REGIONAL GEOLOGY AND HYDROSTRATIGRAPHY IN NORTHEAST ALBERTA

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by

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ALBERTA GEOLOGICAL SURVEY
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The Alberta Oil Sands Technology and Research Authority (AOSTRA) is currently planning to expand the Underground Test Facility (UTF) near Fort McMurray in northeast Alberta to a commercial size operation. As part of this expansion, it is envisaged to dispose of produced residual waters by on-site deep well injection. Selection of a disposal zone is currently under way. The upgrading of the UTF operations provides an opportunity for monitoring possible environmental effects related to the deep disposal of waste water resulting from the in situ extraction of bitumen from oil sands. With this in mind, and the additional objective of developing strategies for similar future activities, Environment Canada and the Alberta Research Council initiated a collaborative study of the effects of deep waste injection at the UTF site, with data support and cooperation from AOSTRA.

The evaluation of the effects of deep injection of waste water is based on predictive modelling, which requires knowledge of the initial baseline hydrogeological conditions. Because the data are very scarce and incomplete at the local scale, a regional-scale hydrogeological study is required for the identification and characterization of the hydrostratigraphic units at the UTF site. For this purpose, a regional-scale study area is defined in northeast Alberta between latitudes 55°N and 58°N, and longitudes 110°W to 114°W (Tp 70-103, R 1-26, W4 Mer). The first step in the hydrogeological characterization is the description of the geology and the delineation of the hydrostratigraphy, which form the content of this progress report.

The geology and hydrostratigraphy of the Phanerozoic sedimentary rocks in northeast Alberta are extremely complex due to various depositional, salt dissolution and erosional events. The shales interbedded with sandstones, red beds and evaporitic units of the Lower Elk Point Subgroup (Lower Devonian) overlying the impervious crystalline Precambrian basement form a dominantly aquiclude system at the base of the succession. The overlying carbonates of the Winnipegosis aquifer are separated from the mainly carbonate Beaverhill Lake aquifer system by the halite and shale of the Prairie-Watt Mountain aquiclude system. The argillaceous Ireton aquitard separates the Beaverhill Lake and Grosmont-Wabamun aquifer systems. All the Devonian strata have been eroded and subcrop at the sub-Cretaceous unconformity. They are overlain by the succession of the McMurray, Clearwater and Grand Rapids formations of the Lower Cretaceous Mannville Group. These are defined as weak aquifer-aquitards because of a complex combination of interbedded sands, shales and oil sands. The Colorado aquitard system (mainly shales with a few sandy units) lies at the top of the hydrostratigraphic succession.

The hydrogeological characterization (porosity and permeability, formation pressure, and chemistry of formation waters) of the hydrostratigraphic units identified in this progress report will form the subject of the next research stage.

INTRODUCTION

For the last few years, the Alberta Oil Sands Technology and Research Authority (AOSTRA) has been developing an Underground Test Facility (UTF) for the extraction of bitumen from oil sands deposits using a steam-stimulated and gravity-drainage recovery process. Phase A of the operations had the objective of evaluating the Shaft and Tunnell Access Concept (SATAC) to produce bitumen, and to test the new concept and technology. Phase A proved successful beyond the initial predictions based on numerical process simulations, and the facility is currently expanding to a commercial phase. One of the byproducts of the bitumen extraction is liquid waste, which was trucked to a disposal site during Phase A of the operations. It is currently being planned to dispose of the much larger volume of residual water produced by a commercial size operation by on site deep well injection. Selection of a disposal zone is currently under way. AOSTRA has and is addressing environmental problems related to the UTF operation, including the issue of subsurface disposal of residual water. Nevertheless, the upgrading of the UTF operations to commercial scale provides an opportunity for the monitoring, from the start, of possible environmental effects related to the exploitation of the oil sands deposits, and for the development of strategies and guidelines for similar future activities. With this broad objective in mind, Environment Canada and the Alberta Research Council initiated the present collaborative study, with data support and cooperation from AOSTRA.

In order to identify possible environmental effects of deep well injection of liquid waste at the UTF site, predictive modelling of the associated hydrodynamic, geomechanical and geochemical processes is required. To do this, it is necessary to know the initial baseline hydrogeological conditions existing prior to the start of injection, and the relevant parameters and characteristics of the subsurface environment. Proper monitoring during injection will allow continuous model calibration and updating. AOSTRA implemented and is currently running a program of detailed data collection and monitoring around the steam chambers forming as a result of bitumen extraction. However, the data needed for the evaluation of the effects of deep waste disposal are scarce, requiring the extension of any related hydrogeological study beyond the UTF site itself (Basin Analysis Group, 1988).

The UTF site is located on about 9 ha (22 acres) situated some 50 km northwest of Fort McMurray and 20 km southwest of Fort McKay, in Sections 7 and 8, Tp 93, R 12, W4 Mer (Figure 1). Some of the selection criteria used in choosing the location of the UTF site (Suggett, 1987) were an overburden depth greater than 90 m, a pay zone of at least 13 m with greater than 10 wt % bitumen, and total in-place reserves of 16 x 10^6 m^3 (100 x 10^6 bbls). The pay zone is the lower 20 m of the McMurray Formation, which rests unconformably on Devonian limestone at a depth of 163 m (Edmunds, 1987). Two vertical shafts have been sunk to a depth of about 213 m into the underlying limestone of the Waterways Formation, providing access to horizontal tunnels from which horizontal injection and production well pairs have been drilled into the oil sands. The dual-well process uses the top horizontal well for steam injection at sub-fracture pressures and the bottom well for producing oil, formation water, and

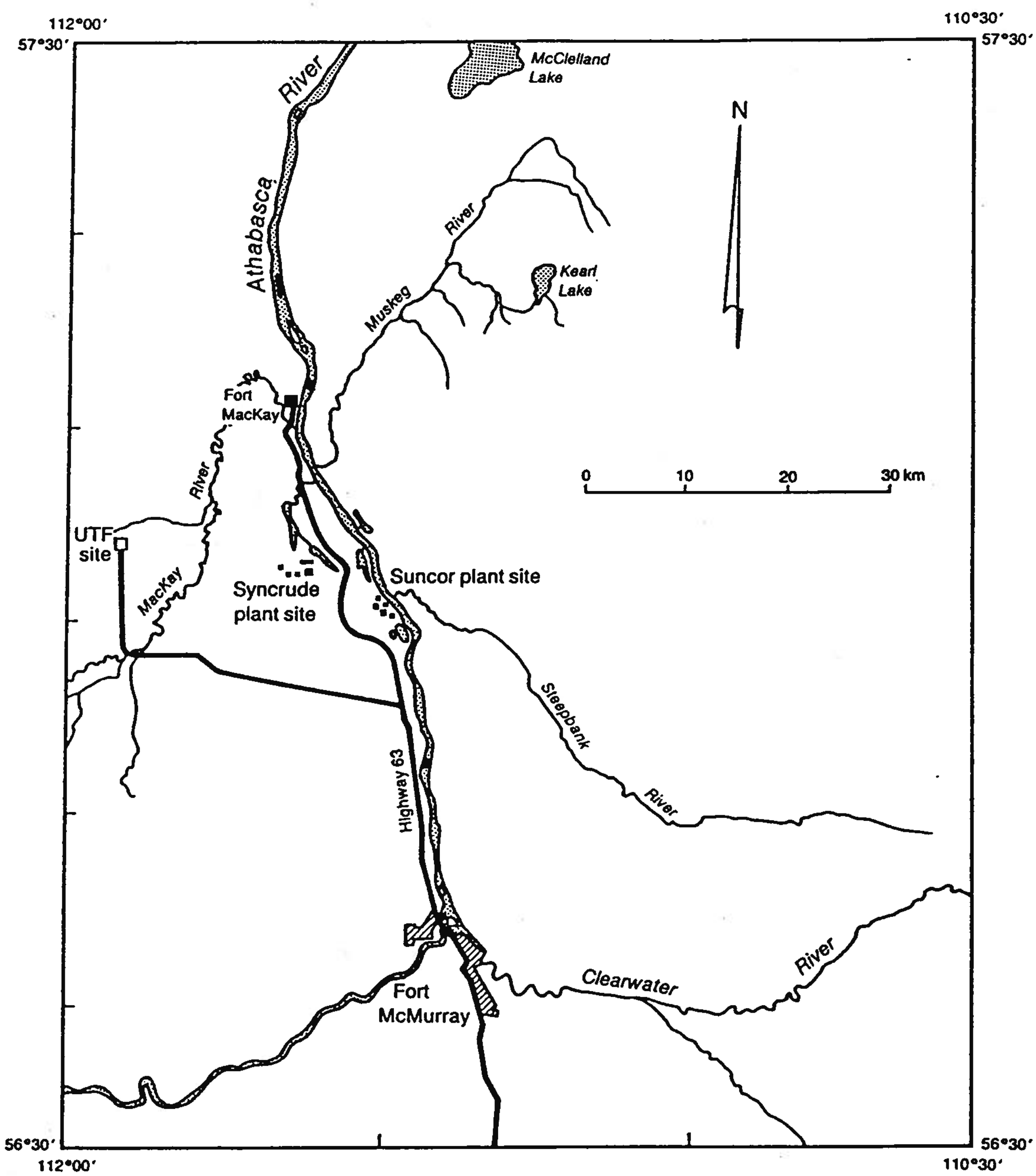


Figure 1: Location map showing the UTF site.

condensed steam. Surface facilities at the site include the water treatment plant, separators, storage tanks and produced-water disposal systems. Figure 2 shows a diagrammatic representation of the UTF site. A deep disposal well will be added in the commercial phase.

In order to use predictive modelling in the evaluation of the environmental effects of deep injection of liquid waste, there is need to emplace the hydrogeological and transport processes in a three-dimensional geological frame. This means that the sedimentary rocks have to be described and characterized first, particularly in terms of lithology and variability of hydrodynamic properties. Subsequently, hydrostratigraphic units (aquifers, aquitards and aquicludes) must be delineated and characterized by their properties, particularly if one considers that permeability varies over several orders of magnitude. The pressure regime and the chemical composition of formation waters have to be analyzed and defined. A previous analysis of data availability for predictive modelling at the UTF site (Basin Analysis Group, 1988) identified four different scales (Figure 3): a detail scale covering the steaming zone, a local scale covering the UTF site, an intermediate scale covering four townships around the site, and a regional scale defined as Tp 89-97, R 6-18, W4 Mer. The identification of these four scales was dictated by the very uneven distribution of various data categories both areally and with depth. While there is extensive information for the Cretaceous strata at the local scale, data for the Paleozoic strata are scarce (the nearest deep well to the UTF site is more than 10 km away). The main recommendation of the previous study on data availability (Basin Analysis Group, 1988) was to perform predictive modelling and monitoring at

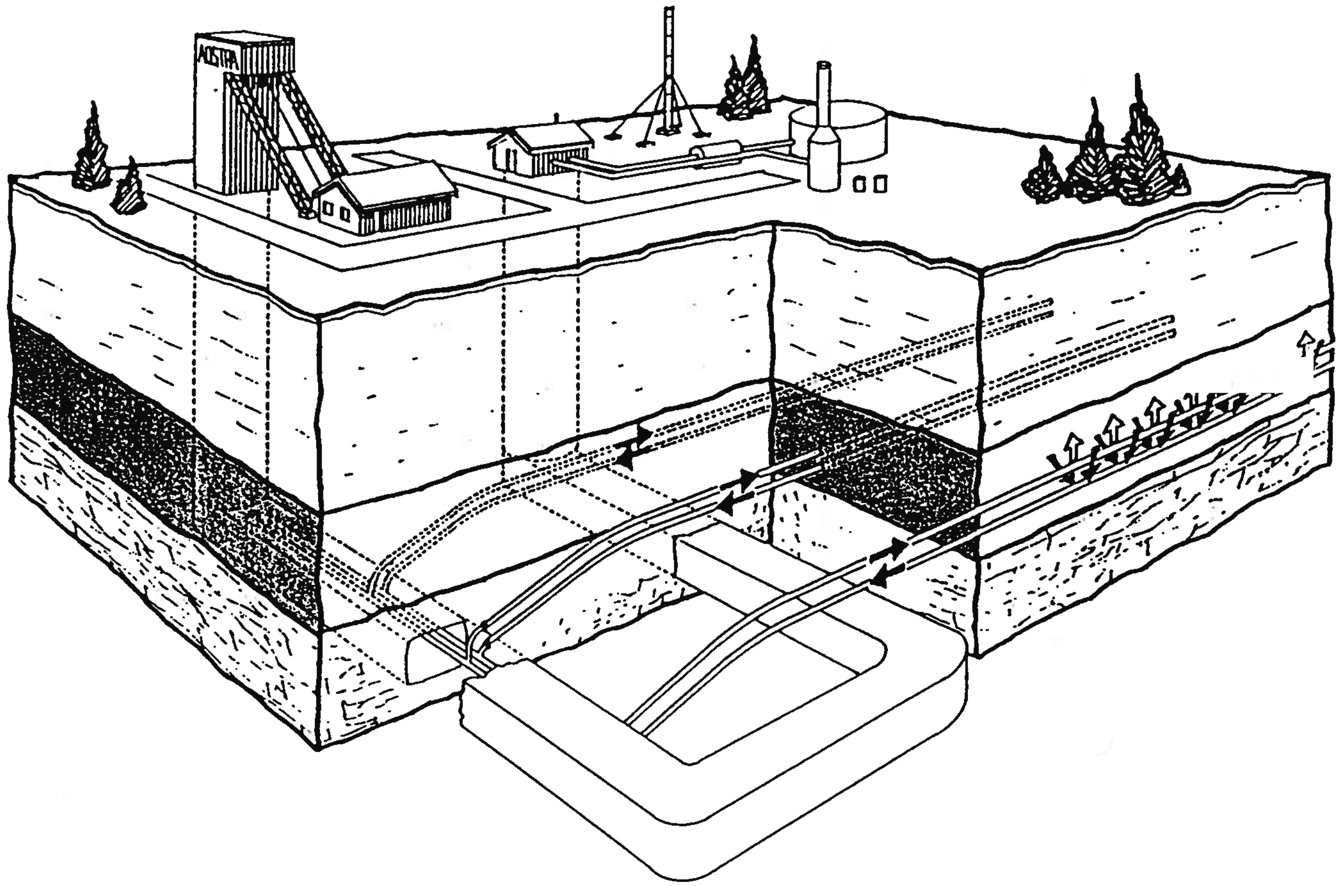


Figure 2: Conceptual diagram of the Underground Test Facility.

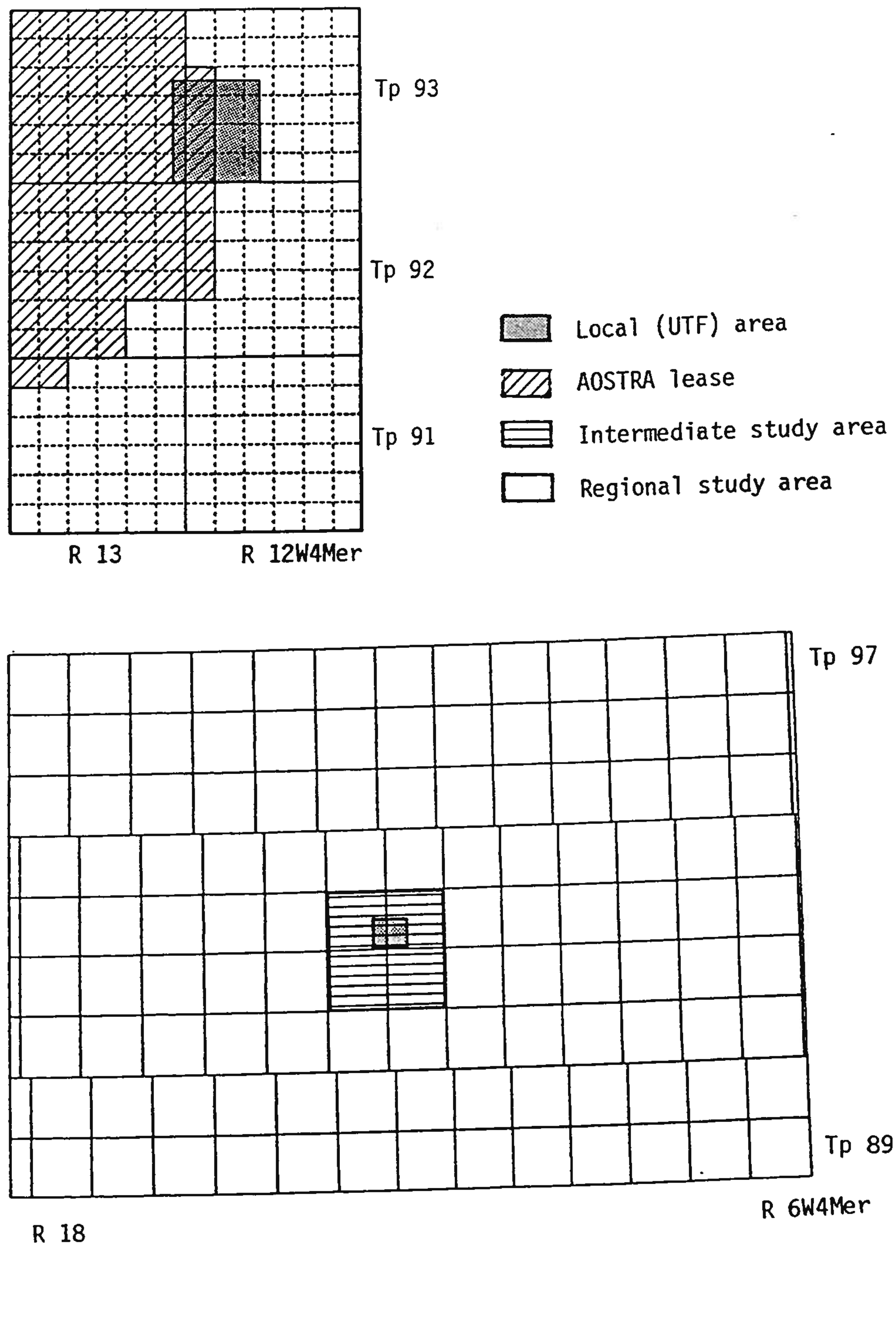


Figure 3: Delineation of the detail, local, intermediate and regional scales recommended for hydrogeological studies (Basin Analysis Group, 1988).

the local scale. In order to define the distribution field of variables such as pressure (hydraulic head) and salinity, the study also recommended performing a hydrogeological characterization at a regional scale.

The present study of the effects of deep liquid waste disposal at the AOSTRA-UTF site was approached bearing in mind the previous recommendations. Namely, a regional-scale hydrogeological study was to be carried out first for the definition of the initial baseline conditions, followed by local-scale hydrodynamic and geochemical modelling. In 1990, the Petroleum Geology and Basin Analysis Section of the Alberta Geological Survey, Alberta Research Council, started a regional, basin-scale study of the Phanerozoic sediments in northeast Alberta. The study area, defined by Tps 70-126, east of the 5th Meridian to the edge of the Western Canada Sedimentary Basin (Figure 4), includes the regional scale area defined for the purpose of evaluation of the effects of deep waste disposal at the AOSTRA-UTF site (Basin Analysis Group, 1988). Thus, when Environment Canada and the Alberta Research Council agreed on a collaborative study regarding environmental aspects at the UTF site, it was decided to adopt the Northeast Alberta study area (Figure 4) as the regional-scale extent of the hydrogeological characterization.

This progress report presents results achieved to date regarding the geological, stratigraphic and hydrostratigraphic delineation and characterization on a regional scale of the Phanerozoic sedimentary rocks of northeast Alberta. It will be followed by a regional scale hydrogeological characterization, scheduled for the fall

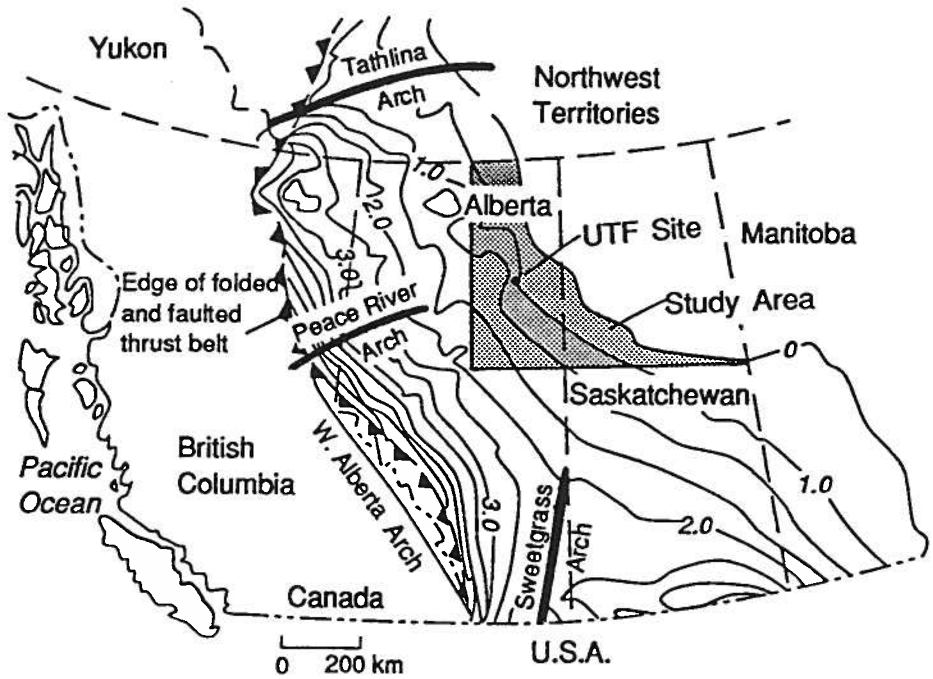


Figure 4: Location of the Northeast Alberta regional-scale study area in (isopach of sediments in the Western Canada Sedimentary Basin in kilometers; after Porter et al., 1982).

of 1991, and by local scale hydrodynamic and geochemical predictive modelling to be carried out in 1991 and 1992. The analysis and processing of the geological data was carried out by Darrell Cotterill, Don McPhee and Jim Underschultz. Technical and clerical support was provided by Mika Madunicky and Margaret Booth, respectively. The support and cooperation of Neil Edmunds, UTF Project Manager, and Jane Stevens, AOSTRA Senior Geologist, is gratefully acknowledged.

PROCESSING OF GEOLOGICAL DATA

The Western Canada Sedimentary basin comprises two entities of interest to this study: (1) the rock framework, and (2) the contained fluids, which are dominantly formation waters with effectively minor, but economically important, amounts of hydrocarbons (natural gas, condensate, conventional crude oil, heavy oil, and bitumen). A computer based Dynamic Basin Analysis approach (Hitchon et al., 1987) as described by Bachu et al. (1987) was used to develop a comprehensive, qualitative, and quantitative understanding of dynamic processes in the basin, specifically, sedimentary processes, fluid flow, heat transfer, and mass transport. This chapter presents the computer based methodology applied to the rock framework (excluding rock flow properties) within the Northeast Alberta study area.

DATA SOURCES AND DATA BASE

The data set used for describing the stratigraphy is a mosaic of information obtained from previous studies which either wholly or partially lie within the Northeast Alberta study area, supplemented by data from the files of the Alberta Energy Resources Conservation Board (ERCB) (a public data repository). The electronic stratigraphic-picks data files from Kramers and Prost (1986), Flach (1984), Keith et al. (1987), McPhee and Wightman (1988), and MacGillivray et al., (1989), together with hard-copy stratigraphic-picks data from Hamilton (1971), Hackbarth and Brulotte (1981) and Harrison (1986), were checked for consistency, and either converted or entered into a standard format (picks data converted to elevations) for inclusion in a customized project data base (a subset of the Alberta Geological Survey Well Data Base, or AGSWDB). Figure 5 shows the total data distribution (12,479 wells) for the Northeast Alberta study area. Regions of high well density reflect the location of major oil sands deposits and oil and gas discoveries. Because there are no wells north of 58°N and only 4 wells east of the 4th Meridian, the area for which stratigraphic surfaces were gridded, contoured and discussed subsequently is the Alberta portion of the study area south of 58°N. The data density decreases sharply for Paleozoic units. Only 110 wells reach the Precambrian basement in this area (Figure 6).

All data are characterized by geographic position and depth, but the interrelations between the various types of data are very complex. Because of this complexity an appropriate data base management system (DBMS) is essential for the analysis of the hydrogeological regime in large sedimentary basins. The basic concept of a DBMS is to separate the description of the data from applications, and to provide a set of basic tools for adding, deleting, and retrieving data. The current implementation of the Alberta Geological Survey Well Data Base (AGSWDB) uses the INGRES DBMS, and contains on-line data for more than 200,000 wells in the Western Canada Sedimentary Basin. INGRES implements a relational data model, which has the attribute that new relations can be easily created. This is coupled with the relatively standard SQL language for data definition and retrieval, thus allowing much flexibility in supporting nonstandard ad-hoc data retrieval.

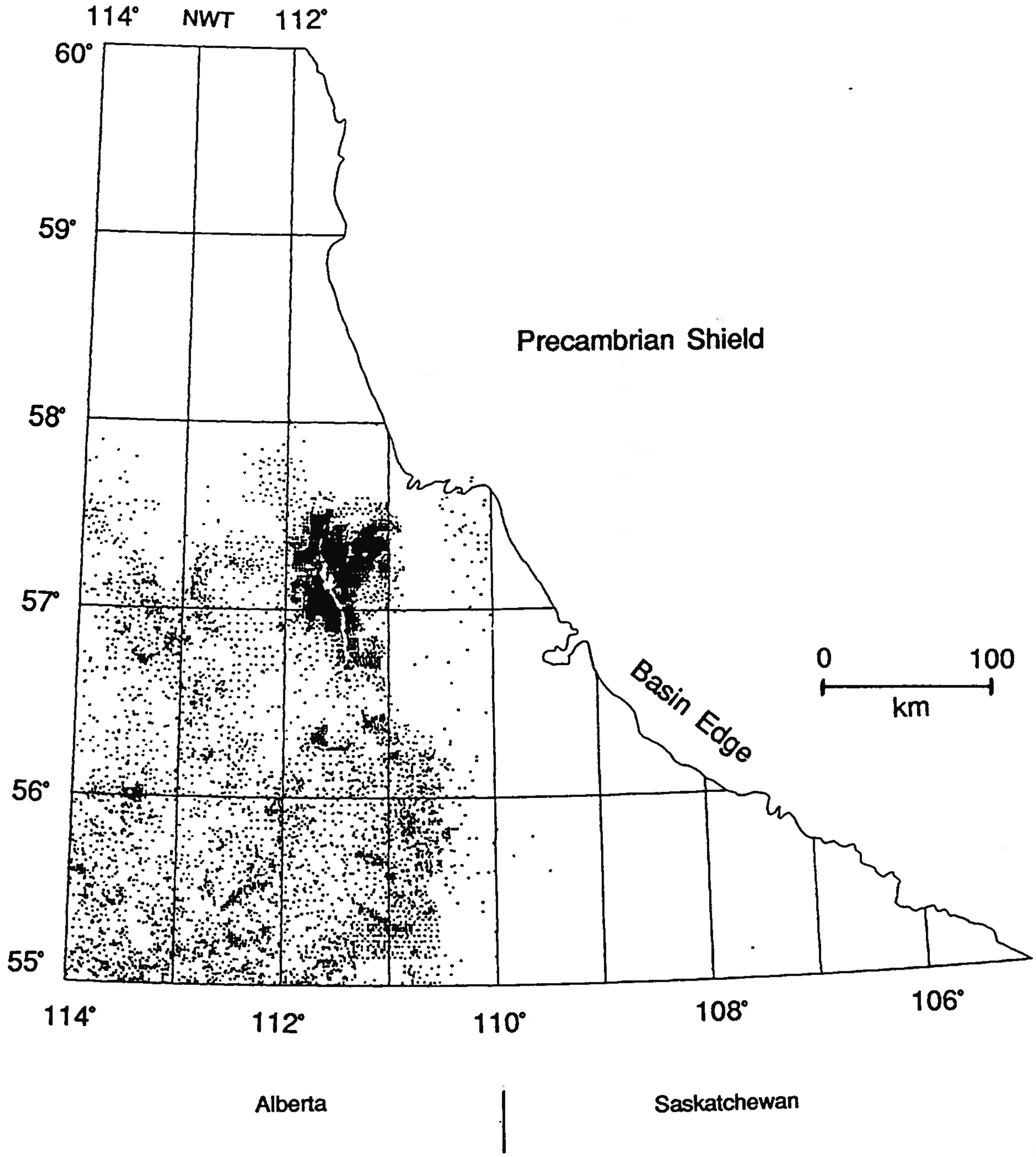


Figure 5: Distribution of wells in the Northeast Alberta regional-scale study area.

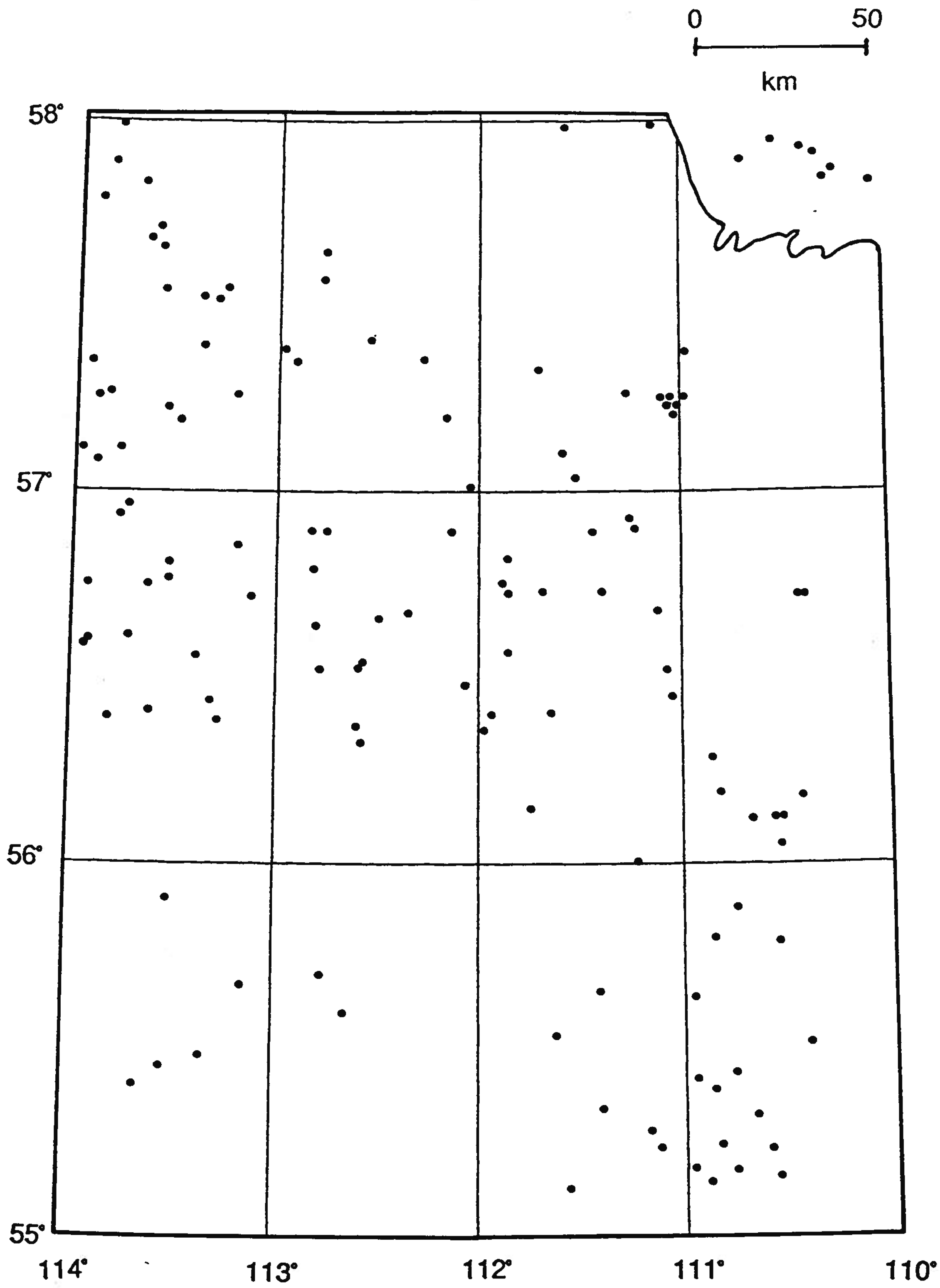


Figure 6: Distribution of wells reaching the Precambrian basement, northeast Alberta.

AUTOMATED GRIDDING AND CONTOURING

Gridding refers to the process by which an irregular data distribution is converted into a data set of estimated values at the nodes of a uniform grid. A map is then generated by interpolating and contouring the grid-node values. The CPS3 software developed by Radian Corporation was used for automated gridding and contouring. Alberta Research Council cartographic software (AGSSYS, AGSDIG, and AGSCPS) was used to process stratigraphic picks data, and to obtain Dominion Land Survey (DLS) and latitude-longitude displays.

In an integrated basin analysis approach, as is the case in this study, it is important to select a gridding algorithm producing grids and maps which meet criteria essential for all aspects of the project. The main criteria for algorithm selection are: (1) where data exist, the resultant grid must accurately represent the observed values; (2) for modelling purposes, the stratigraphy is required to be realistically characterized everywhere it is thought to exist, including the areas for which there are little or no data; and (3) the gridding must take into account the high variability in data density both areally and with depth, and various degrees of data clustering. With these constraints in mind, a convergent gridding algorithm was selected whereby grid-node values are converged upon through several iterations. The z-value at a given node is estimated by using a distance-weighing technique such that control points closer to the node have a larger effect on the outcome of the z-value at the node (Graf and Thomas, 1988).

In the convergent gridding process, a series of steps is performed within each iteration. In the first iteration, a coarse grid (13 x 16 nodes) is used and each data point is considered at 16 surrounding nodes. The grid is smoothed and tied to the data using a biharmonic filter (Graf and Thomas, 1988). A series of up to 10 gridding iterations follows, in which, at each successive iteration, a data point is considered at fewer surrounding nodes and the number of nodes increases. In the last pass, the grid is refined to 130 x 127 nodes and the data values are considered only at the nearest node. This iterative process produces a trend-like solution in areas of sparse or no data, and an accurate representation where data exist. During each iteration, the goodness of fit between the grid and the data is monitored to determine if more iterations, up to a maximum of 10, are necessary (Graf and Thomas, 1988). The final map is generated by contouring the grid produced by the convergent algorithm.

STRATIGRAPHIC GEOMETRY

For a sedimentary basin, the rock framework refers to the geology, stratigraphy, and geometry of the sedimentary rocks, and their characteristic flow properties (porosity and permeability). Here, only methods used for characterizing the stratigraphy of the sedimentary rocks are considered. The strata within the study area were divided into 29 units (Table 1) and are constrained by picks from 12,479 wells (Figure 5). Because of the large number of stratigraphic units and associated picks, and the need to meet various criteria for all aspects of the project, automated processing was the only way to process the data and characterize the rock

EON	ERA	Period	Epoch	Group	Subgroup	Formation	Data Points	Order
Phanerozoic	Cenozoic	Quaternary Tertiary				Ground	12479	1
Phanerozoic	Mesozoic	Cretaceous	Upper	Colorado		2 White Specks	565	3
Phanerozoic	Mesozoic	Cretaceous	Upper	Colorado		Base of Fish Scales	1855	4
Phanerozoic	Mesozoic	Cretaceous	Lower	Colorado		Viking	1121	4
Phanerozoic	Mesozoic	Cretaceous	Lower	Colorado		Joli Fou	1634	2
Phanerozoic	Mesozoic	Cretaceous	Lower	Mannville		Grand Rapids	3767	2
Phanerozoic	Mesozoic	Cretaceous	Lower	Mannville		Clearwater	3991	3
Phanerozoic	Mesozoic	Cretaceous	Lower	Mannville		Wabiskaw	5668	3
Phanerozoic	Mesozoic	Cretaceous	Lower	Mannville		McMurray	9016	3
Phanerozoic	Mesozoic	Jurassic						
Phanerozoic	Mesozoic	Triassic						
Phanerozoic	Paleozoic	Permian						
Phanerozoic	Paleozoic	Carboniferous				Subcretaceous Unconformity	5051	1
Phanerozoic	Paleozoic	Devonian	Upper			Wabamun	417	2
Phanerozoic	Paleozoic	Devonian	Upper			Winterburn	144	3
Phanerozoic	Paleozoic	Devonian	Upper	Woodbend		Upper Ireton	133	3
Phanerozoic	Paleozoic	Devonian	Upper	Woodbend		Grosmont	770	2
Phanerozoic	Paleozoic	Devonian	Upper	Woodbend		Lower Ireton	222	3
Phanerozoic	Paleozoic	Devonian	Upper	Woodbend		Cooking Lake	142	4
Phanerozoic	Paleozoic	Devonian	Upper	Beaverhill Lake		Mildred Moberly Christina Calumet Firebag Slave Point Fort Vermilion	3427	2
Phanerozoic	Paleozoic	Devonian	Middle	Elk Point	Upper	Watt Mountain	311	2
Phanerozoic	Paleozoic	Devonian	Middle	Elk Point	Upper	Prairie	152	3
Phanerozoic	Paleozoic	Devonian	Middle	Elk Point	Upper	Winipegosis (Keg River)	163	3
Phanerozoic	Paleozoic	Devonian	Middle	Elk Point	Lower	Contact Rapids	236	2
Phanerozoic	Paleozoic	Devonian	Lower	Elk Point	Lower	Cold Lake	34	3
Phanerozoic	Paleozoic	Devonian	Lower	Elk Point	Lower	Ernestina Lake	153	3
Phanerozoic	Paleozoic	Devonian	Lower	Elk Point	Lower	Upper Lotsberg	56	3
Phanerozoic	Paleozoic	Devonian	Lower	Elk Point	Lower	Lower Lotsberg	24	3
Phanerozoic	Paleozoic	Devonian	Lower	Elk Point	Lower	Basal Red Beds	110	4
Phanerozoic	Paleozoic				Lower	Granite Wash		
Phanerozoic	Paleozoic	Silurian						
Phanerozoic	Paleozoic	Ordovician						
Phanerozoic	Paleozoic	Cambrian						
Pre-cambrian							110	1

Table 1. Generalized stratigraphic nomenclature, associated number of control points, and confidence ranking.

framework. In order to obtain a geologically realistic delineation of the stratigraphy, the following three-step approach as defined by Bachu et al. (1987) was taken: (1) interpreting and defining major geological events and stratigraphic considerations; (2) data processing; and (3) checking and correcting the resulting grids and maps for internal consistency.

The method of building stratigraphic surfaces from "control surfaces" has been described by Jones and Johnson (1983) and Bachu et al. (1987). This method was refined for the stratigraphic delineation within the Northeast Alberta study area. Jones and Johnson (1983) and Bachu et al. (1987) define two categories of surfaces. The first category comprises "control surfaces", of which there is typically one for each package of conformable strata. The control surface is usually at the top of the stratigraphic package, has a large number of data points, and is either a structure top or bottom of a unit. Control surfaces are not based on isopach data, but on elevations. The second category comprises "non-control surfaces", which make up the rest of the surfaces in a particular stratigraphic package. Non-control surfaces can either be directly based on structure pick data, or can be calculated from isopach data. The approach described by Jones and Johnson (1983) and Bachu et al. (1987) is to start with defining a grid and contour map for the control surface within a particular stratigraphic package. This grid and map represent the surface with the highest confidence level in that package. The non-control surfaces are then sequentially gridded and contoured, starting from the one nearest to the control surface. If inconsistencies between surfaces arise (usually within zones of extrapolation), the non-control surfaces are modified by either adding or subtracting a geologically acceptable isopach from the control surface. In this way, all inconsistencies are resolved with respect to the control surface.

The "control surface" approach was improved in this study in that rather than subdividing surfaces within a given stratigraphic package into two levels of confidence, a hierarchy of 4 confidence levels was developed (Table 1). First order surfaces are those marking significant breaks in the stratigraphic column; in this study they are the ground, Precambrian basement, and sub-Cretaceous unconformity surfaces. Second order surfaces are those which have a relatively large number of evenly distributed data points and correspond to units which have a commonly recognized and distinctive signature on geophysical logs. Third order surfaces have either sparsely distributed or highly clustered data points, or less distinctive signatures on geophysical logs (more difficult to correlate). Fourth order surfaces are those for which either the data are very sparse or the data set is of questionable quality or consistency. The approach used to assemble the surfaces follows that described by Jones and Johnson (1983) and Bachu et al. (1987) where inconsistencies between any two surfaces are resolved by modifying the surface with the least degree of confidence. Methods used to map unconformities, subcrops, and onlap are described by Bachu et al. (1987). The stratigraphic surfaces were sequentially gridded and mapped from first to fourth order, with inconsistencies resolved at each step.

STRUCTURE SURFACES AND ISOPACHS

There are two methods in generating internally consistent structure and isopach grids. The first approach involves gridding pick data for each structure surface and subtracting the base structure grid from the top structure grid of the respective unit, resulting in a "pseudo-isopach". Pseudo refers to the fact that the grid is calculated by subtracting two structure grids rather than gridding thickness data directly. In this case the isopach grid is controlled in areas of little or no data by extrapolation of the upper and lower structure surfaces. This approach is best suited to the cases in which the spatial frequency of thickness variation is greater than can be resolved by the data density. The McMurray Formation is an example of the application of this method. In this case the lower bounding surface is the sub-Cretaceous unconformity (a first order control surface) and the upper surface is the top of the McMurray Formation. Because the McMurray Formation fills in the relief at the top of the Paleozoic, yet has a relatively smoothly trending structure surface, the grid of the structure top and base have a higher confidence level than the grid of the isopach data because the thickness of this unit is highly variable. Thus, structure picks were gridded for the top and base of the unit for which the isopach was calculated.

The second approach is to produce directly isopachs from thickness data and, starting from the nearest higher order surface, either add or subtract the isopach grid to generate a "pseudo-structure" grid. In this case the resultant structure grid is controlled in areas of little or no data by extrapolation of the isopach grid. This approach is best suited to cases in which the spatial frequency of elevation variation of a unit is greater than can be resolved by the data, while that of the isopach is not. In this study, the Elk Point Group units are best characterized in this fashion because they tend to have uniform thickness but variable structure surfaces because of salt dissolution resulting in the collapse of the overlying units. For the Elk Point Group, the base of the Upper Lotsberg Salt is stratigraphically the highest surface unaffected by salt dissolution. This surface was first constrained by the Precambrian structure surface (a first order surface) and then used as a base upon which directly gridded isopachs were successively added, producing structure surface grids for each unit. These were in turn also constrained above by the Beaverhill Lake Group structure surface (a second order control surface).

This hierarchical approach to mapping stratigraphic geometries on a regional basis for the purposes of Dynamic Basin Analysis is particularly appropriate in that the highest number of constraints are applied to areas where data are absent and extrapolation is necessary. This results in the best possible estimation of stratigraphic geometries which are geologically acceptable.

GEOLOGICAL HISTORY OF THE WESTERN CANADA SEDIMENTARY BASIN

An overview of the Phanerozoic strata of northeast Alberta is presented in the next chapters in the context of the major depositional and erosional events that have taken place in the Western Canada Sedimentary Basin. In order to understand better the structure, lithology, and subsequently the hydrogeology of the strata, knowledge of the geological history of the basin is required, presented succinctly in the following paragraphs.

The Western Canada Sedimentary Basin is a sedimentary wedge that thickens westward from a zero-edge at the Canadian Shield to more than 6 km in the foreland thrustfold belt (Figure 4). Adjacent to the Canadian Shield, the regional dip of Paleozoic strata is approximately 4 m/km, while that of the overlying Mesozoic strata is only 1.4 m/km. Approaching the foreland thrust belt, the regional dip of the Phanerozoic strata increases to 10 m/km. McCrossan and Glaister (1964), Parsons (1973), Porter et al. (1982), Stearn et al. (1979), and Ricketts (1989) describe the geological history and geology of the Western Canada Sedimentary Basin.

Major divisions of the Western Canada Sedimentary Basin, when explained in terms of current plate tectonic theory, comprise two fundamentally different tectono-sedimentary realms: the long-lived passive margin, and the foreland basin. The passive margin or platformal phase was initiated during the Proterozoic by rifting of the North American craton resulting in the generation of a miogeosynclineplatform. Thermal contraction (McKenzie, 1978; Bond and Kominz, 1984), following the initial rifting event, led to the transgressive onlap of the North American cratonic platform from Middle Cambrian to Middle Jurassic time. During this time interval, the platform was overlain by four unconformity-bounded sequences: Sauk, Tippecanoe, Kaskaskia, and Absaroka (Figure 7) (Ricketts, 1989). All of the sequences except the Sauk are dominantly shallow water carbonate and evaporite successions. The Sauk sequence is a dominantly clastic succession. Following the deposition of the Sauk (Cambrian) sequence, epeirogenic arches and basins developed on the cratonic platform and locally controlled sedimentation throughout the passive-margin phase.

The foreland basin developed in two stages: Middle Jurassic to early Cretaceous (Colombian Orogeny) and late Cretaceous to Paleocene (Laramide Orogeny), as a result of the collision of allocthonous terranes with the western margin of the craton. During these orogenies, the miogeosynclinal succession was compressed, detached from its basement and thrust over the flank of the craton to form the present eastern part of the Cordillera (Porter et al., 1982). The continental lithosphere responded to the tectonic loading by isostatic flexure, initiating the development of a foreland basin to the east. Erosion of the evolving Cordillera, from the Middle Jurassic to about the Oligocene, filled the foreland basin with clastic detritus comprising the Zuni sequence (Cant, 1989; Leckie, 1989), the uppermost sequence of the Western Canada Sedimentary Basin.

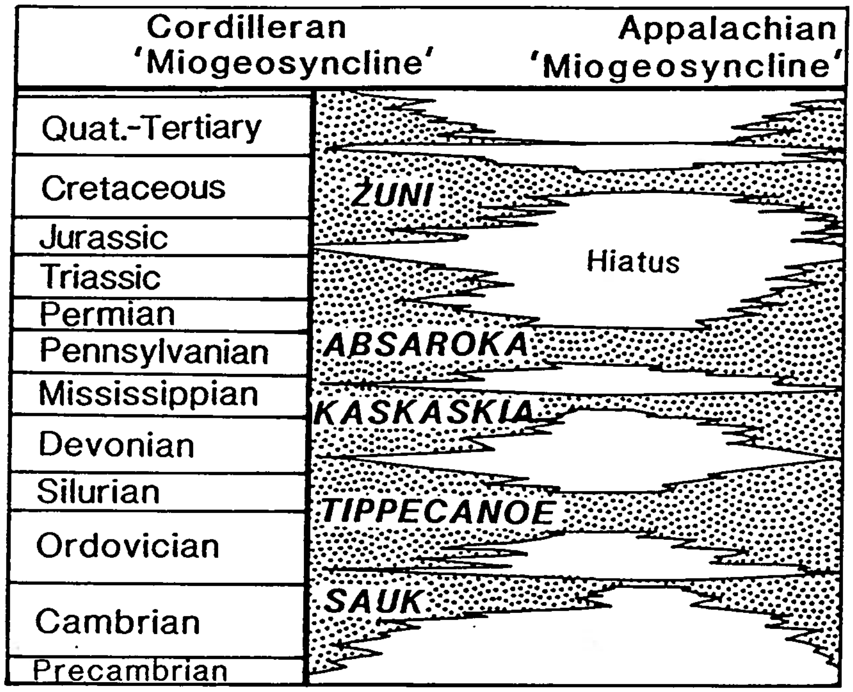


Figure 7: Comparison of North American stratigraphic sequences with time stratigraphy (after Ricketts, 1989).

PRECAMBRIAN BASEMENT

The Precambrian platform beneath the Western Canada Sedimentary Basin is the western extension of the Canadian Shield. This portion of the shield consists primarily of Archean crystalline rocks of the Slave, Rae, Hearne, and Superior Provinces (Figure 8) (Ross and Stephenson, 1989). The crystalline basement in Alberta is segmented by two crustal discontinuities: the Snowbird Tectonic Zone in central Alberta and the Great Slave Lake Shear Zone in northern Alberta, both of which can be traced eastward into the Canadian Shield. Contours drawn on the surface of the Precambrian indicate the existence of three basins and two arches in the Interior Plains area between latitudes 49° and 60°N (Figure 9). From northwest to southeast, the basement features are: the Northern Alberta Basin, the Peace River Arch, the Central Alberta Basin, the Sweetgrass Arch and the Williston Basin. The Peace River Arch and the Sweetgrass Arch both trend at a high angle to basement structure surface. Ross and Stephenson (1989) suggest that the origin of these structures is not linked directly to basement structure, but more likely to crustal properties on a broader wavelength than tectonic domains. Ross and Stephenson (1989), Stephenson et al., (1989), and Cant (1988) suggest an origin related to a subtle thermo-extensional rifting event for the Peace River Arch.

