Hydrogeology of the Post-Devonian Sedimentary Succession at the AOSTRA Underground Test Facility

Prepared for
Conservation and Protection,
Environment Canada

by

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DISCLAIMER

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EXECUTIVE SUMMARY

This report presents the geology and hydrogeology of the post-Devonian sedimentary strata at the Underground Test Facility (UTF) near Fort McMurray in northeastern Alberta where bitumen is extracted from the McMurray oil sands using the Steam Assisted Gravity Drainage (SAGD) process. The report is the result of a collaborative agreement between Environment Canada and the Alberta Research Council to study the possibility of shallow groundwater contamination at the UTF site by fluids escaping the production zone and migrating upwards. The Oil Sands and Research Division of the Alberta Department of Energy (formerly the Alberta Oil Sands Technology and Research Authority) supported the study by providing access to relevant data.

The post-Devonian sedimentary succession at the UTF site comprises the McMurray, Clearwater and Grand Rapids formations of the Cretaceous Mannville Group, overlain by post-Cretaceous unconsolidated sediments mainly of glacial origin. Lithologically, the Clearwater and Grand Rapids formations are shale dominated, except for a thin sandstone layer in the Wabiskaw Member at the base of the Clearwater Formation. The sands of the McMurray Formation are saturated with bitumen. A buried Pleistocene paleo-channel cuts deep into the bedrock south of the UTF site, reaching the Clearwater Formation. Most of the sediment within the channel consists of coarse sand and gravel, with a thin layer of till and stratified glacial sediments at the top.

Hydrogeologically, the shale-dominated parts of the thick Clearwater and Grand Rapids formations form aquitards with very low permeability (less than 10^{-17} m^2 or 10^{-5} darcies). The McMurray Formation is practically an aquitard because the solid bitumen filling the pore space impedes fluid movement. The glacial till in the unconsolidated sediments is also an aquitard of low permeability. The Wabiskaw Member sandstone is an aquifer characterized by a permeability of 4×10^{-12} m^2 (4 darcies) on average. The sand-and-gravel buried Pleistocene channel, characterized by a permeability of 2×10^{-10} m^2 (20 darcies), is the shallow groundwater aquifer used as a source of water supply for the UTF operations.

The water table at the site is at depths in the 3 to 6 m range. An unsaturated zone several meters thick exists in the Pleistocene buried channel. Hydraulic heads in the saturated zone are in the 400 m range. The flow in this aquifer is lateral toward outcrop. The flow of formation water in the Wabiskaw aquifer is oriented northeastward, toward aquifer outcrop at the McKay and Dover rivers east of the UTF site. Hydraulic heads at the site in this aquifer are in the 320 to 330 m range, well below the hydrostatic pressure of 430 m corresponding to the ground elevation. Thus, the potential for downward flow from the unconsolidated shallow aquifers to the Wabiskaw aquifer exists. Hydraulic heads in the McMurray Formation decrease from 330 m on average in the upper part to 320 m on average in the lower part, suggesting again potential downward flow toward the sub-Cretaceous unconformity.

The SAGD process is based on injecting steam at high temperature and sub-fracturing pressure into the McMurray Formation, in order to decrease the bitumen viscosity. The steam cools off and condenses, draining gravitationally downward toward the production well. Basically, no fluids (steam condensate, oil or formation water) can escape the production zone. Even if, theoretically, some fluids would move upward, they will have to cross the tight Wabiskaw shale aquitard, before reaching the Wabiskaw sandstone aquifer. At this point, still theoretical, any fluids possibly escaping from the production zone will move laterally northeastward with the natural flow of formation water in the Wabiskaw aquifer. Further upward movement of such fluids toward the shallow Pleistocene groundwater aquifer is practically impossible because of the thick, tight intervening Clearwater and Grand Rapids aquitards, and because of the adverse hydraulic gradient these fluids would have to overcome in order to move upward from lower to higher hydraulic heads. Thus, both the hydrostratigraphy and hydrogeology of the post-Devonian strata at the UTF site make practically impossible the contamination of the shallow Pleistocene groundwater aquifer by fluids possibly escaping from the production zone, unless artificial conduits are created by fracturing or improper well completion and/or abandonment.

INTRODUCTION

The Lower Cretaceous strata in the Athabasca area in northeastern Alberta contain huge oil sands deposits. The shallow deposits are commercially exploited using surface mine operations at the Syncrude and Suncor sites. Deeper deposits have generally been exploited using in-situ enhanced oil recovery (EOR) processes. A novel approach has been developed since the early '80s and implemented by the Oil Sands and Research Division (OSRD) (formerly the Alberta Oil Sands Technology and Research Authority — AOSTRA) of the Alberta Department of Energy (ADOE), at its Underground Test Facility (UTF) northwest of Fort McMurray (Figure 1). The Steam Assisted Gravity Drainage (SAGD) process is based on increasing bitumen fluidity by decreasing its viscosity as a result of heating by injected steam. The technology consists of pairs of horizontal injection-production wells. Steam is injected through one well, forming a steam-chamber within the pay zone. As a result of increased local temperature, a mixture of fluidized bitumen, formation water and steam-condensate drain naturally toward the bottom of the steam chamber, where they collect and are pumped to the surface by the production well. The oil and water are then separated at the surface. The economic success of any EOR operation, including the one being commercially developed at the UTF, depends, among other factors, on the environmentally safe management of water resources. Regarding the UTF operations, water resources aspects relate to the deep disposal of residual water, groundwater pumping for steam production, and possible contamination of shallow aquifers in the case of steam and/or other fluids escaping from the pay zone being exploited for bitumen extraction (Basin Analysis Group, 1988).

Throughout the development of the Underground Test Facility, AOSTRA has continuously paid attention to the environmental impact of its operations by implementing a program for monitoring the evolution of steam chambers, of changes in the temperature, chemistry, pressure and stress of the rocks and fluids at the site, and of surface and groundwater quality. As a result of earlier analysis (Basin Analysis Group, 1988), Environment Canada and Alberta Research Council initiated in 1994 a jointly funded study regarding possible

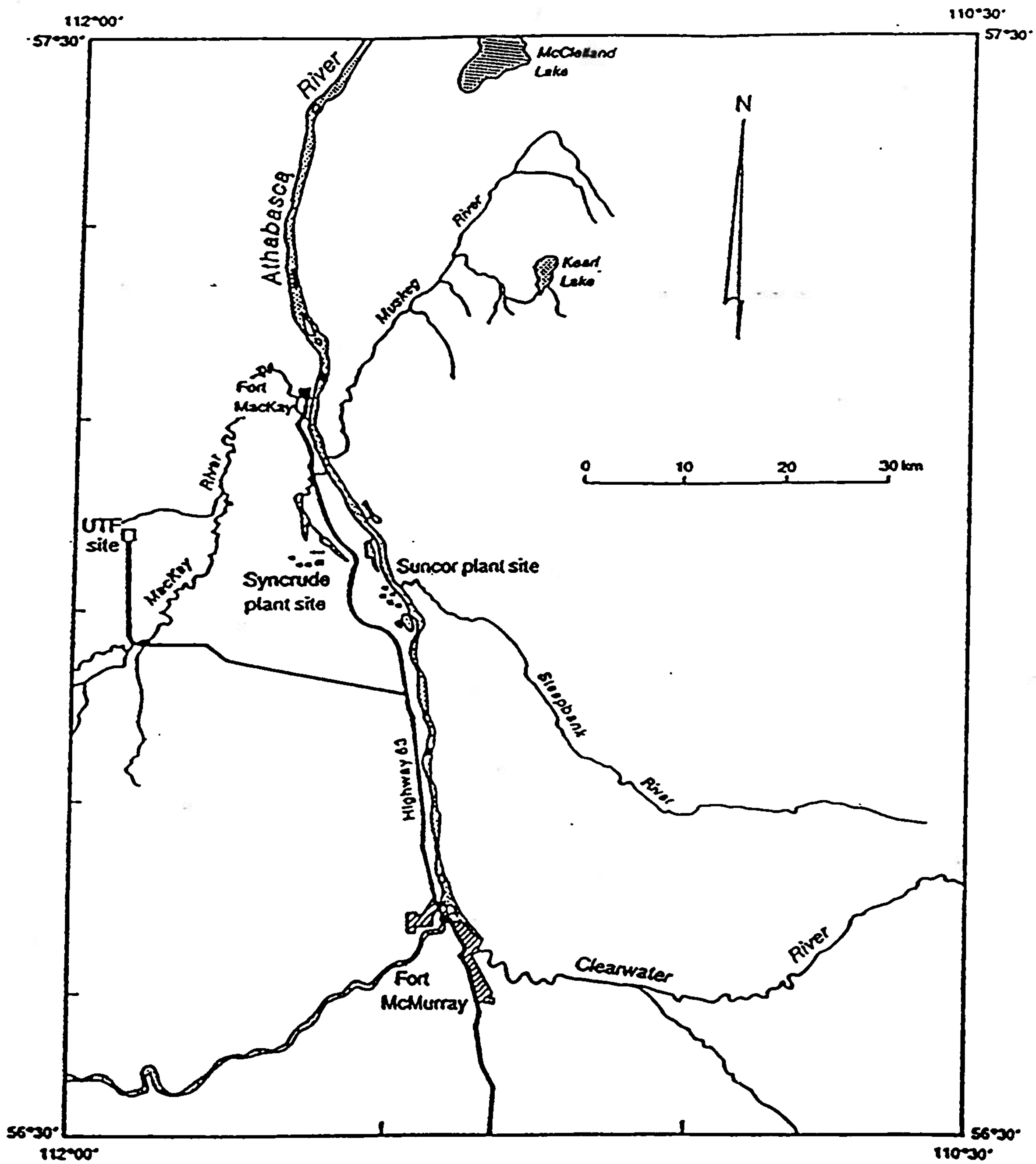

Figure 1. Location map of the UTF site in northeast Alberta.

shallow hydrogeological effects of bitumen extraction at the UTF site. The purpose of the study is to establish, during the period June 1994 to March 1995, a geological and hydrogeological model of the post-Devonian sedimentary succession at the UTF site and to assess the need and feasibility of conducting predictive modelling of possible shallow aquifer contamination. OSRD is supporting the study by providing access to site-specific surface and groundwater monitoring data. Because the main purpose of the current study relates to the theoretical possibility of fluids migrating upward and reaching the shallow unconfined aquifer, the study is stratigraphically and geographically restricted to the post-Devonian strata in a region encompassing the UTF lease area. For ease of reference and data manipulation in the Dominion Land Survey (DLS) system of coordinates used in Alberta, a detail-scale study area of 4 x 4 sections (approximately 41 km^2) was chosen for hydrogeological characterization (Figure 2). A section is 1 x 1 sq. miles and is subdivided into 16 Legal Sub-Divisions (LSDs) of 0.25 x 0.25 sq. miles each. Figure 3 shows the detail-scale study area with the numbering system used for section identification within a township, and the distribution of all 75 wells used to construct the geological and hydrostratigraphic model of the post-Cretaceous strata in the study area. Figure 3 also shows the actual site of Phases A and B of UTF operations. This report presents the resulting hydrogeological model and analysis based on the information available to date.

The authors wish to express their gratitude to all agencies, organizations and individuals involved in supporting their work, and in particular to the Oil Sands and Research Division of the ADOE for providing access to needed information. Also, we would like to acknowledge the help provided by L. Andriashek in defining the top of the bedrock in the area, by M. Brulotte in extracting and processing data from the data base, by K. Roberts in producing the report figures, and by S. Binda in timely and accurately typing the report.

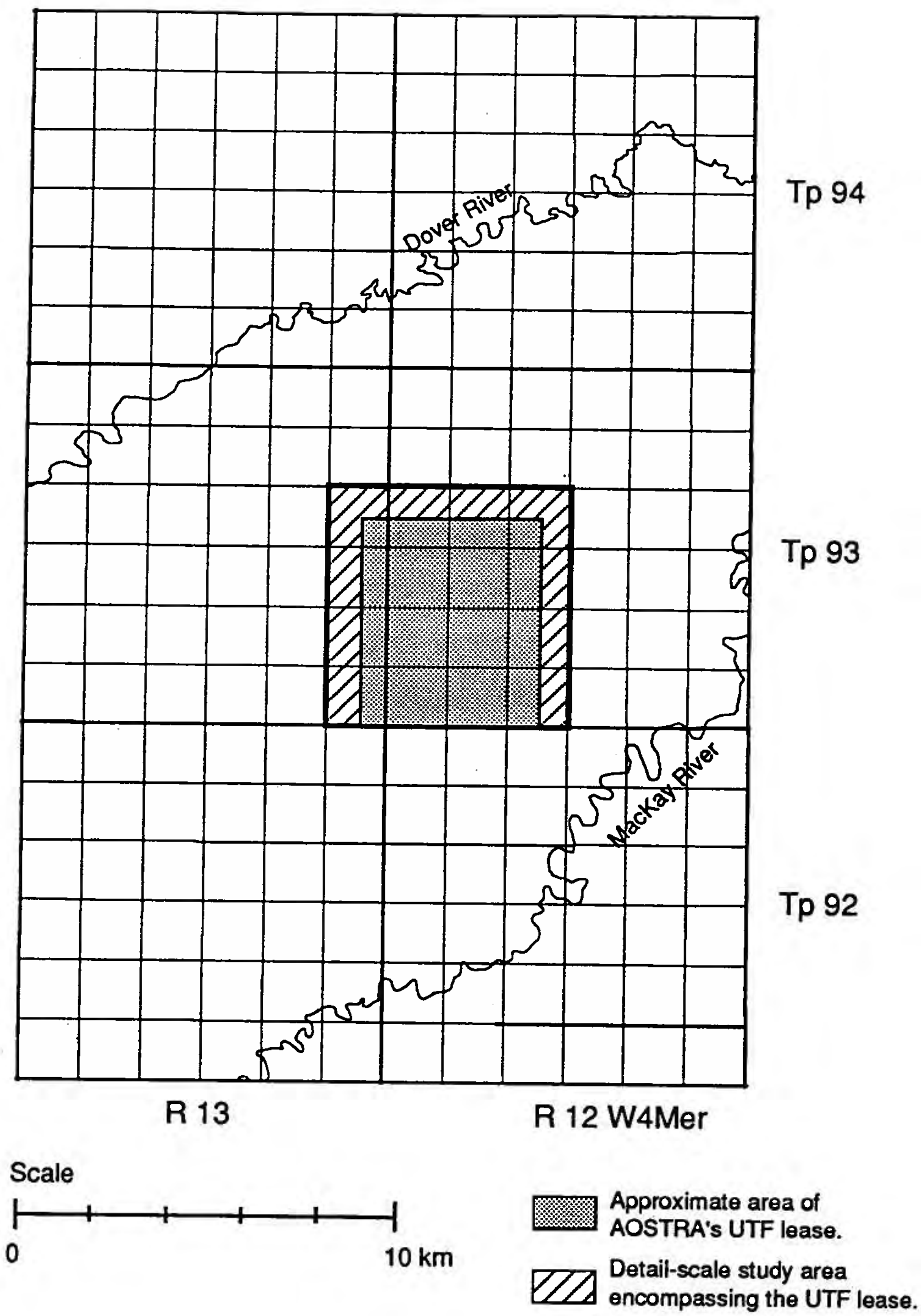

Figure 2. Local and detail-scale study areas around the UTF site.

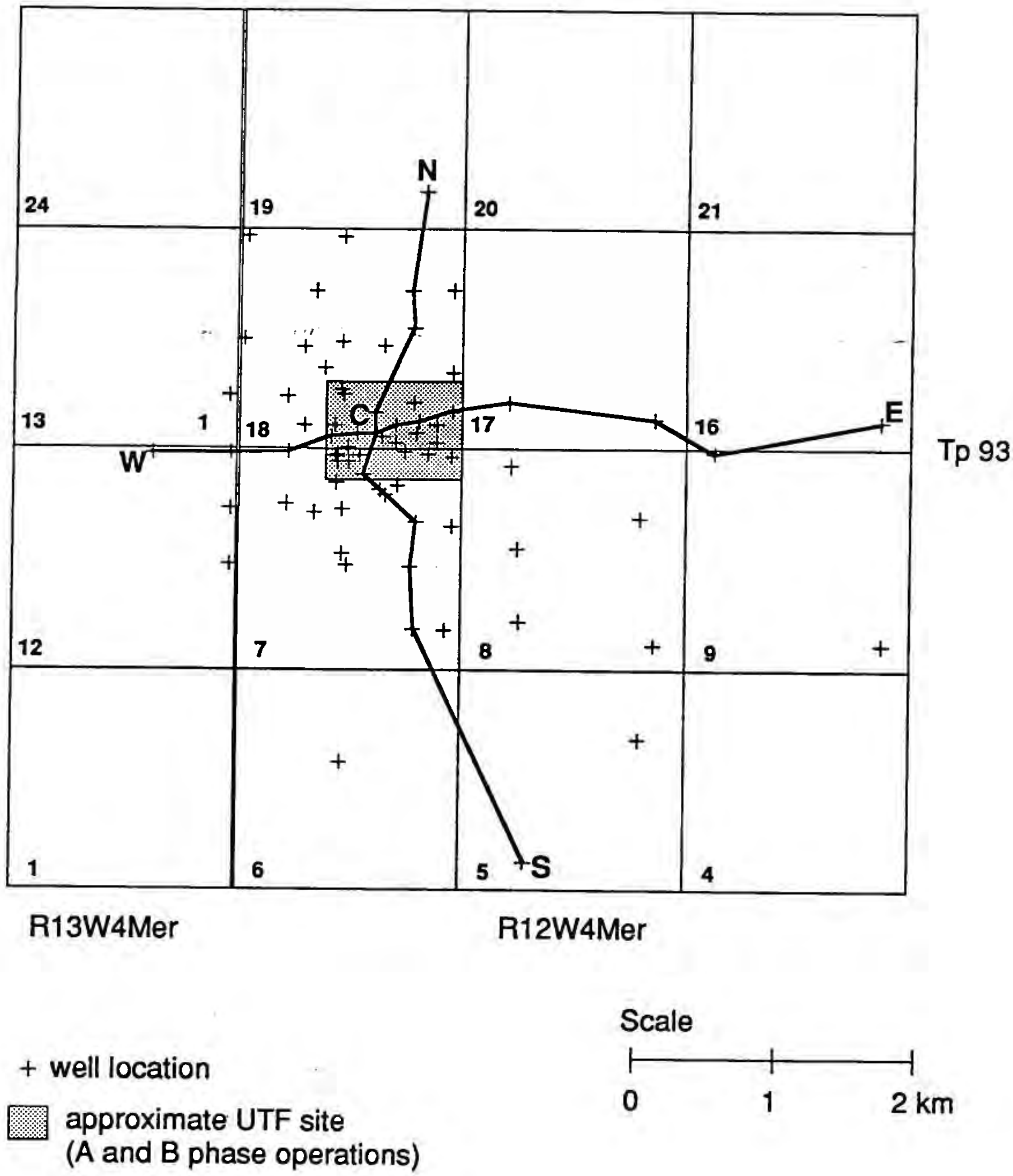

Figure 3. Well distribution and lines of cross-section in the detail-scale study area around the UTF.

