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BASELINE HYDROGEOLOGICAL REGIME AT THE INTERMEDIATE SCALE, AOSTRA UNDERGROUND TEST FACILITY

Prepared For
Conservation and Protection, Environment Canada

by

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ALBERTA GEOLOGICAL SURVEY
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DISCLAIMER

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EXECUTIVE SUMMARY

This report presents the baseline hydrogeological regime of formation waters in the Phanerozoic sedimentary succession in an area of approximately 4000 km^2 (5x8 townships) surrounding the Alberta Oil Sands Technology and Research Authority (AOSTRA) Underground Test Facility (UTF) near Fort McMurray in northeast Alberta. The study was prompted by the AOSTRA plans to expand the Underground Test Facility to a pilot operation. As part of this expansion, it is envisaged to dispose of residual waters by on-site deep well injection. Environment Canada and the Alberta Research Council initiated in 1990 a collaborative study on the effects of deep injection of residual water at the UTF site, with data support and cooperation from AOSTRA. The evaluation of the effects of deep injection of residual water is based on predictive modelling, which requires knowledge of the initial baseline hydrogeological conditions. Previous regional-scale studies of the hydrogeological regime in the sedimentary succession in northeast Alberta are too coarse for the resolution needed for predictive modelling at the UTF site. On the other hand, the data are very scarce and incomplete at the local scale. Thus, an intermediate-scale hydrogeological study is required for the identification and characterization of the hydrostratigraphic units at the UTF site, which form the content of this report.

The intermediate-scale hydrostratigraphy around the UTF site is less complex than at the regional scale because of the absence of Lower Elk Point Group halite beds and

of extensive pre-Cretaceous erosion of Devonian strata. The sedimentary succession can be broadly divided into four main flow units (aquifers) separated by three barriers (aquitards or aquicludes). The flow of formation waters in the lowermost unit, the Winnipegosis-Basal aquifer, is regional in nature. The formation waters are very saline, with depth related trends. The halite and shale Prairie-Watt Mountain aquiclude separates this aquifer from the Beaverhill Lake aquifer above, which exhibits local flow regime characteristics. The formation water salinity is much fresher, and the flow directions are toward the northeast where the formation waters discharge at outcrop along the Athabasca River and its tributaries. The McMurray-Wabiskaw aquifer also has local flow-regime characteristics, being controlled by the topography and physiography of the area. The bitumen-saturated sands at the McMurray Formation seem to form a strong barrier, separating the flow systems in the Beaverhill Lake below and McMurray-Wabiskaw above, respectively. The shaley Clearwater aquitard, overlying the McMurray-Wabiskaw aquifer, appears to be a strong barrier to flow. However, its integrity in places may be questionable because of recent and present-day erosion. The post-Clearwater aquifers of Grand Rapids and Pleistocene strata are of limited extent, with paleo-valleys cutting down in places into the Clearwater aquitard.

INTRODUCTION

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. One of the byproducts of the bitumen extraction is residual water, which is planned to be disposed of by on-site deep well injection. AOSTRA has and is addressing environmental problems related to the UTF operation, including the issue of subsurface disposal of residual water. However, the UTF operations provide 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 the environmental effects of deep injection of residual water at the UTF site, predictive modelling of the associated hydrodynamic, geochemical and geomechanical processes is required. To perform this, it is necessary to know the initial baseline hydrogeological conditions prior to the start of injection, and the relevant parameters and characteristics of the subsurface environment. The UTF site is located on about 9 ha (22 acres) situated some 50 km northwest of Fort McMurray in sections 7 and 18, Township 93, Range 12, W4 Meridian (Figure 1). A previous analysis of data availability for predictive modelling at the UTF site (Basin Analysis Group, 1988) identified

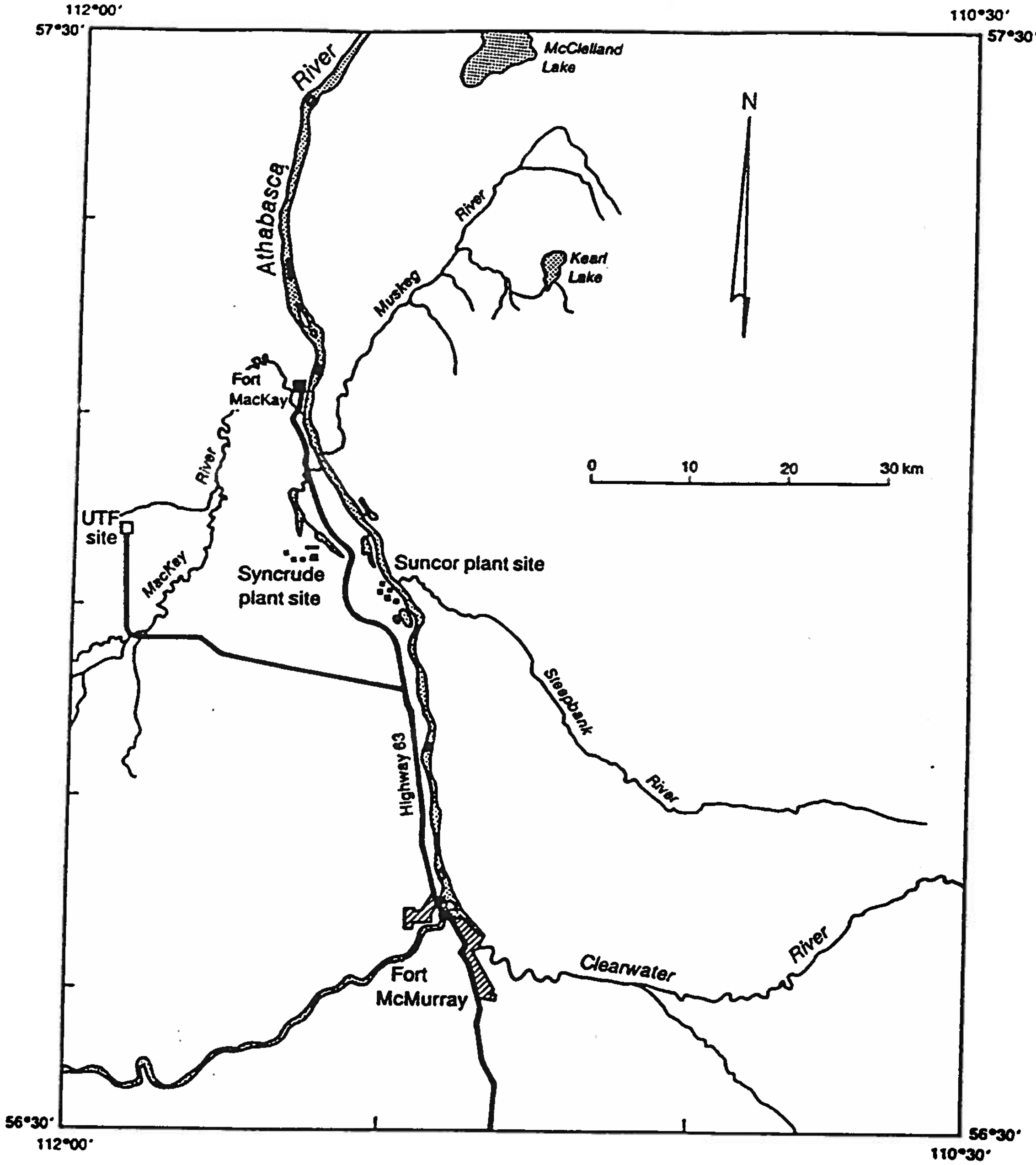


Figure 1. Location map of the UTF site.

four different scales of study: a detailed 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. The main recommendation of the Basin Analysis Group (1988) study was to define at a regional scale the distributions of variables such as pressure (hydraulic head), permeability and salinity, because data required to perform predictive modelling and monitoring at the local scale are unavailable.

Few hydrogeological data exist at or around the UTF site, making any direct evaluation at the local or intermediate scale unreliable. For this reason, a regional-scale hydrogeological characterization of the Phanerozoic succession in northeast Alberta (Figure 2) was conducted (Petroleum Geology and Basin Analysis Group, 1991, 1992), as recommended by the data availability study (Basin Analysis Group, 1988). The regional-scale study shows that the formation waters flow generally from southwest to northeast, with strong local topographic and physiographic control. Formation water salinity is generally depth (temperature) related, with comparably high values in the vicinity of Elk Point evaporite beds. On the basis of flow characteristics, the individual aquifers and aquifer systems, whose main characteristics are shown in Figure 3, can be grouped into pre-Prairie Formation aquifers, Beaverhill Lake-Cooking Lake aquifer system, Grosmont-to-Wabamun aquifers, and Cretaceous aquifers. Pre-Prairie Formation aquifers exhibit regional flow-regime characteristics, with depth (temperature) related salinity trends and a northeastward flow direction. Overall high formation water salinity is associated with the proximity of evaporitic beds. The Beaverhill Lake-Cooking Lake aquifer system

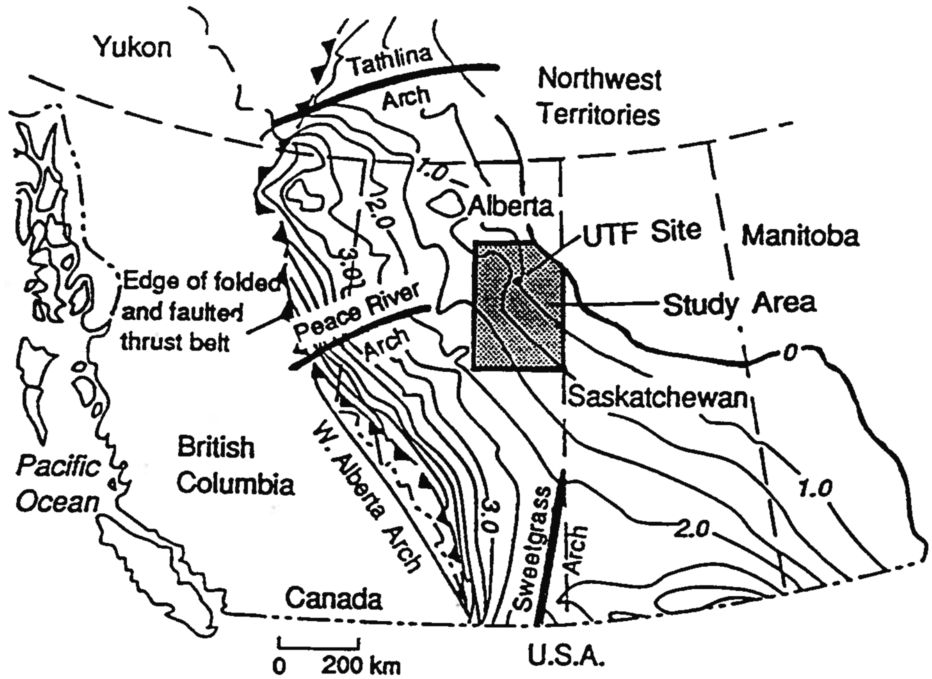


Figure 2. Location of the Northeast Alberta regional-scale study area.

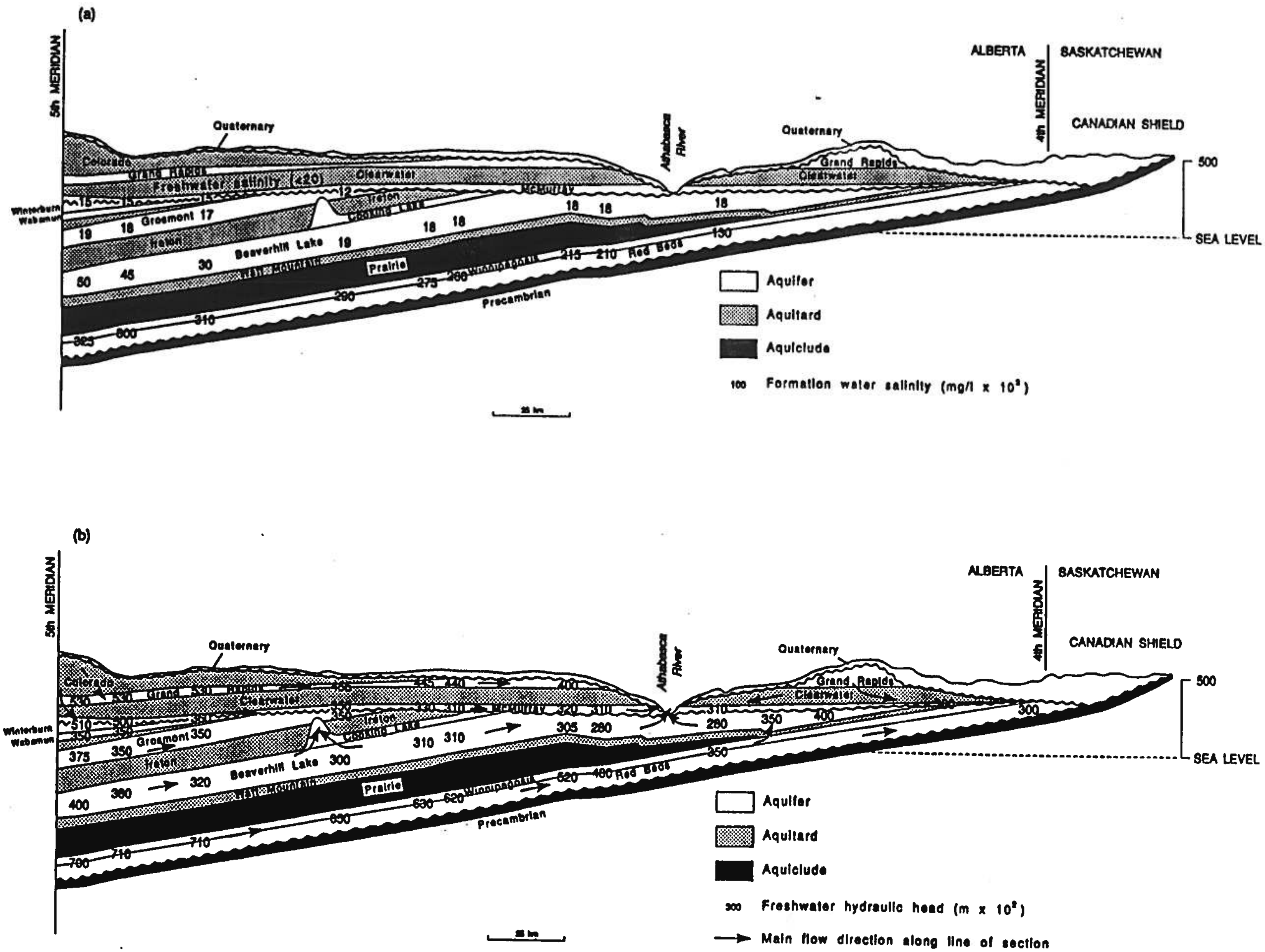


Figure 3. Hydrogeological dip cross-section showing distributions of: (a) salinity of formation waters; and (b) hydraulic head. Cross-section location is shown in Figure 4 (cross-section from Wright, 1984).

has hydraulic characteristics consistent with an intermediate-to-local flow regime. Formation water salinity is lower than that observed for Elk Point aquifers, indicating a lack of hydraulic communication with Elk Point Group evaporites across the Watt Mountain aquitard. Generally, formation fluids flow to the northeast. However, within the subcrop area and along the outcrop edge, local physiographic influences are superimposed over this regional trend. Grosmont-to-Wabamun aquifers are significant in that they may act locally as a "drain" for aquifers in hydraulic continuity above and below. The formation water salinity is low and flow is generally to the northwest, towards the outcrop and discharge along the Peace River northwest of the Birch Mountains. Cretaceous aquifers can all be described as having local flow regime characteristics. Formation water salinity is near fresh water, and flow is strongly influenced by topography and physiographic features. These patterns and trends observed at the regional scale are fundamental to interpreting the hydrogeological regime at the intermediate and local scales from the limited data available.

The regional-scale study (Petroleum Geology and Basin Analysis Group, 1992) covers a broad enough area to contain sufficient data from which distribution fields of hydrogeological variables, such as hydraulic head and formation water salinity, could be established. Also, the regional-scale study area contains enough petrophysical data to characterize statistically individual aquifers. Because data at the local UTF site scale are limited to Lower Cretaceous strata, it is unreasonable and unwise to evaluate the hydrogeological regime at the UTF site directly from the regional-scale characterization.

With no data to tie the regional-scale characterization to the "zoomed in" area, any site specific characterization would simply be a manifestation of computer interpolation at the regional-scale. For this reason, an intermediate-scale characterization is needed, to serve as a basis for local-scale analysis and modelling. The study area forming the object of this report was chosen to include data around the UTF site pertaining to the main aquifers or aquifer systems present at the UTF site itself. The hydrostratigraphic and hydrodynamic delineation at the intermediate-scale and the hydrogeological analysis and characterization presented in this report will form the basis for initial modelling (coarse resolution) of deep injection of residual waters. The initial modelling will serve to delineate the area of influence (impact) that the proposed injection will have on the natural hydrogeological regime. The results of this initial modelling will determine the size of the local, site-specific study area to be used further in detailed (fine resolution) hydrogeological analysis and numerical modelling of the effects of deep injection of residual water at the UTF site.

DATA SOURCES AND PROCESSING

To evaluate properly the hydrogeological regime in the study area, a geological framework must be established within which hydrogeological data and rock properties can be located. The distribution fields of hydraulic head and formation water salinity are mapped for individual units based on information from drillstem tests and formation water analyses, respectively. Rock properties (porosity and permeability) are analyzed statistically for representative values at both the well and formation scale. Drillstem tests and core analyses are the main sources of information for this analysis. The basic data processing procedures are similar to those used for the regional-scale study (Petroleum Geology and Basin Analysis Group, 1992).

Although there is good well control for geological and petrophysical characterization of Lower Mannville strata at the UTF site, the number of core analyses, drillstem tests and formation water analyses for other strata is limited in the vicinity of the UTF site. For this reason, two intermediate-scale areas were chosen, one for the Cretaceous and one for the Paleozoic strata, for which the hydrostratigraphic framework and its contained waters were characterized. Figure 4 shows the UTF site, the intermediate-scale study area for Cretaceous strata (Tp 92 - 95, R 11 -14 W4 Mer) and the larger intermediate-scale study area for Paleozoic strata (Tp 90 - 97, R 10 - 14 W4 Mer) within the regional-scale Northeast Alberta study area (Petroleum Geology and Basin Analysis Group, 1991, 1992). The Paleozoic study area was selected in such a way as to include as much

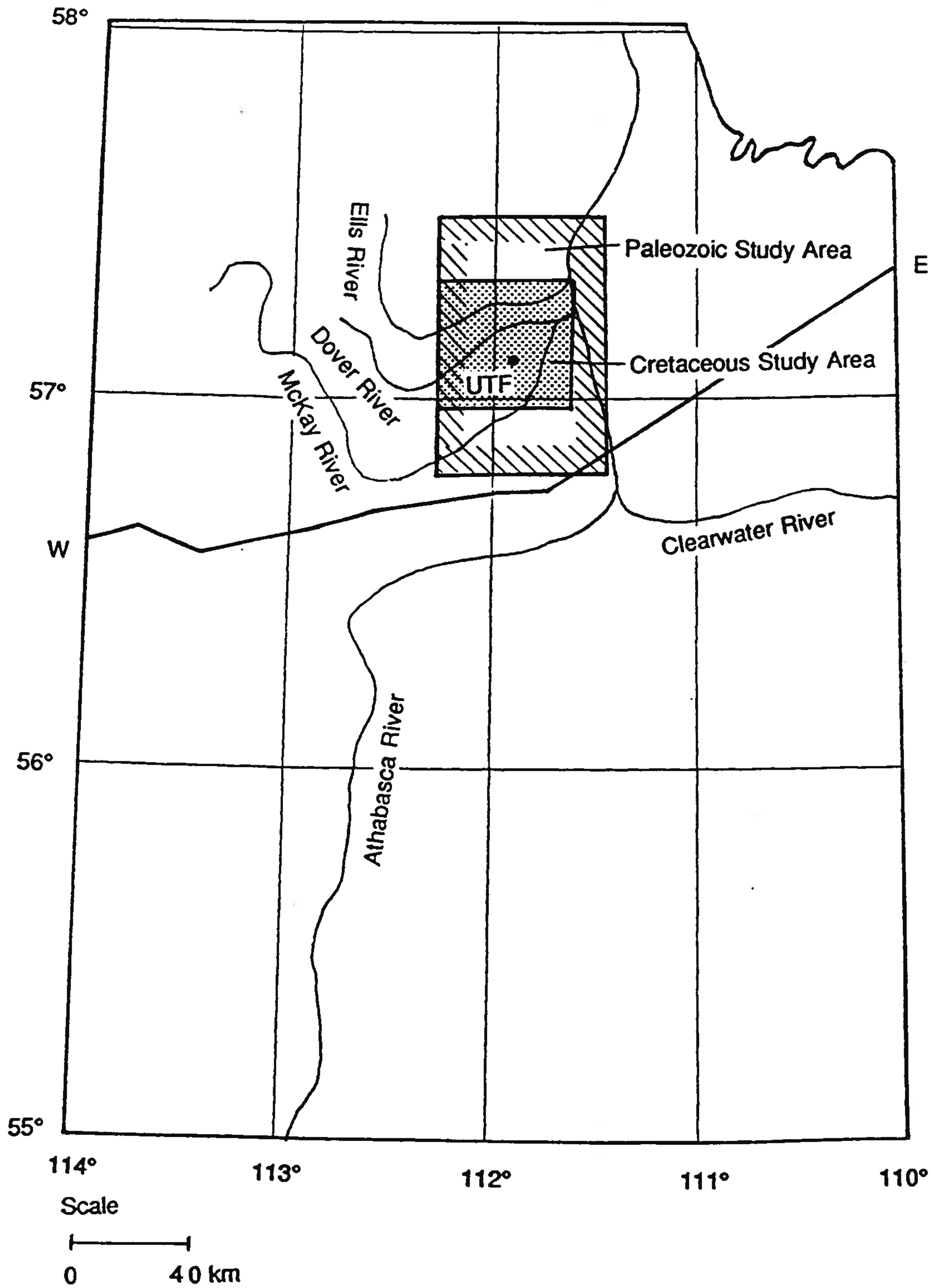


Figure 4. Location map of the Cretaceous and Paleozoic intermediate-scale study areas.

nearby data as possible without becoming unreasonably large. However, there are still too few drillstem tests, core analyses and analyses of formation waters to perform spatial/trend analysis. Information from the regional-scale characterization (Petroleum Geology and Basin Analysis Group, 1992) was used in these cases. Only for some formations are permeability and porosity data plentiful enough to allow processing and analysis without reference to the regional scale.

Because the intermediate-scale stratigraphic, hydrostratigraphic and hydrogeological characterization (hydraulic head and salinity of formation waters) required information from the regional-scale characterization, a "zooming" procedure was used. This was accomplished through the use of various grid manipulation techniques, where a grid is defined as a mathematical re-sampling (interpolation) into an uniformly distributed pattern of irregularly located parameter determinations. A land location was automatically assigned to all the values in the regional-scale grids whose location falls within the intermediate-scale study areas. The grid data were then extracted as a synthetic data set and reinterpolated into a new intermediate-scale grid with higher resolution. This way, the regional-scale characterization based on all available data in northeast Alberta was used for intermediate-scale interpolation where few or no data exist.

GEOLOGICAL DATA

At the intermediate scale around the UTF site, Paleozoic strata consist of the Elk Point and Beaverhill Lake groups, with the Beaverhill Lake Group subcropping at the sub-Cretaceous unconformity throughout the area. Cretaceous strata are represented by the Mannville Group, with more recent strata being completely removed from the area by Tertiary to present erosion. A large number of wells (1663) are located within the Cretaceous local study area, most of which terminate at the sub-Cretaceous unconformity. The stratigraphic nomenclature for the intermediate-scale sedimentary succession is summarized in Table 1.

The regional-scale stratigraphic geometry, based on all the available picks data, is considered sufficiently accurate for the major stratigraphic breaks in the intermediate-scale area. Thus, it was used as a basis for defining the stratigraphic geometry for the intermediate-scale areas. As a check, six cross-sections (three Paleozoic and three Cretaceous) (Figure 4) were constructed and examined in detail to ensure that the picks data used in the regional-scale characterization are appropriate at the intermediate scale. Manual examination of geophysical logs for all the wells penetrating the Paleozoic strata resulted in a breakdown of the Beaverhill Lake Group (mapped regionally as a single unit) into the Fort Vermilion, Slave Point and Waterways formations. The Waterways Formation was in turn subdivided, in ascending order, into the Firebag, Calumet, Christina, Moberly and Mildred members. These horizons were mapped and inserted into

EON	ERA	Period		Group		Formation
Phanerozoic	Cenozoic	Quaternary Tertiary		Pleistocene deposits		
	Mesozoic	Cretaceous	Lower	Mannville		Grand Rapids
						Clearwater
						McMurray
		Jurassic				Sub-Cretaceous Unconformity
		Triassic				
	Paleozoic	Permian				
		Carboniferous				
		Devonian	Upper	Beaverhill Lake		Waterways
						Slave Point
						Fort Vermilion
			Middle	Elk Point	Upper	Watt Mountain
						Prairie
						Winnipegosis (Keg River)
					Lower	Contact Rapids
			Lower			Ernestina
						Granite Wash / Basal Red Beds
		Silurian				
		Ordovician				
		Cambrian				
Pre-cambrian						

Table 1. Stratigraphic succession and nomenclature around the UTF site.

the electronic stratigraphic frame obtained from the regional study. A significant effort was made to ensure that the subcropping areas of the Waterways Formation members, which were mapped individually, match exactly their respective portions of the sub-Cretaceous unconformity, mapped separately. The structure tops and isopachs for the Paleozoic and Cretaceous stratigraphic units are shown in Appendices A and B, respectively. The six cross-sections, both stratigraphic and structural, are shown in Appendix C. The boundaries of the Grand Rapids and Clearwater formations and of the Wabiskaw Member (the basal sandy portion of the Clearwater Formation) have been slightly modified compared to those used in the regional-scale study as a result of field work along the McKay and Dover rivers and of manual geophysical log analysis.

ANALYSES OF FORMATION WATER

All the analyses of formation water chemistry within the intermediate-scale study areas have previously been variously culled as part of the regional-scale evaluation (Petroleum Geology and Basin Analysis Group, 1992), resulting in only four good quality analyses from three wells (one from the Ernestina/Basal Red Beds unit, one from the Beaverhill Lake Group, and two from the McMurray Formation). The location of the wells with analyses of formation water is shown in Figure 5, while the actual analyses are listed in Appendix D. These data provide local control on the distribution of various formation-water ion concentrations. For mapping purposes, it was necessary to use the regional-scale characterization of formation water salinity as the main source of information.

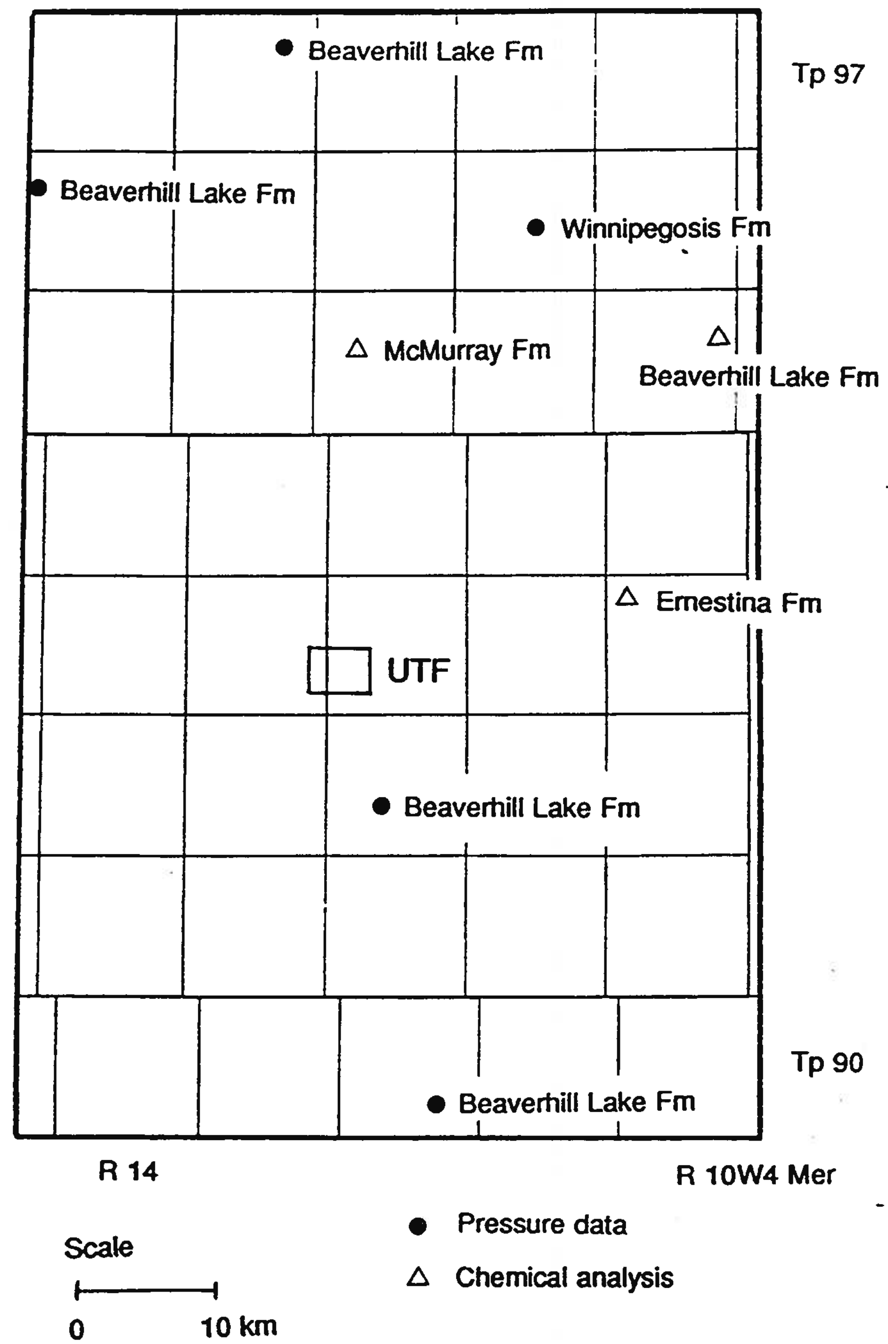


Figure 5. Distribution of formation water chemistry and pressure data.

DRILLSTEM TESTS

Twelve drillstem tests from 8 wells (3 within the same Legal Sub-Division (LSD)) record pressure data suitable for calculating freshwater hydraulic head, none of which are from Cretaceous strata (two from the Winnipegosis Formation and ten from the Beaverhill Lake Group). Figure 5 shows the location of wells with drillstem tests used to calculate site specific freshwater hydraulic heads, whose values are listed in Table 2. Because of the high formation water salinity within the Winnipegosis Formation and to a lesser extent within the Beaverhill Lake Group, density (buoyancy) effects on flow can be significant (Davies, 1987; Dorgarten and Tsang, 1991; Petroleum Geology and Basin Analysis Group, 1992). Therefore, the distributions of freshwater hydraulic head for these units do not represent a potential field driving the flow. The analysis of the relative importance of density versus gravity driven flow (Petroleum Geology and Basin Analysis Group, 1992) can be transposed from the regional scale to the intermediate scale. Similarly to the case of formation water salinity, the existing drillstem test data provide only local values of hydraulic head. Because of insufficient data for deriving accurate distribution maps, the regional-scale hydraulic head distributions were used at the intermediate scale.

Only three drillstem tests from 3 wells (one from each of the Beaverhill Lake, McMurray and Wabiskaw units) record data suitable for calculating formation permeability. Table 2 lists the calculated permeability values, with their distribution shown in Figure 6. The regional-scale characteristic values obtained from drillstem tests (Petroleum Geology

Table 2. Hydraulic head and permeability values from drillstem tests and core analyses around the UTF site.

Unit	Well	Drill Stem Tests			Core Analyses	
		Elevation (m)	Hydraulic Head (m)	k (m^2)	k_m (m^2)	k_v (m^2)
Winnipegosis	08-15-96-11W4 Mer	- 6.78	513.63			
		- 38.40	596.25			
	06-18-93-12W4 Mer				$1.33x10^{-15}$	
Beaverhill Lake	09-26-97-13W4 Mer	221.59	518.54			
	12-30-96-14W4 Mer	128.78	362.68	$4.7x10^{-16}$		
	08-15-96-11W4 Mer	131.36	205.32			
		110.03	230.92			
		95.71	306.37			
	04-15-92-12W4 Mer	179.53	255.48			
		136.25	232.63			
	01-08-92-13W4 Mer	280.15			$1.40x10^{-15}$	
	08-11-90-12W4 Mer	244.91	304.48			
		211.38	401.99			
		177.70	229.51			
McMurray	13-07-95-14W4 Mer	293.74		$3.5x10^{-16}$		
	14-07-93-12W4 Mer				$1.96x10^{-12}$	$1.06x10^{-12}$
	01-13-92-11W4 Mer	256.10			$5.21x10^{-15}$	
	03-13-92-11W4 Mer	282.30			$4.25x10^{-15}$	
	05-13-92-11W4 Mer	261.10			$1.58x10^{-15}$	
Wabiskaw	13-07-95-14W4 Mer	306.84		$8.7x10^{-15}$		

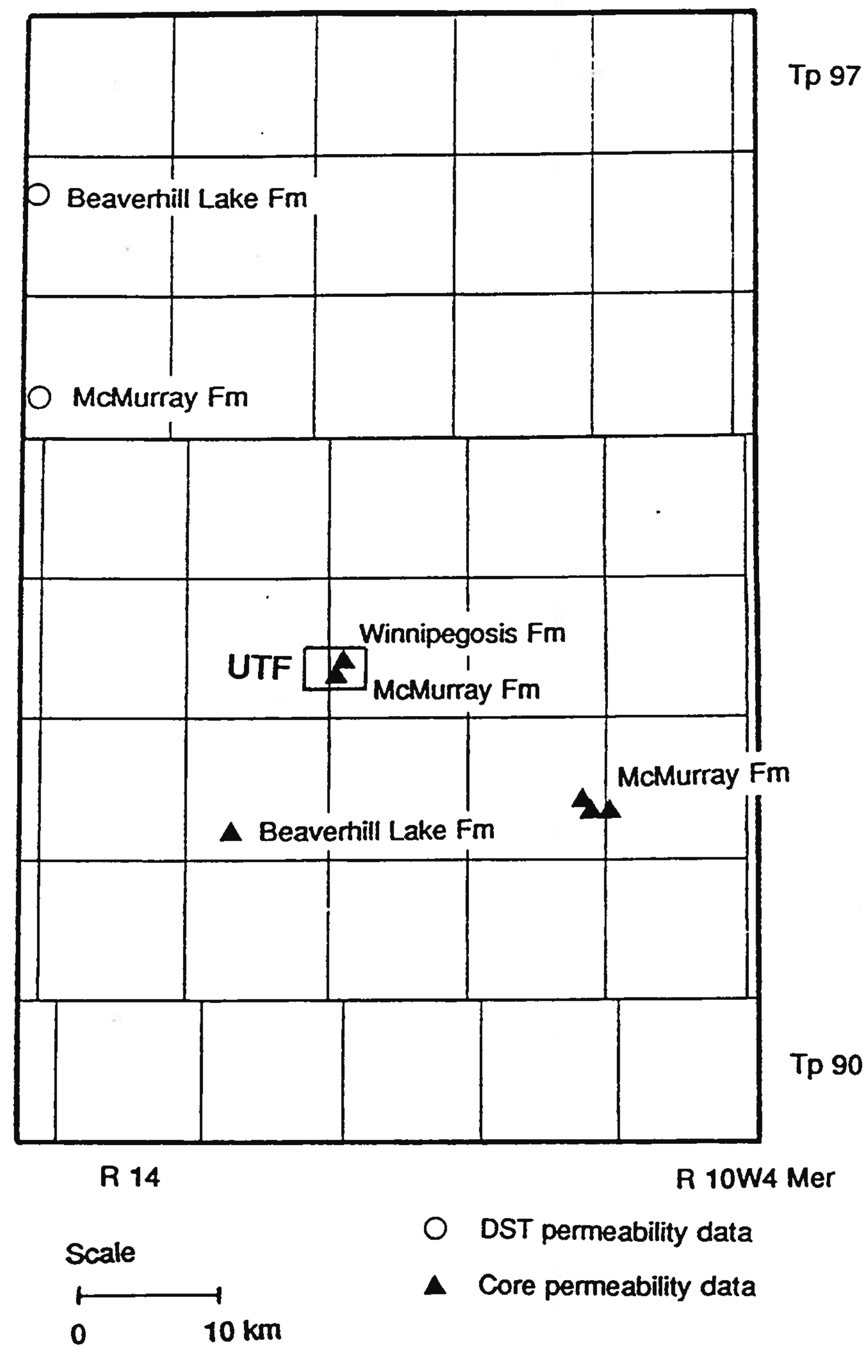


Figure 6. Distribution of drillstem-test and core permeability data.

and Basin Analysis Group, 1992) should be considered for permeability because there are too few data within the intermediate-scale study areas to determine a statistically meaningful characteristic value for each aquifer.

CORE ANALYSES

Many wells within the intermediate-scale study areas have had core taken. However, maximum permeability k_m was measured at only 17 of these (one from the Winnipegosis Formation, one from the Beaverhill Lake Group and 15 from the McMurray Formation). Of these, 12 record the permeability of the McMurray Formation at the UTF site (confined to within a single LSD). Figure 6 shows the distribution of wells containing core analyses with maximum permeability determinations. The well-scale permeability values obtained from core analyses are listed in Table 2. Because of the proximity of the core plug analyses from the 12 UTF wells, they were treated as being at a single location (14-07-93-12W4 Mer) in the intermediate-scale study area. A single well-scale characteristic value for maximum permeability of the McMurray Formation at the UTF site was calculated as the geometric average of all the plug measurements (Dagan, 1989; Bachu and Underschultz, 1992). It should be noted that the well-scale permeability value for the McMurray unconsolidated sands at the UTF site is three orders of magnitude greater than the well-scale values at the other locations. The measurements at the UTF site were performed on bitumen saturated samples after removal of bitumen, and may not be representative for the permeability of McMurray water-saturated sands. There are no permeability determinations in the horizontal plane normal to the maximum permeability, and only 8 wells (all in the McMurray Formation site within the same LSD at the UTF) have permeability measurements in the vertical direction (k_v). Based on 30 k_m-k_v pairs, a vertical anisotropy of 0.79 was calculated for the McMurray Formation at the UTF site. This value should be used with caution because the plot of maximum versus vertical permeability values shows a poor correlation. As in the case of drillstem-test permeability values, data are generally missing or too few for a meaningful statistical analysis. Therefore, the regional-scale characteristic values determined for each unit (Petroleum Geology and Basin Analysis Group, 1992) should be considered when estimating the intermediate-scale permeability for units with insufficient information.

Porosity is the most common rock property analyzed in core from wells in the intermediate-scale study areas. There are 551 wells containing core analyzed for porosity in Beaverhill Lake strata (Figure 7). The distribution of wells containing core associated with porosity determinations within the McMurray and Wabiskaw units is shown in Figure 8. Of these, 716 record porosity in the McMurray Formation and 280 record the porosity of the Wabiskaw Member, the basal sandy member of the Clearwater Formation. There are sufficient data within the Beaverhill Lake, McMurray and Wabiskaw units to calculate intermediate-scale characteristic values for porosity (Table 3). Since porosity is a scalar property of the rocks (Dagan, 1989), the arithmetic weighted average of the plug measurements was used in a scaling-up process to obtain a characteristic value (Bachu and Underschultz, 1992). The regional-scale characteristic values (Petroleum

Geology and Basin Analysis Group, 1992) should be used for strata with no data.

Permeability and porosity measurements were taken in the same plugs only for core from McMurray strata at the UTF site. Statistical analysis of these data indicate no direct relation between the two rock properties, similarly to findings at the regional scale.

Table 3. Intermediate-scale characteristic values for porosity derived from core analyses around the UTF site.