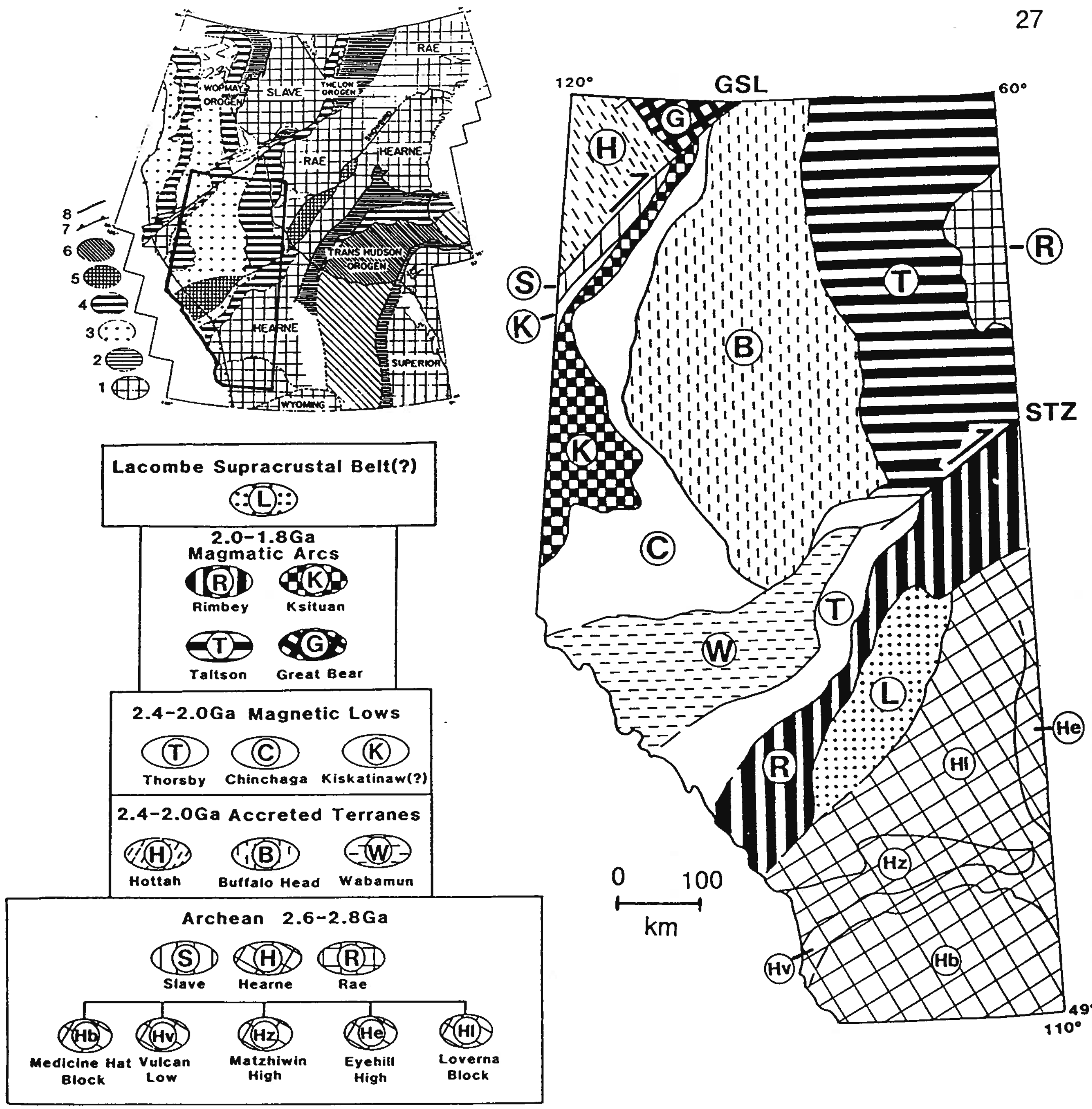


Figure 8: Map of tectonic domains postulated in the basement of Alberta. The outline of the domains corresponds to aeromagnetic boundaries. Ages for each domain are based on U/Pb zircon and monazite geochronology Key for inset: 1. Archean (>2.6 Ga); 2. reactivated Archean crust; 3. Early Proterozoic (2.4-2.1 Ga) crust; 4. 1.97-1.81 Ga magmatic arcs; 5. crustal blocks of uncertain age along Snowbird tectonic zone; 6. juvenile Proterozoic (1.91-1.85 Ga) crust; 7. edge of Cordilleran deformation; 8. edge of Phanerozoic cover (modified from Hoffman, 1988).

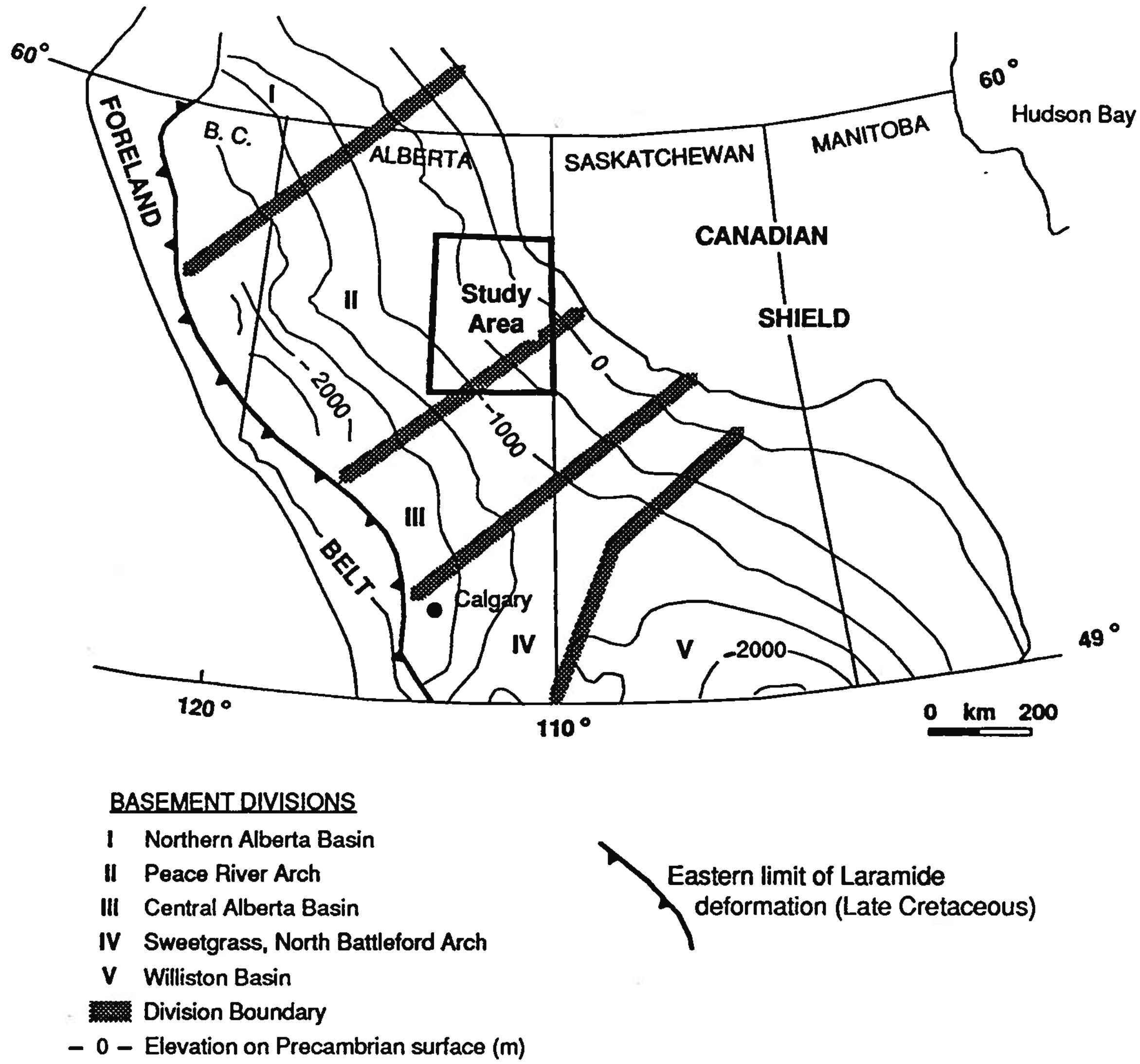


Figure 9: Configuration of the Precambrian basement of the Western Canada Sedimentary Basin (modified after Burwash et al., 1964; Mossop and Shetsen, 1992).

SAUK SEQUENCE (CAMBRIAN TO LOWER ORDOVICIAN)

The Sauk sequence (Figure 10) provides a record of almost continuous sedimentation in the basin. It is constrained by two widespread unconformities: the lower unconformity occurs near the base of the Cambrian, and the upper one near the base of the Middle Ordovician. The sub-Cambrian unconformity indicates a period of progressive onlap onto the craton, while the sub-Middle Ordovician unconformity reflects progressive eastward bevelling of the lower Paleozoic succession. Subsidence of the continental platform, resulting from thermal contraction (Mackenzie, 1978; Bond and Kominz, 1984) after the phase of rifting and continental separation, led to a transgression of the Sauk Sea from the Middle Cambrian to the early Ordovician. Major tectonic elements, which developed on the interior platform during the Middle Cambrian, consist of the Peace-Athabasca Arch and the broad Lloydminster Embayment (Aitken, 1989). Aitken (1989) suggests that the Peace-Athabasca Arch became a more striking feature during the Middle Cambrian but does not rule out its existence earlier in the Cambrian.

In the epeiric seas that covered an increasing proportion of the continent as Cambrian time passed, sediments derived primarily from the North American platform accumulated in three concentric, temporally shifting facies belts (Robinson, 1960). The inner, near-shore belt consisted of light-colored sands, silts, and muds with thin limestone beds. The seaward, intermediate belt was the accumulation site of various types of pure limestones and dolomites. The outer belt, near the marginal geosynclines, was characterized by dark silts, muds and sands, impure limestone,

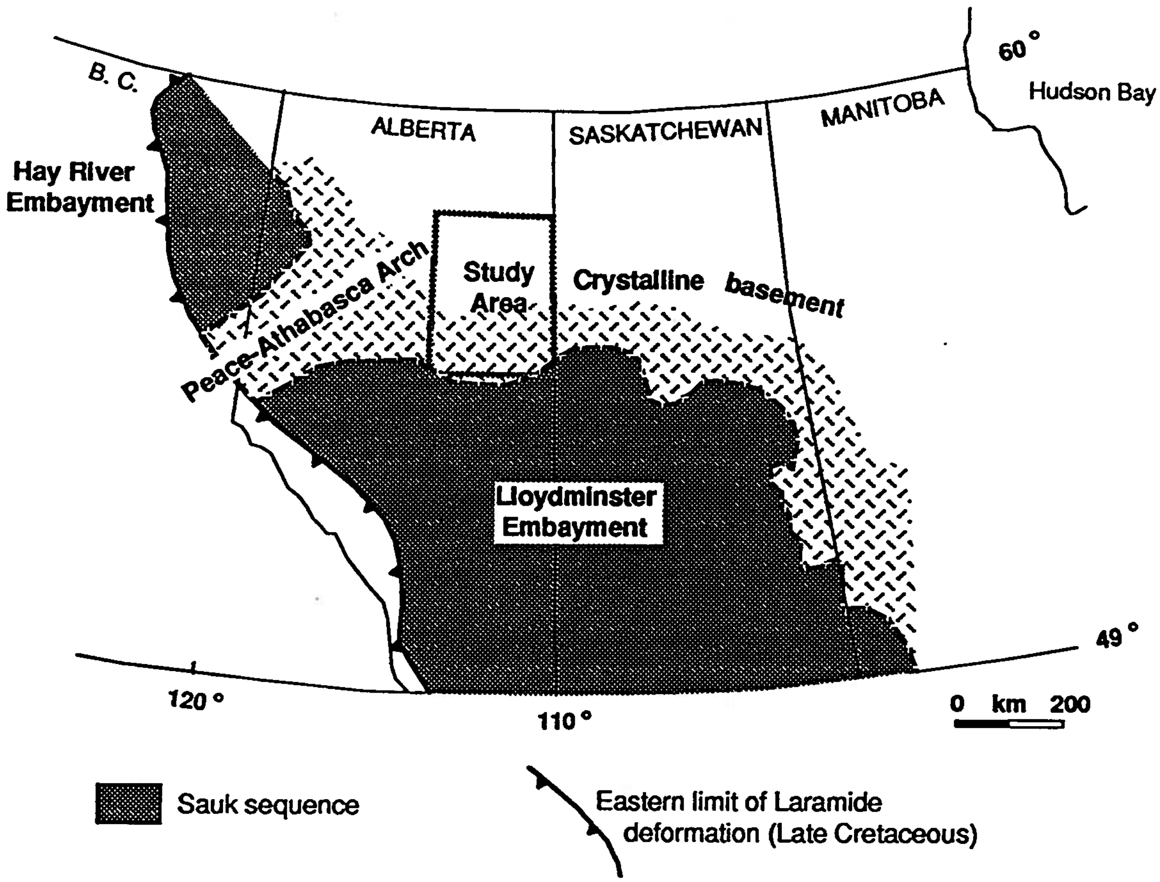


Figure 10: Distribution of Sauk sequence (Cambrian to Lower Ordovician), (modified from Porter et al. 1982).

and chert deposited in deeper water (Stearn et al., 1979).

The pre-Middle Ordovician erosional episode affected the Sauk sequence over the entire Western Canada Sedimentary Basin. Based on the preceding geological history, the equivalents of the Sauk sequence probably onlaped the Peace-Athabasca Arch but may not have buried it. The broad, gentle Precambrian high in the northern half of the study area (Appendix B, Figure 1) probably corresponds to the southern flank of the Peace-Athabasca Arch. Regressions of the epeiric seas during the pre-Ordovician and pre-Devonian removed these onlapping equivalents of the Sauk sequence in the study area.

TIPPECANOE SEQUENCE (MIDDLE ORDOVICIAN TO EARLIEST DEVONIAN)

The Tippecanoe sequence (Figure 11), which includes Middle Ordovician through Lower Devonian strata, comprises with a transgressive basal sandstone overlapping the eastward bevelled upper surface of the Sauk sequence. A succeeding shallow-water carbonate shelf environment persisted until late Silurian time. The carbonate platform deposits of the Tippecanoe sequence were the most widespread and of the longest duration of any of the Phanerozoic sequences (Porter et al., 1982). The maximum transgression probably occurred during the late Ordovician when most of the North American craton was inundated by epeiric seas. The present distribution of the Tippecanoe sequence in the Western Canada Sedimentary Basin is similar to that of the Sauk sequence, being preserved in the Williston Basin and along the passive margin. Differential tectonic adjustment in the

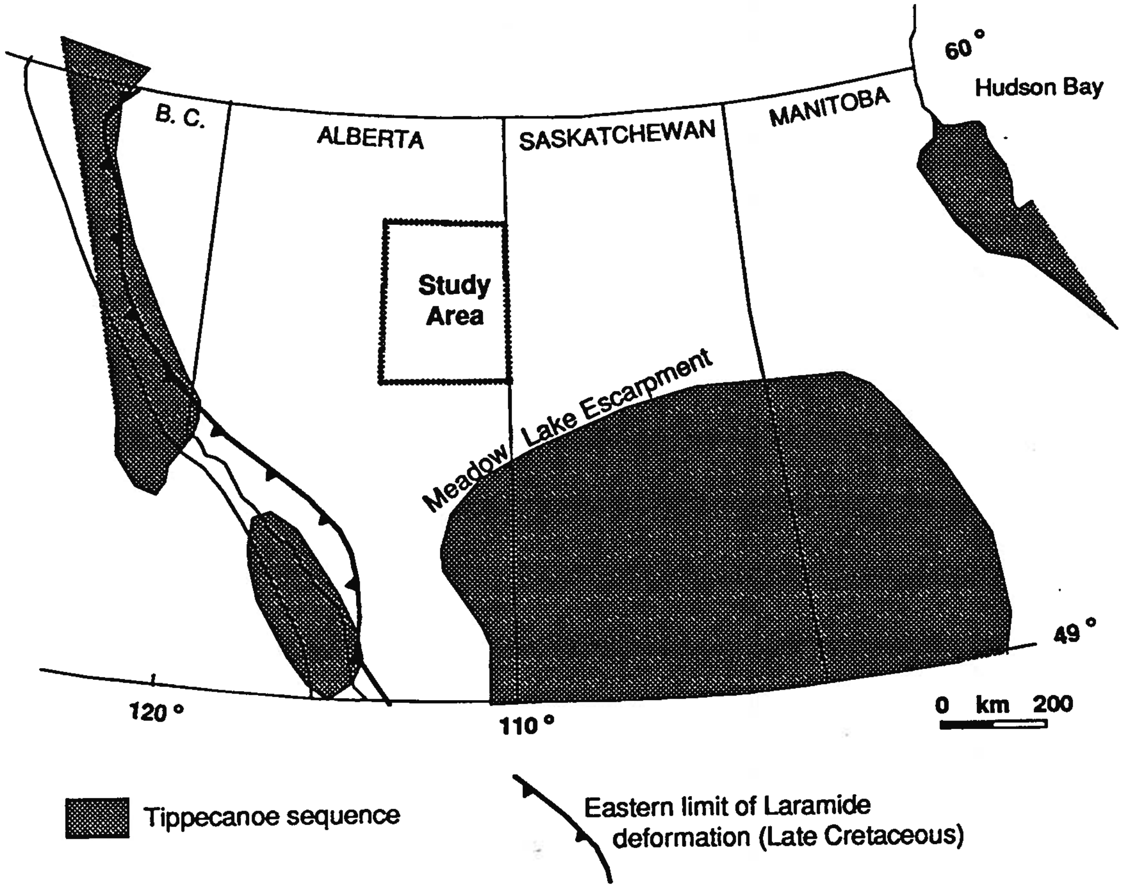


Figure 11: Distribution of Tippecanoe sequence (Middle Ordovician to earliest Devonian), (modified from Porter et al., 1982; Osadetz and Haidl, 1989).

Middle Ordovician gave rise to the embryonic Western Alberta, Peace River, Severn, Transcontinental and Sioux cratonic arches, and the Williston Basin (Porter et al., 1982). During the interval between the withdrawal of the Tippecanoe Sea and the ensuing transgression of the Kaskaskia Sea, Silurian and older strata overlying the rising arches of the craton were removed and the tilted edges of the sedimentary layers were truncated on the margins of the basins. In central Alberta and Saskatchewan, where the protective cover of resistant Ordovician carbonate rocks was breached, deep erosion of the less resistant clastic rocks of the underlying Sauk sequence created the northward-facing Meadow Lake Escarpment. To the south of the Meadow Lake Escarpment, the region of the Williston Basin persisted as a regional depression with little topographic relief.

KASKASKIA SEQUENCE (DEVONIAN-MISSISSIPPIAN)

In the Western Canada Sedimentary Basin, the Kaskaskia sequence includes both Devonian and Mississippian strata. Moore (1989) subdivided the sequence into an upper and lower subsequence. The lower Kaskaskia comprises Devonian strata, and the upper Kaskaskia Mississippian strata. Further, Moore (1989) suggested that the lower Kaskaskia may be separated into five further divisions bounded by disconformities.

During the Devonian, the western ocean advanced eastward over the craton. Surface relief resulting from sub-Devonian epeirogenic uplift of the Tathlina, Western Alberta and Peace River arches forced the seas to transgress from the northwest to the southeast, rather than of from the previous westerly direction. Initial Middle Devonian deposits (Figures 12 and 13), consisting of massive halite beds, associated red mudstones and a basal sandstone, completely filled the topographic depressions that were enclosed by the cratonic arches (Tathlina, Western Alberta and Peace River) and the Meadow Lake Escarpment. As sea-level continued to rise during the Middle Devonian, a major barrier reef developed across the southern flank of the Tathlina Arch (figure 13) (Porter et al., 1982). Behind this barrier (Keg River or Presqu'ile) the sub-basins coalesced, the Meadow Lake Escarpment was breached by the transgression, and the huge interior Elk Point Basin was established (Figure 14). The progressive restriction of circulation between this basin and the western ocean by the barrier reef (Keg River or Presqu'ile) led to the deposition of a succession of clastics, platform carbonates and evaporites. The succession, schematically displayed in Figure 25, includes the interval between the base of the Contact Rapids and the top of Watt Mountain Fm. Regionally, these deposits, as well as the more restricted deposits in the Central and Northern Alberta sub-basins, comprise the Elk Point Group in the Western Canada Sedimentary Basin.

The Elk Point succession is overlain by a lower Middle to Upper Devonian succession that records major back-stepping and onlap of shallow marine carbonate platforms toward the interior of the continent. There is a progressive southeastward shift of platform margins and their associated reef complexes from the Slave Point Edge in northwestern Alberta, to the Leduc shelf-margin complex in southern Alberta. During the deposition of this succession, central Alberta became differen-

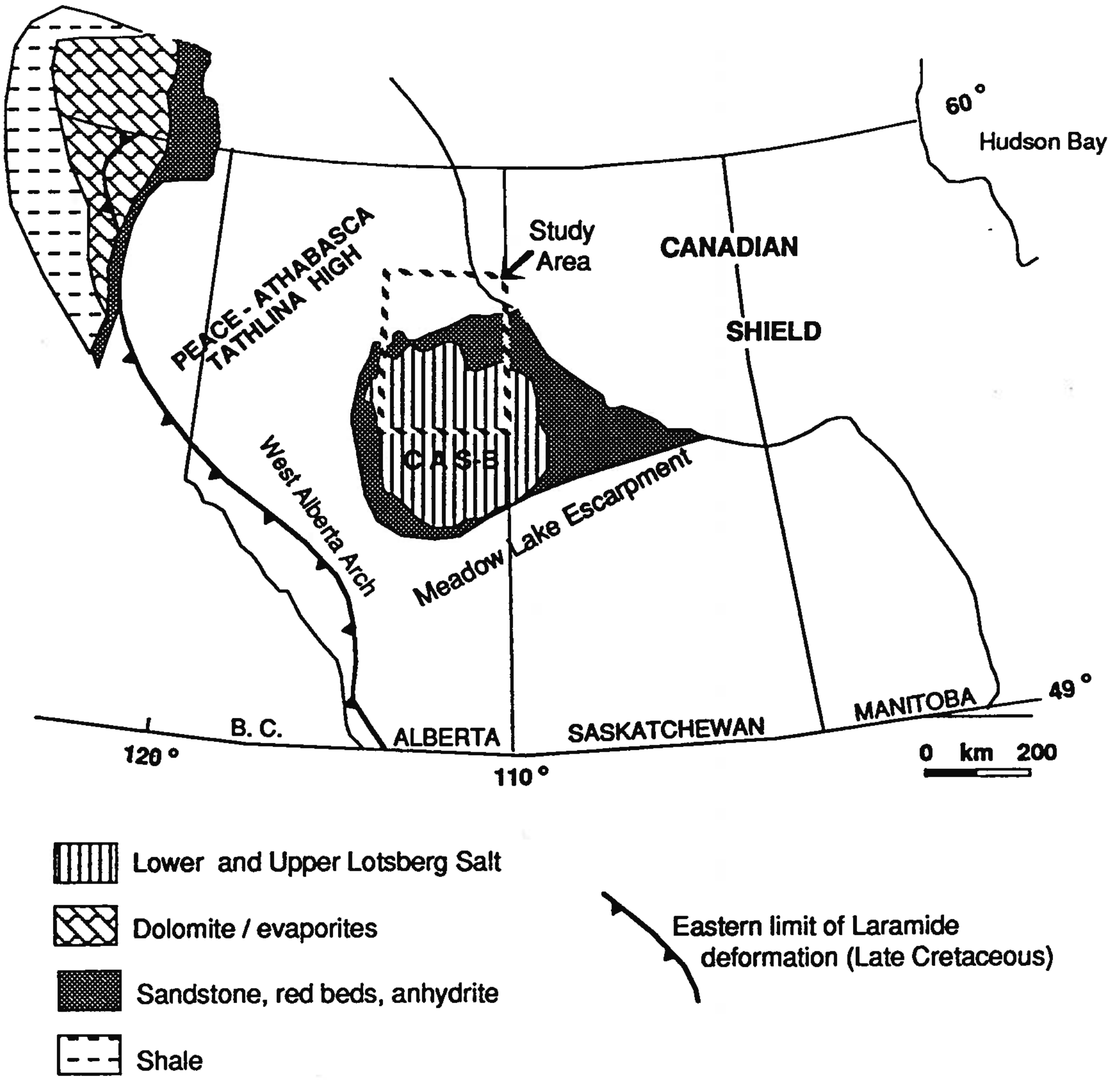


Figure 12: Distribution of Subdivision 1 of Kaskaskia sequence: Lower? - Middle Devonian strata from Basal Red Beds to top of the Upper Lotsberg Salt in the Central Alberta Sub-Basin (C A S-B), (modified after Moore, 1989).

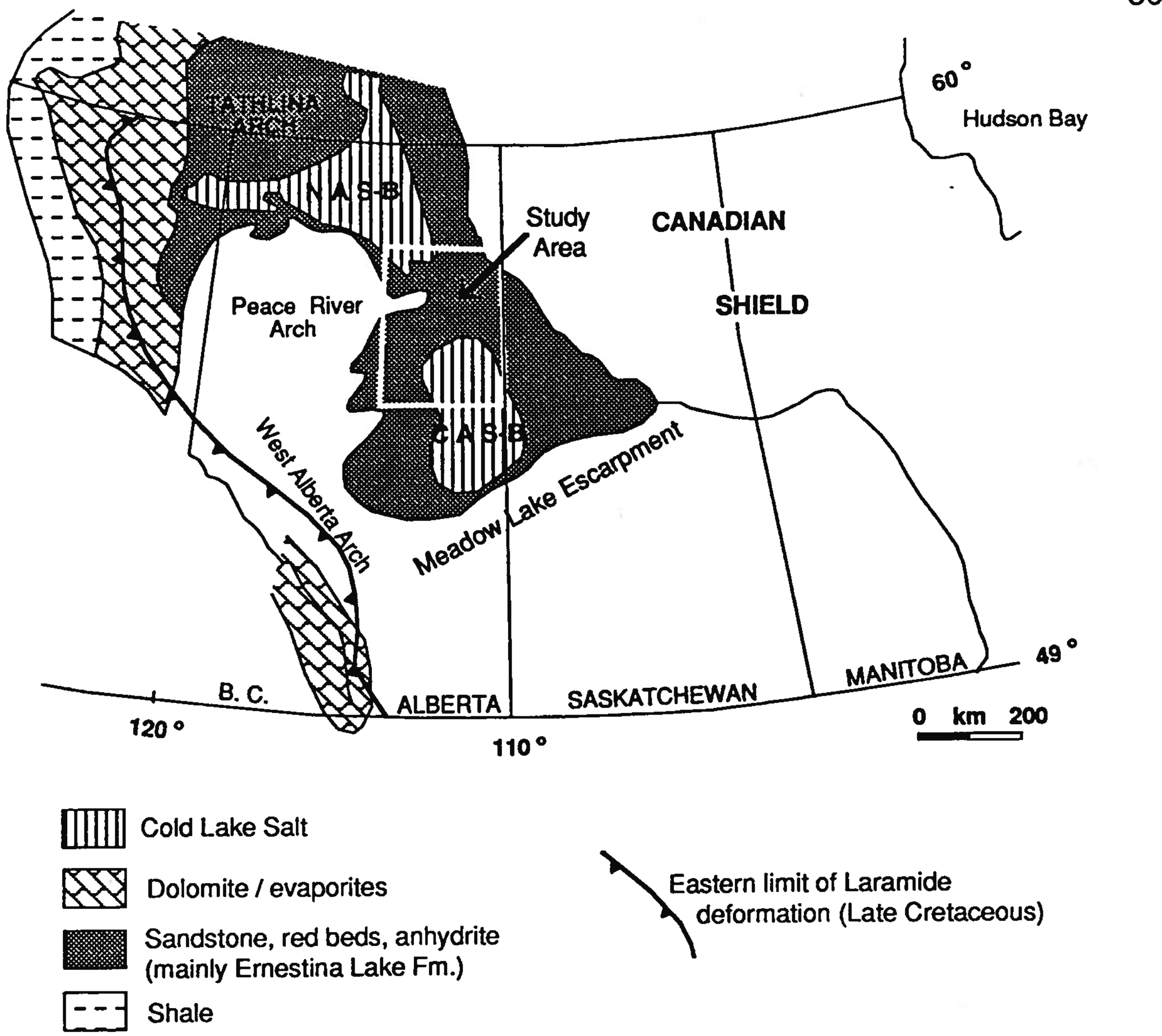


Figure 13: Distribution of Subdivision 2 of Kaskaskia sequence: from the base of Ernestina Lake Formation to the top of the Cold Lake salt in the Middle Devonian Northern Alberta Sub-Basin (N A S-B) and Central Alberta Sub-Basin (C A S-B) (modified after Moore, 1989).

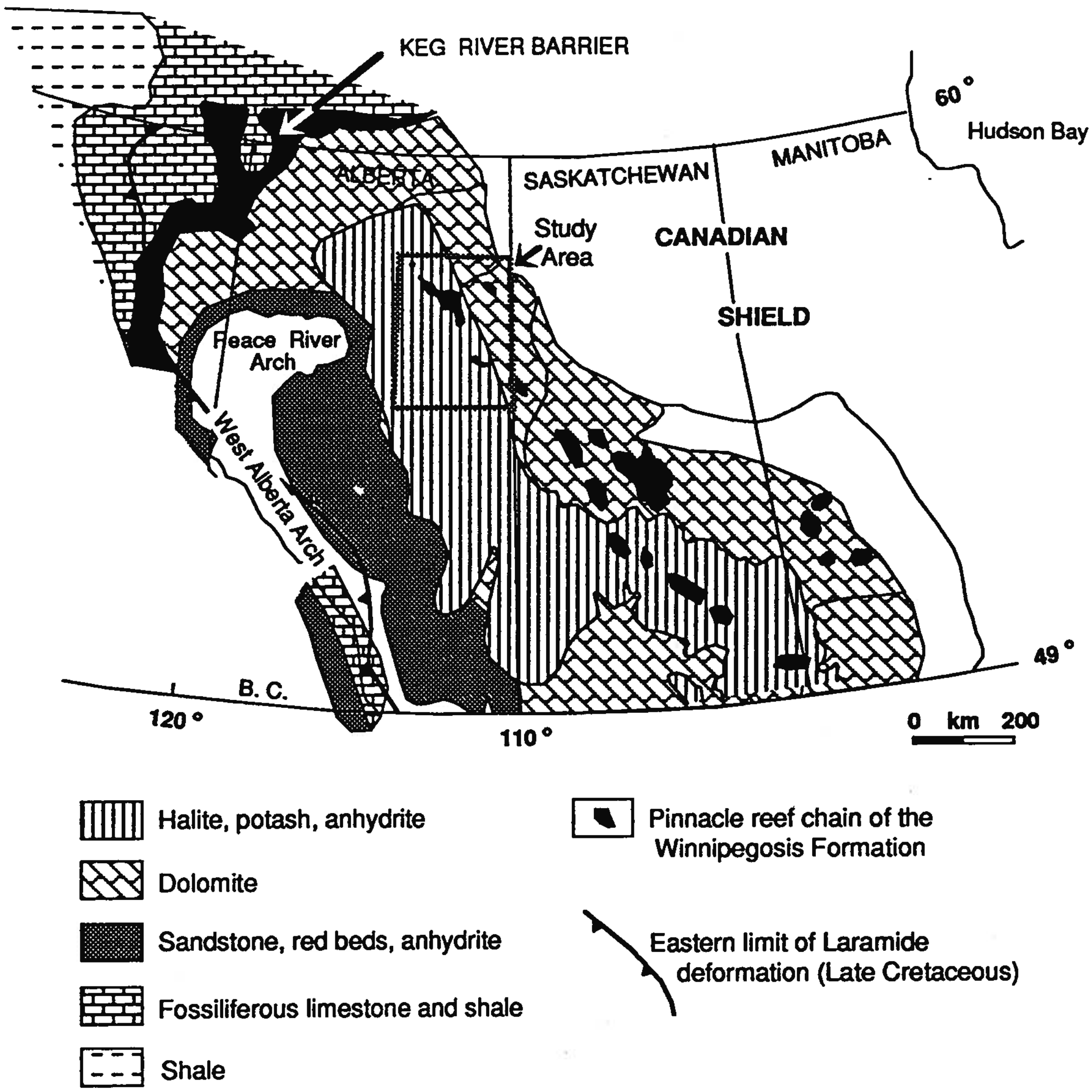


Figure 14: Distribution of Subdivision 3 of Kaskaskia sequence: from the base of the Chinchaga-Contact Rapids formations to the top of the Watt Mountain-Dawson Bay formations in the Middle Devonian Elk Point Basin (modified from Moore, 1989; Hamilton, 1971).

tiated into carbonate platforms and inter-platform bathymetric basins (Moore, 1989). The inter-platform basins passed through two distinct phases: a) an initial deepening phase during which there was a build-up of platform reefs; b) a final infill phase during which the surrounding carbonate platforms prograded into the basins and argillaceous clinothems covered the reefs (Moore, 1989; Stoakes, 1980). The entire succession is characterized by depositional cyclicity, expressed during the deepening phase by a pulsatory build-up of platform reefs and during the infill phase by shale-carbonate couplets. Two major cycles can be recognized in the succession. During the first cycle, three major platforms (Figure 15) developed from late middle to early late Devonian time. These include: the Hay River Platform (Slave Point Formation) of northern Alberta, the Western Platform (Swan Hills and lower part of Cairn Formation) developed along the Peace River and Western Alberta arches, and the Inner Eastern Ramp (Souris River Formation) of southern Saskatchewan. The inter-platform basin which developed in central Alberta was filled with shale-carbonate couplets which comprise the Beaverhill Lake-Waterways formations and the basal part of the Cooking Lake Formation.

The second cycle (Figure 16) records renewed sea-level rise during which the inter-platform basin expanded over the Hay River and Western platforms. The western platform broke up into very large banks and large platform reefs of the Leduc Formation. This was followed by the growth of reefs and reef complexes, known as the Leduc Formation in central Alberta and the Swan Hills Formation along the southeastern edge of the Peach River Arch. The Ireton Formation, consisting of limy shale clinothems originating from carbonate platforms to the south

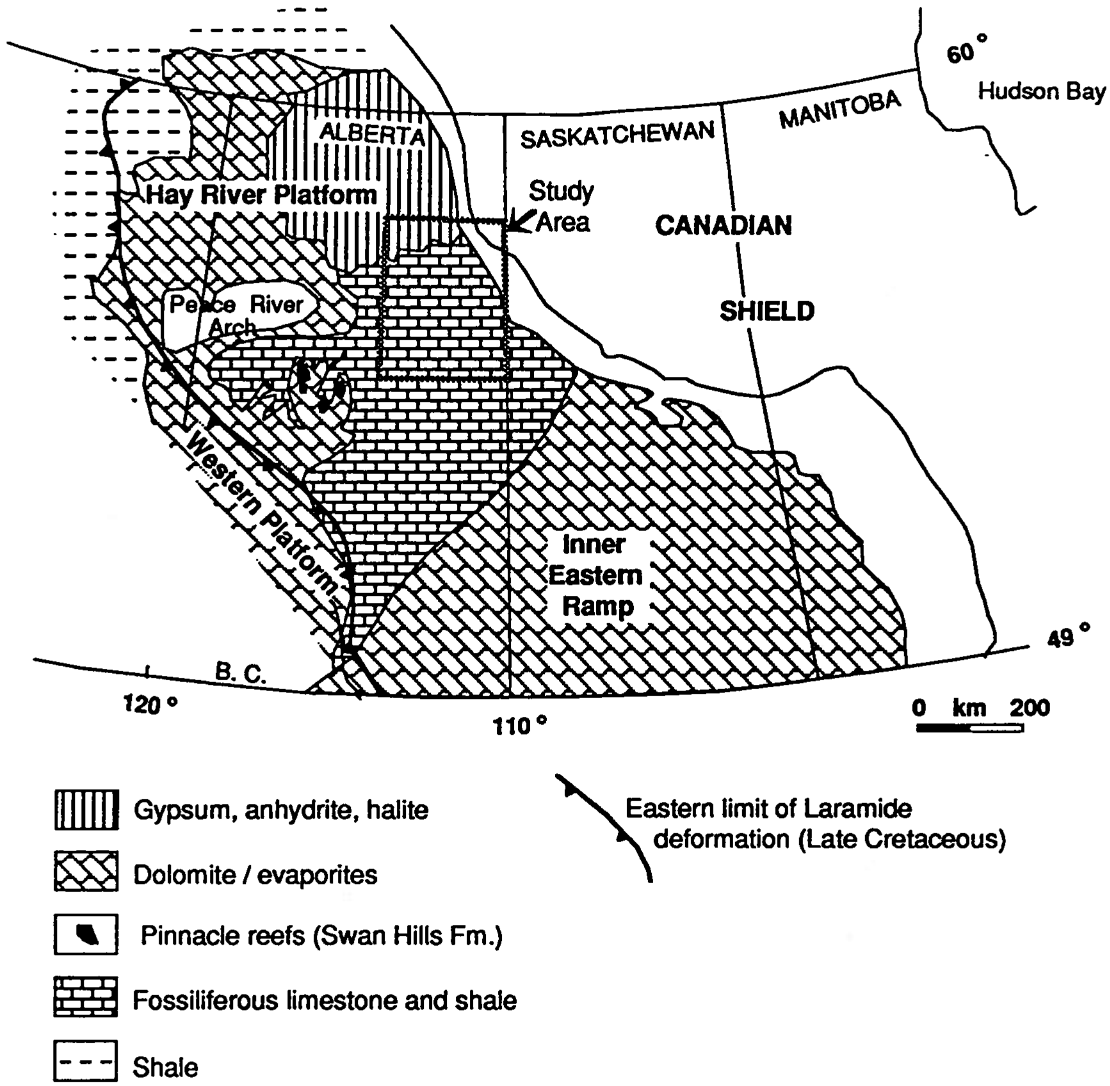


Figure 15: Distribution of Subdivision 4 of - first cycle - Kaskaskia sequence: Souris River Formation in Saskatchewan and Beaverhill Lake Group in Alberta (modified from Moore, 1989).

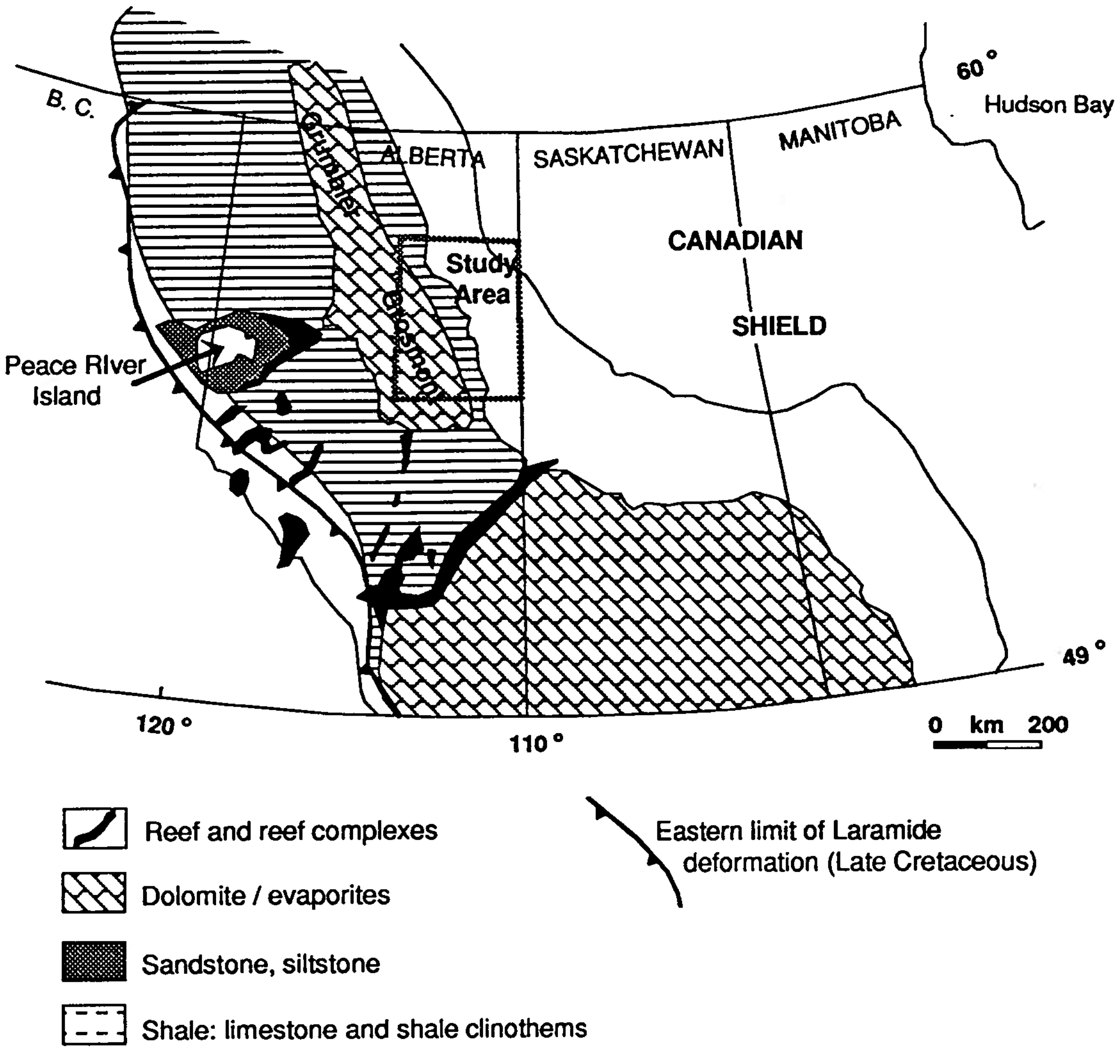


Figure 16: Distribution of Subdivision 4 - second cycle - of Kaskaskia sequence: Saskatchewan Group in Saskatchewan and Woodbend Group in Alberta (modified from Moore, 1989).

and east, is the primary inter-platform basin fill. Carbonate platforms developed in southern Saskatchewan and northeastern Alberta. In Saskatchewan, the carbonate platforms form the extensive Saskatchewan Group while in northeastern Alberta they form the narrow, linear, north-northwest trending Grumbler-Grosmont complex. A temporary regressive event at the close of the Devonian period resulted in the widespread progradation of carbonate platforms (Figure 17). In central Alberta these regressive deposits comprise the Winterburn and Wabamun Groups.

The upper Kaskaskia subsequence comprises Mississippian age strata deposited during a period of renewed transgression. The thin, widespread, dark organic-rich Exshaw-Bakken shale separates Devonian and Mississippian strata. During the transgression, platform and ramp carbonates, and deltaic deposits (Figure 18) were deposited over the cratonic platform. The succession is subdivided into the Banff, Rundle and Mattson lithofacies assemblages (Richards, 1989). Fine-grained siliciclastics and cherty to argillaceous carbonates of the Banff assemblage are overlain by the carbonate dominated Rundle assemblage, which is in turn partly overlain by the sandstone-dominated Mattson assemblage.

ABSAROKA SEQUENCE (PENNSYLVANIAN-LOWER JURASSIC)

The Absaroka sequence (Figure 19) records the long-term regression of the epeiric seas from the craton, a process triggered during deposition of the upper part of the Kaskaskia sequence by the emergence and westward tilt of the craton (Porter et al., 1982). Depositional and preservational limits of the sequence were

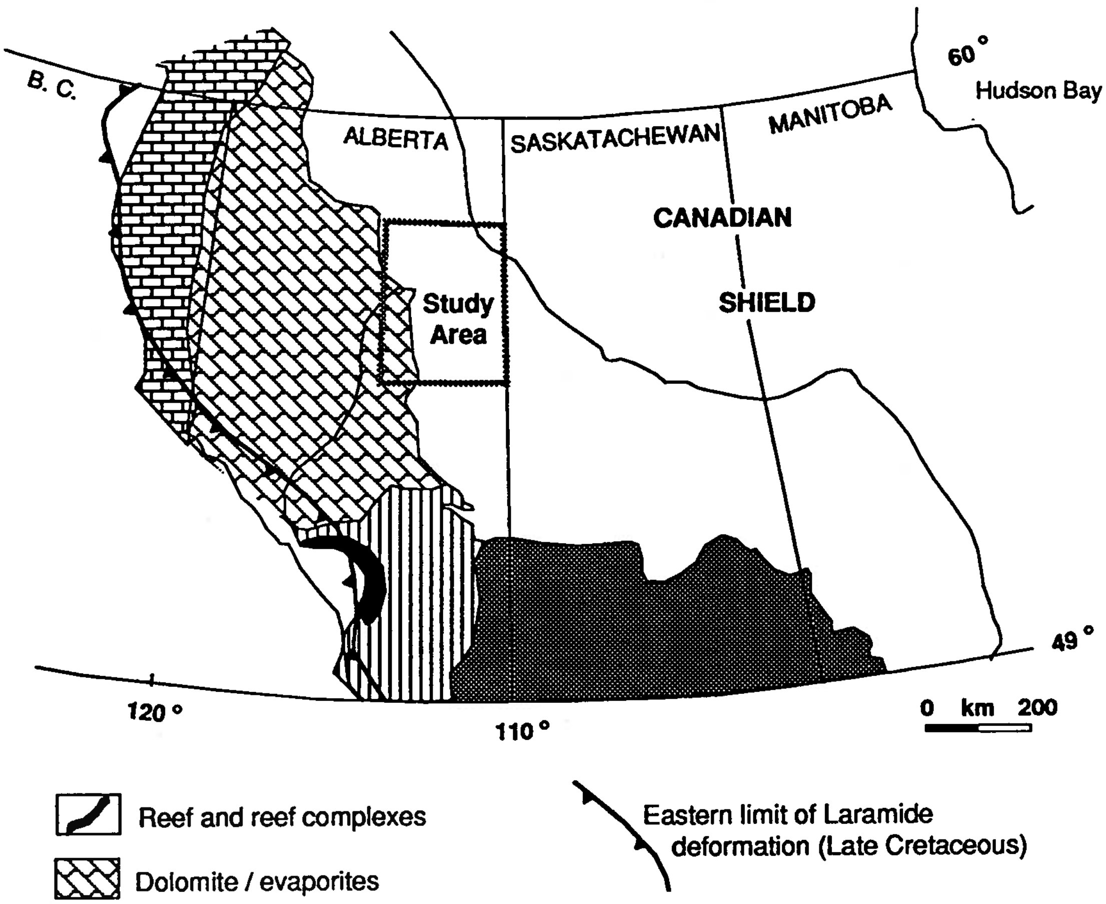


Figure 17: Distribution of Subdivion 5 of Kaskaskia sequence: Winterburn and Wabamun groups in Alberta (modified from Moore, 1989).

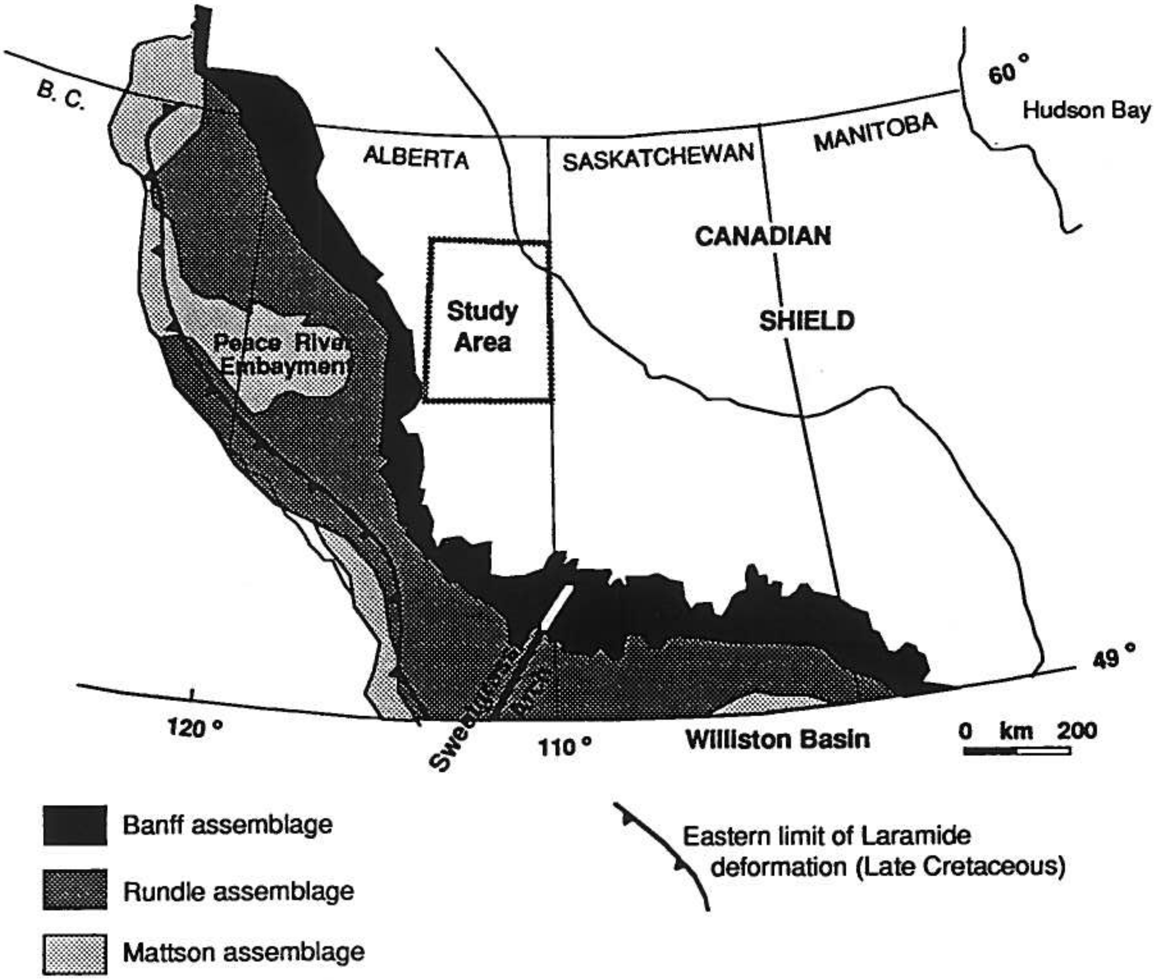


Figure 18: Distribution of upper Kaskaskia sequence: Mississippian (modified from Moore, 1989).