GEOLOGY

The sedimentary succession in the detail-scale study area around the UTF site is broadly divided into Paleozoic Devonian strata dominated by evaporites and carbonates deposited during the passive-margin stage of basin evolution, and Mesozoic Cretaceous siliciclastic strata deposited during the foreland-basin stage. Tertiary to Recent unconsolidated sediments cover the bedrock. Only the post-Devonian geology and hydrogeology is examined in this study because its main purpose is the assessment of the possibility of shallow groundwater contamination by fluids which may escape from the steaming chambers used for bitumen recovery from the Cretaceous McMurray oil sand deposits.

The geological model of the post-Devonian strata in the study area was constructed using the stratigraphic picks, listed in Appendix A, from the wells drilled by AOSTRA in the area. Table 1 presents the stratigraphy, dominant lithology and hydrostratigraphy of the post-Devonian sedimentary succession in the detail-scale study area around the UTF. The Cretaceous strata unconformably overlie the limestone Waterways Formation of the Devonian Beaverhill Lake Group. Because of pre-Cretaceous erosion, the surface of the sub-Cretaceous Unconformity in the study area shows a mild relief in the 10-15 m range (Figure 4). The UTF siting generally corresponds to a relatively flat high on the sub-Cretaceous Unconformity surface. Erosional relief on the unconformity exercised a major influence on subsequent deposition of Cretaceous strata.

McMURRAY FORMATION

Infill of the pre-Cretaceous paleotopography is the most important factor in the facies development of the McMurray Formation. In the Athabasca area, the McMurray Formation has generally been divided into three members based on depositional environments (Flach, 1984), which range from fluvial to estuarine and finally to nearshore marine as the Cretaceous Clearwater sea transgressed from the north. Within the study area, the McMurray Formation is primarily an estuarine channel and comprises thick,

<table>
<tr><th>PERIOD</th><th colspan="3">STRATIGRAPHY</th><th>LITHOLOGY</th><th>HYDROSTRATIGRAPHY</th></tr>
<tr><td>Quaternary</td><td colspan="3">Glacial deposits</td><td>sand and gravel</td><td>post-Cretaceous aquifer/aquitard</td></tr>
<tr><td rowspan="6">Cretaceous</td><td rowspan="6">Mannville Group</td><td colspan="2">Grand Rapids Fm.</td><td>sandstone and shale</td><td>Grand Rapids aquifer-aquitard</td></tr>
<tr><td rowspan="4">Clearwater Fm.</td><td></td><td>Shale</td><td rowspan="2">Clearwater aquitard</td></tr>
<tr><td rowspan="3">Wabiskaw Member</td><td>Shale</td></tr>
<tr><td>Sandstone</td><td>Wabiskaw aquifer</td></tr>
<tr><td>Shale</td><td>Wabiskaw aquitard</td></tr>
<tr><td colspan="2">McMurray Fm.</td><td>Bitumen-saturated sand</td><td>McMurray aquitard</td></tr>
<tr><td>Devonian</td><td colspan="3">Waterways Fm</td><td>Limestone</td><td></td></tr>
</table>

Table 1. Stratigraphy, lithology and hydrostratigraphy of the post-Devonian sedimentary succession at the UTF site.

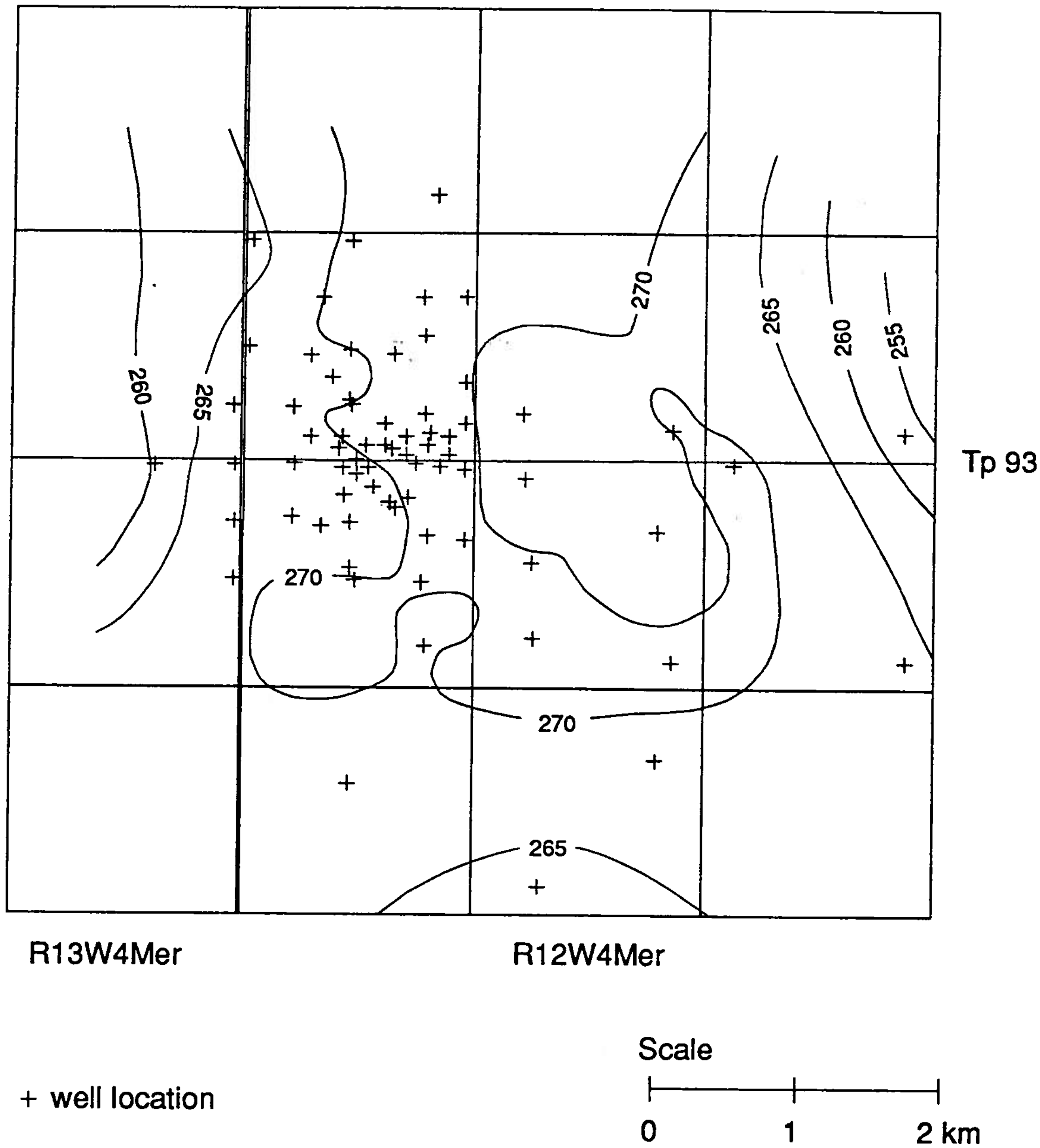

Figure 4. Structure on the top of the sub-Cretaceous unconformity (contour interval: 5 m).

sandy, relatively clean, bitumen-saturated upward fining successions. The structure-top map of the McMurray Formation (Figure 5) shows a local high trending southeastward from the center of the study area.

CLEARWATER FORMATION

The Clearwater Formation disconformably overlies the McMurray Formation and consists of predominantly black to greenish grey shales interbedded with commonly glauconitic sands and silts. At the base of the Clearwater Formation is the Wabiskaw Member. A lower wedge dominated by light to dark grey shale contains isolated, bitumen-saturated sand lenses. The structure-top of this wedge (Figure 6) closely mimics the structure on the top of the McMurray Formation (Figure 5), with a local high in the central and southeastern parts of the study area. The dominantly-shale wedge is overlain by a water-saturated, upward coarsening sandy unit which is gradational with the shale at its base. The Wabiskaw Sandstone unit is thin and consists of medium- to coarse-grained, massive-to-bedded, salt-and-pepper sand which contains some glauconite. The structure on the top of this unit (Figure 7) again closely follows the structures of the underlying Wabiskaw shale wedge (Figure 6) and McMurray Formation (Figure 5). The Wabiskaw Sandstone unit forms a gradational contact with the predominantly shaly remainder of the Clearwater Formation.

The remainder of the Clearwater Formation above the Wabiskaw Member consists of a shaly unit interbedded with sand and silt, and two upward-coarsening sequences which are typically gradational from shale at the base to fine-grained sand or silt at the top. The top of the lower sequence consists of a black shale, approximately two metres thick, which is easily identifiable on resistivity logs. The top of the Clearwater Formation is marked by a thick (5 to 6 m) shale at the top of the upper sequence. Tertiary-to-Recent erosion has removed portions of the Clearwater Formation in some places; however, the erosion is not deep enough to reach the Wabiskaw Member. The structure on the top of the Clearwater Formation (Figure 8) clearly indicates a channel-like erosional feature

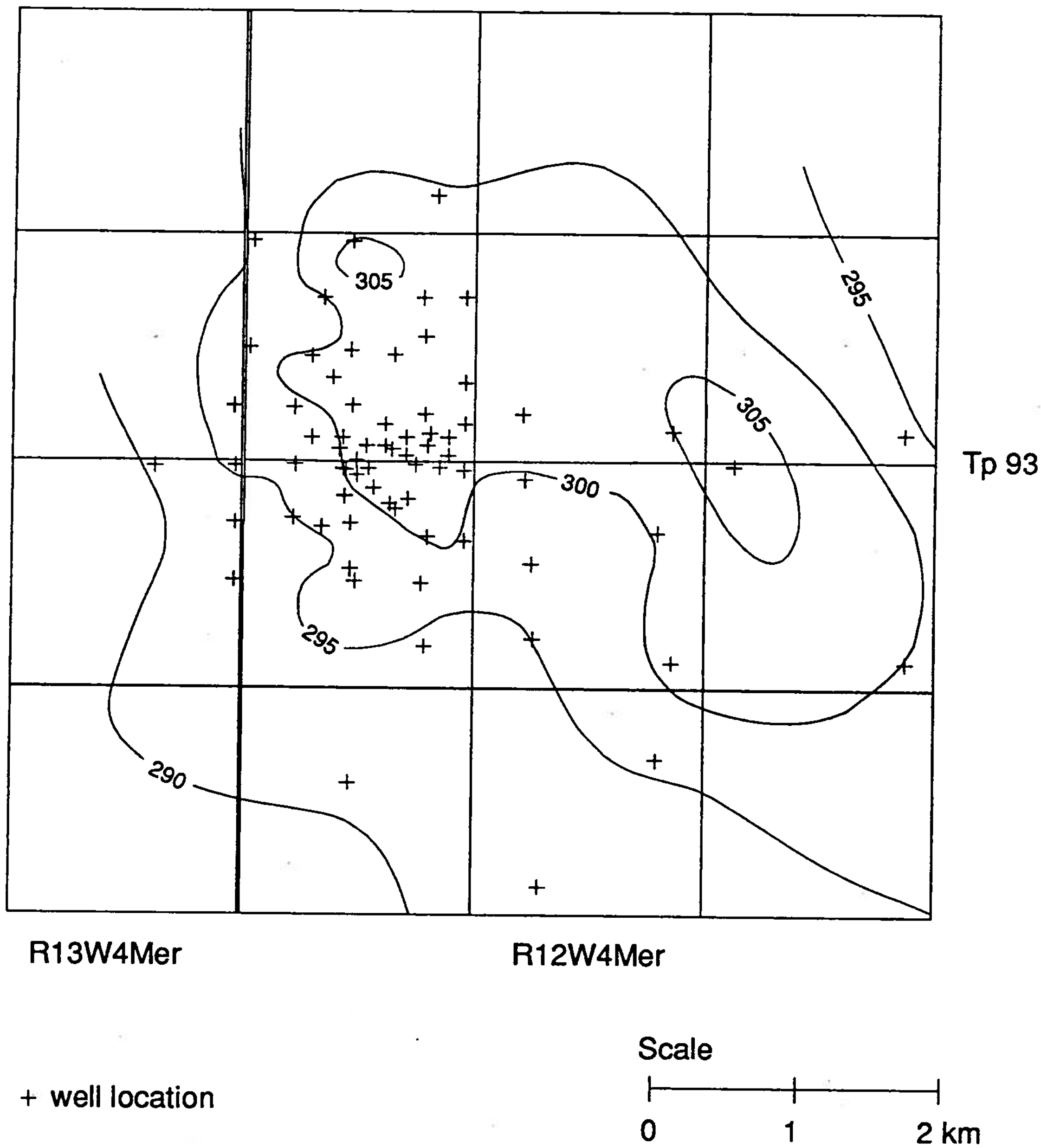

Figure 5. Structure on the top of the McMurray Formation (contour interval: 5 m).

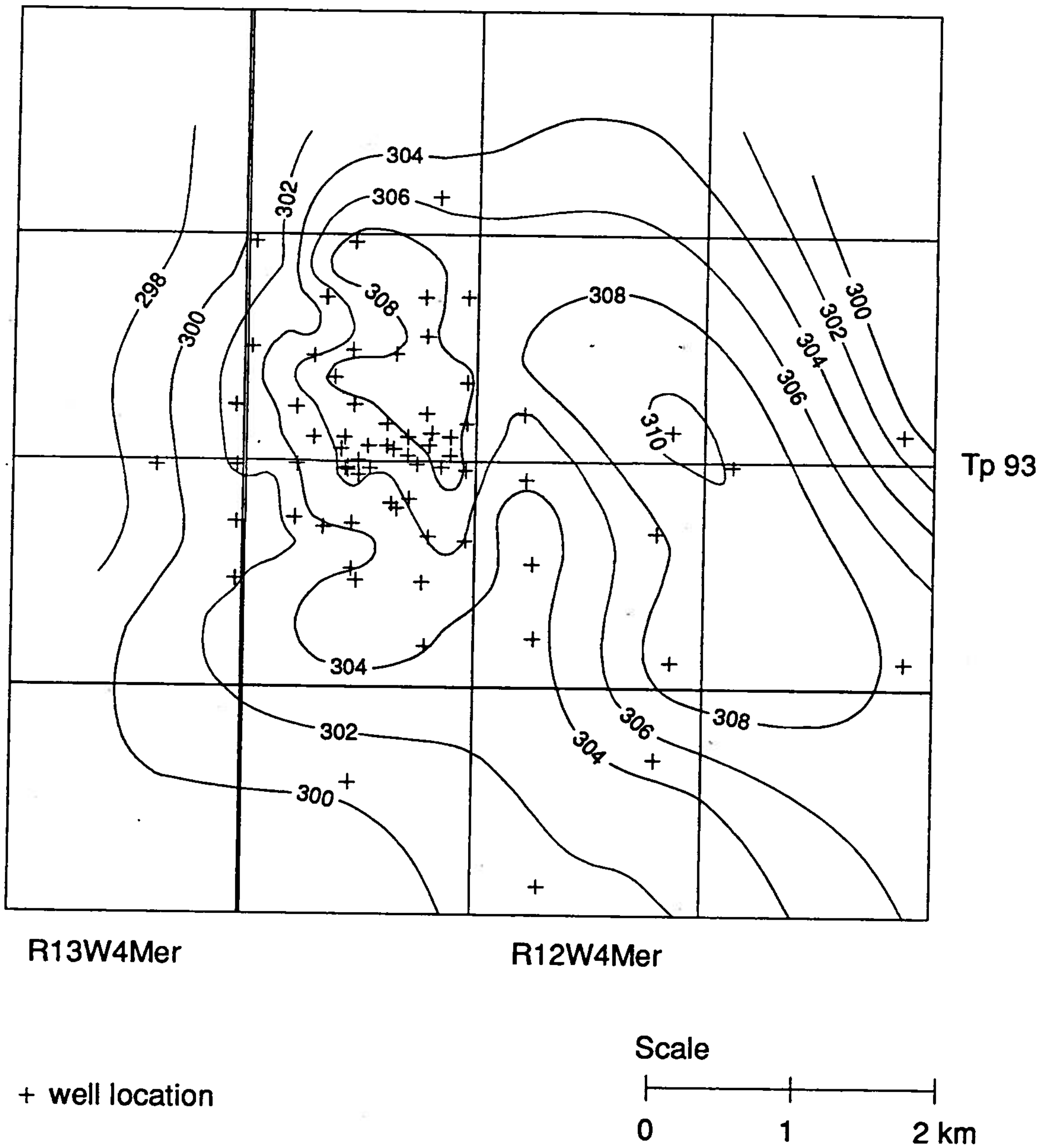

Figure 6. Structure on the top of the first shale layer of the Wabiskaw Member (contour interval: 2 m).

