above (Figures 15–18). The A-A' stratigraphic cross-section (Figure 15) represents the most westerly profile and shows the significant north-south increase in thickness of the Scollard Formation from approximately 70 to 270 m. The coal subzones present are: 'Ml,' 'Mu' and 'S.' The thin 'Ml' coal subzone in the south pinches-out between the range 22 and 23, west of the 5th Meridian, along township 61. The 'Mu' coal subzone shows a more packed presence to the north, but splits to the south into three independent coal seams. The 'S' coal subzone shows continuity in the south and the central part of the cross-section but pinches-out between the townships 60 and 61, ranges 22 and 23, west of the 5th Meridian. The thin 'Ml-Mu' channels assemblage pinches-out together with the 'Ml' coal subzone to the north. The 'S-Mu' alluvial fan assemblage is present to the south as a thick (up to 50 m) package of sandstones showing a major reduction of thickness in the central part of the cross-section and a complete absence to the north. This cross-section also shows an abrupt change in thickness of the lower coal-barren member of the Scollard Formation.

The north-south I-I' stratigraphic cross-section (Figure 16) represents the middle part of the study area. The cross-section depicts a gradual change in Scollard Formation thickness from the north to the south. It also shows a continuing migration of the thickest coal intervals to the south. The associated channels assemblages illustrate a regional distribution with a slight migration of the greatest thickness to the south. The 'N' coal subzone has a quasi-uniform distribution represented by a fairly consistent thin coal interval. The 'Ml' coal subzone appears to be thicker in the central area and pinches-out north of township 60, range 19 west of the 5th Meridian. The 'Mu' coal subunit is the thickest coal subzone illustrated by the cross-section covering consistently the entire area except south of township 54, range 21 west of the 5th Meridian where it abruptly pinches out. The uppermost coal subzone is 'S' and it records a severe erosion in the northern part due to the Paskapoo channels.

The F-F' stratigraphic cross-section (Figure 17) shows a more gradual north-south change of the Scollard Formation thickness and of the coal subzones distribution. The Scollard Formation thickness ranges from approximately 70 m to the north to about 210 m to the south. To the north, the coal subzones represent individual coal units separated by well distributed inter coal subzones channels. The coal subzones correspond to 'N,' 'Ml' and 'Mu' coal subunits. In the central part of the cross-section, the 'Ml' and the 'N' coal subzones are separated by only a very thin mudstone interval of 1–2 m thickness. To the north and to the south from the central area, both coal subzones become separated again by the sandstone channels. The 'Ml-N' channel interval is thicker to the south (~20 m) along with the 'N' coal subzone multiple splits. In the same direction, the 'Ml' coal subzone thins and the 'Mu' coal subunit splits significantly into two major coal seams separated by channels of more than 20 m thickness.

The most eastern north-south stratigraphic cross-section interpreted is G-G' (Figure 18). The cross-section shows a discontinuous coal distribution mainly due to a lack of shallow geophysical log records. Analysing the available log displays the recognized coal subzones, 'N,' 'Ml' and 'Mu.' The 'N' and 'Ml' coal subzones are present mainly in the central part of the cross-section. The 'Mu' coal subzone seems to be continuously present assuming that the interruptions are caused by the lack of the geophysical log information. The 'Ml-N' channels are relatively thin in the central area and pinch-out to the north, whereas to the south it coalesces with the overlying 'Mu-Ml' channel assemblage. The basal Paskapoo channels are in direct contact with the 'Mu' coal subzone due to the total absence of the 'S' coal subzone.

# 3 Ardley Coal Zone Reservoir Characterization

The concept of "coal system" (Warwick, 2006) considers coal as unconventional type of reservoir defined as an anisotropic, non-homogenous organic rock with respect to physical structure and chemical content. The unique characteristic of coal rock is the dual role of source and reservoir of hydrocarbons. The amount of gas generated, stored and expelled can be estimated from general geological models. Lateral migration of gas is limited by the general low or very low permeability matrix (if lack of fractures) and laterally, coal anisotropy and coal discontinuities can induce even more restriction eventually to the total partition. Similar to the conventional reservoirs, vertical gas migration outside of coal reservoir entity can be limited by sealing layers of rocks such as shale and mudstone, predictable from the depositional sequences. The updip gas migration within adjacent sandstones can be favoured by local erosion or non-deposition of sealing layers, nevertheless considerable amount of gas have remained in the coal strata as intimately associated to the coal-reservoir matrix. This particularity allows extending the application of the term 'coal reservoir' furthermore to the cases when coal strata are not completely sealed.

## 3.1 Reservoir Geometry

In the Edson block, coal reservoir geometry has been deciphered through the sequence stratigraphic model (Figure 41) and the set of north-south and west-east stratigraphic cross-sections (Figures 15–18).

### 3.1.1 Internal Structure

The Ardley Coal Zone in the Edson block includes the following coal subzones: 'N,' 'Ml,' 'Mu' and 'S,' in order from the base of the Ardley Coal Zone. The coal subunits represent groups of coal seams genetically related and spatially occupying neighbouring positions. Each coal subzone can be considered as an independent coal reservoir having particular extent, specific coal properties, and being vertically separated by coarse or/and fine clastic units.

The Ardley coal subzones are generally thin and laterally continuous (Figures 15–18). The coal subunits can be represented by one individual coal seam or multiple coal seams packed together or separated by thinner or thicker coal-barren intervals. The number and the thickness of coal seams and the splits or pinch-outs depend upon the depositional characteristics.

#### 3.1.1.1 The 'N' Coal Subzone Geometry

The 'N' coal subzone is the lowest coal unit and represents the debut of the peat-forming conditions in the northern Scollard sub-basin. The study area presents a central-southeast distribution, which suggests that the coal basin extends southerly beyond the study area. The maximum thickness is 51.4 m in the extreme southeast part of the map (Figure 43) corresponding to the depocentre of the peat environment. Within the western digitations the thickness reaches 26 m. Inconsistent lateral extent and high variability of coal quality are the main characteristics of the 'N' coal subzone. The lateral continuity and thickness increase towards the north and east. To the west, the 'N' coal subzone is absent. The coal cumulative thickness can be greater than 5–6 m, up to 13.8 m (Figure 44) and coincides with the maximum number of coal seams of 13 (Figure 45).

#### 3.1.1.2 The 'Ml' Coal Subzone Geometry

The 'Ml' coal subzone isopach map (Figure 46) shows a change in thickness and coal distribution from the central part to the south-central part of the study area. The depocentre of peat environment can be interpreted based on the thickest area of the 'Ml' coal subunit, which is shown by the isopach map in the southwest-central part of the map continuing further south beyond the boundary of the study area. The 'Ml' coals commonly, are very thin, less than 1 m, or absent in isolated areas in the north, northeast and east-central. The 'Ml' coal subzone is commonly 3 to 6 m thick but locally it can reach 19–34 m due to discontinuous distribution of additional coal seams. The cumulative thickness of coal seams shows a distribution of 1 to 3 m with local maximums of 9 m (Figure 47), which corresponds to the increase of the number of coal seams from 3 to 6–8 (Figure 48).

#### 3.1.1.3 The 'Mu' Coal Subzone Geometry

The maximum thickness of the 'Mu' coal zone is 27 m due to local occurrence of multiple coal seams (Figure 49). The most common thickness is 6–11 m. The 'Mu' coal seams pinch-out or are eroded to the east and southeast, but the trend distribution is west-east. The greatest thickness is reached in the central part of the study area and corresponds to the depocentre of the peat environment. Coal cumulative thickness depicts similar distribution of up to 11.3 m in the central part of the study area (Figure 50). The general thickness interval ranges between 3–6 m. The maximum number of 14 coal seams is located in the same area of maximum thickness (Figure 51). The predominant number of coal seams is 4–6.

#### 3.1.1.4 The 'S' Coal Subzone Geometry

The 'S' coal subzone records the last period of peat-forming conditions within the lower Paleocene in the Edson Block. The 'S' unit depicts a distribution limited to the southwestern half of the study area (Figure 52). The thickness is generally small—1.7 to 4 m. Locally, it can reach a maximum thickness of 15 m. In the northeastern half of the map, the 'S' subzone is absent due to erosion or no deposition. The coal cumulative thickness shows a similar distribution to the total thickness—a local increase in coal component up to 5.9 m occurs in the south-central part of the study area (Figure 53)—but the most frequent coal cumulative thickness is 1 to 3 m. The maximum number of coal seams is 5, but most commonly, only 2 coal seams are recorded (Figure 54).

### 3.1.2 Reservoir Seals

Sealing is an important criterion in defining the coal units as reservoir entities. In the Edson coal sub-basin, almost all the coal subzones are generally bounded by thin tonstein beds and/or mudstone-siltstone strata. Locally, the overlying sandstone channels such as the Paskapoo basal channels, 'S-Mu' channels, 'Mu-Ml' and 'Ml-N' channels eroded totally or only superficially, the top of the underlying coal subzones and potentially altered the reservoir conditions of the coal subzones. The erosion effects may include only parts of the coal seams or the coal subzone entirely as shown by the 'S' coal subzone including the underlying sandstones. Thus, some of the initial reservoir characteristics of the coal subzones have been modified during geological time. Gas migration is generally limited by the low or very low permeability and by anisotropic properties of coal beds. Lateral discontinuities of the coal strata can lead to total separation into contemporaneous individual reservoir entities. The direct stratigraphic contact with the overlying or underlying sandstone channels, which are considered potential conventional reservoirs, may allow vertical connectivity among the coal and sandstone reservoir units. The vertical connectivity is amplified by local fractures related to the end of the Laramide Orogeny (Plate 12, Figures A–D).

## 3.2 Coal Properties

Coal properties refer to coal quality (ash content) and coal rank. The potential of high gas content is directly controlled by coal quality or maceral composition and ash content, and by coal rank as a result of burial history. In addition, coal permeability inferred by coal cleat systems is another important criterion associated to the gas production estimation.

### 3.2.1 Coal Quality (Ash Content)

The Pembina study (Pana, 2007) methodology has been used for the Edson block. The distinction among the sub-categories of generic term of "coal" reflecting the variability of the organic content vs. ash content such as 'shaly coal', 'coaly shale' and 'clean coal' itself had been recorded firstly by the detailed description of drillcores. The second step consisted of calibrating the geophysical log response and setting up an estimate of ash content relative to the coal sub-categories, based on gamma ray and complementary density readings compared with the deep induction record (coals <1.7 g/cc, shaly coals 1.7–1.9 g/cc and coaly shale 1.9–2.1 g/cc). In this way, the major source of coal and other lithological data resulted from the log interpretation. Thus, the new coal data set for the Edson CBM exploration block integrates the descriptive coal sub-categories that allow a more detail interpretation.

The variability in ash content in coal seams is the result of internal and external factors. The most important factor is the sediment supply. Depending on the quantity, the sediment supply induces contamination of organic matter with inorganic partitions, and can lead to a split of the coal seams. In the Edson block, the most obvious internal changes within the coal subzones represent coal splits into multiple coal seams that are related to a greater sediment input. The margins of the peat-forming environment are typically subject to an enrichment in inorganic content, generating more splits than in the central part as the N-N' and K-K' and F-F' structural cross-sections illustrate (Figures 17, 21 and 22).

The variability of the 'clean coal' distribution within each coal subzone is illustrated by a set of percentage maps (Figures 55–59). The presence of exclusive 'clean coal' represented here by 'coal' and 'shaly coal' is considered 100% and is shown on the maps as blue squares. Any identified 'coaly shale' beds within the same coal subzone reduces the percentage. On the maps, the locations with smaller content of organic matter due to the presence of coaly shale are shown as a blue square followed by the percentage, which is always smaller than the ideal of 100%.

Coal percentage distribution map of the 'N' coal subzone records a lower content of 'clean coal' to the west and to the east (Figure 55) where the margins of the peat environment can be delineated (Figure 43). In addition, 'Ml' coal sub-zone records only three locations where the 'clean coal' percentage is affected by the presence of the 'coaly shale' (Figure 56) to the margins of the peat (Figure 46). The 'Mu' coal subzone percentage map (Figure 57) shows a very small decrease of the 'clean coal' percentage randomly dispersed. The distribution map of the 'S' clean coal (Figure 59) shows lesser amounts of “clean coal” mainly in the central area of the coal distribution (Figure 52). The total Ardley Coal Zone percentage map (Figure 59) indicates a preferred distribution of the smaller values than 100% to the west that can be explained by the proximity to the sediment source area and, in most instances, indicates the western limit of the successive peat environments.

The coal percentage distribution maps (Figure 56, 56, 57, 58) show that the 'N' and 'S' coal subzones have higher coaly shale content than the 'Ml' and 'Mu' coal subzones. The 'N' clean coal vs. coaly shale distribution map shows a range of 61–100%. Values lower than 100% are recorded in several locations. The 'Ml' coal subzone records infrequently show lower values of 64–94%. The 'Mu' shows a minimum of 88% and the 'S' coal subzone of 37–77%. Locally, the percentage is 38% or 67%.

### 3.2.2 Coal Rank and Burial History

#### 3.2.2.1 Coal Rank

In the study area, vitrinite reflectance measurements range between 0.52% and 0.63% Ro(ran), corresponding to a high-volatile bituminous C coal rank (Figures 60 and 61) within the onset of thermogenic gas generation (Rice, 1993). There is a group of lower vitrinite reflectance values of 0.52%–0.56% measured in the central part of the Edson basin with an increase of 0.63% to the west. The extreme southwest anomalous low value of 0.52%, which interrupts the consistency of the zonal distribution of the vitrinite reflectance, is not confirmed yet by other vitrinite measurements in the same area.

#### 3.2.2.2 Burial History

Burial history of the Ardley Coal Zone began with the deposition of the overlying Paskapoo clastics. Thick and coarse clastic deposits accumulated during the middle and upper Paleocene and overlaid the Scollard Formation. More than 1,600 m of sediments are believed have been deposited in the Alberta foreland basin (Nurkowski, 1984; Bustin, 1991) during the middle and upper Paleocene. Subsequently, an important part of this succession was removed by erosion after upper Paleocene. Today, the Paskapoo Formation is represented by a few metres thickness along the erosional edge and up to 836 m in the subsurface, close to the deformation front. Synchronous to the upper Paskapoo clastic deposition, a period of tectonic compression and uplift led to the deposition of stacked fluvial-channel sandstones (Pana, 2007). “The Triangle Zone” (LeDrew, 1997; Langenberg et al., 2002), southwest of the Edson block, shows that the latest displacement, which affected the Scollard and Paskapoo formations, took place sometime during middle and upper Paleocene. The thick clastic succession, which overlaid the Scollard Formation for a relatively short period, and the tectonic compression were possibly responsible for the coalification process of the Ardley coal strata.

## 3.3 Surface Lineaments Interpretation and Coal Fracture Pattern

Coal fracture systems or orthogonal systems of coal cleats are an important characteristic of the coal strata and important criterion in coal reservoir characterization. Variations in cleat attributes (orientation, abutting, continuity, spacing, lateral and vertical connectivity, infilling) govern coal permeability and regulate the fluid transport in coal and from coal to adjacent reservoirs.

The prediction of the cleat-system orientation is thus critical for coal permeability assessment. Tyler et al., (1993) have shown that cleat system orientation is predictable from models of simple-deformation foreland basins. In this report, the dominant cleat-pattern in the Ardley Coal Zone was interpreted from the surface structural lineaments on the Alberta digital elevation model (DEM) compared with the regional structural pattern and verified by the outcrop observations (Figure 62). As it is demonstrated in other coal basins, the more continuous type of coal fractures known as 'face cleat system' is inferred to be approximately perpendicular to the Cordilleran deformation front (Scott, 2001).

Analysis of the Alberta digital elevation model has led to the interpretation of some relevant surface lineaments. The regional map of the interpreted surface lineaments shows a north-south zonal distribution of the surface lineaments (Figure 62). The north compartment has multiple lineament systems, in contrast to the central and southern part of the Ardley basin that are dominated by a northwest-southeast system composed of two groups. The most frequent group has an azimuth of 335˚, parallel to the south-central segment of the deformation front and is distributed mainly in the central part of the Scollard basin, accompanied by the lineaments with a 300˚ azimuth, almost parallel to the deformation front. As the result of the interpretation of the major surface lineaments, the coal-face cleat system of the Ardley Coal Zone at the basin scale is inferred to be approximately 30º or almost perpendicular to the dominant regional deformation trend of 300º azimuth.

The interpretation of the surface lineaments at the regional scale (Figure 62) shows Edson CBM exploration block located in the north compartment, dominated by multiple lineaments system characterized by different orientations. An abrupt change in the lineaments pattern along the Athabasca River led to the separation of the Edson block in two areas: north of the Athabasca River, the section is dominated by a lineament system composed of $280^{0}$ and $30^{0}$ azimuth, in contrast to the southern section (south side of the Athabasca River), which is dominated by a $310^{0}$ and $60^{0}$ azimuth system (Figure 63). The central part of the study area corresponding to the abrupt change of the flow direction of the Athabasca River to the east, appears to be intersected by multiple trending systems of lineaments

(Figure 63). In this area, the coal seams may have multiple cleat systems, and a resulting increased permeability.

The estimated orientation of the coal-face cleat system is inferred from the major surface lineament system and is assumed to have a $30^0$ azimuth on the south side of the Athabasca River and $60^0$ on the north side of the Athabasca River. The predicted orientation of the coal face cleats of the Ardley Coal Zone in the Edson study area corresponds to the coal 'face cleat' orientation measured in the mine sides and outcrops (Campbell, 1979) and emphasis the potential occurrence of multiple coal cleat systems.

In addition, in the Edson exploration block the younger northwest-southeast structure inferred during post-Ardley Coal Zone deposition time (Figures 26, 27, 28, 29) might be responsible for amplifying the existing coal cleat systems and generating new fracture systems.

### 3.4 Reservoir Conditions

Reservoir conditions are inferred by hydraulic gradient, pressure and temperature regime. Several regional hydrogeologic studies have shown that the Scollard-Paskapoo succession can be considered an aquifer system (ie. Michael and Bachu, 2001; Bachu and Michael, 2002). The publicly available data of formation pressure, water chemical analysis and reservoir temperature for the Scollard and Paskapoo formations are very limited.

Scollard-Paskapoo aquifer characteristics can be summarized as the following: topographically driven, normal to slightly under-pressured and with low salinity content (Michael and Bachu, 2001; Bachu and Michael, 2002). The Scollard-Paskapoo aquifer is confined at the base by the thin layers of tonstein and mudstone of the Battle Formation. The vertical hydraulic communication within the Paskapoo-Scollard aquifer system is not restricted at the basin scale by any laterally consistent confining lithologic interval. However, discontinuous aquitards consisting of mudstone and tonstein beds can locally obstruct the vertical flow between sandstone aquifers (Pana, 2007). Overall, the hydraulic connectivity of the Scollard-Paskapoo system is not significantly impacted by these localized aquitards.

In the Edson exploration block, the Scollard and Paskapoo potentiometric surfaces show similar values and a northeast flow direction to the topographic low represented in the Edson block by the confluent basin of the Athabasca and McLeod rivers (Figures 64 and 65). Vertical connectivity is also amplified by the incidence of fractures generated during later structural adjustments.

## 4 Coal Tonnage and Gas-in-Place

Coal mass and gas-in-place (GIP) were calculated using the following formulas:

**mass = density x volume**

- in situ density = 1.44 g/cc (Beaton et al, 2002).
- volume of coal estimation resulted from the ArcMap GIS surface-volume application based on the coal cumulative thickness grid.

**GIP = volume x density x gas content/unit**

- gas content per unit in the Edson exploration block is between 3.25 and 3.75 $cm^3/g$ (Beaton et al, 2002) and the average is 3.50 $cm^3/g$.

The coal volume, coal mass and gas-in-place calculated for the Edson block, are shown in the following table and comparison chart:

| Coal subzones | Coal volume ($10^9$ $m^3$) | Coal mass ($10^9$ kg) | GIP ($10^9$ $m^3$) |
|---|---|---|---|
| "S" | 6 | 9 072 | 31 |
| "Mu" | 44 | 63 504 | 222 |
| "Ml" | 32 | 47 230 | 165 |
| "N" | 22 | 31 536 | 110 |
| Ardley—total | | | 528 |

The gas-in-place results shown in the previous table represent the most general estimates of gas content because important reservoir parameters such as: coal anisotropy, depth and reservoir pressure data are not included.

## 5 Coal-Sandstone Architecture and Reservoir Connectivity

The clastic succession of the Scollard-Paskapoo formations is described as an aquifer system (Bachu, 2004) consisting of lithological components with attributes of aquifers such as sandstone intervals and discontinuous mudstone and siltstone units considered with attributes of aquitards. Coal strata are also considered aquifers due to the coal fracture systems.

The interpretation of the Scollard-Paskapoo succession based on the sequence stratigraphic model in the Edson CBM exploration block provides an improved framework for correlation of the reservoir units. The Edson sequence stratigraphic model was set up to assist in the characterization of the coal and associated sandstone reservoirs, including the connectivity between them. The two types of reservoirs considered here, are the coal subzones (as unconventional type) and the adjacent fluvial sandstone channels of the Scollard Formation and of the lower part of the Paskapoo Formation (as conventional reservoirs). The Scollard stratigraphic succession shows an alternative position of the two types of reservoirs (Figure 41). In few locations the coal strata and the adjacent sandstone units are in direct stratigraphic contact due to specific paleo-environmental conditions (erosion or non-deposition). Both types of reservoir units have distinct facies, geometries and internal characteristics.

The succession of coal reservoirs within the Edson block consists of 'S,' 'Mu,' 'Ml' and 'N' coal subzones that can be characterized as small-scale anisotropic reservoirs, thin, laterally continuous and naturally fractured (cleated). The coal subzones are bounded by thin and relatively continuous tonstein beds in association with mudstone and siltstone strata.

The adjacent fluvial sandstone channels are considered potential conventional reservoirs. They represent the maximum sediment supply of each of the fluvial cycles. The channels succession recognized in the Edson CBM exploration block consists of the lower and upper channels of the lower part of the Scollard Formation followed by 'Ml-N,' 'Mu-Ml,' 'S-Mu' and basal Paskapoo channels. 'Ml-N,' 'Mu-Ml' and 'S-Mu' assign the sandstone channel intervals between two successive coal subzones. The examined drillcores have shown that the sandstone reservoir heterogeneity is mainly the result of the changes in grain-size, degree of sorting, amount of clay minerals, local diagenesis and additional tectonic fractures. Overall, the decrease in permeability corresponds to the fining-upward stage of the fluvial sequences when the depositional energy and sediment supply declined.

Occasionally, the overlaying sandstone channels eroded the sealing mudstone-siltstone associated with tonstein strata at the top of the coal seams, allowing the direct contact of the two types of reservoirs. The degree of connectivity between sandstones and coal strata varies considerably both vertically and laterally. In addition, the tectonic fractures observed in the examined cores and in outcrop amplify the potential inter-reservoir connectivity.

### 5.1 Sandstone Channels Geometry and their Relationships with Adjacent Coal Seams

One of the key components in defining the coal reservoir characteristics within the Edson coal sub-basin is the channel geometry and the proximity of the sandstone channels to the adjacent coal seams. Locally, in the Edson CBM exploration block, direct contact between the coal seams and the overlaying sandstone channels may allow the exchange of mobile phases. This observation may adjust in part the initial coal reservoir definition and may lead to the consideration of an interconnected coal-sandstone reservoir system in some degree.

The detailed mapping of the Scollard-Paskapoo sequences within the Edson study area yields an image of the 'fluvial channels' architecture (Figures 66-69). Vertical connectivity results from the strata architecture and the associated erosional processes. The variability of horizontal connectivity within the reservoir units depends upon the lateral continuity of the coal strata and the consistency of coal properties (rank, coal quality and fracture system) within the same coal bed. Thus, the permeability is strongly dependent on facies distribution.

The Scollard-basal Paskapoo succession can be subdivided into six architectural intervals and each assemblage contains channels with a particular geometry. In the Edson block there are five important channel intervals possibly connected to the coal strata:

1. Paskapoo basal channels and the underlying 'S' or 'Mu' coal subzones,
2. 'S-Mu' channels and the overlying 'S' coal subzone and underlying 'Mu' coal subzone,
3. 'Mu-Ml' channels and the overlying 'Mu' coal subzone and underlying 'Ml' coal subzone,
4. 'Ml-N' channels and the overlying 'Ml' coal subzone and underlying 'N' coal subzone,
5. 'upper channels of the lower Scollard member' and the overlying 'N' coal subzone.

#### 5.1.1 Paskapoo Basal Channels Assemblage

The Paskapoo basal channels, consisting of one or several stacked channels, are continuous over large distances (Figure 66). The channels eroded completely the 'S' top-coal unit of the Ardley Coal Zone in the northeast part of the study area. Near the 'S' coal subzone erosional edge, the basal Paskapoo channels and the 'S' alluvial fan deposits are in direct stratigraphic contact. Locally the base of the Paskapoo channels cut down to the top of the 'Ml' coal zone as it is shown by the N-N' stratigraphic cross-section (Figure 22).

In the study area, the basal Paskapoo channels can be thicker than 42 m (Figure 66). The Paskapoo basal channels' axis overlies the area of 'S' coals with a small extension to the east.

#### 5.1.2 The 'S-Mu' Alluvial-Fan Assemblage

The sandstone content within the 'S-Mu' interval can reach more than 50 m in thickness (Figure 67). The 'S-Mu' sandstone deposits were eroded towards the northeast along with the overlying 'S' coal seams. The isopachs of the relict 'S-Mu' sandstone unit depict a similar distribution with the 'S' coal subzone only to the southwest. The depositional style of the remnant 'S-Mu' sandstone unit might be interpreted as alluvial-fan system due to the sand sheet aspect of the isopachs, rapid increase in thickness distribution on short distance and to the presence of distal radial digits (Figure 67).

### 5.1.3 The 'Mu-Ml' Channels Assemblage

The isopachs of the 'Mu-Ml' sandstone unit show a thickness of up to 26 m. The channel reconstruction map shows a major west-east axis of the wide channel assemblage (Figure 68). On map view, it appears there may have been two fluvial systems with different flow directions, but the system with the west-east flow axis is dominant. The subordinate fluvial system has a northwest-southeast axis. The main fluvial system can be described as straight (Figure 68).

### 5.1.4 The 'Ml-N' Channels Assemblage

The sandstone isopachs of the 'Mu-Ml' channel assemblage show a thickness of up to 26 m. The channel reconstruction map shows a major southwest-northeast axis of the wide fluvial system (Figure 69). On map view, the fluvial system style can be described as highly sinuous. Another possible interpretation is of three parallel fluvial systems with northwest-southeast axes.

### 5.1.5 Channels of the Lower Scollard Member

There are two generations of channel systems within the lower member of the Scollard Formation separated by an almost continuous thin layer of tonstein defined in the associated database as 'lower Scollard marker.' The 'lower Scollard marker' (Figure 41) allows the interpretation of the overlying sandstone channels as the 'upper channels of the lower member' of the Scollard Formation, whereas the underlying channels are described in the present report as the 'lower channels of the lower member' of the Scollard Formation. The channels thickness within the overlying interval may reach 59 m and they are distributed mainly in the western part of the study area (Figure 70). On vertical views (cross-sections), the upper interval of the lower Scollard Formation shows multilateral coalescent channel fills. On the map view, the fluvial system style is almost straight.

The lower channels of the lower Scollard member show an alluvial-fan type deposit in the southwest part of the study area where the thickness increases rapidly to 35 m (Figure 71). On the map view, two separated long extensions to the north and northeast may indicate the presence of two different drainage systems connected south-easterly through the alluvial-fan deposit. The extensions are relatively narrow and might be slightly diachronous.

The comparison of the channels episodes as a part of the uppermost Maastrichtian–lower-middle Paleocene time interval within the Edson block shows that the axis of each channel system changed over time. For instance, within the lower part of the Scollard Formation the channels (Figures 70 and 71) changed in flow axis from north-south to northwest-southeast during 'Ml-N' channels deposition time (Figure 69), which was followed by a west-east flow axis during 'Ml-Mu' channel assemblage time (Figure 68). During basal Paskapoo deposition time, the flow axis changed again to northwest-southeast (Figure 66). The dominant flow axis over time seems to be northwest-southeast. Not only the flow axis has changed, but also the area covered by the fluvial systems has changed. The drainage systems covered the west part of the study area during lower Scollard deposition time, then in upper Scollard time, the area exposed to the drainage systems was subject to several changes in the central, southwest or west part of the study area.

## 5.2 Discussion on Gas Migration and $CO_2$ Sequestration Potential in Ardley Coal Strata

The general thesis that there is a relationship between the increased concentration of $CO_2$ in the atmosphere and temperature change has sparked concerns that anthropogenic $CO_2$ emissions contribute significantly to global warming (Environment Canada, 2002). At present, there are several options for $CO_2$ geological sequestration (permanently) or for significant time periods (storage): in depleted oil and gas reservoirs, in coal strata, in deep saline aquifers and in salt caverns. Of these, $CO_2$ sequestration strategy in coal strata presents the added benefit of displacing and producing additional energy resources ($CO_2$-Ehanced CBM production). In Alberta, the coal strata may represent an attractive target for the initiation of large-scale $CO_2$ sequestration operations.

Among the criteria applied for the Ardley coal reservoir characterization in the Edson block, such as depth, pressure, reservoir geometry, internal structure, sealing, coal rank, ash and gas content, and fracture pattern, the vertical connectivity between coal strata and the adjacent sandstone units as successive conventional and unconventional reservoirs is very important for $CO_2$ injection strategy.

In the Edson block, the suitability for $CO_2$ sequestration in the Ardley Coal Zone is limited by the increased permeability due to post-Scollard structural re-adjustments.

There are three categories of vertical connectivity between the conventional and unconventional types of reservoirs (sandstone channels and coal strata) identified within the Scollard-basal Paskapoo succession in the Edson block:

a) The direct stratigraphic contact between the coal seams and the overlying sandstone channels as they are shown in multiple locations on the structural cross-sections (Figures 16–22). In some instances, the connectivity is also present at the contact between the older sandstone channels and the overlaying coal seams, recognized on the majority of the structural cross-sections. The dominant area with direct stratigraphic contact between the top of sandstone channel and base of the overlying coal subunit occurs in the central part of the study area. Both types of coal-sandstone direct stratigraphic contact, become more frequent to the east.
b) The post-Scollard structural re-adjustments (Figures 26–29) amplified the existing coal cleats and thus increase the potential vertical connectivity with the adjacent channels in the locations of direct stratigraphic contact.
c) The post-Scollard fractures identified in the outcrop (Vogwill, 1983) within Paskapoo Formation, Twp 52, R 21W5, and in the examined drillcores within the Scollard succession, Twp 50, R19W5, may contribute to vertical connectivity among the reservoirs (Plate 5). According to the structural maps, the structural re-arrangements extend northwesterly within the Edson block (Figures 26, 27, 28).

In light of the present stratigraphic and structural interpretation, the $CO_2$ sequestration/storage and enhanced CBM production strategy ($CO_2$-ECBM) in the Edson block, Ardley coal strata, must consider the potential pathways for geo-fluids migration due to the vertical connectivity of the conventional (sandstone) and unconventional (coal) reservoirs. Additional hydrogeological work needed to fully evaluate $CO_2$ injection strategy within the current stratigraphic model.

# 6 Conclusions

The study of the Ardley Coal Zone in the Edson block yielded the following interpretation:

- Five fluvial sequences have been recognized and interpreted as dynamic responses to cyclic, slow thrusting tectonic stages followed by isostatic rebounding.
- The upper four sequences are capped by coal strata that are considered individual coal subunits with different distribution and coal properties.

- эBanded' coal is the dominant type of coal in the Edson block, followed by 'banded bright' coal and 'banded dull' coal.
- Vitrinite reflectance is 0.52–0.63% within the onset of hydrocarbon generation.
- Interpretation of the surface lineaments suggests two different areas of potential coal fracture system.
- Cleats are generally free of calcite infilling at the macroscopic scale.
- Coal subzones can be defined as potential individual reservoirs due to particular anisotropic characteristics, geometry of each coal subzone and top and base bounding of the coal packages.
- GIP for the Ardley Coal Zone in the Edson CBM block, shows a total of $528 \times 10^9 m^3$ with gas estimates of $> 100 \times 10^9 m^3$ for each of the lower coal subzones ('N,' 'Ml' and 'Mu') and a significant decrease for the uppermost coal subzone to $31 \times 10^9 m^3$ ('S').

The study of coal-sandstone architecture and reservoir connectivity yielded the following results:

- Two types of rocks with potential reservoir characteristics are recognized: coal seams as unconventional type of reservoir and sandstone-channels as conventional reservoirs. Both types of reservoirs may have inherent permeability.
- Vertical connectivity of the two types of reservoirs might be the result of direct stratigraphic contact, as shown in some locations, and a few tectonic fractures as the result of post-Scollard structural re-arrangements.
- Structural re-arrangements resulted in fractures which play a potential role in geo-fluids migration and may limit $CO_2$ injection and $CO_2$-ECBM recovery in the Ardley coal zone, Edson block.

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## Appendix 1. Report Figures

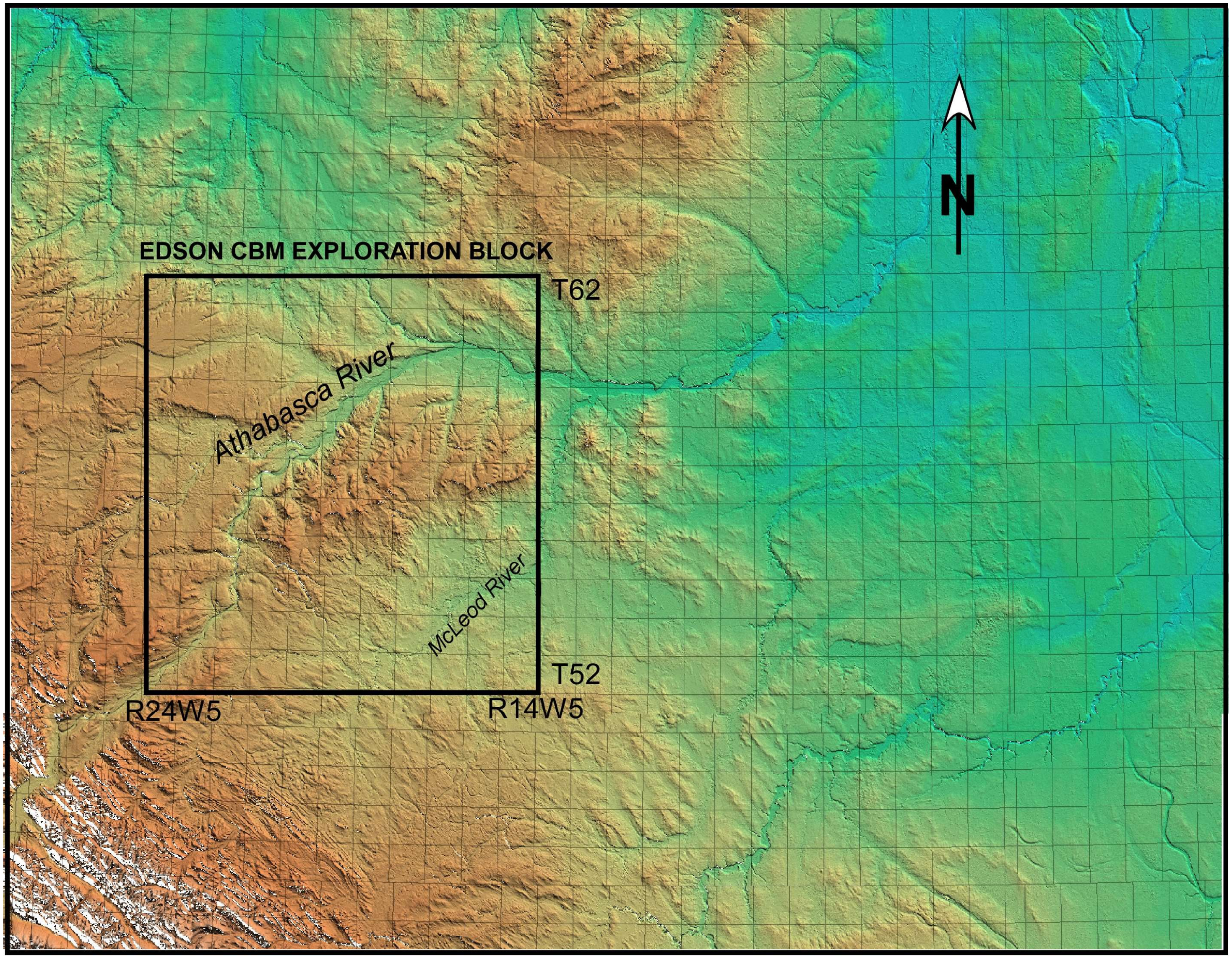

Figure 1. Study area projected on the regional Digital Elevation Model (SRTM).

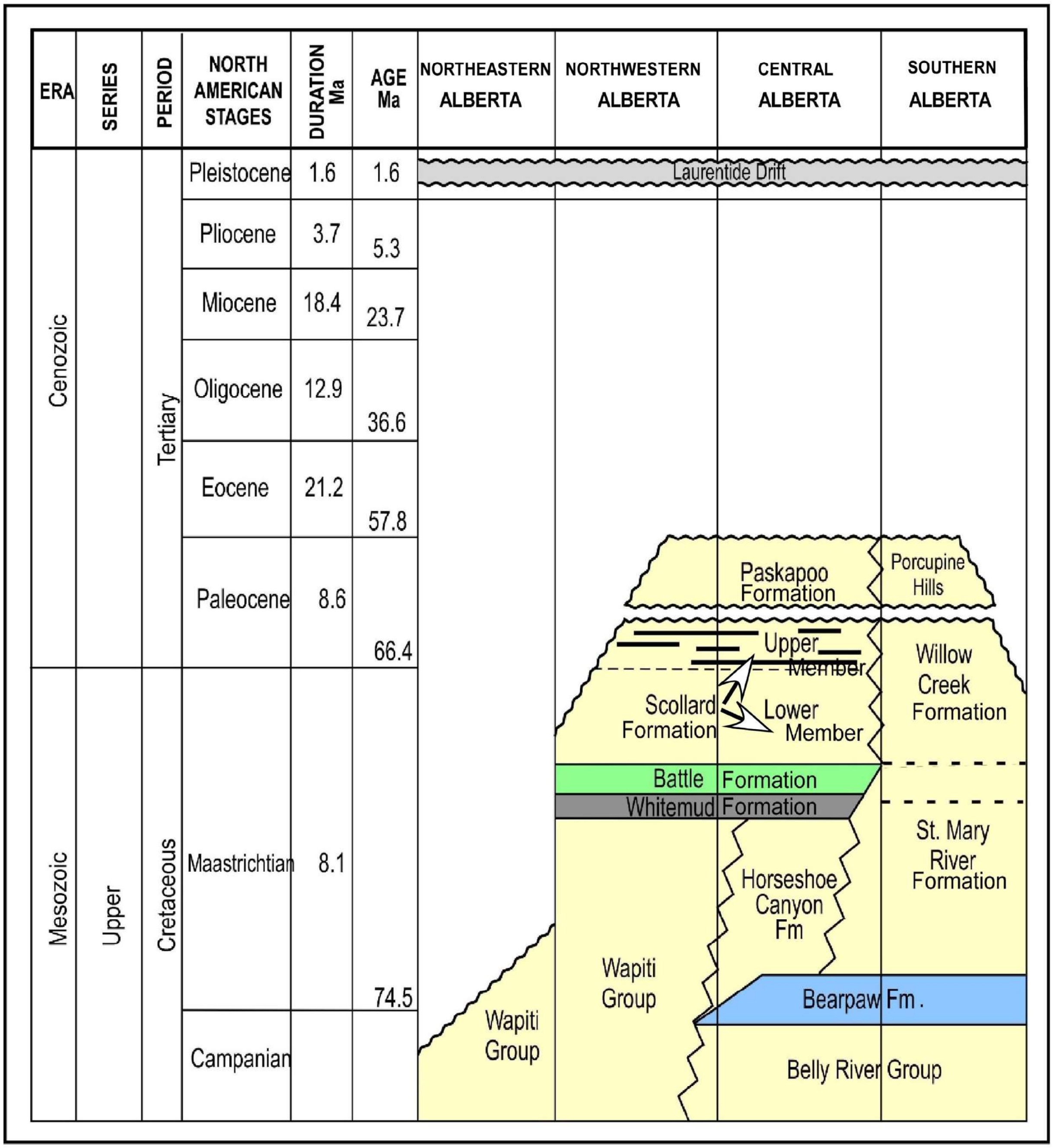

Figure 2. Stratigraphic chart of Upper Cretaceous-Tertiary strata in Alberta.

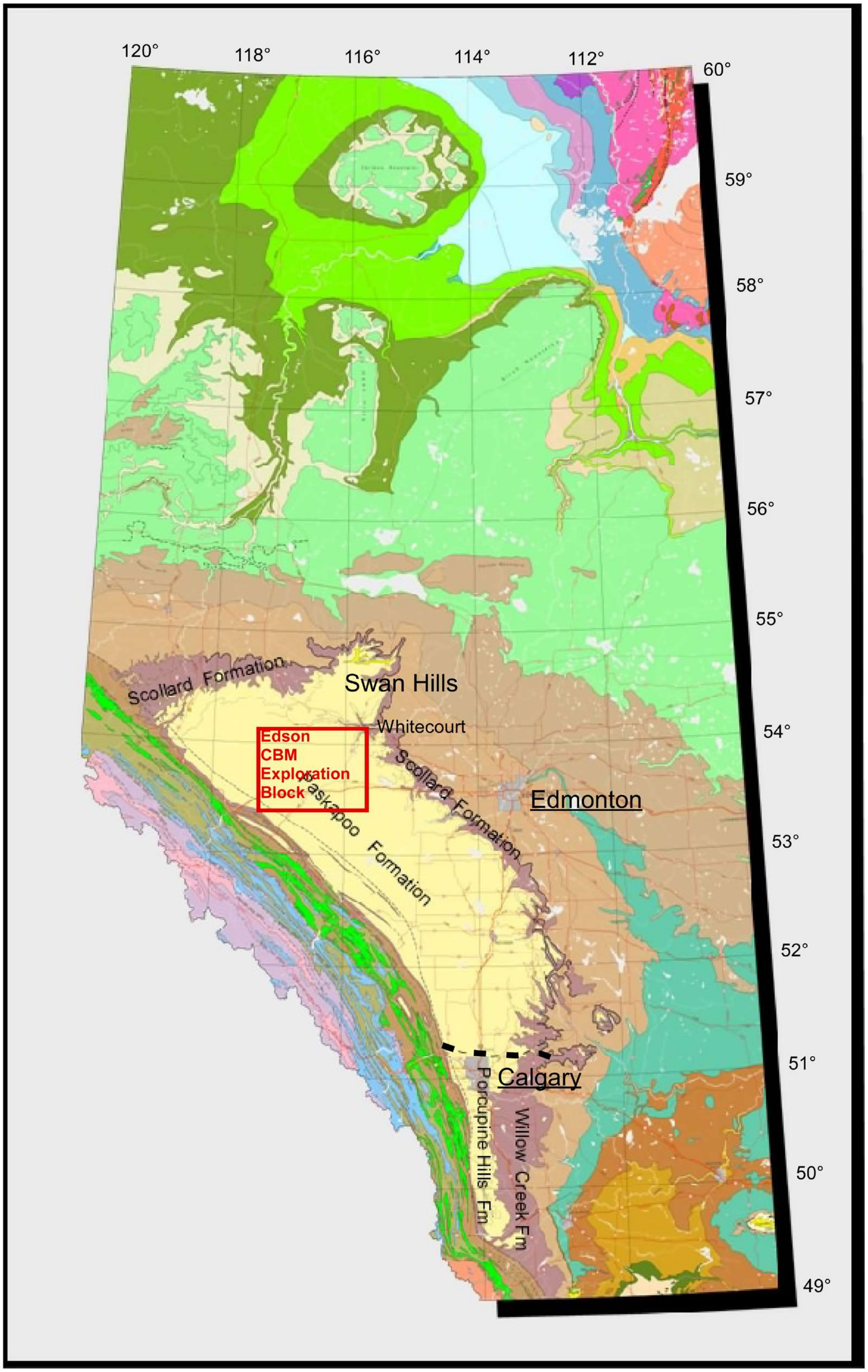

Figure 3. Edson study area on Alberta bedrock map (Hamilton et al., 1999).

