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Regional-Scale Subsurface Hydrogeology in Northeast Alberta

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Abstract

The hydrogeological regime of formation waters in the Phanerozoic sedimentary succession was determined for a region defined as Tp 70-103 W4 Mer (55°-58°N latitude and 110°-114°W longitude) in northeast Alberta, covering most of the Athabasca Oil Sand Deposit. The study was based on information from 12,479 wells, 3187 analyses of formation water, 2531 drillstem tests and 452,030 core analyses. Data management and processing were carried out using the INGRES Data Base Management System and specially designed software developed at the Alberta Geological Survey.

The regional geology was synthesized in terms of definable stratigraphic successions, and 26 individual units were characterized by structure top and isopach maps. The hydrostratigraphy was developed through several iterations starting from the stratigraphy and lithology of the strata. Complex groups of aquifers and/or aquitards exhibiting generally common overall characteristics were grouped into hydrostratigraphic systems. Thirteen hydrostratigraphic units were identified in the Phanerozoic succession. The hydrogeological regime in aquifers was described using isopach, salinity distributions and freshwater hydraulic-head distributions. Cross-formational flow was evaluated using plots of pressure variation with depth in selected wells.

Because the study area is situated at the feather edge of the Alberta Basin, topography and physiographic features exert a strong influence on the flow regime within most aquifers. In the most general sense, fluid flow is to the northeast toward the edge of the basin. Areas of high topography, such as the Birch and Pelican mountains, act as local recharge areas, introducing fresh meteoric water to aquifers unprotected by significant confining strata. The valleys of the Athabasca River system represent discharge areas for aquifers at outcrop or subcropping near them.

The salinity of formation waters generally increases with depth. This is the result of a combination of factors like temperature, hence solubility increase with depth, dissolution of deep Devonian evaporitic beds, and dilution near the surface by meteoric water introduced by local flow systems. In terms of flow regime and overall characteristics, the hydrostratigraphic units can be grouped into pre-Prairie Formation aquifers, Beaverhill Lake-Cooking Lake aquifer system, Grosmont-to-Wabamun aquifers, and Cretaceous aquifers. The aquifers below the Prairie evaporite exhibit regional flow-regime characteristics. Overall high formation water salinity is associated with the proximity of Elk Point Group evaporites. The Beaverhill Lake-Cooking Lake aquifer system has hydrogeological characteristics consistent with an intermediate-to-local flow regime. Within subcrop and outcrop areas, local physiographic influences are superimposed over a regional northeastward flow trend. The Grosmont aquifer and Winterburn-Wabamun aquifer system may act locally as a "drain" for aquifers in hydraulic continuity above and below. The flow of formation waters is generally to the northwest, towards discharge at outcrop along the Peace River. The Cretaceous aquifers are characterized by low salinity and local flow regime.

The synthesis of this vast amount of information on the hydrogeological régime of formation waters in northeast Alberta was carried out under a jointly funded research project by the Alberta Research Council and Environment Canada.

Introduction

In the last few decades, a number of regional-scale studies have been carried out in Alberta relating to the hydrogeological and geothermal regimes of Phanerozoic sedimentary strata. Hitchon (1964) provided the first synthesis of the hydrochemistry and general flow directions of formation waters for various strata at the scale of the Western Canada Sedimentary Basin. Hitchon (1969a, b) also conducted a study of fluid flow in the basin, which included hydraulic-head distributions along various cross-sections and for selected stratigraphic units. These studies showed that the basin-scale flow of formation waters in the Alberta Basin is generally to the northeast.

Other studies have dealt with three-dimensional sedimentary blocks covering large areas in the basin, mainly in central and northern Alberta (Toth, 1978; Hitchon et al., 1989a, b, 1990; Bachu and Underschultz, 1992; Bachu and Cao, 1992) (Figure 1). These studies showed that the flow regime of formation waters in the deep, generally Paleozoic strata is regional in nature, while the flow regime in shallower, Cretaceous and younger strata is local. An intermediate flow regime marks the transition between the two. The flow regime in Paleozoic aquifers is not of the same type across the basin in any given unit, but changes depending on the relation of the aquifer with other hydrostratigraphic units. According to Toth (1978), three different flow systems are present in the Red Earth region (Figure 1). The two upper systems (top or Meso-Cenozoic: post-Clearwater hydrostratigraphic units; and middle or Paleo-Mesozoic: post-Ireton to Clearwater hydrostratigraphic units) are in equilibrium with present day boundary conditions. The lower system (basal or Paleozoic: pre-Ireton hydrostratigraphic units) is generally underpressured and in a transient process of equalization with the present topography. Within the Swan Hills area (Figure 1), Hitchon et al. (1989a) conducted a hydrodynamic investigation which indicated that the major barriers to cross-formational flow in the area are the Joli Fou, Clearwater and Ireton aquitards. In the Cold Lake area (Figure 1), Hitchon et al. (1989b) showed the Joli Fou aquitard to be a significant barrier to flow; however, the Clearwater and Ireton aquitards are weak where they are thin, and have areas where hydraulic communication may exist across them. Most recently, Hitchon et al. (1990) analyzed the flow regime in a comprehensive study of the subsurface hydrogeology within the regionally extensive Peace River Arch area (Figure 1). They identified a regional flow regime within dominantly Paleozoic strata (below the Fernie aquitard), an intermediate flow regime within Jurassic-to-Lower Cretaceous strata (between the Fernie and Colorado aquitards), and a local flow regime within Upper Cretaceous to Recent strata (above the Colorado aquitard). The Clearwater and Ireton aquitards were shown to be the most significant regional flow barriers in the Peace River Arch region. Garven (1989) used numerical modelling of groundwater flow along a dip basin cross-section (Figure 1) from Wright (1984) to investigate the possible role of Tertiary large-scale regional flow in the genesis of the Athabasca oil sands deposits. His simulations of present-basin configuration suggest that differential erosion has dissipated previous regional flow systems into local flow systems.

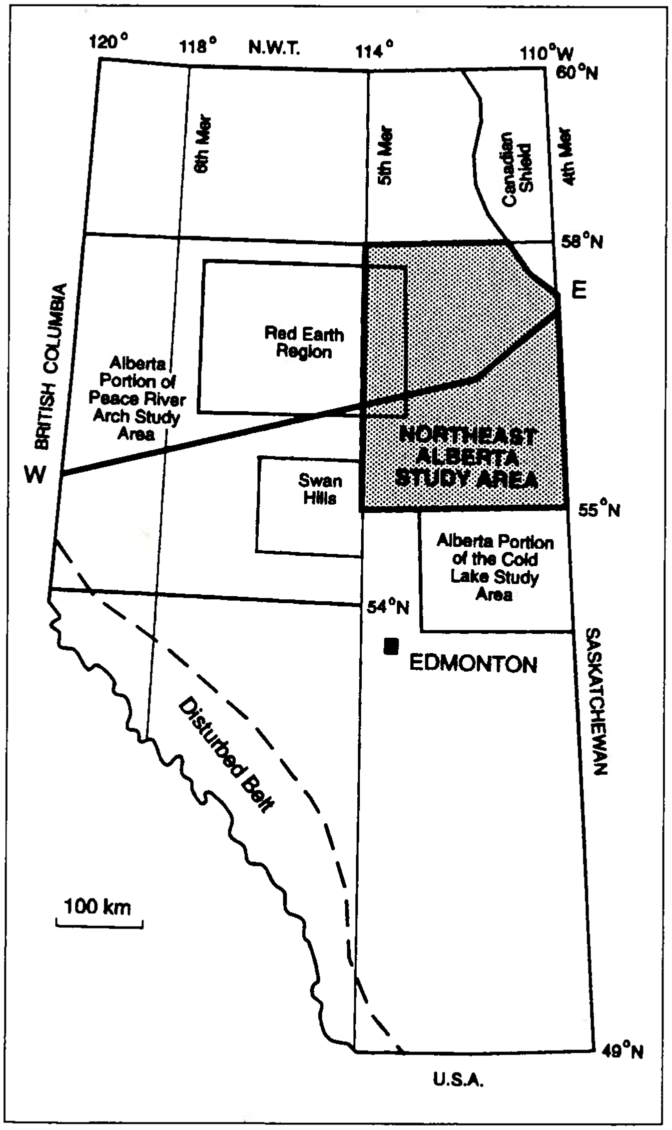

Figure 1. Location of the Northeast Albeta study area and of previous regional-scale subsurface hydrogeological studies in Alberta. Line WE denotes the cross-section of Garven (1989).

Although the studies of Toth (1978) and Hitchon et al. (1989a, b, 1990) cover the entire Phanerozoic stratigraphic succession, from the Precambrian basement to the top of the bedrock, these studies cannot be directly integrated to consider basin-wide flow. The Alberta Basin is part of the Western Canada Sedimentary Basin and is bounded by the Thrustfold Belt in the west, the Sweetgrass Arch in the south, the Canadian Shield in the east and the Tathlina Arch in the north (Figure 2). Thus, in 1990 the Alberta Geological Survey initiated a regional-scale study of the hydrogeological regime in the Phanerozoic strata in the area bounded to the west by the Peace River Arch study area, to the south by the Cold Lake study area, and by the Canadian Shield to the east and north (i.e. east of longitude 114°W and north of latitude 55°N to the basin edge). The stated purpose was to complete the areal coverage in the analysis of the flow of formation waters in the north-central part of the Alberta Basin, along the main flow paths across the basin from recharge areas in the Foothills to discharge areas at the basin edge at the Canadian Shield. Such a study, together with the ones for the Red Earth and Peace River Arch areas (Toth, 1978; Hitchon et al., 1990), would provide the first quantitative characterization based on actual data of the flow of formation waters across the basin, to serve as a basis for future studies of: (1) basin evolution; (2) hydrocarbon generation, maturation and migration; (3) the economic potential of brines; and (4) the effects of possible deep disposal of residual waters resulting from the extraction of bitumen from the Athabasca oil sands. Examination of the well distribution in the proposed study area revealed that there are no wells north of latitude 58°N because of restricted economic activity in the Wood Buffalo National Park, and only four wells east of longitude 110°W. Thus, the Northeast Alberta study area (Figures 1 and 2) is defined by latitudes 55°-58°N and longitudes 110°-114°W (Tp 70-

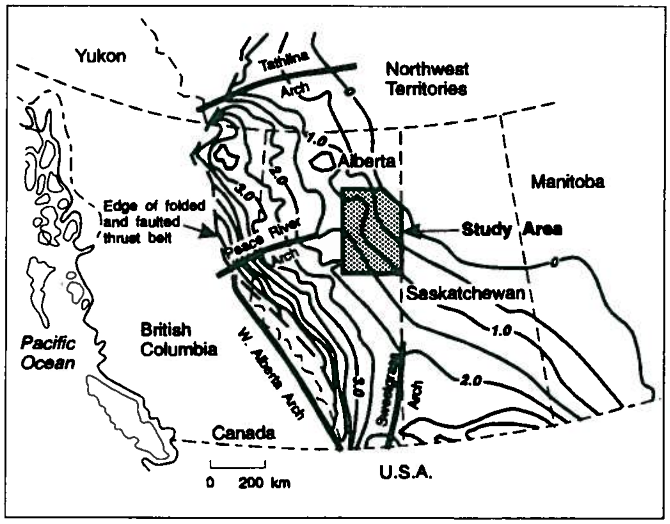

Figure 2. Isopach map of the Western Canada Sedimentary Basin (after Porter et al., 1982) showing location of the Northeast Alberta study area. Contour lines in kilometers.

103, W4 Mer). In the northeast corner, the study area is bounded by the basin edge along the Canadian Shield.

Very little work was previously done pertaining directly to the subsurface flow and chemistry of formation waters in the Northeast Alberta study area. Hackbarth and Nastasa (1979) examined the hydrodynamic regime in shallow aquifers of the Athabasca oil sands area. Subsequently, Hackbarth and Brulotte (1981) conducted a data-gathering program which included twelve deep wells within the present study area. These data were included in the present analysis. Generally, in any hydrogeological analysis and characterization the sedimentary rocks have to be described and characterized first, particularly in terms of lithology and variability of hydrogeological properties. Subsequently, hydrostratigraphic units (aquifers, aquitards and aquicludes) must be delineated and characterized by their rock properties (porosity and permeability). Finally, the pressure regime and the chemical composition of formation waters have to be analyzed and defined. Accordingly, this bulletin is organized in two broad sections: regional geology, and analysis of the hydrogeological regime of formation waters. Because of the very large number of wells in the study area and associated stratigraphic picks, drillstem tests, and core and formation water analyses, computer-based methods were used for the automatic processing of this huge amount of information. Thus, a chapter at the beginning describes first the approach and methodology used to process the data, followed by chapters describing the geology and respectively hydrogeology of the Phanerozoic strata in the Northeast Alberta study area.

Data sources and processing

The Phanerozoic succession in northeast Alberta comprises two entities of interest to this study: (1) the rock framework; and (2) the contained fluids, which are dominantly formation waters with effectively minor, but economically important, amounts of hydrocarbons (natural gas, conventional crude oil, heavy oil and bitumen) and dissolved minerals. A computer-based approach was used to construct the hydrostratigraphic framework, to process the data, and to analyze the subsurface hydrogeological regime (Bachu et al., 1987). The strata within the study area were divided into 26 units (Table 1) constrained by stratigraphic picks from 12,479 wells, whose distribution is shown in Figure 3. Regions of high well density reflect the location of major oil sands deposits and oil and gas discoveries. In the Athabasca oil sands area, between 111°W

EON	ERA	Period		Group			Formation	Data Points	Order
Phanerozoic	Cenozoic	Quaternary Tertiary					Pleistocene deposits	12479	1
	Mesozoic	Cretaceous	Upper	Colorado			Colorado shale		
							2nd White Specks	565	3
			Lower				Base of Fish Scales	1855	4
							Viking	1121	4
							Joli Fou	1634	2
				Mannville			Grand Rapids	3767	2
							Clearwater	9659	3
							McMurray	9016	3
		Jurassic							
		Triassic							
	Paleozoic	Permian							
		Carboniferous					Sub-Cretaceous Unconformity	5051	1
		Devonian	Upper				Wabamun	417	2
							Winterburn	144	3
				Woodbend			Upper Ireton	133	3
							Grosmont	770	2
							Lower Ireton	222	3
							Cooking Lake	142	4
				Beaverhill Lake			Waterways	3427	2
							Slave Point		
							Fort Vermilion		
			Middle	Elk Point	Upper		Watt Mountain	311	2
							Prairie	152	3
							Winnipegosis (Keg River)	163	3
					Lower		Contact Rapids	236	2
			Lower				Cold Lake	34	3
							Ernestina	153	3
						Granite Wash	Upper Lotsberg	56	3
							Lower Lotsberg	24	3
							Basal Red Beds	110	4
		Silurian							
		Ordovician							
		Cambrian							
Precambrian								110	1

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

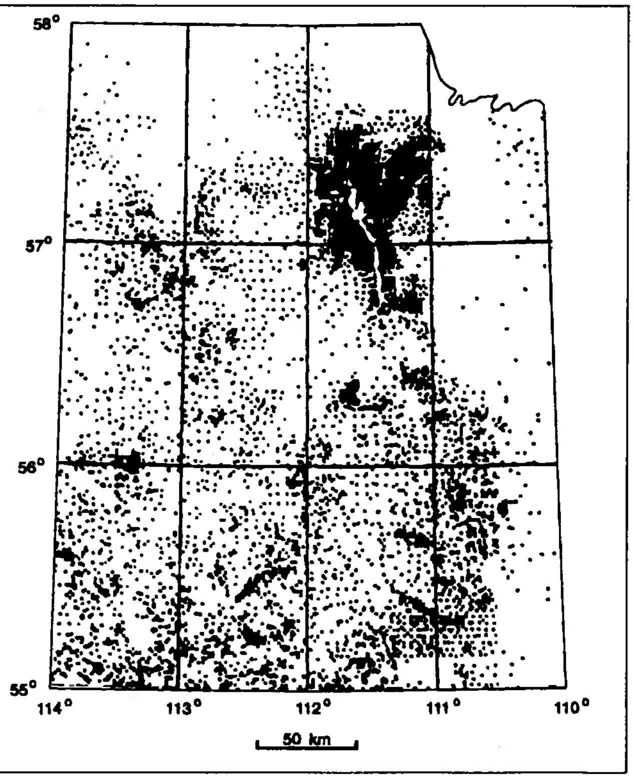

Figure 3. Distribution of wells in the Northeast Alberta study area.

and 112°W and north of 57°N, the well control is overwhelming, while in other areas there are few data. There is also an order-of-magnitude difference in the number of wells penetrating various stratigraphic levels.

Hydrogeological information from 3187 formation water analyses, 2531 drillstem tests and 452,030 core-plug analyses were used in this study. Entire analyses and individual data were automatically rejected because of erroneous values, based on range and threshold criteria. The remainder of the analyses and data were subsequently allocated into the initial hydrostratigraphic framework. The data were then variously interpreted by hydrostratigraphic unit and culled more rigorously for questionable values. Data of all types tend to be clustered both areally and with depth. Table 2 presents a detailed breakdown of the total number of wells recording each stratigraphic unit and the initial data distribution by hydrostratigraphic unit, including the number of formation water analyses, drillstem test phases, and core-plug analyses, together with the respective number of wells from which they were obtained. It is clear that the bulk of the data is concentrated within the economically important units. This results in an inherent bias of most hydrodynamic data toward attributes associated with aquifers.

Stratigraphic picks

The data set used for describing the stratigraphy was assembled from the files of the Alberta Energy Resources Conservation Board (ERCB) and from previous studies which either wholly or partially lie within the Northeast Alberta study area (Kramers and Prost, 1986; Flach, 1984; Keith et al., 1987; MacGillivray et al., 1989; Hamilton, 1971; Hackbarth and Brulotte, 1981; Harrison, 1986). The CPS3 software developed by Radian Corporation was used for automated gridding and contouring. Alberta Research Council cartographic software (AGSSYS, AGSDIG and AGSCPS) was used to process stratigraphic picks data, and to obtain Dominion Land Survey (DLS) and latitude-longitude displays. In an integrated basin analysis approach it is important to select a gridding algorithm producing grids and maps which meet the following criteria: (1) where data exist, the grid must accurately represent the observed values; (2) for consistency and modelling purposes, the stratigraphy is required to be realistically characterized everywhere it is thought to exist, including the areas for which there are little or no data; and (3) the gridding must take into account the high variability in data density both areally and with depth, and various degrees of data clustering. A convergent gridding algo-

Stratigraphic unit	No. of picks	Analyses of formation waters		Drillstem tests		Core analyses	
		No.	Wells	No.	Wells	No.	Wells
Ground-2nd W.S.S.	12686	44	28	13	7	740	81
Colorado	1855	35	34	82	43	-	-
Viking	1120	153	138	479	237	98	17
Grand Rapids	3731	409	318	1151	715	8075	290
Clearwater	3989	147	116	342	164	956	53
Wabiskaw	5666	203	161	587	295	22081	1974
McMurray	9001	383	320	1286	596	381537	6452
Wabamun	417	65	51	127	70	797	30
Winterburn	144	55	46	168	74	1282	56
Grosmont	770	129	106	260	119	18149	195
Lower Ireton	459	-	-	6	3	-	-
Cooking Lake	17	22	18	37	18	406	21
Beaverhill Lake	3428	40	28	121	47	15268	1585
Prairie	203	-	-	12	6	130	10
Winnipegosis	173	35	30	104	47	2353	46
Contact Rapids	277	2	2	5	3	72	6
Ernestina Lake	185	2	1	3	2	-	-
Basal Red Beds	107	5	3	9	6	67	3
Precambrian	141	-	-	-	-	-	-

Table 2. Initial distribution per stratigraphic unit of various analyses and associated number of wells, Northeast Alberta study area.

rithm was used whereby grid-node values are converged upon through several iterations. The z-value at a given node is estimated by using a distance-weighing technique such that control points closer to the node have a larger effect on the outcome of the z-value at the node (Graf and Thomas, 1988). This iterative process produces a trend-like solution in areas of sparse or no data, and an accurate representation where data exist. The final map is generated by contouring the grid produced by the convergent algorithm.

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

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

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

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

Hydrostratigraphic delineation

A preliminary hydrostratigraphic framework was constructed from the stratigraphic geometry and knowledge of the lithology. However, after examining the hydrogeological data subsequent to their automatic allocation, it became evident that the initial hydrostratigraphic delineation required revision. Pressure data from drillstem tests were the main data used in modifying the initial hydrostratigraphic framework. Because, conceptually, it was not expected that any drillstem test would be located within an aquitard or aquiclude, data allocated to this type of hydrostratigraphic unit were examined in detail. First, the drillstem test location and depth were manually checked on geophysical logs to ensure that they were properly allocated within the previously defined stratigraphic framework. The formation pressure and corresponding hydraulic head were then compared to values in the adjacent aquifers. If there was evidence of hydraulic continuity between the drillstem test position in the aquitard or aquiclude and the adjacent aquifer, the drillstem test was flagged to indicate that the initial hydrostratigraphy was in need of modification at that location. Analyses of formation water chemistry and core analyses were used as supporting evidence when determining if a drillstem test position was in hydraulic continuity with an adjacent aquifer.

A large number of drillstem tests fell into this category. Some formation pressure and hydraulic head values showed no relation to those in adjacent aquifers, although the drillstem test and core data indicated hydraulic characteristics associated with those of an aquifer. Subsequent detailed stratigraphic analysis showed that the tested zone generally represented a localized, usually discontinuous arenaceous or calcareous interval, hydraulically isolated by the more regionally extensive aquitard or aquiclude. In these particular cases, the data are included in subsequent summaries (Tables 3-6), but were not considered part of the regional-scale hydrogeological evaluation.

After all questionable drillstem test data were examined in detail, those flagged as being in hydraulic continuity with adjacent aquifers were used to modify the initial hydrostratigraphic framework. A manual re-examination of all the wells (12,479) used to establish the stratigraphic geometry and subsequent initial hydrostratigraphic framework was not feasible. Therefore, an automatic method was developed to update the initial hydrostratigraphy in order to include those drillstem tests flagged as being in hydraulic continuity with an adjacent aquifer. The vertical distance between the drillstem test position and the aquifer with which it is in hydraulic continuity was calculated for each drillstem test. These "distance" or thickness values were then added to or subtracted from the respective aquifer and aquitard/aquiclude isopachs. The final hydrostratigraphic isopachs thus include these updated thicknesses. Despite the revision, there were no boundary changes, no new units were created, and no units were eliminated.

The resulting refined hydrostratigraphic geometry is still only a best approximation of the actual geometry, mainly because of two factors. First, unlike the previously described procedure of using drillstem tests to revise the aquifer thickness in areas of apparent hydraulic continuity, there is no reliable method of determining the aquifer geometry in areas without drillstem test (hydraulic) information. Within these areas, the hydrostratigraphic geometry is based only on the initial lithostratigraphic framework. Second, the corrections made on the basis of drillstem test data and other supporting evidence represent only a minimum correction. In reality, the zone of hydraulic continuity probably extends past the position of the drillstem test to some unknown distance. Without further detailed manual log analysis it is not possible to determine the actual extent of hydraulic continuity with the adjacent aquifer. Thus, there is some uncertainty with respect to the real thickness of the hydrostratigraphic units, but this uncertainty cannot be resolved with the existing data and at the scale of this study.

Analyses of formation waters

Data from 3,013 hard-copy analyses of formation water from the Energy Resources Conservation Board files and 174 hard-copy analyses of surface waters from the Ground Water Resources Information System (Alberta Environment) were entered into an electronic data base. Previous studies in the Western Canada Sedimentary Basin (Hitchon, 1984; Hitchon et al., 1987; Hitchon et al., 1989a, b; Hitchon et al., 1990) have shown that as few as one-fifth of standard formation water analyses in any particular area may be suitable for consideration after culling by appropriate automatic and manual procedures. Typically, analyses can be contaminated, mixed with other samples, or be incomplete in some way. The automatic cull takes into account the presence and values of OH, CO_3, Ca, Mg, Cl, SO_4, HCO_3, acceptable ranges of pH and density, and mixing of formation waters from several intervals.

Of the 3,187 formation water analyses in the data base, 1,729 (54%) passed the initial automatic cull, whose distribution by stratigraphic unit is shown in Table 2. Because of their small number and poor areal distribution, the 355 analyses of formation waters associated with pre-Cretaceous aquifers that passed the automatic cull were examined individually. Formation water analyses from Cretaceous aquifers (79% of those analyses which passed the automatic cull) were subjected to a manual-automatic cull. The final data set comprised 590 analyses or 18.5% of the original data base. Hitchon (1991) has presented a detailed analysis of the chemistry of formation waters in northeast Alberta, which is incorporated in this bulletin.

Drillstem tests

Drillstem tests for the Northeast Alberta study area were acquired from The Canadian Institute of Formation Evaluation Ltd. These tests tend to be biased toward units of economic importance, typically high permeability sandstones and carbonates, and are clustered both areally and vertically. The initial number and hydrostratigraphic distribution of drillstem test data and associated wells considered in this study are shown in Table 2. The original number of data includes all shut-ins (there is often more than one test of pressure build-up recorded for an individual drillstem test).