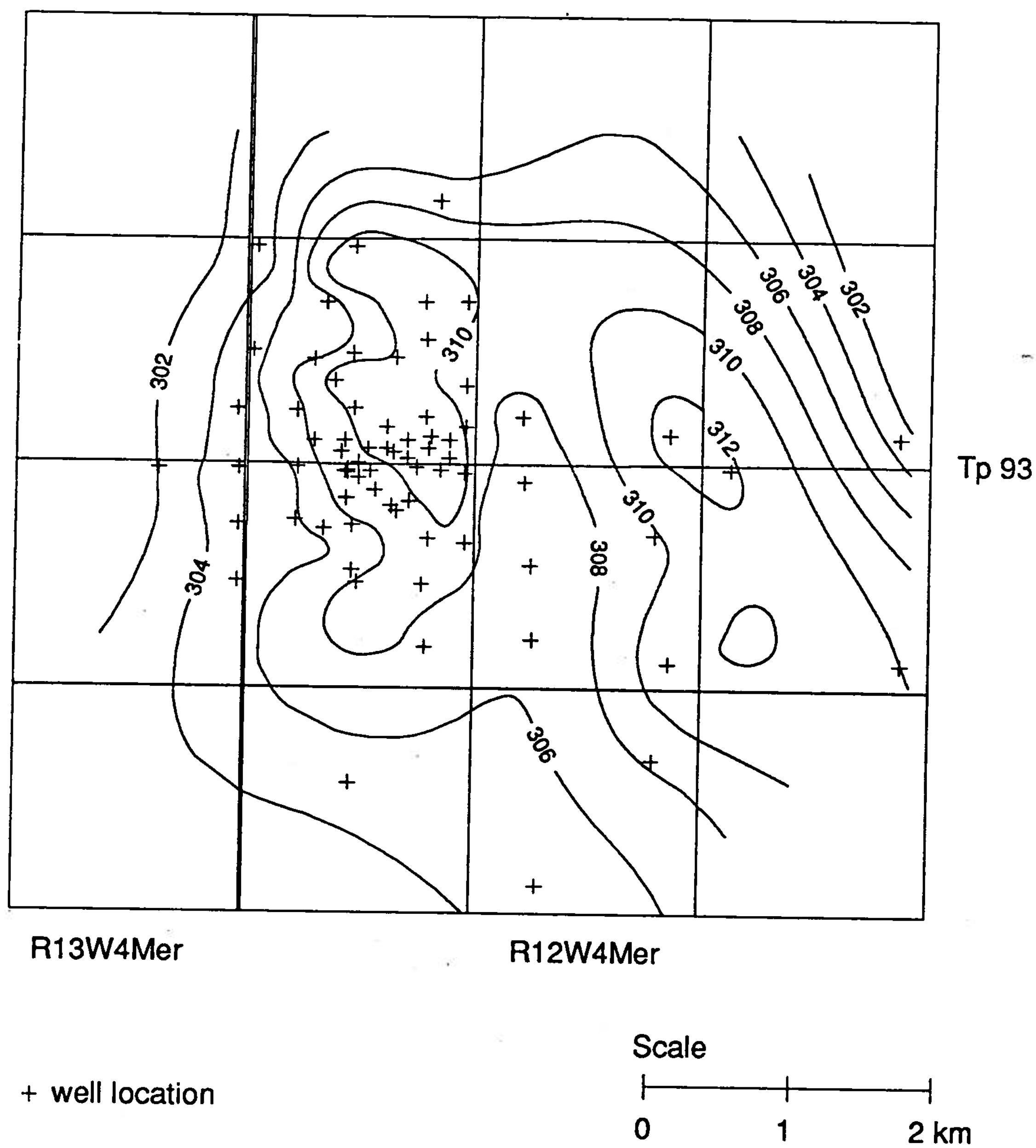

Figure 7. Structure on the top of the sandstone layer of the Wabiskaw Member (contour interval: 2 m).

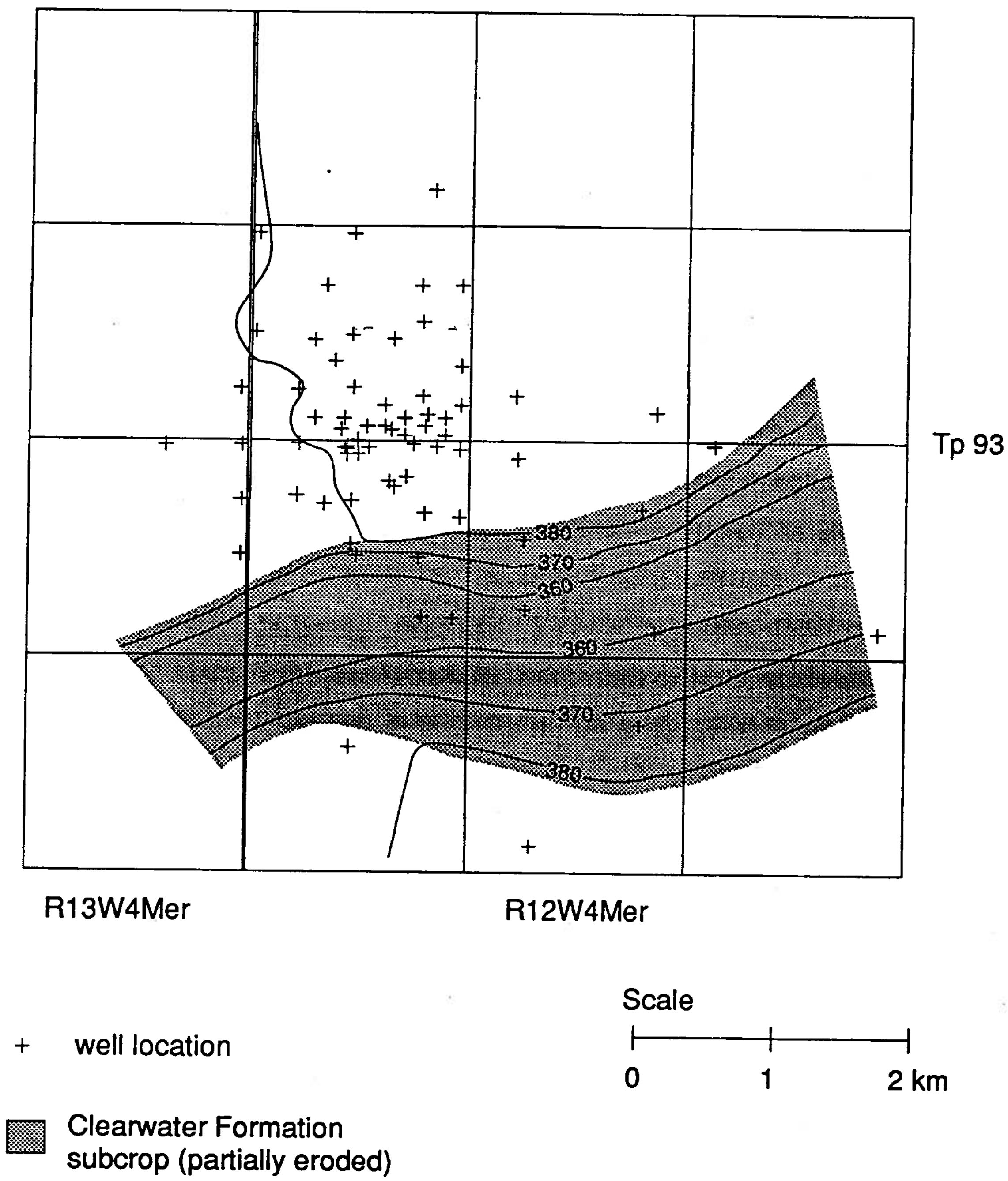

Figure 8. Structure on the top on the of the Clearwater Formation (contour interval: 10 m).

(more than 20 m incision) crossing the study area from east to west in its south-central part. The UTF site is located on the northern flank of the erosional channel suggested by the Clearwater Formation structure top.

GRAND RAPIDS FORMATION

The Grand Rapids Formation conformably overlies the Clearwater Formation and comprises thin, interbedded dark-grey to black shales and light grey sands. This predominantly shaly blocky unit forms the top of the bedrock except in the area where it has been removed by Tertiary-to-Recent erosion. In this area, the eroded top of the Clearwater Formation constitutes the top of the bedrock. Figure 9 shows the structure on the top of the bedrock, with the shaded area indicating where the Grand Rapids Formation is absent and the Clearwater Formation underlies the post-Cretaceous unconsolidated sediments. Everywhere else the Grand Rapids Formation is present throughout the study area as far as the well data distribution can ascertain.

UNCONSOLIDATED DRIFT

Post-Cretaceous erosion and deposition has left a relatively thin layer of unconsolidated sediments over the study area. In the south-central region of the study area, an incised Pleistocene paleo-channel is filled with thick deposits mostly of glacial origin. The channel is buried in the sense that overlying surficial deposits mask its existence. The glacial deposits include (Norwest Resources Consultants, 1983): moraine (mostly till) deposited directly by the glaciers, glacio-fluvial deposits (silty outwash sand and gravel) laid down by glacial meltwater, and glacio-lacustrine deposits (interbedded clay, silt and sand). Since glacial retreat, the surficial deposits have been modified by a variety of erosional and depositional processes. Very little information regarding the lithology of the unconsolidated sediments is available because many of the drill holes in the study area are cased throughout this interval, and the unconsolidated sediments were generally not described in the field. Unconsolidated sediments encountered during drilling in the buried

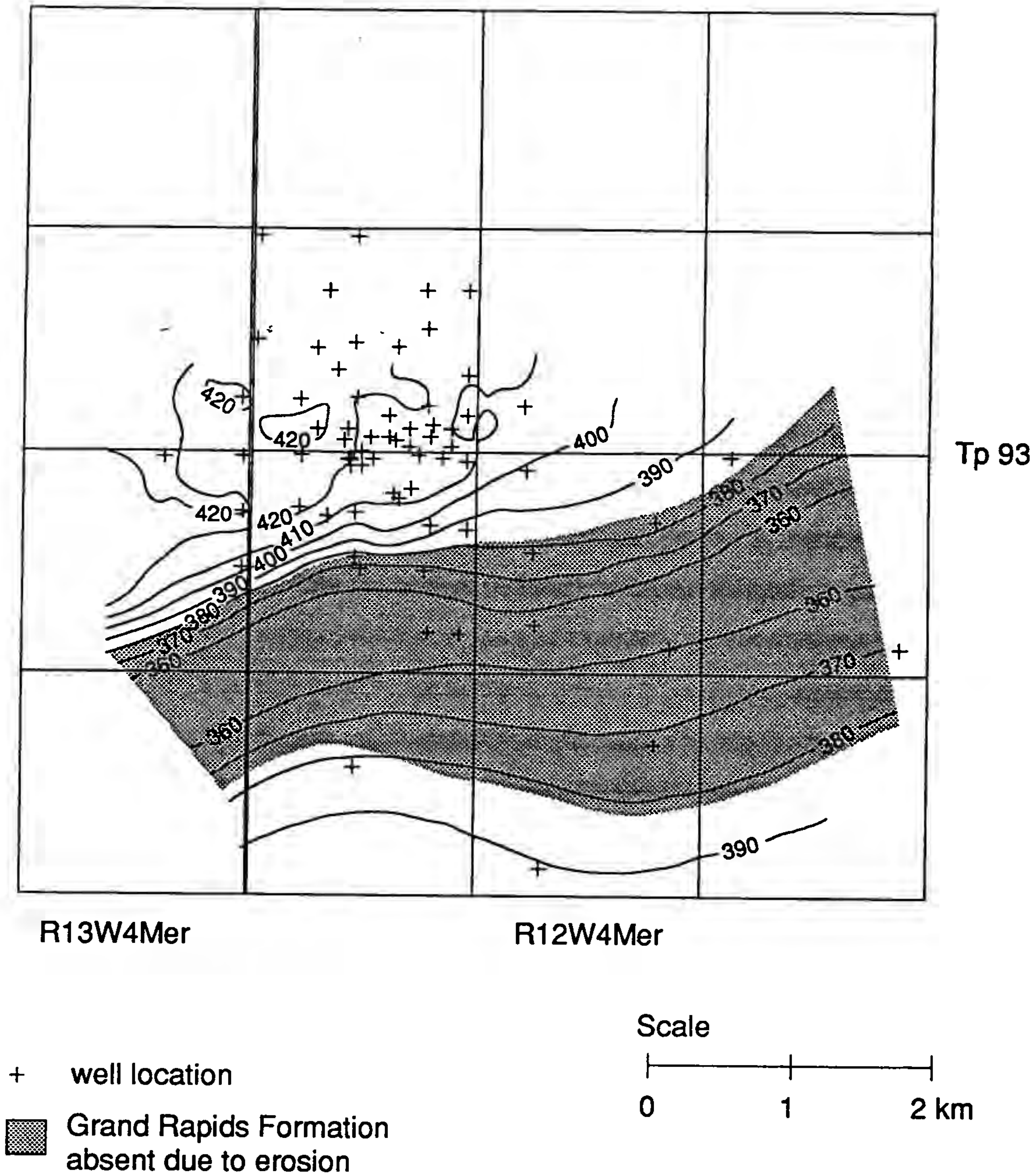

Figure 9. Structure on the top of the bedrock (contour interval: 10 m).

channel at 1-7-93-12W4Mer for water supply (Meneley, 1984) consist of about 15 m of till and glacial stratified sediments overlying approximately 66 m of sand and gravel. A similar buried Pleistocene channel east of the Athabasca River, filled with Pleistocene fluvial sands and gravel, and glacial till, is described by Horne and Seve (1991).

The ground surface (Figure 10) shows a mild relief ranging from more than 440 m elevation in the southwest to less than 380 m elevation in the northeast. The general topographic slope of approximately 1.5% drops toward the McKay and Athabasca rivers situated east of the study area. Figures 11 and 12 show representative cross sections through the post-Devonian sedimentary succession in the detail-scale study area. The lines of cross section (Figure 3) were chosen to be representative of the stratigraphic and hydrostratigraphic structure of the post-Devonian strata in the study area, to pass through the actual UTF site, and to include information from monitoring piezometers installed throughout the area. Figures 11 and 12 show the considerable thickness of the Clearwater Formation compared with other units. The UTF is located on high ground (Figures 10 and 11) at an elevation of approximately 430 m, on the northern flank of the buried channel where the entire Cretaceous Mannville Group succession (McMurray to Grand Rapids) is present (Figures 11 and 12).

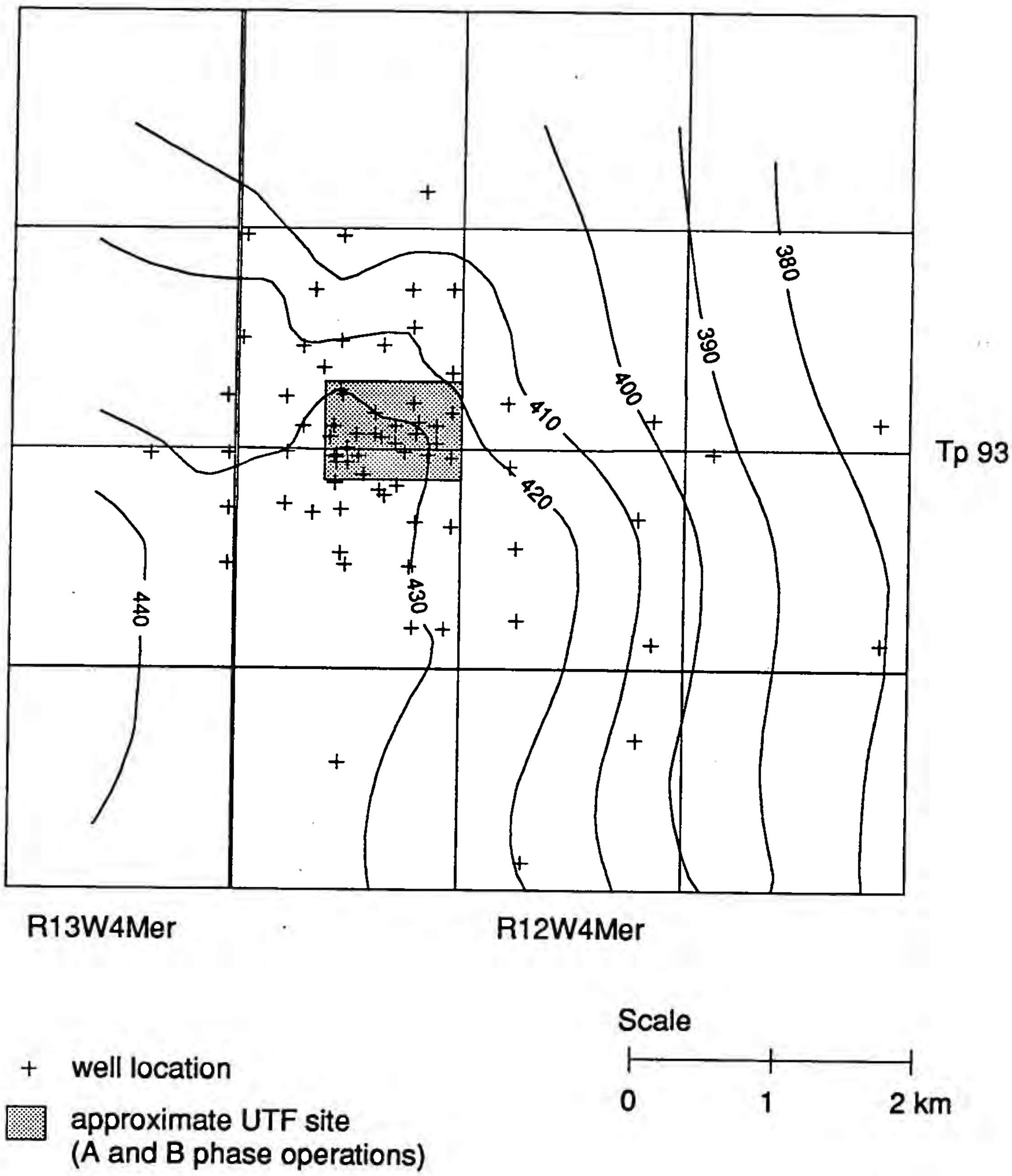

Figure 10. Ground surface elevation map (contour interval: 10 m).