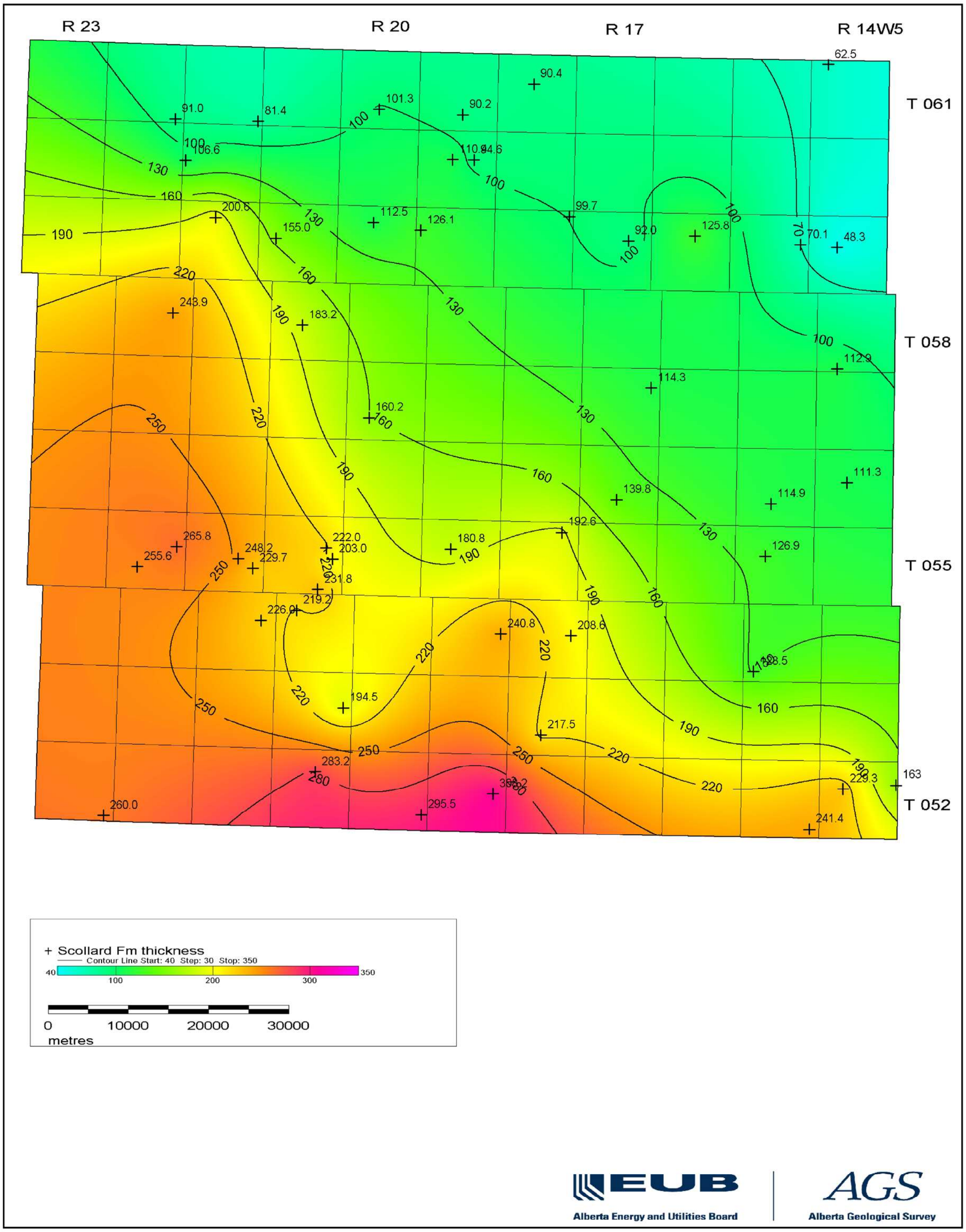

Figure 4. Isopach map of the Scollard Formation, Edson study area.

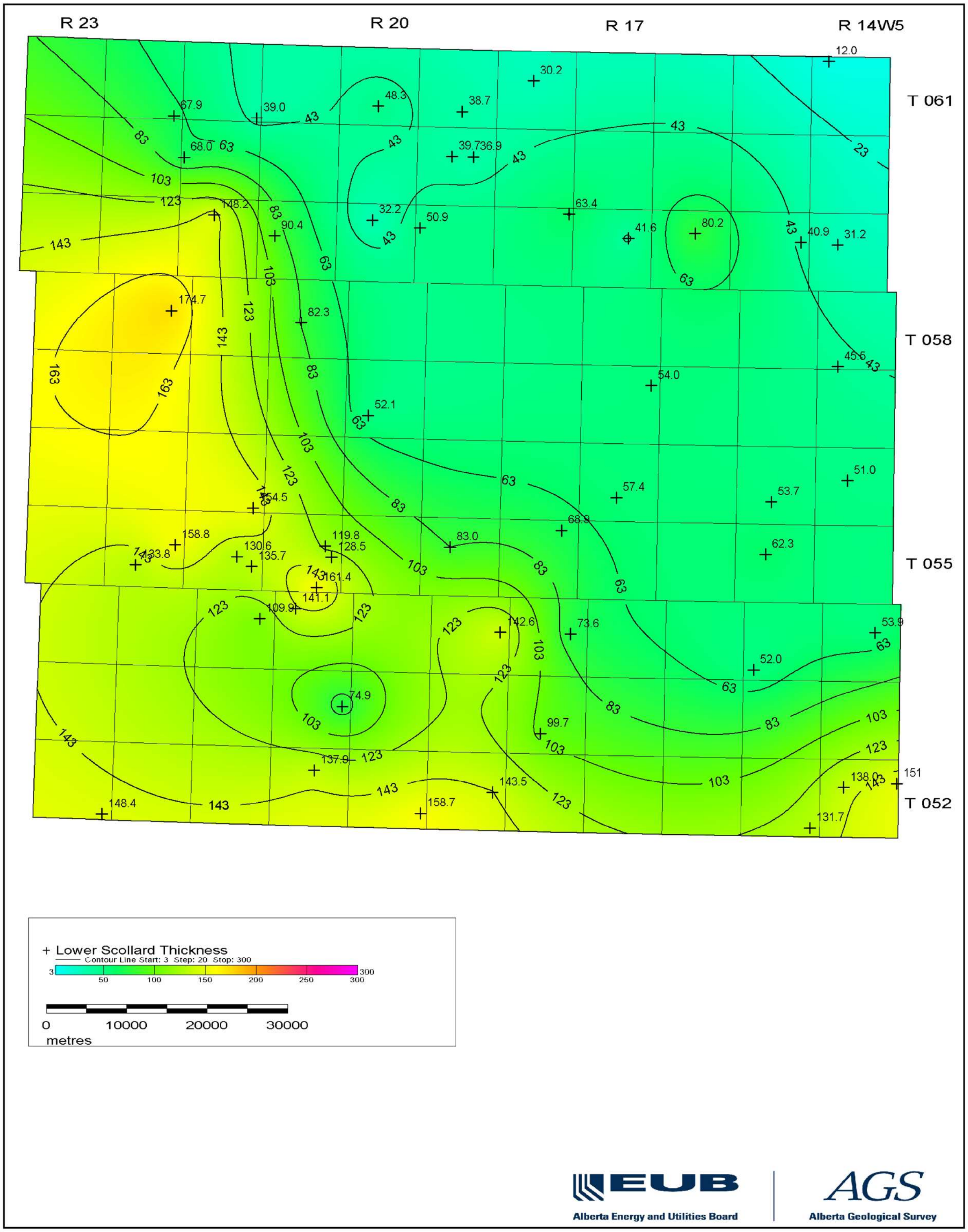

Figure 5. Isopach map of the lower member of the Scollard Formation, Edson study area.

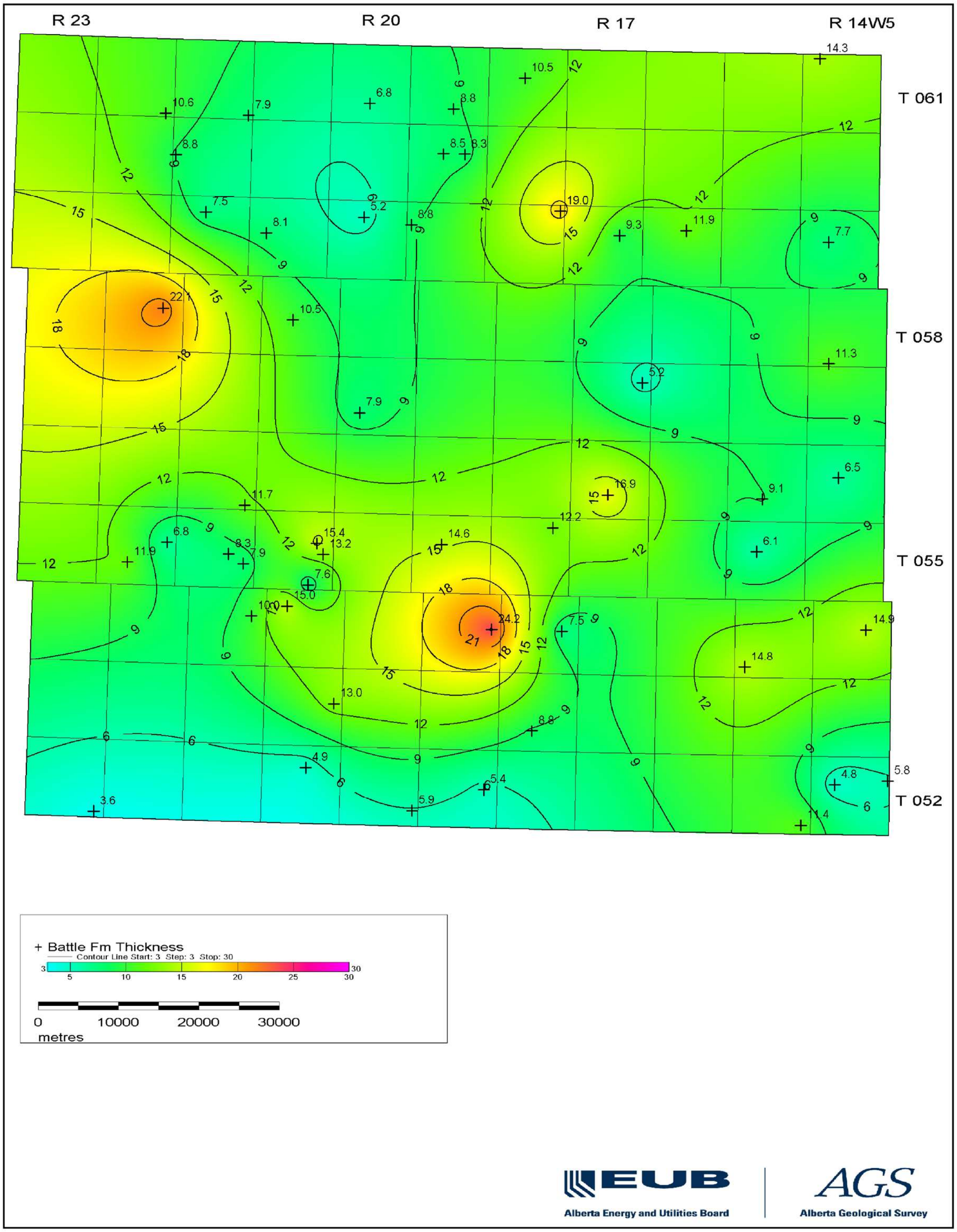

Figure 6. Isopach map of the Battle Formation, Edson study area.

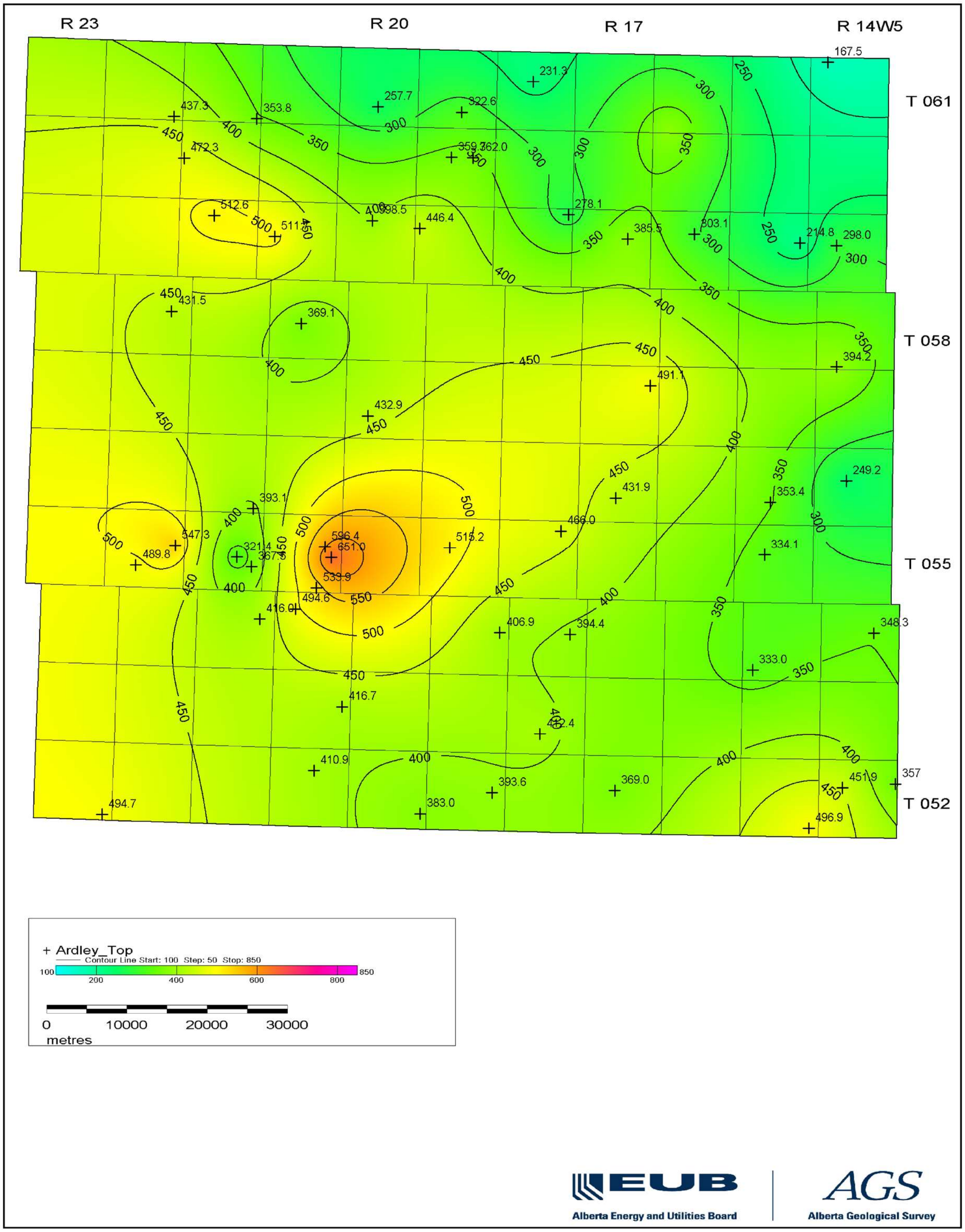

Figure 7. Depth to the top map of the upper member of the Scollard Formation, Edson study area.

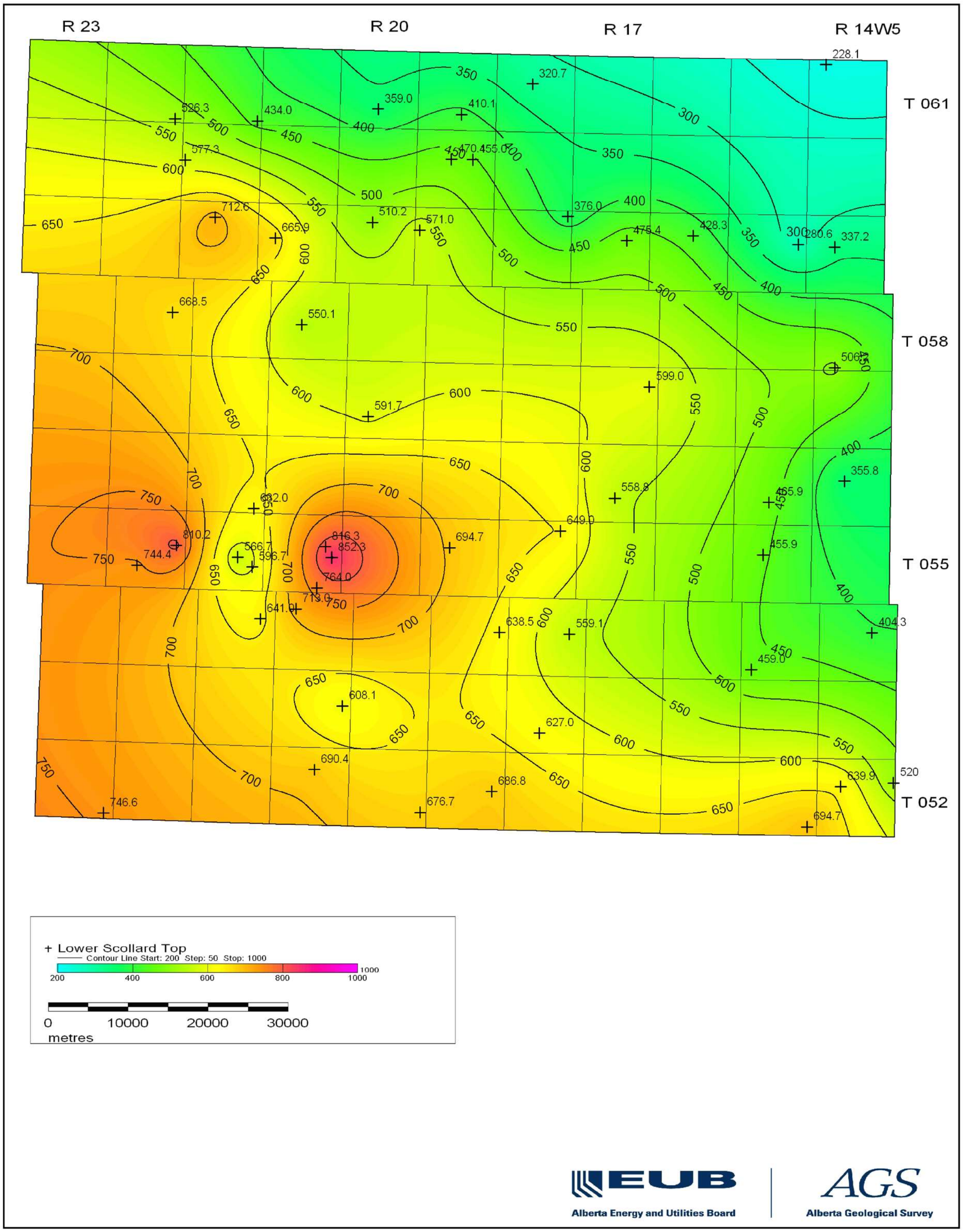

Figure 8. Depth to the top map of the lower member of the Scollard Formation, Edson study area

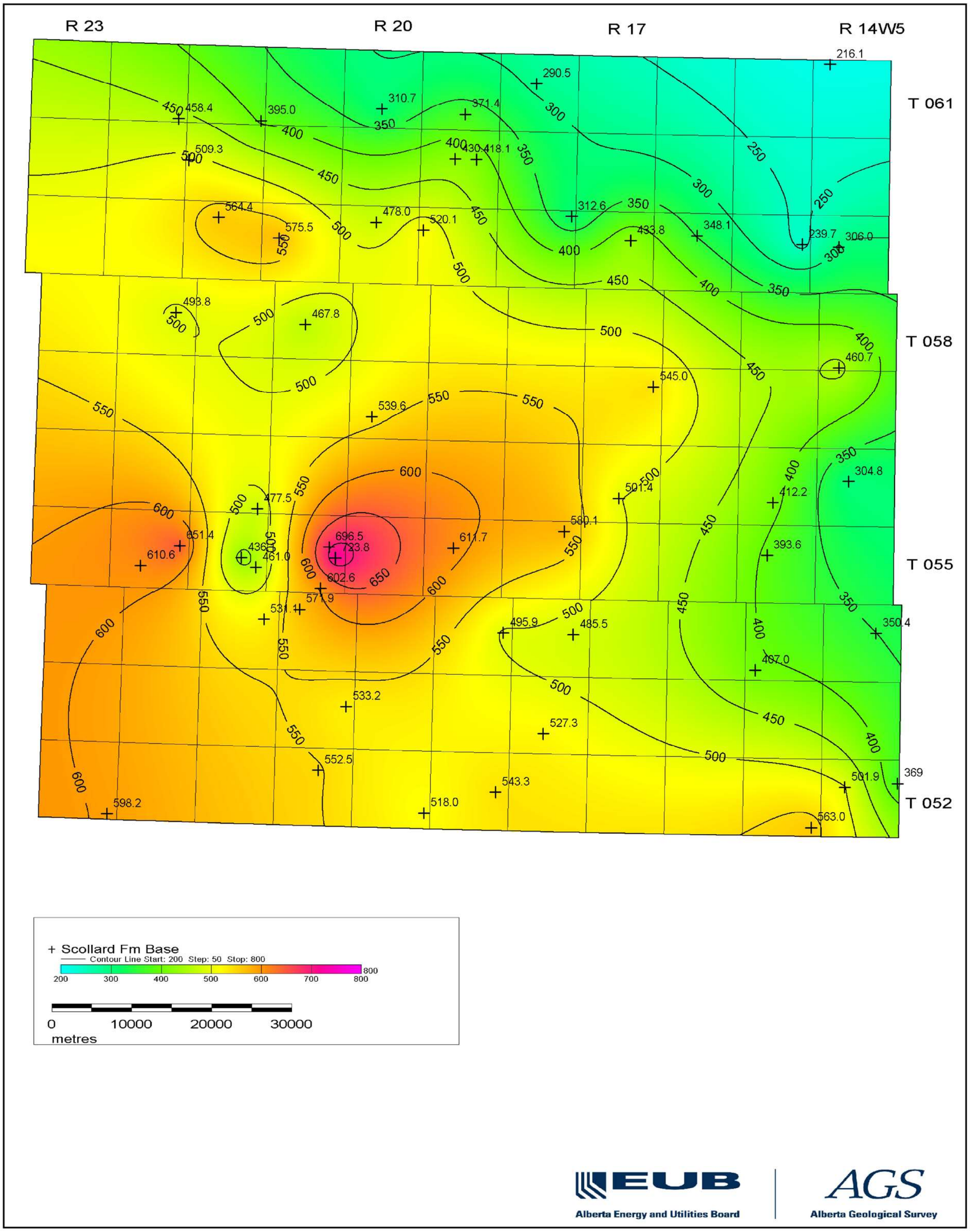

Figure 9. Depth to the top map of the Battle Formation, Edson study area

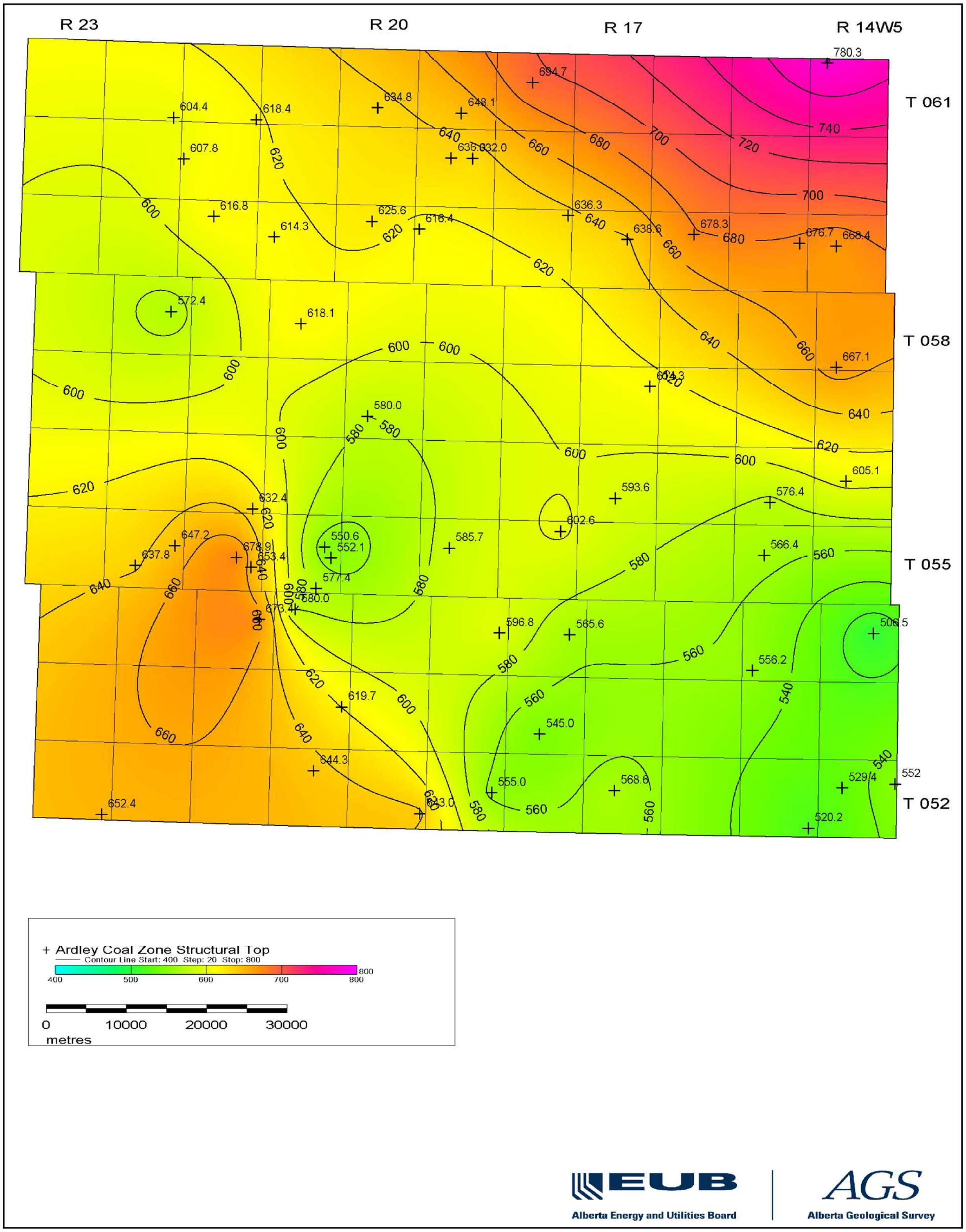

Figure 10. Structural contour map at the top of the upper member of the Scollard Formation, Edson study area.

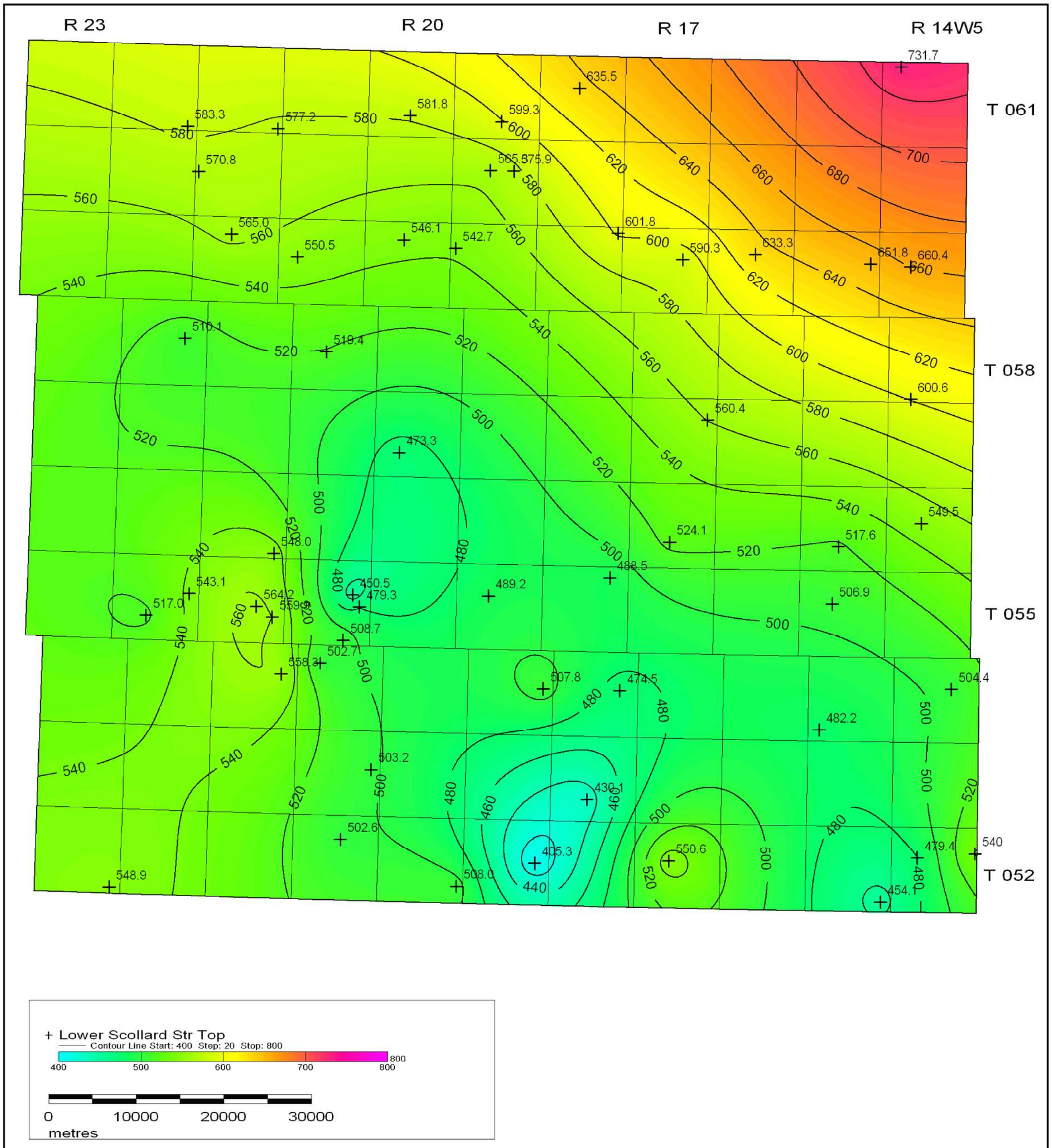

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Figure 11. Structural contour map at the top of the lower member of the Scollard Formation, Edson study area.

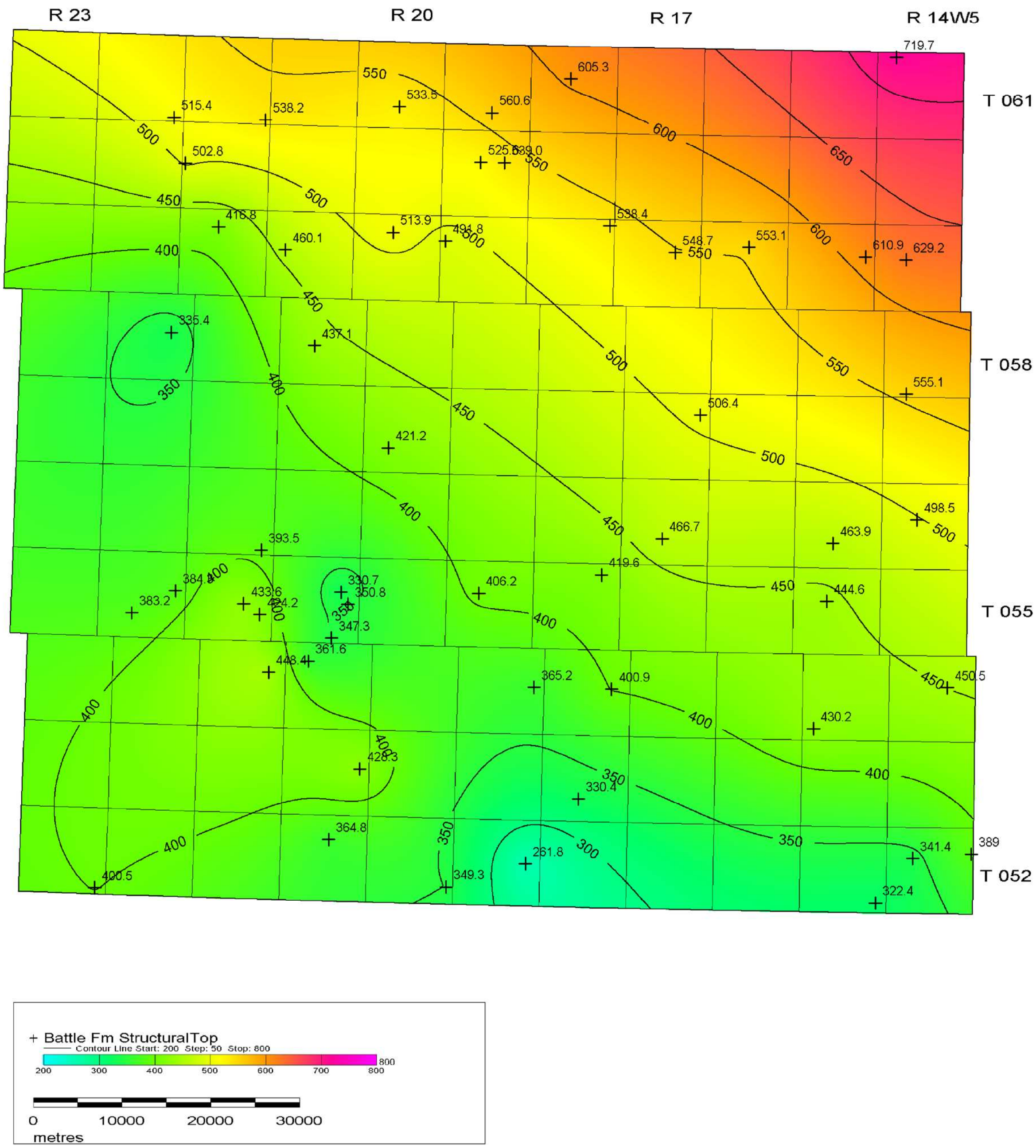

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Figure 12. Structural contour map at the top of the Battle Formation, Edson study area.

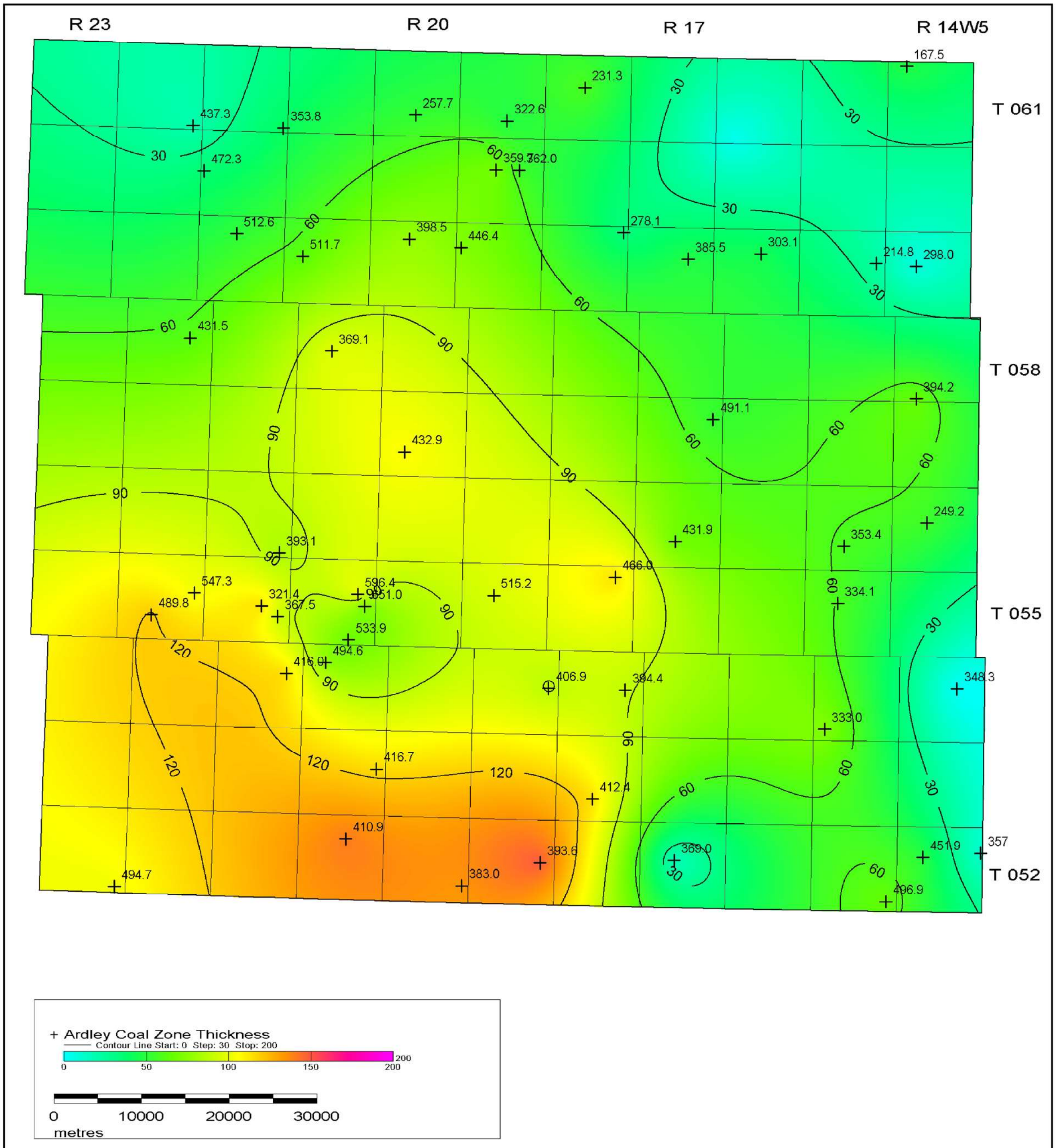


Figure 13. Isopach map of the Ardley Coal Zone, Edson study area.

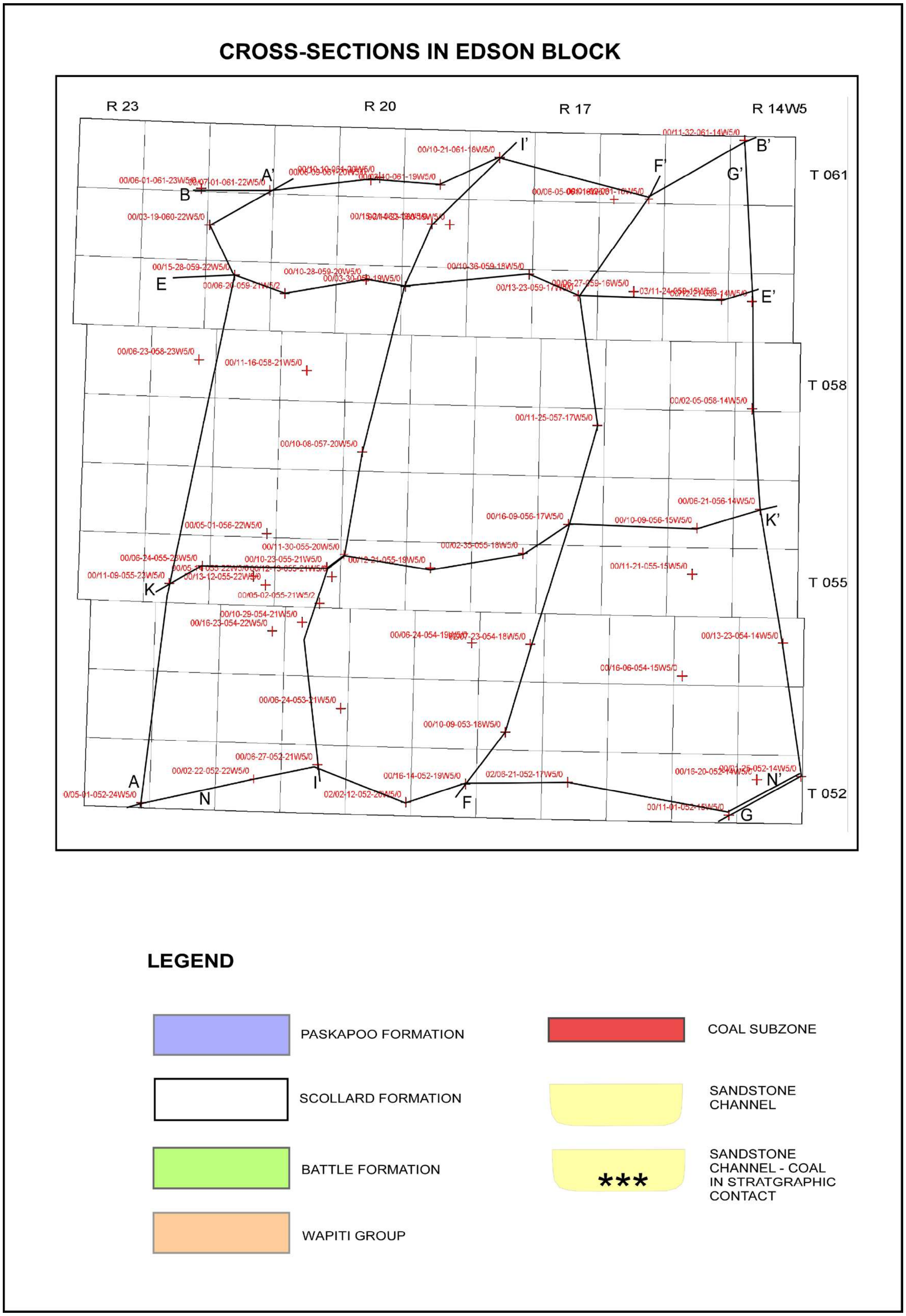


Figure 14. Map of the stratigraphic cross-sections in the Edson study area and the legend of the symbols used for the cross-sections.

