REGIONAL SUBSURFACE HYDROGEOLOGY IN NORTHEAST ALBERTA

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TABLE OF CONTENTS

EXECUTIVE SUMMARY 1
INTRODUCTION 4
PROCESSING OF HYDROGEOLOGICAL DATA 12
    ANALYSES OF FORMATION WATERS 14
    DRILLSTEM TESTS 16
    CORE-PLUG ANALYSES 27
GEOLOGICAL OVERVIEW 48
    PALEOZOIC GEOLOGY 52
    MESOZOIC GEOLOGY 54
HYDROGEOLOGICAL ANALYSIS 56
    HYDROSTRATIGRAPHY 56
    REGIONAL SUBSURFACE HYDROGEOLOGY 64
        Physiography 68
        Precambrian Aquiclude 70
        Basal Aquifer 70
        Lower Elk Point Aquitard-Aquiclude System 71
        Contact Rapids - Winnipegosis Aquifer System 71
        Prairie-Watt Mountain Aquiclude System 75
        Beaverhill Lake - Cooking Lake Aquifer System 76
        Lower Ireton Aquitard 83
        Grosmont Aquifer 84
        Upper Ireton Aquitard 87
        Winterburn-Wabamun Aquifer System 87
        McMurray-Wabiskaw Aquifer/Aquitard System 90
        Clearwater Aquitard 93
        Grand Rapids Aquifer 93
        Joli Fou Aquitard 95
        Viking Aquifer 95
        Post-Viking Aquitard 96
HYDROGEOLOGICAL SYNTHESIS 98
    REGIONAL FLOW REGIME 101
    INTERMEDIATE FLOW REGIME 101
    LOCAL FLOW REGIME 103
    CROSS-FORMATIONAL FLOW 103
SUMMARY AND CONCLUSIONS 112
    PRE-PRAIRIE FORMATION AQUIFERS 114
    BEAVERHILL LAKE-COOKING LAKE AQUIFER SYSTEM 114
    GROSMONT-TO-WABAMUN AQUIFERS 115
    CRETACEOUS AQUIFERS 116
REFERENCES 117
APPENDIX A - DISTRIBUTIONS OF FRESH WATER HYDRAULIC HEAD 124
APPENDIX B - DISTRIBUTIONS OF FORMATION WATER SALINITY 140

LIST OF FIGURES

Figure 1. Location map of the UTF site 6

Figure 2. Location of the Northeast Alberta regional-scale study area 8

Figure 3. Location map of previous hydrogeological studies pertinent to northeast Alberta 10

Figure 4. Frequency distribution of drillstem test permeability values for the sandstone Wabiskaw hydrostratigraphic unit 22

Figure 5. Frequency distribution of drillstem test permeability values for the carbonate Grosmont hydrostratigraphic unit 23

Figure 6. Frequency distribution of core-plug measurements of maximum permeability k_m in a well, Wabiskaw hydrostratigraphic unit 32

Figure 7. Frequency distribution of core-plug measurements of maximum permeability k_m in a well, Grosmont hydrostratigraphic unit 34

Figure 8. Frequency distribution of well-scale values of maximum permeability k_m for the Grand Rapids hydrostratigraphic unit 35

Figure 9. Scatter plot and linear correlation between the horizontal components k_{90} and k_m of plug-scale permeability for the Wabiskaw hydrostratigraphic unit 39

Figure 10. Scatter plot and linear correlation between the vertical and horizontal components k_v and k_m of plug-scale permeability for the Wabiskaw hydrostratigraphic unit 40

Figure 11. Frequency distribution of core-plug porosity measurements in a well, Wabiskaw hydrostratigraphic unit 42

Figure 12. Frequency distribution of well-scale porosity values for the Wabiskaw hydrostratigraphic unit 43

Figure 13. Scatter plot and linear correlation between core-plug maximum permeability, log (k_m), and porosity for the Wabiskaw hydrostratigraphic unit 47

Figure 14. Structural dip cross-section of the Phanerozoic succession in northeast Alberta 50

Figure 15. Structural strike cross-section of the Phanerozoic succession in northeast Alberta 51

Figure 16. 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 62

Figure 17. 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 65

Figure 18. Physiography and major topographic features of the Northeast Alberta study area 69

Figure 19. Hydrogeology of the Contact Rapids-Winnipegosis aquifer system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution 73

Figure 20. Hydrogeology of the Beaverhill Lake-Cooking Lake aquifer system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution 77

Figure 21. Structural cross-section of the Lower Ireton aquitard showing a Cooking Lake Formation reef 81

Figure 22. Hydrogeology of the Grosmont aquifer: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution 85

Figure 23. Freshwater hydraulic-head distribution for the Winterburn-Wabamun aquifer system 89

Figure 24. Hydrogeology of the McMurray-Wabiskaw aquifer/aquitard system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution 92

Figure 25. Hydrogeology of the Grand Rapids aquifer: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution 94

Figure 26. Freshwater hydraulic-head distribution for the Viking aquifer 97

Figure 27. Location of hydrogeological dip cross-section (Figure 28) and of pressure-depth profiles (Figure 29) 99

Figure 28. Hydrogeological dip cross-section showing distributions of: (a) salinity of formation waters; and (b) hydraulic head. Cross-section location is shown in Figure 27 (cross-section from Wright, 1984) 100

Figure 29. Variation of pressure with depth in selected wells (locations shown in Figure 27) 106

Figure 30. Distribution of hydraulic-head variation across the Clearwater aquitard in northeast Alberta 111

LIST OF TABLES

Table 1. Initial distribution by stratigraphic unit of various analyses and associated number of wells, Northeast Alberta study area 13

Table 2. Manual-automatic culling criteria for analyses of formation waters from Cretaceous aquifers, Northeast Alberta study area 15

Table 3. Distribution by hydrostratigraphic unit of total compressibility and Z-factor obtained from drillstem tests 18

Table 4. Distribution by hydrostratigraphic unit of freshwater hydraulic head and permeability values obtained from drillstem tests 20

Table 5. Characteristic regional-scale values for permeability measurements (m^2) obtained from drillstem tests 24

Table 6. Distribution by hydrostratigraphic unit of various types of core-analysis data and associated number of wells 30

Table 7. Characteristic regional-scale values for permeability measurements (md) obtained from core analyses 37

Table 8. Regional-scale horizontal and vertical permeability anisotropy A_H and A_v 38

Table 9. Characteristic regional-scale values for porosity measurements obtained from core analyses 45

Table 10. Correlation coefficient and coefficients of the regression line $\log (k_m) = a\phi + b$ 46

Table 11. Generalized stratigraphic nomenclature, Northeast Alberta study area 49

Table 12. Hydrostratigraphic succession and nomenclature, Northeast Alberta study area 61

EXECUTIVE SUMMARY

This report is the second of a two-part study dealing with the hydrogeology of the Phanerozoic succession in northeast Alberta. The first part, completed in August 1991, described the regional-scale geology and hydrostratigraphy of the sedimentary strata in the area defined by latitudes 55°N to 58°N and longitudes 110°W to 114°W (Tp 70-103, R 1-26, W4 Mer). This report presents the hydrogeological regime of formation waters in this study area.