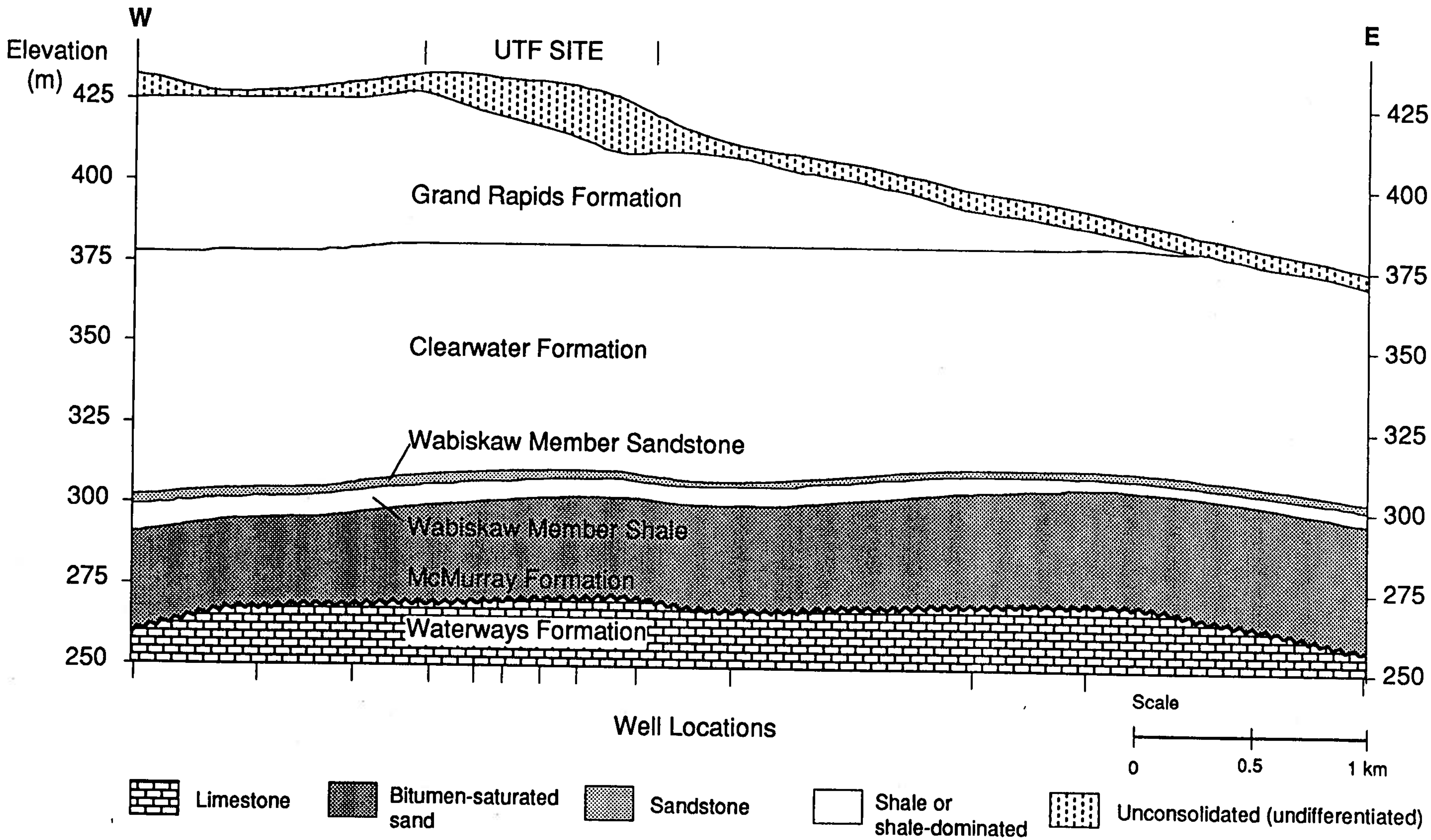

Figure 11. West-east cross section through the post-Devonian strata in the study area.

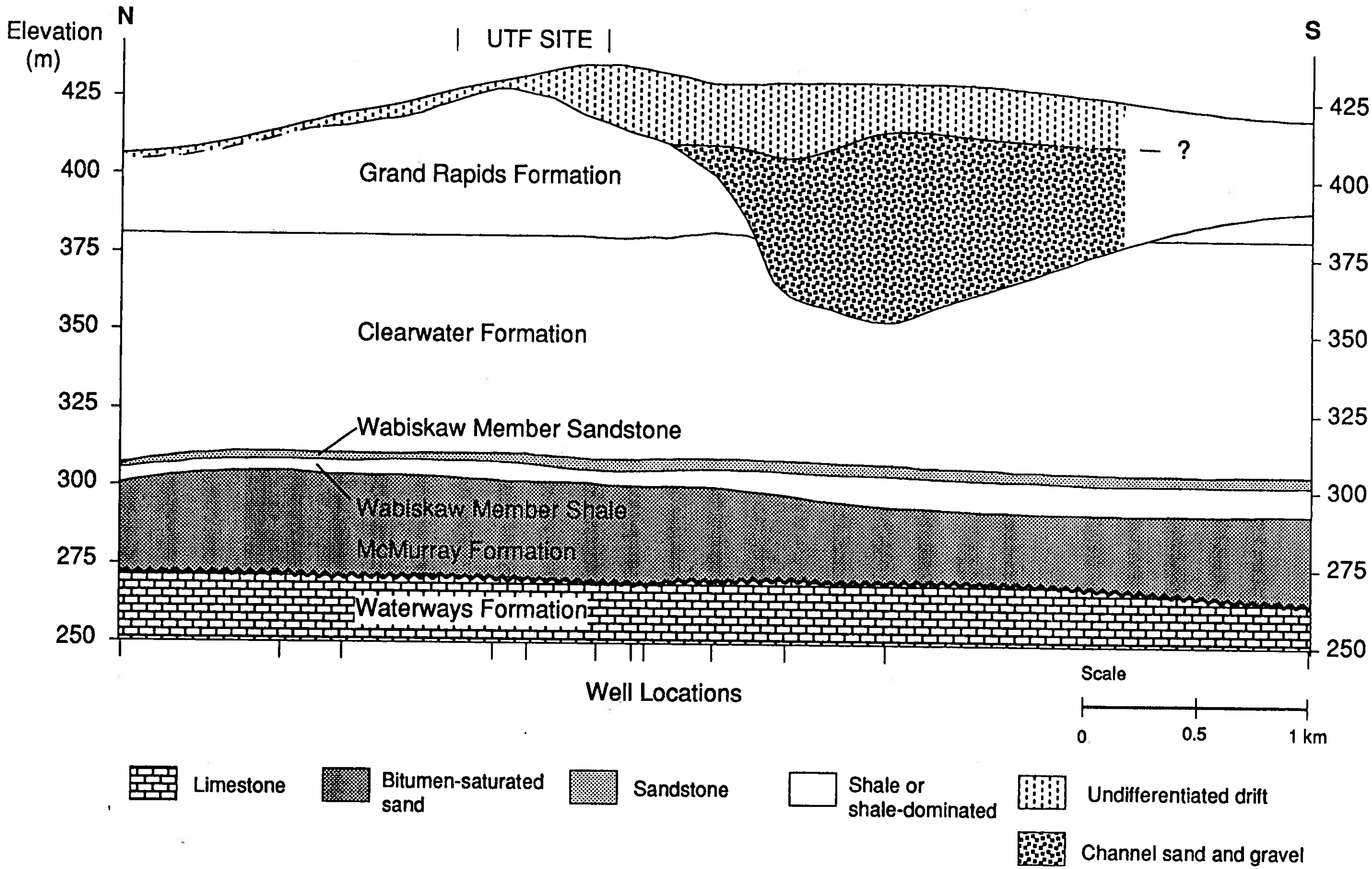

Figure 12. North-south cross section through the post-Devonian strata in the study area.

HYDROGEOLOGY

The hydrogeological model of the post-Devonian strata in the study area is based on the hydrostratigraphic delineation determined mainly from the lithological characteristics of the sedimentary succession, on rock properties determined from core analyses and pumping tests, and on water levels observed in a network of piezometers and water wells installed with the purpose of monitoring the effects of extracting bitumen using the SAGD process.

An aquifer is a layer, formation, or group of formations with a degree of permeability that allows water withdrawal, whereas an aquitard is a less permeable unit from which water cannot be produced through wells, but through which vertical flow is significant enough to feed adjacent aquifers (de Marsily, 1986; p. 115).

HYDROSTRATIGRAPHY

The hydrostratigraphic succession in the detail-scale study area (Table 1) is relatively complex because of the bitumen-saturated sands of the McMurray Formation and Wabiskaw Member, and of interbedded shales in overlying strata. Because of the high content (more than 6% weight) of the extremely viscous bitumen filling the pore space in the McMurray Formation sands, the McMurray Formation has aquitard characteristics in the study area. The aquitard has an average thickness of about 30 m (Figure 13) (particularly at the UTF site) and shows a general thickening to the northeast. The 15 to 20 m difference in thickness is caused mainly by local relief on the underlying surface of the sub-Cretaceous Unconformity. The plug-scale porosity and permeability values obtained from core analyses were scaled-up to the well (formation) scale using generally accepted methodology for scaling up reservoir and aquifer properties (Dagan, 1989; Desbarats and Bachu, 1994). The permeability of the bitumen-free McMurray unconsolidated sand is high, of the order of 4×10^{-12} m^2 (4 darcies), corresponding to a hydraulic conductivity of 4×10^{-5} m/s; however, the solid bitumen filling the pore space renders this unit almost impermeable to water flow. The well-scale porosity of bitumen-free McMurray sands ranges between 25% and 39%, with an average of 33%.

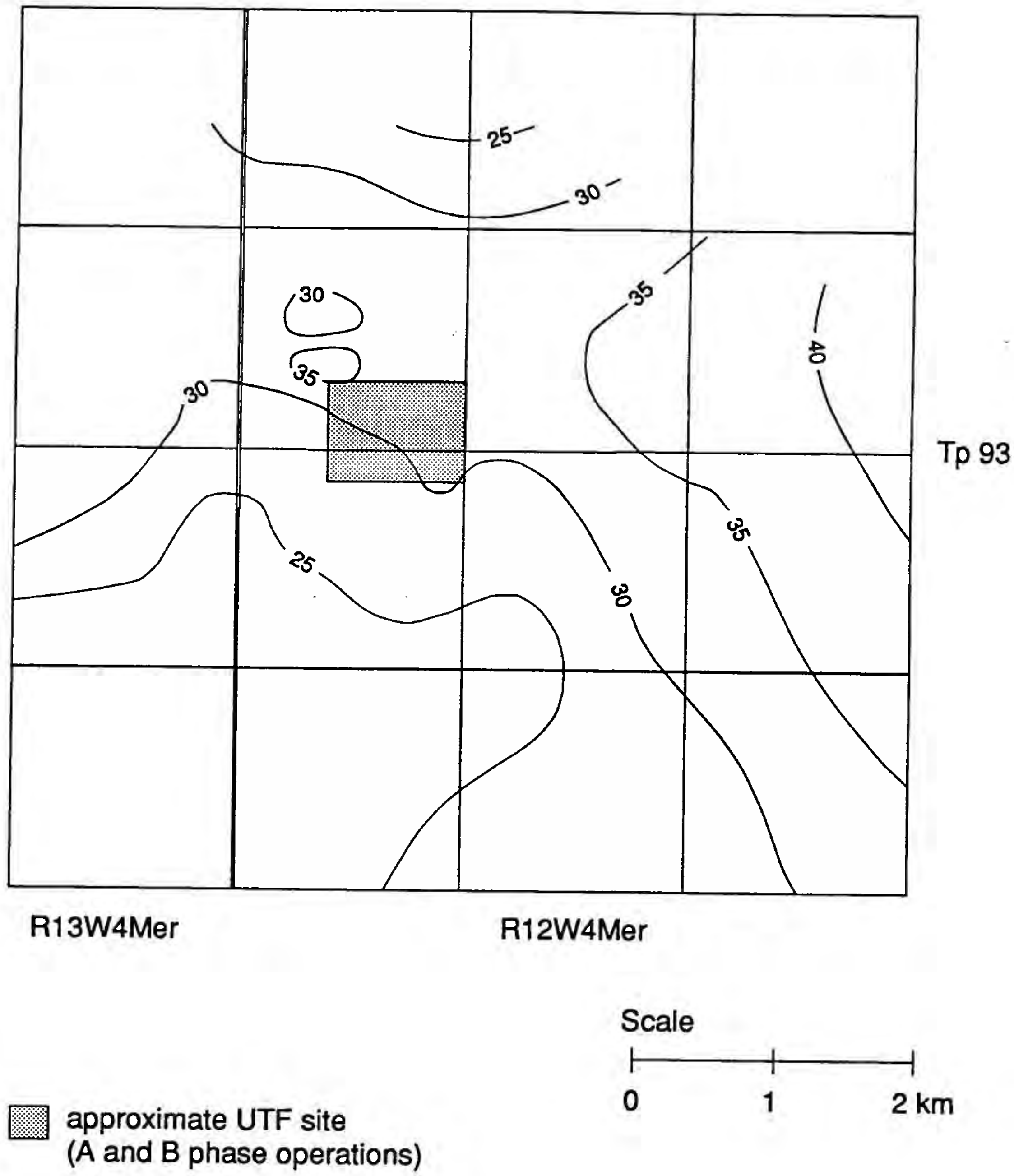

Figure 13. Thickness of the McMurray aquitard (contour interval: 5 m).

The relatively thin layer of Wabiskaw shale (6 m on average, Figure 14), overlying the McMurray bitumen-saturated sands, forms an aquitard which is probably tight. Shale permeability was not directly measured at the UTF site, but data are available for Cretaceous shales elsewhere in Alberta. A laboratory permeameter test conducted on one shale sample taken from bedrock strata north of the UTF site indicates a permeability value of 7×10^{-18} m^2 (7×10^{-6} darcies), corresponding to a hydraulic conductivity value of 7×10^{-11} m/s (Hardy Associates (1978) Ltd., 1984). Laboratory-derived permeability values for Lower Cretaceous shales in western Canada range from 10^{-22} to 10^{-17} m^2 (10^{-10}-10^{-5} darcies), corresponding to hydraulic conductivity values of 10^{-15} to 10^{-10} m/s (Neuzil, 1994). Inverse permeability estimates based on numerical modelling suggest large-scale values one order of magnitude higher than the laboratory ones (Neuzil, 1994), which would account for features like microfractures not captured in plug measurements.

The Wabiskaw aquitard is overlain in turn by the thin (3 m on average, Figure 15) Wabiskaw sandstone aquifer. Its permeability, measured in core and scaled-up to the formation scale, is 4×10^{-12} m^2 (4 darcies), corresponding to a hydraulic conductivity of 4×10^{-5} m/s. Drillstem tests performed outside the detail-scale study area indicate the same order of magnitude for permeability (hydraulic conductivity) (Petroleum Geoscience Section, 1993). The well-scale porosity of Wabiskaw sandstone ranges from 24% to 35%, with an average of 30%. The specific storage of the Wabiskaw aquifer was estimated to be of the order of 1×10^{-5} m^{-1} (Petroleum Geoscience Section, 1993).

The shale-dominated upper portion of the Wabiskaw Member and the overlying remainder of the Clearwater Formation form a thick (approximately 70 m) aquitard (Figure 16), except in the area where the top of the Clearwater Formation was removed by Tertiary-to-Recent erosion. The aquitard has a thickness of more than 40 m in the eroded area, as a result of incision by a Pleistocene paleo-channel most probably of glacial origin. At the UTF site, the Clearwater aquitard is thick (more than 70 m, Figure 16).

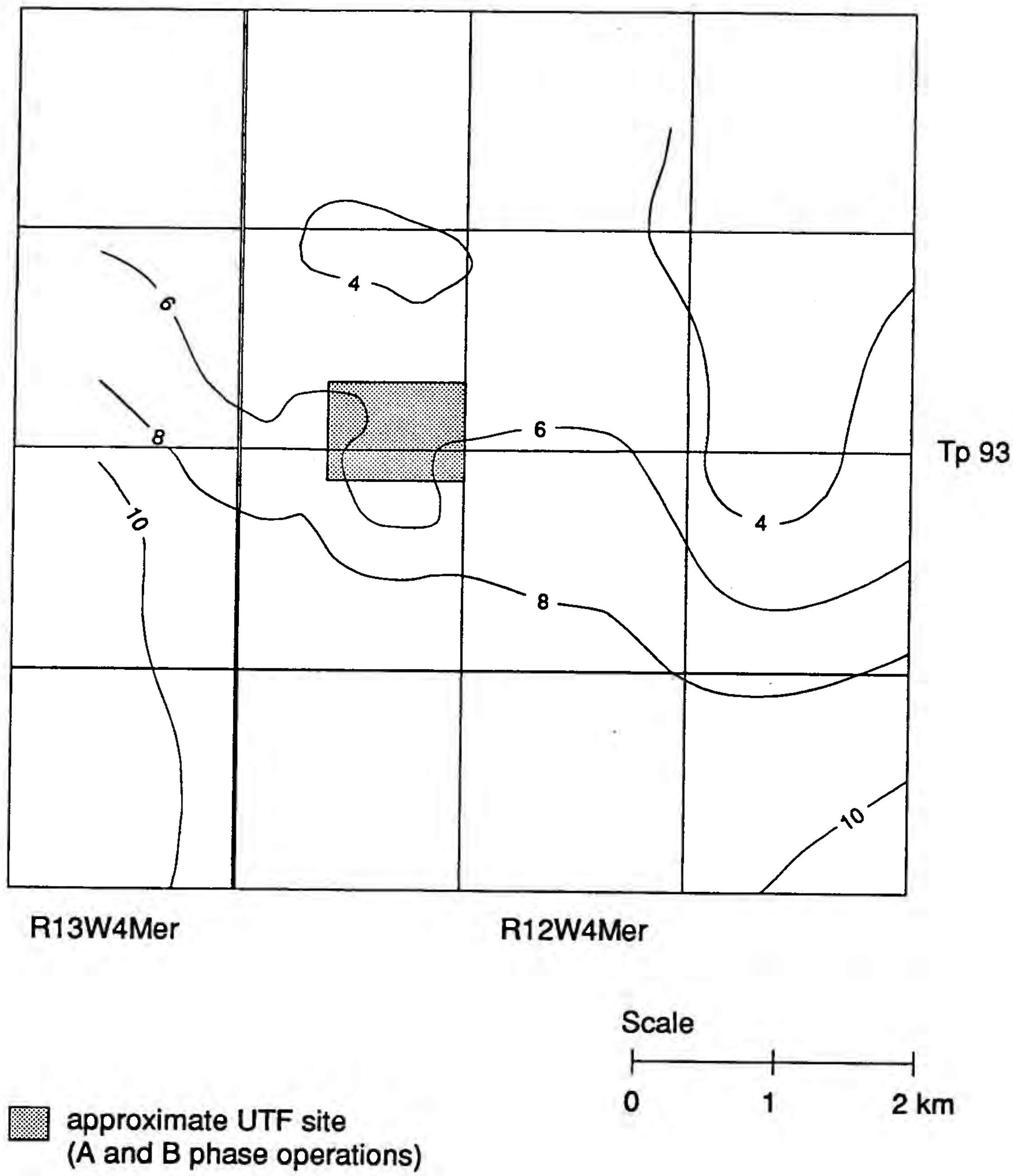

Figure 14: Thickness of the Wabiskaw aquitard (contour interval: 2 m).