Unit	No. of Wells	Porosity			
		Min.	Max.	Ave.	St. Dev.
Slave Point	6	0.100	0.351	0.241	0.094
Firebag	158	0.086	0.400	0.306	0.041
Calumet	16	0.182	0.360	0.291	0.063
Christina	41	0.190	0.410	0.313	0.050
Moberly	419	0.077	0.420	0.295	0.029
McMurray	716	0.151	0.378	0.308	0.016
Wabiskaw	280	0.186	0.396	0.308	0.024

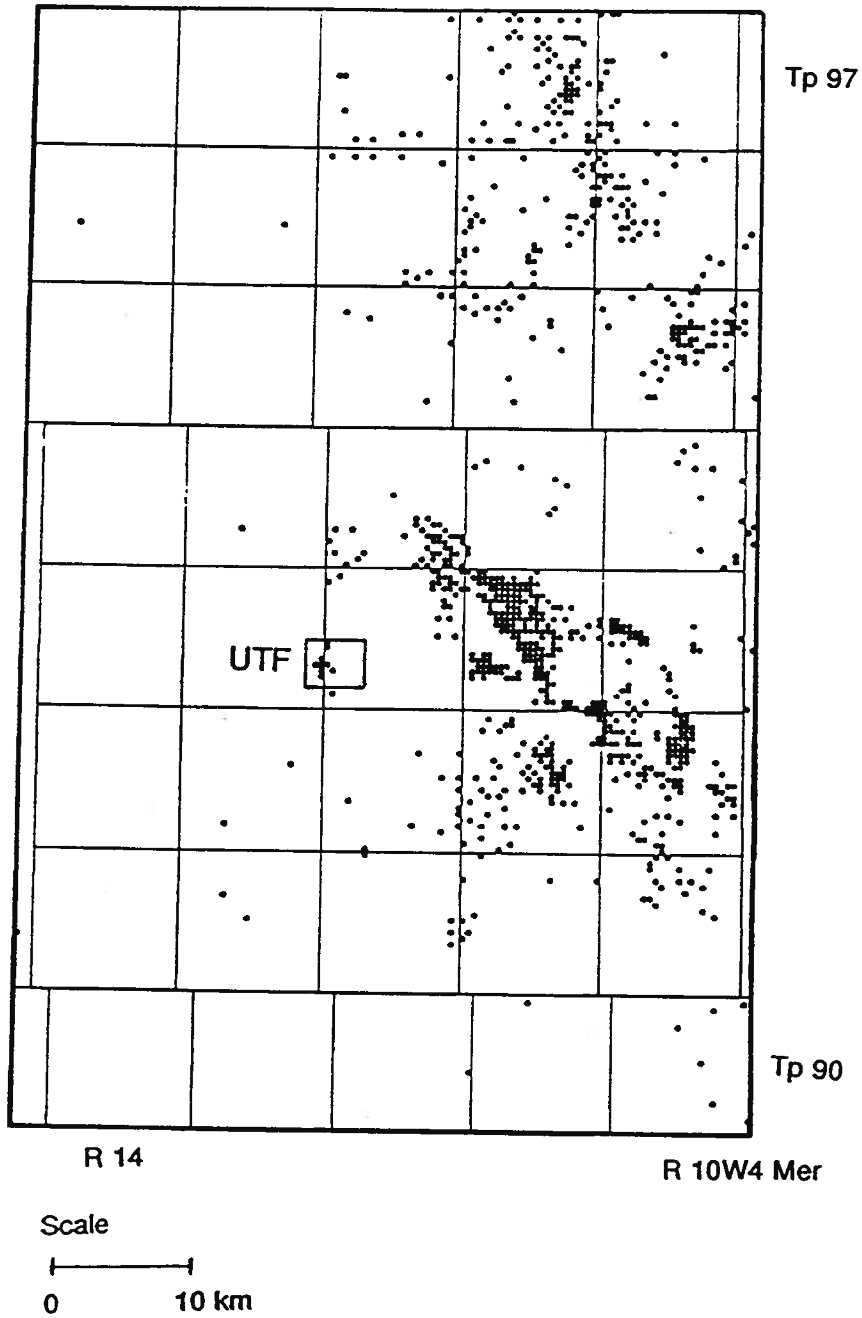


Figure 7. Distribution of wells with porosity measurements in the Beaverhill Lake Group.

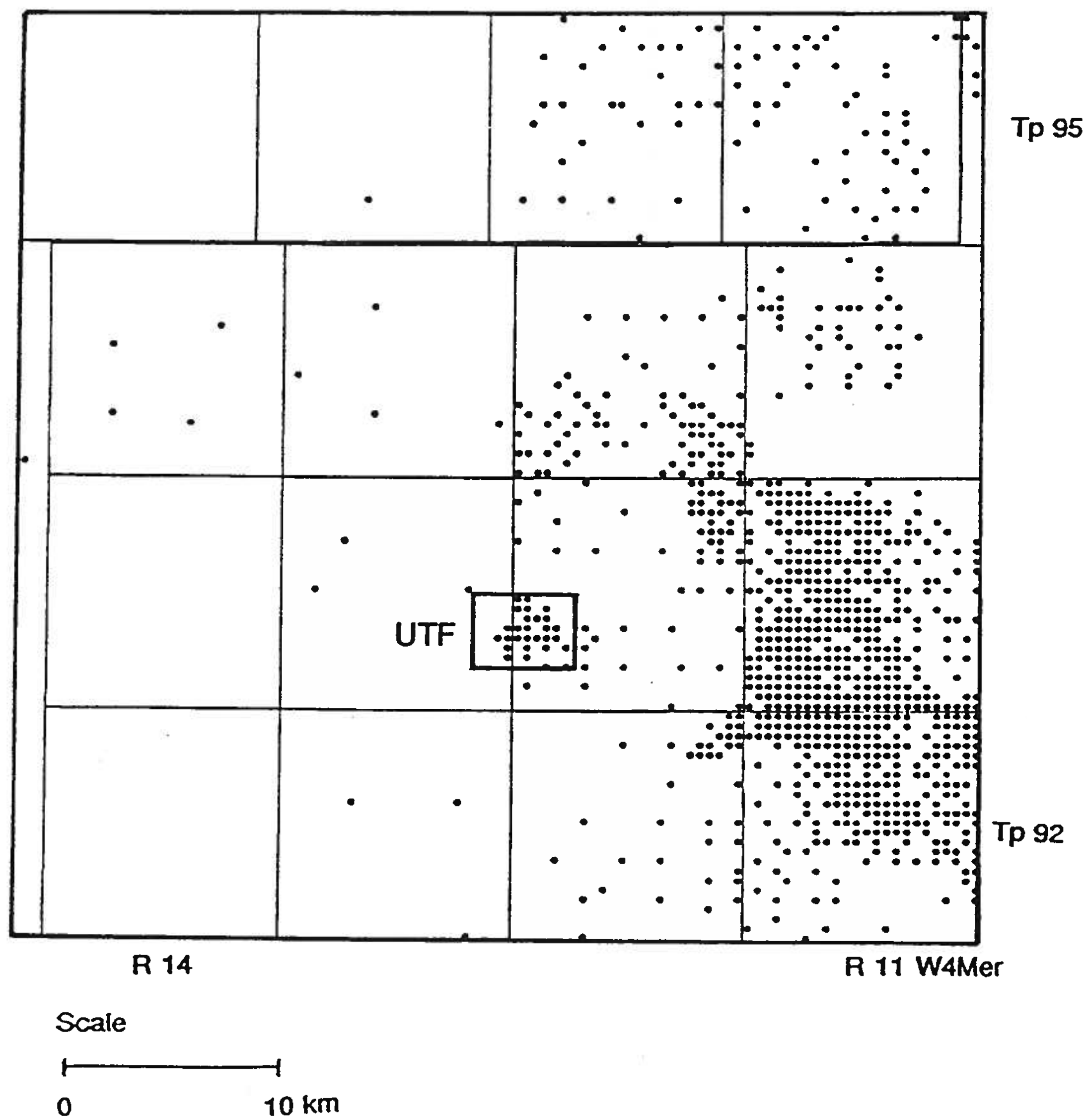


Figure 8. Distribution of wells with porosity measurements in the McMurray Formation and Wabiskaw Member.

GEOLOGY

As mentioned previously, the geological and stratigraphic framework has to be established first, to serve as a basis for the analysis of the hydrogeological regime of formation waters. The sedimentary succession around the UTF site is broadly divided into Paleozoic passive-margin strata and Cretaceous foreland-basin strata (Table 1). The regionally significant sub-Cretaceous angular unconformity separates these stratigraphic successions.

PALEOZOIC

The Paleozoic succession consists of Lower to Upper Devonian strata from the Elk Point and Beaverhill Lake groups (Table 1), shown in a typical well log suite in Figure 9. The Devonian succession is bounded unconformably at the base by the Precambrian basement and at the top by the sub-Cretaceous unconformity. These two bounding unconformities, combined with dissolution of evaporites within Devonian formations, have played a key role in forming the present day configuration of the Paleozoic strata within this study area. The lithology typically consists of evaporites, carbonates and shales, with minor occurrences of sandstone and siltstone. The Paleozoic succession forms a northeast tapering wedge ranging in thickness from 515 m in the southwest to 180 m in the northeast (Appendix A, Figure 1).

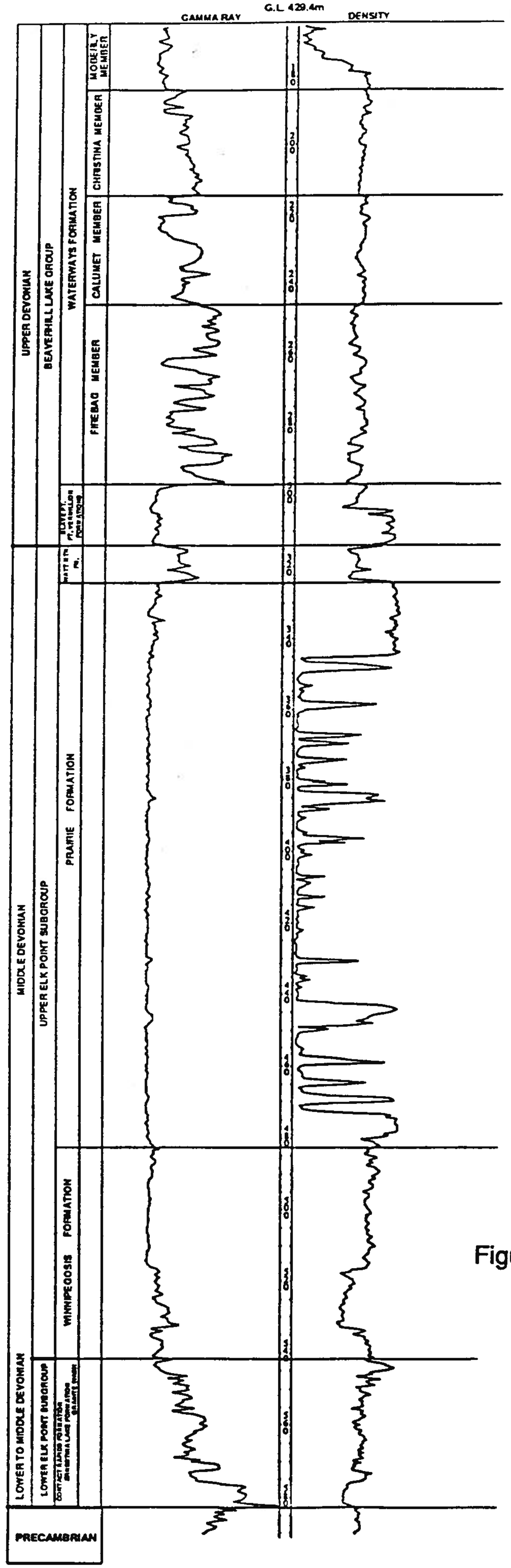


Figure 9. Paleozoic type well.

Paleozoic well control within the study area is sparse, especially for the lowermost portions of the succession (Lower and Upper Elk Point subgroups). The best data control is concentrated within the upper portions of the Beaverhill Lake Group, particularly in areas of active Cretaceous oil sand exploitation.

Precambrian Basement Structure

The structure on the Precambrian basement consists of a relatively uniform surface dipping 4-6 m/km to the southwest (Appendix A, Figure 2). Structure elevations range from -257 m in the southwest to -9 m in the northeast. Several localized control points in the northeast indicate a small structural high at Tp 95-96, R 10-11 W4 Mer. Well control elsewhere within the study area is sparse. Figures 1b and 3b in Appendix C show the regional dip on the Precambrian surface and the localized high in the northeast, respectively.

Lower to Middle Devonian Lower Elk Point Subgroup

Overlying the Precambrian basement is the thin, often absent, succession of Granite Wash and Ernestina Lake Formation strata. Overlying these strata and marking the boundary between the Upper and Lower Elk Point subgroups is the Contact Rapids Formation. The Granite Wash generally consists of regolithic, arkosic sandstones and conglomerates. The Ernestina Lake Formation, identified in only three wells, consists of dolomitic shale, anhydritic limestone and anhydrite. The Contact Rapids Formation consists of argillaceous dolomite and dolomitic shale, which grades from red at the base to grey and green at the top.

The Lower Elk Point Subgroup consists mostly of the Contact Rapids Formation. The combined thickness of the underlying Granite Wash and Ernestina Lake Formation is seldom greater than 5 m. Due to sparse well control and inadequate geophysical log suites, the Granite Wash and Ernestina Lake Formation could not be accurately delineated in the stratigraphic succession. As a result, the strata were combined with the Contact Rapids Formation and mapped as a single entity in this region. The structure on top of the Contact Rapids Formation (Appendix A, Figure 3) closely resembles the structure of the underlying basement. The surface dips at 4-6 m/km to the southwest. The thickness of the interval ranges from 52 m in the southwest to 23 m in the northeast (Appendix A, Figure 4). The succession of strata thins over structurally high regions (Appendix C, Figure 3a).

Middle Devonian Upper Elk Point Subgroup

Formations within the Upper Elk Point Subgroup consist of, in ascending order: Winnipegosis, Prairie, Muskeg, and Watt Mountain.

Winnipegosis Formation

The Winnipegosis Formation conformably overlies the Contact Rapids Formation. The Winnipegosis Formation is generally comprised of reef and non-reef carbonates of variable thickness, becoming increasingly argillaceous towards the base. This formation was recently cored in well 6-18-93-12W4 Mer at the AOSTRA UTF site. Here, the Winnipegosis Formation is relatively thick and is structurally high (Appendix C, Figure 2b). The core, as described by Glaister (1991), is comprised of dolomitized, fossiliferous, wackestones and packestones with lesser amounts of floatstones and rudstones. At this location, zones with intercrystalline and vuggy porosity have been filled with halite.

The structure on top of the Winnipegosis Formation (Appendix A, Figure 5) merely reflects the structure of the underlying surface. The thickness of the Winnipegosis Formation ranges from about 20 m to 80 m (Appendix A, Figure 6). South of Tp 95 the thickness is relatively uniform, averaging about 70 m. The Winnipegosis Formation thins dramatically to the north with the exception of variations occurring proximal to a Precambrian basement high in the northeast (Appendix C, Figures 1a, 2a and 3a).

Muskeg-Prairie Succession

The Prairie Formation is a relatively thick succession of strata consisting of evaporites, carbonates and minor shales. The Prairie Formation is capped by the interbedded evaporite and carbonate strata of the Muskeg Formation. An accurate lithological breakdown of the Muskeg-Prairie succession could not be made with confidence over most of the region because of inadequate log suites. Thus, the Prairie and Muskeg formations have been mapped as a single entity.

The structure on top of the Muskeg-Prairie succession (Appendix A, Figure 7) differs dramatically from the underlying structure surfaces. The structure map reveals a distinct reversal of dip starting at the 120 m structure contour located in the southwest. Figure 1b, Appendix C shows the dip reversal between 11-28-92-13W4 Mer and 6-18-93-12W4 Mer. This region marks the approximate western edge of salt dissolution which occurred within the Prairie Formation. Structure contours become very irregular and localized topographic relief of up to 100 m is apparent, especially in the northeast corner of the study area.

The isopach map of the Muskeg-Prairie interval shows the succession thinning dramatically from southwest to northeast (Appendix A, Figure 8). The thickness ranges from 280 m to 20 m. Extensive thinning occurs northeast of the AOSTRA-Underground Test Facility located in Tp 93, R 12. Figure 1a, Appendix C displays the stratigraphic thinning of the Muskeg-Prairie interval between wells 6-18-93-12W4 Mer (UTF) and 3-29-95-10W4 Mer. The well at the UTF consists of a rhythmic, thick, interbedded succession of salt, anhydrite and minor shale capped by carbonate. To the northeast at 3-29-95-10W4 Mer, essentially all of the salt has been removed by extensive dissolution, leaving only anhydrite and the upper carbonate unit. Dissolution along the Prairie Salt Scarp has produced a distinct, eastward tapering evaporite deposit. This regional structure significantly affects the geometry of the overlying sedimentary succession.

Watt Mountain Formation

The thin Watt Mountain Formation, consisting predominantly of dolomitic shale, disconformably overlies the Muskeg-Prairie succession. Because of its uniform thickness and lateral extent throughout, the structure on top of the Watt Mountain Formation (Appendix A, Figure 9) mimics the structural topography of the underlying Muskeg-Prairie succession. The Watt Mountain Formation ranges from 7 m to 12 m thick (Appendix A, Figure 10). Stratigraphic cross-sections emphasize the consistent thickness of this blanket-like unit (Appendix C, Figures 1a, 2a, 3a).

Upper Devonian Beaverhill Lake Group

Within the confines of study area, the Beaverhill Lake Group is comprised of, in ascending order, the Fort Vermilion, the Slave Point, and the Waterways formations. The Waterways Formation has been further subdivided into the Firebag, Calumet, Christina, Moberly, and Mildred members.

Slave Point-Fort Vermilion Succession

The Fort Vermilion Formation, consisting of anhydrite thinly interbedded with dolomites and limestones, is conformably overlain by the Slave Point Formation. The Slave Point Formation is comprised of limestone, silty limestone, and siltstone. The lack of adequate, lithology-defining geophysical logs combined with sparse well control prohibits obtaining an accurate pick for the boundary between the two units. As a result, the two formations were mapped as a single unit within the study area. Where defined, the Fort Vermilion Formation tends to be of equal thickness or thinner than the overlying Slave Point Formation.

Structural topography on top of the Slave Point Formation (Appendix A, Figure 11) is similar to the structure exhibited by the two underlying surfaces. Extensive salt dissolution within the underlying Prairie Formation is responsible for the present structural topography on top of the Slave Point-Fort Vermilion succession. The thickness ranges from 11 m to 26 m (Appendix A, Figure 12). The succession of strata tends to be thickest along the south and northwest borders of the mapped area and thins in the centre. Figure 1a, Appendix C shows a gradual change in the log character in the Slave Point-Fort Vermilion succession along a southwest-northeast trend. In the southwestern and central regions, gamma-ray logs show the upper section of the succession as being cleaner (less radioactive) than the lower section. The contact between the two sections becomes progressively better defined to the northeast. At 3-29-95-10W4 Mer the succession splits into two distinct units, with the lower unit considerably thinner at 4-12-96-10W4 Mer. A similar transition can be observed from northwest to southeast in Figures 2a and 3a, Appendix C.

Waterways Formation

The Waterways Formation overlies the Slave Point Formation. A major erosional unconformity forms the upper bounding surface.

Firebag Member: The Slave Point Formation is disconformably overlain by olive-green calcareous shale interbedded with thin olive-green argillaceous limestones and non-calcareous shales of the Firebag Member, the basal member of the Waterways Formation (Norris, 1973). Within the study area, the Firebag Member can generally be separated in two units. On well logs, the lower portion of the Firebag Member appears to be comprised of interbedded shale and argillaceous limestone, while the upper portion is dominated by shale with minor thin carbonate-rich beds.

Structural topography on top of the Firebag Member (Appendix A, Figure 13), closely resembles the structure exhibited by the Watt Mountain and Slave Point formations. Thickness variations of the Firebag Member range from 25 m in the northeast to 55 m in the southern region (Appendix A, Figure 14). The isopach map shows a relatively uniform thickness, averaging 50 m throughout the region except for the northeast corner where the Firebag Member thins significantly. Here the Sub-Cretaceous unconformity downcuts deeply into the Waterways Formation (Figure 1a, Appendix C). At 4-12-96-10W4 Mer all that remains of the Waterways Formation is the basal portion of the Firebag Member. Oil sands within the Cretaceous McMurray Formation directly overlie the Firebag Member in this localized area.

Calumet Member: The Firebag Member is overlain by the Calumet Member. The lithology within the Calumet Member consists of grey to buff clastic limestone, variably argillaceous limestone, nodular calcareous shale, and minor amounts of non-calcareous shale (Norris, 1973). Two distinct limestone units separated by a relatively thick shale characterize the Calumet Member within the study area. On a gamma-ray log the two limestones appear very similar with the exception that the lower unit is more argillaceous.

Where the Calumet Member is present, its structure (Appendix A, Figure 15) follows the general trend and displays the same topographic features as the underlying Firebag Member. Regionally, the thickness of the Calumet Member is remarkably uniform. Within the study area the isopach values range from 0 to 33 m

(Appendix A, Figures 15 and 16). In the northern region (Tp 95-96) the Calumet Member has been removed by erosion. The approximate outline of the Calumet Member boundary (Appendix A, Figures 15 and 16) is based on knowledge of the topography (degree of downcutting) on the unconformity, the thickness of the member, and available well control. This large paleovalley present on the sub-Cretaceous unconformity (Appendix A, Figures 15 and 16) is part of a depression likely initiated by extensive salt dissolution within the Prairie Formation.

Christina Member: The Calumet Member is conformably overlain by shales of the Christina Member. The Christina Member is comprised mainly of greenish-grey shale, grey argillaceous limestone, pale brown aphanitic limestone, and minor pale brown fragmental limestone (Norris, 1973).

Where the Christina Member is present, its structure (Appendix A, Figure 17) mimics the topographic expression of the two underlying members. Isopach values for the Christina Member range from 0 to 34 m (Appendix A, Figure 18). The isopach map shows the Christina Member thinning to the western margin of the study area. In the northern region (Tp 95-96) the Christina Member has been removed by erosion. An approximate subcrop outline was constructed in the same manner as the boundary of the underlying Calumet Member.

Moberly Member: The shaley Christina Member is conformably overlain by the

Moberly Member. The Moberly Member is the uppermost mappable unit in the Waterways Formation within the study area. The member consists of alternating, rubbly, thinly-interbedded, variably argillaceous limestone and shale combined with resistive beds of aphanitic, fragmental limestone (Norris, 1973). The succession becomes more argillaceous towards the top. The top of the Moberly Member forms the surface of the sub-Cretaceous unconformity with the exception of the extreme southwest corner and portions of Tp 95-96. Severe erosion of the top of the succession accounts for the extreme variations in thickness which range from 0 m to 62 m (Appendix A, Figure 19). Erosional downcutting has removed the Moberly Member in parts of Tp 95-96, as outlined by the subcrop edge on Figure 19, Appendix A.

The argillaceous limestone making up the Mildred Member, the uppermost member of the Waterways Formation, conformably overlies the Moberly Member west of the study area. The basal portion of the Mildred Member is present only in the extreme southwest corner of the mapped area in well 6-13-91-15W4 Mer.

Sub-Cretaceous Unconformity

The surface of the sub-Cretaceous erosional unconformity consists essentially of strata from the Moberly Member. The structure on top of the unconformity (Appendix A, Figure 20) exhibits a major valley system which, in places, incises deeply into the Waterways Formation. The Underground Test Facility is situated on a local high in Tp 93, R 12 W4 Mer. West of the UTF, the unconformity surface rises continuously, forming an extensive highland. In Tp 96, R 10-11 W4 Mer, erosional downcutting has reached basal strata within the Firebag Member. Erosional incision on the unconformity is best shown by the structural dip section which crosses the valley system (Appendix C, Figure 1b). Individual members within the Waterways Formation are progressively removed by erosion toward the northeast. The shallower portion of the valley system trends southeast-northwest in the southern and central regions. In the central region, the valley progressively widens to the north, where it merges with an east-west trending, deeply incised portion of the valley complex located in the Bitumount area (Appendix A, Figure 20). The region of extreme downcutting shifts abruptly to the north in Tp 96, R 10 W4 Mer, and continues north (Flach, 1984).

The valley system carved into Paleozoic strata was probably initiated by evaporite dissolution within the underlying Middle Devonian Prairie Formation. Dissolution of the evaporites resulted in the collapse of overlying strata (Flach, 1984). This depression provided a flow path for later stage river systems, which incised into the exposed Devonian strata and deposited the siliciclastics sediments of the Cretaceous McMurray Formation.

MESOZOIC GEOLOGY

The study area for the Mesozoic sedimentary succession encompasses Tp 92-95, R 11-14 W4 Mer (Figure 10). The northern boundary is marked by the Ells River which diagonally cuts through Tp 94-95. Other present day drainage systems located within the study area include the Athabasca River along the eastern boundary, the north trending McKay River crossing the area west of the Athabasca River, and the Dover River located south of and paralleling the Ells River (Figure 10). The Mesozoic succession is comprised of Cretaceous-age Mannville Group sediments (Table 1). The Mannville Group is bounded at the base by the sub-Cretaceous erosional unconformity and at the top by Cenozoic glacial drift deposits of Pleistocene age. The succession of strata ranges in thickness from less than 50 m in the east to greater than 150 m in the central region (Appendix B, Figure 1). Sediments of the Mannville Group generally consist of interbedded siliciclastics comprised of sand, shale and silt.

Cretaceous Mannville Group

General Stratigraphy

The Mannville Group in northeast Alberta is comprised of, in ascending order: McMurray, Clearwater and Grand Rapids formations (Table 1), shown in a typical well

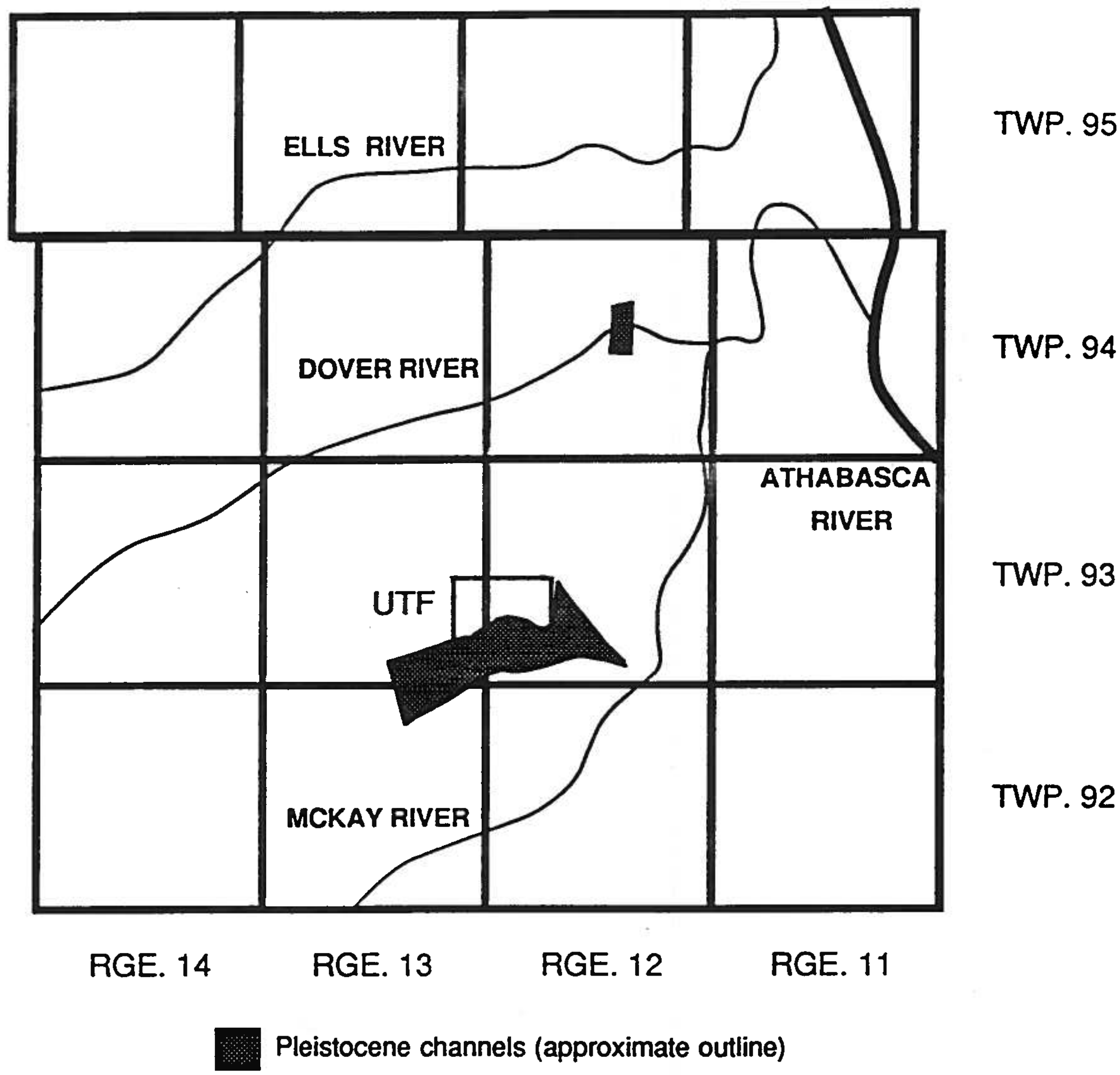


Figure 10. Present day drainage network in the Cretaceous intermediate-scale study area, and location of identified Pleistocene channels.

log suite in Figure 11.

McMurray Formation

The Lower Cretaceous McMurray Formation is a complex succession of strata that directly overlies the sub-Cretaceous unconformity. The McMurray Formation infills the large valley system developed on the unconformity. The most important factor governing the sediment distribution and facies architecture of the McMurray Formation is the paleotopography developed on the surface of the unconformity. Several geological studies of the McMurray Formation have been completed in the northern region of the Athabasca deposit (Carrigy, 1959, 1966, 1967, 1971; Stewart, 1963; Flach, 1977, 1984; James, 1977; James and Oliver, 1978; Mossop and Flach, 1983; Mattison and Pemberton, 1989; Rennie, 1987; and Rottenfusser et al., 1990).

Carrigy (1959) divided the Lower Cretaceous McMurray Formation into lower, middle, and upper members based upon outcrop studies. The following discussion outlining the lithologic characteristics of the McMurray Formation is sourced primarily from the regional-scale study of Flach (1984).

The lower member of the McMurray Formation is generally comprised of blocky, dark gray mudstones and medium to coarse grained unconsolidated sand with occasional localized pebble conglomerates. The lower member is most often found in

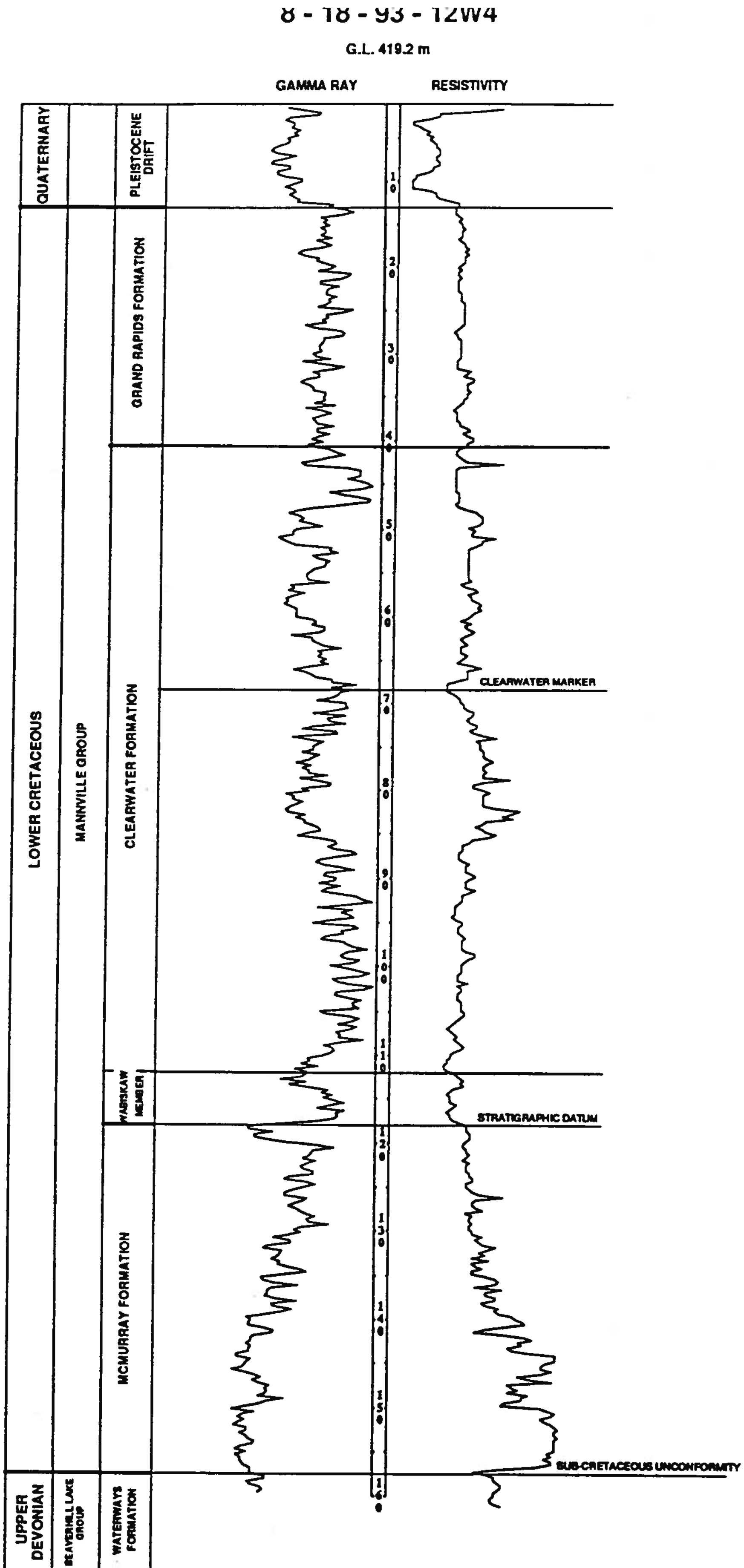


Figure 11. Lower Cretaceous Mannville Group type well.

lows on the sub-Cretaceous unconformity (where the McMurray Formation is greater than 60 m thick). Sands at the base of this member are frequently water-bearing, especially within the Bitumount basin north of the study area.

The middle member of the McMurray Formation consists commonly of bioturbated, interlaminated to interbedded sands and shales which typically overlie bitumen-saturated very fine to fine grained sands. Occasionally, the entire member is comprised of a thick succession of rhythmically interbedded sand and shale. The contact between the middle and lower member ranges from sharp to gradational. Channeling events within the middle member sometimes incise deeply into the lower member. Like the lower member, the middle member generally fines-upward. The volume of shale normally increases upward.

The upper member, 15 to 20 m thick, is characterized by flat-lying, intensely bioturbated, interlaminated to interbedded sand and shale. Shales tend to be light grey and sands are very fine-grained and argillaceous. In outcrop and on well logs the upper member can occur as small fining-upward or coarsening-upward cycles. Coarsening-upward cycles tend to pass from argillaceous sand or shale at the base to cleaner, wave rippled sands at the top.

Structure on top of the McMurray Formation generally dips from southwest to northeast across the study area (Appendix B, Figure 2). In northeast Alberta the

McMurray Formation dips regionally to the southwest; however, approaching the Prairie Salt Scarp the structural dip shifts to the northeast. Within the study area, the reversal of dip to the northeast is likely caused by post-McMurray salt dissolution within the underlying Prairie Formation.

The isopach map shows the McMurray Formation thinning from northeast to southwest (Appendix B, Figure 3). The McMurray Formation thins in the southwest over the paleohigh on the sub-Cretaceous unconformity, and thickens as it approaches the Prairie Salt Scarp east of the UTF. Variations in thickness, caused primarily by relief on the unconformity, can be seen in Figures 4a, 5a and 6a, Appendix C. The McMurray Formation attains more than 80 m in thickness in the extreme northeast corner of the study area (Appendix B, Figure 3). This region lies at the edge of the Bitumount Basin (Appendix A, Figure 20), where erosion on the unconformity has cut deeply into the Beaverhill Lake Group.

Clearwater Formation

The Lower Cretaceous Clearwater Formation disconformably overlies the McMurray Formation in northeast Alberta. The succession is dominated by black to greenish grey shales interbedded with grey and green sands and silts. Many of the sands and silts contain varying amounts of glauconite. Ironstone concretions are common throughout.

The Wabiskaw Member of the Clearwater Formation disconformably overlies the McMurray Formation. Lithologically, the Wabiskaw Member consists of one or more fine-grained, glauconitic, salt-and-pepper sands interbedded with black, fissile, often sandy shale. A datum for stratigraphic correlation was selected within the Wabiskaw Member by Flach (1984). This datum is located at the base of the first regionally correlatable marine shale situated a few meters above the McMurray Formation. Flach (1984) states that the top of the McMurray Formation often can not be picked from well logs with accuracy, therefore the marine shale overlying the McMurray succession serves as a good approximation. Traditionally, the base of the Wabiskaw Member is picked at the base of the datum shale, but, at certain locations which include the study area, discontinuous Wabiskaw sands are found just under the marine shale. Generally, the best sand development does occur under the base of the shale datum as a thin (2 to 3 m), relatively clean, coarsening-upward, bioturbated sand located in the central region of the study area. North and south of the UTF site, the sand generally maintains its configuration (Appendix C, Figure 5a). To the east and west, the sand either gradually shales out or is replaced by stratigraphically equivalent, thick, clean sands of the McMurray Formation (Appendix C, Figure 4a). Wabiskaw Member sand development occurs above the stratigraphic datum in the extreme west (Appendix C, Figure 4a). On well logs the sand appears as a coarsening-upward unit about 10 m thick.

Structurally, the top of the Wabiskaw Member is a relatively uniform, low angle, northeast dipping surface, with the exception of a small elongated low trending northwest along structural strike (Appendix B, Figure 4). Figure 4b, Appendix C, displays the subsurface topography in more detail. The Wabiskaw Member varies in thickness from about 4 to 18 m (Appendix B, Figure 5). The interval maintains a relatively uniform thickness throughout the region except for the western edge, where the succession thickens significantly over the Paleozoic high. Both the structure and isopach maps show the approximate eroded edge of the regional marine shale at the base of the Wabiskaw Member.

Above the Wabiskaw Member, the Clearwater Formation consists of shale interbedded with thin, very fine-grained sand and silt (Appendix C, Figures 4a and 5a). Above the shaley unit are two, stacked, coarsening-upward cycles. Each grades from shale at the base to very fine-grained sand or silt at the top. The top of the lower coarsening-upward unit is marked by a prominent, regionally extensive black shale about two meters thick. This shale displays a distinct response on resistivity logs and is a useful stratigraphic marker bed that can be traced as far south as Tp 85 in the Athabasca area. Unfortunately, the marker bed is missing in the eastern portion of the study area due to post-Cretaceous erosion (Appendix C, Figures 4a and 6a). The upper coarsening-upward unit, where present, is capped by 5 to 6 m of shale which marks the approximate top of the Clearwater Formation.

Subsurface topographic relief of more than 90 m exists on the top of the

Clearwater Formation (Appendix B, Figure 6). The surface dips to the northeast. Structural relief on the Clearwater Formation is primarily a function of post-Cretaceous erosion which has progressively removed much of the upper succession east of the UTF (Tp 93, R 12 W4 Mer) (Appendix C, Figures 4b and 5b). In the extreme eastern portion of the study area, approaching the Athabasca River valley, erosion often downcuts into the basal Wabiskaw Member and sometimes into the McMurray Formation (Appendix C, Figure 6b). A distinct, northeast trending structural nose loops around the UTF site. The entire Clearwater Formation succession is preserved within this isolated area. The isopach map of the remainder of the unit above the Wabiskaw Member demonstrates how erosion has created the present day configuration of the Clearwater succession (Appendix B, Figure 7). West of the UTF, the isopach averages about 70 m in thickness. East of the UTF the Clearwater succession thins significantly (Appendix C, Figure 4a).

Grand Rapids Formation

The Clearwater Formation is conformably overlain by and laterally interfingers with the Grand Rapids Formation. Within the study area, the Grand Rapids Formation consists of thin to very thinly interbedded dark grey to black shales and light grey sands. On well logs the succession appears as a shale dominated blocky unit with occasional sandy intervals (Appendix C, Figures 4a and 5a). The Grand Rapids Formation is confined to the western edge of the study area with the exception of a tongue that extends northeast and terminates just east of the UTF site (Appendix B, Figure 8).

