LOCAL-SCALE BASELINE SUBSURFACE HYDROGEOLOGY AT THE AOSTRA UNDERGROUND TEST FACILITY

Prepared For
Conservation and Protection, Environment Canada

by

Stefan Bachu
J.R. Underschultz
D.K. Cotterill

and

E.H. Perkins

ALBERTA GEOLOGICAL SURVEY
EDMONTON, ALBERTA, CANADA

1993-01-01

DISCLAIMER

This report was prepared as an account of work sponsored by the Alberta Research Council and Environment Canada, Conservation and Protection. Every possible effort was made to ensure that the work conforms to accepted scientific practice. However, neither the Alberta Research Council (ARC), nor any of its employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the ARC. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the ARC.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This report presents the baseline hydrostratigraphy, hydrogeology and aquifer properties in the Phanerozoic sedimentary succession in an area of approximately 500 km^2 (2x3 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 AOSTRA's 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- and intermediate-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. The local-scale hydrostratigraphic delineation and hydrogeological and mineralogical characterization, which form the content of this study, will serve as a basis for numerical modelling of geochemical and hydrodynamic effects of deep injection of residual water at the UTF site.

In the local-scale study area there is sufficient information to refine the hydrostratigraphy and aquifer properties of Cretaceous strata only. Thus, information

from the intermediate-scale study area has to be used for the hydrostratigraphy and hydrogeology of the Paleozoic strata. In the Cretaceous succession, the McMurray Formation is almost completely saturated with more than 3 mass-percent bitumen, thus behaving like an aquitard. The Wabiskaw Member of the Clearwater Formation is divided into a bitumen-saturated basal erosional channel, a lower shale wedge, an upper sand and an upper regional marine shale. Only the Wabiskaw upper sand is an aquifer, possible target for injection. Above the remainder of the Clearwater Formation, which is a shaley aquitard, the Grand Rapids Formation and Pleistocene strata form an unconfined aquifer. Mineralogical analyses show that dolomite is the dominant mineral in Winnipegosis Formation strata, calcite is the dominant mineral in the Calumet Member of the Beaverhill Lake Group, and quartz is the dominant mineral in the Wabiskaw Member sands. The Phanerozoic aquifers at the UTF site are characterized in terms of petrophysical properties such as permeability, porosity and compressibility.

INTRODUCTION

The Alberta Oil Sands Technology and Research Authority (AOSTRA) has been developing an Underground Test Facility (UTF) near Fort McMurray, Alberta, for the extraction of bitumen from oil sand deposits using a steam-stimulated and gravity drainage recovery process. Currently, the facility is being expanded to pilot stage, with plans to go commercial in a few years. 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 this end, 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 (Figure 1) in