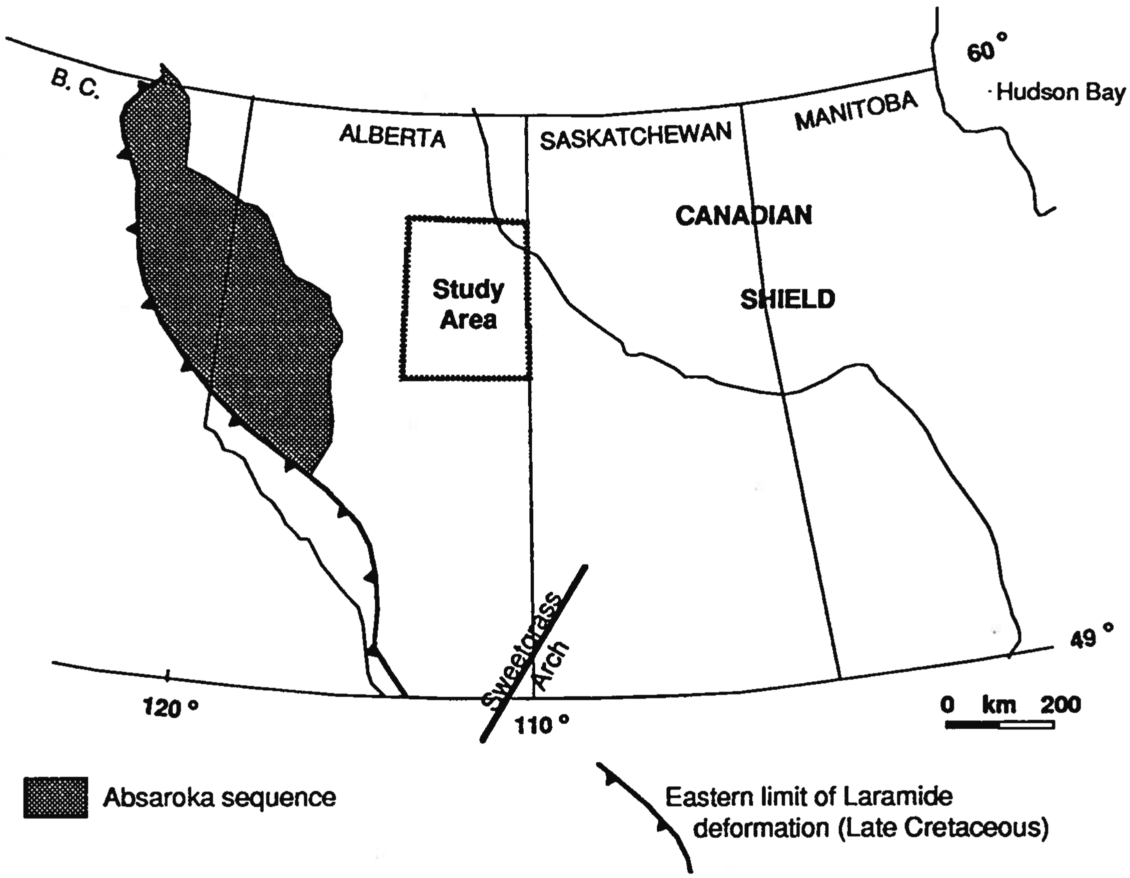


Figure 19: Distribution of Absaroka sequence (Pennsylvanian to Middle Jurrasic), (modified after Porter et al., 1989).

also influenced by the early Pennsylvanian to Middle Jurassic emergence of the northeast-trending Sweetgrass Arch and the subsidence of the Peace River Arch, a process which began in the early Mississippian and continued into the Permian. The emergence of the Sweetgrass Arch effectively separated the Absaroka sequence into two contrasting facies domains. Clastic deposition dominated in the Williston Basin, southeast of the Sweetgrass Arch, while marine deposits dominated to the north.

ZUNI SEQUENCE (MIDDLE JURASSIC TO PALEOCENE)

The Zuni Sequence records the transformation of the Western Canada Sedimentary Basin from a cratonic platform, containing a network of epeirogenic arches and basins, into a foreland basin containing stacked northeast tapering wedges of synorogenic clastic detritus which prograded toward the interior of the craton (Porter et al., 1982) (Figure 20). The sequence was deposited over an erosional surface that was exposed as a result of craton emergence starting in the Mississippian. The combined effect of westward tilt and differential erosion of regionally widespread "layer cake" strata resulted in a surface composed of an alternating system of north-northwest trending ridges and valleys. The development of the Zuni sequence is primarily the result of three events, the late Jurassic Colombian Orogeny, the transgressions of the Cretaceous Arctic and Gulfian seaways, and the late Cretaceous Laramide Orogeny. The accretion of allochthonous terranes to the western continental margin resulted in the thrusting of the marginal deposits eastward. This deformation tectonically loaded the lithosphere

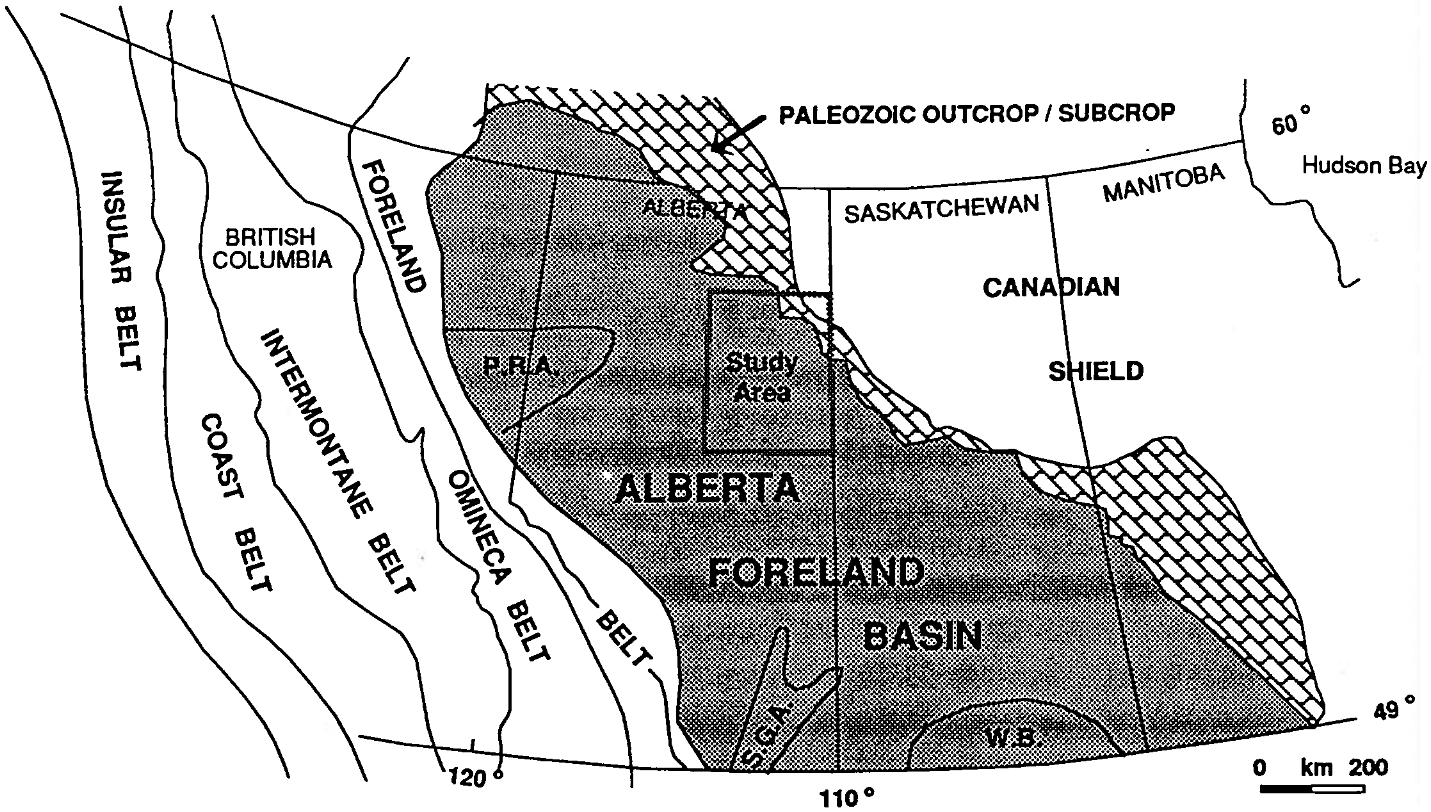
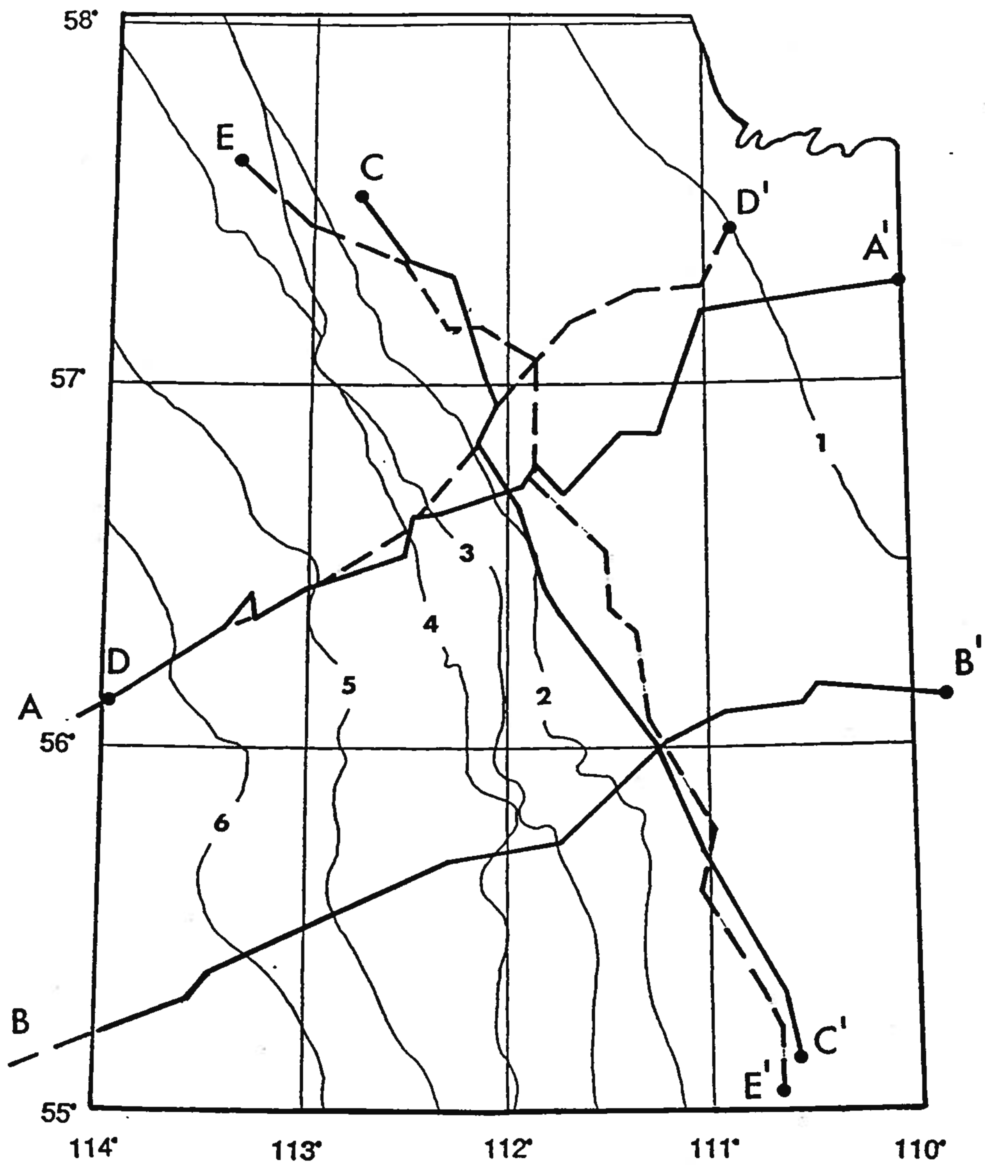


Figure 20: Distribution of Zuni sequence in the foreland basin. Tectonic elements indicated include the Williston Basin (W.B.), the Peace River Arch (P.R.A.) and the Sweetgrass Arch (S.G.A.) (modified after Cant, 1989).

and also provided the source for the continental clastic sediments that filled the foreland basin (Porter et al., 1982). The Arctic seaway influenced the northeastward dispersal and deposition of clastics comprising the Lower Cretaceous Mannville (plains) and Blairmore (disturbed belt) groups. The mid-Cretaceous merging of the Arctic and Gulfian seaways resulted in the deposition of extensive muddy deposits, referred to as the Colorado Group. The late Cretaceous Laramide Orogeny resulted in further tectonic deformation, with thrusting extending farther eastward, and generated a second sequence of terrestrial sediments that covered the entire basin again in the late Cretaceous and Paleocene (Porter et al., 1982).

The stratigraphic succession in the Northeast Alberta study area consists of Middle to Upper Devonian strata resting on the eroded Precambrian crystalline basement, unconformably overlain by a succession of Lower to Upper Cretaceous strata. Both Cretaceous and Paleozoic strata subcrop with increasing age to the northeast, toward the Precambrian Shield (Figures 21, 22 and 23). A thin veneer of Pleistocene glacial deposits overlie Cretaceous, Paleozoic and Precambrian strata. The general lithology and structure of the succession is illustrated through three dip cross-sections, A-A', B-B' and D-D' (Figures 22, 23 and 26, respectively), and two strike cross-sections, C-C' and E-E' (Figures 24 and 27, respectively). The nomenclature and regional stratigraphy applied to the region is summarized in Figure 25. The geological synthesis of the study area is illustrated through a series of isopach and structure contour maps, from the top of the crystalline Precambrian basement to the top of the Phanerozoic succession.



LEGEND:

1. - Beaverhill Lake Group
2. - Cooking Lake Formation
3. - Ireton Formation
4. - Grosmont Formation
5. - Winterburn Group
6. - Wabamun Group

Figure 21: Subcrop boundaries of Devonian strata at the sub-Cretaceous unconformity in northeast Alberta.

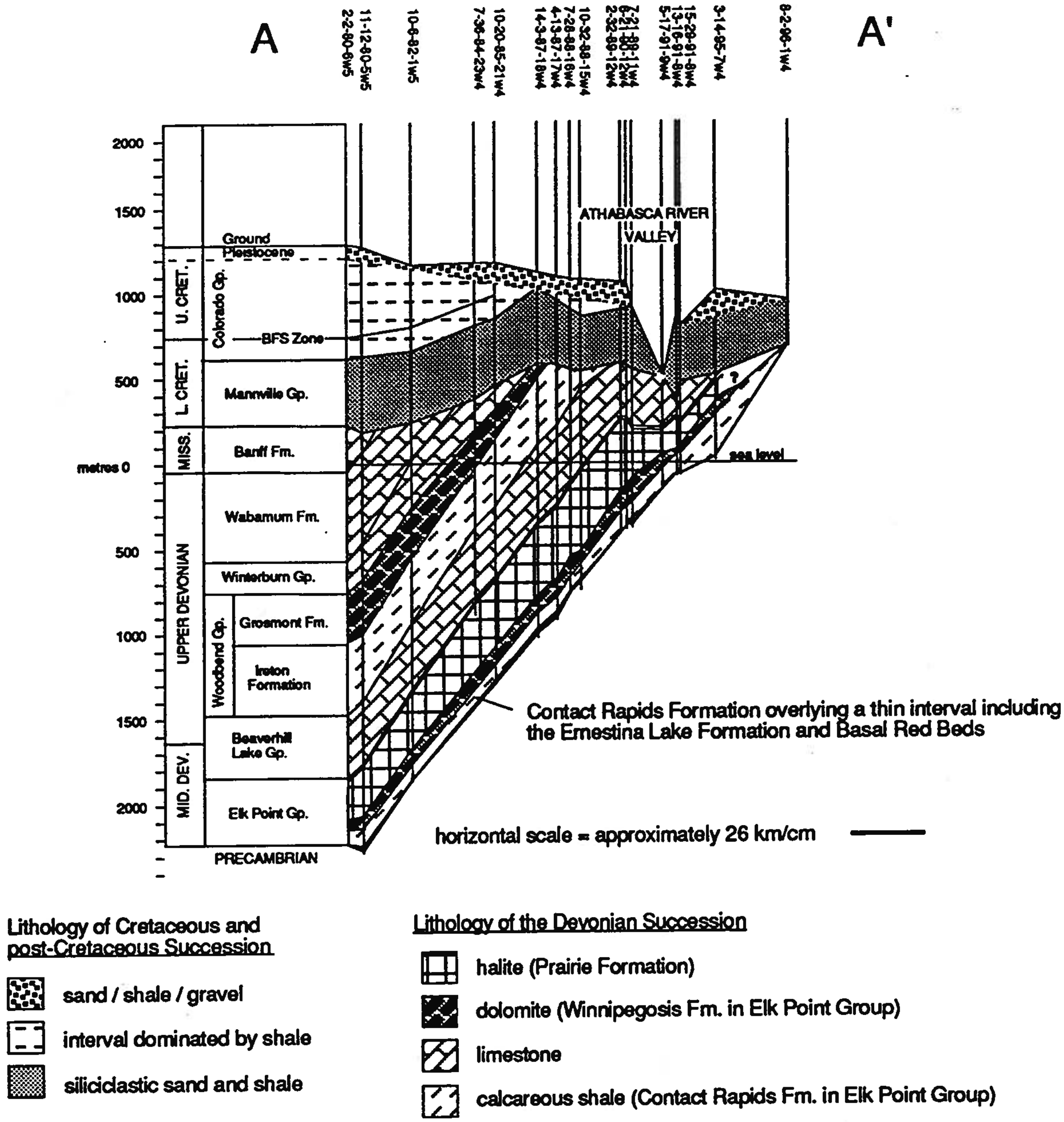


Figure 22. Structural dip section A-A' of Phanerozoic succession (cross-section location on Figure 21).

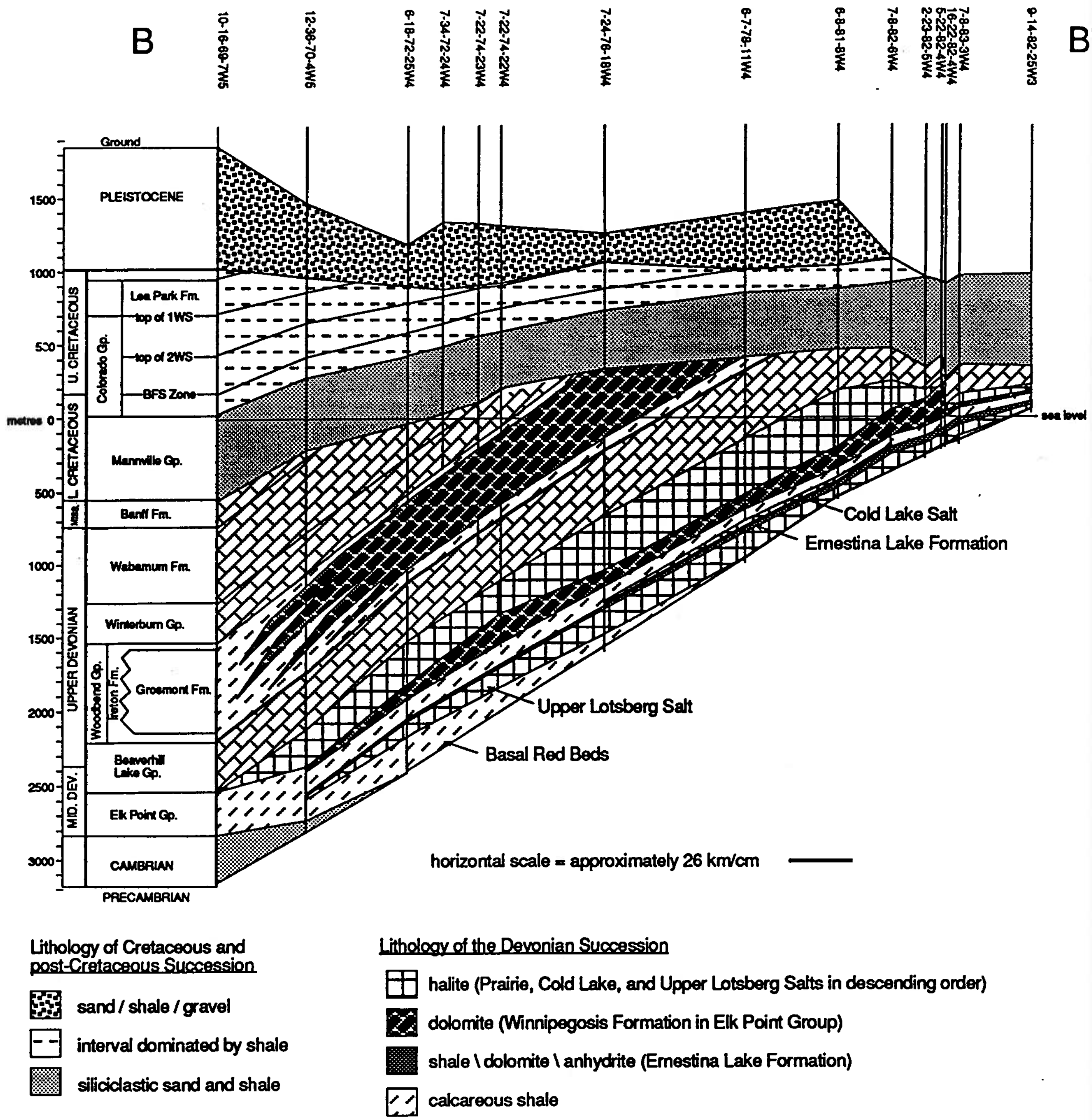


Figure 23: Structural dip section B-B' of Phanerozoic succession (cross-section location on Figure 21).

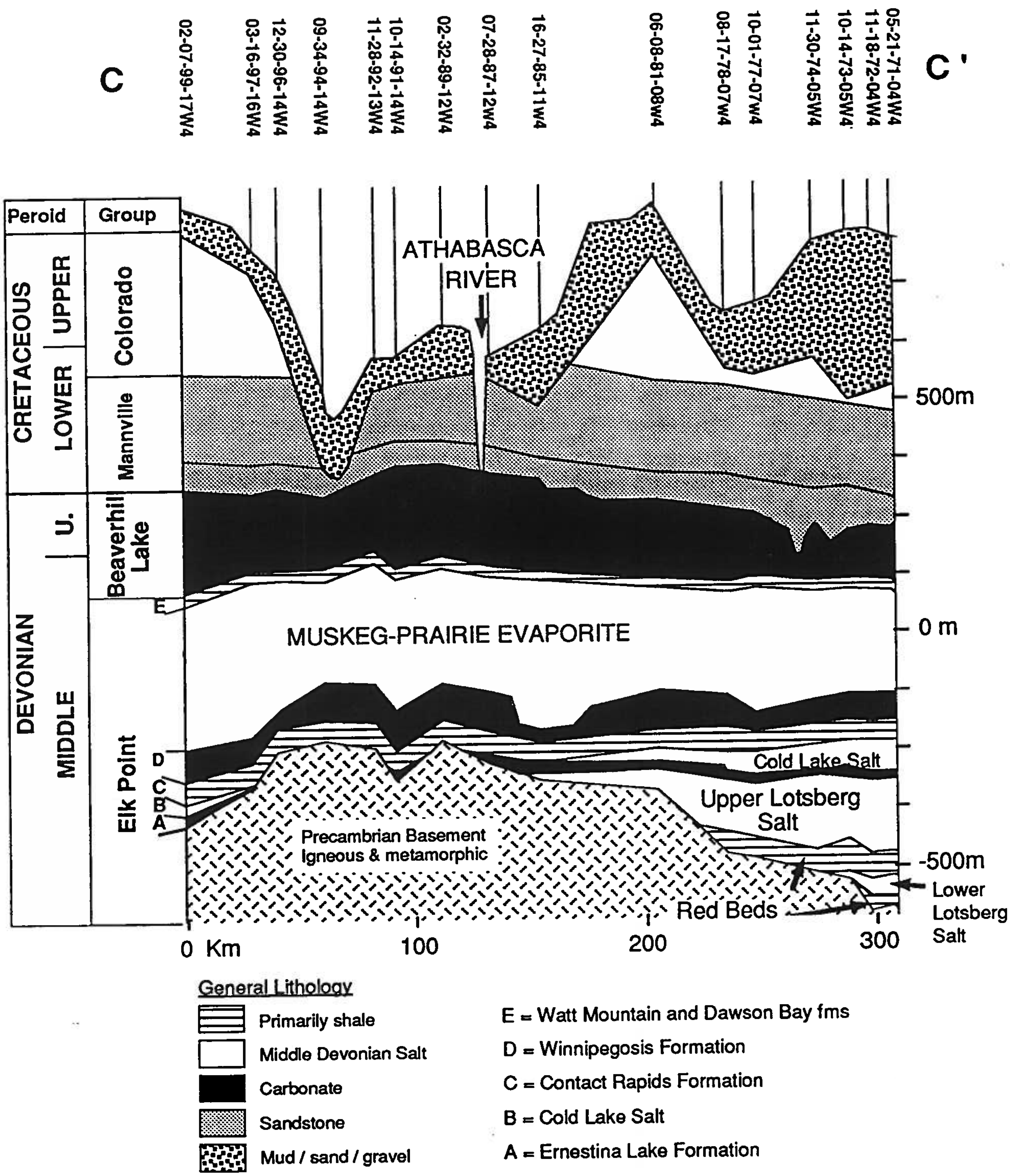
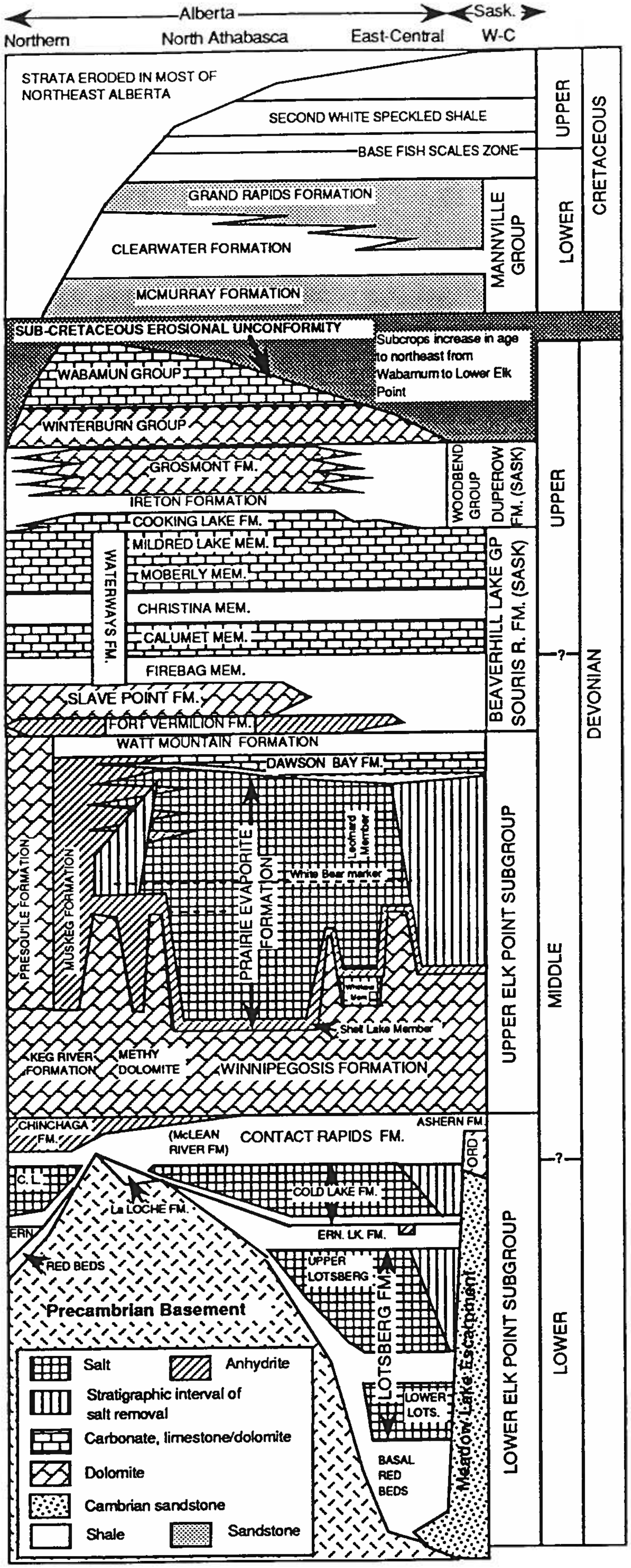


Figure 24: Strike section C-C': Phanerozoic succession (cross-section location on Figure 21).



SOURCES

East-Central Alberta

Sherwin, 1962; Grayston *et al.*, 1964; Geological Staff, Imperial Oil Ltd., Western Division, 1950; Meijer-Drees, 1986.

North Athabasca

Crickmay, 1957; Norris, 1963, 1973; Grayston *et al.*, 1964; Leavitt and Fischbuch, 1968; Meijer-Drees, 1986; Harrison, 1986.

Northern Alberta

Law, 1955.

Figure 25: Stratigraphic succession and nomenclature along a northwest trend from west-central Saskatchewan to northeast Alberta.

PALEOZOIC GEOLOGY OF NORTHEAST ALBERTA

The Paleozoic of northeast Alberta (the lower half of the Kaskaskia Sequence) is discussed in the context of five major subdivisions bounded by discontinuities (Moore, 1989). In general terms, each major subdivision occupies a more extensive region than the one before, as illustrated by the maps on Figures 12-16. This is predominantly the expression of the Kaskaskia transgression.

PRECAMBRIAN STRUCTURE

The structure of the Precambrian basement (Appendix B, Figure 1) forms a surface which gently dips to the southwest at 4-5 m/km. When related to the regional structure of the Precambrian craton in the Western Canada Sedimentary Basin, it is apparent that the northeast-southwest axis of the Peace River Arch extends into northeast Alberta as a low broad ridge. Superimposed on the regional structure are local topographic highs and lows with relief of up to 50 m. These may be contoured into a series of sub-parallel horst and graben structures with a southwest-northeast trend, but are difficult to verify because of the sparse well control. The local topographic elements are muted or not present on the surfaces of overlying Devonian horizons. This indicates that their formation by erosion or tectonism preceded the deposition of the overlying Devonian succession. Several fault systems in the Precambrian basement have been inferred by previous authors. Garland and Bower (1959), Kidd (1951), Sproule (1956), Carrigy (1959) and Norris (1963) have placed faults of a north-south trend in Tp 89 R 3 and as far west as R

5 W4 Mer, with the downthrown side to the west. Hackbarth and Nastasa (1979) suggest two additional faults affected the Precambrian basement. One, crossing the area on a north-northwest trend from Tp 81 R 3 to Tp 97 R 11 W4 Mer, is called the Sewetakun fault in their report. The other fault crosses the area on a west-northwest trend from Tp 77 R 2 to Tp 88 R 25 W4 Mer. Evidence for the latter fault is a noticeable offset of regional geological structural contour trends. Evidence for the Sewetakun fault was based primarily on 1) relief of 83 m (273 ft) on the Precambrian surface between holes located in Ft. McMurray (Tp 89 R 9), and 2) trends on gravity maps (Canada Department of Mines and Technical Surveys, 1963). The Sewetakun fault of Hackbarth and Nastasa (1977) corresponds with the eastern limit of the dissolution scarp of the Prairie Fm. The sparse well control and coarse contour interval of 50 m used in this study and that of McPhee and Wightman (1989) do not support the existence of these faults. However, Ross and Stephenson (1989) map of tectonic domains postulated in the basement of Alberta (Figure 8) would support fault systems orientated along a north-south or southwest-northeast trend.

MIDDLE DEVONIAN ELK POINT GROUP

Subdivision 1 (Middle Devonian, Lotsberg Formation)

In Alberta, Subdivision 1 (Figure 12) consists of two thick red bed-halite successions deposited in the Central Alberta sub-Basin, a paleo-subsiding centre bounded by the Meadow Lake Escarpment and the Western Alberta and Peace

River arches. Subdivision 1 corresponds to the Lower to Middle Devonian Lotsberg Formation, which consists in ascending order of the Basal Red Beds, Lower Lotsberg Salt, unnamed Red Beds, and the Upper Lotsberg Salt. Strata of the subdivision onlap onto the Precambrian basement (Figure 24) from the south, progressively decreasing in thickness from a maximum of 250 m in the south to zero in the northeast corner of the study area.

The Basal Red Beds are considered to extend over the entire region (Appendix A, Figure 1). The area to the south of latitude 56°N is a composite of the Basal Red Beds, Lower Lotsberg Salt and unnamed Red Beds listed in ascending order. The Basal Red Beds range up to 40 m in thickness, but the average regional thickness is rarely more than 7 m, with many wells in the northern half of the study area showing no recorded Basal Red Beds. A linear trend of thicker Basal Red Beds, referred to locally as the La Loche Formation (Sproule, 1951; Norris, 1973), occurs between latitudes 56° and 57°N and longitudes 110° and 112°W, along the trend of the hypothetical Precambrian Sewetakun Fault. South of latitude 56°N, the Basal Red Beds are overlain by the Lower Lotsberg Salt (Appendix A, Figure 2), which forms a wedge-shaped unit uniformly pinching out to the north; average thickness is 40 m. The Lower Lotsberg Salt is overlain by a relatively uniform interval of 40 to 50 m of unnamed Red Beds (Appendix A, Figure 3). North of the northern limit of the Lower Lotsberg Salt, the unnamed Red Beds onlap and pinch-out against the Precambrian basement just south of latitude 56°N. The overlying unit of the Upper Lotsberg Salt (Appendix A, Figure 4) similarly pinches out against the Precambrian basement or a thin veneer of Basal Red Beds in the area along and just north of latitude 56°N. South of latitude 56°N, the Upper Lotsberg Salt gradually thickens to more than 120 m in the southeast portion of the study area. The eastern indent of the northern limit of the Upper Lotsberg Salt (between longitudes 111° to 112°W) is due to complete salt removal, while the western one is a depositional edge.

Subdivision 2 (Ernestina Lake and Cold Lake Formations)

Following the deposition of Subdivision 1, the Tathlina-Peace-Athabasca high collapsed in the centre to form the Northern Alberta sub-Basin and two distinct arches: Peace River and Tathlina. In Alberta, Subdivision 2 (Figure 13) ranges up to 70 m in thickness and is stratigraphically subdivided (in ascending order) into the Middle Devonian Ernestina Lake and Cold Lake formations. Regionally, the Ernestina Lake Formation is an extensive and remarkably consistent succession, with an average thickness of 17 m. It consists of a basal, red, dolomitic shale unit, a middle, anhydritic limestone shale unit, and an upper anhydrite bed (Sherwin, 1962). The threefold subdivision is only present in the area where the formation is underlain by the Upper Lotsberg Salt (Sherwin, 1962). To the north of the Upper Lotsberg Salt, he grouped the basal shale with the "Basal Red Beds" unit. Current regional correlations of the Ernestina Lake Formation from east-central Alberta to the North Athabasca area (region centred around Fort McMurray in Tp 89, R 9 W4 Mer) indicate that the threefold subdivision persists beyond the northern edge of the Upper Lotsberg Salt, and that the basal shale directly overlies the Precambrian basement north of Tp 85. North of latitude 56°N (Appendix A, Figure 5), or the northern limit of the Upper Lotsberg Salt, the Ernestina Lake Formation onlaps and pinches out to the northeast against the Precambrian basement or a thin veneer of Basal Red Beds or the LaLoche Formation. Figure 5 in Appendix A presents the isopach of the interval between the top of the Ernestina Lake Formation and the Precambrian basement. North of latitude 56°N, the mapped interval essentially consists of the Ernestina Lake Formation because the Basal Red Beds unit (with the exception of the La Loche Formation) is a probable equivalent of the basal member of the formation as developed to the south.

The overlying Cold Lake Formation (Sherwin,1962; Hamilton, 1971) is primarily halite with a thin basal shale. In the Fort McMurray area the equivalent of the Cold Lake Formation is a thin, 5 m-thick shale. East of the depositional (erosional ?) edge of the Ernestina Lake Formation it is difficult to distinguish the Cold Lake equivalent from the underlying La Loche Formation. The Cold Lake Salt (Appendix A, Figure 6) occurs as two isolated deposits, located in the southeast and northwest corners of the study area. The southern salt deposit gradually wedges out depositionally to the northwest from a maximum thickness of 42 m. The northern salt deposit gradually wedges out depositionally to the south from a maximum thickness of 27 m. The eastern limits of both salt deposits are the result of salt dissolution.

Subdivision 3 (Middle Devonian, Upper Elk Point Subgroup)

Subdivision 3 (Figure 14) spans the succession from the base of the Middle

Devonian Contact Rapids Formation to the top of the Middle Devonian Watt Mountain Formation. It represents a major advance of the Devonian transgression onto the craton. Following this advance, a major barrier reef developed across the whole region northeast from the Peace River Arch. Behind the barrier the sub-basins coalesced, the Meadow Lake Escarpment was breached by the transgression and the huge interior Upper Elk Point Basin was established.

In sequential order, the subdivision is a succession of clastics, platform carbonates, evaporites and clastics. They are referred to as: the Chinchaga Formation in northern Alberta, a succession of interbedded anhydrite and dolostone (Law, 1955; Meijer-Drees, 1986); the Contact Rapids Formation in central Alberta, a succession of interbedded argillaceous dolostone and shale (Sherwin, 1962); and the Ashern Formation in Saskatchewan, a calcareous shale (Buller, 1958) and the first deposit on the Siluro-Ordovician carbonate (Prairie Plateau) southeast of the Meadow Lake Escarpment. In reference to the north Athabasca area, the McLean River Formation is used in some early reports, which Norris (1963) introduced as the name for the olive green shale, brown siltstone, and sandy dolomite overlying the LaLoche Formation and underlying the Methy (Winnipegosis) Formation at Contact Rapids (Tp 89, between R 22 and 23 W3 Mer) along the Clearwater River. Regional correlations from the type section (Canadian Seaboard Ernestina Lake No. 10-13-60-4W4 well between 935.6 m and 982.0 m) to the North Athabasca area show that the McLean Formation (Norris, 1963, 1973) is an equivalent of the Contact Rapids Formation.

The Contact Rapids Formation (Appendix A, Figure 7) includes the underlying Cold Lake shale equivalent where the Cold Lake Salt is absent. This grouping was used because the boundary between the shales is difficult to correlate and the data set is sparsely distributed. In the northern area, between the two Cold Lake Salt deposits, the shale equivalent is approximately 5 m thick; however, it increases to 20 m in the southwest corner of the study area. The combined interval of the Contact Rapids and the Cold Lake shale forms a widespread blanket that gradually thins from a maximum thickness of 65 m in the southwest to just less than 20 m in the northeast (Appendix A, Figure 7). In the northern third of the study area, a southerly tapering wedge (1-5m thick) of anhydrite, a Chinchaga equivalent, is included at the top of the Contact Rapids Formation.

In northern Alberta, the Contact Rapids Formation is conformably overlain by the widespread platform carbonates of the Keg River Formation (Law, 1955), the Methy dolomite in the north Athabasca area (Nauss, 1950; Greiner, 1956), and the Winnipegosis Formation in central Alberta and Saskatchewan (Baillie,1953; Grayston et al., 1964).

The Winnipegosis-Keg River Formation (Appendix A, Figure 8) is composed of reef and non-reef carbonates ranging from less than 12 m thick in the inter-reef areas to more than 113 m thick in the thickest reef sections. Non-reef carbonates generally have an average thickness of 50 to 60 m. Thinner non-reef carbonates occur along a belt of fringing carbonate reefs that form part of an extensive chain bordering the western edge of the Precambrian Shield from Manitoba to the Northwest Territories (Figure 14). In the study area, the reef trend extends from the southeast to the northwest. The AOSTRA UTF site in Tp 93, R 12 W4 Mer is along this trend.

The base of the Winnipegosis-Keg River interval is composed of microsucrosic dolomite, while the main reef section consists of either structureless, fossiliferous, vuggy dolomite or a cryptocrystalline to microcrystalline, poorly fossiliferous dolomite (Baillie,1953). In the north Athabasca area, Greiner (1956) described the lithology of the Methy dolomite (Winnipegosis) as highly variable. He recognized three arbitrary subdivisions within the formation: a basal, relatively thin-bedded unit; a relatively thick middle unit containing reefal and inter-reefal beds; and a relatively thin upper, distinctly-bedded unit in which fossils are virtually absent. According to Greiner (1956), the lower unit (0.6 to 10.6 m thick) consists of dolomite and evaporite, and silty dolomite with thin interbeds of anhydrite and minor shale. The middle unit (39.6 to 60 m thick) consists mainly of dolomite which is massive in places, poorly to well bedded, flow-layered and brecciated. The upper unit, a 1 to 17 m thick interval, consists of well bedded dolomites, evaporitic dolomite, some oolitic and argillaceous dolomite, and thin beds of anhydrite (Greiner, 1956).

The Winnipegosis-Keg River carbonate succession is overlain by an evaporite succession extending from the Keg River Barrier in northern Alberta, to North Dakota in a belt approximately 250 km wide (Figure 14). The deposit is thickest along the centre of the Elk Point Basin, increasing in thickness from approximately

150 m in central and southern Saskatchewan, to about 215 m in northern Alberta. The eastern boundary of the evaporites, like the southern boundary in Saskatchewan, is delineated by dissolution salt scarps that have migrated towards the centre of the basin since post-Middle Devonian time. In general, the salt scarps have an average width of 20 km. The western boundary reflects thinning over a long distance, with the salt terminating depositionally.

Between the Keg River Barrier and north Athabasca area, the evaporite succession consists of the cyclic carbonate and anhydrite interbeds of the Muskeg Formation (Law, 1955). Anhydrite interbeds decline rapidly in number progressing southward from Tp 100 to Tp 90 in the north Athabasca area. South of Tp 85, the evaporite succession consists primarily of halite (Hamilton, 1971), with anhydrite being restricted to the base of the succession. The anhydrite is generally restricted to an interval of less than 10 m, or as isolated masses up to 50 m thick adjacent to Winnipegosis pinnacle reefs. South of Tp 100 the name Prairie Formation is applied to the evaporite succession. An easterly tapering wedge of anhydrite (0-20 m) overlies the predominantly halite succession between longitude 113° and 114°W. This wedge of the Muskeg Formation was excluded from the present isopach map of the Muskeg-Prairie interval. Within the study area, the Muskeg-Prairie interval (Appendix A, Figure 9) is thickest along a north-northwest trend, increasing from 160 m in the south to 275 m in the northwest. Thinner intervals along this trend are the result of the reef chain of the underlying Winnipegosis Formation. The sharp eastward tapering of the deposit reflects the salt dissolution scarp.

In northern and central Alberta, the Muskeg-Prairie evaporite succession is overlain by a widespread succession of dolomitic shales called the Watt Mountain Formation (Law, 1955). Regionally, the Watt Mountain interval ranges from 15 to 2-0 m in thickness. The Watt Mountain Formation isopach (Appendix A, Figure 10) presented here includes the tapering wedge of Muskeg anhydrite underlying the Watt Mountain shales along the western edge of the study area, and the residual of the Muskeg-Prairie evaporite down to the top of the Winnipegosis Formation along and to the east of the Prairie salt scarp. Interval thicknesses greater than 20 m along the western edge of the study area reflect the tapering wedge of Muskeg anhydrite, while to the east they reflect shale and gypsum residuals left after the dissolution of the Muskeg-Prairie evaporite succession.

UPPER DEVONIAN

Subdivision 4 (Beaverhill Lake and Woodbend Groups)

In northeast Alberta, the Beaverhill Lake Group (Figure 15) is primarily an inter-platform basin deposit consisting, in ascending order, of the Fort Vermilion, Slave Point, and Waterways formations. Both the Fort Vermilion and Slave Point formations are relatively thin units, restricted to the very northwest of the study area, but much more extensively developed north and west of the study area. The Waterways Formation is an alternating succession of calcareous shales and carbonates, subdivided in ascending order into the Firebag, Calumet, Christina, Moberly and Mildred Lake members. Post-Devonian erosion of the Beaverhill Lake Group has resulted in a 90 km wide subcrop belt (Figure 21; Appendix A, Figure 11) along the eastern half of the study area. West of the subcrop belt, the group has an average thickness of 200 m.

The Beaverhill Lake Group is overlain by the Woodbend Group (Figure 16), which consists of both inter-reef basin fill and carbonate platforms. The Woodbend Group of northeast Alberta consists, in ascending order, of the Cooking Lake, Ireton and Grosmont formations. Subcrops forming the updip eastern limit of the units of the Woodbend Group progressively shift to the west, progressing up-section (Figure 21).

The Cooking Lake Formation (Appendix A, Figure 12) is the remnant of a more widespread westward prograding carbonate platform. The eastern limit is a relatively linear north-northwest trending subcrop belt approximately 18 km wide. West of longitude 113°N, the Cooking Lake Formation thins depositionally to a few metres in thickness.

Basinward (west) of the Cooking Lake carbonate platform, the limy shales of the lower Ireton Formation (Appendix A, Figure 13) fill the inter-platform basin. Thinning of the shales eastward, from a maximum of 150 m, primarily reflects the build-up of the underlying Cooking Lake carbonate platform. A narrow subcrop belt ranging in thickness up to 25 m, defines the eastern margin of the lower Ireton Formation.

The lower Ireton Formation is overlain by the Grosmont Formation, a carbonate platform (Appendix A, Figure 14) which prograded to the east, similarly to the Cooking Lake carbonate platform. The Grosmost Formation has a relatively uniform thickness of 170 m in the southwestern portion of the study area, and thins to the northeast over a 30 km-wide subcrop belt. The Grosmont Formation is separated from the overlying Winterburn Group by a thin (less than 20 m) shale, referred to as the upper Ireton Formation (Appendix A, Figure 15). West of the Grosmont carbonate platform (approximately west of the 5th Meridian), the upper and lower Ireton shales merge into one unit, forming the Ireton Formation.

Subdivision 5 (Winterburn Group and Wabamum Formation)

The Winterburn Group and the overlying Wabamum Formation reflect the basinwide progradation of carbonate platforms as a result of the regression of the Kaskaskia Sea at the end of the late Devonian (Figure 17). The effect of basin tilting to the west and later erosion has restricted these units to the very southwest corner of the study area. The Winterburn Group consists primarily of dolomitic rocks and has a maximum thickness of 125 m (Appendix A, Figure 16). The Wabamum Formation, a massive limestone deposit, is represented by an incomplete interval with a maximum thickness of 125 m (Appendix A, Figure 17).

PALEOZOIC ISOPACH AND STRUCTURE

The Paleozoic strata of northeast Alberta form a wedge (Appendix A, Figure 18) that tapers to a zero edge in the northeast along the western boundary of the Canadian Shield. The wedge thins at a uniform rate of approximately 4-4.5 m/km, from a maximum thickness of 1150 m in the southwest corner of the study area. South of latitude 56° 30' N there is a slight, but overall increase in the thickness of the wedge, reflecting the Lotsberg Formation which occurs only in the Central Alberta sub-Basin. Other local variations of thickness are caused by the effects of erosional relief on the sub-Cretaceous unconformity, and the dissolution of Middle Devonian Elk Point Group evaporites.

Strata throughout the Devonian of northeast Alberta form relatively planar sub-parallel units that gently dip to the southwest at a rate of 4 to 4.5 m/km (Appendix B, Figures 2 - 19). Their structure is similar to that of the Precambrian basement, except that they lack local erosional topographic relief. Dissolution of the Middle Devonian Prairie Formation has resulted in a linear north-northwest trending salt scarp (Appendix B, Figure 12). All the horizons overlying the salt scarp (Appendix B, Figures 11, 12, 13 and 20) closely reflect its structure, suggesting a significant post-Devonian period of dissolution. The regional reversal of dip along the Prairie salt scarp forms the Athabasca anticline-syncline pair, a linear north-northwest trending feature also expressed in the overlying Cretaceous succession. The effect of salt dissolution in the Upper Lotsberg and Cold Lake salts is less significant, and therefore less easily detected by the contouring interval used in this study. Dissolution in the Upper Lotsberg Salt (Appendix A, Figure 4) occurred just north of latitude 56°N between longitudes 110° and 112°W, with a maximum thickness of 25 m being removed. Dissolution in the Cold Lake Salt (Appendix A, Figure 6) took place along its eastern limit, between longitudes 110° and 111°N, with a maximum of 30 m of salt being removed.

The surface of the Paleozoic section is a composite of the Middle to Upper Devonian subcrop belts which increase in age to the northeast (Figure 21). This surface forms the sub-Cretaceous unconformity of northeast Alberta, a surface which dips gently to the southwest at 2 m/km or less (Appendix B, Figure 20). The strike of the structure contours, in relation to underlying Paleozoic horizons, is rotated to the southeast. In addition to expressing the Athabasca anticline-syncline pair, the structure of the sub-Cretaceous unconformity reflects local relief greater than 50 m, primarily the result of post-Devonian erosion. Differential erosion of tilted, tabular Paleozoic strata resulted in a series of north-northwest trending valleys and ridges (Appendix B, Figure 20) that developed into northerly flowing river systems during the Lower Cretaceous (Jackson, 1984).

MESOZOIC GEOLOGY OF NORTHEAST ALBERTA

Mesozoic strata in northeast Alberta consist of Cretaceous sediments that are bounded by the sub-Cretaceous unconformity at the base and covered by a thin veneer of Pleistocene deposits at the top. Sediments include the successions of the Lower Cretaceous Mannville Group and Upper Cretaceous Colorado Group. Post-Cretaceous erosional events have removed thick successions of strata from northeast Alberta, especially along present-day drainage systems which cut through the Cretaceous rocks into Paleozoic strata in several places.

LOWER CRETACEOUS MANNVILLE GROUP

Lower Cretaceous deposits of the Mannville Group lie unconformably on the sub-Cretaceous erosional surface in northeast Alberta. A three-fold subdivision of the Lower Cretaceous Mannville Group into lower, middle, and upper aids in discussing this thick succession by linking distinct, basin-wide events to discrete periods of Mannville sedimentation. Cant (1989) divides the Mannville Group into a lower non-marine phase, a middle transgressive phase, and an upper regressive phase. Basin subsidence, sediment supply, and fluctuations of sea level were the major contributing factors affecting the deposition of the Mannville Group. An isopach map of the entire Mannville succession within the study area (Appendix A, Figure 22) displays a sedimentary package of relatively uniform thickness.

Lower Mannville (Lower Cretaceous McMurray Formation)

Lower Mannville sediments in northeast Alberta make up the sand-dominated McMurray Formation. These sands are a fining upward sequence giving a distinct, bell shaped geophysical log signature. A structure map on top of the McMurray Formation (Appendix B, Figure 21) shows a relatively uniform, southwest dipping trend except for the east-central and southeast regions of the study area, where the structure contours are very irregular. An isopach map (Appendix A, Figure 19) of the McMurray Formation reveals significant variations in thickness from east to west. In the west, the McMurray Formation is generally thin (less than 50 m). East of longitude 112°W, sands and associated shales of the McMurray Formation thicken rapidly. In a north - south direction, the thickness trends are generally constant. The isopach map reflects the topography of the sub-Cretaceous unconformity. Thin areas generally indicate ridges or paleohighs, while thick areas correspond to valleys or paleolows. Two structural cross-sections, one oriented southwest to northeast (structural dip cross-section, Figure 26) and the other northwest to southeast (structural strike cross-section, Figure 27) depict these regional thickness variations and their relation with the unconformity. From a depositional standpoint, the ridge and valley system was critical for lower Mannville sedimentation patterns in northeast Alberta.