The structure on top of the succession accentuates the tongue-like morphology in the area. Detailed structural relief is suppressed due to poor well control west of the UTF. The Grands Rapids Formation is more than 40 m thick in the centre of the preserved section and quickly thins to 0 m at the approximated erosional edge (Appendix B, Figure 9). Post-Cretaceous erosional events have removed the Grand Rapids Formation from small localized areas within the confines of the erosional boundary. These features are too small to be mapped at the resolution and scale of the study, but are nonetheless important.

POST-MESOZOIC GEOLOGY

Pleistocene Drift

Pleistocene age drift and other sediments of recent geologic age are comprised primarily of unconsolidated sands and gravels, which generally exist as a thin veneer covering the Lower Cretaceous Mannville Group. However, localized drift accumulations within the study area have been measured to be more than 90 m thick. Figure 10 in Appendix B shows the structure on top of the Cretaceous bedrock upon which the cover was deposited. The topography shown is merely the combined structural surfaces of the Grand Rapids Formation, where present, and the underlying Clearwater Formation. The elongated northeast trending high located in the southwestern and central regions simply outlines the edge of the Grand Rapids Formation. Elsewhere, the structure represents the Clearwater Formation. An isopach map shows the drift to vary from 0 to more than 60 m in thickness (Appendix B, Figure 11), with most variability in the western and central regions (poor well control in the west). Near Syncrude, the drift averages around 10 m thick. Some of the extreme variations in thickness displayed on the map may be a function of automated computer mapping which may project trends into areas containing sparse well control.

As mentioned previously, some drift accumulations have greater thickness than that shown on the drift isopach. One such localized site exists in the southern portion of the AOSTRA UTF lease. Drift has been documented here as being more than 99 m thick in one well (Basin Analysis Group, 1988). The deposit generally consists of unconsolidated till and glacially stratified sediments overlying a thick succession of sands and gravels. The deposit at the UTF forms an elongated linear feature with an west-southwest to east-northeast orientation (Figure 10) indicating a major buried valley. The paleo-valley is 1.5 to 2.5 km wide and has been traced for about 8 km in length (Basin Analysis Group, 1988). Sparse well control at either end of the valley prohibits further delineation. A well in Tp 92, R 13 W4 Mer, indicates over 55 m of similar deposits. This well may be situated within the same valley system (Figure 10). The paleo-valley has downcut deeply into the underlying Cretaceous strata at the UTF.

In well AO-10 (1-7-93-12W4 Mer), located presumably along the axis of the valley, erosional incisement has removed the entire Grand Rapids Formation and more than half of the Clearwater Formation. Well 3-8-93-12W4 Mer displays erosional downcutting into underlying Lower Cretaceous formations by the post-Cretaceous valley (Appendix C, Figure 5a). Structure and isopach maps of the Clearwater Formation show the general outline of the valley and the erosional thinning in the southern portion of the UTF lease, respectively (Appendix B, Figures 6 and 7). Previous work (Basin Analysis Group, 1988) deems the buried valley system as an important hydrostratigraphic unit and indicates that more work is needed to delineate its geometry, stratigraphy, and hydraulic parameters. At one point within the deeper portion of the valley system (1-7-93-12W4 Mer), its base is only 33 m from the sands of the Wabiskaw Member. Similar thick Pleistocene successions have been observed during field work along the Dover and McKay rivers east and north of the study area. Also, Pleistocene burried valleys have been documented east of the Athabasca River (Horne and Seve, 1991).

Surficial Topography

The topography at ground level (Appendix B, Figure 12) is similar to the underlying bedrock surface. The structural high located in the southwest and central region, resulting from preserved Grand Rapids Formation strata, is evident at the ground surface. Structural lows on either side of the high are defined more clearly than the underlying bedrock surface. East of the UTF, structural dip and strike closely correspond to the underlying bedrock structure.

HYDROSTRATIGRAPHY

Hydrostratigraphy provides a breakdown of strata according to certain hydrogeological characteristics. Largely, the hydrostratigraphy for the intermediate-scale study areas was derived from the regional-scale hydrostratigraphic delineation (Petroleum Geology and Basin Analysis Group, 1992). The hydrostratigraphic nomenclature is defined as follows: an aquifer is a rock unit which allows the flow of formation fluids, an aquitard retards it, and an aquiclude does not allow any flow. Complex successions of aquifers and aquitards exhibiting certain overall characteristics where grouped into hydrostratigraphic systems. An aquifer system behaves mostly like an aquifer even if minor aquitards are present, and an aquitard system behaves mostly like an aquitard even if some aquifers are present.

The hydrostratigraphy at the intermediate scale around the UTF site is simpler than that at the regional scale because many units are not present. Differences in the thickness and boundary location of some units between the regional and intermediate scale studies reflect the increased detail of the latter. Table 4 presents the hydrostratigraphic nomenclature for the intermediate-scale study areas. Because the Lotsberg and Cold Lake Formations (salt deposits) are absent, the Contact Rapids-Winnipegosis aquifer system sits directly on the Basal aquifer. The latter is of negligible thickness, being composed of the thin to absent Basal Red Beds and Ernestina Lake formations; therefore, the strata from the Basal Red Beds to the Winnipegosis formations

Group		Formation	Hydrostratigraphic Type	Hydrostratigraphic System
		Pleistocene deposits	aquifer	
Mannville		Grand Rapids	aquifer	Grand Rapids
		Clearwater	aquitard	Clearwater
			aquifer	McMurray-Wabiskaw aquifer/aquitard system
		McMurray	aquifer	
Beaverhill Lake		Waterways	aquifer - aquitard	Beaverhill Lake aquifer system
		Slave Point	aquifer	
		Fort Vermilion	aquiclude	Prairie-Watt Mountain aquiclude system
Elk Point	Upper	Watt Mountain	aquitard	
		Prairie	aquiclude	
		Winnipegosis (Keg River)	aquifer	Winnipegosis - Basal aquifer system
	Lower	Contact Rapids	aquifer - aquitard	
		Ernestina	aquifer - aquitard	
		Granite Wash / Basal Red Beds	aquifer - aquitard	
		Precambrian	aquiclude	

Table 4. Hydrostratigraphic succession and nomenclature around the UTF site.

were grouped at the intermediate-scale into the Winnipegosis-Basal aquifer system. The various members of the Waterways Formation subcrop at the Sub-Cretaceous unconformity throughout the area, leaving the Beaverhill Lake Group as the only unit in the Beaverhill Lake-Cooking Lake aquifer system defined at the regional scale (Petroleum Geology and Basin Analysis Group, 1992). The McMurray Formation lies directly on the Sub-Cretaceous unconformity surface and, on a regional scale, has the hydrodynamic properties of an aquifer (Petroleum Geology and Basin Analysis Group, 1992). Bitumen accumulations within the McMurray Formation act as barriers to flow such that this flow unit has aquitard characteristics in places. For this reason it is classified here as an aquifer/aquitard. The overlying Wabiskaw Member represents the sandy lower portion of the Clearwater Formation and when combined with the McMurray aquifer/aquitard forms the McMurray-Wabiskaw aquifer/aquitard system. The remaining upper portion of the Clearwater Formation is shale dominated and is designated as the Clearwater aquitard. Occurring over only a limited part of the study area, the Grand Rapids Formation forms an aquifer above the Clearwater aquitard. In most of the area, Pleistocene deposits form a thin veneer of glacial sediments on top of the bedrock. However, locally they may reach 100 m in thickness. The boundaries of various units which outcrop within the Paleozoic intermediate-scale study area are shown in Figure 12. Field work and manual geophysical log interpretation resulted in the subdivision of the Beaverhill Lake Group and the modification and update of the Cretaceous unit boundaries with respect to the regional-scale study (Petroleum Geology and Basin Analysis Group, 1992).

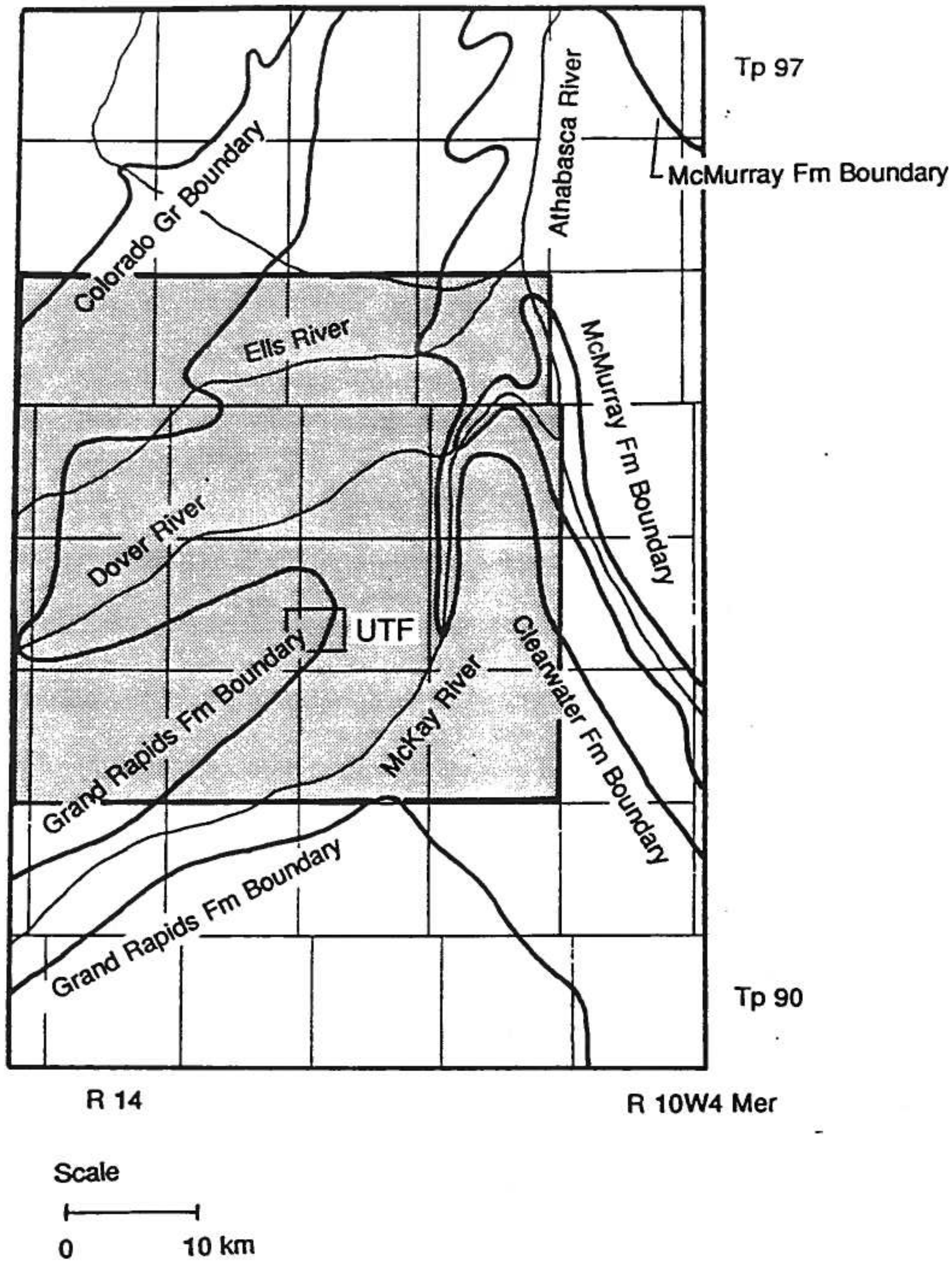


Figure 12. Outcrop boundaries of various units in the Paleozoic intermediate-scale study area.

The isopach of the Winnipegosis-Basal aquifer system (Figure 13) ranges from less than 100 m thick in the north to over 200 m thick in the southwest. The thickness of the Beaverhill Lake aquifer ranges from 40 m in the northeast to 180 m in the southwest (Figure 14). Stratigraphically, the Beaverhill Lake Group is complex and can be divided into three formations: Fort Vermilion, Slave Point and Waterways (Tables 1 and 4). The Waterways Formation is further divided into the Firebag, Calumet, Christina, Moberly and Mildred members. Although there are not enough hydraulic data for the hydrogeological characterization of each subdivision, some inferences can be drawn from the stratigraphy alone. The Fort Vermilion Formation consists mostly of anhydrite and as such is grouped with the Prairie-Watt Mountain aquiclude system. The Slave Point Formation has a lithology ranging from limestone to siltstone and probably has aquifer characteristics, although, as discussed in the geology chapter, the available geophysical logs are not adequate for separating it from the Fort Vermilion Formation. The shale-dominated Firebag Member (the basal member of the Waterways Formation) probably has aquitard characteristics. Overlying the Firebag Member, the limestone dominated Calumet member likely has aquifer characteristics. Immediately above, the Christina Member is composed mostly of shale and probably has aquitard characteristics. The Moberly Member is the uppermost mappable member of the Waterways Formation within the intermediate-scale study area. The Moberly Member consists mainly of interbedded rubbly argillaceous limestone and most likely has weak-aquitard to aquifer characteristics. The Mildred Member is present only in the extreme southwest part of the study area and is inconsequential with respect to fluid flow within the intermediate-scale study area.

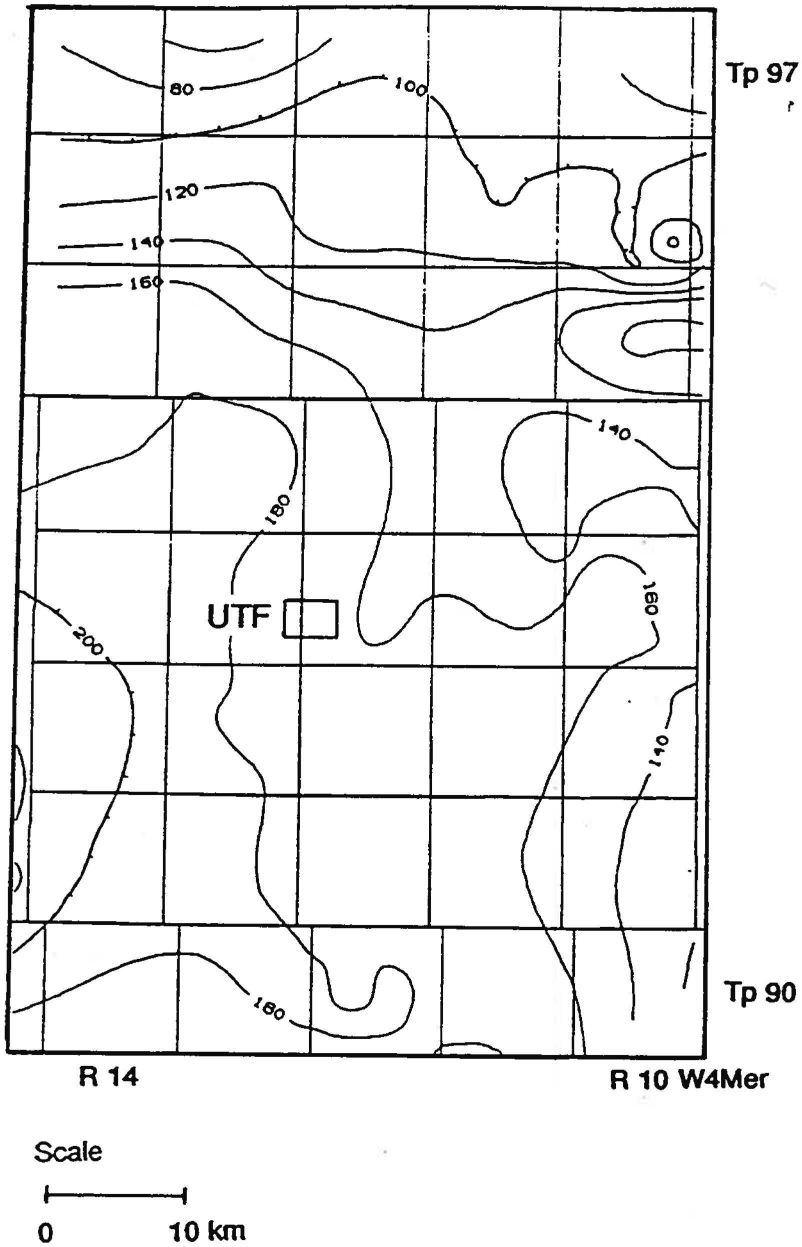


Figure 13. Isopach of the Winnipegosis-Basal aquifer system.

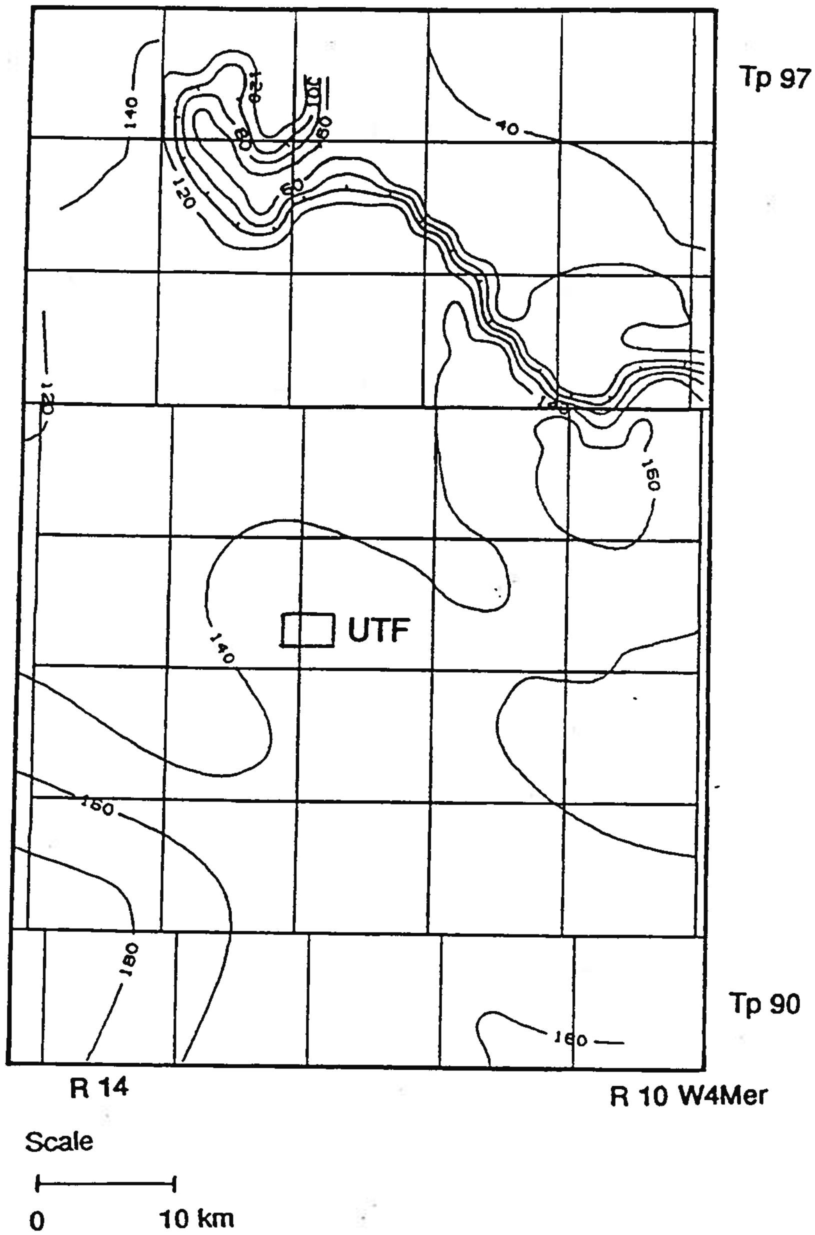


Figure 14. Isopach of the Beaverhill Lake aquifer.

The Cretaceous hydrostratigraphy is markedly different from the original stratigraphic geometry, mostly because of the variability in the lithology of the Clearwater Formation. Areas of the Clearwater Formation above the Wabiskaw Member have been shown in the regional-scale study to be in hydraulic continuity with the adjacent aquifer. Because few data (drillstem tests) are available in the Cretaceous intermediate-scale study area, the regional-scale hydrostratigraphy was used to define the geometry of the Wabiskaw aquifer and the Clearwater aquitard (Figures 15 and 16, respectively). The McMurray and Wabiskaw aquifers together form the McMurray-Wabiskaw aquifer/aquitard system which ranges in thickness from 30 to 80 m (Figure 17). The aquitard characteristics of this unit are the result of bitumen accumulations. Figure 18 shows the thickness of sands in the McMurray Formation having more than 8 percent bitumen saturation by weight. This plan view representation does not indicate the connectivity of the bitumen-saturated sand bodies, which may occur at different stratigraphic levels in the McMurray Formation. For future modelling at a detailed UTF site-scale, the water bearing and bitumen-saturated sands will be characterized in detail. The Grand Rapids aquifer is present only within a small part of the area and is nearly devoid of data.

Within the intermediate-scale study area, Pleistocene deposits may be locally important flow units. As discussed previously in the geology section, in some cases paleo-channels cut down close to the Sub-Cretaceous unconformity. These channels are often filled with till of variable lithology and generally form unconfined aquifers.

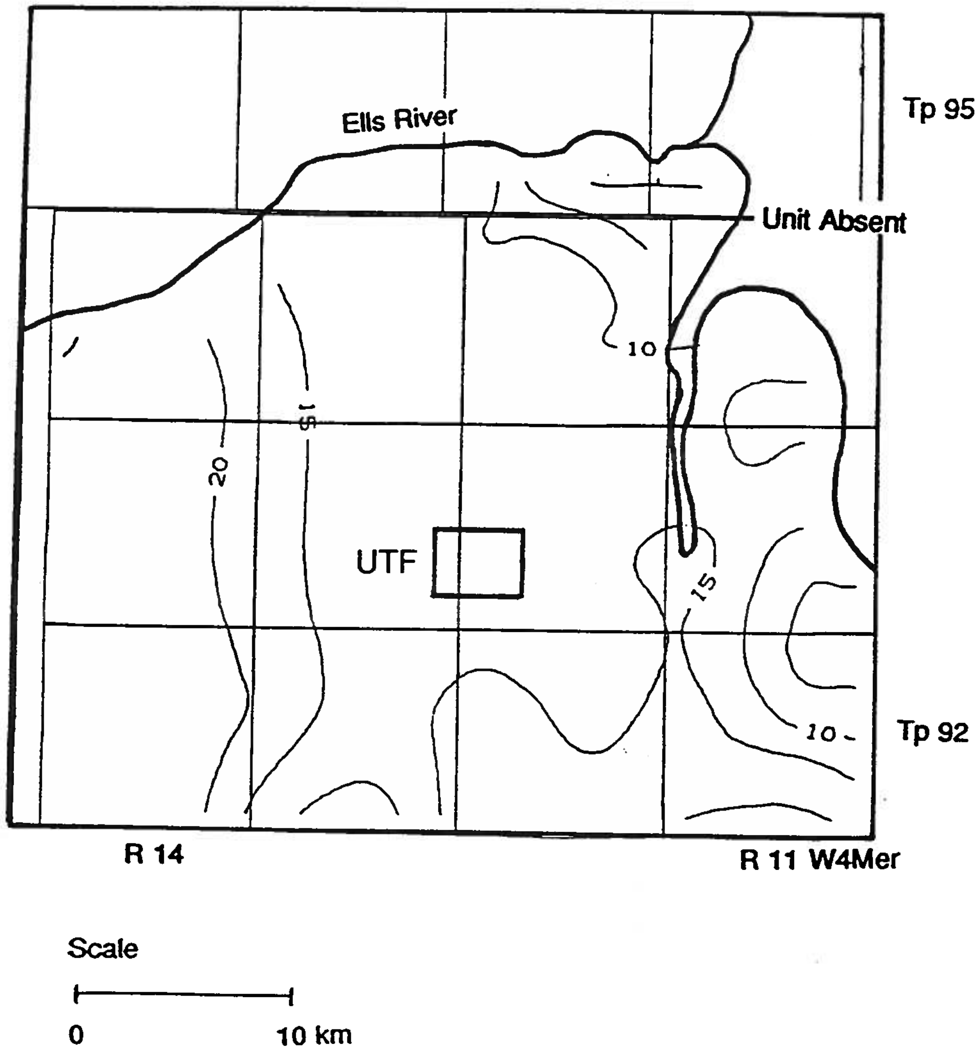


Figure 15. Isopach of the Wabiskaw aquifer.

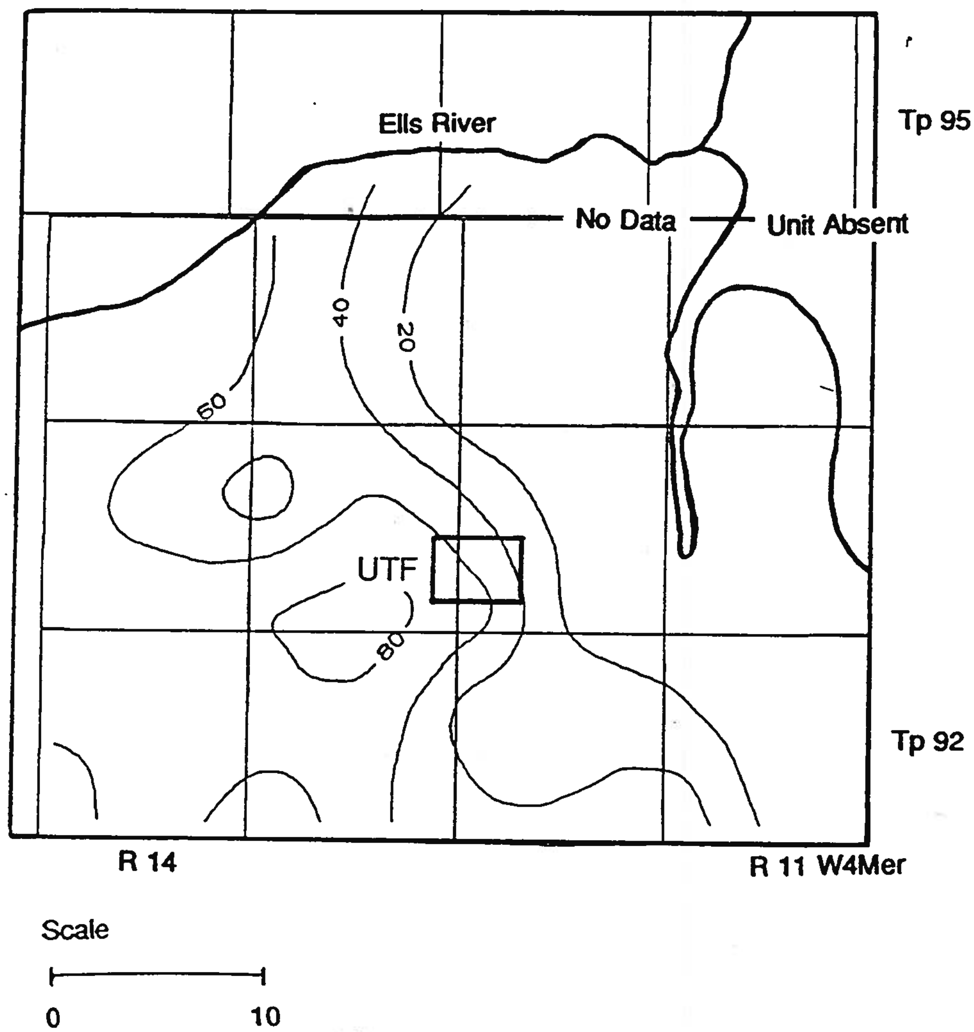


Figure 16. Isopach of the Clearwater aquitard.

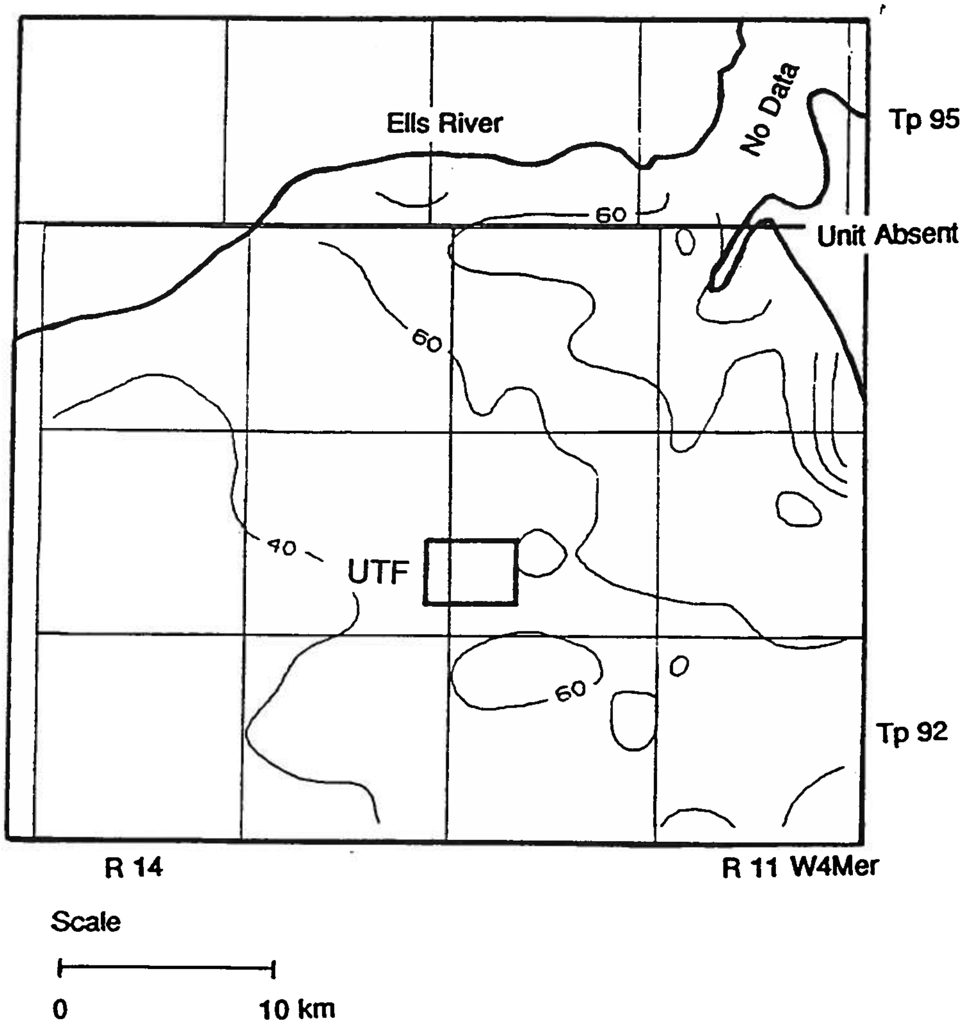


Figure 17. Isopach of the McMurray/Wabiskaw aquifer/aquitard system.

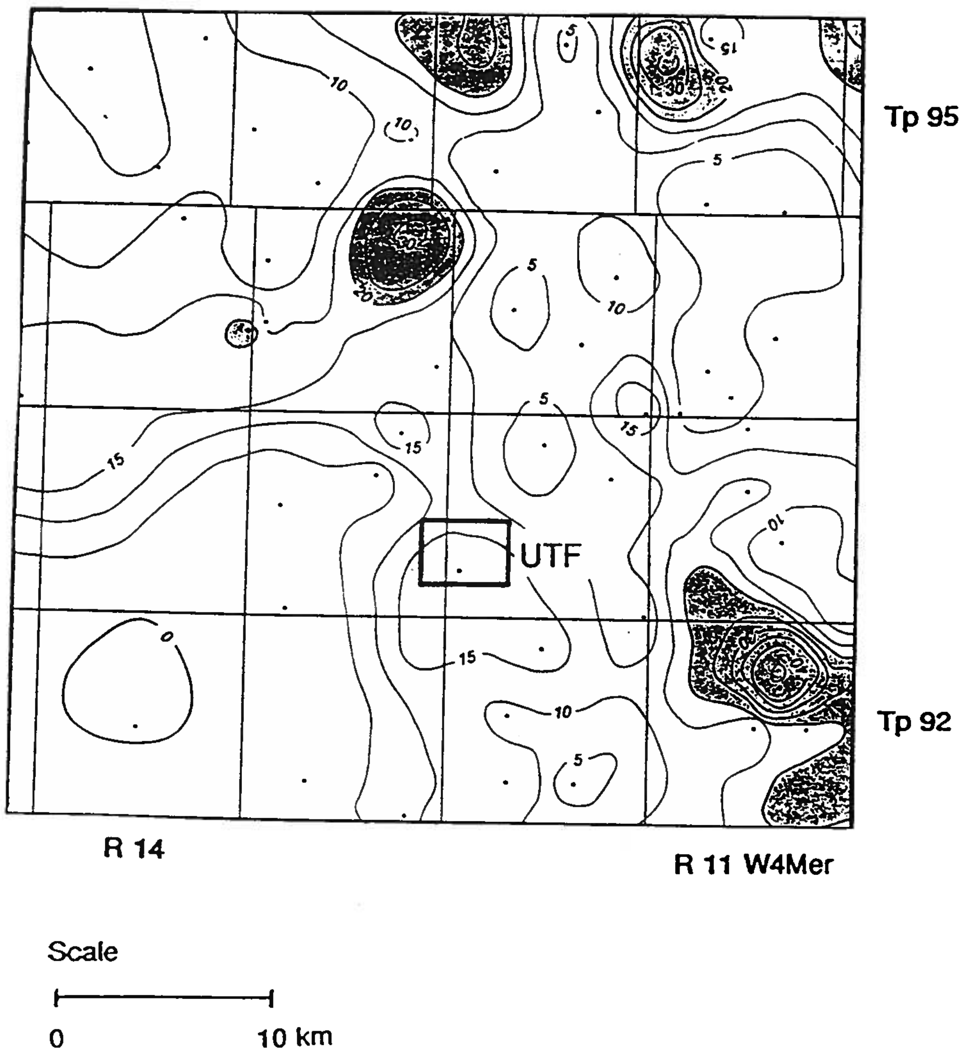


Figure 18. Cumulated thickness of sands in the McMurray Formation with more than 8% weight bitumen saturation.

OUTCROP OF LOWER CRETACEOUS STRATA NEAR THE UTF SITE

A short field reconnaissance program was completed during the summer of 1991 in the Fort McMurray area with the objective to determine if and where Cretaceous basal water sands of the McMurray Formation or sands of the Wabiskaw Member crop out along the present-day drainage system near the AOSTRA Underground Test Facility. The MacKay River is located about 8 km east and the Dover River about 9 km north of the UTF site (Figure 19).

Along the MacKay River from south to north the Lower Cretaceous succession consists of the Clearwater Formation (shale, silt and sand), the Wabiskaw Member (sandy shale), and the McMurray Formation (bitumen saturated sands). A glauconite rich marker at the base of the Wabiskaw Member was found east of the UTF site (Figure 19). The marker occurs at river level and consists of green, very glauconitic, unconsolidated, sandy clay. The marker, up to 2 m above the river level, can be traced for a few km north of the first exposure. As the Wabiskaw Member rises structurally downstream (northward), it is progressively removed from the succession by post-Cretaceous erosion. The McMurray Formation crops out about 4 km north of the initial sighting of the glauconite marker (Figure 19). The sands of the McMurray succession tend to be bitumen saturated throughout. The sharp, unconformable contact between the McMurray Formation and the underlying Beaverhill Lake carbonates is exposed just south of the confluence of the Dover and MacKay rivers. No basal water sands within the McMurray Formation were

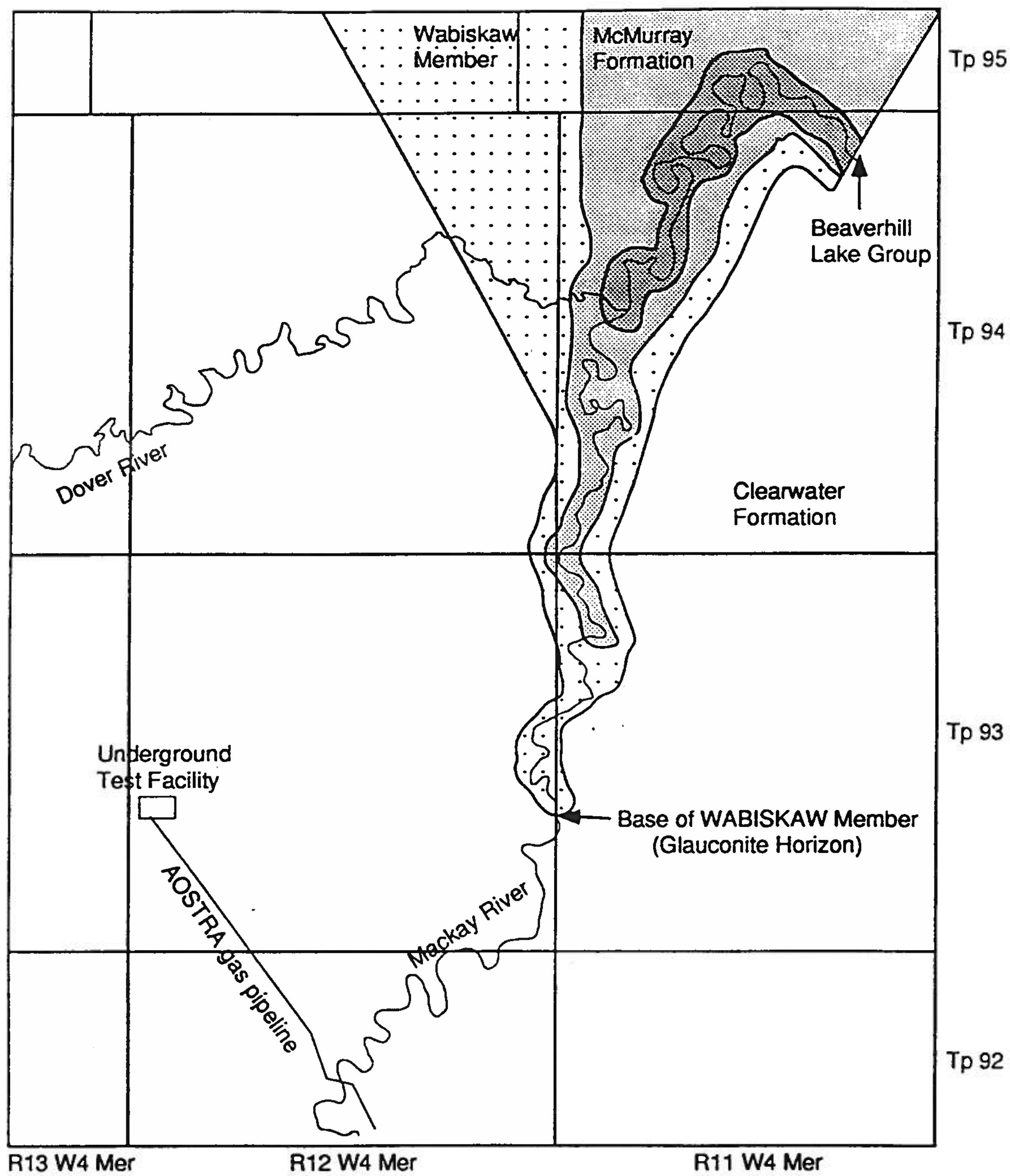


Figure 19. Outcrop map of Phanerozoic strata along the McKay and Dover rivers near the UTF site.

found overlying the unconformity.

The valley walls along the Dover River represent the same stratigraphic succession as along the MacKay River, with the exception of some thick intervals of Pleistocene sands and gravels that occasionally cut deep into the Lower Cretaceous strata. Overall, the succession becomes younger from east to west, consisting of Beaverhill Lake carbonates (Sub-Cretaceous unconformity), the McMurray Formation, the Wabiskaw Member, and the Clearwater Formation.

HYDROGEOLOGY

The lateral (horizontal) component of the flow of formation waters was evaluated by examining individually the aquifers in the hydrostratigraphic succession. The interaction between aquifers and the magnitude of cross-formational flow across aquitards was evaluated by comparing the hydraulic head distributions between individual units. Because of the scarcity of data at the intermediate scale, regional-scale distributions of formation water salinity and freshwater hydraulic head (Petroleum Geology and Basin Analysis Group, 1992) were used as the main source of information. The distribution of fresh water hydraulic head is not truly indicative of the magnitude and direction of the hydraulic gradient driving the flow of variable-density formation waters in dipping aquifers. As discussed in the regional-scale study of the hydrogeological regime of formation waters in northeast Alberta (Petroleum Geology and Basin Analysis Group, 1992), the error associated with using freshwater hydraulic head is likely to be minor for aquifers with a gentle slope and/or low salinity.