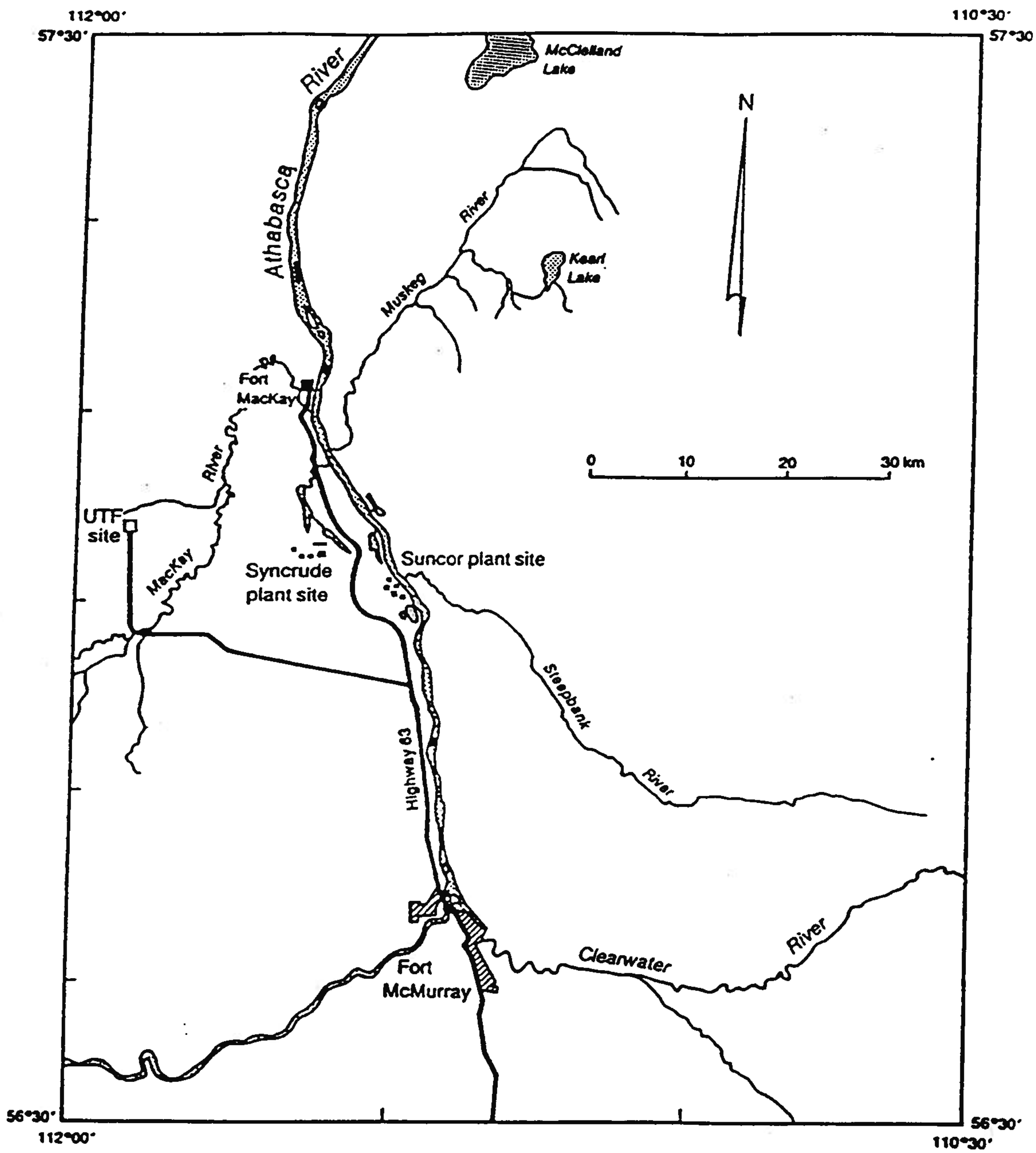

Figure 1. Location map of the UTF site in northeast Alberta.

sections 7 and 8, Tp 93, R 12 , W4 Mer. A previous analysis of data availability for predictive modelling at the UTF site (Basin Analysis Group, 1988) identified 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. Few hydrogeological data exist at or around the UTF site, making any direct evaluation at the local and intermediate scales unreliable. A regional-scale hydrogeological characterization of the Phanerozoic succession in northeast Alberta (Figure 2) was conducted first (Petroleum Geology and Basin Analysis Group, 1991, 1992a), as recommended by the data availability study (Basin Analysis Group, 1988).

The regional-scale study (Petroleum Geology and Basin Analysis Group, 1992a) covers a large area containing 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 permeability and porosity data to characterize the aquifers identified in the stratigraphic succession. Data at the local UTF-site scale are limited to Lower Cretaceous McMurray and Wabiskaw strata and consist mostly of porosity and some permeability measurements. Thus, it is difficult 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 (Petroleum Geology and Basin Analysis Group, 1992b) was performed