The study was prompted in part by plans of the Alberta Oil Sands Technology and Research Authority (AOSTRA) to expand the Underground Test Facility (UTF) near Fort McMurray in northeast Alberta to a pilot operation. As part of this expansion, disposal of residual waters by on-site deep well injection has been proposed. Environment Canada and the Alberta Research Council initiated in 1990 a collaborative study on the effects of deep injection of residual water at the UTF site, with data support and cooperation from AOSTRA. The evaluation of the effects of deep injection of residual water is based on predictive modelling, which requires knowledge of the initial baseline hydrogeological conditions. Because the data are very scarce and incomplete at the local scale, it was necessary to use regional-scale data for the identification and characterization of the hydrostratigraphic units at the UTF site. The hydrodynamic and hydrochemical characterization (porosity and

permeability, formation pressure, and chemistry of formation waters) of the Phanerozoic hydrostratigraphic units in northeast Alberta forms the content of this report.

The hydrogeological regime of formation waters in the Phanerozoic succession in northeast Alberta is very complex because of variability in geometry and lithology of the Phanerozoic strata. Erosion by the Athabasca River system as far down as Paleozoic strata adds to this complexity. As a result, topography and physiographic features exert a strong influence on the flow regime within most aquifers. Local recharge, which introduces fresh meteoric water, takes place in areas of high topography, such as the Birch and Pelican mountains. The valleys of the Athabasca and Clearwater rivers represent discharge areas for aquifers exposed or subcroping near them.

From the point of view of the hydrogeological regime, the Phanerozoic aquifers can be divided into four groups. The aquifers below the thick halite beds of the Prairie Formation exhibit regional flow characteristics, with a northeastward flow direction and depth-related salinity trends. High formation water salinity is associated with the proximity of Elk Point Group evaporites. Buoyancy (density) effects are significant, likely retarding the flow. The flow in the Beaverhill Lake-Cooking Lake aquifer system is intermediate-to-local in nature. Within the subcrop area and along the outcrop, local physiographic influences are superimposed over a regional northeastward trend. The formation water salinity, while depth related, is lower than for the pre-Prairie aquifers. As a result, buoyancy effects are not important when compared with gravity induced flow. The Grosmont, Winterburn and Wabamun aquifers, present only in the western part of the area, act most probably as a drain for aquifers in hydraulic continuity above and below. The flow is likely toward the northwest, where the Grosmont aquifer is exposed and there the formation waters discharge into the Peace River. Because of very low gravity induced hydraulic gradients, buoyancy effects could be important locally, but not on a regional scale. The flow regime in the Cretaceous aquifers is local, with recharge in topographically high areas, and discharge where the aquifers are exposed. The salinity of formation waters is low, with depth (temperature) related trends noticeable only in the southwest. The flow in these aquifers is basically gravity driven.

INTRODUCTION

For the last few years, the Alberta Oil Sands Technology and Research Authority (AOSTRA) has been developing an Underground Test Facility (UTF) for the extraction of bitumen from oil sands deposits using a steam-stimulated and gravity-drainage recovery process. Phase A of the operations sought to evaluate the "Shaft and Tunnel Access Concept" to produce bitumen, and to test the concept and technology. Phase A proved successful beyond the initial predictions based on numerical process simulations, and the facility is currently expanding to a pilot phase. One of the byproducts of the bitumen extraction is residual water, which was trucked to a disposal site during Phase A of the operations. It is currently being planned to dispose of the much larger volume of residual water produced by the pilot operation by on-site deep well injection. AOSTRA has and is addressing environmental problems related to the UTF operation, including the issue of subsurface disposal of residual water. However, the upgrading of the UTF operations provides an opportunity for the monitoring, from the start, of possible environmental effects related to the exploitation of the oil sands deposits, and for the development of strategies and guidelines for similar future activities. With this broad objective in mind, Environment Canada and the Alberta Research Council initiated the present collaborative study, with data support and cooperation from AOSTRA.

In order to identify possible environmental effects of deep injection of residual water at the UTF site, predictive modelling of the associated hydrodynamic, geomechanical and geochemical processes is required. To perform this, it is necessary to know the initial hydrogeological baseline conditions prior to the start of injection, and the relevant parameters and characteristics of the subsurface environment. Proper monitoring during injection will allow continuous model calibration and updating. AOSTRA implemented and is currently running a program of detailed data collection and monitoring around the steam chambers formed as a result of bitumen extraction. However, the data needed for evaluating the effects of deep disposal of residual water are scarce around the disposal site, therefore requiring the extension of any related hydrogeological study beyond the UTF site itself (Basin Analysis Group, 1988).