TOPOGRAPHY

The topographic relief and physiographic features of the area exert a strong influence on the hydrogeological regime. Figure 12 shows the main rivers in the area and the associated outcropping strata. The Cretaceous intermediate-scale study area is bounded by the Ells River to the north, while the Dover and MacKay rivers pass through the study area forming topographic lows (Appendix B, Figure 12). The edge of the Athabasca river valley can be seen in the northeast part of the study area. The most pronounced local topographic high (Appendix B, Figure 12) is located between the Dover and MacKay Rivers. The physiography and topographic relief associated with the Dover, MacKay and Athabasca rivers are the main features influencing the hydrogeological regime of post Prairie Formation aquifers in the area; however, this influence may not be recognizable for units where the available data are more widely spaced than these topographic features.

WINNIPEGOSIS-BASAL AQUIFER SYSTEM

The Winnipegosis-Basal aquifer system includes strata from the Precambrian basement to the top of the Winnipegosis Formation. The Precambrian basement below and the Prairie Formation above the aquifer system are considered impermeable aquicludes which do not allow any flow. As a result, the Winnipegosis-Basal aquifer system is the only aquifer in the area which is unaffected by the local topography. The distribution of formation water salinity shows a smoothly increasing trend to the southwest (Figure 20). One salinity value of 97,000 mg/l (Tp 93 R 10 W4 Mer) provides the only local control on a distribution otherwise obtained from the regional-scale study (Petroleum Geology and Basin Analysis Group, 1992). The vicinity of Prairie formation evaporites results in high formation water salinity, with extrapolated values of over 200,000 mg/l in the southwest. Because of the high salinity, it is expected that buoyancy effects could

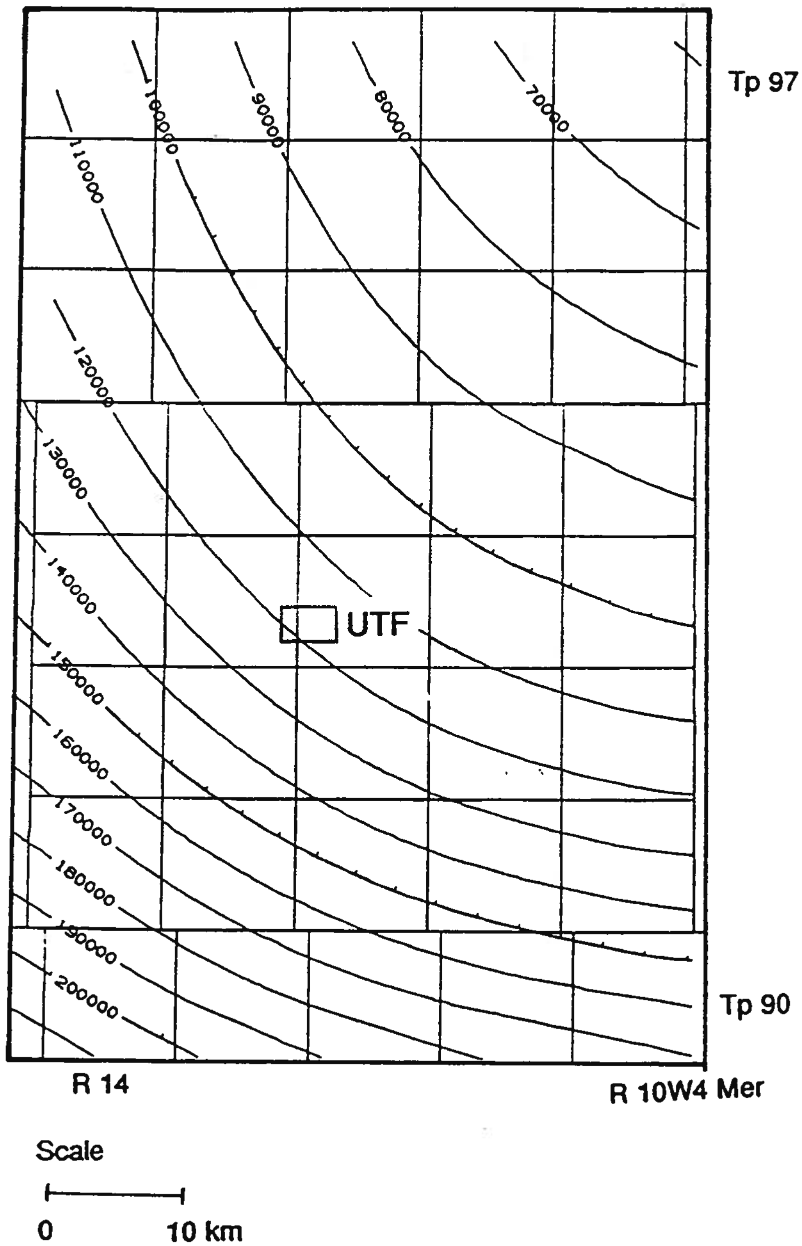


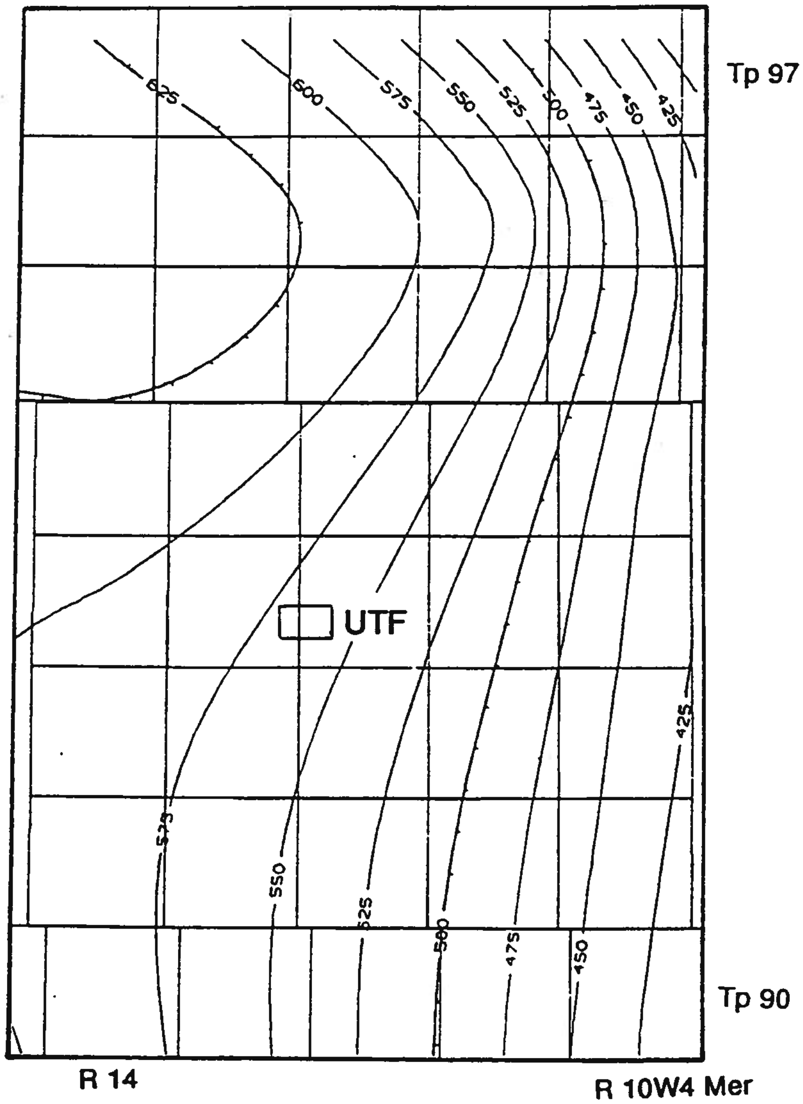
Figure 20. Salinity distribution (mg/l) in the Winnipegosis-Basal aquifer system.

be significant. The southwest increase in salinity is attributed to increasing solubility with temperature hence with depth (Petroleum Geology and Basin Analysis Group 1992).

The distribution of freshwater hydraulic head shows a decreasing trend from west to east, with the highest values in the northwest (Figure 21). Two drillstem tests in the same well in Tp 96 R 11 W4 Mer indicate an average hydraulic head value of about 550 m which provides some local control on the otherwise regionally derived distribution field. Because the formation water salinity is high, the magnitude and direction of flow indicated by the freshwater head distribution is expected to be significantly altered by buoyancy forces associated with variable density of formation fluids. Caution should be exercised in evaluating the flow direction and magnitude for this unit.

PRAIRIE-WATT MOUNTAIN AQUICLUDE SYSTEM

The Prairie Formation evaporites and Watt Mountain Formation shales are present throughout the entire intermediate-scale study area. The UTF site is located above the edge of the Prairie Formation salt scarp produced by dissolution and removal of salt deposits; however, some salt and anhydrite remain in the northeast. The Prairie-Watt Mountain aquiclude system effectively isolates the regional flow in the Winnipegosis-Basal aquifer system below from the intermediate and local flow systems in aquifers above. The shale dominated Watt Mountain and anhydrite dominated Fort Vermilion aquitards appear to be an effective barrier to flow in their own right based on the very much fresher



Scale

0 10 km

Figure 21. Distribution of freshwater hydraulic head (m) in the Winnipegosis-Basal aquifer system.

formation water salinity in the Beaverhill Lake aquifer system immediately above. The lower formation water salinity in this aquifer system suggests that the Watt Mountain and Fort Vermilion aquitards effectively separate the formation waters in the Beaverhill Lake aquifer system from the influence of salts in the Prairie Formation.

BEAVERHILL LAKE AQUIFER SYSTEM

The Beaverhill Lake aquifer system is present throughout the study area. It is exposed to atmospheric conditions at outcrop regions in the extreme northeast and along parts of the Athabasca and MacKay rivers. One formation-water salinity value (22,000 mg/l) located at Tp 95 R 10 W4 Mer provides the only control on the otherwise regionally derived distribution (Figure 22). The formation water salinity is much fresher than for the Winnipegosis-Basal aquifer system, with extrapolated values trending from 13,000 mg/l in the south to over 26,000 mg/l in the northwest.

The Beaverhill Lake aquifer system has better data control on the distribution of hydraulic head than any other strata in the study area. Twelve drillstem tests at 5 different land locations provide local control points. In addition, artificial control was placed on this distribution by calculating the hydraulic head at atmospheric conditions along the outcrop boundaries. Figure 23 shows the distribution of hydraulic head with high values in the northwest and southwest and low values in the center and to the east. The northwest part of the Paleozoic intermediate-scale study area is located on the

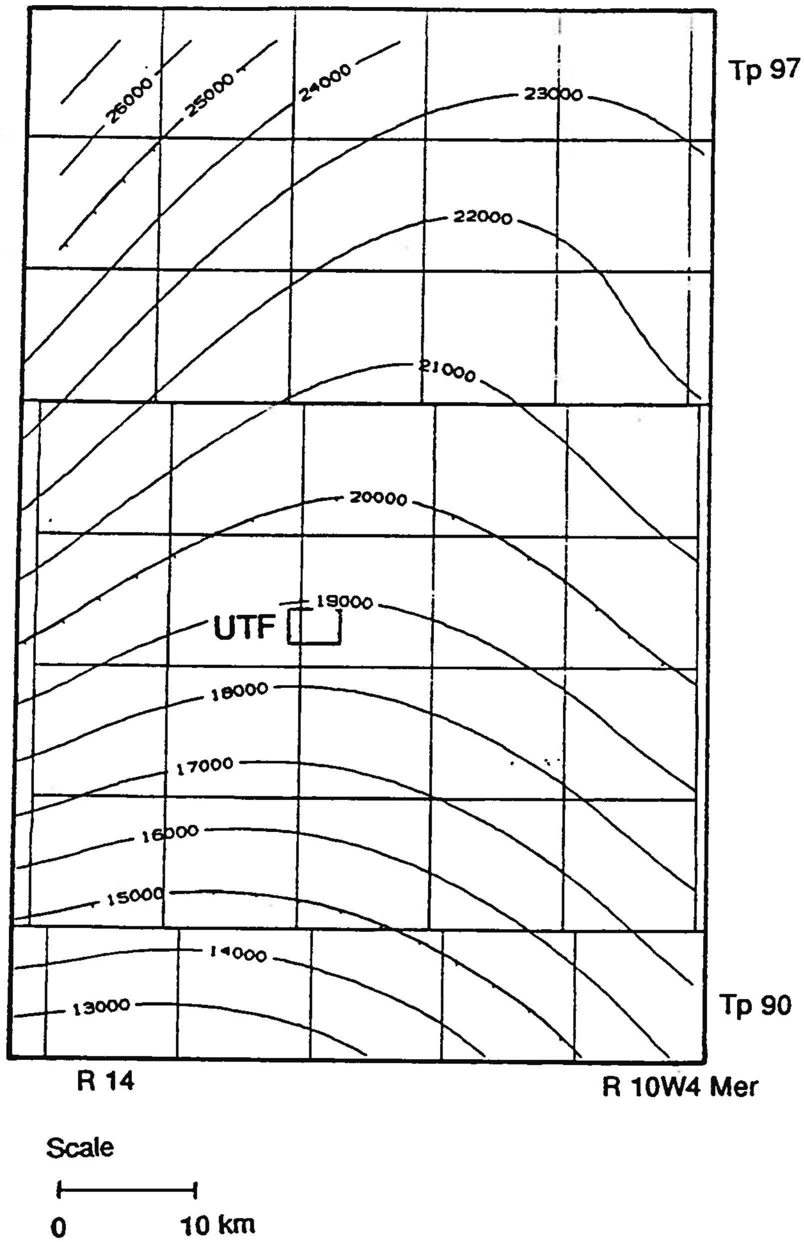


Figure 22. Salinity distribution (mg/l) in the Beaverhill Lake aquifer system.

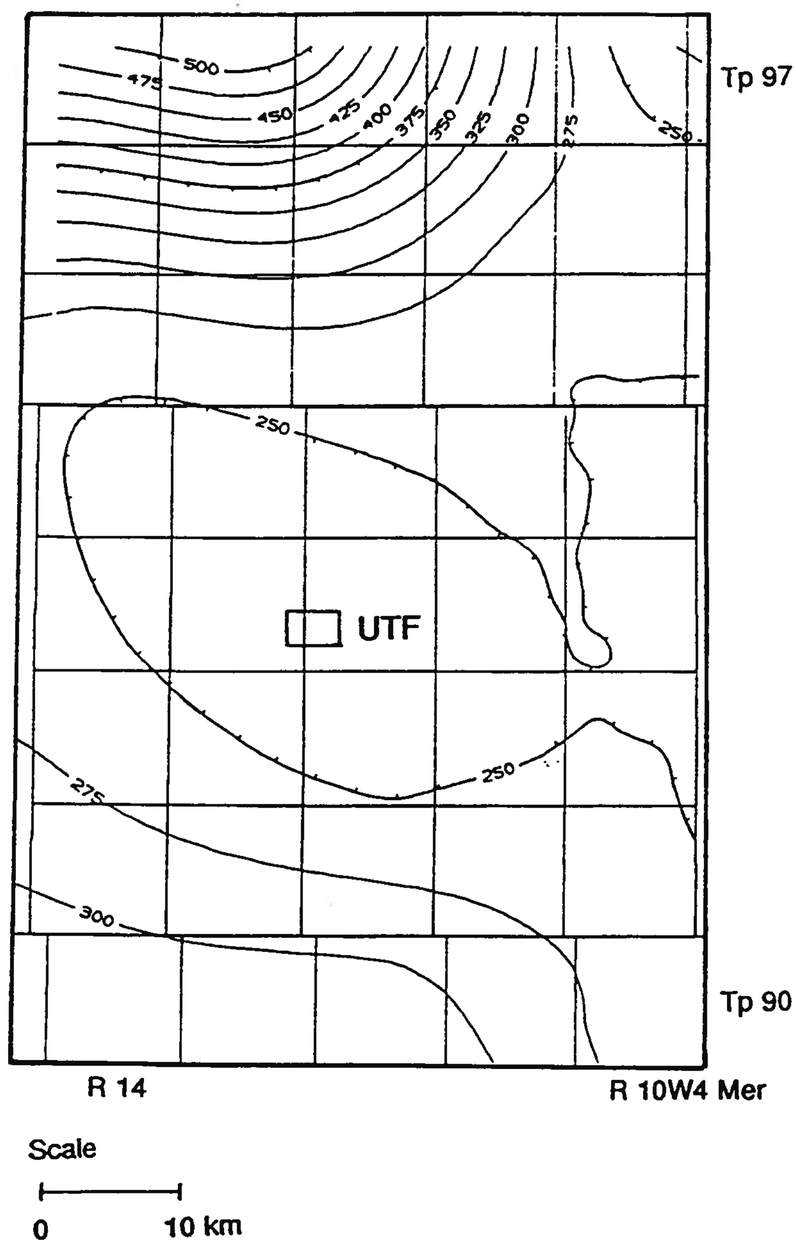


Figure 23. Distribution of freshwater hydraulic head (m) in the Beaverhill Lake aquifer system.

southern edge of the Birch Mountains (Petroleum Geology and Basin Analysis Group, 1992), which act as a recharge zone. The low values in central regions are induced by discharge along the outcrop, and by the low topography along the river valleys. Fluid flow is from the northwest and southwest towards the outcrop regions. The topographic high between the MacKay and Dover rivers (Appendix B, Figure 12) is not reflected in the hydraulic head distribution for the Beaverhill Lake aquifer. This is either a real physical effect of the intervening shales of the Clearwater Formation, which may isolate the Beaverhill Lake aquifer from local topographic effects, or it is simply an artifact caused by the lack of data control in this area.

MCMURRAY AQUIFER/AQUITARD

The McMurray Formation forms the lowermost Cretaceous hydrostratigraphic unit. Rock properties associated with McMurray strata reflect those of an aquifer, but occurrences of bitumen accumulations prevent in places the flow of formation fluids, resulting in an aquifer/aquitard classification for the unit. Two formation water analyses from a well in Tp 95 R 12 W4 Mer (just north of the Ells River) have an average salinity of 3500 mg/l. They provide local control to the otherwise regionally derived distribution of formation water salinity (Figure 24). The formation waters of the McMurray aquifer/aquitard are relatively fresh (3400 to 6200 mg/l), with a slight increase in salinity to the southeast, consistent with an increase in solubility with temperature (depth).

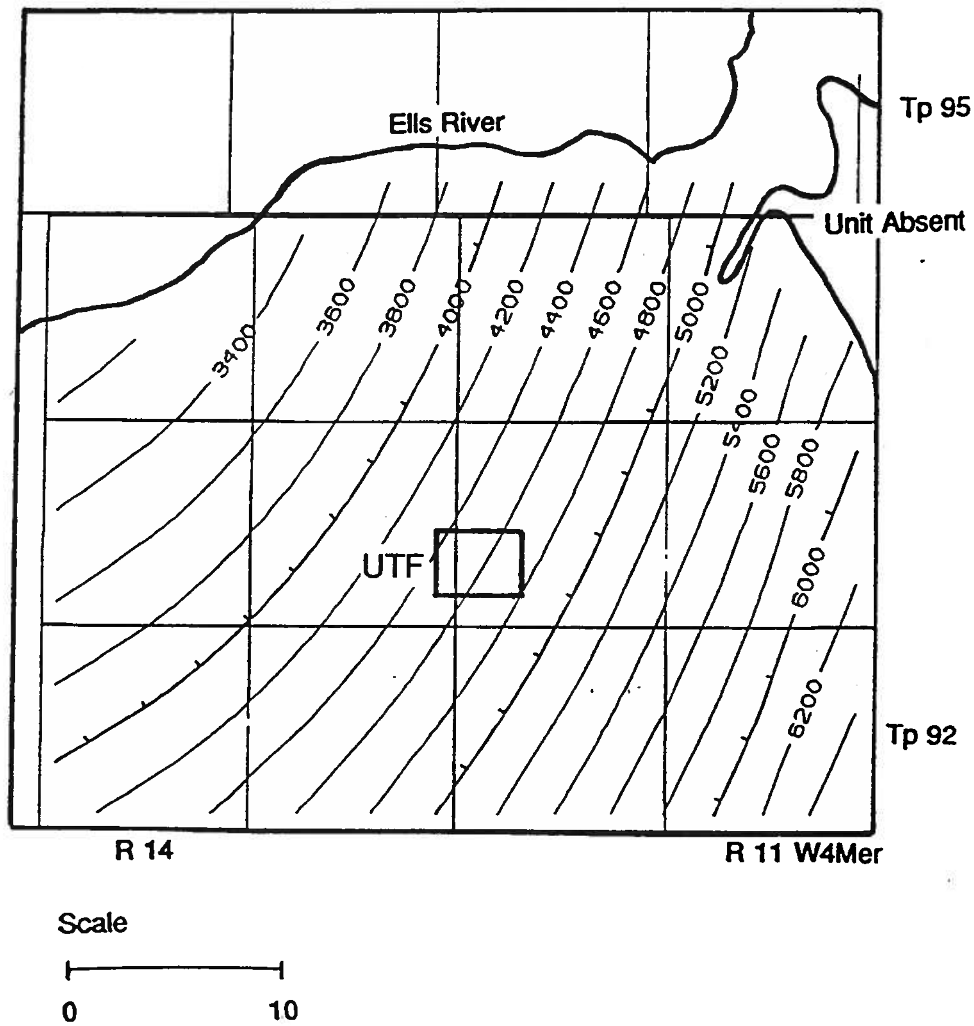


Figure 24. Salinity distribution (mg/l) in the McMurray aquifer system.

There are no drillstem tests within the Cretaceous intermediate-scale study area. The regional-scale study of the hydrogeological regime of formation waters in northeast Alberta (Petroleum Geology and Basin Analysis Group, 1992) provides the main source of information on hydraulic head distributions at the intermediate scale. The hydraulic head in McMurray strata decreases from 380 m in the west to less than 300 m in the east along the outcrop region (Figure 25). Because of the sparse data control at the regional-scale, the local topographic high is not reflected in the hydraulic head distribution. In reality, the values of hydraulic head are probably higher in the southwest, reflecting local recharge at the topographic high.

For two aquifers in vertical contact like the McMurray and Beaverhill Lake, the equilibrated hydraulic head at any location should be the same in both, or with very small differences when there is a vertical flow component. The distribution of oil sands (Flach, 1984) and the lack of hydrogeological data in an interval otherwise penetrated by hundreds of wells indicate that much of the McMurray stratigraphic interval is bitumen saturated, creating probably a significant barrier to flow within the intermediate-scale study area. The large difference in hydraulic head between the Wabiskaw aquifer and the Beaverhill Lake aquifer system is arguably based largely on extrapolated trends from the regional-scale characterization (Petroleum Geology and Basin Analysis Group, 1992). However, the intermediate-scale area covers large portions of both AOSTRA's and SYNCRUDE's leases where bitumen deposits are deemed to be the richest and most continuous both laterally and vertically. The bitumen is most often concentrated at the

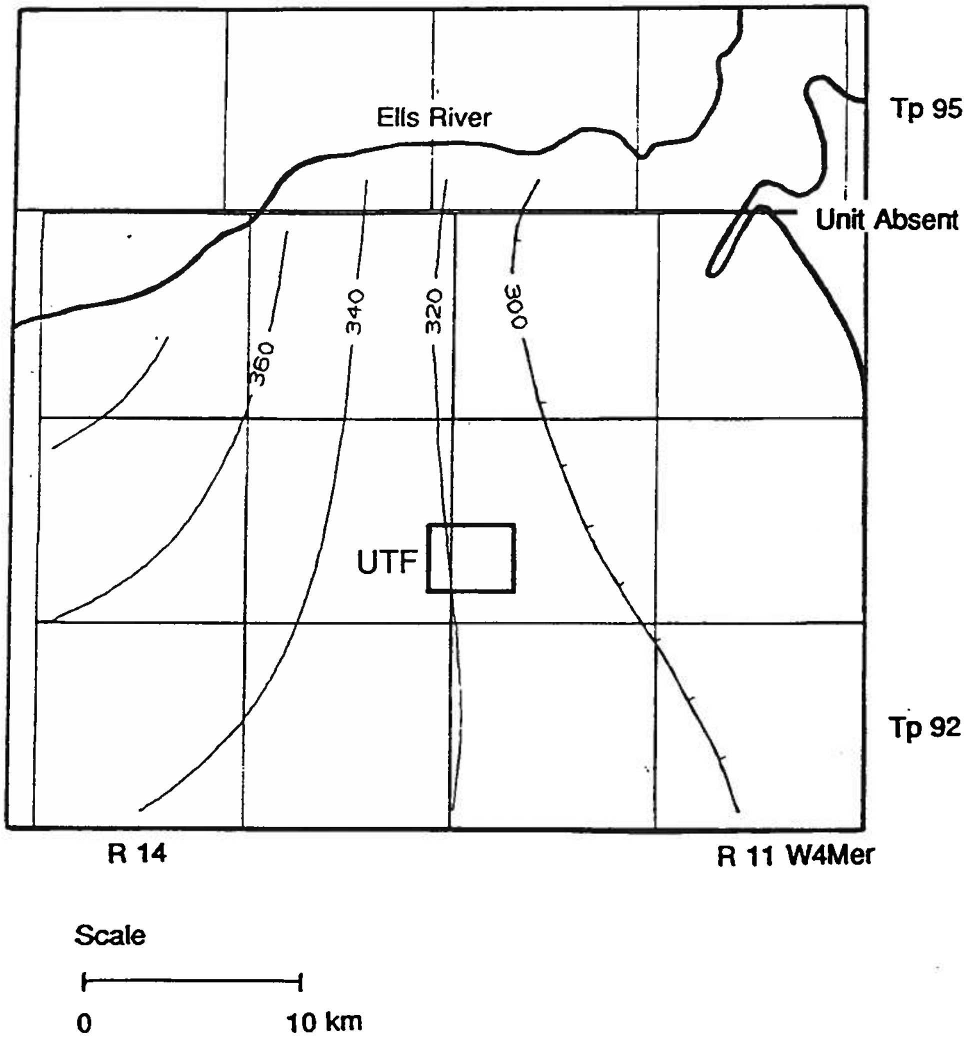


Figure 25. Distribution of freshwater hydraulic head (m) in the McMurray aquifer system.

base of the McMurray succession, becoming leaner toward the top. Only small isolated areas of water sand at the base of the McMurray have been mapped in this area (Flach, 1984). If the bitumen saturated sands are continuous over much of the area, then they form a significant flow barrier (aquitard) at the intermediate-scale and could explain the large difference in hydraulic heads between the McMurray and Beaverhill Lake aquifers.

WABISKAW AQUIFER

The Wabiskaw aquifer contains no formation water analyses within the intermediate-scale study area. The distribution of formation water salinity obtained from the regional-scale study (Petroleum Geology and Basin Analysis Group, 1992) shows values slightly higher and trending differently than those in the underlying McMurray unit (Figure 26). For the Wabiskaw aquifer, the extrapolated values range from 11500 mg/l in the southwest, to over 12000 mg/l in the northeast by the outcrop region. The small differences between this aquifer and the underlying McMurray aquifer are likely the result of data distribution and computer extrapolation.

The distribution of hydraulic head shows a decreasing trend from 380 m in the west to 300 m in the east along the outcrop region (Figure 27). Based on the hydraulic head distributions obtained from the regional-scale study (Petroleum Geology and Basin Analysis Group 1992), the McMurray and Wabiskaw hydrostratigraphic units can be considered to be in hydraulic continuity.

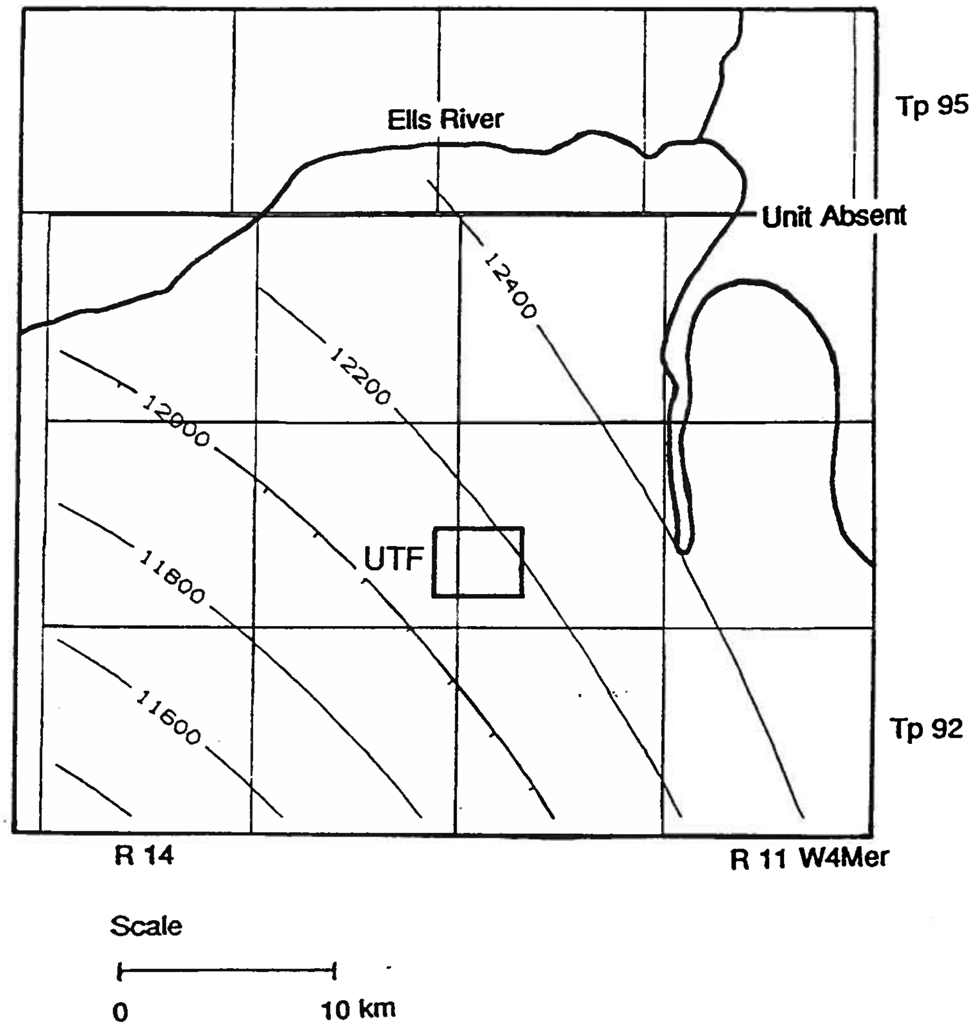


Figure 26. Salinity distribution (mg/l) in the Wabiskaw aquifer system.

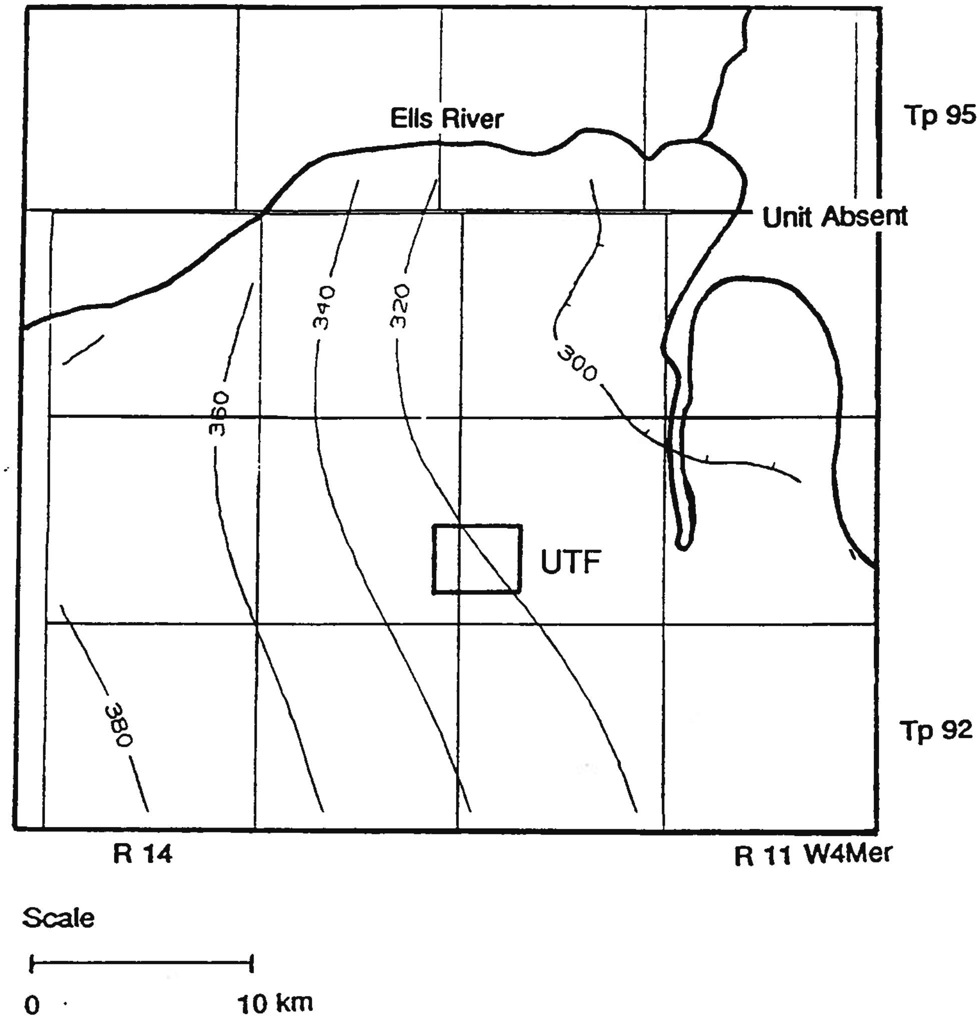


Figure 27. Distribution of freshwater hydraulic head (m) in the Wabiskaw aquifer system.

CLEARWATER AQUITARD

The Clearwater Formation represents a highly variable unit, with lithology ranging from fine grained sandstone to black marine shale. Most of the unit consists of interbedded silts and muds. Based on trends from the regional-scale characterization (Petroleum Geology and Basin Analysis Group, 1992), the thickness of the Clearwater aquitard ranges from over 80 m in the southwest to zero at the outcrop along the Athabasca River and its tributaries (Figure 16). It is difficult to assess the integrity and strength of the Clearwater aquitard in the intermediate-scale study area with few local hydrodynamic data above or below it. If the values of hydraulic head obtained for the intermediate-scale area for the Grand Rapids and Wabiskaw aquifers from the regional-scale distributions (Petroleum Geology and Basin Analysis Group, 1992) are considered representative, then it seems that the Clearwater aquitard is strong. In some areas, erosion and the existence of paleo-valleys may jeopardize the integrity of the Clearwater aquitard.

GRAND RAPIDS AQUIFER

The Grand Rapids aquifer is present only over a small region in the southwestern part of the study area, coincident with the high topography. Although there are no formation water analyses within or near the intermediate-scale study area for this unit, the formation water salinity is expected to be considerably fresher than that of the McMurray aquifer. The distribution of hydraulic head at the regional-scale (Petroleum Geology and Basin Analysis Group, 1992) suggests that values may be in the range of 500 m within the intermediate-scale study area.

PLEISTOCENE AQUIFER

The Pleistocene cover, often in the form of glacial drift or till, is normally present in thin sheets overlying the bedrock surface. Occasionally, paleo-channel systems filled with Pleistocene sediments cut though underlying bedrock to depths of up to 100 m (Figure 10). The loosely consolidated to unconsolidated sediments of these deposits generally form highly permeable unconfined aquifers (Basin Analysis Group, 1988).

CROSS-FORMATIONAL FLOW

Within the intermediate-scale study areas, there are three main units which form barriers to flow. The Prairie-Watt Mountain aquiclude system has been shown to be a significant flow barrier which isolates the regional flow system in the Winnipegosis-Basal aquifer system from the aquifers above. The oil sand deposits of the McMurray Formation and the Clearwater aquitard are the other major flow barriers in the area; however, their integrity and strength are more difficult to asses. Local barriers to flow within the Beaverhill Lake aquifer system are not assessed at the intermediate-scale. In order to evaluate the significance of cross-formational flow in the intermediate-scale study area, the distributions of hydraulic head in individual aquifers above and below aquitards or aquicludes are compared in map and cross-sectional form. There are no data from which pressure-depth plots can be constructed. Without any supporting evidence and because most of the hydraulic head distributions are based on trends established at the regional scale (Petroleum Geology and Basin Analysis Group, 1992), inferences on cross-formational flow for the intermediate-scale study area are somewhat qualitative.

Two hydrogeological cross-sections (Figure 28) were constructed from the Paleozoic lines of section shown in the geological charter of this report. Values obtained from the distribution maps of formation water salinity and freshwater hydraulic head were plotted on dip and strike cross-sections, to indicate flow directions and the relation between the aquifers above and below the main flow barriers in the area. Figure 29 shows the distribution of formation water salinity along the dip cross-section. Formation water salinity in the aquifers below the Prairie Formation is an order of magnitude higher than salinity in aquifers above the Watt Mountain aquitard. The formation water salinity in the Winnipegosis-Basal aquifer system also shows an increasing trend with depth. As discussed in the regional-scale study (Petroleum Geology and Basin Analysis Group, 1992), this trend is likely temperature related. Figure 30 shows the distribution of freshwater hydraulic head along the dip cross-section. It is evident from the large difference in hydraulic head across the Prairie-Watt Mountain aquiclude system that it effectively separates the flow systems in the aquifers below from that in the aquifers above. Although the freshwater hydraulic head decreases in an updip direction within the

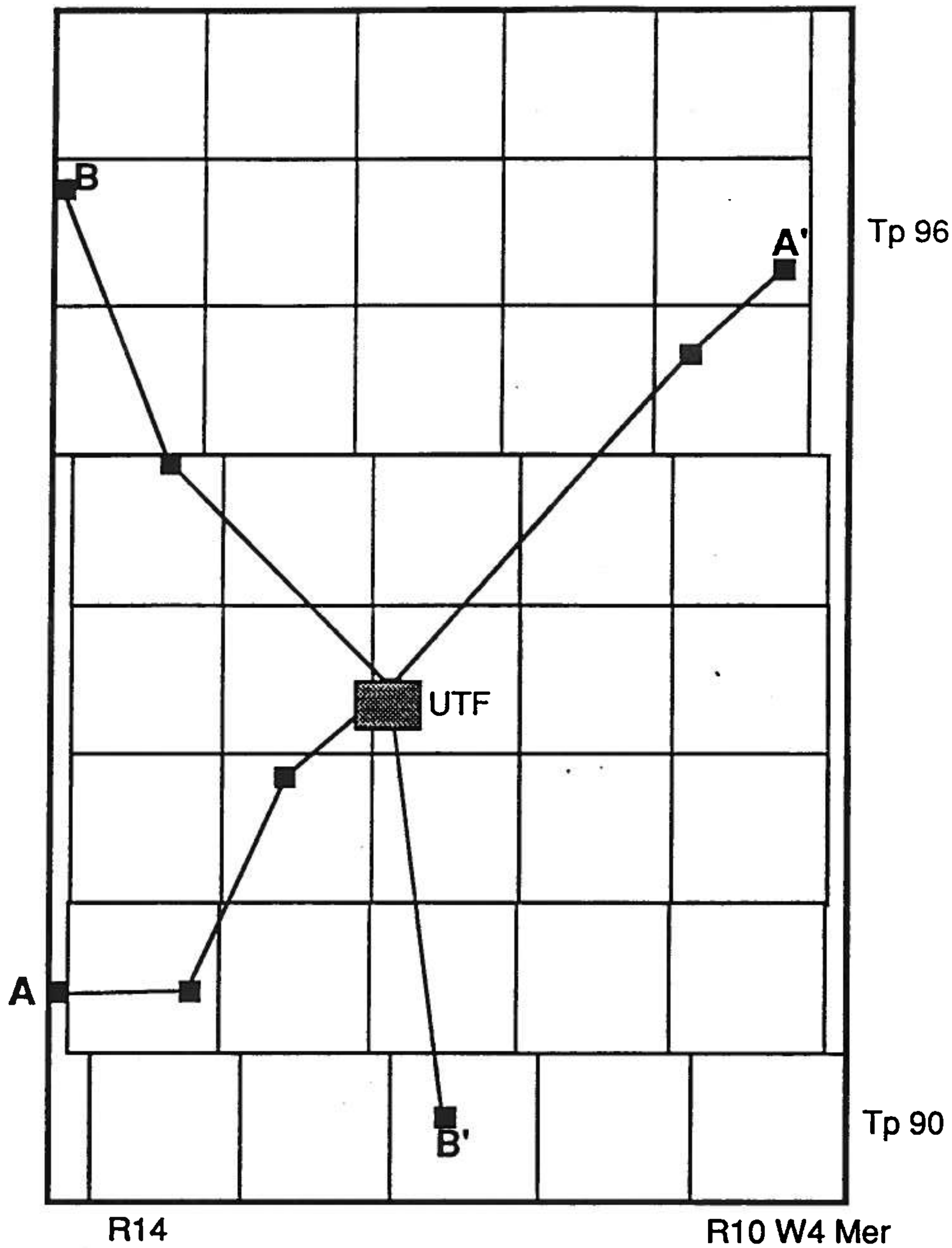


Figure 28. Location of hydrogeological dip and strike cross-sections.