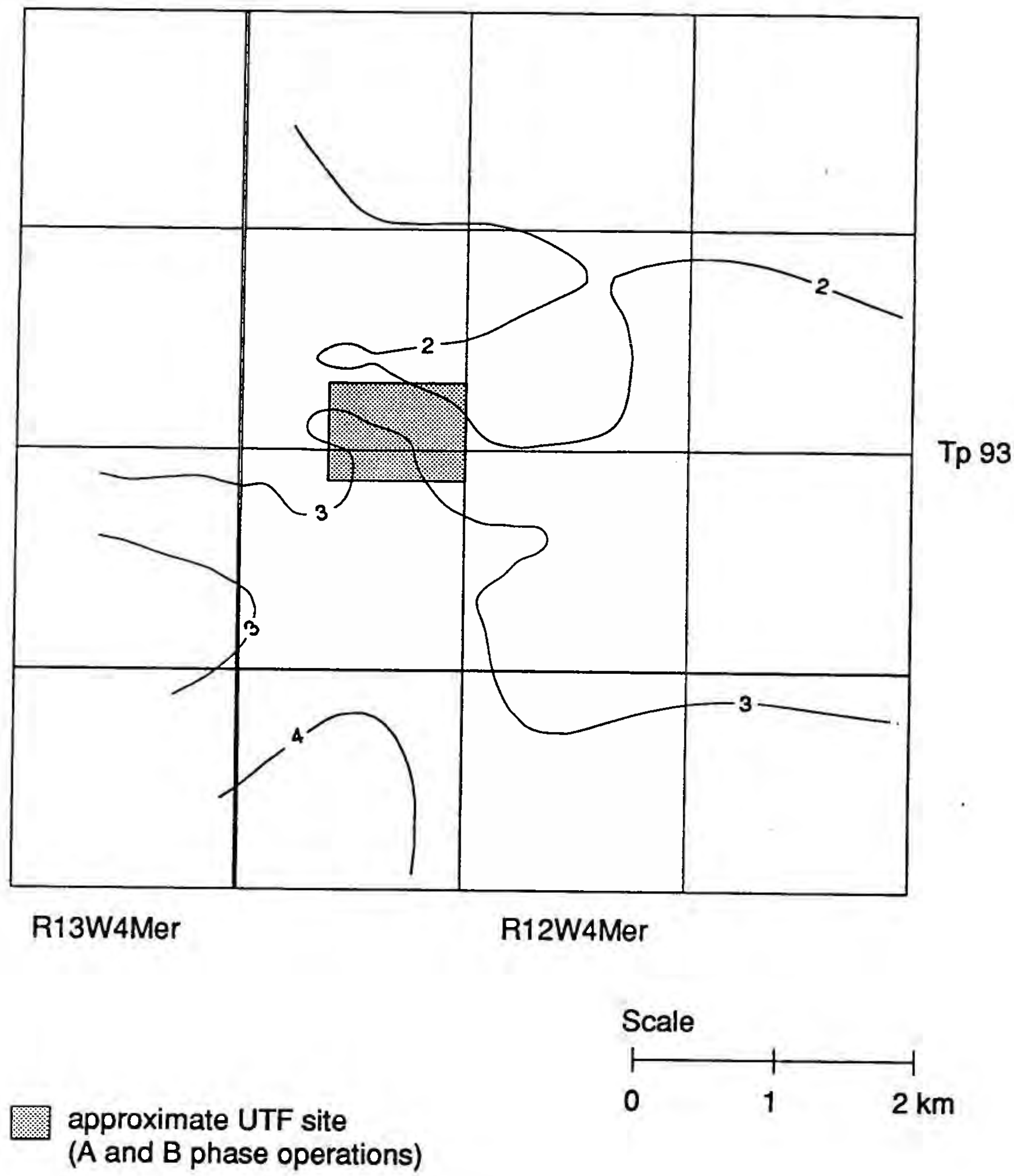

Figure 15. Thickness of the Wabiskaw aquifer (contour interval: 1 m).

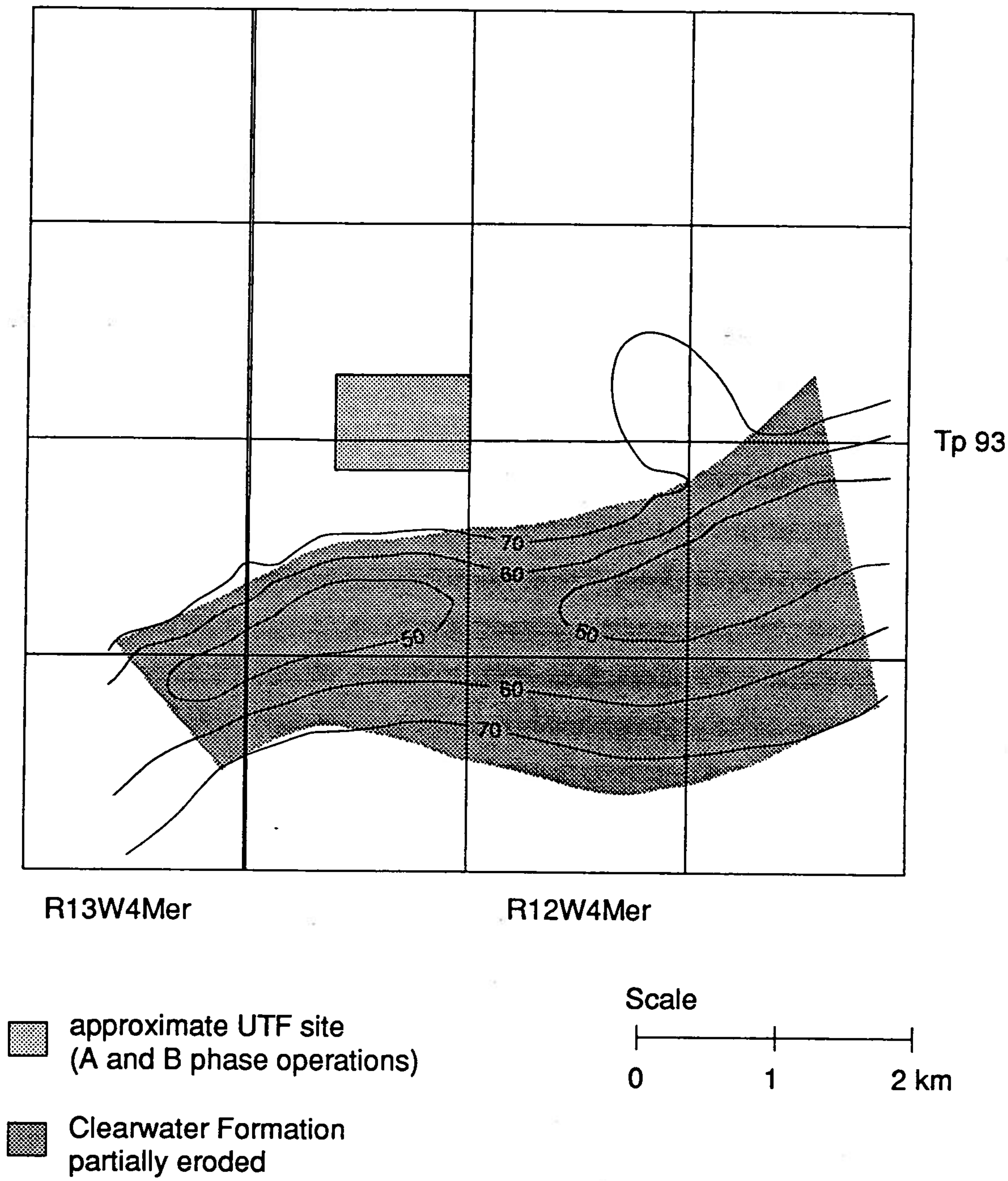

Figure 16. Thickness of the Clearwater aquitard (contour interval: 10 m).

South and north of the erosional incision, the Clearwater aquitard is overlain by the Grand Rapids aquifer-aquitard, classified as such because it consists of interbedded shale and sand layers. However, from the point of view of vertical fluid migration, the Grand Rapids has characteristics more appropriate for an aquitard because of the orientation along bedding of the shale layers (Bachu, 1991). South of the erosional incision, the Grand Rapids is relatively thin (up to slightly more than 10 m in thickness), but its thickness increases rapidly to more than 30 m north of the channel (Figure 17). At the UTF site this unit has a thickness of approximately 35 m. Slug tests performed at shallow depths (upper 5 to 25 m) in the Grand Rapids Formation (Hardy Associates (1978) Ltd., 1984; Piteau Engineering Ltd., 1989) indicate horizontal hydraulic conductivity values in the 9×10^{-8} to 7.7×10^{-7} m/s range, with an average of 2.2×10^{-7} m/s corresponding to an average horizontal permeability of 2.2 darcies. The vertical permeability and corresponding hydraulic conductivity are probably at least one order of magnitude less in this part of the formation. The relatively high permeability (hydraulic conductivity) in the upper part of the Grand Rapids Formation is most probably due to a combination of variable lithology (sand lenses present throughout) and fractures caused by glaciation. In the deeper parts of the Grand Rapids Formation permeability and corresponding hydraulic conductivity values are expected to be at least one order of magnitude less than in the upper part. The presence of extensive shale layers and lenses most probably contribute to lowering the effective vertical permeability of the lower Grand Rapids Formation even more (Bachu, 1991), bringing it closer to permeability values in the underlying Clearwater Formation.

Finally, the post-Cretaceous sediments covering the bedrock form probably two hydrostratigraphic units at the top of the sedimentary succession. The total thickness of the unconsolidated sediments ranges from more than 80 m downdip in the southwest (Figure 18), to less than 10 m along the flanks of the paleo-channel and in areas where the channel is absent, as well as updip to the northeast where the topography drops toward the McKay and Athabasca rivers (Figures 11 and 18). At the UTF site, the thickness of unconsolidated sediments ranges from 2 to 15 m (Figure 18). Precise

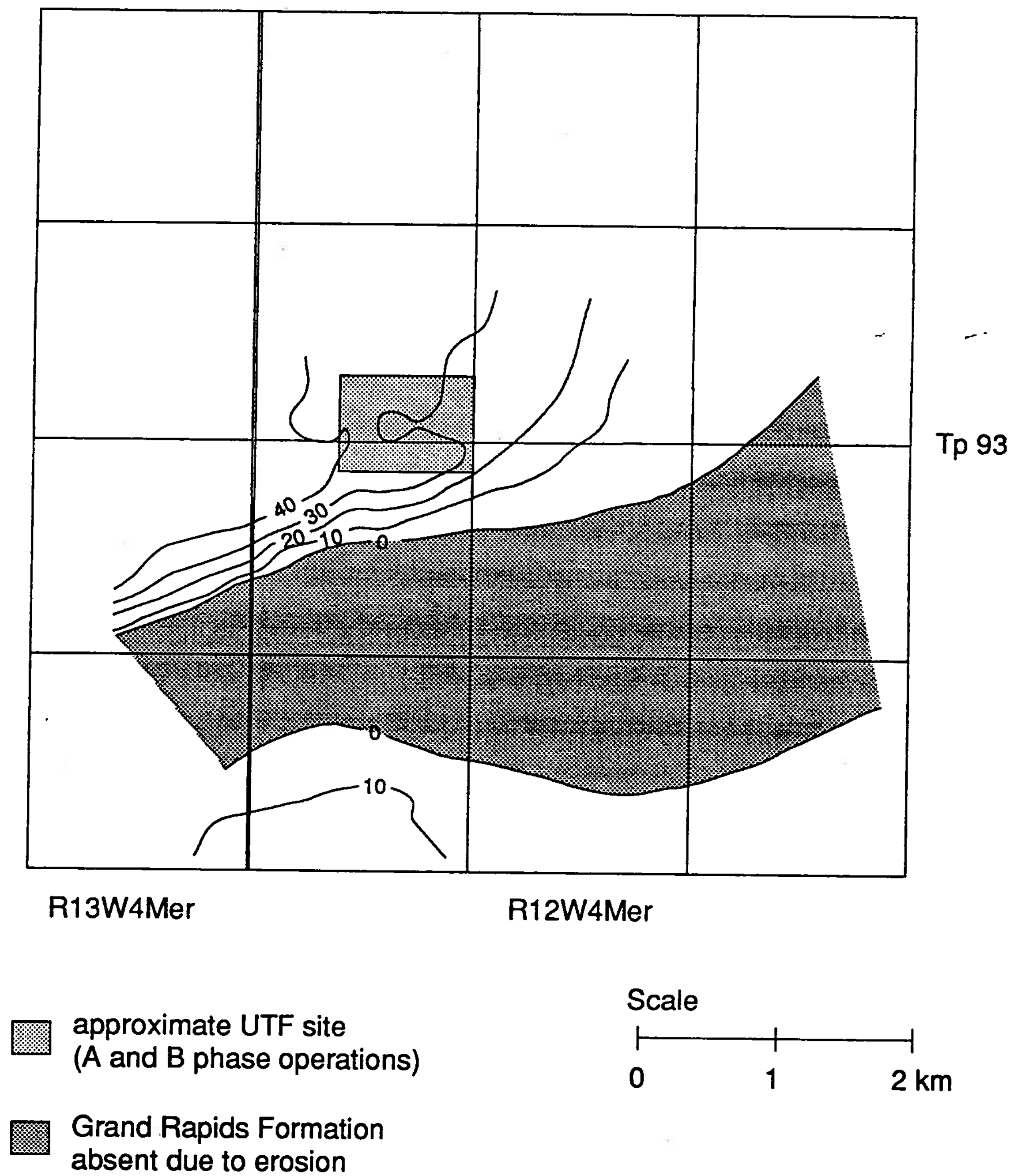

Figure 17. Thickness of the Grand Rapids aquifer-aquitard (contour interval: 10 m).

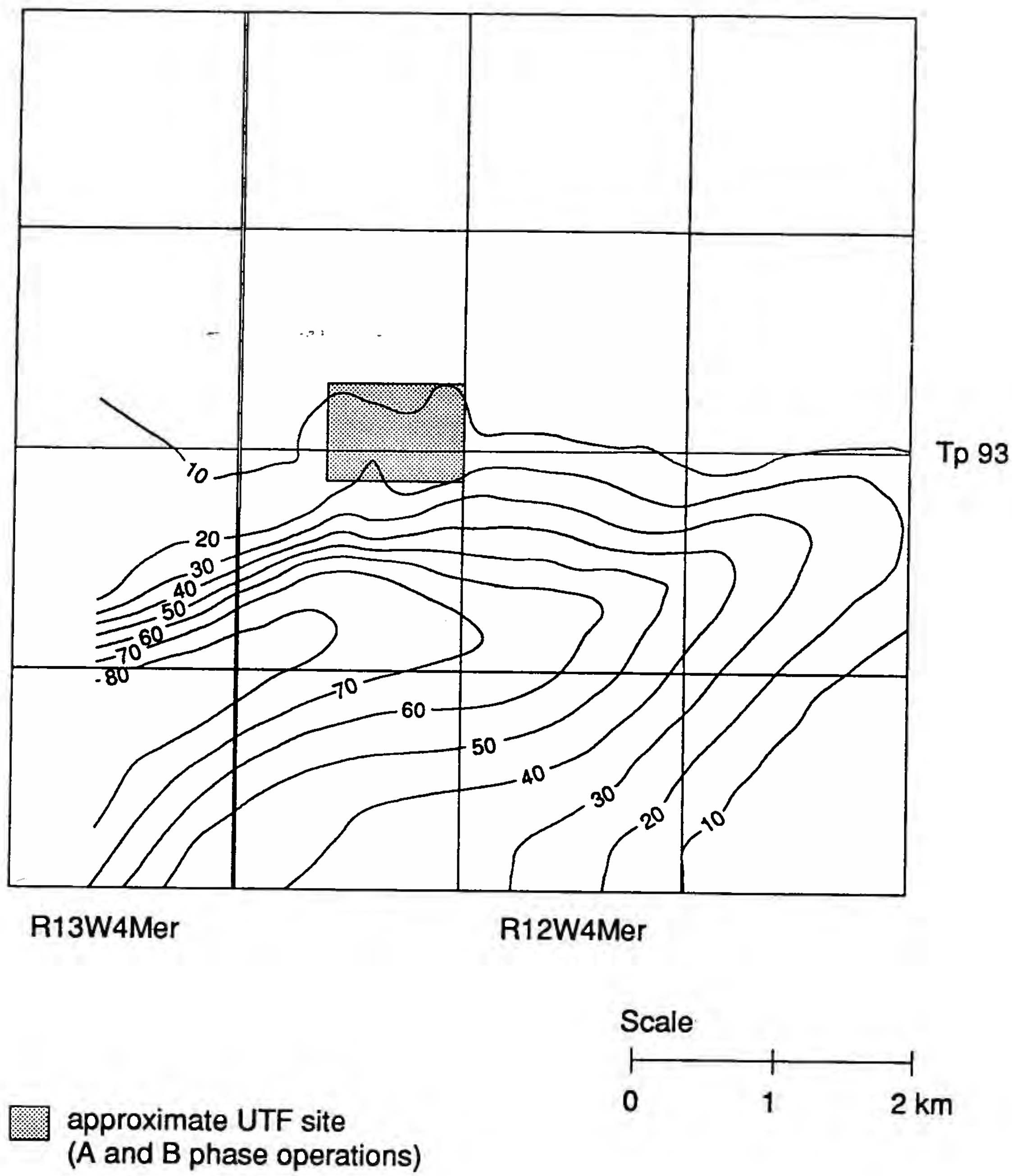

Figure 18. Thickness of the post-Cretaceous unconsolidated sediments (contour interval: 10 m).

delineation of the unconsolidated hydrostratigraphic units is difficult at this time because of a lack of data, but they most probably consist of a thick sand-and-gravel aquifer in the paleo-channel, overlain by a thin aquitard of glacial-till origin, which is overlain in turn by undifferentiated glacial stratified sediments (Meneley, 1984).