The UTF site is located on about 9 ha (22 acres) situated some 50 km northwest of Fort McMurray and 20 km southwest of Fort McKay, in Sections 7 and 8, Township 93, Range 12, W4 Mer (Figure 1). In order to use predictive modelling in the evaluation of the environmental effects related to deep injection of residual water, it is necessary to consider the hydrogeological and transport processes within a three-dimensional geological frame. A previous analysis of data availability for predictive modelling at the UTF site (Basin Analysis Group, 1988) identified four different scales: 1) a detailed scale covering the steaming zone; 2) a local scale covering the UTF site; 3) an intermediate scale covering four townships around the site; and 4) a regional scale. The identification of these four scales was dictated by the uneven distribution of

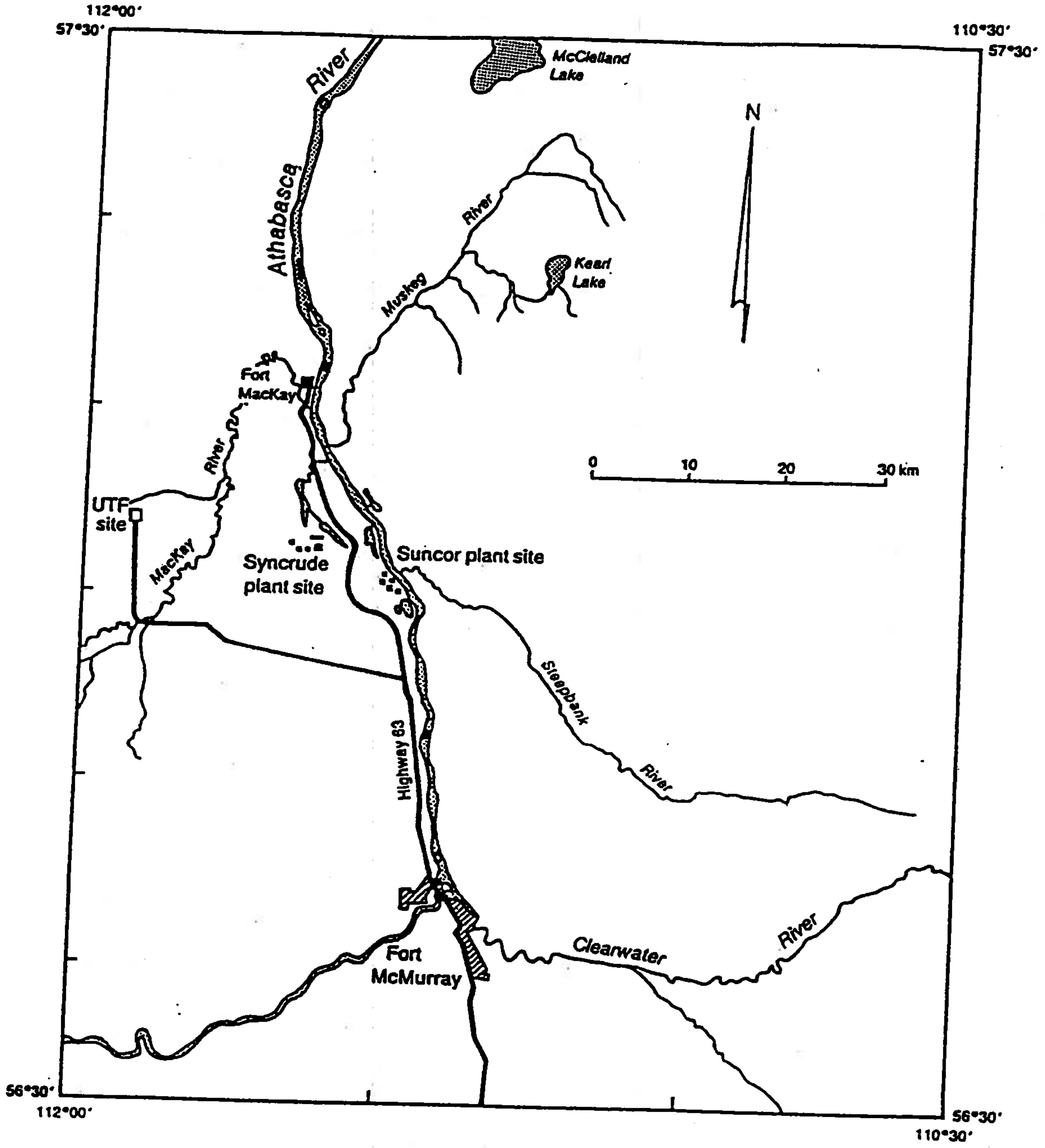


Figure 1. Location map of the UTF site.

various data categories both areally and with depth. While there is extensive information forthe Cretaceous strata at the local scale, data for the Paleozoic strata is scarce (the nearest deep well to the UTF site is more than 10 km away). The main recommendation of the previous study on the data availability (Basin Analysis Group, 1988) was to perform predictive modelling and monitoring at the local scale. In order to define the distribution field of variables such as pressure (hydraulic head) and salinity, the study also recommended performing a hydrogeological characterization at a regional scale. In 1990, the Petroleum Geology and Basin Analysis Section of the Alberta Geological Survey, Alberta Research Council, started a regional, basin-scale study of the Phanerozoic strata in northeast Alberta. The study area, defined by Tp. 70-103, R. 1-26 W 4 Mer (Figure 2), includes the regional-scale area recommended previously for the evaluation of effects related to deep disposal of residual water at the AOSTRA-UTF site (Basin Analysis Group, 1988).

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 mostly in shallow aquifers of the Athabasca oil sands area. Subsequently, Hackbarth and Brulotte (1981) conducted a data gathering program which included 12 deep wells within the present study area. These data were included in the present analysis. Besides these studies, a number of investigations of the subsurface fluid flow in regions around the northeast Alberta study area have been conducted. Hitchon (1964) provided the first synthesis of the

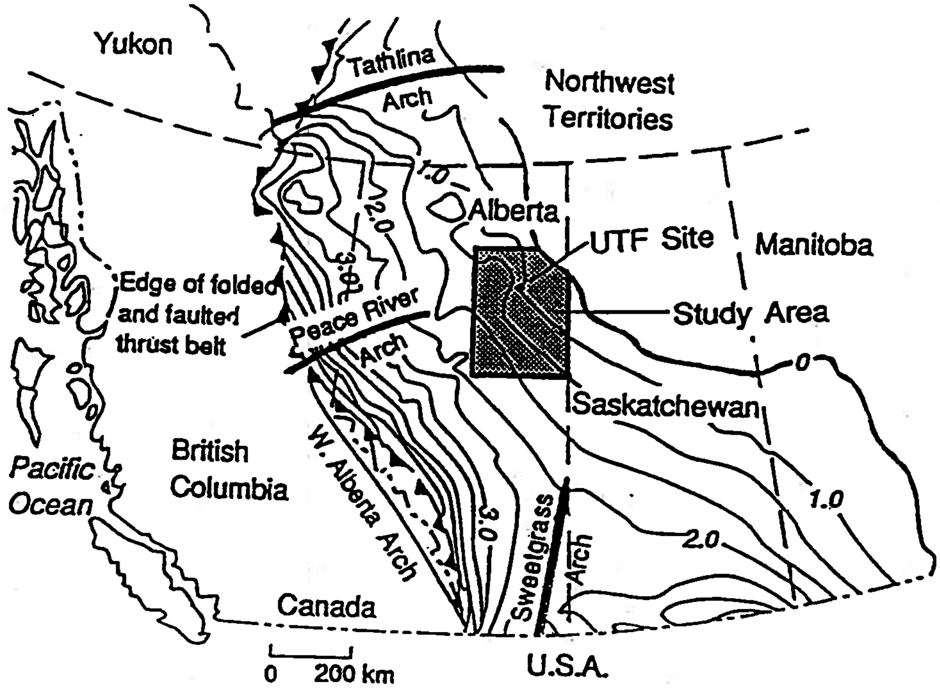


Figure 2. Location of the Northeast Alberta regional-scale study area.