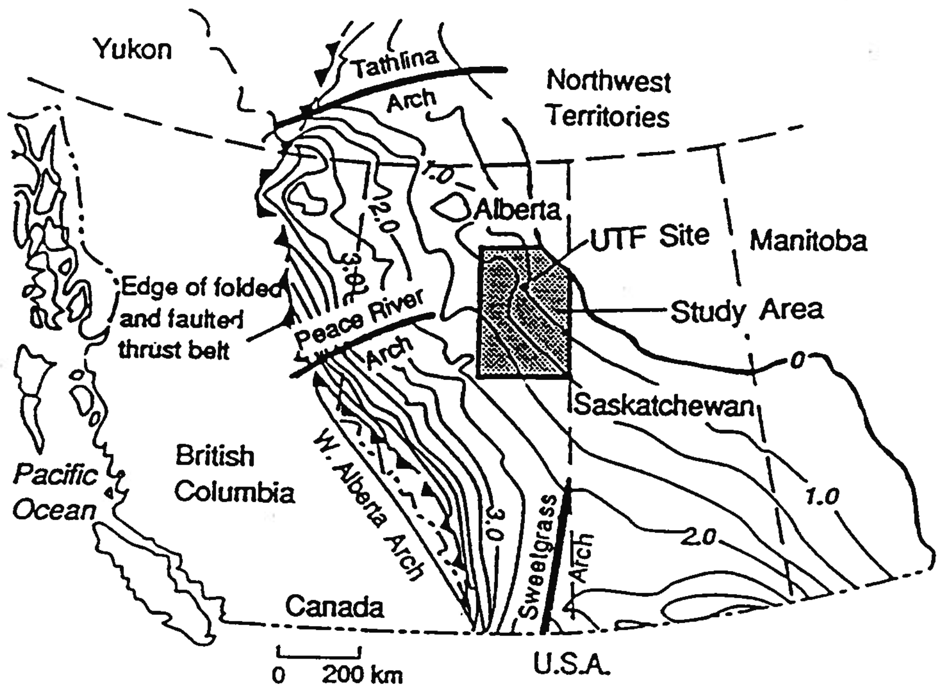

Figure 2. Location of the Northeast Alberta regional-scale study area (Petroleum Geology and Basin Analysis Group, 1992a).

subsequent to the regional-scale study, to serve as a basis for local-scale analysis and modelling. Because of different data distributions, two intermediate-scale study areas were defined (Figure 3), one for the Paleozoic strata (Tp 90-97, R 10-14, W4 Mer) and one for the Cretaceous strata (Tp 92-95, R 11-14, W4 Mer). They are different from the four township area recommended in the data analysis study (Basin Analysis Group, 1988) and represent, respectively, the smallest areas still containing sufficient hydrogeological data to anchor the scaling-down process from the regional to the local scale. Therefore, the intermediate-scale analysis presents the most detailed analysis of hydraulic head and formation-water chemistry possible with the available data. More information is available for lithostratigraphy and petrophysical rock properties at more detailed scales, making a further breakdown of the hydrostratigraphy possible and meaningful.

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 evaporitic beds. On the basis of flow regime, the individual aquifers and aquifer systems, whose main characteristics are shown in Figure 4, 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