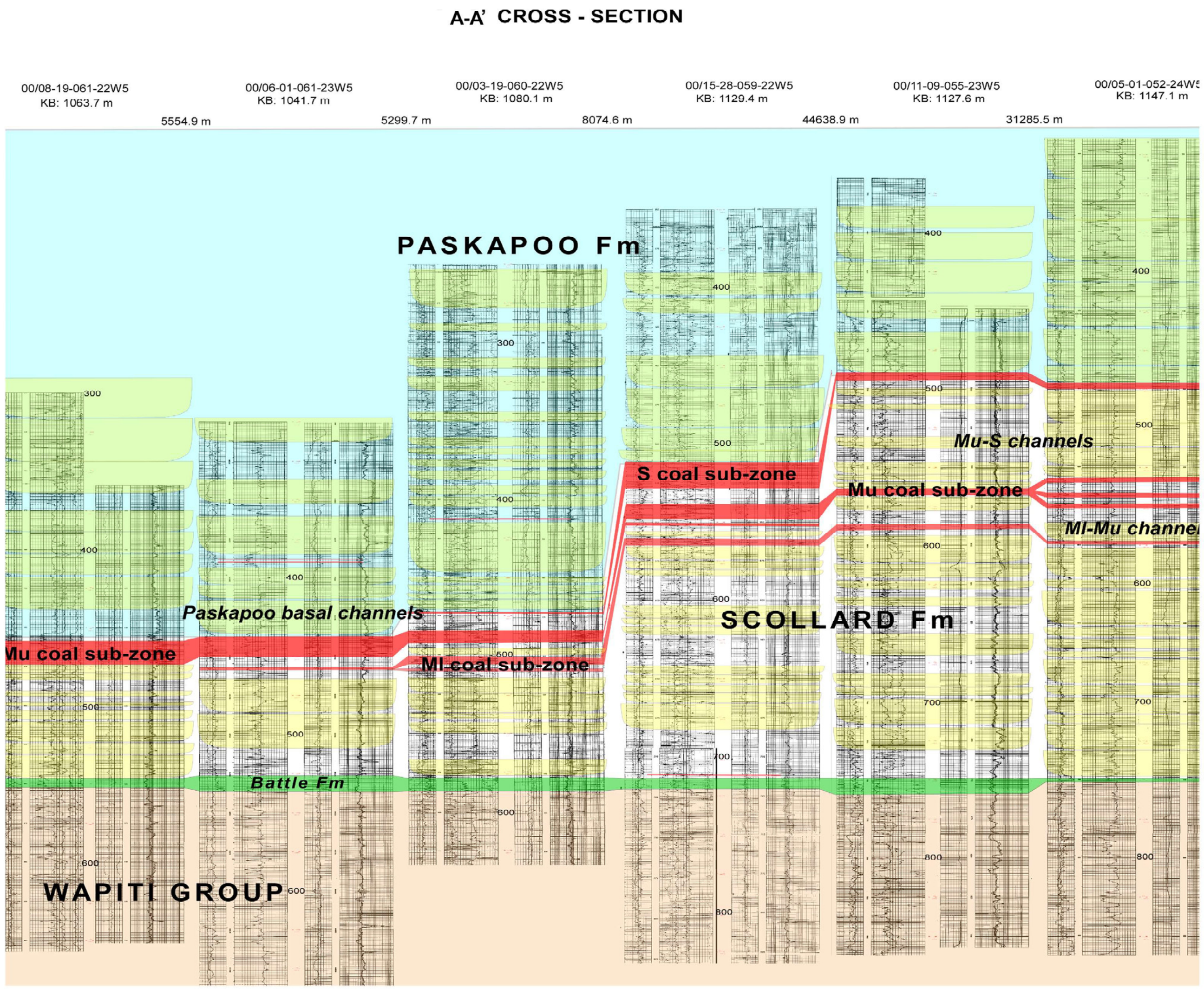


Figure 15. A-A' north-south stratigraphic cross-section, Edson study area.

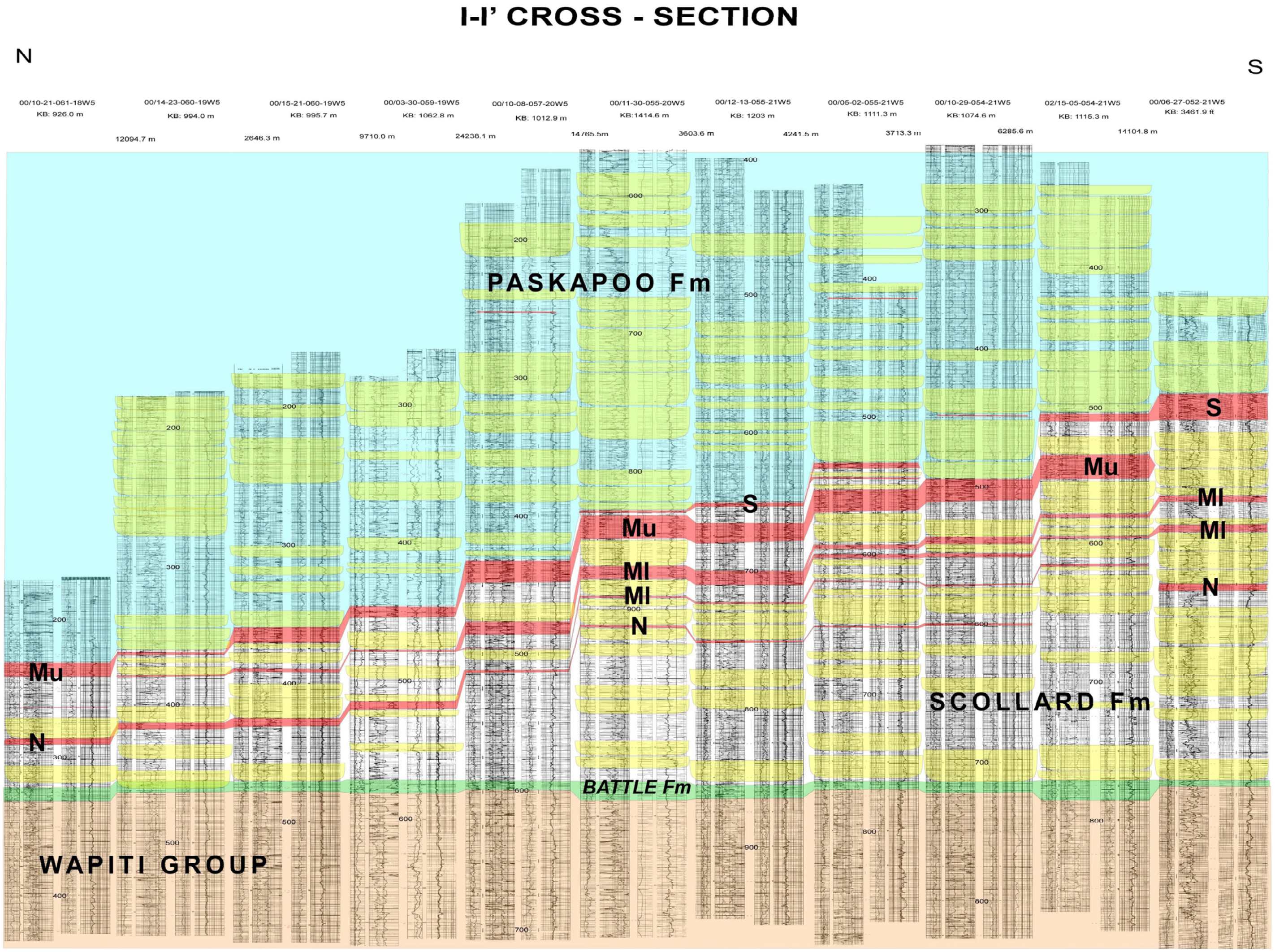


Figure 16. I-I' north-south stratigraphic cross-section, Edson study area.

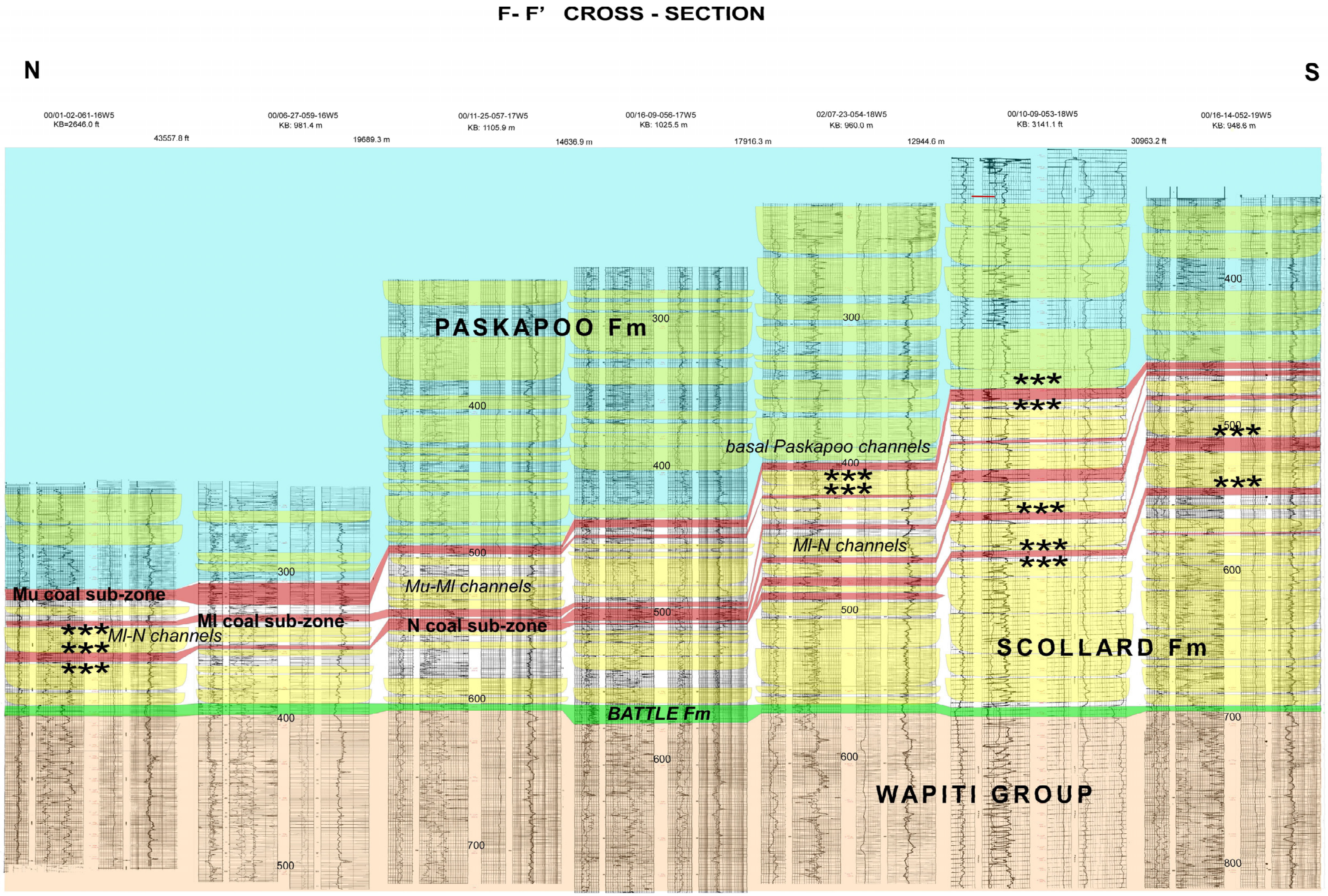


Figure 17. F-F' north-south stratigraphic cross-section, Edson study area.

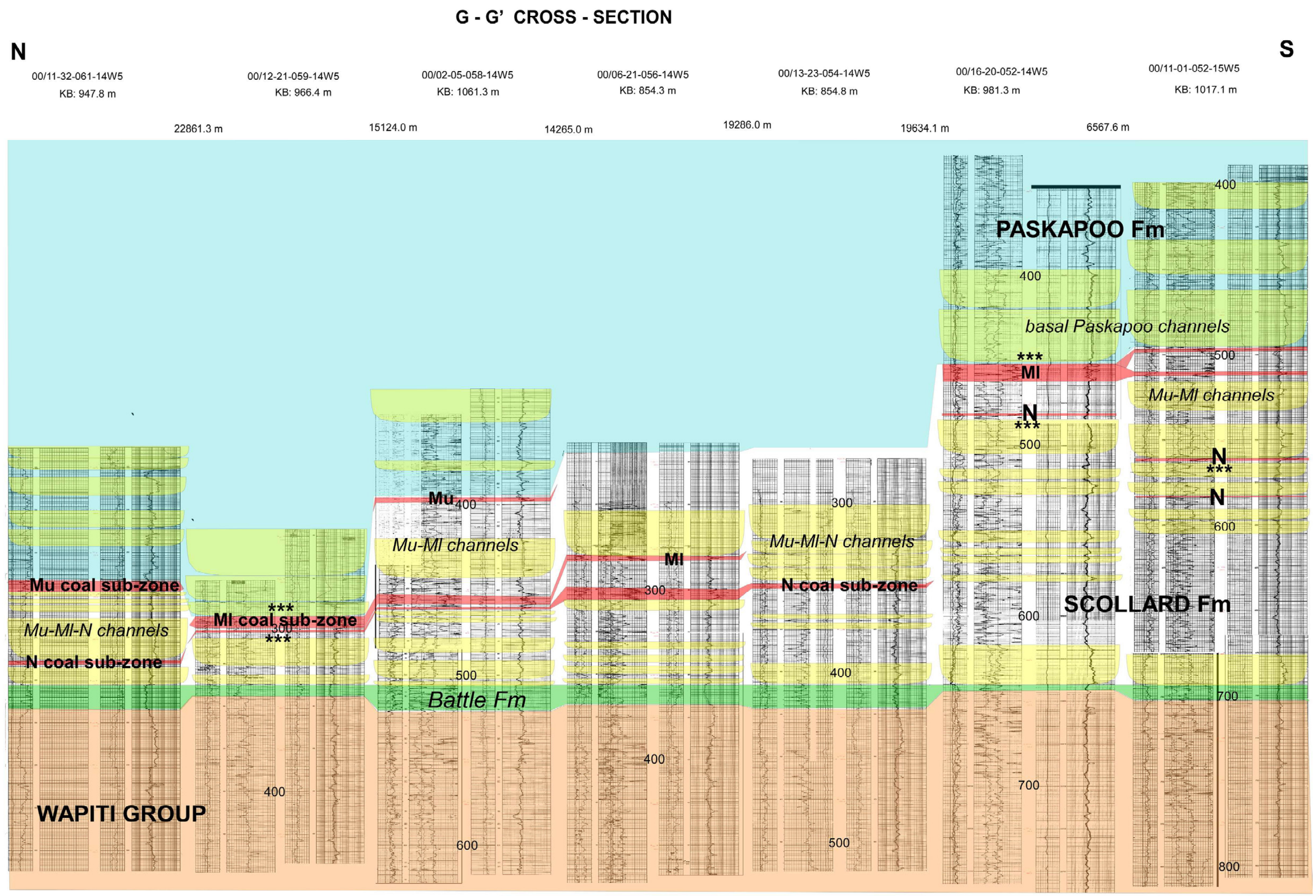


Figure 18. G-G' north-south stratigraphic cross-section, Edson study area.

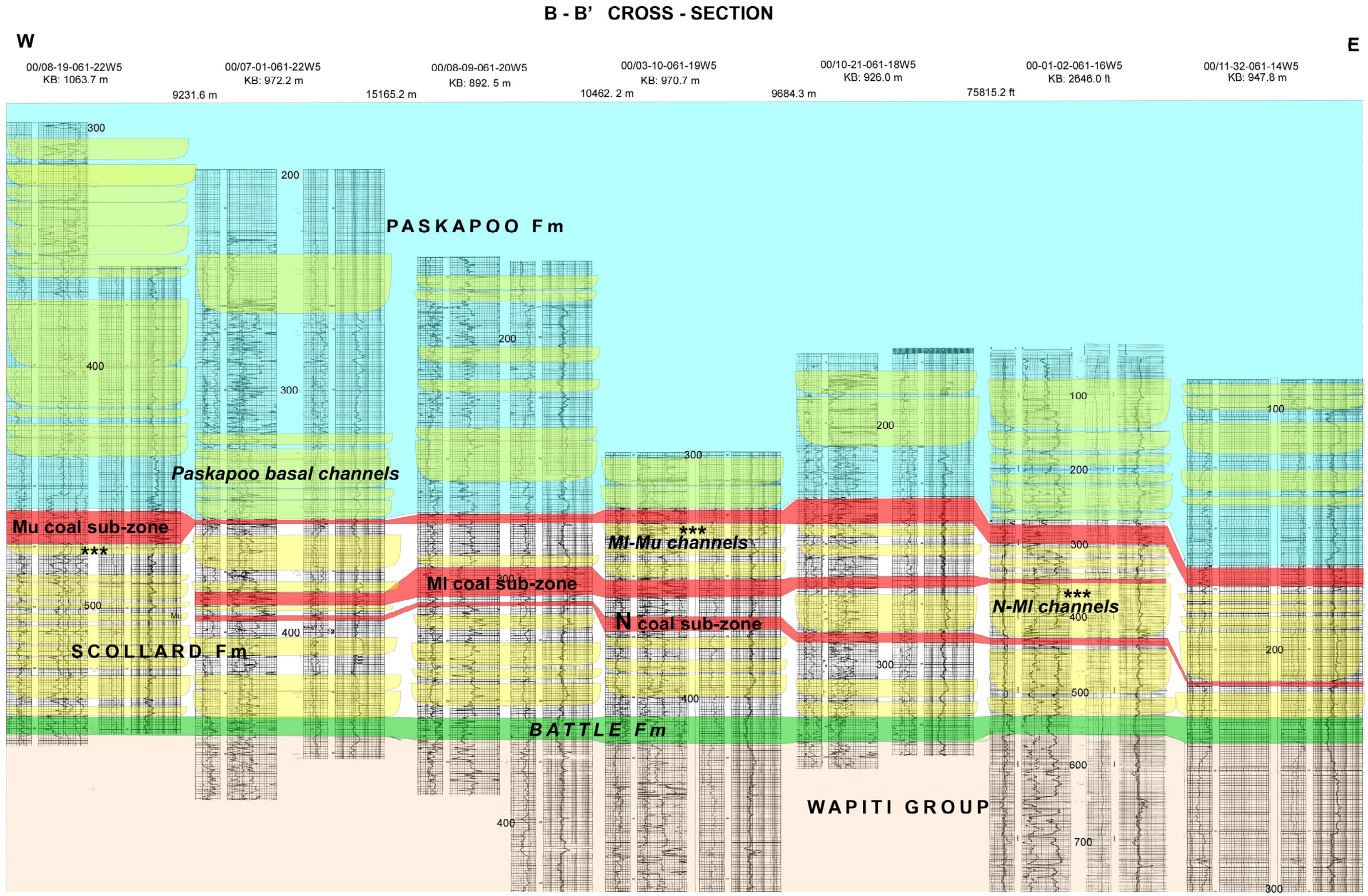


Figure 19. B-B' west-east stratigraphic cross-section, Edson study area.

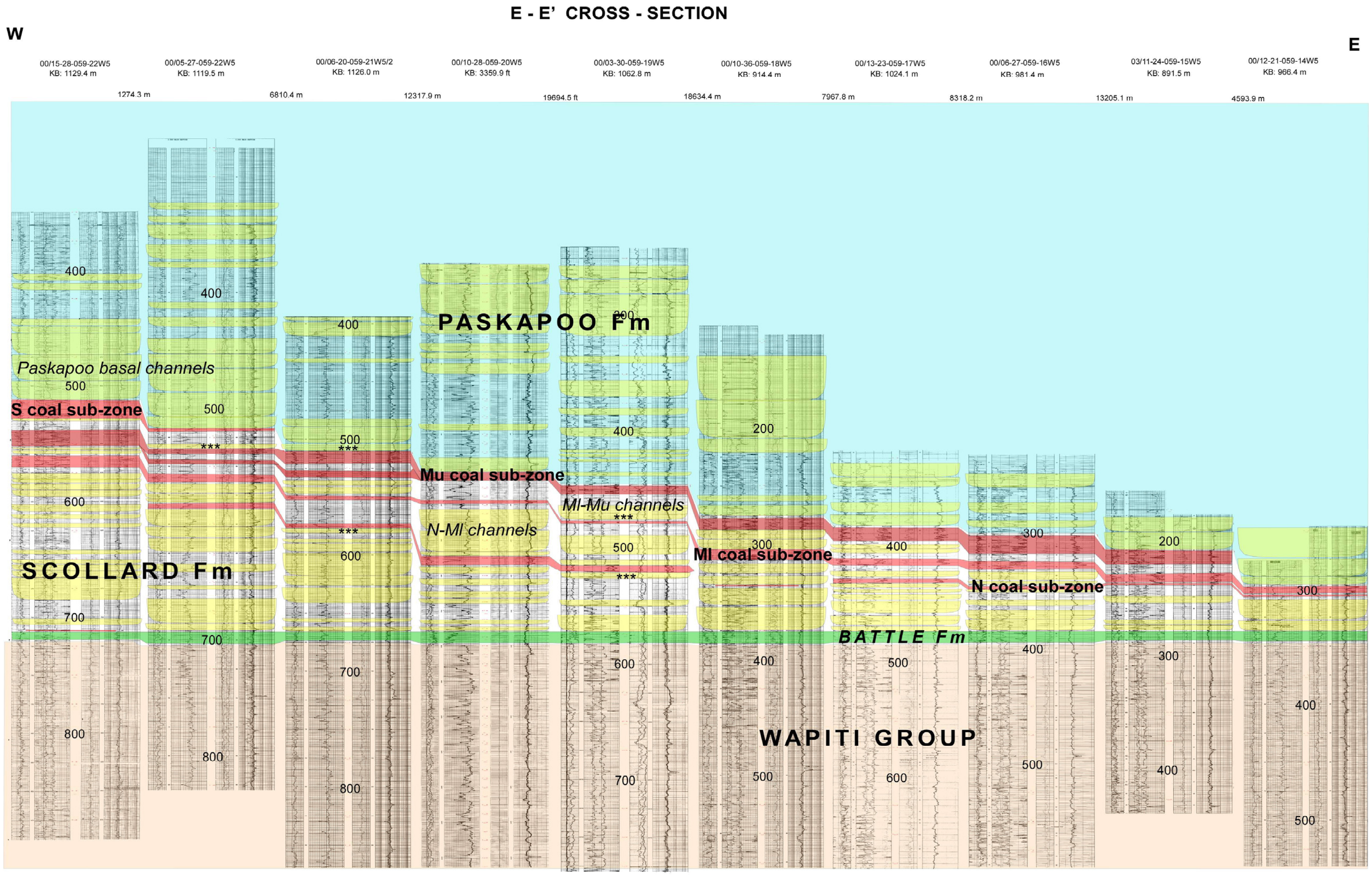


Figure 20. E-E' west-east stratigraphic cross-section, Edson study area.

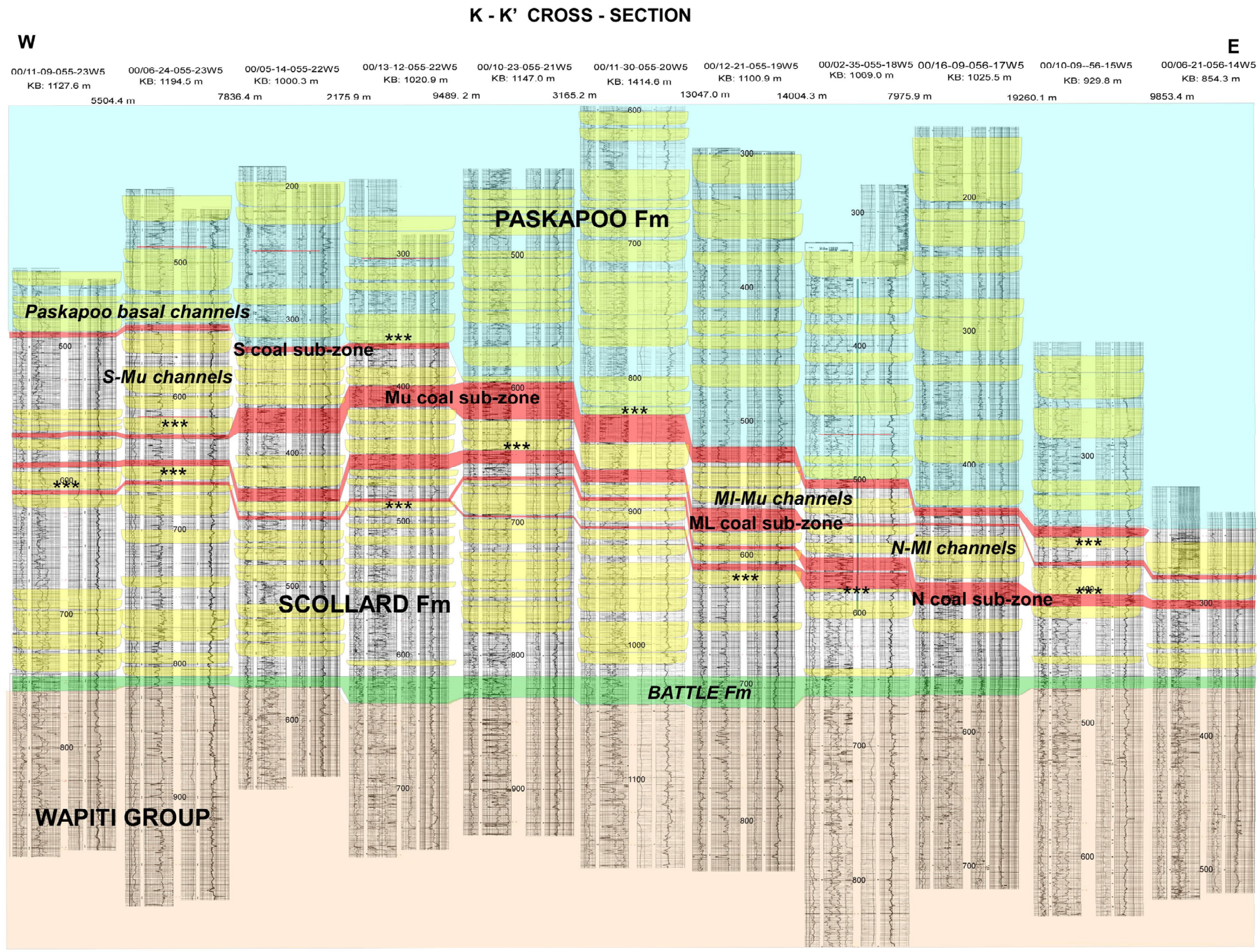


Figure 21. K-K' west-east stratigraphic cross-section, Edson study area.

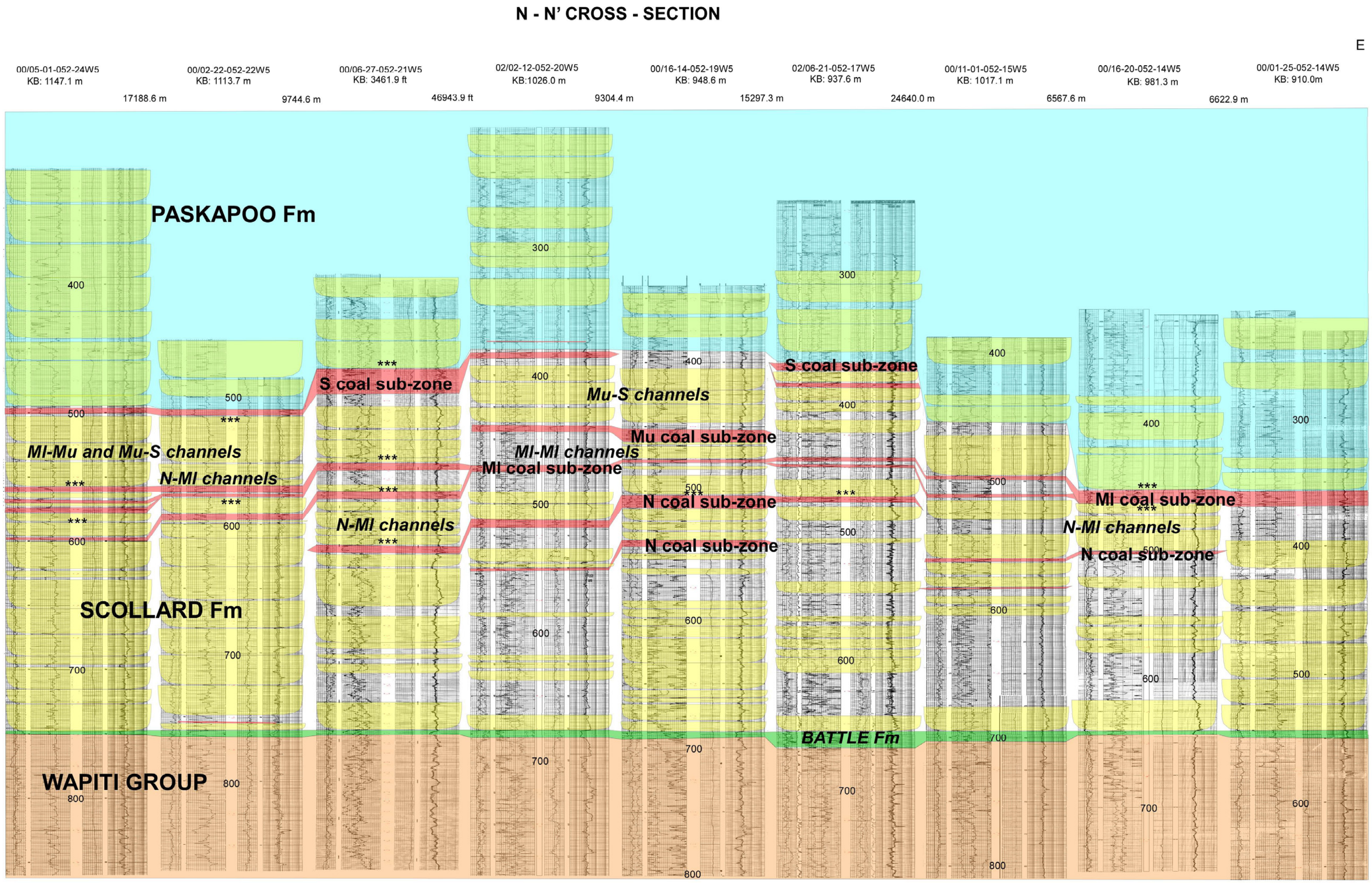
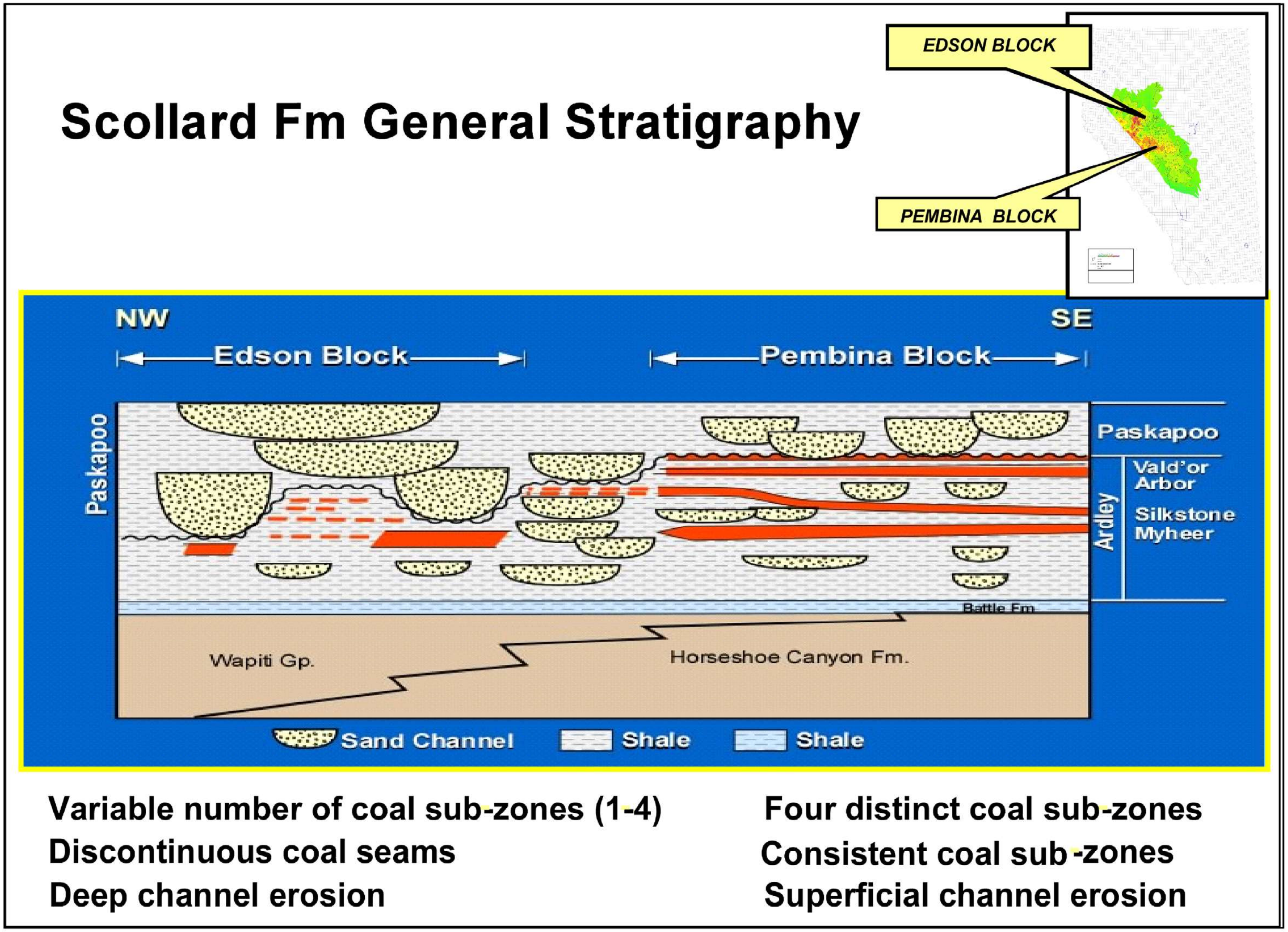


Figure 22. N-N' west-east stratigraphic cross-section, Edson study area.



Scollard Fm General Stratigraphy

Variable number of coal sub-zones (1-4)
Discontinuous coal seams
Deep channel erosion

Four distinct coal sub-zones
Consistent coal sub-zones
Superficial channel erosion

Figure 23. Schematic stratigraphic chart of the coal subunits distribution in the Edson and Pembina sub-basins; top-right: coal sub-basins location on the coal cumulative map of the Ardley Coal Zone at the basin scale; bottom: comparison chart of the main stratigraphic characteristics of the coal subunits (Edson sub-basin to the left, Pembina sub-basin to the right).

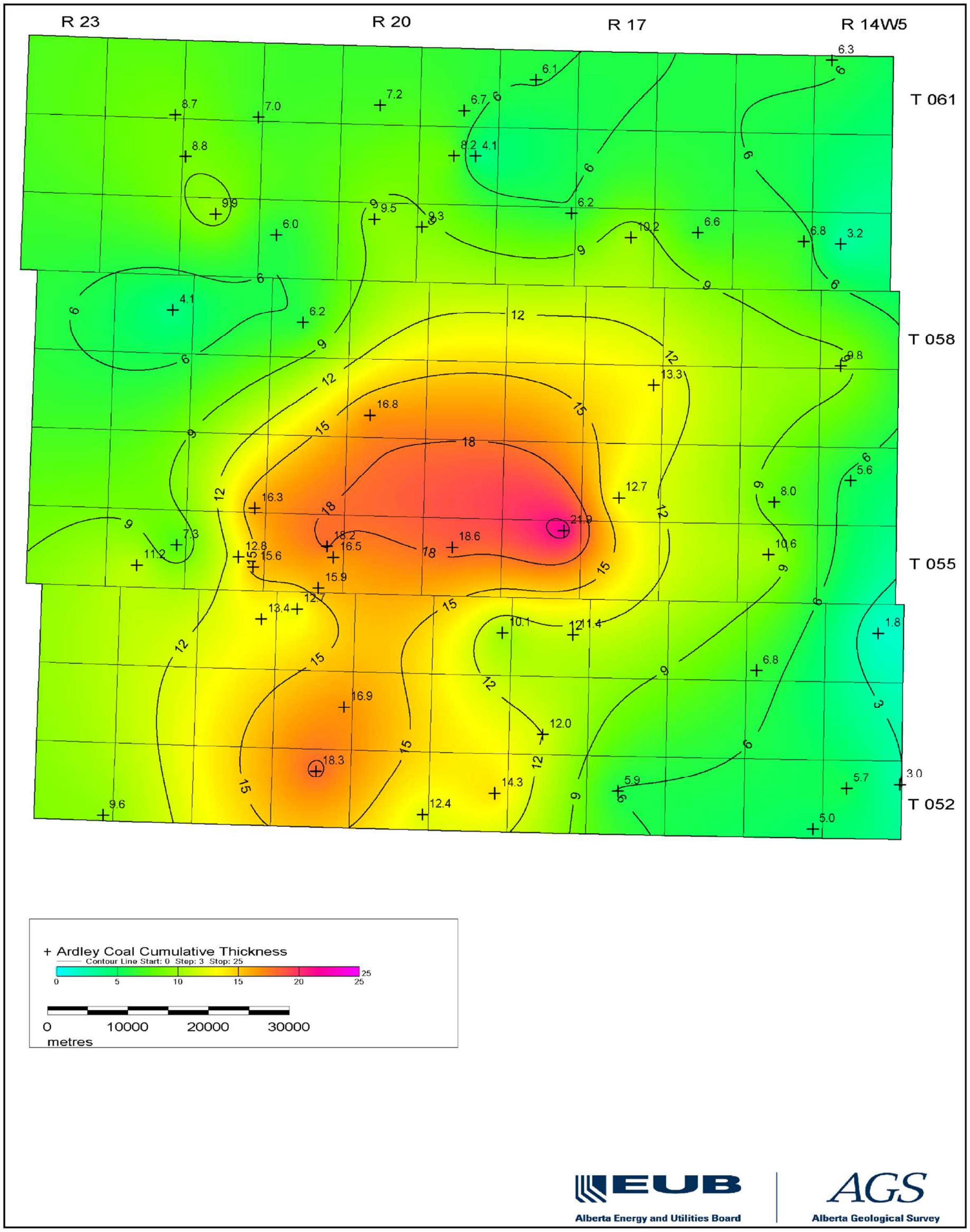


Figure 24. Ardley Coal Zone coal cumulative thickness map, Edson study area.

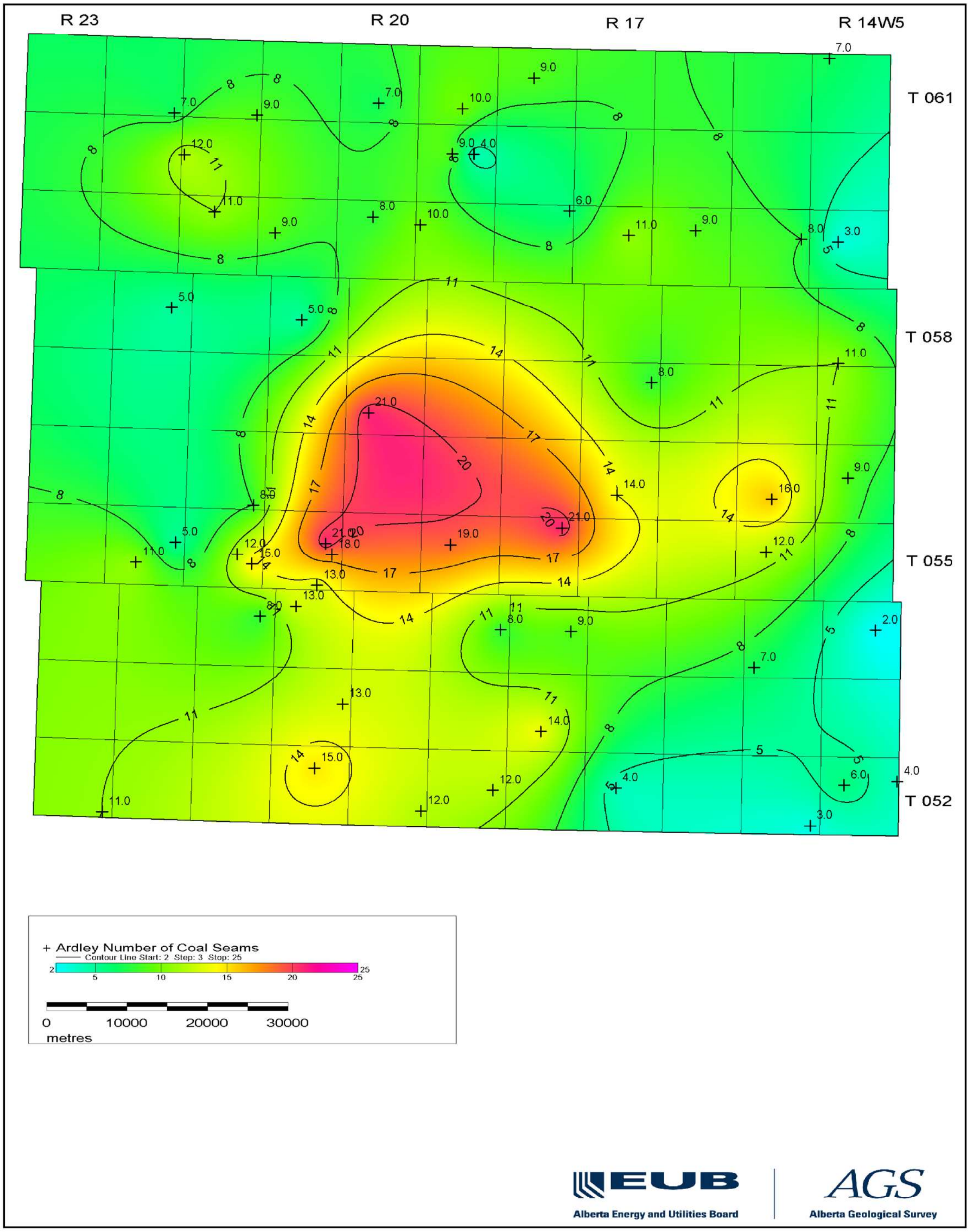


Figure 25. Ardley Coal Zone number of coal seams map, Edson study area.