Regarding the hydraulic properties of the unconsolidated sediments, a hydraulic test performed in the lower 3 m of the channel fill indicates a permeability of 2 x 10^{-10} m^2 (200 darcies), corresponding to a hydraulic conductivity of 2 x 10^{-3} m/s, and a storage coefficient of 8 x 10^{-2} (Meneley, 1984, 1985). Based on grain size analysis, Hardy Associates (1978) Ltd. (1984) suggests permeability values for sand in the range of 10^{-10} to 10^{-9} m^2 (100-1000 darcies), corresponding to hydraulic conductivity values of 10^{-5} to 10^{-4} m/s, and in the range of 10^{-15} to 10^{-13} m^2 (10^{-3} to 10^{-1} darcies) for till, corresponding to hydraulic conductivities of 10^{-8} to 10^{-6} m/s. Based on hydraulic tests, Piteau Engineering Ltd. (1989) estimates for the surficial deposits a permeability of 10^{-15} to 10^{-14} m^2 (10^{-3} to 10^{-2} darcies), corresponding to hydraulic conductivities of 10^{-8} to 10^{-6} m/s.

GROUNDWATER FLOW

Data Sources and Quality

The analysis of groundwater flow in the post-Devonian sedimentary succession in the study area is based on water levels (hydraulic heads) observed in a network of piezometers which have been installed at different times, and at various stratigraphic levels, within individual formations in the study area. Their distribution is shown on Figure 19 and locations are listed in Appendix B.

The piezometer network was installed during four main programs. First, a series of stand-pipe piezometers was installed at horizons representing all major stratigraphic units of the area (Hardy Associates (1978) Ltd., 1983). These piezometers were installed at drill sites AO4 through AO20 before any other major operations, such as tunnelling and production, occurred at the UTF. Second, a series of vibrating wire piezometers were installed during

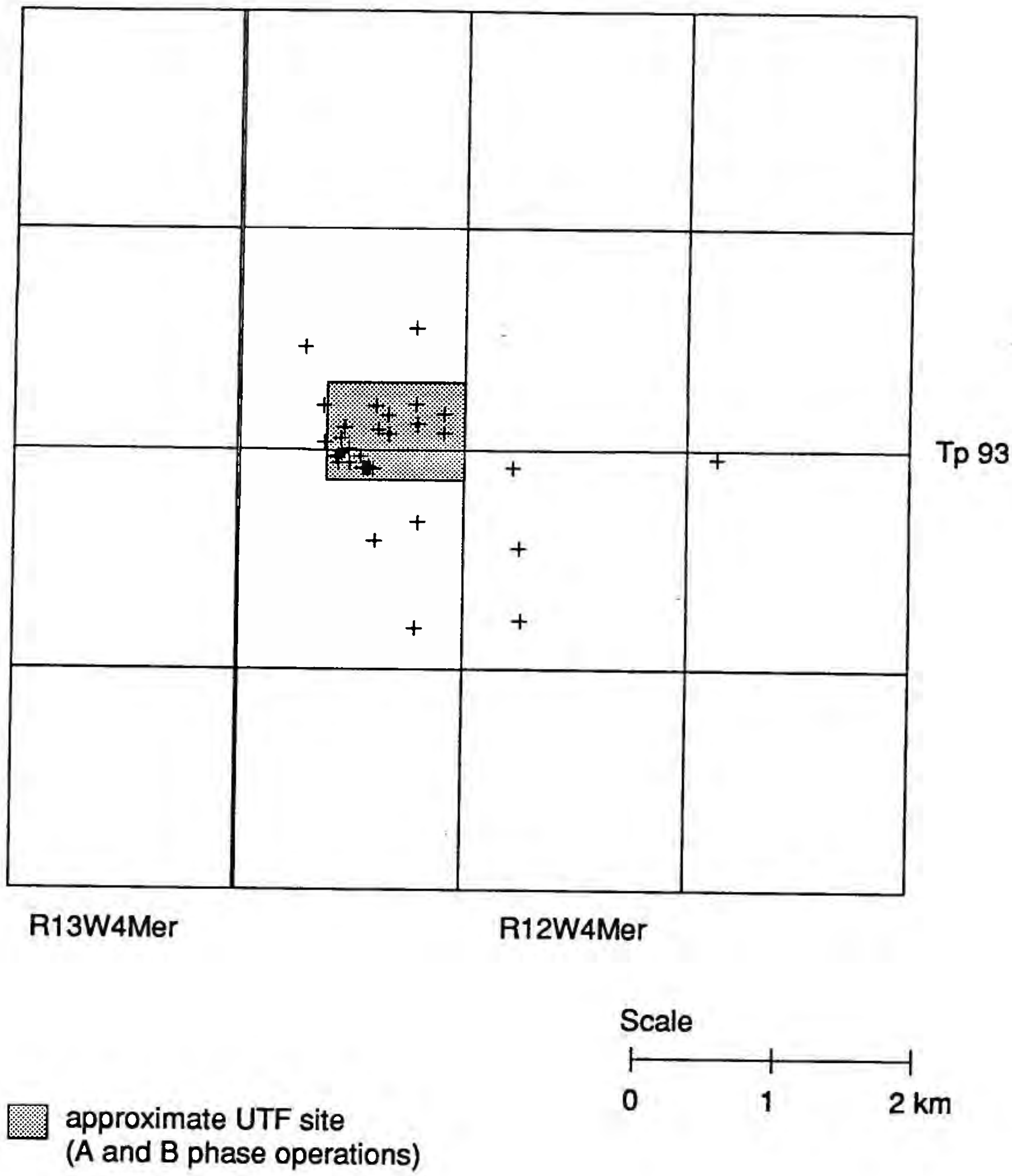

Figure 19. Distribution of monitoring piezometers in the study area.

a major phase of installation of a variety of geotechnical instrumentation in 1987 (AOSTRA, 1988). These piezometers were installed to monitor production effects in the immediate vicinity of Phase A operations in horizons of the Wabiskaw, McMurray and uppermost Devonian strata. This second set of piezometers was installed about two years after access tunnels were constructed in the Devonian limestone. Third, a series of shallow (25 m or less) stand-pipe piezometers were installed in the vicinity of the Phase A Plant Site (Piteau Engineering Ltd., 1989). This set included water table wells and extended from Quaternary strata through uppermost parts of the Grand Rapids Formation sediments. And fourth, a series of vibrating-wire piezometers were installed to monitor effects of Phase B operations in the vicinity of that facility. This last set of piezometers included completions in the Wabiskaw sandstone, McMurray and Devonian strata. A set of piezometers (Site BGB1) was installed about 2.5 km east of the Phase B operation to provide remote baseline information. At this last site the horizons monitored are the lowermost part of the Clearwater Formation, Wabiskaw sandstone and shale, and the sub-Cretaceous unconformity.

Piezometer data were not available to the authors for the entire duration of monitoring, but are representative of the following times or intervals. Data for the first piezometer set (AO Series) were available for February through July of 1983 and represent conditions before any tunnel construction or production began. Data for geotechnical monitoring of Phase A and B operations were one-time readings in December 1987 for Phase A, and during October-November 1991 for Phase B. These readings represent conditions after access tunnels were constructed, but before production began, at the respective sites. Data for Sites BGI3 and BGB1 were also one-time readings for April 1992 and February 1993, respectively. For the Piteau Engineering Ltd. (1989) series of shallow plant-site piezometers, data are available as monitored during 1989 through 1990 (Piteau Engineering Ltd., 1990). The various dates for which piezometer readings were used are given in Appendix B.

From the above discussion it is apparent that some hydraulic heads, particularly those representing horizons in Devonian strata, may be affected by the presence of access tunnels and may not represent pre-construction conditions. Further to this difficulty, the authors found that a number of other problems may have affected the reliability of other water level readings available from the various piezometer installations. These are described in the following paragraphs.

Stand-pipe piezometers of the 1983-AO series were constructed of 1.9, 3.8 and 6.4 cm (nominal .75, 1.5, and 2.5 inch) plastic pipe, and where more than one piezometer was installed at one site, these were installed in one borehole. Because of potential hole-caving problems and to facilitate borehole geophysical logging, drilling mud was maintained in the boreholes for unspecified times before piezometer installations. These conditions could have resulted in filter-caking opposite highly permeable horizons, and inadequate hydraulic communication in low permeability horizons. These conditions, the small diameter of many of the piezometers, and the low permeability of many of the completion horizons, resulted in difficulties in piezometer cleaning and development. For these reasons, some of the water level readings from those piezometers had not stabilized and are not representative of true hydraulic heads (water levels).

In other piezometers, namely AO14 and AO15, which each have completions installed opposite Wabiskaw sandstone and Devonian limestone, water levels in the deep and shallow zones recovered to exactly the same level during the period of monitoring in 1983. A third one (AO10) shows water levels in the Wabiskaw sandstone aquifer slowly approaching those of the higher-up sand and gravel of the buried Pleistocene channel. During field monitoring, Hardy Associates (1978) Ltd. (1983) reported that "equipment failure" prevented monitoring at sites AO4, AO5, AO8, AO9, and AO10. These failures, along with problems associated with AO14 and AO15, may represent the type discussed here. These conditions led the authors to suspect that some form of piezometer failure (for example crushing or fracturing of plastic pipe) may have occurred and that hydraulic communication between horizons of high and low hydraulic head may be occurring by means of such failures. Hydraulic communication of this type could cause artificially high water levels in piezometers completed in some of the deeper units. Persistent communication over a long period of time (several years) could eventually cause hydraulic heads in the deeper geologic units to increase also. Because of these potential problems, water levels reported for piezometers AO4, AO7, AO11, and AO10 have not been used in this study in interpreting the groundwater flow at the UTF site.

The last potential problem regarding piezometric data relates to the accuracy of hydraulic heads obtained from vibrating wire piezometers. The accuracy depends on two factors: a precise knowledge of the elevation at which the piezometer tip is placed, and the accuracy of the piezometer itself. The completion depth of many of these piezometers is in the range of 150 m or more, and it is not unreasonable to expect piezometer tip placement to be within ± 1 m of the targeted horizon. Vibrating-wire piezometers typically have accuracy ranges of some small percent of the total measuring range. Because those installed at the UTF site would have to be capable of reading pressures as high as those generated during production, this range must be quite high and potential error concomitantly so. It is suspected that a further potential error of about ± 5 m may be introduced in this way.

Because of the various potential data problems outlined above, the patterns of hydraulic heads and groundwater flow for the study area can only be crudely determined. The following interpretation and discussion is based only on those piezometric data which the authors believe were not affected by the above mentioned problems. Water level readings that were not used are indicated in Appendix B.

Flow Pattern

The main features of the groundwater flow in the post-Devonian strata in the study area are shown in Figures 20 and 21. Based on information from Piteau Engineering Ltd. (1990), the water table at the UTF plant site ranges in depth from about 3.5 to more than

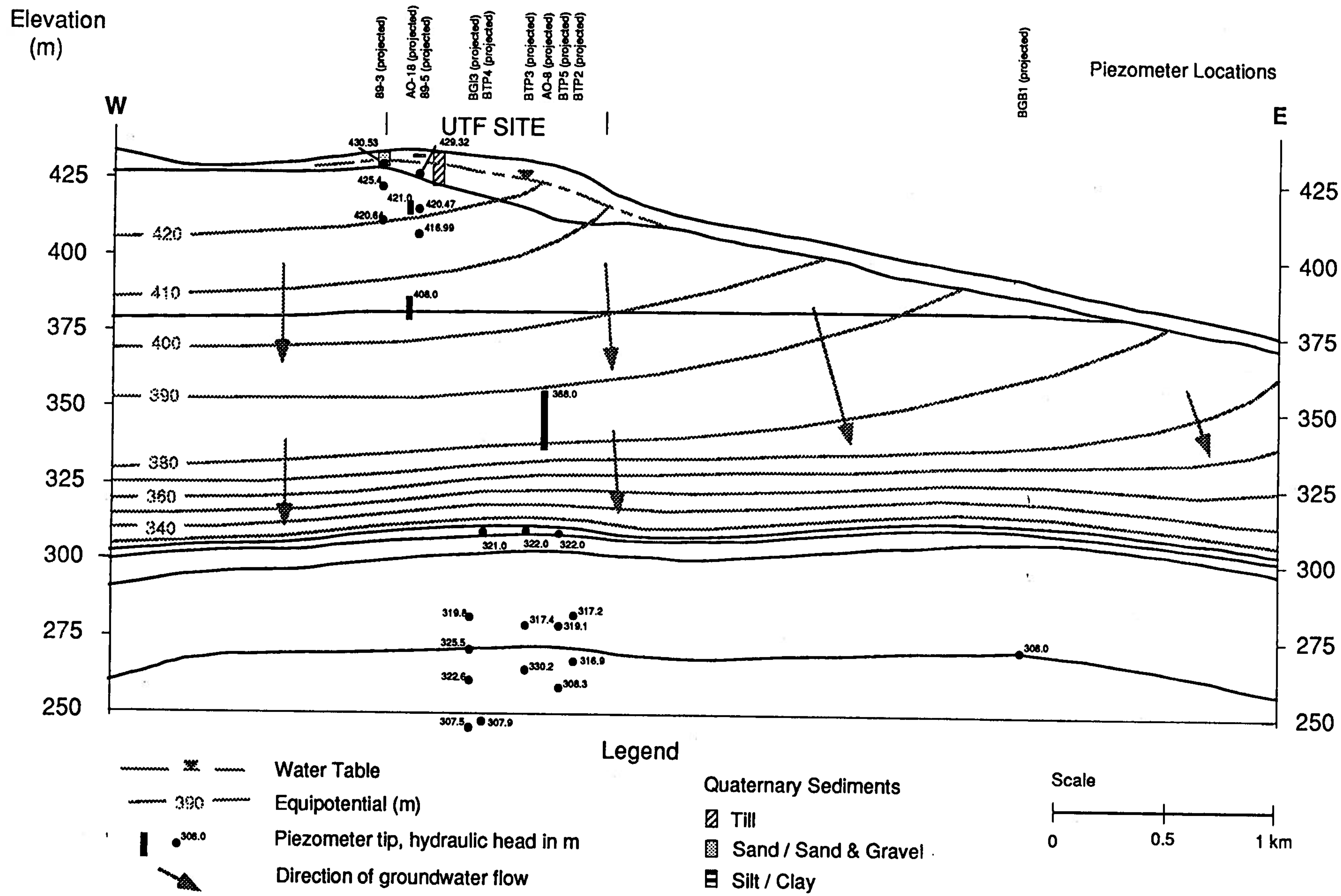

Figure 20. Hydraulic head distribution in the post-Devonian sedimentary succession at the UTF site, along the west-east cross section.