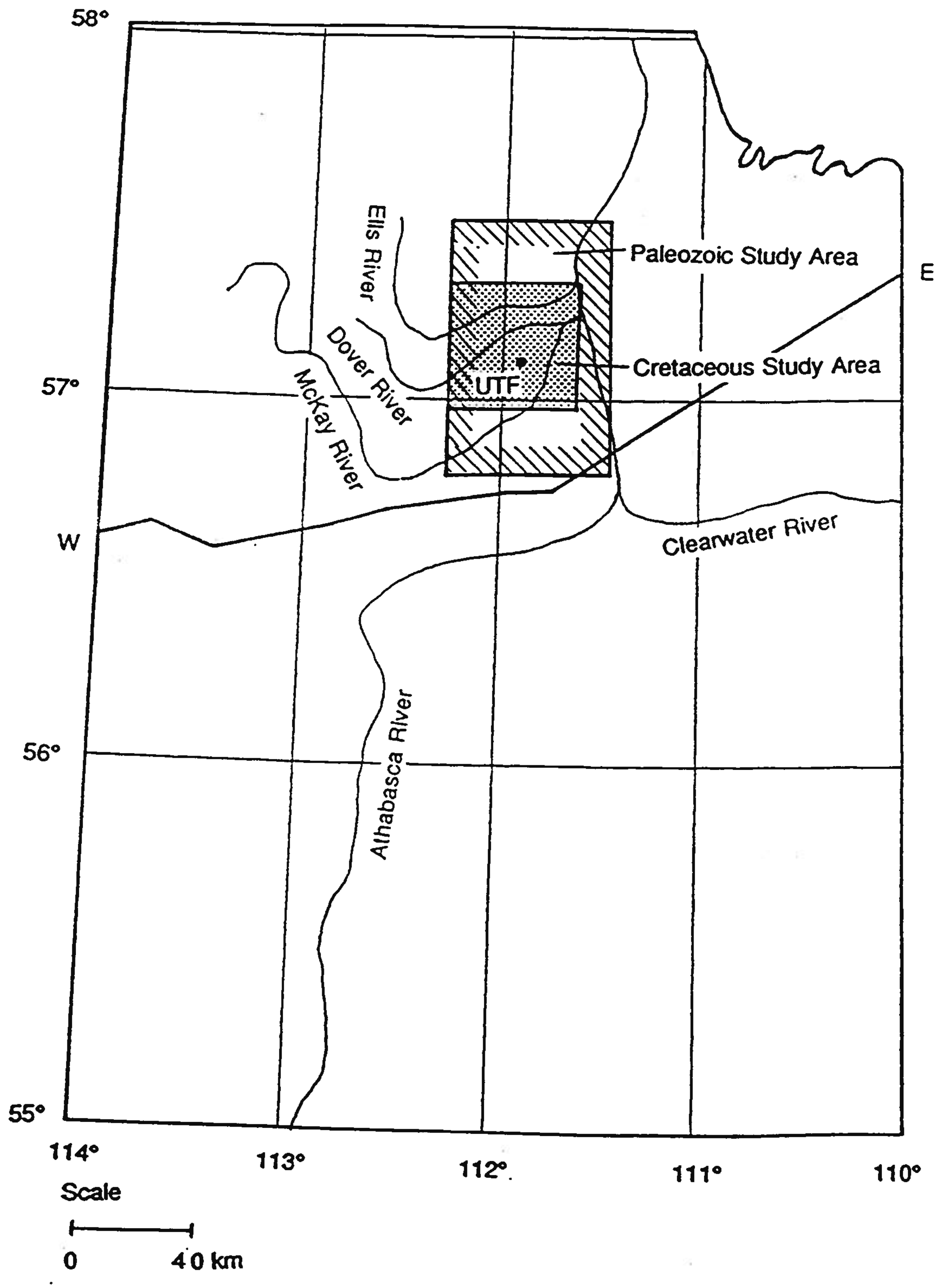

Figure 3. Location map of the Cretaceous and Paleozoic intermediate-scale study areas around the UTF site (Petroleum Geology and Basin Analysis Group, 1992b). Line W-E shows the position of the hydrogeological cross-section of Figure 4.

