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

Prepared For
Conservation and Protection, Environment Canada

by

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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

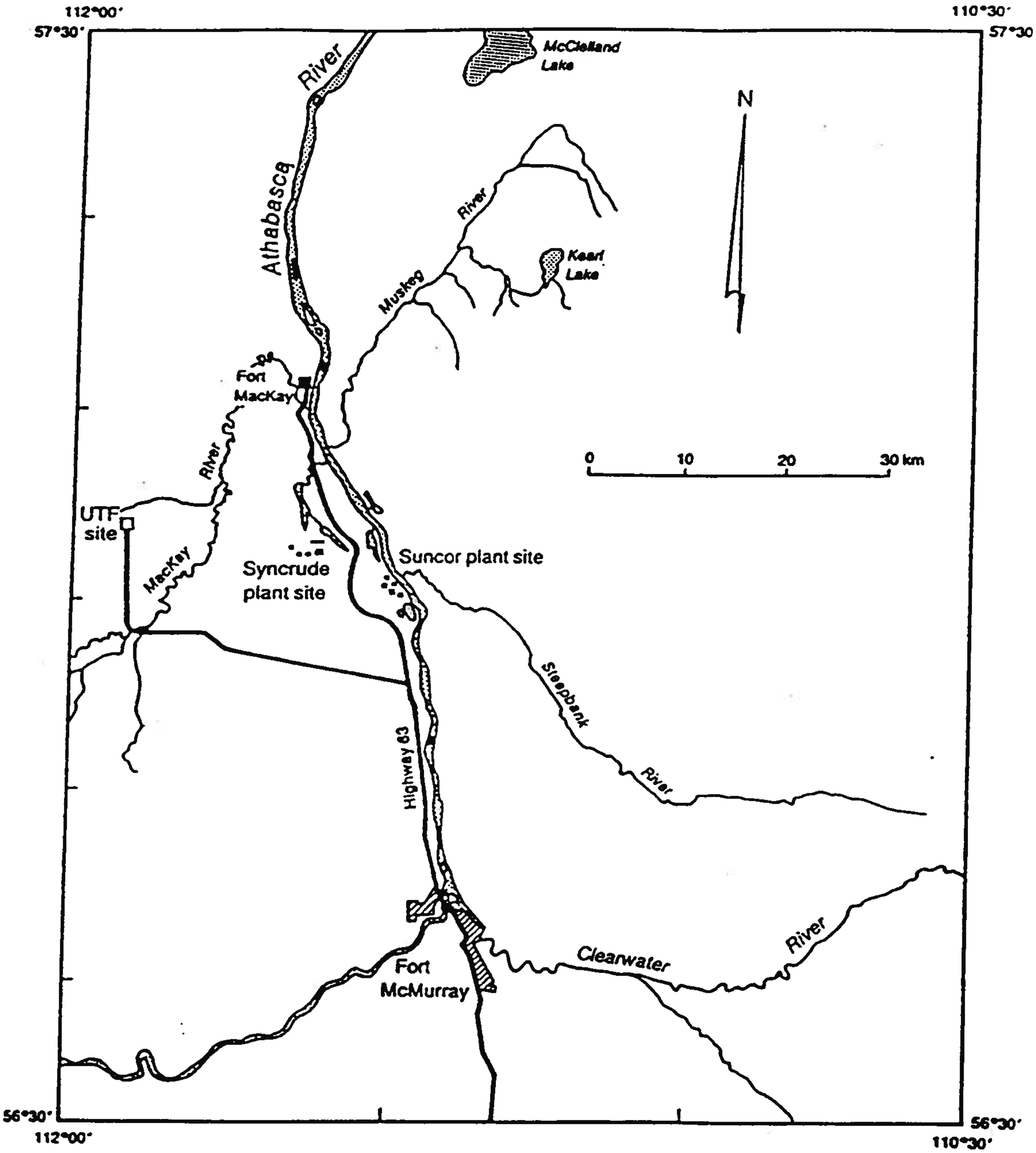

Figure 1. Location map of the UTF site in northeast Alberta.

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

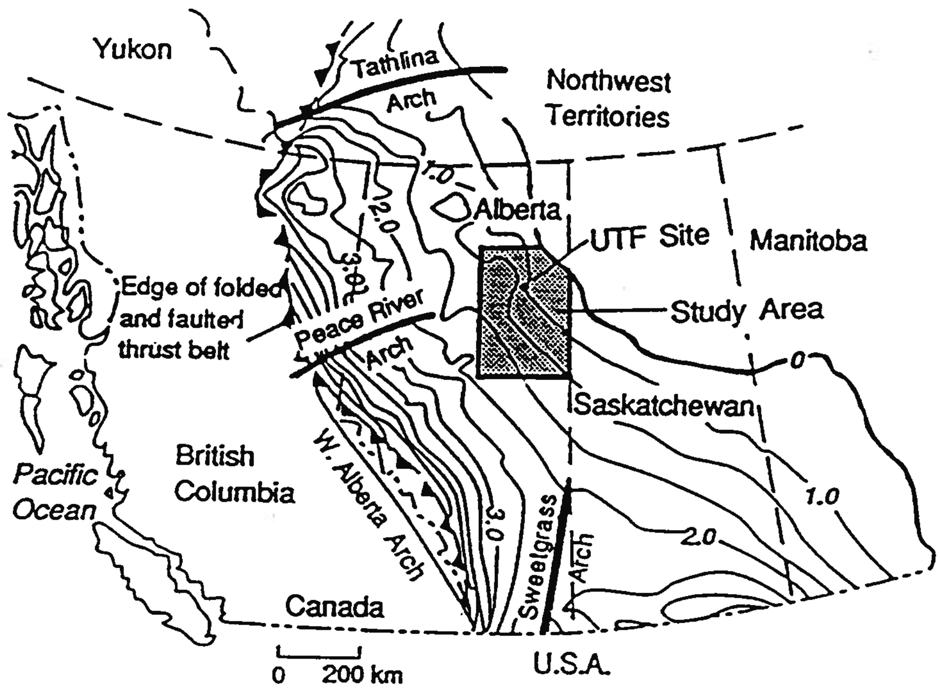

Figure 2. Location of the Northeast Alberta regional-scale study area (Petroleum Geology and Basin Analysis Group, 1992a).

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

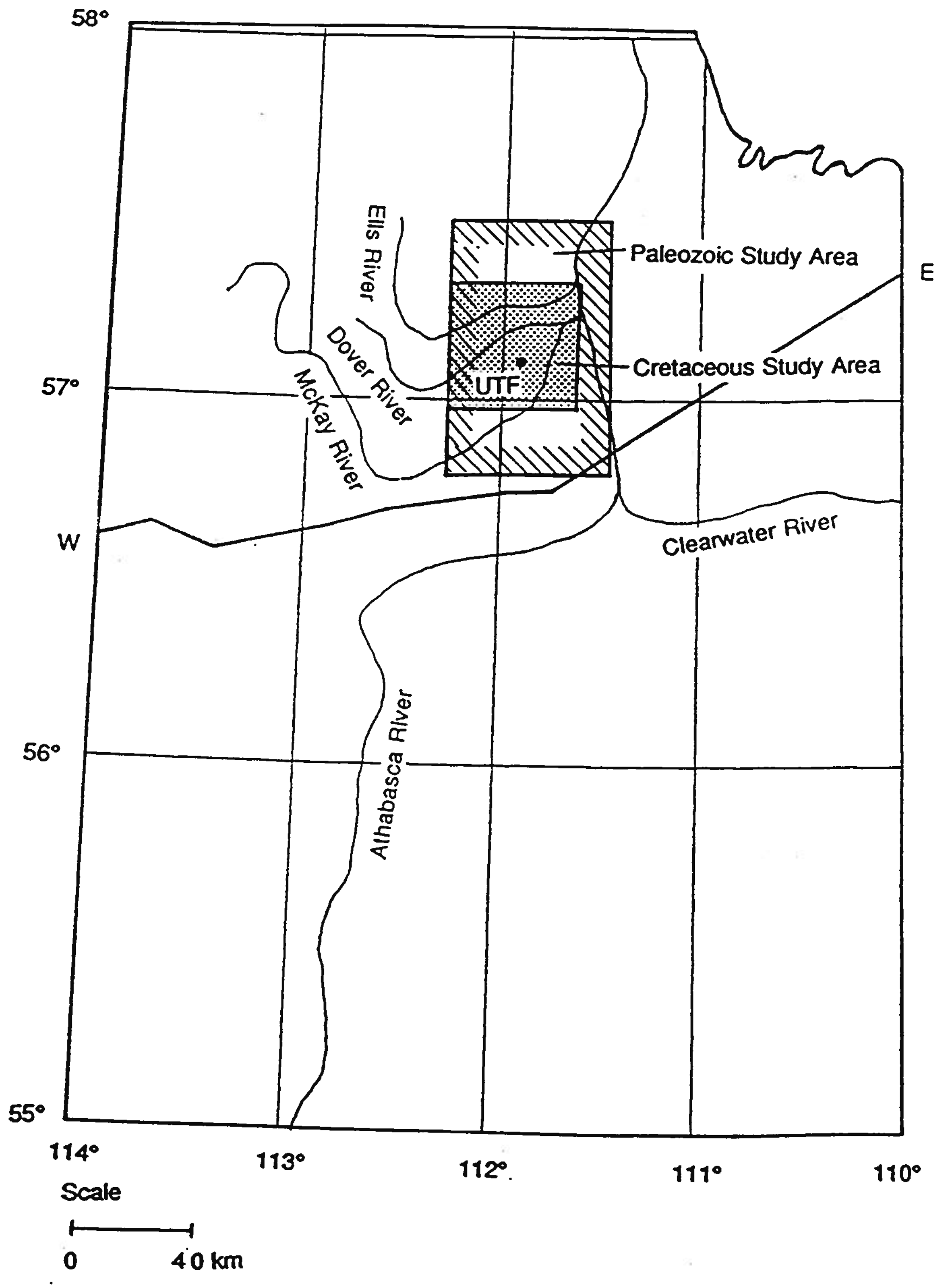

Figure 3. Location map of the Cretaceous and Paleozoic intermediate-scale study areas around the UTF site (Petroleum Geology and Basin Analysis Group, 1992b). Line W-E shows the position of the hydrogeological cross-section of Figure 4.

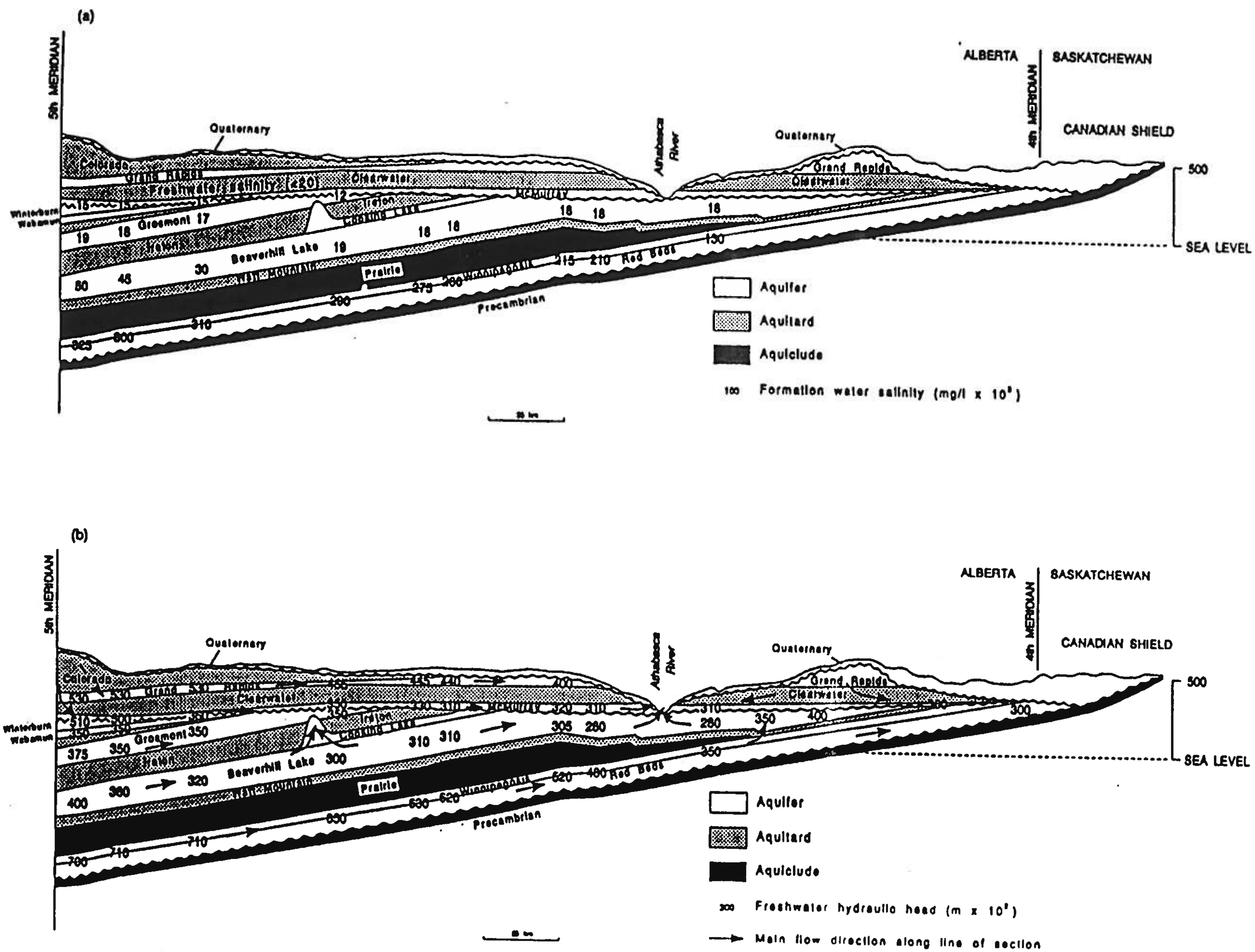

Figure 4 Regional-scale hydrogeological dip cross-section showing distributions of: (a) salinity of formation waters; and (b) hydraulic head. Cross-section location is shown in Figure 3 (cross-section

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

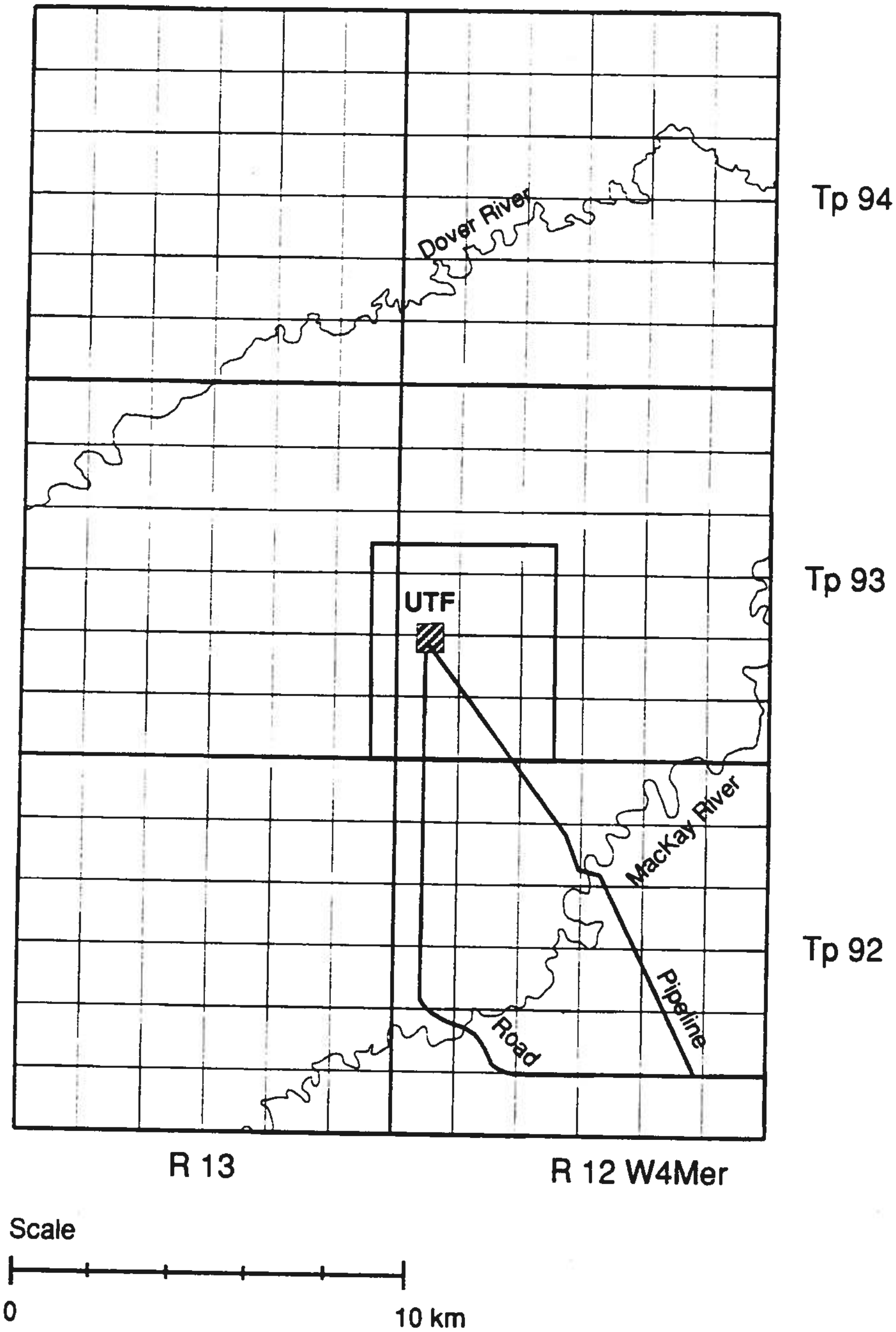

Figure 5. Location map of the local-scale study area showing the UTF site and the Dover and MacKay rivers.

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		
	Mesozoic	Cretaceous	Lower	Mannville		Grand Rapids
						Clearwater
						McMurray
		Jurassic				
		Triassic				
	Paleozoic	Permian				
		Carboniferous				Sub-Cretaceous Unconformity
		Devonian	Upper	Beaverhill Lake		Waterways
						Slave Point
						Fort Vermilion
			Middle	Elk Point	Upper	Watt Mountain
						Prairie
						Winnipegosis (Keg River)
					Lower	Contact Rapids
						Ernestina
			Lower			Granite Wash / Basal Red Beds
		Silurian				
		Ordovician				
		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

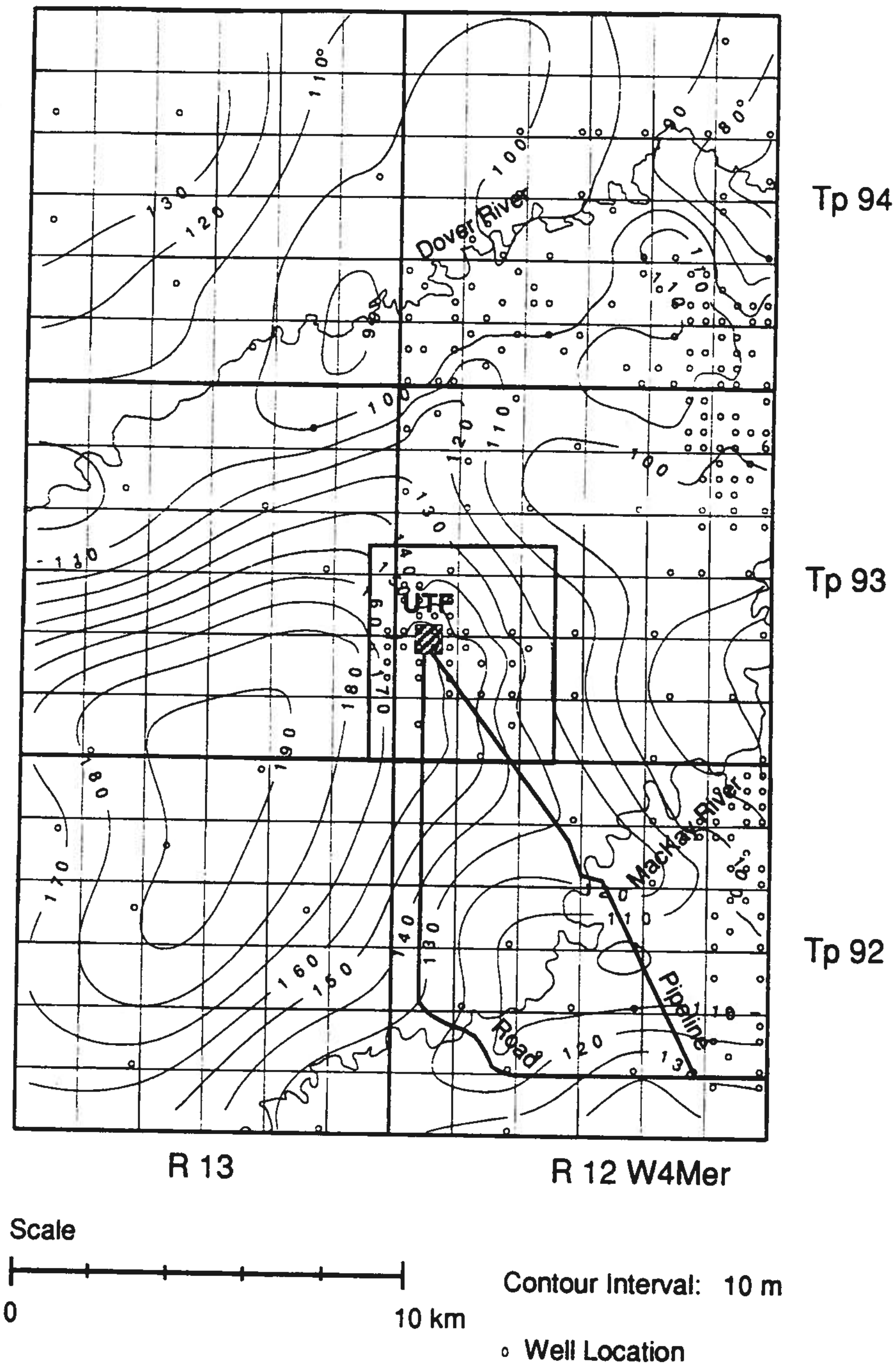

Figure 6. Isopach of Cretaceous strata.

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 evaporite 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.

The isopach map from the top of the McMurray Formation (E1) to the overlying, laterally extensive erosional surface E2 presents the geometry of the basal erosional channel (Appendix B, Figure 4). Both valley fill successions trend northwest to southeast and contain up to 20 m of sediment. The sand-dominated valley fill deposits are distinguishable from the underlying McMurray Formation by the trace fossil assemblage, shale color and composition, and well log profile. The geometry of the northeast valley is defined more precisely because of denser well control in the area. The zero-contour line approximates the intersection between the older, localized erosional valley base (E1) and the younger, regional erosional surface (E2).

The isopach map from the regional erosional surface (E2) to the base of the upper sand shows a gradual thinning of the succession from southwest to northeast (Appendix B, Figure 6). The thick area in the south is dominated by a sandy shale. The unit grades into shaley sands and silts as the unit thins to the northeast. The transition between the two lithologies occurs along a northwest-southeast trend through the central region of the study area. The structure map of the base of the upper sand displays a relatively flat surface throughout the region, except for the pronounced low area in the northeast (Appendix B, Figure 7). This structural low correlates to the erosional valley present on the sub-Cretaceous unconformity surface.

The isopach of the upper sand shows a gradual thinning of this unit from southwest to northeast (Appendix B, Figure 8). The sand is best developed southwest of the UTF

Within this region, the unit typically consists of a clean, bioturbated, upward coarsening, salt and pepper sand approximately 2 to 3 m thick. Northeast of the UTF, the sand thins and becomes progressively shaley and silty. The structure map of the top of the upper sand shows a relatively flat surface, with the exception of a prominent northeast valley (Appendix B, Figure 9).

Overlying the upper sand is a uniformly thick, black, often sandy/silty shale, termed the upper regional marine shale, which was used as a regional datum for characterizing the McMurray Formation in the northern portion of the Athabasca deposit (Flach, 1984). This shale is approximately 9 m thick throughout the study area (Appendix B, Figure 10). A silty horizon, containing a distinct log marker (Wabiskaw marker), overlies the upper regional marine shale. The Wabiskaw marker is used to define the top of the Wabiskaw Member within the Clearwater Formation. The structure of the Wabiskaw Member top dips gently to the northeast (Appendix B, Figure 11). A structural low is still evident in the northeast corner of the study area.

Upper Clearwater Formation

Above the Wabiskaw Member, the remainder of the Clearwater Formation consists of shale interbedded with thin, very fine-grained sand and silt. Overlying the Wabiskaw marker is a relatively thick shale (more than 20 m). Above the shaley unit are two, stacked, coarsening-upward cycles. Each grades from shale at the base to very fine sand or silt at the top. The top of the lower coarsening-upward unit is marked by a prominent, regionally extensive black shale about 2 m thick called the Clearwater A marker (Appendix B, Figure 12). The upper coarsening-upward unit, where present, is capped by about 5 m of shale which marks the top of the Clearwater Formation. Post-Cretaceous erosional events have removed significant portions of the Clearwater Formation within the study area. The boundary outlined on the structure map of the Clearwater Formation (Appendix B, Figure 13) defines the region where its top is preserved. East of this boundary, the Clearwater Formation is progressively eroded towards the Athabasca River. Also within the confines of this boundary, an elongate gap appears trending east-northeast. This gap in the data represents an erosional boundary which defines an area where a Pleistocene-age valley complex has incised into the Clearwater Formation. The valley complex is best delineated within the confines of the UTF lease area shown on the map. The erosional boundary is somewhat speculative southwest of the UTF because of sparse well control.

Grand Rapids Formation

The Clearwater Formation is conformably overlain by and laterally interfingers with the Grand Rapids Formation. Where preserved in the study area, the Grand Rapids Formation consists of thinly, interbedded, dark grey to black shales and light grey sands. The Grand Rapids Formation, confined to within the Clearwater Formation's boundary, attains in places a thickness of more than 40 m. Its isopach (Appendix B, Figure 17) and structure top (Appendix B, Figure 18) reflect control by the surface topography. The Pleistocene valley complex has completely removed the Grand Rapids succession from within the inner erosional boundary.

POST-MESOZOIC SUCCESSION

Pleistocene-age drift and other sediments of recent geological age are comprised primarily of unconsolidated sands and gravels, which generally exist as a veneer covering the Lower Cretaceous Mannville Group. However, localized drift accumulations in excess of 90 m thick have been measured within the study area. The top of the bedrock structure surface (Appendix B, Figure 18) forms the base on which the drift was deposited. This surface represents a composite of the top of the subcropping Clearwater and Grand Rapids formations. An isopach of the drift (Appendix B, Figure 19) shows generally less than 10 m of sediment, with some notable exceptions. In the northeast, a thick accumulation of drift is shown and was confirmed by outcrop work along the Dover River. Other areas of thick drift occur in the south and near the UTF. The area of thick drift in the southwest is based on very little data control and may be an artifact caused by computer extrapolation. Several wells near the UTF record thick drift accumulations (Basin Analysis Group, 1988). The deposit generally consists of unconsolidated till and glacially stratified sediments overlying a thick succession of sands and gravels. The geometry of the deposit near the UTF indicates a major valley fill deposit 1.5 to 2.5 km wide and traceable for some 8 km (Basin Analysis Group, 1988). Sparse well control at either end of the valley prohibits further delineation. This particular valley cuts well into the Clearwater Formation.

Surficial Topography

The topography within the study area is related to the main physiographic features. A ridge of high ground extends northeast between the MacKay and Dover rivers (Appendix B, Figure 20). Along the two rivers there are topographically low valleys, creating over 100 m of relief across the study area.

HYDROSTRATIGRAPHY AND HYDROGEOLOGY

The hydrostratigraphy provides a breakdown of strata according to certain hydrogeological characteristics. The hydrostratigraphic nomenclature is defined as follows: an aquifer is a layer, formation or group of formations saturated with water and with a degree of permeability that allows water withdrawal (de Marsily, 1986, p. 115); an aquitard is a less permeable unit from which water cannot be produced through wells, but where the flow is significant enough to feed adjacent aquifers through vertical leakage; and an aquiclude has very low permeability and cannot give rise to any appreciable leakage (de Marsily, 1986, p. 131). Hydraulic communication between two aquifers may occur across a weak aquitard, in which case there is significant cross-formational flow between the two aquifers. Hydraulic continuity between two aquifers occurs when they are in direct contact. According to Toth (1963), the flow in a local hydrogeological system is from a recharge area at a topographic high to a discharge area at a topographic low that are adjacent to each other, while the flow in a regional system is from a recharge area at the major topographic high to a discharge area at the major topographic low in the basin. Intermediate flow systems are transitional between the two.

The local-scale hydrostratigraphy (Table 2), derived mainly from the intermediate scale hydrostratigraphic delineation (Petroleum Geology and Basin Analysis Group 1992b), is more detailed because the bitumen deposits were included, the Wabiskaw Member has been subdivided, and a lithological analysis of Cretaceous strata has been

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

Table 2. Hydrostratigraphic succession and nomenclature at the UTF site.

conducted. The lithological analysis is based on petrophysical log-analysis of 88 wells in the study area.

PETROPHYSICAL LOG-ANALYSIS

The analysis of lithology and bitumen content for 88 wells with digitized geophysical logs was conducted using the INTELLOG computerized geophysical log analysis software package. The electronic geophysical logs were obtained either from previous UTF studies conducted by AOSTRA and the Alberta Geological Survey, or by digitizing hard-copy geophysical logs. The INTELLOG-based system is calibrated to information from core analyses and produces for each well a lithological and mass-percent bitumen breakdown at a 0.25 m interval. In the absence of other hydrogeological data, the petrophysical analysis is critical for assessing the hydrostratigraphy and estimating rock property values. Lithological and mass-percent bitumen determinations can be associated with particular hydrodynamic properties when other information is absent.

Lithological categories obtained from the INTELLOG analysis are sand, shaley sand, sandy shale, shale and cemented sand. From a manual (human) log-analysis it was determined that the sandy shale category can usually be considered equivalent to a fine silt. Similarly, the cemented sand category was determined to consist normally of sands with nearly all the original porosity filled by cement. As a result, the five-fold lithological division was reduced to two hydrogeological divisions. The shale and cemented sand categories are associated with aquitard characteristics, and the sand, shaley sand and sandy shale categories are associated to various degrees with aquifer characteristics. Based on bitumen saturation, sands containing more than 3 mass-percent bitumen are considered to have aquitard-to-aquiclude characteristics, while those with less bitumen content are associated with aquifer characteristics. The results of the INTELLOG analysis were incorporated into the detailed stratigraphic and hydrostratigraphic geometry in order to characterize the strata in the vicinity of the proposed injection site.

PALEOZOIC HYDROSTRATIGRAPHY

Because the Lotsberg and Cold Lake Formations (salt deposits) are absent, the Contact Rapids-Winnipegosis aquifer system directly overlies the Basal aquifer. The latter is of negligible thickness, being comprised of the thin-to-absent Basal Red Beds and Ernestina Lake formations. Therefore, the strata from the Basal Red Beds to the Winnipegosis formations were grouped at the local scale into the Winnipegosis-Basal aquifer system. Overlying this aquifer system is the Prairie-Watt Mountain aquiclude.

Stratigraphically, the Beaverhill Lake Group is complex and can be divided into three formations: Fort Vermilion, Slave Point and Waterways (Tables 1 and 2). The Waterways Formation is further divided from bottom to top into the Firebag, Calumet, Christina, Moberly and Mildred members. Although there are not enough data for the hydrogeological characterization of each subdivision, some inferences can be drawn from the stratigraphy and lithology 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 the geophysical logs available 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 is a low porosity unit (based on geophysical logs) of likely weak-aquitard to aquifer characteristics. Immediately above, the Christina Member is comprised mostly of shale and probably has aquitard characteristics. The Moberly Member is the uppermost mappable member of the Waterways Formation within the 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 local-scale study area.

CRETACEOUS HYDROSTRATIGRAPHY

The Cretaceous hydrostratigraphy is markedly different from the stratigraphy, mostly because of the variability in the lithology of the Cretaceous formations and the presence of bitumen deposits. The McMurray Formation lies directly on the sub-Cretaceous unconformity surface and, at the regional scale, has generally the hydrodynamic properties of an aquifer. Bitumen accumulations within the McMurray Formation act as local barriers to flow such that this flow unit has in places the characteristics of an aquitard. For this reason it was previously classified as an aquifer/aquitard (Petroleum Geology and Basin Analysis Group, 1992a). The INTELLOG analysis showed that, throughout the local-scale study area, the McMurray Formation either is saturated with bitumen in excess of 3 mass-percent, or has a shaley lithology, with the exception of thin isolated regions at the base of the succession, where sands may occur with little or no bitumen content. Figure 9 shows the distribution and thickness of these basal "water sands" which have aquifer characteristics. The basal water sands are in physical and hydraulic contact with the Moberly unit below, and separated from the aquifers above.