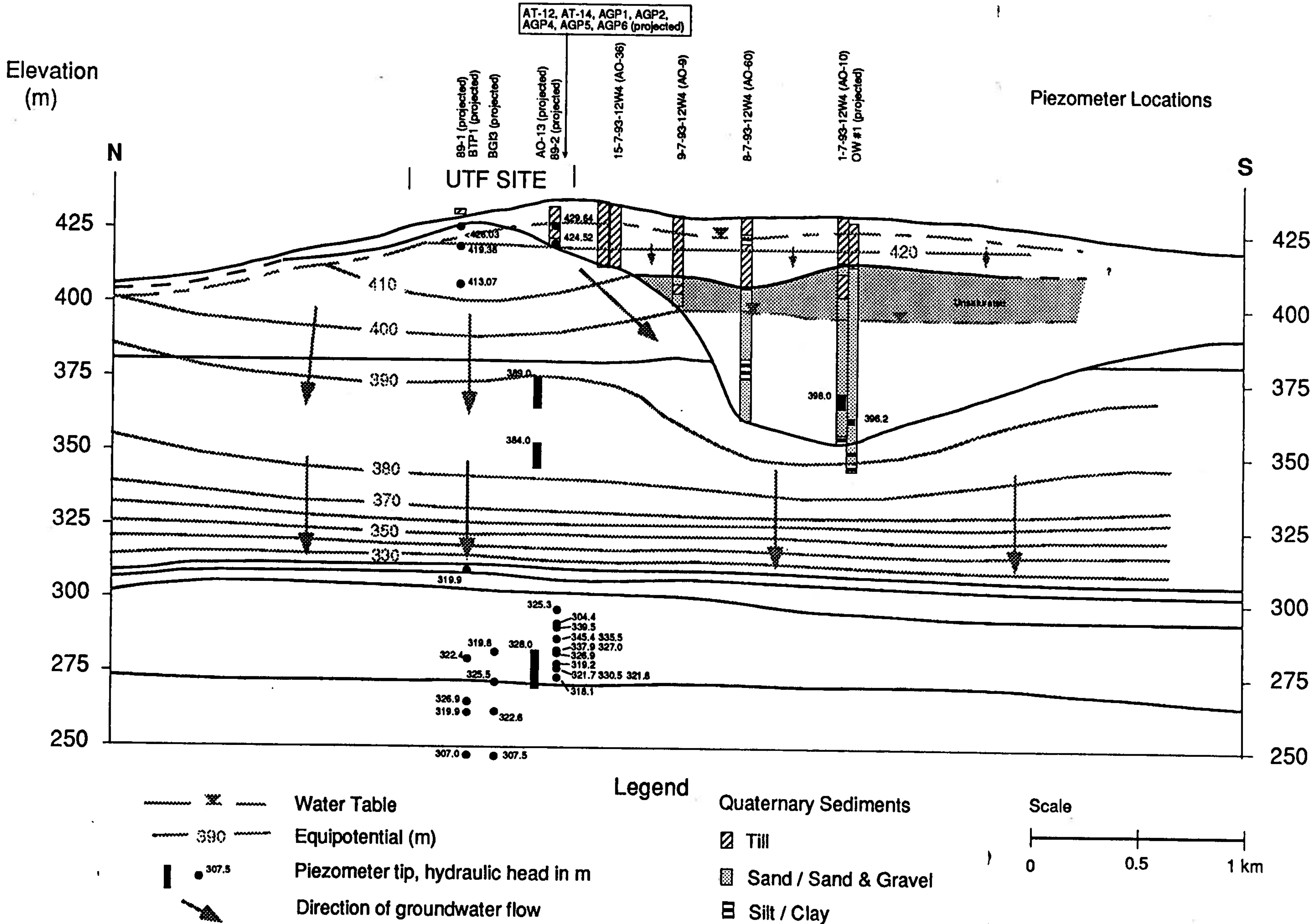

Figure 21. Hydraulic head distribution in the post-Devonian sedimentary succession at the UTF site, along the north-south cross section.

6 m, and this range for depth is expected to be reasonable for the entire study area. The water table thus occurs in either unconsolidated drift sediments or in the uppermost part of the Grand Rapids Formation, depending on the depth to bedrock, and is expected to follow within about 3 to 6 m of the ground surface. An important feature about the water table is that it is perched in places where the highly permeable sand and gravel unit of the Pleistocene channel are present underneath glacial till. This feature results from the fact that groundwater flow in the permeable channel unit is primarily lateral along the channel toward the outcrop and the permeability of the channel fill is high enough that water moves away faster laterally than it can be replenished by recharge through the overlying glacial till. This results in an unsaturated zone, as much as 10 m thick, that exists in the upper part of the channel deposits below the glacial till (Figure 21). Where the channel occurs south of the UTF, the elevation of the water table within the channel ranges from about 396 to 400 m.

Based on the hydraulic head data that were not rejected for the various reasons discussed previously, the following picture for hydraulic head and groundwater flow patterns emerges. The most important feature is that hydraulic heads decrease everywhere with depth and that, except in the Pleistocene channel, the main component of groundwater flow is downward. Figures 20 and 21 show that hydraulic heads decrease downward from about 420 to about 390 m in the Grand Rapids Formation, and from 390 to about 320 m across the Clearwater Formation. The main loss in hydraulic head in the Clearwater Formation occurs across the lowermost 25 m which is known to consist almost entirely of marine shale (tight aquitard). This last condition is supported by a pressure vs. depth analysis (data not presented) which was performed by Hardy Associates (1978) Ltd. (1983) as part of their evaluation of data from the AO4 to AO20 piezometer series. Their analysis indicates that a major drop in pressure head exists across this aquitard. Above the aquitard the slope of the pressure-head line is steeper than hydrostatic, indicating primarily a downward flow component. Below the aquitard the slope is about equal to, or slightly less than hydrostatic, indicating that vertical flow components are negligible to slightly upward.

Hydraulic heads accepted as representative for the Wabiskaw sandstone aquifer in the study area fall in the range of 320 to 330 m. Groundwater flow is thus toward this aquifer from above and, while acceptable data are not available for the regional scale, it is anticipated that flow within the Wabiskaw sandstone aquifer is lateral, most likely northeast and east toward its outcrops along the Dover and MacKay rivers, respectively.

Hydraulic heads measured in the McMurray and Devonian strata exhibit an extreme degree of variability, even in closely spaced piezometers. The reason for this distribution is not understood at this time, but most probably is the result of accuracy problems associated with vibrating-wire piezometers, as discussed previously. Hydraulic heads measured in the McMurray Formation range from about 330 m in upper parts to about 320 m in lower parts, indicating that a slight downward gradient exists across this unit. Again, these values must be treated with caution because of the extreme variability and probable inaccuracies.

Hydraulic heads in Devonian strata to within about 20 m below the sub-Cretaceous Unconformity range from about 300 to 330 m, decreasing generally downward and to the east. The downward gradient noted at the UTF site may represent decreases in hydraulic head caused by the presence of access tunnels and is probably not representative of natural flow conditions. The eastward component is probably natural, driven by discharge along the Athabasca River where Devonian strata crop out.

DISCUSSION

Bitumen is extracted from the McMurray Formation oil sands at the UTF site using the Steam Assisted Gravity Drainage (SAGD) process based on dual injector-producer horizontal wells drilled in the lower part of the McMurray Formation from tunnels dug in the underlying tight limestone of the Devonian Waterways Formation. The top horizontal well is used for steam injection at sub-fracture pressures and temperatures around 250°C, while the bottom well is used for producing oil, formation water and condensed steam. The steam rises and releases heat to the formation as it cools and condenses, and the hot, lower-viscosity bitumen and water gravitationally drain to the bottom well. During the process, an upwardly and laterally advancing steam chamber is formed (Edmunds, 1987), reaching several metres in diameter. The temperature in the steam chamber reaches approximately 200°C on average, but decays rapidly outside the steam chamber, reaching virgin formation values of around 7°C in the overlying McMurray Formation strata, as exemplified in a typical temperature profile (Figure 22) based on measurements at various depths in an observation well. It is obvious that no steam remains in the formation, to attempt upward propagation driven by buoyancy, and that, as the process proved in both A and B phases, the fluid mixture (oil, formation water and condensate) drains gravitationally downward toward the producer well. Thus, counter current flow of steam and a liquid mixture takes place in the steam chamber, while no flow takes place outside the steam chambers in the McMurray Formation aquitard.

For the sake of theoretical analysis, let's assume hypothetically that a liquid mixture of steam condensate, oil and formation water forms at the top of the steam chamber in the McMurray Formation, and that, contrary to the SAGD process at work, this liquid mixture does not drain downward toward the production well. To migrate upward, the liquid mixture would have to cross the remainder (upper part) of the McMurray aquitard and the shaly Wabiskaw aquitard characterized by very low permeability (less than 10^{-6} d, or 10^{-10} m/s hydraulic conductivity), which both constitute very strong barriers to flow unless major fractures (undetected so far) are present.

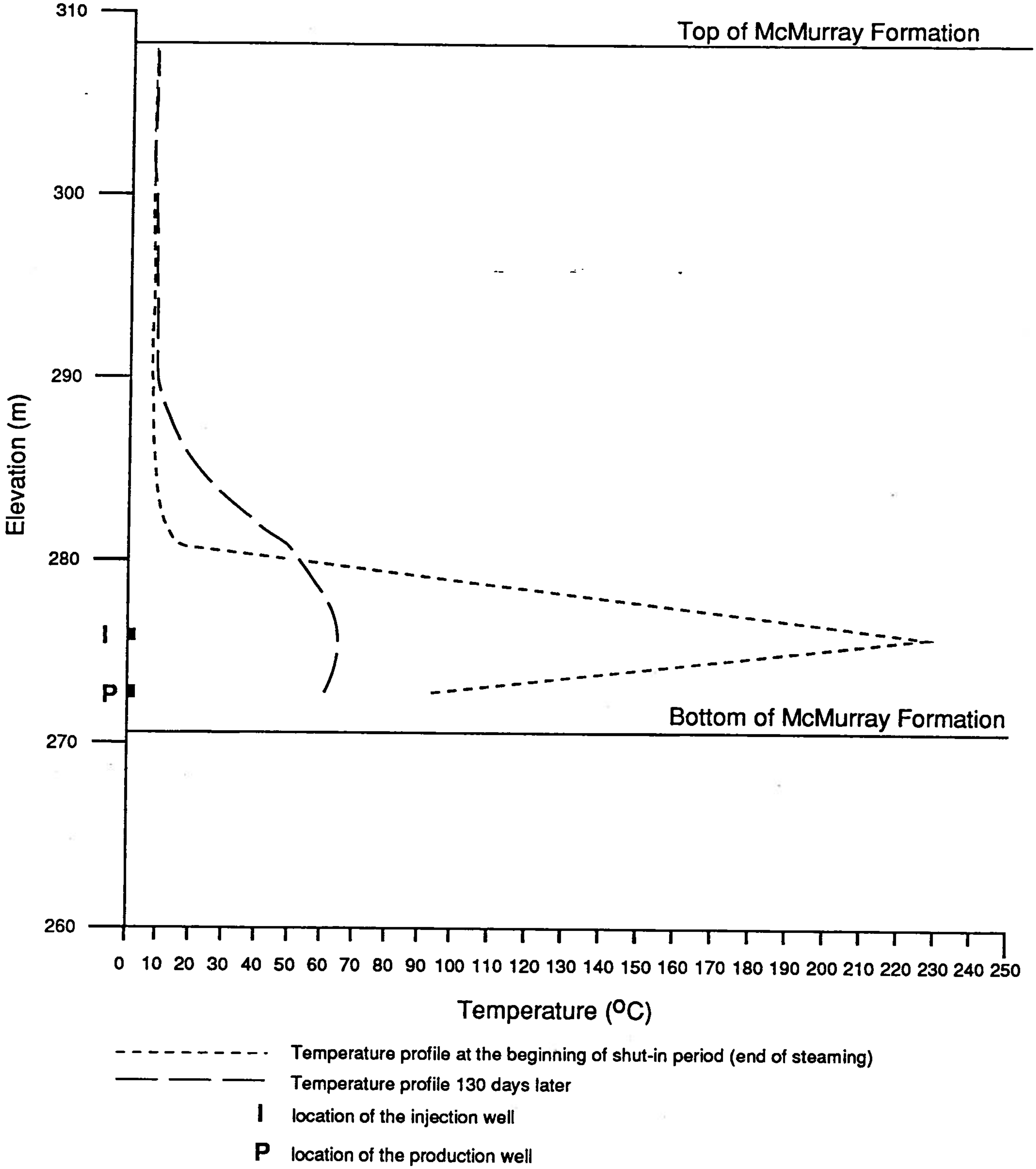

Figure 22. Typical temperature profile in the McMurray Formation in an observation well at the UTF site during a shut-in test.

At this stage, continuing the same hypothetical line of reasoning, it would be an impossibility for any liquids theoretically escaping upward from the production zone to reach the shallow Pleistocene groundwater aquifer for the following three reasons. First, such liquids would be entrained by the lateral flow of formation water in the Wabiskaw aquifer, flowing to the east-northeast toward aquifer outcrop along the McKay and Dover rivers (Petroleum Geoscience Section, 1993). Although the aquifer permeability is comparatively high (4 darcies), the natural velocity of the flow of formation water in this aquifer is low, of the order of 2.5 m/yr. Second, the Wabiskaw aquifer is separated from the shallow groundwater aquifer by the thick and tight Clearwater and Grand Rapids aquitards, characterized by permeability values less than 10^{-5} darcies and by an aggregate thickness ranging, depending on location, between more than 40 m at the deepest point of the paleo-channel, and more than 100 m at the UTF site (Figures 12, 16 and 17). Third, notwithstanding the thick and tight intervening aquitard, in order to reach the shallow groundwater aquifer, any liquids and formation water in the Wabiskaw aquifer would have to overcome an adverse hydraulic gradient potentially driving flow downward from the Pleistocene channel to the Wabiskaw aquifer. This hydraulic gradient is due to a difference in hydraulic heads of approximately 70-90 m, corresponding to a pressure of 700-900 kPa, between the Pleistocene aquifer, where hydraulic heads are in the 400 m range, and the Wabiskaw aquifer, where hydraulic heads are in the 330 m range. Thus, the hydrostratigraphy, aquifer and aquitard properties and hydrogeology of the post-Devonian sedimentary succession at the UTF site, together with the SAGD process itself, indicate that contamination of the shallow Pleistocene groundwater aquifer by liquids escaping from the production zone is highly improbable (practically impossible according to the present knowledge).

SUMMARY AND CONCLUSIONS

Bitumen is extracted using the steam Assisted Gravity Drainage (SAGD) process from the McMurray oil sands deposit at the Underground Test Facility (UTF) near Fort McMurray in northeastern Alberta. The post-Devonian sedimentary succession at the UTF site comprises the Cretaceous Mannville Group, overlain by unconsolidated post-Cretaceous sediments mostly of glacial origin. The bitumen-saturated McMurray Formation, at the base of the succession, unconformably overlies the Devonian limestone Waterways Formation. The McMurray Formation is overlain by the thick Clearwater Formation, whose Wabiskaw member at the base comprises a succession of thin shale, sandstone, and again shale layers. The remainder of the Clearwater Formation is shale dominated. The Clearwater Formation is overlain by shale-and-sandstone of the Grand Rapids Formation, which is absent south of the UTF site because of post-Cretaceous erosion by a deeply incised, sand-and-gravel buried Pleistocene channel which reaches in places more than 80 m in depth. Elsewhere, the Grand Rapids Formation, still eroded, is covered by up to 15 m of glacial deposits, mostly till.

Hydrostratigraphically, the post-Devonian sedimentary succession at the UTF site comprises mostly low permeability aquitards: the bitumen-saturated McMurray Formation, the Wabiskaw Member shale, and the shale-dominated Clearwater and Grand Rapids formations. The till of glacial origin at the top is also an aquitard of low permeability. The thin Wabiskaw Member sandstone is an aquifer of relatively high permeability for consolidated rocks, in which the flow of formation water is to the northeast, toward aquifer outcrop at the McKay and Dover rivers. Hydraulic heads in this aquifer are in the 330 m range at the UTF site. The buried sand-and-gravel Pleistocene channel is a shallow groundwater aquifer of high permeability, characterized by an unsaturated zone of several metres in thickness at the top, and a thick water-saturated zone at the bottom, which is used as a source for water supply. Hydraulic heads (water levels) in the Pleistocene aquifer are in the 400 m range, while the ground elevation drops northeastward from around 430 m at the UTF site to less than 380 m toward the confluence of the McKay and Dover rivers.

Fluids from the production zone in the lower part of the McMurray Formation cannot reach, by upward vertical migration, and contaminate the shallow Pleistocene groundwater aquifer for several reasons. First, the SAGD process itself is based on downward gravity drainage of these fluid toward the production well. Second, there are several thick, low-permeability aquitards between the production zone and the shallow aquifer, which would impede any fluid movement. Third, any production fluids, if they would ever migrate upward, will be intercepted by the Wabiskaw aquifer, whose lateral flow of formation water will entrain them to the northeast with velocities of the order of 2.5 m/yr. Fourth, a natural drop in hydraulic heads between the Pleistocene and Wabiskaw aquifers would oppose any upward fluid movement across the intervening thick Clearwater and Grand Rapids aquitards. Given the extremely low probability of fluids escaping the McMurray production zone and reaching the shallow groundwater aquifer, it is considered by the authors, based on existing information and qualitative reasoning, that there is no need for further mathematical and numerical modelling of this hypothesis unsupported by the hydrogeological reality at the site.