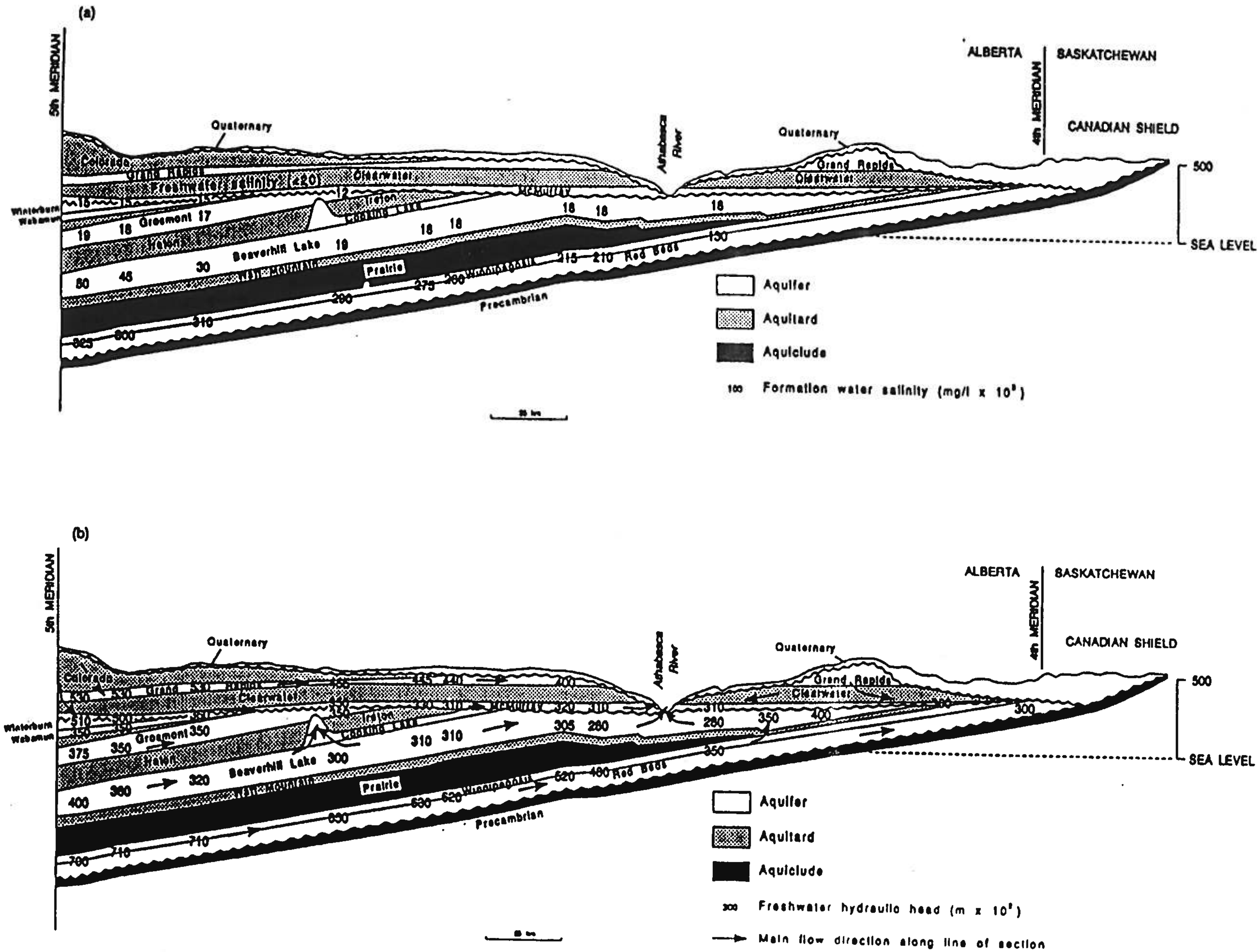

Figure 4 Regional-scale hydrogeological dip cross-section showing distributions of: (a) salinity of formation waters; and (b) hydraulic head. Cross-section location is shown in Figure 3 (cross-section

Lake aquifer system 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 the aquifers in hydraulic continuity above and below. The formation water salinity is low and the flow is generally to the northwest towards the aquifer outcrop along the Peace River. 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 where data are limited.

The hydrostratigraphy in the intermediate-scale study areas could be broadly divided into four main flow units separated by three main flow barriers (Petroleum Geology and Basin Analysis Group, 1992b). 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 regional topographically-driven flow component directed updip to the northeast. The Beaverhill Lake aquifer system exhibits intermediate-to-local flow-regime characteristics, being separated from the aquifers above by the bitumen accumulations in the McMurray Formation. Generally, the formation water salinity is fresh, and flow directions are toward the northeast where the aquifer crops out and discharges along the Athabasca River and its tributaries. The McMurray-Wabiskaw aquifer/aquitard system (above the McMurray Formation bitumen deposits) has local flow-regime characteristics, with the flow oriented generally toward the Athabasca River 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, but few hydrodynamic data are available for a quantitative evaluation of its effectiveness. The post-Clearwater aquifers of Grand Rapids and Pleistocene strata are of limited extent.

The study area forming the object of this report is shown in Figure 5 (Tp 92-94, R 12-13, W4 Mer) and covers a region chosen for preliminary modelling (coarse resolution) of deep injection of residual waters. It is planed to inject approximately 900,000 m^3 of residual water over a period of two years, and it is assumed that the effects of injection will not propagate beyond this area. The area was selected to include the Dover and MacKay rivers which form natural hydrogeological boundaries.

In order to evaluate properly the hydrogeological regime in the study area, a geological framework must be established within which hydrogeological and rock-property