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 at the scale of the entire 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. According to Toth (1978), three different flow systems are present in the Red Earth region (Figure 3). The two upper systems (Meso-Cenozoic: post-Clearwater hydrostratigraphic units; and Paleo-Mesozoic: post Ireton to Clearwater hydrostratigraphic units) are in equilibrium with present day hydraulic boundary conditions. The lower system (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 3), Hitchon et al. (1989a) conducted a hydrogeological 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 3), Hitchon et al. (1989b) showed that the Joli Fou aquitard is a significant barrier to flow; however, the Clearwater and Ireton aquitards are weak where they are thin, with areas where hydraulic continuity 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 3). 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

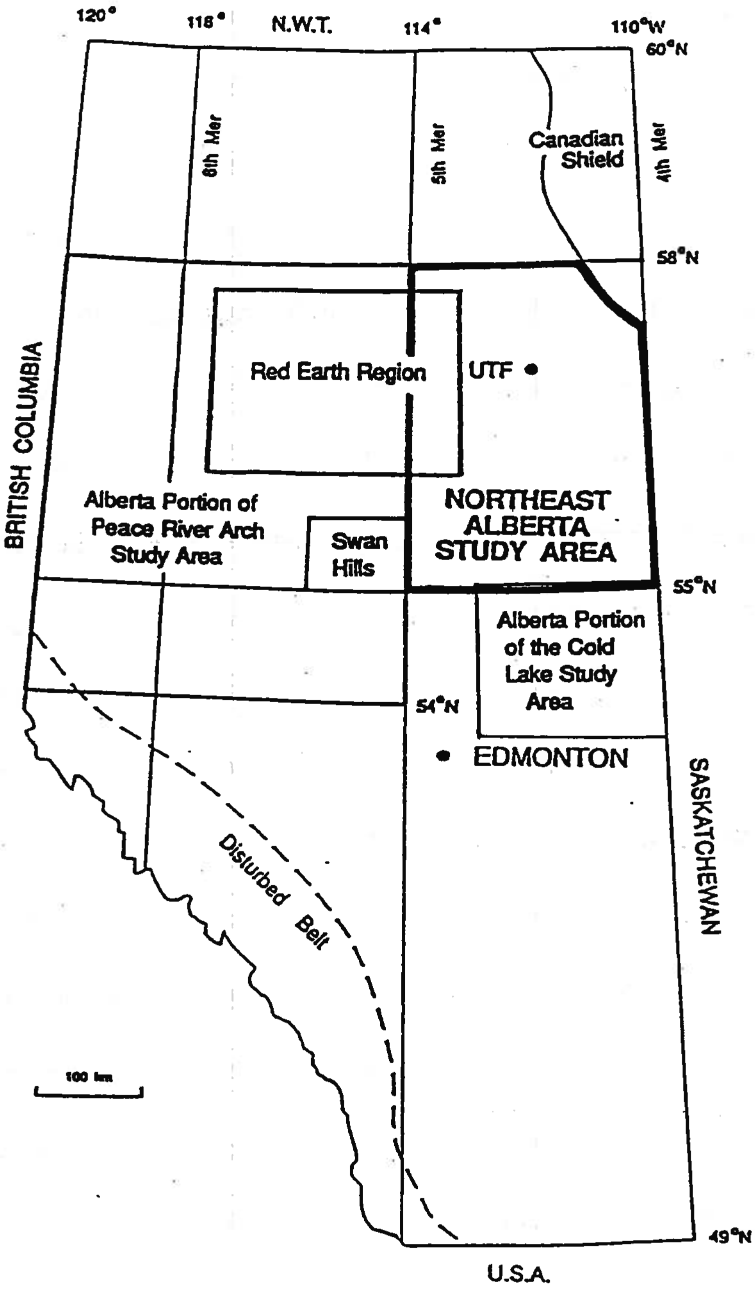


Figure 3. Location map of previous hydrogeological studies pertinent to northeast Alberta.

flow regime within Upper Cretaceous to Recent strata (above the Colorado aquitard). The Clearwater and Ireton aquitards are the most significant regional flow barriers in the Peace River Arch region.

The present investigation of the effects of deep disposal of residual water at the AOSTRA-UTF site was approached bearing in mind the results and recommendations of previous studies. This is the second part of a regional-scale hydrogeological study to define the initial baseline conditions, to be followed by local-scale hydrodynamic and geochemical modelling. In the first part of the present study, the geology, stratigraphy and hydrostratigraphy of the Phanerozoic succession in northeast Alberta were described and delineated (Petroleum Geology and Basin Analysis Group, 1991). The present report continues with the hydrogeological characterization and analysis of the flow regime of formation waters in the study area.

The processing and analysis of the geochemical and hydrogeological data were carried out by Stefan Bachu, Brian Hitchon, and Jim Underschultz. Technical support was provided by Michel Brulotte, Mika Madunicky and Kelly Roberts, and Margaret Booth provided clerical support. Data, support and cooperation from Jack Suggett (UTF Project Manager) and Jane Stevens (AOSTRA Senior Geologist) are gratefully acknowledged.