The overlying Wabiskaw Member can be divided into four separate units, as discussed previously. The basal erosional channel which cuts down into McMurray strata is dominantly sandy. However, the INTELLOG analysis showed this sand to be saturated with bitumen more than 3-mass percent throughout. Stratigraphically above the basal erosional channel, the lower shale wedge consists of shale in most of the region, and bitumen-saturated silts and sands in the northeast. Thus, the McMurray and Wabiskaw bitumen-saturated sands, and the Wabiskaw lower shale wedge can be grouped into a single aquitard unit separating the McMurray water sands and Moberly aquifer unit below from the Wabiskaw upper sand above. This aquitard is present throughout the entire local-scale study area. Figure 10 shows the thickness of this aquitard to be more than 20 m throughout most of the area. The upper sand itself appears to be free of bitumen throughout the local-scale study area, with the exception of a few places where the upper portion of the unit has more than 3 mass-percent bitumen. The INTELLOG analysis also

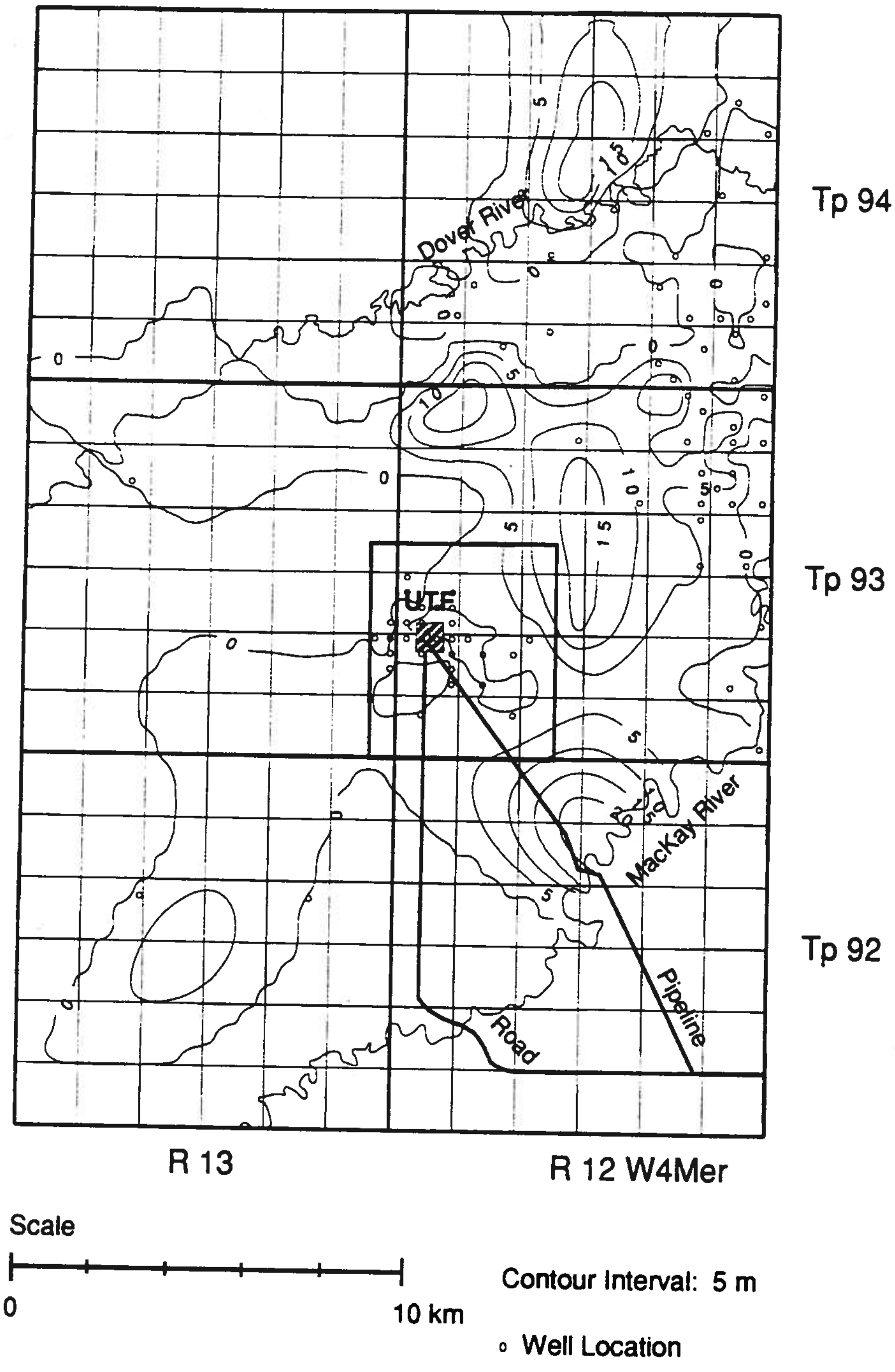

Figure 9. Isopach of the water sands at the base of the McMurray Formation.

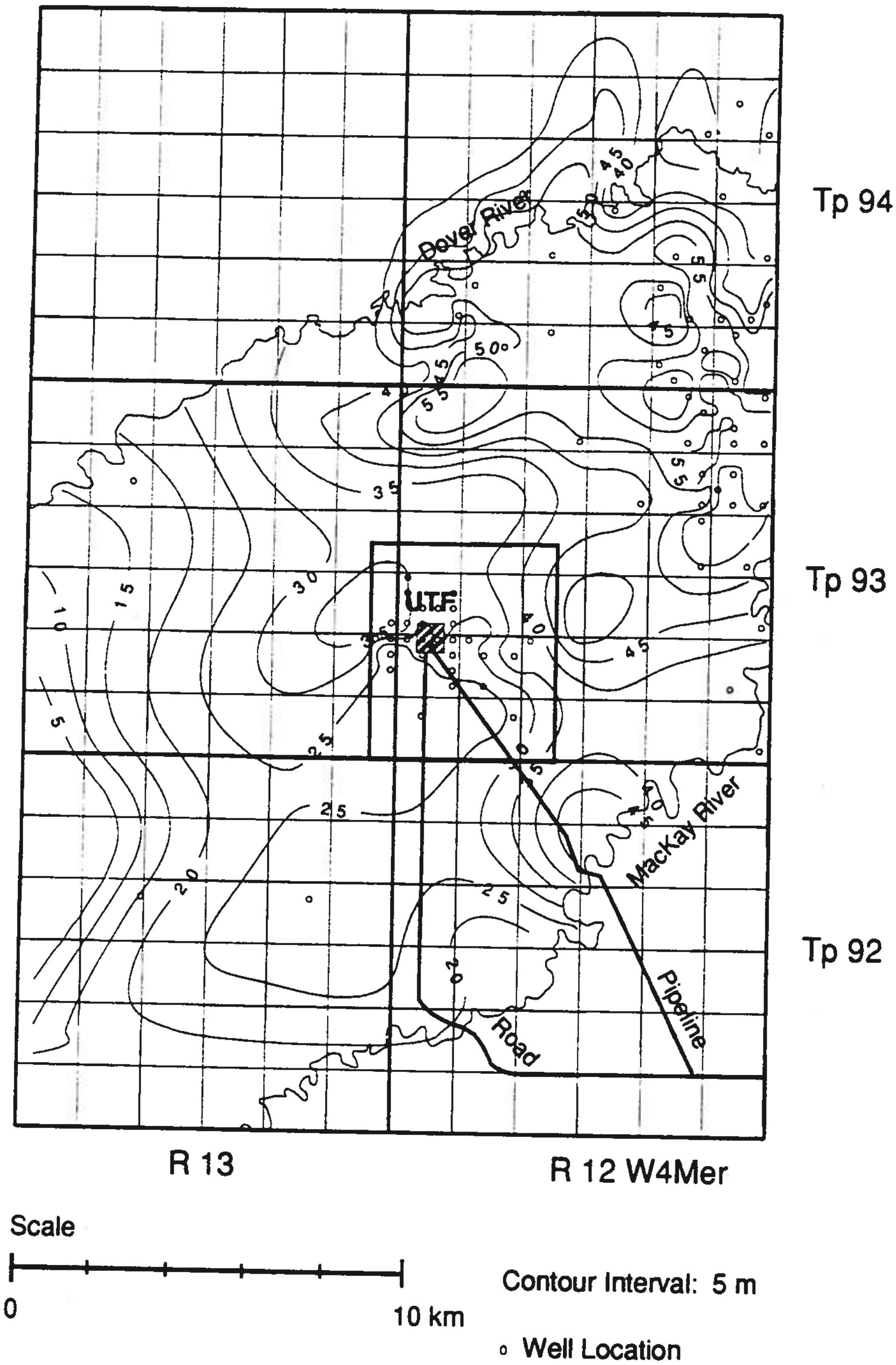

Figure 10. Isopach of the McMurray-Wabiskaw aquitard.

showed that the unit becomes progressively more silty to the northeast and east. Figure 11 shows the isopach of this upper sand, which has aquifer characteristics. The upper regional marine shale above the upper sand has aquitard characteristics.

Lithological analysis of the Upper Clearwater Formation, performed using the INTELLOG system, indicated an extremely variable distribution of lithologies, covering the range from sand to shale. However, throughout the local-scale study area there is a continuous shale zone at the base of the unit, which forms an aquitard overlying the upper sand aquifer. Figure 12 shows the isopach of this aquitard, picked with the INTELLOG system, as the shale thickness from the top of the upper sand aquifer to the base of the first sandy portion in the overlying upper Clearwater Formation. Above this aquitard, the upper Clearwater Formation consists of a variable mixture of shale, sand and silt, with poor lateral continuity. The uppermost part of the Clearwater is considered to be a weak aquitard.

Occurring over only a limited part of the local-scale study area, the Grand Rapids Formation forms an aquifer above the Clearwater aquitard. The Grand Rapids aquifer is present only within a small part of the area and is nearly devoid of data. The Pleistocene deposits together with the Grand Rapids Formation, where present, form an unconfined aquifer system at the top of the hydrostratigraphic succession.

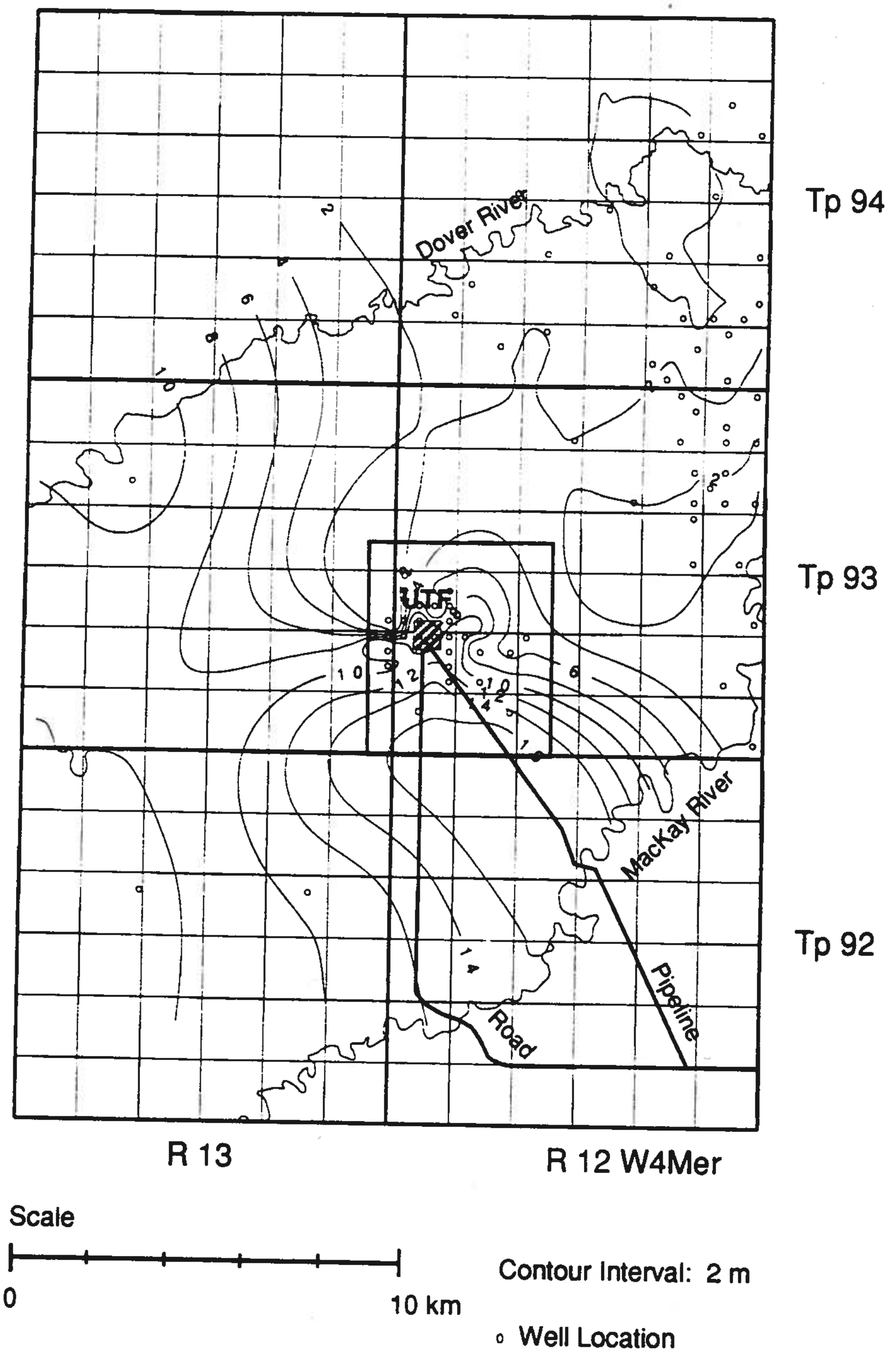

Figure 11. Isopach of the Wabiskaw upper sand aquifer.

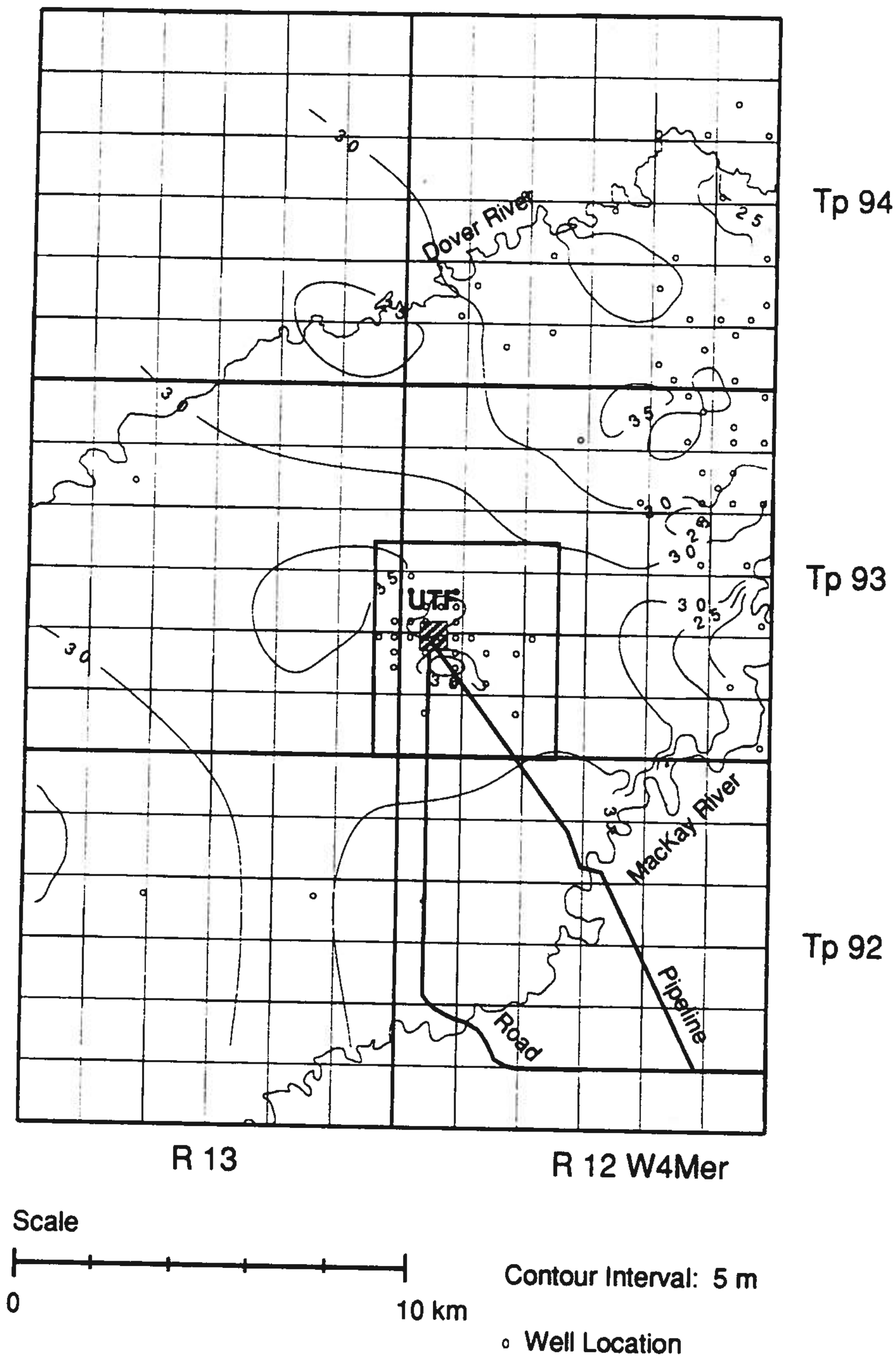

Figure 12. Isopach of the Wabiskaw-Clearwater aquitard.

HYDROGEOLOGY

With only one drillstem test and no formation water analyses in the local-scale study area, it is impossible to refine the distributions of formation water salinity and hydraulic head presented previously at the intermediate-scale (Petroleum Geology and Basin Analysis Group, 1992b). At the local-scale, only the hydrostratigraphy, aquifer and aquitard geometry, and associated characteristic rock properties could be refined. Nevertheless, this limited refinement is still important and needed for numerical simulations of residual water injection. It is assumed that the previous characterization of the Wabiskaw aquifer can be applied to the upper sand defined at the local scale study area. The characterization for the Beaverhill Lake aquifer at the intermediate scale can not be associated with any individual subdivision described in the local-scale study area. Because of lack of hydrogeological data, the distributions of hydraulic head and formation water salinity are somewhat ill constrained. The previously conducted regional- and intermediate-scale studies do provide an estimate of these parameters within the area around the UTF site (Appendix C), but the error associated with these estimates is probably high.

AQUIFER PROPERTIES

The flow in a confined aquifer of a slightly compressible fluid like water is described (de Marsily, 1986, p. 109) by the diffusion equation:

$$\nabla(\mathbf{K}\nabla H) = S_s \frac{\partial H}{\partial t} \tag{1}$$

where **K** is the hydraulic conductivity tensor, H is hydraulic head, S_s is the specific storage coefficient and t is time. The hydraulic conductivity is defined as:

$$\mathbf{K} = \frac{\rho g \mathbf{k}}{\mu} \tag{2}$$

where ρ is fluid density, g is the gravitational constant, **k** is medium permeability and μ is the fluid dynamic viscosity. The specific storage coefficient S_s of the aquifer is defined (de Marsily, 1986, p. 108) as:

$$S_s = \rho g \left[\alpha + \phi \left(\beta_f - \beta_s\right)\right] \tag{3}$$

where α is the compressibility of the porous medium (volume available for water storage), ϕ is porosity, and β_f and β_s are the fluid and solid compressibility, respectively. For water, $\beta_f \approx 5 \times 10^{-10}\,Pa^{-1}$, while $\beta_s \approx 2 \times 10^{-11}\,Pa^{-1}$ for quartz and most minerals (de Marsily, 1986, p. 108). In practice, β_s is most often neglected.

Examination of relations (1) - (3) shows that, in order to simulate numerically the flow of formation waters and injection of residual water in aquifers, there is need to know various fluid, solid and porous medium characteristics. Values for fluid and solid parameters, like viscosity, density and compressibility, are measured in laboratory and are usually found in literature. The characterization of porous-medium properties, like permeability, porosity and compressibility, should be based, as much as possible, on actual data. If geochemical reactions are expected between the injected fluid and the formation water and rock, then there is need to know the mineralogy of the host rock, besides the chemistry of formation and injected fluids. Thus, in order to evaluate later on the effects of injecting residual water at the UTF site, there is need to characterize the potential injection aquifers in terms of their mineralogy and hydraulic properties.

MINERALOGY

Core samples have been collected from three theoretically possible injection zones and analyzed for their mineralogy. Rock samples were collected from the Wabiskaw upper sand (a primary injection target), the Calumet limestone within the Beaverhill Lake Formation, and the Winnipegosis Formation limestone. The samples were powdered and a bulk X-ray diffraction pattern of a randomly oriented sample was used for mineral determination. Copper K-alpha radiation was used as a radiation source. One-second measurements of peak intensities were undertaken at 0.05 degree steps over the range of 0 to 65 degrees 2θ, resulting in a total X-ray run time for each sample of slightly over twenty minutes. The mineral assemblage of each sample is dominated by a single mineral, either quartz (silicon dioxide), calcite (calcium carbonate) or dolomite (calcium magnesium carbonate). Separate clay determinations were not considered necessary because of the small amounts present. Therefore, the separation of smectite and illite was not undertaken.

The formation mineralogy of the Wabiskaw Member was determined from core selected from the well AO58 (LSD 15, Section 12, Tp 93, R 12, W4 Mer). Samples 1, 2 and 3 were taken from the upper regional marine shale (123.09 m depth), the upper sand (124.16 m depth) and the lower shale wedge (125.88 m depth), respectively. The mineralogical analyses for these samples are summarized in Table 3 and shown in Appendix D, Figures 1, 2 and 3. The dominant mineral in all three samples is quartz. Minor amounts of feldspar are present in the upper sand, while carbonate minerals and clays are present in the bounding shales. The dominant clay mineral appears to be illite/smectite, with only minor amounts of kaolinite present. The upper regional marine shale contains ankerite (iron carbonate) and the lower shale wedge contains dolomite.

The mineralogy of the Calumet limestone was determined from sample 4 taken at 221.21 meters depth from well BC03 (LSD 01, Section 18, Tp 93, R 12, W4 Mer). Its mineralogy is summarized in Table 3 and shown in Appendix D, Figure 4. Only one sample was taken, as visual inspection of the core indicated that the mineralogy

Unit	Well	Sample	Depth (m)	Minerals
Wabiskaw Member, Clearwater Fm.	AO58	1	123.09	Dominantly quartz. Minor clays and ankerite.
		2	124.16	Dominantly quartz. Minor feldspar
		3	125.88	Dominantly quartz. Minor dolomite and clays.
Calumet Member, Waterways Fm.	BC03	4	221.21	Dominantly calcite. Minor quartz and clays. Trace of halite.
Winnipegosis Formation	06-18-93-12W4 Mer	5	502.46	Dominantly dolomite. Minor clays Trace of halite.
		6	516.61	Dominantly dolomite. Minor quartz. halite and clays.
		7	531.10	Dominantly domite. Minor quartz, halite and kaolinite. Trace of other clays

Table 3: Mineralogy of rocks from selected strata at the UTF site.

and physical features of the core were constant over a large length. As expected for a limestone, calcite is the dominant mineral present. Between 5% and 10% of the sample is quartz, with a very small amount (much less than 1%) of halite (sodium chloride) present. The sample contains a minor amount of clay which is likely illite/smectite. Kaolinite can be assumed to be absent because there is no peak for it on the X-ray scan (Appendix D, Figure 4).

Three samples from the Winnipegosis Formation were taken from a well at LSD 06, Section 18, Tp 93, R 12, W4 Mer. They are refered to as samples 5, 6 and 7 in the text, tables and figures, and were taken from 502.46 m, 516.61 m and 531.10 m depth, respectively. The mineralogy of these samples is summarized in Table 3 and the X-ray scans for each are shown in Appendix D, Figures 5, 6 and 7, respectively. The dominant mineral for all three samples is dolomite. In addition, sample 5 contains a minor amount of clay (illite/smectite) and a trace of halite. Sample 6 contains minor amounts of quartz, halite and illite/smectite clay. Sample 7 contains minor amounts of quartz, halite and kaolinite. A very small amount of other clay minerals may be present in sample 7.

PERMEABILITY AND POROSITY

Core has been taken from many wells within the local-scale study area. However, maximum permeability, k_m, was measured at only 14 of these (one core from the Winnipegosis Formation, 11 from the McMurray Formation, all located in the same LSD, and 2 from the Wabiskaw upper sand, also located in the same LSD). Figure 13 shows the distribution of wells containing core analyses with maximum permeability determinations. The well-scale permeability values, listed in Table 4, were obtained from core analyses using scaling-up procedures described by Bachu and Underschultz (1992). It should be noted that the well-scale permeability values for the McMurray unconsolidated sands at the UTF site are generally three orders of magnitude greater than the well-scale values at surrounding locations reported in the intermediate-scale study area (Petroleum Geology and Basin Analysis Group, 1992b). The measurements at the UTF site were performed on bitumen-saturated samples after bitumen

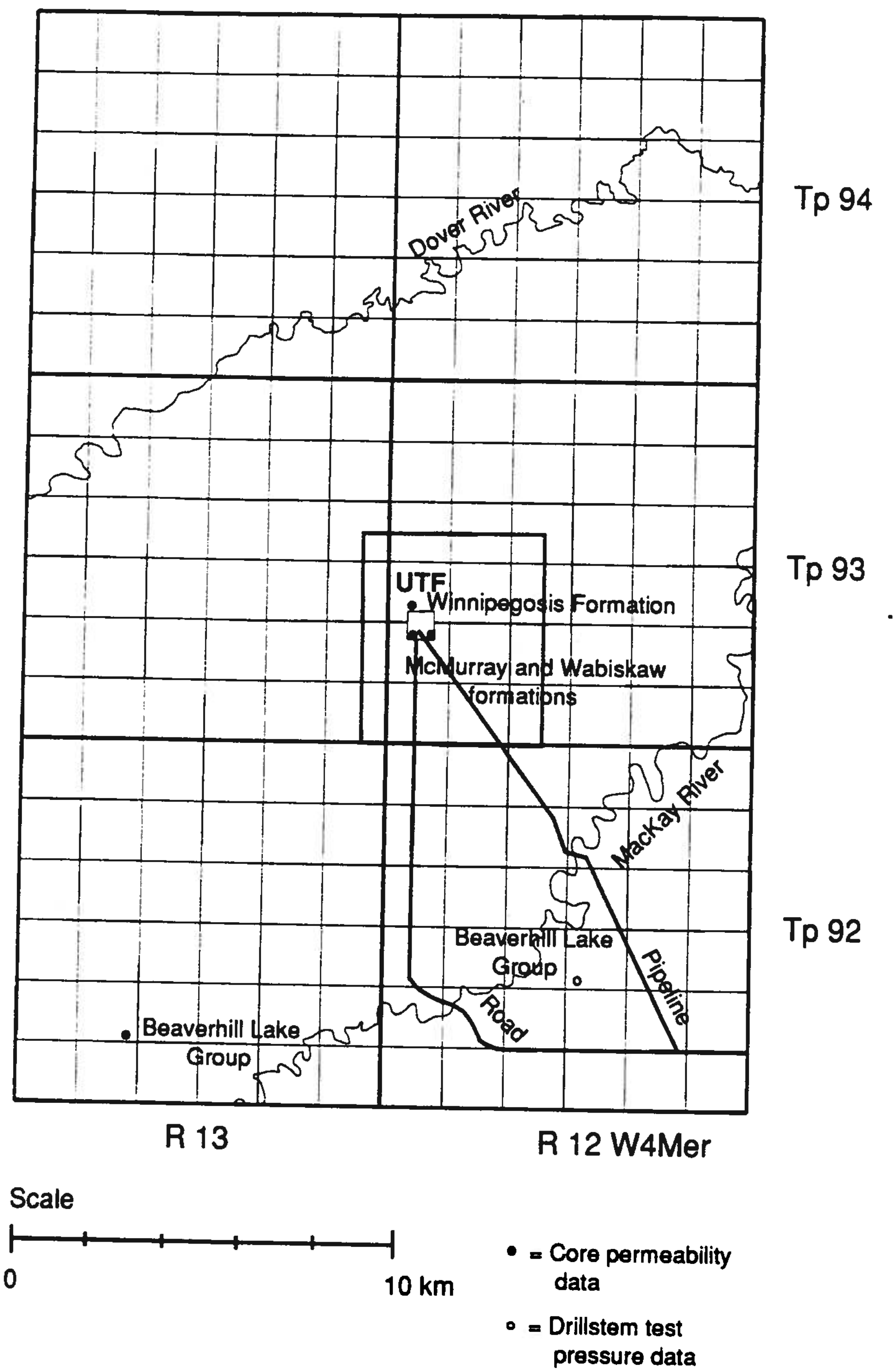

Figure 13. Distribution of wells with drillstem-test and core permeability data.

Unit	Well	Maximum Permeability (m^2)
Wabiskaw	003-14-07-93-12W4 Mer	2.69×10^{-11}
	013-14-07-93-12W4 Mer	6.39×10^{-11}
McMurray	AT7-14-07-93-12W4 Mer	2.69×10^{-12}
	GI1-14-07-93-12W4 Mer	5.97×10^{-12}
	GI2-14-07-93-12W4 Mer	1.50×10^{-13}
	GI3-14-07-93-12W4 Mer	2.20×10^{-12}
	AG1-14-07-93-12W4 Mer	1.82×10^{-11}
	AT3-14-07-93-12W4 Mer	3.15×10^{-12}
	AB0-14-07-93-12W4 Mer	2.66×10^{-11}
	003-14-07-93-12W4 Mer	5.61×10^{-11}
	007-14-07-93-12W4 Mer	7.46×10^{-11}
	010-14-07-93-12W4 Mer	5.86×10^{-11}
	011-14-07-93-12W4 Mer	7.36×10^{-11}
Beaverhill Lake	01-08-92-13W4 Mer	1.40×10^{-15}
Winnipegosis	06-18-93-12W4 Mer	1.33×10^{-15}

1 darcy ~ 10^{-12} m^2

Table 4: Well-scale permeability values derived from core analyses at the UTF site.

removal, and probably are not representative for the permeability of the 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 and within the same LSD) have measurements of vertical permeability, k_v. Based on 30 k_m-k_v pairs, a vertical anisotropy of 0.79 was calculated for the permeability of 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. For other hydrostratigraphic units, data are generally missing or too few for a meaningful statistical analysis. The regional- or intermediate-scale characteristic values (Petroleum Geology and Basin Analysis Group, 1992a, b) should be considered when estimating the local-scale permeability for these units.