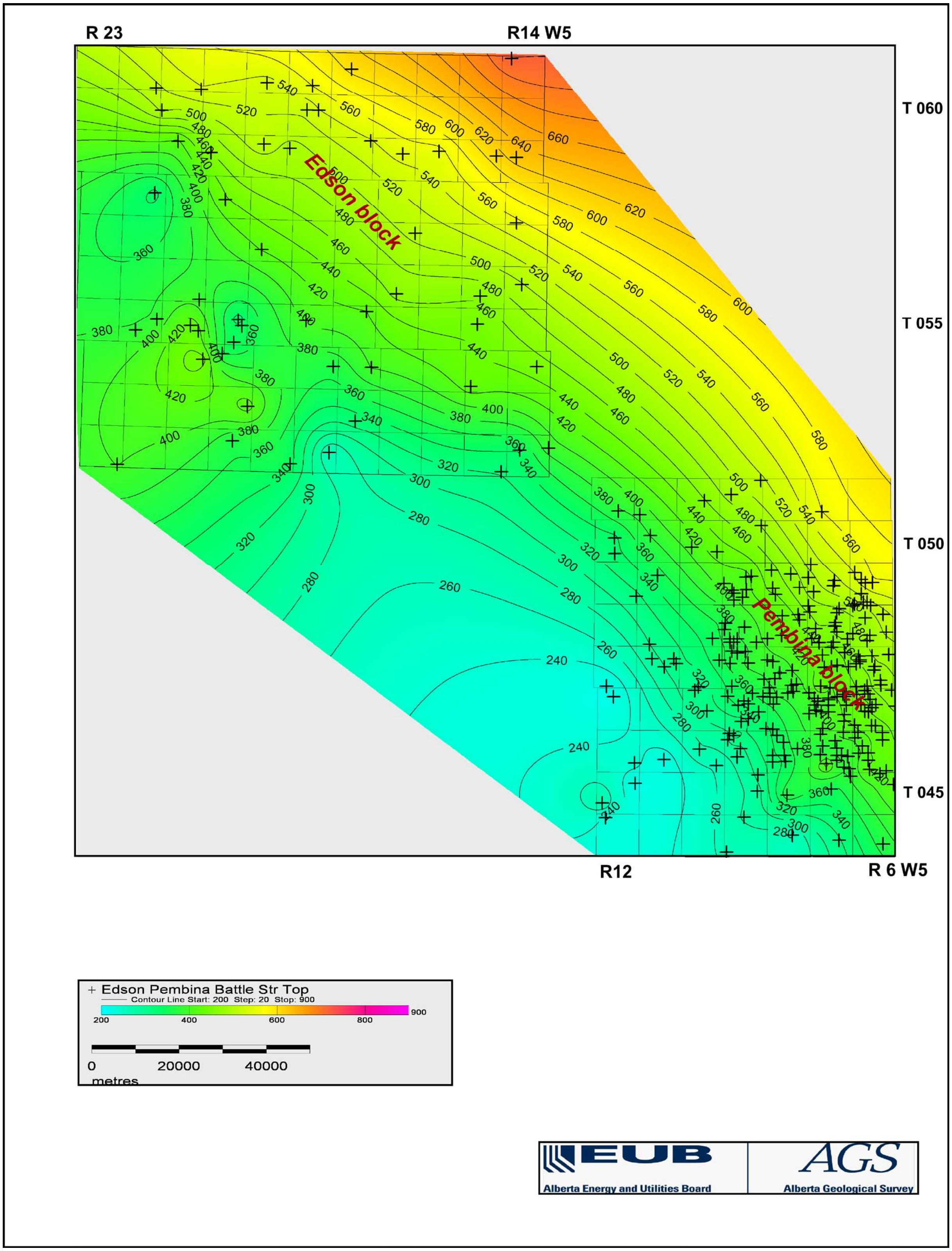


Figure 26. Structural contour map at the top of the Battle Formation, Pembina and Edson study areas.

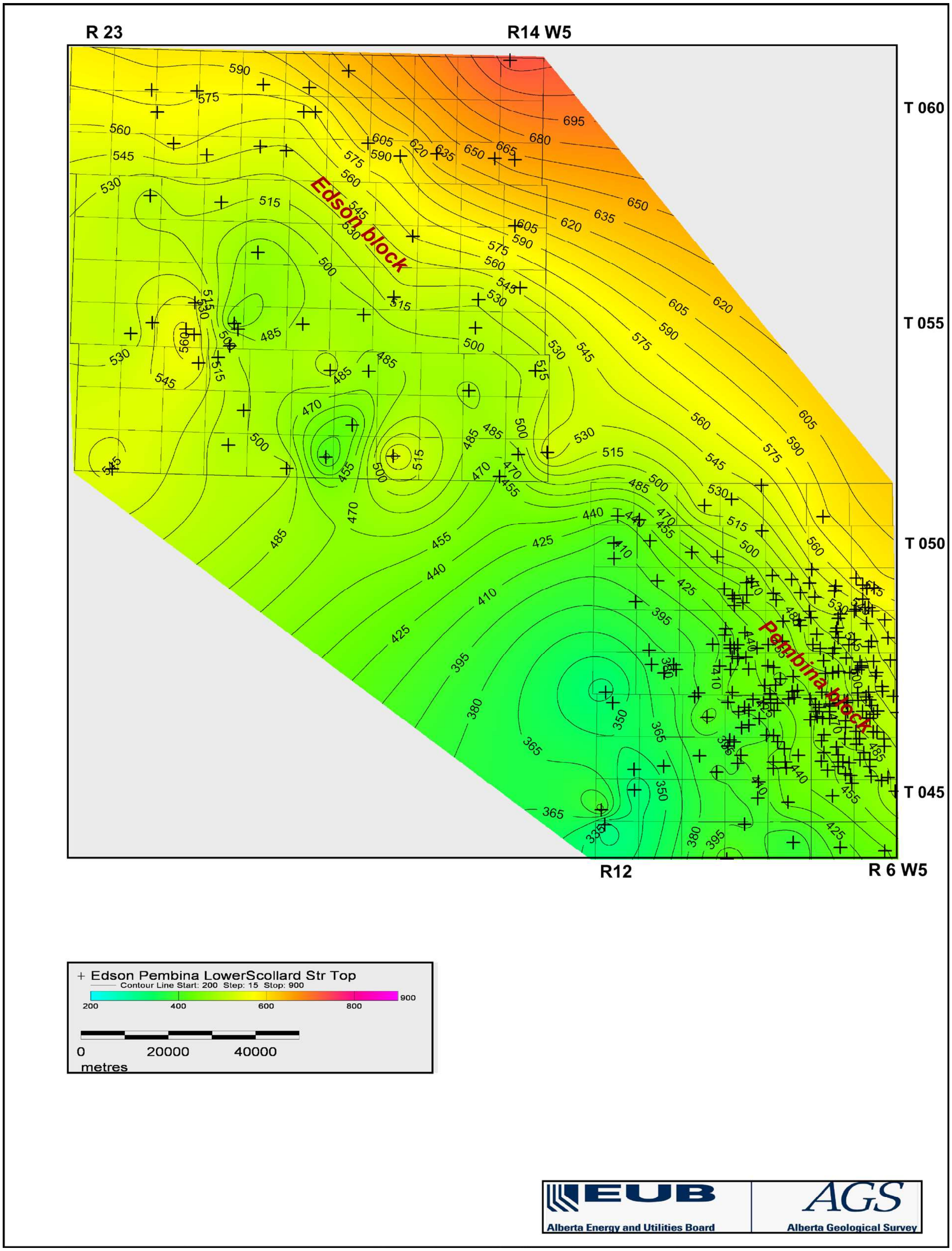


Figure 27. Structural contour map at the top of the lower member of the Scollard Formation, Pembina and Edson study areas.

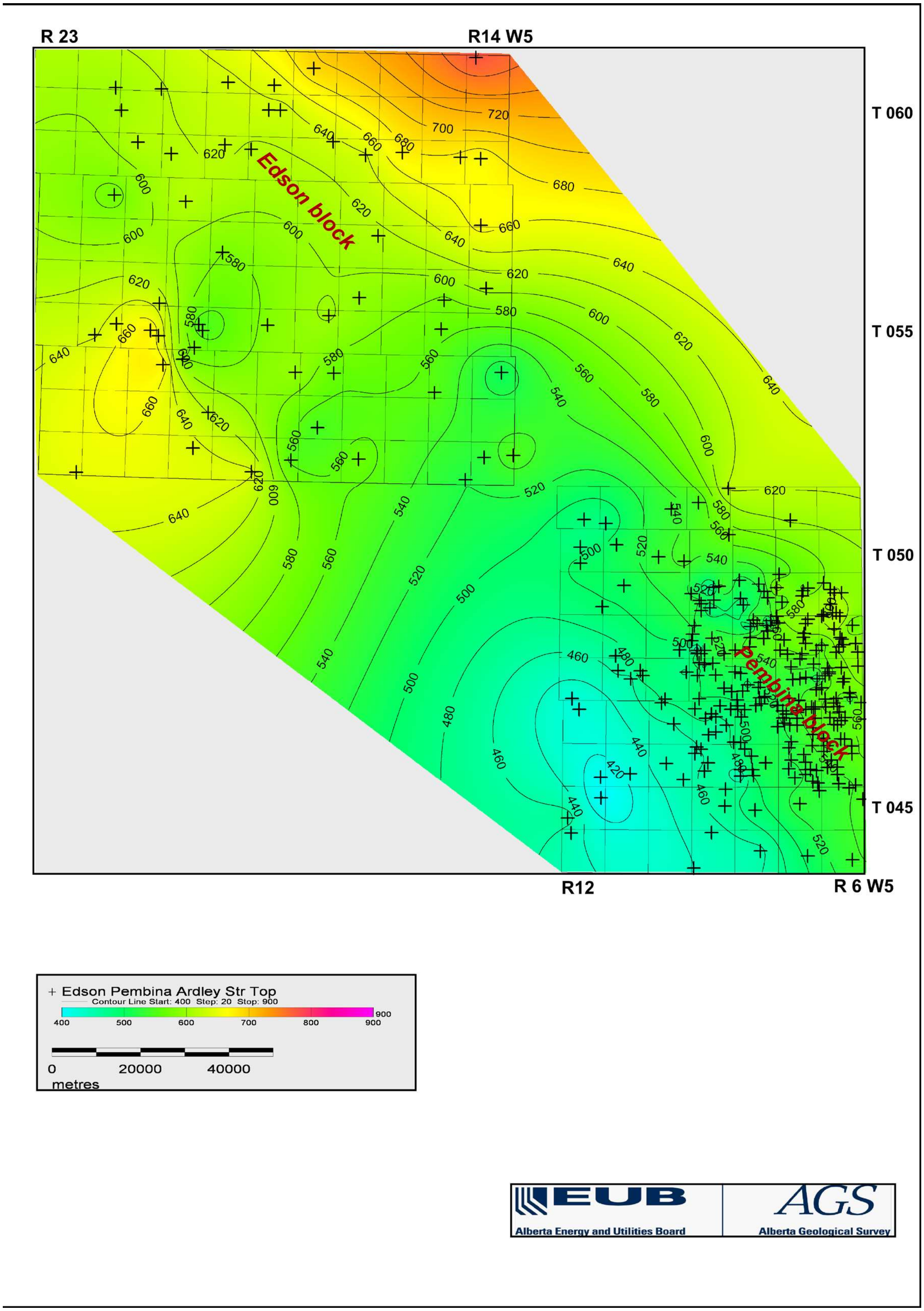


Figure 28. Structural contour map at the top of the upper member of the Scollard Formation, Pembina and Edson study areas.

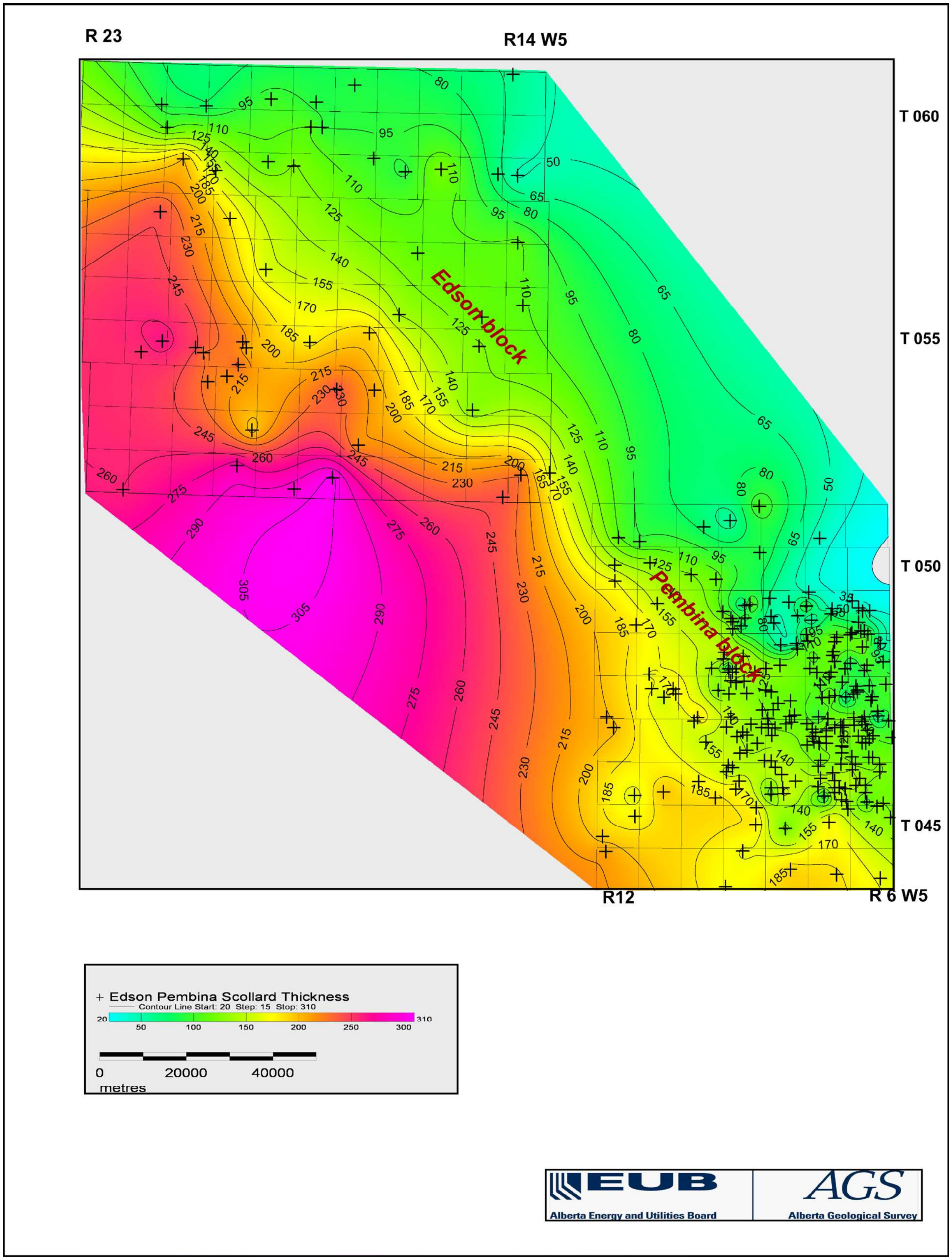


Figure 29. Isopach map of the Scollard Formation thickness, Pembina and Edson study areas.

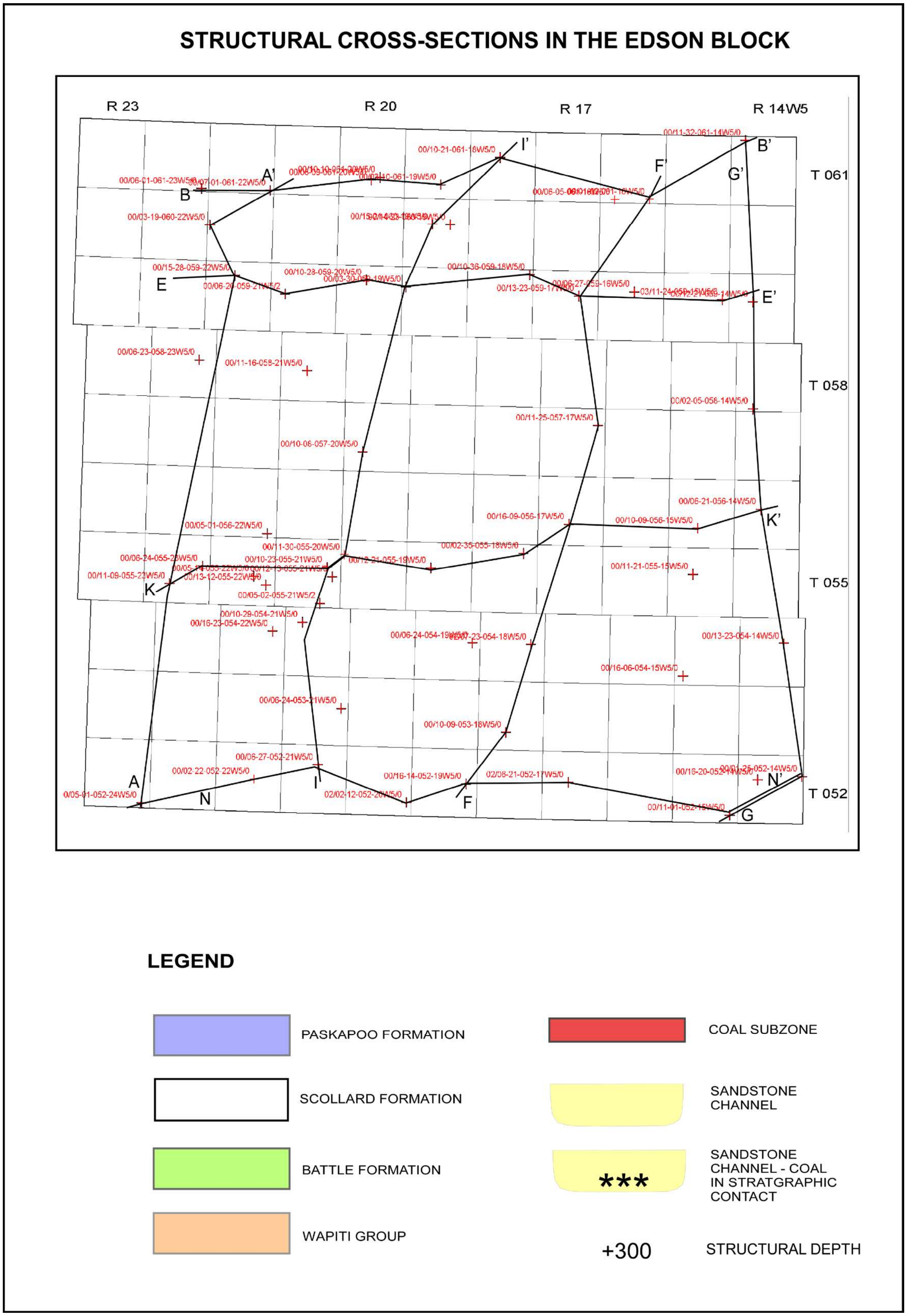


Figure 30. Map of the structural cross-sections in the Edson study area and the legend of the symbols used in the cross-sections.

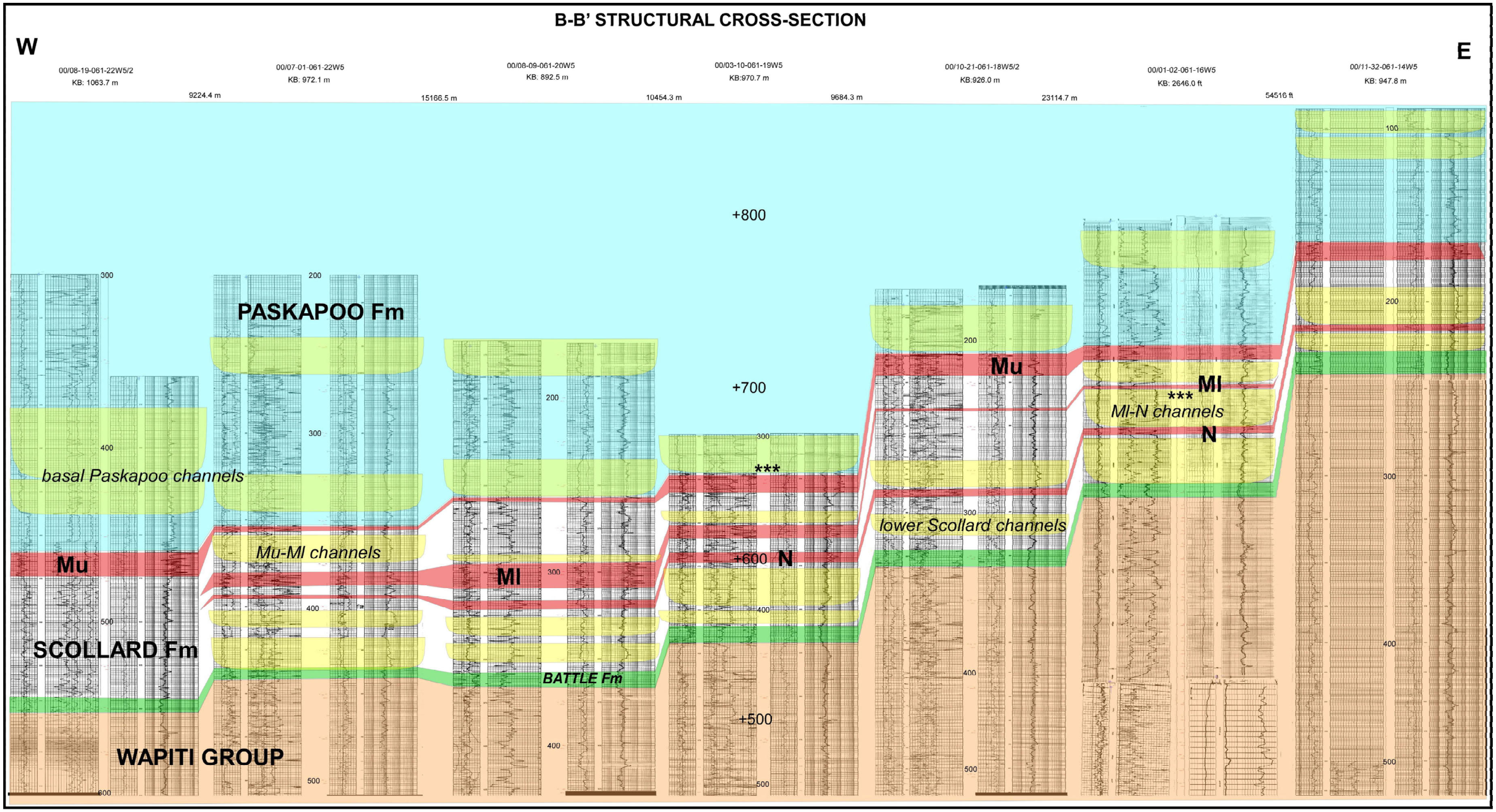


Figure 31. B-B' west-east structural cross-section, Edson study area.

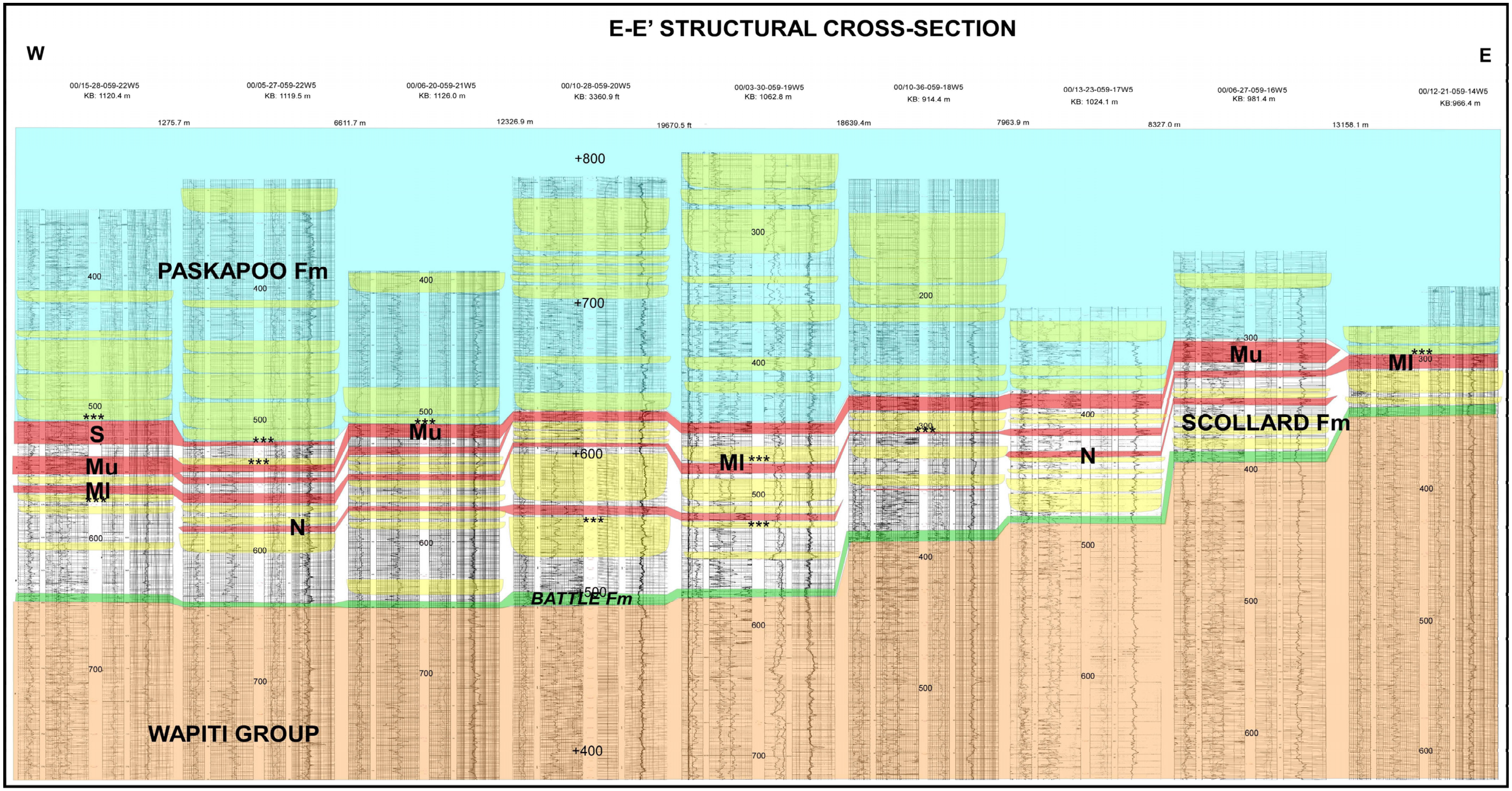


Figure 32. E-E' west-east structural cross-section, Edson study area.

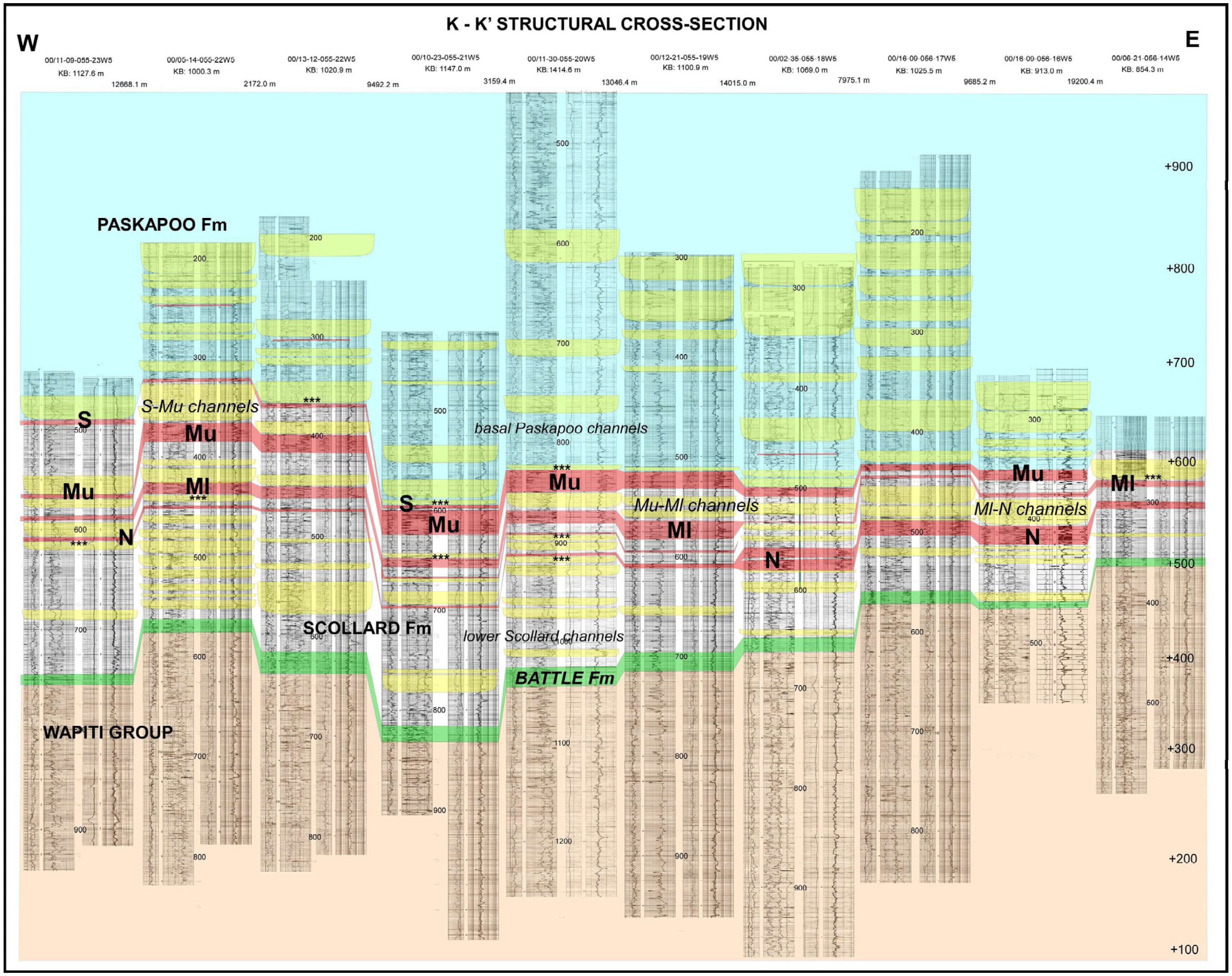


Figure 33. K-K' west-east structural cross-section, Edson study area.

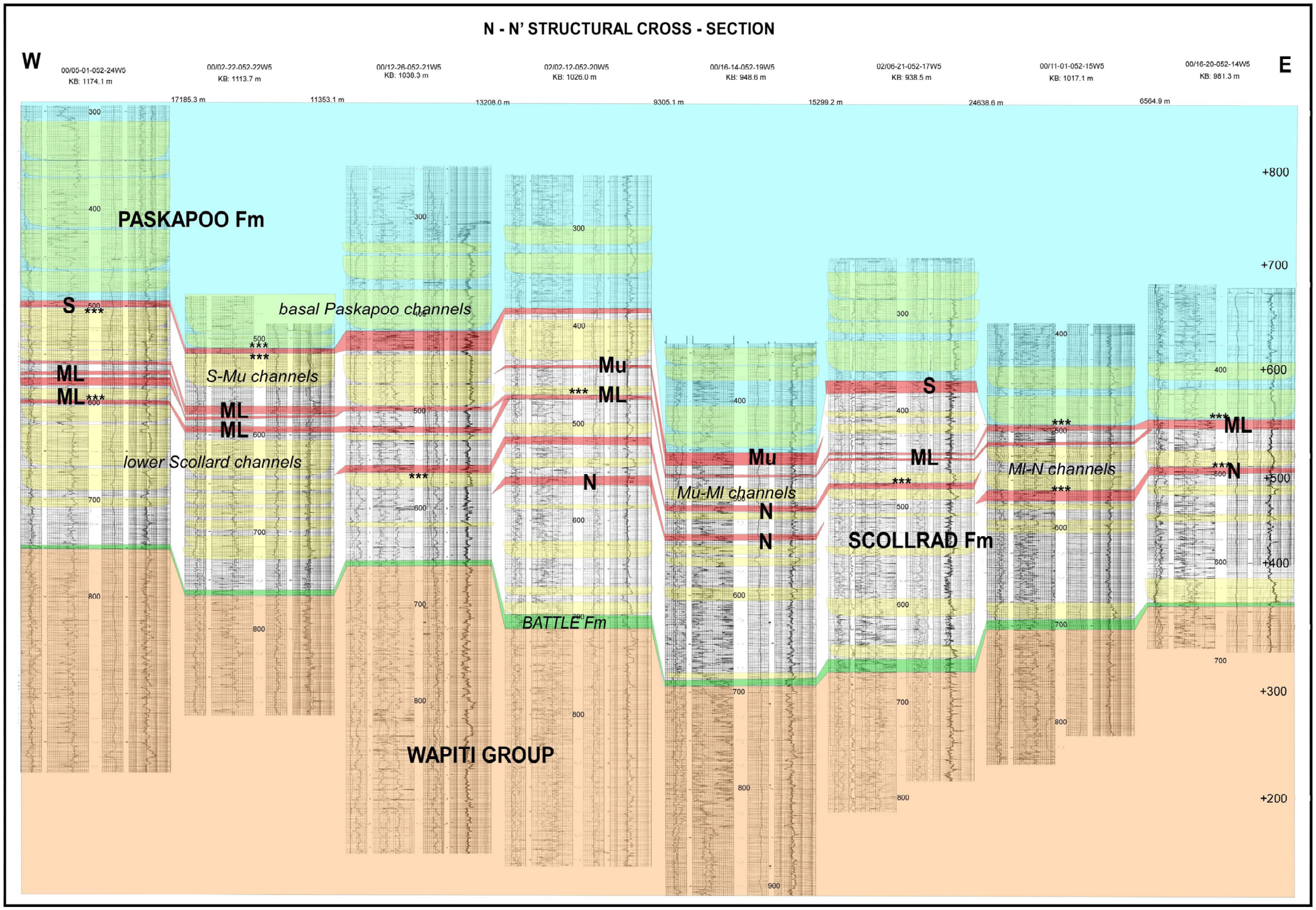


Figure 34. N-N' west-east structural cross-section, Edson study area.

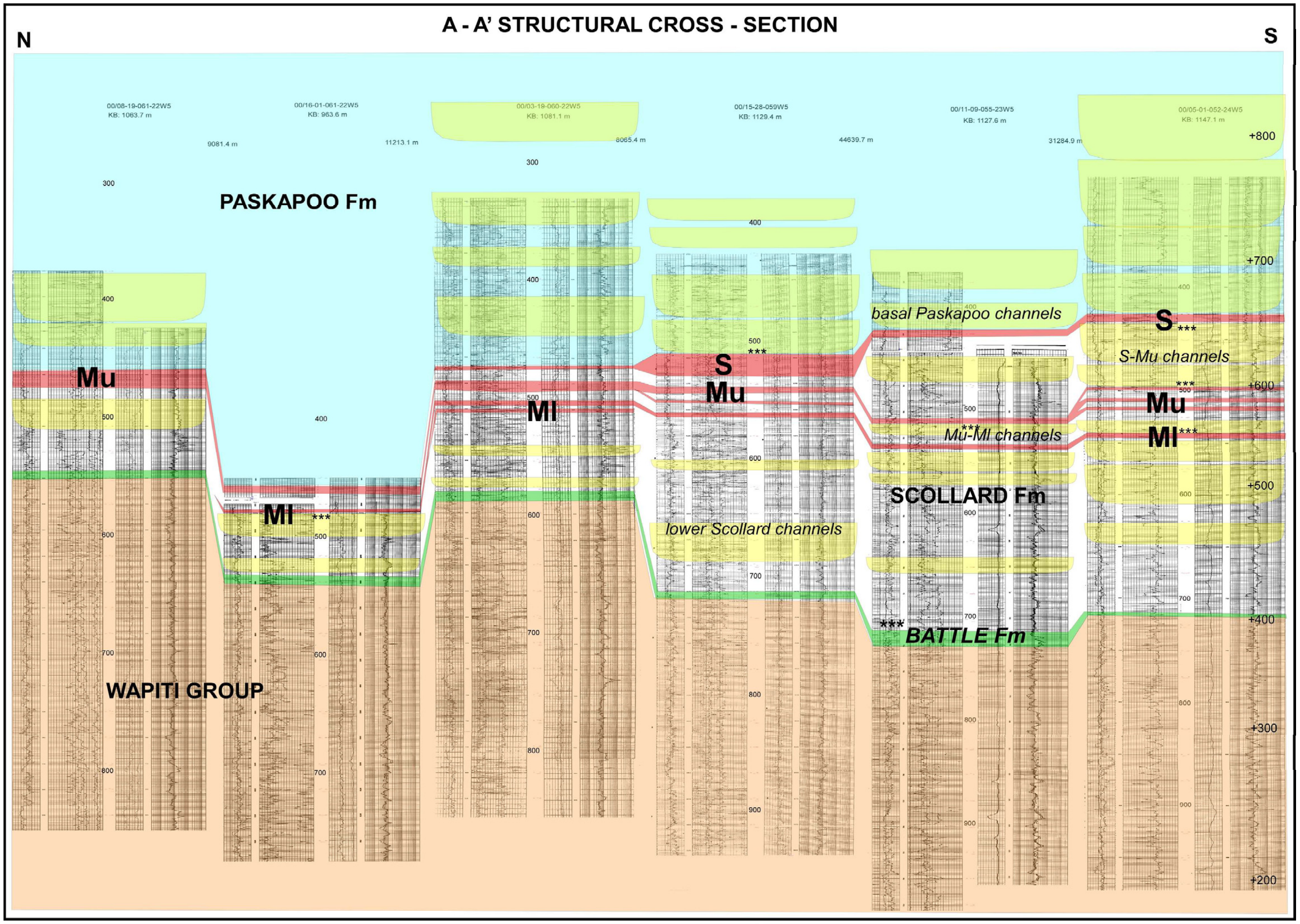


Figure 35. A-A' north-south structural cross-section, Edson study area.

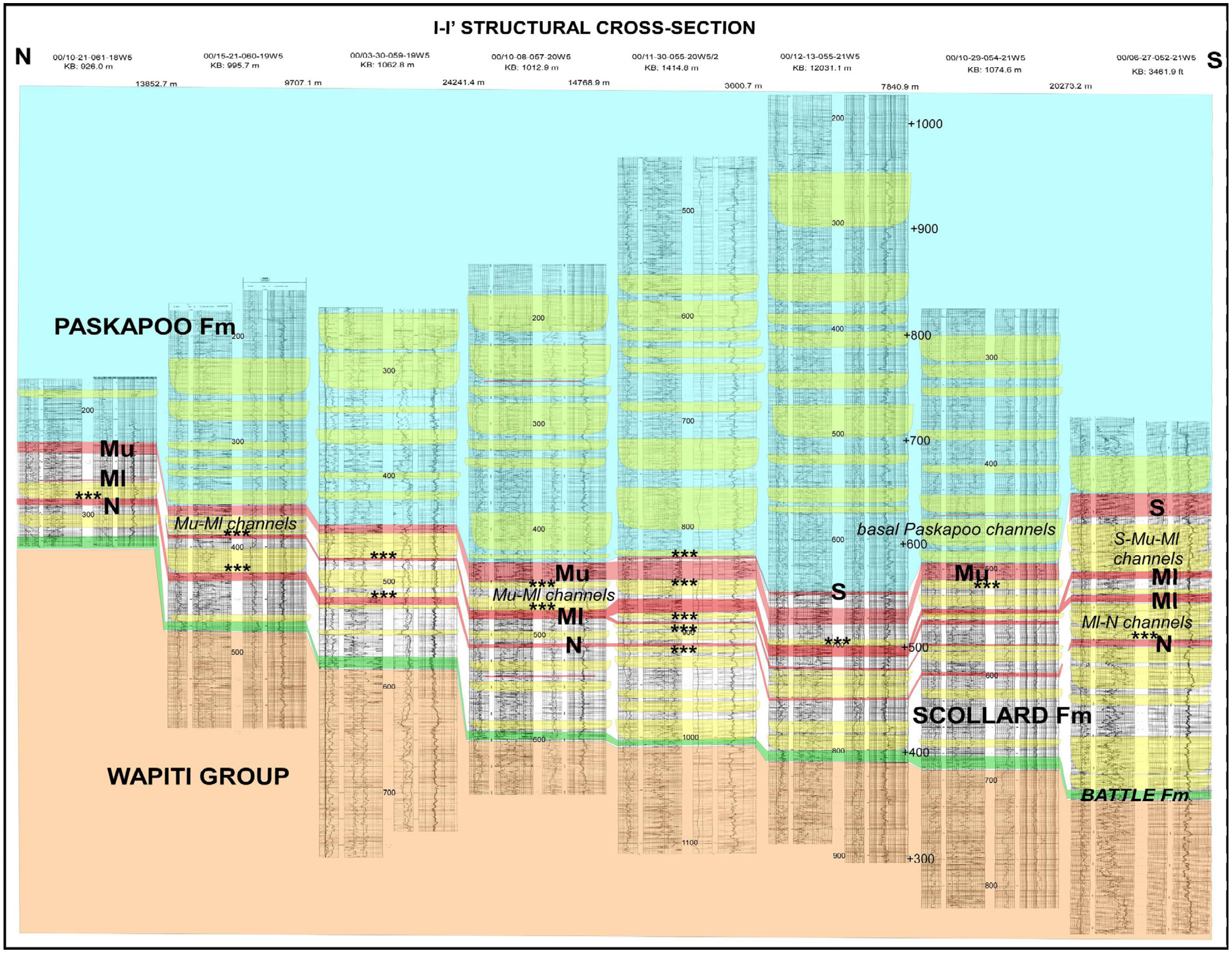


Figure 36. I-I' north-south structural cross-section, Edson study area.