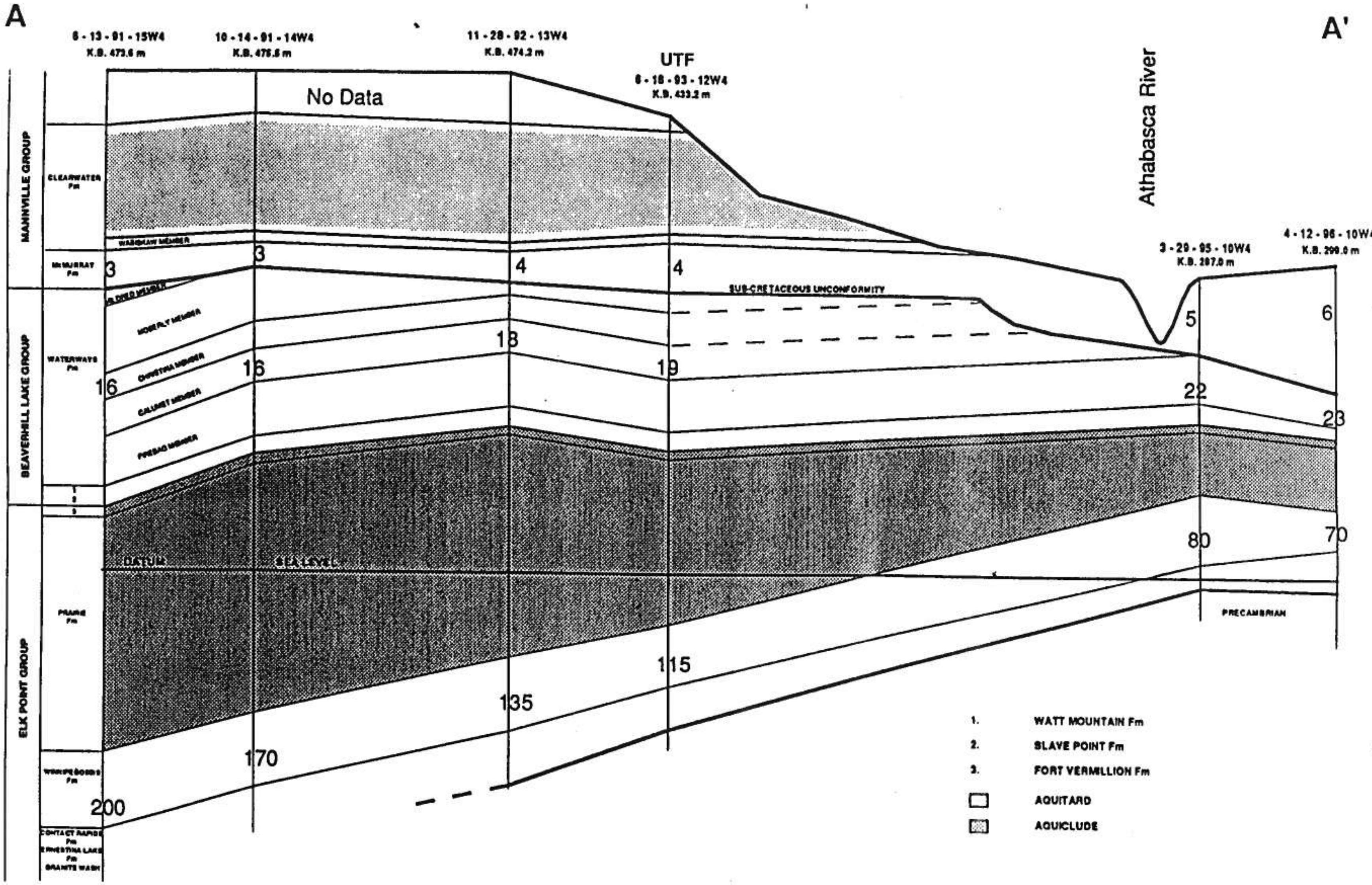


Figure 29. Distribution of formation water salinity (10^3mg/l) along dip hydrogeological cross-section.

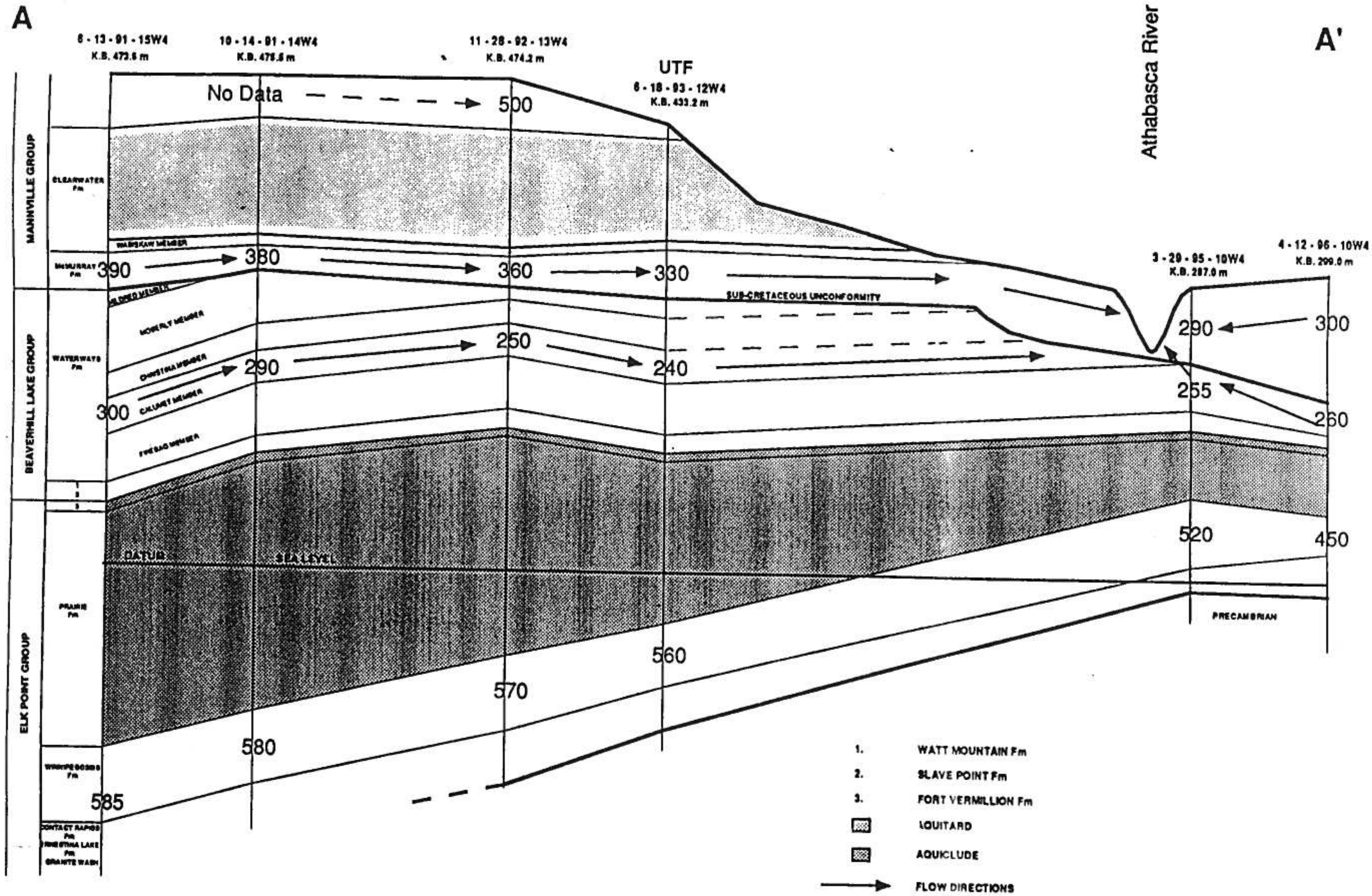


Figure 30. Distribution of freshwater hydraulic head (m) along dip hydrogeological cross-section.

Contact Rapids-Winnipegosis aquifer system, the effects of density driven flow likely are significant (Petroleum Geology and Basin Analysis Group, 1992). The density (buoyancy) component related to the high formation water salinity results in a downward component counteracting the gravity driven updip component. The effect of density driven flow is likely negligible for the aquifers above the Prairie-Watt Mountain aquiclude system because of much lower formation water salinity (Petroleum Geology and Basin Analysis Group, 1992) and gentler dip of Cretaceous aquifers. The Beaverhill Lake, McMurray and Wabiskaw aquifers show similar distributions of hydraulic head, driving the flow of formation waters towards the Athabasca River system where they discharge. In the vertical direction, with the exception of the discharge area at the river, the hydraulic head values decrease downward from the uppermost (Grand Rapids) aquifer to the McMurray-Wabiskaw aquifer/aquitard system and to the Beaverhill Lake aquifer system, indicating a downward flow component. This is consistent with topographic control on the local flow regime as described in the regional-scale hydrogeological study (Petroleum Geology and Basin Analysis Group, 1992). At the regional-scale, a downward flow component is present in topographically high areas of recharge (southwest from the UTF site in Figure 30) and an upward component in topographically low areas of discharge such as along the Athabasca River valley. Notwithstanding this gravitationally induced vertical flow component, the large difference in hydraulic head between the McMurray-Wabiskaw and Beaverhill Lake aquifer systems suggests that a barrier to flow exists between them. Bitumen accumulations in the McMurray Formation are likely responsible for isolating the flow system in the upper part of the McMurray-Wabiskaw aquifer system from that in the

Beaverhill Lake aquifer system below. Very little information is available for the uppermost aquifers (Grand Rapids and Pleistocene strata).

Trends in the formation water salinity and hydraulic head distributions along the strike cross-section B-B' are less evident since the cross-section is oriented perpendicular to the main flow directions and is located southwest of outcrop regions along the Athabasca river system (Figure 28). Figure 31 shows the distribution of formation water salinity. The topography along this line of section is variable, with the UTF site located on a high between the Dover (northwest) and MacKay (southeast) river valleys. Along this line of section, the two rivers cut down into the Clearwater Formation but the underlying aquifers are still isolated from the surface by the remainder of the Clearwater aquitard. This is not the case to the northeast, as seen in the previous dip cross-section (Figures 30 and 31). The salinity in the Winnipegosis-Basal aquifer system is high. Because the cross-section is along strike to basin structure, there is little variation in the depth of the strata along the section. Thus, the depth (temperature) related salinity trend observed in the dip cross-section (Figure 29) can not be detected here.

Figure 32 shows the distribution of freshwater hydraulic head along the strike cross-section. Because the main flow directions are perpendicular to the line of section, the distribution for freshwater hydraulic head shows less evident trends. The Contact Rapids-Winnipegosis aquifer system is effectively isolated from aquifers above as indicated by the large difference in hydraulic head values compared with the overlying

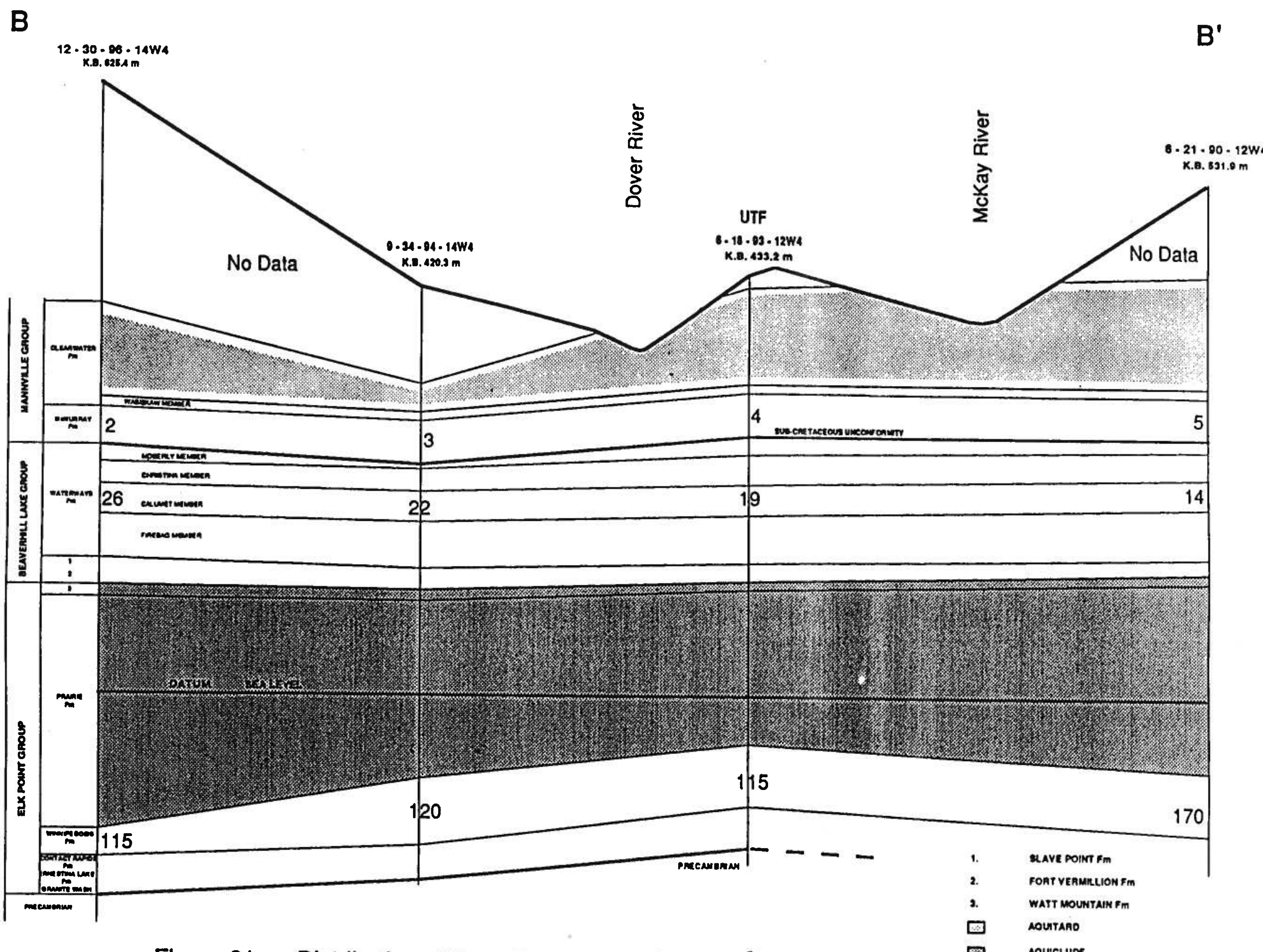


Figure 31. Distribution of formation water salinity (10^3mg/l) along strike hydrogeological cross-section.

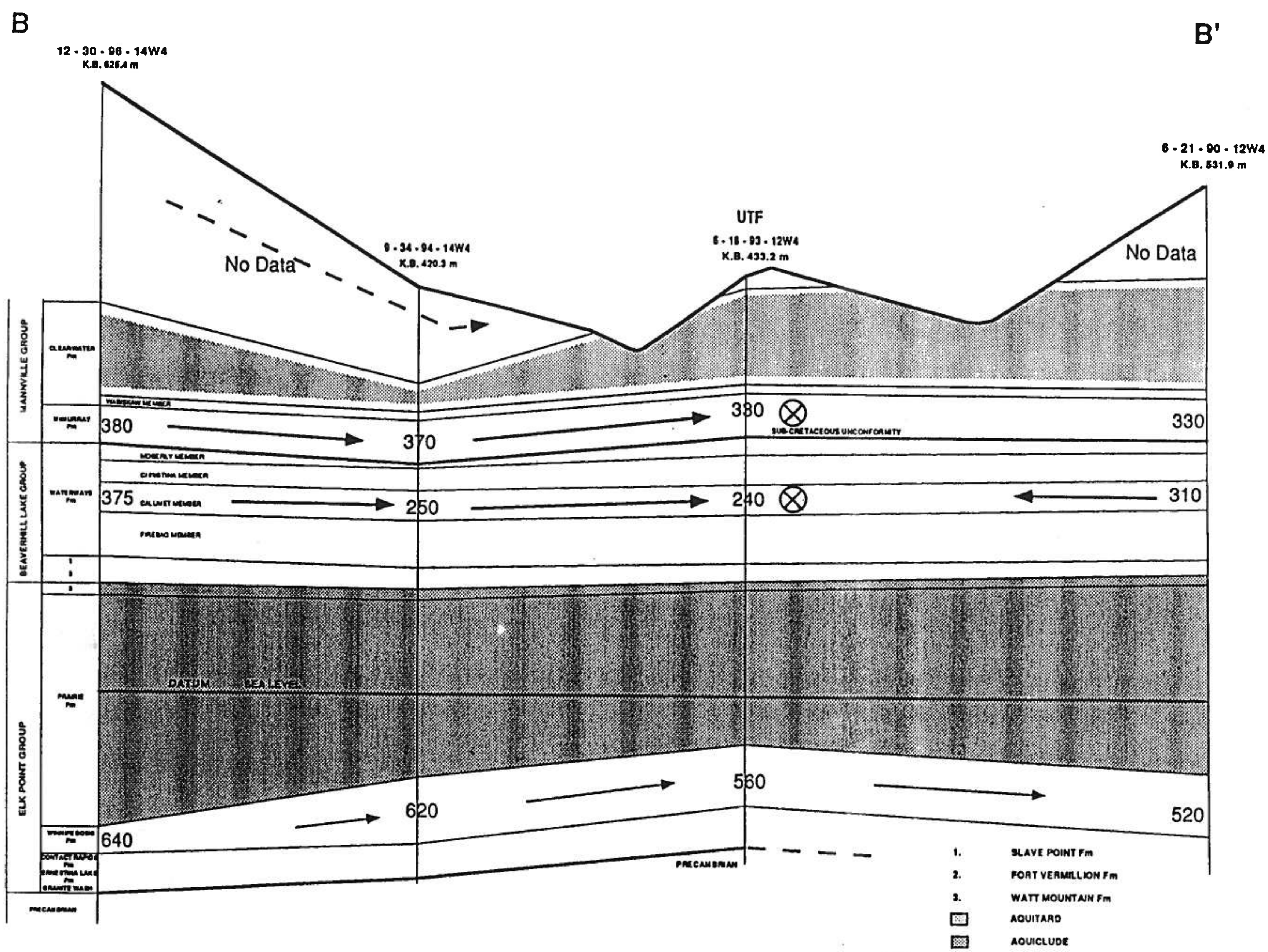


Figure 32. Distribution of freshwater hydraulic head (m) along strike hydrogeological cross-section.

Beaverhill Lake aquifer system. The Beaverhill Lake, McMurray and Wabiskaw aquifers generally show flow from the topographically high areas in the northwest and southeast towards the center of the line of section. Actually, a large flow component is directed into the cross-section to the northeast towards the Athabasca River system as shown in the previous dip cross-section (Figure 30). The generally higher values of hydraulic head in the Cretaceous McMurray and Wabiskaw aquifers indicate the potential for a downward component of the flow into the underlying Beaverhill Lake aquifer system. However, within the intermediate-scale study area, bitumen accumulations in the McMurray Formation most probably isolate the flow system in the Beaverhill Lake aquifer system from that in aquifers above. No hydraulic information is available for the Grand Rapids aquifer along the line of section; however, based on observations at the regional-scale (Petroleum Geology and Basin Analysis Group, 1992) and the local nature of the flow regime, flow directions are inferred to be from topographically high recharge areas to topographically low discharge areas.

From both hydraulic head maps and hydrogeological cross-sections it is evident that the Prairie-Watt Mountain aquiclude system is a strong and effective flow barrier within the intermediate-scale study area. It isolates the regional flow system in the Winnipegosis-Basal aquifer system from the local flow systems in the aquifers above the aquitard system. From the hydraulic head distributions extrapolated from the regional-scale characterization (Petroleum Geology and Basin Analysis Group, 1992) and previous oils sands resource studies (Flach, 1984), it appears that the bitumen-saturated portions of the McMurray Formation form a significant flow barrier within the intermediate-scale study area. Although in the study area data are lacking for the aquifers above the Clearwater aquitard, it appears that nevertheless it is an effective barrier to flow where its physical integrity is preserved. In places where present day and paleo erosion have removed the Clearwater Formation either partially or completely, the integrity of the Clearwater aquitard is questionable. The existence of paleo-channels which often cut down into Cretaceous bedrock and have subsequently been filled with Pleistocene sediments present a serious threat to the integrity of the Clearwater aquitard. Caution with regard to this problem is especially important because paleo-channel geometries are often difficult to discern.

CONCLUSIONS

There are very few hydrodogeological data at and immediately around the AOSTRA UTF site. For this reason, two intermediate-scale study areas were selected to include the limited data around the UTF site for hydrogeological characterization, one for Paleozoic and one for Cretaceous strata. The intermediate-scale characterization presented here will be used to run a preliminary numerical simulation of deep injection of residual water. This preliminary simulation will define the radius of impact that the proposed injection is expected to have on the currently natural hydrogeological regime. The intermediate-scale characterization will also serve as a basis for further "zooming" down to the local-scale UTF study area, which is to be modelled in detail. Data from the UTF site itself will be used as control on this final "zooming-in" process.

The hydrostratigraphy of the intermediate-scale study area can be broadly divided into four main flow units separated by three main flow barriers. The flow of formation waters in the Winnipegosis-Basal aquifer system is regional, being isolated from the aquifers above by the overlying Prairie-Watt Mountain aquiclude system. The formation waters are very saline, with depth (temperature) related trends. Because of the high formation water salinity, a downdip density driven flow component is expected to be significant and acting in opposition to the gravity driven flow component directed updip to the northeast. The Beaverhill Lake aquifer system exhibits local flow regime characteristics but has a pressure regime separated from aquifers above by bitumen accumulations in parts of the McMurray Formation. Generally, the formation water salinity is fresh and flow directions are towards the northeast where the aquifers outcrop and discharge along the Athabasca River and its tributaries. The McMurray-Wabiskaw aquifer/aquitard system (above the McMurray Formation bitumen deposits) has local flow regime characteristics and generally shows flow towards the Athabasca River system. With the exception of the outcrop regions, the Cretaceous aquifers show the potential for a downward flow component into the underlying Beaverhill Lake aquifer system. This is caused by downward directed recharge in areas of high topography and discharge along the topographically low river valleys, consistent with a local flow regime. The Clearwater aquitard appears to be a strong barrier to flow. However, caution should be exercised because present day erosion and difficult to detect paleo-valleys often cut down into this unit. The present and paleo erosion and associated potential fracturing may locally jeopardize the integrity of the Clearwater aquitard. The post-Clearwater aquifers of Grand Rapids and Pleistocene strata are of limited extent within the area and are nearly devoid of information.

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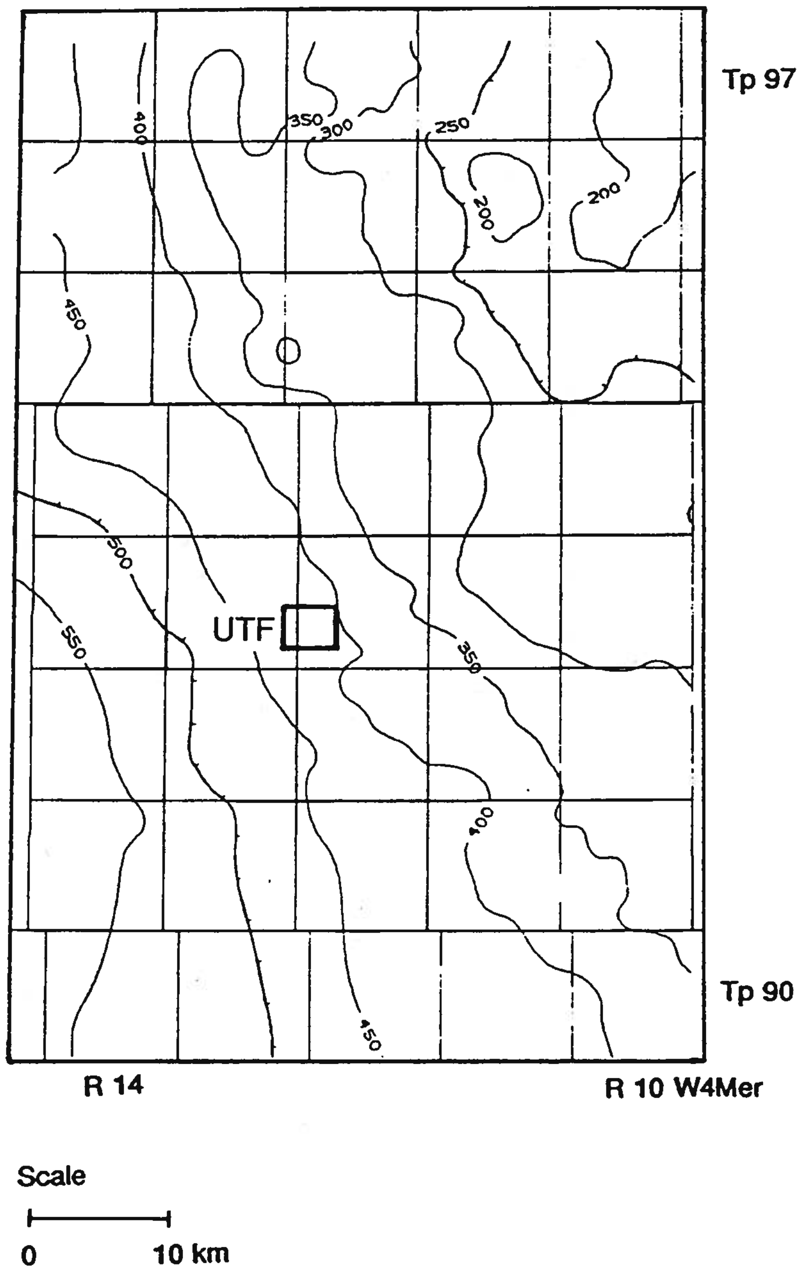
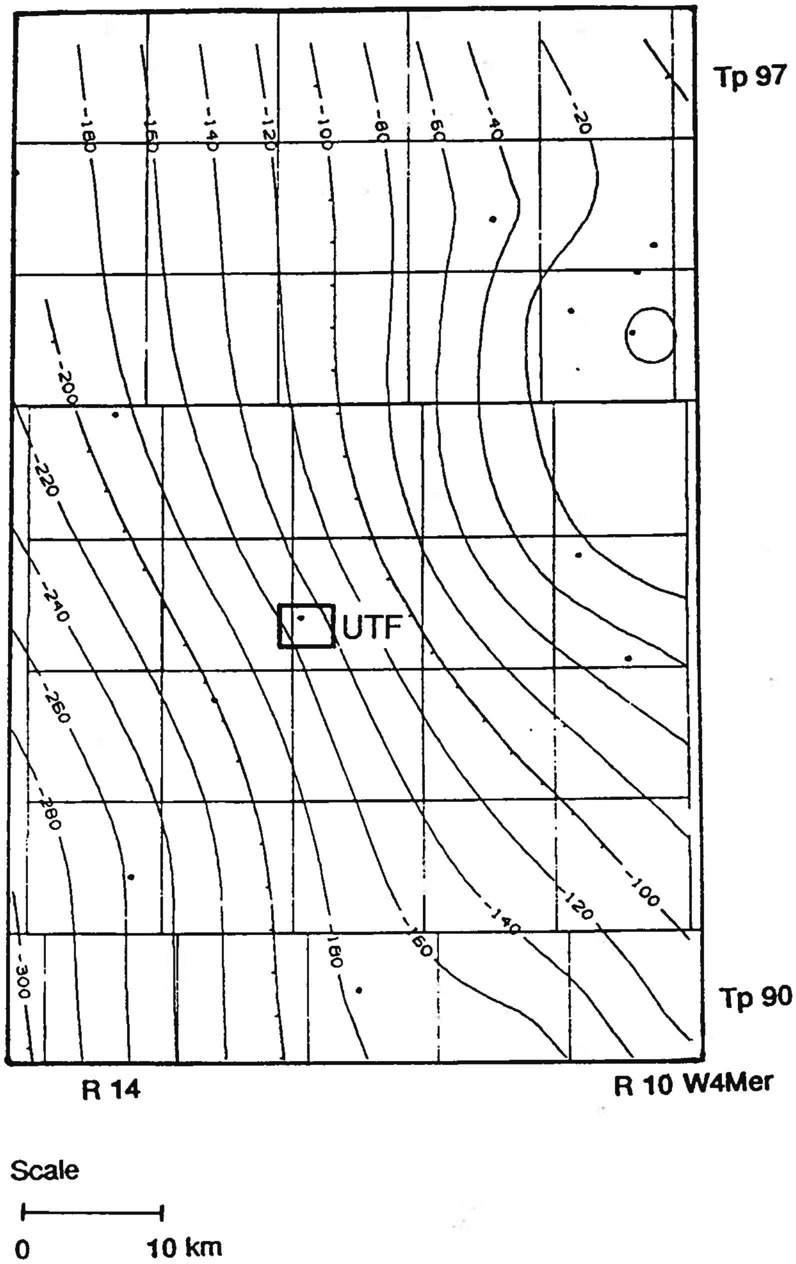
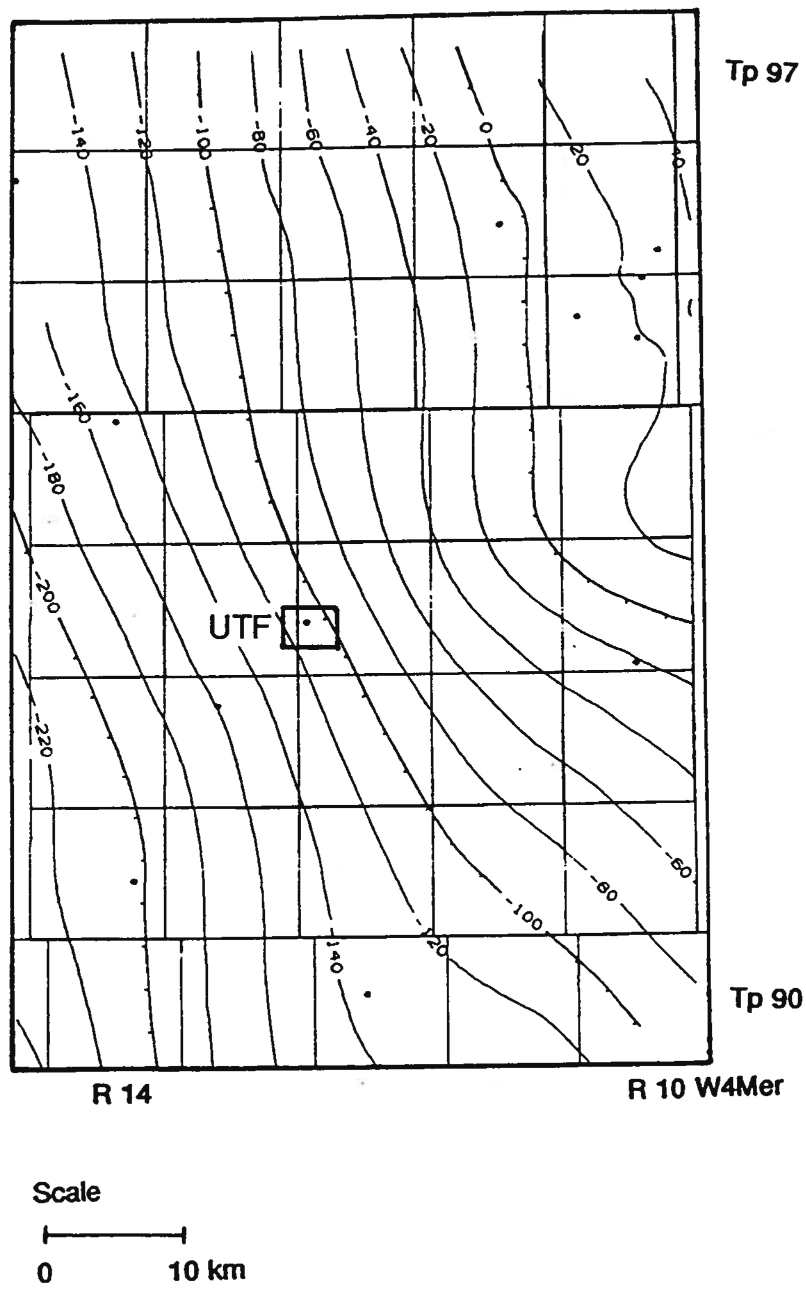
APPENDIX A - STRUCTURE AND ISOPACH MAPS OF PALEOZOIC STRATA



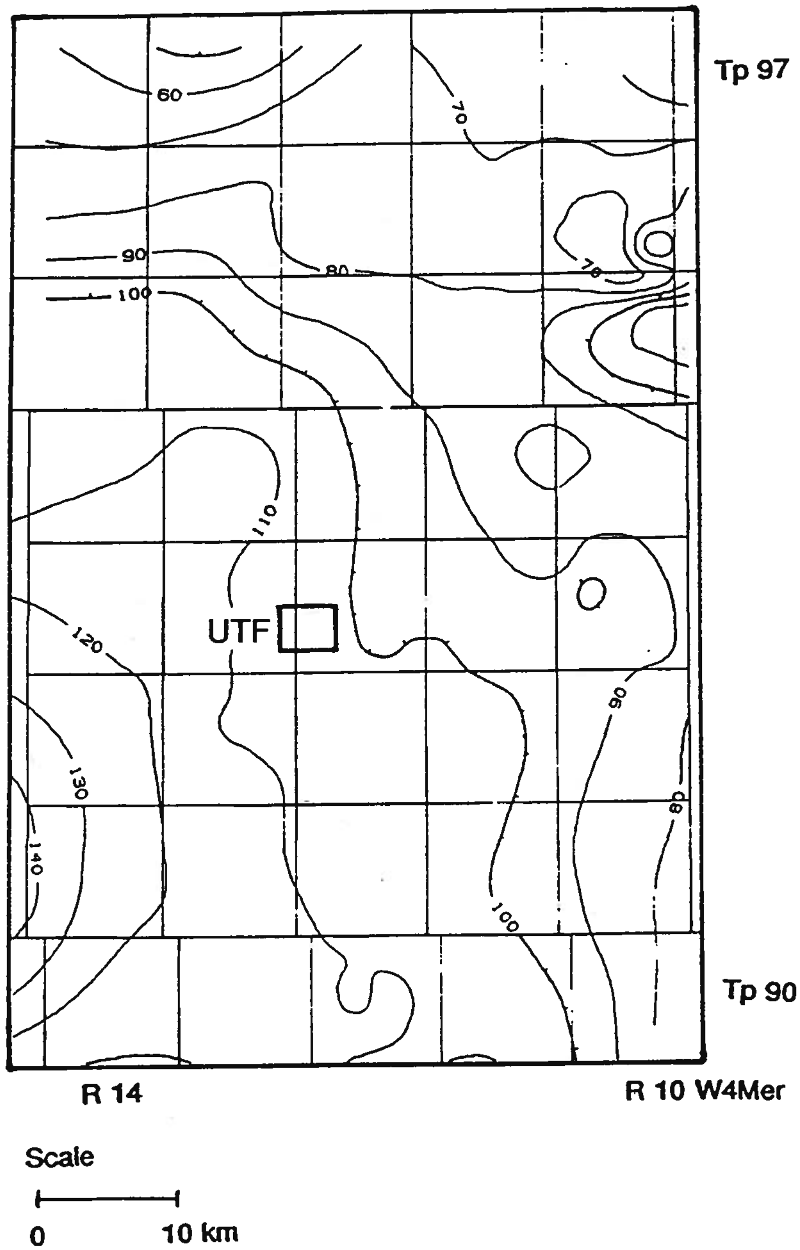
A- 1. Paleozoic isopach map.



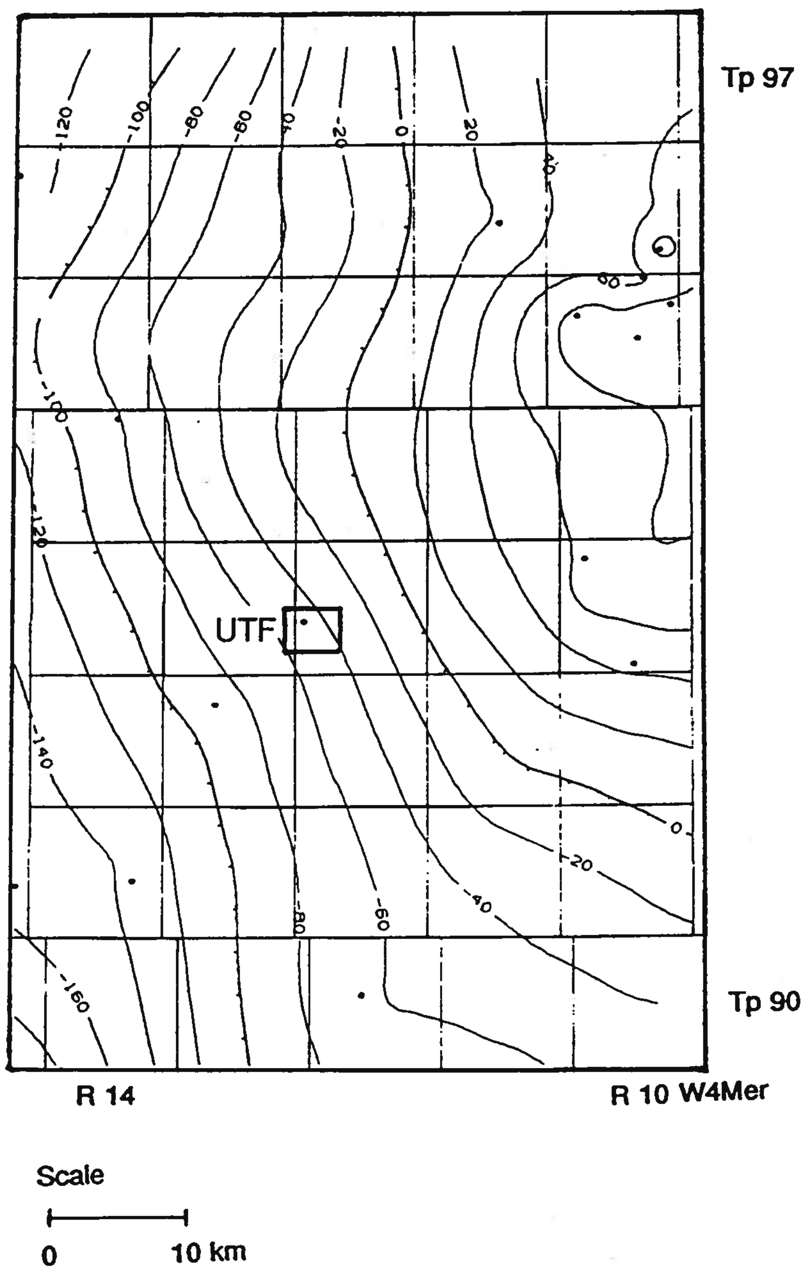
A- 2. Precambrian structure map.