During lower Mannville time, northward oriented valley systems in northeast Alberta (Figure 28) acted as conduits for siliciclastic sediments shed mostly from the stable Precambrian Shield to the east (Cant, 1989). The McMurray Formation

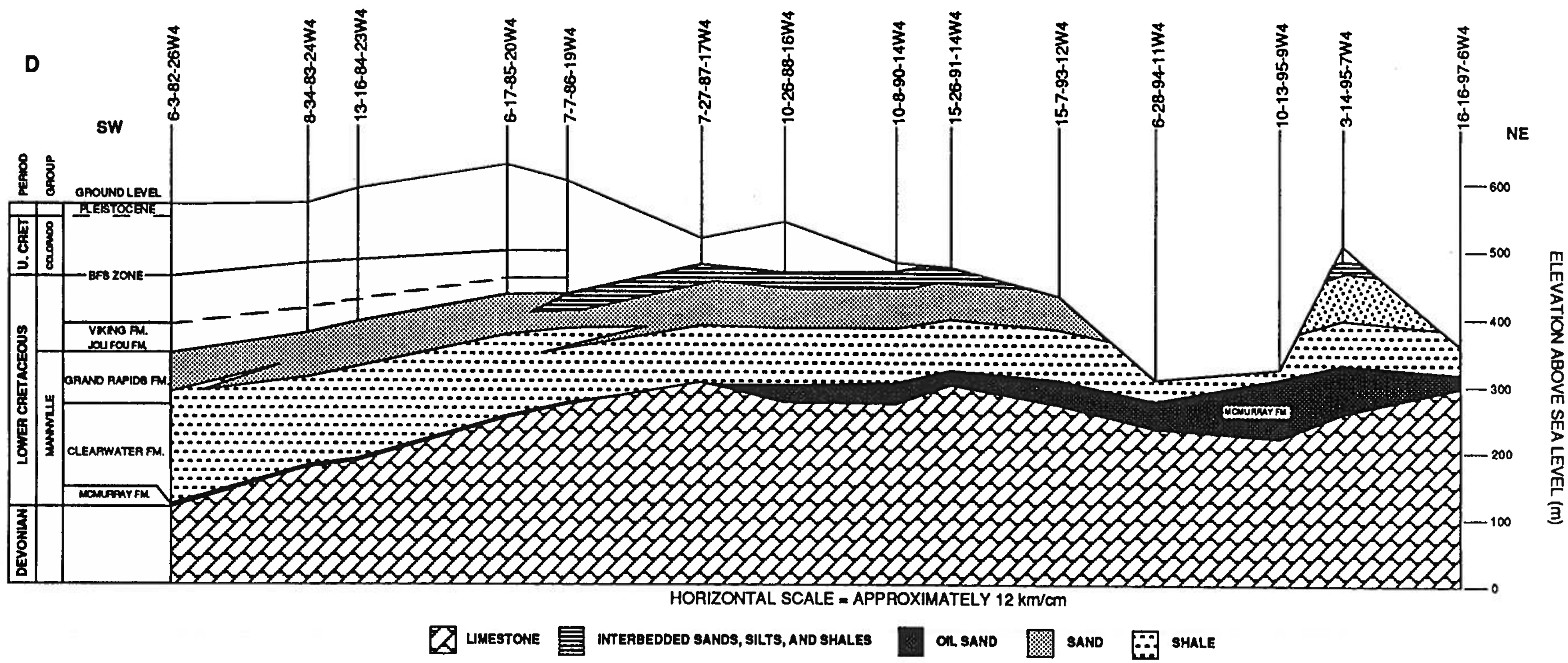


Figure 26: Structural dip cross-section D-D' of the Cretaceous succession overlying the sub-Cretaceous unconfirmity.

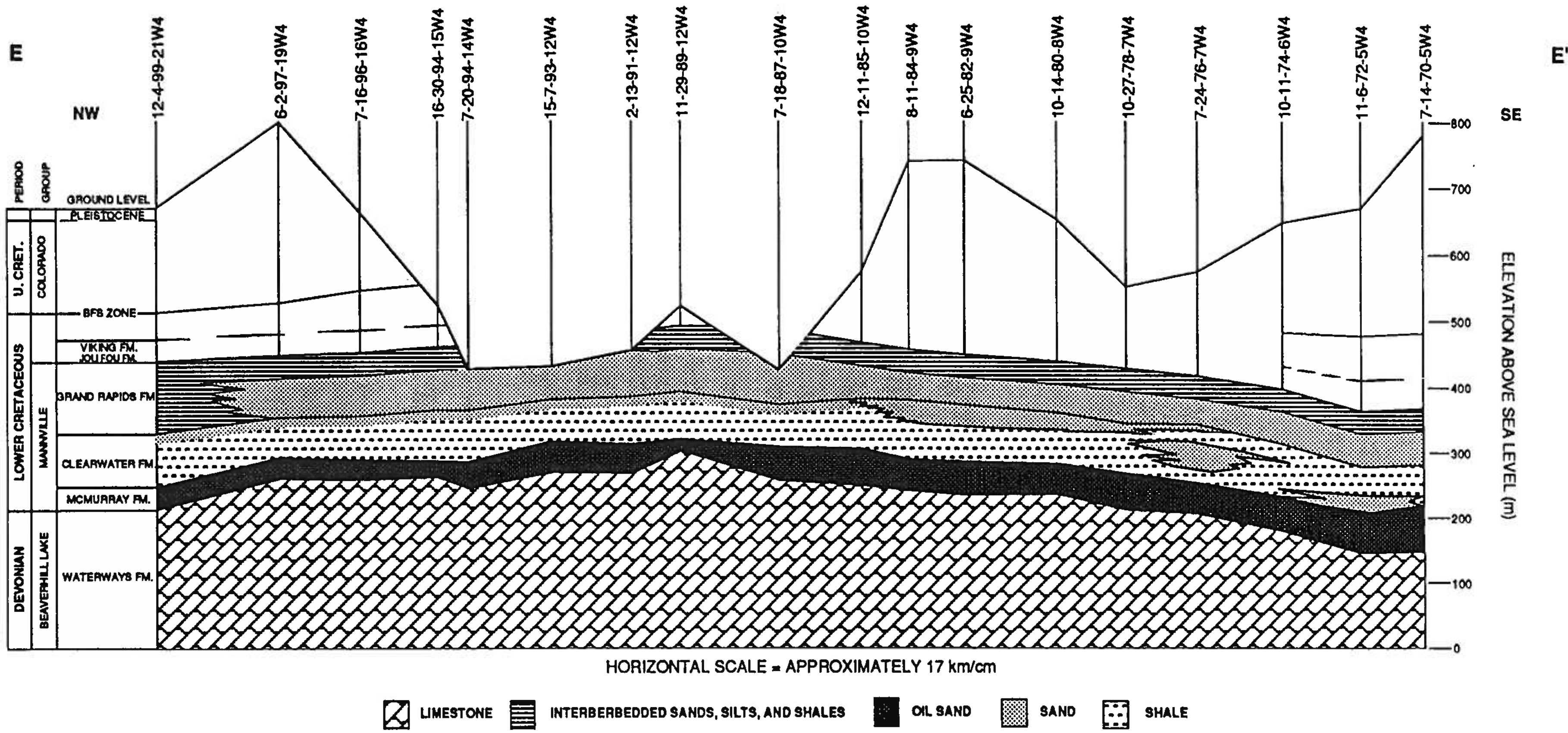
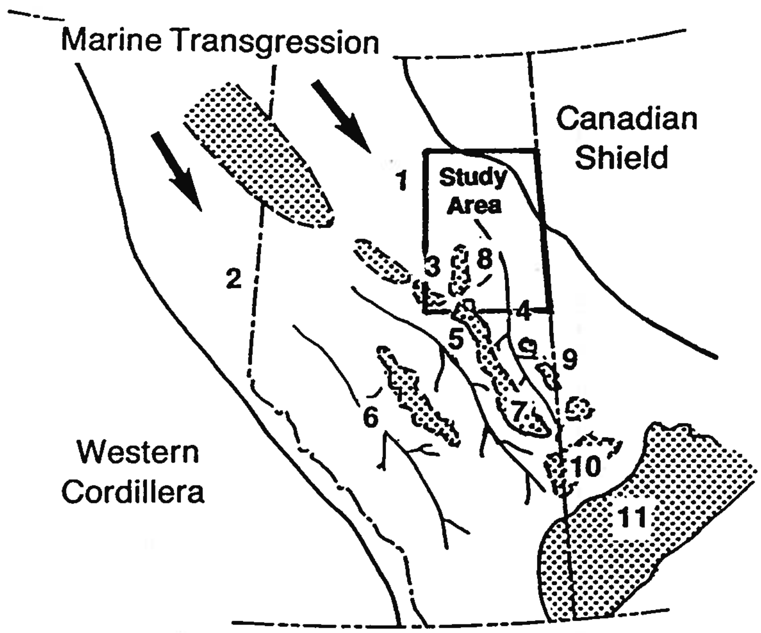


Figure 27: Structural strike cross-section E-E' of the Cretaceous succession overlying the sub-Cretaceous unconformity.



1. Athabasca Basin
2. Gething Basin
3. Wabasca Sub-Basin
4. St. Paul Channel
5. Edmonton Channel
6. Spirit River Channel
7. Wainwright High
8. Grosmont High
9. Lindbergh High
10. North Battleford High
11. Swift Current Platform

Figure 28: Approximate Mannville paleogeography at the Aptian-Albian boundary, showing basin outlines and topographically high areas with inferred drainage (after O'Connell, 1985).

occupies one of these channel systems, described by Jackson (1984) as the St. Paul Channel complex, which is located near the eastern edge of the basin and corresponds to a structural low on the sub-Cretaceous unconformity that may be the result of underlying Devonian salt dissolution prior to and during McMurray time. This also explains the thicker sediment accumulation in the area. The area of irregular structure contours (Appendix B, Figure 21) described earlier is the result of continuing salt dissolution.

The McMurray Formation can be subdivided into three sedimentologically distinct units. Lower McMurray sediments, consisting of fluvial dominated deposits, first occupied the paleovalley complex. Infilling of this valley system was triggered by a southerly transgression of the Bullhead Sea (Caldwell, 1984). This marine incursion reduced river gradients, which resulted in an aggradational phase consisting of interdistributary bays and estuarine channels (Cant, 1989). In the Fort McMurray area, middle and upper McMurray sediments display distinct estuarine and marine signatures. In some northern portions of the study area, a thin, coarse grained transgressive sand sharply separates the estuarine assemblage of the middle McMurray from the marine sediments of the upper McMurray.

The McMurray Formation is the time equivalent of the Cadomin, lower Gething, and Ellerslie formations elsewhere in the foreland basin. Sediments on the eastern flank of the Cordillera consist of alluvial fan and braided stream deposits forming the conglomeratic Cadomin and the fluvial sediments of the lower Gething formations. These deposits occupy the Spirit River Channel system (Figure 28).

Deposits of the Ellerslie Formation are dispersed within the Edmonton Channel system, situated in central Alberta (Jackson, 1984). These deposits, like the McMurray, were influenced by the southerly advance of the northern sea.

Middle Mannville (Lower Cretaceous Wabiskaw Member, Clearwater Formation)

Sediments of the middle Mannville in northeast Alberta are represented by the Wabiskaw Member, the basal sands of the Clearwater Formation. The Wabiskaw Member is generally thin (less than 15 m), but in some locations in the southeastern portion of the study area it thickens considerably. Generally, the Wabiskaw Member is a coarsening upward sequence giving a funnel shaped signature on geophysical logs. Individual sands within the Wabiskaw Member are generally continuous over tens of kilometers. The sands blanket the underlying McMurray Formation and the exposed paleohighs on the sub-Cretaceous unconformity

Middle Mannville sediments reflect a continued transgression that started during lower McMurray time. During the middle Mannville, the transgressive system was interrupted by relatively minor, regressive, progradational pulses that may imply tectonic influences. The Wabiskaw sand succession is one of several transgressive-regressive packages in the foreland basin that represent rapid shifts of base level (Cant,1989). The short-lived regressive pulses of the Wabiskaw formed nearshore and shallow marine systems consisting of beaches, barrier islands, and offshore bar trends (Jackson, 1984).

Time-equivalent successions within other parts of the foreland basin include the Bluesky Formation and Glauconitic complex (Cant, 1989). The Bluesky Formation was deposited in northern Alberta and British Columbia as a shoreline system surrounding a low relief landmass. Deposits of the Glauconitic complex started as northerly prograding coastal plain deposits in southern Alberta. The system eventually reached south-central Alberta where it merged with barrier island and offshore complexes which were developing during the same period (Jackson, 1984).

Upper Mannville (Lower Cretaceous, Clearwater and Grands Rapids Formations)

The upper Mannville in northeast Alberta is subdivided into the Clearwater and Grand Rapids formations. These are two genetically related successions defined by a diachronous boundary separating the sandy facies of the Grand Rapids Formation from the shaly facies of the Clearwater Formation (Kramers and Prost, 1986).

Within the study area, the Clearwater Formation interfingers with, is laterally equivalent to, and is overlain by the Grand Rapids Formation. The Clearwater Formation is generally shaly in the north and becomes progressively sandier to the south. In the southwest region there are three distinct sand bodies (Figure 27). These sands, individually up to 30 m or more in thickness, appear in the subsurface as coarsening upward, stacked, lenticular bodies. In vertical succession, each stratigraphically higher sand body has its leading depositional edge terminating in a more northerly position than the preceding one (Figure 27). Apart from the thick, southerly sand bodies, the Clearwater Formation is a dominantly shaly succession (D. McPhee, pers. comm.). The regional structural trend (Appendix B, Figure 22) dips gently to the southwest. Structure contours, although subdued compared to those of the McMurray Formation, show irregularities when crossing the area of underlying Devonian salt dissolution in the southeastern region. The isopach of the Clearwater Formation (Appendix A, Figure 20) shows a gradual thickening to more than 150 m in the northwest. Several distinct, laterally continuous shale markers within the Clearwater Formation have been used by Kramers and Prost (1986), Keith et al (1987) , and MacGillivray et al. (1989), to correlate and map portions of the Clearwater and vertically adjacent successions.

By upper Mannville time, the northern portions of the basin reflected deeper marine conditions caused by the transgressive southerly shift of the Boreal Sea (Cant, 1989). In addition, a shale basin had been developing to the west for some time, due to the subsidence of the Peace River Arch. Initiation of a major regressive phase followed this transgressive event. Regressive conditions were caused by an increased supply of clastics shed into the basin arising from reactivation of Cordilleran deformation. During early upper Mannville time, this clastic influx, combined with a northerly transport direction, shifted coastal margins seaward (north), resulting in the stacked sand bodies of the Clearwater Formation in northeast and east-central Alberta. These Clearwater sands record the easterly extent of Cordilleran-sourced clastics. Time-equivalent successions elsewhere in the basin include shoreline trends of the lower Falher and Gates formations in western Alberta, and the Sparky and Lloyd sands in the Lloydminister-Cold Lake areas of eastern Alberta (Smith and Meckel, 1989).

The Grand Rapids Formation of northeast Alberta is disconformably overlain by marine shales of the Joli Fou Formation belonging to the Colorado Group. In the western portion of the study area (Tp 69 to 87, R 12 W4 Mer to 3 W5 Mer), the contact between the Grand Rapids and the Clearwater formations is distinct and considered to be related to sediment supply (Kramers and Prost, 1986). In the Wabasca area, southwest of Fort McMurray, the Grand Rapids Formation comprises three stacked, laterally continuous, coarsening-upward sand successions. The sand bodies are bounded by shales and silty beds. They are designated, in descending order as the A, B, and C sands. The northerly depositional limit of each successive sand body, averaging approximately 30 m in thickness, is positioned farther basinward than the previous one (Kramers and Prost, 1986). Structure contours on top of the Grand Rapids Formation (equivalent to the top of the Mannville, Figure 23 in Appendix B) are similar to the underlying structure surface of the Clearwater Formation (Appendix B, Figure 22). The isopach map of the Grand Rapids Formation (Appendix A, Figure 21) shows the succession to be generally of constant thickness except for slight thinning in the northern and eastern regions. Structural cross-sections (Figures 26 and 27) depict the gross lithology and distribution of the Grand Rapids Formation within the study area.

Late upper Mannville time saw the continued northerly progradation of coastal margins to the northern regions of Alberta. Prograding sands within the Grand Rapids Formation are considered to reflect three sediment pulses introduced into the Clearwater Sea as a result of Cordilleran deformation. Vertically within each individual coarsening upward sand unit, detailed sedimentological studies indicate depositional environments ranging from offshore marine at the base through beach/barrier island/coastal plain systems at the top (Kramers and Prost, 1986). An extensive bay evolved south of the Grand Rapids shoreline trend. By the end of upper Mannville time, the bay had been partially filled with sediments of the Colony Member situated south of the study area (Smith and Meckel, 1989). The northerly progradation of the Grand Rapids shoreline complex was restricted by a rapidly subsiding basin (Leckie, 1989) in the area of the former Peace River Arch. Accommodation space provided by subsidence of the arch allowed the accumulation of thick shales and silts of the Clearwater Formation, but, as advancing coastal systems of the Grand Rapids Formation approached the edge of the basin, shoreline sands thickened, and became stacked within multi-cycle successions. To the north, the sands shale out into time-equivalent offshore facies (Jackson, 1984).

The end of Mannville time is marked by a disconformity which resulted from a short-lived relative drop in sea level and a period of tectonic quiescence (Jackson, 1984). However, the disconformity is not present in western Alberta because the continued subsidence of the Peace River Arch area was able to outpace the relative fall of sea level (Cant, 1989).

Elsewhere in the basin, time-equivalent strata consist of the Falher and Notikewan sand trends of the Elmworth Deep Basin. These two packages are comprised of stacked shorelines successions that advanced into the Peace River area of Alberta and there, like the Grand Rapids, were restricted by the subsiding shale basin.

LOWER TO UPPER CRETACEOUS COLORADO GROUP

The Colorado Group spans the time period from the early Cretaceous (Upper Albian) to approximately the middle of the late Cretaceous. In general, the Colorado Group consists of thick successions of shale intercalated with several thin sandstone zone. The Viking Formation is the only significant sand zone in the study area. The Base of Fish Scale Zone and the Second White Speckled Shale horizons are prominent log markers within the shales overlying the Viking Formation. The onset of Colorado deposition marked significant changes in sedimentation within the basin. Cant (1989) suggested that this change is the result of a lull in Cordilleran tectonic activity combined with an overall period of rising sea level. Coalescence of the Gulfian Sea from the south and the Boreal Sea from the north inundated the western interior, forming a seaway that extended from the Gulf of Mexico to the Arctic (Williams and Stelck, 1975).

Lower Cretaceous Colorado (Joli Fou and Viking Formations)

The upper Mannville surface in northeast Alberta is disconformably overlain by the Joli Fou Formation. It consists primarily of shale, but does contain some basal sandstones along the western limit. Shales of the Joli Fou Formation are generally thin (less than 15 m). In some regions the division between the top of the Joli Fou Formation and the base of the Viking Formation is difficult to discern. For this reason, coupled with inconsistent picks within the data base, maps for this formation were not produced.

Sandstones and shales of the Viking Formation overlie the Joli Fou Formation. Within northeast Alberta, the sandstones of the Viking Formation, also referred to as the Pelican Formation, consist of clean, coarsening-upward cycles. The sands thicken to the east where present, and grade laterally into stacked, shaly cycles from north to south. The entire Viking succession is of the order of 25 m thick throughout the region (Appendix A, Figure 23). The structure on the top of the Viking Formation (Appendix B, Figure 24) has a similar trend to that of the underlying Mannville Group.

Sediments of the Viking Formation were deposited as shoreline complexes around the margins of the basin, with sand sourced from erosion of the basin edges. These deposits are thought to reflect a lowstand of sea level (Cant, 1989).

Upper Cretaceous Colorado

The Viking Formation is overlain by a thick interval of Colorado shale. Two prominent, radioactive marker zones known as the Base of Fish Scale Zone and the Second White Speckled Shale are found in this succession. Both marker zones are rich in organic carbon and terminate thick, shaly, coarsening upward cycles.

The Fish Scale Zone, the first lower marker located stratigraphically above the Viking Formation, is considered as the boundary between the Upper and Lower Cretaceous. The Fish Scale Zone generally consists of laminated sands and silts containing abundant fish-scales and vertebrae (Leckie, 1989). A structure map on top of the Base of the Fish Scale zone (Appendix B, Figure 25) displays the same southwesterly dipping regional trend shown by previous Cretaceous strata. An isopach map from the top of the Base of Fish Scale Zone to the top of the Viking Formation (Appendix A, Figure 24) shows the variation in thickness of the interven-ing shale succession. The shaly unit maintains thicknesses in the range 20 to 40 m within the study area, except for the northernmost region where it thickens to more than 60 m.

The coccolith-rich Second White Speckled Shale (second marker), where present, is separated from the lower Base of Fish Scale Zone by a second shale succession up to 100 m thick (Appendix A, Figure 25). A structure map on top of the Second White Speckled Shale (Appendix B, Figure 26) generally follows the regional trend common throughout the Cretaceous.

Both the Base of Fish Scale Zone and the Second White Speckled Shale are relatively thin, flat marker zones that are laterally continuous throughout most of the foreland basin. For this reason, either one can serve as an excellent stratigrap-hic datum for correlating and mapping Cretaceous successions. Both markers have been suggested to reflect deposition during relative maxima of sea level (Cant, 1989; Leckie, 1989). Unfortunately, post-Colorado erosion has removed these marker beds and post-Colorado strata from large portions of the study area.

MESOZOIC ISOPACH

Glacial and post-glacial deposits of Quaternary age blanket much of the Cretaceous bedrock. Pleistocene deposits consist primarily of unconsolidated sands and gravels. These deposits are generally isolated by casing during the drilling process, resulting in few well logs recording the contact between the Pleistocene sediments and the underlying bedrock. Because picks for the structure on top of the Cretaceous bedrock are unavailable, the ground surface was used as the upper boundary for the Mesozoic isopach map (Appendix A, Figure 26). A structure map (Appendix B, Figure 27) of the present-day ground surface depicts the topography within northeast Alberta. The Mesozoic succession thickens from zero at the eastern edge of the basin to more than 600 m in the west.

REGIONAL HYDROGEOLOGICAL FRAMEWORK

The sedimentary rocks in the basin constitute the framework through which the formation fluids move. The most important rock properties with respect to fluid flow are porosity and permeability, which define the capacity of the rock for storing fluids and allowing their movement. The existence of high porosity does not necessarily mean that a particular rock system is an aquifer (e.g. shales can have high porosity, but have very low permeability and therefore generally constitute aquitards). A proper hydrogeological delineation and characterization requires the analysis of rock properties fundamental to fluid flow. In addition, an analysis of the contained fluids (chemical composition, direction and strength of flow, etc.) is required for a complete characterization of the hydrogeological regime in any package of rocks. Nevertheless, lithology provides a preliminary indication of the hydrogeological characteristics of the rock framework because various rock types have different corresponding properties with regard to fluid flow (permeability and porosity). For example, sandstones and carbonates generally constitute aquifers, shales are generally aquitards, and halite beds commonly form aquicludes. Thus, the regional synthesis of the geology in terms of definable stratigraphic successions, as described by isopach and structure contour maps, and knowledge of their lithology, provide the basis for a preliminary hydrostratigraphic delineation. This delineation can be finalized based on the analysis of the hydrodynamic characteristics of the rocks and contained fluids.

The geometry, alone, of individual aquifers, aquitards and aquicludes is not sufficient for hydrostratigraphic delineation. Juxtaposition or contact with similar hydrostratigraphic units, even if of different lithology and geological origin, creates whole hydrostratigraphic systems. In this context, an aquifer system is defined as consisting mostly of aquifers, although it may contain isolated aquitards of limited extent, and so on a regional scale behaves generally like an aquifer. An aquitard system consists mostly of continuous aquitards, may contain isolated aquifers, and behaves like an aquitard. Hydraulic continuity is the main control on the grouping of various individual aquifers, aquitards and aquicludes into hydrostratigraphic systems.

The hydrostratigraphy of the Phanerozoic strata in northeast Alberta is extremely complex due to various depositional and erosional events. Four basic hydrostratigraphic types can be defined based only on knowledge of the stratigraphy and lithology of the strata (Figure 25). The crystalline Precambrian constitutes an impervious base to the entire succession. The evaporitic beds (Lotsberg, Cold Lake and Prairie) are aquicludes which do not allow fluid movement, although Bredehoeft (1988) reports some permeability for salt beds (extremely low, of the order of $10^{-22}m^2$). Further, fracturing can result in permeability. The shale strata (Watt Mountain, some Beaverhill Lake Group members, Ireton, and most of the Colorado Group) are aquitards. The carbonates (Winnipegosis, most of the Beaverhill Lake Group, Cooking Lake, Grosmont, Winterburn Group and Wabamun) are aquifers. Sandstones, mainly in the Mannville Group, should constitute aquifers. However, the presence in places of high viscosity, almost solid bitumen in the oil sands deposits of the Mannville Group has the effect of transforming the behaviour of these sandstones into that of aquitards wherever bitumen is present (Hitchon et al., 1989). Their delineation will be completed prior to finalizing the analysis of the hydrogeological regime. Because of this dual behaviour, aquifer or aquitard in places, the *weak aquifer-aquitard* hydrostratigraphic type is introduced for the units which, in this preliminary delineation, do not fit into any other category. The Clearwater Formation, a combination of sandstones and shales, is also placed in this category. The non-evaporitic units of the Lower Elk Point Group (Figure 25) are a mixture of shales and sandstones, and are also considered at this stage as weak aquifer-aquitards. Analysis of rock porosity and permeability, formation pressure and chemistry of formation fluids (water, oil, gas, bitumen) will be used later on in deciding if these ambiguous hydrostratigraphic units are either aquifers or aquitards. Figure 29 and Table 2 present the preliminary hydrostratigraphic delineation of the Phanerozoic sedimentary rocks in northeast Alberta.

Because of salt dissolution and of pre- and post-Cretaceous erosion, many hydrostratigraphic units, which where isolated during previous stages of basin evolution, are now in physical contact and probably in hydraulic continuity. Figure 30 presents the dissolution and depositional boundaries of the various evaporitic beds in the Lower Elk Point Subgroup. The absence in places of these impervious beds allows hydraulic continuity among the non-evaporitic units: Red Beds, Ernestina Lake and Contact Rapids formations. The thick Prairie Formation evaporites covered by the shales of the Watt Mountain Formation constitute an aquiclude separating the Winnipegosis aquifer from the Beaverhill Lake aquifer system. However, east of the salt dissolution edge (Appendix B, Figure 11), the

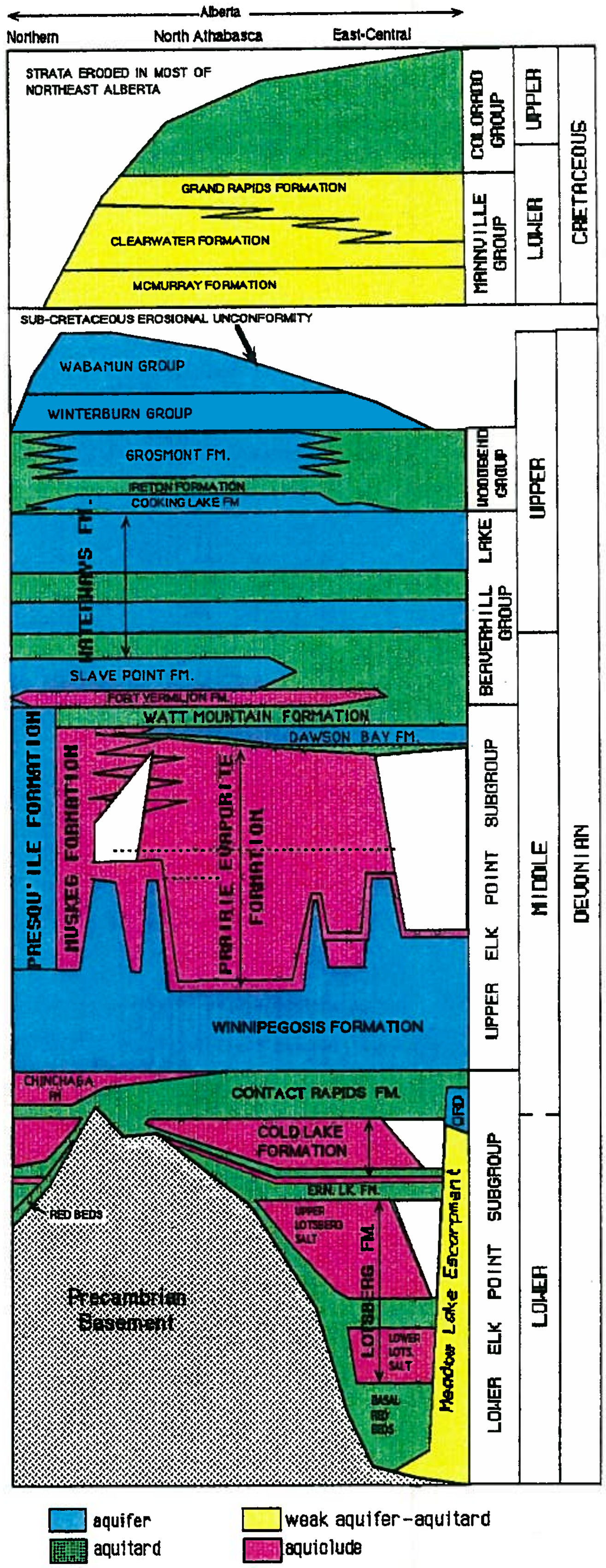
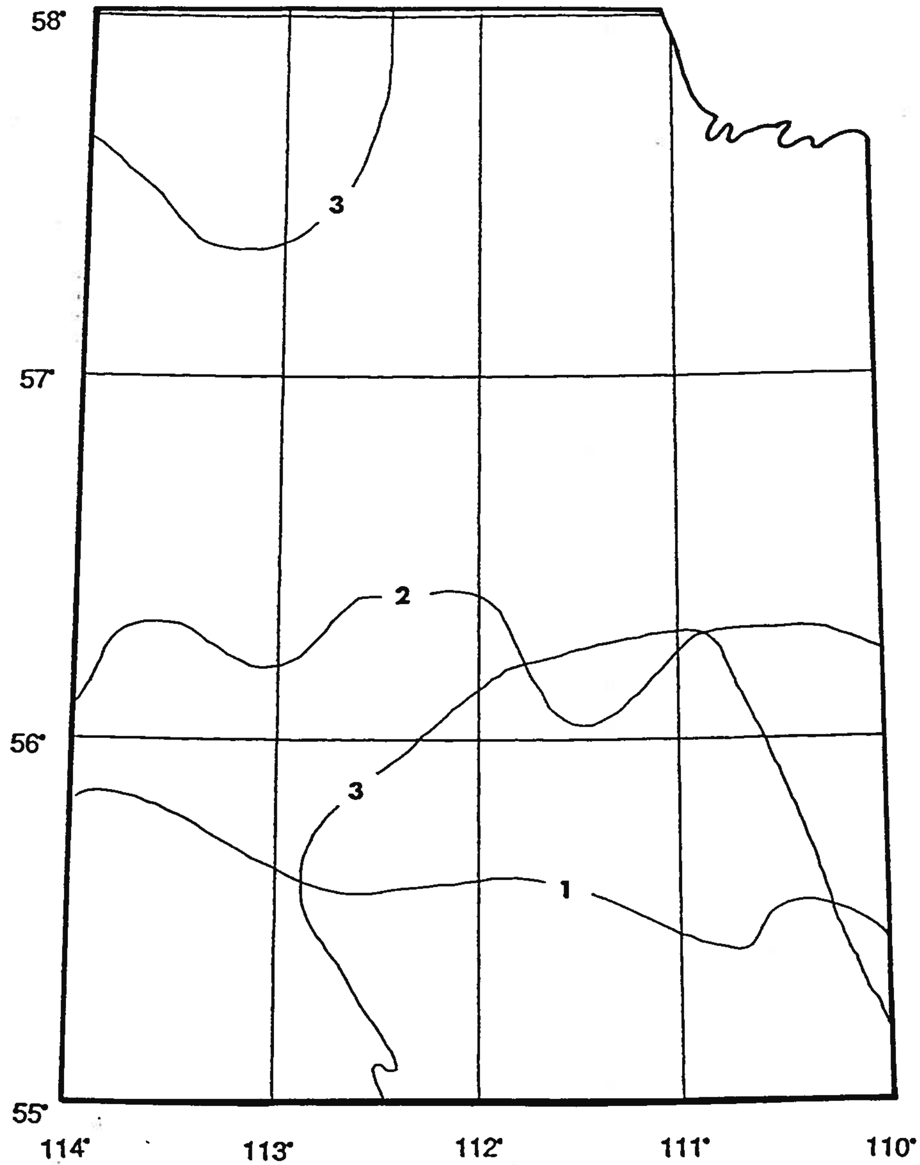


Figure 29: Phanerozoic hydrostratigraphic units in northeast Alberta study area.

Stratigraphic Unit		Group		Formation	Hydrostratigraphic Unit: Type	Hydrostratigraphic Unit: System
Cretaceous	Upper	Colorado		2 White Specks	aquitard	Colorado aquitard system
Cretaceous	Upper	Colorado		Base of Fish Scales	aquitard	Colorado aquitard system
Cretaceous	Lower	Colorado		Viking	aquifer	Colorado aquitard system
Cretaceous	Lower	Colorado		Joli Fou	aquitard	Colorado aquitard system
Cretaceous	Lower	Mannville		Grand Rapids	aquifer - aquitard	
Cretaceous	Lower	Mannville		Clearwater	aquifer - aquitard	
Cretaceous	Lower	Mannville		Wabiskaw	aquifer	McMurray-Wabiskaw aquifer-aquitard system
Cretaceous	Lower	Mannville		McMurray	aquifer - aquitard	McMurray-Wabiskaw aquifer-aquitard system
Devonian	Upper			Wabamun	aquifer	Grosmont-Wabamun aquifer system
Devonian	Upper	Winterburn			aquifer	Grosmont-Wabamun aquifer system
Devonian	Upper	Wood-bend		Grosmont / Upper Ireton	aquifer	Grosmont-Wabamun aquifer system
Devonian	Upper	Wood-bend		Lower Ireton	aquitard	
Devonian	Upper	Wood-bend		Cooking Lake	aquifer	Beaverhill Lake aquifer system
Devonian	Upper	Beaverhill Lake		Mildred	aquifer	Beaverhill Lake aquifer system
Devonian	Upper	Beaverhill Lake		Moberly	aquifer	Beaverhill Lake aquifer system
Devonian	Upper	Beaverhill Lake		Christina	aquitard	Beaverhill Lake aquifer system
Devonian	Upper	Beaverhill Lake		Calumet	aquifer	Beaverhill Lake aquifer system
Devonian	Upper	Beaverhill Lake		Firebag	aquitard	Beaverhill Lake aquifer system
Devonian	Upper	Beaverhill Lake		Slave Point	aquifer	Beaverhill Lake aquifer system
Devonian	Upper	Beaverhill Lake		Fort Vermilion	aquiclude	Beaverhill Lake aquifer system
Devonian	Middle	Elk Point	Upper	Watt Mountain	aquitard	Prairie-Watt Mountain aquiclude system
Devonian	Middle	Elk Point	Upper	Prairie	aquiclude	Prairie-Watt Mountain aquiclude system
Devonian	Middle	Elk Point	Upper	Winipegosis (Keg River)	aquifer	
Devonian	Middle	Elk Point	Lower	Granite Wash / Contact Rapids	aquifer - aquitard	Lower Elk Point aquitard-aquiclude system
Devonian	Lower	Elk Point	Lower	Granite Wash / Cold Lake	aquiclude	Lower Elk Point aquitard-aquiclude system
Devonian	Lower	Elk Point	Lower	Granite Wash / Ernestina Lake	aquifer - aquitard	Lower Elk Point aquitard-aquiclude system
Devonian	Lower	Elk Point	Lower	Granite Wash / Upper Lotsberg	aquiclude	Lower Elk Point aquitard-aquiclude system
Devonian	Lower	Elk Point	Lower	Granite Wash / Lower Lotsberg	aquiclude	Lower Elk Point aquitard-aquiclude system
Devonian	Lower	Elk Point	Lower	Granite Wash / Basal Red Beds	aquifer - aquitard	Lower Elk Point aquitard-aquiclude system
Precambrian					aquiclude	

Table 2. Hydrostratigraphic delineation and nomenclature.



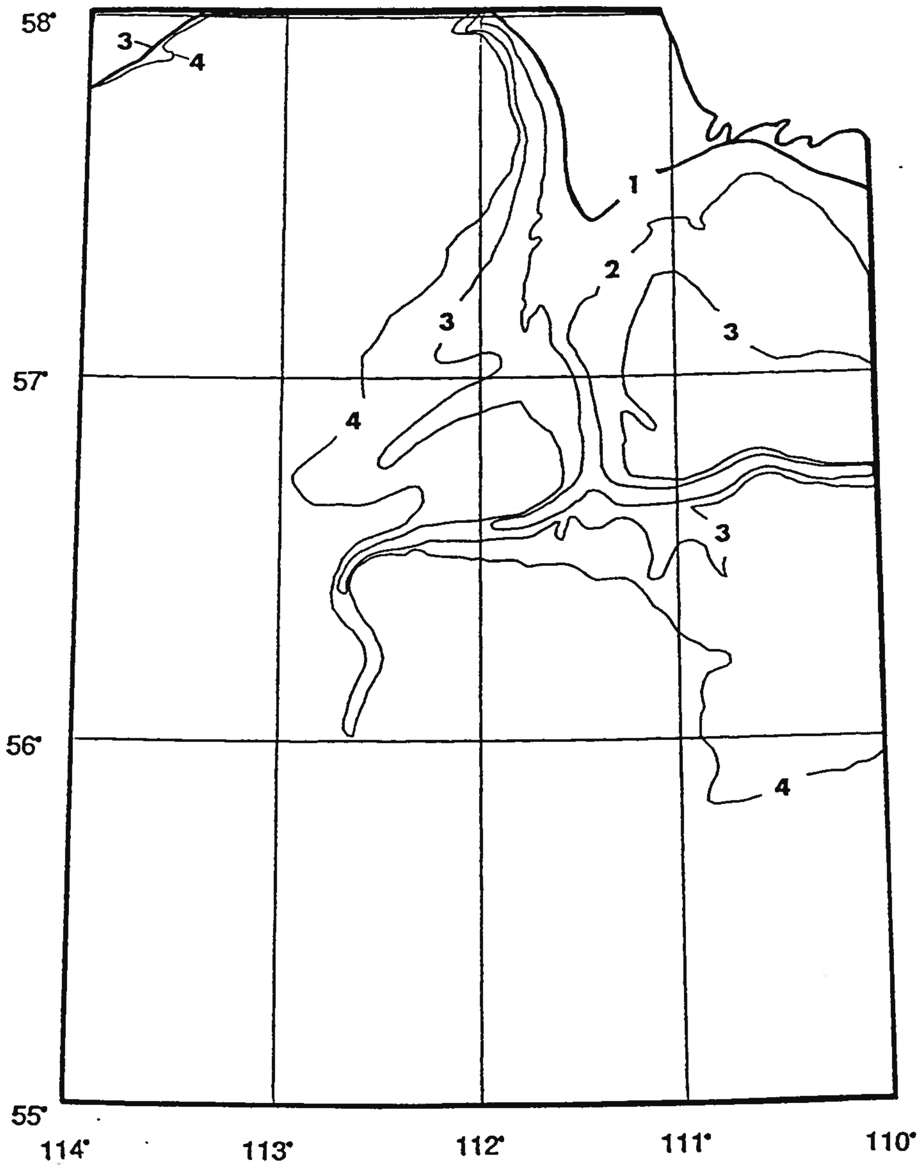
LEGEND:

1. - Northern edge of Lower Lotsberg Salt
2. - Northern edge of Upper Lotsberg Salt
3. - Edge of Cold Lake Salt

Figure 30: Depositional and dissolution boundaries of Lower Elk Point Subgroup evaporitic beds.

two aquifers are separated only by the thin Watt Mountain aquitard. Of particular importance is the progressive subcrop of Paleozoic strata at the sub-Cretaceous unconformity (Figure 21), which is in turn overlain by the McMurray Formation. The sub-Cretaceous unconformity allows for hydraulic continuity across a wide range of strata. Also, it may be associated with regoliths or karst development, both of which may enhance flow along the unconformity and short-circuit flow systems. In addition, the hydrogeological regime in northeast Alberta is probably controlled by the progressive outcrop of various units toward the eastern edge of the basin, and by the outcrop of Cretaceous and Devonian units along the Athabasca River valley system which cuts down through the sediments (Figure 31). Based on the preliminary delineation and on the identified contacts between individual units, the following hydrostratigraphic systems are defined in ascending order for northeast Alberta (Figure 29 and Table 2):

- Lower Elk Point aquitard-aquiclude system;
- Winnipegosis aquifer;
- Prairie-Watt Mountain aquiclude;
- Beaverhill Lake aquifer system;
- Ireton aquitard;
- Grosmont-Wabamun aquifer system;
- McMurray-Wabiscaw aquifer-aquitard system;
- Clearwater aquifer-aquitard system;
- Grand Rapids aquifer-aquitard system;
- Colorado aquitard system.



LEGEND:

1. - McMurray Formation
2. - Clearwater Formation
3. - Mannville Group
4. - Colorado Group

Figure 31: Outcroup boundaries of Phanerozoic strata in northeast Alberta.

This preliminary hydrostratigraphic framework and grouping into systems, based only on the geometry and lithology of the strata, has to be confirmed and characterized by a proper hydrogeological analysis of rock and fluid properties (porosity, permeability, formation pressure, and chemistry of formation waters) using core, drillstem test and chemical analysis data.

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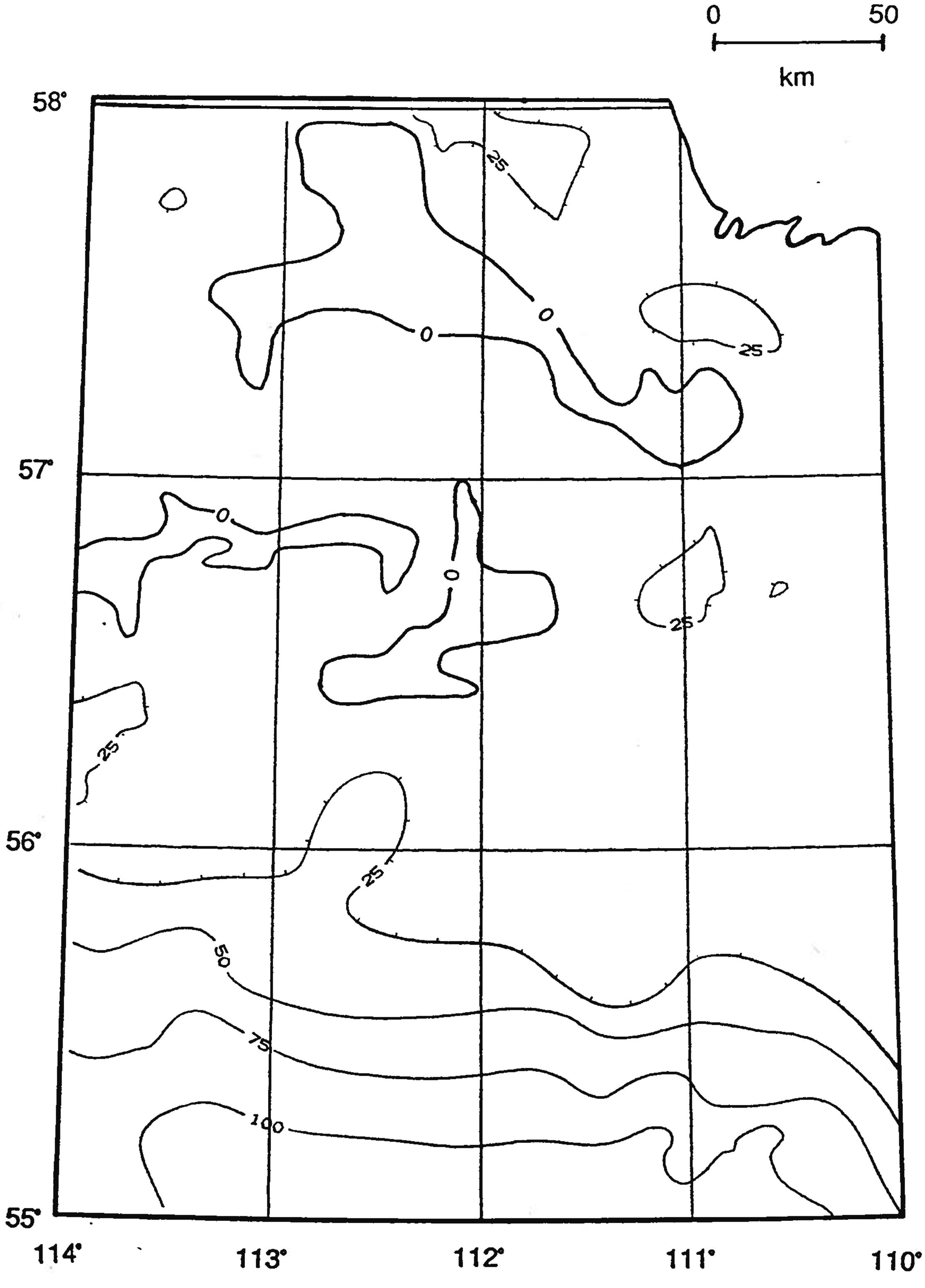
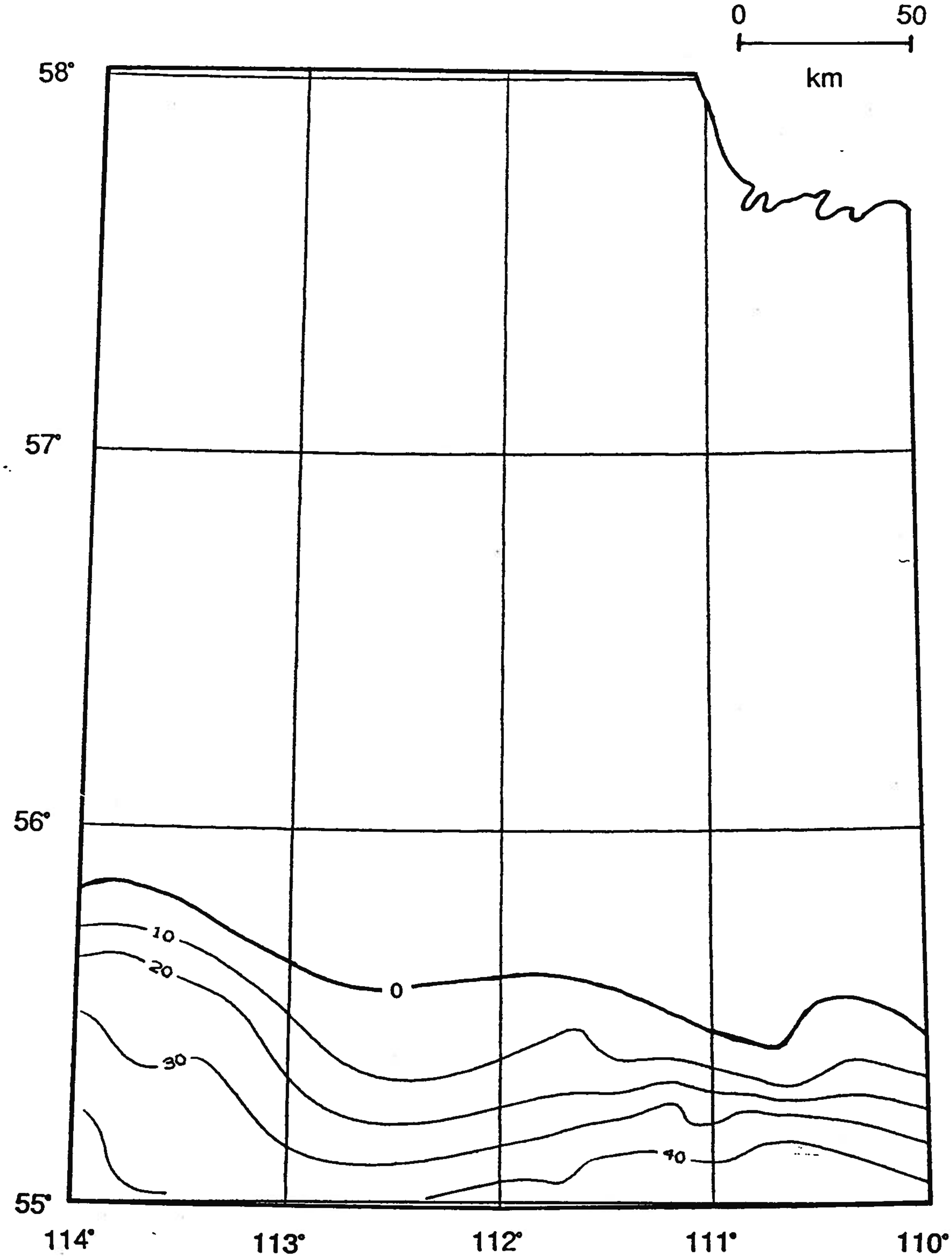
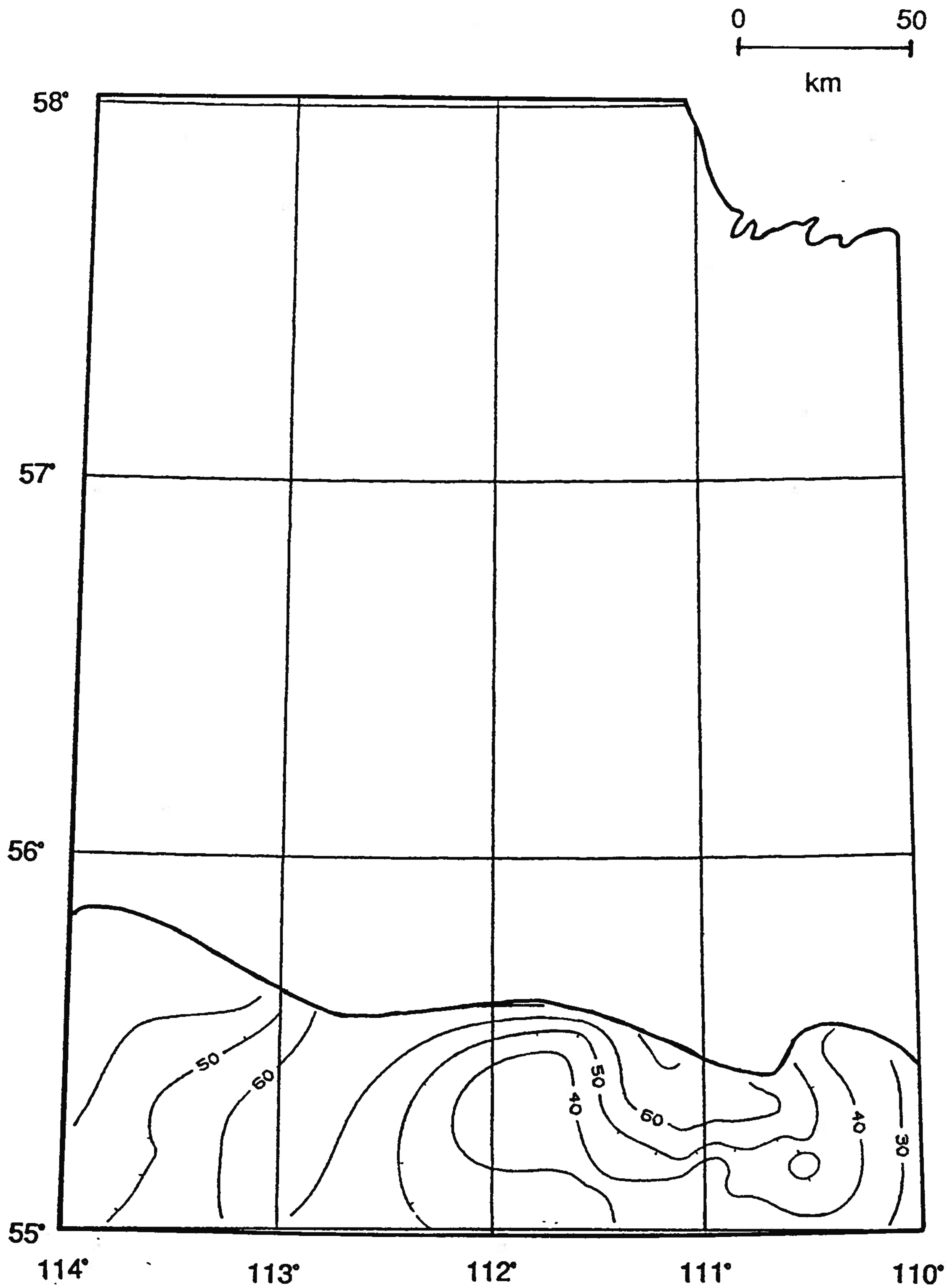
APPENDIX A - ISOPACH MAPS



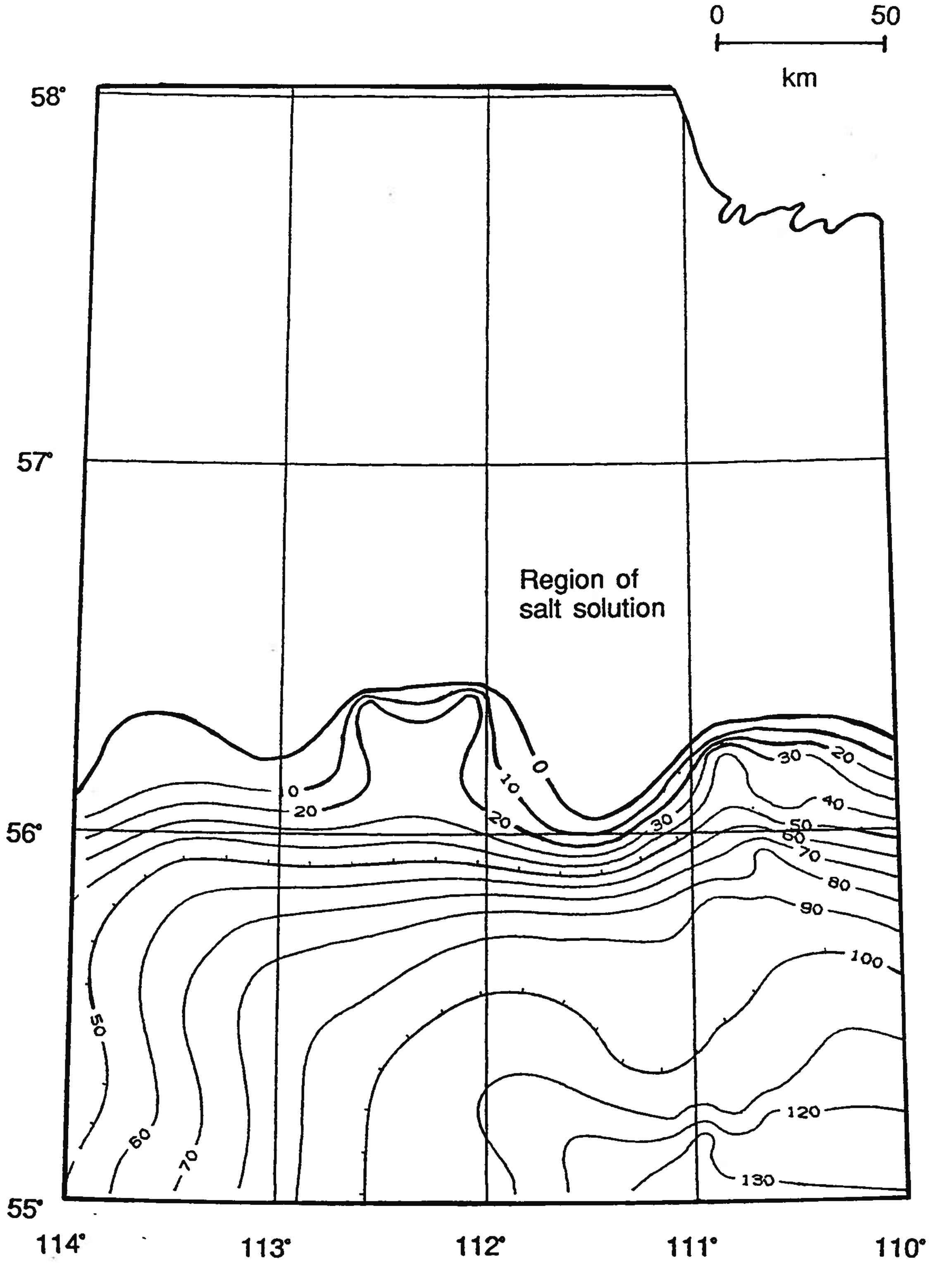
A - 1. Basal Red Beds isopach map (including the Lower Lotsberg Salt).