The main parameters of interest which are obtained from drillstem tests are permeability and pressure. The slope of the Horner plot together with Cl and temperature estimates are used to calculate the formation permeability (Timmerman and Van Poollen, 1972; Bachu et al., 1987). The Cl and temperature are needed to calculate the density and viscosity of formation waters according to relations published by Kestin et al. (1981) and Rowe and Chou (1970). Because information on formation water Cl content and temperature is not normally included in standard drillstem test reports, the electronic maps of Cl distribution obtained in the hydrogeochemical analysis were used to estimate the Cl content of formation water at each drillstem test location. An estimate of the formation temperature T at each location was obtained from the surface temperature T_0 and geothermal gradient G according to:

$$T = T_0 + GD$$

where D is the drillstem-test depth. Surface temperature and geothermal gradient values were obtained from a regional-scale analysis of the geothermal regime in the Western Canada Sedimentary Basin (Bachu and Burwash, 1991, 1993). Drillstem tests which recover gas require additional terms to be used in the calculation of various hydrodynamic parameters (Bachu et al., 1987). According to the drillstem test reports, standard gas viscosity and total compressibility values of 1.0×10^{-4} (Pa•s) and 1.0×10^{-5}(1/kPa), respectively, were used in calculations. The reported gas supercompressibility Z-factor ranges in value between 0.90 and 0.97.

Permeability values obtained from drillstem tests are already at the well scale, even though several measurements are often made within a stratigraphic interval in the same well. Unlike the core-plug analyses, drillstem tests sample in-situ a large volume of rock, potentially reflecting features of the porous media not sampled by plug-scale measurements, such as vugs in carbonate rocks, small shale lenses or clasts, or small fractures. In addition, the flow toward the well during a drillstem test is three dimensional in nature; thus, the measurement is not direction dependent and produces only a single permeability value. In general, the second shut-in of the drillstem test is used for permeability determinations because it normally has a longer flow time than the initial shut-in, and therefore samples a larger volume of rock. The variation of permeability in uniform sedimentary rocks has been shown by various studies (Dagan, 1989; Freeze, 1975) to be characterized by a lognormal frequency distribution. Assuming a lognormal distribution, the geometric average of the well-scale permeability values is the best estimate of the representative permeability at the formation (basin) scale for the respective hydrostratigraphic unit. The lognormality assumption was confirmed for most of the well-scale drillstem-test permeability distributions characteristic of the aquifers in northeast Alberta by applying the χ^2 test. Table 3 presents the characteristic regional-scale permeability values for the aquifers in northeast Alberta.

The formation pressure is obtained by extrapolating the Horner plot of pressure measurements. The first shut-in of a drillstem test is generally preferred for pressure data because the flow time is usually shorter and the formation has been less disturbed. This leads to an intercept on the Horner plot with a higher degree of confidence. For constant density waters, a potential field driving the flow can be defined. Potentiometric surfaces are used in this case to represent the hydrodynamic field, identify horizontal flow directions, and calculate horizontal hydraulic gradients. The potentiometric surfaces are constructed based on distributions of freshwater hydraulic head H_0, calculated according to the formula:

$$H_0 = p/(\rho_0 g) + z$$

where z is elevation, p is pressure, ρ_0 is freshwater density, and g is the gravitational constant. In the case of variable density waters, a potential field cannot be defined (Hubbert, 1940, 1953) unless the pressure and density fields are collinear, implying that density is a function solely of pressure (Oberlander, 1989). The motion of a variable-density fluid may be interpreted as being caused by two driving forces: a potential force resulting from piezometric head differences, and a buoyancy force resulting from density differences (Hubbert, 1940; Bear, 1972, p. 654). The flow resulting from potentiometric differences is driven by topography, and is sometimes referred to as gravity-driven flow, although in a way buoyancy too is a driving force due to gravity. A measure of the relative importance

Hydrostratigraphic unit	No. tests	Minimum	Maximum	Geometric average	Y=ln(k)	σ_Y
Viking	51	0.046	5,207	18.59	2.92	2.4808
Grand Rapids	416	0.008	6,712	41.73	3.73	2.4675
Wabiskaw	200	0.009	5,464	8.41	2.13	2.4525
McMurray	365	0.002	8,085	13.66	2.61	2.5948
Wabamun	24	0.124	1,465	24.33	3.19	2.8952
Winterburn	34	0.134	1,900	9.81	2.28	2.5110
Wabamun-Winterburn	58	0.124	1,900	14.28	2.66	2.7030
Grosmont	55	0.028	1,591	10.75	2.37	2.2530
Cooking Lake	7	0.003	1,556	1.80	0.59	4.6362
Beaverhill Lake-Cooking Lake	22	0.036	1,122	91.16	-0.09	2.1980
Contact Rapids-Winnipegosis	31	0.001	272	1.03	0.034	3.1296

Table 3. Characteristic regional-scale values for permeability measurements (md) obtained from drillstem tests (1 darcy = 0.987×10^{-12}m^2).

of the two driving forces is given by the ratio $(\Delta\rho/\rho_o)/|\nabla H_o|_v$ (Bear, 1972, p. 654), where ρ_o is the reference density, $\Delta\rho$ is the fluid-density difference and $|\nabla H_o|_v$ is the magnitude of the vertical component of the freshwater hydraulic-head gradient ∇H_o. Although the distribution of freshwater hydraulic head does not represent a potential field driving variable-density flow, for horizontal aquifers it indicates the horizontal component of the hydraulic gradient within that aquifer (de Marsily, 1986).

In sedimentary basins, the density of formation waters is a function mainly of salinity and temperature. Therefore, the distributions of freshwater hydraulic head do not represent a potential field driving the flow. If the aquifer is sloping, as is the case in the Alberta Basin, the flow of formation waters is driven by both external (potential) and internal (buoyancy) forces. Density-driven flow enhances or retards the gravity-driven flow of formation waters, depending on density distribution, hydraulic gradient, and aquifer slope, as shown by analytical and numerical studies (Davies, 1987; Dorgarten and Tsang, 1991). Use of freshwater hydraulic-head distributions introduces errors, which may be significant, in the representation and evaluation of the flow regime. The errors are associated with both flow magnitude and direction (Davies, 1987). However, it is not the absolute value of the density-related flow component which is important, but the relative magnitude of this term versus the magnitude of the gravity-related term that determines whether buoyancy (density) effects are significant in any given situation (Davies, 1987). An indication of the relative error introduced by using freshwater hydraulic-head distributions is given by the dimensionless Driving-Force Ratio (DFR), defined by Davies (1987) as:

$$\mathrm{DFR} = \frac{\Delta\rho}{\rho_o} \; \frac{|\nabla E|}{|\nabla H_o|_h}$$

where $|\nabla E|$ and $|\nabla H_o|_h$ are the magnitude of the elevation gradient (aquifer slope) and of the horizontal component of the freshwater hydraulic-head gradient, respectively. For an isotropic porous medium, Davies (1987) showed through numerical experiments that the value DFR = 0.5 is an approximate threshold at which the use of freshwater hydraulic-head distributions may introduce significant errors in the representation and evaluation of the flow regime.

In the absence of a potential field, there is no method to represent the horizontal flow in sloping (dipping) aquifers. However, if the DFR for an aquifer is below the threshold value, the error in using distributions of freshwater hydraulic head is minor to acceptable, such that these distributions can still be used in representing and analyzing the fluid flow. Previous hydrogeological studies in the Western Canada Sedimentary Basin (Hitchon et al., 1989a, b; 1990) have shown that the salinity of Cretaceous aquifers is generally low, close to freshwater, and their slope is also lower than for Paleozoic aquifers. The salinity of the latter could be significant, particularly for deep aquifers or for aquifers adjacent to evaporitic rocks. Thus, this pattern is expected to be encountered also in the Northeast Alberta study area. Based on the previous discussion and on the expected density variations, maps of freshwater hydraulic-head distributions were used in the analysis of the flow regime of formation waters in the study area, together with pressure-depth profiles in selected wells. Assessment of the regional-scale Driving-Force Ratio (DFR) in each aquifer was used as an indication of the possible errors in the evaluation of the flow regimes.

Core-plug analyses

A total of 452,011 core-plug analyses were obtained from the electronic files of the Energy Resources Conservation Board (ERCB) and used in the analysis of porosity and permeability of the Phanerozoic rocks within the study area. The core-plug analysis data constitute a large volume of information; however, like the drillstem tests, their distribution is biased toward the more porous and permeable units of economic interest such as sandstones and carbonates. Even within these lithological units, the data tend to be clustered both areally and with depth. The initial hydrostratigraphic distribution of the core-plug analyses and associated wells is shown in Table 2. Most core plugs were analyzed for porosity, less than half were analyzed for maximum permeability, and very few have the other horizontal or vertical permeability determinations. If the rock was originally saturated with bitumen, the normal procedure is to extract the bitumen and then perform the measurements.

Because of the large number of core analyses, an automatic electronic screening procedure was required to cull erroneous data from the data base. Of the 452,011 core analyses in the study area, 63,305 do not contain data relevant to this study. The remainder of the data set was checked for physically unacceptable values. Various core laboratories which analyze core plugs suggest that the error associated with the measurement increases dramatically for extremely high permeability values. Therefore, any permeability value greater than $12 \times 10^{-12} m^2$ (12,000 md) was considered erroneous and was not used. Permeability in the horizontal plane is normally measured in four directions. The highest value and the one measured normal to it are taken as k_m and k_{90}, respectively. Therefore, analyses with horizontal permeability anisotropy values greater than 1.1 were rejected. Because there is no preferential compaction in the horizontal plane, horizontal anisotropy values less than 0.1 were also considered erroneous. Vertical permeability is normally smaller than the horizontal permeability because of compaction by sediment loading. However, because of the possible existence of vuggy carbonates or microfractures, vertical anisotropy values of up to 1.5 were accepted. Measurements which exceeded this limit were rejected. Porosity determinations greater than 43% (near the value characteristic for unconsolidated sediment) were also considered erroneous and were rejected. As a result of this process, 6688 core-plug analyses were rejected. Although the criteria for the initial screening are somewhat arbitrary, overall very few analyses were rejected (1.5% of the original number). The core analyses which passed this initial screening were allocated into the final hydrostratigraphic geometry.

Porosity and permeability data obtained from core analyses represent volume-averaged values corresponding to the plug-scale (Baveye and Sposito, 1984). Because of the large difference in magnitude between the plug and regional scale, a sequential scaling-up process is required (Cushman, 1984). Therefore, once the porosity and maximum permeability data were partitioned by hydrostratigraphic unit, they were scaled-up first to the well scale and then the characteristic well-scale values were scaled-up to the formation (basin) scale using the same procedure employed by Bachu and Underschultz (1992) in the analysis of porosity and permeability variation in the Peace River Arch area. Because the regional-scale values of porosity and maximum permeability were generated from plug-scale measurements, they are characteristic for the movement of fluids through the pore space only. Unlike permeability values obtained from drillstem tests, they do not characterize the movement of fluids through larger features such as vugs, caverns or fractures, which are beyond the resolution of plug-scale measurements.

The distributions of well-scale permeability values were analyzed by hydrostratigraphic unit for spatial variability. The distributions of maximum permeability k_m do not show any areal trend. Because various studies have shown that aquifer transmissivity values (the product between the hydraulic conductivity of an aquifer and its thickness) are lognormally distributed (Hoeksema and Kitanidis, 1985), it was expected that the well-scale permeability values would also be lognormally distributed. However, in the case of the Cretaceous strata in northeast Alberta, the frequency distributions of well-scale maximum permeability values do not to exhibit lognormality. Similarly, the Paleozoic units do not show lognormal well-scale permeability distributions, but they are generally closer to lognormal than the Cretaceous units. This may be due to the extremely variable lithology of the Cretaceous units compared to the more uniform lithology of the Paleozoic units. It is also suggested that the measurement procedure associated with core analyses in general (removal from in situ conditions) and bitumen-saturated core in particular (extraction of bitumen prior to taking measurements) results in errors which contribute to the non-lognormal characteristic of core permeability distributions. Regardless of the type of frequency distribution, the representative regional-scale value of maximum permeability is the geometric average of the well-scale permeability values (Dagan, 1989). Table 4 shows, by hydrostratigraphic unit, the formation (basin) scale characteristic values for maximum permeability k_m and the associated statistics.

Comparison of tables 3 and 4 shows that, for the Cretaceous units, the regional-scale permeability values obtained from core analyses are higher by more than one order of magnitude than the corresponding values obtained from drillstem tests. This could be due to the sample size, the sampling procedure, or to the fact that the core has been disturbed and depressured. In addition, core plug measurements made using air as the fluid have been found to give higher permeability values than those made using water or brine. The fact that the flow through a core sample is one-dimensional and direction dependent, while in a drillstem test it is three-dimensional, could also con-

Hydrostratigraphic unit	No. of wells	Minimum	Maximum	Geometric average	$Y=\ln(k_m)$	σ_Y
Ground-2nd W.S.S.	1	-	-	1840.00	7.52	-
Viking	12	26.30	5960	697.86	6.55	1.78
Grand Rapids	101	0.04	6270	488.12	6.19	2.09
Clearwater	30	0.48	4720	180.60	5.20	2.59
Wabiskaw	269	0.10	6900	254.50	5.54	1.92
McMurray	382	0.01	9980	262.81	5.57	2.97
Wabamun	24	1.52	2460	32.31	3.48	2.01
Winterburn	39	0.06	1370	14.53	2.68	2.17
Grosmont	178	0.02	6870	14.83	2.70	2.20
Cooking Lake	6	0.25	96	6.50	1.87	2.36
Beaverhill Lake	34	0.01	10200	39.67	3.68	5.31
Prairie	9	0.01	9	0.20	-1.63	2.79
Winnipegosis	43	0.01	175	0.43	-0.85	2.21
Contact Rapids	6	0.01	2	0.05	-3.08	2.10
Basal Red Beds	3	0.08	262	14.65	2.68	4.48

Table 4. Characteristic regional-scale values for permeability measurements (md) obtained from core analyses (1 darcy = 0.987 x 10^{-12}m^2).

tribute to the observed difference. There is currently no recognized methodology for reconciling the discrepancy between the two types of measurement. For the Devonian units, the regional-scale permeability values obtained from core analyses and drillstem tests are of the same order of magnitude, sometimes very close (tables 3 and 4).

Unlike the maximum permeability k_m, data regarding the horizontal permeability k_{90} normal to the direction of maximum permeability, and vertical permeability k_v are scarce. Thus, statistical averaging at the well-scale is not representative and is meaningless. Nevertheless, a horizontal and vertical anisotropy was calculated for each well where data exist in order to check if there is any areal trend in anisotropy which could be due to depositional factors. No trend was detected for any hydrostratigraphic unit. Thus, values for horizontal and vertical permeability anisotropy were calculated by regression analysis applied directly to all the analyses in a unit recording either both k_m and k_{90} or k_m and k_v. Table 5 shows, for each hydrostratigraphic unit, the number of measurements, the coefficient of correlation R^2 of the linear regression between the corresponding values of the two respective permeability components, and the formation average of core-scale anisotropy values A_H and A_v. It must be emphasized that these anisotropy values do not necessarily represent the basin-scale anisotropy of the respective formations, because vertical anisotropy at the formation scale may arise in a layered or heterogeneous system consisting of locally isotropic beds (Freeze and Cherry, 1979; Bachu, 1991). Core-scale measurements in such a system would not reveal the effective formation-scale anisotropy. Thus, the values A_H and A_v in Table 5 represent a basin-scale average of core-scale anisotropy, and not the true basin-scale anisotropy.

Porosity, unlike permeability, is a scalar property of the porous media and has a much smaller variance than permeability. It is generally accepted (Dagan, 1989) that the local-scale porosity in uniform sediments and sedimentary rocks can be described by a normal probability density function. However, non-normal distributions are typical of well porosity distributions for most units in northeast Alberta, suggesting that the normality assumption is not valid, at least in the study area. The representative well-scale porosity value was calculated as the arithmetic average of the plug-scale values weighted by the length of the representative interval. The formation (basin) scale distributions of well-scale porosity values were analyzed for spatial variability by hydrostratigraphic unit. Well-scale porosity distributions show no regional trend for any hydrostratigraphic unit. Like the plug-scale measurements, well-scale porosity values tend not to show the expected normal frequency distribution. The arithmetic average of the representative well-scale values is used for the regional-scale characterization of porosity for each unit. Table 6 shows the representative formation (basin) scale porosity value and associated statistics for each hydrostratigraphic unit.

Hydrostratigraphic unit	Horizontal anisotropy			Vertical anisotropy		
	No. of samples	R^2	A_H	No. of samples	R^2	A_v
Viking	-	-	-	7	0.63	0.75
Grand Rapids	95	0.98	0.86	116	0.87	0.57
Clearwater	52	0.99	0.87	60	0.92	0.50
Wabiskaw	355	0.93	0.87	387	0.83	0.64
McMurray	527	0.83	0.55	496	0.37	0.14
Wabamun	533	0.71	0.49	485	0.40	0.15
Winterburn	370	0.70	0.51	344	0.38	0.17
Grosmont	6742	0.81	0.59	6248	0.34	0.15
Cooking Lake	153	0.53	0.31	154	0.63	0.17
Beaverhill Lake	304	1.00	0.85	304	0.06	0.03
Prairie	98	1.00	0.91	98	0.95	0.61
Winnipegosis	1804	0.83	0.77	1801	0.13	0.12
Contact Rapids	58	0.92	0.78	58	0.32	0.12
Basal Red Beds	54	0.99	0.90	54	0.61	0.33

Table 5. Regional-scale averages of core-scale horizontal and vertical permeability anisotropy, A_H and A_v, expressed by the correlations of k_{90} and k_v with k_m, respectively.

Hydrostratigraphic unit	No. of wells	Minimum	Maximum	Arithmetic average	σ_ϕ
Ground-2nd W.S.S.	38	0.26	0.43	0.34	4.26×10^{-2}
Viking	16	0.27	0.38	0.33	3.81×10^{-2}
Grand Rapids	285	0.09	0.42	0.35	2.76×10^{-2}
Clearwater	53	0.15	0.40	0.31	5.72×10^{-2}
Wabiskaw	1558	0.06	0.42	0.31	1.58×10^{-2}
McMurray	4822	0.02	0.43	0.32	9.18×10^{-2}
Wabamun	30	0.03	0.34	0.17	6.40×10^{-2}
Winterburn	56	0.04	0.33	0.20	5.99×10^{-2}
Grosmont	193	0.02	0.36	0.15	3.79×10^{-2}
Cooking Lake	19	0.01	0.36	0.26	8.38×10^{-2}
Beaverhill Lake	1057	0.003	0.42	0.31	1.94×10^{-2}
Prairie	10	0.02	0.33	0.08	8.83×10^{-2}
Winnipegosis	46	0.01	0.38	0.09	6.71×10^{-2}
Contact Rapids	6	0.01	0.10	0.05	4.06×10^{-2}
Basal Red Beds	3	0.02	0.18	0.10	6.52×10^{-2}

Table 6. Characteristic regional-scale values for porosity measurements obtained from core analyses.

Subsurface geology

The following is an overview of the Phanerozoic geological history in the Northeast Alberta study area in the context of the major depositional and erosional events which have occurred in this part of the Western Canada Sedimentary Basin. The stratigraphy is subdivided into discrete sedimentary packages, each representing deposition in a distinct paleogeographic configuration with characteristic geometry and facies patterns. This characterization provides the background information fundamental to the hydrogeological analysis presented in this study.

Basin history

The Western Canada Sedimentary Basin is a wedge of sedimentary strata that thickens westward from a zero-edge at the Canadian Shield to more than 6 km at the foreland thrust-fold belt (Figure 2). Adjacent to the Canadian Shield, the regional dip of strata ranges from 1 to 5 m/km. McCrossan and Glaister (1964), Parsons (1973), Porter et al. (1982), Stearn et al. (1979) and Ricketts (1989) described the overall geological history and detailed geology of the Western Canada Sedimentary Basin which is pertinent to this study.

The geological history of the Western Canada Sedimentary Basin can be divided into passive-margin and foreland-basin sedimentation, largely the result of two fundamentally different tectonic realms which influenced basin dynamics. The passive margin, or platformal, phase was initiated during the late Proterozoic by rifting of the North American craton resulting in the generation of a miogeosyncline-platform. Following the initial rifting event, thermal contraction (Bond and Kominz, 1984) initiated the transgressive onlap of the North American cratonic platform from middle Cambrian to middle Jurassic time. During this time interval, sedimentation was initially dominated by easterly, shield-derived clastics, followed by the development of epeirogenic arches and basins on the cratonic platform dominated by carbonate and evaporite deposition in shallow seas.

The foreland basin developed as a result of the collision of allocthonous terranes with the western margin of the craton. It can be divided into two stages: middle Jurassic to early Cretaceous (Columbian Orogeny) and late Cretaceous to Paleocene (Laramide Orogeny). During these orogenies, the miogeoclinal succession was compressed, detached from its basement, and thrust over the flank of the craton to form the present eastern part of the Cordillera (Porter et al., 1982). The continental lithosphere responded to the tectonic loading by isostatic flexure, initiating the development of a foreland basin to the east. Erosion of the evolving Cordillera provided a source of sediments which were shed into the basin to the east and separated from passive margin sediments by an erosional angular unconformity.

Within the context of this two-fold subdivision of the sedimentary strata, Table 1 shows the detailed nomencla-

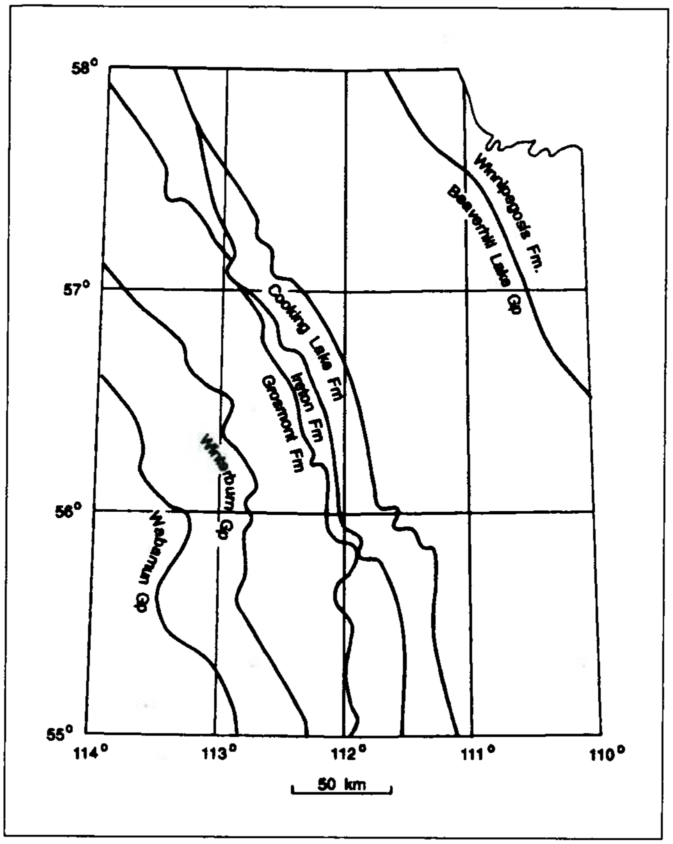

Figure 4. Subcrop boundaries of Devonian strata at the sub-Cretaceous unconformity in northeast Alberta.

ture referring to the specific stratigraphic intervals present within the Northeast Alberta study area. The passive margin succession between the Precambrian basement and the sub-Cretaceous unconformity is divided into 18 units, while foreland basin strata are divided into 8 units. The regional geology is discussed in terms of these subdivisions.

Passive-margin development

Within the study area, the strata making up the passive-margin phase of basin development form a wedge tapering from more than 1800 m in the southwest to 0 m in the northeast and are bounded by the Precambrian crystalline basement below and the sub-Cretaceous unconformity above. At the sub-Cretaceous unconformity, Devonian strata subcrop with increasing age to the northeast, toward the exposed Precambrian Shield (Figures 4 and 5). The general lithology and structure of the succession is illustrated through dip and strike cross-sections, A-A' (Figure 5) and B-B' (Figure 6), respectively.

Precambrian basement

The Precambrian continental craton consists mainly of Archaean crystalline rocks and Aphebian (2500-1750 Ma) supracrustal rocks that were modified by deformation, metamorphism, and magmatism during the early Proterozoic Hudsonian Orogeny (1750 Ma) (Porter et al., 1982).