Porosity is the most common rock property analyzed within the local-scale study area. Figure 14 shows the distribution of the 12 wells with porosity determinations within the Moberly Member of the Beaverhill Lake Group. Figure 15 shows the distribution of the 81 wells with porosity measurements in the McMurray Formation. Figures 16, 17, 18 and 19 show the distribution of wells with porosity determinations in the Wabiskaw Member (41 in the erosional channel, 59 in the lower shale wedge, 44 in the injection sand, and 13 in the upper regional marine shale, respectively). In addition, there is one porosity measurement in the Winnipegosis Formation and one in the Pleistocene drift. Since porosity is a scalar property of the rocks (Dagan, 1989), the arithmetic weighted average of the plug measurements was used in the scaling-up process to obtain the well-scale characteristic value (Bachu and Underschultz, 1992). Local-scale characteristic values

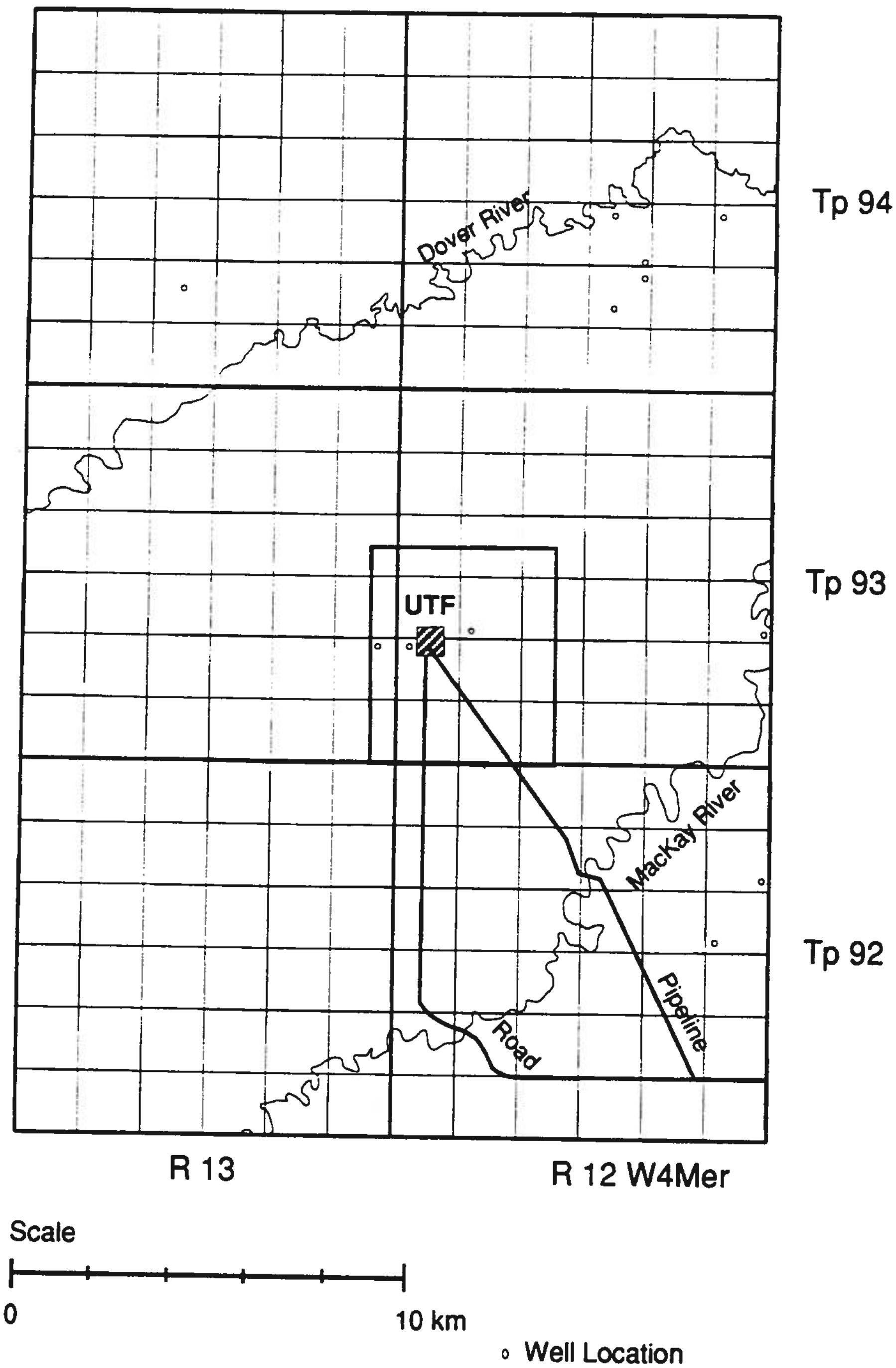

Figure 14. Distribution of wells with porosity data in the Moberly Member of the Beaverhill Lake Group.

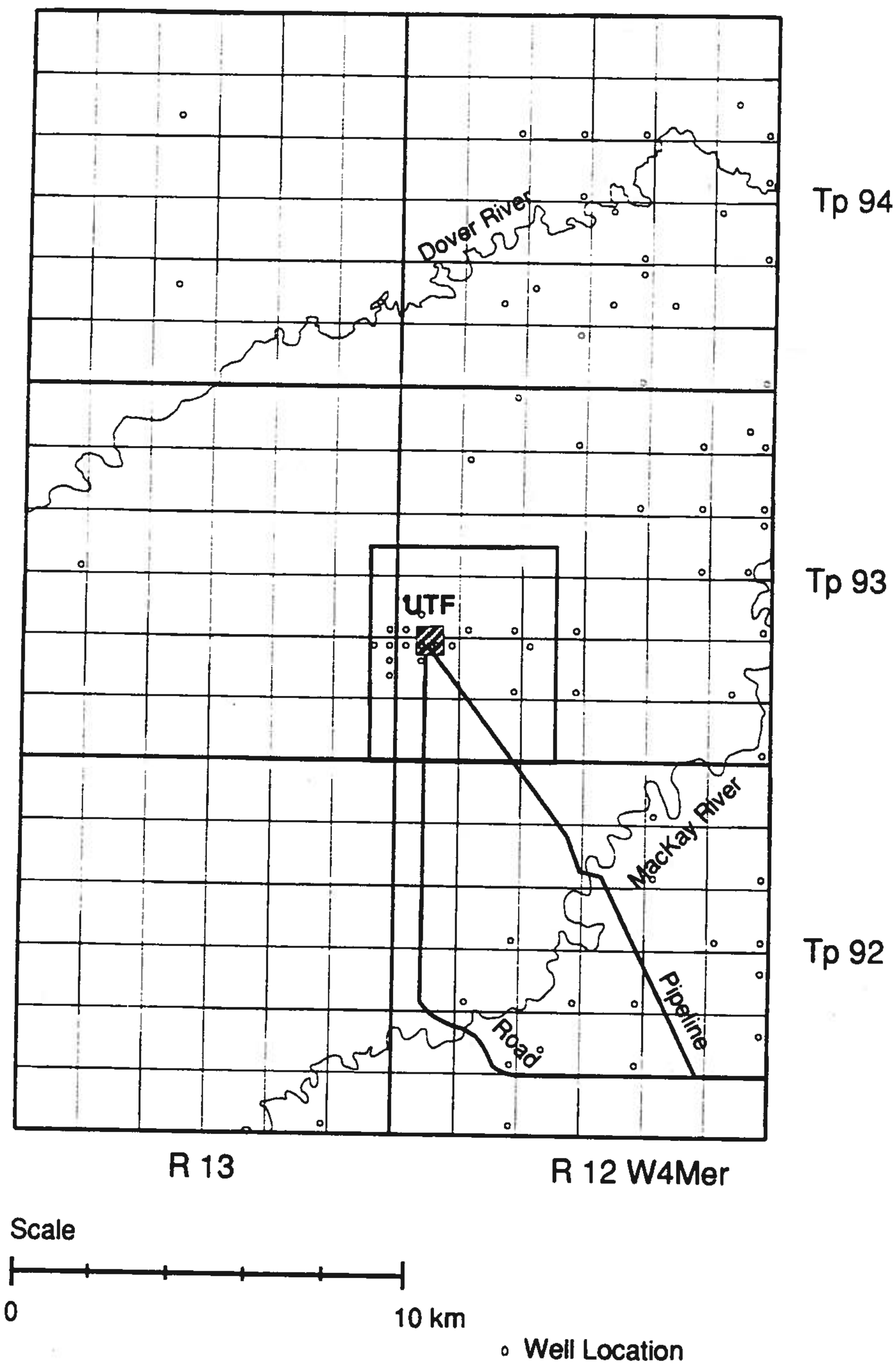

Figure 15. Distribution of wells with porosity data in the McMurray Formation.

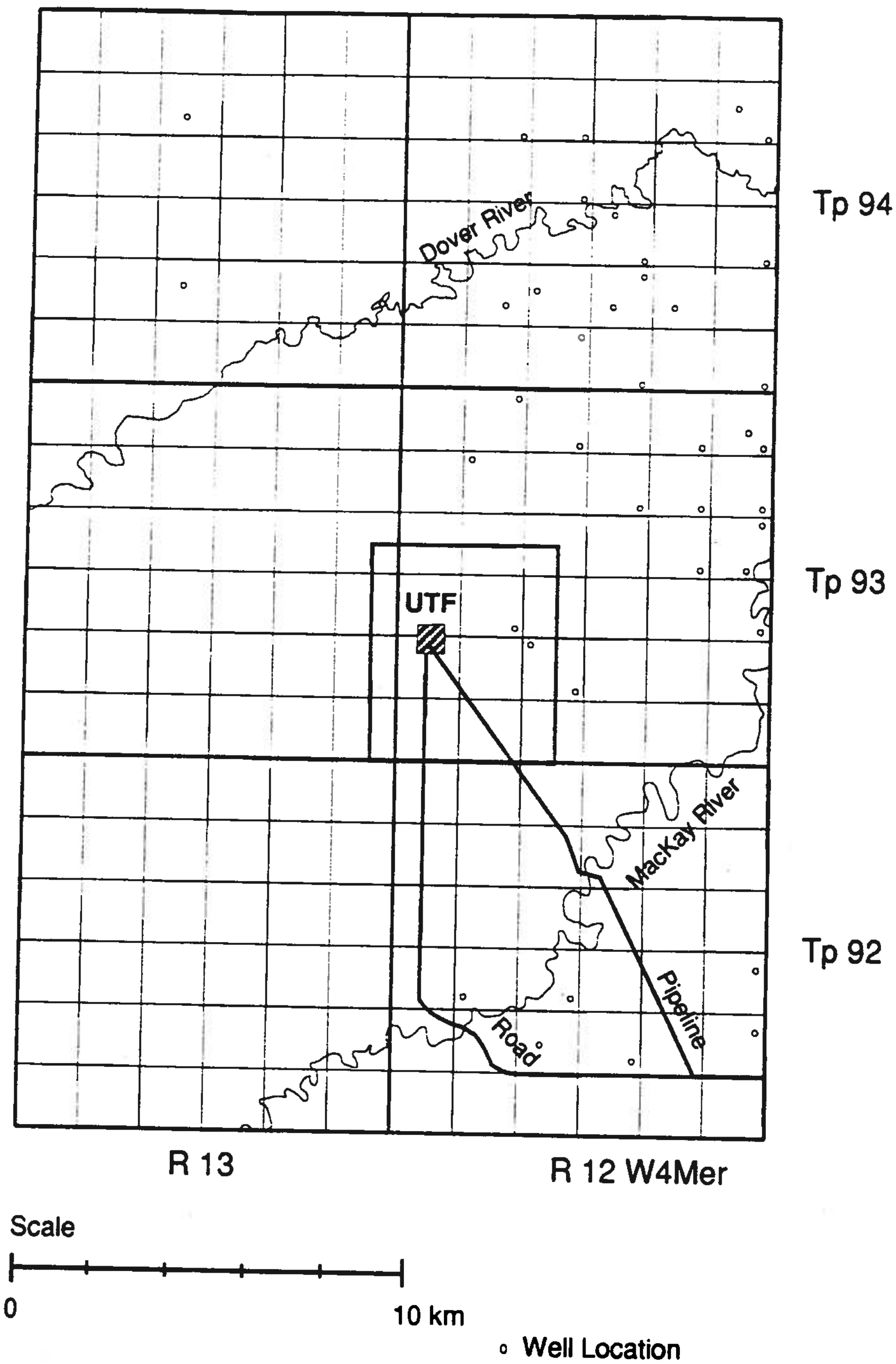

Figure 16. Distribution of wells with porosity data in the basal erosional channel of the Wabiskaw Member.

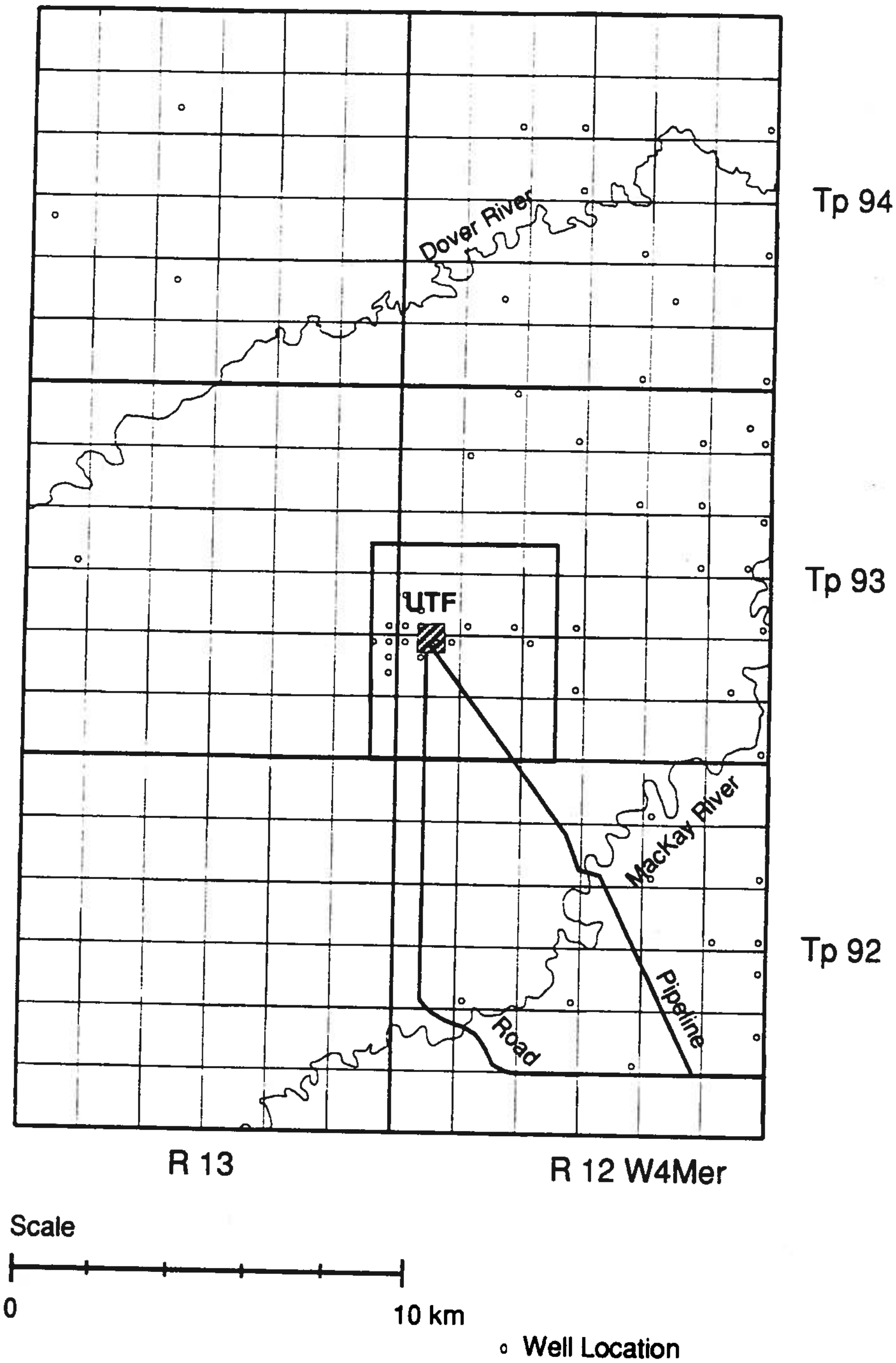

Figure 17. Distribution of wells with porosity data in the lower shale wedge of the Wabiskaw Member.

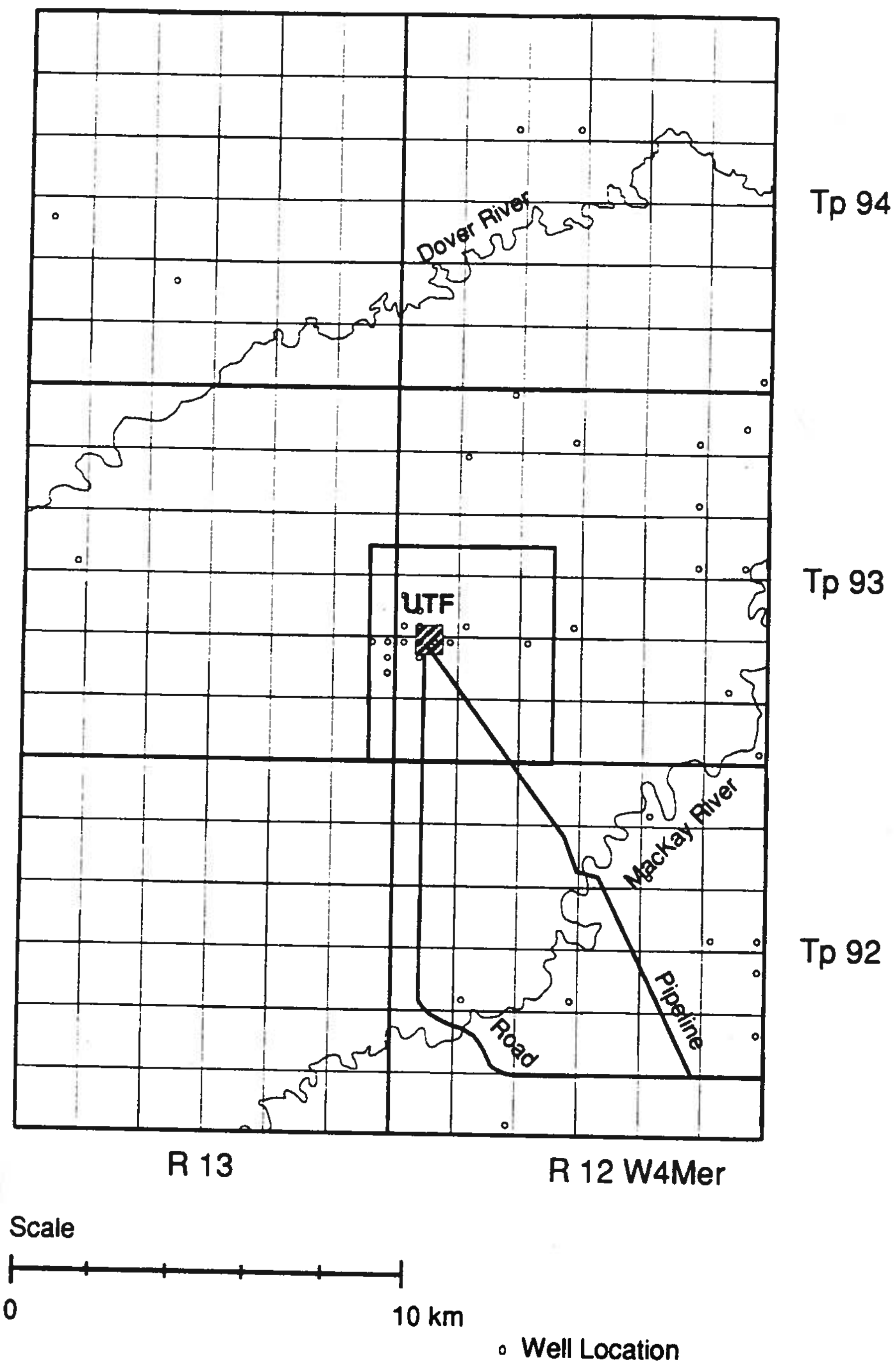

Figure 18. Distribution of wells with porosity data in the upper sand of the Wabiskaw Member.

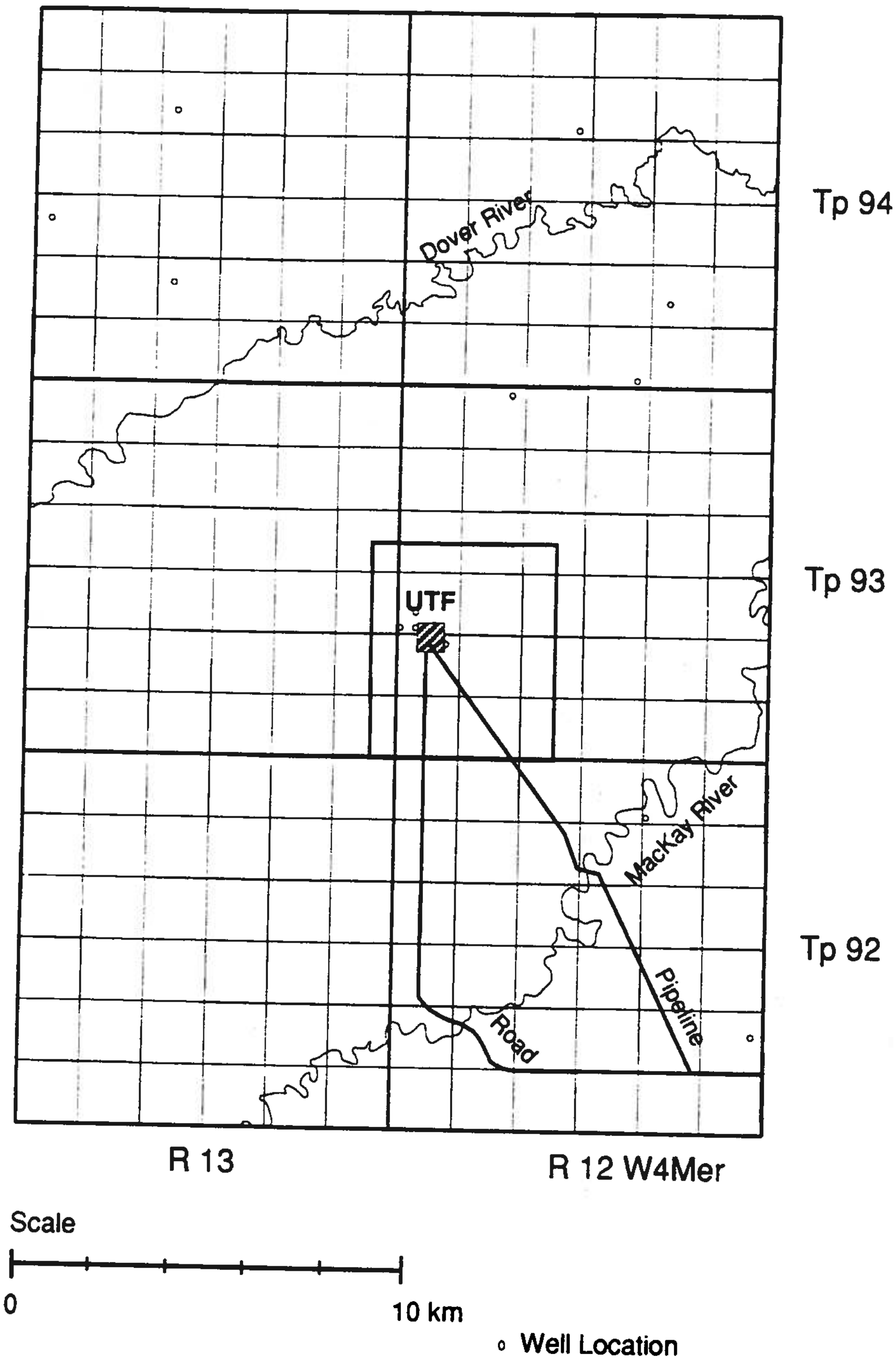

Figure 19. Distribution of wells with porosity data in the upper regional marine shale of the Wabiskaw Member.

of porosity (averaged well-scale values) for these strata are presented in Table 5. The intermediate- or regional-scale characteristic values (Petroleum Geology and Basin Analysis Group, 1992a, b) should be used for strata with no local-scale data.

Hydrostratigraphic Unit	No. of Wells	Porosity			
		Min.	Max.	Average	Standard Deviation
Pleistocene	1	-	-	0.32	-
Wabiskaw Upper Shale	13	0.26	0.36	0.32	0.03
Wabiskaw Upper Sand	44	0.20	0.39	0.31	0.04
Wabiskaw Lower Shale	59	0.12	0.38	0.29	0.04
Wabiskaw Channel	41	0.20	0.38	0.32	0.03
McMurray	81	0.15	0.37	0.31	0.04
Moberly	12	0.23	0.37	0.32	0.05
Winnipegosis	1	-	-	0.05	-

Table 5: Characteristic porosity values derived from core analyses in wells at the UTF site.

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

SPECIFIC STORAGE

In geotechnical and reservoir engineering the symbol c rather than α is used for compressibility, and it will be used in the following. Various tests are conducted in laboratory to measure the compressibility of a porous medium. Different compressibilities are measured, depending on the type of apparatus being used (Chalaturnyk and Scott, 1991). In triaxial tests, the change in the mean effective stress, σ_m', is measured directly, and the isotropic bulk compressibility c_b is calculated. In oedometer (unidirectional) testing, the vertical effective stress σ_v' and the constrained bulk compressibility c_{cb} are being measured and calculated, respectively. The theory of linear eleasticity can be used, however, to calculate σ_m' from σ_v' using the formula:

$$\sigma_m' = \frac{\sigma_v' (1+\nu)}{3(1-\nu)} \tag{4}$$

where ν is Poisson's ratio (usually $\nu = 0.3$). Manipulation of various relations between stress, volume change and compressibility (Chalaturnyk and Scott, 1991) leads to the following relation between the bulk compressibility c_b, pore volume compressibility c_ϕ and solid (or grain) compressibility c_s:

$$c_\phi = c_b (1-\phi) - c_s \tag{5}$$

According to its definition, the compressibility α used in the calculation of the specific storage coefficient is the pore volume compressibility c_ϕ. In triaxial compressibility tests, the bulk compressibility c_b is calculated according to:

$$c_b = \frac{(\Delta V/V_o)}{\Delta\sigma_m'} \tag{6}$$

where ΔV is the change in the initial volume V_o for a change $\Delta\sigma_m'$ in the mean effective stress. In oedometer tests c_b is calculated using the equivalence relation (4) for $\nu = 0.3$, leading to:

$$c_b = 1.615384615 \frac{(\Delta V/V_o)}{\sigma_v'} \tag{7}$$

A high temperature oedometer cell was installed at the University of Alberta to measure one-dimensional compressibility under vertical stresses up to 30 MPa, pore fluid pressures up to 27 MPa and temperatures up to 300°C (Chalaturnyk and Scott, 1991). This oedometer cell was used to measure the compressibility of McMurray shale, McMurray oil sands and Beaverhill Lake Group limestone at the UTF site (Chalaturnyk, 1993). The change in the vertical stress σ_v' during the first unloading cycle was used together with the corresponding change in volume $(\Delta V/V_o)$ to calculate the bulk compressibility c_b and specific storage S_s for these three rock types at the

UTF site. The results are presented in Table 6. Literature values (de Marsily, 1986) were used for water compressibility ($\beta_f = 4.7 \times 10^{-10} Pa^{-1}$) and solid compressibility (Lama and Vutukuri, 1978). Characteristic values from Table 5 were used for porosity ϕ.

Unit	$\Delta V/V_o$ (%)	$\Delta\sigma_v'$ (MPa)	c_b (Pa^{-1})	c_ϕ (Pa^{-1})	S_s (m^{-1})
McMurray Shale	1.00	9	1.80×10^{-9}	14×10^{-10}	1.50×10^{5}
McMurray Oil Sand	0.50	6	1.35×10^{-9}	8.8×10^{-10}	1.00×10^{5}
Beaverhill Lake Limestone	0.25	7	0.58×10^{-9}	5.4×10^{-10}	0.55×10^{5}

Table 6: Calculated values of compressibility c and specific storage S_s for selected rock units at the UTF site.

SUMMARY AND CONCLUSIONS

Although the local-scale study area around the UTF site does not contain enough pressure or formation-water chemistry data to refine further the hydrogeological characterization presented in previous studies (Petroleum Geology and Basin Analysis Group, 1992a, b), there is sufficient information available to refine the hydrostratigraphy of Cretaceous but not of Paleozoic strata in the immediate vicinity of the UTF. A detailed geophysical log analysis was used to determine the lithology and bitumen content of Cretaceous strata. This information, together with the refined stratigraphy, provided a means for subdividing the hydrostratigraphy of the Cretaceous strata and to associate hydraulic parameters and rock properties with each subdivision.

The McMurray Formation sand is almost completely saturated with more than 3 mass-percent bitumen, with the exception of thin isolated basal water sands which are in contact with the underlying Moberly limestone aquifer of the Paleozoic Beaverhill Lake Group. Because of the high bitumen content, the McMurray Formation generally has aquitard characteristics. Overlying the bitumen deposits of the McMurray Formation, the Wabiskaw Member of the Clearwater Formation was divided into four stratigraphic units: a basal erosional channel, a lower shale wedge, an upper sand, and an upper regional marine shale. The strata below the upper sand are either shaley or they have bitumen saturations of greater than 3 mass-percent. As a result, there is a continuous aquitard between the basal McMurray water sands and the base of the Wabiskaw upper sand. The upper sand is free of bitumen and represents an aquifer. Above the upper sand aquifer, the regional marine shale and the remainder of the Clearwater Formation shales form an aquitard. Above the Clearwater Formation shale aquitard, the Grand Rapids Formation and Pleistocene strata form an unconfined aquifer, whose erosional base cuts in places into the Clearwater Formation.

Mineralogical analyses of the Paleozoic Winnipegosis Formation, Calumet Member of the Paleozoic Beaverhill Lake Group and Wabiskaw Member of the Cretaceous Clearwater Formation provided a detailed breakdown of rock mineralogy, which will be used for simulating potential geochemical reactions between the injected residual water and the formation water and rocks. Dolomite is the dominant mineral in the Winnipegosis Formation strata, with a minor amount of clay minerals and a trace of halite. The dominant mineral in the Calumet Member of the Beaverhill Lake Group strata is calcite, with less than 10% quartz and only a small amount of halite and clay minerals. The Wabiskaw Member sands are comprised dominantly of quartz, with minor amounts of feldspar in the sandy portions and minor amounts of carbonate and clay minerals in the shaley portions of the unit.

Although core has been taken from many wells within the local-scale study area, few permeability measurements were performed. More data exist for porosity, at least within Cretaceous strata. Permeability and porosity characteristic values for the units with data were obtained through a scaling-up procedure. The regional or intermediate-scale characteristic values obtained previously (Petroleum Geology and Basin Analysis Group, 1992a, b) should be used for units with no data. Compressibility and specific storage values were calculated for the Beaverhill Lake Group limestone and McMurray Formation oil sands and shales.

The previous hydrogeological studies at the regional and intermediate scales (Petroleum Geology and Basin analysis Group, 1992a, b), together with the local-scale mineralogical analysis, detailed examination of Cretaceous hydrostratigraphy, and characterization of hydraulic parameters, provide needed information for geochemical and fluid flow modelling of injection of residual water at the UTF site.