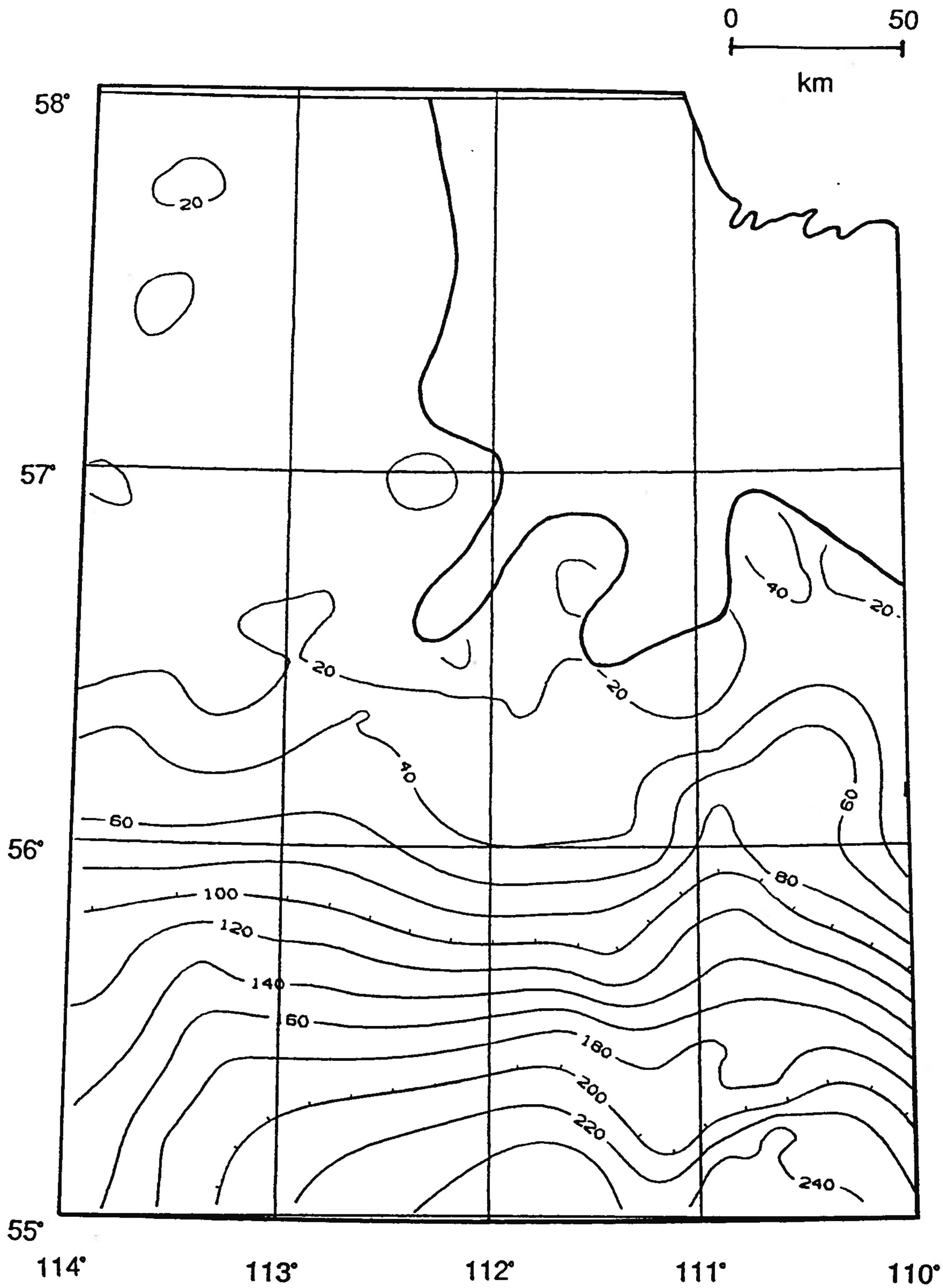
A - 2. Lower Lotsberg Salt isopach map.



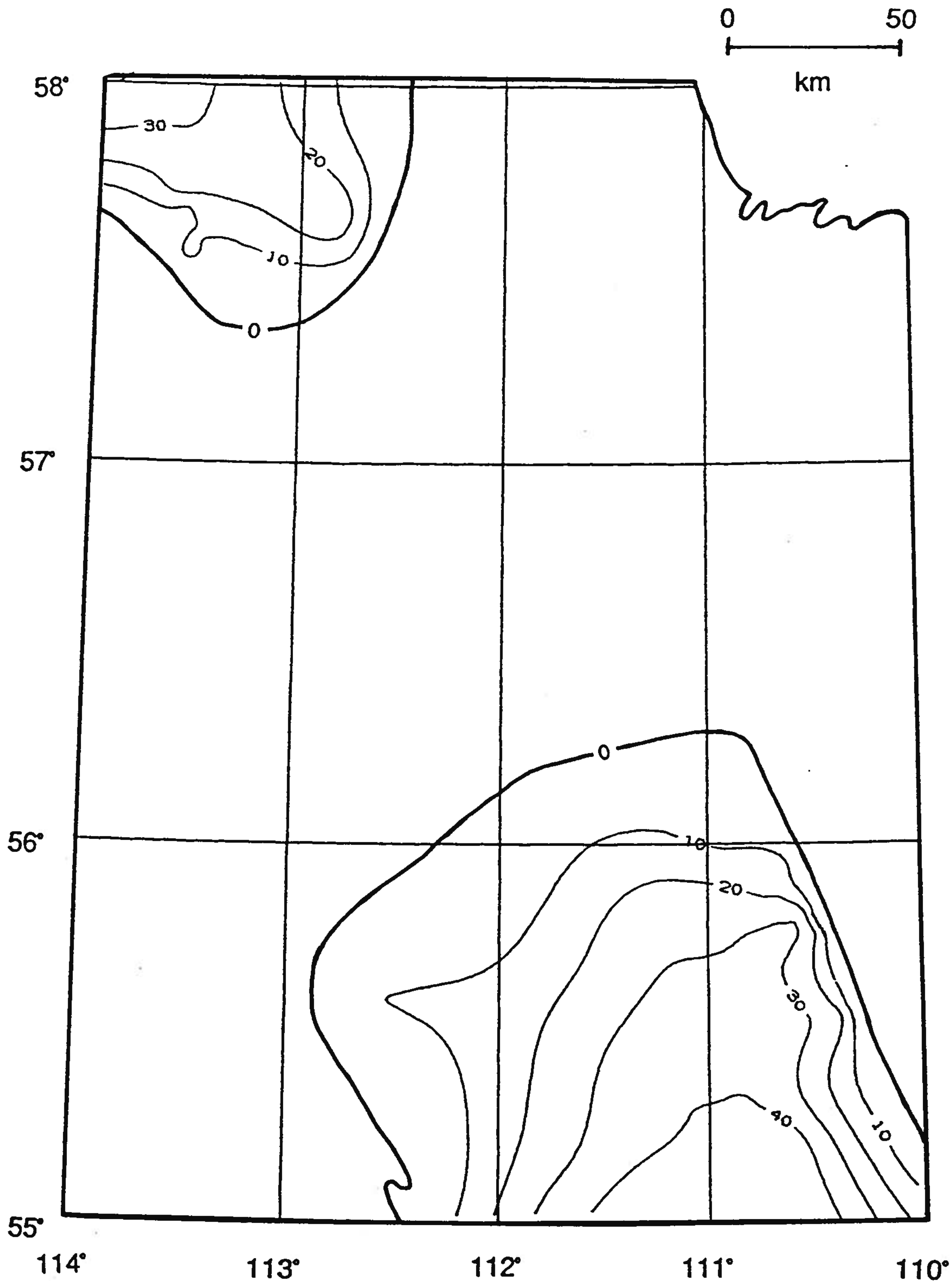
A - 3. Unnamed Red Beds isopach map (above the Lower Lotsberg Salt).



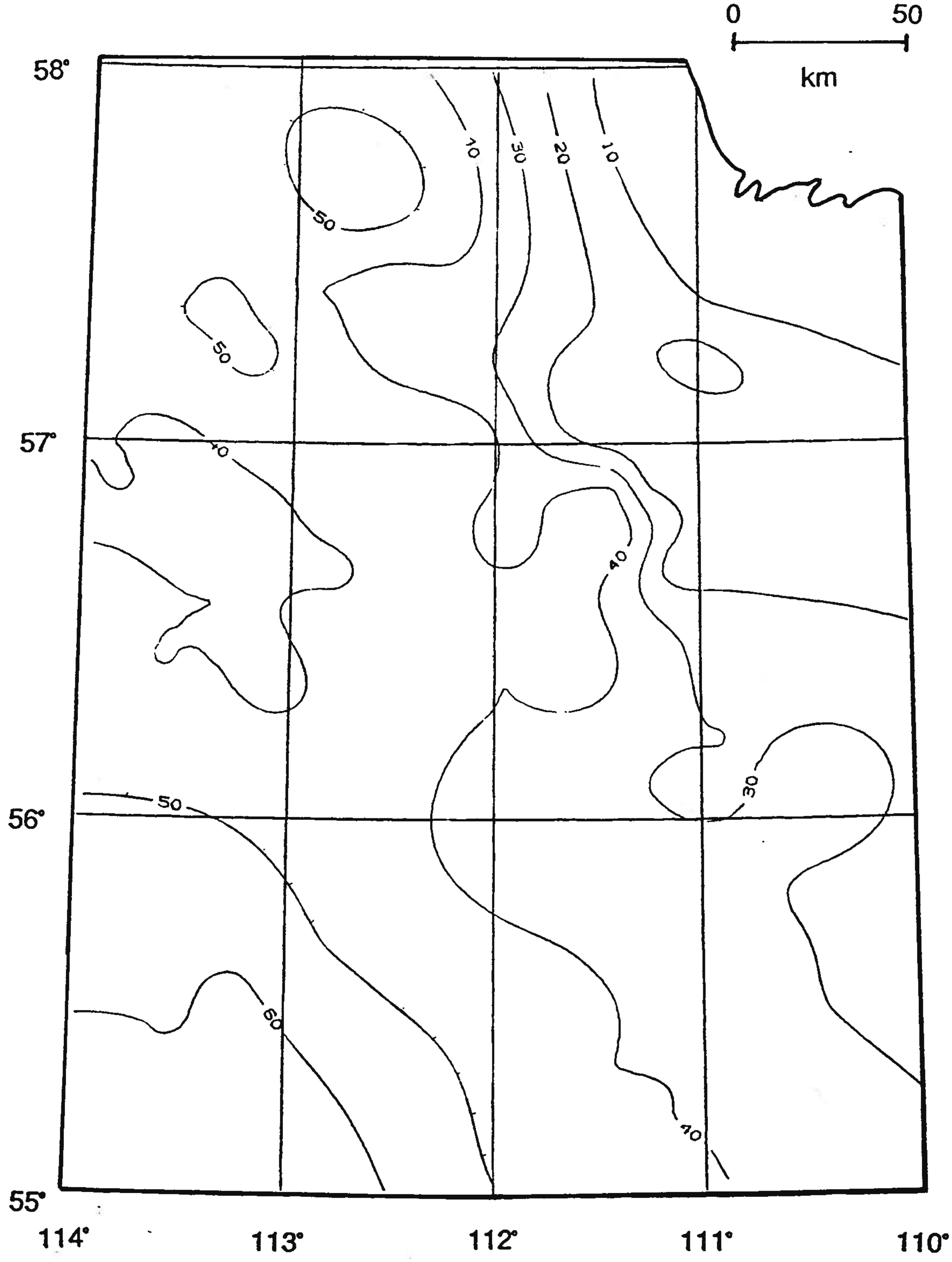
A - 4. Upper Lotsberg Salt isopach map.



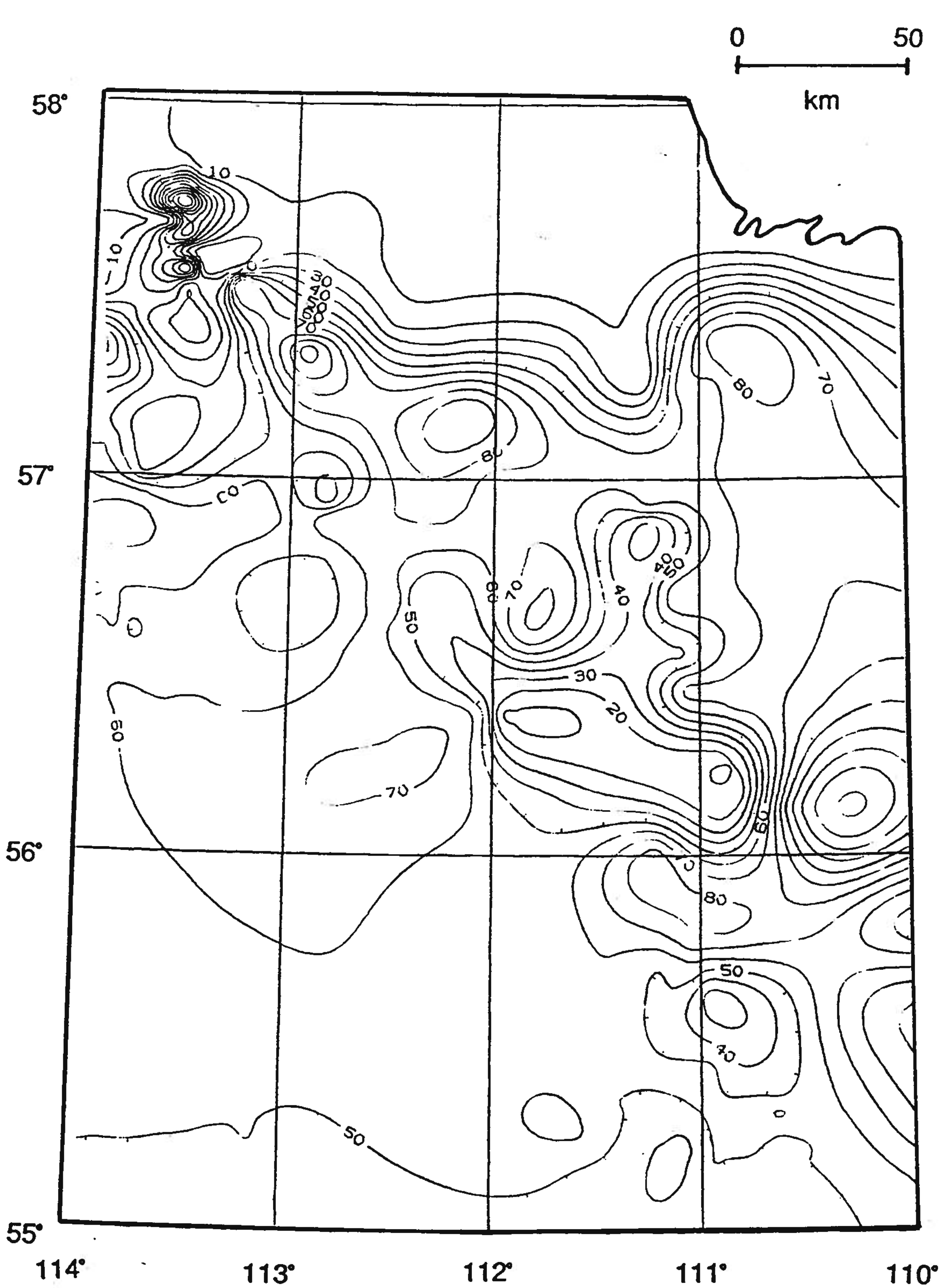
A - 5. Top of Ernestina Lake Formation to Precambrian isopach map.



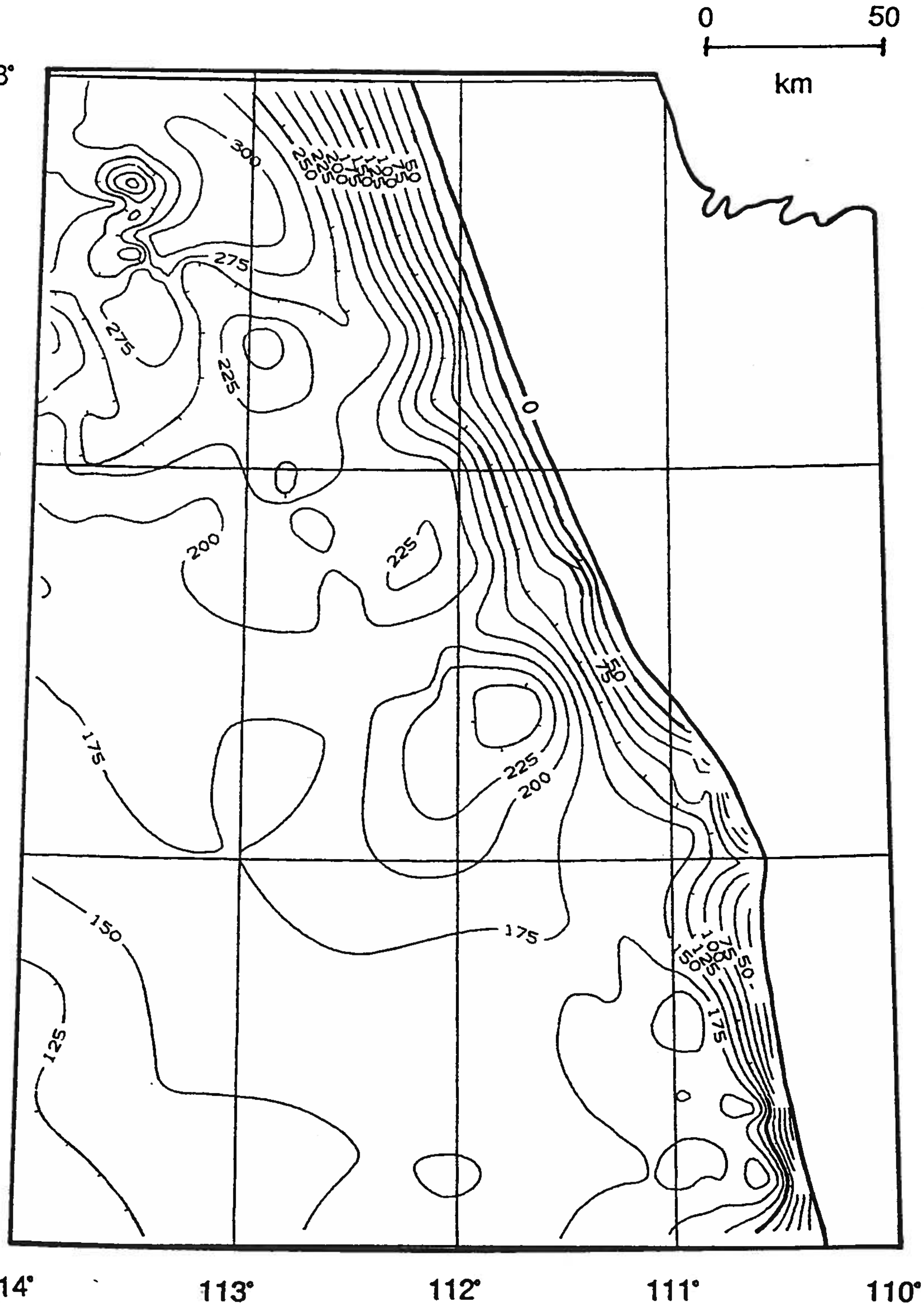
A - 6. Cold Lake Salt isopach map.



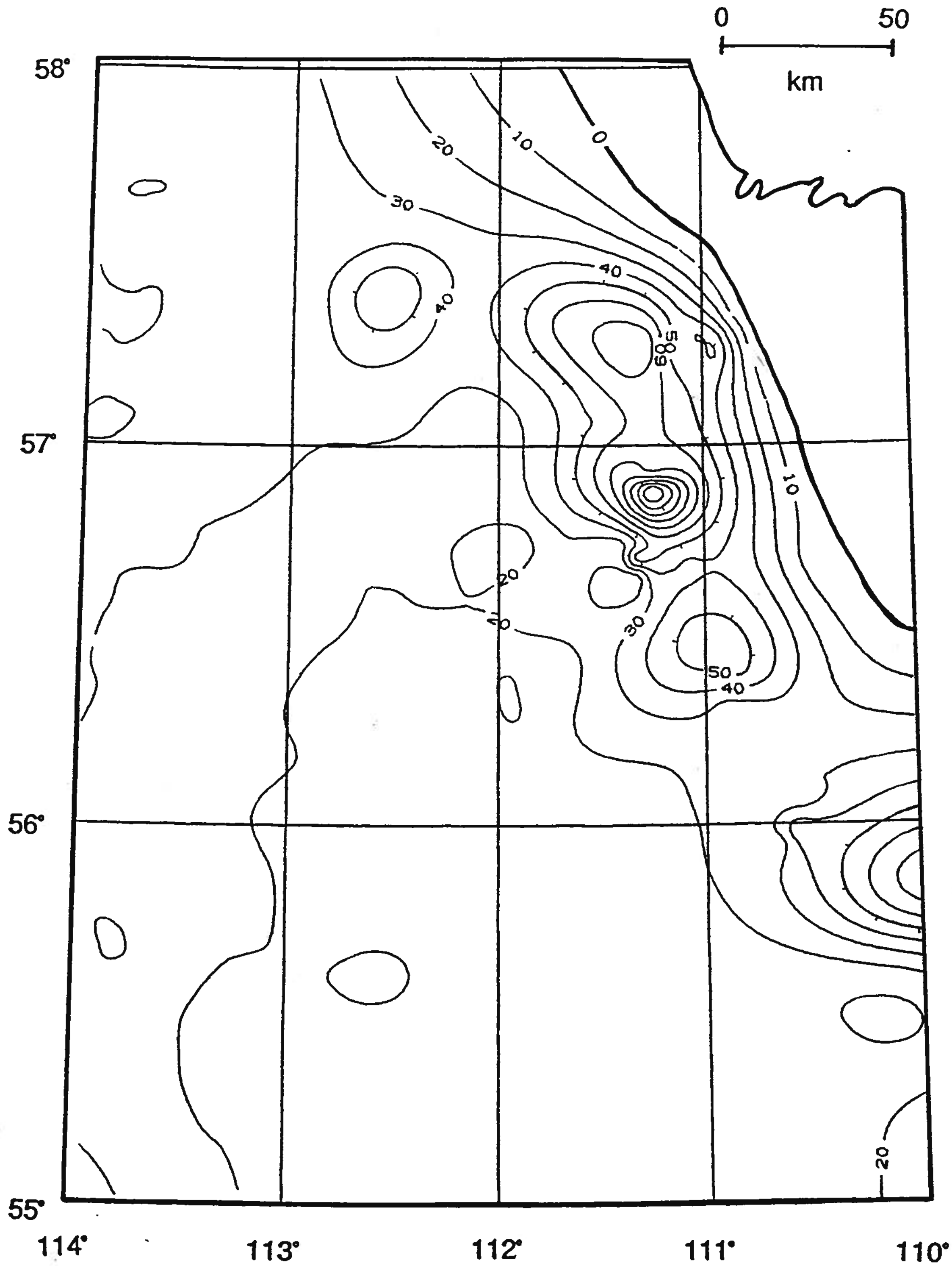
A - 7. Contact Rapids Formation isopach map.



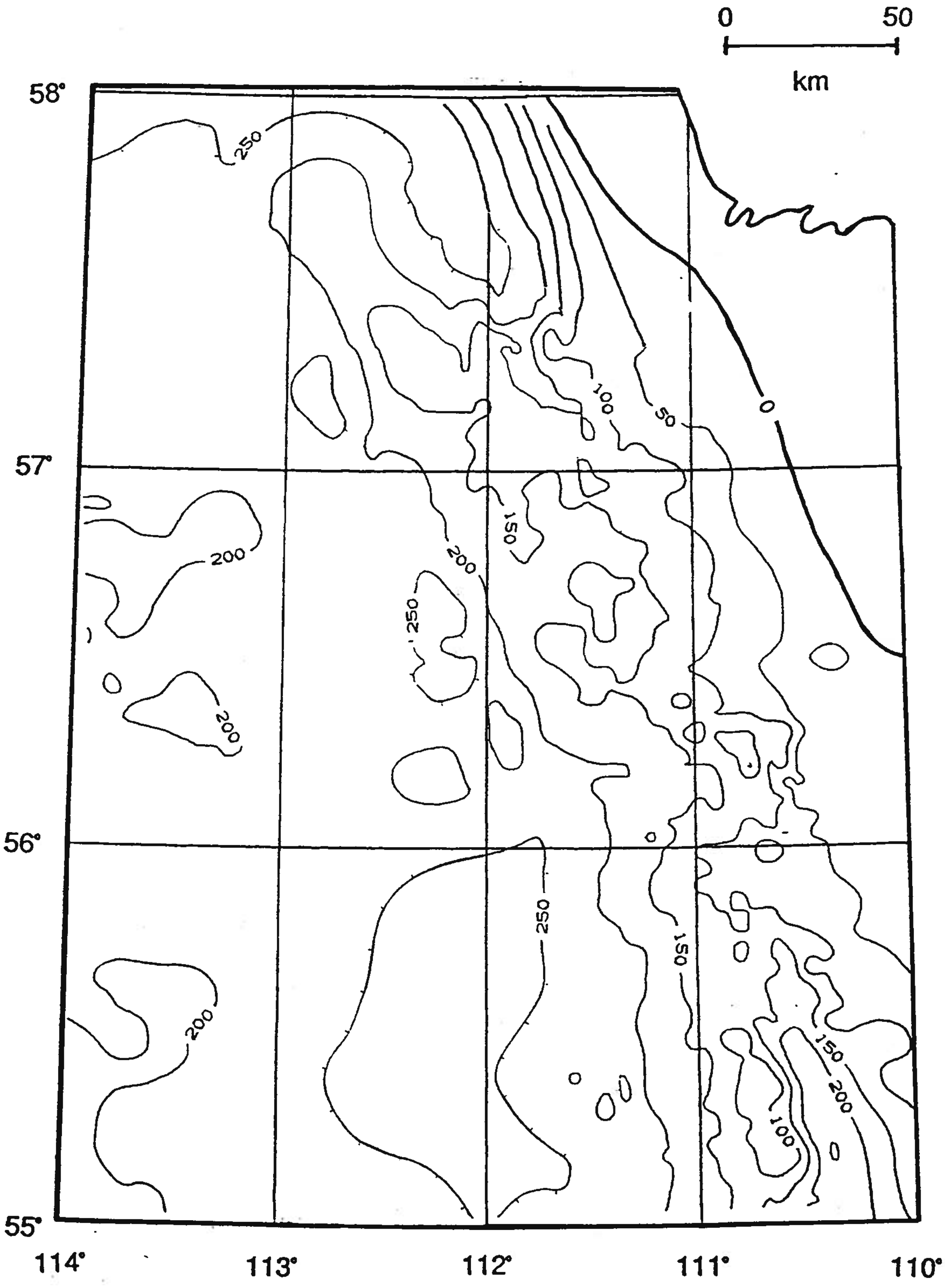
A - 8. Winnipegosis-Keg River interval isopach map.



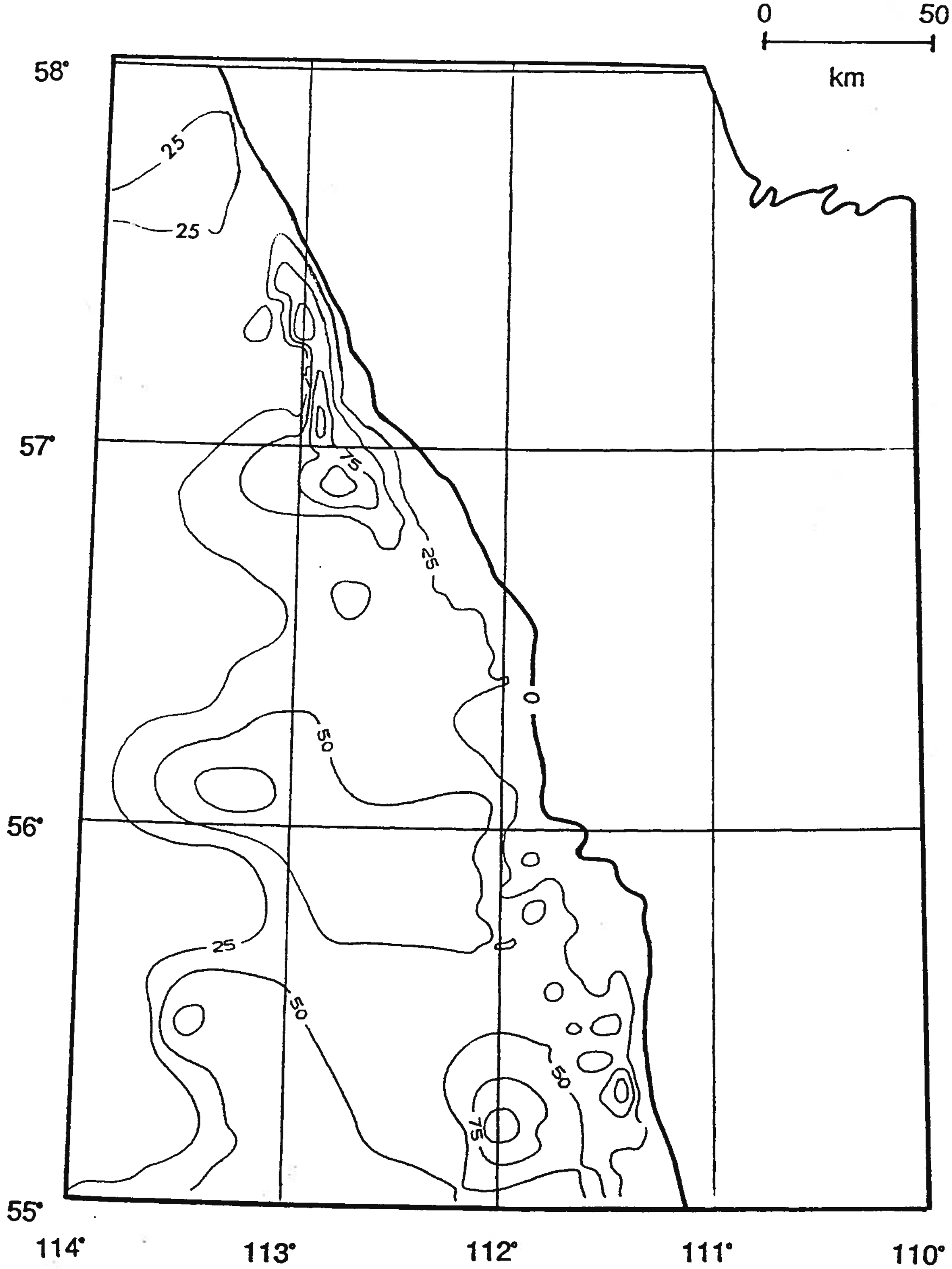
A - 9. Prairie Formation isopach map.



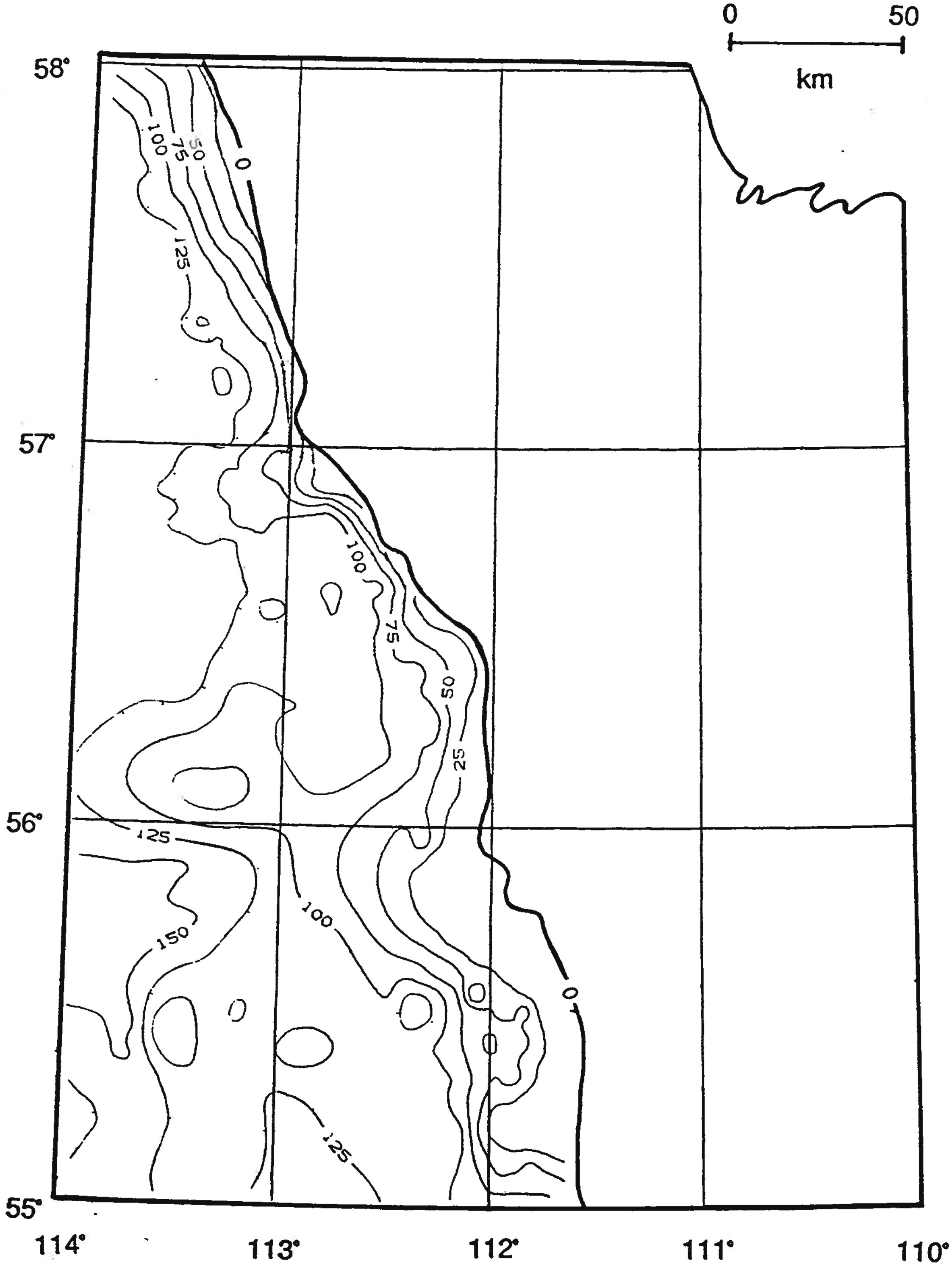
A - 10. Watt Mountain Formation isopach map.



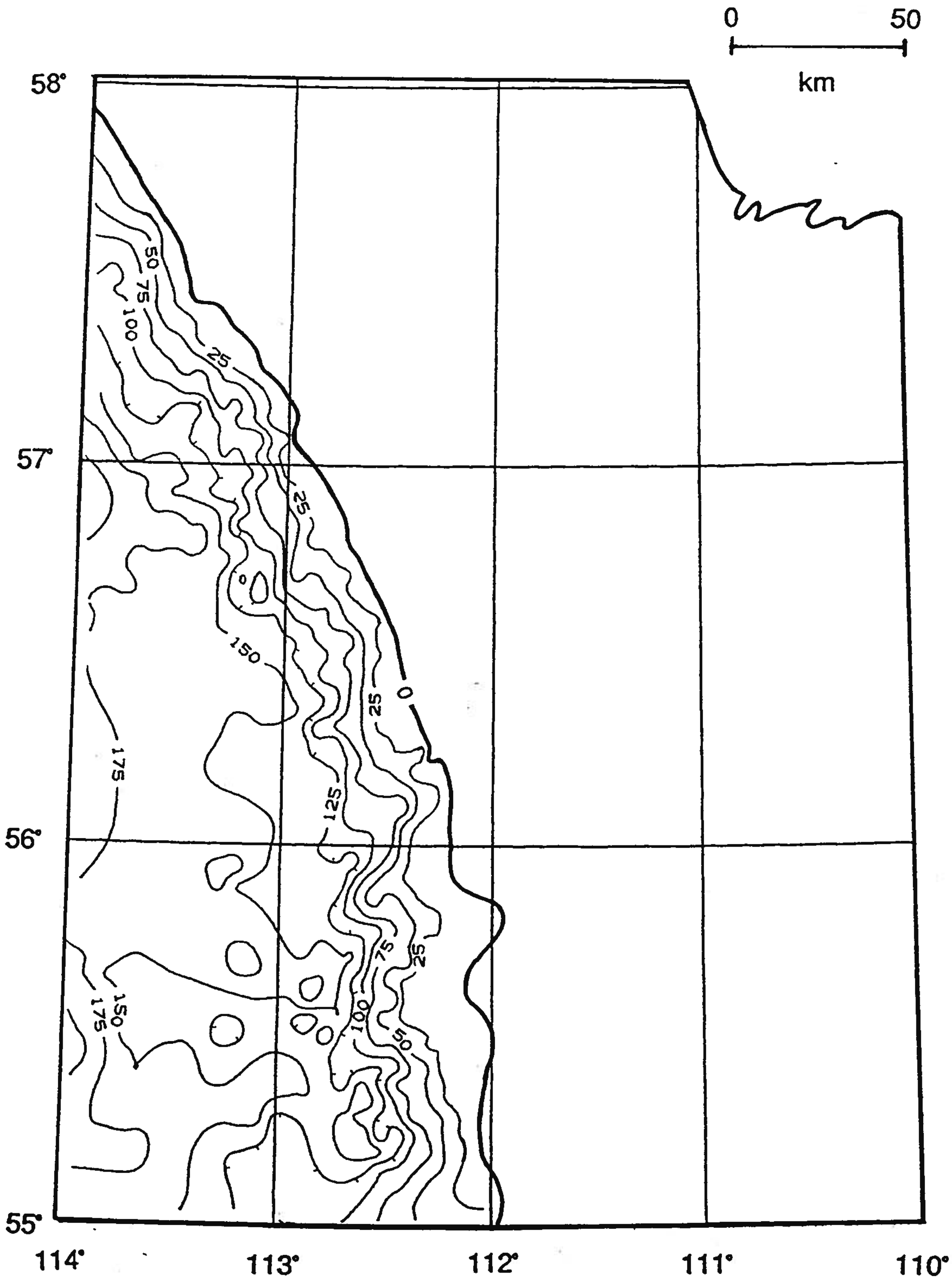
A - 11. Beaverhill Lake Group isopach map.



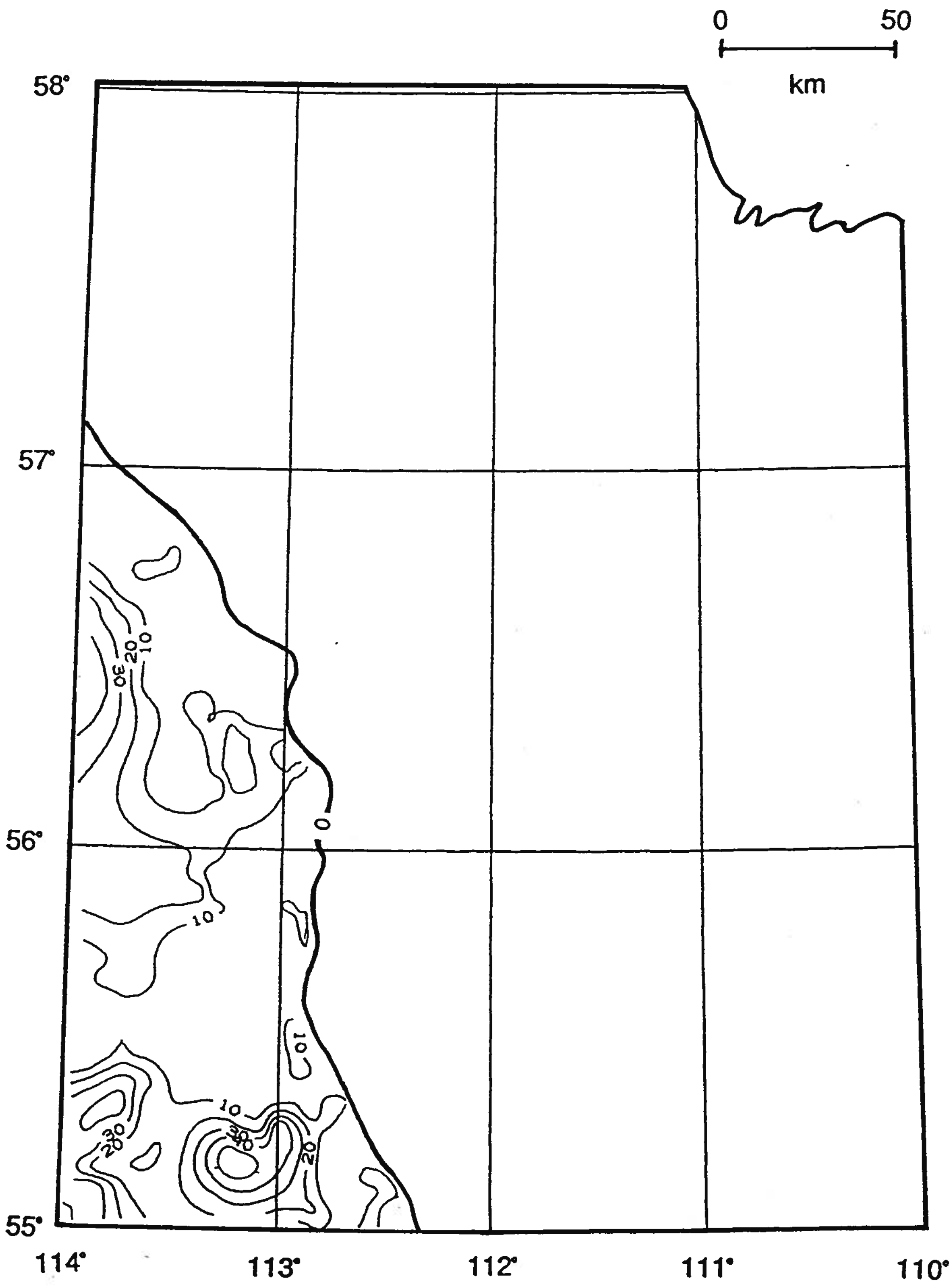
A - 12. Cooking Lake Formation isopach map.