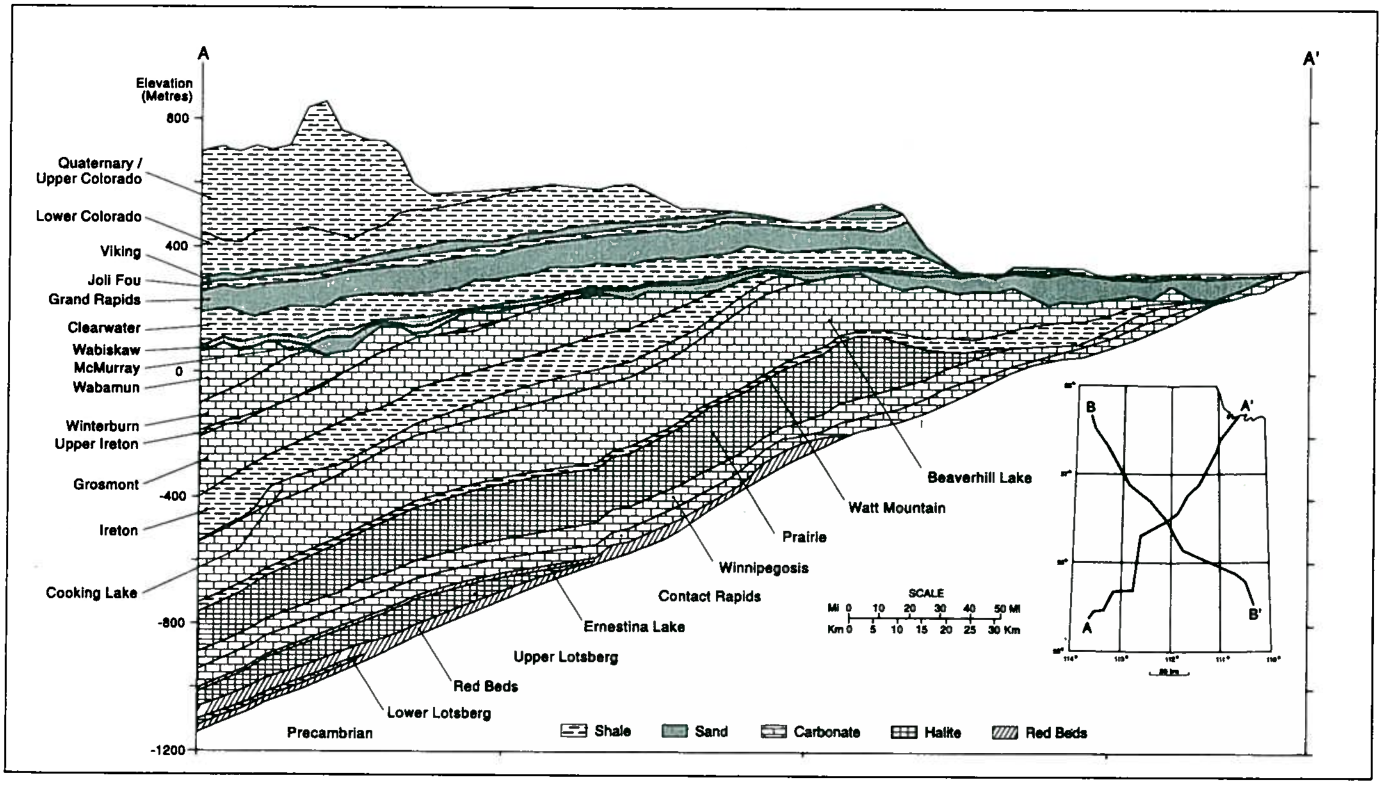

Figure 5. Structural dip cross-section A-A' of Phanerozoic succession.

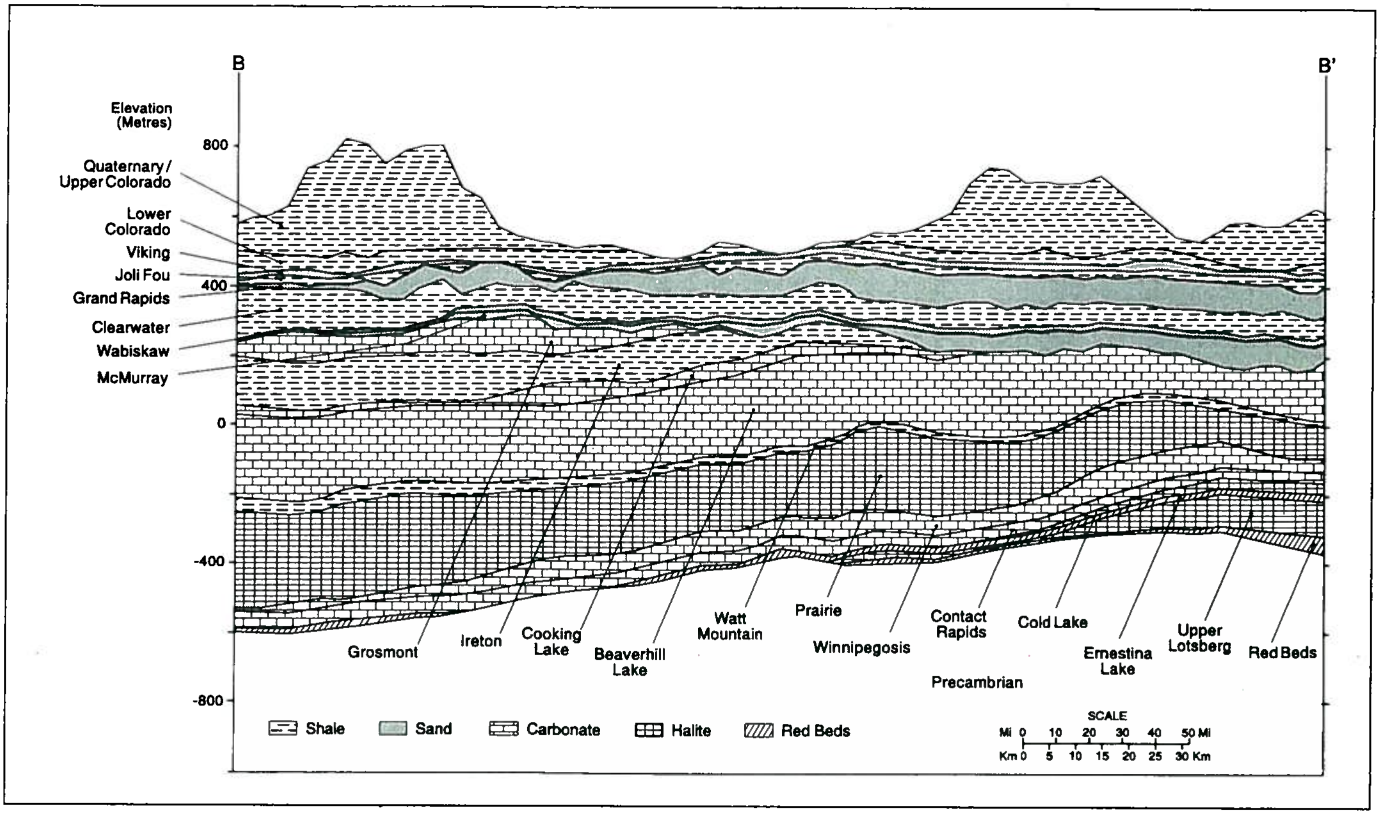

Figure 6. Structural strike cross-section B-B' of Phanerozoic succession.

The Precambrian basement dips gently to the southwest at 4-5 m/km, with local relief of up to 50 m (Figure 7a). A low broad east-northeast trending ridge separates the Northern Alberta sub-Basin from the Central Alberta sub-Basin. This ridge may be an extension of the Peace River Arch located to the southwest (O'Connell et al., 1990).

Elk Point Group

The Lower to Middle Devonian Elk Point Group unconformably overlies the Precambrian basement. From oldest to youngest, the Elk Point Group strata can be divided into three red bed-evaporite successions, called the Lotsberg, Ernestina Lake and Cold Lake formations, respectively, followed by a more widespread succession of clastics, platform carbonates, evaporites and clastics, called the Contact Rapids, Winnipegosis, Prairie Evaporite and Watt Mountain formations, respectively. The earlier Elk Point Group strata onlap the Precambrian basement filling in relief on the Precambrian surface, resulting in relatively smooth structure surfaces for the top of each formation.

The Lotsberg Formation forms a complex wedge of red bed and evaporite deposits consisting of the Basal Red Beds unit overlying the Precambrian basement (Figure 6) (Meijer-Drees, 1986), followed by the Lower Lotsberg Salt, an unnamed red bed unit and the Upper Lotsberg Salt. Each of these units thickens to the south, reaching maximum thicknesses of 70, 40, 45 and 120 m, respectively. The limits of the salt deposits (Figure 8) are depositional except for the northern limit of the Upper Lotsberg Salt, between longitudes 110° and 112° W, where a maximum thickness of 25 m is estimated to have been removed by salt dissolution (McPhee and Wightman, 1991). North of the salt edge, the Lotsberg Formation ranges from 0 to 7 m, and consists only of red beds. Progressing eastward between latitudes 56° and 57°N and longitudes 110° and 112°W, the red beds merge with coarser grained clastics referred to as the La Loche Formation (Sproule, 1951: Norris, 1973).

The Ernestina Lake Formation conformably overlies and extends beyond the Lotsberg Formation, forming an extensive, remarkably consistent unit with an average thickness of 17 m. It consists of a basal red dolomitic shale, a middle anhydritic calcareous shale and an upper anhydrite bed (Sherwin, 1962). North of latitude 56°N, the Ernestina Lake Formation onlaps and pinches out against the Precambrian basement or underlying La Loche Formation. North of the Lotsberg salt deposits it is difficult to separate the Ernestina Lake Formation and the underlying Lotsberg Formation.

The Cold Lake Formation consists of a basal red bed unit overlain by two isolated salt deposits located in the southeast and northwest corners of the study area (Figure 8) (Sherwin, 1962; Hamilton, 1971). The basal red bed unit increases in thickness from about 5 m in the east-central part of the study area to 20 m in the southwest corner. East of the Ernestina Lake Formation boundary, the basal red bed unit of the Cold Lake Formation becomes difficult to distinguish from the underlying La Loche Formation. The salt deposit in the south thickens southward from its depositional limit to more than 40 m in the southwest

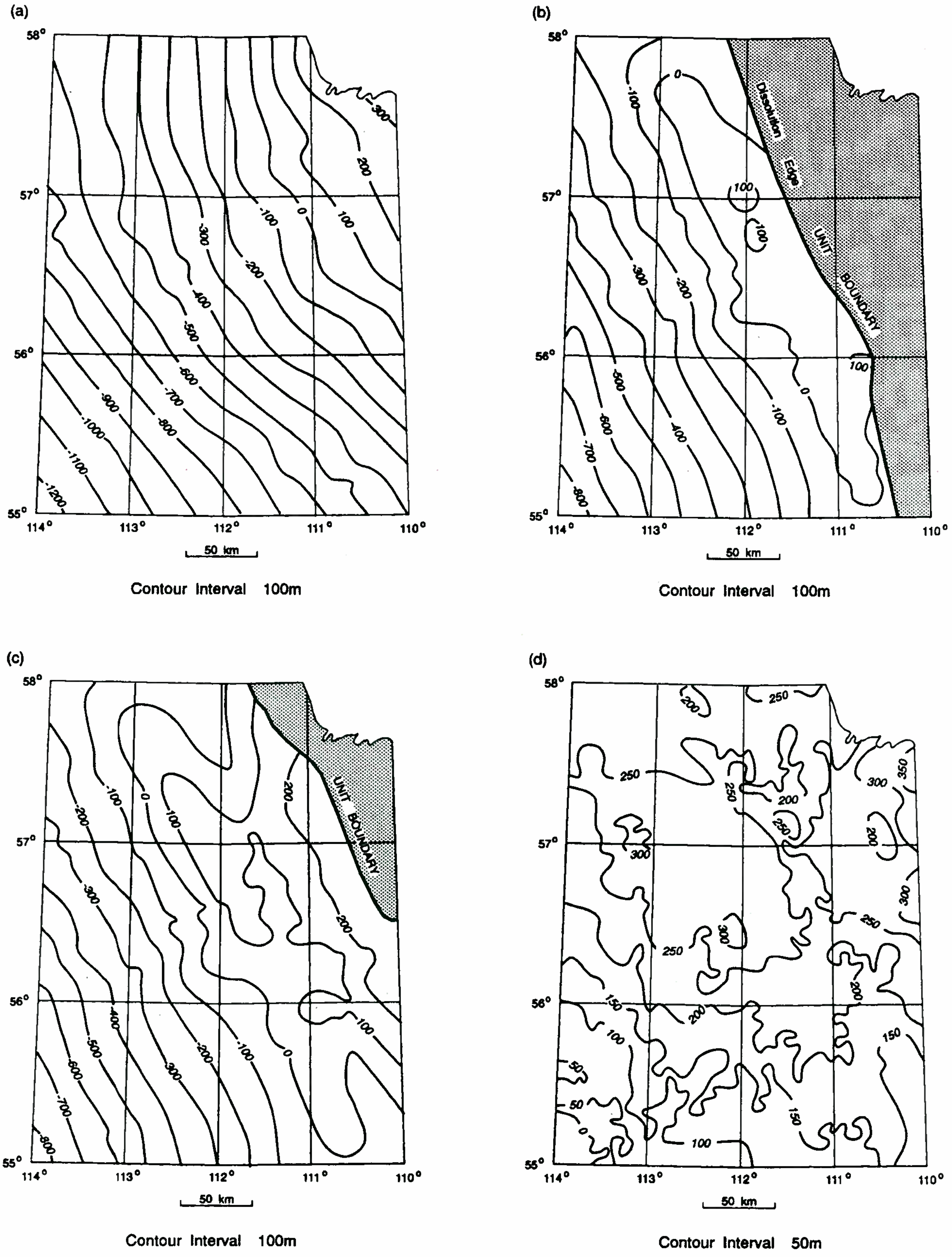

Figure 7. Paleozoic structure maps in northeast Alberta: (a) Precambrian basement; (b) top of Prairie Formation; (c) top of Watt Mountain Formation; and (d) sub-Cretaceous Unconformity.

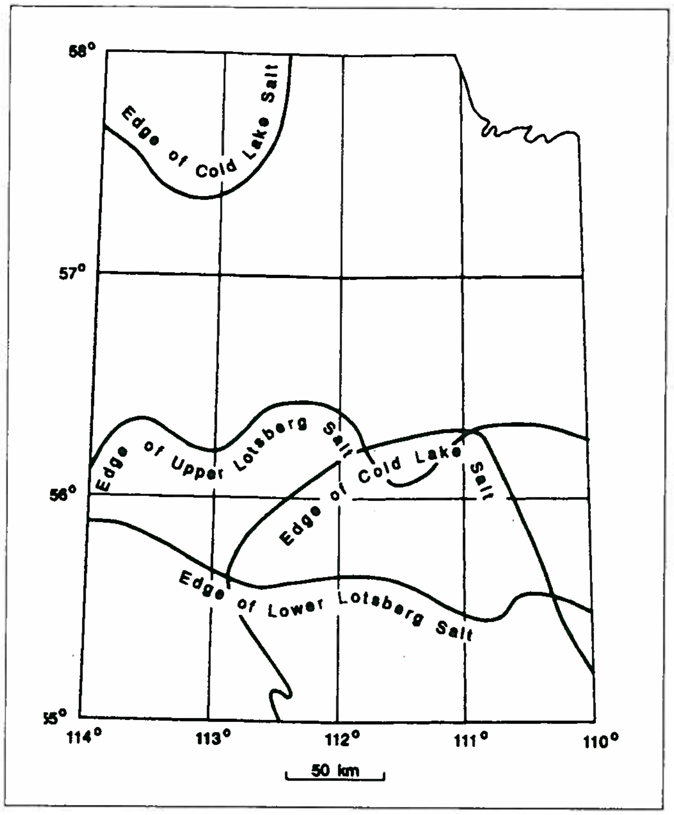

Figure 8. Depositional and dissolution boundaries of Lower Elk Point subgroup evaporitic beds.

corner of the study area. The northern salt thickens from its depositional edge to near 30 m at the northern edge of the study area. The eastern limit of both salt deposits is the result of salt dissolution. Where the salt is absent there is a 5-20 m shale equivalent. Because this shale is difficult to correlate, it is grouped with the overlying Contact Rapids Formation.

The Contact Rapids Formation consists of interbedded argillaceous dolostone and shale (Sherwin, 1962) that grades laterally into the Chinchaga Formation of northern Alberta, an interbedded succession of anhydrite and dolostone (Law, 1955; Meijer-Drees, 1986). It is up to 45 m thick in the southwest and thins to 20 m in the northeast. The base of the Contact Rapids Formation is distinct where it is underlain by the Cold Lake Salt deposits, but it is difficult to define where basal shale beds of the Contact Rapids Formation overlie the Cold Lake shale equivalent.

The Contact Rapids Formation is conformably overlain by reef and non-reef carbonates of the Keg River Formation in the northwest (Law, 1955), the Methy Formation dolomites in the central-north Athabasca area (Nauss, 1950; Greiner, 1956), and the Winnipegosis Formation to the south (Baillie, 1953; Grayston et al., 1964). In the present study, these carbonate units are collectively referred to as the Winnipegosis-Keg River succession. Reef carbonates, up to 115 m thick, form a southeast-northwest linear trend (Figure 9a). Non-reef carbonates generally have an average thickness of 50 to 60 m, thinning to 12 m in some inter-reef areas.

The Muskeg-Prairie Evaporite succession, shown in Figure 9b, is thickest along a north-northwest trend, increasing from 160 m in the south to more than 300 m in the northwest. Thinner intervals along this trend are the result of relief on the underlying Winnipegosis Formation reefs.The unit is termed the Muskeg Formation in the northwest and the Prairie Formation in the south, reflecting a lithofacies change from anhydrite to halite between Tp 100 and 85 (Baillie, 1953; Law, 1955; Grayston et al., 1964). The eastern boundary of the evaporite succession is a 20 km wide dissolution salt scarp (Figure 9b) which has migrated toward the center of the basin since late Devonian time. The regional reversal of dip on the eastern side of the Prairie salt scarp (Figure 7b) forms the Athabasca anticline-syncline pair and can be recognized in overlying strata ranging from Devonian to Cretaceous age.

The Watt Mountain Formation conformably overlies the Muskeg-Prairie Evaporite succession (Law, 1955), and consists of a widespread 15 to 20 m thick succession of dolomitic shales. Structure on top of the Watt Mountain Formation (Figure 7c) mimics that of the underlying Muskeg-Prairie Evaporite succession, indicating that salt dissolution occurred after the deposition of the Watt Mountain Formation.

Beaverhill Lake Group

The Beaverhill Lake Group consists in ascending order of the Fort Vermilion, Slave Point and Waterways formations. The anhydrite-dominated Fort Vermilion Formation and the limestone-dominated Slave Point Formation occur only in the northwest as thin southerly tapering wedges. The Waterways Formation is an alternating succession of calcareous shales and carbonates, subdivided in ascending order into the Firebag, Calumet, Christina, Moberly and Mildred Lake members. Post-Devonian erosion has resulted in the Beaverhill Lake Group thinning from more than 200 m in the southwestern half of the study area to a zero edge along a wide subcrop belt at the sub-Cretaceous unconformity (Figure 9c).

Woodbend Group

The Woodbend Group consists of two stacked carbonate platforms, the Cooking Lake Formation and the Grosmont Formation, which are separated by and partially contemporaneous with the limy shales of the lower Ireton Formation. The Grosmont Formation is capped by thin shales of the upper Ireton Formation.

In the study area, the Cooking Lake Formation carbonate platform subcrops to the east of 113°W across a 18 km wide zone (Figure 4). Near the subcrop zone, the formation locally thickens due to the presence of carbonate build-ups (Figure 9d). West of 113°W, the Cooking Lake Formation thins depositionally to a few meters.

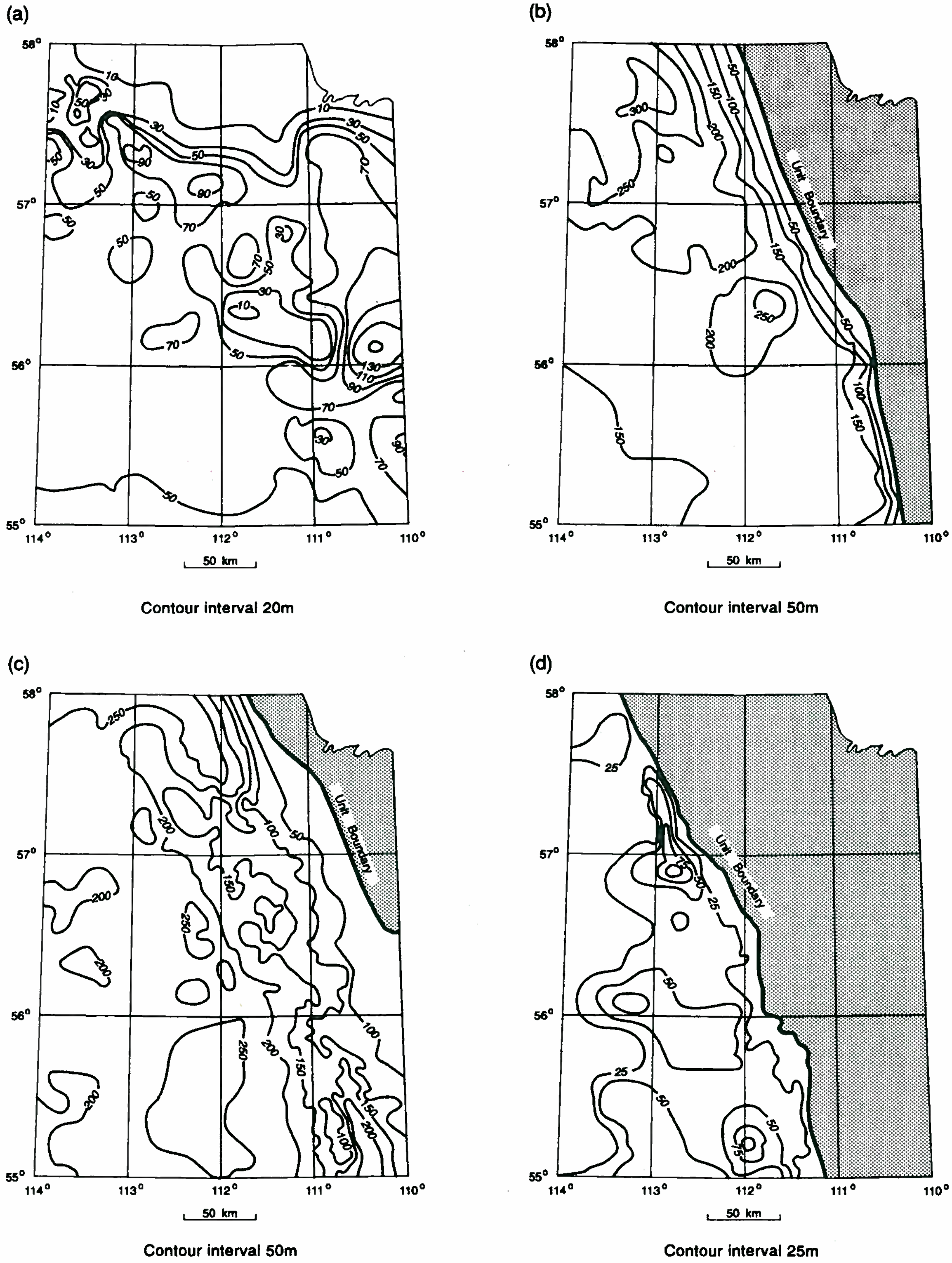

Figure 9. Isopach maps of Paleozoic strata in northeast Alberta: (a) Winnipegosis-Keg River Formation; (b) Prairie Formation; (c) Beaverhill Lake Group; and (d) Cooking Lake Formation.

The limy shales deposited basinward (west) and overlying the Cooking Lake platform make up the Lower Ireton Formation. They range from 100 to 150 m in thickness except along the subcrop belt, and separate the carbonates of the Cooking Lake Formation and Grosmont Formation. In areas where there are reefs in the underlying Cooking Lake Formation, there are occasional thin shales separating the Cooking Lake and Grosmont carbonates.

The Grosmont Formation represents a carbonate platform which prograded to the west similar to the Cooking Lake Formation. It tapers uniformly to the northeast, over a 30 km wide subcrop belt, with an average thickness of 170 m. The Grosmont Formation is capped by a thin (less than 20 m) shale, referred to as the upper Ireton Formation. West of the Grosmont carbonate platform (approximately west of the 5th meridian), the upper and lower Ireton shales merge into a single unit.

Winterburn and Wabamun Groups

The Winterburn Group and the overlying Wabamun Group represent the basinward progradation of carbonate platforms as a result of the regression of the Kaskaskia Sea at the end of late Devonian time. Subsequent erosion has removed these rocks over most of the study area, with only small areas of subcrop in the southwest. The Winterburn Group consists primarily of dolomitic rocks and has a maximum thickness of 125 m. The Wabamun Group comprises a massive 125 m thick limestone unit.

Sub-Cretaceous Unconformity

The structure top of the Paleozoic succession is a composite of Middle to Upper Devonian subcrop belts which increase in age to the northeast (Figure 4). The surface forms the sub-Cretaceous unconformity of northeast Alberta, which gently dips to the southwest with slopes of 2 m/km or less (Figure 7d). Post-Devonian subareal erosion has resulted in more than 50m of local relief on this structure surface. Differential erosion of tilted, tabular Paleozoic strata resulted in a series of north-northwest trending ridges and valleys that developed into northerly flowing river systems during the early Cretaceous (Jackson, 1984).