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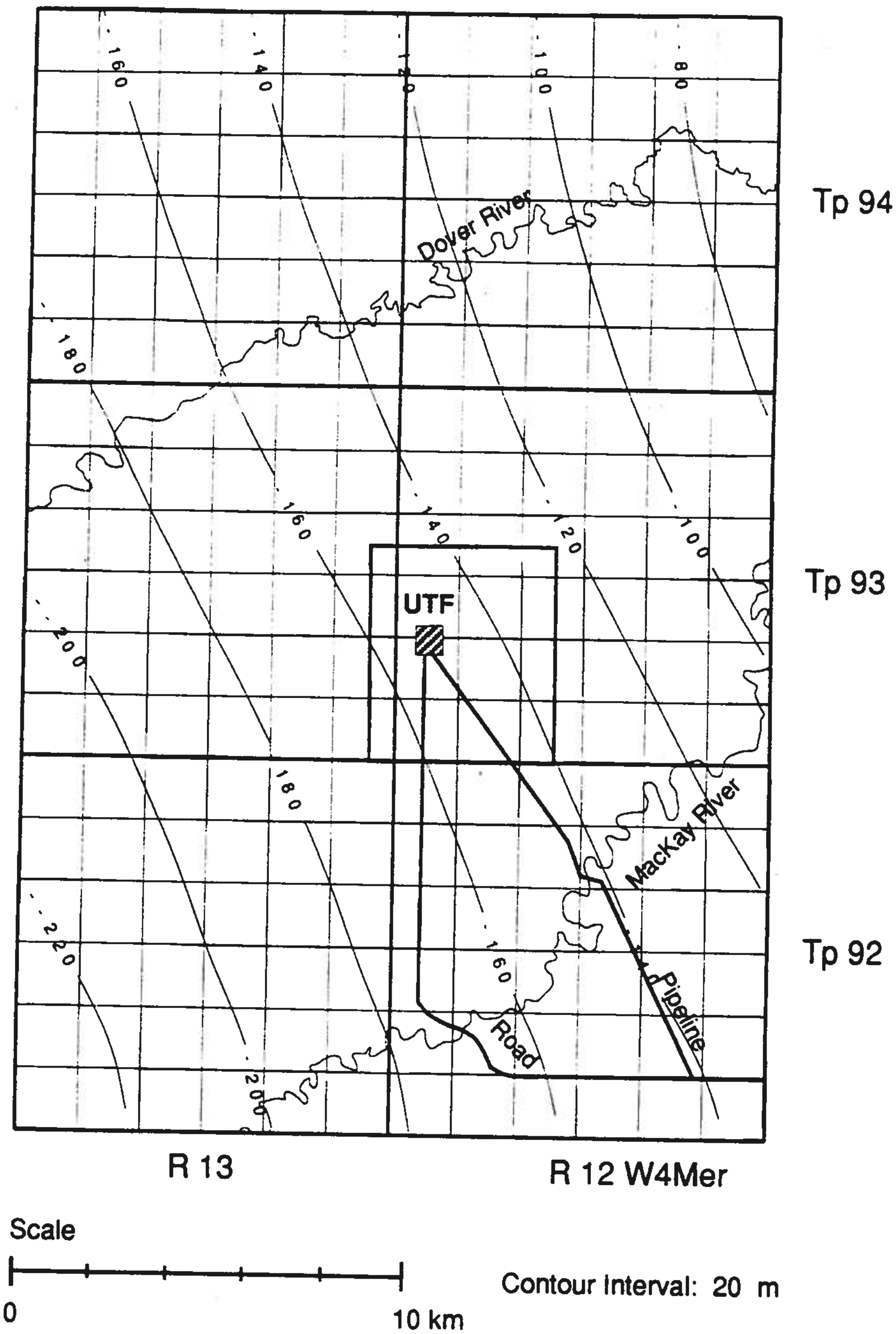
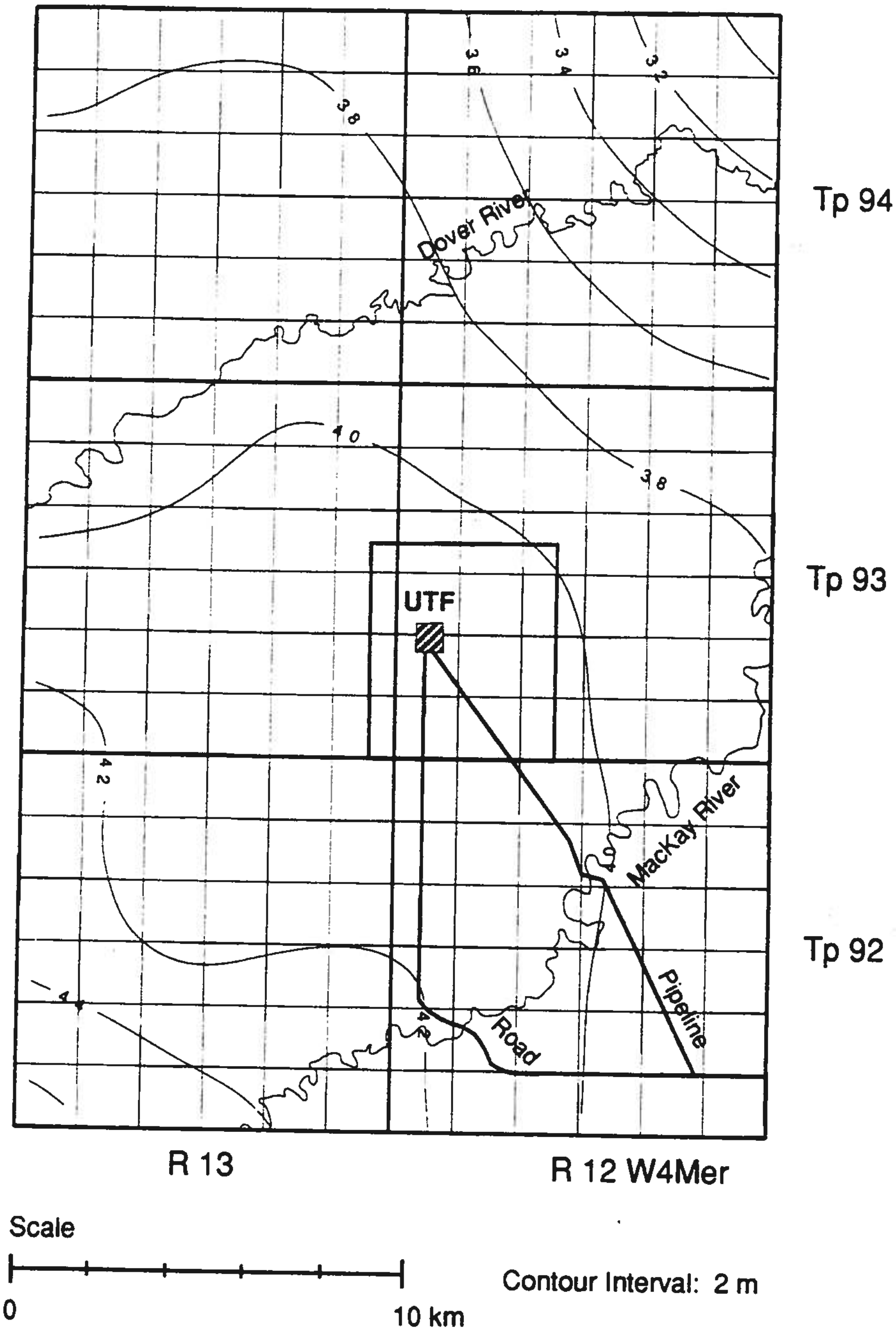
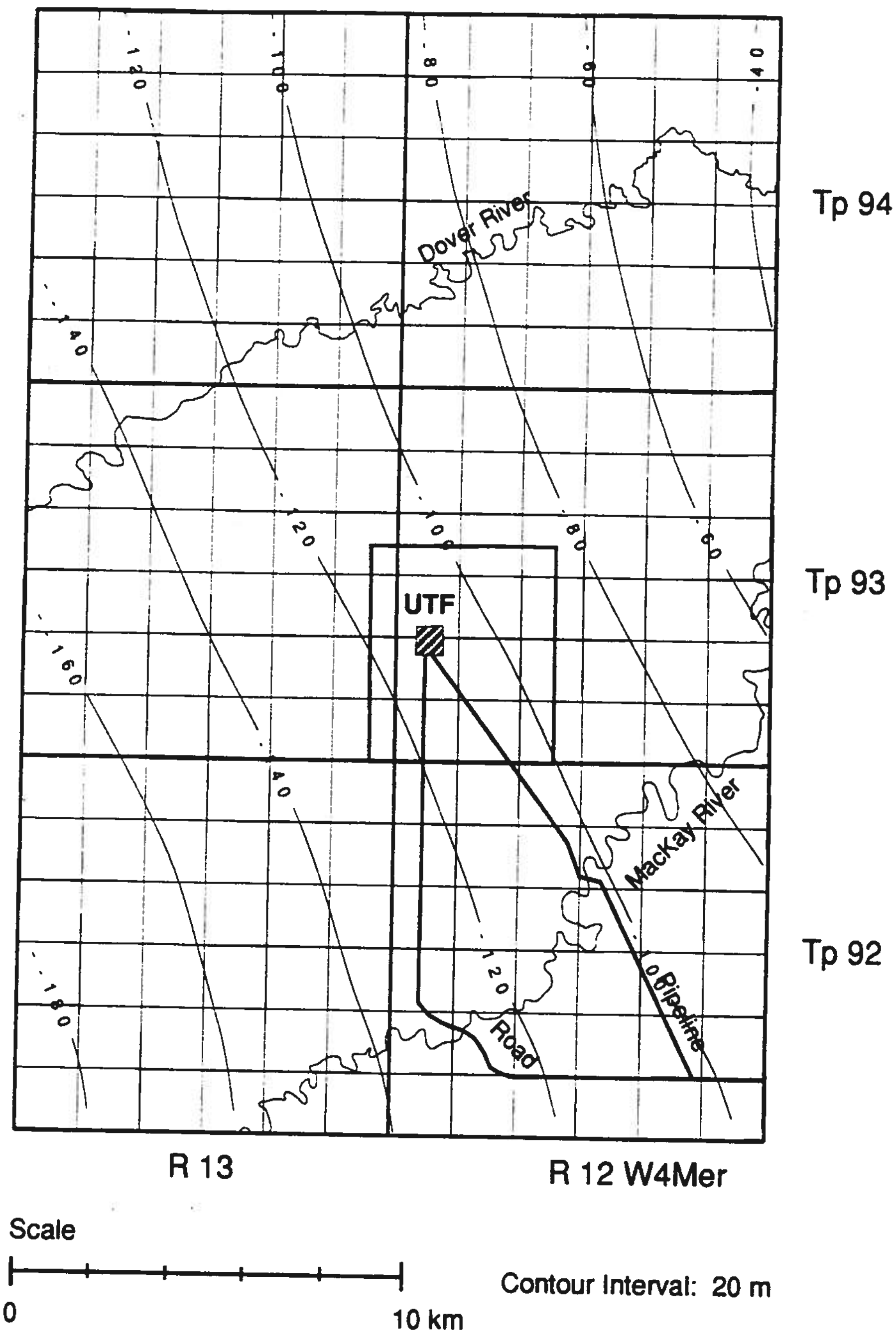
APPENDIX A - STRUCTURE AND ISOPACH MAPS OF PALEOZOIC STRATA



A- 1. Precambrian structure map.



A- 2. Contact Rapids Formation isopach map.



A- 3. Contact Rapids Formation structure map.

James, D.P., and Oliver, T.A., (1978): The sedimentology of the McMurray Formation, East Athabasca; in Redford, D.A., and Winestock, A.G., (eds): The Oilsands of Canada - Venezuela, Special Volume 17; Canadian Institute of Mining and Metallurgy, pp. 17-26.

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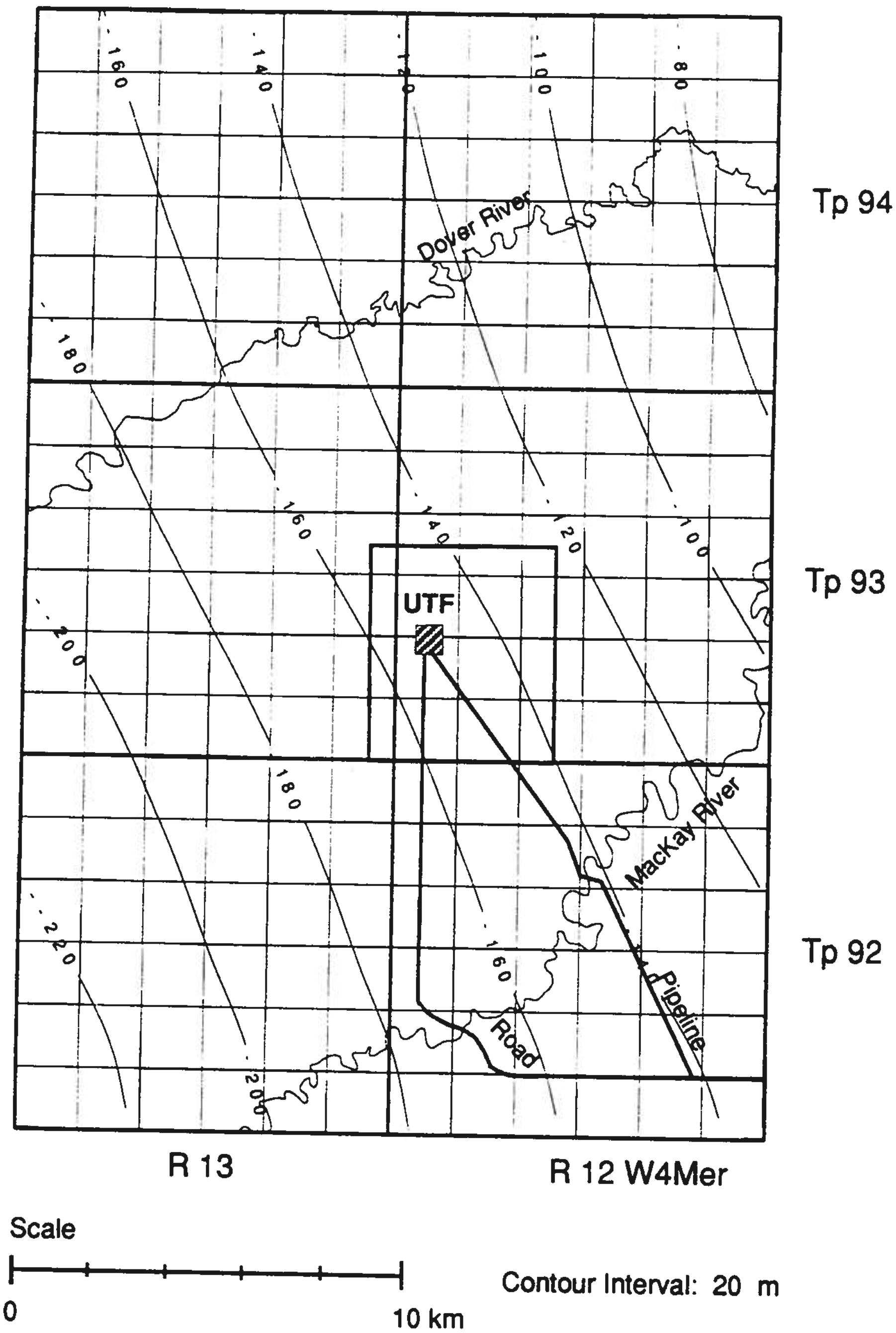
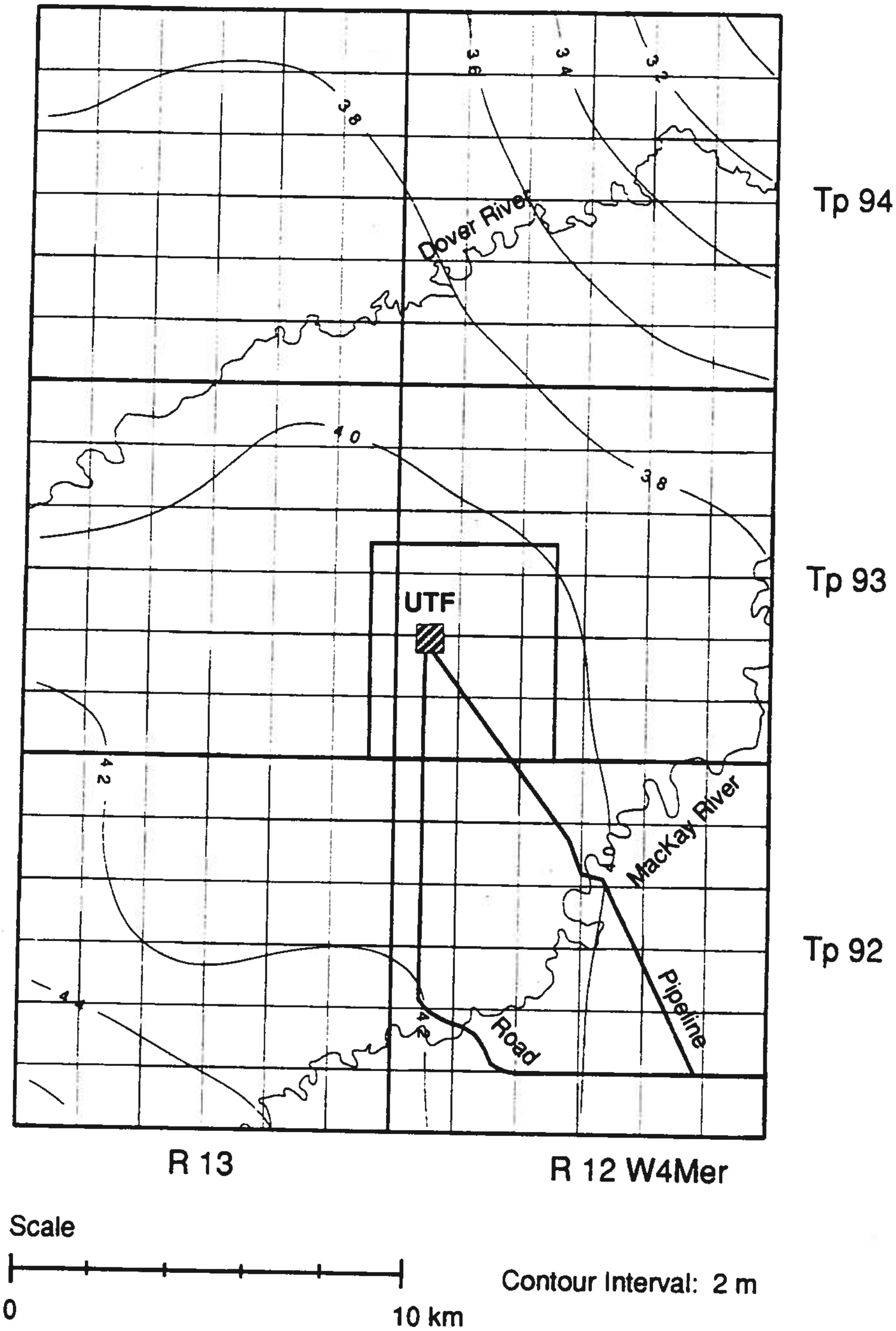
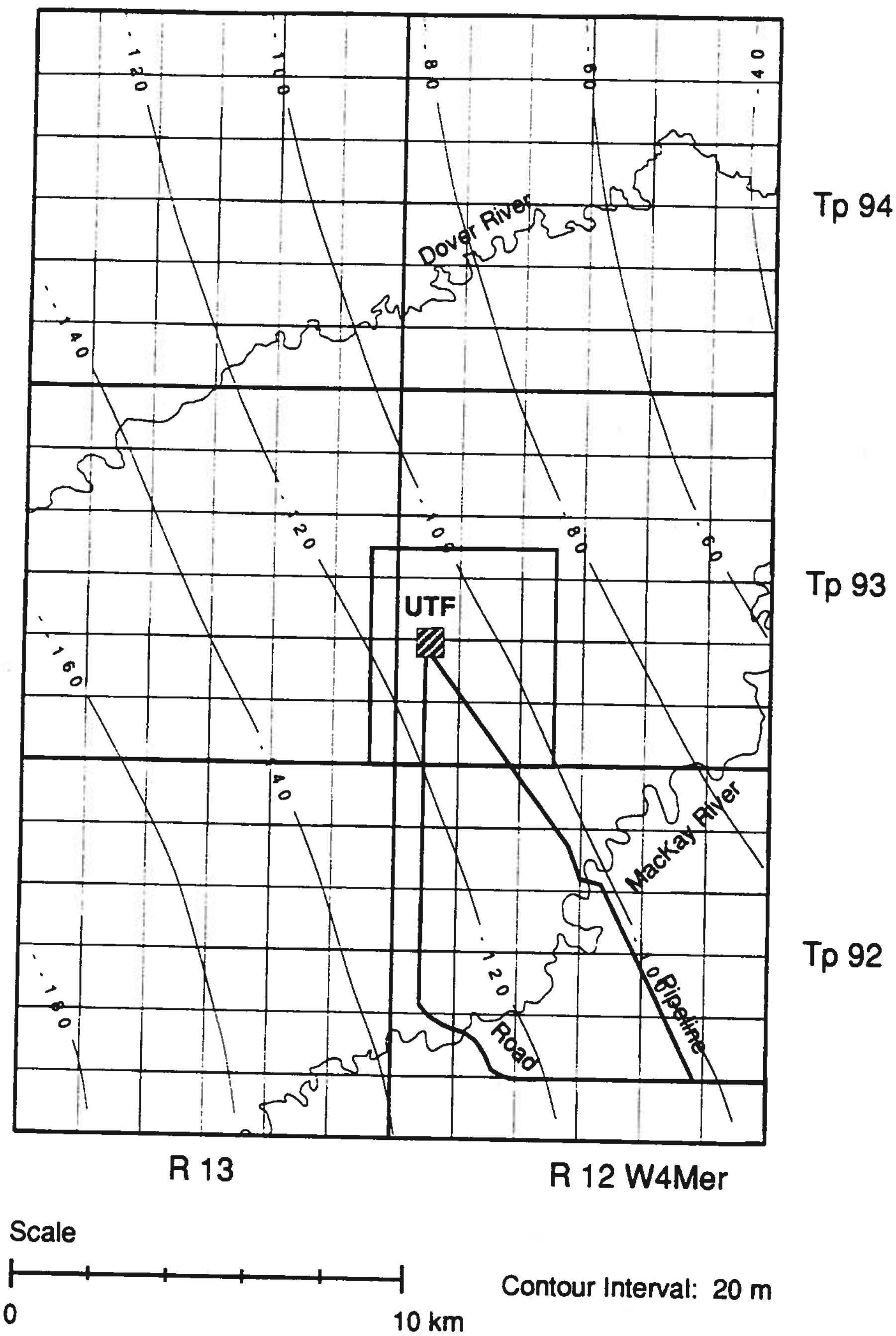
APPENDIX A - STRUCTURE AND ISOPACH MAPS OF PALEOZOIC STRATA



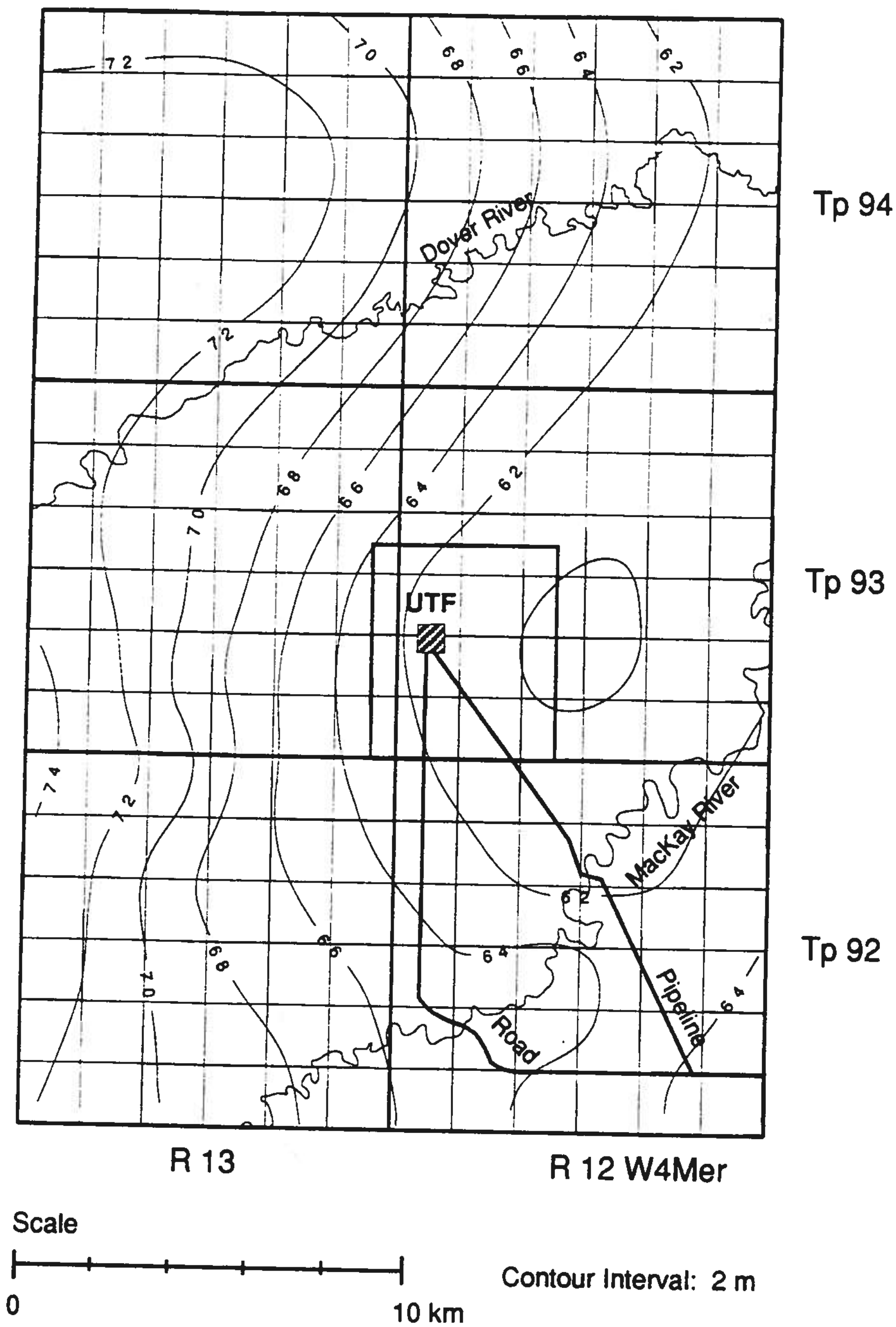
A- 1. Precambrian structure map.



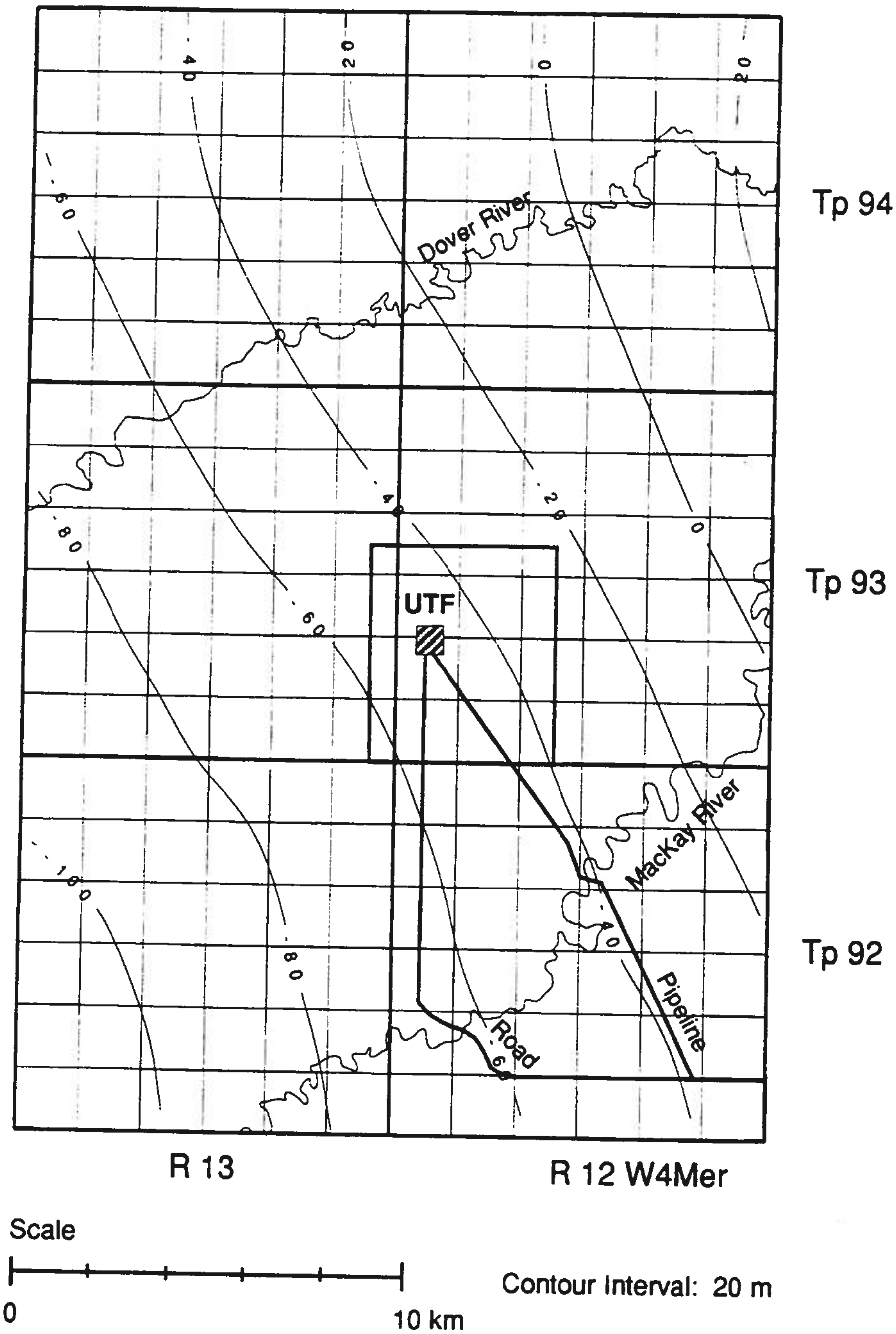
A- 2. Contact Rapids Formation isopach map.



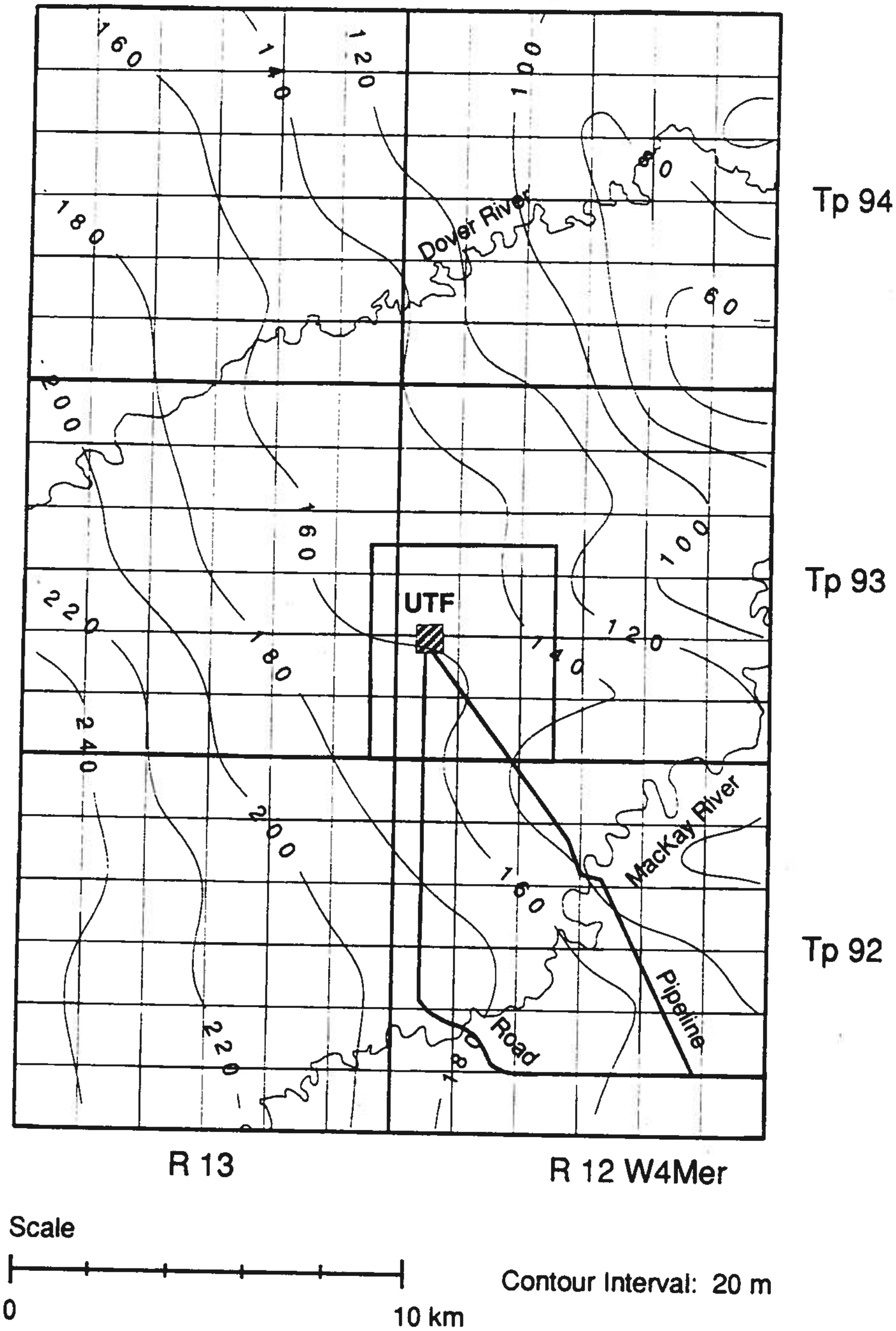
A- 3. Contact Rapids Formation structure map.



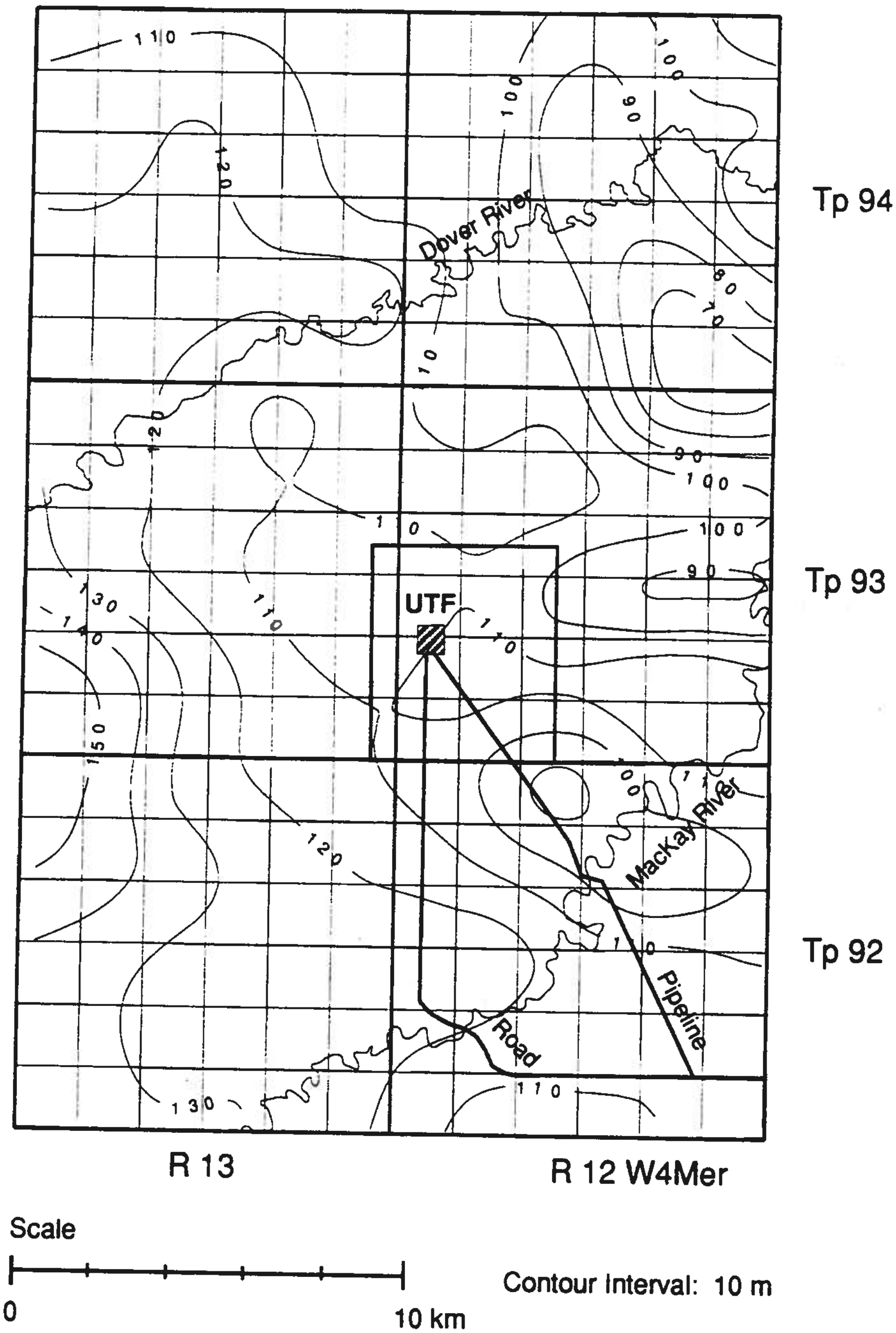
A- 4. Winnipegosis Formation isopach map.