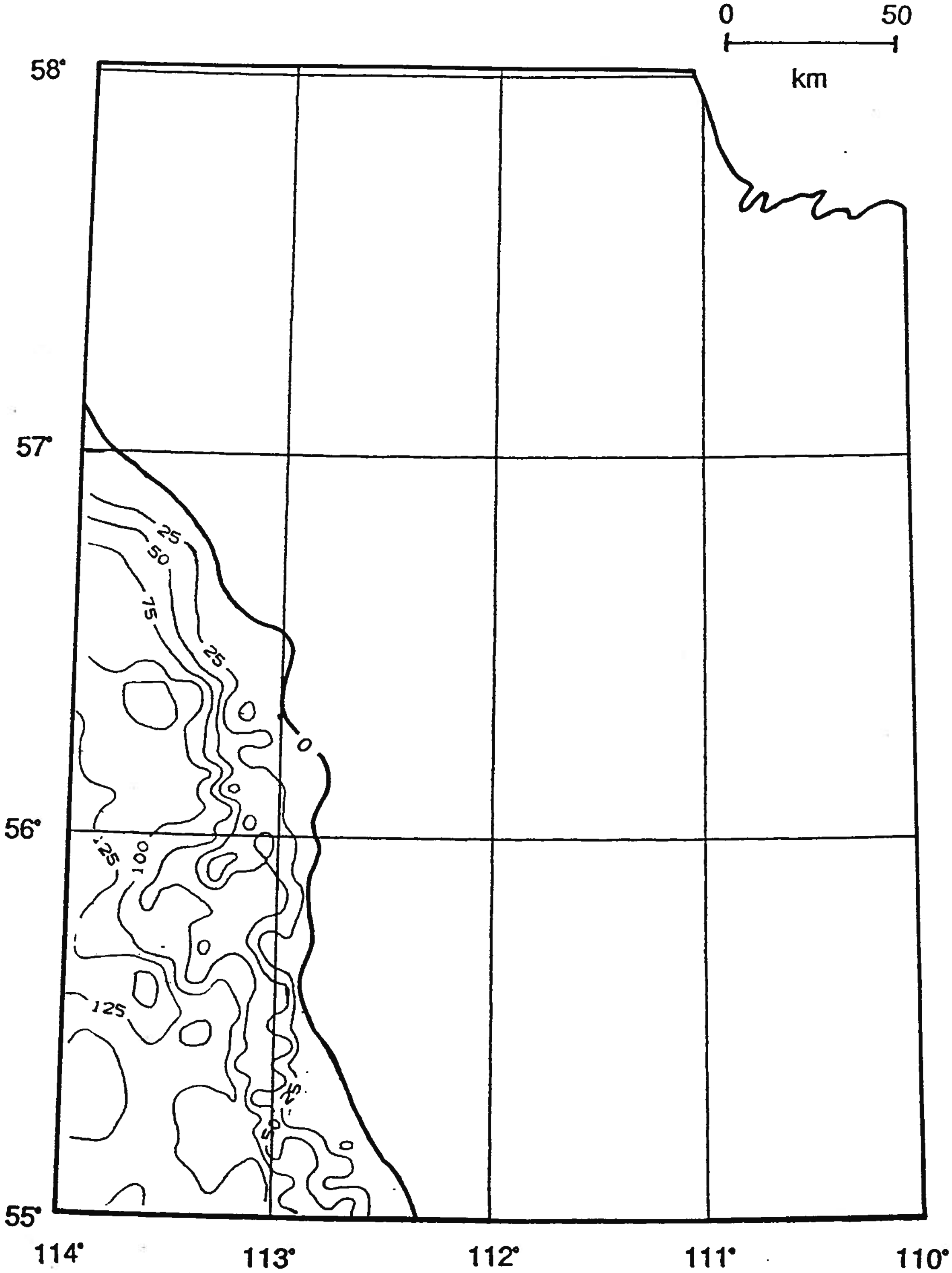
A - 13. Lower Ireton Formation isopach map.



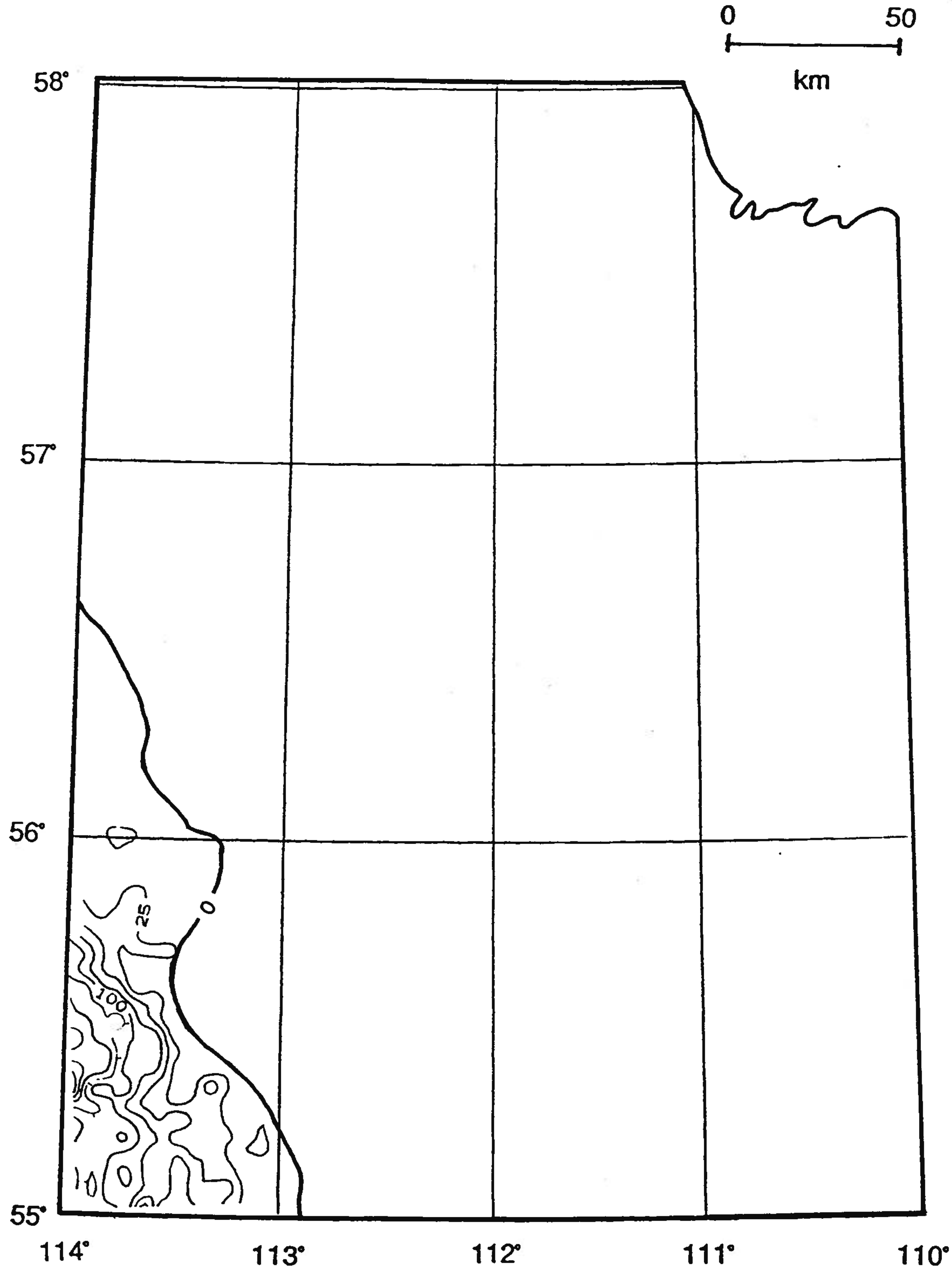
A - 14. Grosmont Formation isopach map.



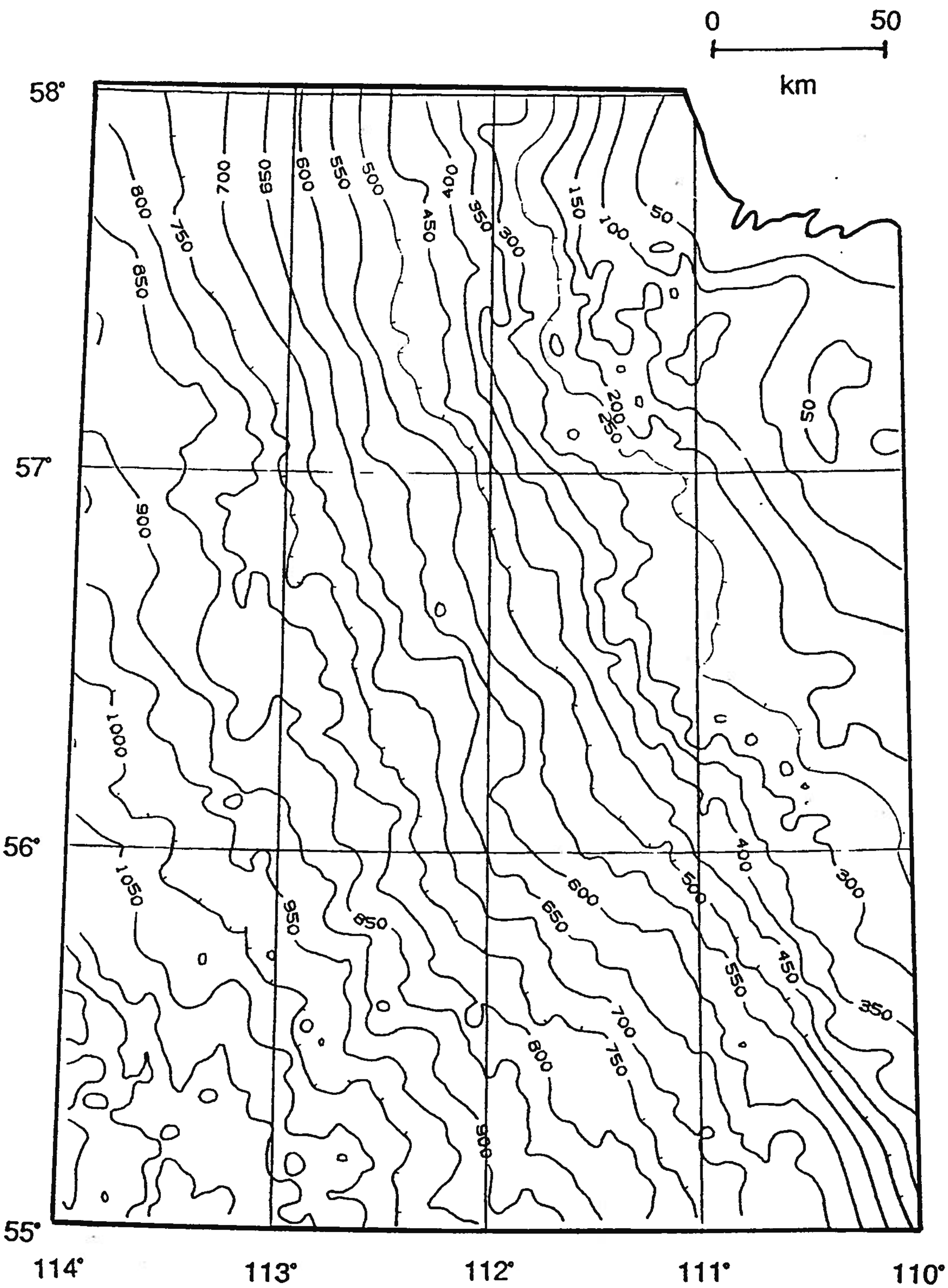
A - 15. Upper Ireton Formation isopach map.



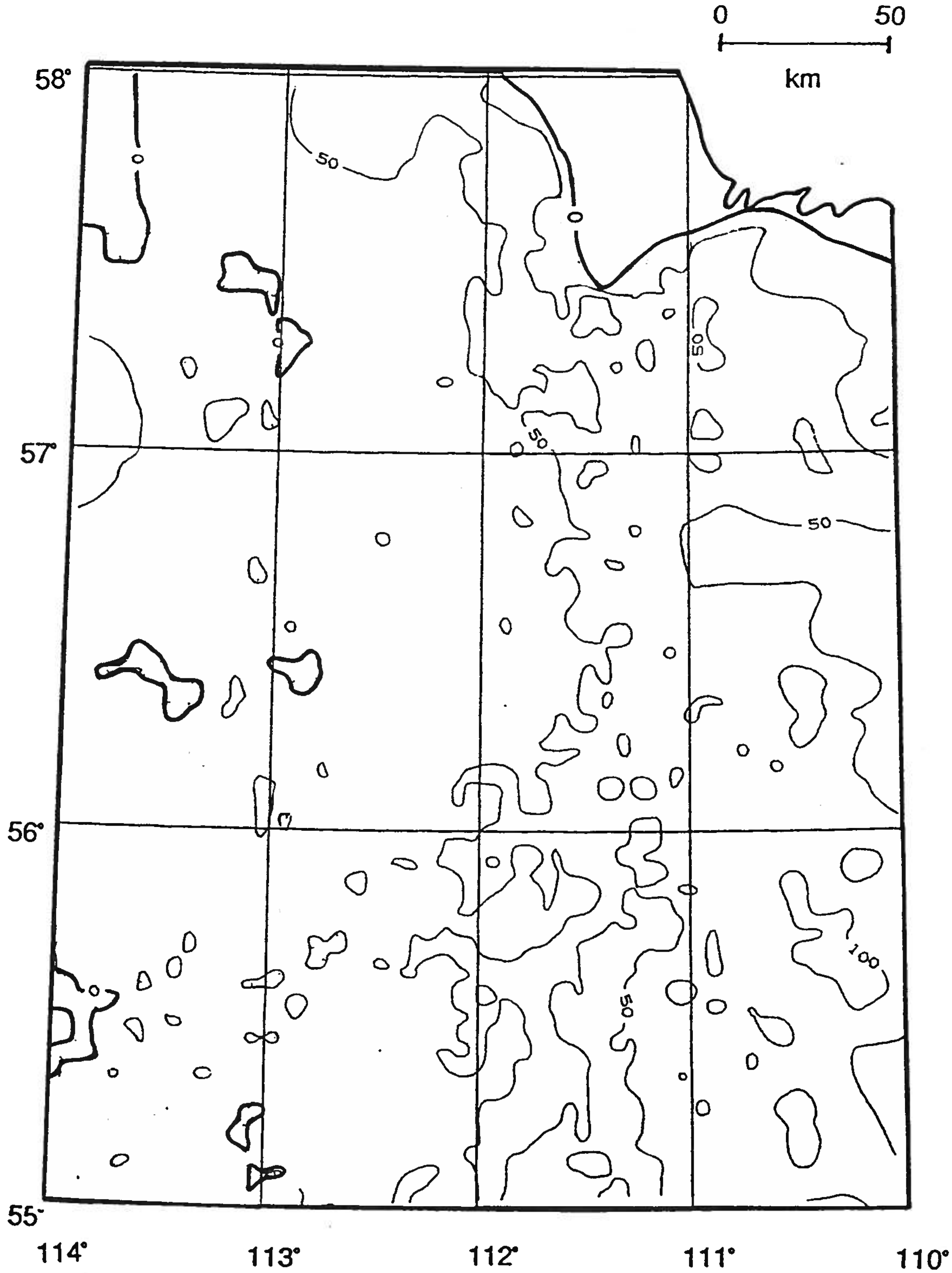
A - 16. Winterburn Group isopach map.



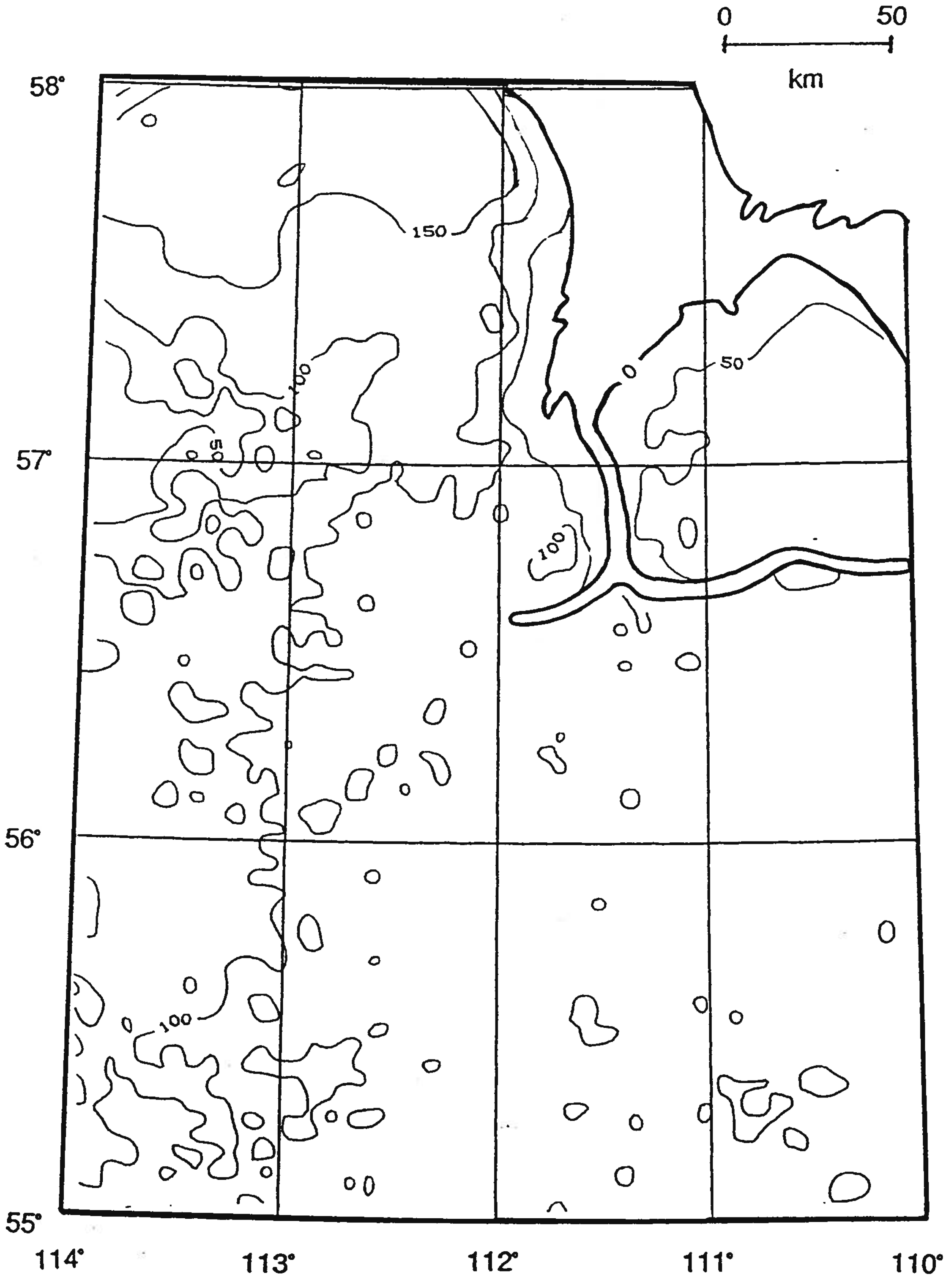
A - 17. Wabamum Group isopach map.



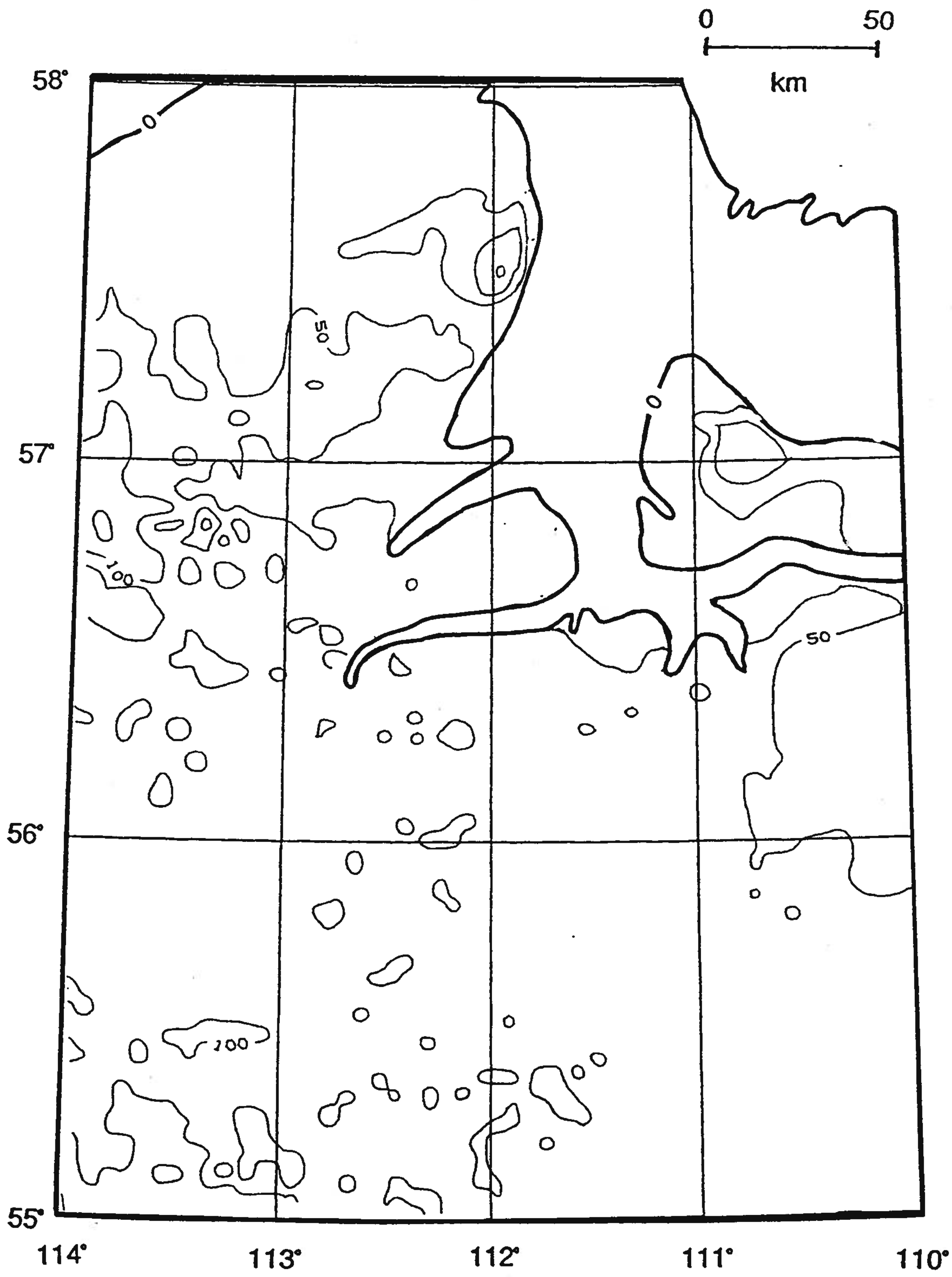
A - 18. Paleozoic isopach map.



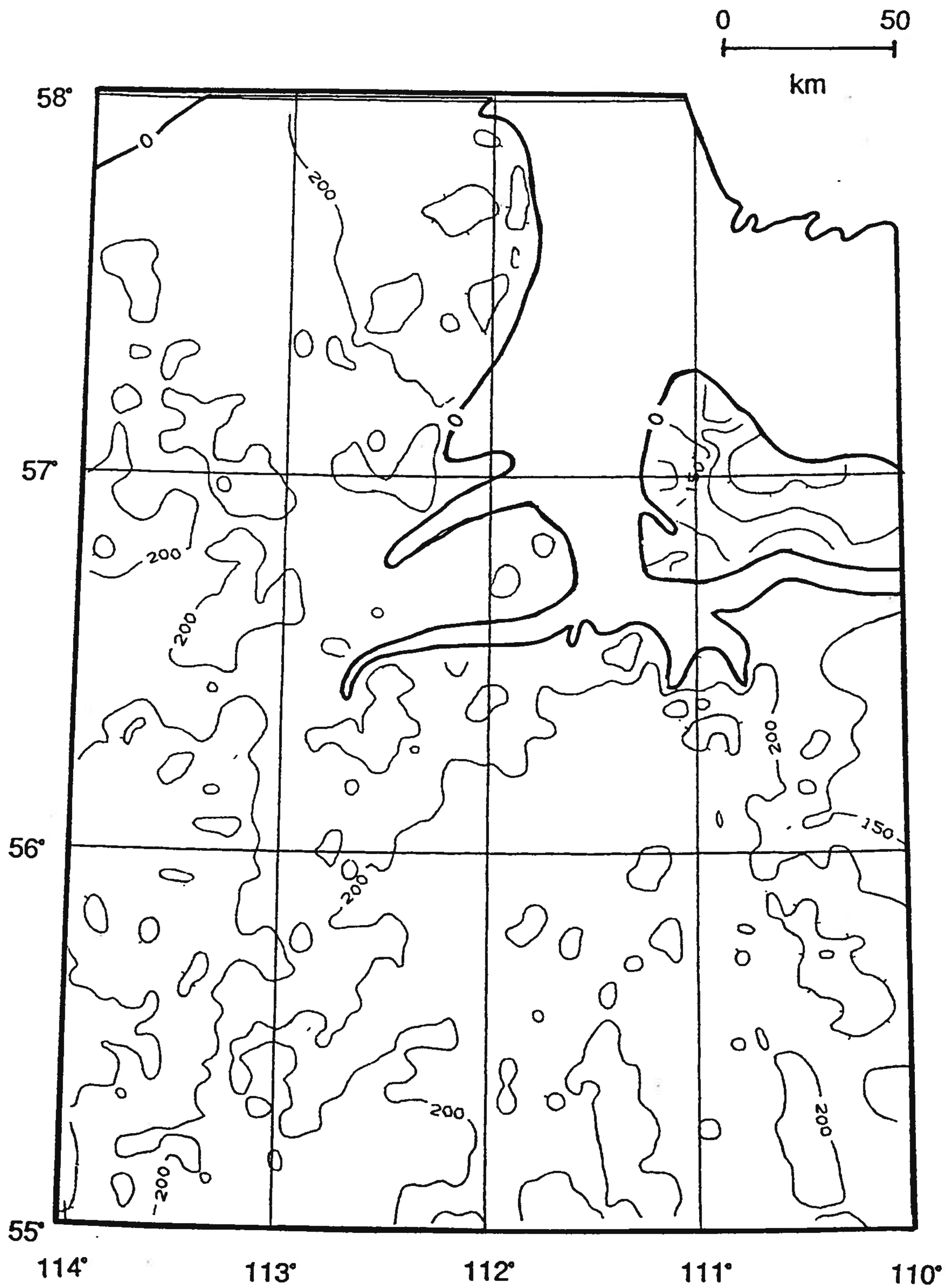
A - 19. McMurray Formation isopach map.



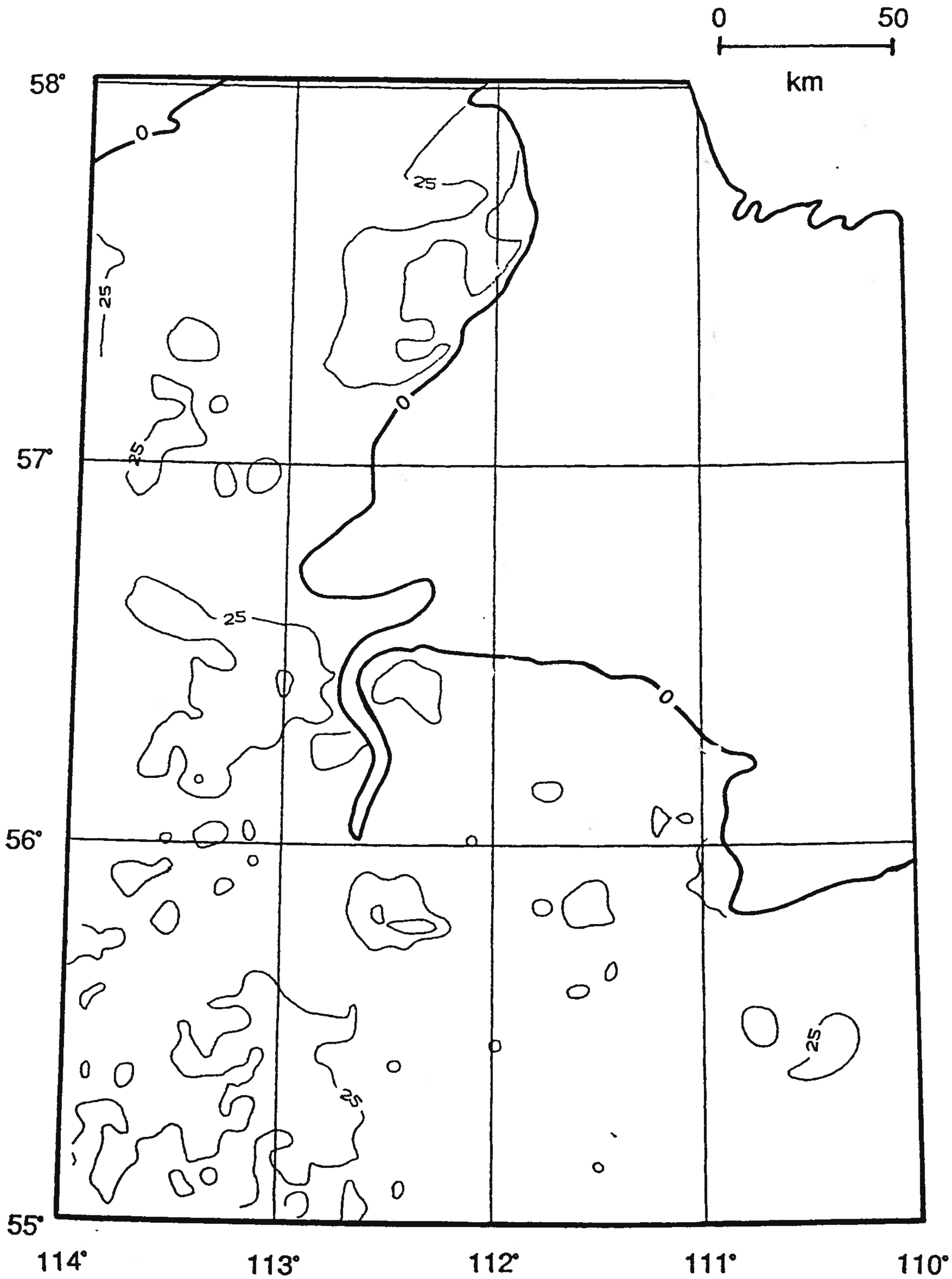
A - 20. Clearwater Formation isopach map.



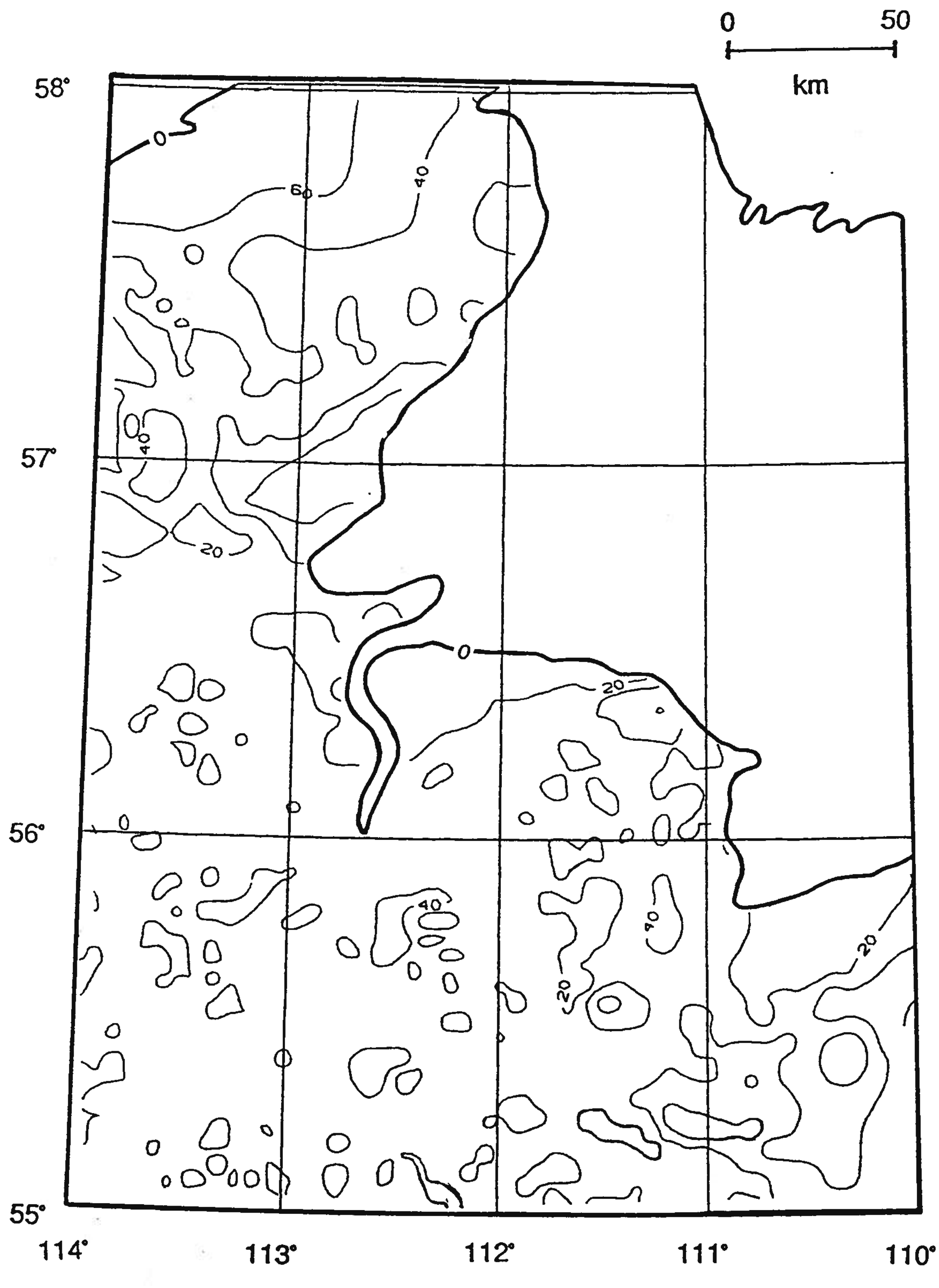
A - 21. Grand Rapids Formation isopach map.



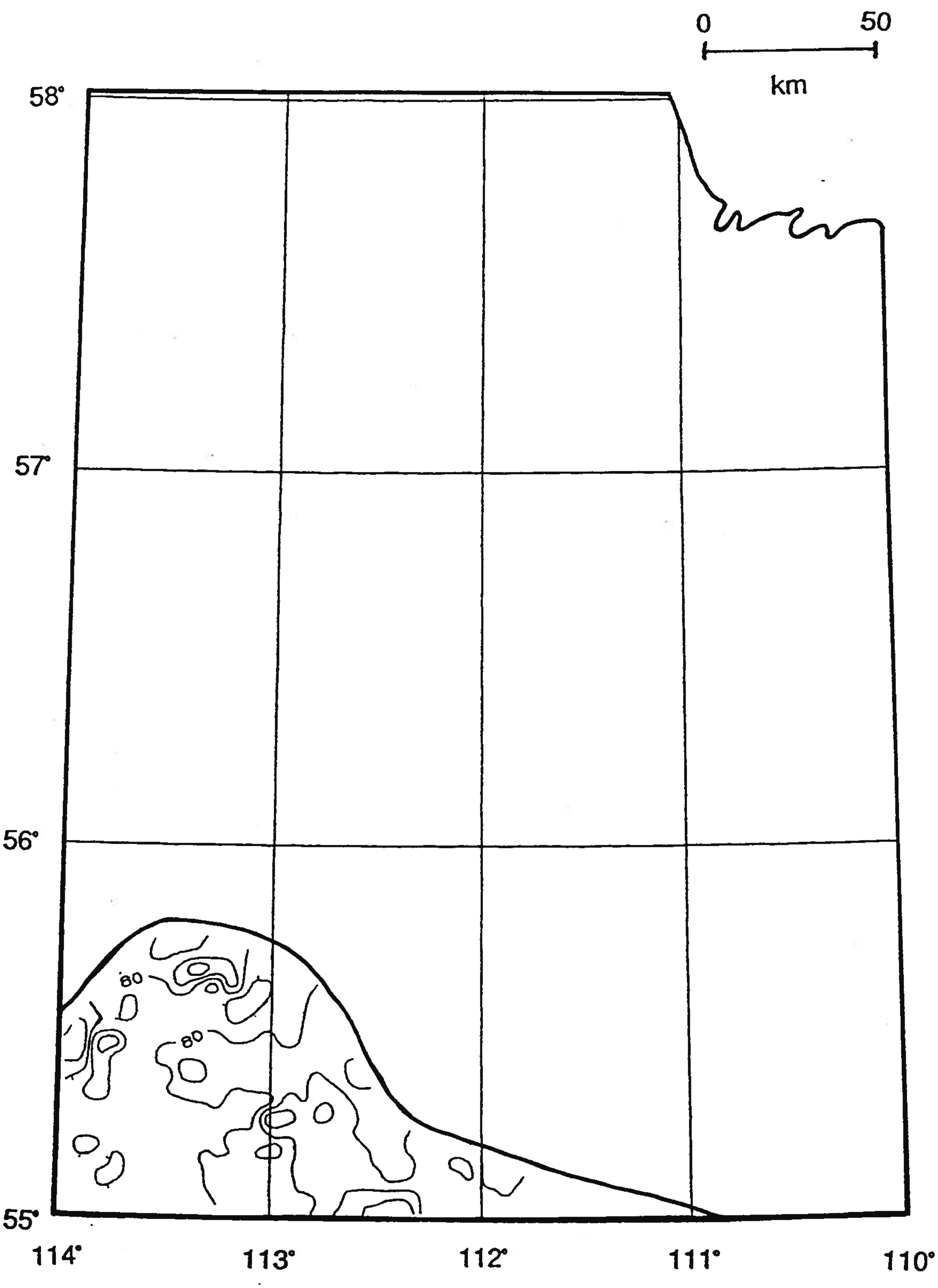
A - 22. Mannville Group isopach map.



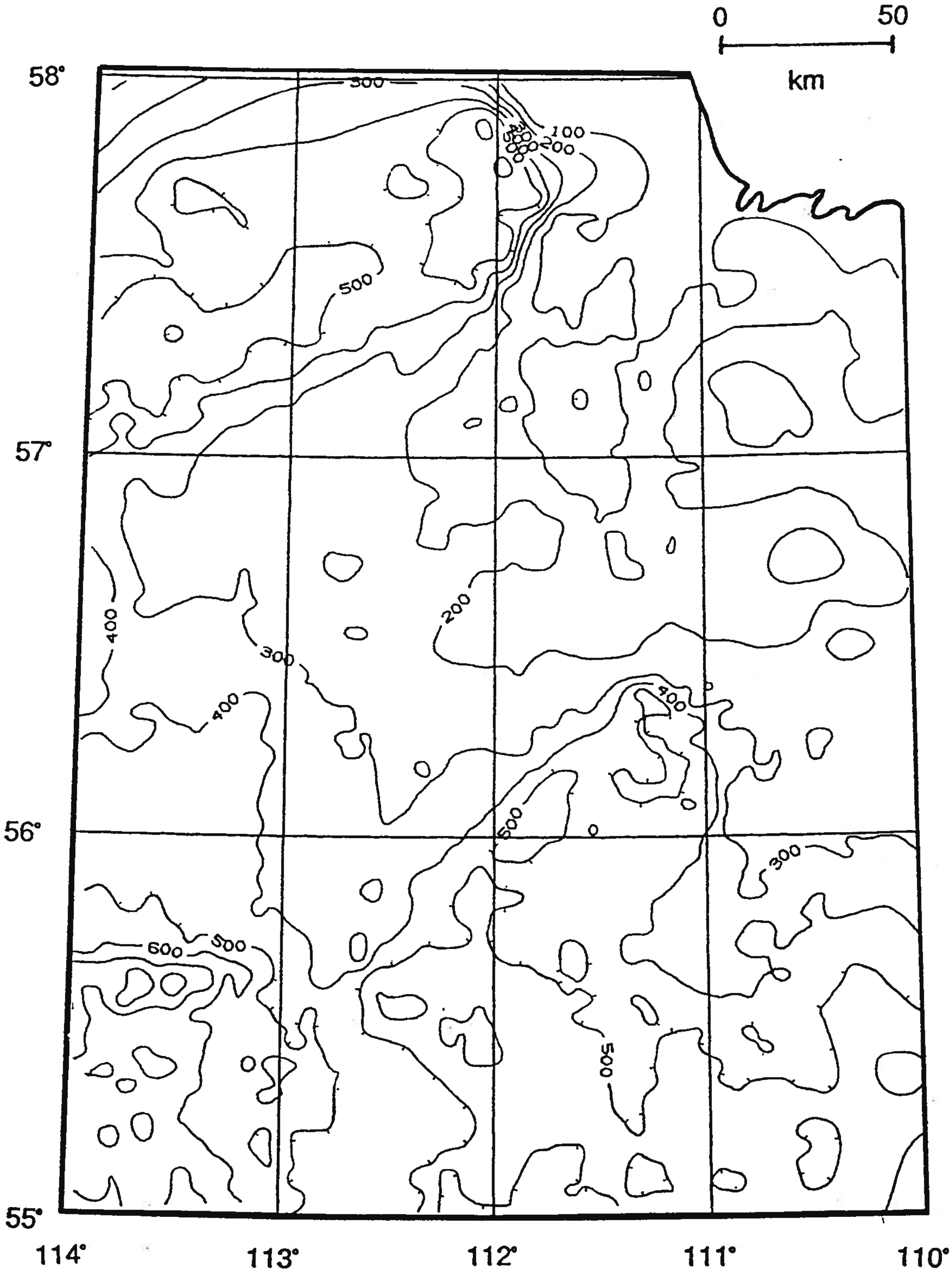
A - 23. Viking Formation isopach map.



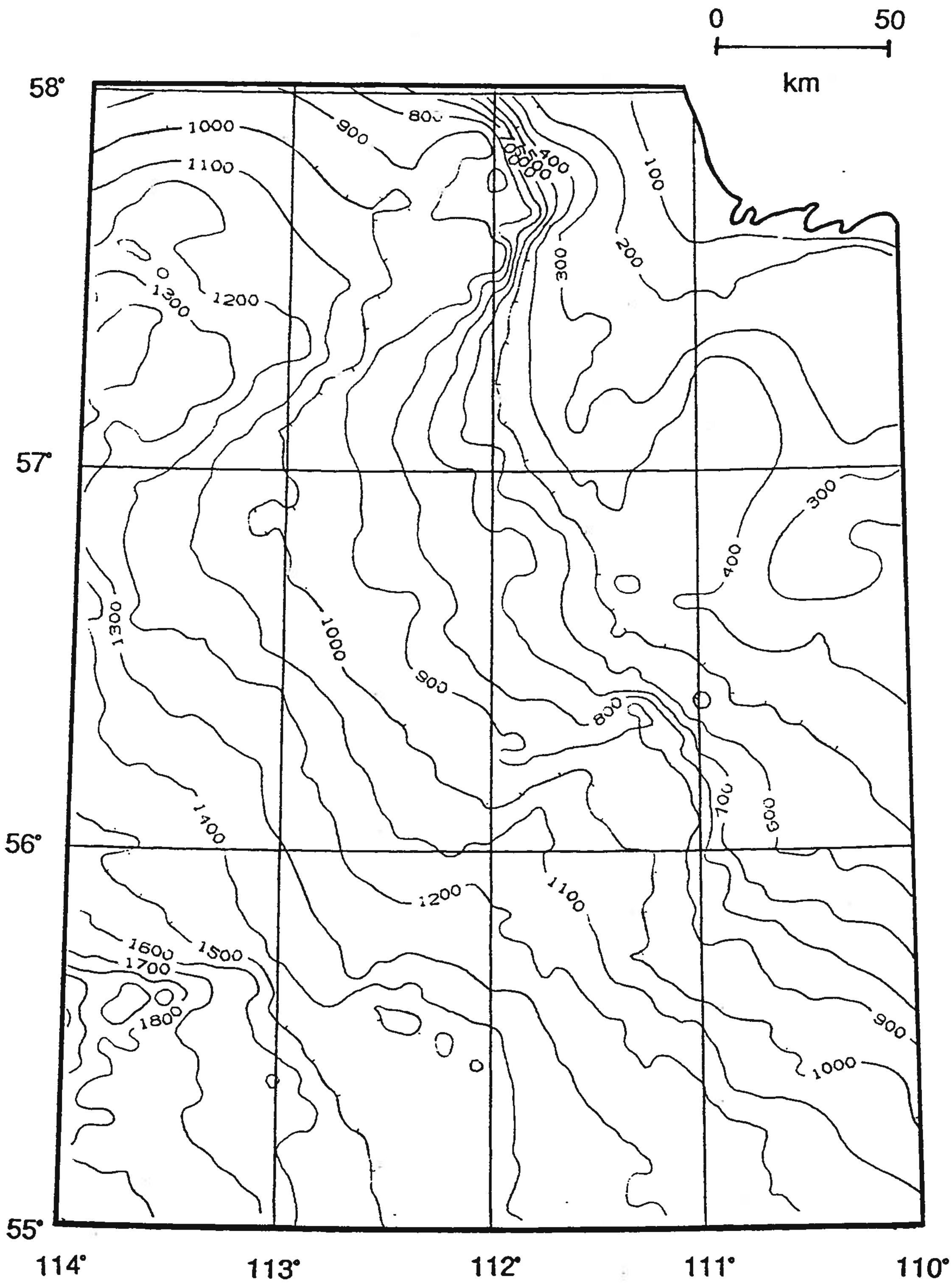
A - 24. Fish Scale Zone isopach map.



A - 25. Second White Speckled Shale isopach map.



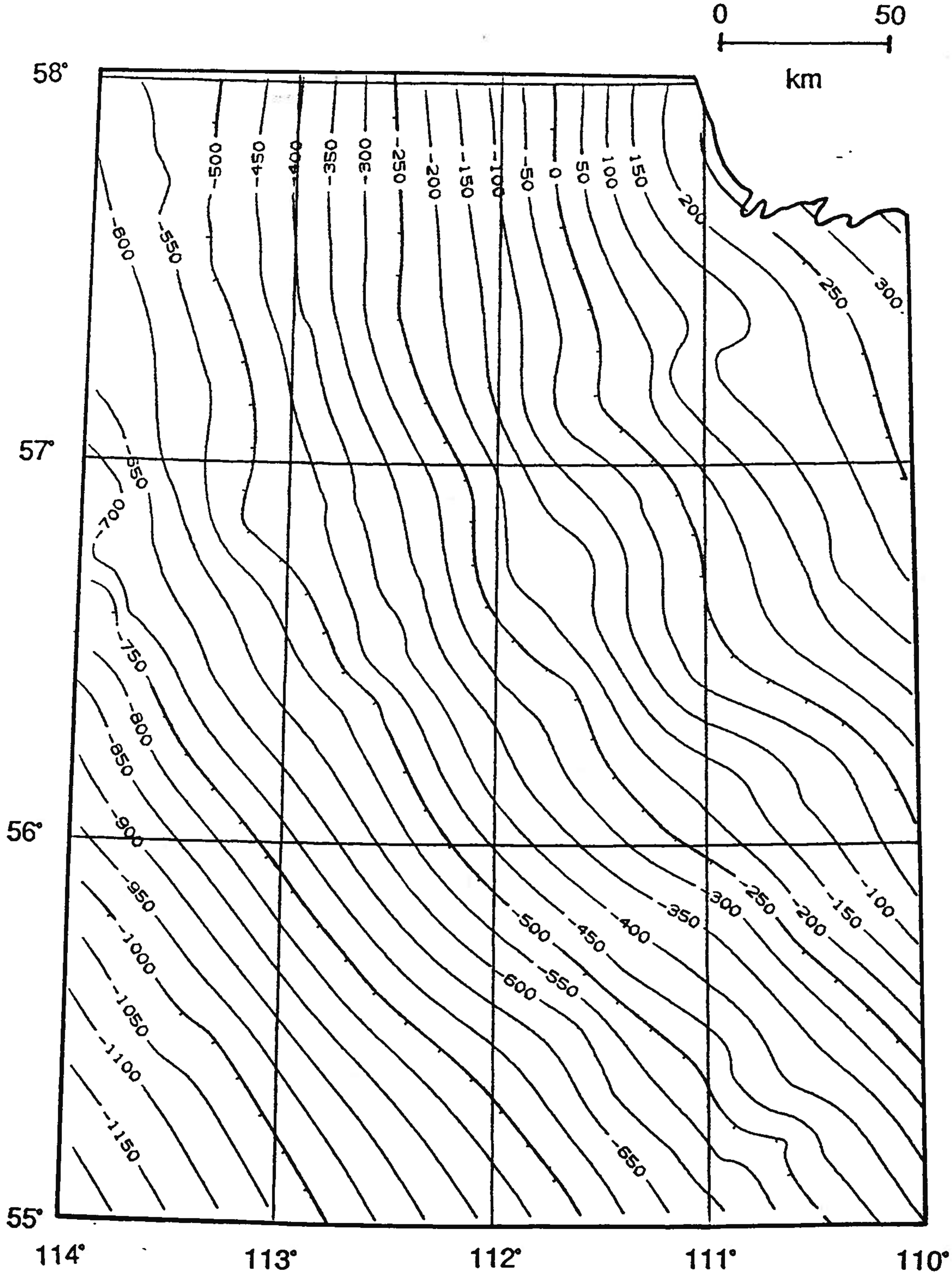
A - 26. Mesozoic isopach map.



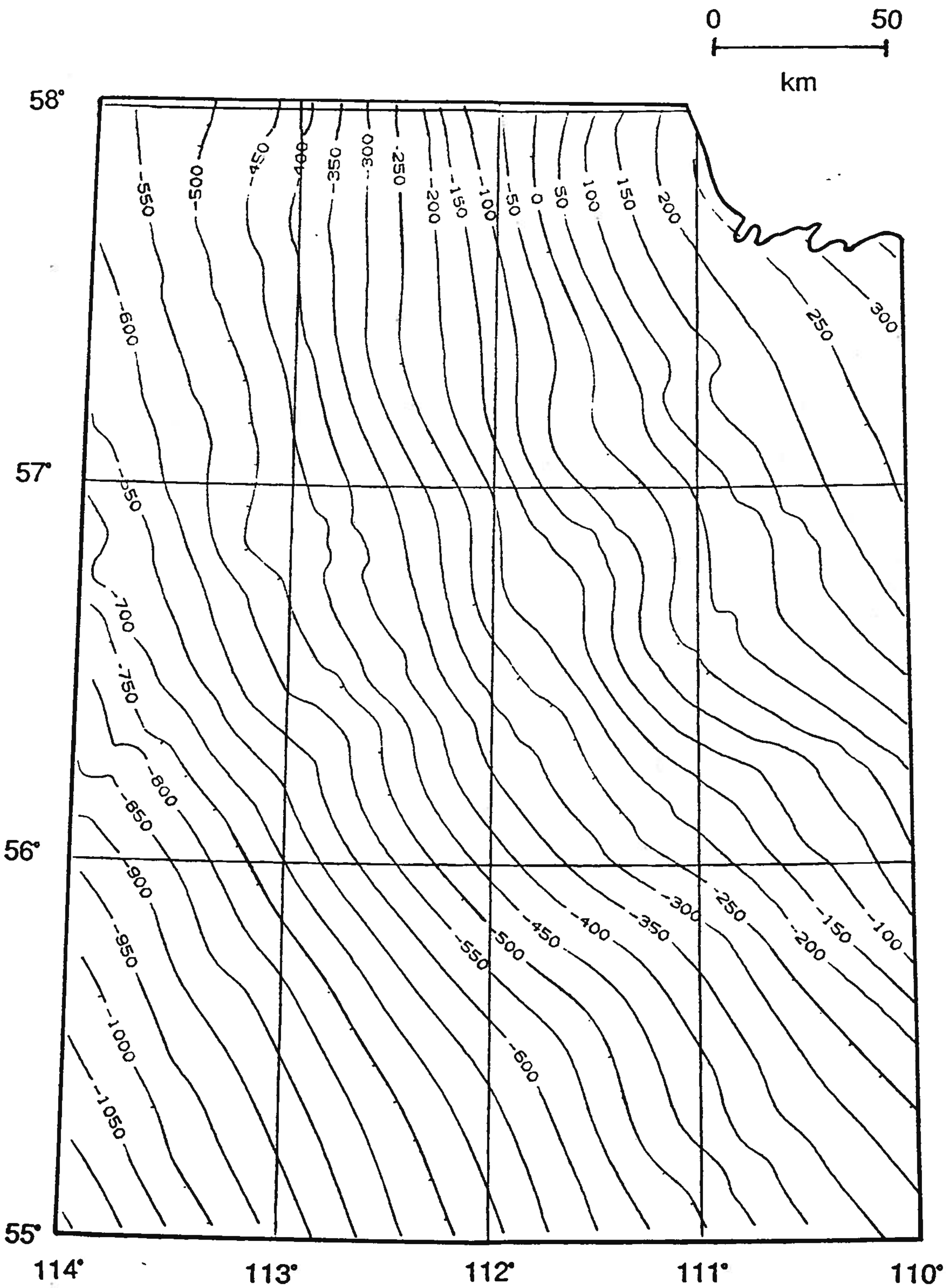
A - 27. Phanerozoic isopach map.