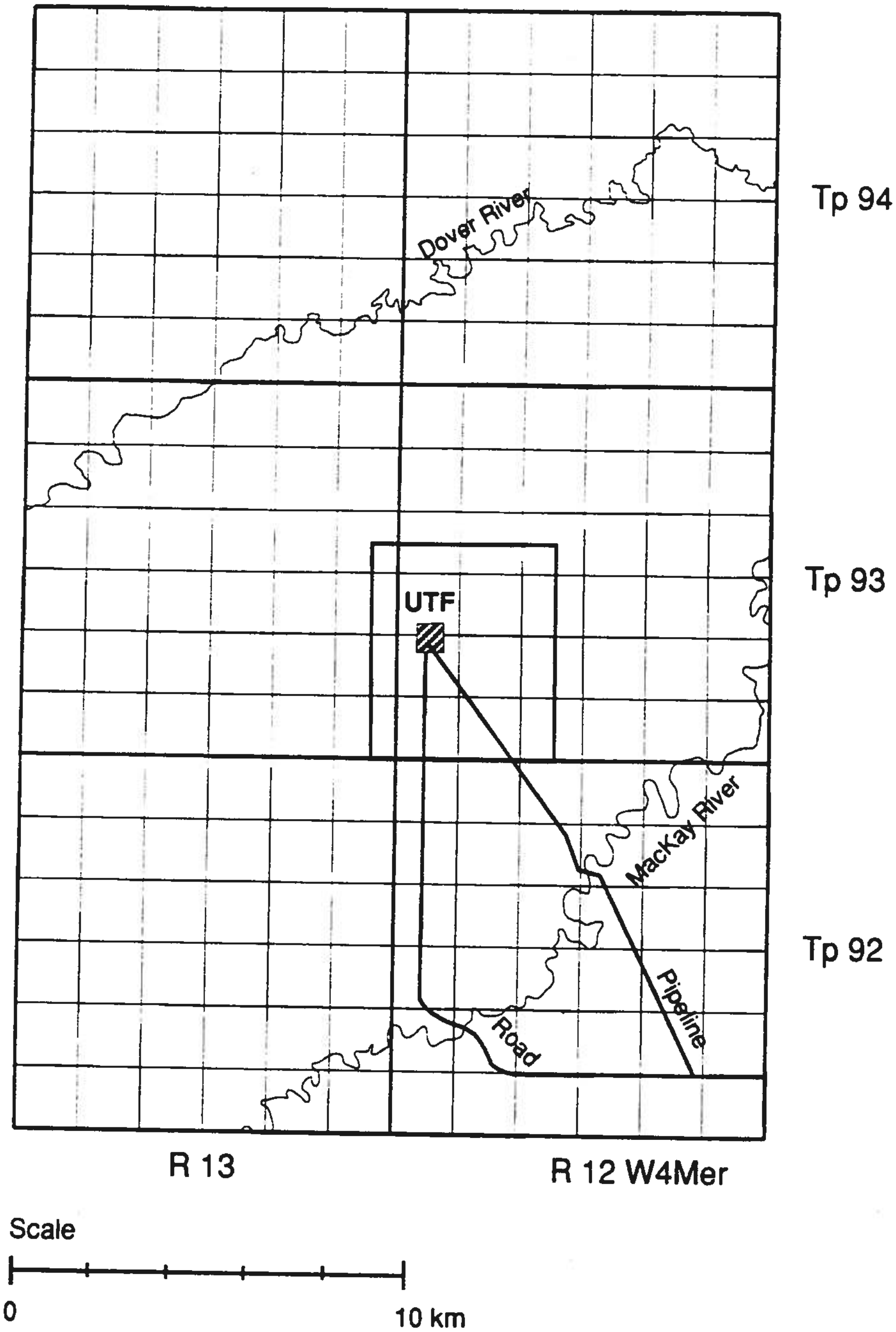

Figure 5. Location map of the local-scale study area showing the UTF site and the Dover and MacKay rivers.

data can be located. A total of 267 wells are located within the local-scale study area, most of which terminate at the sub-Cretaceous unconformity. Stratigraphic information from these wells and 4955 core-plug analyses were used to refine the geology, stratigraphy and hydrostratigraphy, and characterize the associated petrophysical properties of Cretaceous strata. In addition, petrophysical log-analysis of 88 wells was completed in order to evaluate the lithology and distribution of bitumen deposits. Because of the lack of well control, no further refinement was possible neither for the Paleozoic stratigraphy and hydrostratigraphy defined previously at the intermediate scale, nor for the petrophysical characterization of Paleozoic strata (Petroleum Geology and Basin Analysis Group, 1992). Thus, the isopach and structure maps for Paleozoic strata in the intermediate-scale study area are shown at the local scale without any revision (Appendix A), while the isopach and structure maps for Cretaceous strata (Appendix B) include a significantly increased detail, both stratigraphically and areally, compared to the intermediate-scale study area.

No formation water analyses and only one drillstem test are located within the local-scale study area. Because the Paleozoic and Cretaceous intermediate-scale areas described and analyzed previously (Petroleum Geology and Basin Analysis Group, 1992b) are the smallest areas within which there are enough drillstem test and formation-water analyses data to constrain more regional trends, no new knowledge or better understanding was gained at the local scale with respect to hydraulic head or formation-water salinity distributions. Therefore, the hydraulic head and formation-water salinity distributions presented at the intermediate scale were simply redisplayed at the local scale in Appendix C with no additional processing.

A mineralogical analysis of 7 samples from 3 stratigraphic units at the site was conducted to provide a detailed breakdown of rock mineralogy. This information will be used for simulating potential geochemical reactions between the injected residual water and the formation water and rocks.

GEOLOGY

The geological and stratigraphic framework must be established first, to serve as a basis for the analysis of the hydrogeological regime of formation waters. The sedimentary succession around the Underground Test Facility (UTF) is broadly divided into Paleozoic passive-margin strata and Cretaceous foreland-basin strata (Table 1). A regionally significant sub-Cretaceous angular unconformity separates these stratigraphic successions. In the study area, Paleozoic strata consist of the Elk Point and Beaverhill Lake groups, with the latter subcropping at the sub-Cretaceous unconformity everywhere 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.

Cretaceous strata are penetrated by a sufficient number of wells to allow a very detailed stratigraphic delineation. In particular, the top of the bedrock is consistently picked and the Wabiskaw Member is divided into four separate stratigraphic entities. From the oldest to youngest, the Wabiskaw subdivisions are: a basal erosional channel, a lower shale wedge, an upper sand, and an upper regional marine shale. A petrophysical log-analysis based on digital geophysical logs from 88 wells was used to define the lithology and bitumen content of the Cretaceous strata.