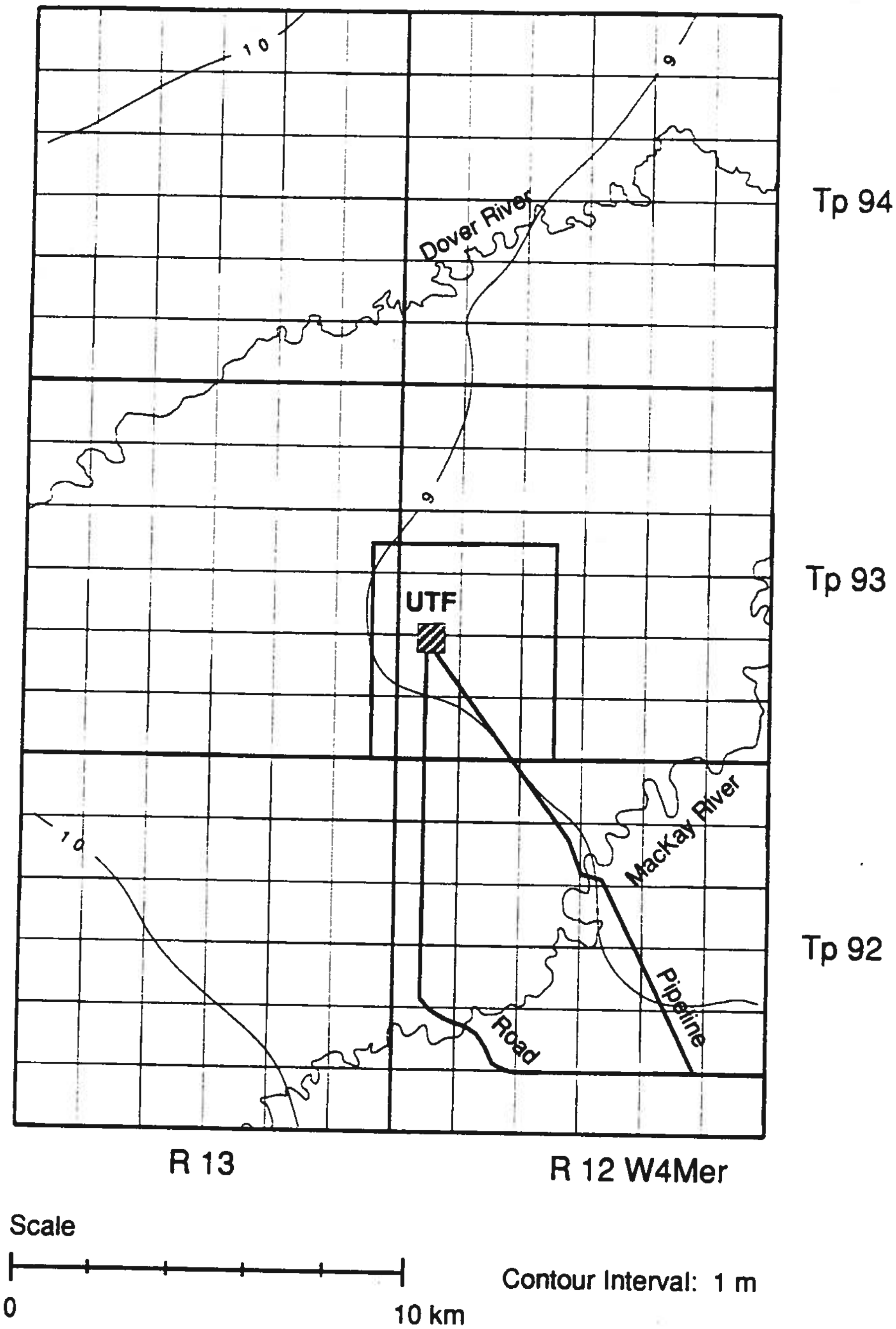
A- 5. Winnipegosis Formation structure map.



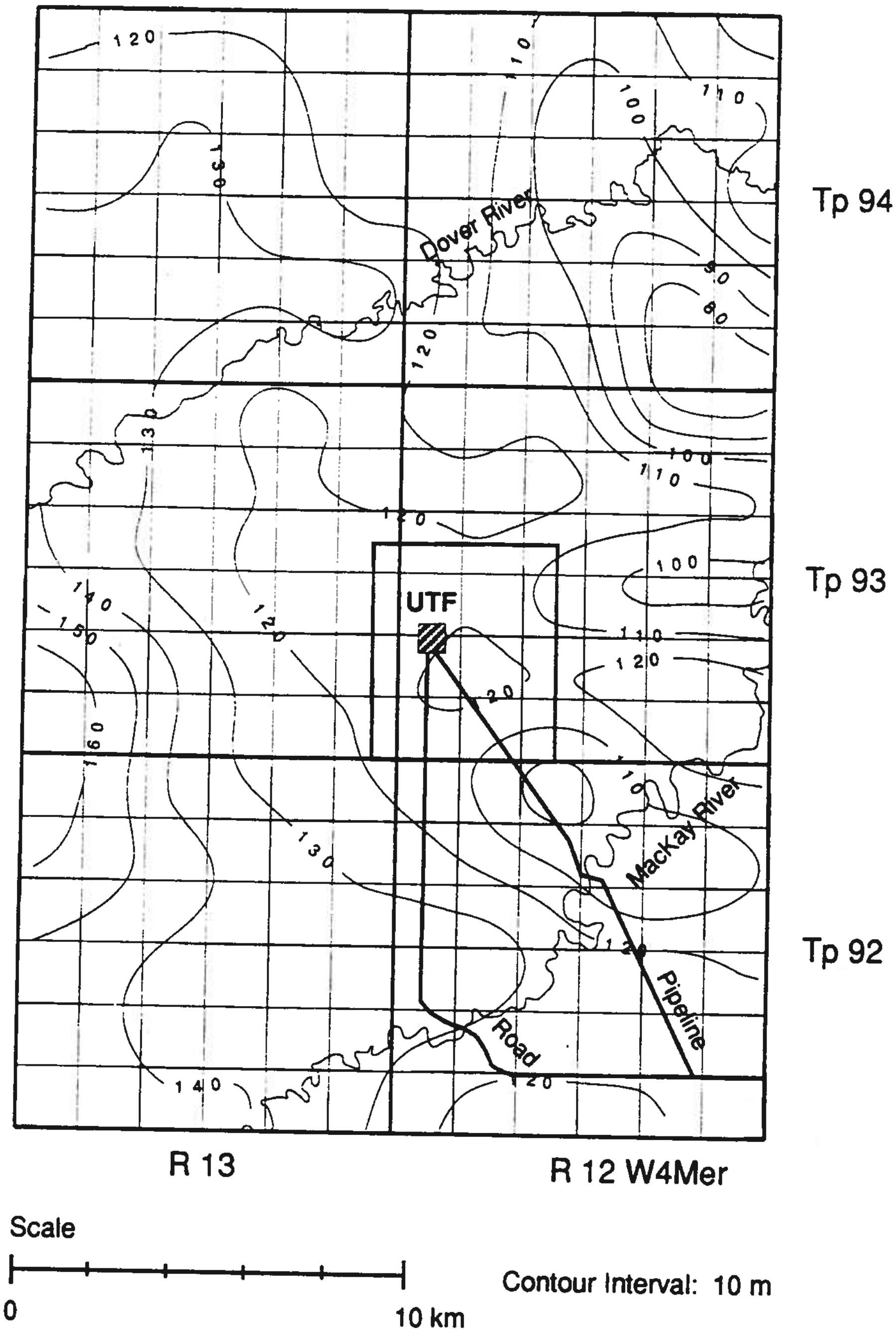
A- 6. Prairie Formation isopach map.



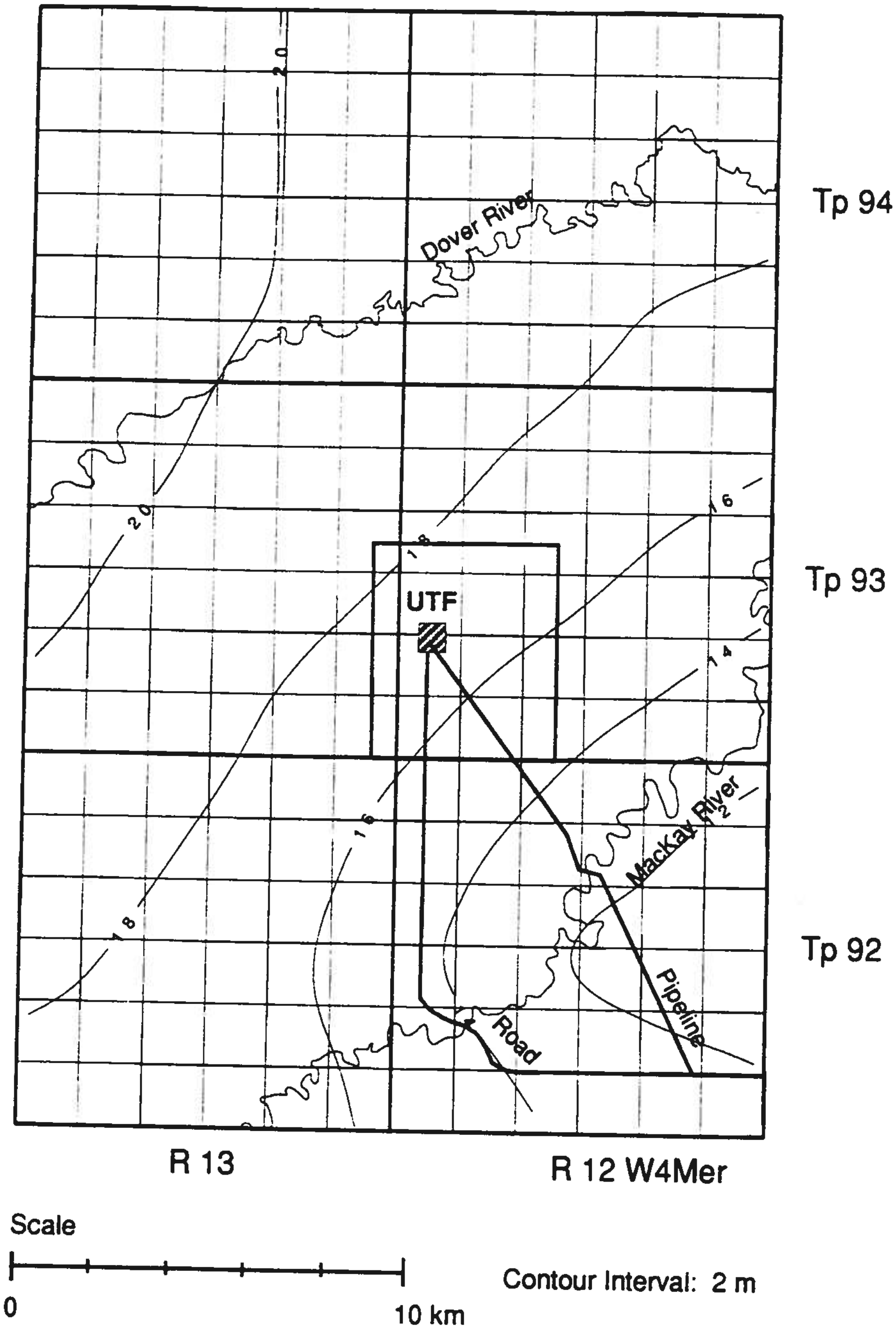
A- 7. Prairie Formation structure map.



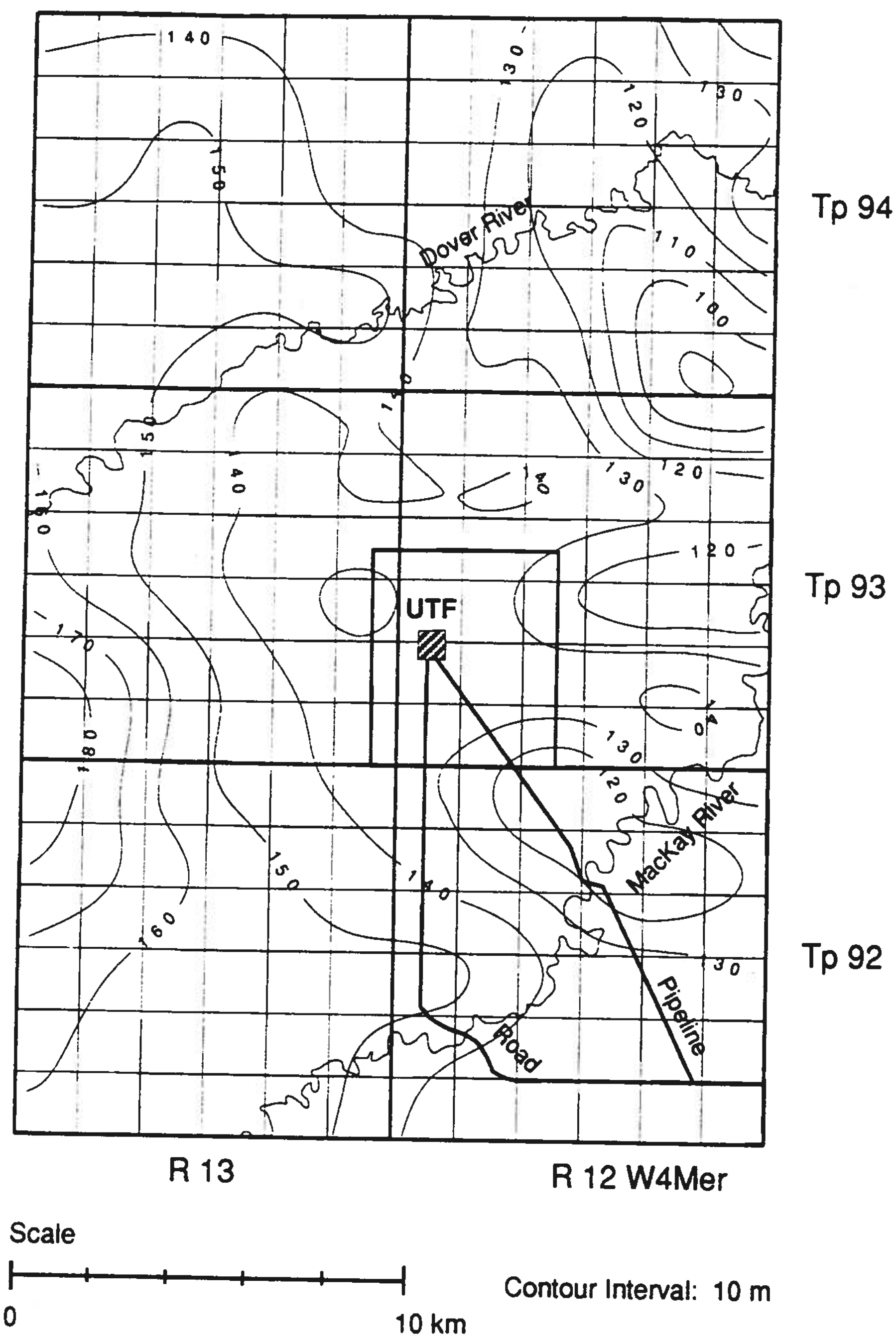
A- 8. Watt Mountain Formation isopach map.



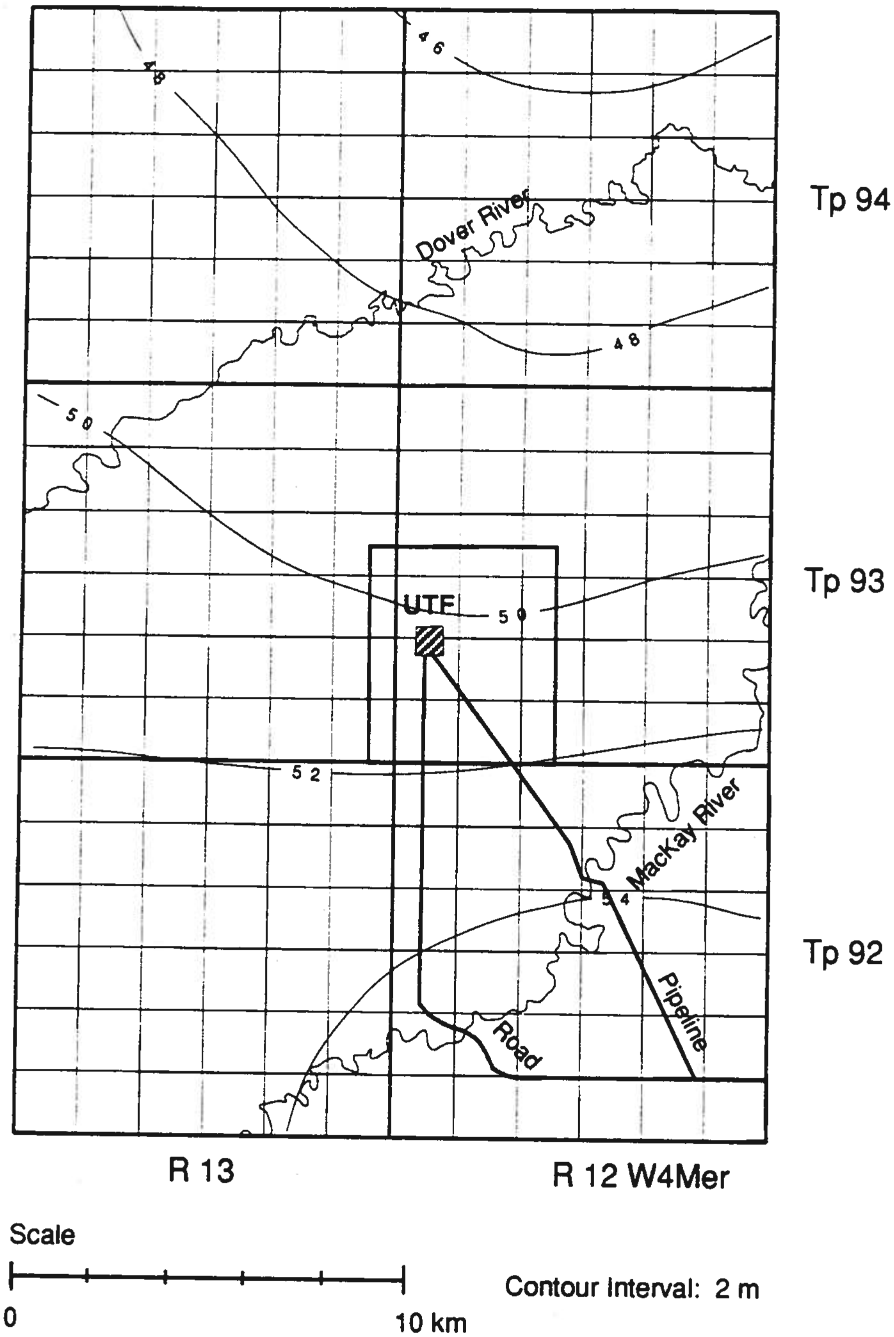
A- 9. Watt Mountain Formation structure map.



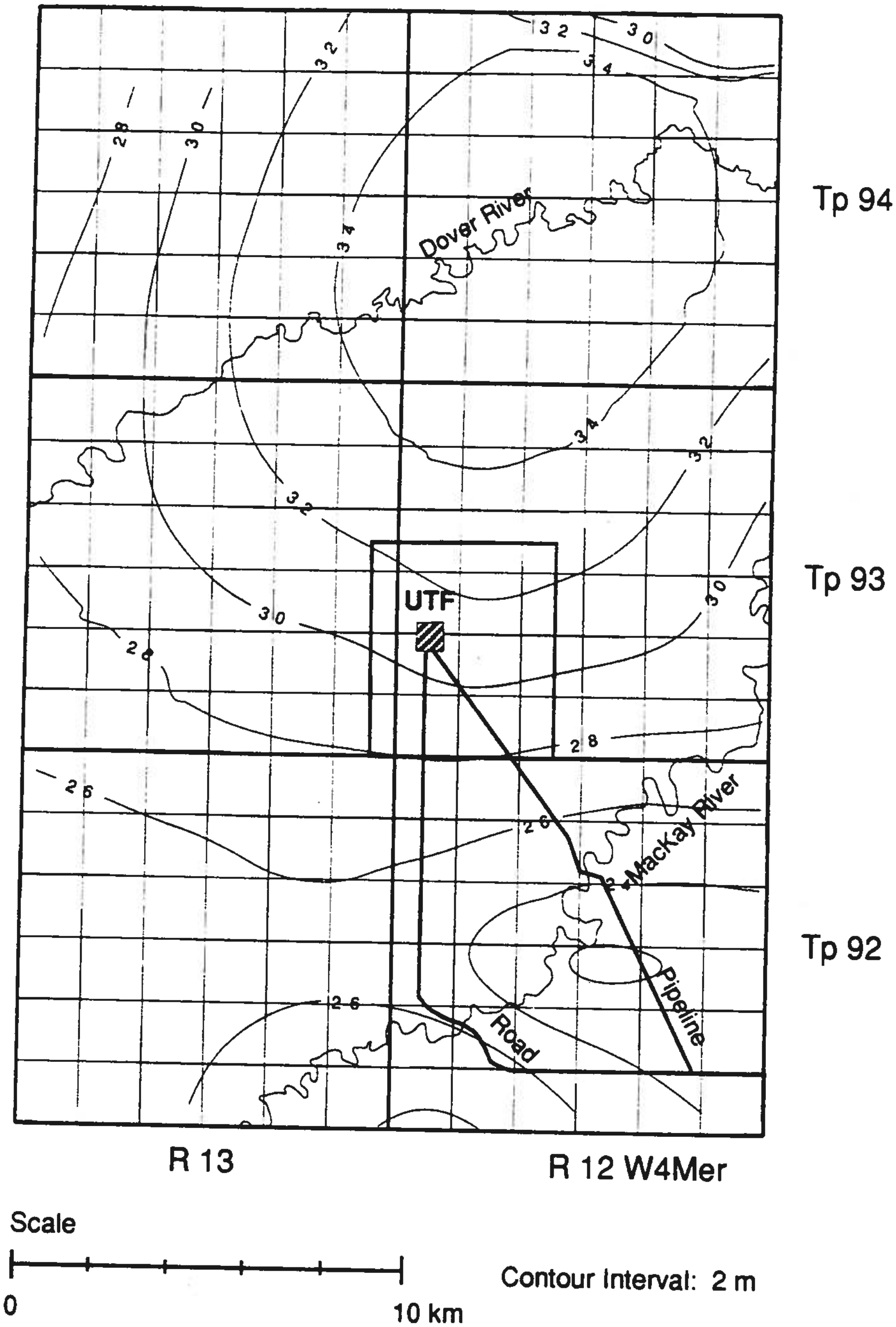
A-10. Slave Point Formation isopach map.



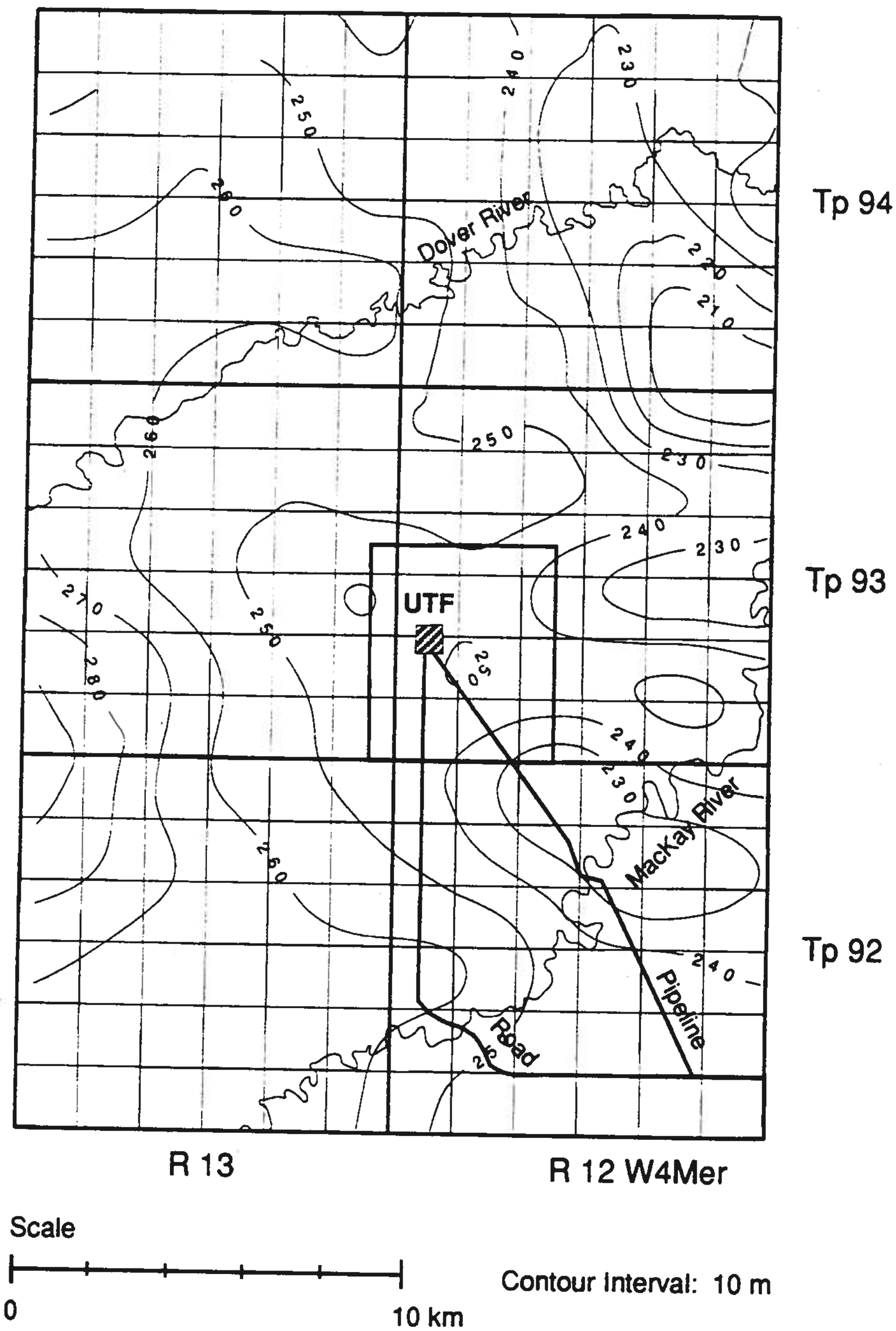
A-11. Slave Point Formation structure map.



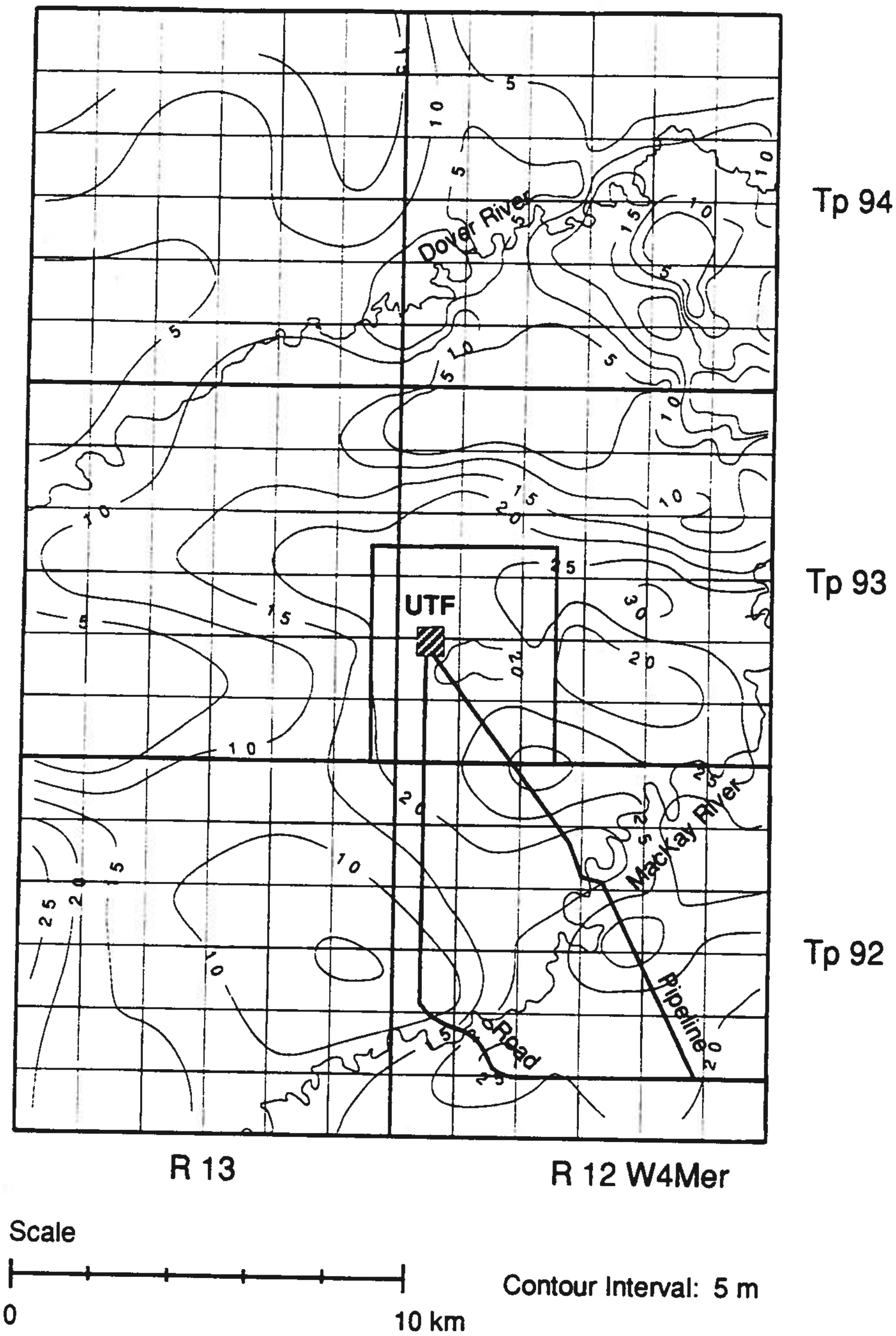
A-12. Firebag Member isopach map.



A-16. Christina Member isopach map.