Foreland-basin development

In northeast Alberta, foreland-basin strata consist of Cretaceous siliciclastic sediments that are bounded at the base by the sub-Cretaceous unconformity and covered by a variable thickness veneer of Pleistocene deposits. The succession, thickening from 0 m at the eastern edge to more than 600 m in the west, is subdivided into the Lower Cretaceous Mannville Group and Upper Cretaceous Colorado Group. Post-Cretaceous erosional events have removed a considerable thickness of strata from northeast Alberta, especially along present day drainage systems which are often incised down to the sub-Cretaceous unconformitty. Quaternary glacial and post-glacial deposits blanket much of the Cretaceous and Devonian bedrock. Pleistocene deposits consist primarily of unconsolidated sands and gravels.

Mannville Group

The deposits of the Lower Cretaceous Mannville Group are of relatively uniform thickness, and lie unconformably on the sub-Cretaceous unconformity. The Mannville Group can be divided into the McMurray, Clearwater and Grand Rapids formations. Paleotopography on the sub-Cretaceous unconformity, sediment supply, and fluctuations of sea level were the major factors affecting the deposition of the Mannville Group.

Lower Mannville sediments in northeast Alberta make up the sand-dominated McMurray Formation. The structure map on top of the McMurray Formation (Figure 10a) shows a relatively uniform southwest dip except for the east-central and southeast regions of the study area. In these areas, a reversal of regional dip occurs reflecting the dissolution of salt in the underlying Devonian Prairie Evaporite Formation. In the west, the McMurray Formation is generally thin (less than 50 m), while east of longitude 112°W, sands and associated shales of the McMurray Formation thicken significantly (Figure 11a). Thin areas generally indicate ridges or paleo-highs on the sub-Cretaceous unconformity, while thick areas correspond to valleys or paleo-lows. Dip and strike cross-sections (Figures 5 and 6, respectively) depict these regional thickness variations and their relation with the unconformity. The ridge and valley system was critical to Lower Mannville sedimentation patterns in northeast Alberta. A northerly trending valley system in northeast Alberta acted as conduits for siliciclastic sediments shed mostly from the stable Precambrian Shield to the east (Cant, 1989). The McMurray Formation primarily occupies a major valley system developed along the toe of the Prairie Evaporite Salt scarp (McPhee and Wightman, 1991) located near the eastern edge of the basin.

The Upper Mannville in northeast Alberta is subdivided into the Clearwater and Grand Rapids formations (Badgley, 1952). These formations are two genetically related successions defined by a diachronous boundary which separates the sand-dominated facies of the Grand Rapids Formation from the shale-dominated facies of the Clearwater Formation (Kramers and Prost, 1986).

The basal part of the Clearwater Formation, referred to as the Wabiskaw Member, generally comprises sandy to silty shales with occassional thin, clean sand buildups. The Wabiskaw Member disconformably overlies the McMurray Formation and represents the basal deposits of the major Clearwater transgression. It is marked at the top by a regionally correlatable marker horizon. The Wabiskaw Member is generally less than 15 m thick, with the exception of the western margin of the study area and an anomalous, localized thick accumulation in the southeast. The remainder of the Clearwater Formation (the portion above the Wabiskaw Member) is generally shaly in the

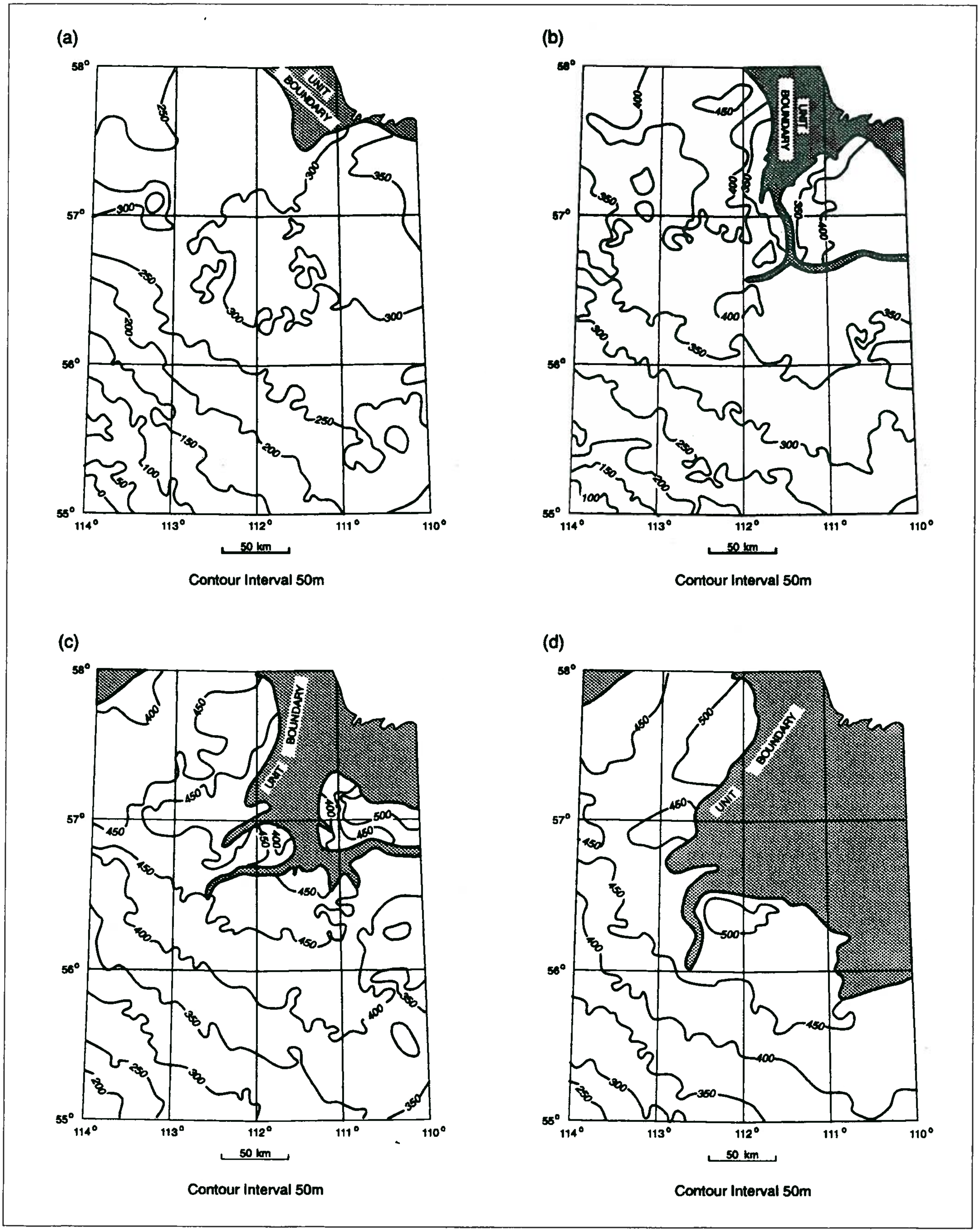

Figure 10. Top structure maps of Cretaceous strata in northeast Alberta: (a) McMurray Formation; (b) Clearwater Formation; (c) Mannville Group (Grand Rapids Formation); and (d) Viking Formation.

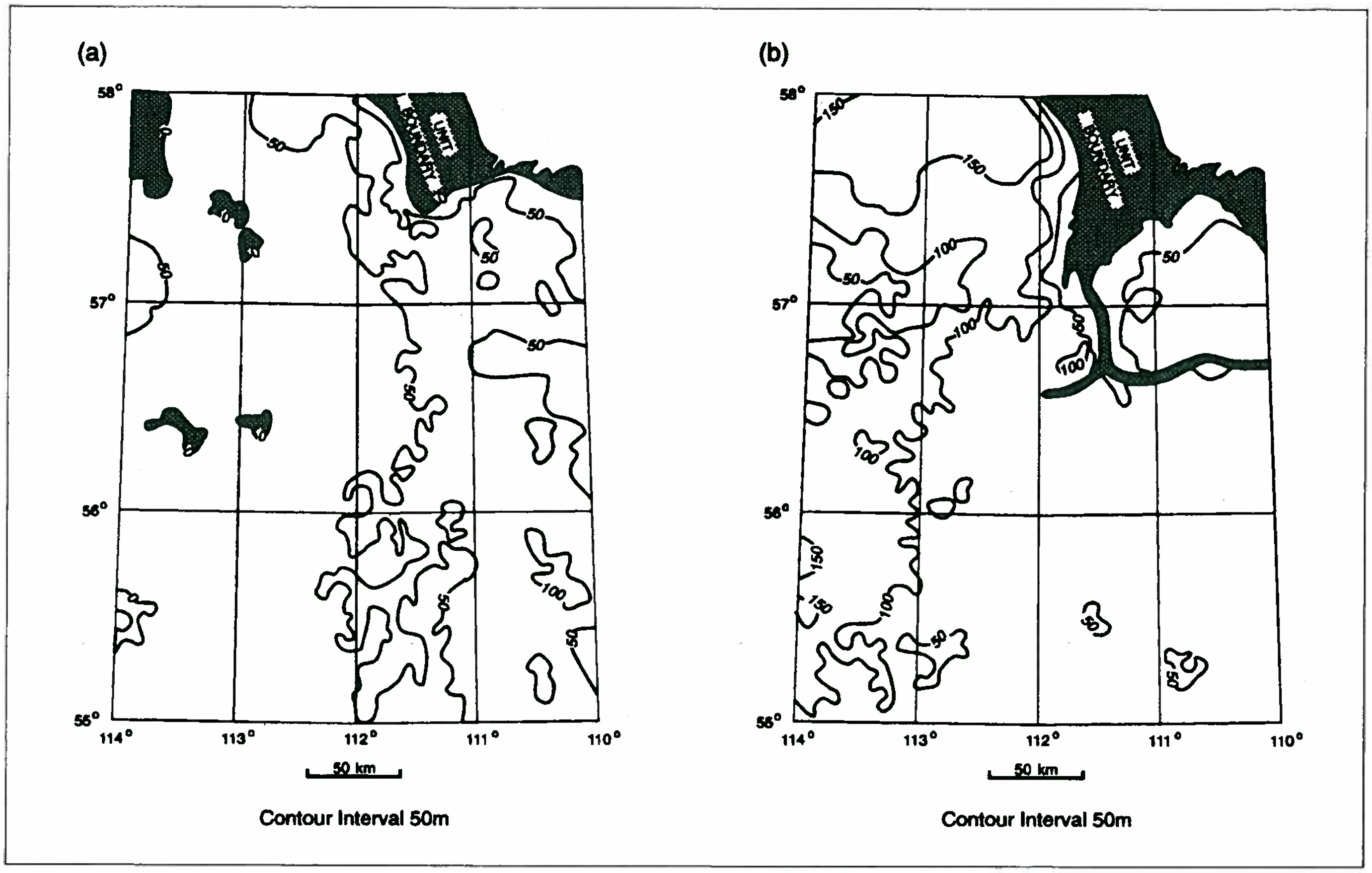

Figure 11. Isopach maps of the (a) McMurray and (b) Clearwater formations in northeast Alberta.

north and becomes progressively sandier to the south. In the southern region there are three distinct sand bodies. These units, individually up to 30 m or more in thickness, appear in the subsurface as coarsening-upward, stacked, sand bodies. In vertical succession, each stratigraphically higher sand body has its leading depositional edge terminating in a more northerly position than the preceding one. The top of the Clearwater Formation generally dips gently to the southwest (Figure 10b). Structure contours, although subdued compared to those of the McMurray Formation, show irregularities over the area of the underlying Devonian salt dissolution edge in the southeast. The isopach of the Clearwater Formation (Figure 11b) shows a gradual thickening to more than 150 m in the northwest. Several distinct, laterally continuous shale markers within the Clearwater Formation have been used as stratigraphic datums by Kramers and Prost (1986), Keith et al. (1987) and MacGillivray et al. (1989), to correlate and map successions within the Mannville Group.

Overlying and laterally interfingering with the Clearwater Formation is the Grand Rapids Formation, which represents a regional regression as the Clearwater sea withdrew to the north and northwest. In the western part of the study area (Wabasca area, Tp 69 to 87, R 12 W4 Mer to R 3 W5 Mer), the contact between the Grand Rapids Formation and the Clearwater Formation is diachronous, but distinct, and considered to be related to sediment supply (Kramers and Prost, 1986). Within other parts of northeast Alberta, the diachronous, interfingering boundary is less clear. In the Wabasca area, southwest of Fort McMurray, the Grand Rapids Formation comprises three stacked, laterally continuous, coarsening-upward sand successions. The sand bodies are bounded by shales and silty beds. Like the Clearwater Formation, the northerly depositional limit of each successive sand body, averaging approximately 30 m in thickness, is positioned farther basinward than the previous one (Kramers and Prost, 1986). Structure contours on top of the Grand Rapids Formation (Figure 10c), equivalent to the top of the Mannville Group, are similar to the underlying structure surface of the Clearwater Formation. The Grand Rapids Formation is of generally uniform thickness except for slight thinning in the northern and eastern regions.

Colorado Group

The Colorado Group ranges in age from the early Cretaceous (Upper Albian) to approximately the middle of the late Cretaceous. In general, the Colorado Group consists of thick successions of shale intercalated with several thin sandstones. The onset of Colorado deposition marked significant changes in sedimentation within the basin. Cant (1989) suggested that this change is the result of a lull in Cordilleran tectonic activity combined with an overall period of rising sea level. Coalescence of the Gulfian Sea from the south and the Boreal Sea from the north inundated the western interior, forming a seaway that extended from the Gulf of Mexico to the Arctic (Williams and Stelck, 1975).

The top of the Mannville Group in northeast Alberta is disconformably overlain by the Joli Fou Formation, which consists primarily of shale, but contains some basal sandstones along the western limit. Shales of the Joli Fou Formation are generally thin (less than 15 m). Over most of the study area, the division between the top of the Joli Fou Formation and the base of the Viking Formation is difficult to discern.

Sandstones and shales of the Viking Formation overlie the Joli Fou Formation. Within northeast Alberta, the sandstones of the Viking Formation, also referred to as the Pelican Formation, often consist of clean, coarsening-upward cycles which thicken to the east. The entire Viking succession is of the order of 25 m thick throughout the region. The structure on the top of the Viking Formation (Figure 10d) has a similar trend to that of the underlying Mannville Group.

In the Western Canada Sedimentary Basin the Viking Formation is overlain by a thick interval of Colorado shale. Two prominent, radioactive marker horizons known as the Base of the Fish Scale Zone and the Second White Speckled Shale are found in this succession. In the study area, post-Colorado erosion has removed most of the Colorado Group shales.

The Fish Scale Zone, the first marker located stratigraphically above the Viking Formation, is considered the boundary between the Upper and Lower Cretaceous. The Fish Scale Zone generally consists of laminated sands and silts containing abundant fish-scales and vertebrae (Leckie, 1989). The top of the Base of the Fish Scale zone displays the same southwesterly dipping regional trend shown by earlier Cretaceous strata. The shaly unit between the top of the Viking Formation and the Base of the Fish Scale Zone, where preserved, maintains thicknesses in the range 20 to 40 m within the study area, except for the northernmost region where it thickens to more than 60 m. The coccolith-rich Second White Speckled Shale (second marker), present only in the southwest corner of the study area, is separated from the Base of the Fish Scale Zone by a second shale succession up to 100 m thick.

Pleistocene glacial deposits and other Quaternary aged sediments form a veneer over much of the Cretaceous bedrock. Pleistocene deposits consist primarily of unconsolidated sands and gravels less than 50 m thick, with localized paleo-valley deposits up to 100 m thick. Because these sediments are generally isolated by casing during the drilling process, few geophysical logs recording the contact between Pleistocene strata and the underlying bedrock are available.

Hydrogeological analysis

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 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 Northeast Alberta study area is located on the eastern edge of the Alberta basin where regional-scale aquifers either subcrop near or crop out at the ground surface. In this area, the regional flow systems described in the basin to the west (Hitchon et al., 1990) approach the surface and come under the influence of local conditions. In addition, aquitards which are effective regional barriers to flow in the deeper part of the basin to the west often become more arenaceous and less effective toward the eastern basin edge, thus allowing more significant cross-formational flow.

The strata within northeast Alberta are divided into 13 hydrostratigraphic systems based on their geometry, lithology and hydrodynamic characteristics. Each hydrostratigraphic unit is examined individually to determine its flow regime. Subsequently, the entire hydrodynamic system is analyzed, including the interaction of hydrostratigraphic units and cross-formational flow.

Hydrostratigraphy

The hydrostratigraphy for the Northeast Alberta study area was developed through several iterations starting from the stratigraphy and lithology of the strata. Complex groups of aquifers and/or aquitards exhibiting generally common overall characteristics were grouped into hydrostratigraphic systems. An aquifer system behaves mostly like an aquifer even if minor aquitards are present, and an aquitard system behaves mostly like an aquitard even if some aquifers are present. Table 7 shows the final hydrostratigraphic succession and nomenclature for the strata in the Northeast Alberta study area. Within the Lower Elk Point aquitard-aquiclude system, hydrogeological data exist only for the Basal Red Beds/Granite Wash and Ernestina Lake aquifers/aquitards. In addition, the data for the Ernestina Lake aquifer/aquitard are located only where the Lotsberg Salt beds are absent, in which areas the Ernestina Lake Formation becomes nearly indistinguishable from the underlying Basal Red Beds. Thus, the Ernestina Lake and Basal Red Beds were combined and defined as the "basal aquifer" (Basal Red Beds where the Lotsberg Salt is present and the combined Basal Red Beds and Ernestina Lake aquifers elsewhere). The Contact Rapids unit, defined initially as being part of the Lower Elk Point aquitard-aquiclude system, was subsequently found to have characteristics more consistent with the overlying Winnipegosis aquifer. As a result, the Contact Rapids and Winnipegosis aquifers were grouped in a single aquifer system whose isopach is shown in Figure 12a. Similarly, Figure 12b shows the combined Beaverhill Lake-Cooking Lake isopach. These aquifers, which are in contact, have similar hydraulic characteristics, indicating that they act as a single flow unit. Some drillstem tests, initially allocated within the Lower Ireton Formation near the boundary with the overlying Grosmont Formation, had hydraulic characteristics consistent with those of the latter. The final isopach of the Grosmont aquifer is thus modified (Figure 12c) in order to incorporate the corresponding parts of the Lower Ireton unit. Initially, it was expected that the Grosmont, Winterburn and Wabamun aquifers would exhibit similar hydraulic characteristics and could be considered a single flow unit. The formation water analyses show, however, that the Grosmont aquifer has particular geochemical characteristics which require it to be considered separately (Hitchon, 1991). Nonetheless, the Winterburn and Wabamun have nearly identical hydraulic characteristics and are considered as a single aquifer whose isopach is shown in Figure 12d.

Within the Cretaceous succession, the McMurray and Wabiskaw aquifers show similar regional hydraulic characteristics despite the existence locally of bitumen deposits and shale lenses. The initial geometry defined for the upper Clearwater shaley unit (from the top of the Clearwater Formation to the top of the Wabiskaw Member), which was associated with aquitard characteristics, resulted in a large number of drillstem test data being allocated to this unit. The extreme variability in the lithology of the Clearwater Formation in northeast Alberta (from black marine shale to fine sand, with much of the strata consisting of unconsolidated silts) required significant revision of the Clearwater aquitard geometry. Portions of its base and top were included with the McMurray-Wabiskaw and Grand Rapids aquifers, respectively, whose isopachs are shown in Figures 13a and 13c. The remainder of the Clearwater Formation comprises the Clearwater aquitard (Figure 13b). The isopach of the Viking aquifer (Figure 13d) required little change from the original stratigraphic geometry.

				Stratigraphy				Hydrostratigraphy	
EON	ERA	Period		Group			Formation	Unit	System
Phanerozoic	Cenozoic	Quaternary Tertiary					Pleistocene deposits	aquifer	
	Mesozoic	Cretaceous	Upper	Colorado			Colorado shale	aquitard	Colorado aquitard system
							2nd White Specks		
							Base of Fish Scales	aquitard	
			Lower				Viking	aquifer	
							Joli Fou	aquitard	
				Mannville			Grand Rapids	aquifer	Grand Rapids
							Clearwater	aquitard	Clearwater
								aquifer	McMurray-Wabiskaw aquifer/aquitard system
							McMurray	aquifer	
		Jurassic							
		Triassic							
	Paleozoic	Permian							
		Carboniferous					Sub-Cretaceous Unconformity		
		Devonian	Upper				Wabamun	aquifer	Winterburn - Wabamun aquifer system
							Winterburn	aquifer	
				Woodbend			Upper Ireton	aquitard	Upper Ireton
							Grosmont	aquifer	Grosmont
							Lower Ireton	aquitard	Lower Ireton
							Cooking Lake	aquifer	
				Beaverhill Lake			Waterways	aquifer - aquitard	Beaverhill Lake - Cooking Lake aquifer system
							Slave Point	aquifer	
							Fort Vermilion	aquiclude	Prairie-Watt Mountain aquiclude system
			Middle	Elk Point	Upper		Watt Mountain	aquitard	
							Prairie	aquiclude	
							Winnipegosis (Keg River)	aquifer	Contact Rapids - Winnipegosis aquifer system
							Contact Rapids	aquifer - aquitard	
			Lower		Lower	Granite Wash	Cold Lake	aquiclude	Lower Elk Point aquitard-aquiclude system
							Ernestina Lake	aquifer - aquitard	
							Upper Lotsberg	aquiclude	
							Lower Lotsberg	aquiclude	
							Basal Red Beds	aquifer - aquitard	Basal aquifer
		Silurian							
		Ordovician							
		Cambrian							
Precambrian								aquiclude	

Table 7. Hydrostratigraphic succession and nomenclature, Northeast Alberta study area.

The hydrostratigraphic nomenclature and geometry, shown in Table 7, Figures 12 and 13 and dip and strike cross-sections (Figures 14 and 15), respectively, represent a best estimate based on all the available electronic data. The result is a grouping of strata into flow units which exhibit similar hydraulic characteristics. Undoubtedly, the detailed geometry of the boundaries between these units could be slightly modified if a detailed lithological analysis using geophysical logs from the 12,479 wells in the area could be performed. However, the hydrostratigraphic geometry defined here is more than adequate for the regional-scale characterization of the flow regime.

Physiography

In northeast Alberta, much of the Cretaceous and younger strata has been removed by erosion, and therefore Paleozoic strata are near to the surface or are exposed, leading to complex flow patterns. In most cases, the flow is influenced by intermediate to local-scale features (mainly topographic and physiographic), and a complex overprinting of hydraulic signatures occurs.

Figure 16 shows the topography and the main physiographic features within the northeast Alberta study area. The surface drainage system (Athabasca, Clearwater and Wabasca rivers and associated tributaries) forms a bird-

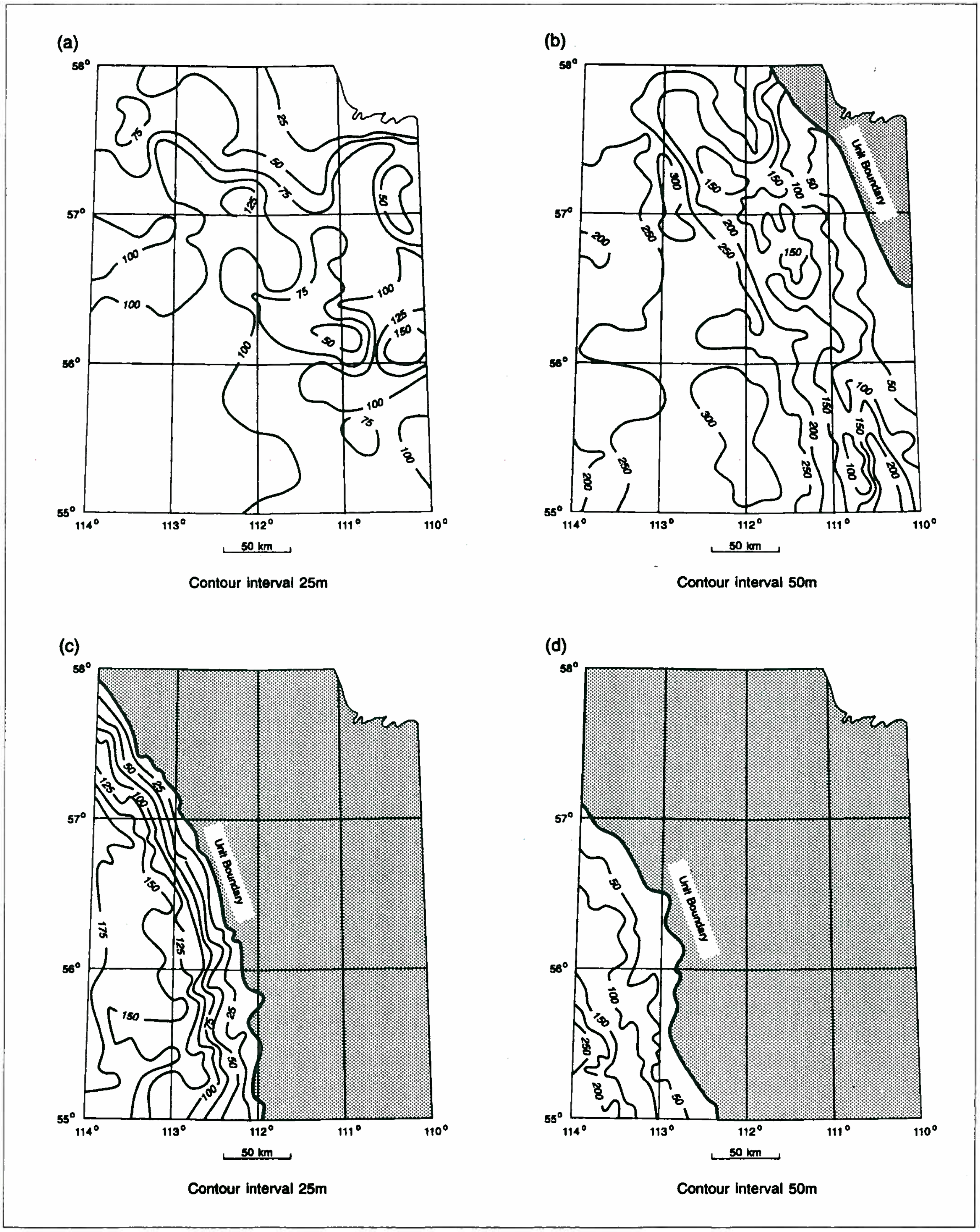

Figure 12. Isopach maps of Paleozoic hydrostratigraphic units in northeast Alberta: (a) Contact Rapids-Winnipegosis aquifer system; (b) Beaverhill Lake-Cooking Lake aquifer system; (c) Grosmont aquifer; and (d) Winterburn-Wabamun aquifer system.