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

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

MESOZOIC SUCCESSION

The Mesozoic succession within the study area is comprised only of the Cretaceous Mannville Group (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 to Recent age. Mesozoic strata thicken from 70 m in the northeast to more than 180 m in the southwest (Figure 6). Post-Cretaceous erosional events account for most of the thickness variation within the Mannville stratigraphy. Strata are progressively eroded eastward approaching the Athabasca River drainage basin. Paleo-topography on the sub-Cretaceous unconformity also influenced the distribution of sediments within the area, especially within the lower strata in the succession. Mannville Group strata generally consist of interbedded siliciclastics comprised of sand, shale and silt. For description purposes, the Mannville Group is divided into the McMurray Formation, the Wabiskaw Member (basal portion of the Clearwater Formation), the upper Clearwater Formation (the Clearwater Formation above the Wabiskaw Member), and the Grand Rapids Formation.

Sub-Cretaceous Unconformity

The surface of the sub-Cretaceous erosional unconformity consists of the subcropping Moberly Member of the Devonian Waterways Formation (Beaverhill Lake Group). The surface has up to 90 m of topographic relief in the study area. The UTF is

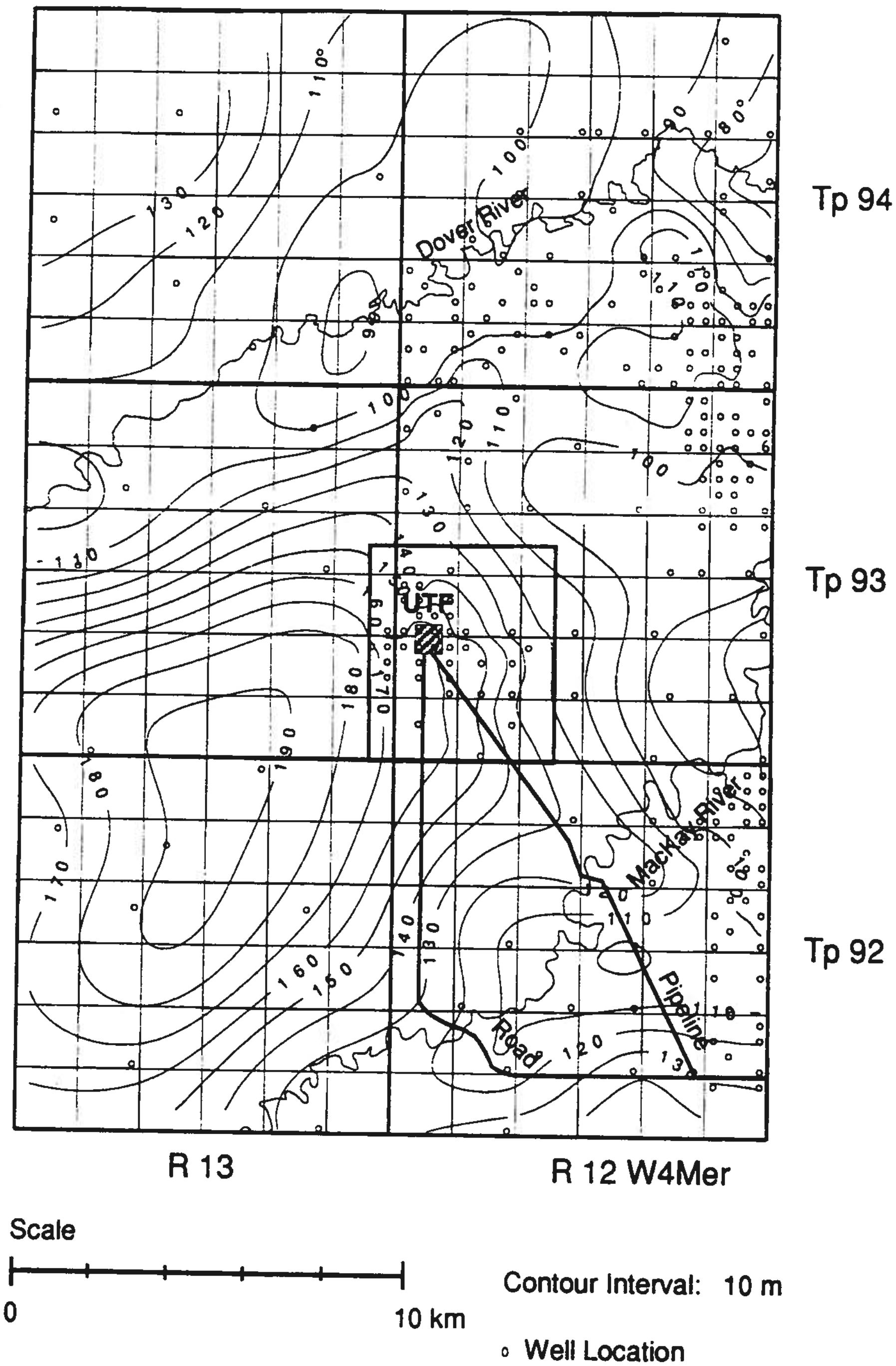

Figure 6. Isopach of Cretaceous strata.

situated in the middle of a large, relatively flat terrace, bounded to the southwest by a paleo-high and to the northeast by an extensive erosional valley (Appendix B, Figure 1). A structural low of limited areal extent is located southeast of the UTF. The paleo-valley system in the northeast was likely initiated by évaporite dissolution within the underlying Middle Devonian Prairie Formation (Flach, 1984). Topographic relief on the sub-Cretaceous unconformity exerted the major control on the subsequent deposition of the McMurray Formation.

McMurray Formation

The Lower Cretaceous McMurray Formation is a complex succession of strata that infill erosional topography on the sub-Cretaceous unconformity. The paleo-geography of the unconformity governed the sediment distribution and facies architecture of the McMurray Formation. Several previous studies describe in detail the economically important McMurray Formation (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). Although many previous studies have subdivided the McMurray Formation into three members, for the purposes of this study it is mapped as a single unit. Bitumen deposits are identified within the McMurray Formation in order to delineate further the hydrostratigraphic nature of this complex succession.

The McMurray Formation is comprised primarily of thick, relatively clean, bitumen saturated, fining upward, sandy successions. Exceptions are in the northern portion of Tp 93, R 12, W5 Mer and in the east along parts of the MacKay River. These areas contain some shale-dominated successions.