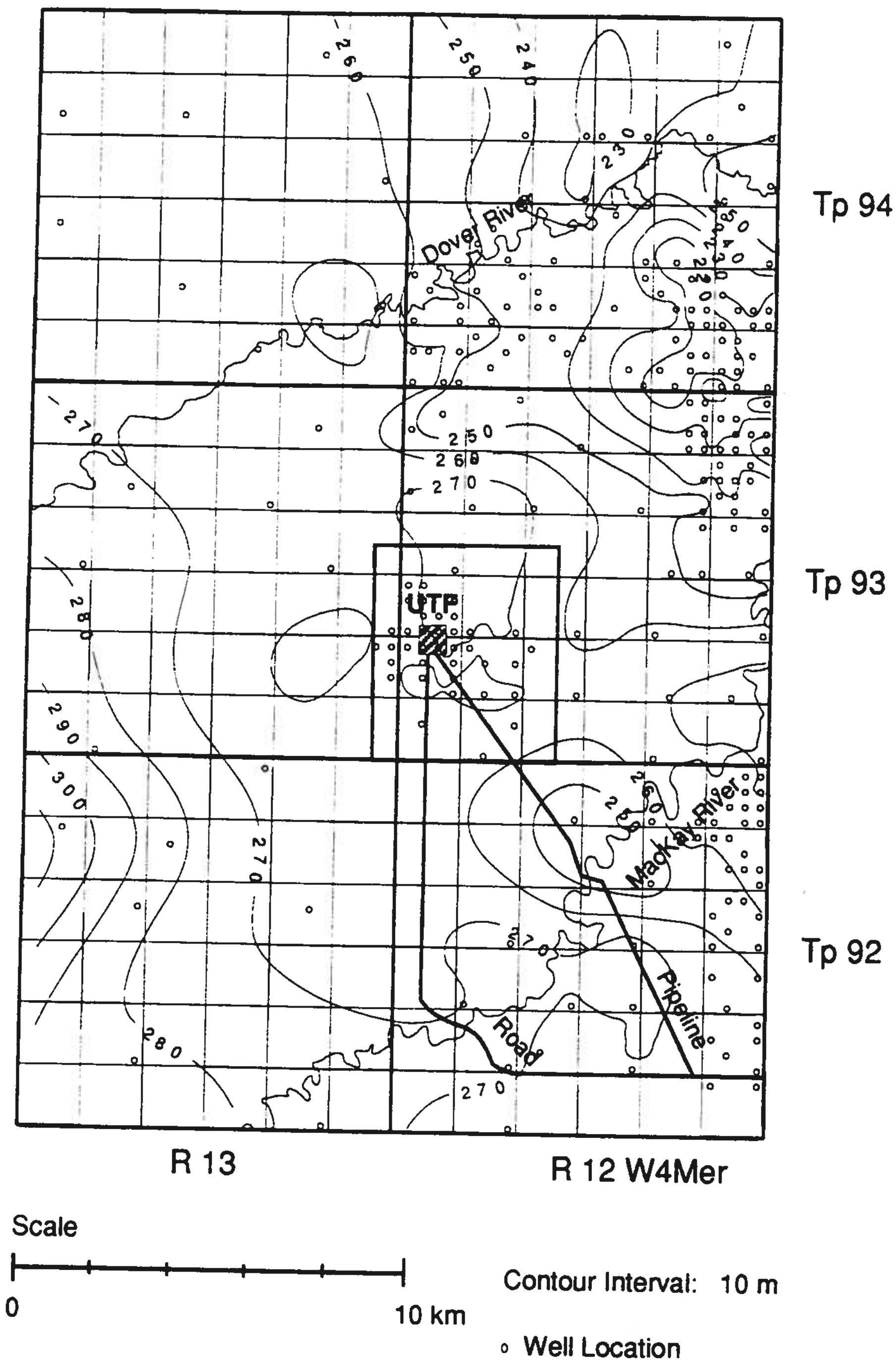


A-17. Christina Member structure map.

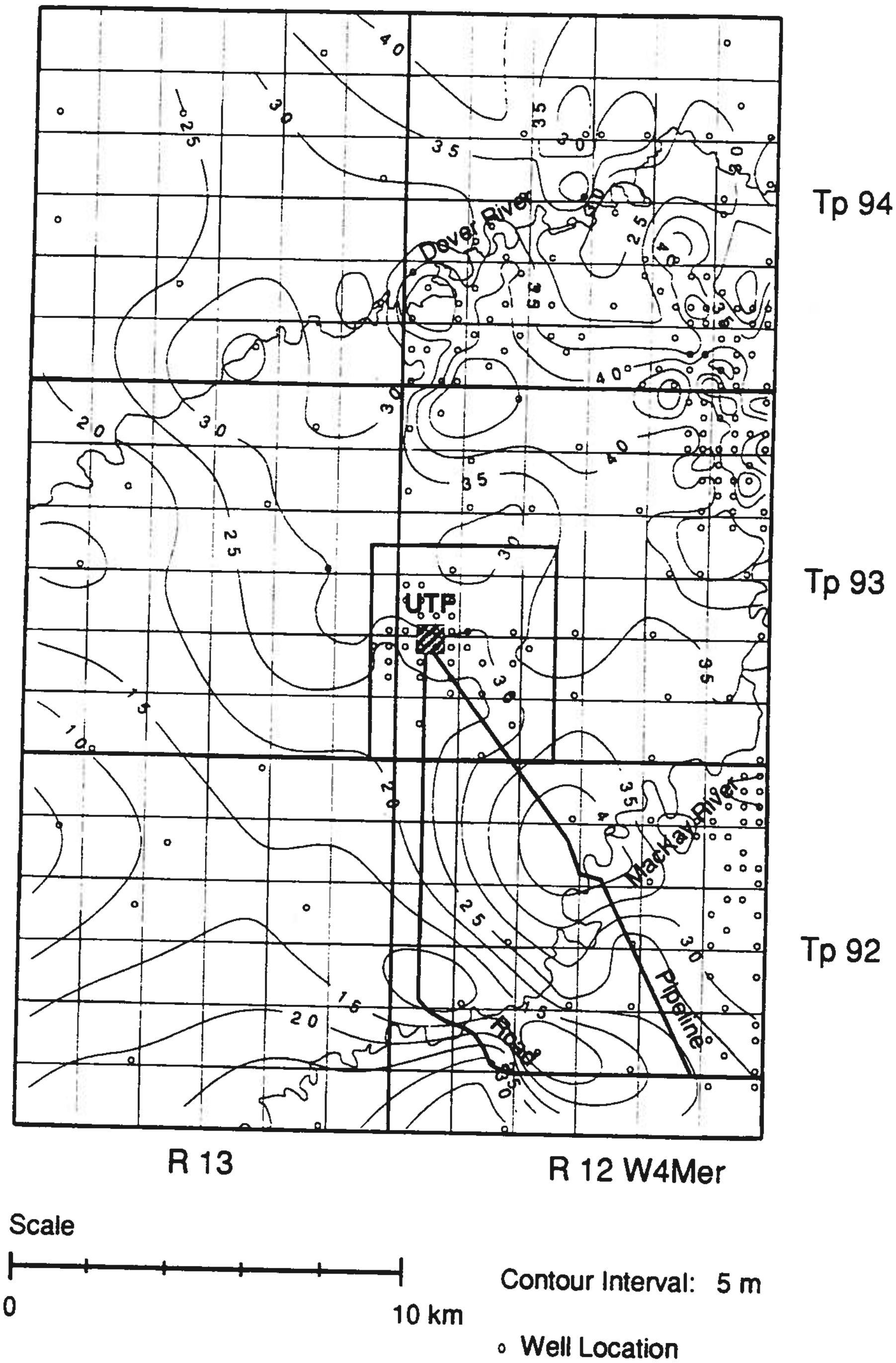


A-18. Moberly Member isopach map.

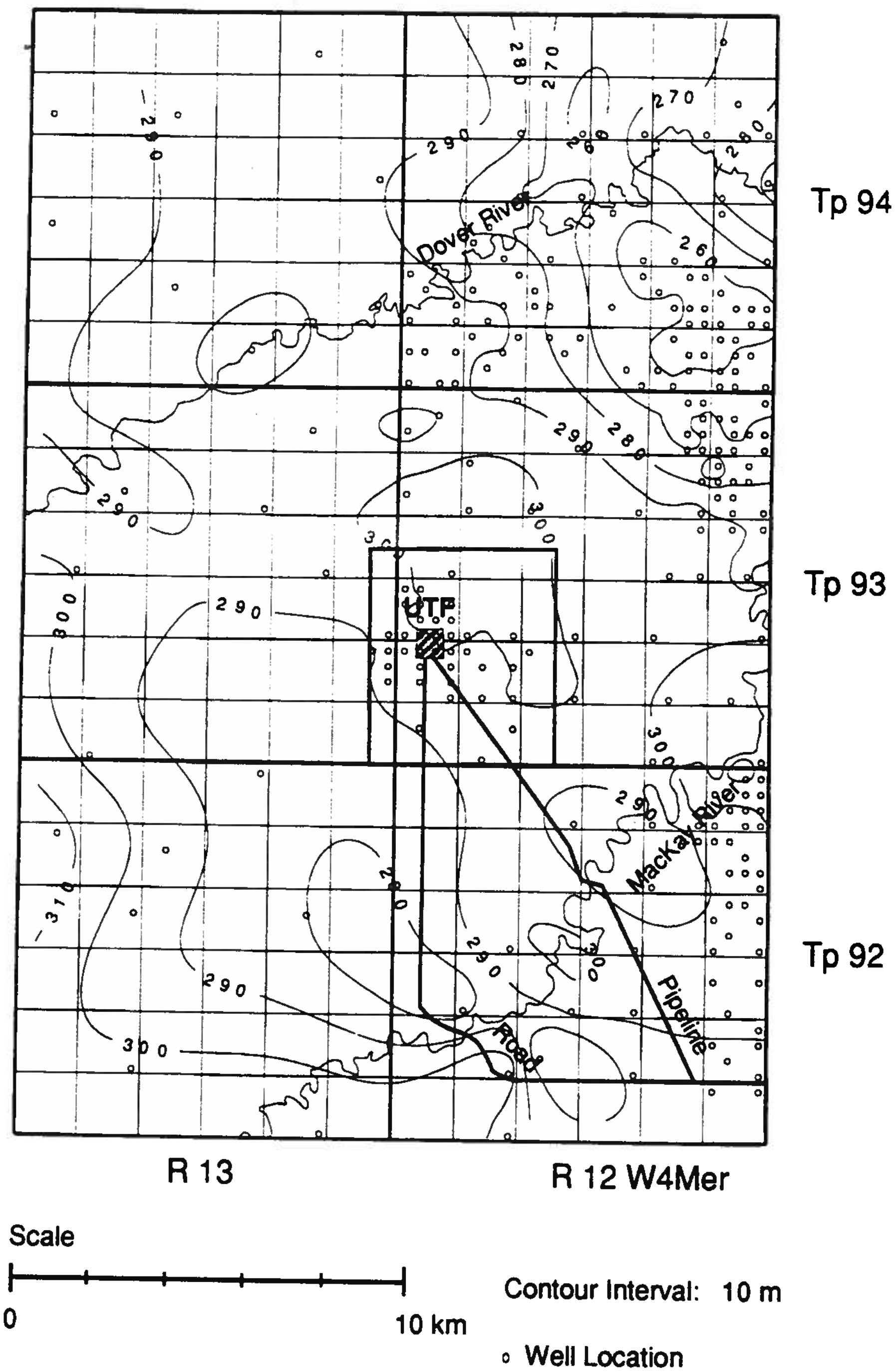
APPENDIX B - STRUCTURE AND ISOPACH MAPS OF CRETACEOUS STRATA



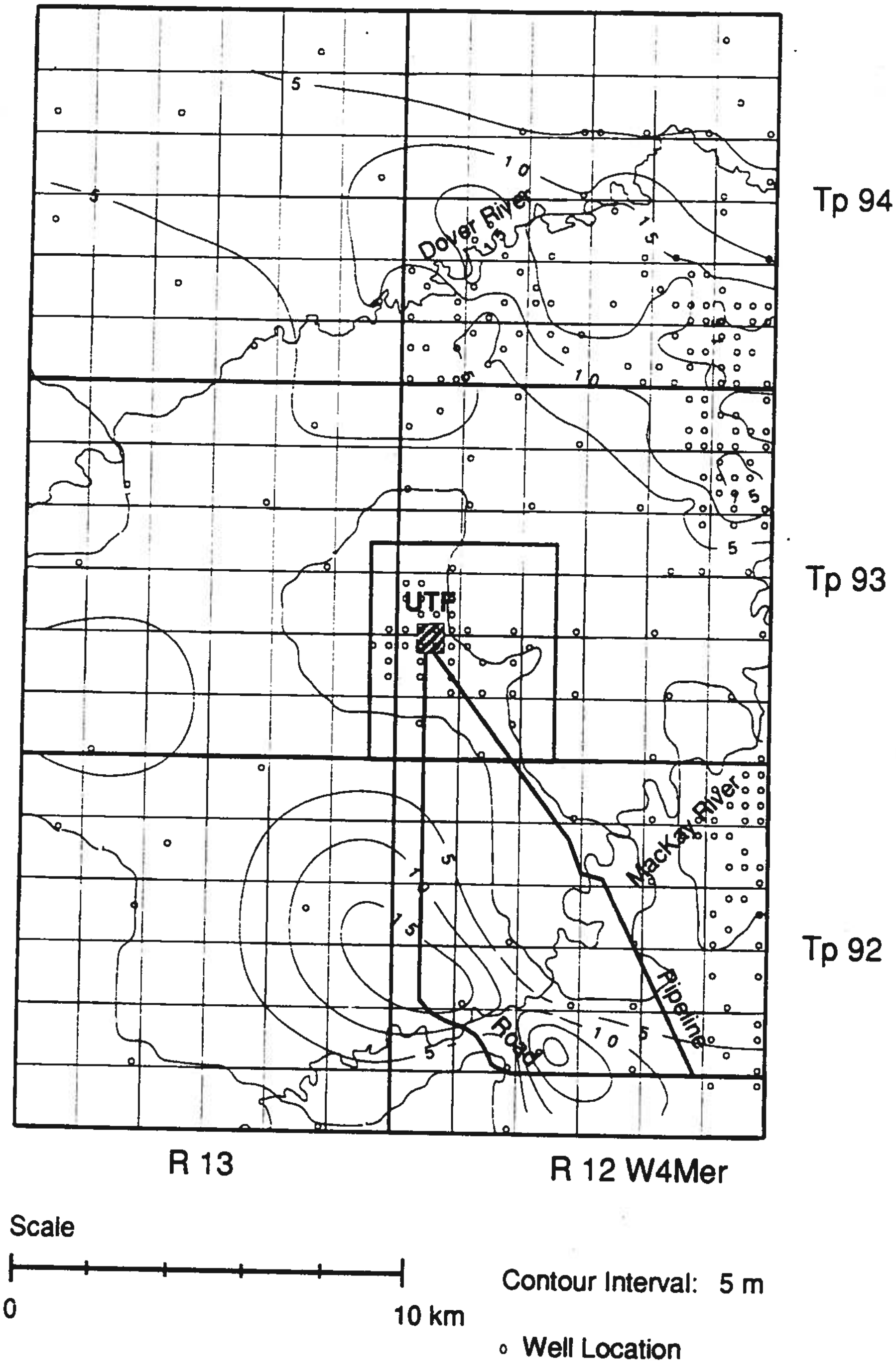
B- 1. Sub-Cretaceous unconformity structure map.



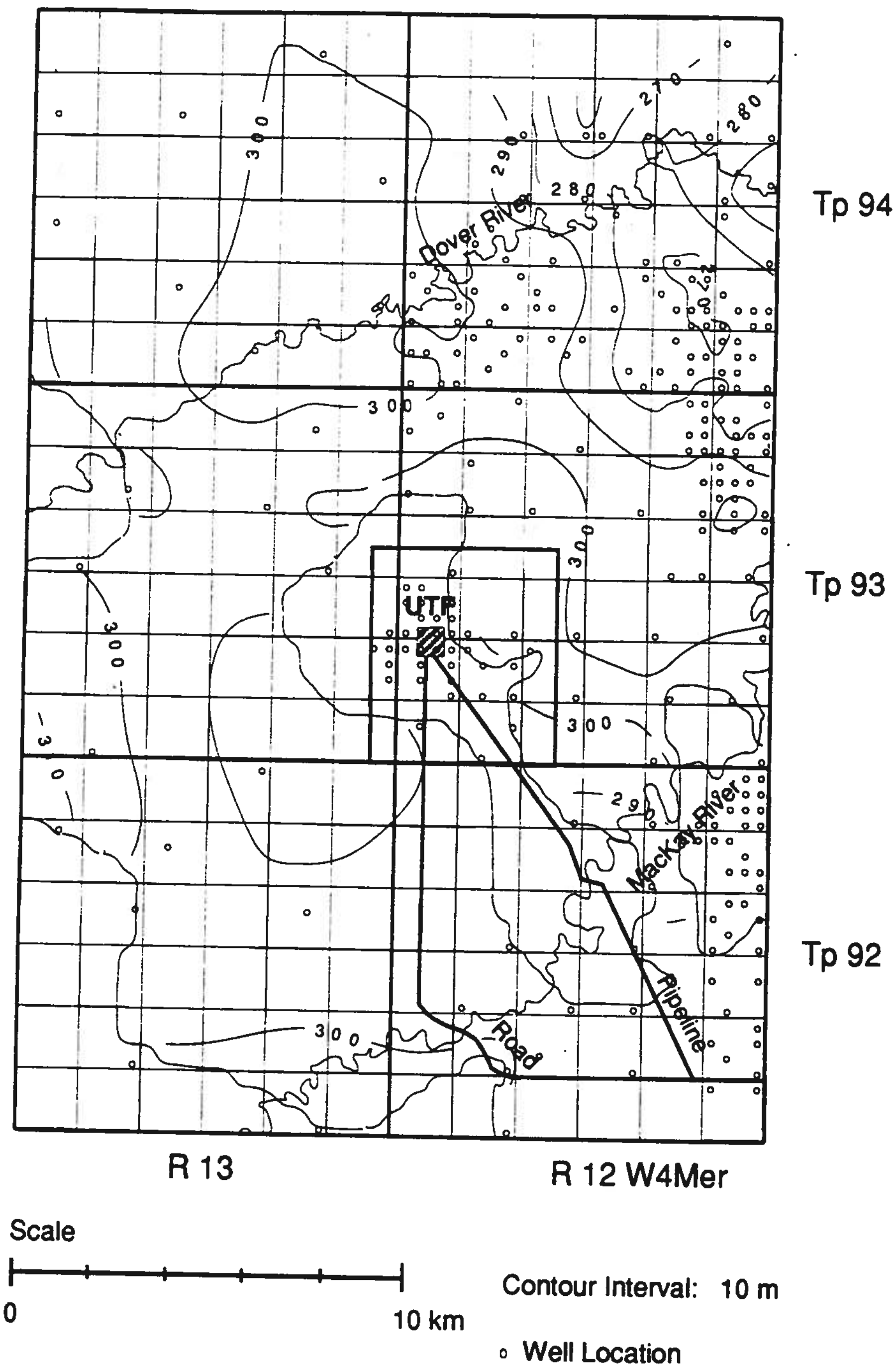
B- 2. McMurray Formation isopach map.



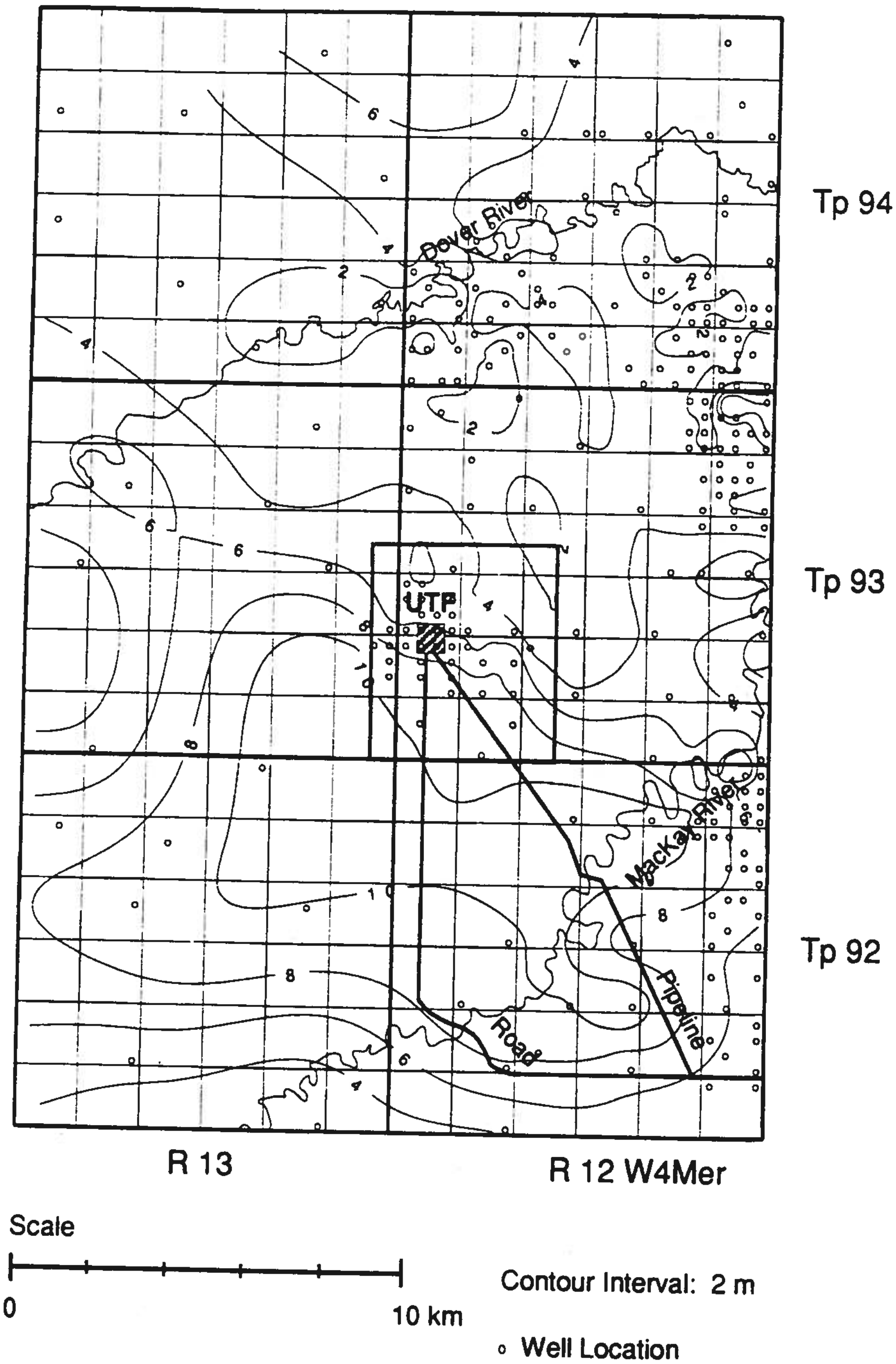
B- 3. McMurray Formation structure map (E1).



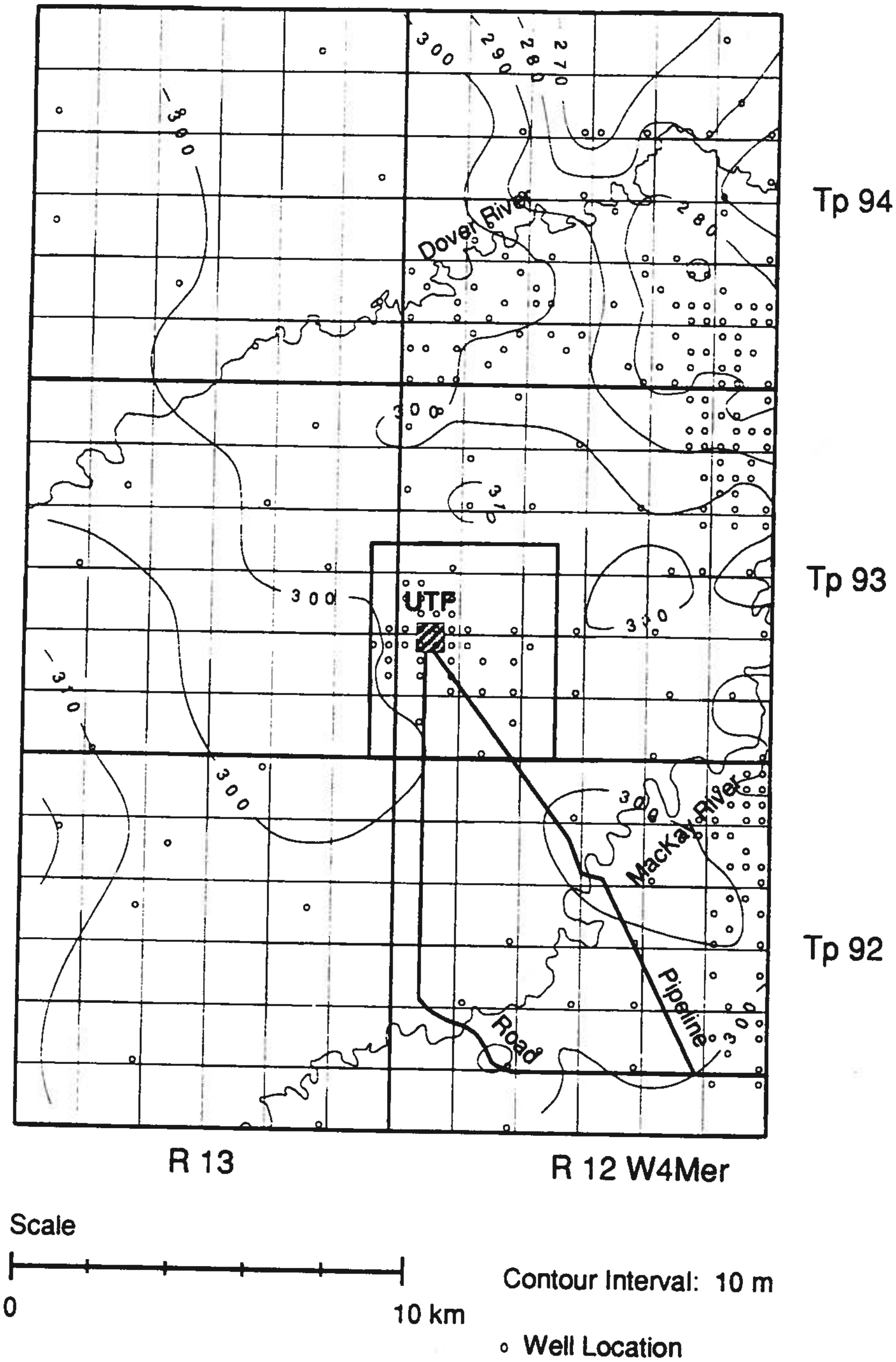
B- 4. Basal erosional channel (Wabiskaw Member) isopach map.



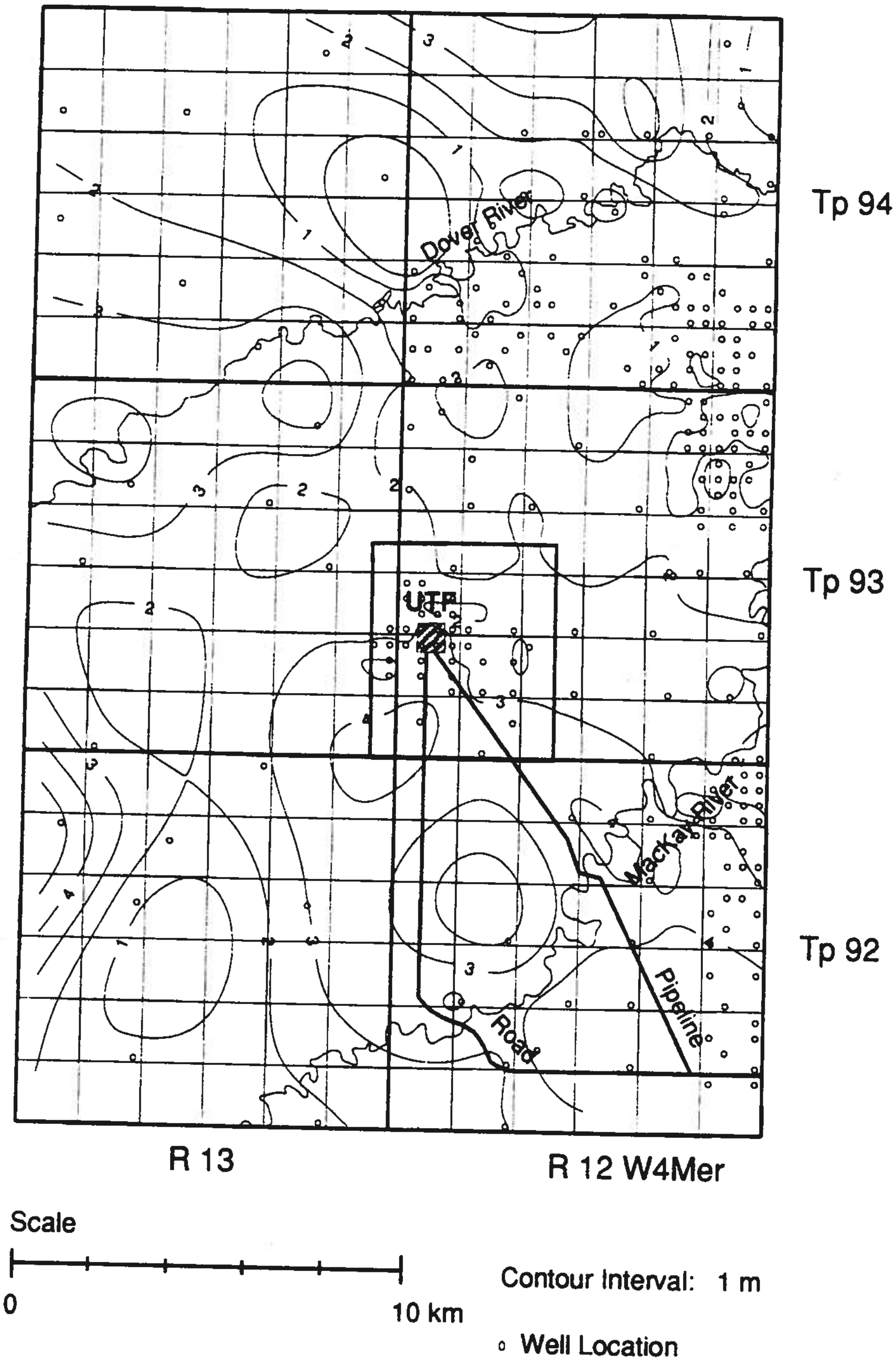
B- 5. Basal erosional channel (Wabiskaw Member) structure map (E2).



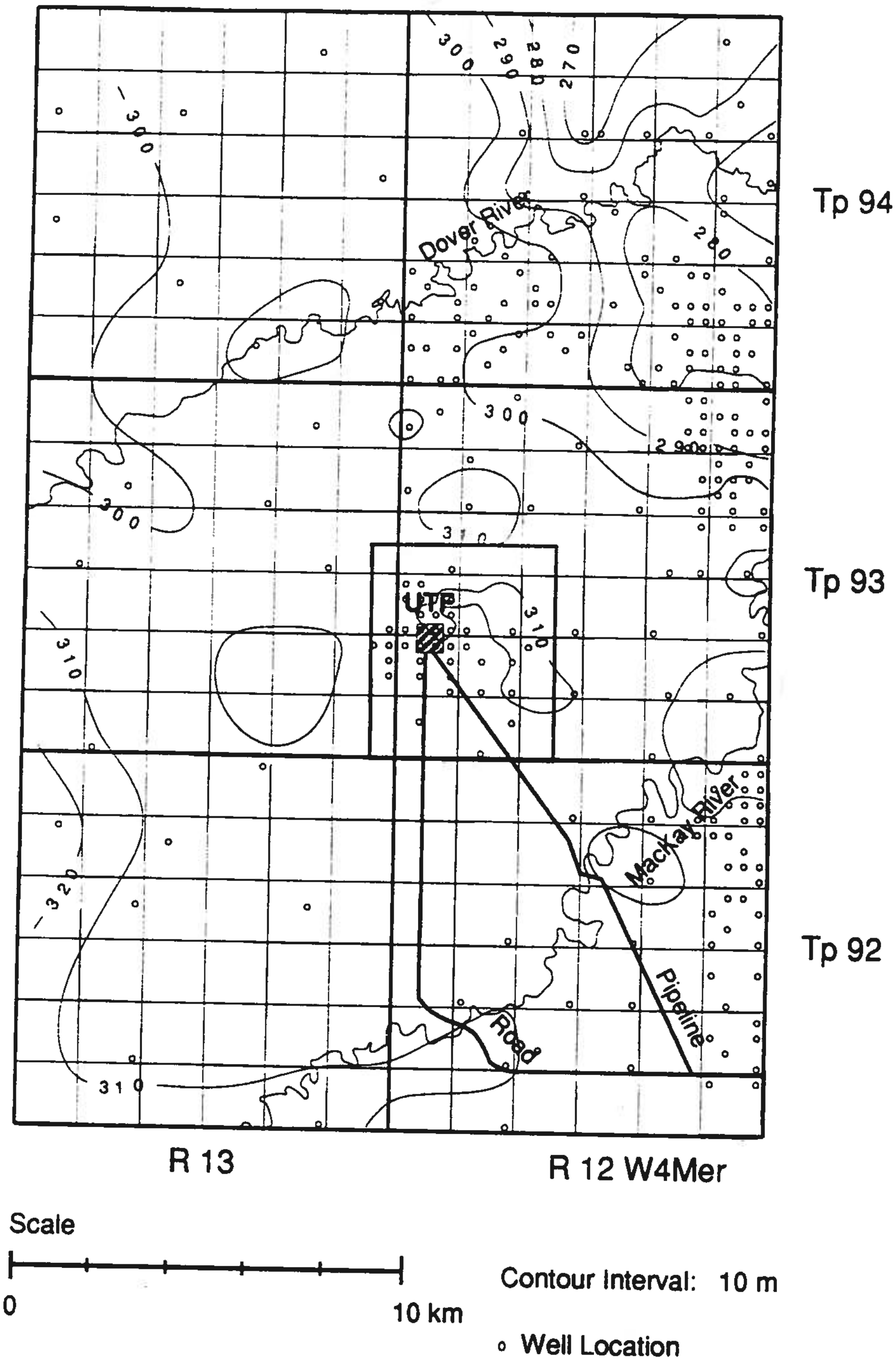
B- 6. Lower shale wedge (Wabiskaw Member) isopach map.