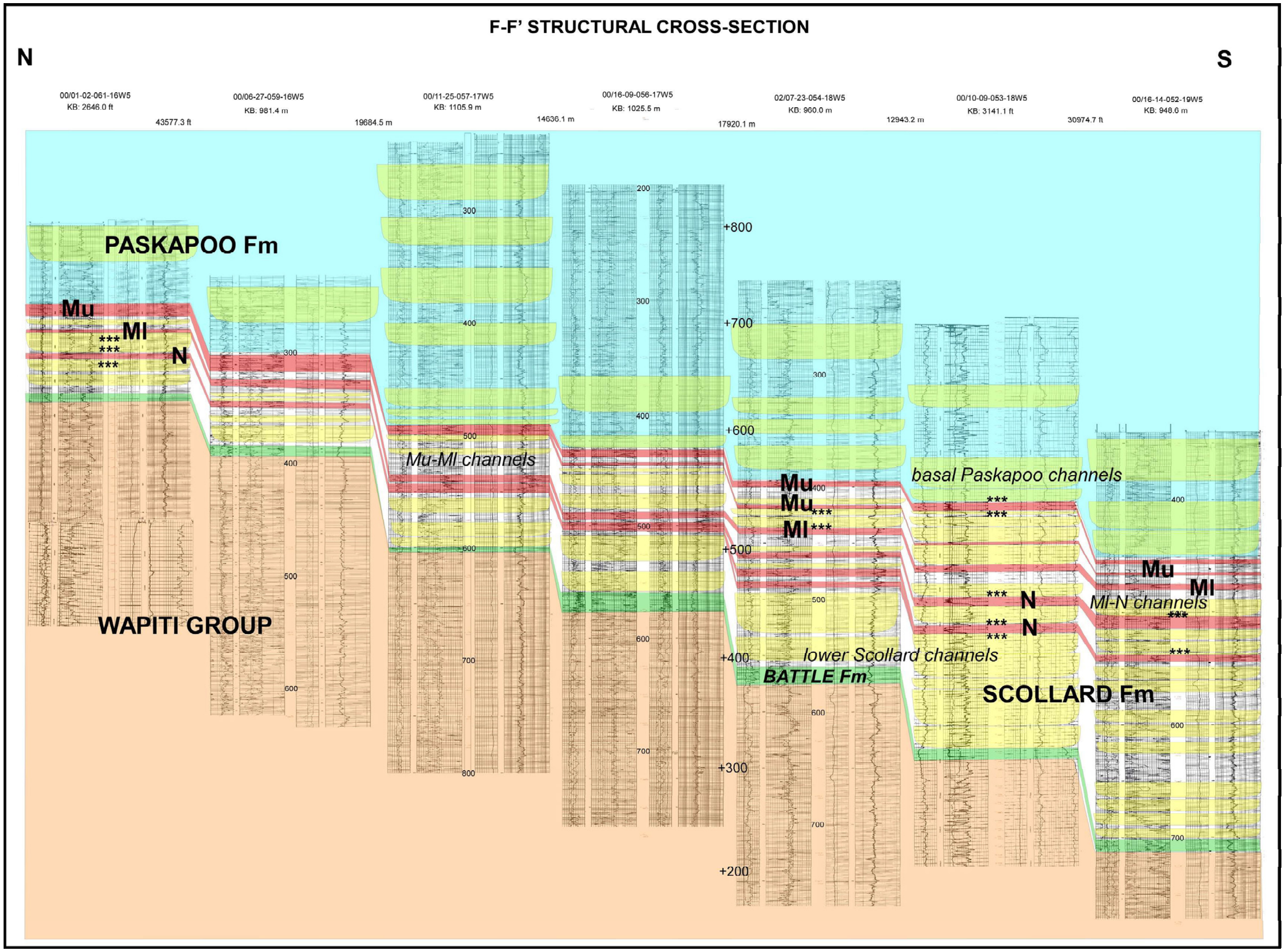


Figure 37. F-F' north-south structural cross-section, Edson study area.

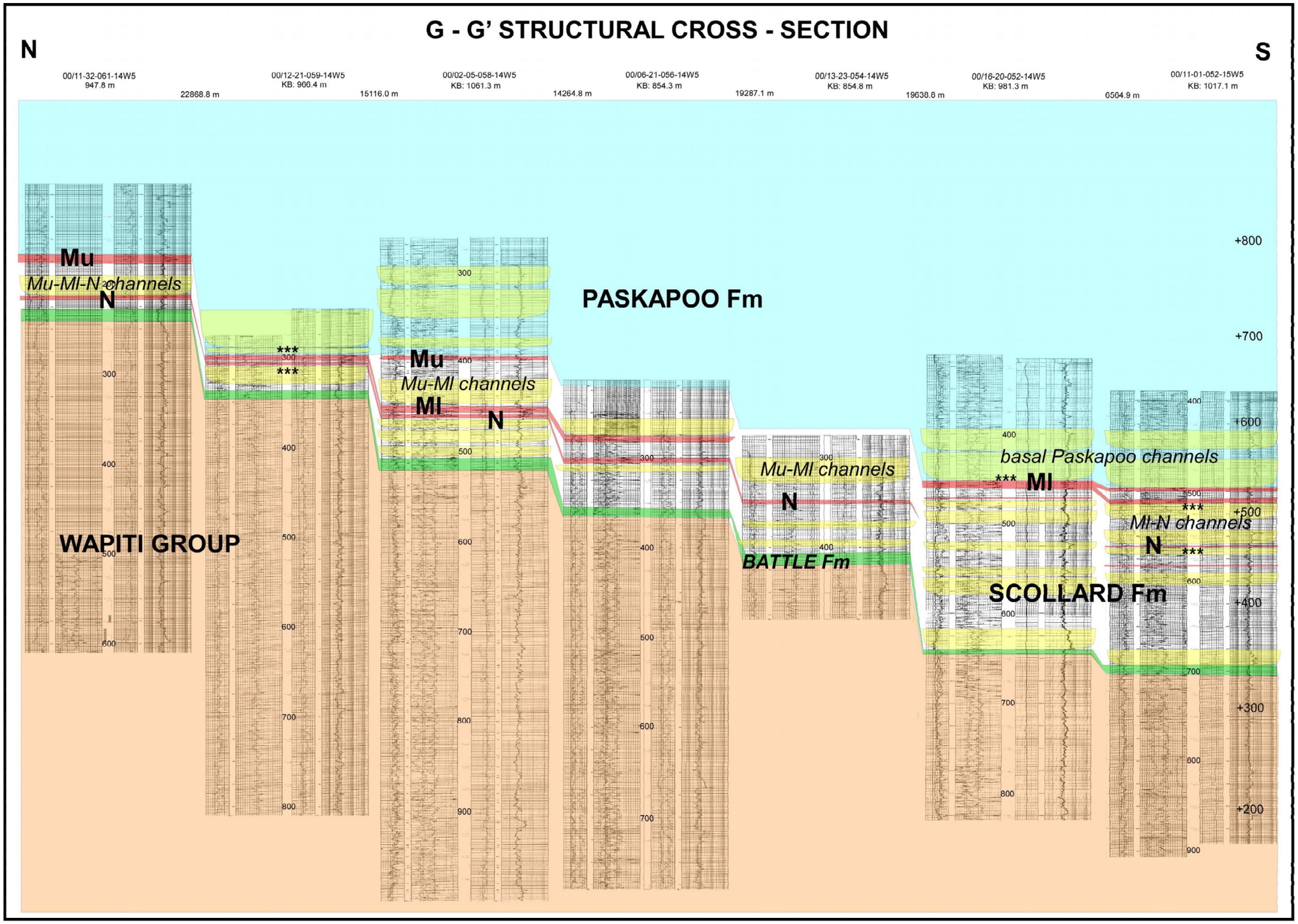


Figure 38. G-G' north-south structural cross-section, Edson study area.

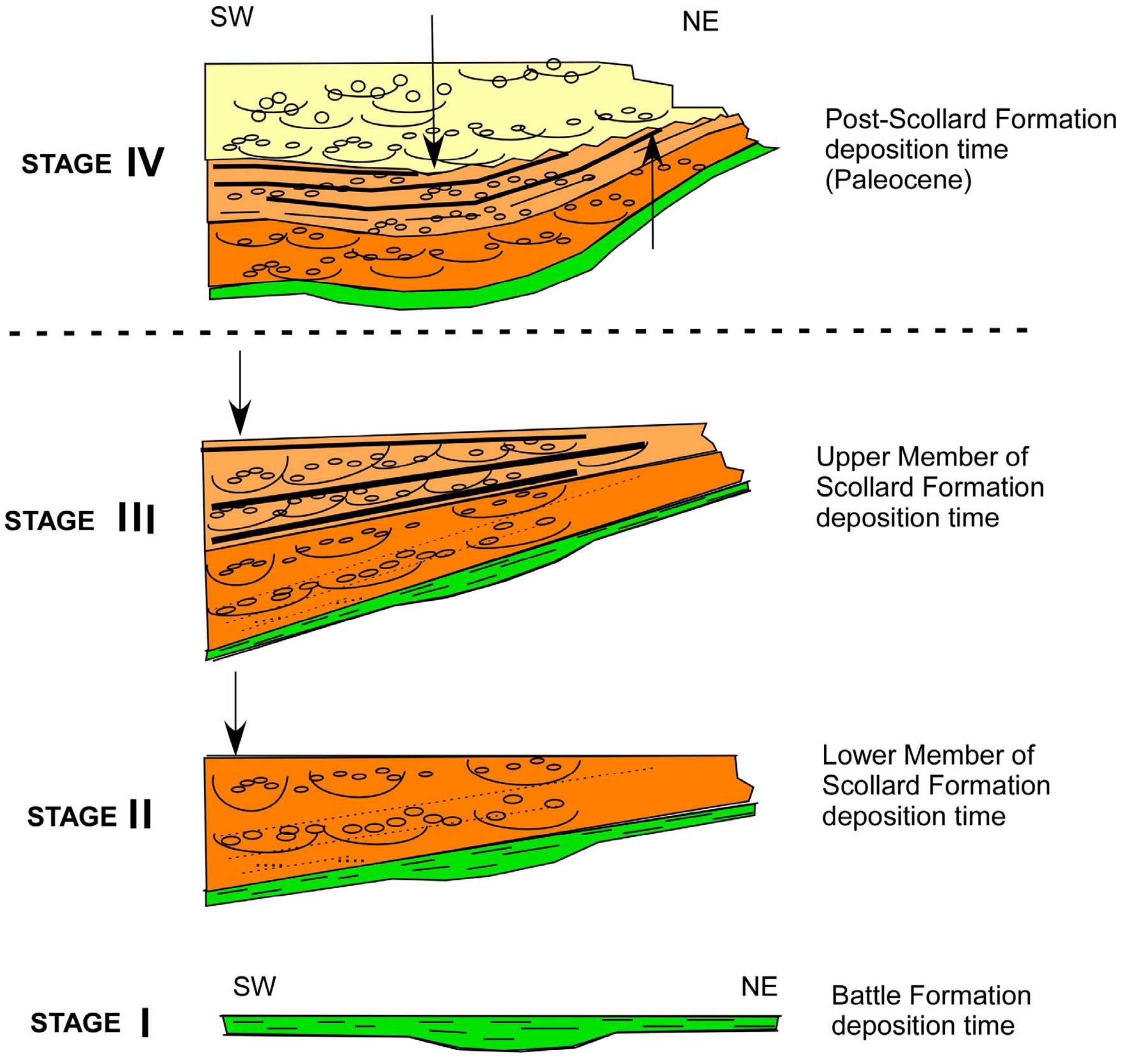


Figure 39. Structural re-adjustments model, Edson study area.

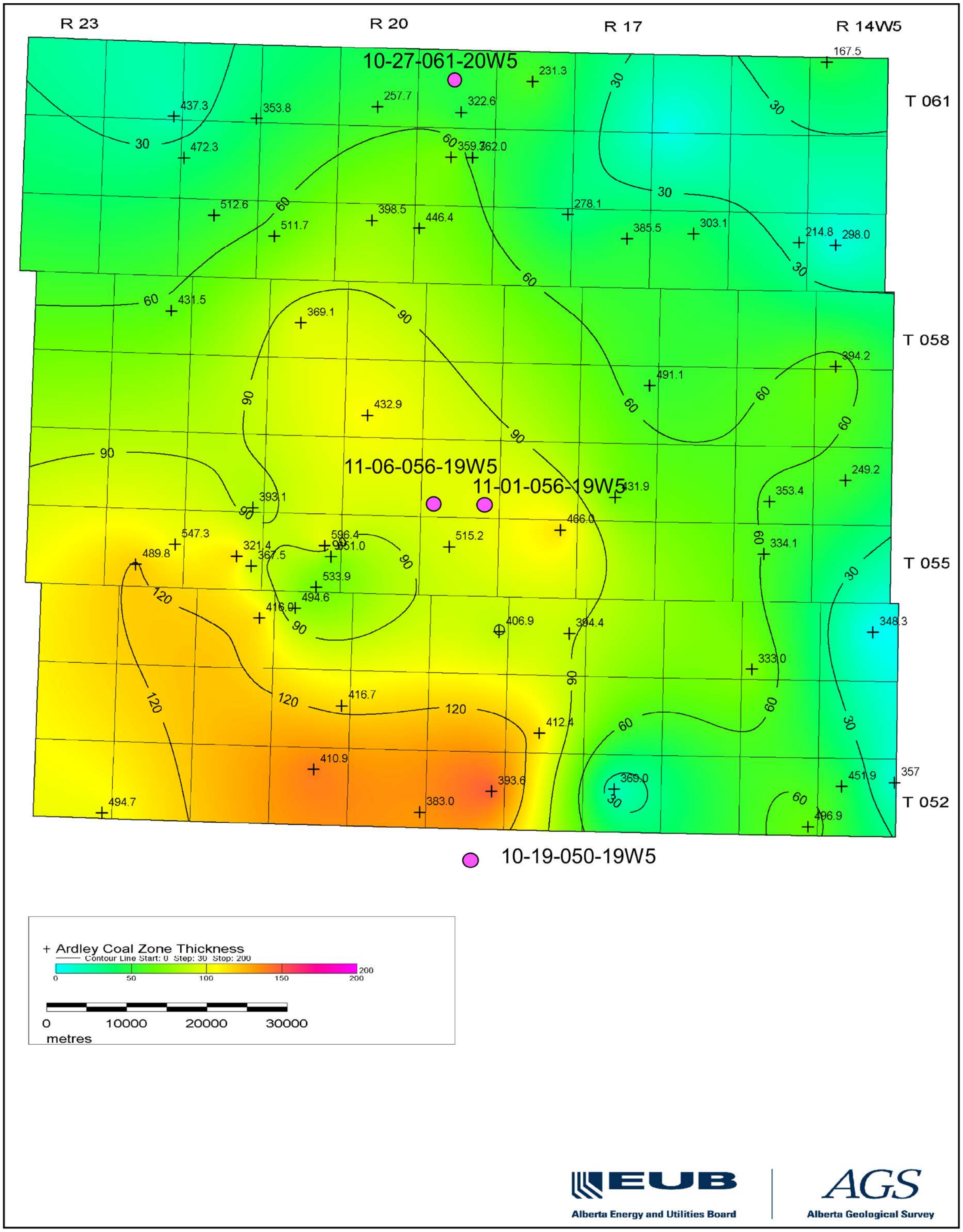


Figure 40. Location of the examined drillcores projected on the Ardley Coal Zone isopach map, Edson study area.

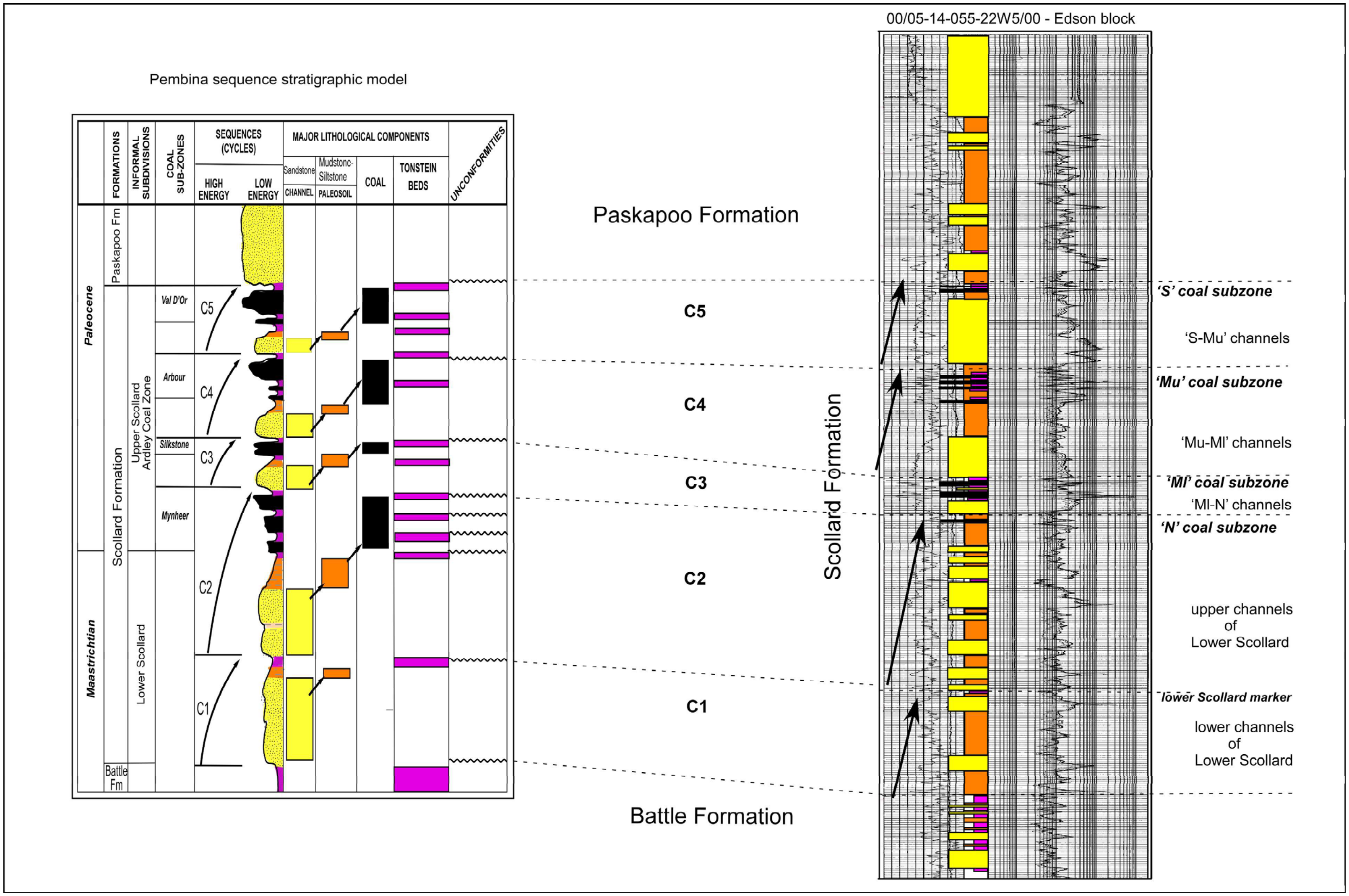


Figure 41. The comparison of the Pembina stratigraphic model with a geophysical log record of the Battle-Scollard-basal Paskapoo succession from the Edson block.

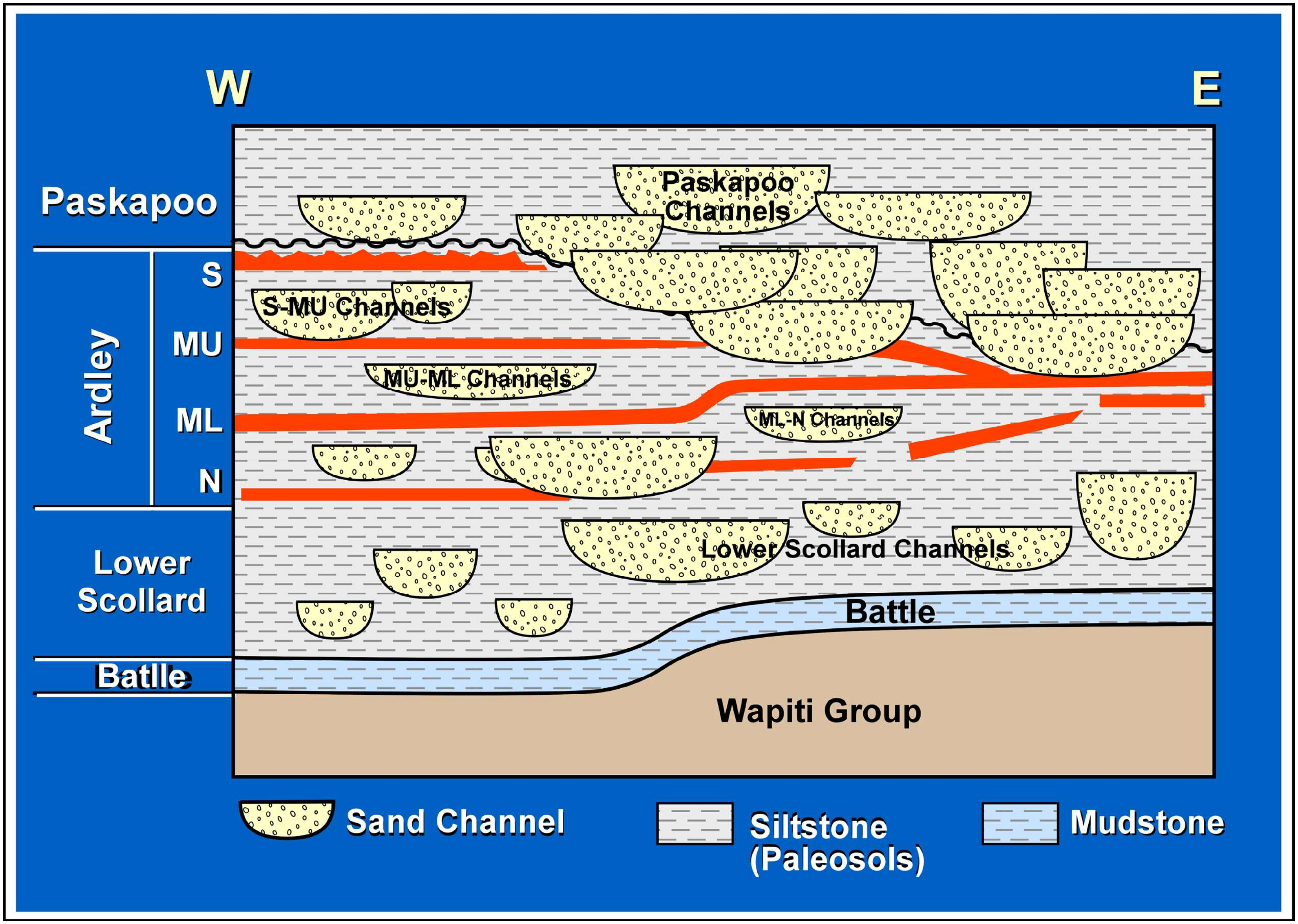


Figure 42. Schematic chart of the coal subzones and sandstone channels distribution in the Edson study area.

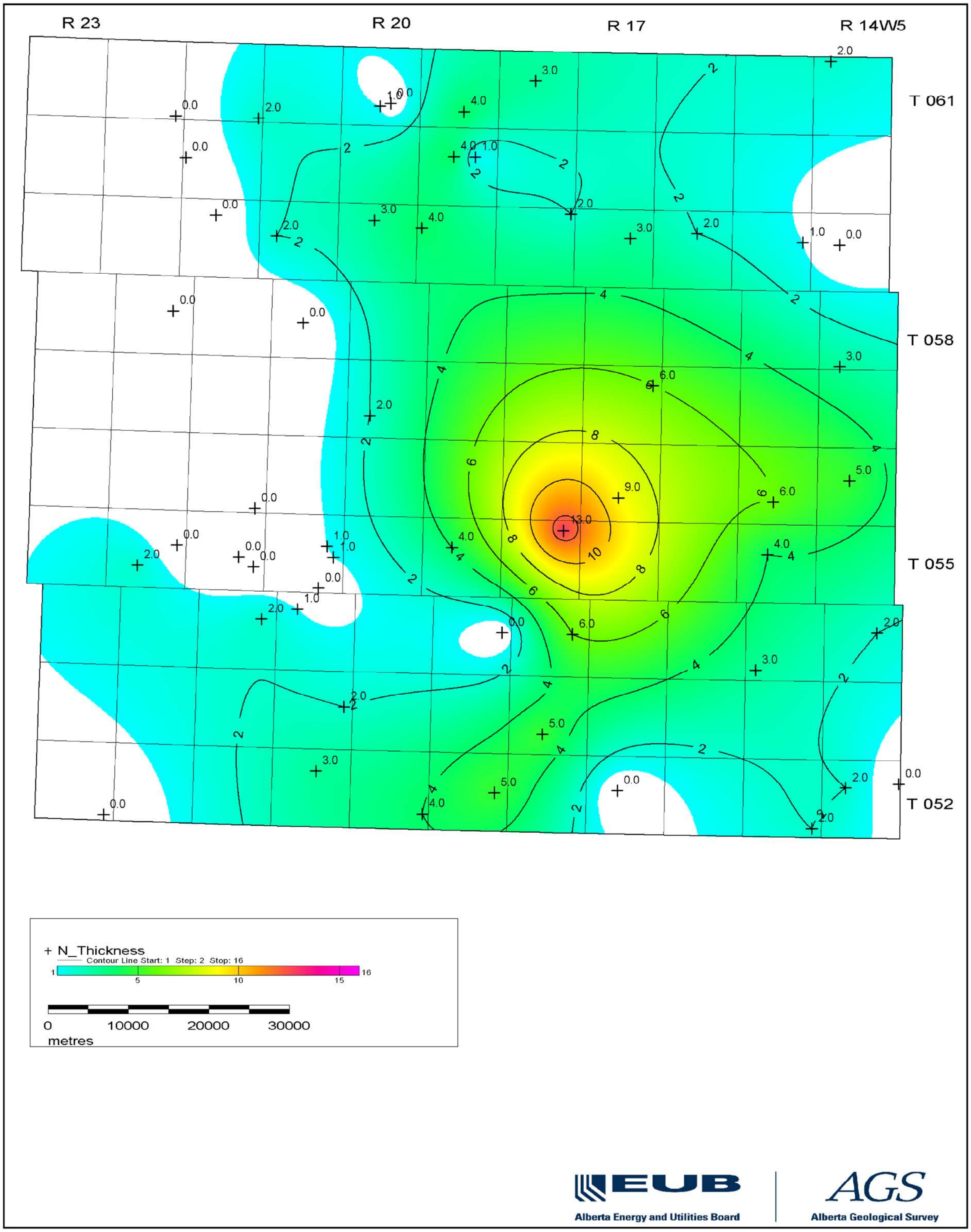


Figure 43. Isopach map of the 'N' coal subzone thickness, Edson study area.

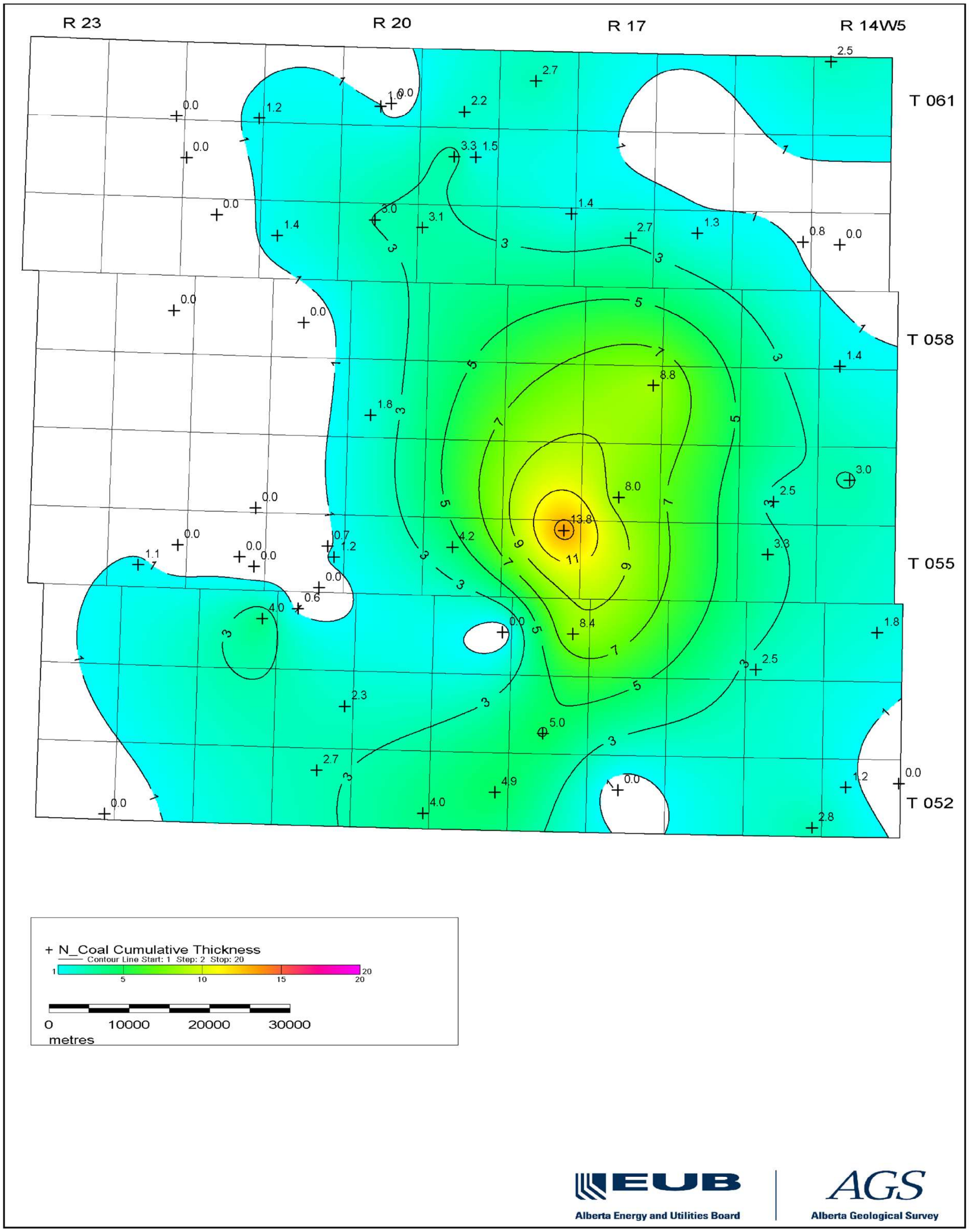


Figure 44. 'N' coal subzone coal cumulative thickness, Edson study area.

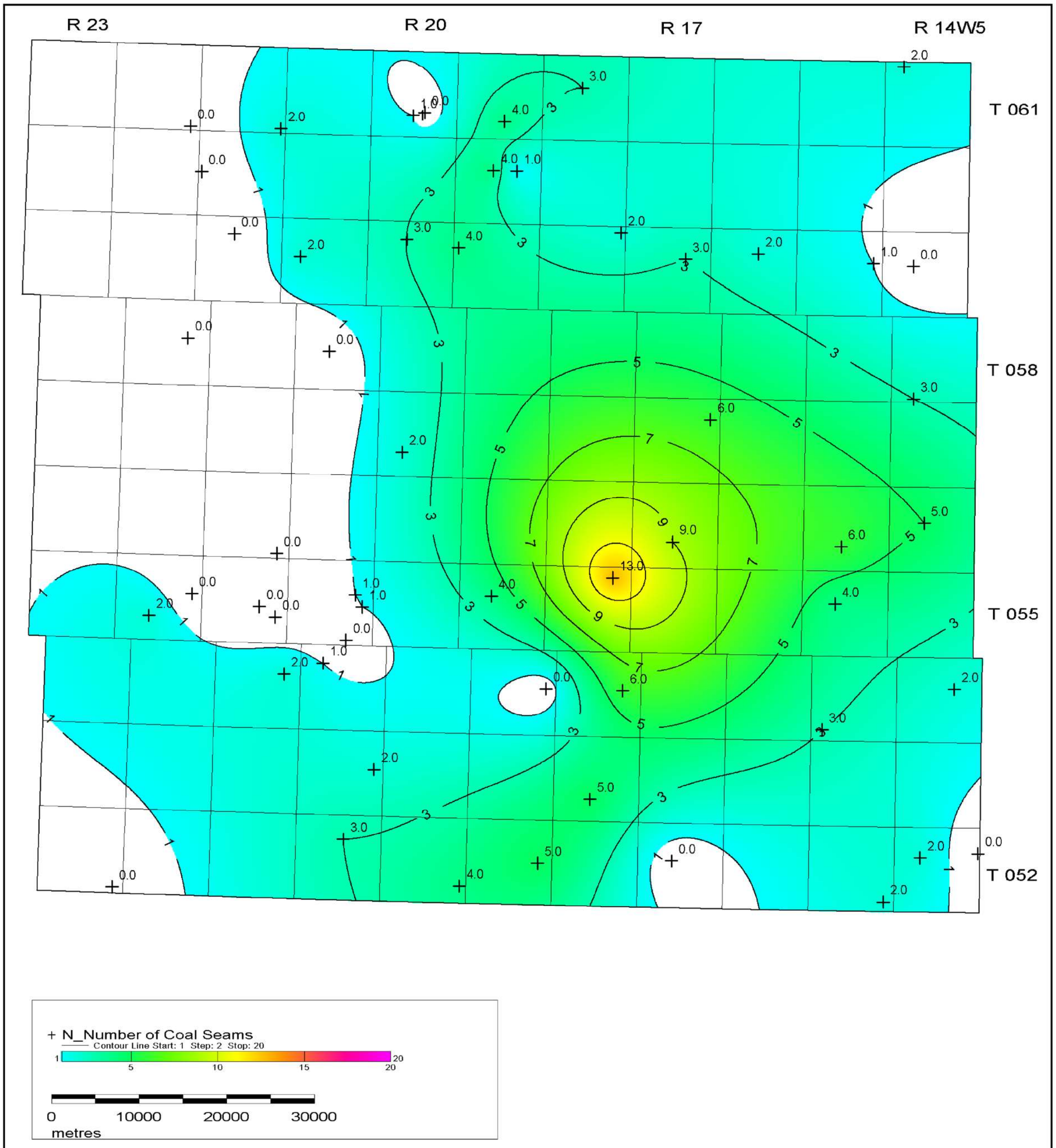


Figure 45. 'N' coal subzone number of coal seams, Edson study area.

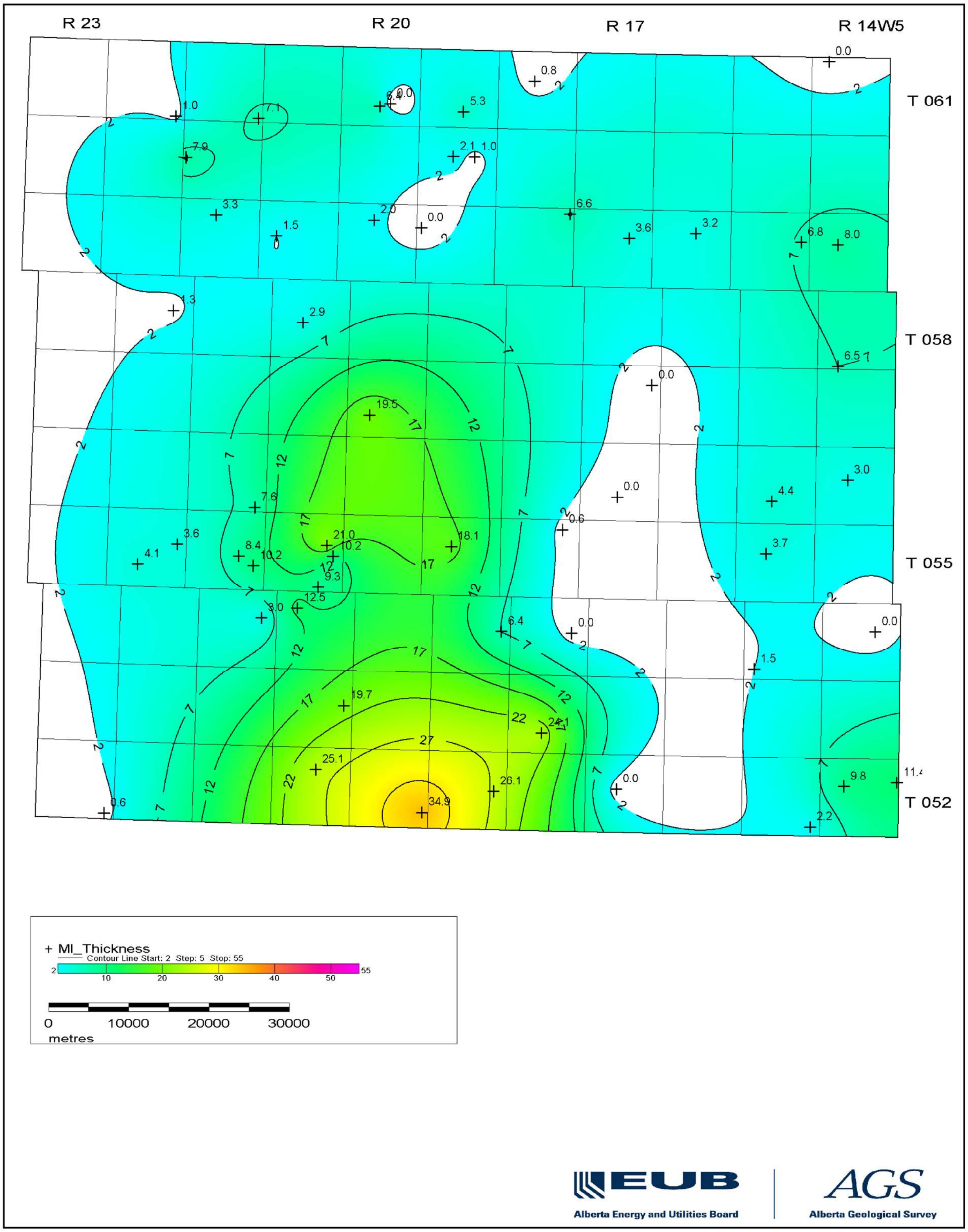


Figure 46. Isopach map of the 'MI' coal subzone thickness, Edson study area.

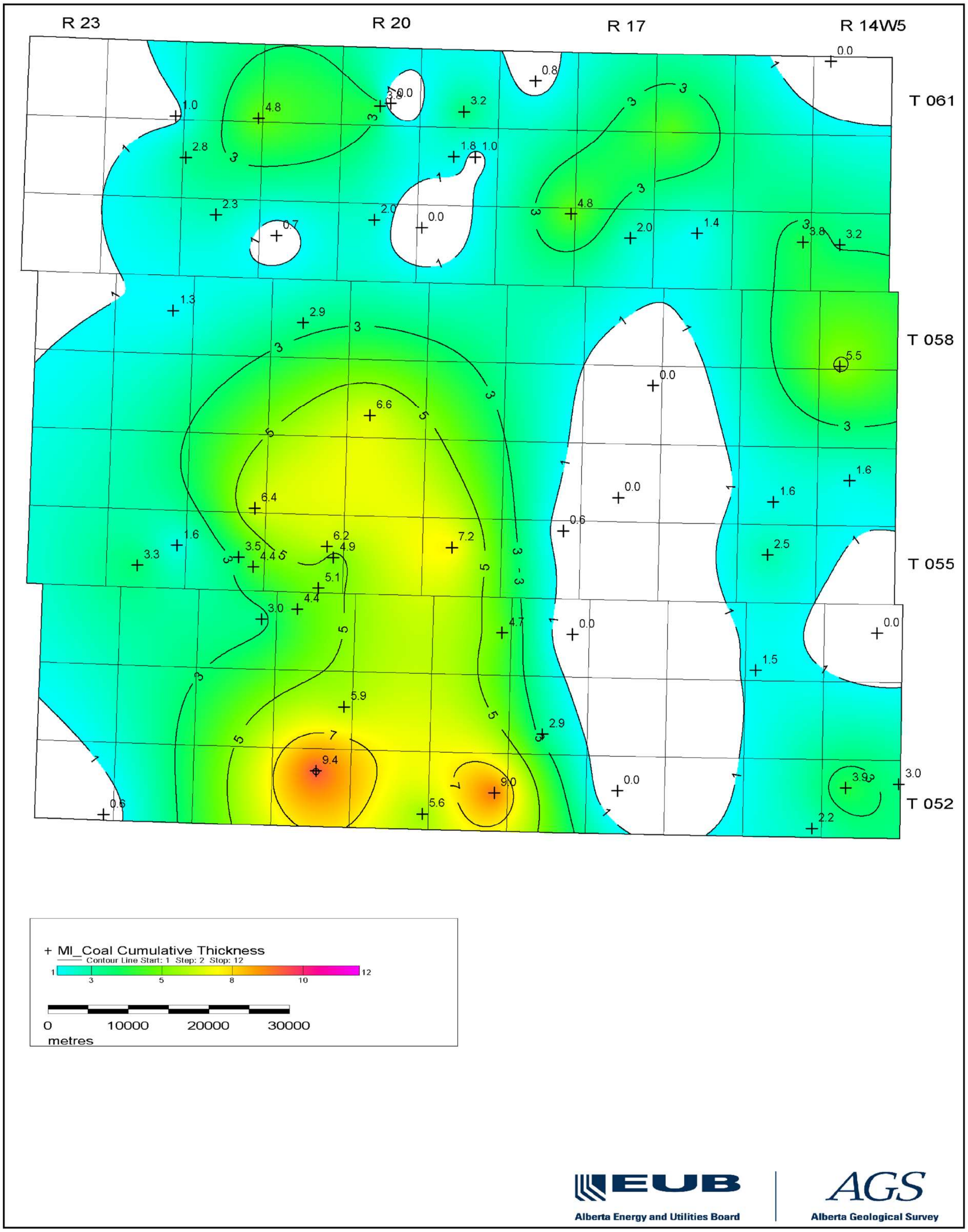


Figure 47. 'MI' coal subzone coal cumulative thickness, Edson study area.