APPENDIX B - STRUCTURE CONTOUR MAPS

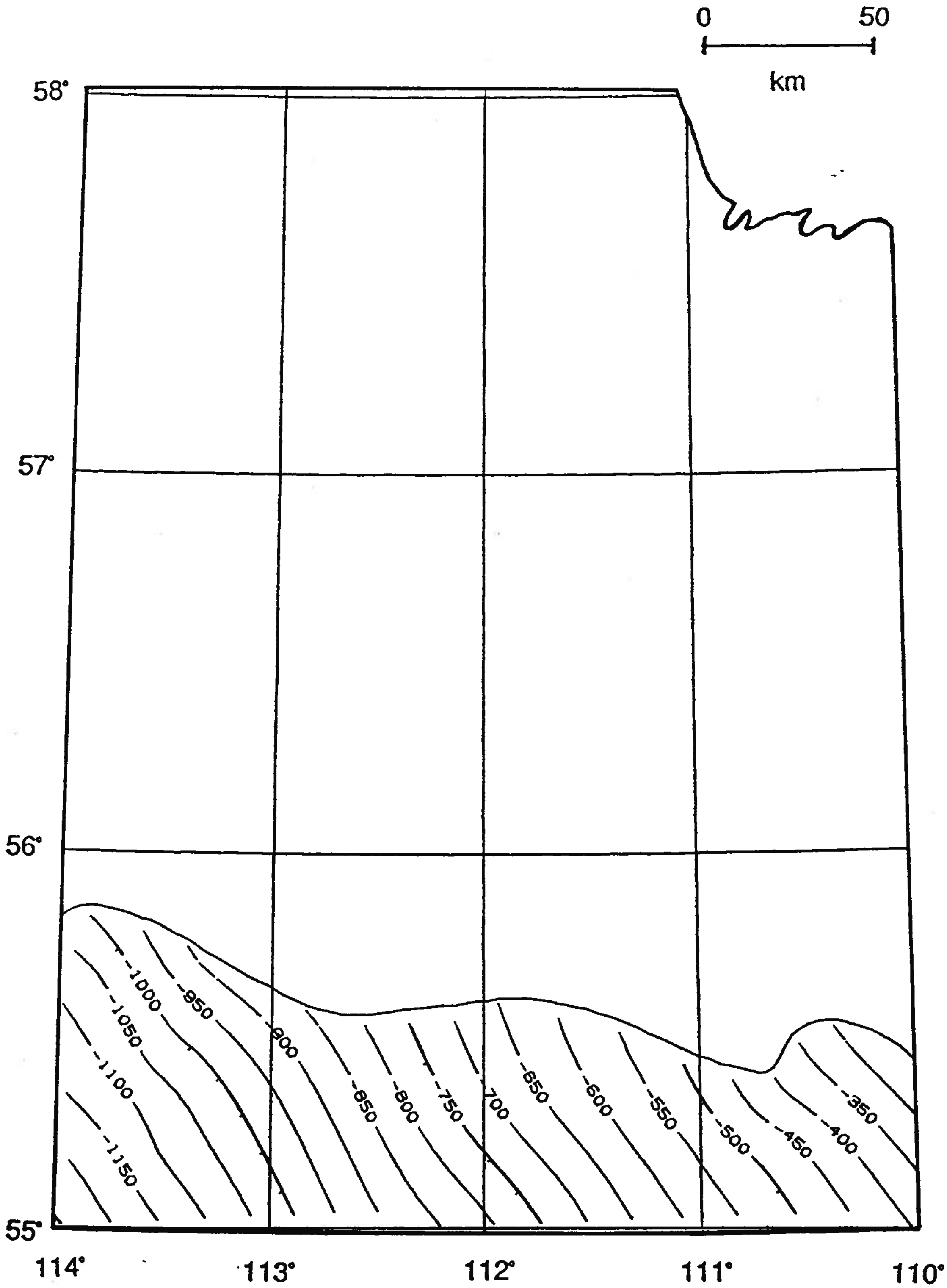
All structure maps c.i. = 50 m



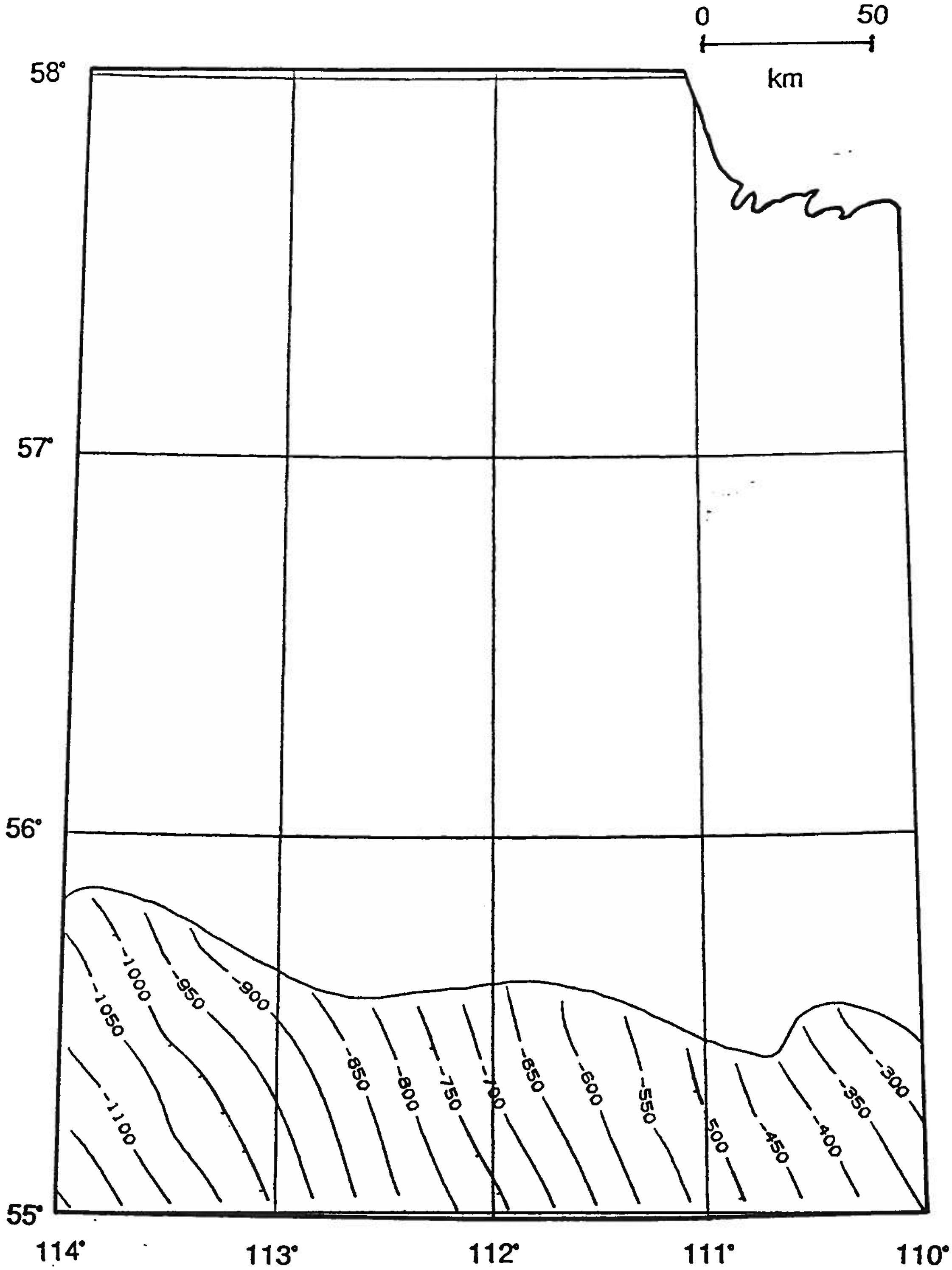
B - 1. Precambrian structure map.



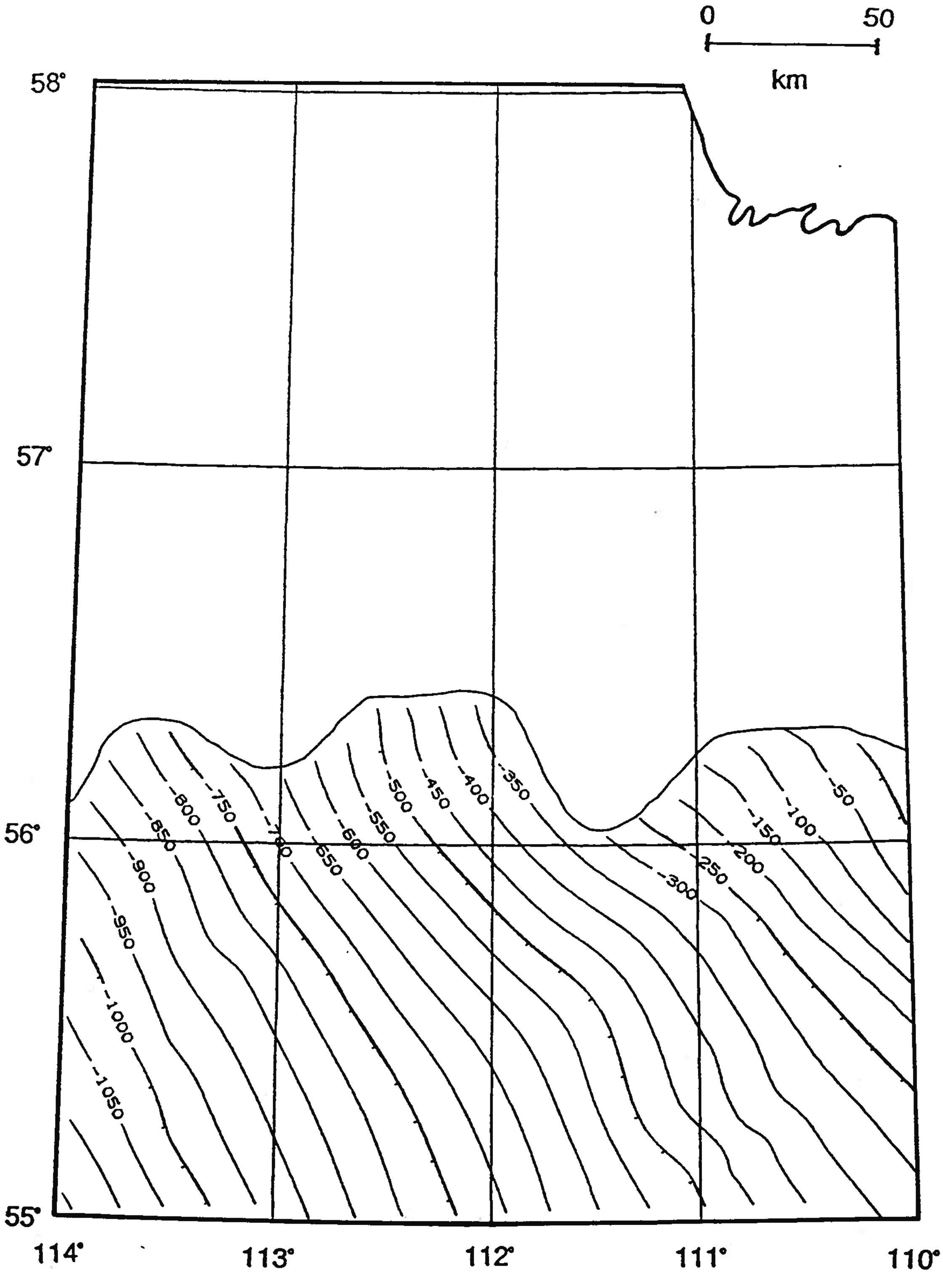
B - 2. Basal Red Beds structure map.



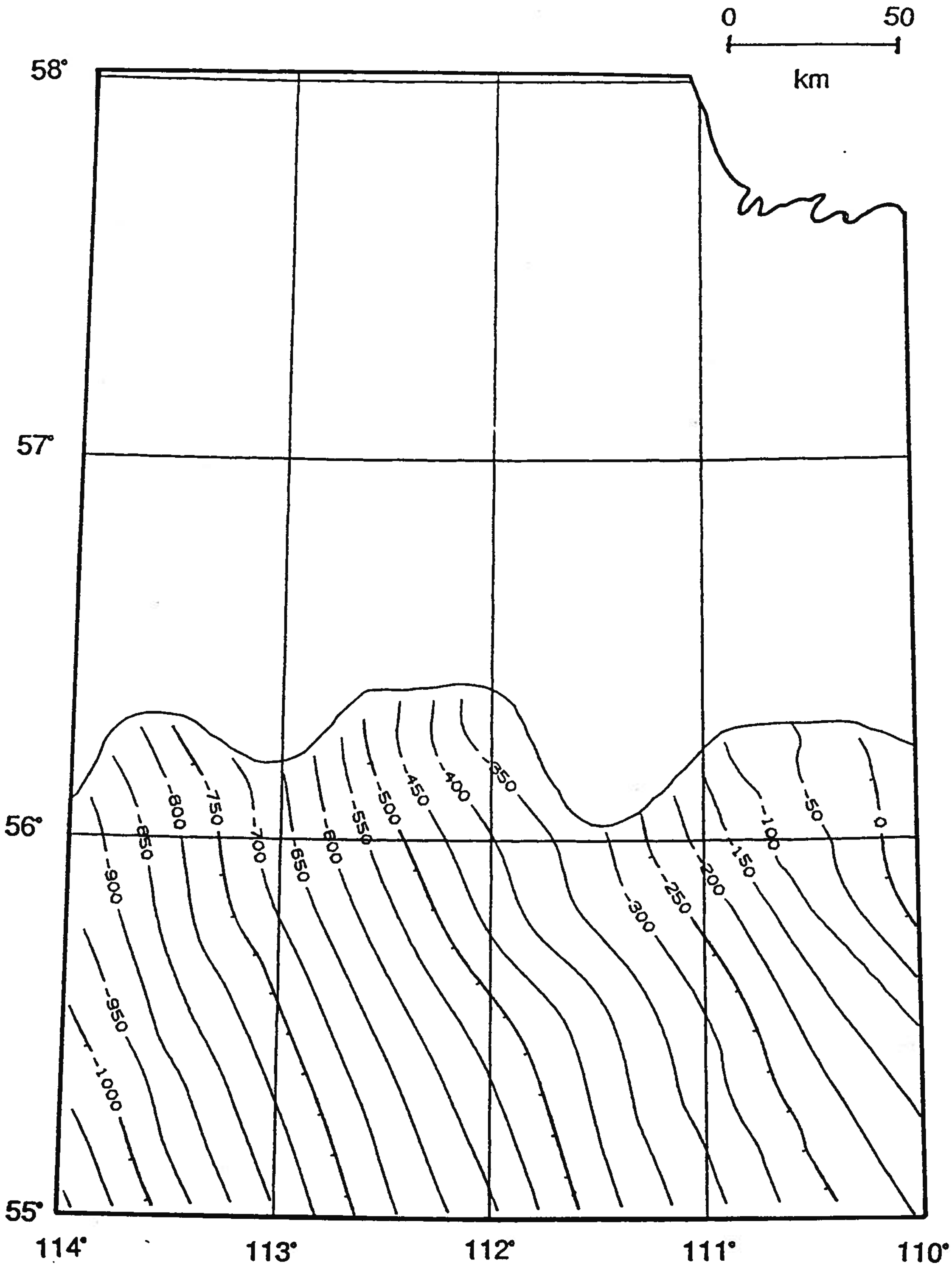
B - 3. Base of Lower Lotsberg Salt structure map.



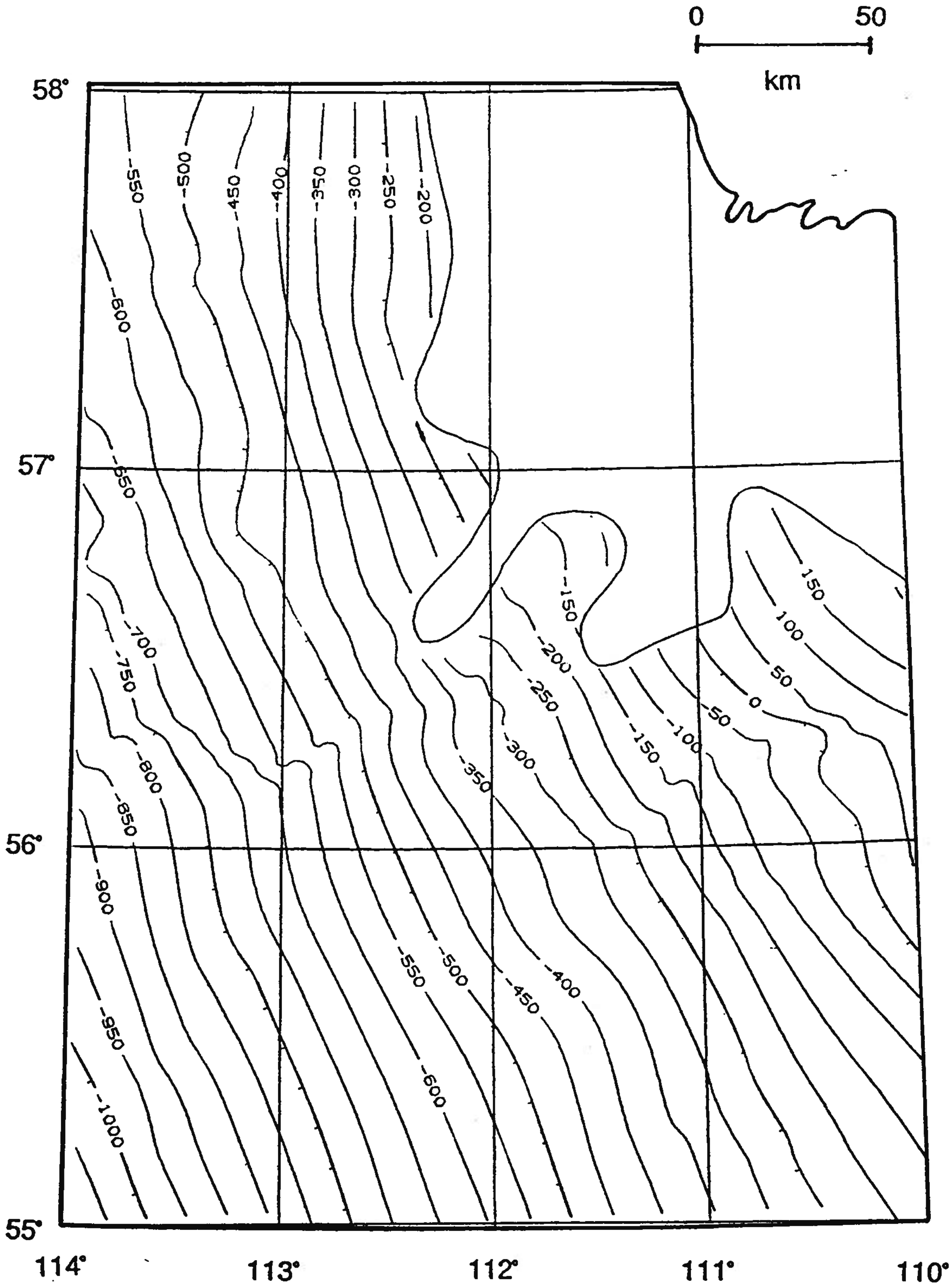
B - 4. Lower Lotsberg Salt structure map.



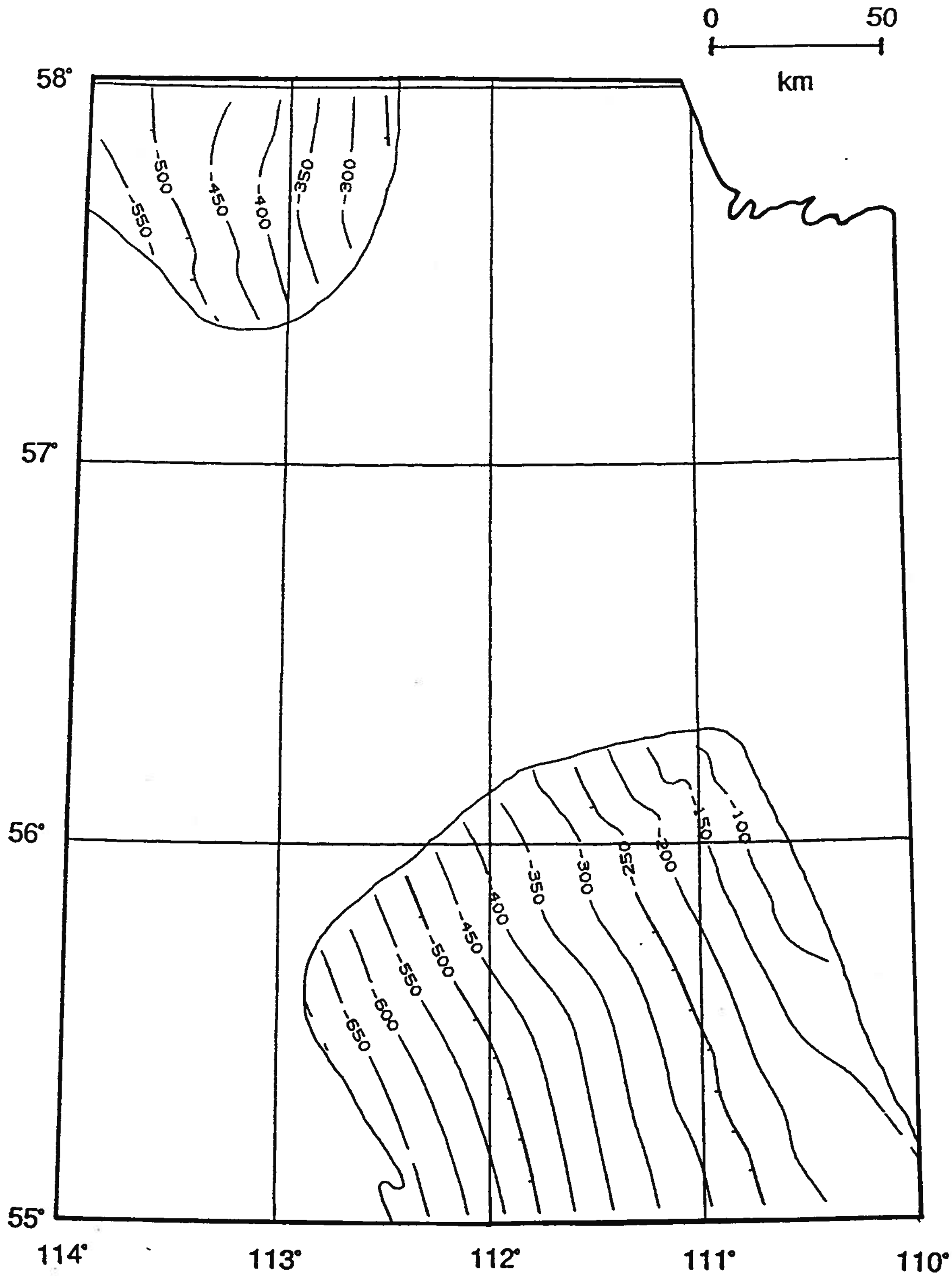
B - 5. Base of Upper Lotsberg Salt structure map.



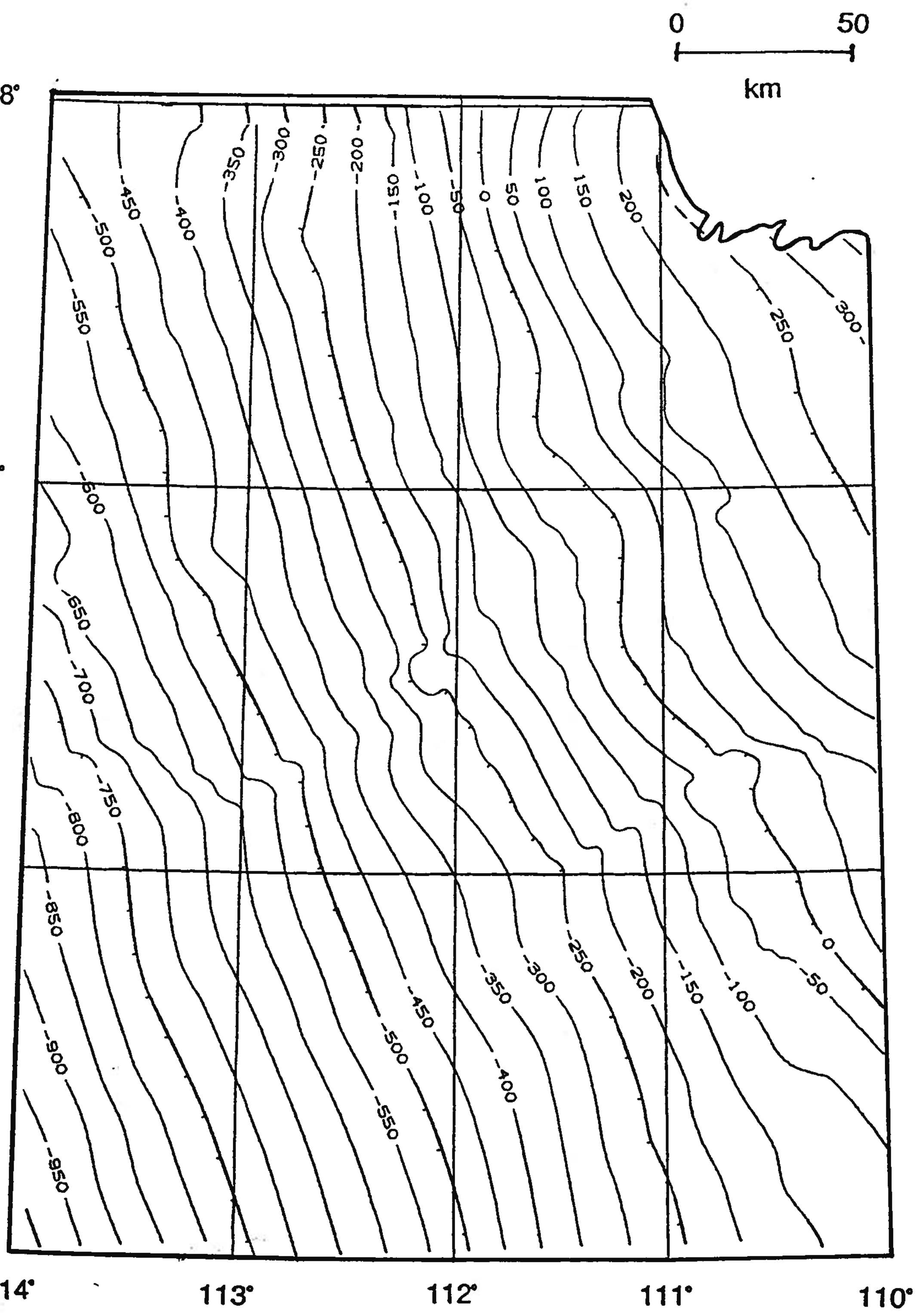
B - 6. Upper Lotsberg Salt structure map.



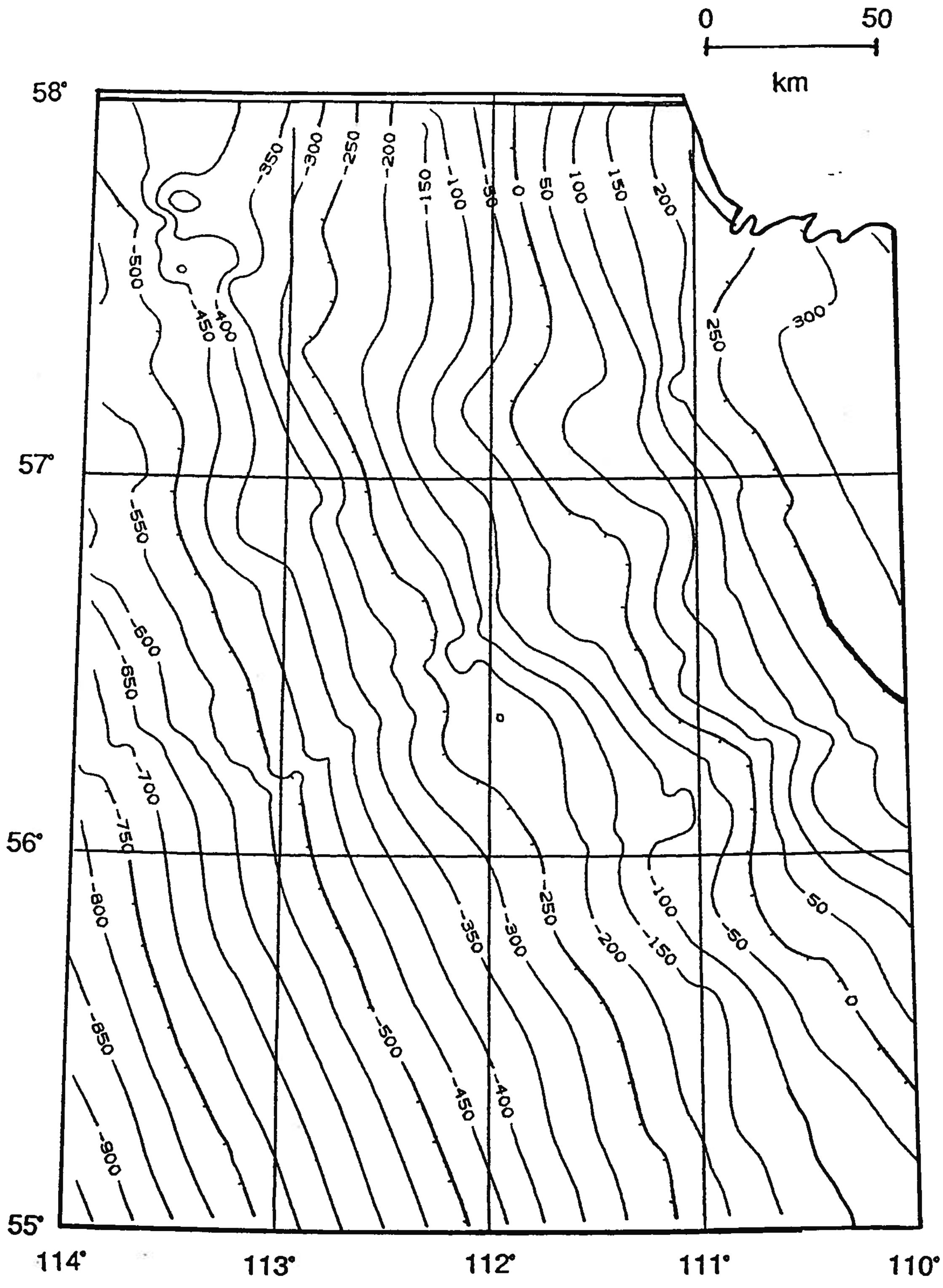
B - 7. Ernestina Lake Formation structure map.



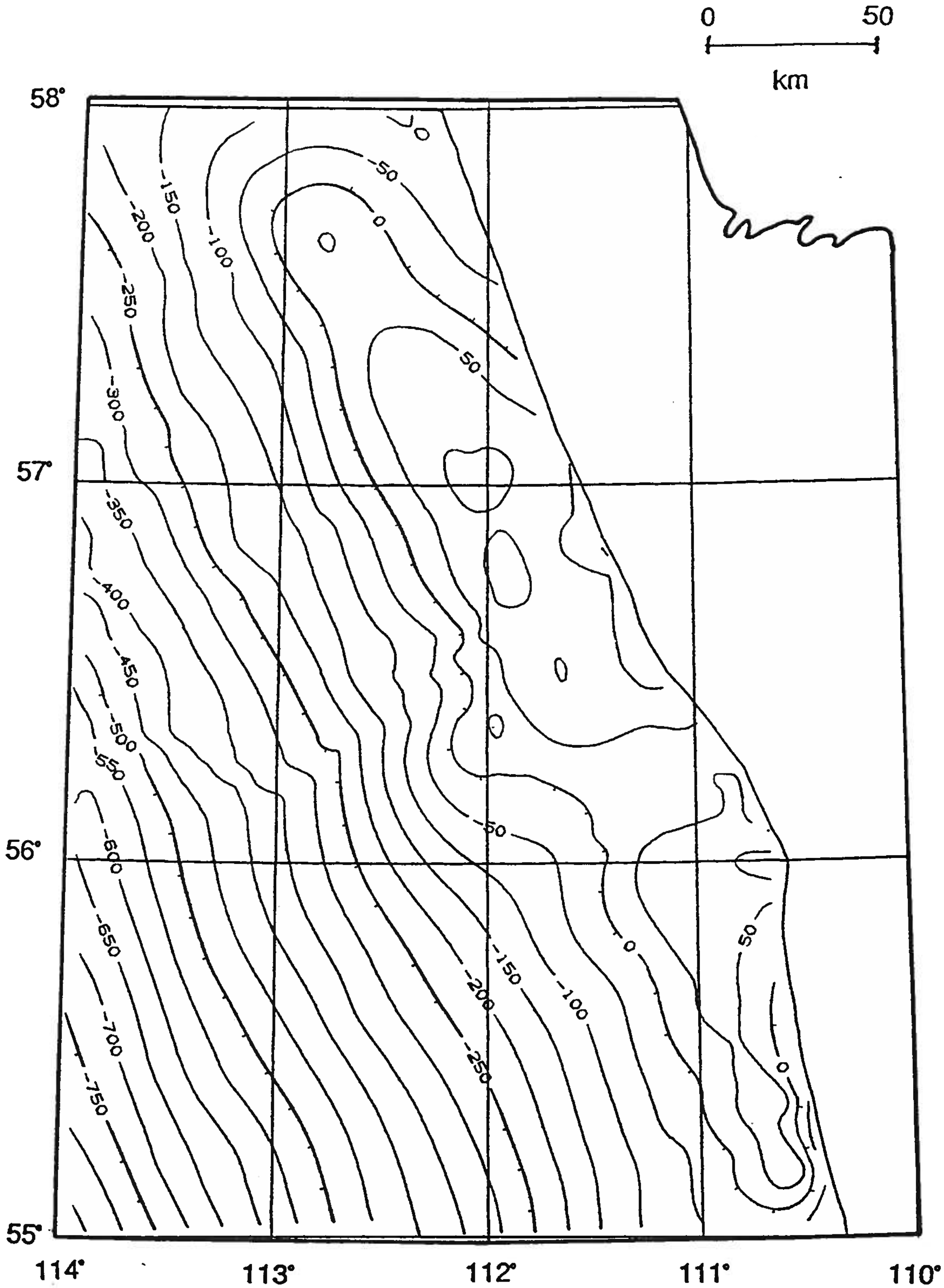
B - 8. Cold Lake Salt structure map.



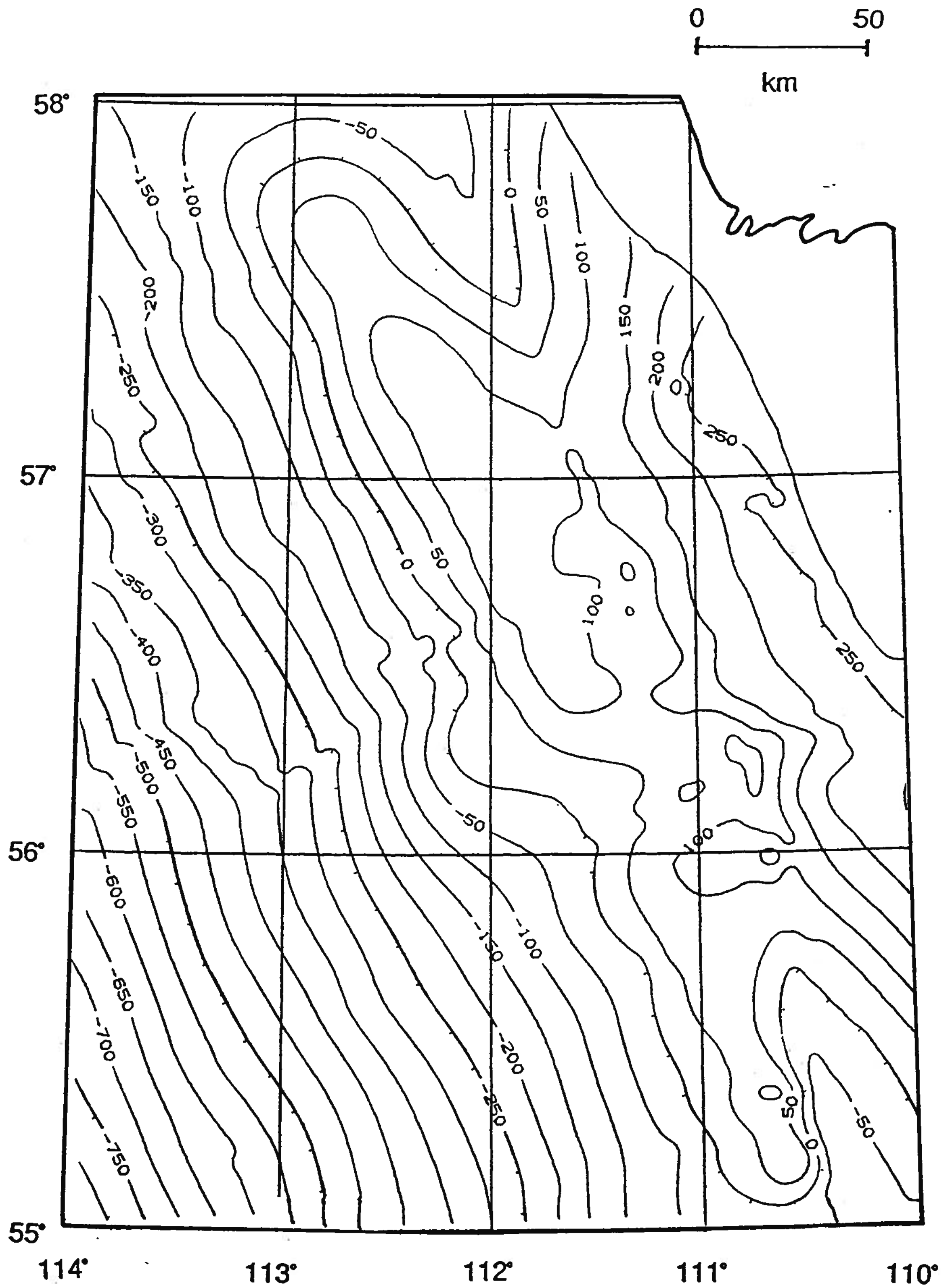
B - 9. Contact Rapids Formation structure map.



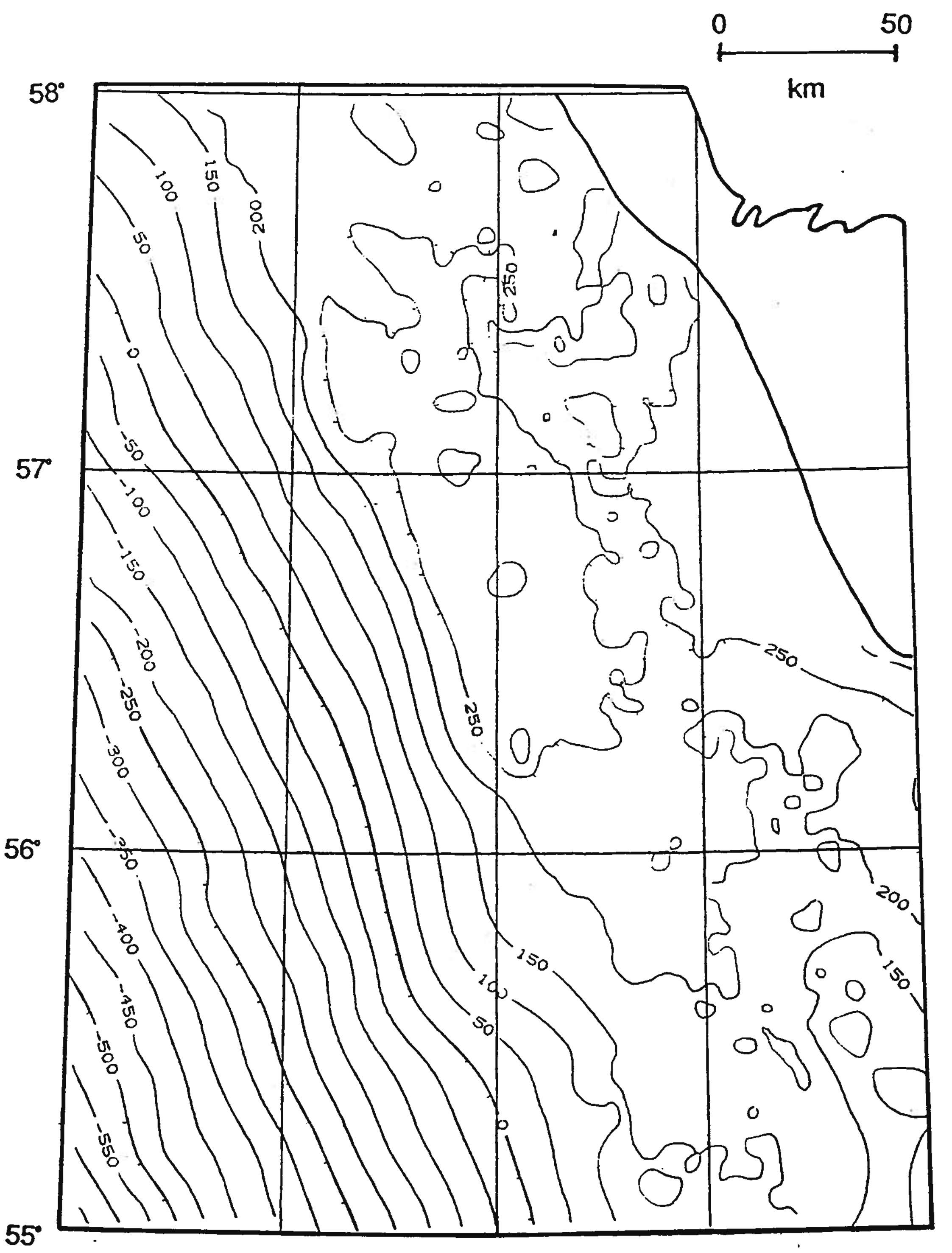
B - 10. Winnipegosis Formation structure map.



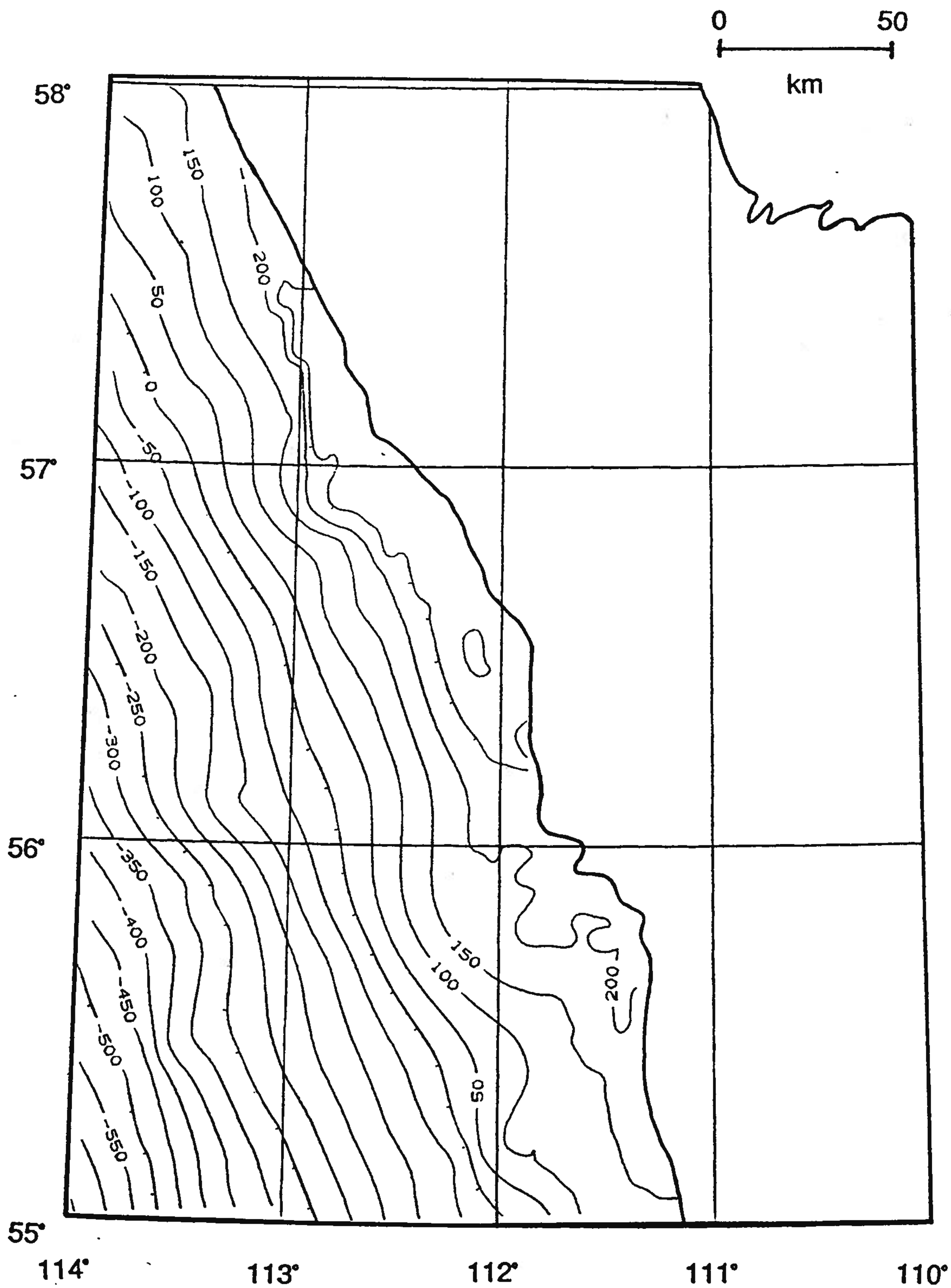
B - 11. Prairie Formation structure map.



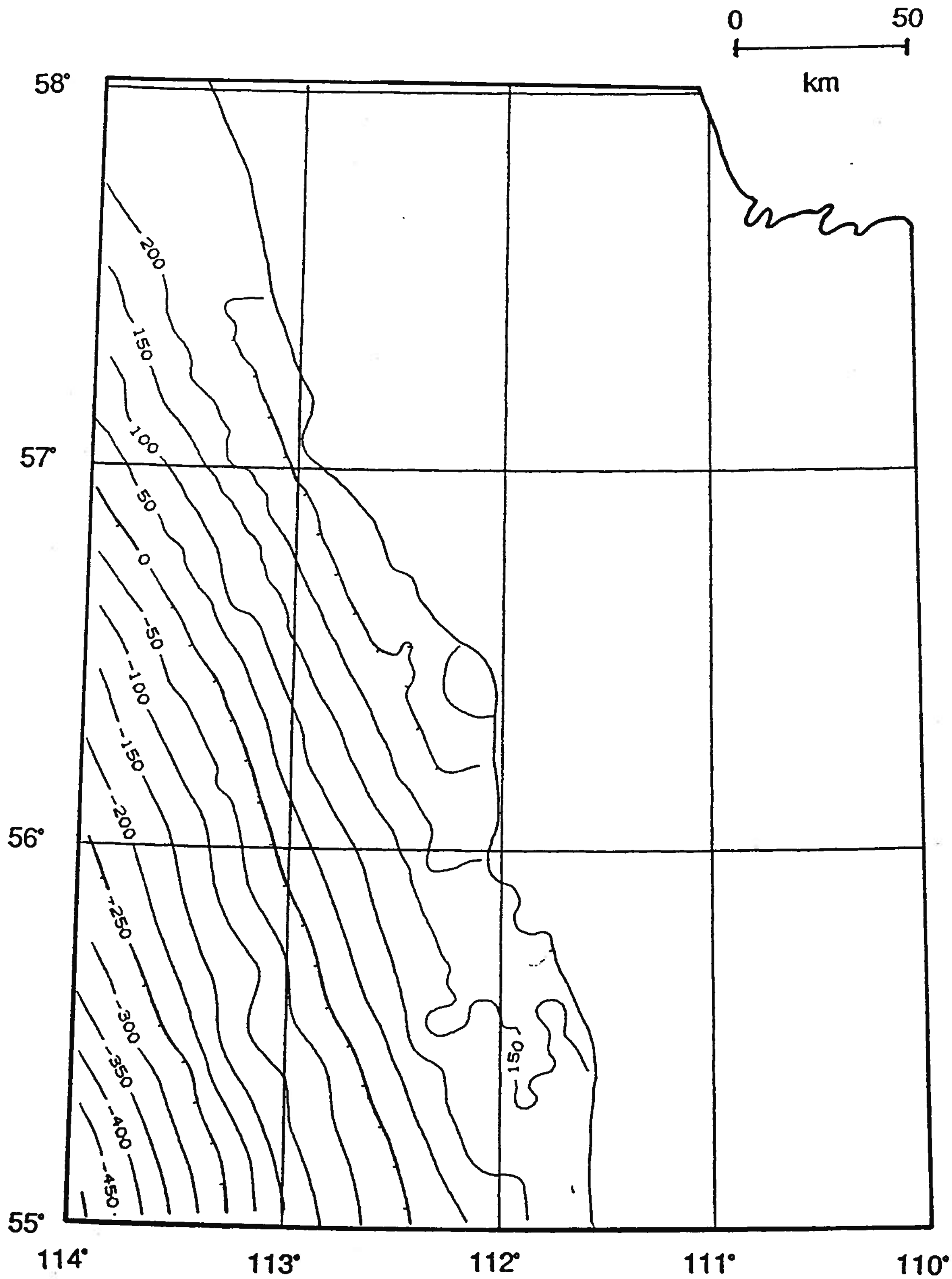
B - 12. Watt Mountain Formation structure map.