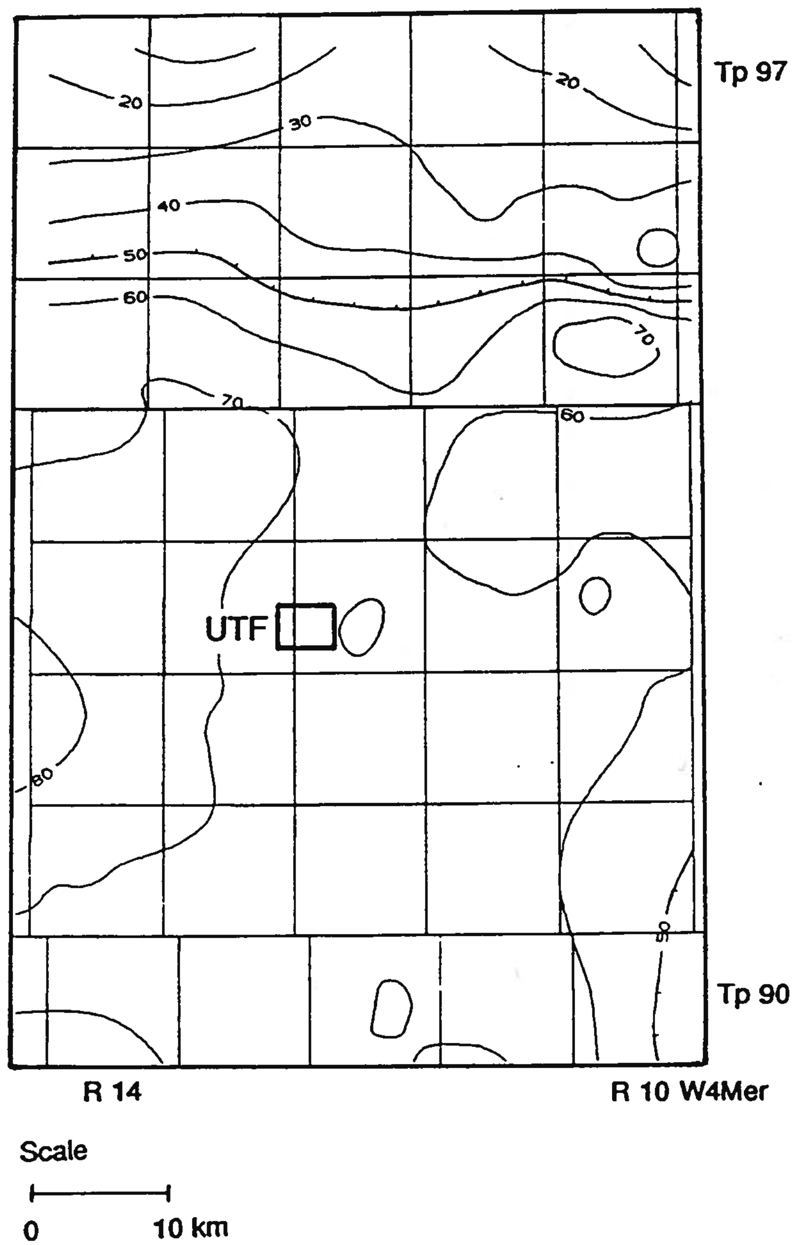
A- 3. Contact Rapids Formation structure map.



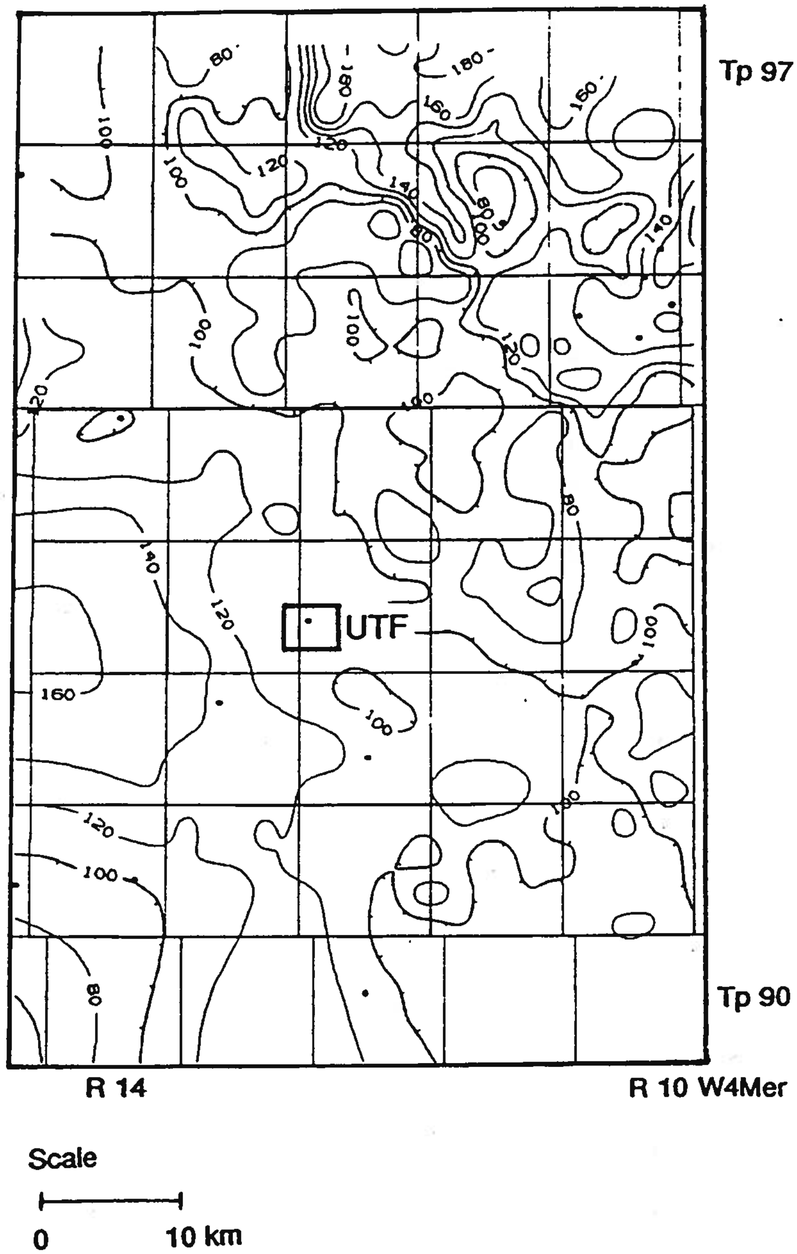
A- 4. Isopach map from the top of the Contract Rapids Formation to the Precambrian basement.



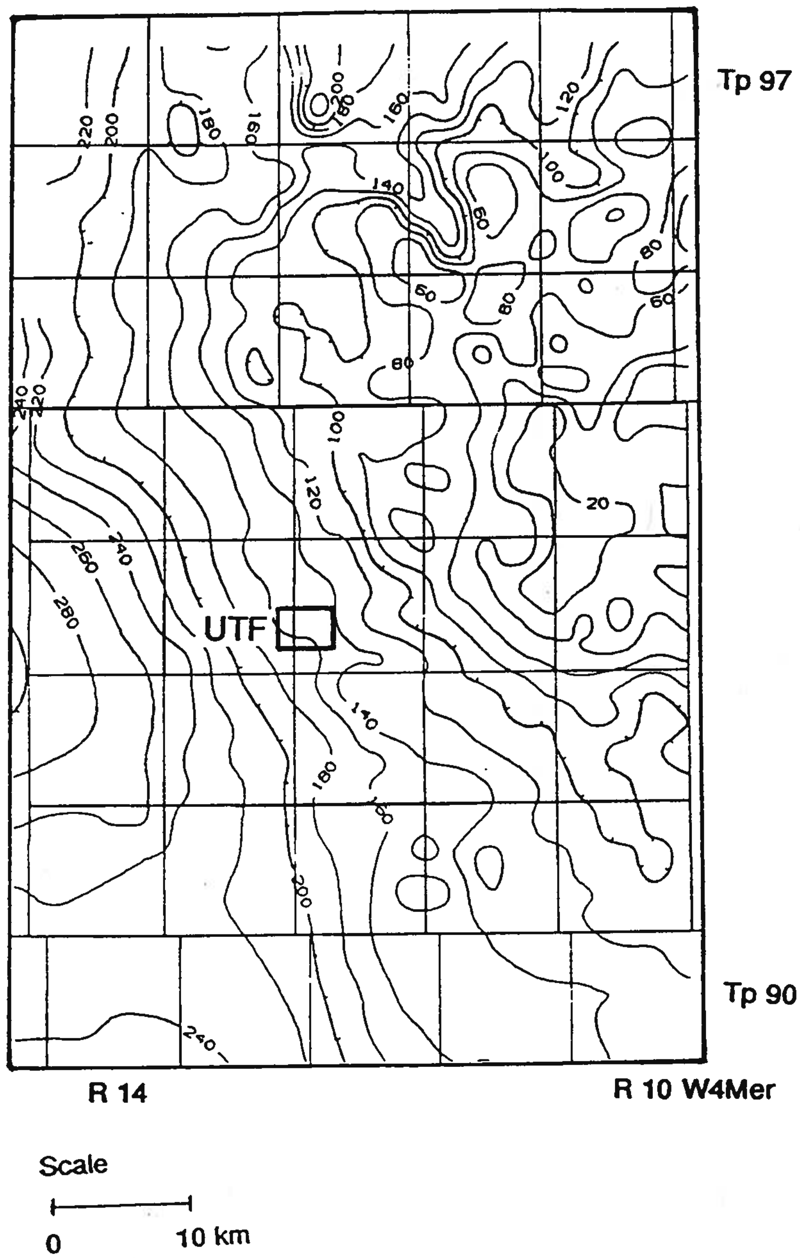
A- 5. Winnipegosis Formation structure map.



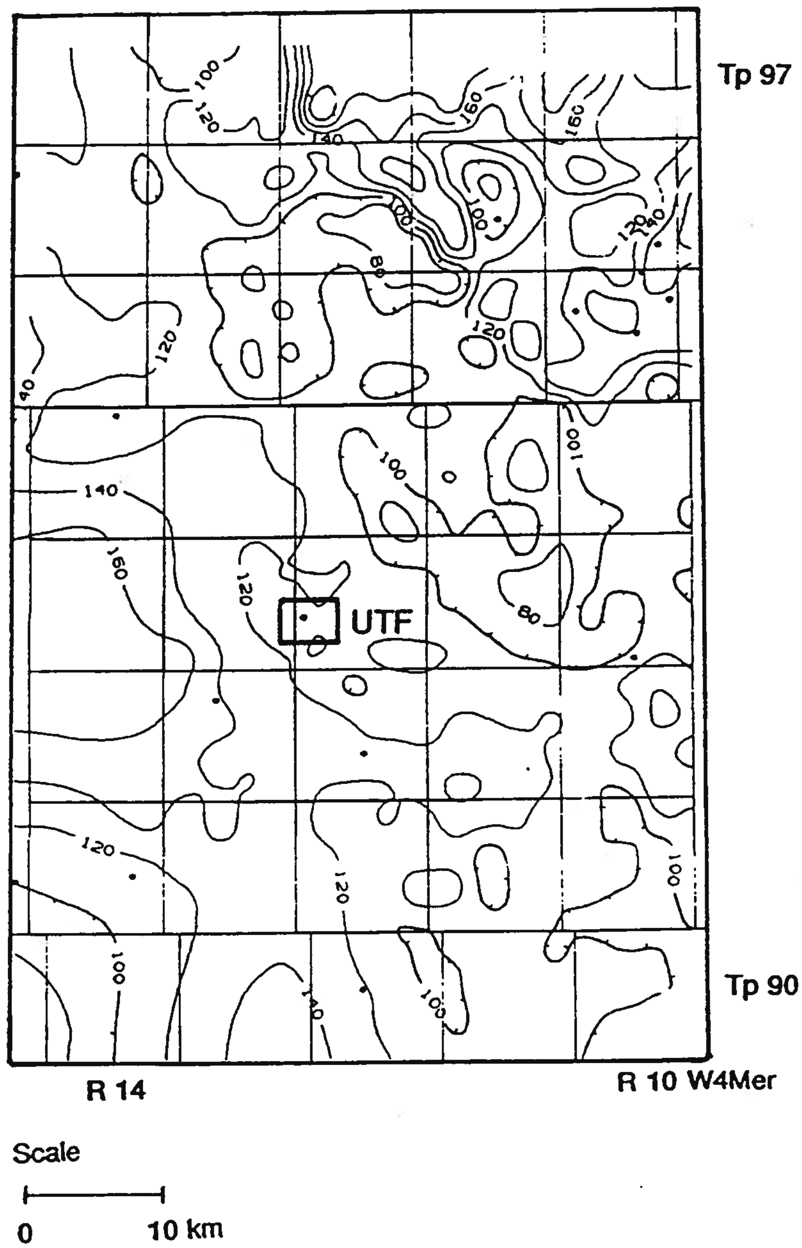
A- 6. Winnipegosis Formation isopach map.



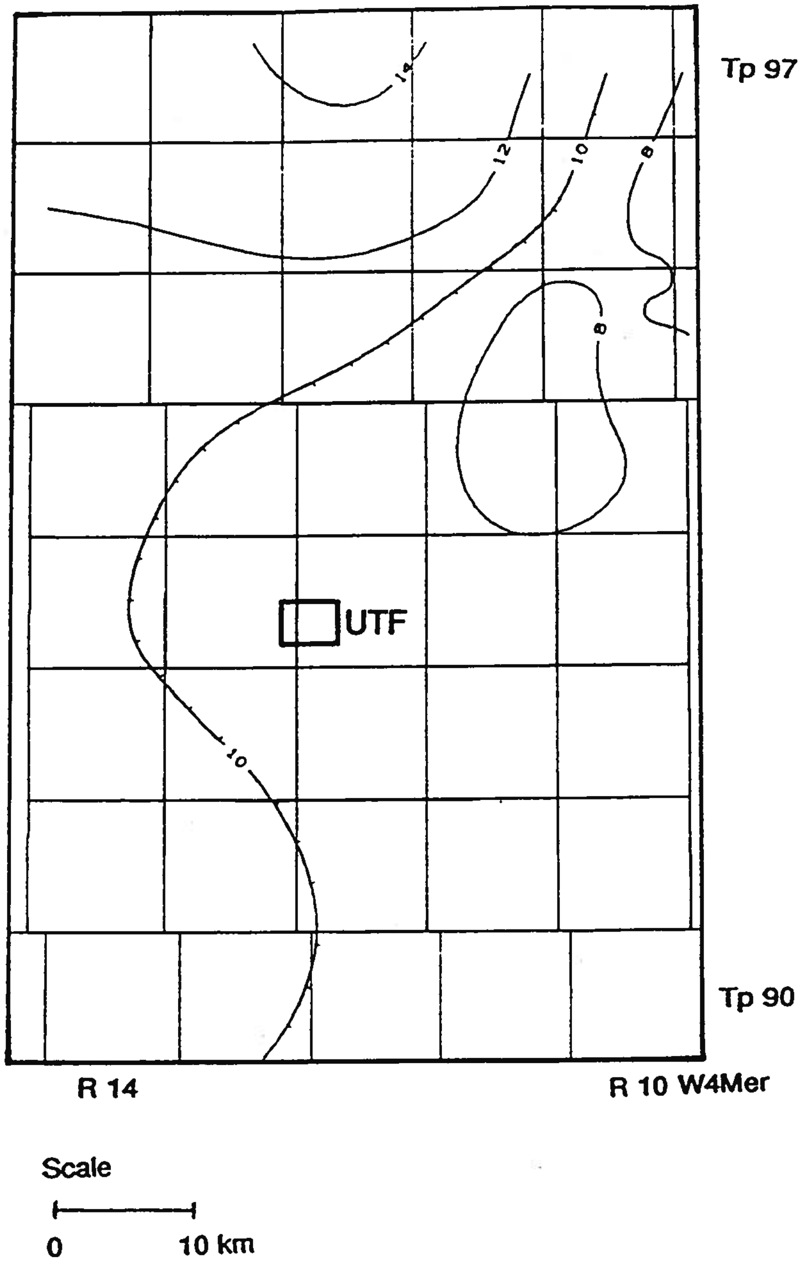
A- 7. Muskeg-Prairie interval structure map.



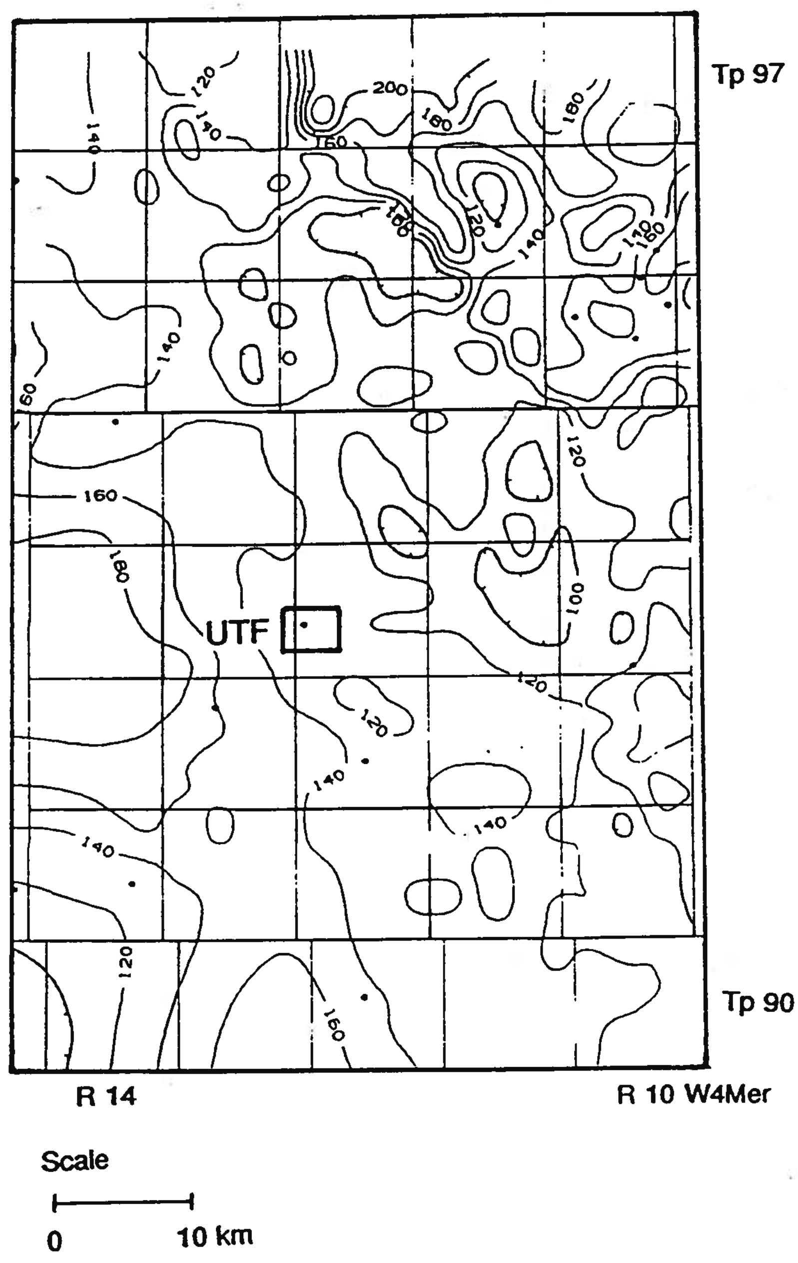
A- 8. Muskeg-Prairie interval isopach map.



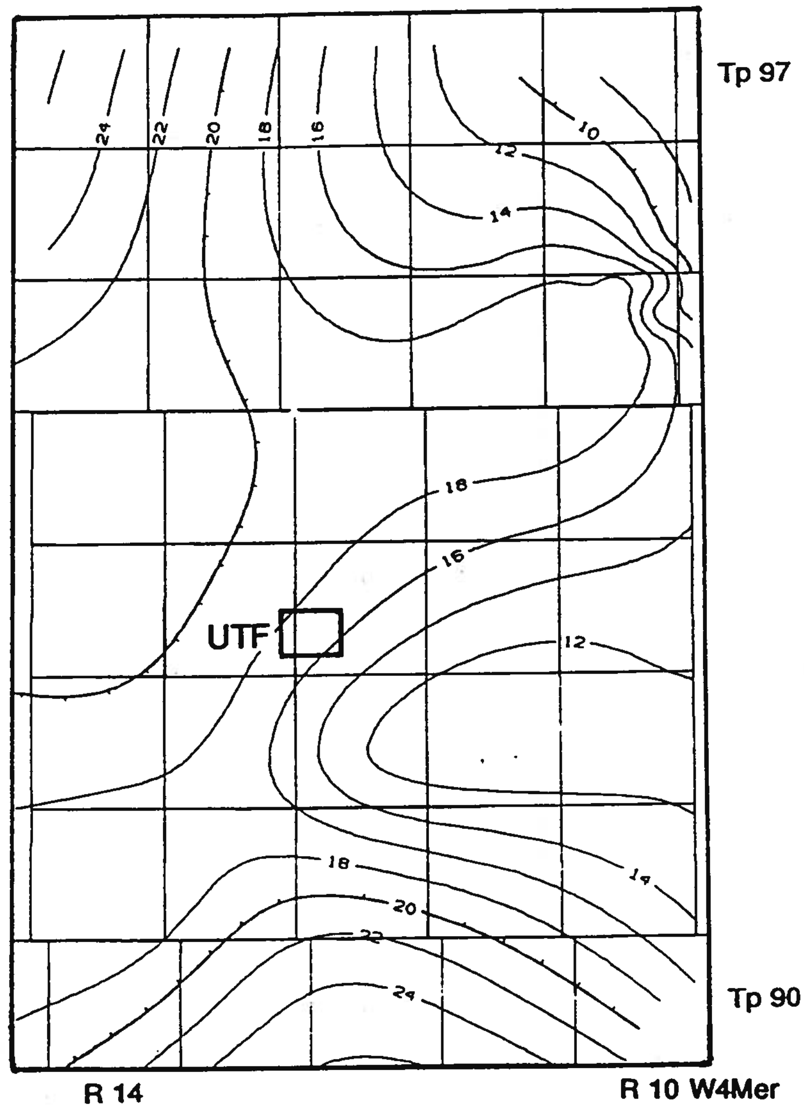
A- 9. Watt Mountain Formation structure map.



A-10. Watt Mountain Formation isopach map.



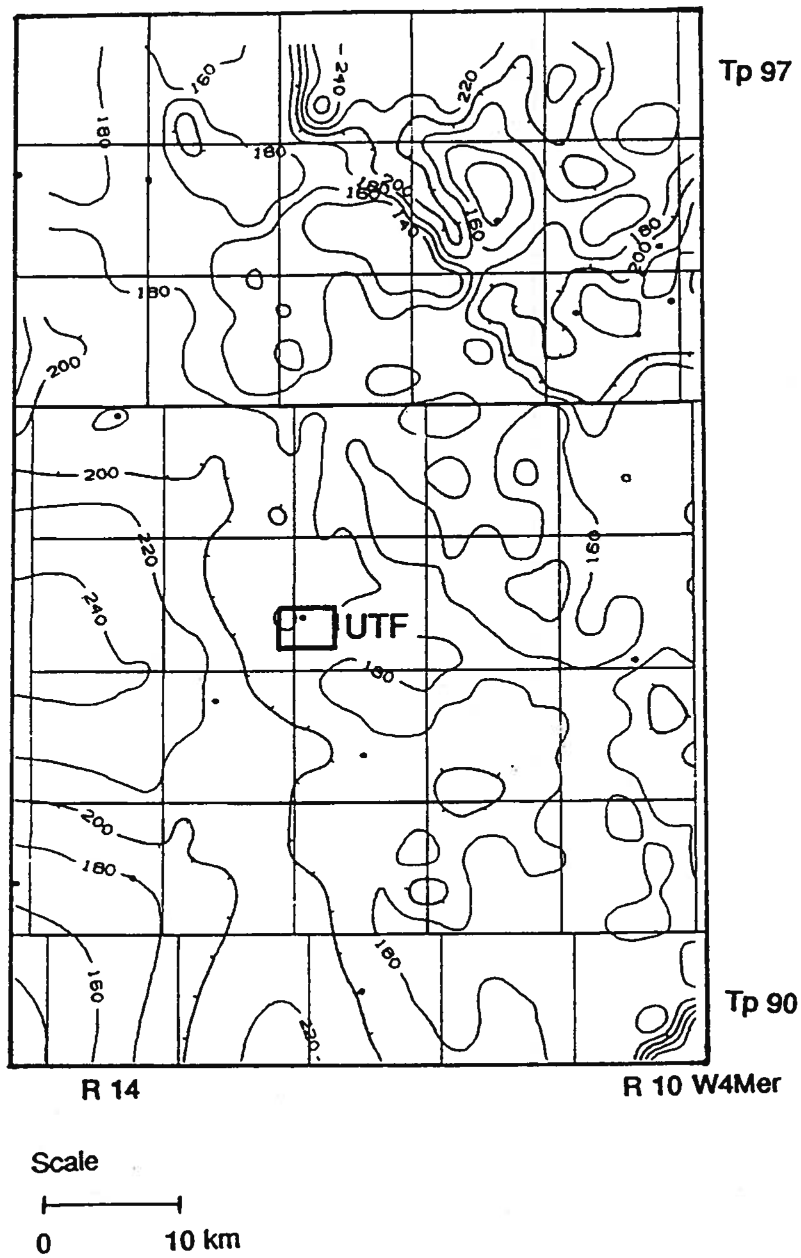
A-11. Slave Point Formation structure map.



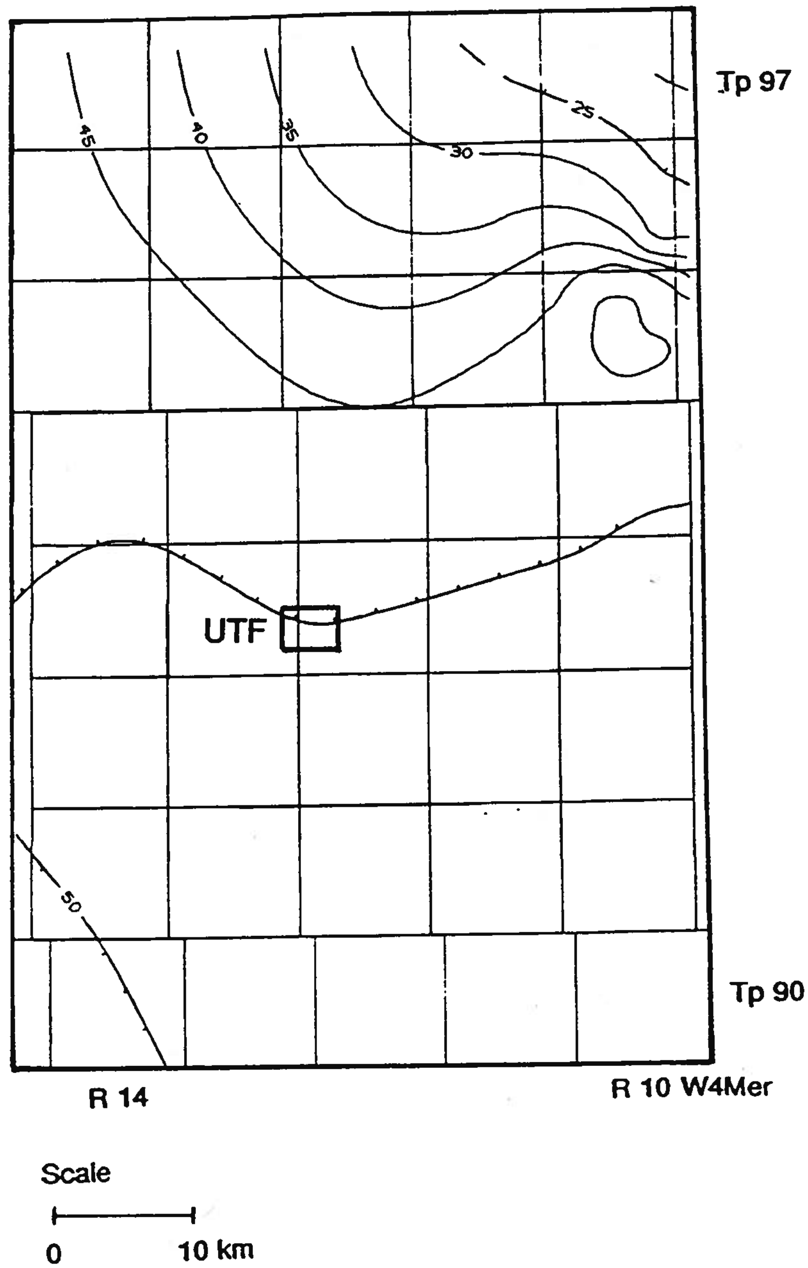
Scale

0 10 km

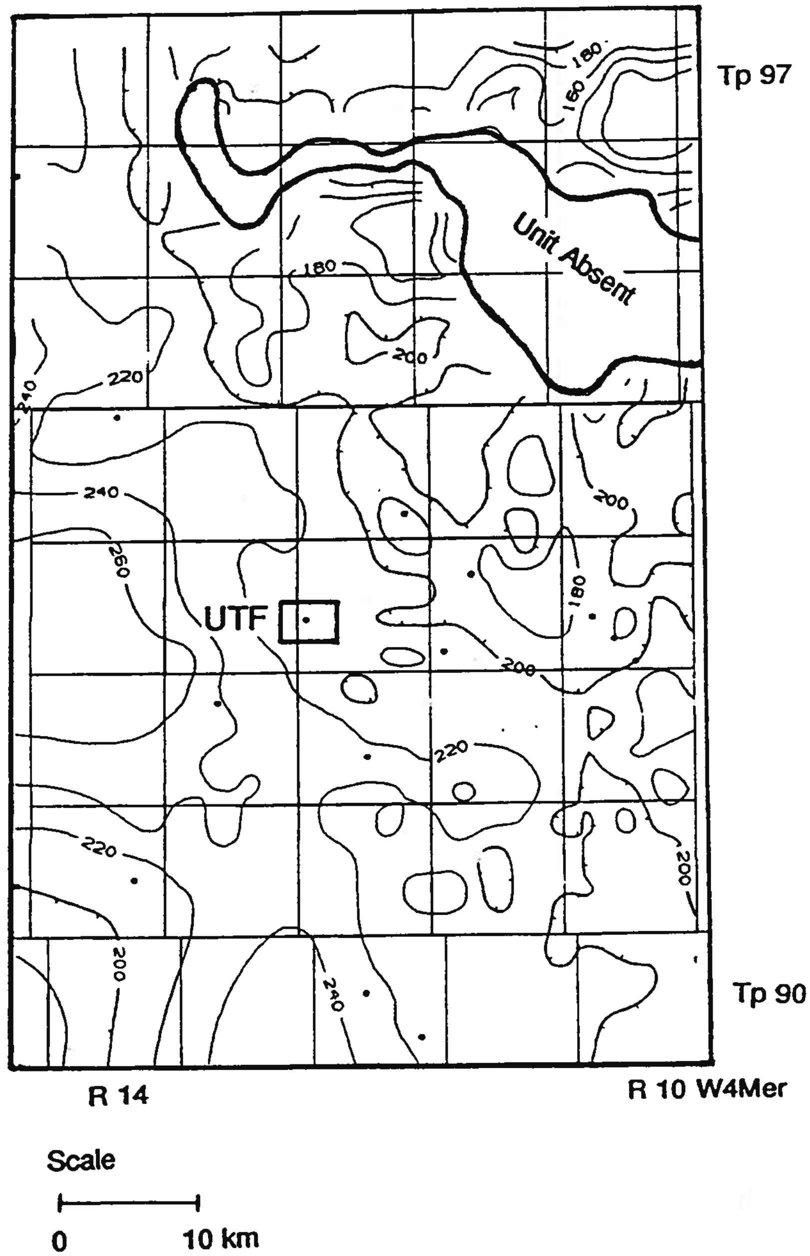
A-12. Slave Point-Fort Vermilion interval isopach map.



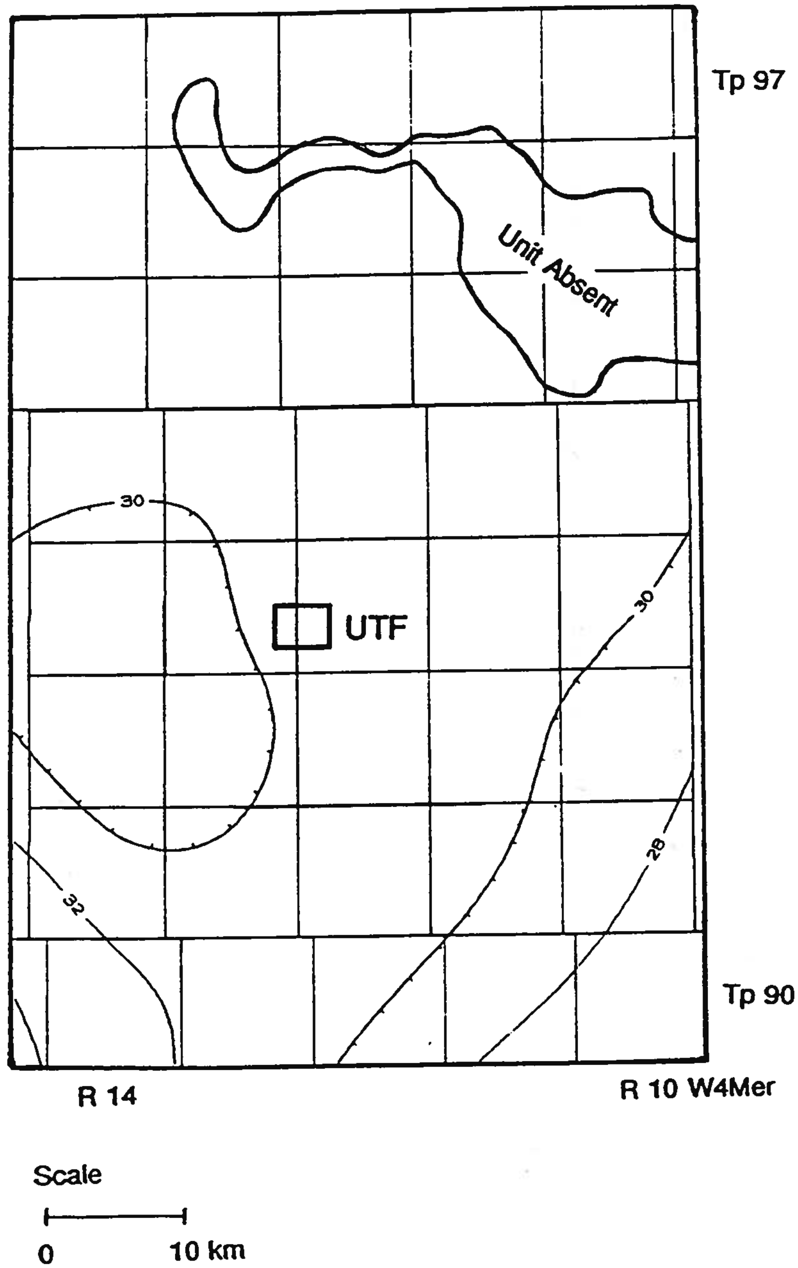
A-13. Firebag Member structure map.



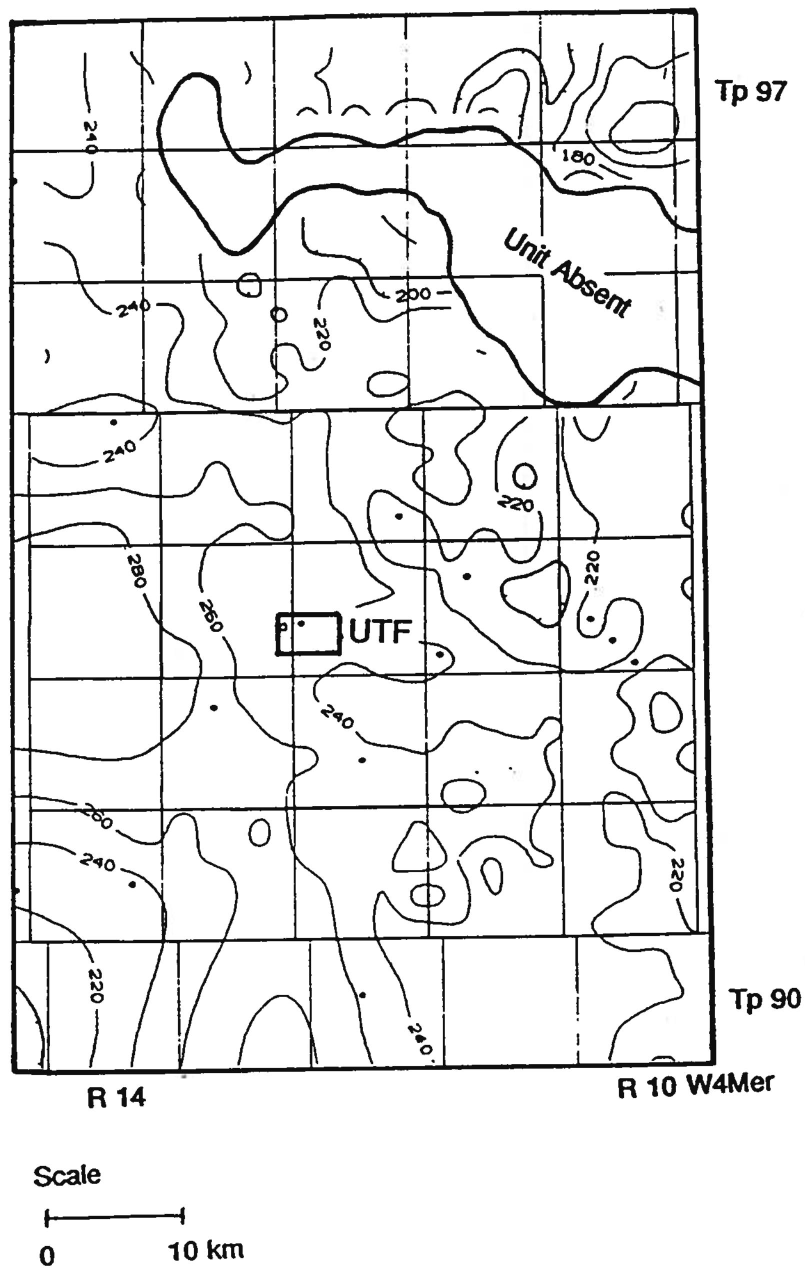
A-14. Firebag Member isopach map.



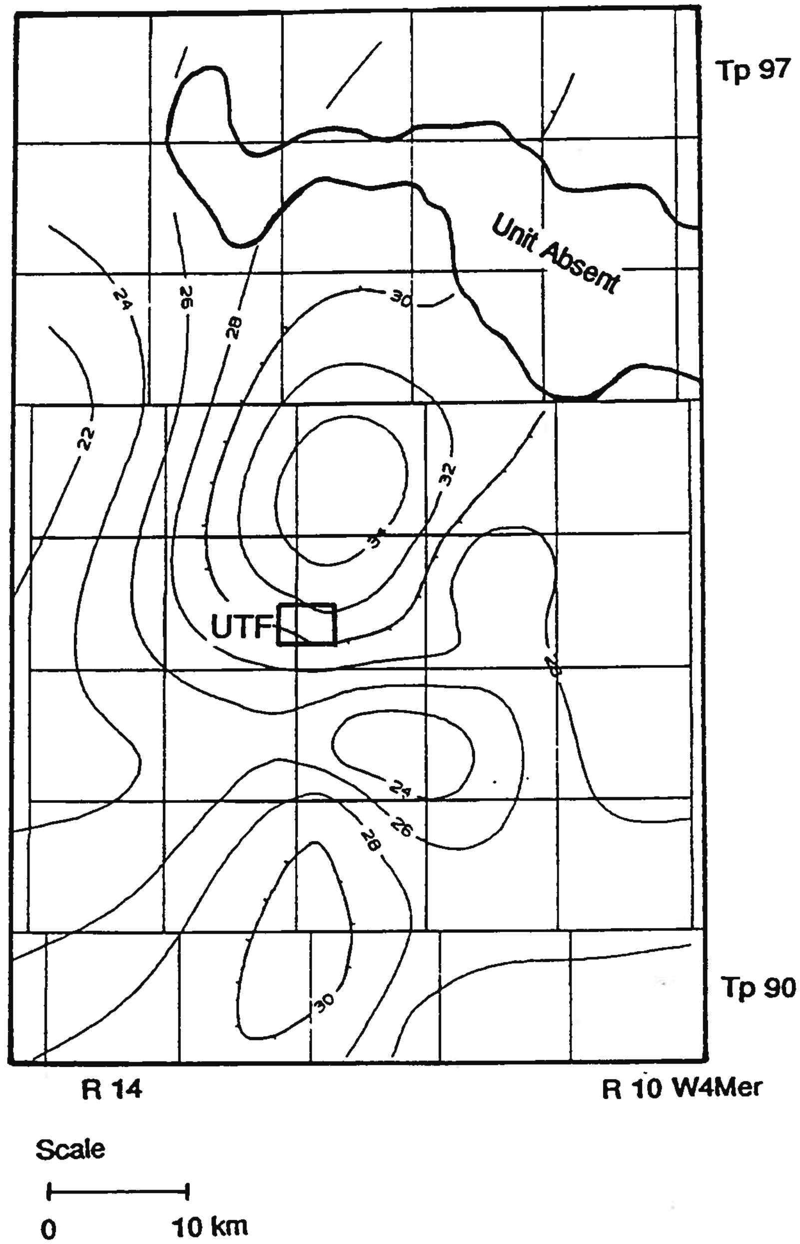
A-15. Calumet Member structure map.