PROCESSING OF HYDROGEOLOGICAL DATA

Hydrogeological information from 3187 formation water analyses, 2531 drillstem tests and 452,030 core-plug analyses were used in this study. Areally, these data are located at the 12,479 drill holes within the study area. Entire analyses and individual data were automatically rejected because of erroneous values, based on range and threshold criteria. The remainder of analyses and data were subsequently allocated into the initial hydrostratigraphic framework defined previously in the study of the regional geology. The data were then variously interpreted per hydrostratigraphic unit and culled more rigorously for questionable values. Each type of data required specific processing. The basic processing procedures are described in Bachu et al. (1987). Data of all types tend to be clustered both areally and with depth. In the oil sands area, between 111°W and 112°W and north of 57°N, the well control is overwhelming, while in other areas there is little or no data. There is also an order-of-magnitude difference in the number of wells penetrating various hydrostratigraphic levels. Table 1 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 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 Group	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 1. Initial distribution by stratigraphic unit of various analyses and associated number of wells, Northeast Alberta study area.

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. Generally, these analyses are extremely subject to errors. Previous studies in the Western Canada Sedimentary Basin (Hitchon, 1984; Hitchon et al., 1987; Hitchon et al., 1989a, b; and 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 (55%) passed the initial automatic cull. Because of their small number and poor areal distribution, the 294 analyses of formation waters associated with pre-Cretaceous aquifers that passed the automatic cull were examined individually. Formation water analyses from Cretaceous aquifers (83% of those analyses which passed the automatic cull) were subjected to a manual-automatic cull, the criteria and results of which are given in Table 2. The final data set comprised 590 analyses or 18.5% of the original data

Stratigraphic Unit	No. after Automatic Culling	Criteria for Manual-Automatic Culling			No. after Manual-Automatic Culling
		Presence of Carbonate	Upper Limit for SO_4 (mg/l)	Lower Limit for Cl (mg/l)	
Ground/2nd W.S.S.	135	Yes	-	-	129
Colorado Group	35	Yes	100	-	4
Viking	153	Yes	100	1000	44
Grand Rapids	409	Yes	500	1000	117
Clearwater	147	Yes	500	1000	54
Wabiskaw	203	Yes	500	1000	97
McMurray	383	Yes	500	1000	207

Table 2. Manual-automatic culling criteria for analyses of formation waters from Cretaceous aquifers, Northeast Alberta study area.

base. Hitchon (1991) presented a detailed analysis of the chemistry of formation waters in northeast Alberta, which is incorporated in this report in the analysis of the hydrogeological regime.

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 towards 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 1. The original number of data includes all phases (there is often more than one test of pressure build-up recorded for an individual drillstem test).

The main parameters of interest in this study which are obtained from drillstem tests are permeability and pressure. Drillstem tests are interpreted using Horner analysis (Timmerman and Van Poollen, 1972). The slope of the Horner plot together with Cl and temperature estimates are used to calculate the formation permeability (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). Information on formation water Cl content and temperature is not normally included in standard drillstem test reports. Therefore, the electronic maps of Cl distribution obtained in the hydro-geochemical 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_o and geothermal gradient G according to:

$$T = T_o + GD$$

where D is the drillstem-test depth. Surface temperature and geothermal gradient values were obtained from a regional scale study of the geothermal regime in the Western Canada Sedimentary Basin by Bachu and Burwash (1991, 1992).

Drillstem tests which recover gas require additional terms to be used in the calculation of various hydrodynamic parameters (Bachu et al., 1987). Table 3 shows the number and hydrostratigraphic distribution of total compressibility and gas supercompressibility Z-factor values. All total compressibility values were reported as 1.0×10^{-5} (1/kPa). The gas supercompressibility Z-factor is obtained by comparing the collected gas with a standard, resulting in a dimensionless value. In addition, a standard gas viscosity value of 1.0×10^{-4} (Pa•s) was used.

Hydrostratigraphic Unit	No. of Total Compressibility Measurements	Z FACTOR			
		No. of Measurements	Minimum	Maximum	Average
Viking	8	10	.93	.95	.940
Grand Rapids	-	2	.92	.92	.920
Clearwater	35	54	.57	.97	.910
Wabiskaw	10	12	.82	.95	.920
McMurray	34	54	.84	.98	.940
Wabamun	2	4	.93	.95	.940
Winterburn	4	4	.95	.96	.955
Grosmont	2	4	.90	.95	.925

Table 3. Distribution by hydrostratigraphic unit of total compressibility and Z-factor obtained from drillstem test.

The stratigraphic distribution of the drillstem test data shown in Table 1 is the result of allocating the data into the initial hydrostratigraphic frame defined previously in the study of the regional-scale geology of northeast Alberta. The initial hydrostratigraphy was based only on the three-dimensional geometry of the stratigraphic units and their spatial relations to one another, and the dominant lithology of those units. With the added information from the analysis of the chemistry of formation waters and pressure data from drillstem tests, it was possible and necessary to revise the initial hydrostratigraphic geometry, and reallocate the hydrodynamic data accordingly. Modifications to the initial hydrostratigraphic geometry consist of changes only in the thickness of some units. The unit boundaries and nomenclature are the same, with no previously defined unit being eliminated and no new unit being added. The hydrostratigraphic distributions of freshwater hydraulic head and permeability data shown in Table 4 reflect the updated hydrostratigraphic geometry. The number of freshwater hydraulic-head data is based on one phase only per drillstem test (as opposed to Table 1) and also includes values obtained from the elevation of units along outcrop boundaries. These values are based on the assumption that the respective unit is at atmospheric pressure where it crops out.

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

Hydrostratigraphic Unit	No. of Freshwater Hydraulic Head Values (including boundaries)	No. of Permeability Values
Ground/2nd W.S.S.	5	-
Viking	230	51
Grand Rapids	848	420
Clearwater	3	-
Wabiskaw	405	202
McMurray	718	369
Wabamun	67	25
Winterburn	92	34
Grosmont	143	55
Cooking Lake	21	7
Beaverhill Lake	57	22
Winnipegosis	47	29
Contact Rapids	2	2
Ernestina Lake	1	-
Basal Red Beds	5	-

Table 4. Distribution by hydrostratigraphic unit of freshwater hydraulic head and permeability values obtained from drillstem tests.

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 phase of the drillstem test is used for permeability determinations because it normally has a longer flow time than the first phase, 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 appears to be confirmed for the well-scale drillstem-test permeability distributions characteristic of the aquifers in northeast Alberta. As an example, Figures 4 and 5 show the frequency distributions for a clastic and carbonate unit, respectively. The frequency distribution plots were constructed by plotting the individual permeability values after compiling them in ascending order. Each plot shows how many times (% of the population) that a particular permeability value or lower was encountered in the sample. Table 5 presents the characteristic regional-scale permeability values for the aquifers in northeast Alberta. For consistency with the hydrogeological literature, the average value $\overline{Y}$ and standard deviation σ_Y of the lognormal distribution $Y = \ln(k_M)$ are also given.