The McMurray Formation isopach shows a variable thickness of 5 to 50 m (Appendix B, Figure 2). Variations are due primarily to the underlying paleo-topography. Generally, the McMurray Formation thins to the southwest as relief on the unconformity rises. The valley system, outlined by the structurally low areas on the sub-Cretaceous unconformity, contains the thickest McMurray deposits. Erosional events during the deposition of the overlying Wabiskaw Member have also affected the thickness of the McMurray Formation. It is thought that two separate erosional events occurred within this particular region during the deposition of the Wabiskaw Member. The lowermost erosion surface carved two distinct, localized valleys within the area. The valley fill successions are likely of Wabiskaw affinity. These incised valleys have removed significant portions of the McMurray Formation, the most obvious being an elongate thin region in the southeast, shown on the McMurray Formation isopach (Appendix B, Figure 2). Identification of these erosional features is based on detailed well log correlation and examination of relevant core. The structure map of the top of the McMurray Formation (Appendix B, Figure 3) shows a general dip to the northeast and the two northwest-southeast trending topographic lows produced by Wabiskaw erosion. The dip cross-section (Figure 7) shows the correlation used for the top of the McMurray Formation (surface E1) in the northeast region, where it has been eroded by the Wabiskaw channel.

Wabiskaw Member

The Wabiskaw Member of the Clearwater Formation disconformably overlies the McMurray Formation. Geophysical well logs and a study of several cores from the area indicate that the internal stratigraphy of the Wabiskaw Member can be subdivided into four mappable units. The stratigraphically lowermost unit, a basal erosional channel, consists of two localized sandy deposits of variable thickness which appear to infill valleys incised into the underlying McMurray Formation. The base of the basal erosional channel is referred to as the E1 surface (Figures 7 and 8) and is coincident with the top of the McMurray Formation. Above these localized deposits, separated by an extensive erosional surface named E2 (Figures 7 and 8), there is a wedge of sediments which thickens and becomes progressively shaley to the southwest, termed the lower shale wedge. Overlying this lower shale wedge is an upward coarsening, bioturbated sand typically less than 3 m thick. This unit is referred to as the upper sand (Figures 7 and 8). This sand is best developed in the central and south-central region and becomes thinner and silty to the north. This sandy unit of the Wabiskaw Member is a primary target for the injection of residual waters. Above the upper sand there is a regionally correlatable black shale which becomes silty at the top, having a regionally distinct log marker commonly known as the Wabiskaw marker. This marker defines the top of the Wabiskaw Member and is used as a stratigraphic datum.