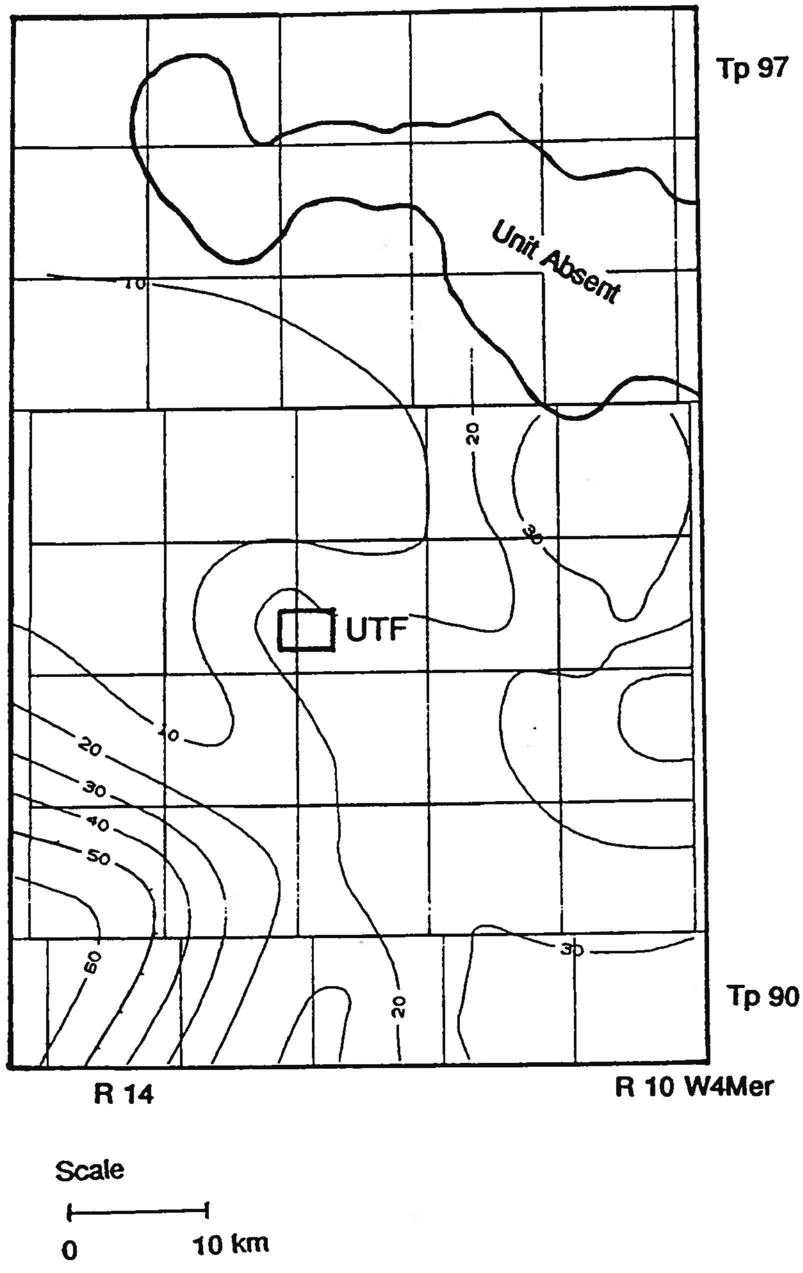
A-16. Calumet Member isopach map.



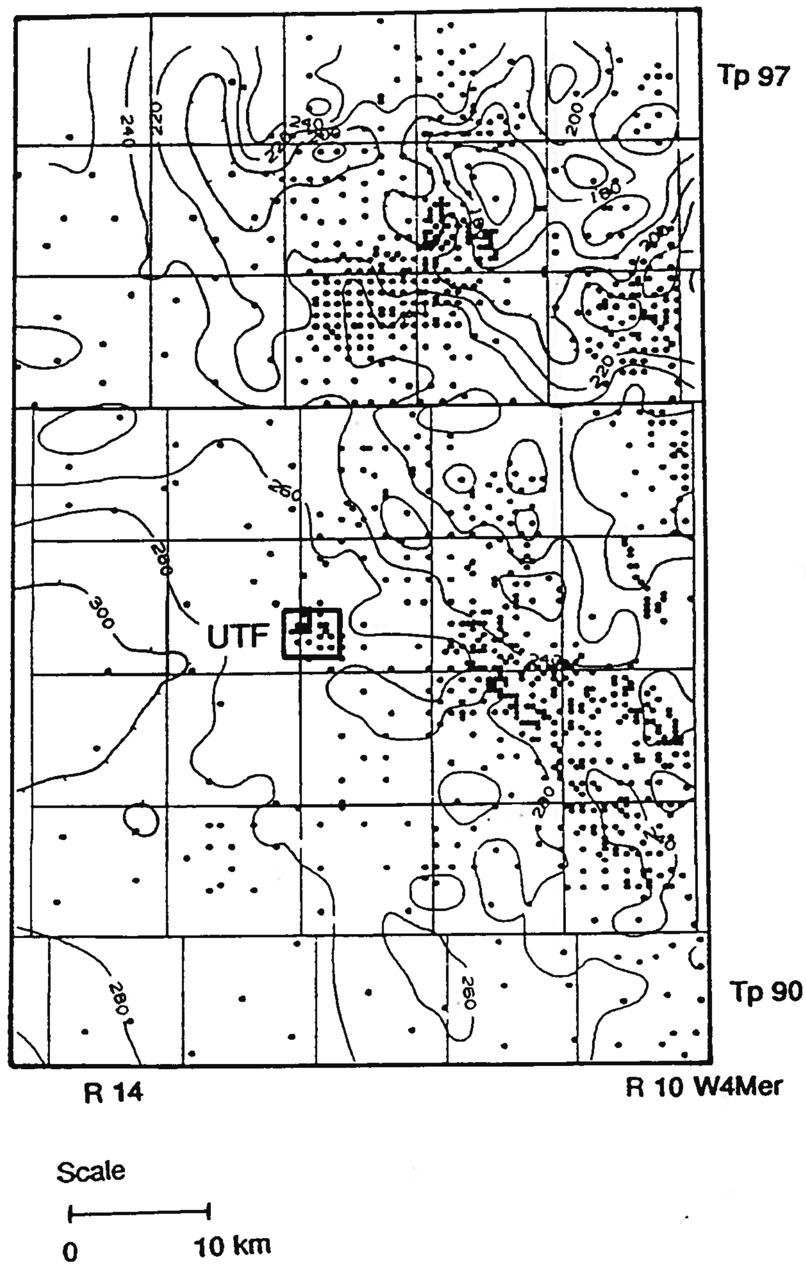
A-17. Christina Member structure map.



A-18. Christina Member isopach map.

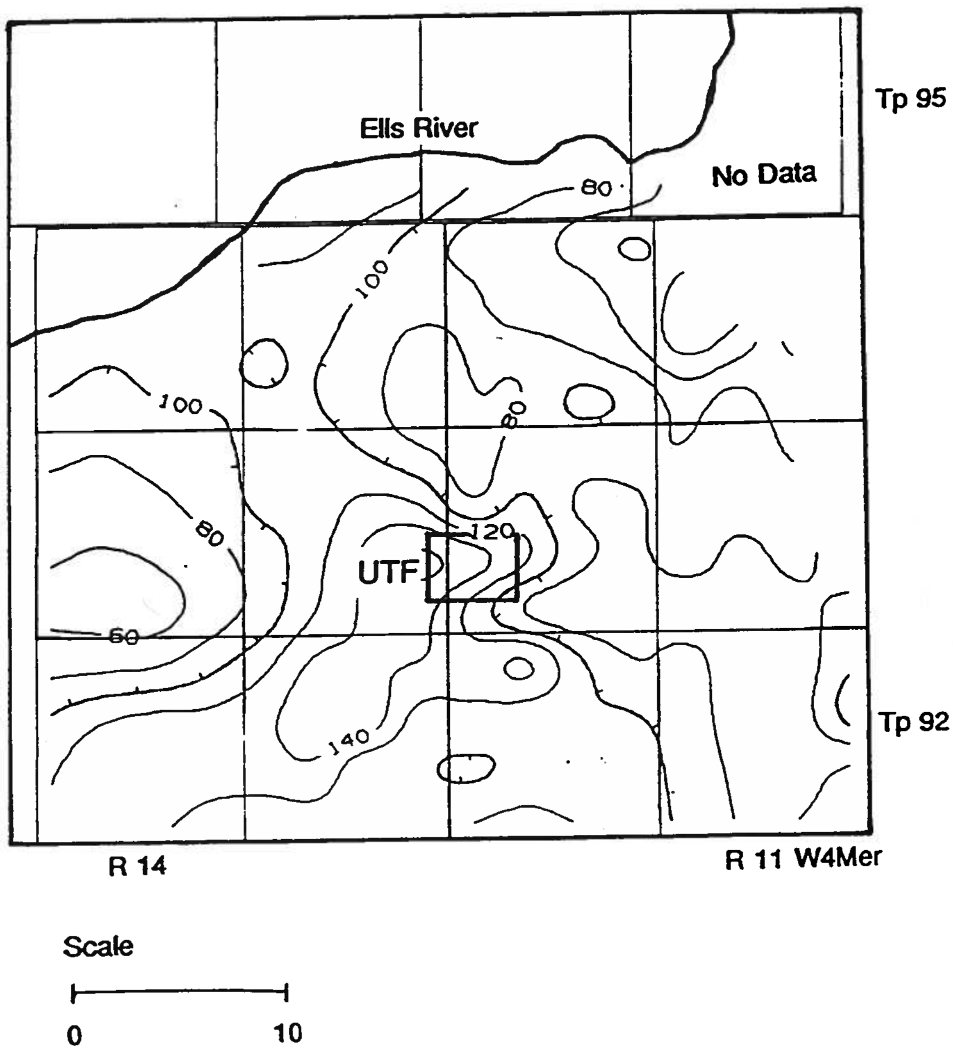


A-19. Moberly Member isopach map.

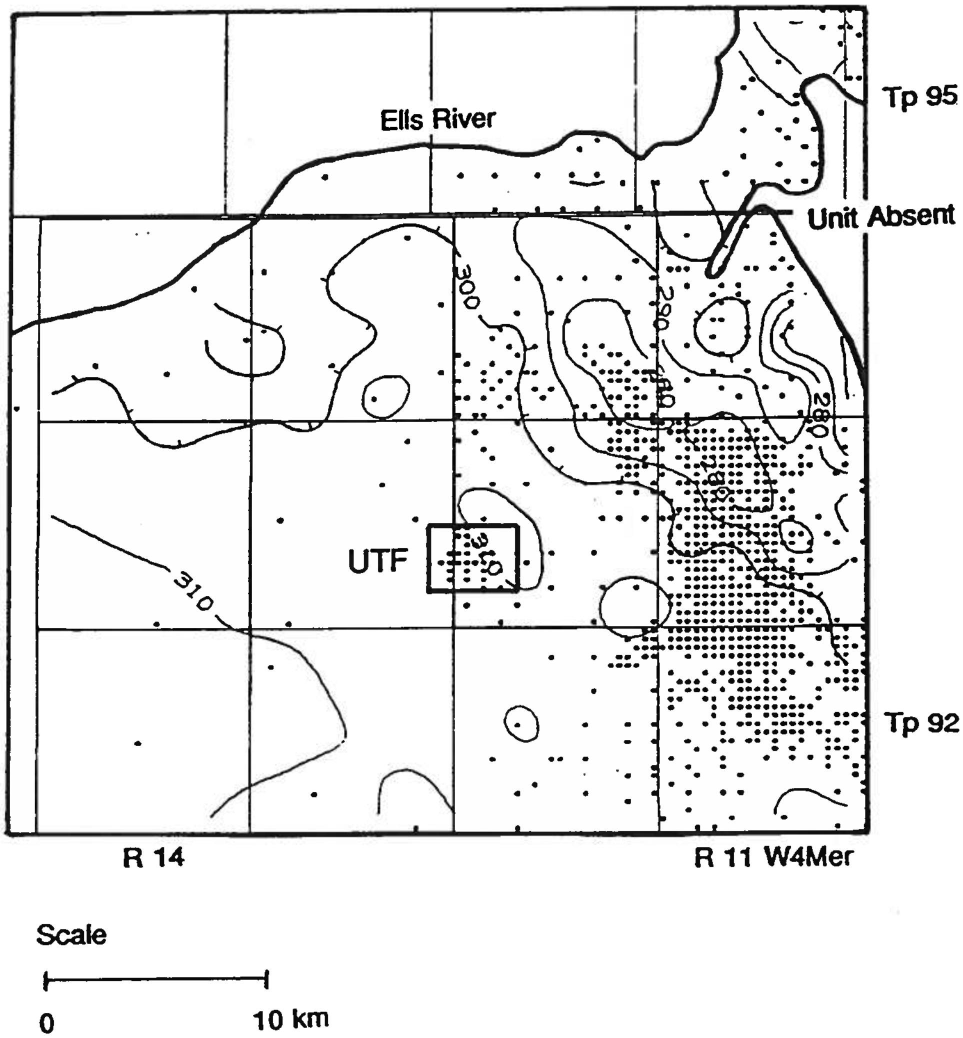


A-20. Sub-Cretaceous unconformity structure map.

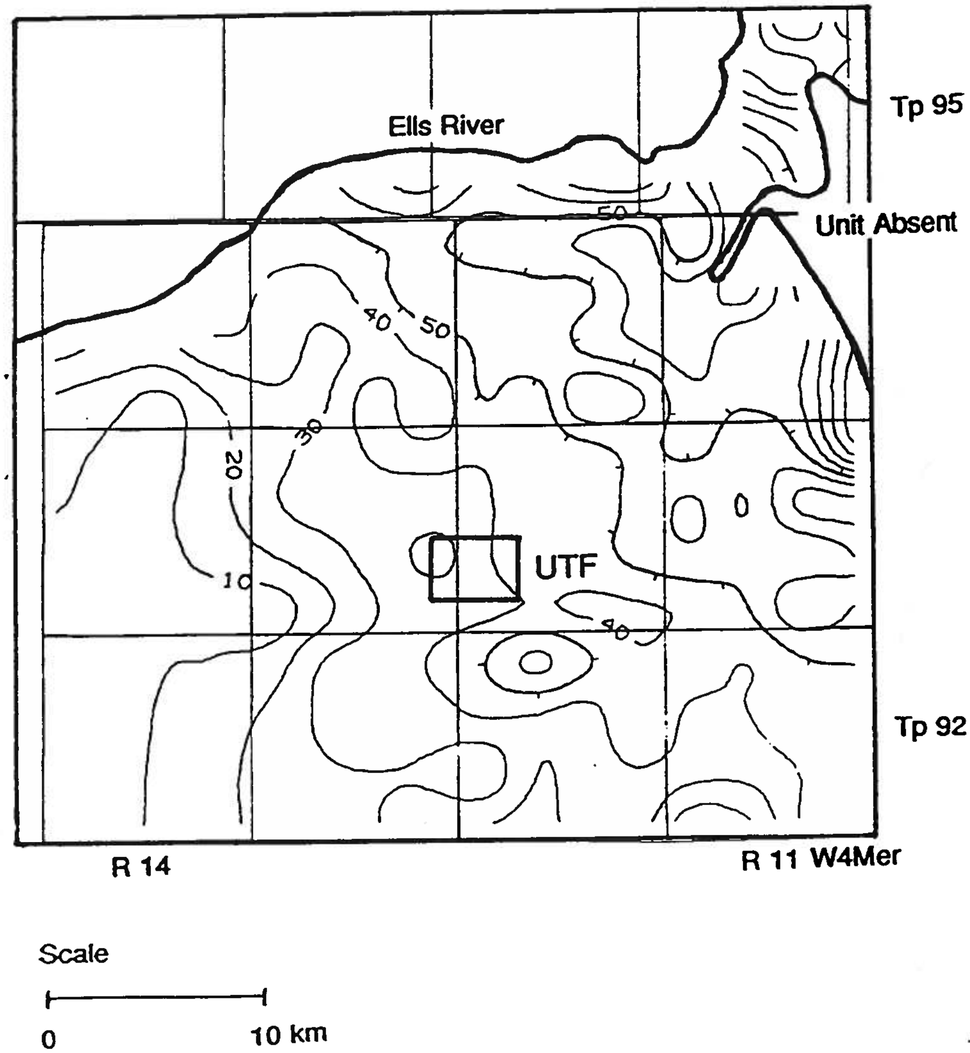
APPENDIX B - STRUCTURE AND ISOPACH MAPS OF CRETACEOUS STRATA



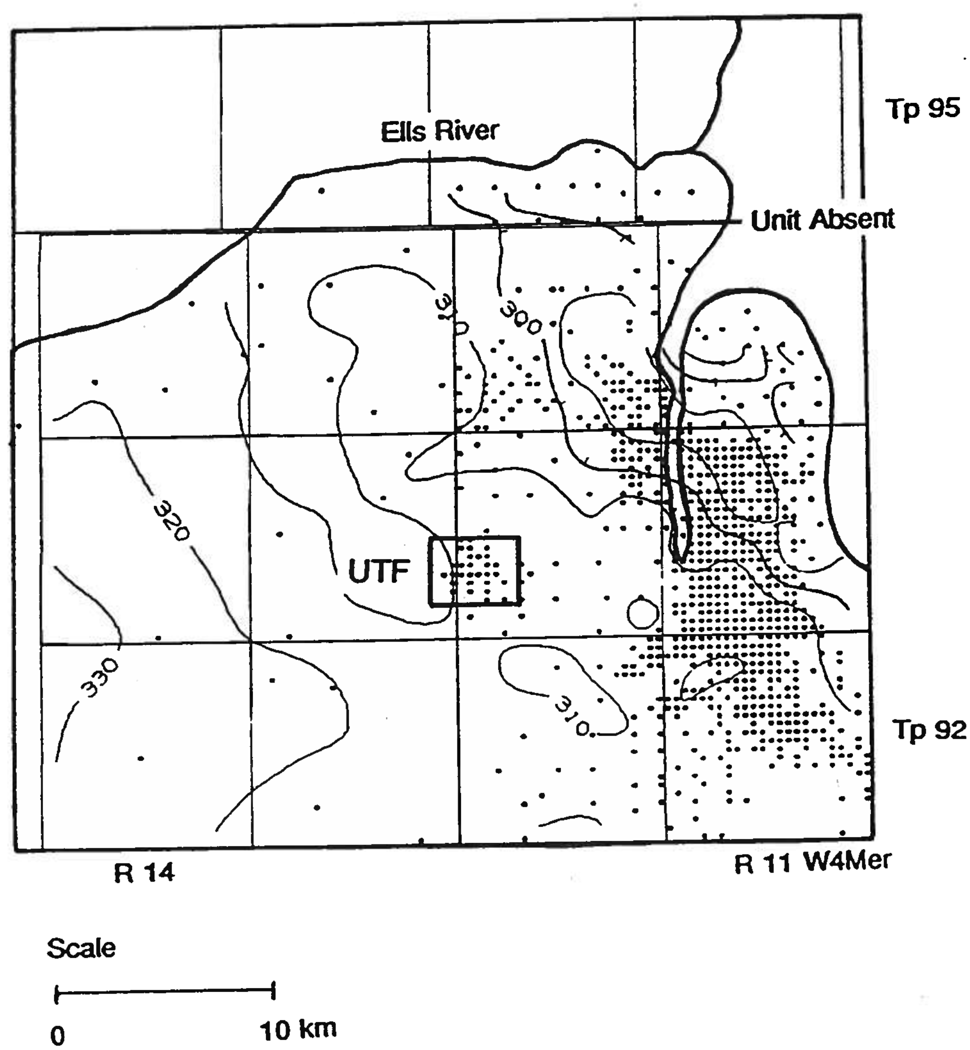
B- 1. Lower Cretaceous Mannville Group isopach map.



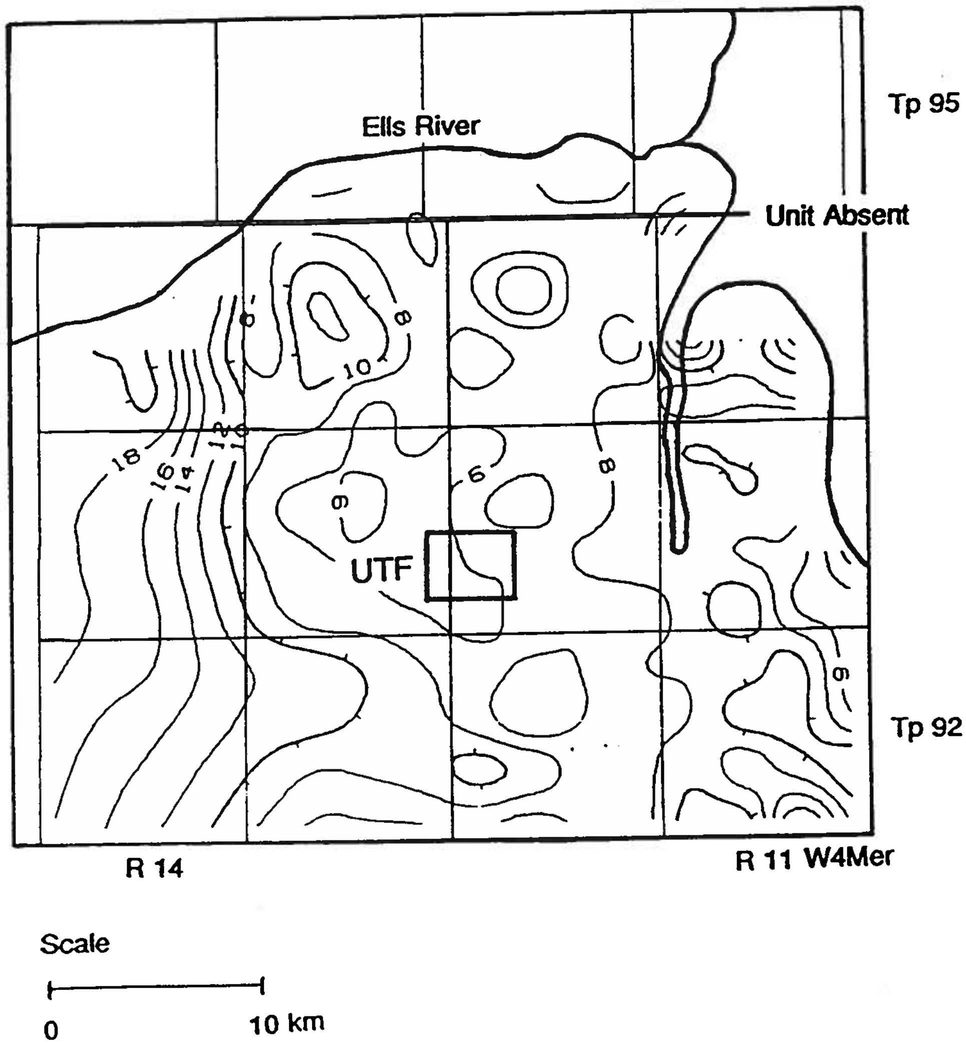
B- 2. McMurray Formation structure map.



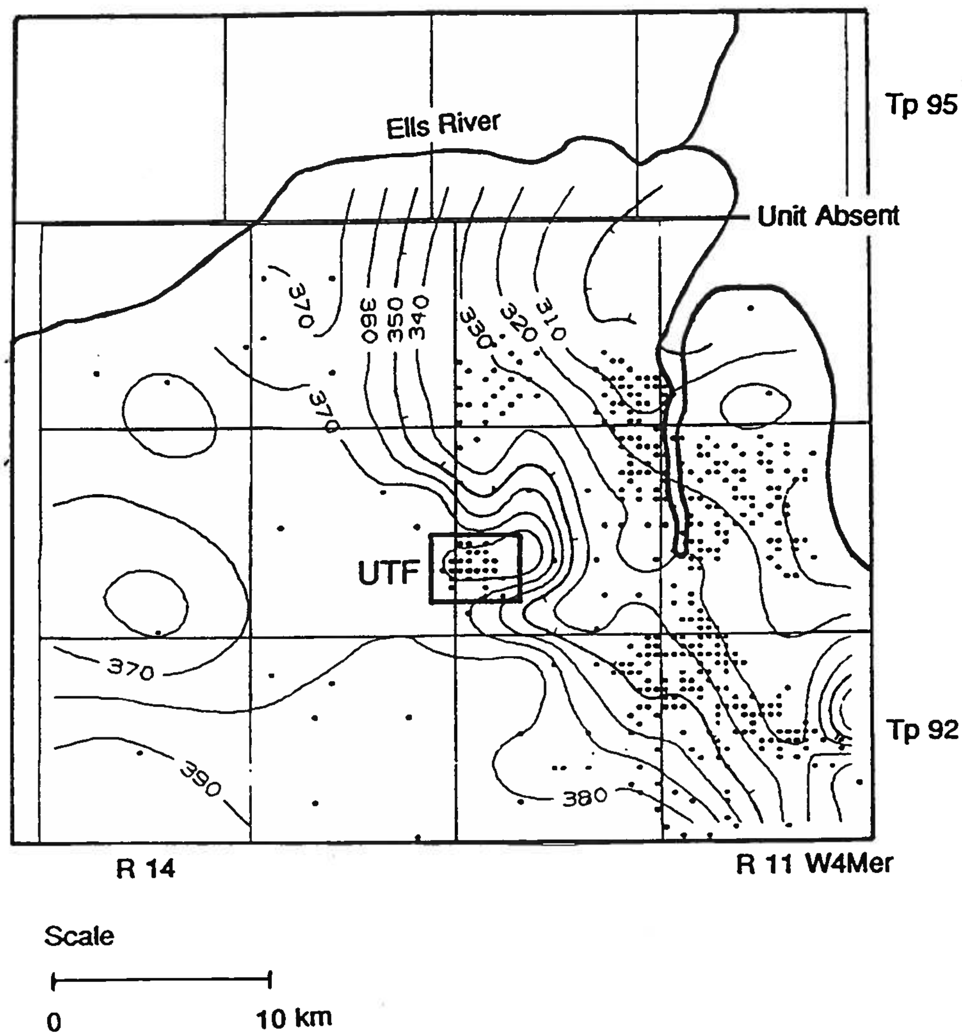
B- 3. McMurray Formation isopach map.



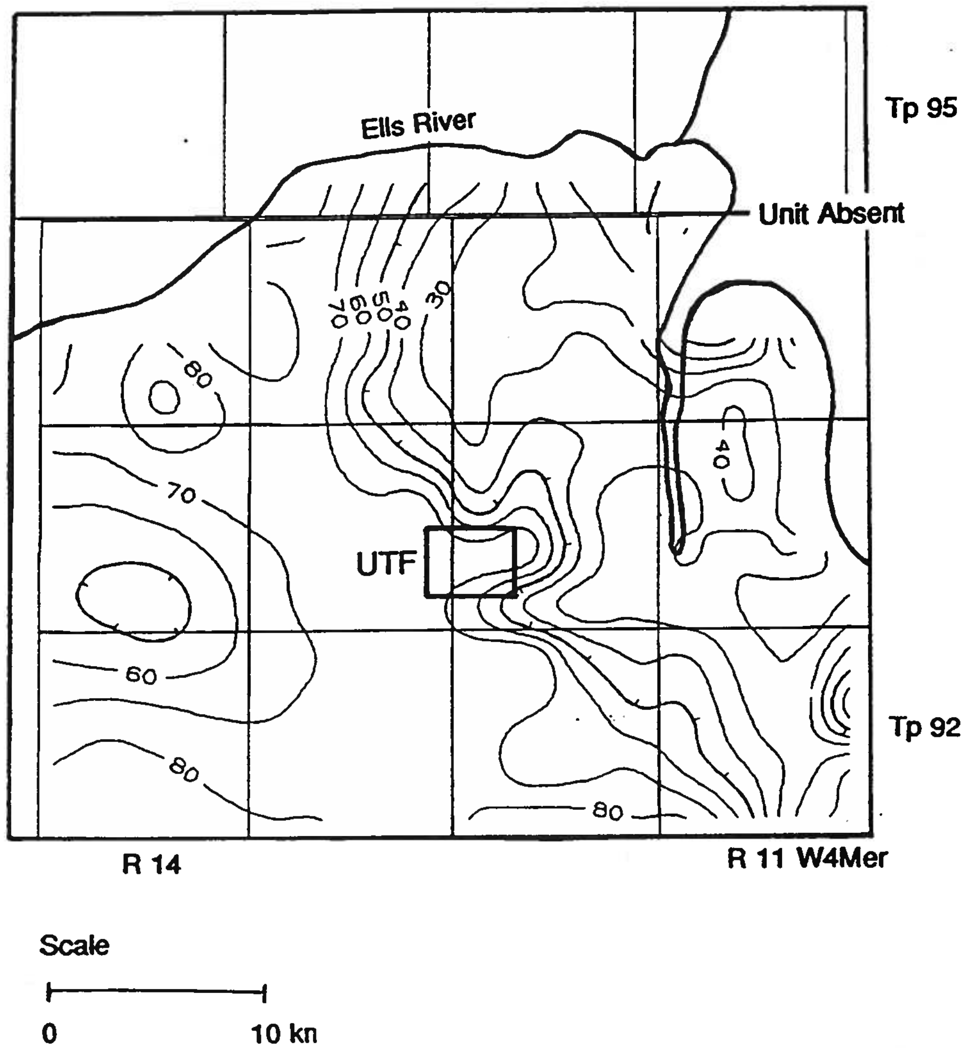
B- 4. Wabiskaw Member structure map.



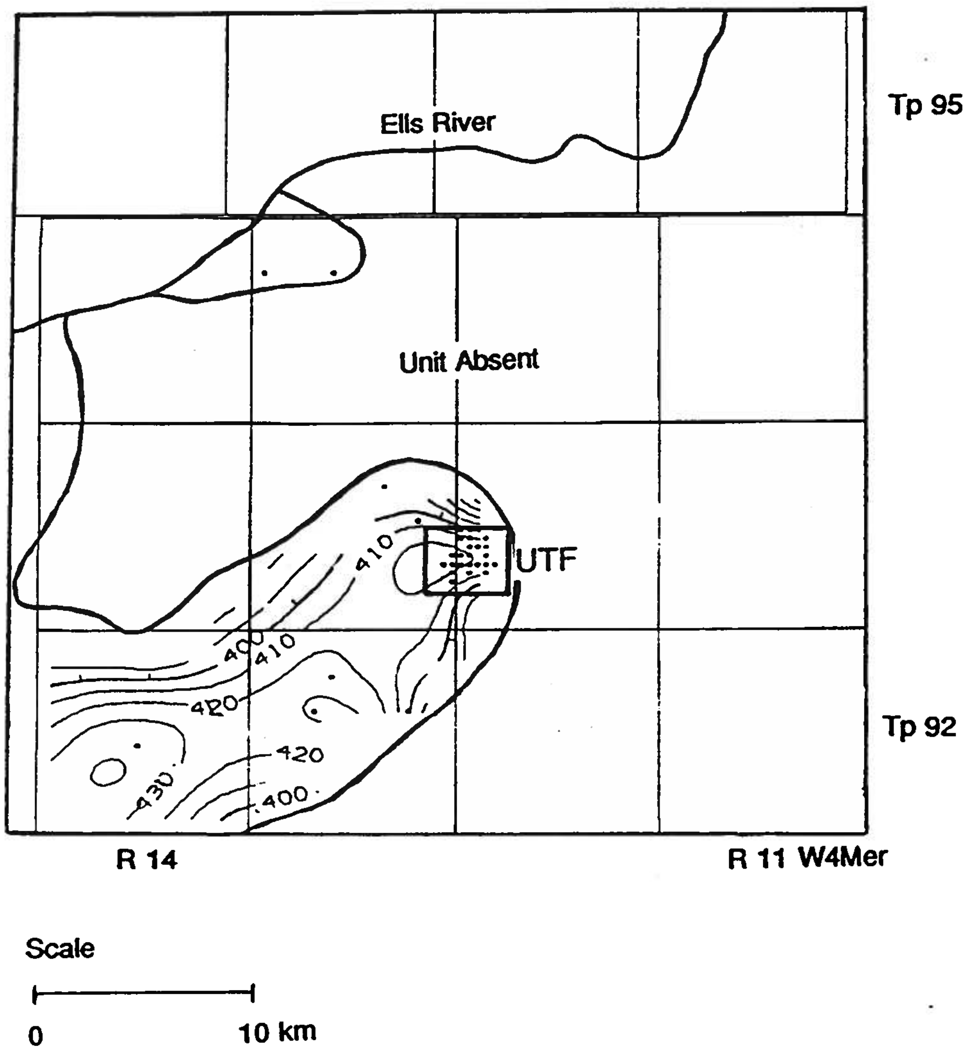
B- 5. Wabiskaw Member isopach map.



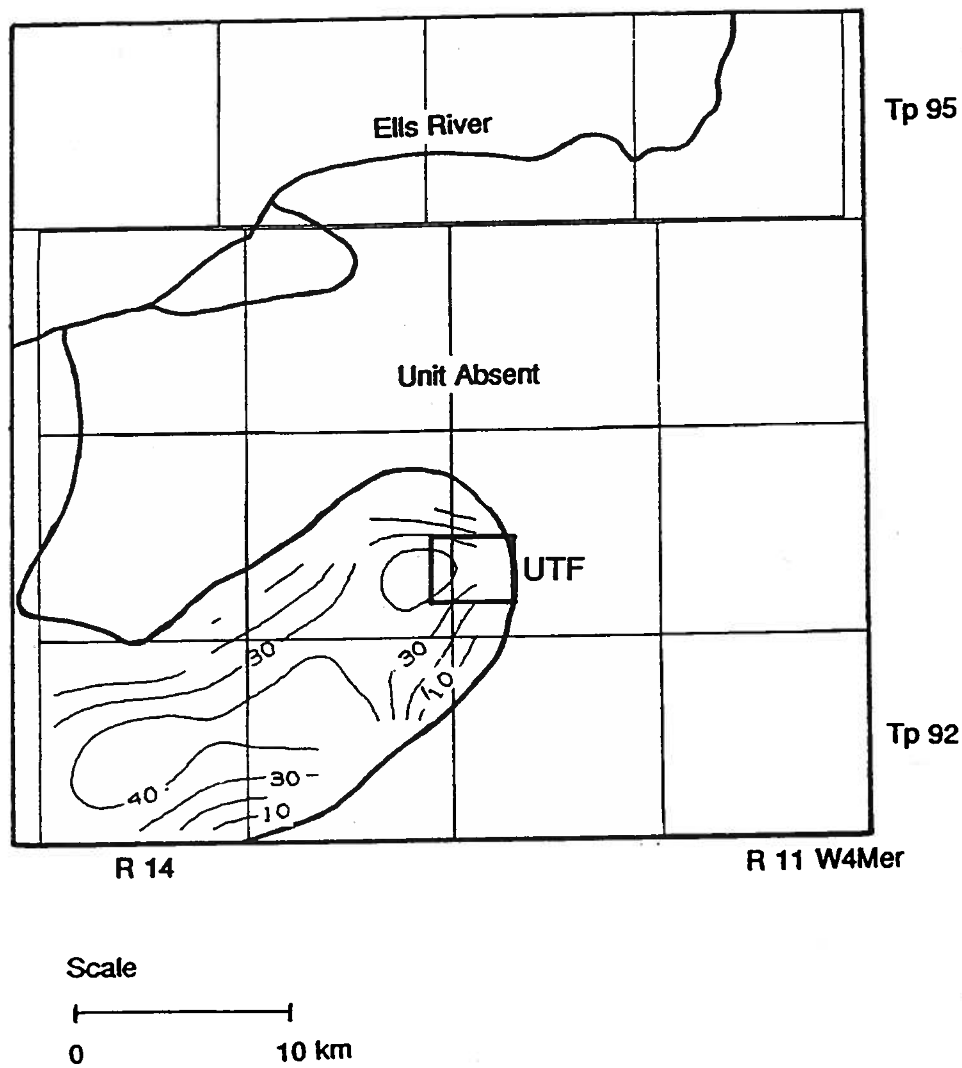
B- 6. Clearwater Formation structure map.



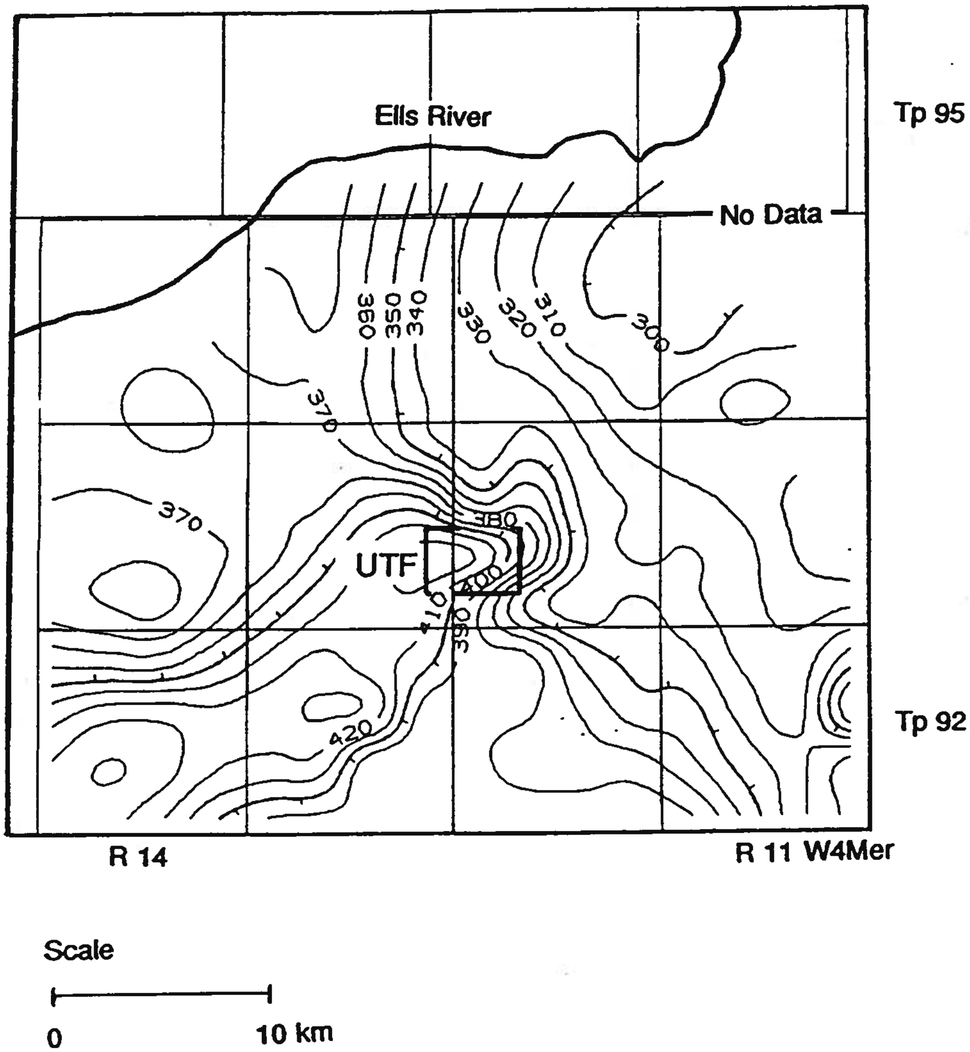
B- 7. Isopach map of the remainder of Clearwater Formation above the Wabiskaw Member.