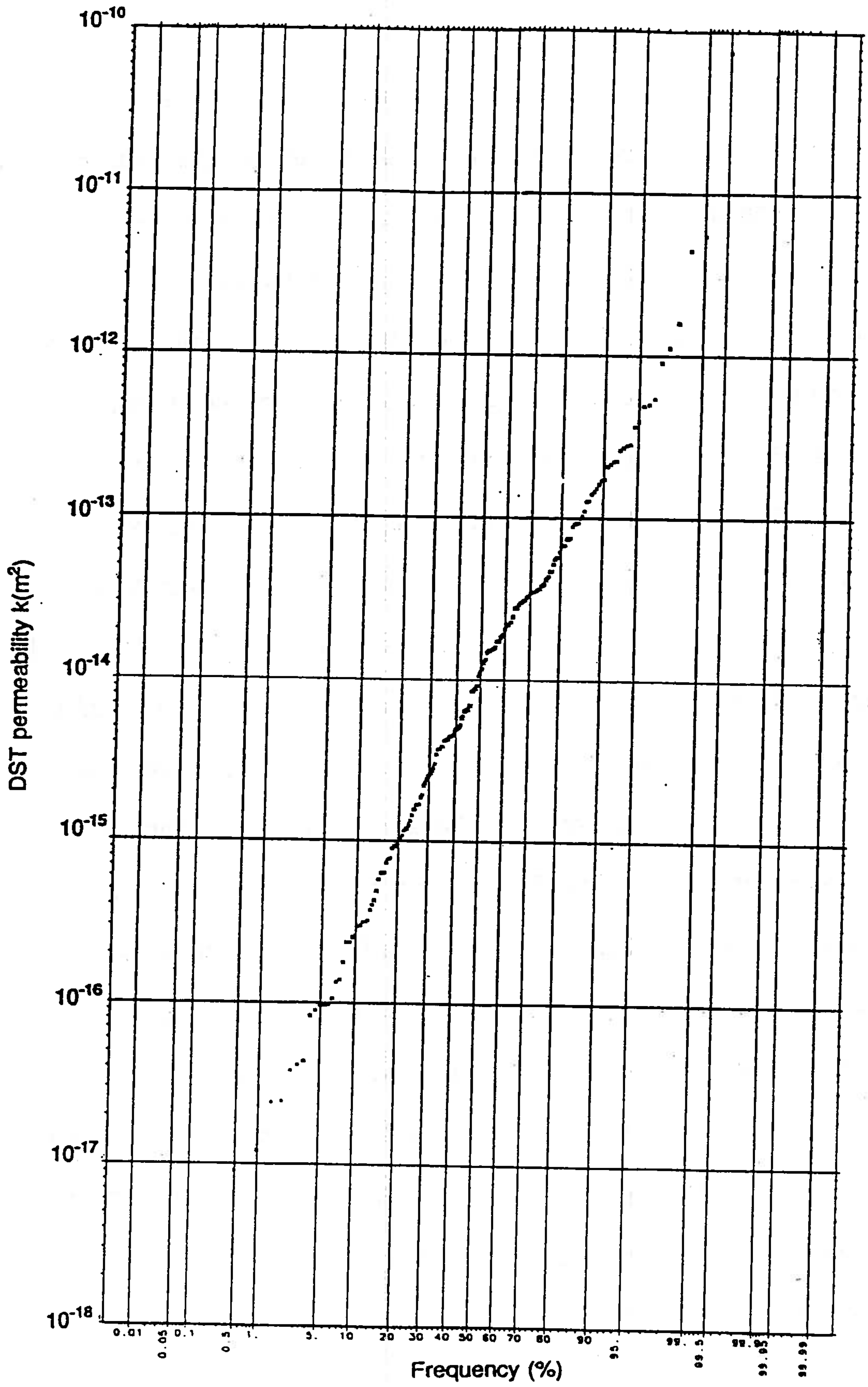


Figure 4. Frequency distribution of drillstem test permeability values for the sandstone Wabiskaw hydrostratigraphic unit.