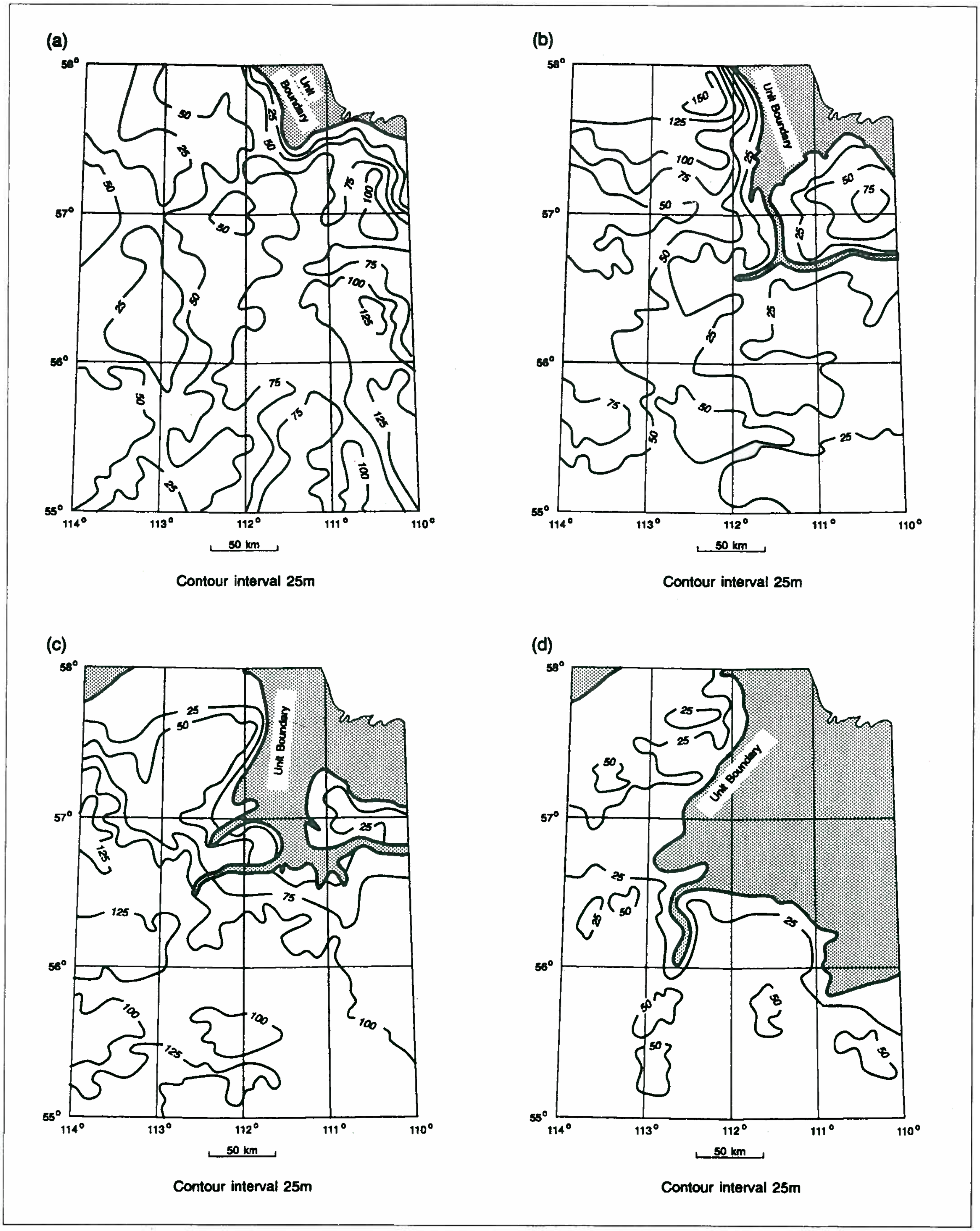

Figure 13. Isopach maps of Cretaceous hydrostratigraphic units in northeast Alberta: (a) McMurray-Wabiskaw aquifer system; (b) Clearwater aquitard; (c) Grand Rapids aquifer; and (d) Viking aquifer.

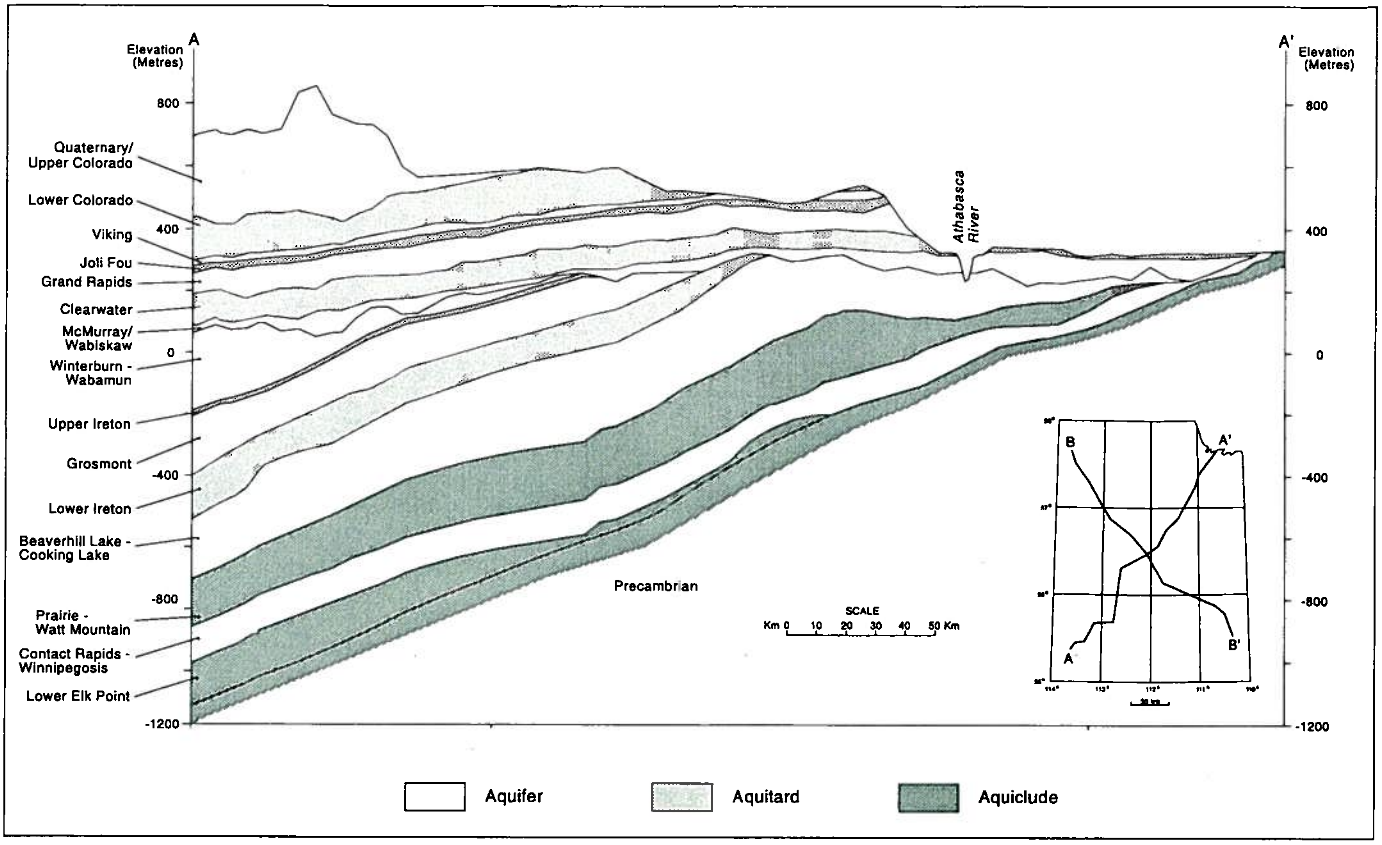

Figure 14. Hydrostratigraphic dip cross-section A-A'.

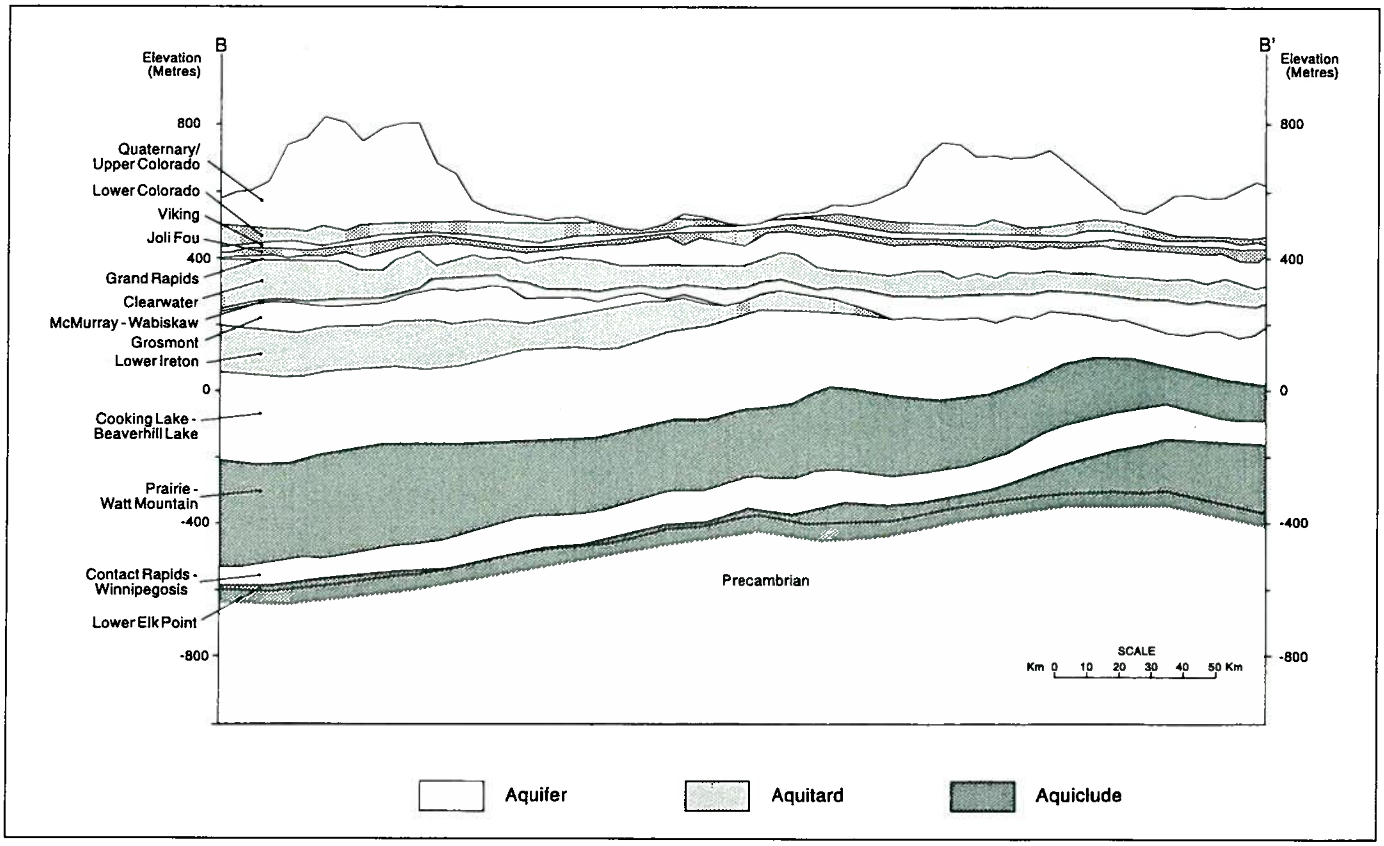

Figure 15. Hydrostratigraphic dip cross-section B-B'.

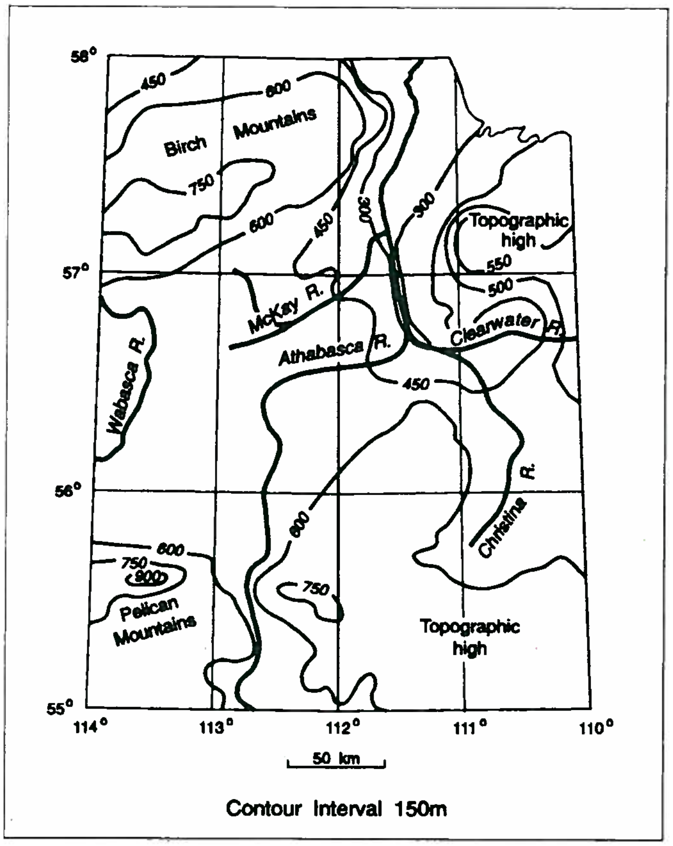

Figure 16. Physiography and major topographic features of the Northeast Alberta study area.

foot shaped area of topographic lows, which isolate four areas of topographically high ground. In places, the Athabasca and Clearwater rivers cut completely through Cretaceous strata, exposing Paleozoic units. In terms of fluid flow, the river valley system acts as a discharge zone for formation waters in nearby aquifers, including units which exhibit regional flow characteristics at the scale of the basin. The four areas of high topography include the Birch Mountains in the northwest, the Pelican Mountains in the southwest, and two unnamed topographically high areas in the northeast and southeast (see Figure 16). These regions act as major local recharge areas where meteoric water enters the nearsurface groundwater system. Often, formation waters moving within basin-wide regional flow systems show decreased salinity and modified flow paths near local recharge and discharge areas in this region at the northeastern edge of the basin. These topographic features, when combined with the complex stratigraphic geometry associated with the feather edge of the basin, play an important role in controlling the nature of the subsurface flow regime in northeast Alberta.

Regional subsurface hydrogeology

The distribution of salinity within most of the aquifers in the study area shows a general trend of increasing salinity with depth below the surface. A similar relation has been observed in the Swan Hills area to the southwest (Hitchon et al., 1989a), the Cold Lake area to the south (Hitchon et al., 1989b), and in the Peace River Arch area to the west (Hitchon et al., 1990). Using dimensional analysis based on geothermal and hydrogeological data, Bachu (1985, 1988) and Bachu and Cao (1992) have shown that, because of low rock permeability, the flow of formation waters in the basin is too weak to distort the temperature and salinity fields by carrying heat and dissolved substances from recharge to discharge areas. This conclusion is supported by the regional-scale analysis of the geothermal regime in the Western Canada Sedimentary Basin performed by Bachu and Burwash (1991) and by the numerical study of disequilibrium fluid pressures and groundwater flow in the Western Canada Sedimentary Basin of Corbet and Bethke (1992). Also, Deming and Nunn (1991) showed that in several million years a basin would be totally flushed of saline water if the flow of formation waters were strong enough to carry heat by convection, even if up to 5% of the basin rock mass were to dissolve in order to provide solute supply. In the absence of a strong advective component, the main mechanism for the transport of substances in solution is diffusion. Because formation waters retain more ions in solution at higher temperatures, the commonly observed basin-scale relation between salinity and depth is most probably the result of temperature control. This conclusion is corroborated by the trend of increasing salinity with depth observed for most of the aquifers in this and other studies (Hitchon et al., 1989b, 1990). More localized effects superimposed over this basin-wide trend are induced by the presence of evaporitic beds (Hitchon et al., 1990) and by continuous dilution by meteoric water in the upper strata.

As discussed previously in the chapter on processing of hydrogeological data, distributions of freshwater hydraulic heads are not truly indicative of the magnitude and direction of the hydraulic gradient driving the flow of variable density formation waters in dipping aquifers. However, the error is likely to be minor for aquifers with a gentle slope and/or low salinity, as is the case for Cretaceous aquifers. The error is probably significant for deep aquifers, particularly those adjacent to evaporitic beds, like the Contact Rapids-Winnipegosis aquifer system. The regional-scale Driving-Force Ratio (DFR) was evaluated for each hydrostratigraphic unit to provide an indication about error significance. As expected, the DFR for the Viking, Grand Rapids and McMurray-Wabiskaw hydrostratigraphic units is very low (less than 0.1), indicating that the error in using freshwater hydraulic-head distributions is indeed negligible. Thus, the maps of freshwater hydraulic head distributions for these aquifers are truly representative of the flow regime. For the Paleozoic aquifers, the effect of buoyancy-driven flow may be important and will be addressed in each individual case.

Precambrian aquiclude

The Precambrian basement is assumed to be an aquiclude or a zero-flow boundary. Although saline formation water has been found at depths greater than 1 km in the exposed Canadian Shield (Frape and Fritz, 1987), there are no data with respect to formation waters in rocks making up the Precambrian basement in northeast Alberta.

Basal aquifer

The basal aquifer is located directly on the Precambrian basement at the base of the hydrostratigraphic succession. It is overlain by evaporitic deposits of the Lower Elk Point aquitard-aquiclude system. The basal aquifer consists of the Basal Red Beds unit below the Lotsberg aquiclude in the south, and the combined Basal Red Beds and Ernestina Lake units in the north. It is thin, or locally absent, and contains extremely sparse hydrodynamic data. There are only 6 drillstem tests and no reliable analyses of formation water chemistry for this aquifer. The freshwater hydraulic-head data, ranging between 256 m and 780 m, indicate a general west to east and northeast regional flow direction consistent with a regional flow regime. Although no data are available for a quantitative assessment, it is expected that buoyancy plays a significant role in driving the flow in this aquifer.

Lower Elk Point aquitard-aquiclude system

The Lower Elk Point aquitard-aquiclude system consists of a series of evaporitic deposits (aquicludes) including the Lower Lotsberg, Upper Lotsberg and Cold Lake salts. Often, thin red bed type units consisting of interbedded evaporitic, carbonate and clastic rocks separate the evaporite deposits. These intervening strata contain no hydraulic data, and are associated with aquitard type hydraulic characteristics. The Lower Elk Point aquitard-aquiclude system not only acts as a regional flow barrier, but also induces high salinity in formation waters within adjacent aquifers.

Contact Rapids-Winnipegosis aquifer system

The distribution of formation water salinity (Figure 17a) shows two important features. First, a general increase in salinity to the southwest is evident, opposite to the northeast flow direction (Figure 17b). This trend indicates temperature control as formation waters become warmer in the deeper portions of the aquifer to the southwest. Second, the salinity is very high, locally reaching values greater than 350,000 mg/l. These high overall values are attributed to the adjacent Elk Point Group evaporitic units which provide a local source of soluble ions. In addition, the high formation water temperature in these deep strata enables formation waters to maintain a higher concentration of dissolved compounds. A steep formation water salinity gradient exists in the region coincident with the solution edge of Prairie Formation salt (Figure 17a), with salinity values decrease to less than 100,000 mg/l east of the salt edge. Beyond the overlying protective salt aquiclude and source of soluble ions, the Contact Rapids-Winnipegosis aquifer is subject to mixing with fresher waters of local flow systems.

The distribution of freshwater hydraulic head (Figure 17b) shows a transition from regional to local flow regimes. The regional flow regime, with flow from the southwest to the northeast, is present only where the overlying Prairie aquiclude maintains its integrity. Beyond the eastern edge of the Prairie aquiclude, local topographic features exert primary control on the flow directions. In the east, where the aquifer system is close to the surface beneath the Clearwater River, a local low in the potentiometric surface is induced. This significantly alters the regional trend, directing formation waters toward the Clearwater River where they discharge. Similarly, the Athabasca River and the outcrop edge in the northeast induce a low hydraulic head, indicating discharge areas. In the northwest there is a closed local freshwater hydraulic-head high (Figure 17b). This high could be an artifact produced by relatively poor data control and/or by the use of freshwater hydraulic heads in an area of significant buoyancy effects induced by salinity variations (Figure 17a). On the other hand, this closed hydraulic high, associated in theory with vertical flow, coincides with a Winnipegosis Formation reef penetrating the Prairie aquiclude. Examination of the logs in well 3-31-100-22 W4 Mer indicated that, although of significant thickness, the Prairie Formation above this reef is comprised of interbedded anhydrite and carbonaceous strata of questionable integrity. Thus, hydraulic communication may be possible between the Contact Rapids-Winnipegosis aquifer system and the Beaverhill Lake-Cooking Lake aquifer system. The freshwater hydraulic head in the Contact Rapids-Winnipegosis aquifer system (Figure 17b) is higher than the one in the Beaverhill Lake-Cooking Lake aquifer system (Figure 18b), inaccurately suggesting upward flow. Calculations showed that the actual flow, if present, is downwards because of buoyancy effects caused by much higher salinity of formation waters in the Contact Rapids-Winnipegosis aquifer system (Figure 17a) than in the Beaverhill Lake-Cooking Lake aquifer system (Figure 18a).