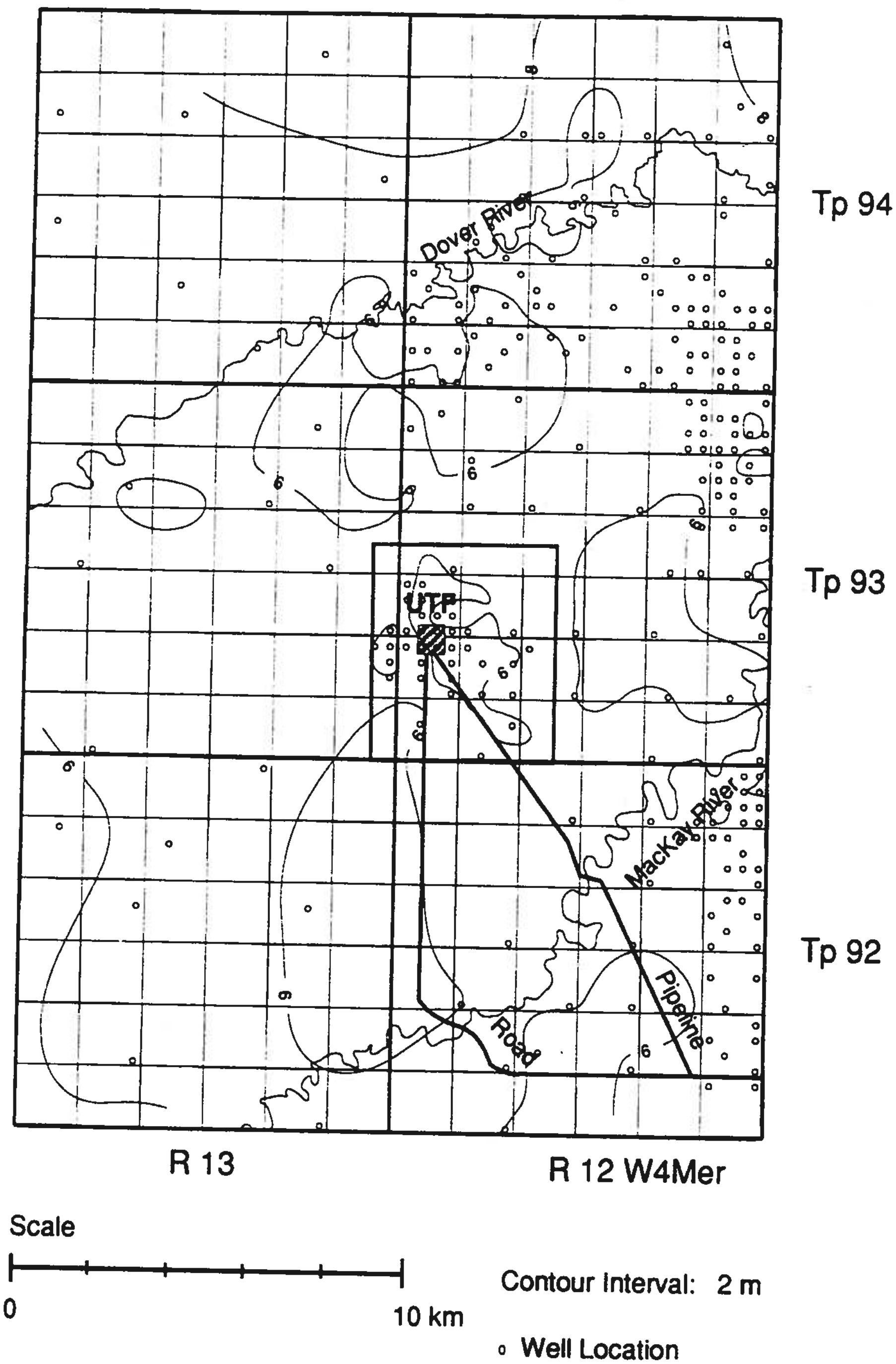
B- 7. Lower shale wedge (Wabiskaw Member) structure map.



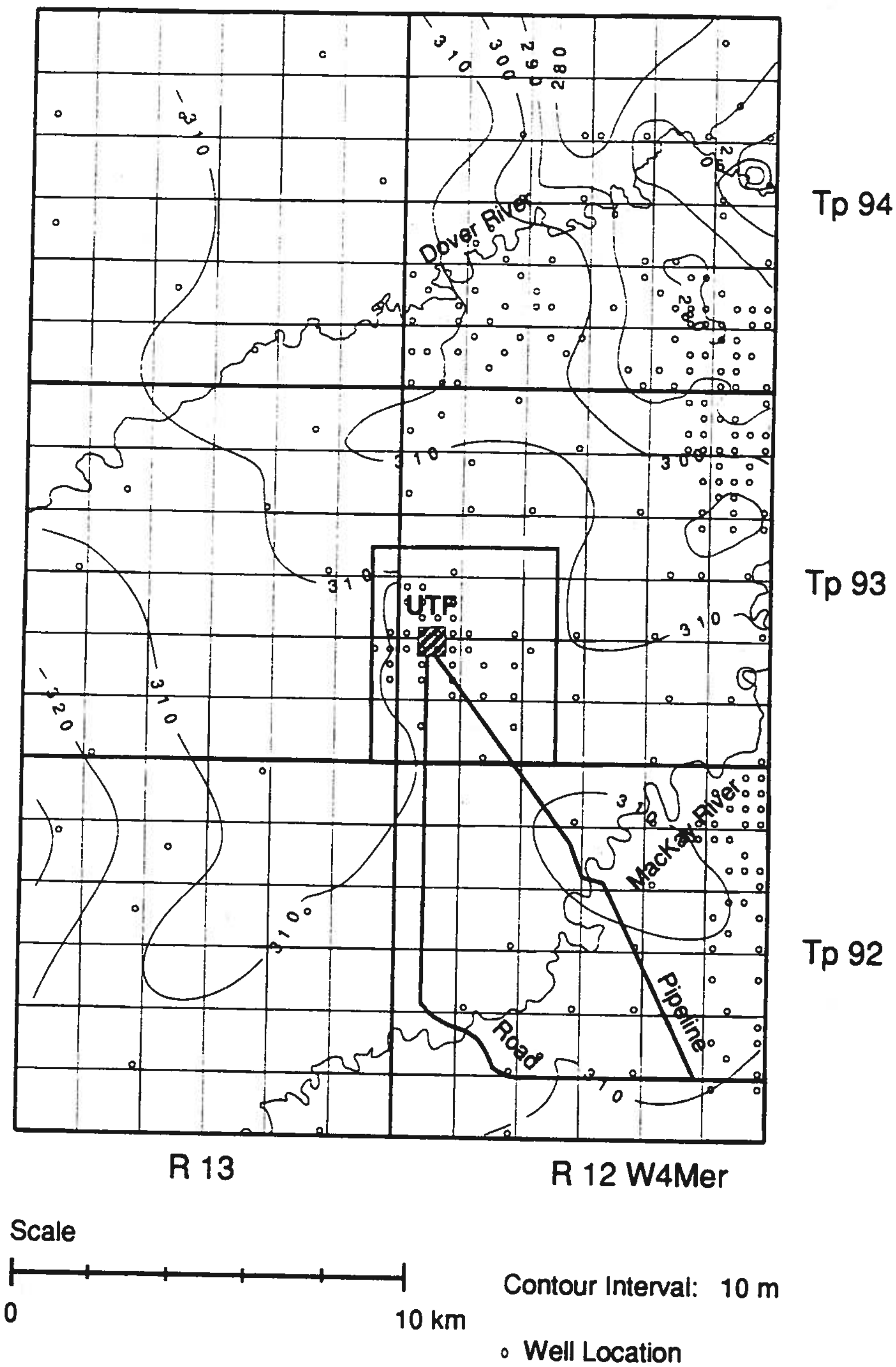
B- 8. Upper sand (Wabiskaw Member) isopach map.



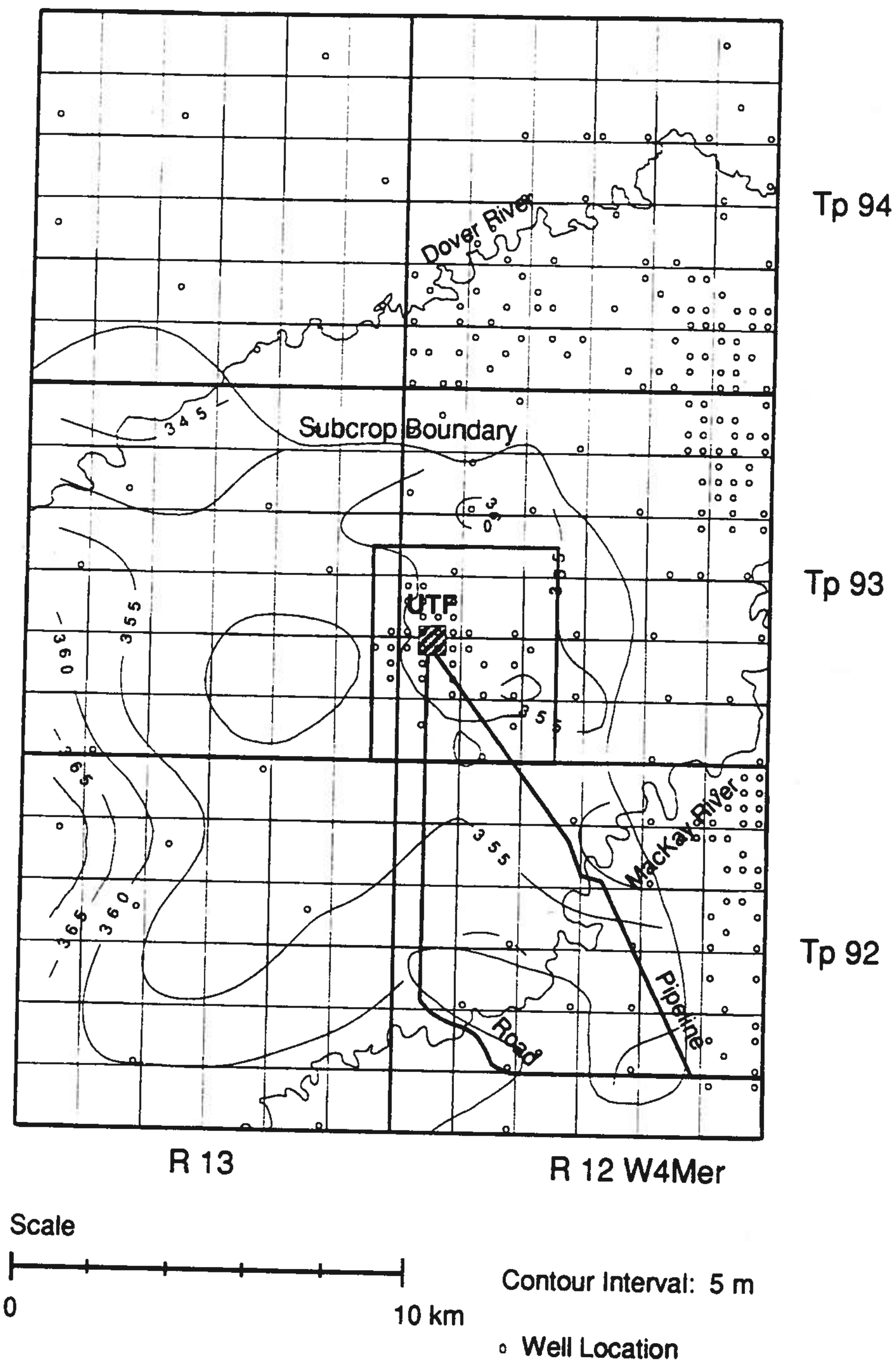
B- 9. Upper sand (Wabiskaw Member) structure map.



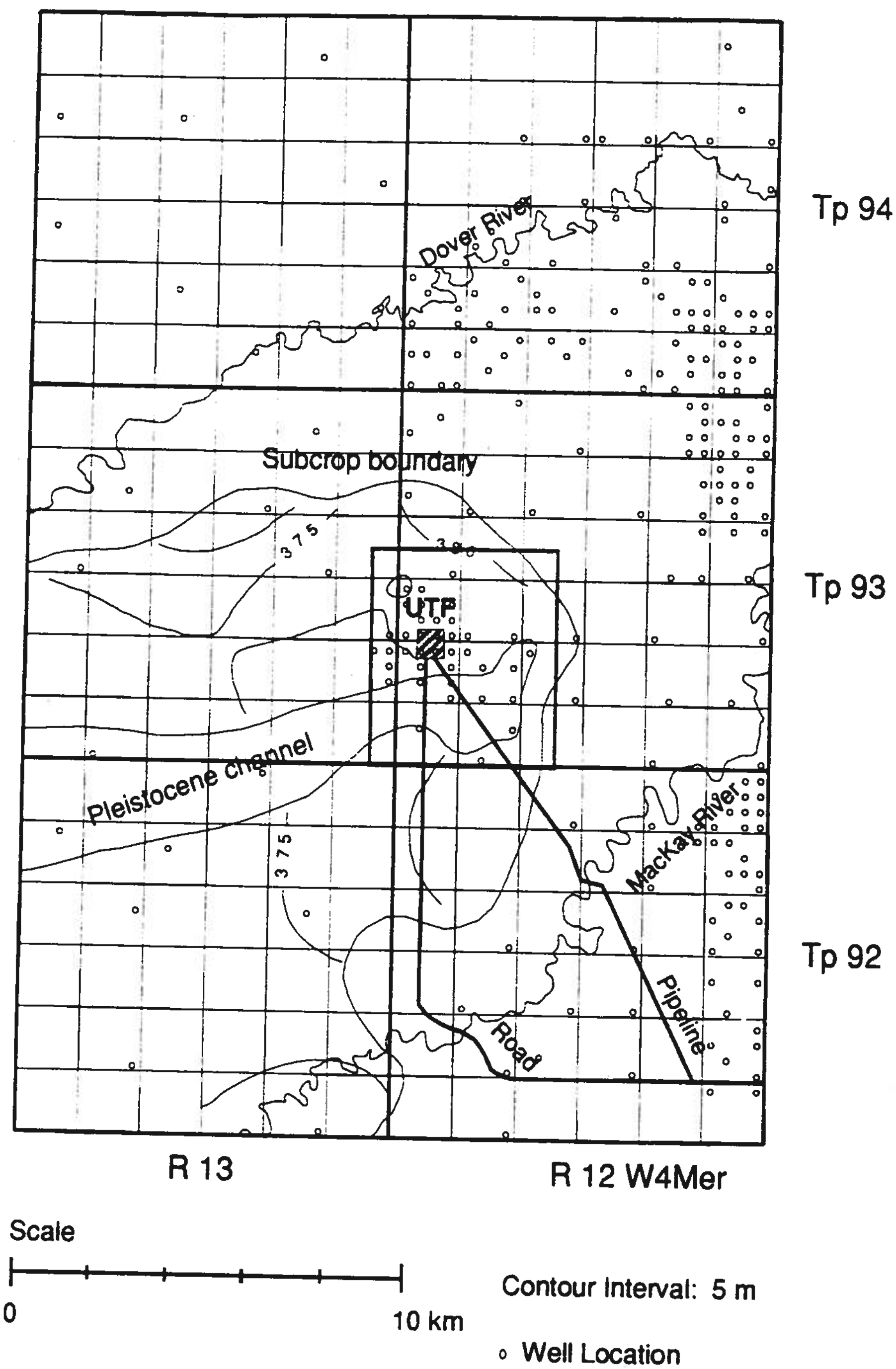
B-10. Upper regional marine shale (Wabiskaw Member) isopach map.



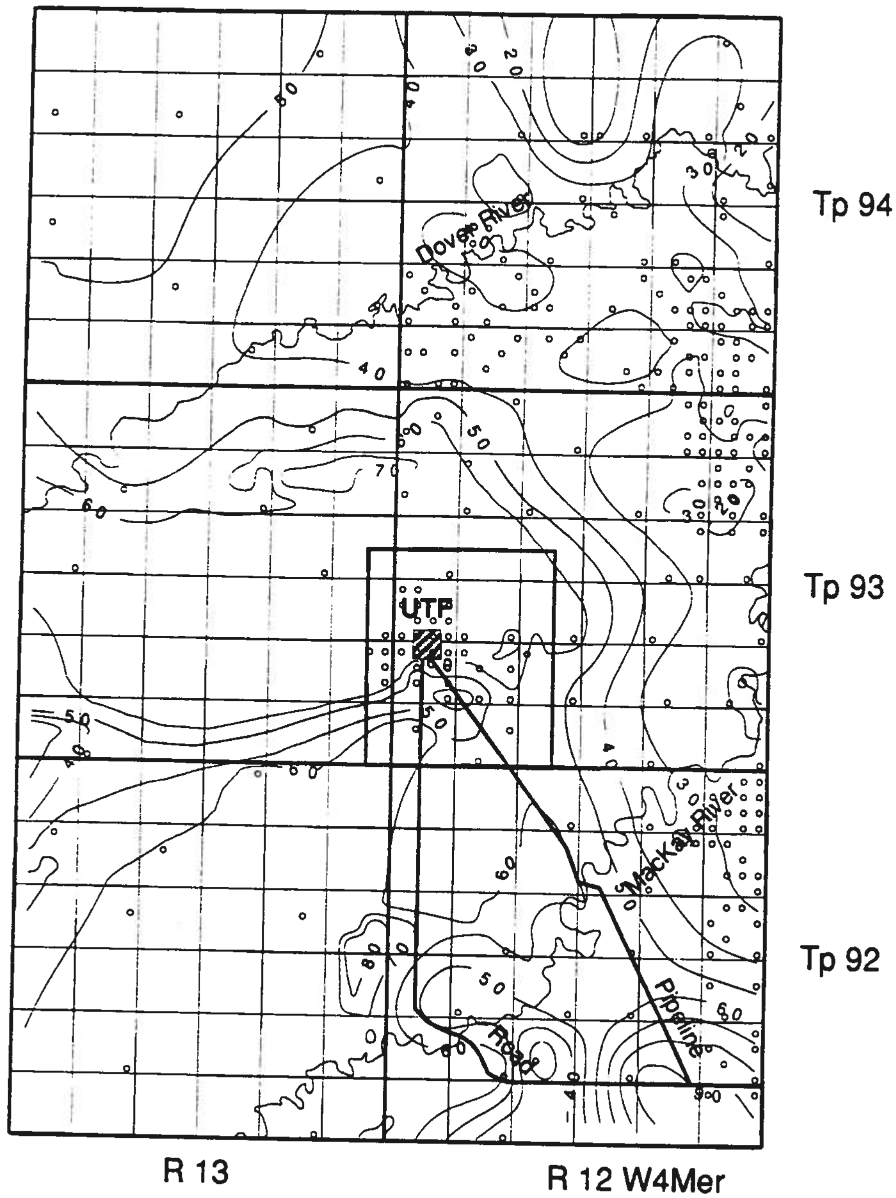
B-11. Wabiskaw Member structure map (Wabiskaw marker).



B-12. Clearwater A marker structure map.



B-13. Uneroded Clearwater Formation structure map.



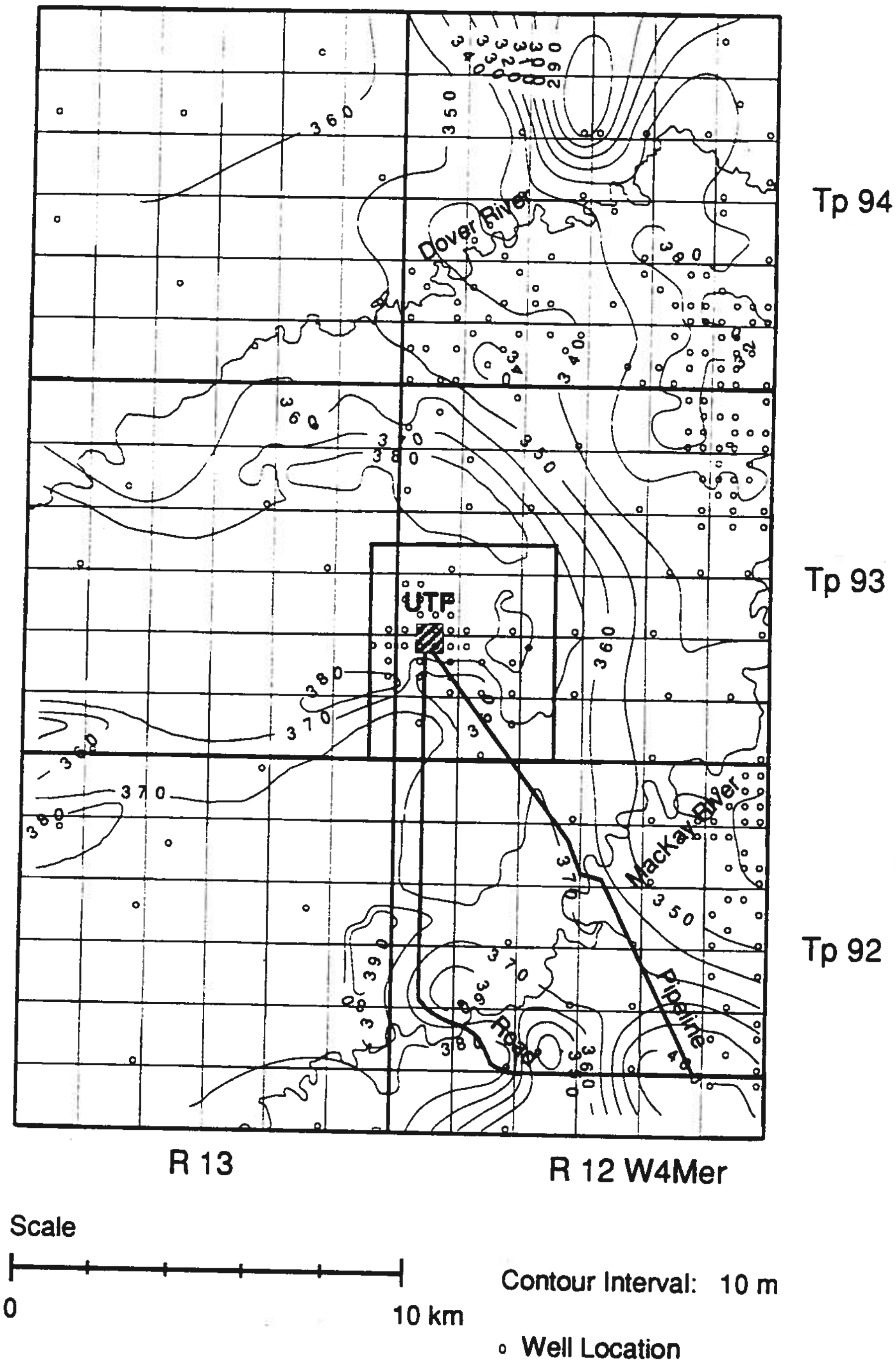
Scale

0 10 km

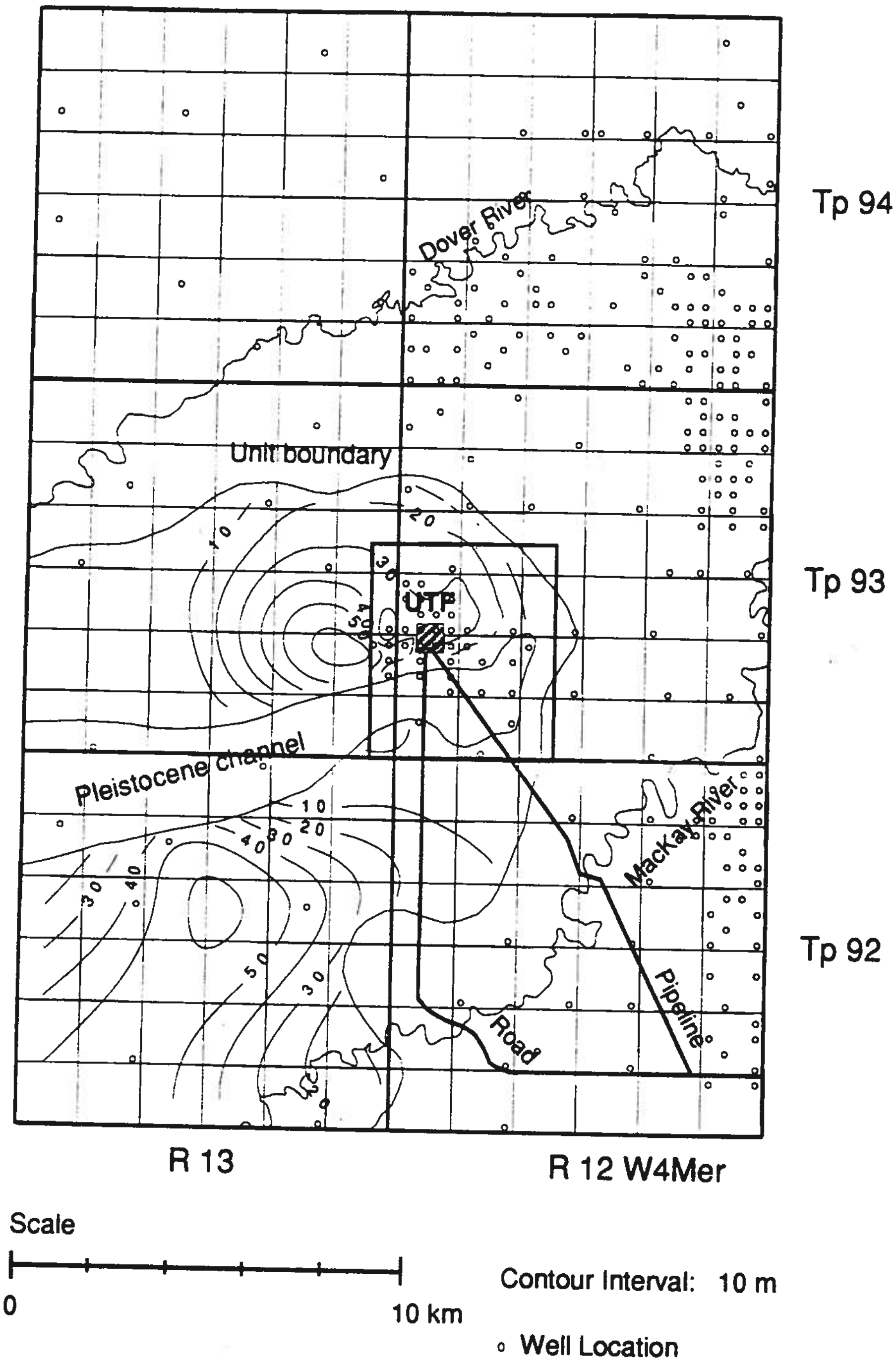
Contour Interval: 10 m

o Well Location

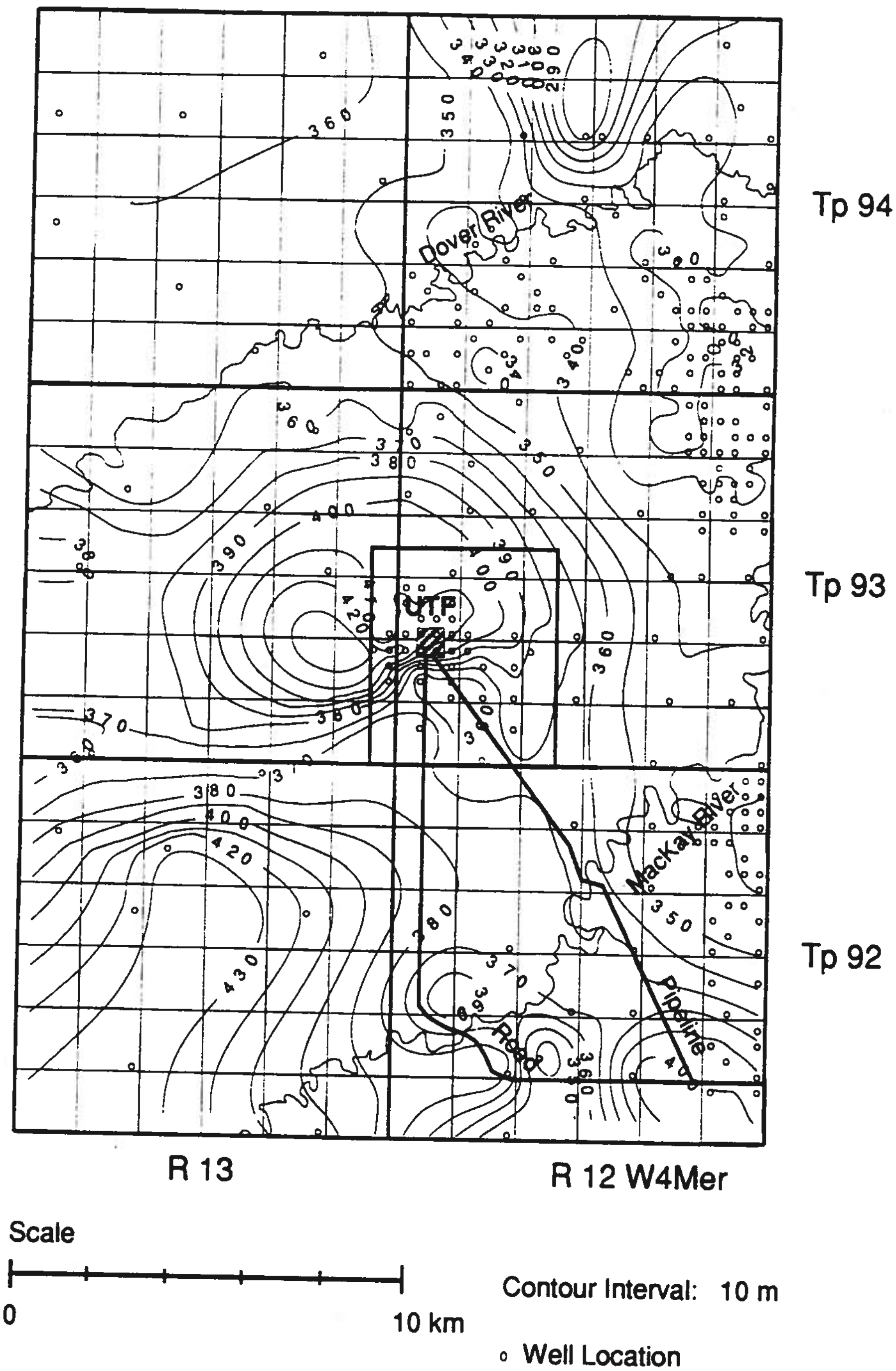
B-14. Isopach map from the top of the Clearwater Formation to the top of the Wabiskaw Member.



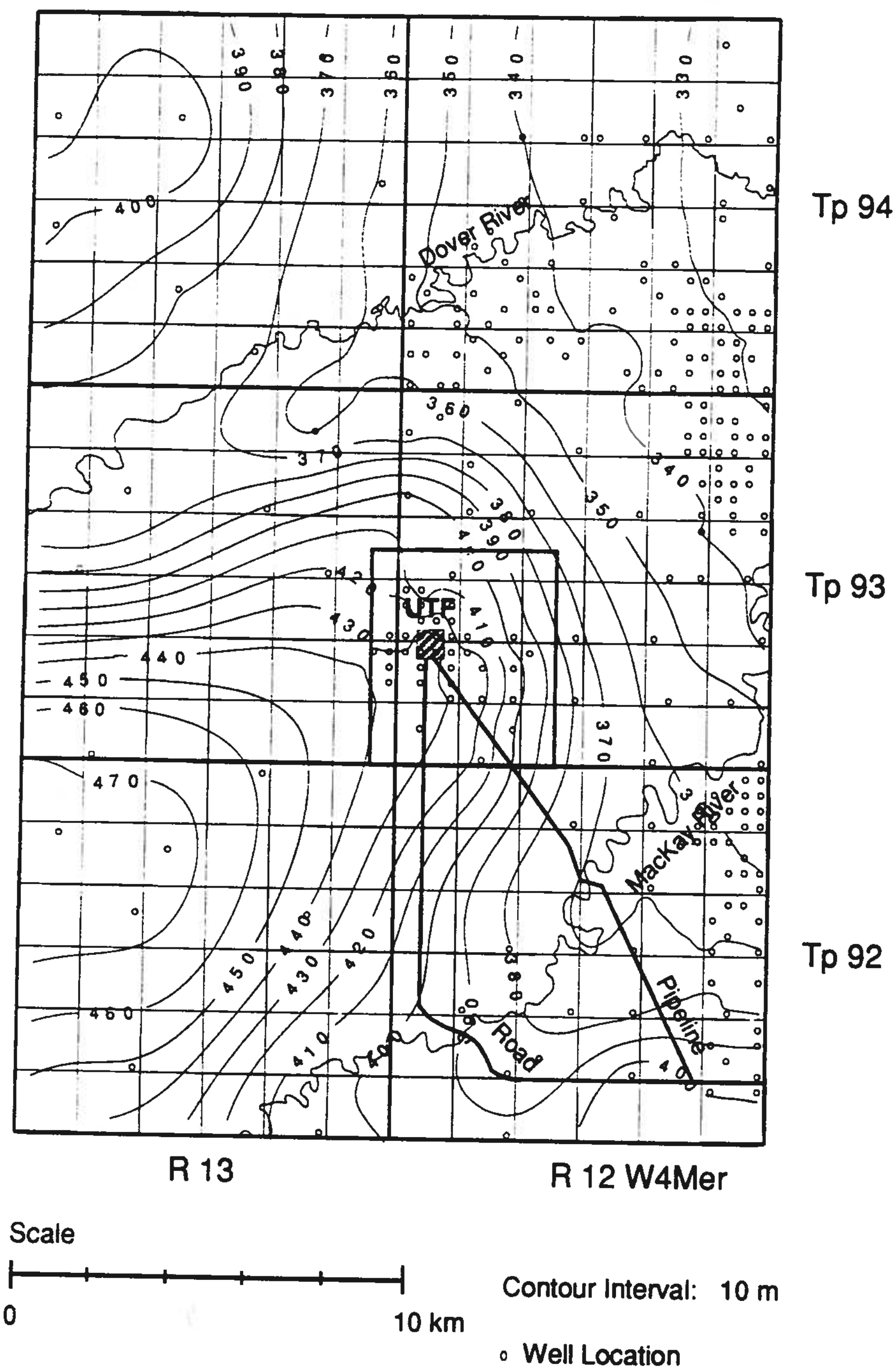
B-15. Clearwater Formation structure map.