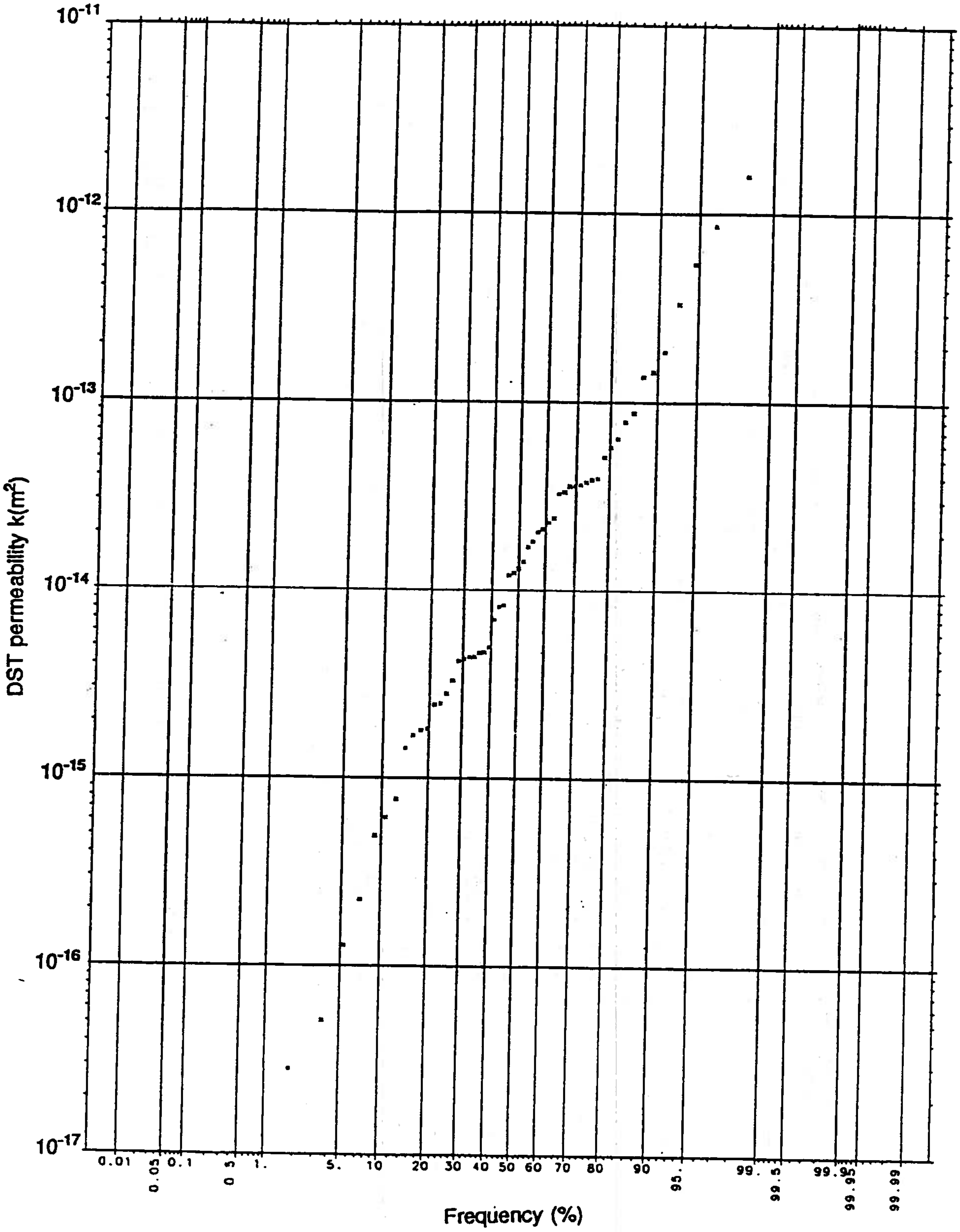


Figure 5. Frequency distribution of drillstem test permeability values for the carbonate Grosmont hydrostratigraphic unit.

Hydrostratigraphic Unit	No.	Minimum	Maximum	Geometric Average	$Y=\ln(k)$	σ_Y
Viking	51	4.567×10^{-17}	5.207×10^{-12}	1.859×10^{-14}	-31.616	2.4808
Grand Rapids	420	8.470×10^{-18}	3.598×10^{-11}	4.273×10^{-14}	-30.784	2.5433
Wabiskaw	202	9.075×10^{-18}	7.444×10^{-11}	8.498×10^{-15}	-32.399	2.5687
McMurray	369	2.233×10^{-18}	1.154×10^{-10}	1.421×10^{-14}	-31.885	2.7140
Wabamun	25	1.239×10^{-16}	1.622×10^{-11}	3.156×10^{-14}	-31.087	3.1184
Winterburn	34	1.345×10^{-16}	1.900×10^{-12}	9.814×10^{-15}	-32.255	2.5110
Wabamun/Winterburn	59	1.239×10^{-16}	1.622×10^{-11}	1.610×10^{-14}	-31.760	2.8196
Grosmont	55	2.829×10^{-17}	1.591×10^{-12}	1.075×10^{-14}	-32.164	2.2530
Cooking Lake	7	2.645×10^{-18}	1.556×10^{-12}	1.799×10^{-15}	-33.952	4.6362
Beaverhill Lake	22	3.603×10^{-17}	1.122×10^{-12}	9.116×10^{-14}	-34.446	2.1980
Cooking/Beaver. Lk.	30	2.567×10^{-18}	1.556×10^{-12}	1.006×10^{-15}	-34.533	3.0434
Winnipeg./Contact R.	31	9.584×10^{-19}	2.725×10^{-13}	1.034×10^{-15}	-34.505	3.1296

Table 5. Characteristic regional-scale values for permeability measurements (m^2) obtained from drillstem tests.

The formation pressure is obtained by extrapolating the Horner plot of pressure measurements. The first phase 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, calculated according to the formula:

$$H_o = p/(\rho_o g) + z$$

where z is elevation, p is pressure, ρ_o is freshwater density, and g is the gravitational constant. In the case of variable density waters, a potential field cannot be defined unless the pressure and density fields are collinear, implying that density is a function solely of pressure (Oberlander, 1989). 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. However, if an aquifer is horizontal, the distribution of freshwater hydraulic head indicates the horizontal component of the hydraulic gradient within that aquifer (Hitchon et al., 1989b). If the aquifer is sloping, as is the case in the Western Canada Sedimentary Basin, the flow of formation waters is driven by both external (gravitational) 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 vs the magnitude of the gravity-related term that determines whether buoyancy (density) effects are significant in any given situation (Davies, 1987). A measure of the relative importance of buoyancy-vs-gravity effects is given by the dimensionless Driving-Force Ratio (DFR), defined as (Davies, 1987; also Bear, 1972, p. 654):

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

where $\Delta\rho$ is the fluid-density difference in the aquifer, and $|\nabla E|$ and $|\nabla H_o|$ are respectively the magnitude of the elevation gradient (aquifer slope) and of the freshwater hydraulic-head gradient. For an isotropic porous medium, Davies (1987) showed through numerical experiments that the value DFR = 0.5 is an approximate threshold at which buoyancy effects may become significant.

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 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 strata. 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 from 10,819 wells were obtained from the electronic files of the Energy Resources Conservation Board (ERCB), a public data repository, 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 1.

A typical core-plug analysis contains information about the maximum permeability in the horizontal plane k_m, the permeability k_{90} in the horizontal plane normal to the direction of maximum permeability, the permeability in the vertical direction k_v, grain density, porosity ϕ, and the length of the characteristic interval. If the rock was originally saturated with bitumen, the normal procedure is to extract the bitumen and then perform the measurements. 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.

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 12,000 md was considered erroneous and was not used. Permeability in the horizontal plane is normally measured in four orthogonal directions. The highest value and the one measured normal to it are taken as k_m and k_{90}, respectively. Therefore, by definition, the horizontal anisotropy should be always less than unity. Thus, allowing only for a small margin of error, analyses with horizontal permeability anisotropy values greater than 1.1 were rejected. Because there is no preferential compaction in the horizontal plane, very high horizontal anisotropy (much smaller than unity) is not expected. Thus, 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 (1.7% of the original number). The core analyses which passed this initial screening were allocated into the final hydrostratigraphic geometry. The results of the initial automatic screening and the hydrostratigraphic distribution of the remaining core-plug data and associated wells are shown in Table 6.