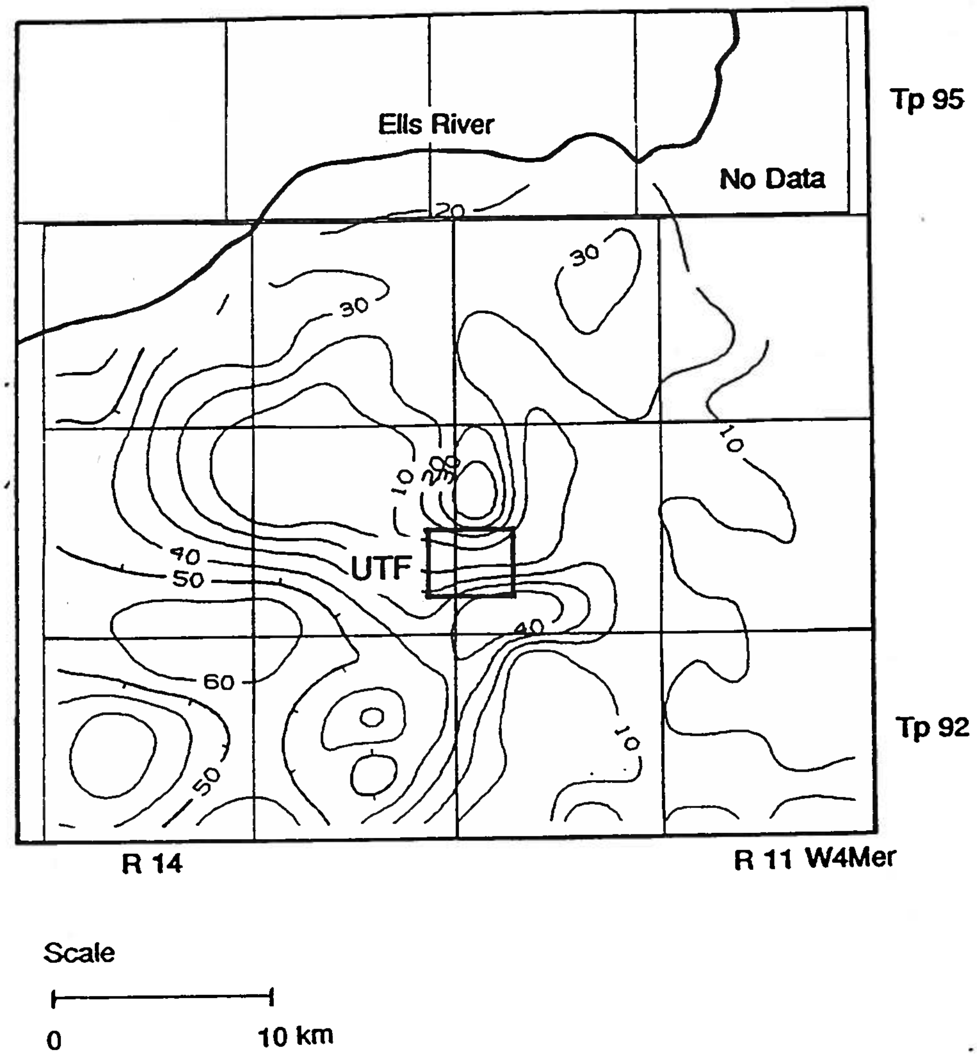
B- 8. Grand Rapids Formation structure map.



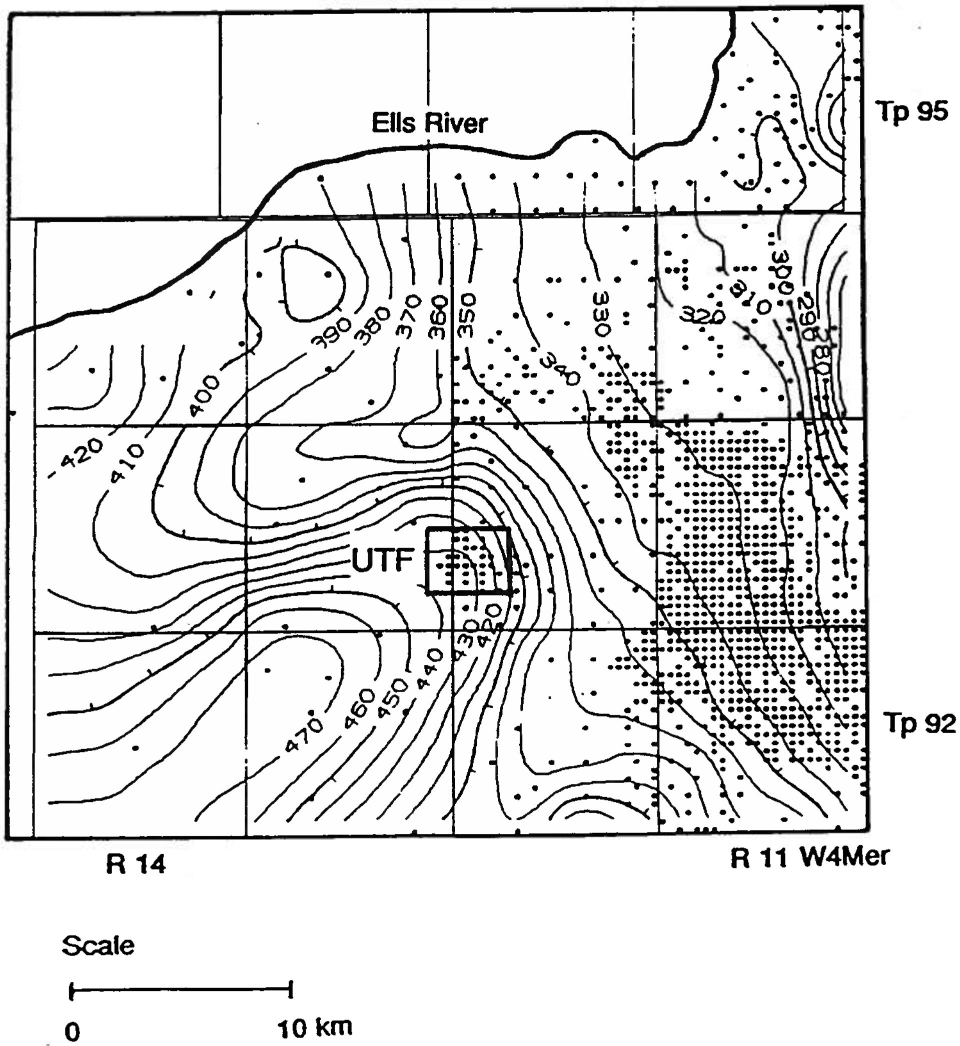
B- 9. Grand Rapids Formation isopach map.



B-10. Bedrock structure map.



B-11. Pleistocene drift isopach map.



B-12. Ground level structure map.

APPENDIX C - STRATIGRAPHIC AND STRUCTURAL CROSS-SECTIONS

C-1. Cross-section A-A' of the Paleozoic succession
a) Stratigraphic, and
b) Structural.

C-2. Cross-section B-B' of the Paleozoic succession
a) Stratigraphic, and
b) Structural.

C-3. Cross-section C-C' of the Paleozoic succession
a) Stratigraphic, and
b) Structural.

C-4. Cross-section D-D' of the Mannville Group
a) Stratigraphic, and
b) Structural.

C-5. Cross-section E-E' of the Mannville Group
a) Stratigraphic, and
b) Structural.

C-6. Cross-section F-F' of the Mannville Group
a) Stratigraphic, and
b) Structural.

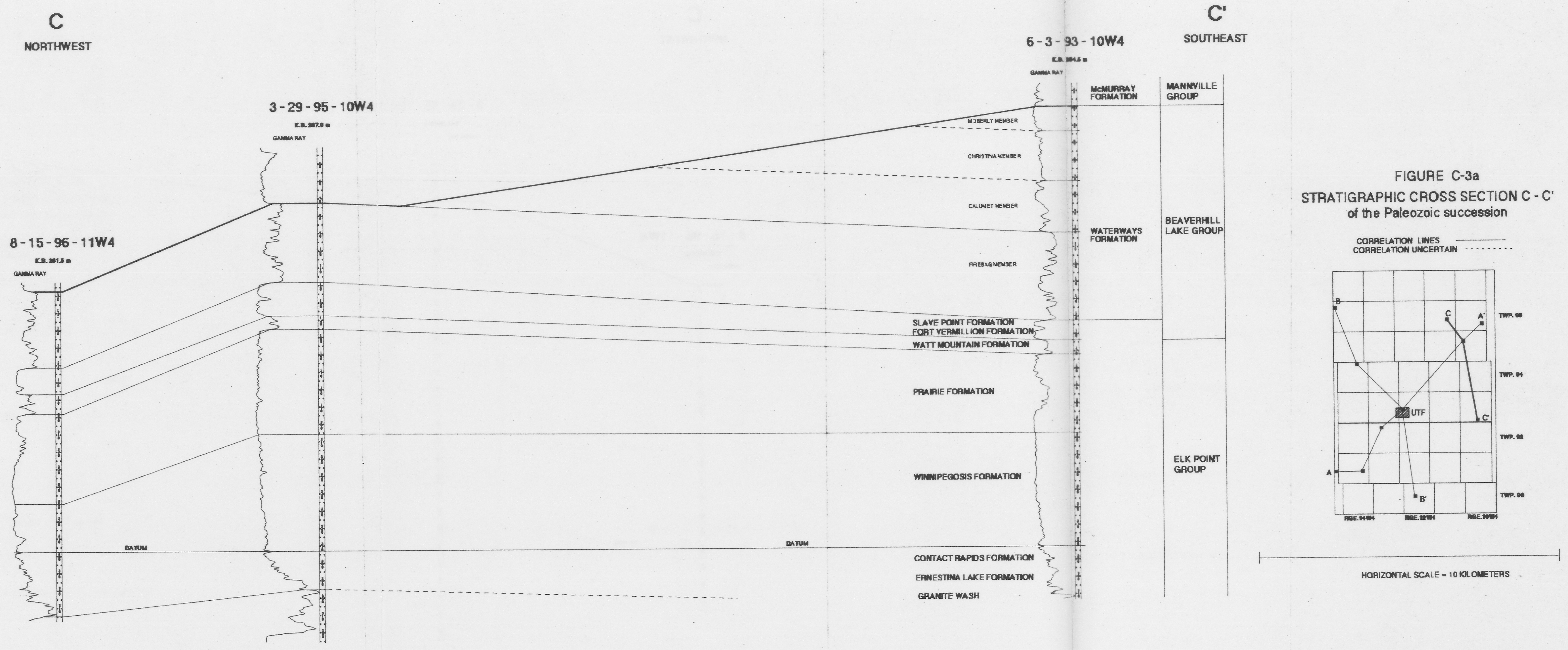


FIGURE C-3a
STRATIGRAPHIC CROSS SECTION C - C'
of the Paleozoic succession

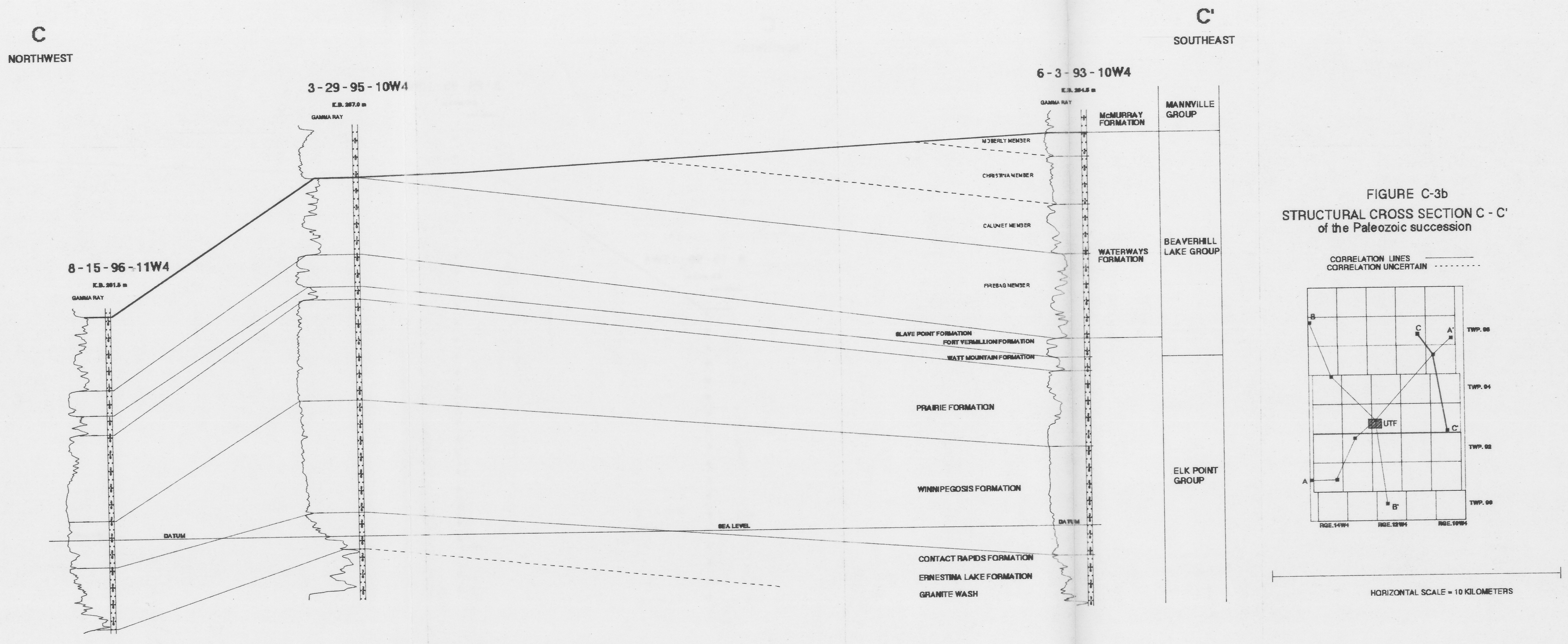


FIGURE C-3b
STRUCTURAL CROSS SECTION C - C'
of the Paleozoic succession

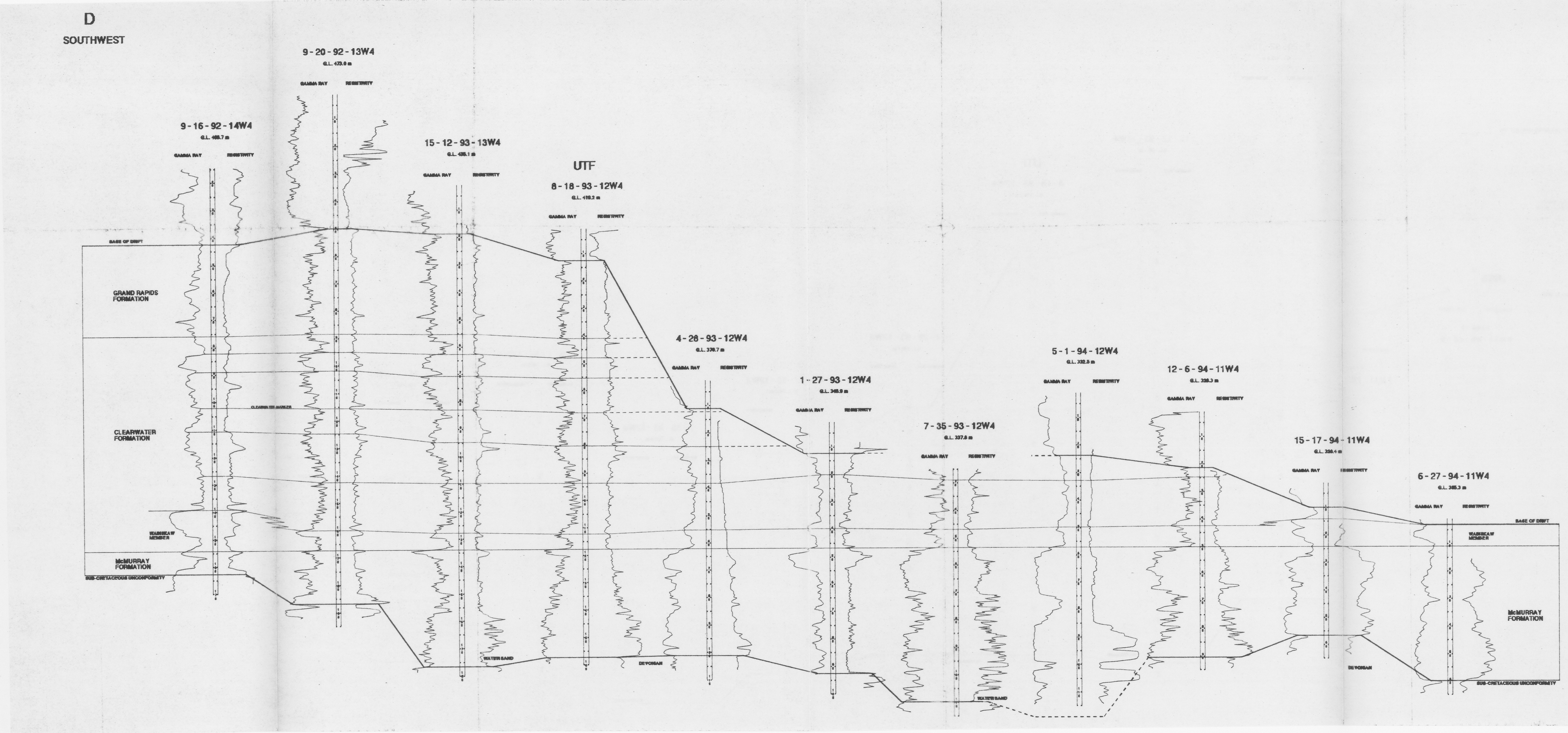
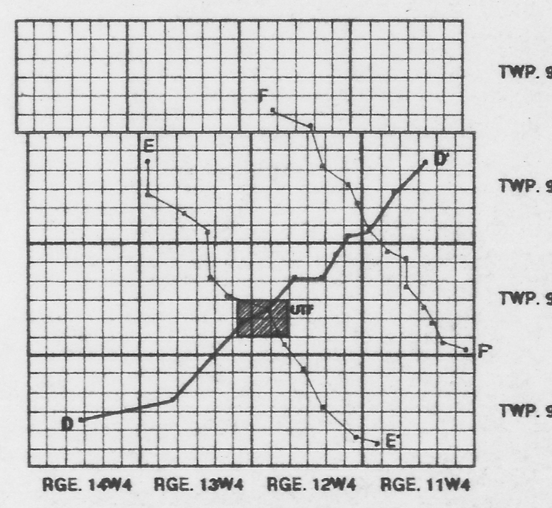


FIGURE C-4a

STRATIGRAPHIC CROSS SECTION D - D'
of the Mannville Group

CORRELATION LINES ————
CORRELATION UNCERTAIN - - - - - -



CROSS SECTION LOCATIONS

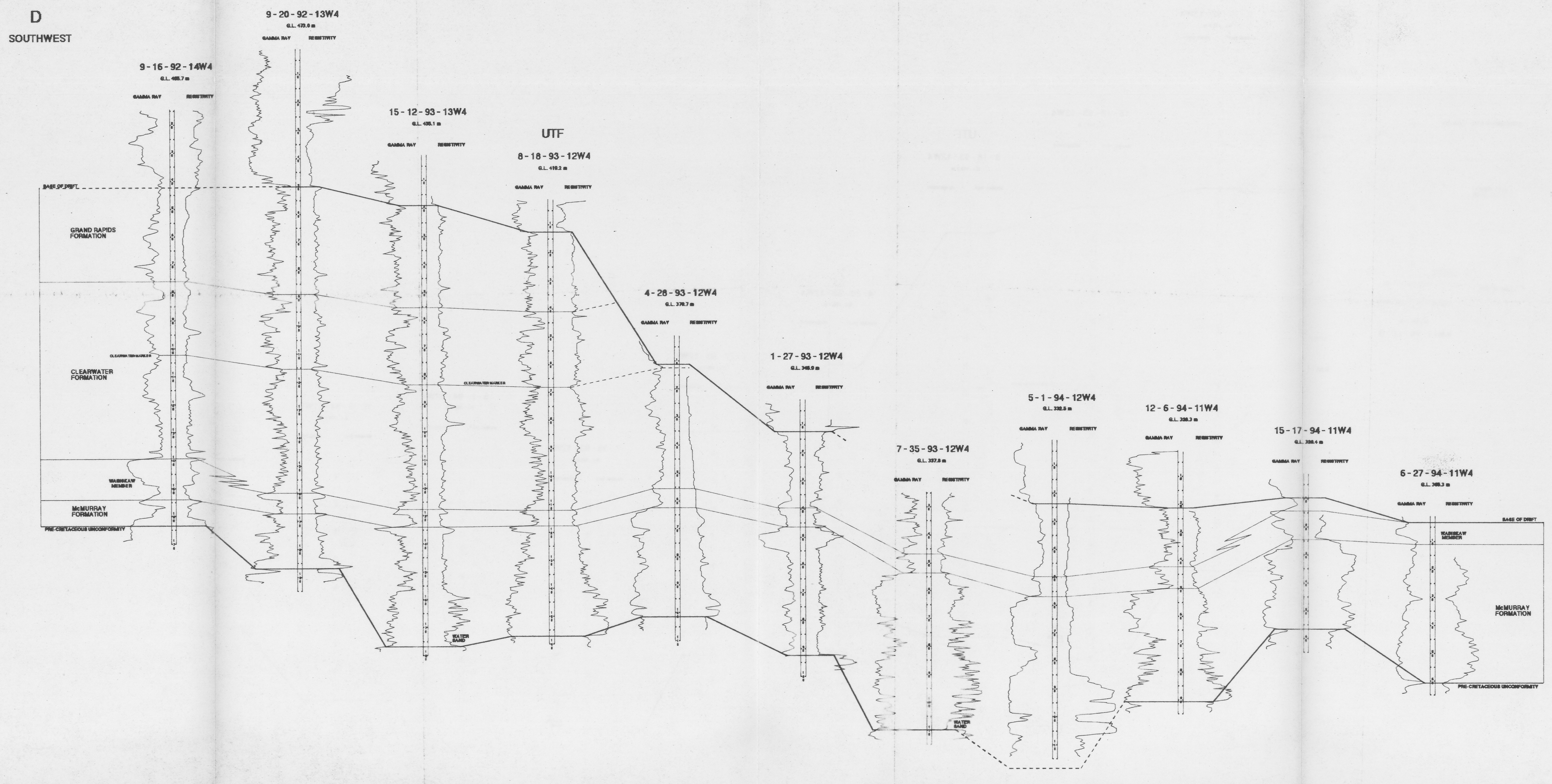
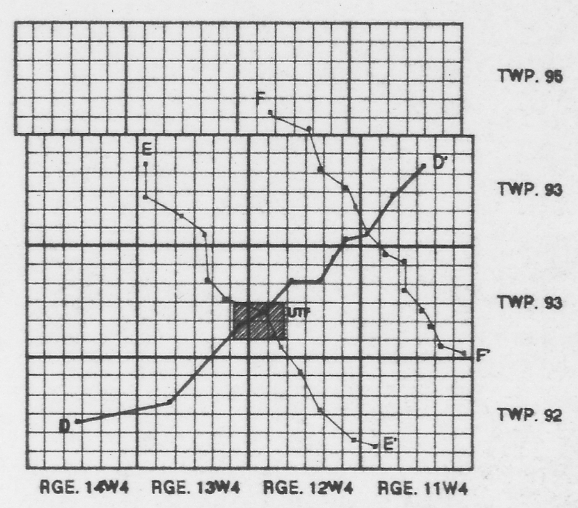


FIGURE C-4b

STRUCTURAL CROSS SECTION D - D'
of the Mannville Group

CORRELATION LINES ————————
CORRELATION UNCERTAIN - - - - - - - - - - - -



CROSS SECTION LOCATIONS

FIGURE C-5a

STRATIGRAPHIC CROSS SECTION E - E' of the Mannville Group

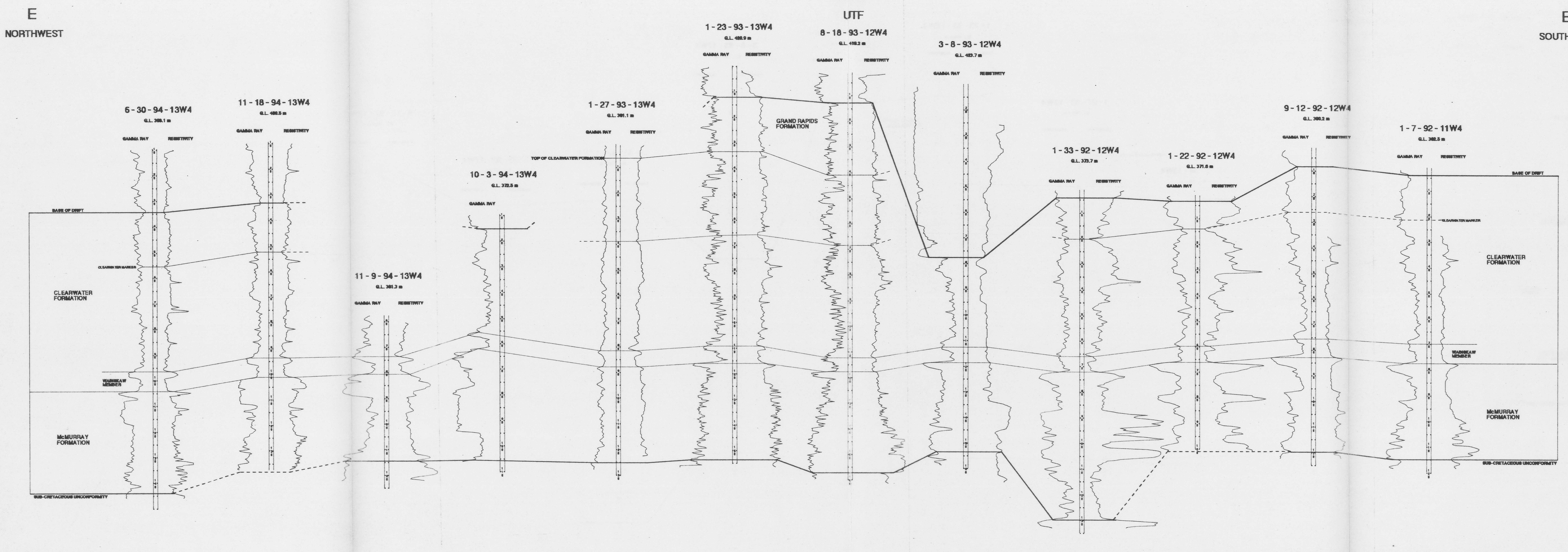
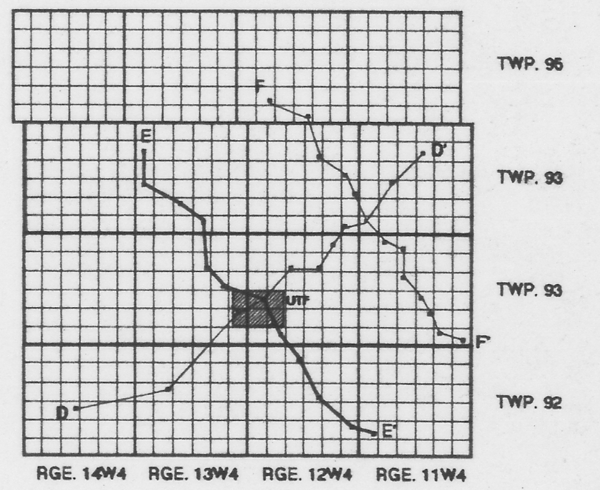


FIGURE C-5b

STRUCTURAL CROSS SECTION E - E'
of the Mannville Group

CORRELATION LINES ————

CORRELATION UNCERTAIN - - - - - -



CROSS SECTION LOCATIONS

FIGURE C-6a

STRATIGRAPHIC CROSS SECTION F - F' of the Mannville Group

FIGURE C-6b

STRUCTURAL CROSS SECTION F - F' of the Mannville Group

APPENDIX D - ANALYSES OF FORMATION WATER AROUND THE UTF SITE

AGSWDB WATER ANALYSIS REPORT

AGSWDB Well site identifier (SITID): 123495 Chemistry number: 2
AGSWDB Hard copy number (HRDCPNO): 46142

ALBERTA RESEARCH COUNCIL Lab. Sample ID.

Well identifier	Well name	KB elev.	Gr. elev
0954122105AA0	SUPTST 3W ATHA OV 5-21-95-12	343.50	343.50

Interval Sampled from: 100.90 to: 110.00 meters KB

Sample produced by: bailed Sampling point:
Date: Sampled: 1980/07/02

CATIONS

ION	mg/l	%MEQ	MEQ/L
Na	975.	47.038	42.4
K	9.	0.255	0.2
Ca	13.	0.719	0.6
Mg	12.	1.095	1.0
Ca A	7.	0.365	0.3
Mg A	10.	0.904	0.8

ANIONS

ION	mg/l	%MEQ	MEQ/L
Cl	1290.	40.357	36.4
HCO3	464.	8.434	7.6
SO4	36.	0.831	0.7

Other Determinations

Parameter	mg/l
nitrate	7.
silica	2.
fluoride	0.30000
	424.
	43.

PH 8.40 @ 0. C
Calculated sodium: 991. Calculated TDS : 2570.
TDS by Evapor. @ 110 C: 2576.

Remarks:

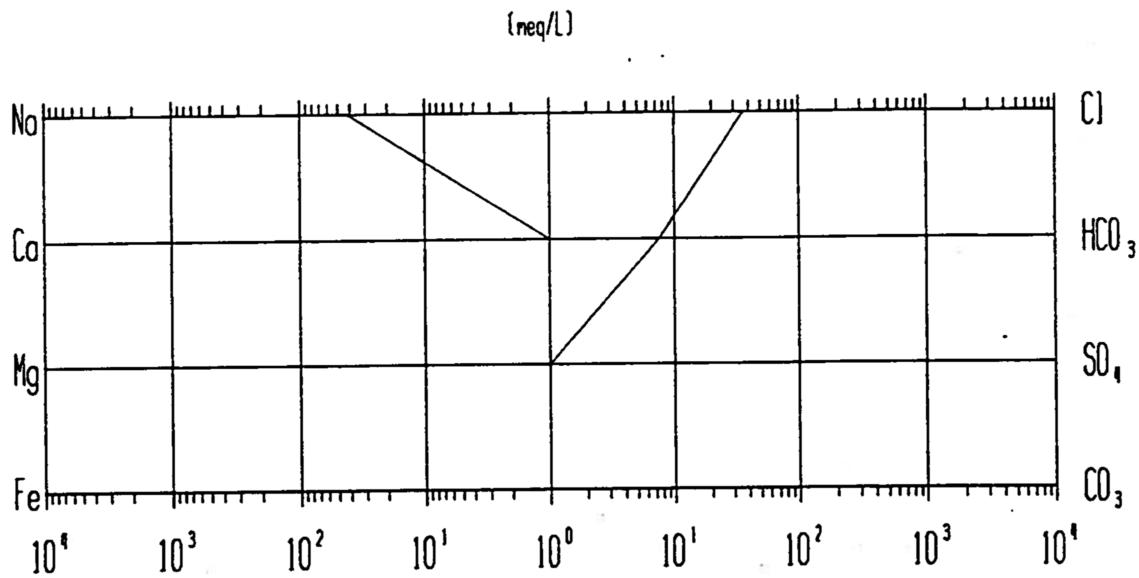
FIELD: TEMP. 5.50 C. PH 9.0

WELL: 0954122105AA0 SITID: 123495

Chemistry Number: 2

Hard copy Number: 46142

LOGARITHMIC PATTERN OF DISSOLVED IONS



AGSWDB WATER ANALYSIS REPORT

AGSWDB Well site identifier (SITID): 123495 Chemistry number: 5
AGSWDB Hard copy number (HRDCPNO): 46171

ALBERTA RESEARCH COUNCIL Lab. Sample ID.

Well identifier	Well name	KB elev.	Gr. elev
0954122105AA0	SUPTST 3W ATHA OV 5-21-95-12	343.50	343.50

Interval Sampled from: 100.90 to: 110.00 meters KB

Sample produced by: bailed Sampling point:
Date: Sampled: 1976/07/15

CATIONS

ION	mg/l	%MEQ	MEQ/L
Na	1650.	43.377	71.8
K	18.	0.277	0.5
Ca	43.	1.297	2.1
Mg	42.	2.089	3.5
Ca A	44.	1.327	2.2
Mg A	37.	1.860	3.1
Fe	0.14000	0.003	0.0

ANIONS

ION	mg/l	%MEQ	MEQ/L
Cl	2340.	39.891	66.0
HCO3	947.	9.380	15.5
SO4	40.	0.500	0.8

Other Determinations

Parameter	mg/l
nitrate	1.
silica	15.
fluoride	0.30000
aluminum	0.11000
arsenic	<0.38000E-01
barium	<0.20000
beryllium	<0.10000E-02
boron	1.
cadmium	<0.20000E-02
chromium	<0.60000E-02
cobalt	<0.10000E-01
copper	0.15000E-01
gold	<0.30000E-02
lead	<0.88000E-01
manganese	0.19900
molybdenum	<0.60000E-02
nickel	<0.10000E-01
phosphorus	<0.11000
selenium	<0.60000E-01
silver	<0.20000E-02
tin	<0.45000E-01
titanium	<0.90000E-03
uranium	<0.20000E-01
vanadium	0.60000E-02
zinc	0.16500

	1039.
strontium	1.
Europium	<0.15000E-01
TUNGSTEN	<0.78000E-01
TELLURIUM	<0.65000E-01

PH 7.80 @ 0. C
Calculated sodium: 1765. Calculated TDS : 4695.
TDS by Evapor. @ 110 C: 4420.

Remarks:

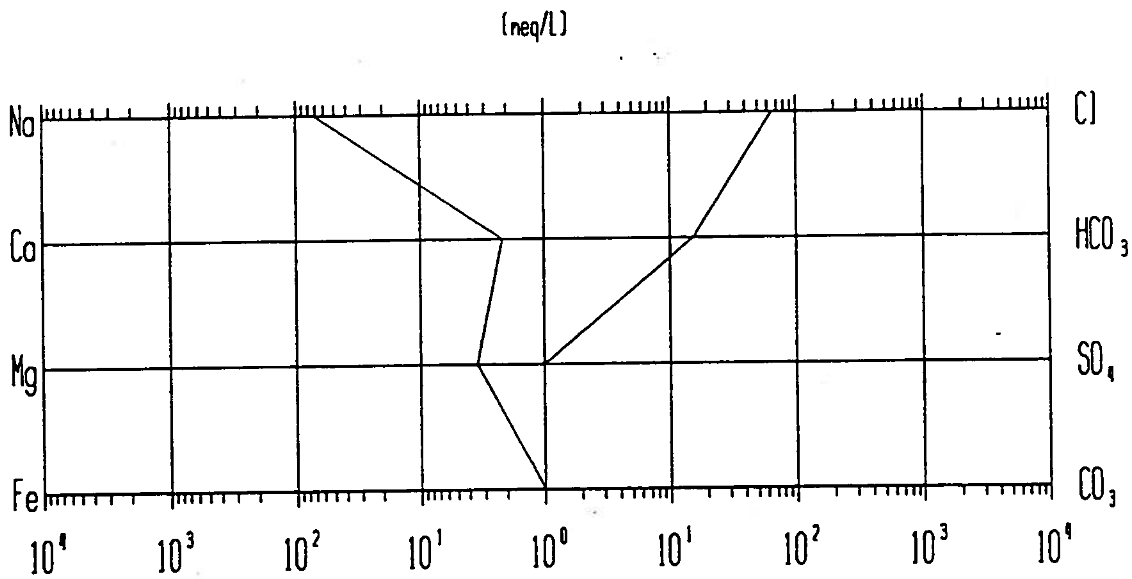
FIELD: TEMP 6 C. PH 7.4

WELL: 0954122105AA0   SITID: 123495

Chemistry Number: 5

Hard copy Number: 46171

LOGARITHMIC PATTERN OF DISSOLVED IONS



AGSWDB WATER ANALYSIS REPORT

AGSWDB Well site identifier (SITID): 123166 Chemistry number: 6
AGSWDB Hard copy number (HRDCPNO): 46179

ALBERTA RESEARCH COUNCIL

Lab. Sample ID.

Well identifier: 0954102510AR0
Well name: SHELL MUSKEG OV 10-25-95-10
KB elev.: 290.50 Gr. elev: 290.50

Interval Sampled from: 112.00 to: 229.00 meters KB

Sample produced by:

Sampling point:

Date: Sampled: 1972/08/17

CATIONS

ION	mg/l	%MEQ	MEQ/L
Na+K	6960.		
Ca	1032.	11.437	51.5
Mg	271.	4.953	22.3

ANIONS

ION	mg/l	%MEQ	MEQ/L
Cl	10947.	68.577	308.8
HCO3	390.	1.420	6.4
SO4	2944.	13.614	61.3

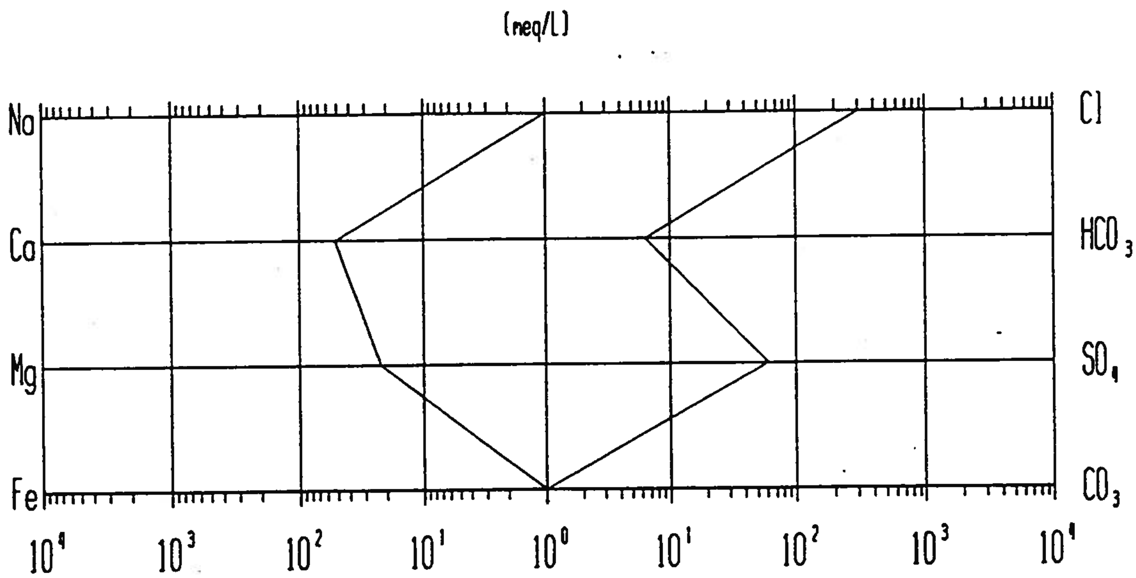
PH 7.10 @ 0. C
Calculated sodium: 6959.
Calculated TDS : 22345.

WELL: 0954102510AR0 SITID: 123166

Chemistry Number: 6

Hard copy Number: 46179

LOGARITHMIC PATTERN OF DISSOLVED IONS



AGSWDB WATER ANALYSIS REPORT

AGSWDB Well site identifier (SITID): 120758 Chemistry number: 1
AGSWDB Hard copy number (HRDCPNO): 32263

CHEMICAL & GEOLOGICAL LAB LTD Lab. Sample ID. 238

Well identifier	Well name	KB elev.	Gr. elev
0934103204000	BEAR VAMPIRE #2	241.70	241.70

Interval Sampled from: 269.14 to: meters KB

Formation Sampled: PRE-CAMBRIAN

Sample produced by: Sampling point: SURFACE CASING

CATIONS

ION	mg/l	%MEQ	MEQ/L
Ca	2015.	5.589	100.5
Mg	559.	2.557	46.0

ANIONS

ION	mg/l	%MEQ	MEQ/L
Cl	54509.	85.457	1537.5
HCO3	475.	0.433	7.8
SO4	5154.	5.965	107.3

PH 6.95 @ 0. C
Hydrogen Sulfide Description:
Calculated sodium: 34627.

Calculated TDS : 97097.
TDS at Ignition : 93710.

Remarks:

PRIM SALI 90.94; SEC SALI 8.6; SEC ALK .46; CL SALI 93.47; SO4 SALI 6.53

WELL: 0934103204000 SITID: 120758

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