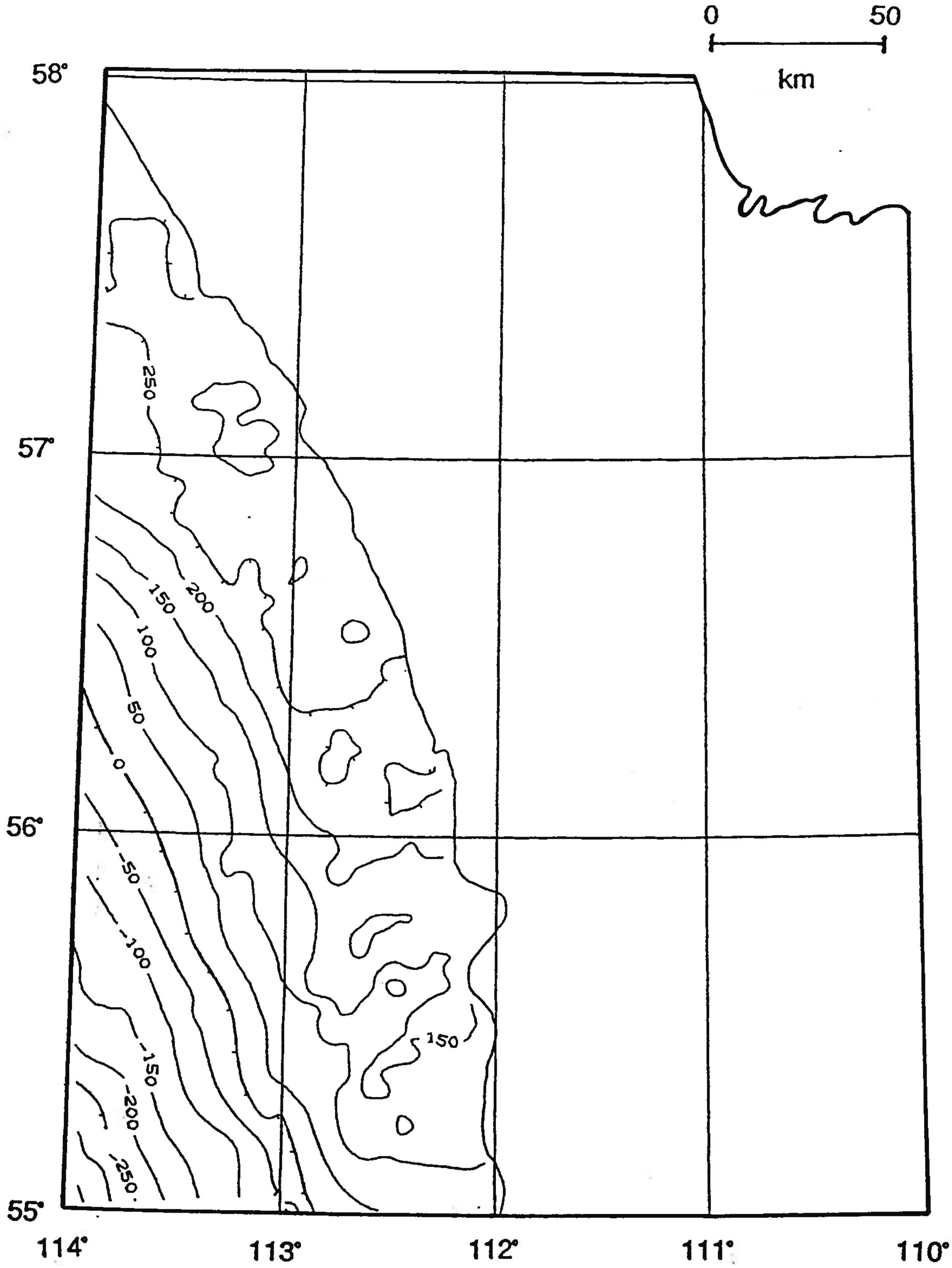
B - 13. Beaverhill Lake Group structure map.



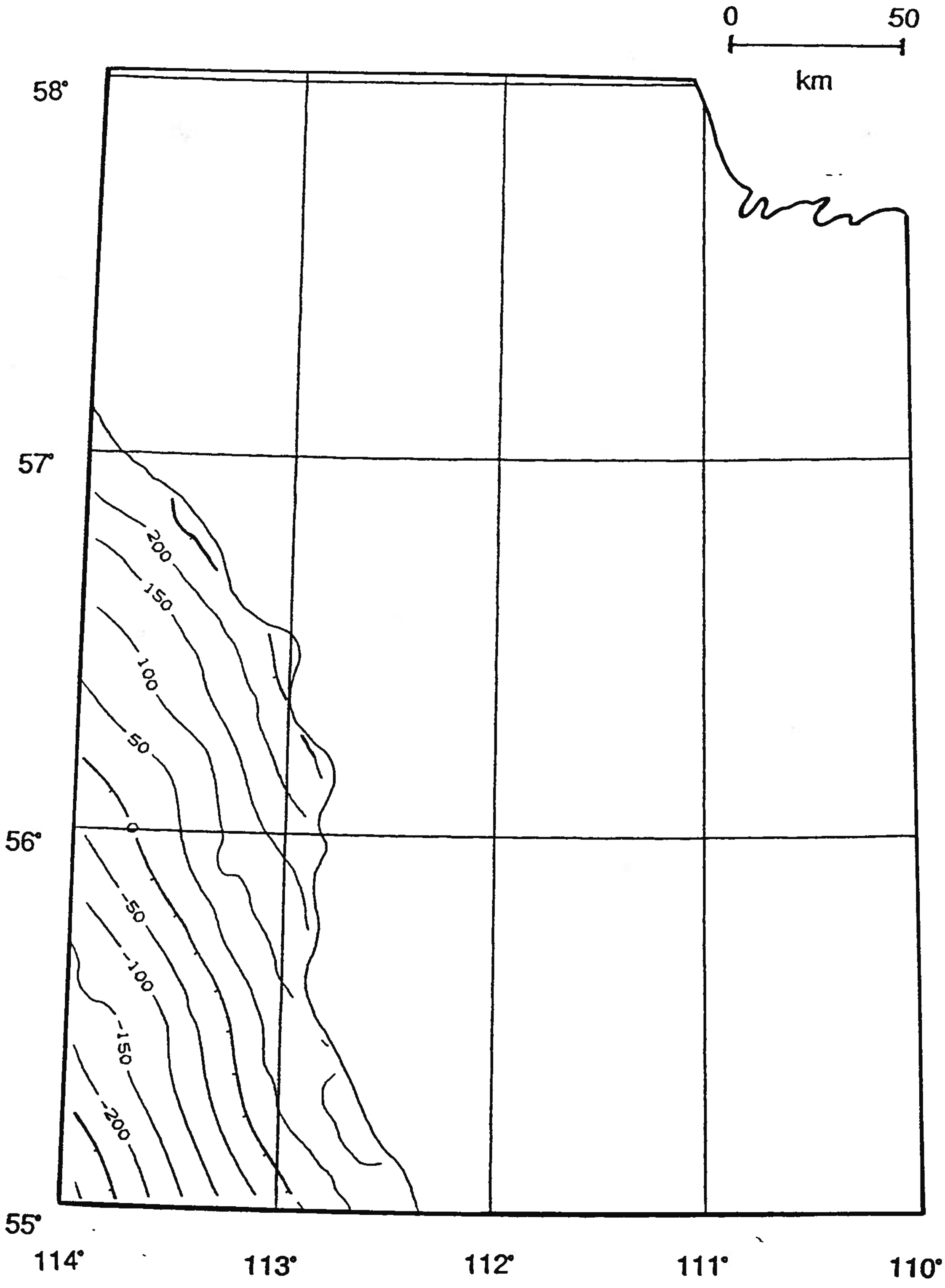
B - 14. Cooking Lake Formation structure map.



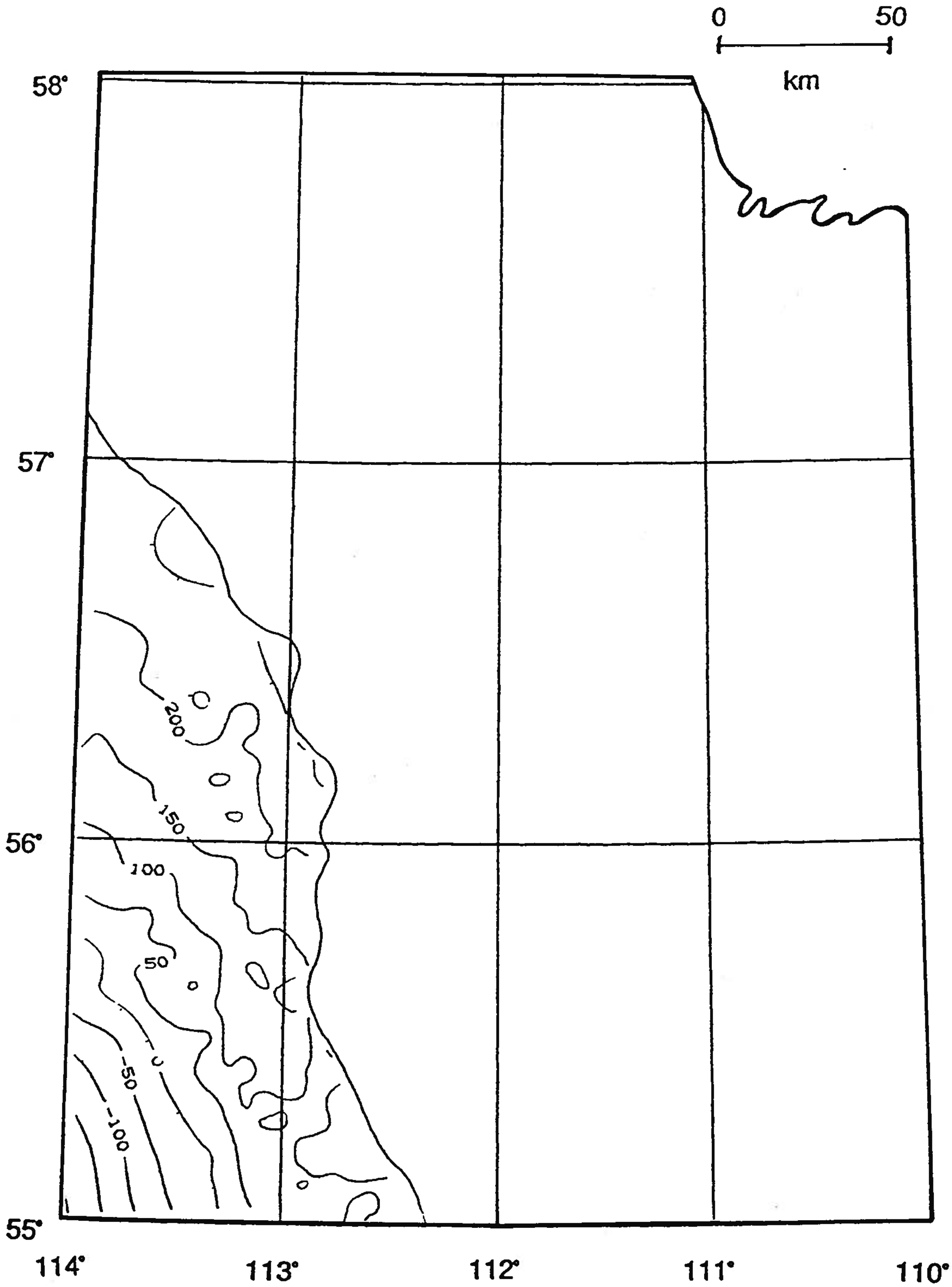
B - 15. Lower Ireton Formation structure map.



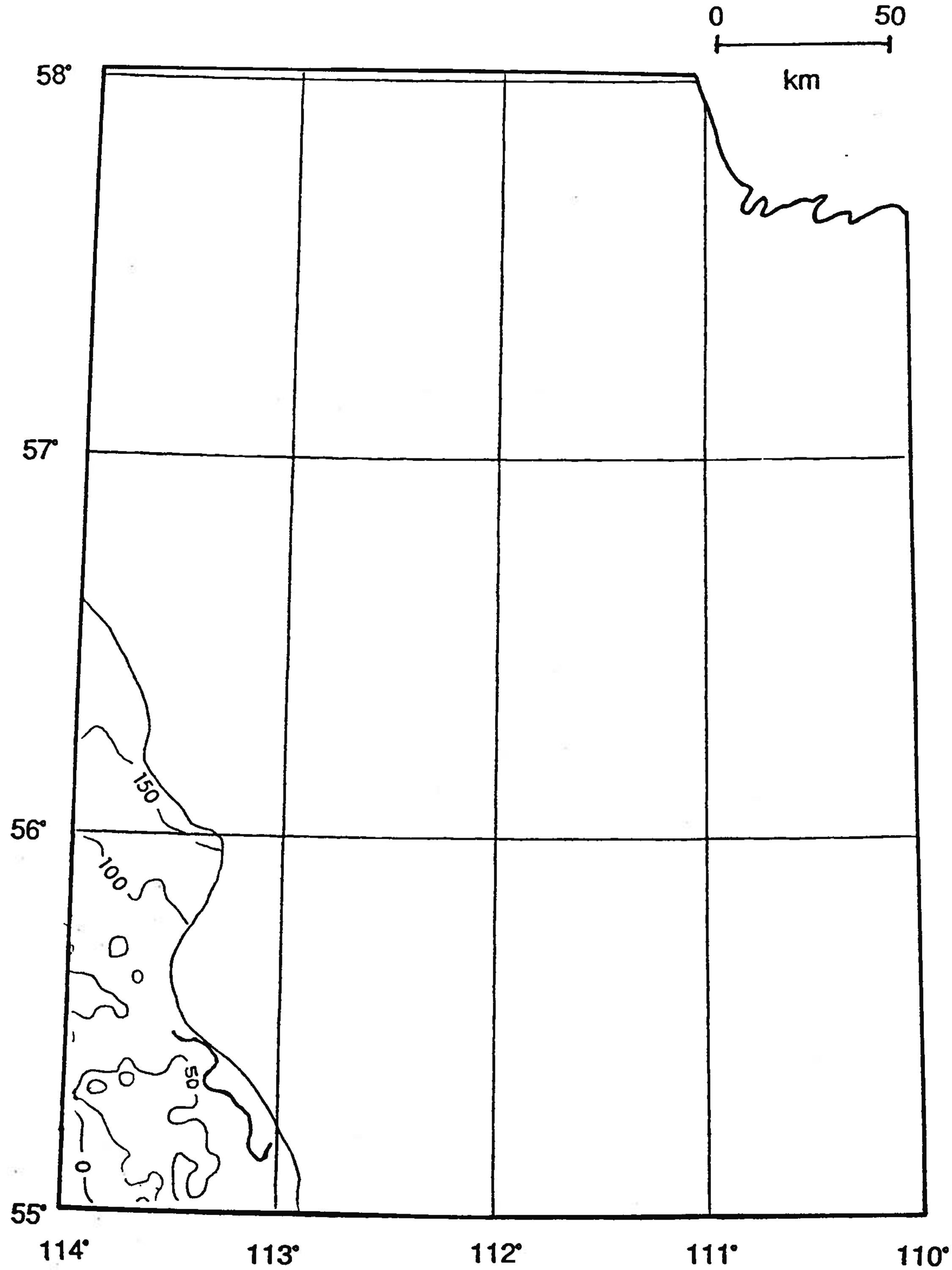
B - 16. Grosmont Formation structure map.



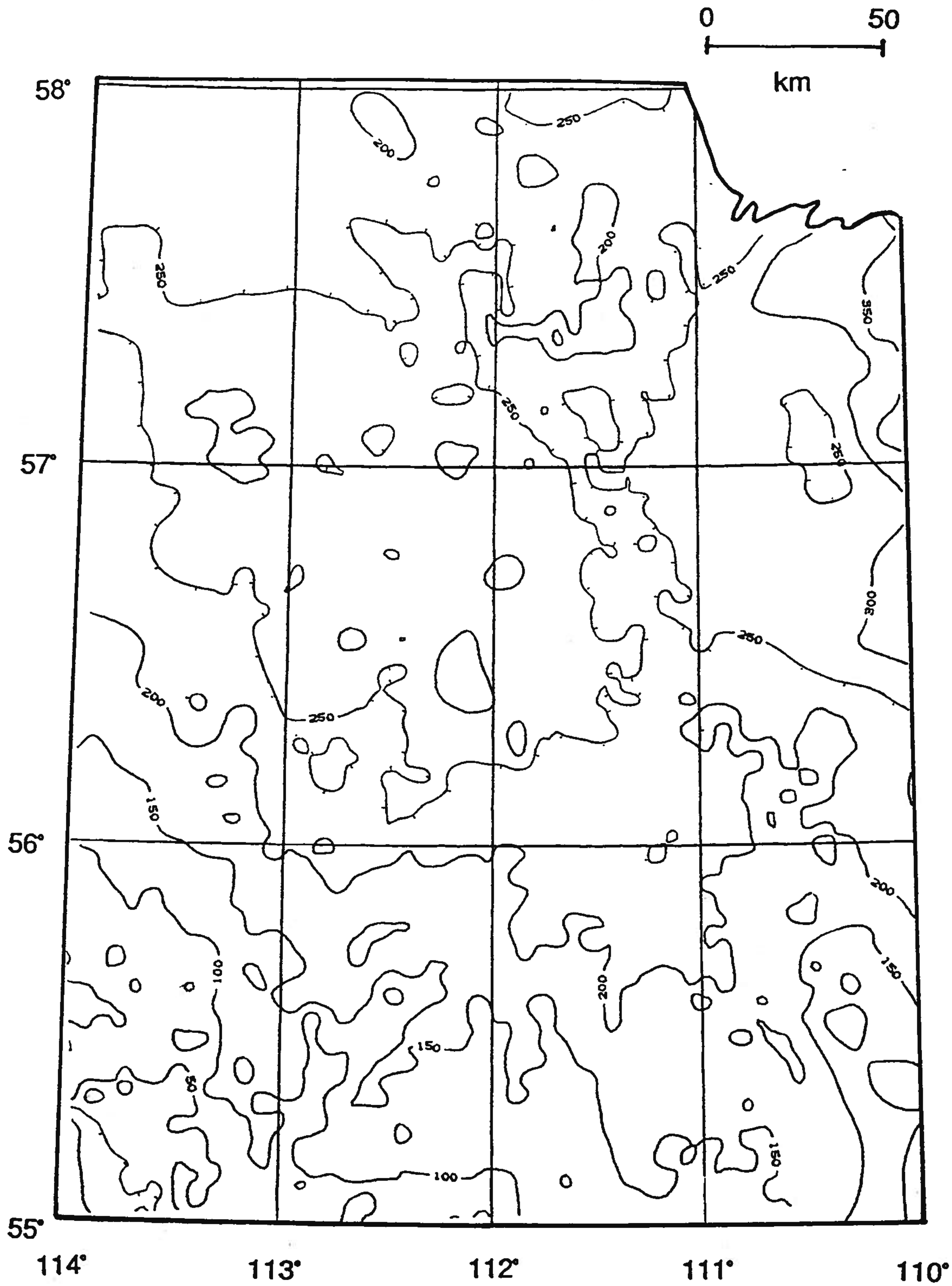
B - 17. Upper Ireton Formation structure map.



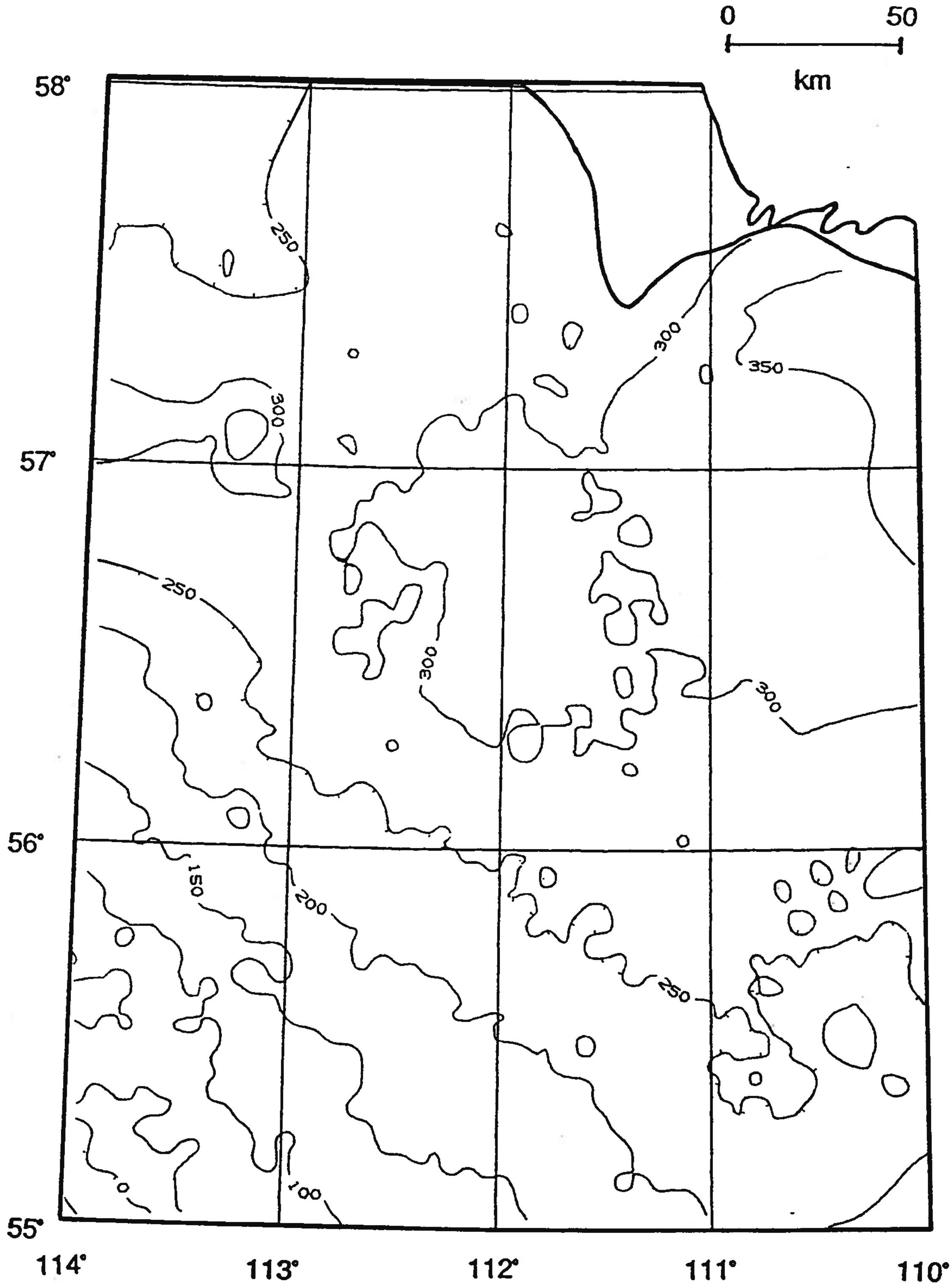
B - 18. Winterburn Group structure map.



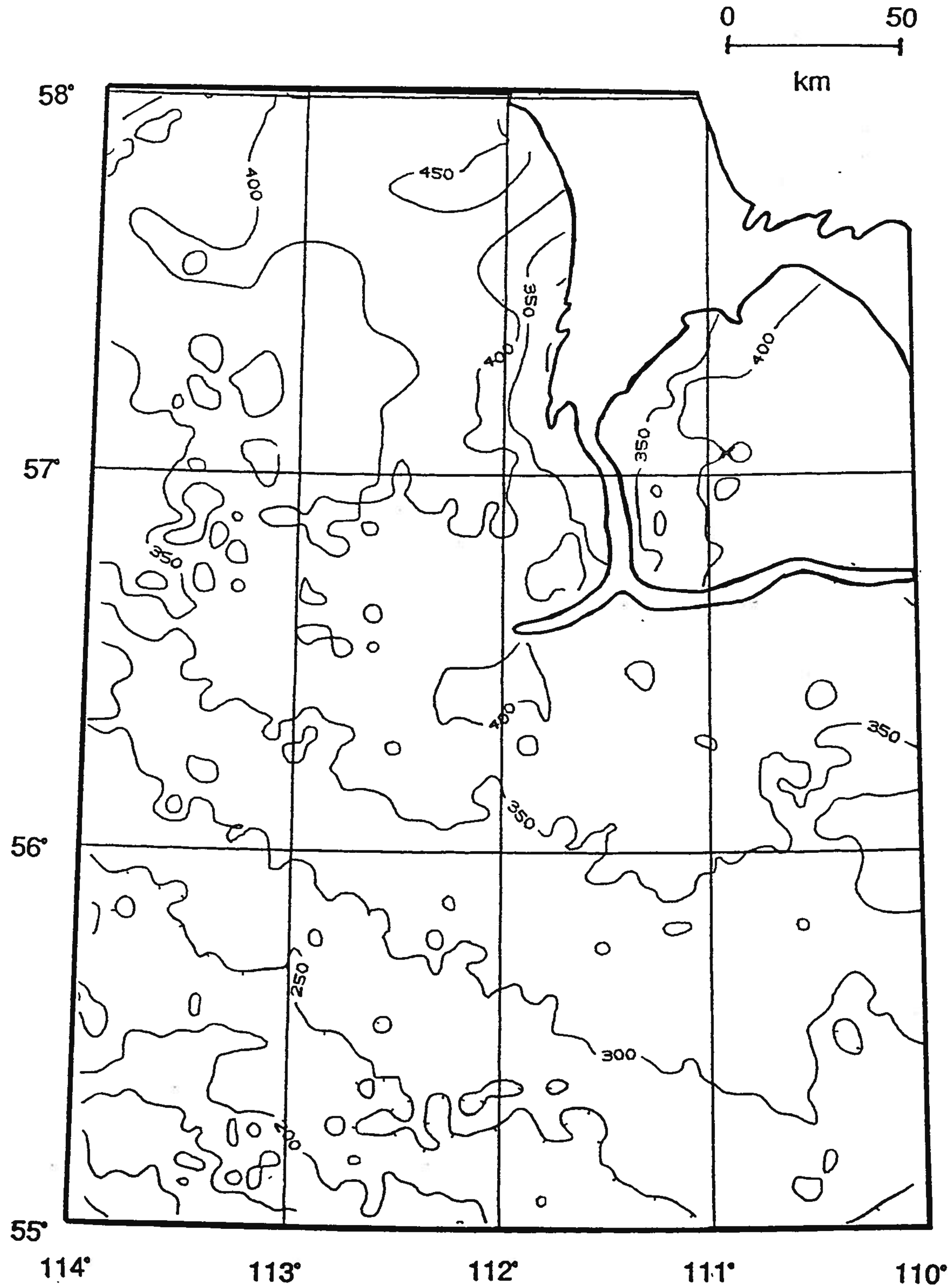
B - 19. Wabamum Group structure map.



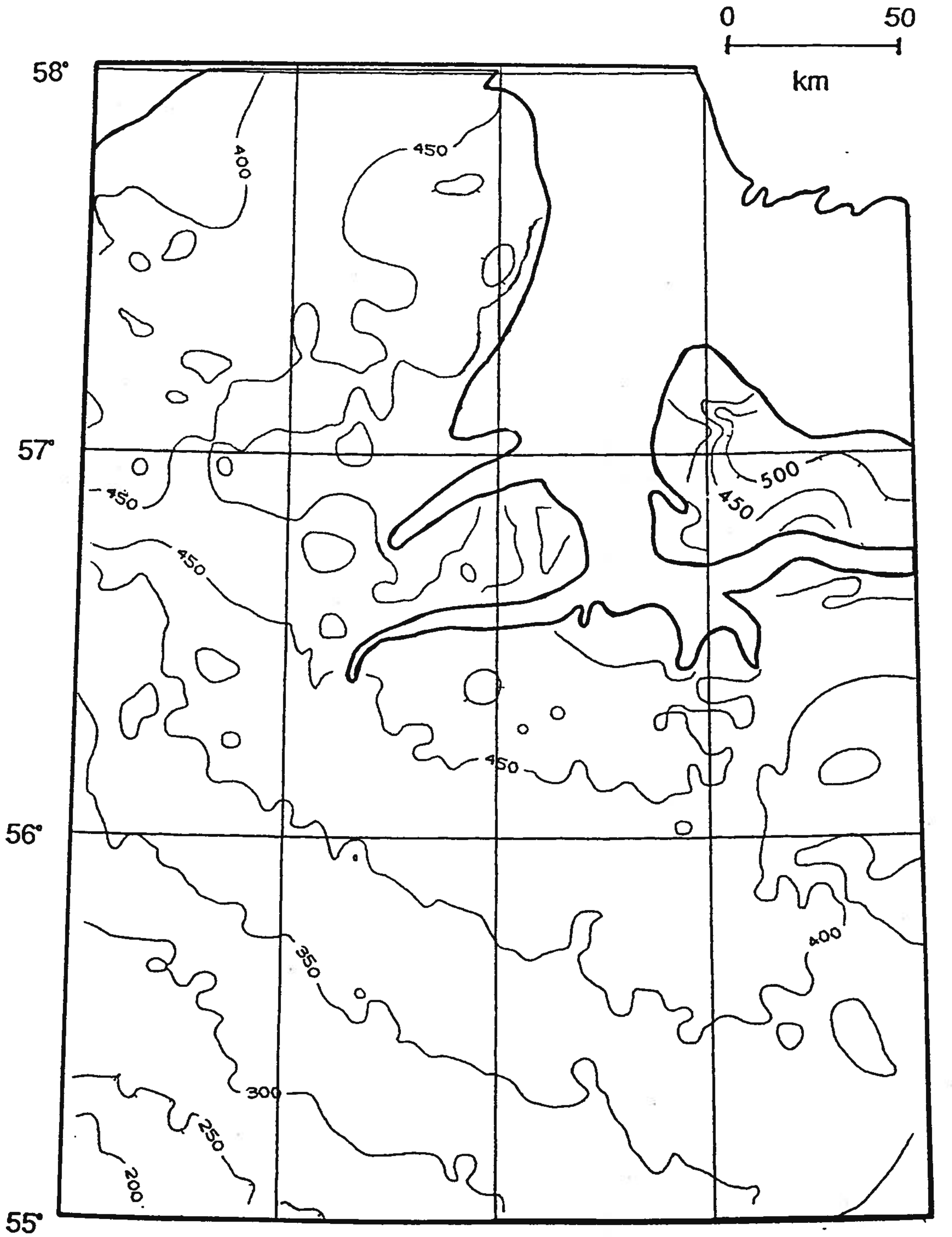
B - 20. Sub-Cretaceous Unconformity structure map.



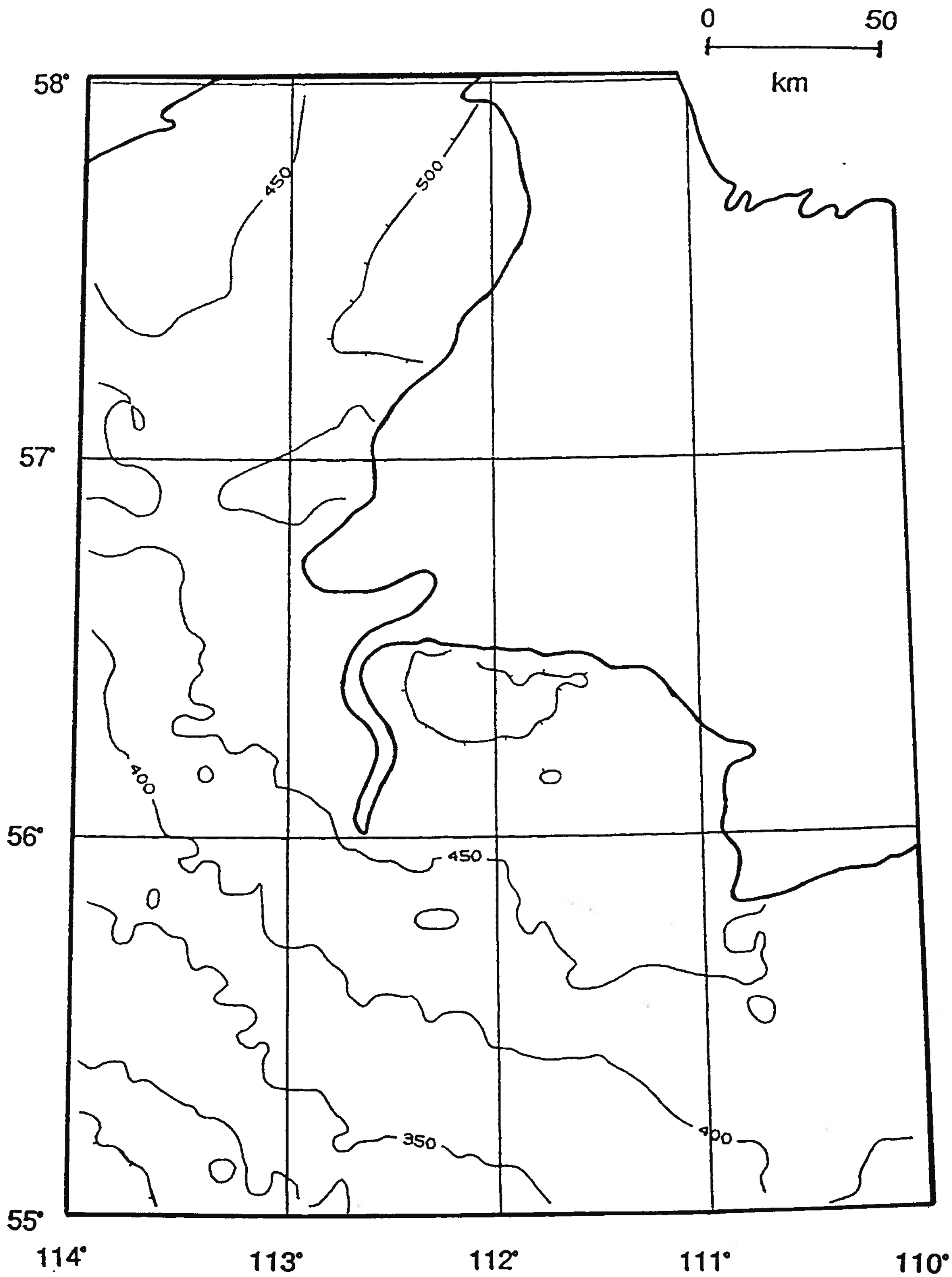
B - 21. McMurray Formation structure map.



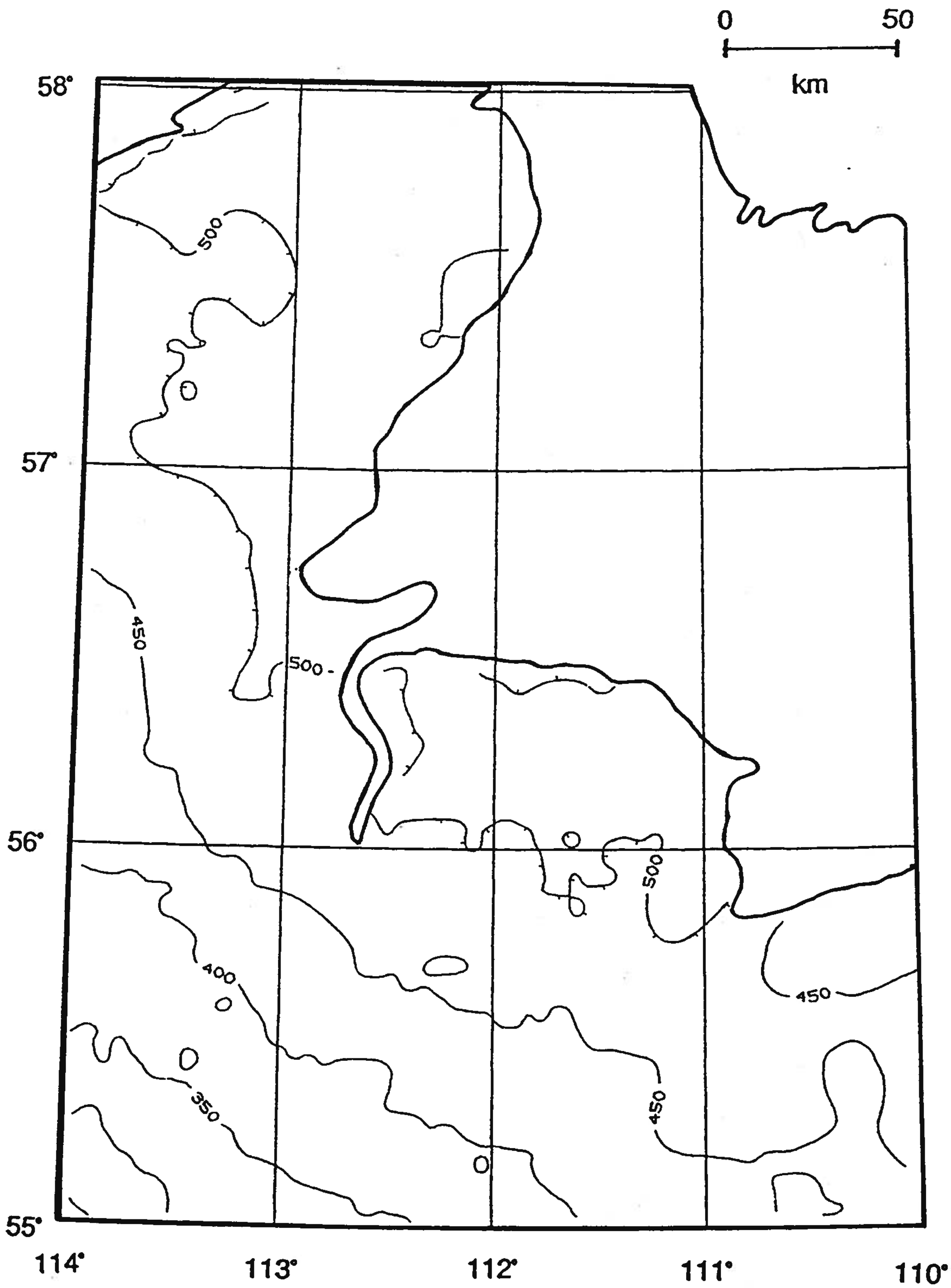
B - 22. Clearwater Formation structure map.



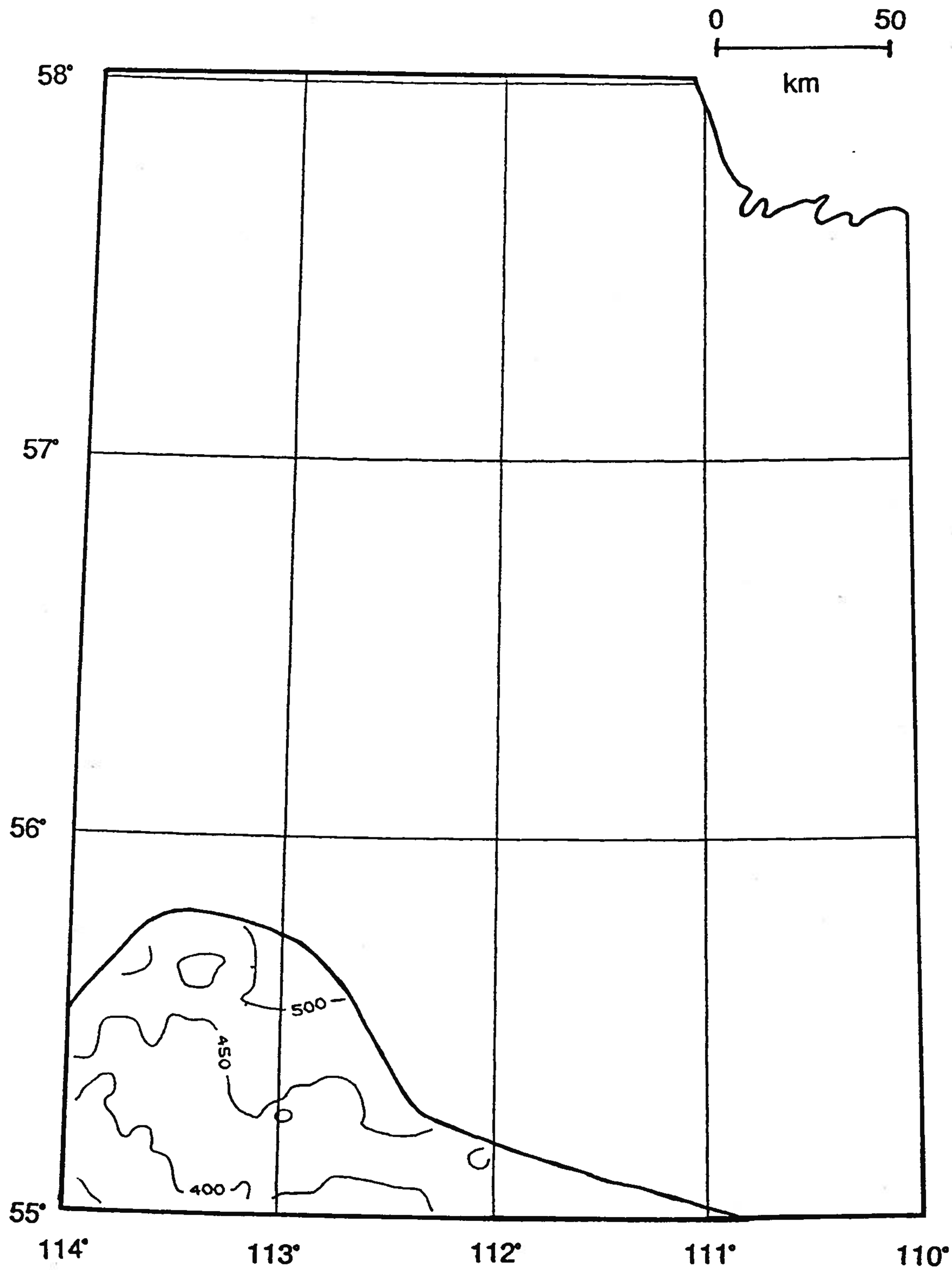
B - 23. Mannville Group structure map.



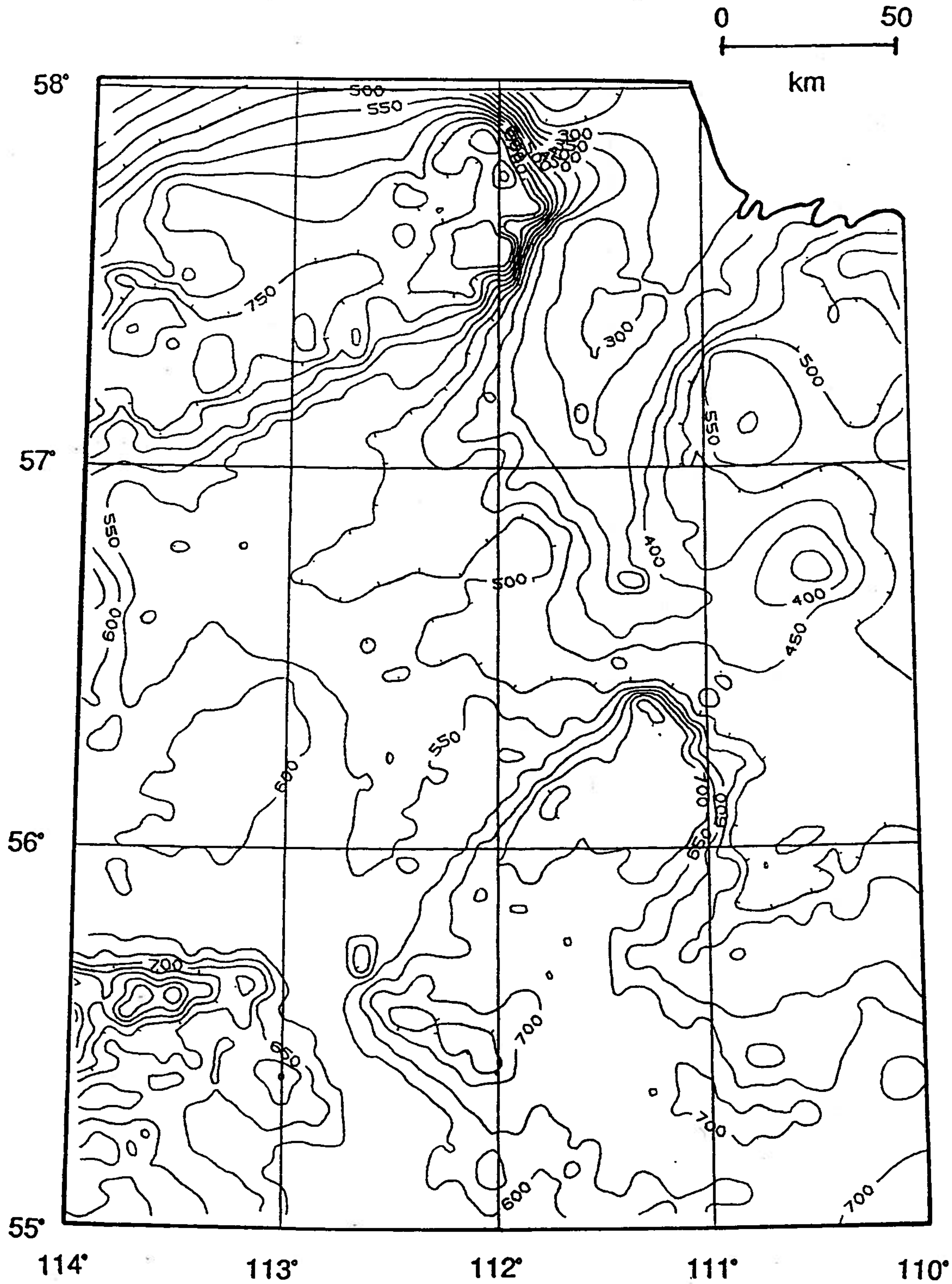
B - 24. Viking Formation structure map.



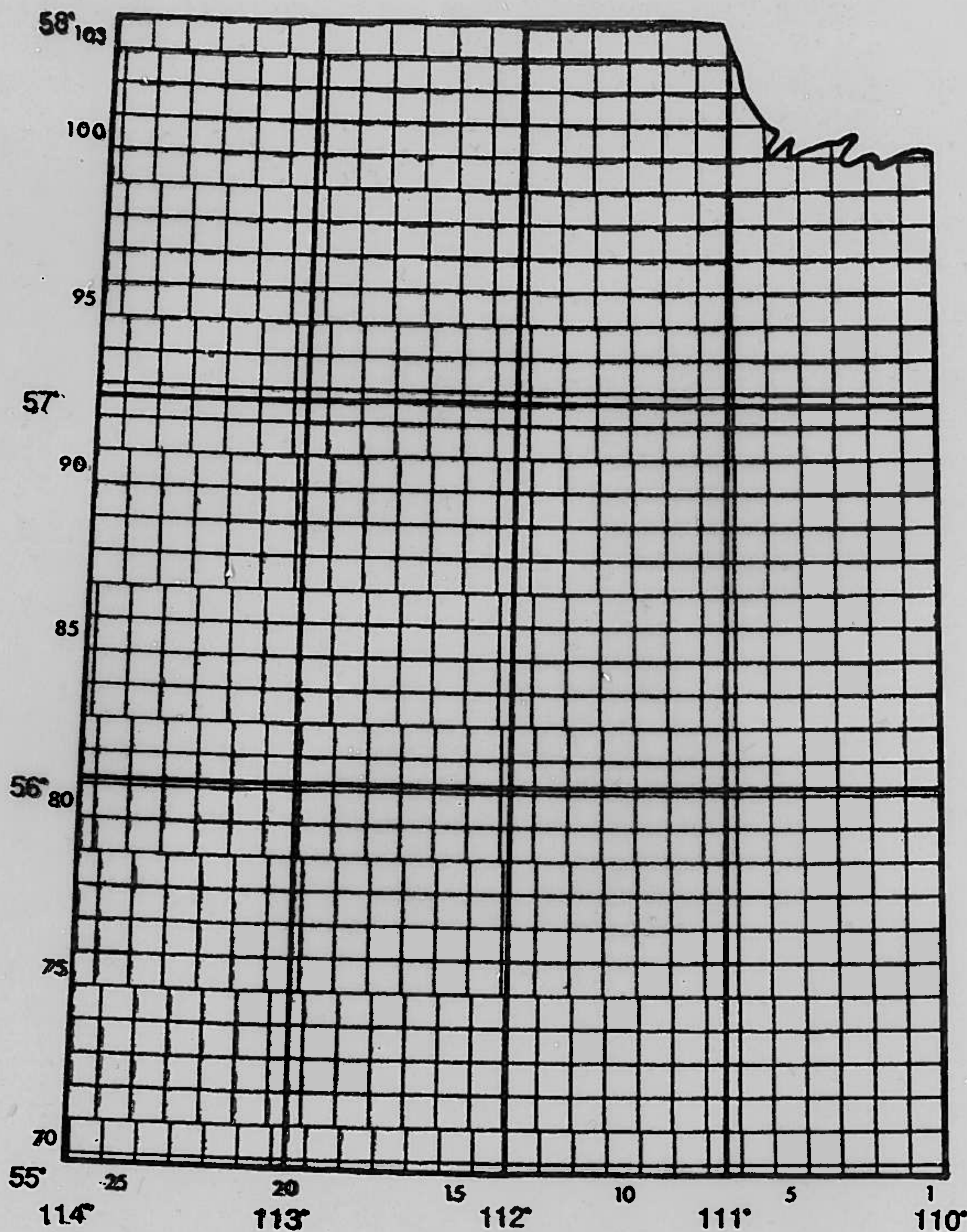
B - 25. Fish Scale Zone structure map.



B - 26. Second White Speckled Shale structure map.



B - 27. Ground Surface elevation map.


58°
103
100
95
57°
90
85
56°
80
75
70
55°
25
20
15
10
5
1
114°
113°
112°
111°
110°