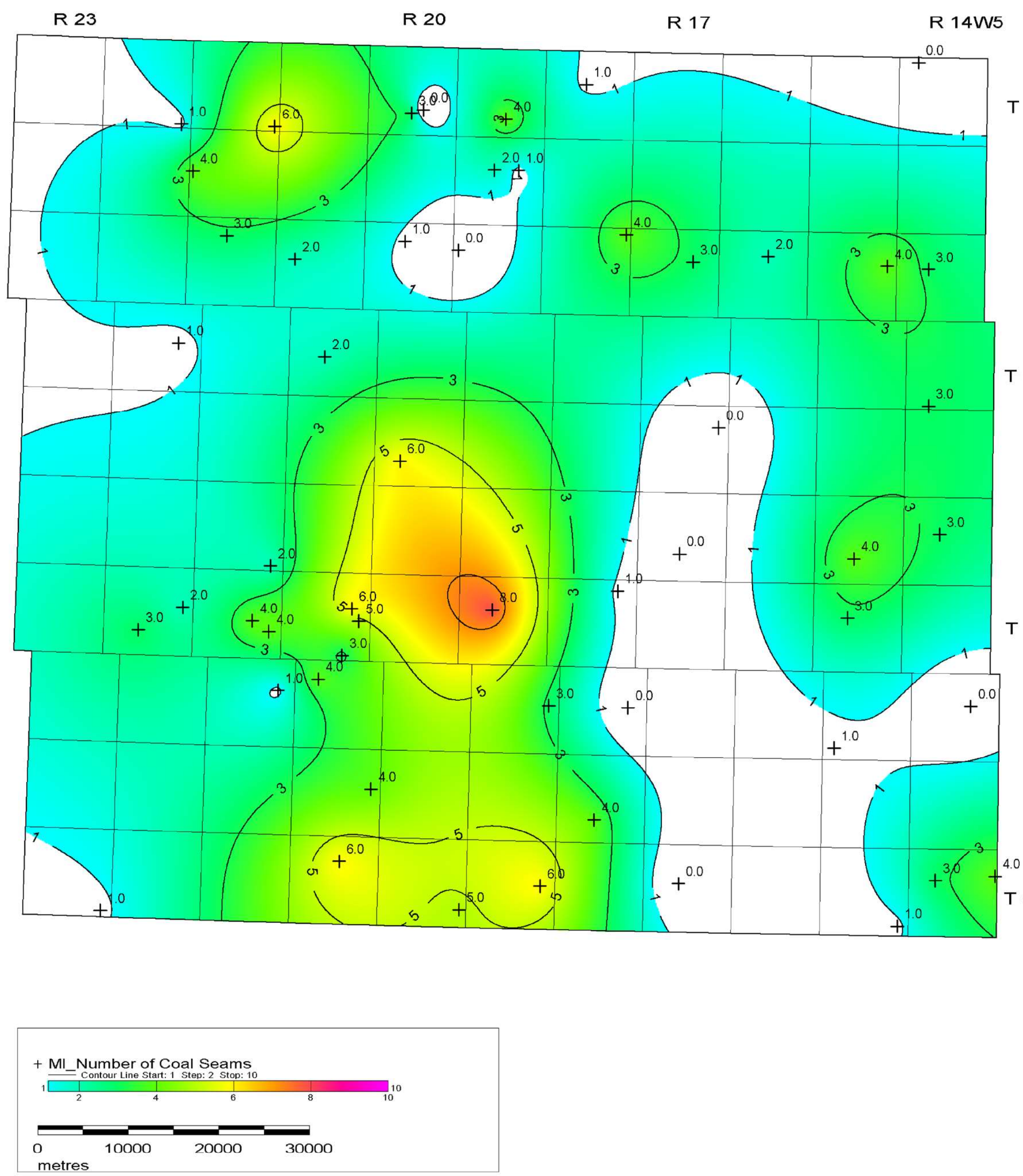


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Figure 48. 'MI' coal subzone number of coal seams, Edson study area.

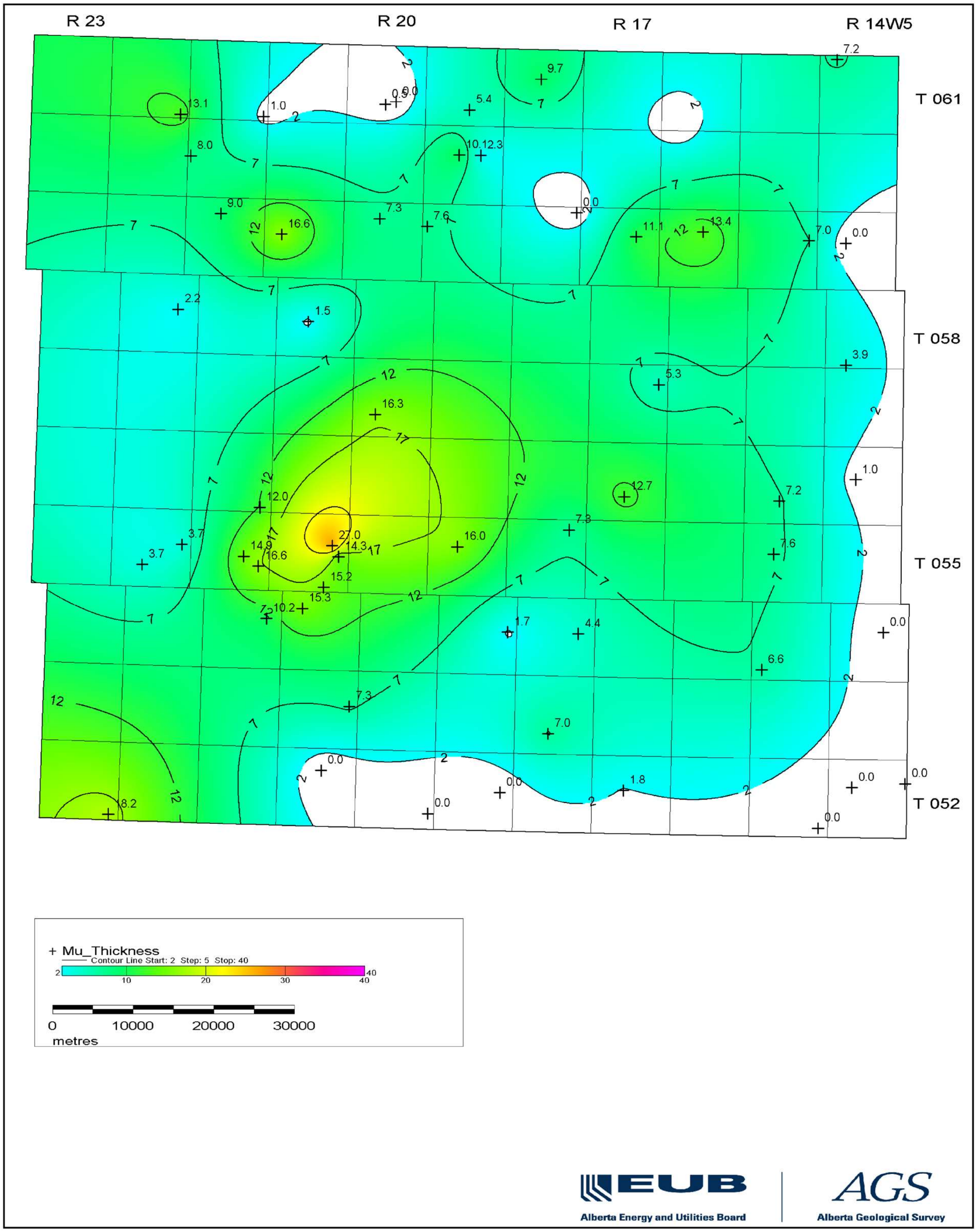

Figure 49. Isopach map of the 'Mu' coal subzone thickness, Edson study area.

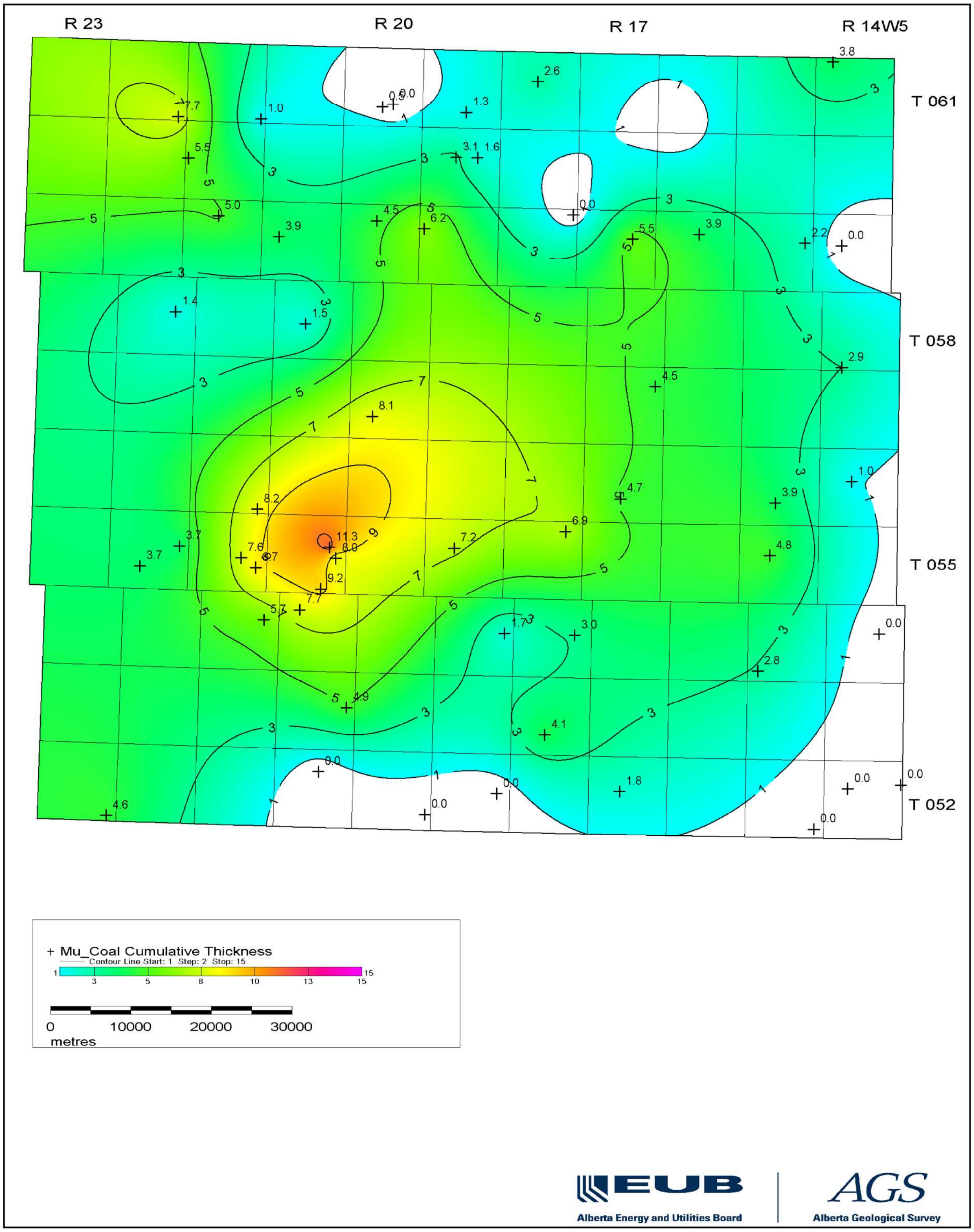

Figure 50. 'Mu' coal subzone coal cumulative thickness, Edson study area.

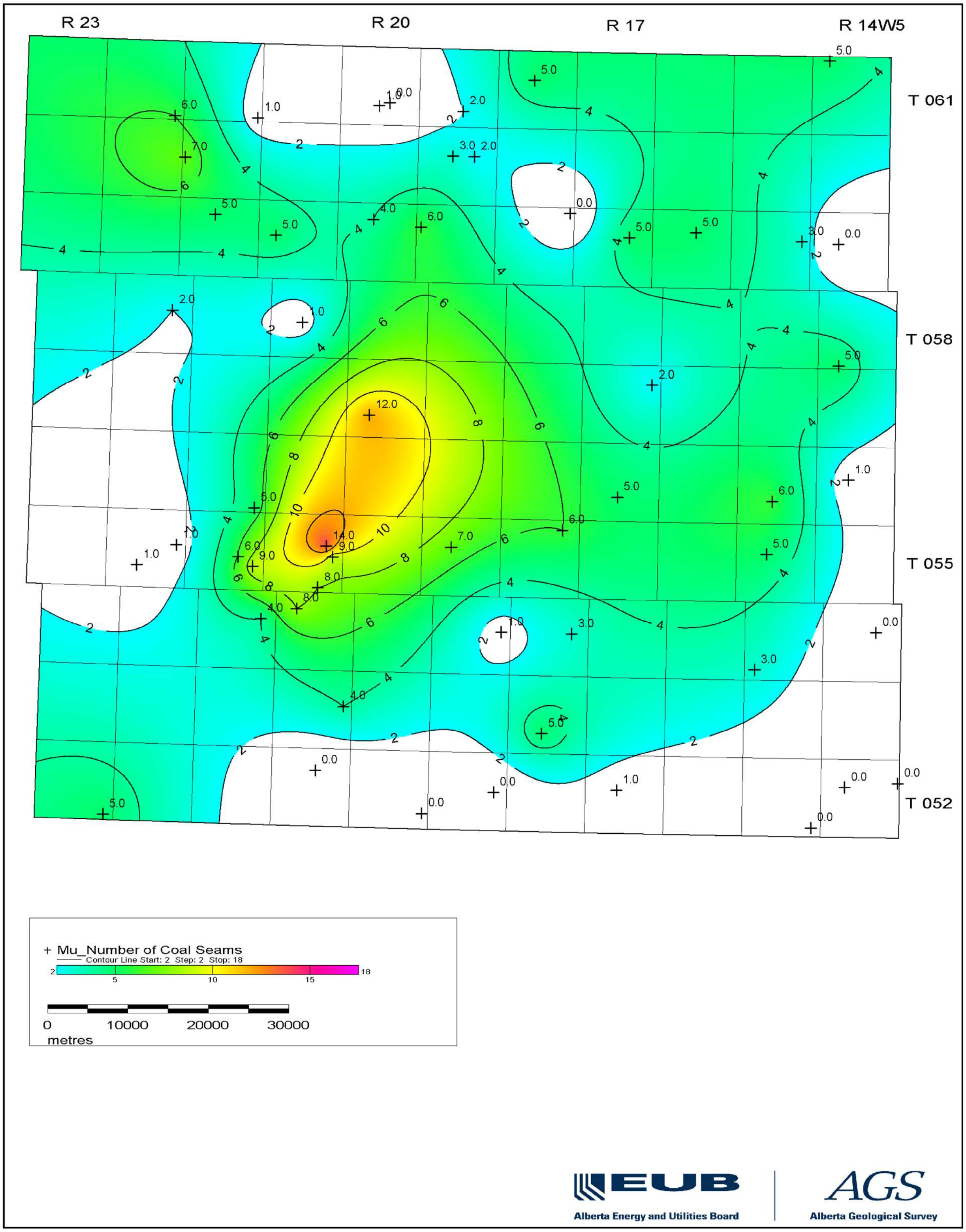

Figure 51. 'Mu' coal subzone number of coal seams, Edson study area.

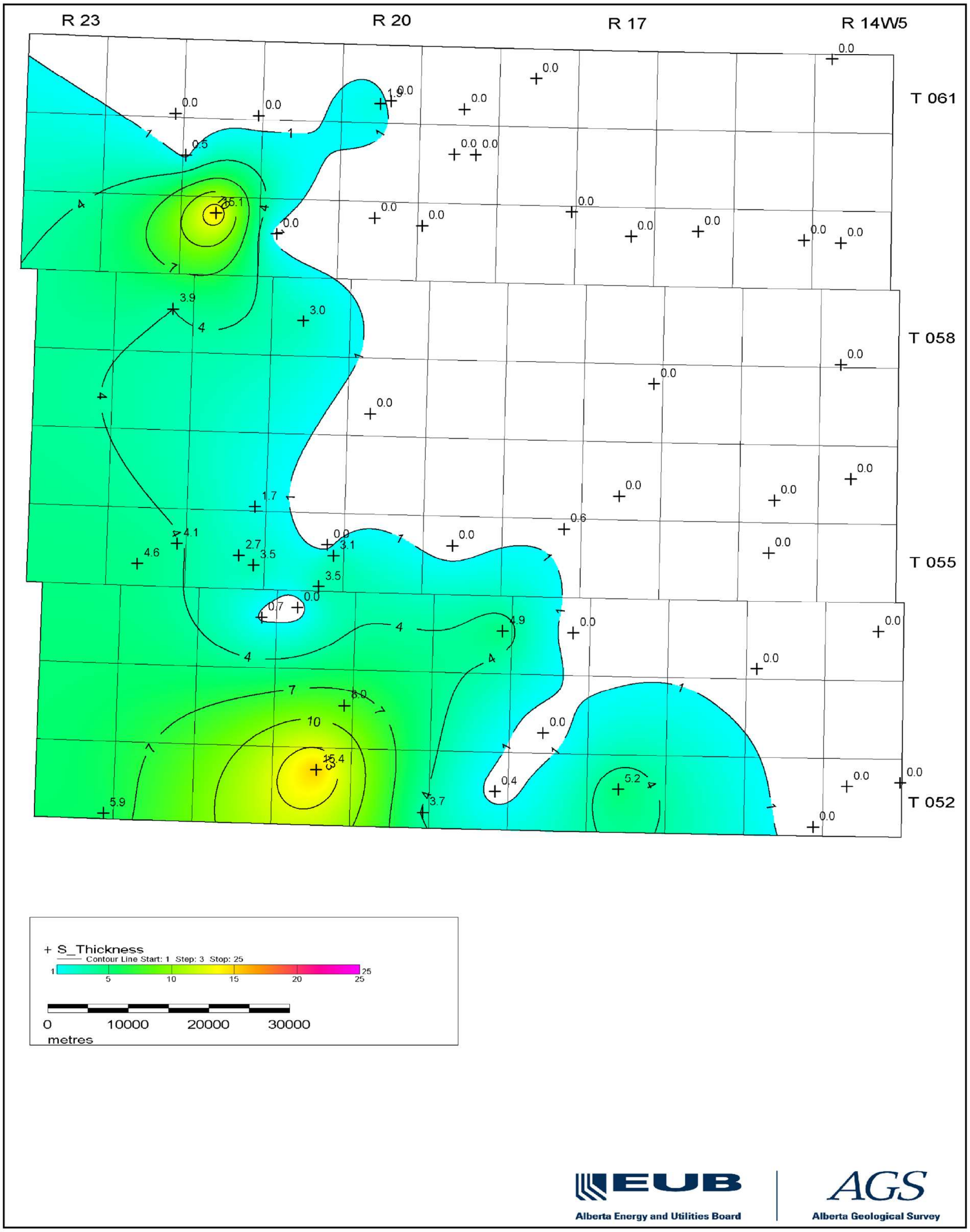

Figure 52. Isopach map of the 'S' coal subzone thickness, Edson study area.

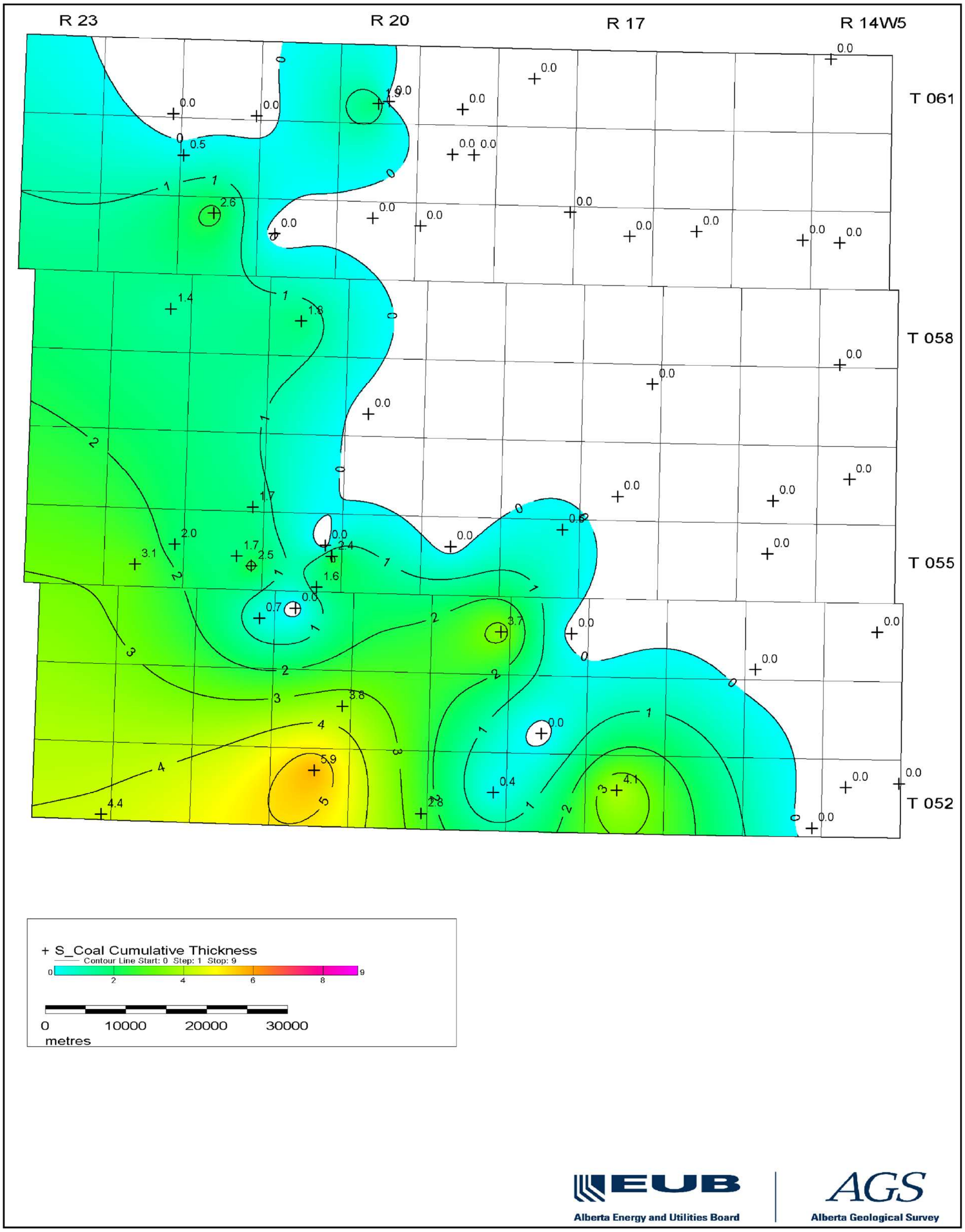

Figure 53. 'S' coal subzone coal cumulative thickness, Edson study area.

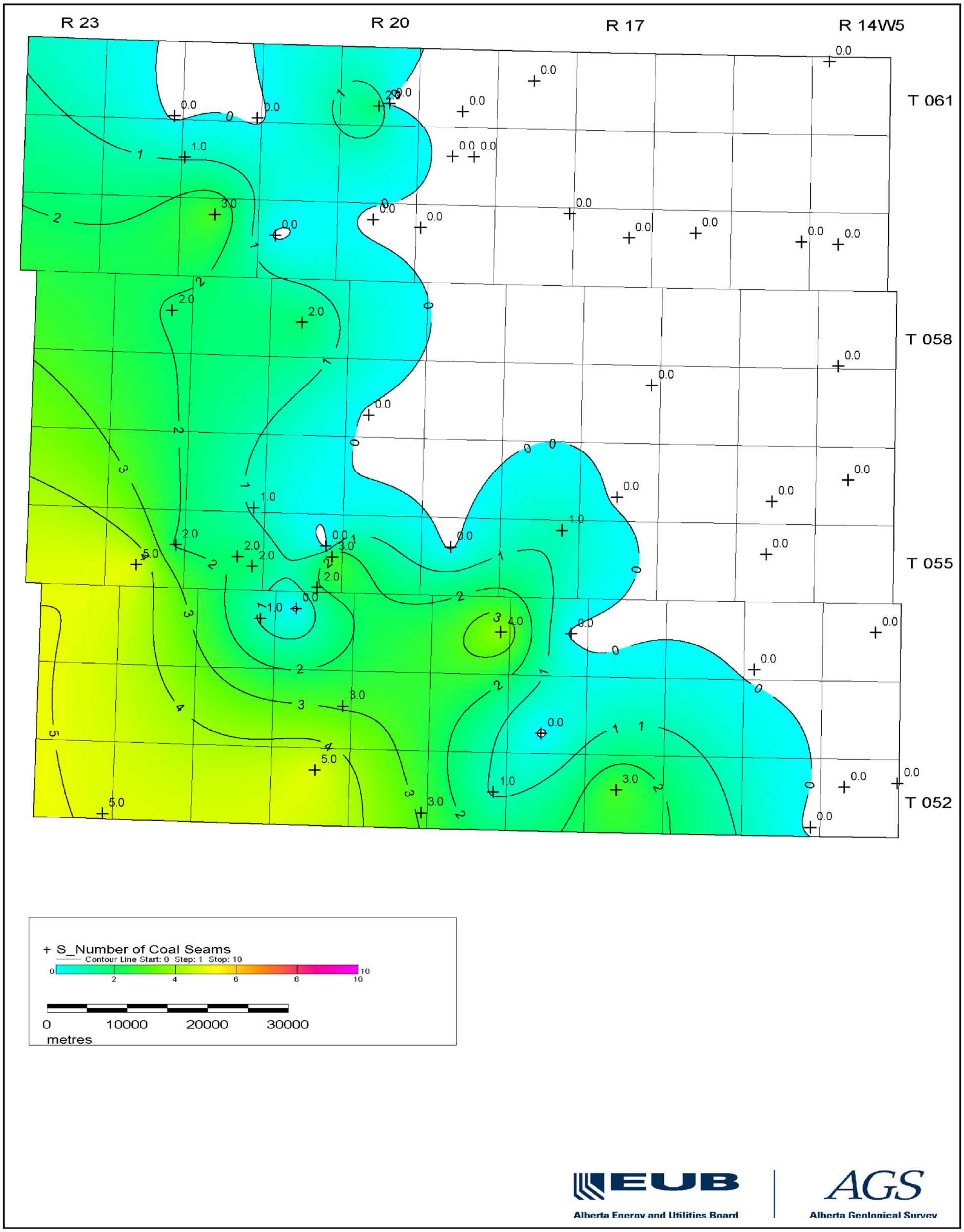

Figure 54. 'S' coal subzone number of coal seams, Edson study area.

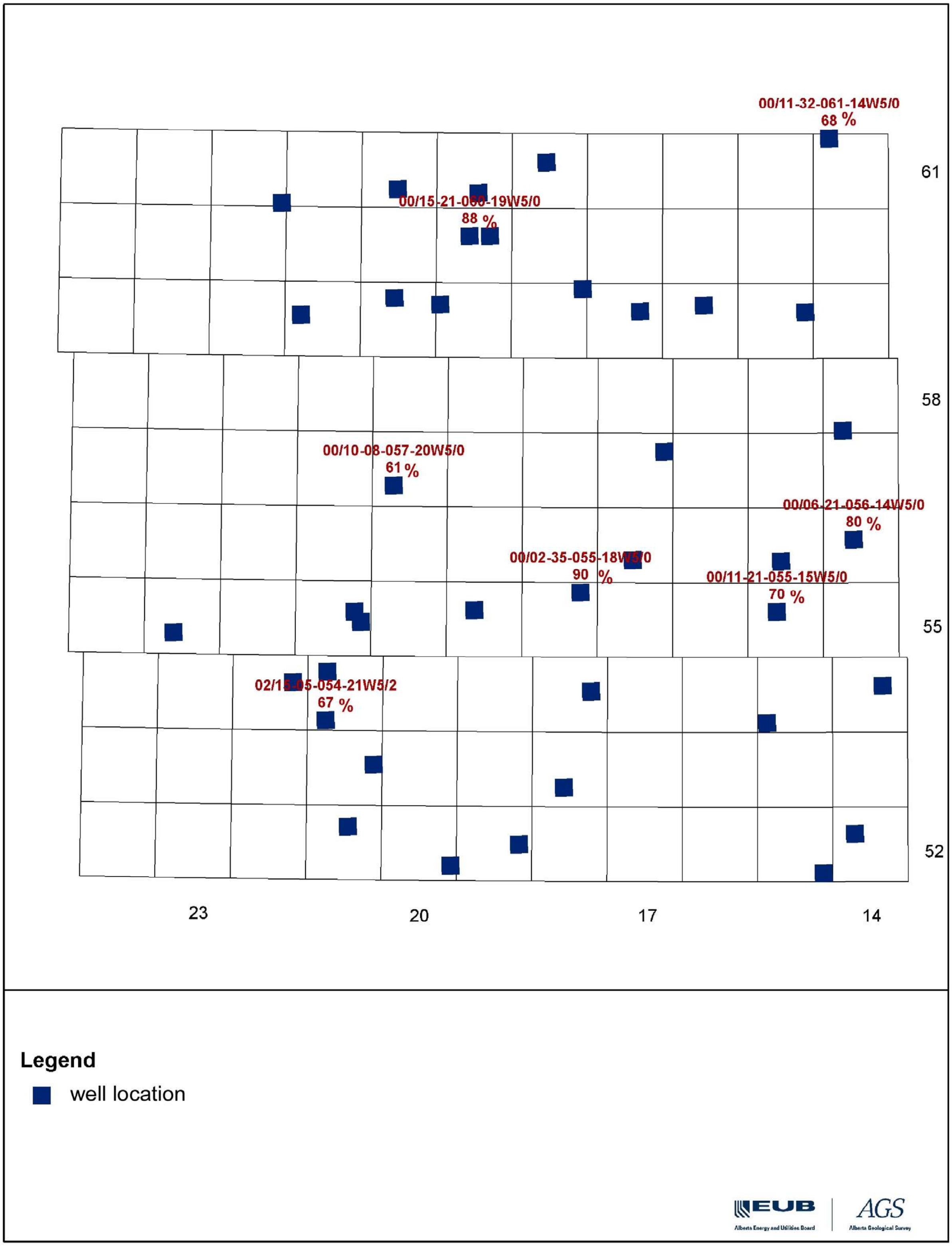

Figure 55. Coal and shaly coal versus coaly shale percentage map, 'N' coal subzone, Edson study area.

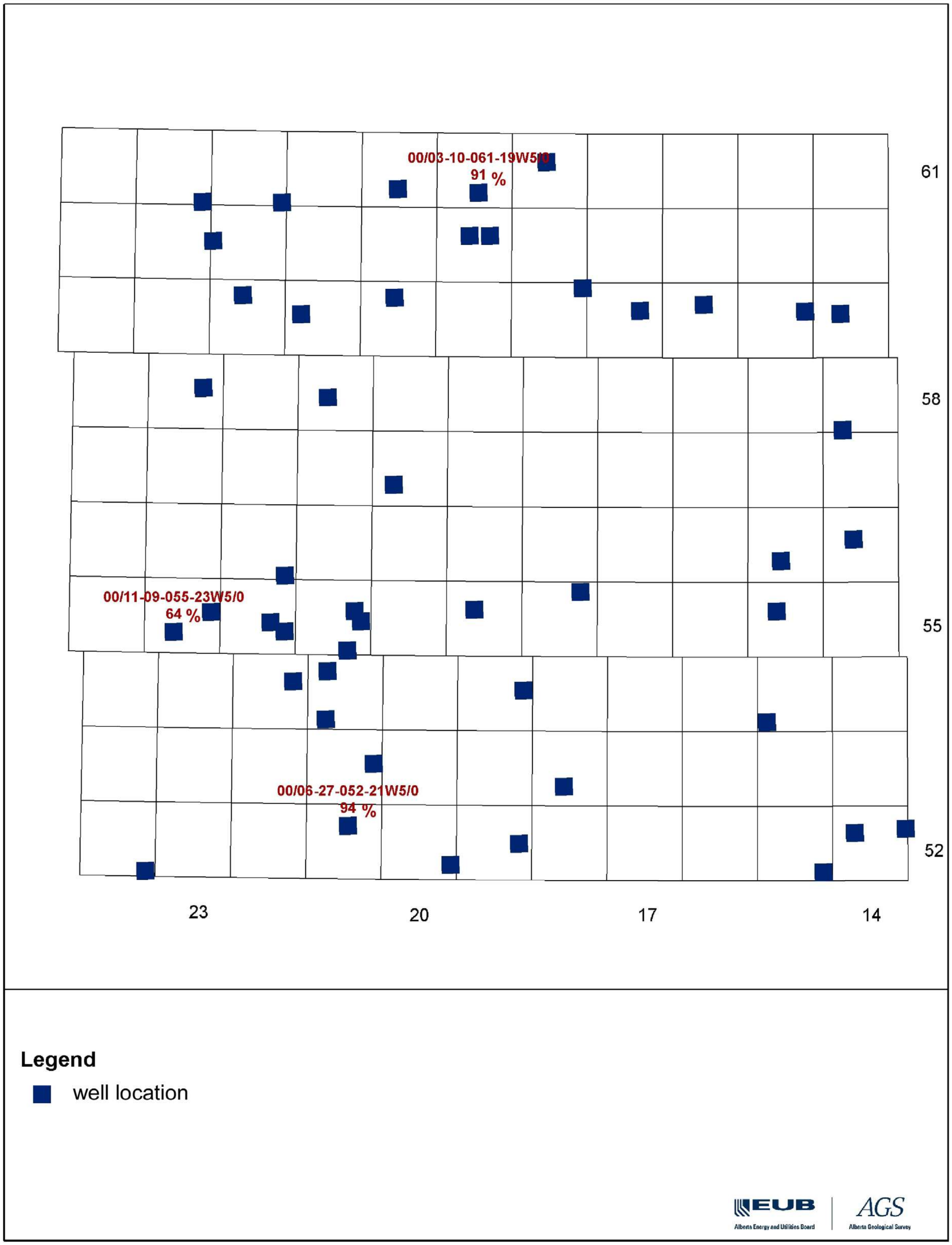

Figure 56. Coal and shaly coal versus coaly shale percentage map, 'Ml' coal subzone, Edson study area.

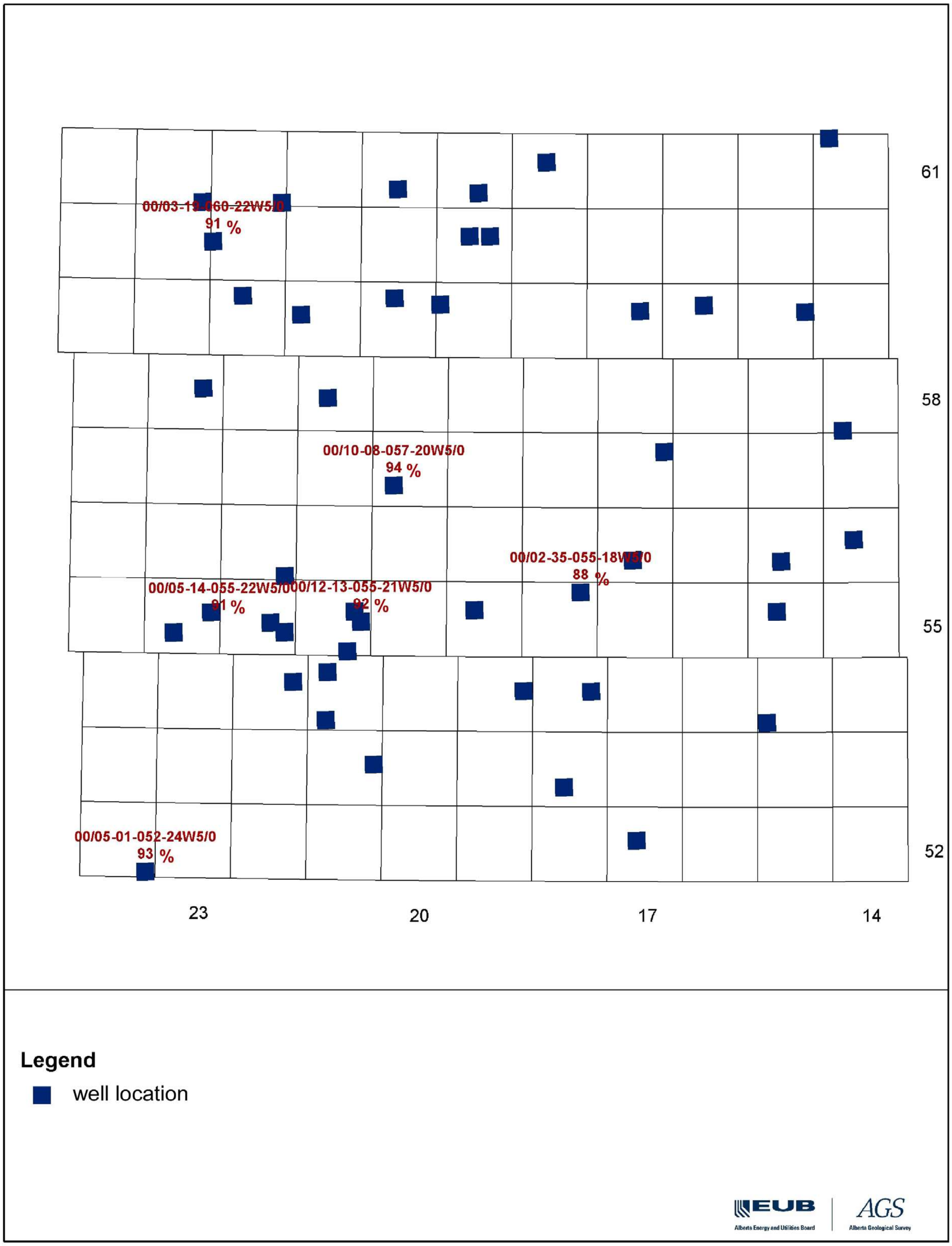

Figure 57. Coal and shaly coal versus coaly shale percentage map, 'Mu' coal subzone, Edson study area.

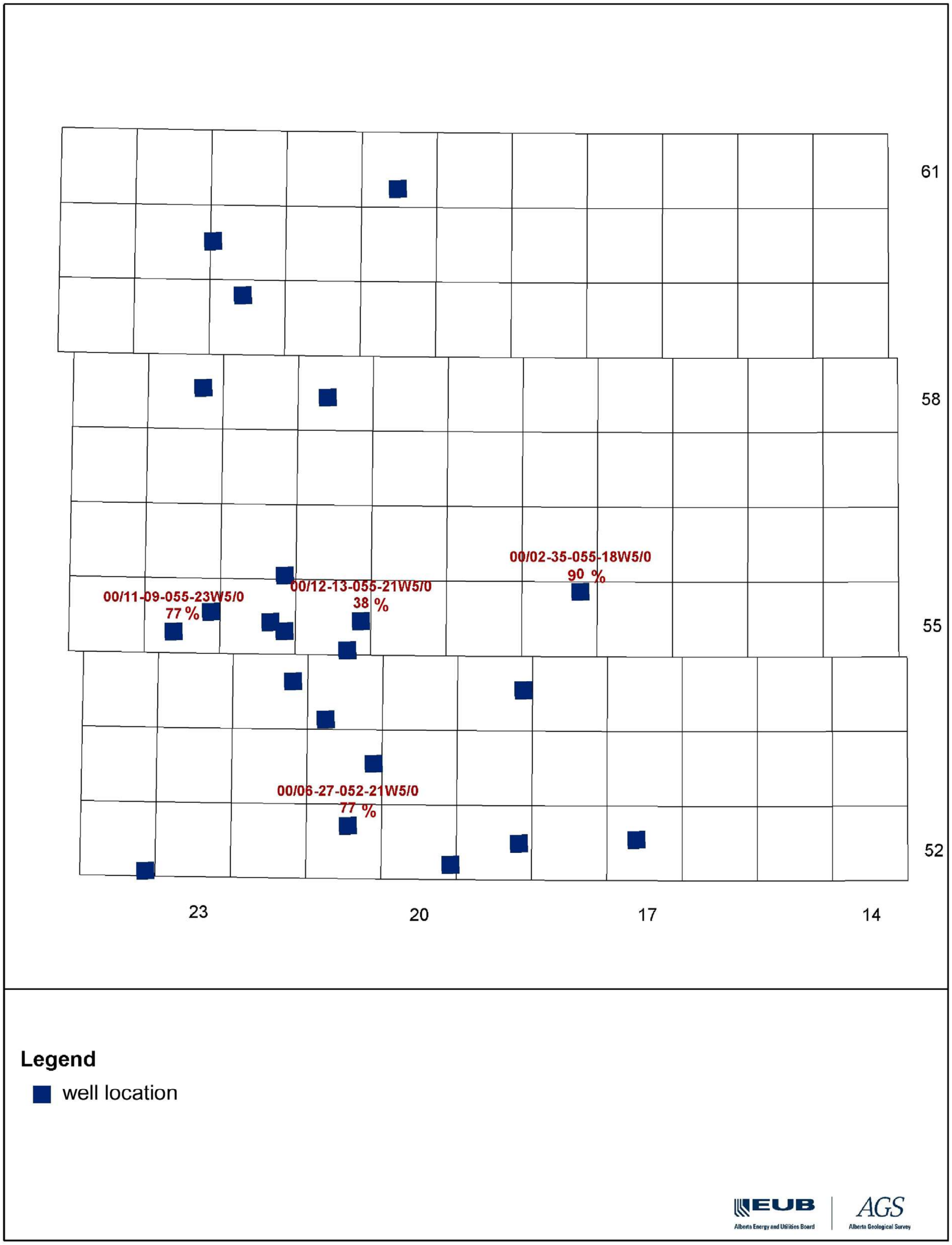

Figure 58. Coal and shaly coal versus coaly shale percentage map, 'S' coal subzone, Edson study area.