It is emphasized that the regional and intermediate-to-local flow regimes identified for this aquifer on the basis of freshwater hydraulic heads are qualitative in nature. The hydraulic-head distribution map should not be used to assess the magnitude and local direction of the hydraulic gradient because of significant buoyancy effects. The Driving-Force Ratio for the regional flow system below the Prairie aquiclude is actually less than the threshold value of 0.5. However, with salinity (density) increasing downdip southwestward, the true hydraulic gradient is probably much smaller because of buoyancy forces opposing (retarding) the northeastward topographically-induced flow. The general flow direction is probably correct. For the intermediate-to-local flow regime in the northwest, in the

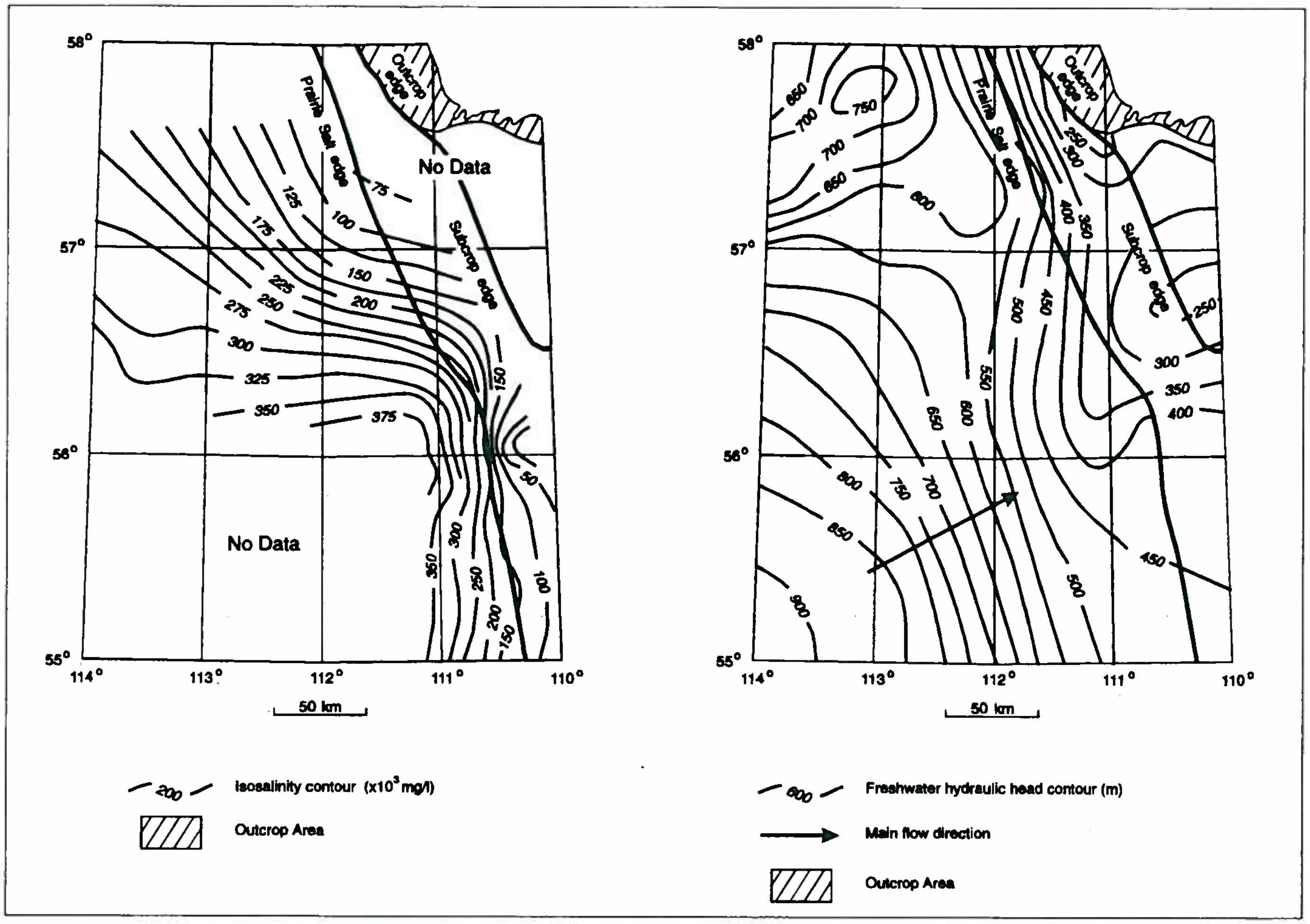

Figure 17. Hydrogeology of the Contact Rapids-Winnipegosis aquifer system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

subcrop/outcrop areas and across the Prairie Formation salt scarp, the Driving-Force Ratio is significantly greater than 0.5, showing that buoyancy effects are important and that the error in using freshwater hydraulic heads is significant. Both the magnitude and direction of flow are not truly represented because of the interaction between aquifer slope, density (salinity) gradient and hydraulic gradient. The flow is significantly retarded by buoyancy effects. Discharge is at the outcrop in the northeast, but the actual directions of the flow in the local regime cannot be properly evaluated without numerical modelling of variable density flow.

Prairie-Watt Mountain aquiclude system

Within the Prairie-Watt Mountain aquiclude system, the Prairie Formation evaporite forms a significant barrier to flow. Overlying the Prairie Formation, a thin Watt Mountain Formation shale extends eastward past the Prairie salt solution edge to approximately the boundary of the Beaverhill Lake Group. The Fort Vermilion anhydrite aquiclude, which forms a thin succession at the base of the Beaverhill Lake Group and is present only in the northwest part of the study area, is included in the Prairie-Watt Mountain aquiclude system. In areas of thick Prairie evaporite, the formation water analyses and the hydraulic heads in overlying and underlying units demonstrate the Prairie to be an aquiclude, as expected. The Watt Mountain Formation has weak aquitard characteristics, evident in regions where the Prairie evaporite is absent. In these regions, the hydraulic head distributions in the Contact Rapids-Winnipegosis aquifer system below and the Beaverhill Lake-Cooking Lake aquifer system above are similar, indicating hydraulic communication.

Beaverhill Lake-Cooking Lake aquifer system

At the basin-scale, the Beaverhill Lake Group comprises a complex, regionally variable succession of carbonates, shales and evaporites. In the Red Earth region, Toth (1978) classified the Beaverhill Lake Group strata as an aquitard. In the Peace River Arch area, Hitchon et al. (1990) divided the Beaverhill Lake Group strata into the Fort Vermilion aquiclude (anhydrite), a basal carbonate unit exhibiting mostly aquitard characteristics, and the Waterways aquifer at the top of the succession. To the south, Hitchon et al. (1989b) described the Beaverhill Lake Group as an aquifer. Within the Northeast Alberta study area, the Beaverhill Lake Group is composed of a series of shales and carbonates which together with the overlying

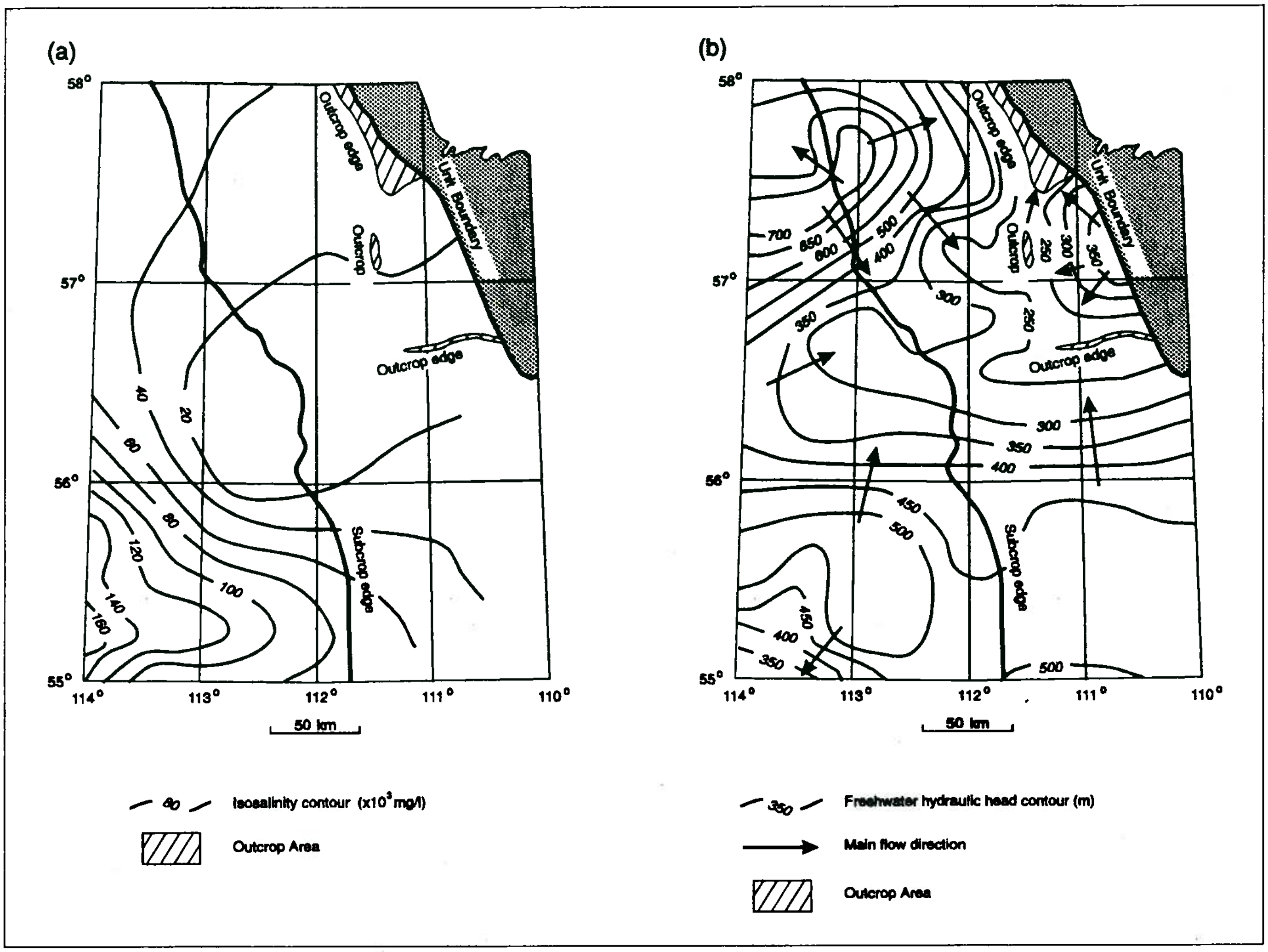

Figure 18. Hydrogeology of the Beaverhill Lake-Cooking Lake aquifer system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

carbonate-dominated Cooking Lake Formation make up the Beaverhill Lake-Cooking Lake aquifer system. Although there are only a few analyses of formation waters, they show a depth (temperature) related trend, with higher salinity values in the southwest and lower values generally to the northeast (Figure 18a). Because the formation waters in the Beaverhill Lake-Cooking Lake aquifer system are isolated from the Prairie Formation salts by the thin shaley Watt Mountain Formation and the anhydrite-dominated Fort Vermilion aquiclude, they are considerably less saline (with values reaching only 160,000 mg/l in the extreme southwest) than in underlying aquifers. Thus, the influence of the Prairie Formation salt is less important.

The distribution map of freshwater hydraulic head for the Beaverhill Lake-Cooking Lake aquifer system (Figure 18b) has characteristics associated with an intermediate-to-local flow regime. The distribution of hydraulic head values within this flow unit shows the most complex trends within the entire hydrostratigraphic system, due to several interacting influences. To the west of the study area, Hitchon et al. (1990) showed the Beaverhill Lake-Cooking Lake aquifer system to have regional flow-regime characteristics. In that area, the formation waters move generally to the northeast, being separated from aquifers below by the Elk Point evaporites (aquiclude) and from aquifers above by the thick regionally continuous Ireton shale (aquitard). In the Northeast Alberta study area, the regional flow regime changes to intermediate and local where the unit passes east of the overlying Ireton Formation edge and subcrops across a broad area at the sub-Cretaceous unconformity (Figure 18b). In the northeast, the Clearwater and Athabasca rivers cut down to Paleozoic strata, exposing the Beaverhill Lake-Cooking Lake aquifer system to atmospheric conditions. However, the saline springs which discharge into the Athabasca River and the Slave River at the Beaverhill Lake-Cooking Lake aquifer outcrop are from solution by meteoric water of halite and anhydrite in the Elk Point Group (Hitchon et al., 1969). In the northwest, the topographic relief of the Birch Mountains influences the flow in the Beaverhill Lake-Cooking Lake aquifer system through the directly overlying Cretaceous aquifers east of the Ireton aquitard subcrop edge.

In the northeast part of the study area, the freshwater hydraulic head distribution is strongly influenced by the Athabasca and Clearwater rivers and the local topographic high (Figure 16). The areas of outcrop along the rivers are the prime control on the hydraulic head distribution, resulting in flow toward them from all directions (Figure 18b). The topographic high in the northeast is a local recharge area, with formation waters moving away from the high and toward the rivers. In the central part of the study area, the Athabasca River system induces a low hydraulic head (less than 350 m). In the northwest portion of the study area, the hydraulic head distribution shows a high potential area (Figure 18b) coincident with the topographically high Birch Mountains. The flow is toward the Athabasca River system to the east and south, and probably toward the Peace River to the northwest of the study area. To the east of the Lower Ireton subcrop edge (Figure 18b), the Beaverhill Lake-Cooking Lake aquifer system subcrops at the sub-Cretaceous unconformity and is in direct contact with Lower Cretaceous aquifers which show strong local topographic control of their flow regime. It is suggested that, east of the Lower Ireton aquitard subcrop edge, the Beaverhill Lake-Cooking Lake aquifer system is influenced by the high topography of the Birch Mountains. The westward propagation of this topographic influence below the Lower Ireton aquitard could be real, but could also be an artifact produced by uneven data control.

There is an area of low freshwater hydraulic head in the southwest corner of the study area, with flow directions to the southwest, opposite to the overall regional trend (Figure 18b). In this general area, Belyea (1964) and Wright (1984) indicate the possibility of a continuous carbonate reefal connection between the Cooking Lake Formation reefs and the overlying Grosmont Formation carbonates, with little or no intervening Ireton Formation shale. Figure 19 shows a three-well cross-section across five townships in the northeast Alberta study area demonstrating one example of Cooking Lake Formation carbonates locally extending upward almost to the base of the Grosmont Formation carbonates, with only a meter or less of shale separating the two carbonate units. It is speculated that the existence of several such reefal connections, which may not be documented in the literature because of their isolated and local nature, provides hydraulic continuity between the Beaverhill Lake-Cooking Lake aquifer system and the overlying Grosmont aquifer characterized by lower hydraulic heads (Figure 20b). Based on the hydraulic head distributions within the Northeast Alberta study area and in surrounding areas (Hitchon et al., 1989b), it is postulated that hydraulic communication and possibly contact exists between the Beaverhill Lake-Cooking Lake aquifer system and the Grosmont aquifer in the southwest portion of the study area and farther to the south.

In the southwestern part of the study area, the aquifer is in a regional flow regime and the formation waters are characterized by the greatest density (salinity) (Figure 18). The corresponding Driving-Force Ratio is around 0.2, well below the threshold of 0.5. In all other regions the density (salinity) difference is even lower, while the fresh-water hydraulic gradient is locally higher due to local flow systems, resulting in lower DFR values. Therefore, buoyancy effects are probably small and the error in using freshwater hydraulic heads in analyzing the flow is acceptable at the scale and resolution of the study. In this regard, the main difference between the Contact Rapids-Winnipegosis and Beaverhill Lake-Cooking Lake aquifer systems is in formation water salinity (greater than 350,000 mg/l in the former versus up to 160,000 mg/l in the latter), a difference caused by the influence of the Lower Elk Point Group evaporitic beds on the lower unit.

Lower Ireton aquitard

The Lower Ireton aquitard is present only in the southwestern half of the area and represents a strong barrier to flow (particularly because of its thickness), except in the extreme southwest where there are thick Cooking Lake reefs. Here, the Lower Ireton is a weak aquitard (thin shales) separating the Beaverhill Lake-Cooking Lake aquifer system below and the Grosmont aquifer above (Figure 19). From the perspective of fluid flow, the absence of the Ireton aquitard over much of the area is significant, in that both Toth (1978) and Hitchon et al. (1990) showed the Lower Ireton aquitard to be the most significant barrier to cross-formational flow in the Red Earth and Peace River Arch areas, respectively. In both areas, the Lower Ireton aquitard isolates the regional flow regimes in aquifers below from the influence of intermediate to local flow regimes observed in aquifers above. In the Northeast Alberta study area, where the Beaverhill Lake-Cooking Lake aquifer system is not protected by the overlying Ireton Formation, flow in it is strongly influenced by flow in stratigraphically younger aquifers having local flow regime characteristics.

Grosmont aquifer

Formation water salinity in the Grosmont aquifer (Figure 20a) decreases in a southwest to northeast direction, similar to that in the underlying Beaverhill Lake-Cooking Lake aquifer system, but with a generally decreased range (70,000 to 10,000 mg/l).

Overall, the salinity distribution appears to be depth (temperature) related. Relatively high salinity (greater than 70,000 mg/l) and high SO_4 content (up to 5000 mg/l) in the deeper southwest part of the study area are indicative of evaporite (anhydrite) dissolution (Hitchon, 1991). The higher salinity and SO_4 concentration are the principal features distinguishing the formation waters in the Grosmont aquifer from those in the overlying Winterburn-Wabamun aquifer system. On the basis of these differences, the two flow units are considered separately, even though the hydraulic head distributions are similar.

The hydraulic head distribution for the Grosmont aquifer is relatively flat, with values in the range of 350-375 m

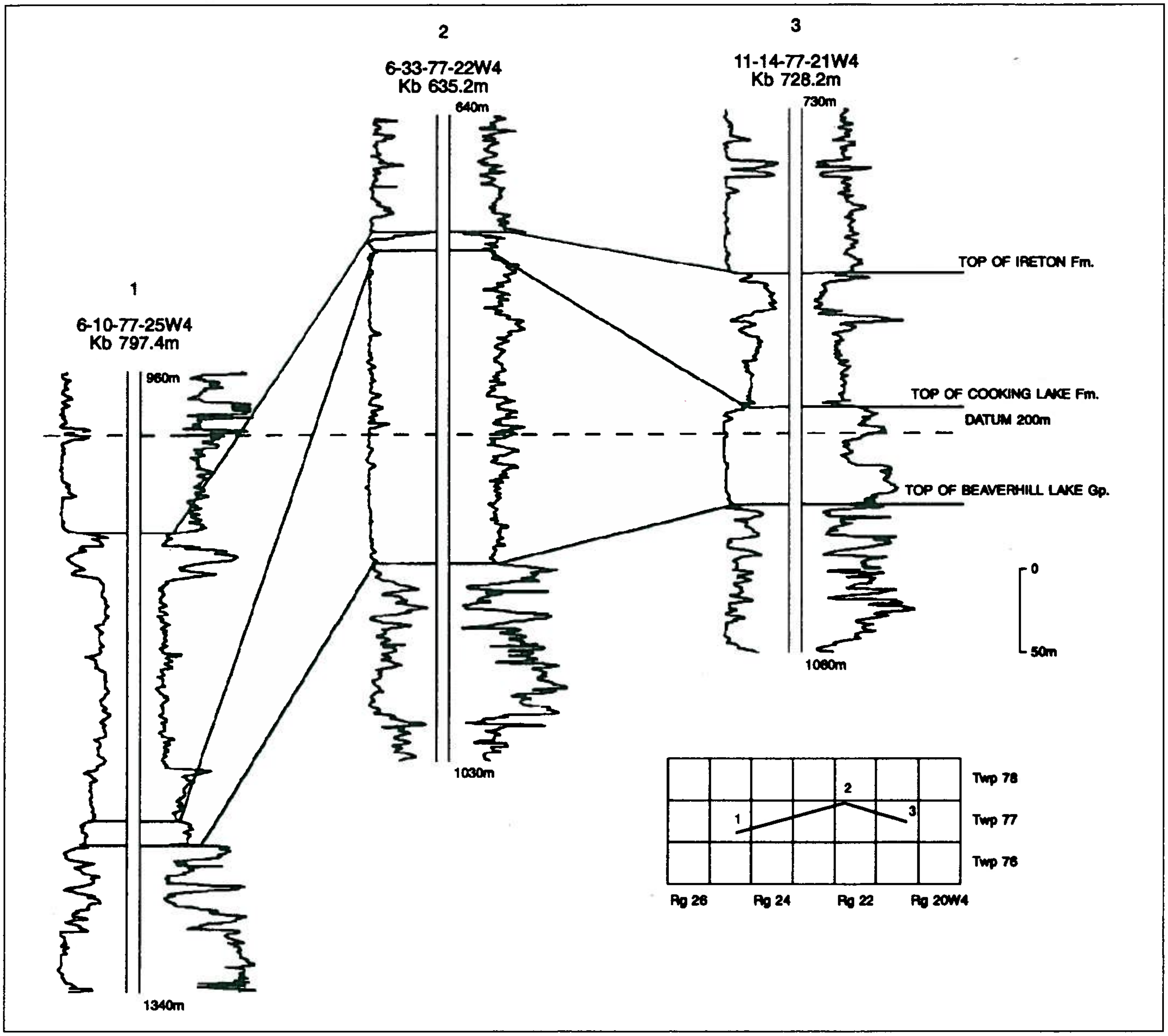

Figure 19. Structural cross-section of the Lower Ireton aquitard showing a Cooking Lake Formation reef.

throughout the study area (Figure 20b). The Grosmont aquifer, together with the overlying Winterburn-Wabamun aquifer system, generally exhibit the lowest values of hydraulic head in the study area, particularly the western half. Similar low hydraulic head values have also been noted by Hitchon et al. (1989b) in the Cold Lake area to the south. The low hydraulic head in the Grosmont and Winterburn-Wabamun flow units, their high permeability (Tables 3 and 4), and corresponding regions of anomalously low hydraulic head in the Beaverhill Lake-Cooking Lake aquifer system below and the McMurray-Wabiskaw aquifer system above, suggest that, given hydraulic continuity, the Grosmont aquifer and possibly the Winterburn-Wabamun aquifer system act as a "drain" into which aquifers above and below discharge locally. The Beaverhill Lake-Cooking Lake aquifer system has hydraulic head values similar to those in the Grosmont aquifer in the southwest, where it is postulated that Cooking Lake reefs provide hydraulic communication and even continuity between the two aquifers across the Lower Ireton aquitard. The overlying Winterburn-Wabamun and McMurray-Wabiskaw aquifer systems also have hydraulic head values similar to the Grosmont aquifer in the southwest region. In addition, analyses of formation waters in Upper Devonian aquifers (Winterburn-Wabamun and the eastern portion of the Grosmont) have relatively low salinity and high HCO_3 content, suggesting incursion of formation water from overlying Cretaceous aquifers (Hitchon, 1991; Hitchon et al., 1989b). The Grosmont aquifer, and possibly the Winterburn-Wabamun aquifer system, likely discharge into the

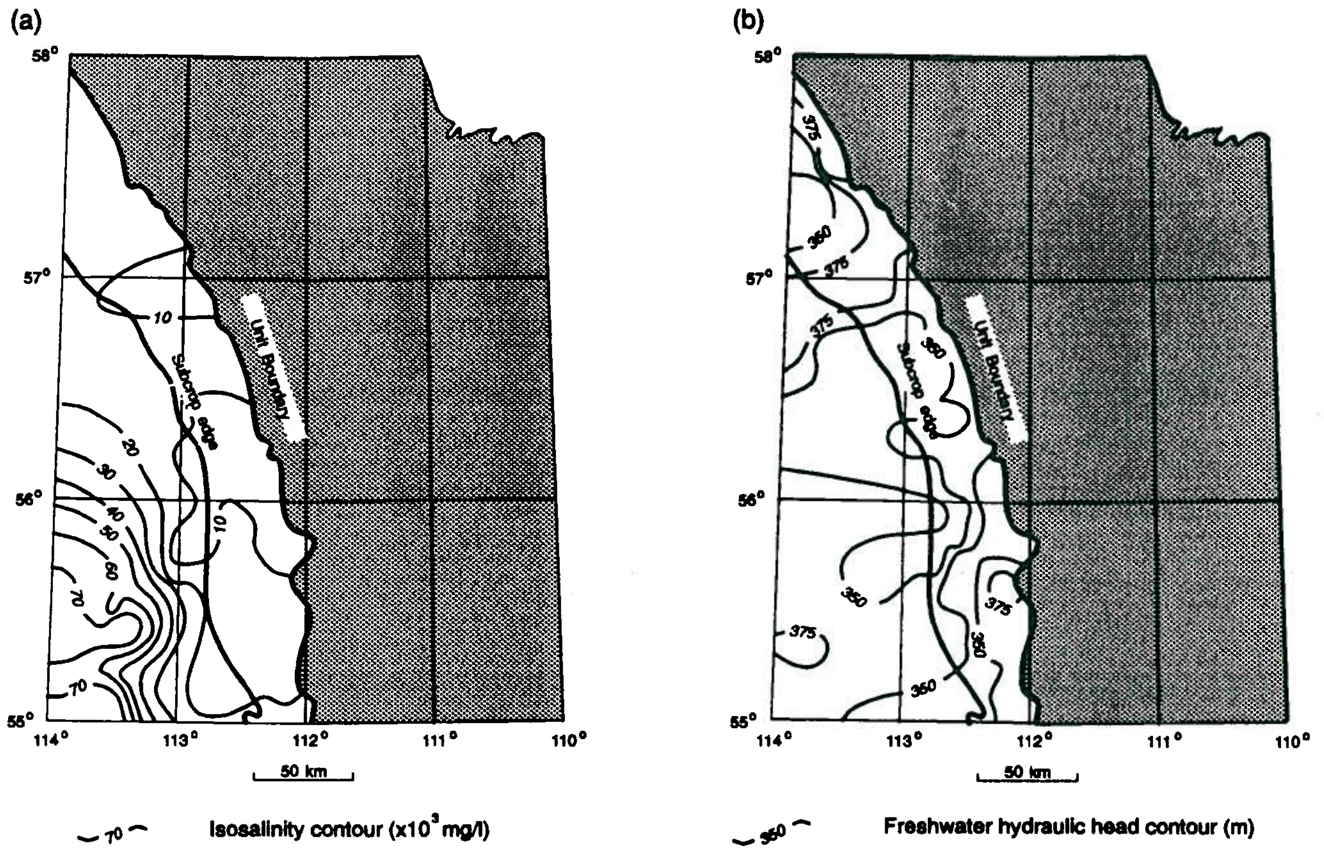

Figure 20. Hydrogeology of the Grosmont aquifer system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

Peace River to the northwest of the study area (northwest of the Birch Mountains) where the Grosmont Formation crops out at an elevation of approximately 240m.