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APPENDIX A

Geological data used in the stratigraphic

delineation at the UTF site

WELL LOCATION	NAME	ELEVATION (m) Sub-Cretaceous Unconformity	Top of McMurray Formation	Base of Wabiskaw Member Sand	Top of Wabiskaw Member Sand	Top of Clearwater Formation	Top of the Bedrock	Ground Surface
0934120503AA0	SHELL	263.9	292.6	301.8	305.1	384.1	389.5	417.6
0934120509AA0	AO-2	267.9	295.5	304.5	308.2	372.2	372.2	403.2
0934120611AA0	AO-74E	268.4	290.9	300.7	304.9	378.3	383.8	432.9
0934120701AA0	AO-10	270.1	294.1	303.6	307.1	352.1	352.1	430.1
0934120701NE	WW#1	-	-	-	-	-	343.8	428.6
0934120706AA0	IMP.OIL TH#9	271.0	295.7	304.5	307.9	362.1	362.1	434.4
0934120708AA0	AO-60	269.5	295.8	304.6	307.8	362.1	362.1	428.8
0934120709AA0	AO-9	270.8	300.8	306.8	309.8	381.8	400.0	428.8
0934120709AB0	AO-56	271.5	299.1	305.5	309.1	381.1	383.0	426.1
0934120711AA0	AO-24	267.8	297.3	304.8	307.8	380.3	410.3	434.3
0934120711AB0	AO-57	267.1	293.6	300.6	304.6	379.1	418.6	434.6
0934120711AC0	AO-61	267.9	293.3	302.3	305.8	372.0	372.0	433.3
0934120713AA0	AO-23	268.2	293.9	301.2	304.2	379.7	421.2	435.7
0934120713AB0	AO-27	269.0	295.5	302.5	305.3	379.5	426.0	431.0
0934120714AA0	AO-12	269.3	298.8	305.8	308.3	382.3	423.8	433.3
0934120714AB0	AO-15	268.9	297.7	304.7	307.7	381.2	423.7	433.7
0934120714AC0	AO-16	-	298.7	305.7	308.7	381.2	423.7	433.7
0934120714AD0	AO-17	-	-	304.5	306.7	379.3	423.3	433.3
0934120714AE0	AO-19	-	-	-	-	381.2	423.7	433.7
0934120715000		266.9	305.9	-	309.4	-	-	435.9
0934120715020		271.9	308.7	-	311.1	-	-	435.9
0934120715AA0	AO-13	269.0	297.5	305.8	308.8	381.5	422.5	432.5
0934120715AB0	AO-35R	269.3	298.0	305.2	308.0	382.0	407.7	433.0
0934120715AC0	AO-36R	270.3	298.3	305.3	308.6	381.8	413.8	432.8
0934120715AD0	AO-58	270.1	298.8	305.8	308.8	381.3	407.0	431.3
0934120716AA0	AO-28	272.1	302.4	308.4	310.9	383.9	424.0	429.9
0934120716AB0	AO-59	271.2	301.5	307.0	310.0	383.0	421.0	429.5
0934120716AC0	AO-70	271.1	301.6	308.1	311.1	383.6	421.1	429.1
0934120801AA0	SINCLAIR #20	270.6	301.1	309.0	311.2	360.5	360.5	406.6
0934120803AA0	AO-6	271.2	295.5	304.2	306.7	353.7	353.7	423.7
0934120809AA0	AO-1	267.6	301.1	308.1	310.1	382.1	382.1	407.1
0934120811AA0	AO-5	269.9	297.4	303.9	306.9	375.9	375.9	423.9
0934120813AA0	AO-4	269.2	298.2	304.7	307.2	380.7	399.7	422.2
0934120901AA0	SINCLAIR #34	265.8	299.9	307.5	310.0	371.9	371.9	380.7
0934120913AA0	PETRO-CAN	270.9	306.1	309.9	312.1	352.0	352.0	397.1
0934121601AA0	SINCLAIR #21	256.9	296.3	300.8	302.9	-	-	374.6
0934121701AA0	SINCLAIR #35	270.0	305.0	310.3	312.4	380.4	-	398.7
0934121704AA0		268.8	300.3	306.1	307.9	383.8	407.8	417.0
0934121801AA0	AO-8	271.4	302.4	308.8	311.4	383.4	421.4	428.4
0934121801AB0	AO-81	272.2	302.3	307.8	309.8	378.3	409.8	424.8
0934121801AC0	AO-85	271.3	303.1	307.6	310.1	383.2	416.1	428.1
0934121801AD0	AO-88	272.0	302.7	308.7	311.7	379.7	415.2	429.2
0934121801AE0	AO-90	270.8	302.0	308.0	310.0	383.0	421.0	429.0
0934121801AF0	AO-91	271.7	303.1	308.1	311.1	384.1	414.1	428.1
0934121802AA0	AO-80	271.2	302.5	308.5	311.5	379.5	418.5	430.5
0934121802AB0		272.2	302.1	308.1	311.1	380.1	417.1	429.1
0934121802AC0	AO-86	270.4	300.9	306.9	309.9	384.9	422.7	433.9
0934121802AD0	AO-87	270.4	301.7	307.7	310.2	378.7	418.7	430.7
0934121802AE0	AO-89	270.9	301.2	307.2	310.2	378.2	405.2	429.2
0934121802AF0	AO-92	270.8	302.2	308.2	311.2	384.2	416.2	430.2
0934121803AA0	AO-14	269.6	299.6	306.6	309.6	382.3	422.6	432.6
0934121803AC0	AO-29	269.1	299.1	305.6	308.6	381.1	420.0	432.1
0934121803AD0	AO-32	269.5	301.6	307.6	310.1	384.1	422.1	430.1
0934121803AE0	AO-82	272.1	300.1	306.1	309.1	383.0	419.0	429.1
0934121803AF0	AO-83	268.7	299.0	305.0	308.5	381.3	419.9	431.5
0934121804AA0	AO-31	269.5	297.8	303.8	306.3	380.0	411.2	423.3

WELL LOCATION	NAME	ELEVATION (m)						
		Sub-Cretaceous Unconformity	Top of McMurray Formation	Base of Wabiskaw Member Sand	Top of Wabiskaw Member Sand	Top of Clearwater Formation	Top of the Bedrock	Ground Surface
0934121806000		254.2	-	-	-	-	-	433.2
0934121806AA0	AO-11	269.8	299.3	305.1	307.3	381.0	412.3	422.3
0934121806AB0	AO-34	270.3	304.9	307.9	309.3	383.4	410.9	422.9
0934121806AC0	AO-93	269.9	306.5	311.5	314.0	383.3	412.9	425.9
0934121807AA0	AO-63	271.4	303.4	308.4	310.4	383.4	419.4	425.4
0934121808AA0	AO-64	270.8	303.7	308.2	309.7	383.4	413.2	419.2
0934121809AA0	AO-7	270.7	303.7	307.7	310.2	382.7	404.7	419.7
0934121809AB0	AO-66	272.5	304.7	308.7	311.2	384.7	411.7	416.7
0934121809AC0	AO-67	269.7	302.9	307.4	309.9	382.4	407.8	412.9
0934121811AA0	AO-65	270.5	300.0	305.3	307.5	381.5	408.5	414.5
0934121812AA0	AO-33	267.5	298.5	303.5	305.9	380.5	411.5	423.5
0934121813AA0	AO-62	265.1	296.7	301.7	304.5	379.7	408.7	414.7
0934121814AA0	AO-68	270.0	304.5	308.0	310.3	384.0	403.0	409.0
0934121901AA0	SINCLAIR #25	271.9	301.1	305.7	307.5	382.5	-	406.9
0934131208AA0	AO-21	268.7	292.9	301.9	304.7	377.7	407.0	437.7
0934131209AA0	AO-22	268.3	292.0	300.9	304.2	378.4	416.0	437.9
0934131215AA0	AO-25	260.9	290.1	299.1	302.1	377.6	426.0	435.1
0934131216AA0	AO-26	268.0	294.0	301.5	304.5	379.0	426.0	430.5
0934131301AA0	AO-30	266.2	295.2	301.7	304.2	379.2	419.0	424.2

-Stratigraphic pick not recorded.

APPENDIX B

Piezometric data used in the hydrogeological analysis at the UTF site

Location (DLS)	Well Name	Ground Elevation (m)	Casing Elevation (m)	Piezometer Number	Bottom (m)	Top (m)	Formation	Date Reading Taken	Hydraulic Head (m)	Hydraulic Conductivity (m/s)	Notes
13-08-93-12W4 /AA	AO4	422.20		1	253.10	261.20	Devonian	1/6/83	347.00	1.1x10-10(s?)	Not used
11-08-93-12W4 /AA	AO5	423.90		1	313.00	334.00	Clearwater	1/6/83	415.00		
09-18-93-12W4 /AA	AO7	419.70		1	263.70	269.00	Devonian	1/6/83	382.50	3.0x10-9(s)	Not used
01-18-93-12W4 /AA	AO8	428.40		1	336.40	355.90	Clearwater	1/6/83	388.00	3x10-8(s)	
09-07-93-12W4 /AA	AO9	428.80		1	255.80	262.50	Devonian	1/6/83	378.00	1.4x10-9(s)	Not used
01-07-93-12W4 /AA	AO10	430.10		1	293.10	305.70	McMurray/Wabiskaw Shale	1/6/83	372.00		Not used
01-07-93-12W4 /AA	AO10	430.10		2	365.10	370.60	Quaternary	1/6/83	398.00	5.3x10-7(g)	
06-18-93-12W4 /AA	AO11	422.30		1	259.10	266.70	Devonian	1/6/83	377.00	1.8x10-9(s)	Not used
15-07-93-12W4 /AA	AO13	432.50		1	225.00	232.50	Devonian	19/7/83	338.00	1.1x10-11(s?)	Not used
15-07-93-12W4 /AA	AO13	432.50		2	269.40	281.60	McMurray	19/7/83	328.00		
15-07-93-12W4 /AA	AO13	432.50		3	344.70	352.50	Clearwater	19/7/83	384.00		
15-07-93-12W4 /AA	AO13	432.50		4	365.00	375.10	Clearwater	19/7/83	389.00		
03-18-93-12W4 /AA	AO14	432.60		1	246.70	260.40	Devonian	19/7/83	327.00		Not used
03-18-93-12W4 /AA	AO14	432.60		2	306.70	312.20	Wabiskaw Sand	19/7/83	327.00		Not used
14-07-93-12W4 /AB	AO15	433.70		1	220.10	233.10	Devonian	19/7/83	330.00	1.1x10-10(s?)	Not used
14-07-93-12W4 /AB	AO15	433.70		2	293.70	313.00	McMurray/Wabiskaw Shale/Wabiskaw Sand	19/7/83	330.00		Not used
14-07-93-12W4 /AC	AO16	433.70		1	287.40	294.10	McMurray	19/7/83	327.00	1.2x10-7(g)	
03-18-93-12W4 /00	AO18	433.00		1	378.10	385.40	Clearwater/Grand Rapids	19/7/83	408.00		
03-18-93-12W4 /00	AO18	433.00		2	413.20	417.80	Grand Rapids	19/7/83	421.00	9.1x10-8(s)	
14-07-93-12W4 /AE	AO19	433.70		1	332.50	345.90	Clearwater	19/7/83	399.00		
14-07-93-12W4 /AE	AO19	433.70		2	369.70	377.30	Clearwater	19/7/83	392.00		
14-07-93-12W4 /AE	AO19	433.70		3	421.80	425.80	Grand Rapids/Quaternary	19/7/83	432.00		
14-07-93-12W4 /00	AO20	433.50		1	384.70	389.50	Clearwater	19/7/83	408.00		
14-07-93-12W4 /00	AO20	433.50		2	412.00	416.50	Grand Rapids	19/7/83	422.00	1.2x10-7(g)	
14-07-93-12W4 /00	AO20	433.50		3	426.10	429.10	Quaternary	19/7/83	433.00	2.2x10-7(g)	
15-07-93-12W4 /00	AT4	432.90		1	382.50		McMurray	1/12/87	413.70		
15-07-93-12W4 /00	AT4	432.90		2	289.40		McMurray	1/12/87	529.80		Not used
15-07-93-12W4 /00	AT4	432.90		3	295.60		McMurray	1/12/87	341.50		
15-07-93-12W4 /00	AT9	432.80		1	281.60		McMurray	1/12/87	318.20		
15-07-93-12W4 /00	AT9	432.80		2	289.30		McMurray	1/12/87	335.60		
15-07-93-12W4 /00	AT12	433.30		1	289.10		McMurray	1/12/87	339.50		
15-07-93-12W4 /00	AT12	433.30		2	295.20		McMurray	1/12/87	325.30		
15-07-93-12W4 /00	AT14	433.20		1	275.60		McMurray	1/12/87	321.70		
15-07-93-12W4 /00	AGP1	433.40		1	275.80		McMurray	1/12/87	330.50		
15-07-93-12W4 /00	AGP1	433.40		2	280.50		McMurray	1/12/87	326.90		
15-07-93-12W4 /00	AGP2	433.10		1	275.50		McMurray	1/12/87	321.80		
15-07-93-12W4 /00	AGP2	433.10		2	282.30		McMurray	4/12/87	337.90		
15-07-93-12W4 /00	AGP4	432.80		1	272.80		McMurray	1/12/87	318.10		
15-07-93-12W4 /00	AGP4	432.80		2	285.10		McMurray	1/12/87	345.40		
15-07-93-12W4 /00	AGP5	432.70		1	281.70		McMurray	1/12/87	327.00		
15-07-93-12W4 /00	AGP5	432.70		2	290.90		McMurray	1/12/87	304.40		
15-07-93-12W4 /00	AGP5	432.70		3	307.10		Wabiskaw Sand	1/12/87	344.20		
15-07-93-12W4 /00	AGP6	432.70		1	277.90		McMurray	2/12/87	319.20		
15-07-93-12W4 /00	AGP6	432.70		2	285.30		McMurray	2/12/87	335.50		
14-07-93-12W4 /NW	AGB1	432.70		1	280.70		McMurray	1/12/87	323.60		
14-07-93-12W4 /NW	AGB1	432.70		2	286.70		McMurray	1/12/87	329.60		
10-07-93-12W4 /00	AGB2	432.20		1	278.90		McMurray	1/12/87	293.40		
10-07-93-12W4 /00	AGB2	432.20		2	289.70		McMurray	1/12/87	325.40		
10-07-93-12W4 /00	AGB2	432.20		3	305.90		Wabiskaw Sand	1/12/87	354.70		

g=Good Test
s=Satisfactory Test
s?=Satisfactory Test

Location (DLS)	Well Name	Ground Elevation (m)	Casing Elevation (m)	Piezometer Number	Bottom (m)	Top (m)	Formation	Date Reading Taken	Hydraulic Head (m)	Hydraulic Conductivity (m/s)	Notes
02-18-93-12W4 /00	BGI3	431.10		1	246.50		Devonian	29/4/92	307.50		
02-18-93-12W4 /00	BGI3	431.10		2	261.10		Devonian	29/4/92	322.60		
02-18-93-12W4 /00	BGI3	431.10		3	271.10		McMurray	29/4/92	325.50		
02-18-93-12W4 /00	BGI3	431.10		4	281.80		McMurray	29/4/92	319.80		
02-18-93-12W4 /00	BTP1	430.30		1	248.10		Devonian	24/10/91	307.00		
02-18-93-12W4 /00	BTP1	430.30		2	260.20		Devonian	24/10/91	319.90		
02-18-93-12W4 /00	BTP1	430.30		3	264.80		Devonian	14/11/91	326.90		
02-18-93-12W4 /00	BTP1	430.30		4	279.30		McMurray	24/10/91	322.40		
02-18-93-12W4 /00	BTP1	430.30		5	308.60		Wabiskaw Sand	24/10/91	319.90		
01-18-93-12W4 /00	BTP2	428.20		1	267.80		Devonian	24/10/91	316.90		
01-18-93-12W4 /00	BTP2	428.20		2	282.40		McMurray	24/10/91	317.20		
01-18-93-12W4 /00	BTP2	428.20		3	308.50		Wabiskaw Sand	24/10/91	331.70		Not used
01-18-93-12W4 /00	BTP3	428.80		1	264.10		Devonian	24/10/91	330.20		
01-18-93-12W4 /00	BTP3	428.80		2	278.90		McMurray	24/10/91	317.40		
01-18-93-12W4 /00	BTP3	428.80		3	309.40		Wabiskaw Sand	24/10/91	322.00		
02-18-93-12W4 /00	BTP4	430.60		1	248.00		Devonian	24/10/91	307.90		
02-18-93-12W4 /00	BTP4	430.60		2	260.20		Devonian	24/10/91	303.90		Not used
02-18-93-12W4 /00	BTP4	430.60		3	265.00		Devonian	24/10/91	301.60		Not used
02-18-93-12W4 /00	BTP4	430.60		4	280.50		McMurray	24/10/91	293.30		Not used
02-18-93-12W4 /00	BTP4	430.60		5	309.30		Wabiskaw Sand	24/10/91	321.00		
01-18-93-12W4 /SE	BTP5	429.30		1	259.00		Devonian	24/10/91	308.30		
01-18-93-12W4 /SE	BTP5	429.30		2	279.00		McMurray	24/10/91	319.10		
01-18-93-12W4 /SE	BTP5	429.30		3	309.60		Wabiskaw Sand/Clearwater	24/10/91	322.00		
13-09-93-12W4 /NW	BGB1	391.50		1	271.00		Devonian/McMurray	9/2/93	308.00		
13-09-93-12W4 /NW	BGB1	391.50		2	307.50		Wabiskaw Shale	9/2/93	327.60		Not used
13-09-93-12W4 /NW	BGB1	391.50		3	309.70		Wabiskaw Shale	9/2/93	353.20		Not used
13-09-93-12W4 /NW	BGB1	391.50		4	311.20		Wabiskaw Sand	9/2/93	355.00		Not used
13-09-93-12W4 /NW	BGB1	391.50		5	314.40		Clearwater	9/2/93	361.90		Not used
02-18-93-12W4 /NW	89-1A	432.07	432.81	1	426.03		Grand Rapids	19/10/92	<426.03	3.3×10^{-7}	
02-18-93-12W4 /NW	89-1	432.02	432.78	1	419.33		Grand Rapids	19/10/92	419.38	4.4×10^{-7}	
02-18-93-12W4 /NW	89-1B	432.11	432.81	1	406.78		Grand Rapids	19/10/92	413.07	7×10^{-7}	
15-07-93-12W4 /SW	89-2A	433.14	433.86	1	426.23		Quaternary	19/10/92	429.64	1.6×10^{-7}	
15-07-93-12W4 /SW	89-2	433.13	433.78	1	420.09		Quaternary	19/10/92	424.52	1.1×10^{-7}	
03-18-93-12W4 /00	89-3A	432.90	433.67	1	428.76		Quaternary	19/10/92	430.53	1.3×10^{-7}	
03-18-93-12W4 /00	89-3	432.90	433.67	1	411.36		Grand Rapids	19/10/92	420.64	1.4×10^{-7}	
03-18-93-12W4 /00	89-3B	432.94	433.61	1	421.54		Grand Rapids	19/10/92	425.40	1.9×10^{-7}	
03-18-93-12W4 /00	89-4A	426.99	427.66	1	420.89		Quaternary	19/10/92	425.54	5.1×10^{-7}	
03-18-93-12W4 /00	89-4	426.99	427.66	1	412.02		Grand Rapids	19/10/92	420.46	1.1×10^{-7}	
03-18-93-12W4 /00	89-4B	426.97	427.63	1	403.08		Grand Rapids	19/10/92	413.19	2.1×10^{-7}	
03-18-93-12W4 /00	89-5A	431.87	432.51	1	425.69		Quaternary	19/10/92	429.32	3.2×10^{-7}	
03-18-93-12W4 /00	89-5	431.87	432.51	1	414.27		Grand Rapids	19/10/92	420.47	1.2×10^{-7}	
03-18-93-12W4 /00	89-5B	431.89	432.52	1	406.59		Grand Rapids	19/10/92	416.99	7.7×10^{-7}	
01-07-93-12W4 /NE	WW#1	428.60	429.31	1	360.30	362.00	Quaternary	3/2/84	396.20	2×10^{-3}	

g=Good Test
s=Satisfactory Test
s?=Satisfactory Test