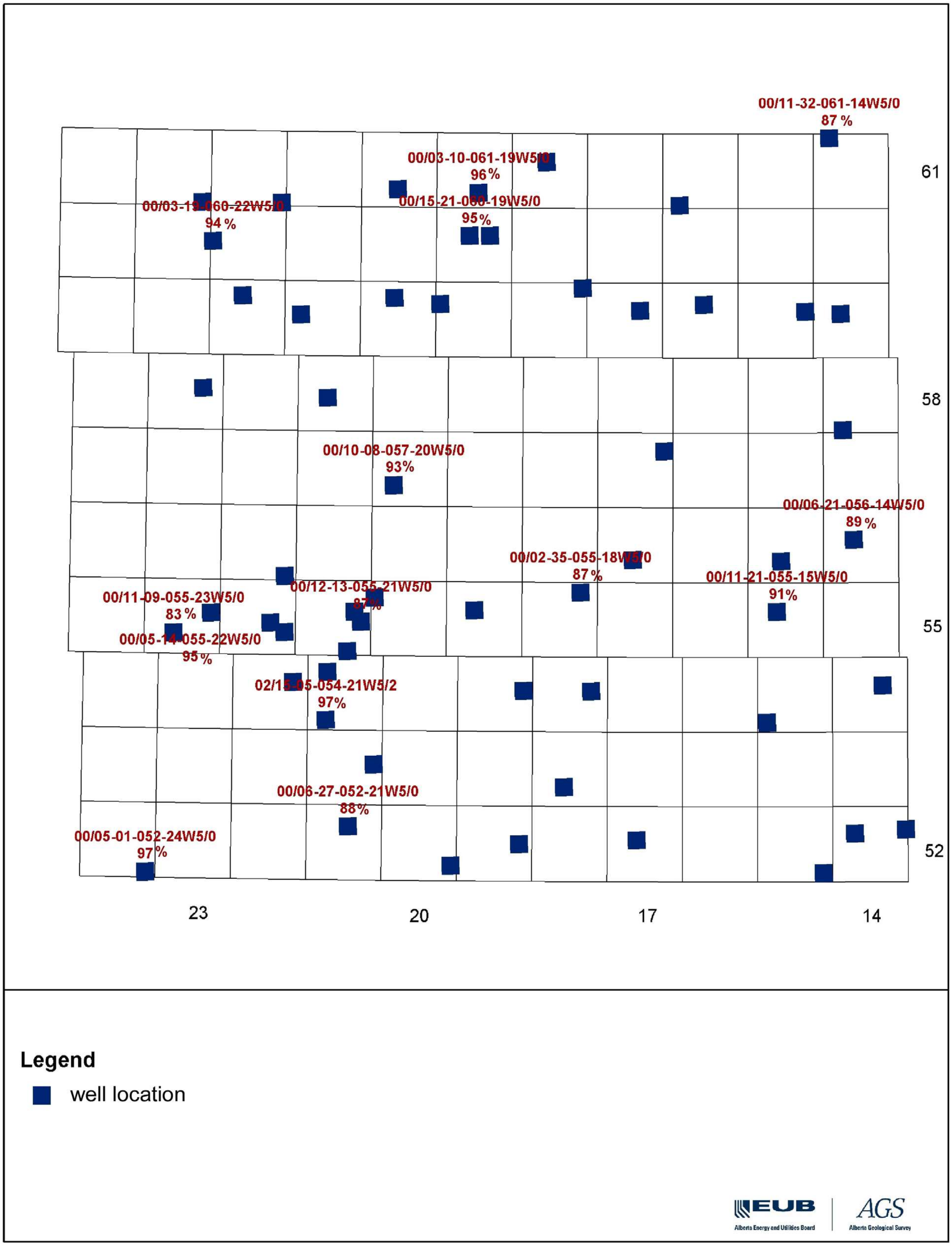

Figure 59. Coal and shaly coal versus coaly shale percentage map, Ardley Coal Zone, Edson study area.

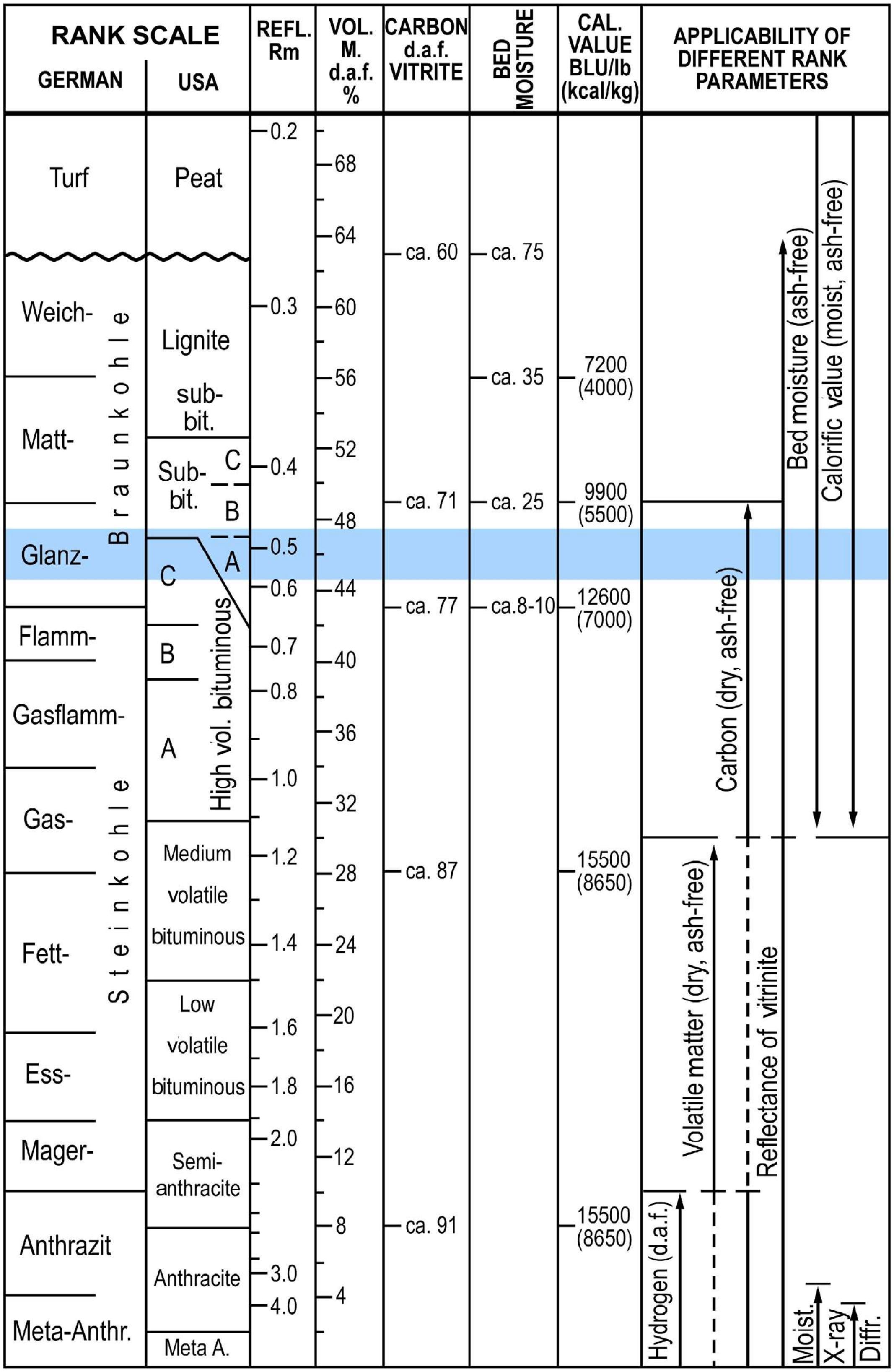

Figure 60. Coal rank scale based on coal vitrinite reflectance (Bustin et al., 1983).

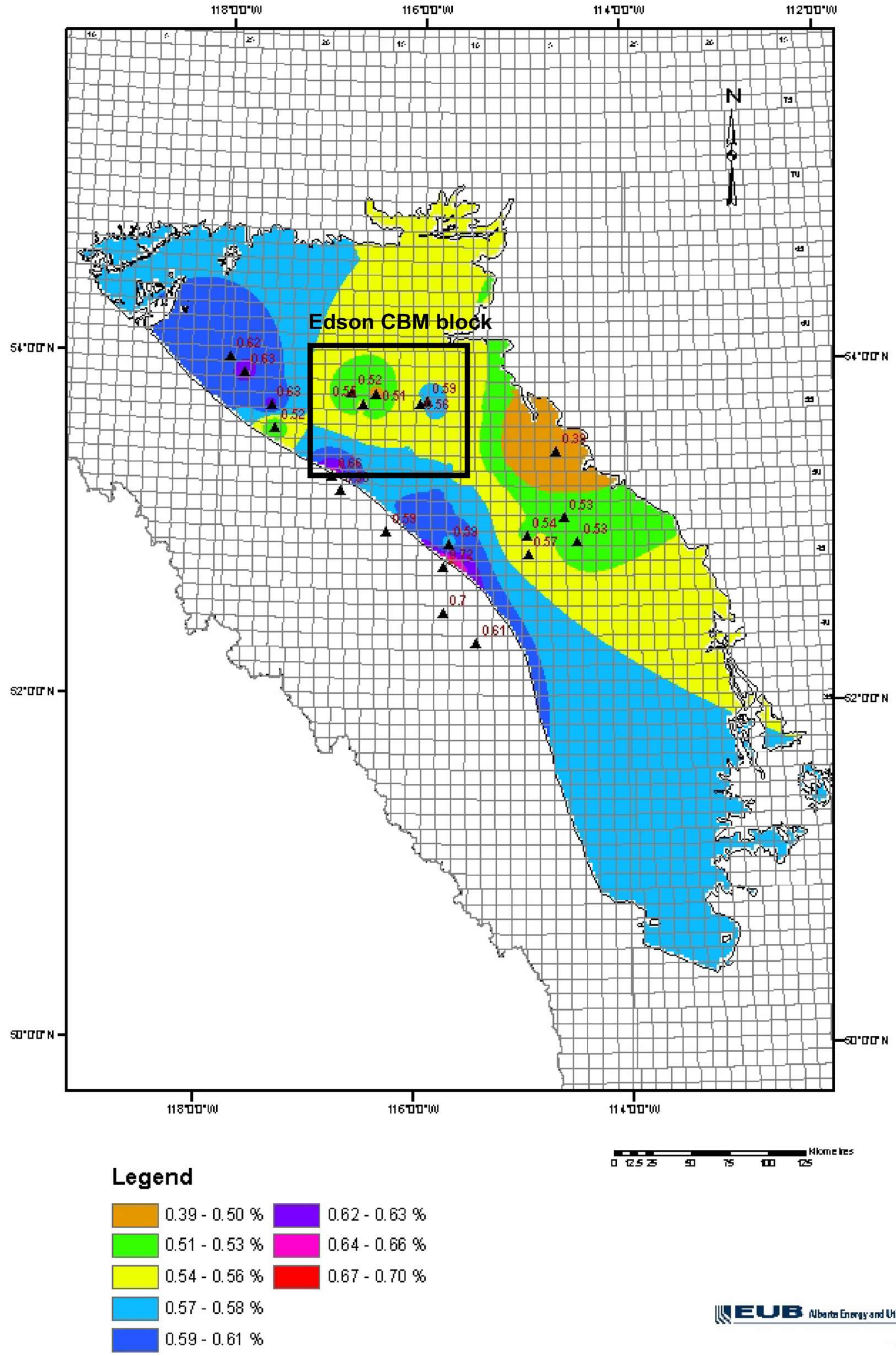

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Figure 61. Map of vitrinite reflectance data (random), Edson study area.

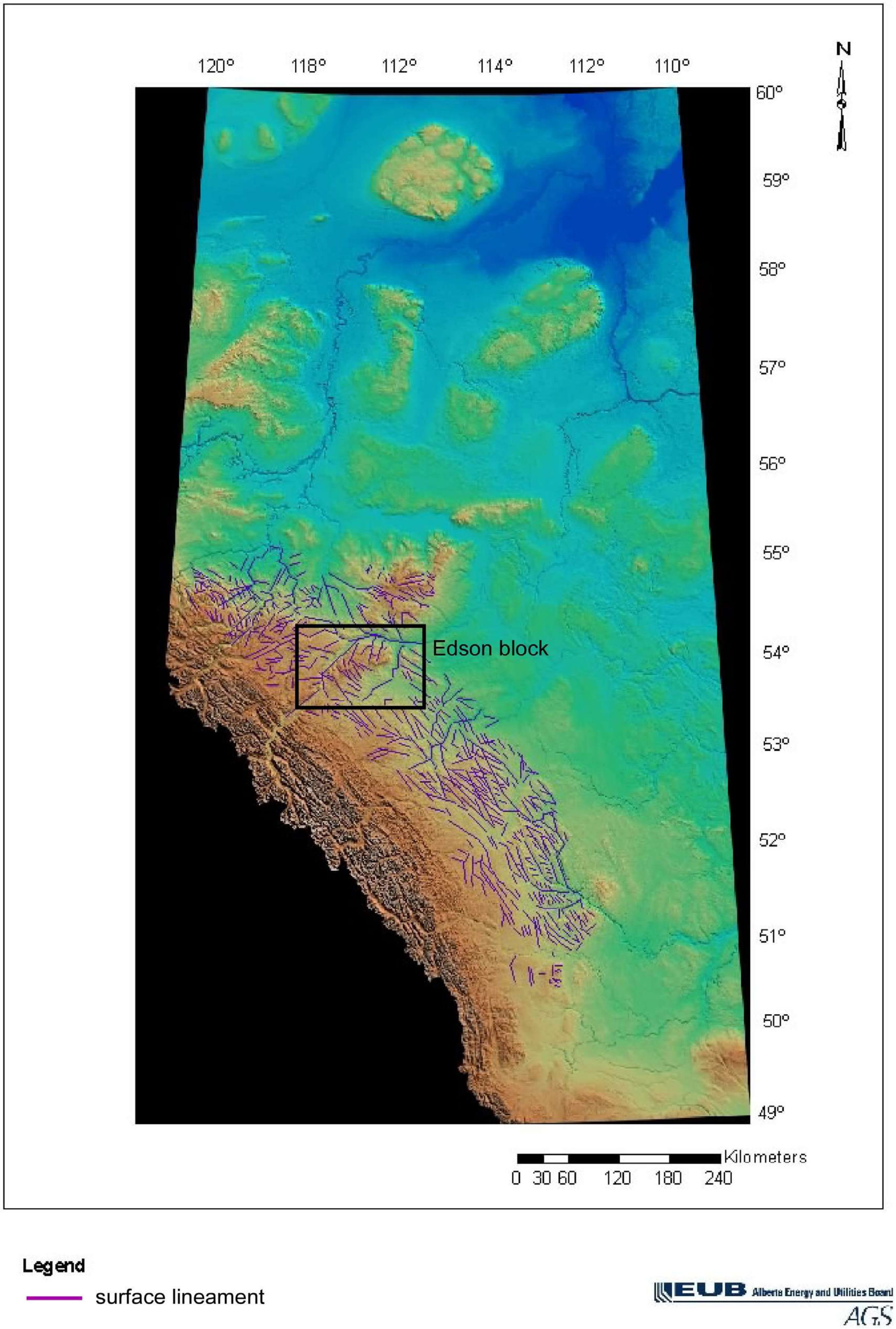

Figure 62. Interpreted surface lineaments on the Alberta Digital Elevation Model.

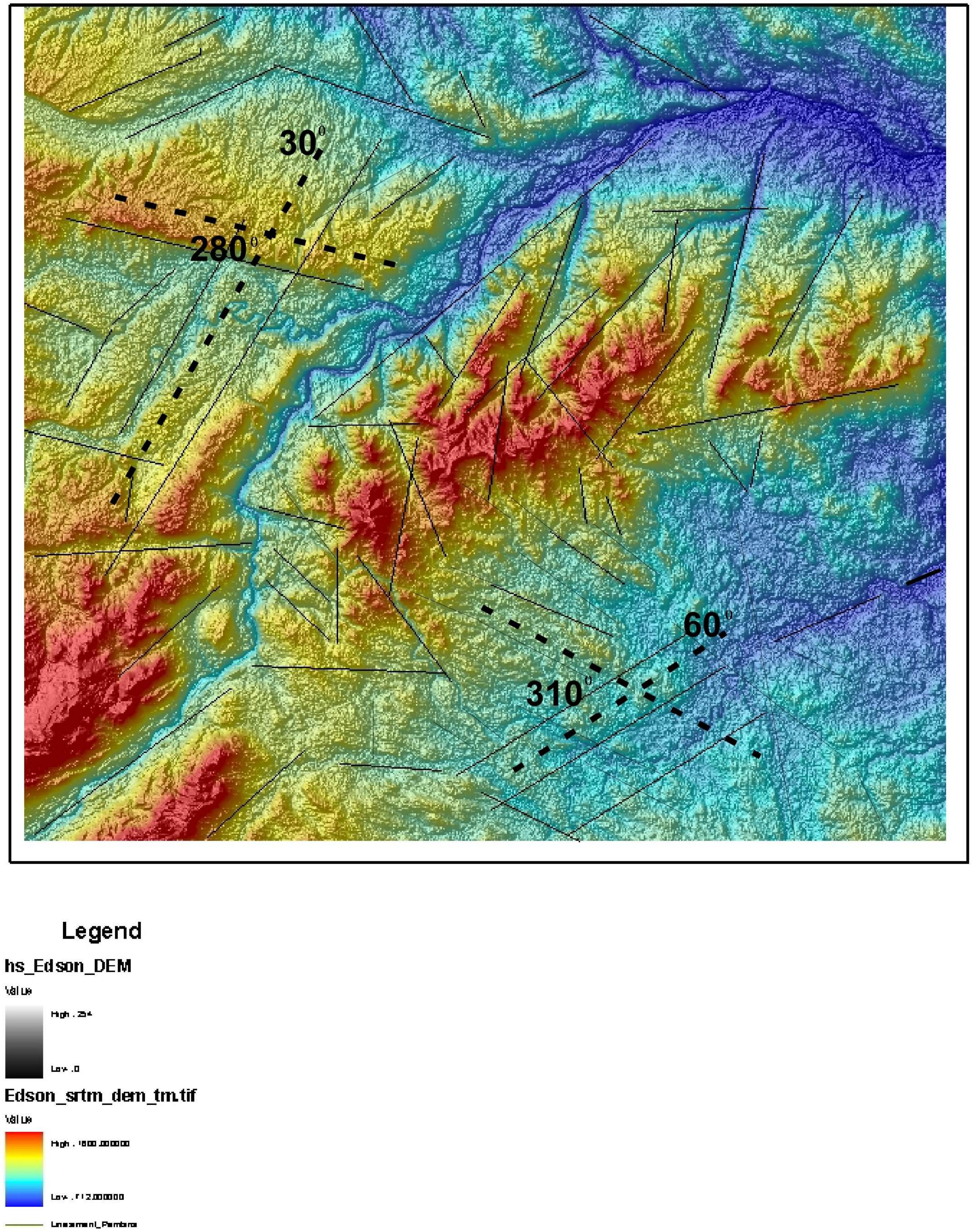

Figure 63. Interpreted surface lineaments, Edson study area.

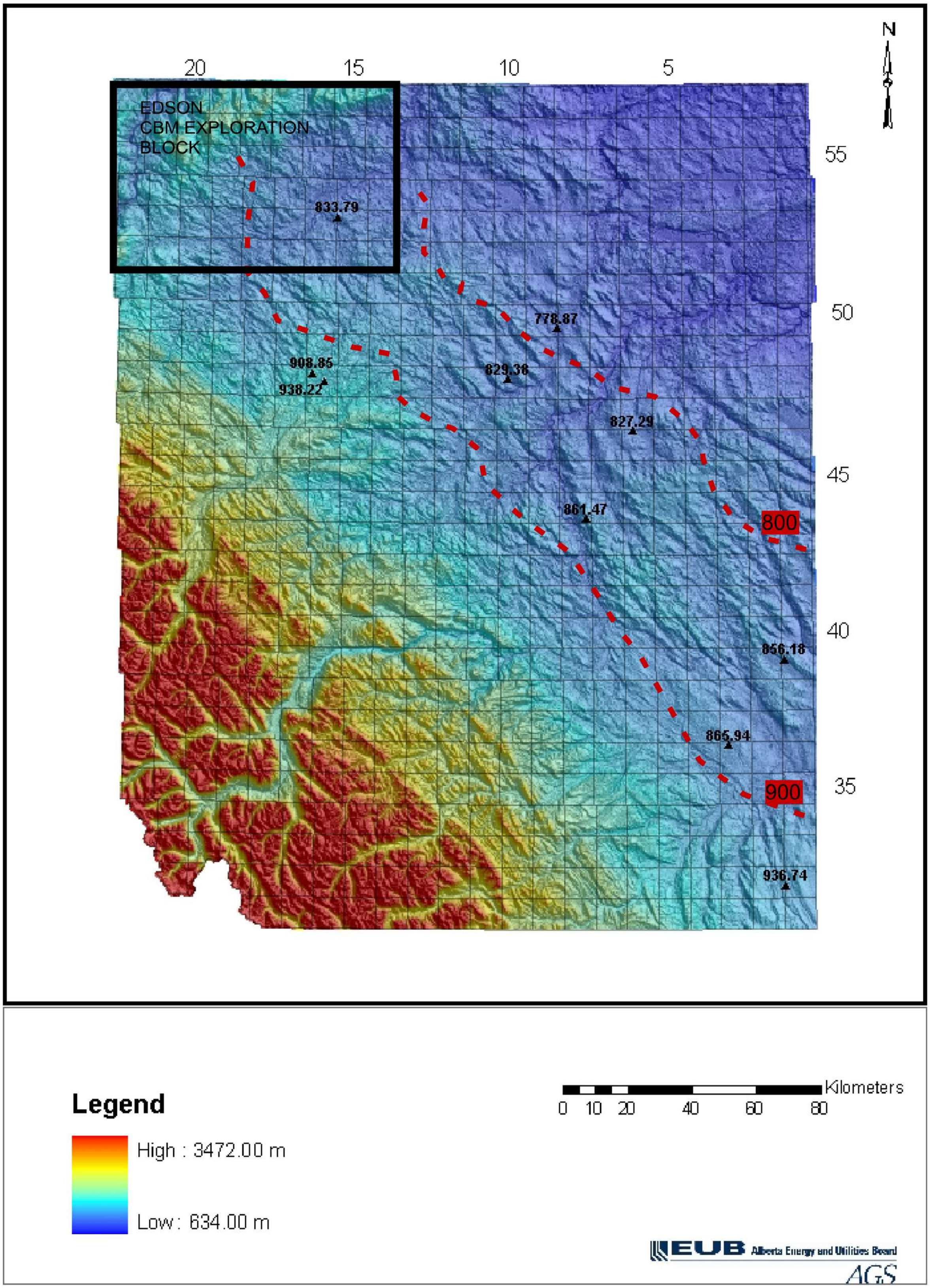

Figure 64. Potentiometric map of the Paskapoo Formation, Edson study area.

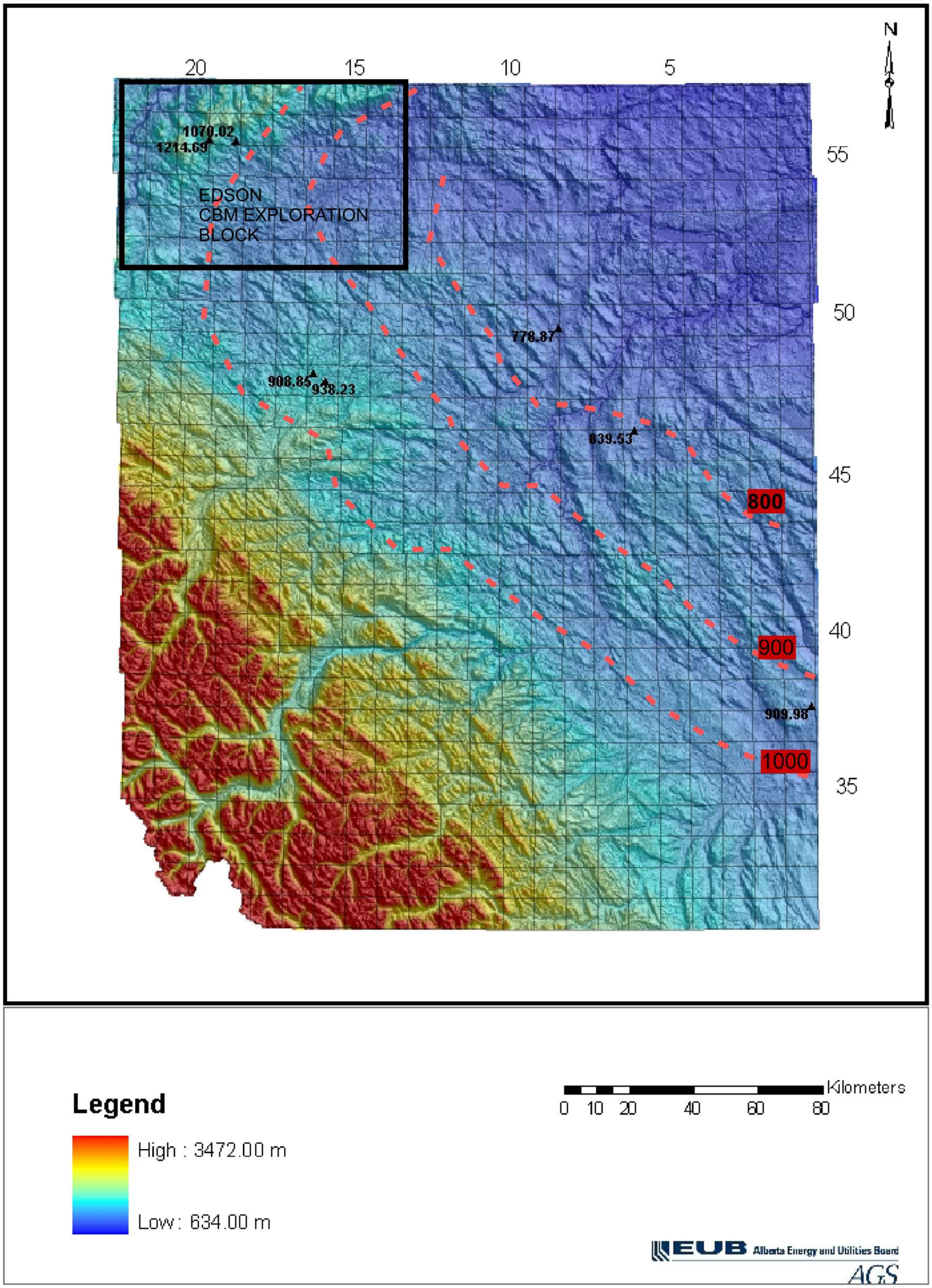

Figure 65. Potentiometric map of the Scollard Formation, Edson study area.

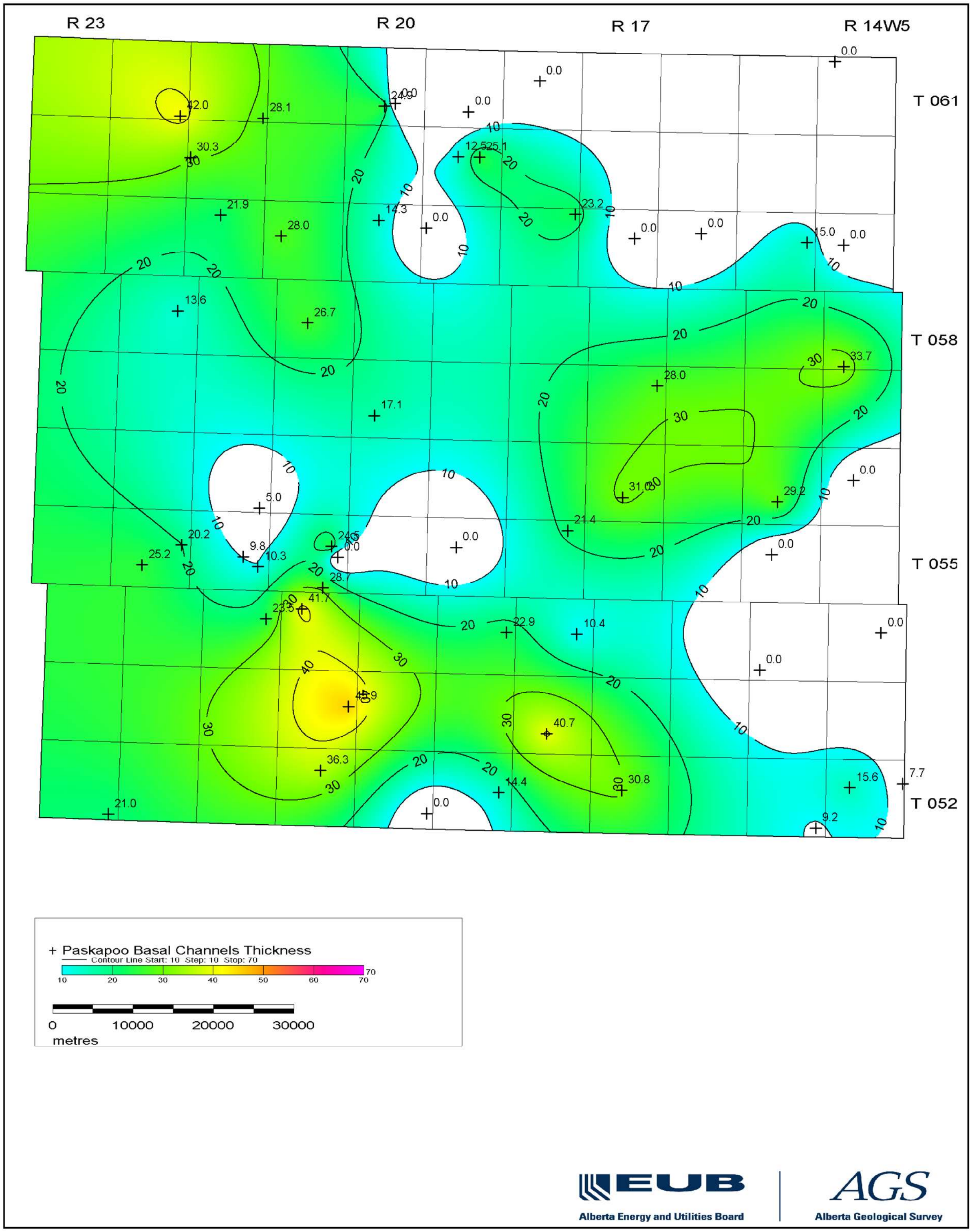

Figure 66. Isopach map of the basal Paskapoo channels, Edson study area.

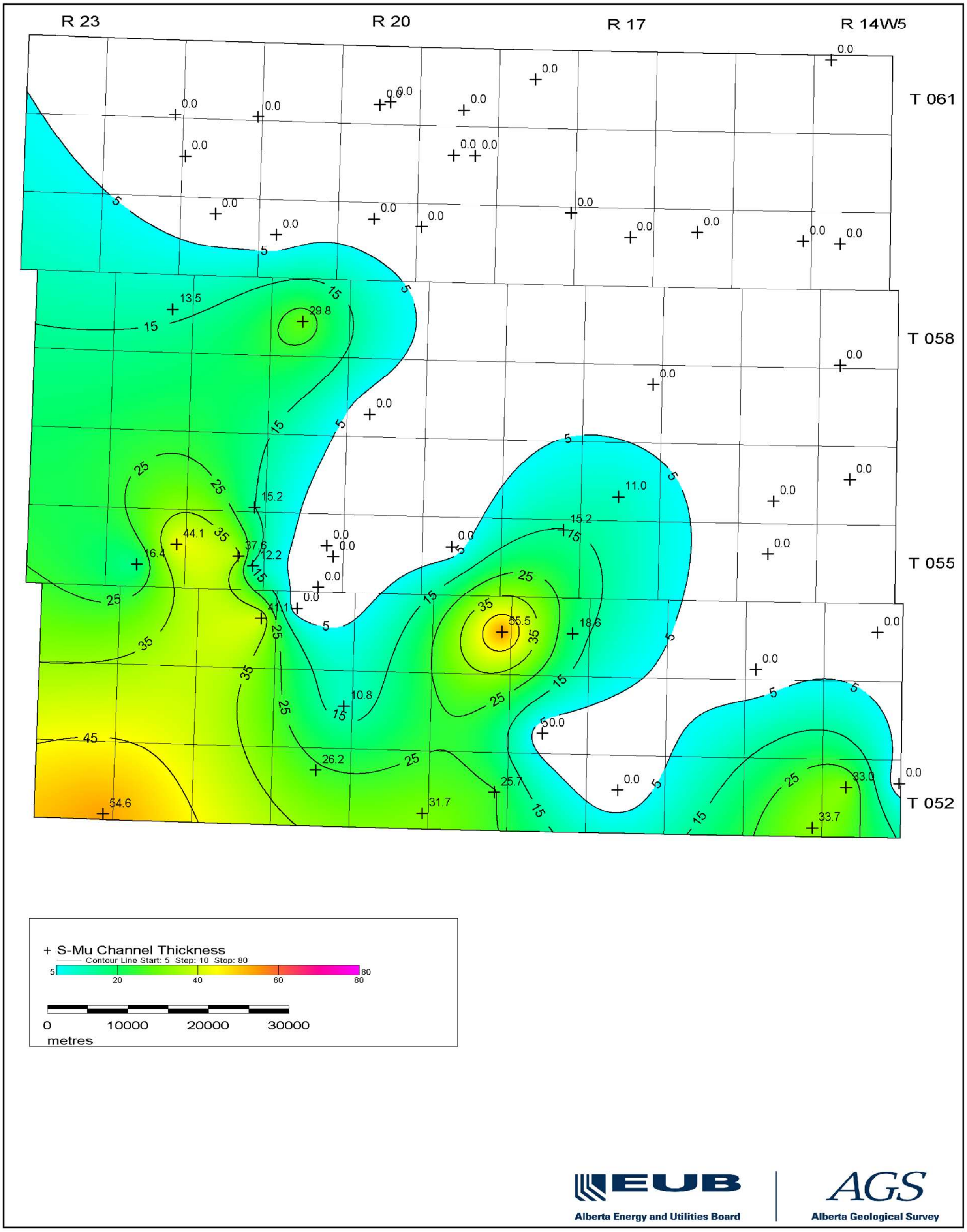

Figure 67. Isopach map of the 'S-Mu' channels, Edson study area.

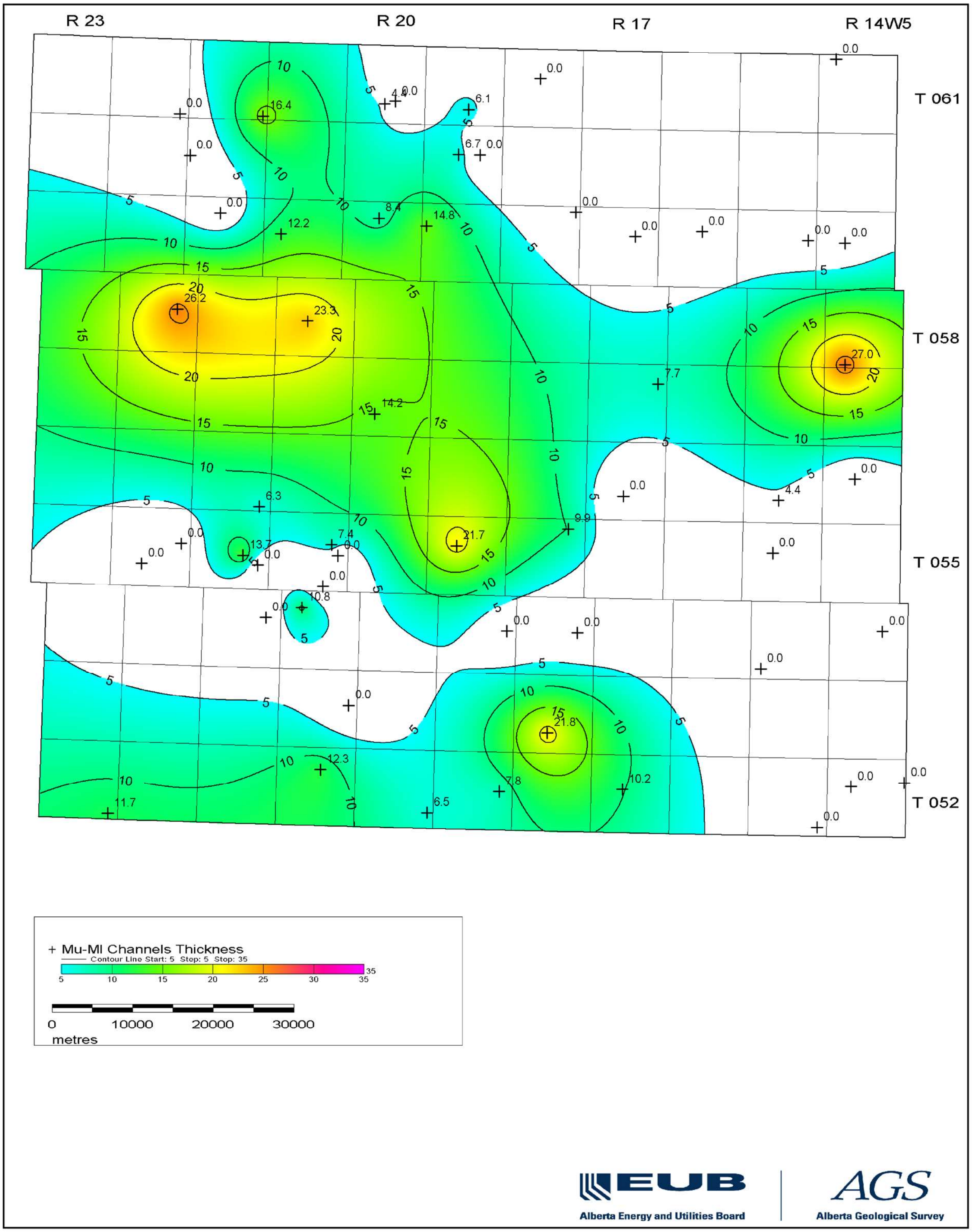

Figure 68. Isopach map of the 'Mu-Ml' channels, Edson study area.

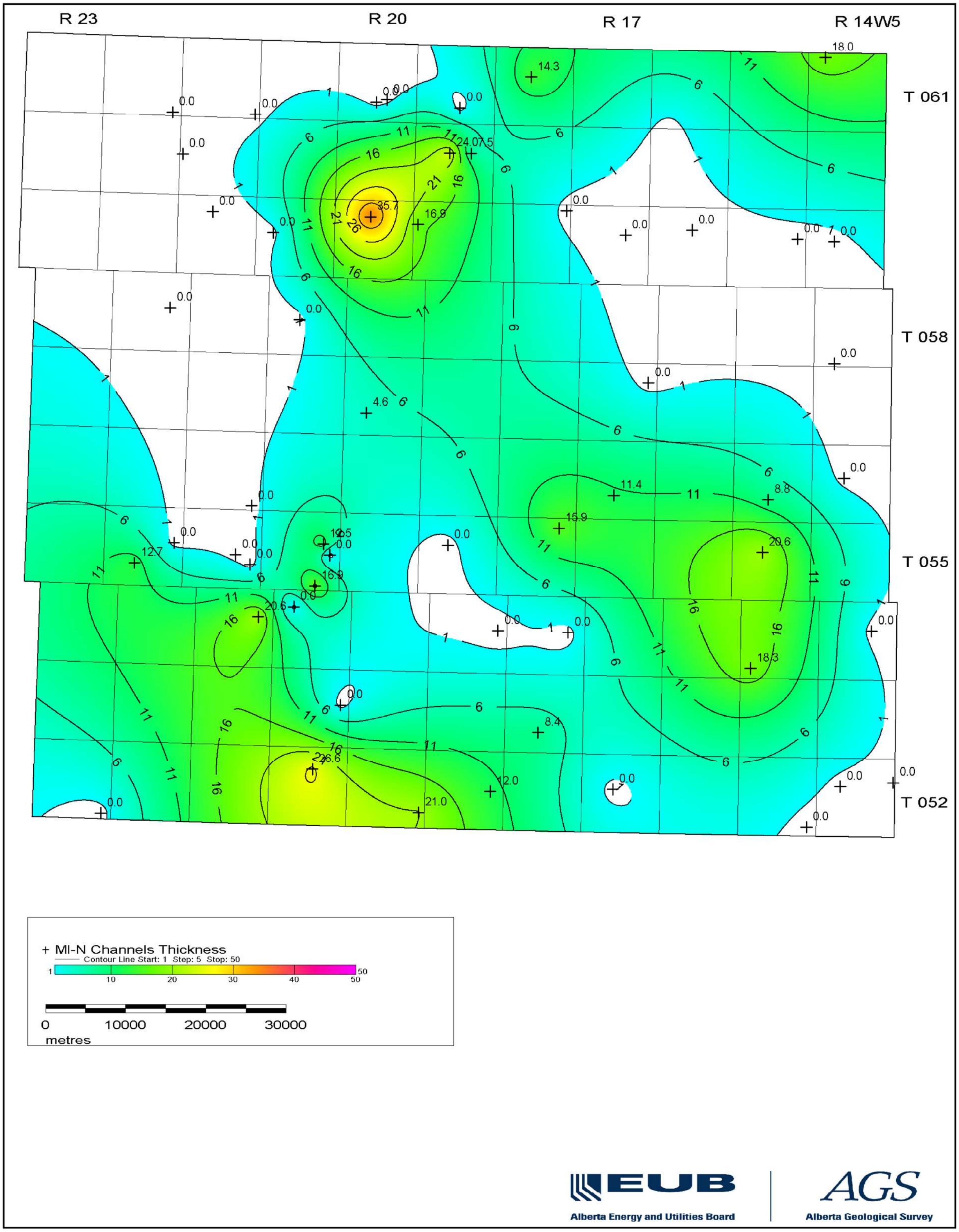

Figure 69. Isopach map of the 'MI-N' channels, Edson study area.