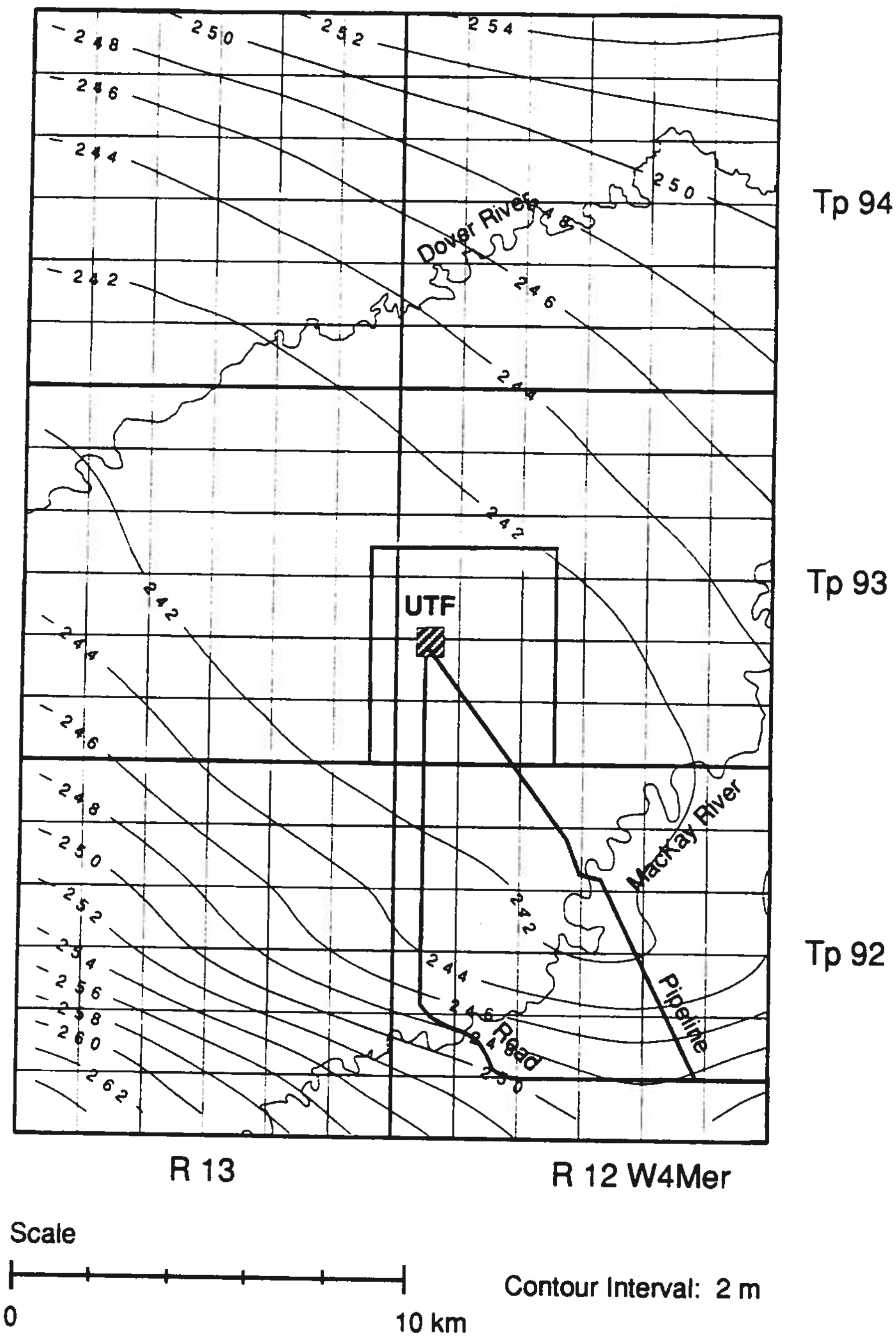
B-16. Grand Rapids Formation isopach map.



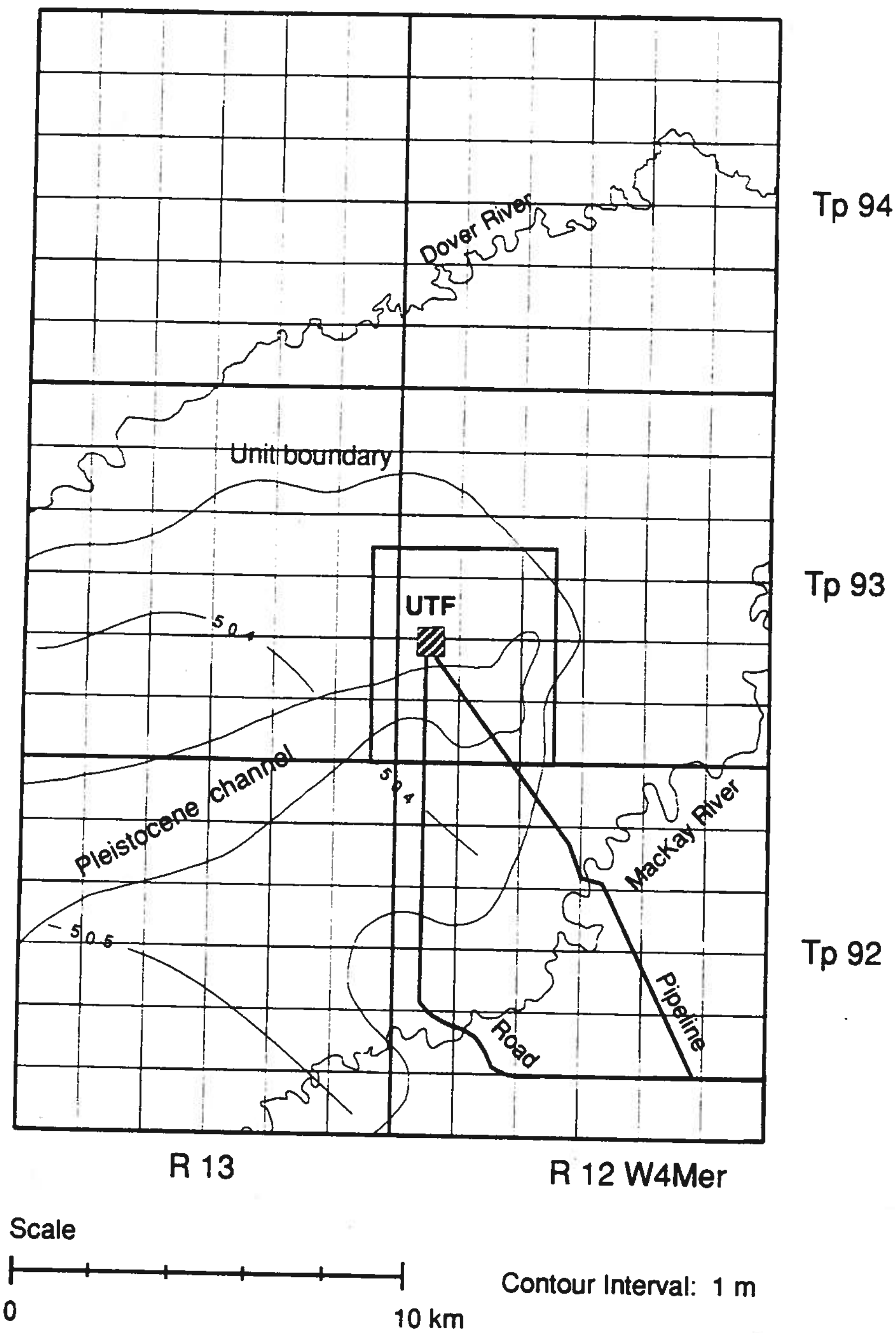
B-17. Structure map for the top of the bedrock.



B-19. Ground surface elevation map.

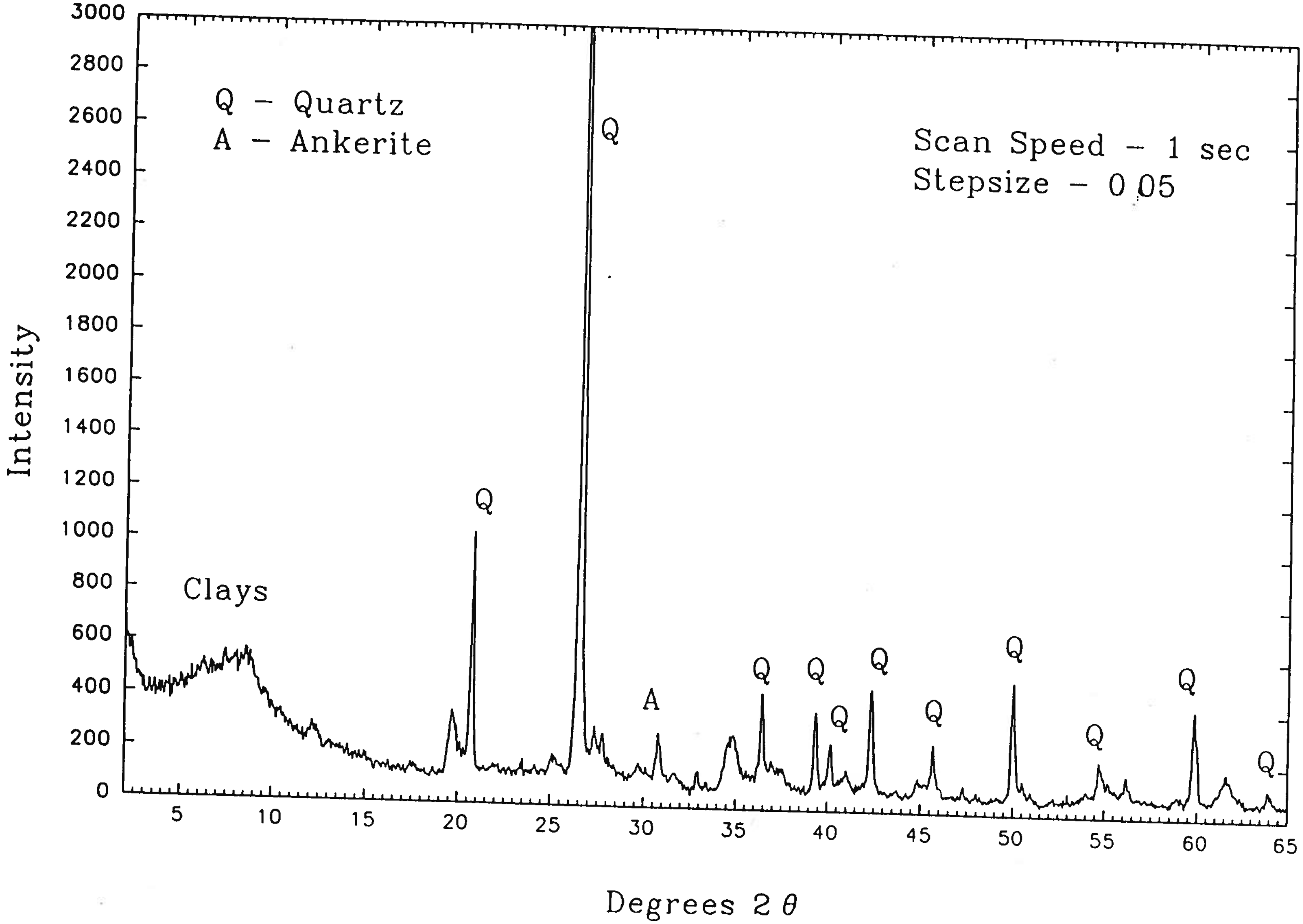


C- 3. Distribution of freshwater hydraulic head (m) in the Beaverhill Lake aquifer system.

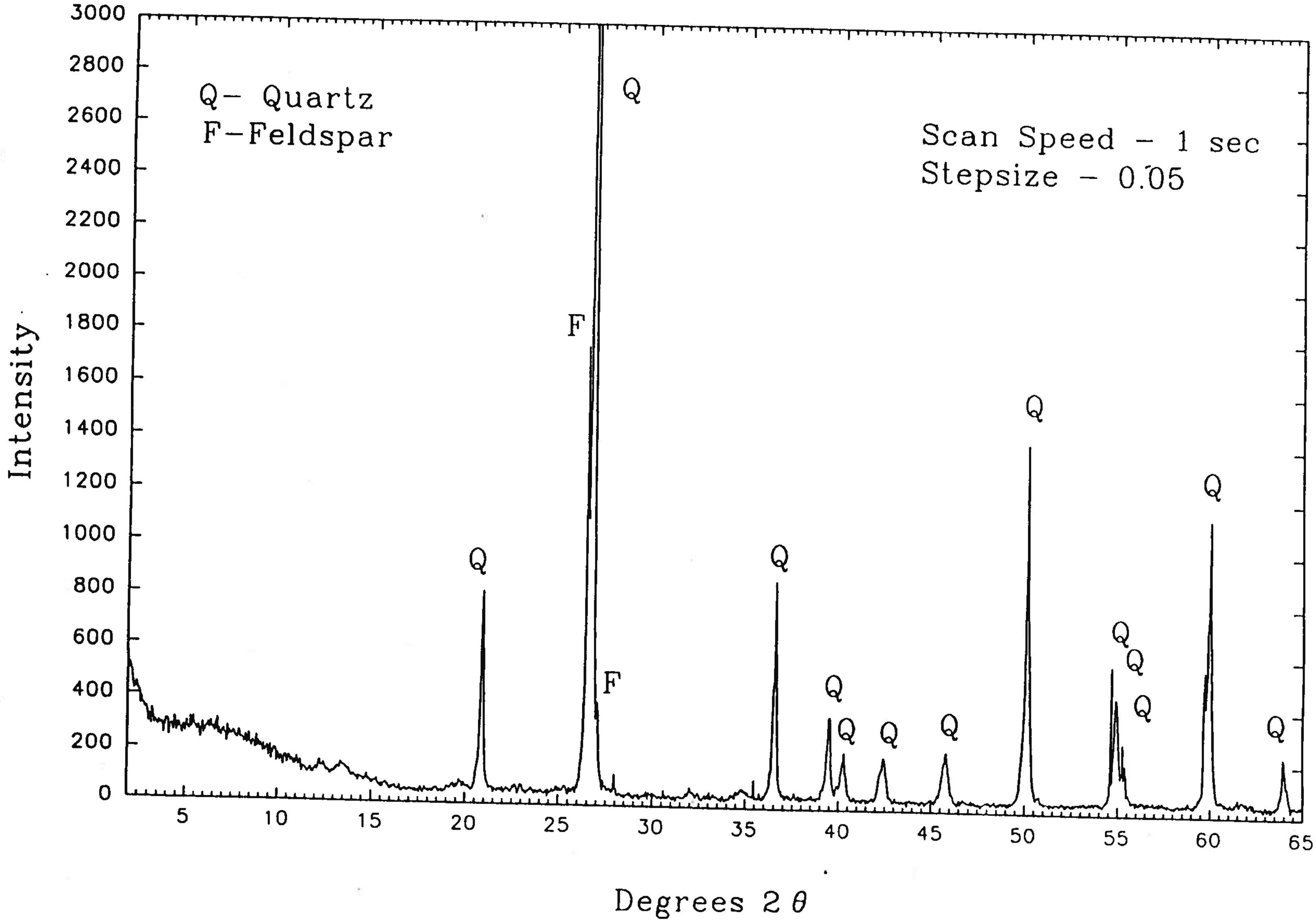


C- 6. Distribution of freshwater hydraulic head (m) in the Grand Rapids aquifer.

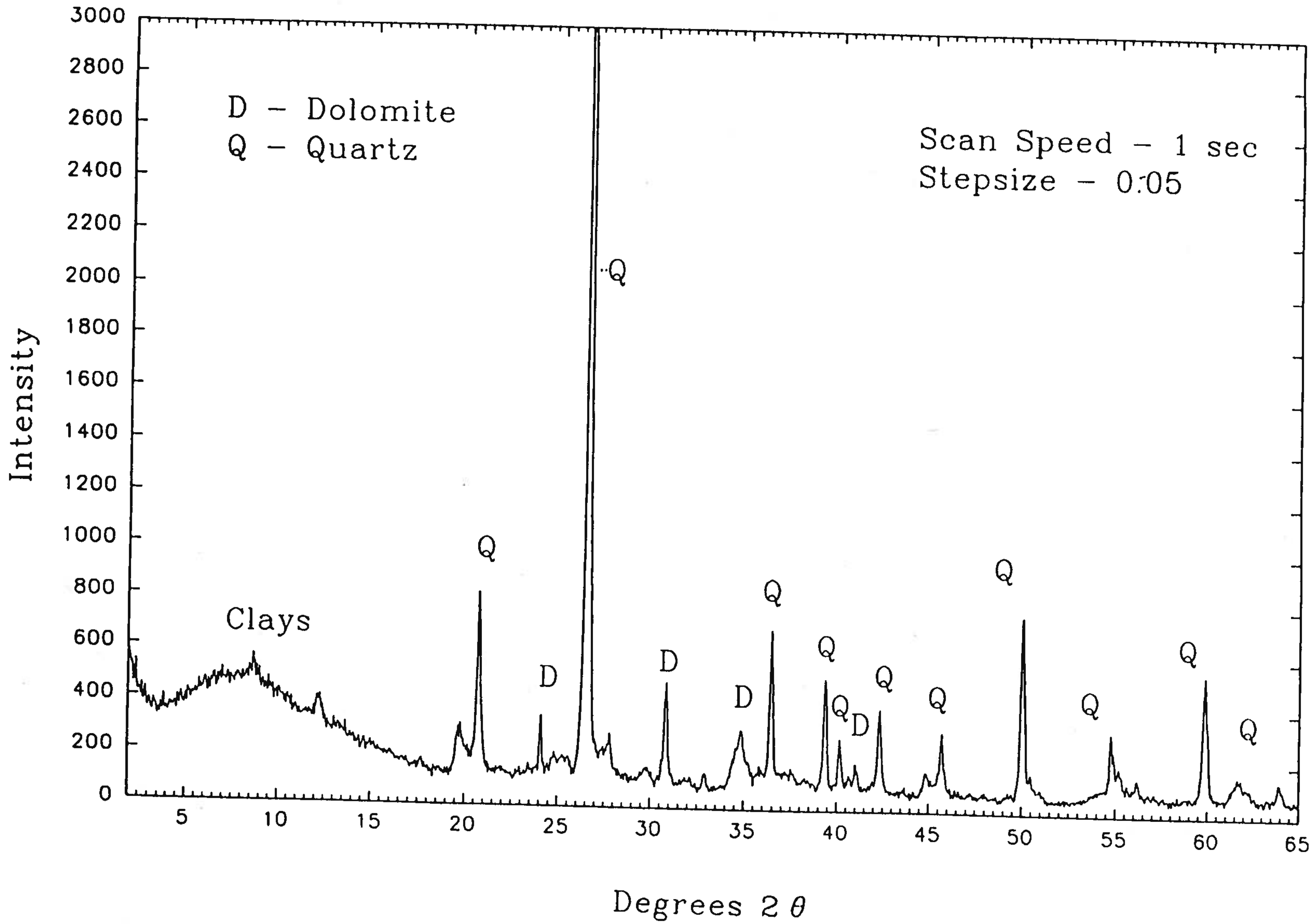
APPENDIX D - MINERALOGICAL ANALYSES



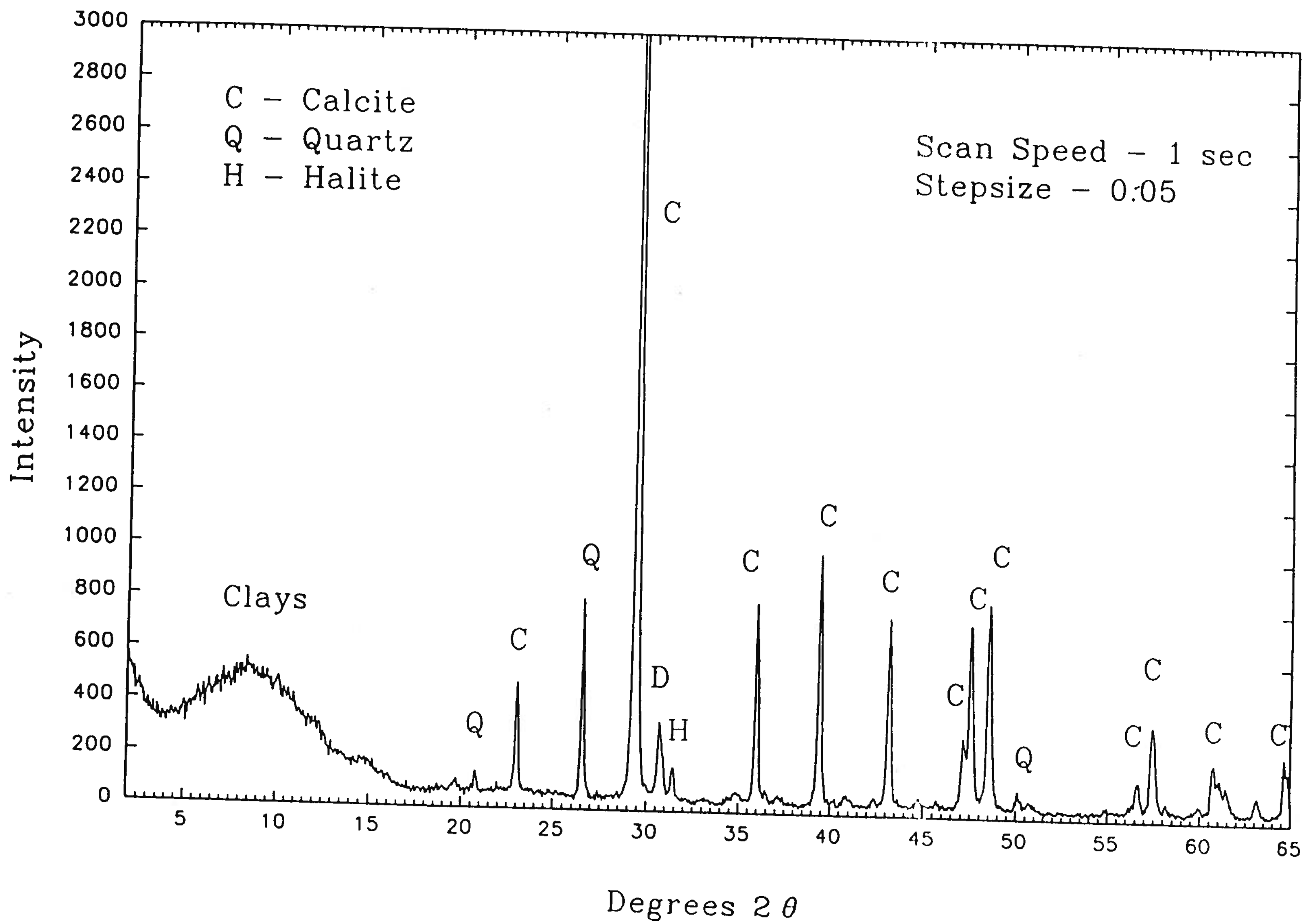
D-1. X-Ray diffraction results for Sample 1 at 123.09 m depth in well AO58 15-12-93 12W4 Mer, Wabiskaw Member, Clearwater Formation.



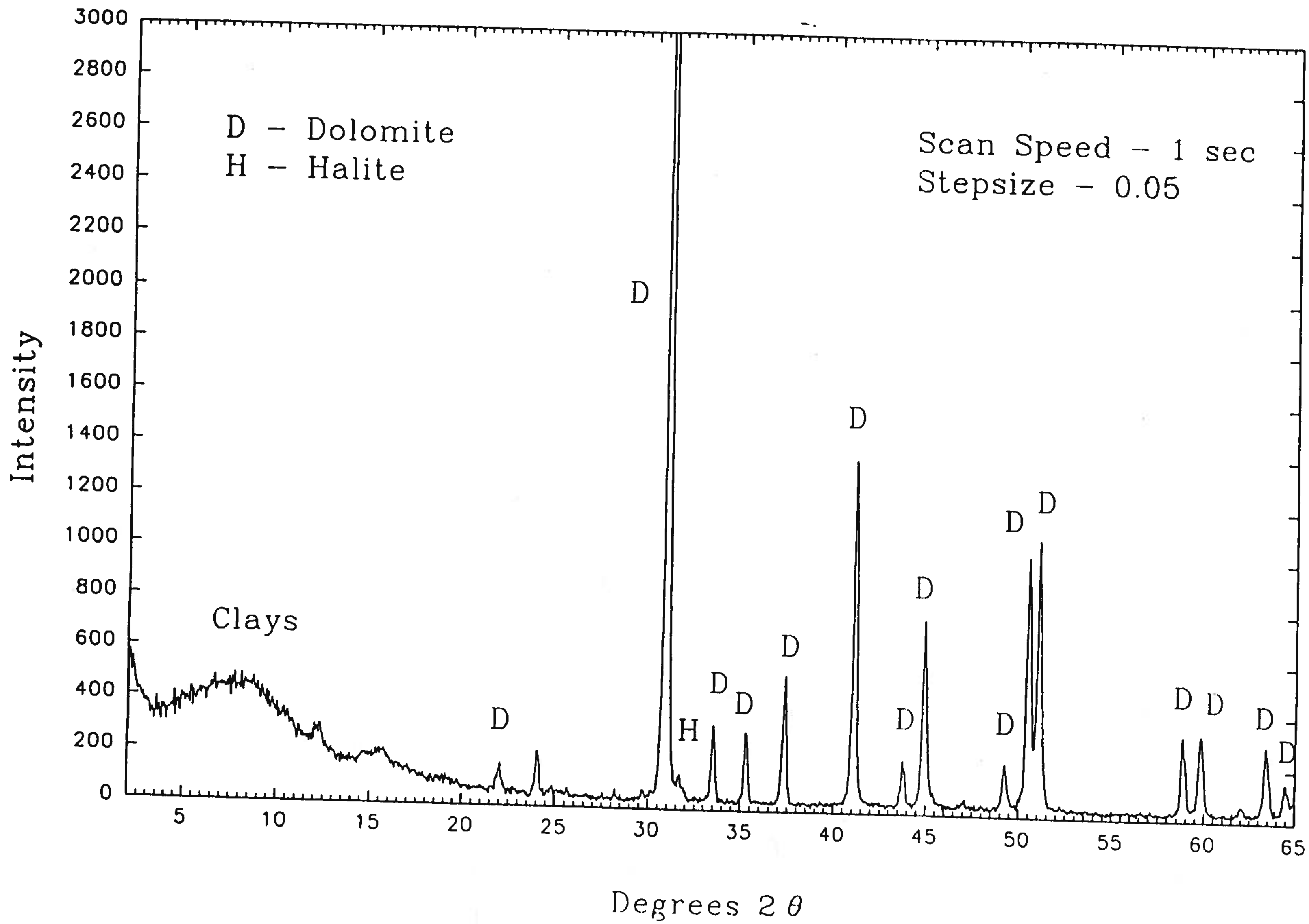
D-2. X-Ray diffraction results for Sample 2 at 124.16 m depth in well AO58 15-12-93 12W4 Mer, Wabiskaw Member, Clearwater Formation.



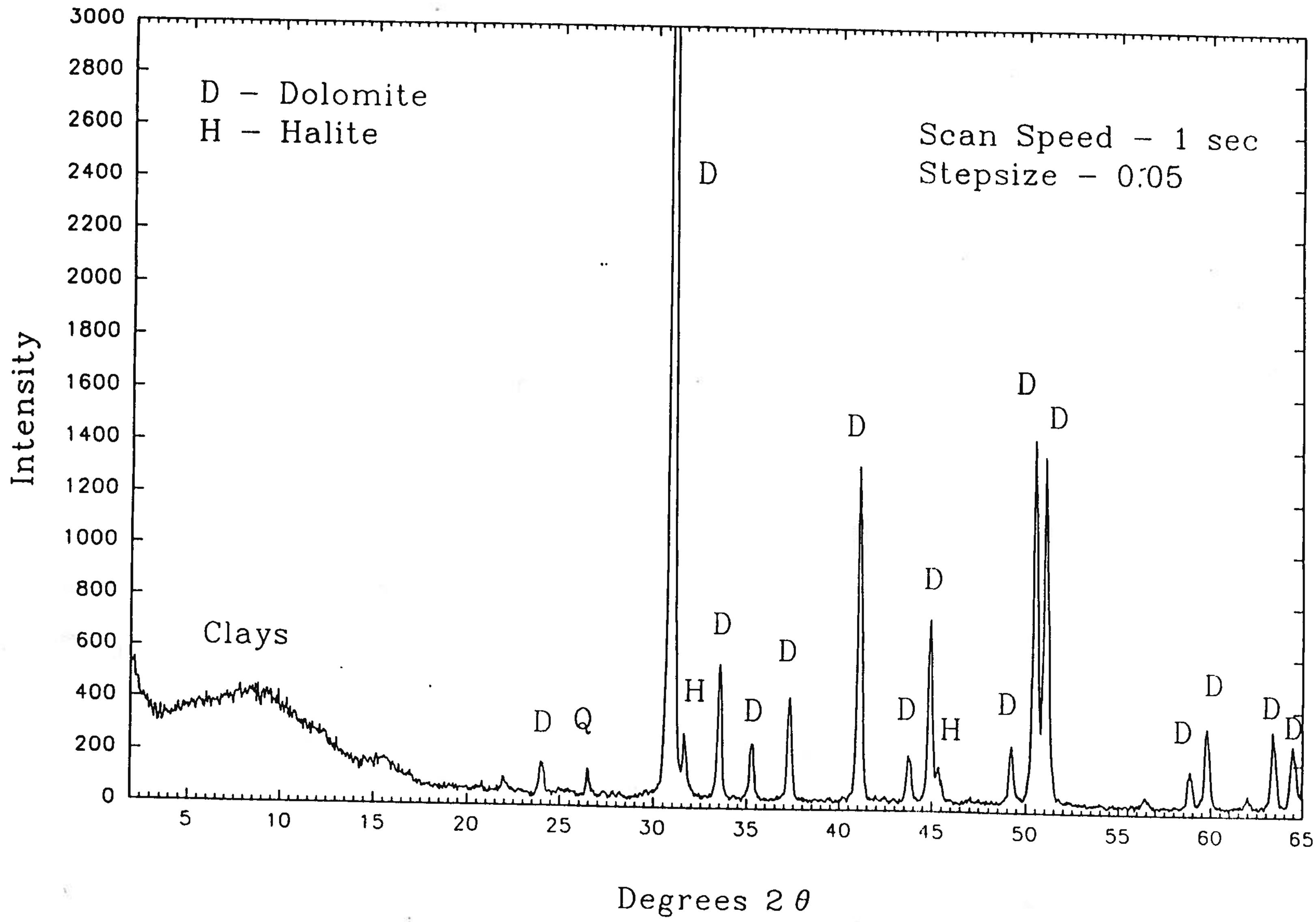
D-3. X-Ray diffraction results for Sample 3 at 125.88 m depth in well AO58 15-12-93 12W4 Mer, Wabiskaw Member, Clearwater Formation.



D-4. X-Ray diffraction results for Sample 4 at 221.21 m depth in well BC03 01-18-93 12W4 Mer, Calumet Member, Beaverhill Lake Group.



D 5 X-Ray diffraction results for Sample 5 at 502 46 m depth in well 06-18-93 12W4 Mer, Winnipegosis Formation



D-6. X-Ray diffraction results for Sample 6 at 516.61 m depth in well 06-18-93 12W4 Mer, Winnipegosis Formation.