Although the density (salinity) difference in the Grosmont aquifer is not high, the Driving-Force Ratio in the southwestern corner of the study area (Figure 20) is only slightly below the threshold value of 0.5. This is because of a very small freshwater hydraulic gradient. Furthermore, the hydraulic and salinity gradients diverge. Thus, buoyancy effects could be locally significant in this area, retarding the flow and modifying its direction. Nevertheless, the density (salinity) difference decreases toward the northwest. Thus, on a regional scale, there is no error in the northwestward flow direction assessed for this aquifer.

Upper Ireton aquitard

The Upper Ireton aquitard consists of a thin shale between the Grosmont aquifer and the Winterburn-Wabamun aquifer system. On a regional scale, the distributions of hydraulic heads in the Grosmont and Winterburn-Wabamun flow units show no indication of an intervening aquitard; however, the analyses of formation water indicate a subtle difference between the two flow units and suggest that the Upper Ireton Formation is a weak aquitard (Hitchon, 1991).

Winterburn-Wabamun aquifer system

The Winterburn-Wabamun aquifer system is present in the southwest portion of the study area where it subcrops at the sub-Cretaceous unconformity. The formation water salinity is generally lower (up to 55,000 mg/l) than that observed in the Grosmont aquifer and there are no obvious effects of evaporites. Because it is suggested that formation waters generally move from the Winterburn-Wabamun aquifer system downward into the Grosmont aquifer, it is to be expected that the formation water chemistry of the aquifers above the Grosmont Formation would not show the signature of evaporites present within the Grosmont Formation. Within the study area, the highest salinity values for this unit occur anomalously in the northwest, producing a distribution not related to depth.

The distribution of hydraulic head in the Winterburn-Wabamun aquifer system is similar to that in the Grosmont aquifer, with a flat potentiometric surface and values ranging around 350 m (Figure 21). This indicates that the intervening Upper Ireton aquitard is very weak and that there is hydraulic communication between the two units. It is assumed that flow is regionally to the northwest, and there is likely extensive interaction between the Winterburn-Wabamun aquifer system and the Grosmont aquifer. Contrary to the suggested northwest regional flow direction, the Grosmont aquifer has a local high in the area north of 57°N (Figure 18b). The Winterburn-Wabamun aquifer system does not have a locally high potential in this area (Figure 21). It is inferred that in the western part of the study area near 57°N, the flow is locally from the Grosmont aquifer up to the Winterburn-Wabamun aquifer system. If this hypothesis is correct, it lends support to the suggestion that the Grosmont aquifer and the Winterburn-Wabamun aquifer system together act as a "drain" to the northwest, with sufficiently strong flow to alter locally the depth related salinity distributions observed for most other aquifers.

The Driving-Force Ratio for the Winterburn-Wabamun aquifer system is smaller than for the Grosmont aquifer (around 0.2) because of a smaller density (salinity) variation. Thus, the distribution of freshwater hydraulic head is closer to reflecting the actual hydrodynamic conditions in this aquifer, with generally negligible buoyancy effects.

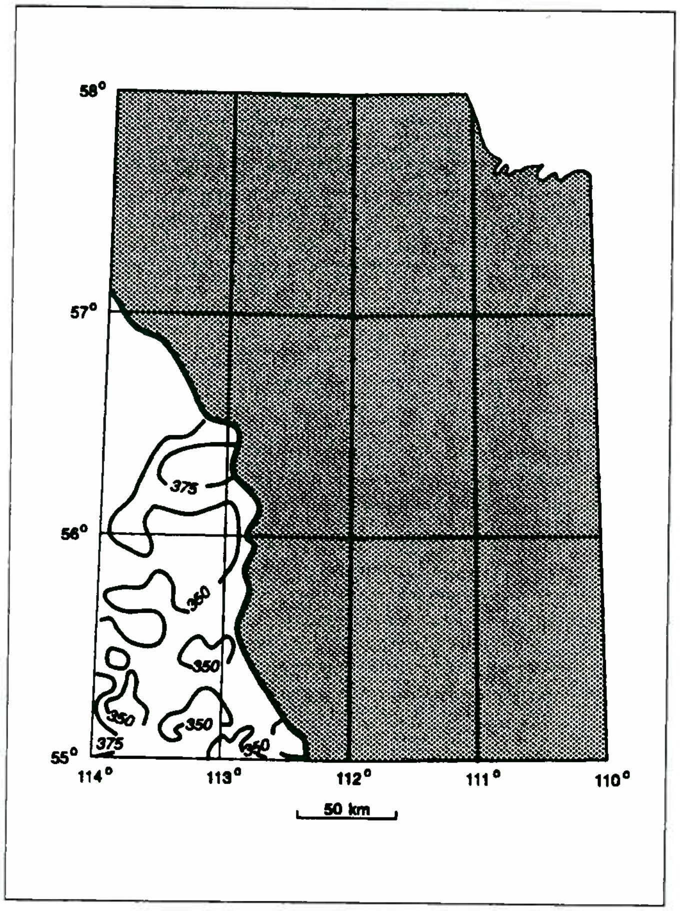

Figure 21. Freshwater hydraulic-head distribution for the Winterburn-Wabamun aquifer system.

McMurray-Wabiskaw aquifer/aquitard system

The McMurray-Wabiskaw system is the first unit above the sub-Cretaceous unconformity and is regionally continuous across the area except in the extreme northeast where it has been removed by erosion. Lithologically, Cretaceous units tend to be more complex, with interbedded sands, shales and silts. In particular, the McMurray-Wabiskaw system contains discontinuous sand and shale lenses and large areas of bitumen-saturated sands which locally act as flow barriers; however, regionally (basin-scale) the unit can be considered to have aquifer characteristics. Because this system has aquifer characteristics on a regional scale, but aquitard characteristics on intermediate-to-local scales, it is defined as an aquifer/aquitard system.

Reliable formation water chemistry data for the McMurray-Wabiskaw aquifer/aquitard system are confined to the southern part of the study area. Within this region, the data show freshwater salinities (less than 10,000 mg/l), with locally higher values (up to 25,000 mg/l) in the south (Figure 22a). Here, the salinity distribution is comparable to that of the underlying Winterburn-Wabamun aquifer system, indicating hydraulic continuity across the sub-Cretaceous unconformity (Hitchon, 1991).

Flow within the McMurray-Wabiskaw aquifer/aquitard system is entirely local in nature, with local topography and physiographic features exerting a strong influence. The hydraulic head distribution for the McMurray-Wabiskaw aquifer/aquitard system (Figure 22b) shows an area of low hydraulic heads in the southwest similar to those in the underlying Paleozoic aquifers, indicating hydraulic continuity and the probable flow of formation waters down to the Winterburn-Wabamun and Grosmont aquifers below. This trend is consistent with that observed by Hitchon et al. (1989b) in the Cold Lake area to the south. In other regions of the study area, local physiographic features dominate the hydraulic head distribution. In particular, the hydraulic head distribution in topographically high areas (in the northeast, central, and in the Birch Mountains to the northwest) shows correspondingly high values associated with local recharge. Conversely, the hydraulic heads are low along the Athabasca and Clearwater river valleys, indicating discharge. This strong physiographically controlled local flow regime is prevalent throughout the remainder of the Cretaceous flow units.

Clearwater aquitard

In regions to the west of the study area, the Clearwater aquitard has been shown to be a regionally significant barrier to flow (Hitchon et al., 1989a; 1990). In the Northeast Alberta study area, as the Clearwater aquitard becomes shallower and eventually is exposed along the Athabasca and Clearwater rivers, its internal stratigraphy becomes complex, with extremely variable lithology. Although the Clearwater aquitard is generally shaley, the unit grades into silt or even fine sand lithologies over large areas. Hydraulic head distributions in the McMurray-

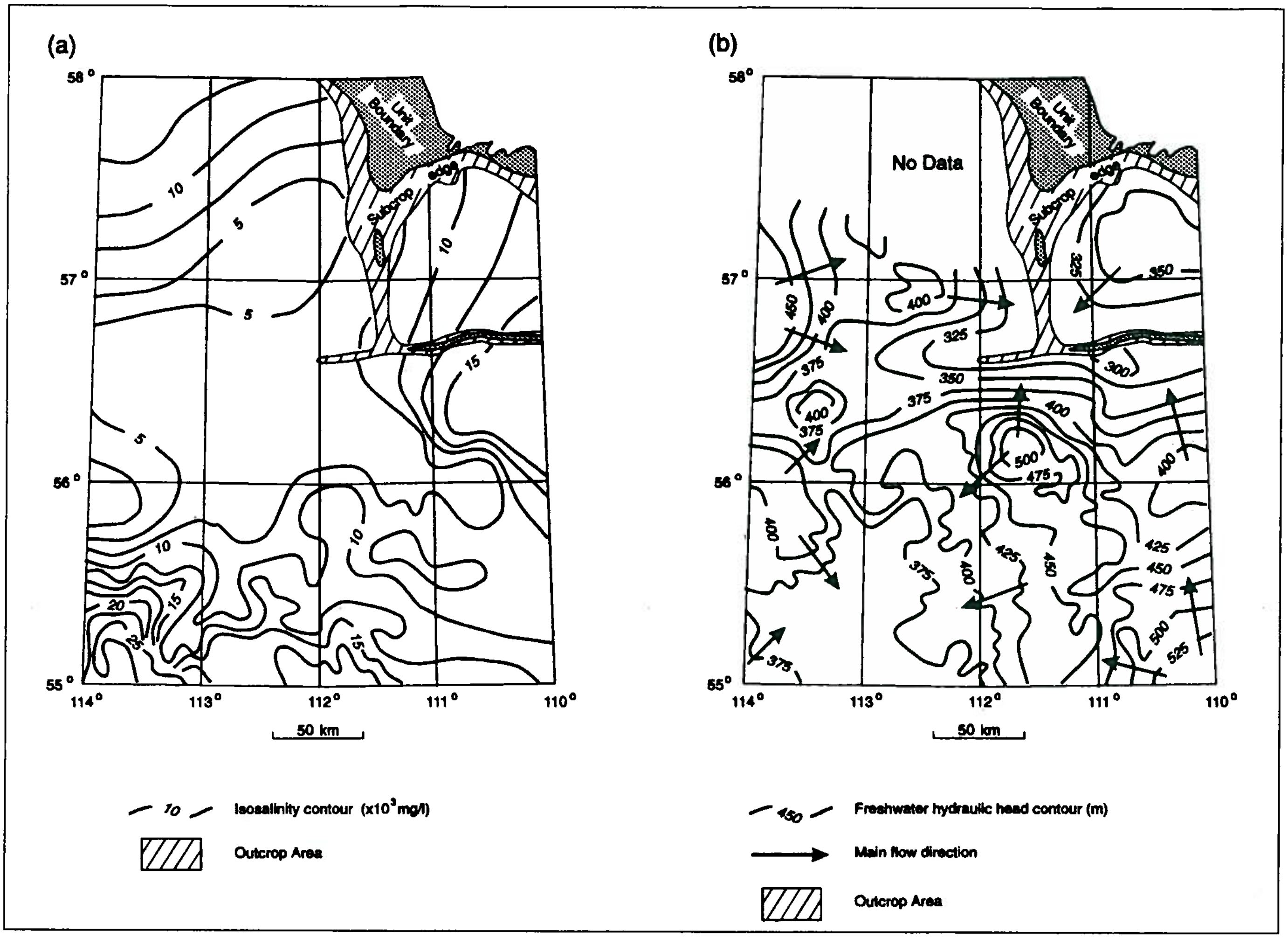

Figure 22. Hydrogeology of the McMurray-Wabiskaw aquifer/aquitard system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

Wabiskaw aquifer/aquitard system below and the Grand Rapids aquifer above indicate a dichotomous nature for the Clearwater aquitard, which in places acts as a hydraulic barrier and in other areas it allows hydraulic communication or even continuity.

Grand Rapids aquifer

Information on the geochemistry of formation waters in the Grand Rapids aquifer is sparse, with the majority of the data concentrated in the southwest. This region exhibits freshwater salinity distributed in a depth (temperature) related trend (Figure 23a), with values reaching a maximum of 20,000 mg/l in the extreme southwest. In this part of the study area, the analyses of formation waters suggest that the Clearwater aquitard is a significant barrier to cross-formational flow.

The distribution of hydraulic head for the Grand Rapids aquifer is dominated by the effects of the Athabasca River system (Figure 23b), along which the aquifer discharges. The arrows shown in Figure 23b indicate the general flow direction toward the center of the area where the aquifer crops out. Topographically high regions generally correspond to areas of recharge.

Joli Fou aquitard

The Joli Fou aquitard is present in the southwestern half of the study area and consists of shales which grade upward into sandstones of the overlying Viking aquifer. Data for the Joli Fou aquitard and Viking aquifer above are confined to the southern portion of the study area. In these areas, the hydraulic data suggest that the Joli Fou is a relatively strong aquitard.

Viking aquifer

The geochemical data for the Viking aquifer are sparse and confined to the extreme southwest corner of the study area. These data show freshwater salinity with characteristics similar to those observed in the underlying Grand Rapids aquifer. This similarity is probably coincidental, caused by the increasing temperature with southwest dip in both units which are otherwise separated by the Joli Fou aquitard. The hydrodynamic data, also confined to the

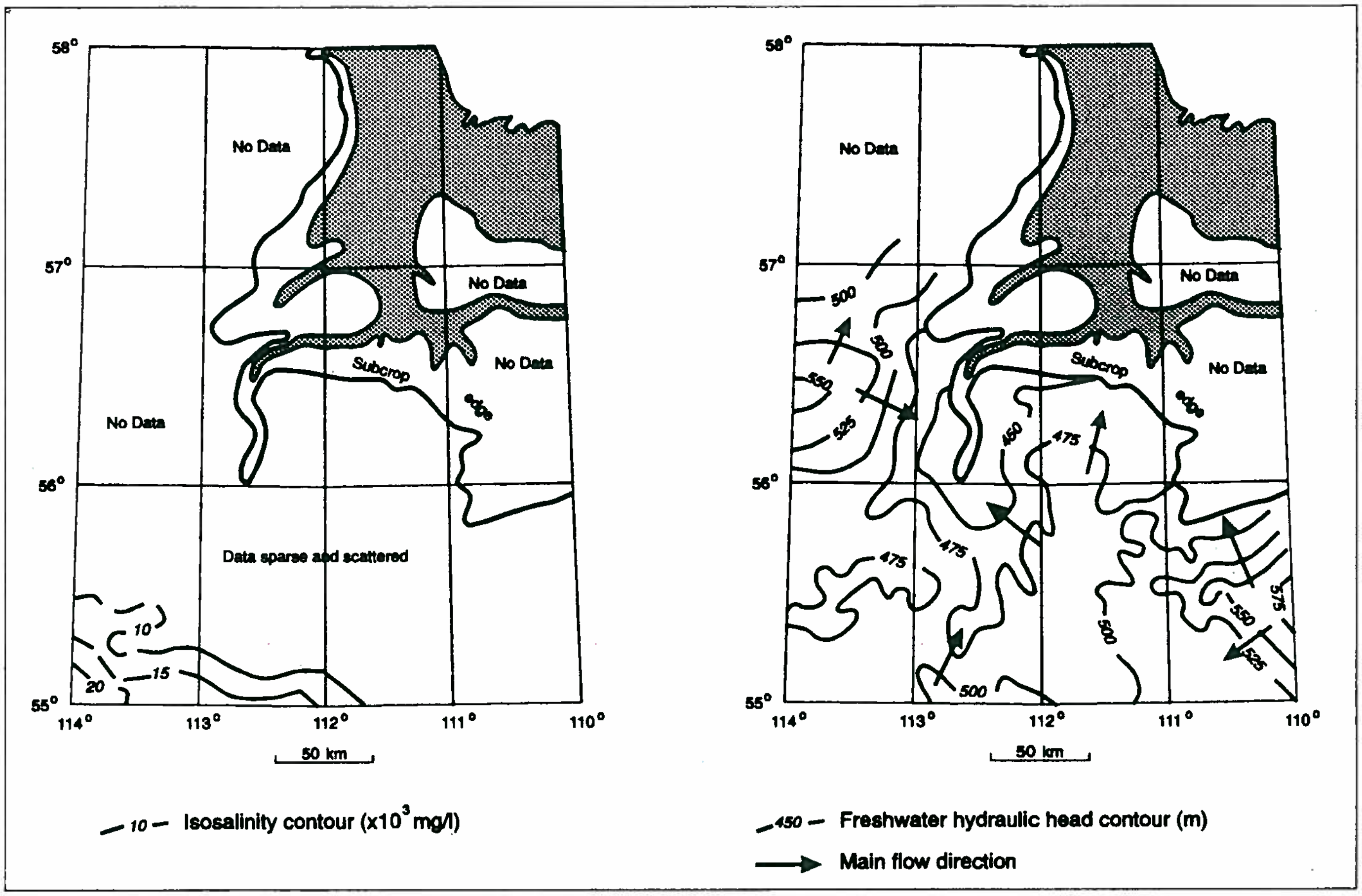

Figure 23. Hydrogeology of the Grand Rapids aquifer: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

southwest, indicate strong local influence of the Athabasca River (Figure 24). The hydraulic-head values in the Viking aquifer show definite differences from the underlying Grand Rapids aquifer, suggesting that the Joli Fou is a strong aquitard.

Post-Viking aquitard

Post-Viking strata generally consist of Cretaceous Upper Colorado Group shales overlain by a thin veneer of Pleistocene to Quaternary cover. Discontinuous silty to sandy lenses are prevalent within the Cretaceous shale-dominated succession. Few geochemical or hydrodynamic data are available for the Cretaceous strata, which are generally considered to have aquitard characteristics. In places, the Pleistocene cover can reach significant thickness where paleo-valleys have been filled with drift. These shallow Quaternary aquifers are not significant at the regional (basin) scale, but may be important locally because they often cut stratigraphically as deep as the sub-Cretaceous unconformity.

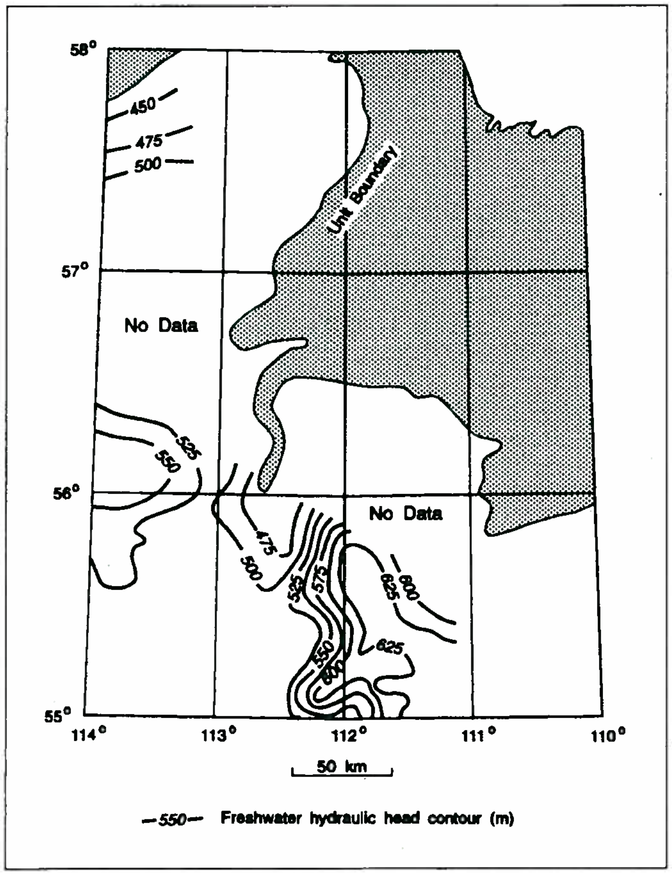

Figure 24. Freshwater hydraulic-head distribution for the Viking aquifer.

Hydrogeological synthesis

The flow characteristics described on the basis of individual hydrostratigraphic units relate essentially to the two-dimensional horizontal flow component. Flow within aquifers is generally dominated by the horizontal component while flow through aquitards is essentially vertical. Some inferences have already been made about the nature of flow across various aquitards by comparing the distributions of hydraulic head and formation water salinity in the aquifers above and below. However, a more detailed analysis requires the examination of pressure-depth profiles at individual well locations, and hydraulic head distributions in cross-section. Dip and strike cross-sections were used to plot the variation of formation water salinity (Figure 25) and hydraulic head (Figure 26). In general, regional flow paths are mainly in the plane of the dip cross-section; however, with the local nature of flow in the northeast Alberta study area, a significant flow component is actually in the plane of the strike cross-section. Topographically, the cross-sections show the high ground in the southwest, the Athabasca River valley and the high area to the northeast of the Athabasca and Clearwater rivers. The following three flow regimes have been identified in the area.

Regional flow regime

From examination of the regional hydrogeological cross-sections (Figures 25 and 26) and of the areal distributions of formation water salinity and hydraulic head described before, it is evident that there are few aquifers in a truly regional flow regime at the northeastern edge of the Western Canada Sedimentary Basin. Only the aquifers below the Prairie aquiclude (Basal aquifer and Contact Rapids-Winnipegosis aquifer system), and so isolated from local topographic influences, are in a regional flow system characterized by an updip flow direction to the northeast (Figure 26). These aquifers show depth related salinity distributions, with generally high values is the vicinity of the Elk Point evaporitic units (Figure 25). Buoyancy effects are probably important, partially or completely balancing the updip topographic driving force, with the net effect of retarding the flow of formation waters. The aquifers in this zone correspond to the basal zone of Toth (1978), or Paleozoic of Hitchon et al. (1990), cut off from continued recharge and protected by the Prairie and Lower Elk Point aquitards. The flow in these aquifers is probably not adjusted yet to the present day boundary conditions (topography) and is in a transient stage of equalization.

Intermediate flow regime

The Paleozoic aquifers above the Prairie aquiclude are best described as having intermediate flow-regime characteristics. They show some local topographic influence while still maintaining a background regional trend in the distributions of hydraulic head and formation water salinity. The Beaverhill Lake-Cooking Lake aquifer system, which is part of the basal, or Paleozoic zone of Toth (1978) and Hitchon et al. (1990) to the west, becomes part of the middle, or Paleo-Mesozoic zone in this area, as the aquifer subcrops at the sub-Cretaceous unconformity and is influenced by present-day topography and physiography. It generally shows updip flow toward the northeast, and depth dependent salinity. This pattern is interrupted locally by Cooking Lake reefs (the "chimneys" of Toth, 1978), which may breach the Lower Ireton shale and allow hydraulic communication with the Grosmont aquifer above, and by significant topographic features such as the Athabasca River valley (Figure 26). At the cross-section location, the hydraulic head values in the Beaverhill Lake-Cooking Lake aquifer system are uncharacteristically low with respect to their regional trend. These locally low values are the result of drawdown by discharge along outcrop at the Athabasca River system (Figure 18b) and poor data control to the west. Based on the hydraulic head distributions in the Beaverhill Lake-Cooking Lake aquifer system and the Grosmont aquifer (Figures 18b and 20b, respectively), hydraulic communication between the two flow units, possibly facilitated by Cooking Lake Formation reefs such as the one shown in Figure 19, is expected farther to the south and southwest. The Grosmont aquifer and Winterburn-Wabamun aquifer system show little variability in the hydraulic head distribution along the cross-section (Figure 26) because the main flow direction is to the northwest, normal to the plane of the section. The distributions of formation water salinity for these intermediate flow-regime units no longer show the high values associated with the evaporitic Elk Point Group strata. As a result of the lower density (salinity) variability of formation waters in these aquifers, buoyancy effects are not significant on a regional scale, with the flow of formation waters being mainly topographically driven. The post-Prairie Paleozoic aquifers are part of the Paleo-Mesozoic zone of Toth (1978) and Hitchon et al. (1990) characterized mainly by flow along the sub-Cretaceous unconformity and equilibrium with the present-day topography and physiography.