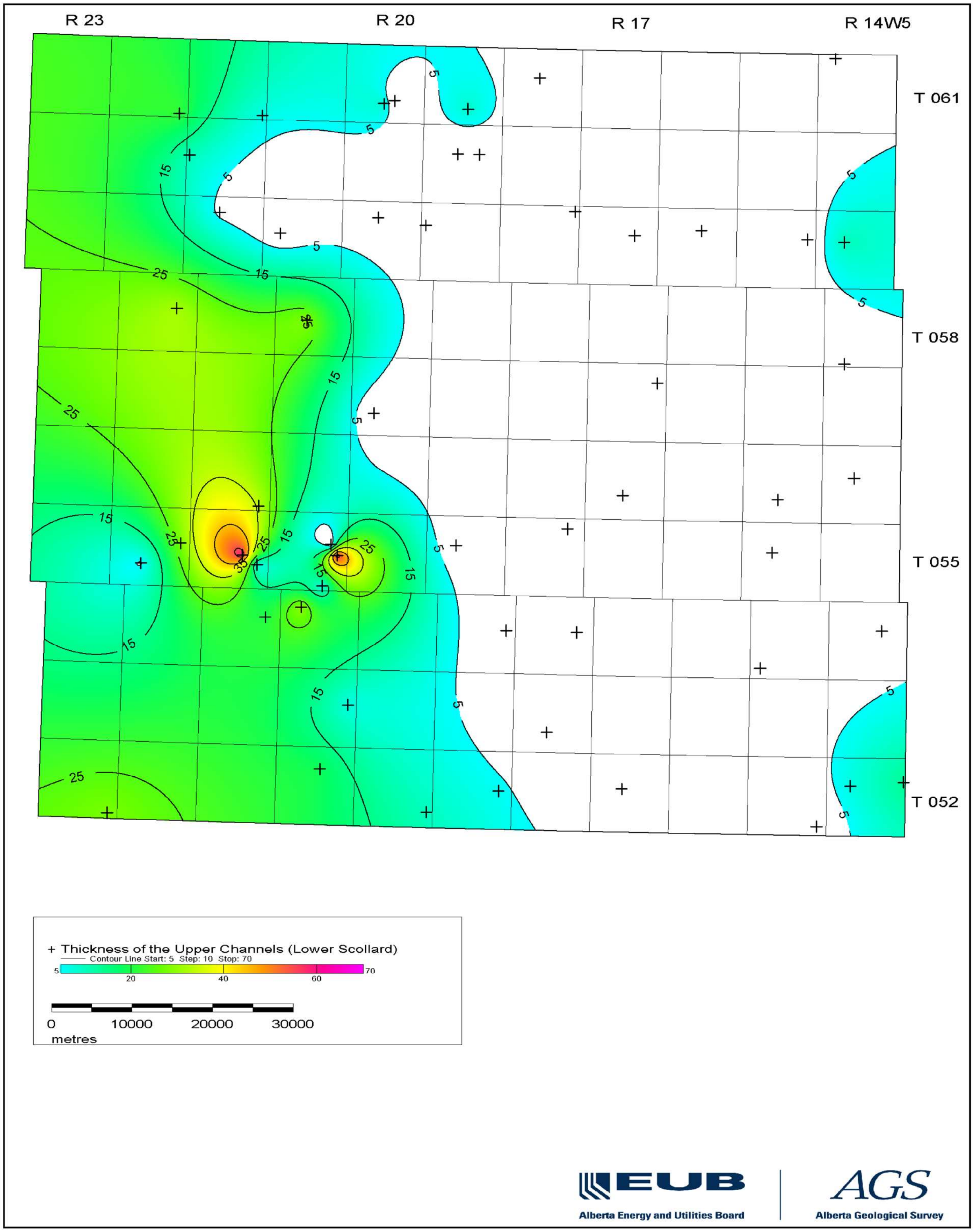

Figure 70. Isopach map of the upper channels of the lower Scollard member, Edson study area.

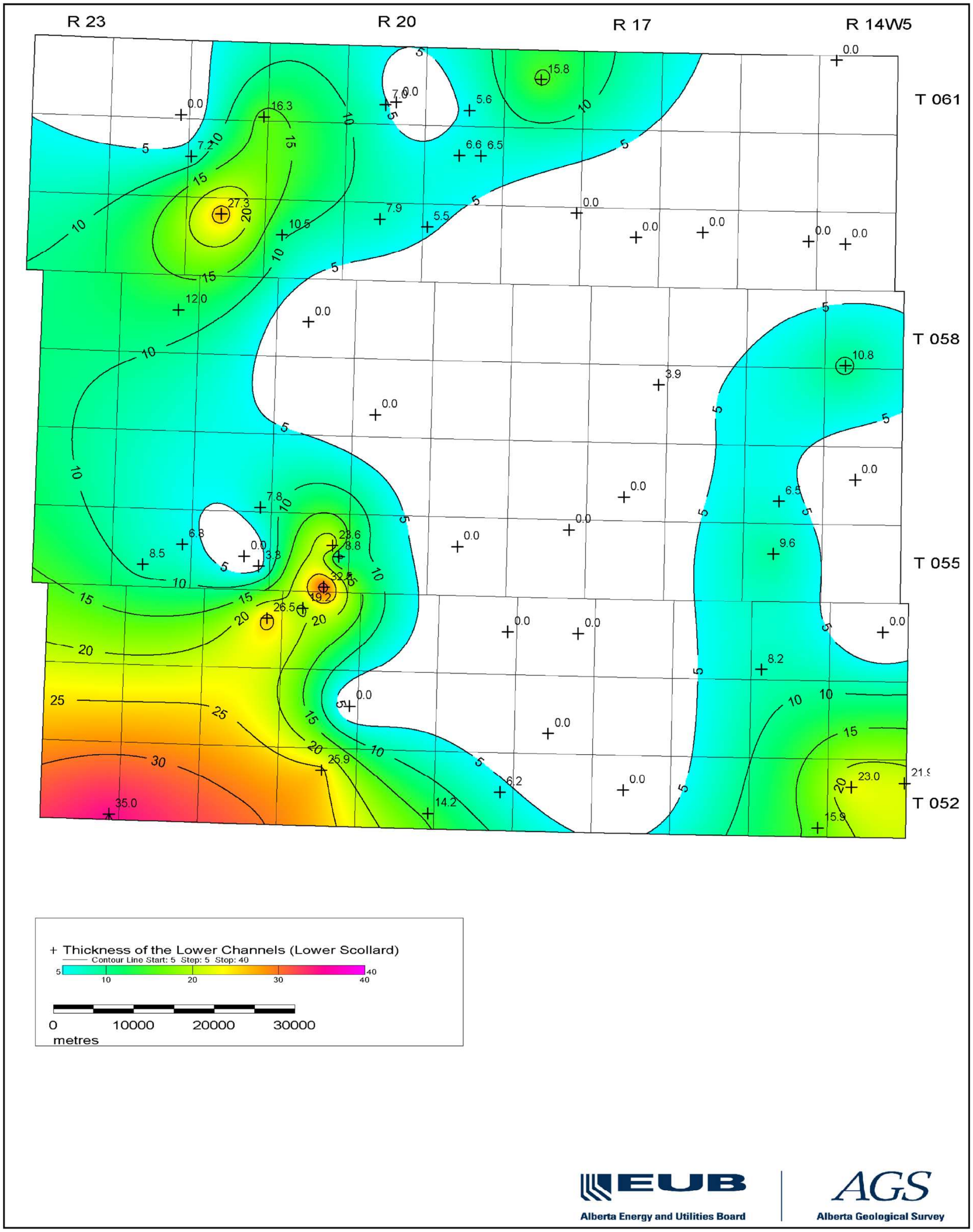

Figure 71. Isopach map of the lower channels of the lower Scollard member, Edson study area.

## Appendix 2. Core Photographs

### Plate 1

| | |
|---|---|
| Figure A | Medium-fine lithic sandstone (11-01-056-19W5—560 m log depth; "Mu-Ml" channel). |
| Figure B | Medium-fine lithic sandstone (10-27-061-20W5—630 m log depth; "Ml-N" channel). |
| Figure C | Medium fine lithic sandstone with coal spars (10-19-050-19W5—590 m log depth). |
| Figure D | Medium-fine to fine lithic sandstone with carbonised fragments of wood parallel to bedding; subtle cross-stratification shown by grain-size variation associated with fine vegetal streaks (10-19-050-19W5—592 m log depth; basal part of "Ml-N" channel). |
| Figure E | Medium-fine lithic sandstone with carbonised fragments of roots in alive position (10-19-050-19W5— 542 m log depth; basal part of "Mu-Ml" channel). |
| Figure F | Grey mudstone with paleosol structure containing a fragment of carbonised root preserved in growth position; slickenside at the bottom of the photograph (11-01-056-19W5—593 m log depth; base of "Ml" coal seams). |
| Figure G | Very coarse to fine lithic grey sandstone with small size pebbles (<1 cm) within the basal part and almost horizontal carbonized plant fragments (11-01-056-19W5—600 m log depth; "Ml-N" channel). |
| Figure H | Small scale lag deposit within fine to coarser lithic sandstone with sub-round pebbles showing the increase in flow energy; carbonised vegetal matter is associated; (10-19-050-19W5—580 m log depth; Ml-N channels). |
| Figure I | Very fine light grey sandstone altering with dark grey laminar mudstone strakes; wavy structures more continuous at the base; low energy environment; (10-19-050-19W5—592 m log depth; base of "Ml-N" channel). |
| Figure J | Fine light grey sandstone altering discontinuously with dark grey mudstone laminas; very fine carbonised plant fragments are associated sporadically (11-01-056-19W5—594.5 m log depth; base of "Ml-N" channel). |
| Figure K | Erosional contact of channel sandstone (light grey, fine lithic sandstone (a) within grey silt (b) (11-01-056-19W5—615 m log depth; upper channels of the lower member of Scollard Formation). |

### Plate 2

| | |
|---|---|
| Figure A | Core view of the upper part of Mu-Ml channel showing light grey "salt-and-pepper" medium to fine grain size lithic sandstone (11-01-056-19W5—542–544 m). |
| Figure B | Core view of the upper channel of the lower member of the Scollard Formation showing light grey "salt-and-pepper" coarse to medium-fine grain size lithic sandstone (11-01-056-19W5—624–630 m). |

### Plate 3

| | |
|---|---|
| Figure A | Grey silty-mudstone with carbonized roots and vegetal fragments; "soil peds" are associated (11-01-56-19W5—581 m). |
| Figure B | Core-view showing the succession of the paleosol units; the top unit represents grey-green mudstone with root traces; (10-27-61-20W5—270–274.5 m). |
| Figure C | Detail of the "mature paleosol unit"; (10-27-61-20W5—270–274.5 m). |

### Plate 4

| | |
|---|---|
| Figure A1-A2 | Core-view of mudstone with paleosol structure overlying the "N" coal seams; Figure A2 detail of slickensides (10-19-050-19W5—600 m log depth). |
| Figure B | Slickensides within silty-mudstone (10-19-050-19W5—600 m log depth). |

Figure C. Coaly shale consisting of thin bands of coal (<1 cm) and mudstone, slickenside at the coal-mud contact (10-19-050-19W5—600 m log depth).

Figure D. Silty-mudstone with root traces interpreted as paleosol unit (10-19-050-19W5—600 m log depth).

### Plate 5

| | |
|---|---|
| Figure A-C | Slickensides in grey silt with secondary calcite deposits (10-19-50-19W5—593–597 m above "N" coal subzone). |
| Figure D | Fractures in Paskapoo Sandstones (Vogwill, 1983). |

### Plate 6

| | |
|---|---|
| Figure A | Banded coal (10-27-61-20W5—260–270 m; "Ml" coal subzone). |
| Figure B | Banded coal 10-27-61-20W5—263 m; "Ml" coal subzone). |
| Figure C | Banded coal (10-27-61-20W5—295 m; "Ml" coal subzone). |
| Figure D | Banded coal (10-27-61-20W5—263 m; "Ml" coal subzone). |
| Figure E | Banded coal (10-27-61-20W5—269 m; "Ml" coal subzone). |

### Plate 7

| | |
|---|---|
| Figure A | Banded coal ((10-27-61-20W5 – 263 m; "Ml" coal subzone). |
| Figure B | Banded coal ((10-27-61-20W5 – 269 m; "Ml" coal subzone). |
| Figure C | Banded coal ((10-27-61-20W5 – 295 m; "Ml" coal subzone). |

### Plate 8

| | |
|---|---|
| Figure A | Banded bright coal (11-06-56-19W5—728–735 m; "Mu" coal subzone). |
| Figure B | Banded bright coal (11-06-56-19W5—728–735 m; "Mu" coal subzone). |
| Figure C | Banded coal (11-01-56-19W5—591 m; "Ml" coal subzone). |
| Figure D | Banded coal (11-01-56-19W5—591 m; "Ml" coal subzone). |

### Plate 9

| | |
|---|---|
| Figure A | Banded coal (11-01-56-19W5—583 m; "Ml" coal subzone). |
| Figure B | Banded coal (11-01-56-19W5—585 m; "Ml" coal subzone). |
| Figure C | Dull coal (11-01-56-19W5—610 m; "N" coal subzone). |
| Figure D | Banded coal (11-01-56-19W5—583 m; "Ml" coal subzone). |
| Figure E | Banded coal (11-01-56-19W5—598 m; "Ml" coal subzone). |

### Plate 10

| | |
|---|---|
| Figure A | Banded bright coal (11-06-56-19W5—725 m; "Mu" coal subzone). |
| Figure B | Banded coal (11-01-56-19W5—580 m; "Ml" coal subzone). |
| Figure C | Banded coal (11-06-56-19W5—728–735 m; "Mu" coal subzone). |
| Figure D | Banded dull coal and vitrinite (>3cm) (11-01-56-19W5—610 m; "N" coal subzone). |

### Plate 11

| | |
|---|---|
| Figure A | Banded bright coal (10-19-50-19W5; "N" coal subzone). |
| Figure B | Transverse view of the core of banded coal with calcite infillings along the cleats (10-19-50-19W5). |
| Figure C | Transverse view of the core of banded coal with calcite infillings along the cleats (11-01-56-19W5—613 m; "N" coal subzone). |
| Figure D | Banded bright coal (10-19-50-19W5; "N" coal subzone). |
| Figure E | Banded bright coal (10-19-50-19W5; "N" coal subzone). |

| | |
|---|---|
| Figure F | Banded coal with “Spider-web” calcite infilling (11-01-56-19W5—609 m; “N” coal subzone). |
| Figure G | Transverse view of the core showing the face and butt cleat system; the banded coal lithotype is parted on the dull coal layer (10-27-61-20W5—272 m; “Ml” coal subzone). |
| Figure H | Transverse view of the core showing the face-cleat system (10-27-61-20W5—263 m; “Ml” coal subzone). |
| Figure I | Transverse view of the core showing the face and butt cleat system (10-27-61-20W5—263 m; “Ml” coal subzone). |

## Plate 12

| | |
|---|---|
| Figure A | Coaly-shale interbedded with tonstein (T) (10-27-61-20W5—260 m). |
| Figure B | Coaly-shale interbedded with tonstein (T) (10-27-61-20W5—263 m). |
| Figure C | Thin bed of tonstein within coal zone (11-06-56-19W5). |
| Figure D | Coaly-shale interbedded with tonstein (T) (10-27-61-20W5—263 m). |
| Figure E | Thin bed of tonstein within coal (11-01-56-19W5—573 m). |
| Figure F | Tonstein: detail (11-01-56-19W5—590 m). |

Plate 1

Plate 1. Figure A. Medium-fine lithic sandstone (11-01-056-19W5—560 m log depth; “Mu-Ml” channel). Figure B. Medium-fine lithic sandstone (10-27-061-20W5—630 m log depth; “Ml-N” channel). Figure C. Medium fine lithic sandstone with coal spars (10-19-050-19W5—590 m log depth). Figure D. Medium-fine to fine lithic sandstone with carbonised fragments of wood parallel to bedding; subtle cross-stratification shown by grain-size variation associated with fine vegetal streaks (10-19-050-19W5—592 m log depth; basal part of “Ml-N” channel). Figure E. Medium-fine lithic sandstone with carbonised fragments of roots in alive position (10-19-050-19W5— 542 m log depth; basal part of “Mu-Ml” channel). Figure F. Grey mudstone with paleosol structure containing a fragment of carbonised root preserved in growth position; slickenside at the bottom of the photograph (11-01-056-19W5—593 m log depth; base of “Ml” coal seams). Figure G. Very coarse to fine lithic grey sandstone with small size pebbles (<1 cm) within the basal part and almost horizontal carbonized plant fragments (11-01-056-19W5—600 m log depth; “Ml-N” channel). Figure H. Small scale lag deposit within fine to coarser lithic sandstone with sub-round pebbles showing the increase in flow energy; carbonised vegetal matter is associated; (10-19-050-19W5—580 m log depth; Ml-N channels). Figure I. Very fine light grey sandstone altering with dark grey laminar mudstone strakes; wavy structures more continuous at the base; low energy environment; (10-19-050-19W5—592 m log depth; base of “Ml-N” channel). Figure J. Fine light grey sandstone altering discontinuously with dark grey mudstone laminas; very fine carbonised plant fragments are associated sporadically (11-01-056-19W5—594.5 m log depth; base of “Ml-N” channel). Figure K. Erosional contact of channel sandstone (light grey, fine lithic sandstone (a) within grey silt (b) (11-01-056-19W5—615 m log depth; upper channels of the lower member of Scollard Formation).

Plate 2. Figure A. Core view of the upper part of Mu-Ml channel showing light grey “salt-and-pepper” medium to fine grain size lithic sandstone (11-01-056-19W5—542–544 m). Figure B. Core view of the upper channel of the lower member of the Scollard Formation showing light grey “salt-and-pepper” coarse to medium-fine grain size lithic sandstone (11-01-056-19W5—624–630 m).

Plate 3

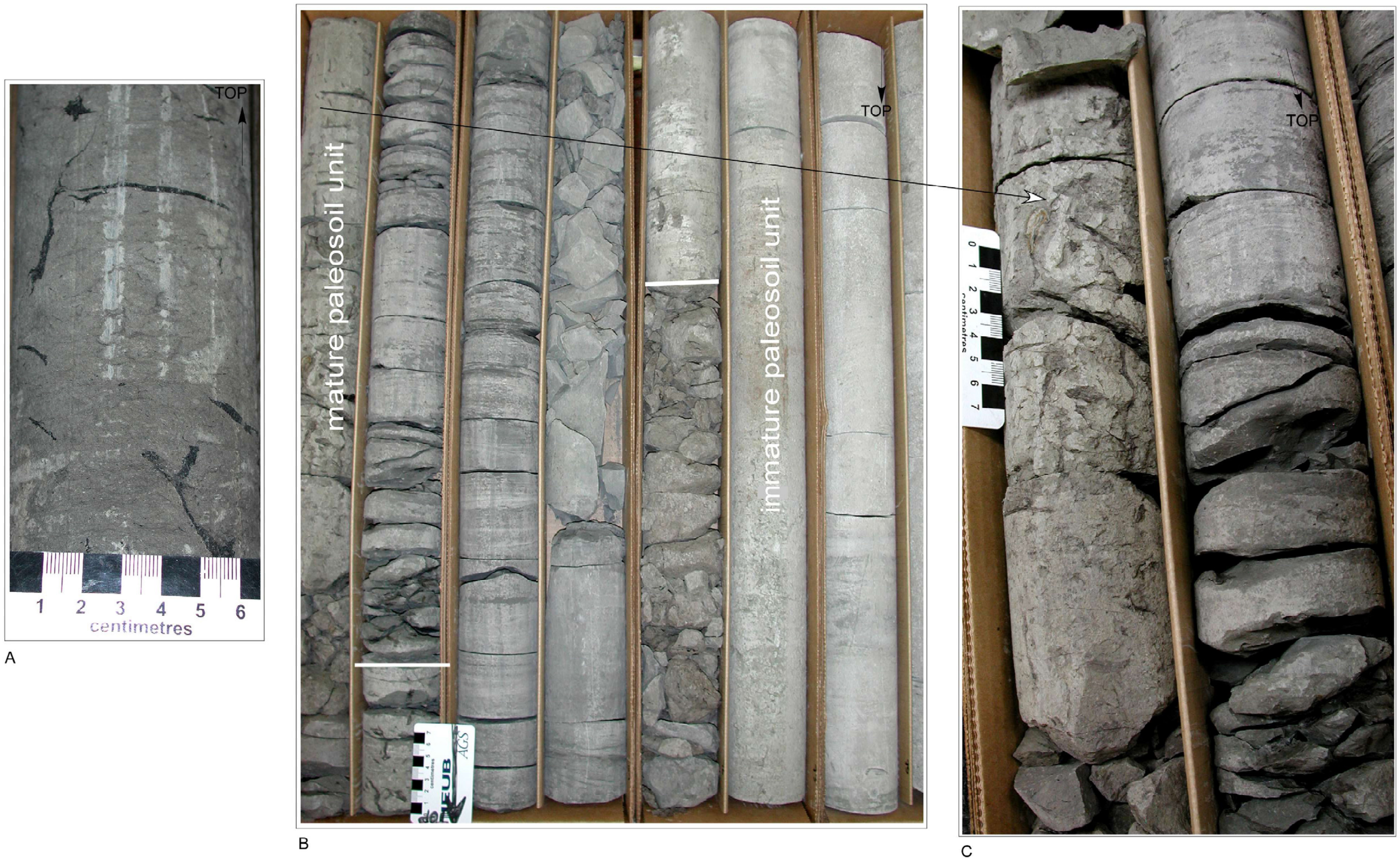

Plate 3. Figure A. Grey silty-mudstone with carbonized roots and vegetal fragments; “soil peds” are associated (11-01-56-19W5—581 m). Figure B. Core-view showing the succession of the paleosol units; the top unit represents grey-green mudstone with root traces; (10-27-61-20W5—270–274.5 m). Figure C. Detail of the “mature paleosol unit”; (10-27-61-20W5—270–274.5 m).

Plate 4

Plate 4. Figure A1-A2. Core-view of mudstone with paleosol structure overlying the “N” coal seams; Figure A2 detail of slickensides (10-19-050-19W5—600 m log depth). Figure B. Slickensides within silty-mudstone (10-19-050-19W5—600 m log depth). Figure C. Coaly shale consisting of thin bands of coal (<1 cm) and mudstone, slickenside at the coal-mud contact (10-19-050-19W5—600 m log depth). Figure D. Silty-mudstone with root traces interpreted as paleosol unit (10-19-050-19W5—600 m log depth).

Plate 5

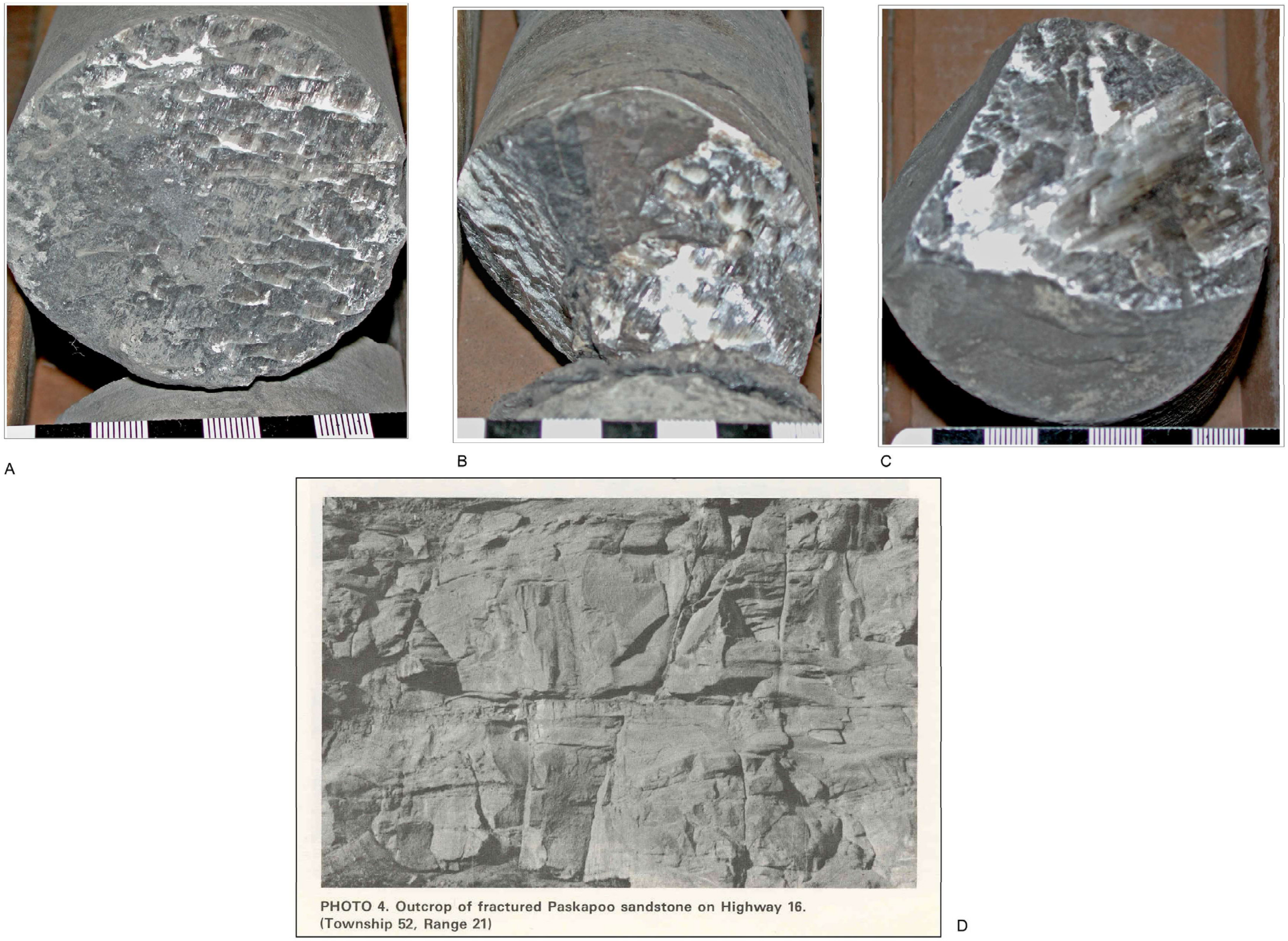

PHOTO 4. Outcrop of fractured Paskapoo sandstone on Highway 16.
(Township 52, Range 21)

Plate 5. Figures A-C. Slickensides in grey silt with secondary calcite deposits (10-19-50-19W5—593–597 m above “N” coal subzone). D. Fractures in Paskapoo Sandstones (Vogwill, 1983).

Plate 6

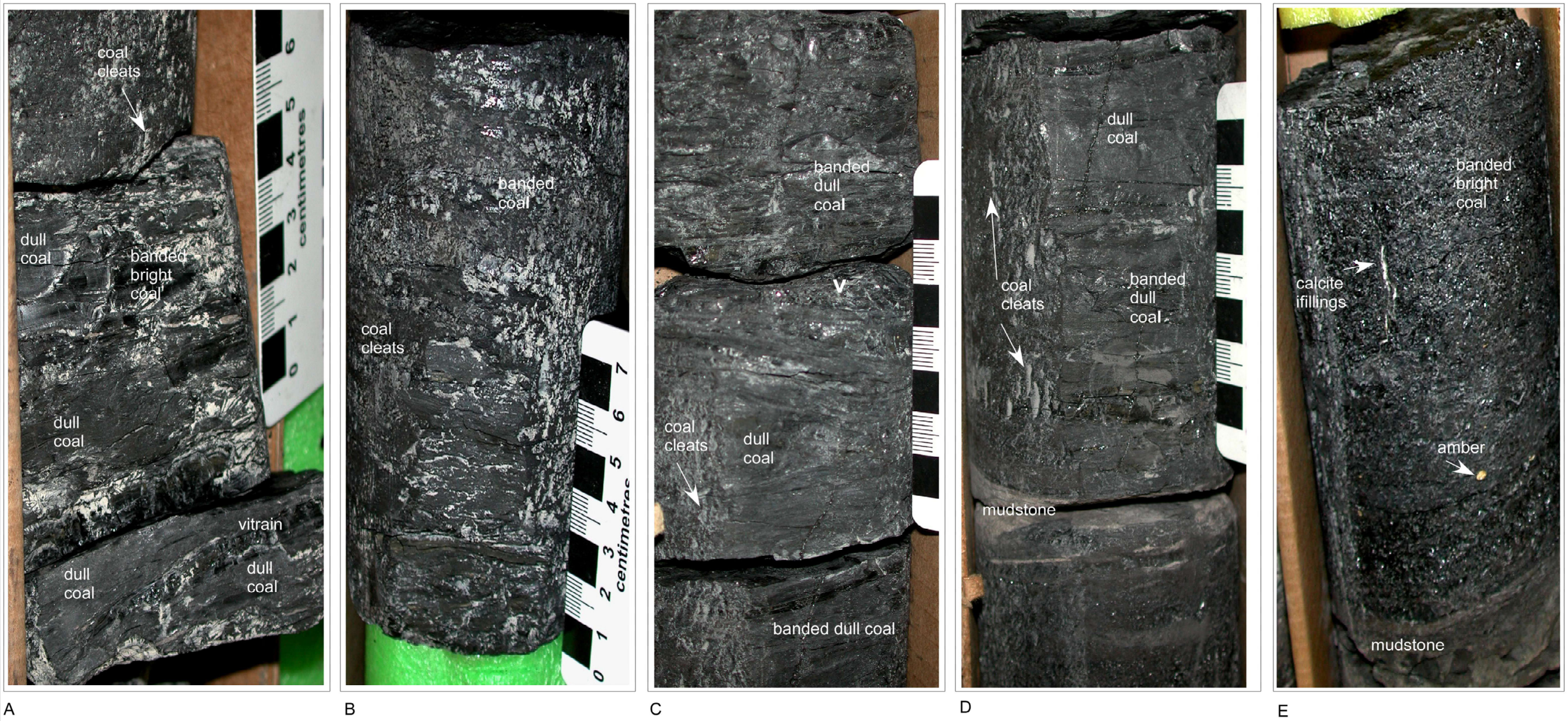

Plate 6. Figure A. Banded coal (10-27-61-20W5—260–270 m; “MI” coal subzone). Figure B. Banded coal 10-27-61-20W5—263 m; “MI” coal subzone). Figure C. Banded coal (10-27-61-20W5—295 m; “MI” coal subzone). Figure D. Banded coal (10-27-61-20W5—263 m; “MI” coal subzone). Figure E. Banded coal (10-27-61-20W5—269 m; “MI” coal subzone).

Plate 7

Plate 7. Figure A. Banded coal ((10-27-61-20W5 – 263 m; “MI” coal subzone). Figure B. Banded coal ((10-27-61-20W5 – 269 m; “MI” coal subzone). Figure C. Banded coal ((10-27-61-20W5 – 295 m; “MI” coal subzone).

Plate 8

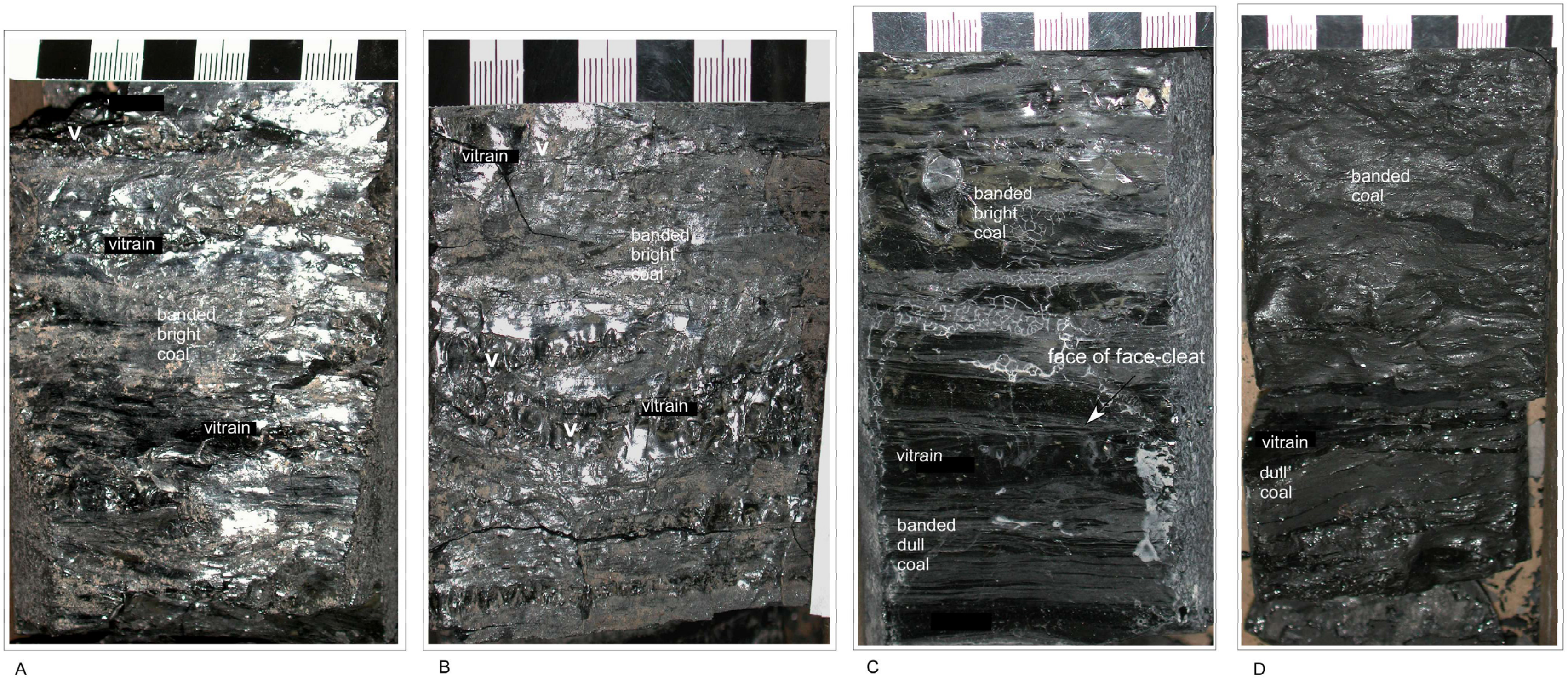

Plate 8. Figure A. Banded bright coal (11-06-56-19W5—728–735 m; "Mu" coal subzone). Figure B. Banded bright coal (11-06-56-19W5—728–735 m; "Mu" coal subzone). Figure C. Banded coal (11-01-56-19W5—591 m; "Ml" coal subzone).Figure D. Banded coal (11-01-56-19W5—591 m; "Ml" coal subzone).

Plate 9

Plate 9. Figure A. Banded coal (11-01-56-19W5—583 m; "MI" coal subzone). Figure B. Banded coal (11-01-56-19W5—585 m; "MI" coal subzone). Figure C. Dull coal (11-01-56-19W5—610 m; "N" coal subzone). Figure D. Banded coal (11-01-56-19W5—583 m; "MI" coal subzone). Figure E. Banded coal (11-01-56-19W5—598 m; "MI" coal subzone).

Plate 10

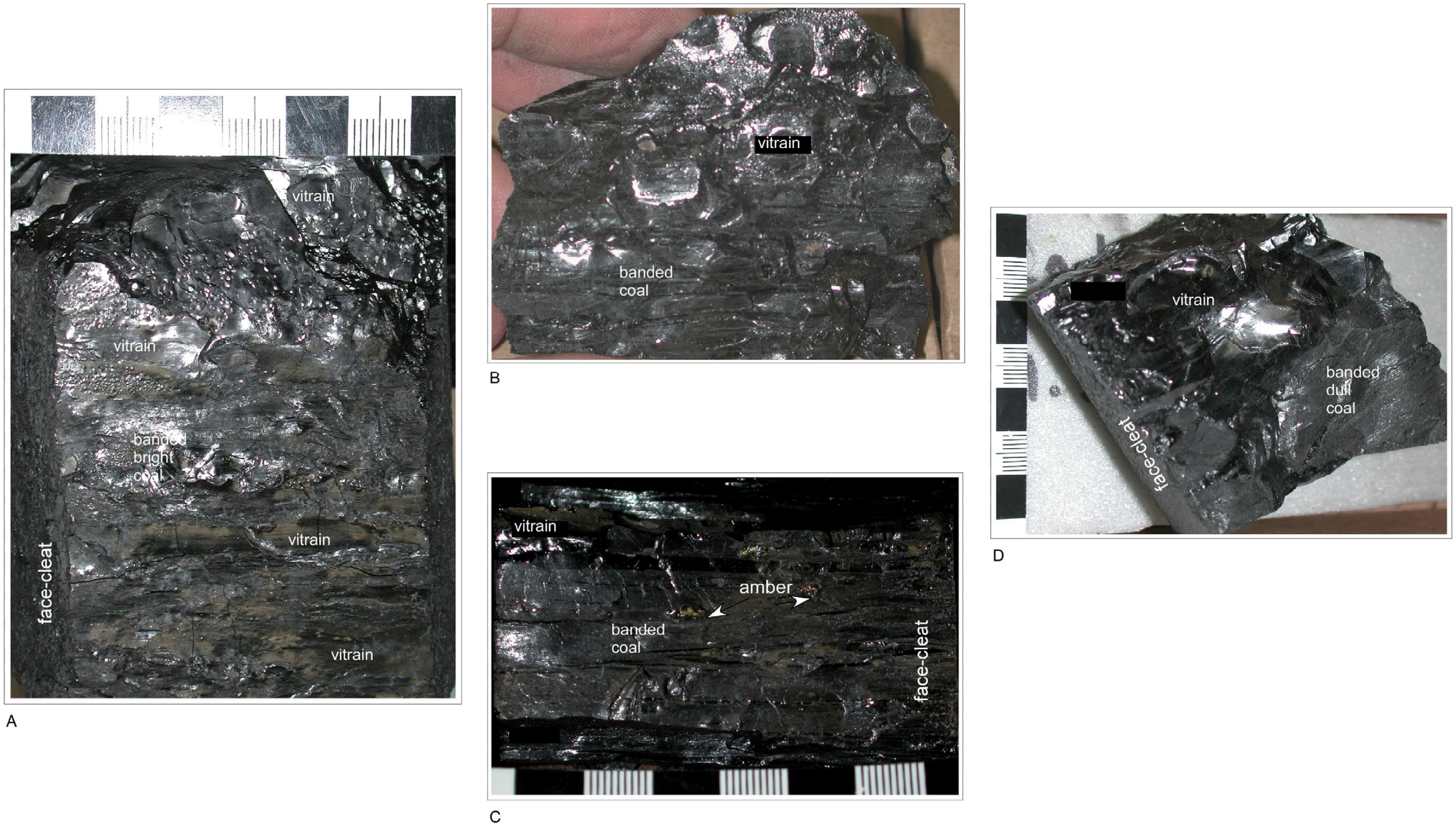

Plate 10. Figure A. Banded bright coal (11-06-56-19W5—725 m; “Mu” coal subzone). Figure B. Banded coal (11-01-56-19W5—580 m; “Ml” coal subzone). Figure C. Banded coal (11-06-56-19W5—728–735 m; “Mu” coal subzone). Figure D. Banded dull coal and vitrinite (>3cm) (11-01-56-19W5—610 m; “N” coal subzone).

Plate 11

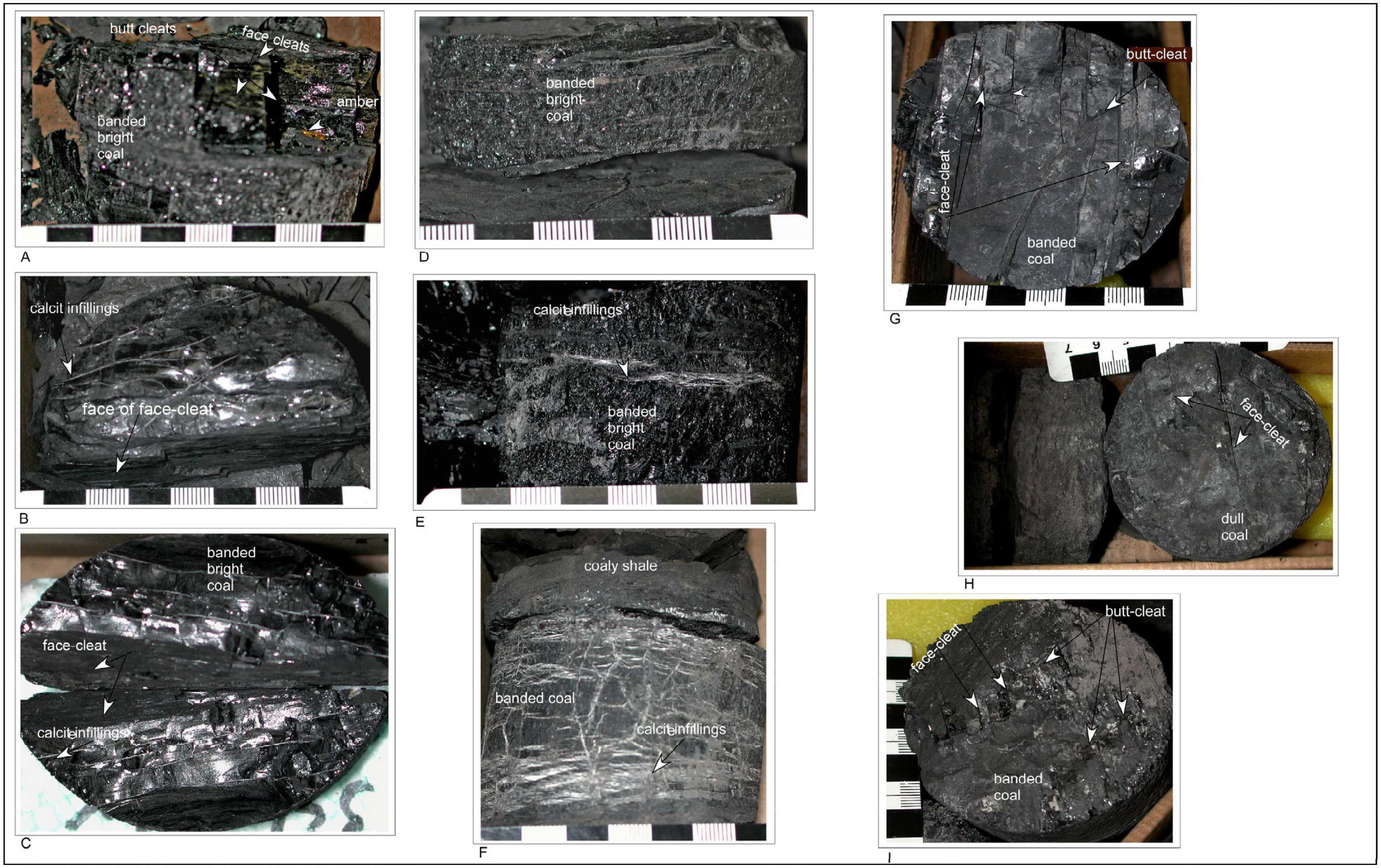

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Plate12

Plate 12. Figure A. Coaly-shale interbedded with tonstein (T) (10-27-61-20W5—260 m). Figure B. Coaly-shale interbedded with tonstein (T) (10-27-61-20W5—263 m). Figure C. Thin bed of tonstein within coal zone (11-06-56-19W5). Figure D. Coaly-shale interbedded with tonstein (T) (10-27-61-20W5—263 m). Figure E. Thin bed of tonstein within coal (11-01-56-19W5—573 m). Figure F. Tonstein: detail (11-01-56-19W5—590 m).