Local flow regime

Cretaceous aquifers show strong local flow-regime characteristics, in which major physiographic features can be matched to corresponding features in the hydraulic head distribution (Figure 26). The Lower Cretaceous McMurray-Wabiskaw aquifer system, immediately above the sub-Cretaceous unconformity, is part of the middle or Paleo-Mesozoic zone of Toth (1978). The aquifers above the Clearwater aquitard are part of the Meso-Cenozoic zone of Toth (1978), or local of Hitchon et al. (1990), in complete equilibrium and controlled by the present-day boundary conditions. The formation water salinity within

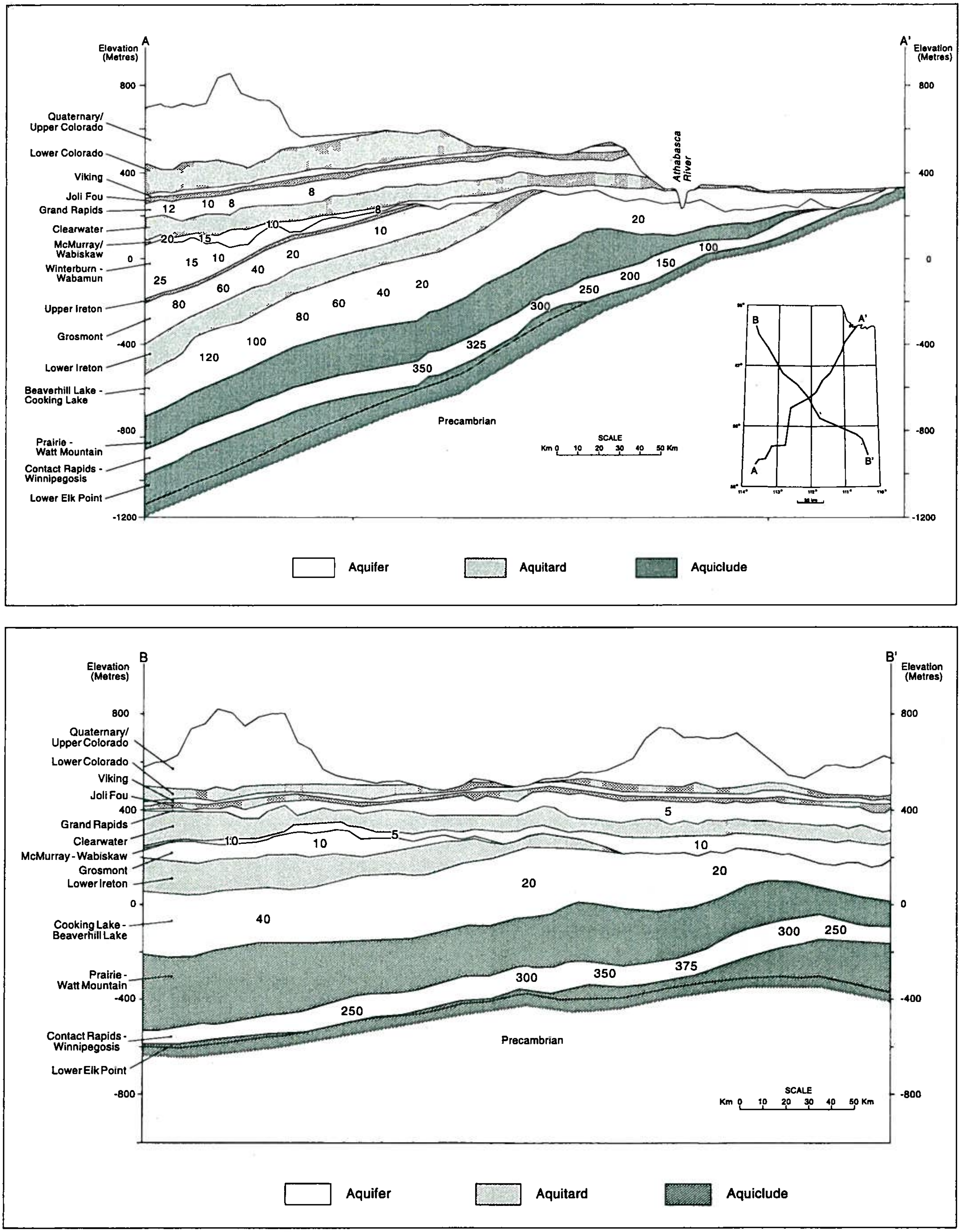

Figure 25. Hydrogeological cross-sections showing the distribution of formation water salinity: (a) dip, and (b) strike.

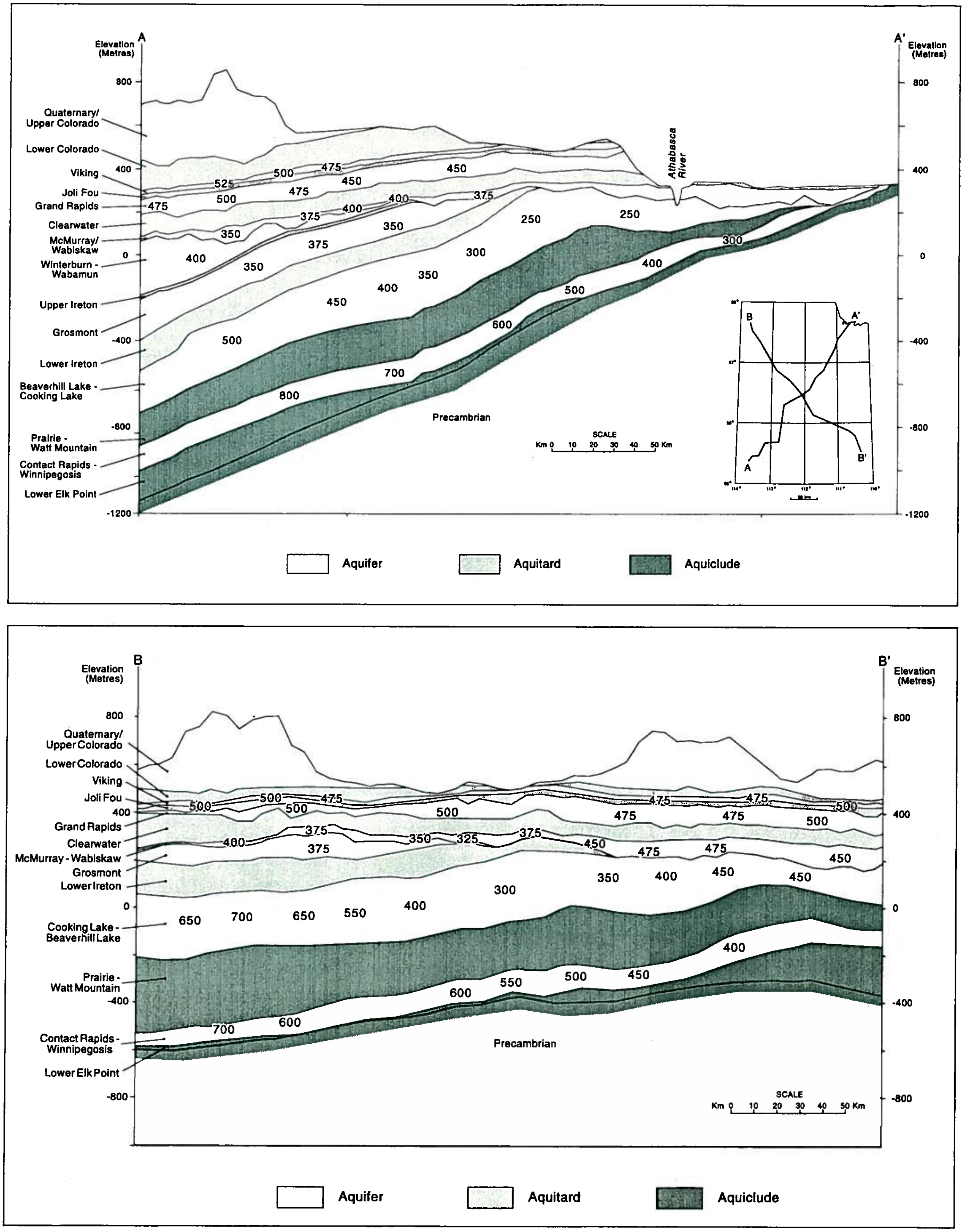

Figure 26. Hydrogeological cross-sections showing hydraulic-head distributions: (a) dip, and (b) strike.

Cretaceous aquifers is extremely low, confirming the influence of meteoric waters being introduced by topographically controlled local flow systems (Figure 25). Buoyancy effects are negligible to nonexistent in these aquifers.

Cross-formational flow

The extent to which there is vertical hydraulic communication and sometimes continuity across aquitards is best assessed by examining pressure-depth profiles at individual locations, and by comparing salinity and hydraulic head distributions between the respective aquifers above and below. If the formation pressure increases continuously across an aquitard, it indicates either that locally the aquitard is not an effective barrier to flow (weak aquitard), or that there is no energy difference across the aquitard. In the latter case, the implication is that the two adjacent aquifers must be in hydraulic communication upstream and that the energy loss between that point and the well location must be approximately the same for the flow in both aquifers. Lack of continuity in the variation of pressure with depth after crossing an aquitard indicates that the intervening aquitard is an effective barrier to fluid flow (strong aquitard). Within an aquifer, the slope of the constantly increasing pressure-vs-depth line is an indicator of the strength of the vertical flow component. A steeper or shallower slope than hydrostatic corresponds to a downward or upward component to the flow, respectively. A higher angle with the hydrostatic slope indicates a stronger vertical component to flow than a lower angle. Because pressure-vs-depth profiles require the data to be from the same well, only a few locations had enough data (DSTs) to allow this type of analysis.

Figure 27 shows pressure-depth profiles at four locations in the study area. Lack of data precluded construction of pressure-vs-depth profiles at other locations, particularly in the central and northern parts of the study area. Figure 27a shows pressure data within strata ranging from the Viking to Winterburn aquifers at well location 01-01-076-23W4 Mer. At this location, the Joli Fou shale is a strong aquitard which effectively isolates the flow in the Viking aquifer above from that in the Grand Rapids aquifer below. The pressure data within the Grand Rapids Formation and in the upper portion of the Clearwater Formation, which together make up the Grand Rapids aquifer, show a constant pressure increase with depth nearly parallel to the hydrostatic line, indicating only a slight vertical component to the flow. Pressure data in the McMurray and Wabiskaw units show a constant pressure increase with depth. However, there is a sharp break between these and pressure measurements in the Grand Rapids aquifer above, indicating that the Clearwater aquitard effectively isolates the flow regime in the McMurray-Wabiskaw aquifer/aquitard system from that in the overlying Grand Rapids aquifer. The slope of the pressure increase with depth in the McMurray-Wabiskaw aquifer/aquitard system shows a strong vertical gradient. This steep slope suggests the probable presence of gas or low permeability shales within the unit. Two pressure measurements in the Winterburn Group show a significant change in slope when compared with the overlying McMurray-Wabiskaw aquifer/aquitard system.

Figure 27b shows the pressure-depth profile at well location 16-36-071-24W4 Mer. This well has pressure measurements from Viking to Grosmont strata. Several features noted at the well shown in Figure 27a are also present here. Pressure measurements in the Viking aquifer have a constant slope indicating a slight upward component to flow. This slope is significantly different from that determined by pressure data in the Grand Rapids aquifer below, confirming that the thin shales of the intervening Joli Fou Formation are a strong aquitard in this area. The slope of the pressure distribution in the Grand Rapids aquifer indicates a strong upward flow component in contrast to the slight downward flow component displayed by the data in Figure 27a. This is further evidence that the Cretaceous strata show extremely variable flow directions, associated with a topographically controlled local flow regime. Two pressure measurements within the Clearwater Formation show no relation to the aquifers above or below and may represent the characteristics of isolated sand lenses within the Clearwater aquitard at this location. The Clearwater aquitard is a strong aquitard, indicated by the lack of continuity in the pressure distribution with depth in the aquifers above and below. Although there are no drillstem tests within the thin McMurray-Wabiskaw aquifer/aquitard system, an extensive suite of pressure measurements in the Wabamun aquifer show similar characteristics to those observed in Figure 27a. There appears to be a transition zone at the top of the Wabamun aquifer (possibly associated with the sub-Cretaceous unconformity) where the pressure regime changes from that in the McMurray-Wabiskaw aquifer/aquitard system to a different regime in the Winterburn-Wabamun aquifer system. Here, as in the case displayed in Figure 27a, the McMurray-Wabiskaw unit exhibits aquitard characteristics. The slope of pressure increase with depth in the Wabamun aquifer is similar to that displayed by two pressure measurements in the Grosmont aquifer below. This indicates hydraulic communication across the weak Upper Ireton aquitard. The observed near hydrostatic slope is expected, especially in the Grosmont aquifer, because the Winterburn-Wabamun aquifer system and the Grosmont aquifer are thought to be acting as a hydraulic drain with predominantly horizontal flow.

The pressure-vs-depth profile at well location 06-18-072-25W4 Mer is shown in Figure 27c. This well has the greatest stratigraphic range in pressure data, covering from the Viking aquifer to the Beaverhill Lake aquifer. There are not enough data in the Cretaceous portion of the well to establish pressure-depth relations in any particular aquifer. There is clearly no continuity between the flow in the Viking aquifer and that of the Winterburn-Wabamun and Grosmont aquifer systems, indicating that at this location the Joli Fou and/or Clearwater aquitards are significant barriers to flow. The pressure value within the

McMurray-Wabiskaw aquifer/aquitard system shows the same relation to the underlying Wabamun aquifer as observed in the other wells (Figure 27a and b), suggesting that the McMurray-Wabiskaw unit has aquitard characteristics in this area. If the Winterburn-Wabamun and Grosmont aquifers are assumed to be in hydraulic communication as shown in Figure 27b, then the slope of pressure increase with depth at this location indicates a slight downward component to the flow within this aquifer system.

The three pressure-depth profiles, although all located in the southwest part of the study area, indicate certain general features related to hydraulic continuity and the magnitude of cross-formational flow within the Northeast Alberta study area. These features are used to support the comparative analysis of flow in individual aquifers. It is evident that the Elk Point Group salt deposits are significant barriers to flow. Salinity values are high and hydraulic head distributions in the aquifers below the Prairie aquiclude have regional flow characteristics. Northeast of the Prairie aquiclude, similar hydraulic head values between the Contact Rapids-Winnipegosis aquifer system and the Beaverhill Lake-Cooking Lake aquifer system indicate that the Watt Mountain aquitard is weak. The Lower Ireton aquitard, where it exists, appears to be a significant barrier to flow. This is confirmed by the different hydraulic head

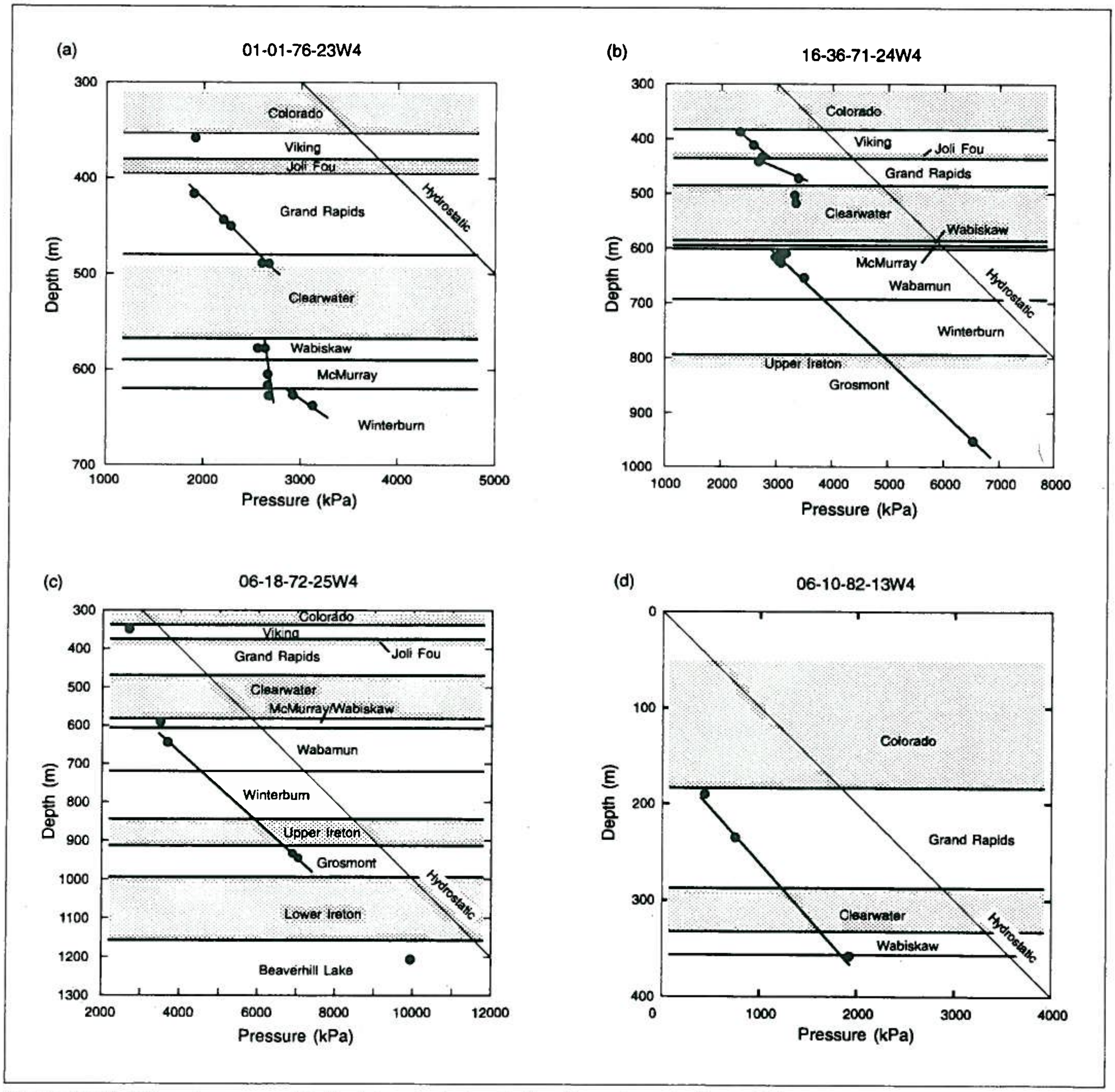

Figure 27. Variation of pressure with depth in selected wells (locations shown in Figure 23).

distributions in the Beaverhill Lake-Cooking Lake aquifer system (Figure 18b) and the Grosmont aquifer (Figure 20b). The Upper Ireton aquitard, which separates the Winterburn-Wabamun and Grosmont aquifer systems, is weak to non-existent based on pressure-vs-depth data and the similarity of hydraulic head distributions below and above the aquitard (Figures 20b and 21b, respectively). At the scale of the study, the McMurray and Wabiskaw aquifers show common hydraulic characteristics despite the presence of local bitumen accumulations and shaley zones, and can be considered a single aquifer/aquitard system. However, they are distinctly different from the underlying Wabamun-to-Grosmont aquifers. In the southwest region of the study area, the Clearwater aquitard is a barrier to flow, effectively isolating the Grand Rapids aquitard from those below. In parts of the study area, the Clearwater aquitard locally has a low shale content and hydraulic communication is apparent between the Grand Rapids aquifer and the McMurray-Wabiskaw aquifer/aquitard system. Figure 27d shows a pressure-depth profile at well location 06-10-082-13W4Mer, which demonstrates this communication (constant slope between pressure measurements above and below the aquitard). In order to evaluate the hydraulic character of the Clearwater aquitard over a larger area, a map of the hydraulic-head difference across the aquitard (Figure 28) was produced by subtracting the distribution of hydraulic head in the McMurray-Wabiskaw aquifer/aquitard system from the distribution of hydraulic head in the Grand Rapids aquifer. Areas of near zero difference correspond to areas in which the Clearwater aquitard is likely weak, while areas of large differences indicate that the Clearwater aquitard is strong. There is a large region trending east-west along 56°N, and regions in the southeast and northwest part of the study area which indicate the existence of a weak Clearwater aquitard (Figure 28). The Joli Fou aquitard is present only in the southwest, where it constitutes a strong barrier to cross-formational flow.

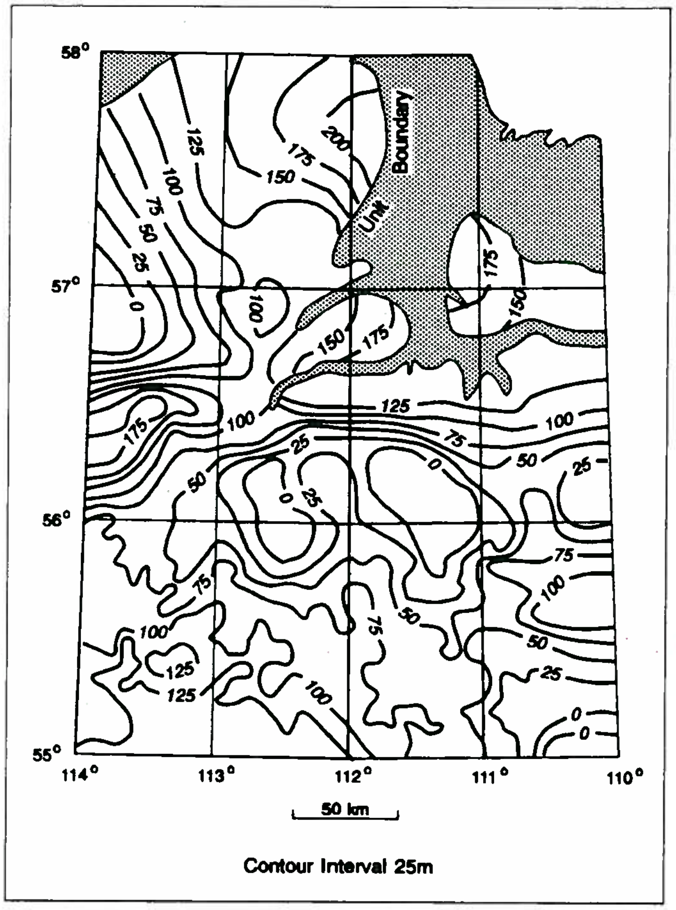

Figure 28. Distribution of hydraulic-head drop across the Clearwater aquitard in northeast Alberta.

Conclusions

The Northeast Alberta study area is located at the feather edge of the Western Canada Sedimentary Basin where Devonian strata are exposed, basinward regional shale zones grade into sands toward the basin edge, and erosion cuts down as far as Paleozoic strata, exposing them to atmospheric conditions. As a result, topography and physiographic features exert a strong influence on the flow regime within most aquifers. In the most general sense, fluid flow is to the northeast toward the edge of the basin. The valleys of the Athabasca River system represent discharge areas for aquifers at outcrop or subcropping near them. Conversely, areas of high topography act as local recharge areas, introducing fresh meteoric water to aquifers unprotected by a significant overlying aquitard and/or aquiclude. The formation water salinity and hydraulic head distributions for the Phanerozoic aquifers in the Northeast Alberta study area generally match those observed by Hitchon et al. (1989b, 1990) for equivalent strata in the Cold Lake and Peace River Arch areas to the south and west, respectively. Local differences along boundaries are likely the result of lack of data, computer extrapolation, or differences in the stratigraphic definition of hydrostratigraphic units between the various areas.

The salinity distributions are influenced by fluid flow only when local flow systems introduce fresh meteoric water, resulting in mixing and dilution of formation waters. The temperature of formation waters, which is generally a function of depth, exerts the main control on salinity distributions. The presence of nearby evaporitic beds tends to increase the overall salinity in adjacent aquifers.

Besides these general observations regarding the entire flow system, the individual aquifers and aquifer systems can be grouped into pre-Prairie Formation aquifers, Beaverhill Lake-Cooking Lake aquifer system, Grosmont-to-Wabamun aquifers, and Cretaceous aquifers. Each group exhibits certain common characteristics particular to the hydrodynamic conditions and external influences which are present.

Pre-Prairie formation aquifers

Aquifers below the Prairie evaporite exhibit regional flow-regime characteristics, with depth related salinity trends and a northeastward flow direction. Overall high formation water salinity is associated with the proximity of Elk Point Group evaporites. Buoyancy effects are significant, opposing the regional topographically induced flow of formation waters. In the northeastern part of the study area past the edge of Prairie Formation salt solution, the flow in these aquifers is under the influence of local flow systems controlled by the Athabasca and Clearwater rivers.

Beaverhill Lake-Cooking Lake aquifer system

The Beaverhill Lake-Cooking Lake aquifer system has hydrogeological 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. As a result, buoyancy effects are not significant on a regional scale in controlling the flow regime. Generally, formation waters flow to the northeast. However, within the subcrop area and at the outcrop, local physiographic influences are superimposed over this regional trend. These include discharge along the Athabasca and Clearwater rivers in the northeast, and a high potential induced by the topography of the Birch Mountains to the northwest. In the southwest, hydraulic continuity is inferred across the Lower Ireton aquitard between the Grosmont aquifer and the Beaverhill Lake-Cooking Lake aquifer system, through Cooking Lake Formation reefs, resulting in southwest flow directions.

Grosmont-to-Wabamun aquifers

The Grosmont aquifer and the overlying Winterburn-Wabamun aquifer system are regionally significant in that they may act locally as a "drain" for aquifers in hydraulic continuity above and below. The relatively high hydraulic conductivity associated with these units results in low hydraulic heads and gradients, which are postulated to direct flow regionally to the northwest where the Grosmont aquifer eventually is exposed at the surface and formation waters discharge into the Peace River northwest of the Birch Mountains. Although the salinity in these aquifers is relatively low compared to other Paleozoic aquifers, buoyancy effects can be locally significant because of very low gravity-induced hydraulic gradients. The Lower Ireton aquitard isolates the Grosmont aquifer from units below except where the Cooking Lake Formation reefs breach the Ireton Formation shales. The thin Upper Ireton aquitard above it is weak, allowing hydraulic communication with the overlying aquifers. The Grosmont and Wabamun-Winterburn aquifers are in direct contact with overlying Cretaceous aquifers along their respective subcrop at the sub-Cretaceous unconformity.

Cretaceous aquifers

Cretaceous aquifers can all be described as having local flow regime characteristics with no buoyancy effects. This is the result of recharge in topographically high regions, and discharge in regions where the aquifers are exposed at the surface. Formation water salinity is generally low, with depth related trends noticeable in the southwest.

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