Porosity and permeability data obtained from core analyses represent volume-averaged values corresponding to the plug-scale (Baveye and Sposito, 1984). In order

Hydrostratigraphic Unit	No. of Plugs			k_m		k_{90}	k_v	ϕ	
	Initial	No k or ϕ	Rejected	Plugs	Wells	Plugs	Plugs	Plugs	Wells
Ground/2nd W.S.S.	740	471	5	33	1	-	-	264	38
Viking	98	5	1	71	12	-	8	93	16
Grand Rapids	8075	205	370	1644	101	95	119	7505	285
Clearwater	956	-	12	671	30	52	64	949	53
Wabiskaw	22081	1597	382	3953	269	368	400	20180	1558
McMurray	381537	57237	3405	6420	382	527	490	321087	4822
Wabumun	797	3	129	640	24	561	513	727	30
Winterburn	1282	-	129	659	39	407	387	1275	56
Grosmont	18149	46	1891	10379	178	7599	7061	18039	193
Cooking Lake	406	3	49	237	6	161	163	402	19
Beaverhill Lake	15268	3738	158	525	34	323	323	11395	1057
Prairie	130	-	7	121	9	99	99	130	10
Winnipegosis	2353	-	215	2088	43	1920	1866	2353	46
Contact Rapids	72	-	6	66	6	63	63	72	6
Basal Red Beds	67	-	11	56	3	54	54	67	3

Table 6. Distribution by hydrostratigraphic unit of various types of core-analysis data and associated number of wells.

to characterize a hydrostratigraphic unit at the regional scale, a scaling-up process must be used. 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.

During this study, it was observed that the assumption of a lognormal distribution for permeability values obtained from core-plug analyses does not appear always to apply, as it generally does for drillstem test permeability data. Figure 6 shows the distribution of core-plug maximum permeability k_m for samples from the Wabiskaw Member within a single well. This type of non-lognormal distribution is typical for the Cretaceous units in northeast Alberta, in particular the Grand Rapids, Wabiskaw and McMurray hydrostratigraphic units. The Viking, the only other Cretaceous clastic aquifer within the area, does not contain enough permeability data

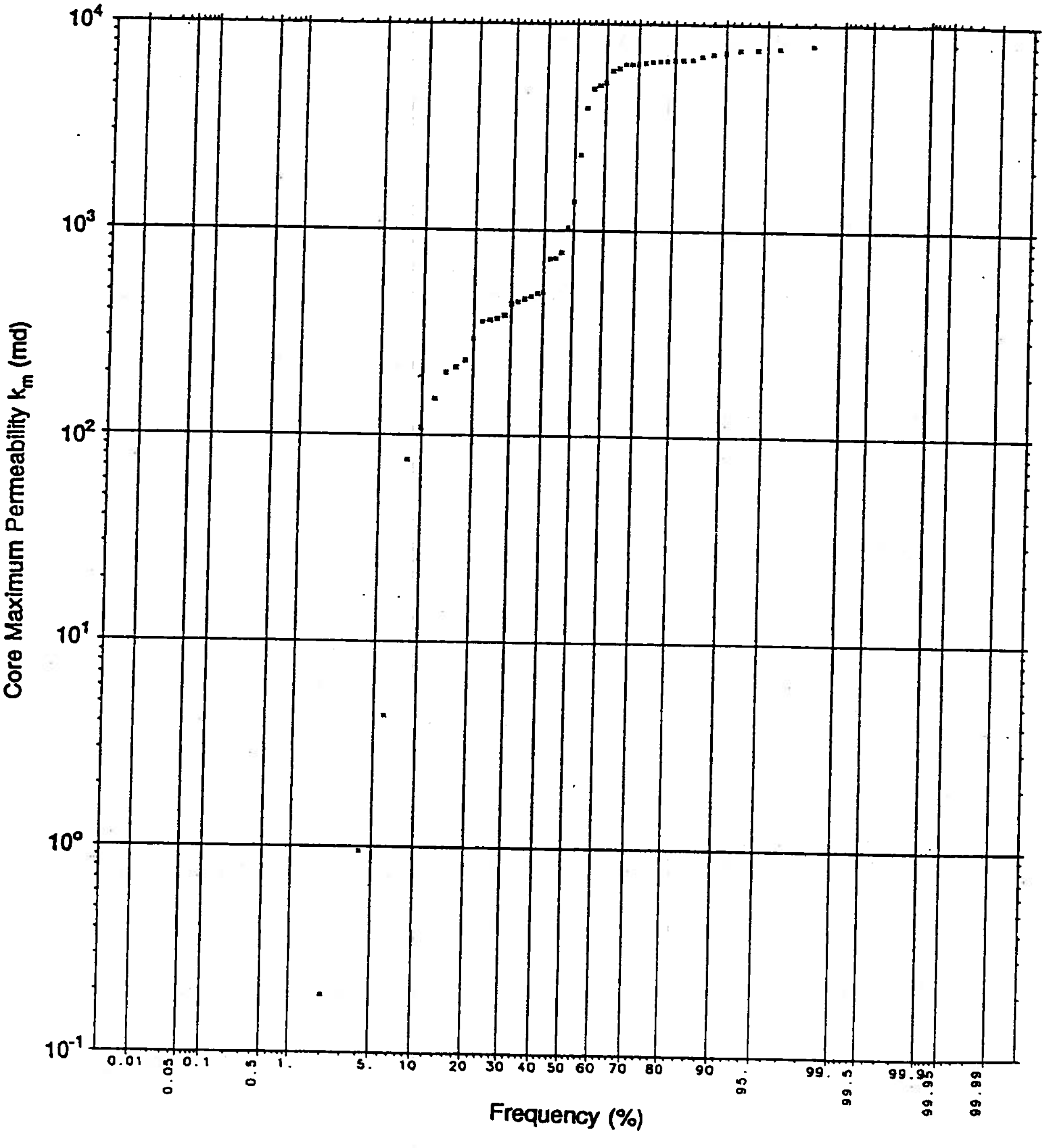


Figure 6. Frequency distribution of core-plug measurements of maximum permeability k_m in a well, Wabiskaw hydrostratigraphic unit.

to be statistically significant at either the well-scale or the formation (basin) scale. For Paleozoic units, core-plug permeability values at a single well often exhibit a lognormal distribution (Figure 7). In all cases the core-plug permeability data were averaged geometrically to obtain representative well-scale values.

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 (Figure 8). 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

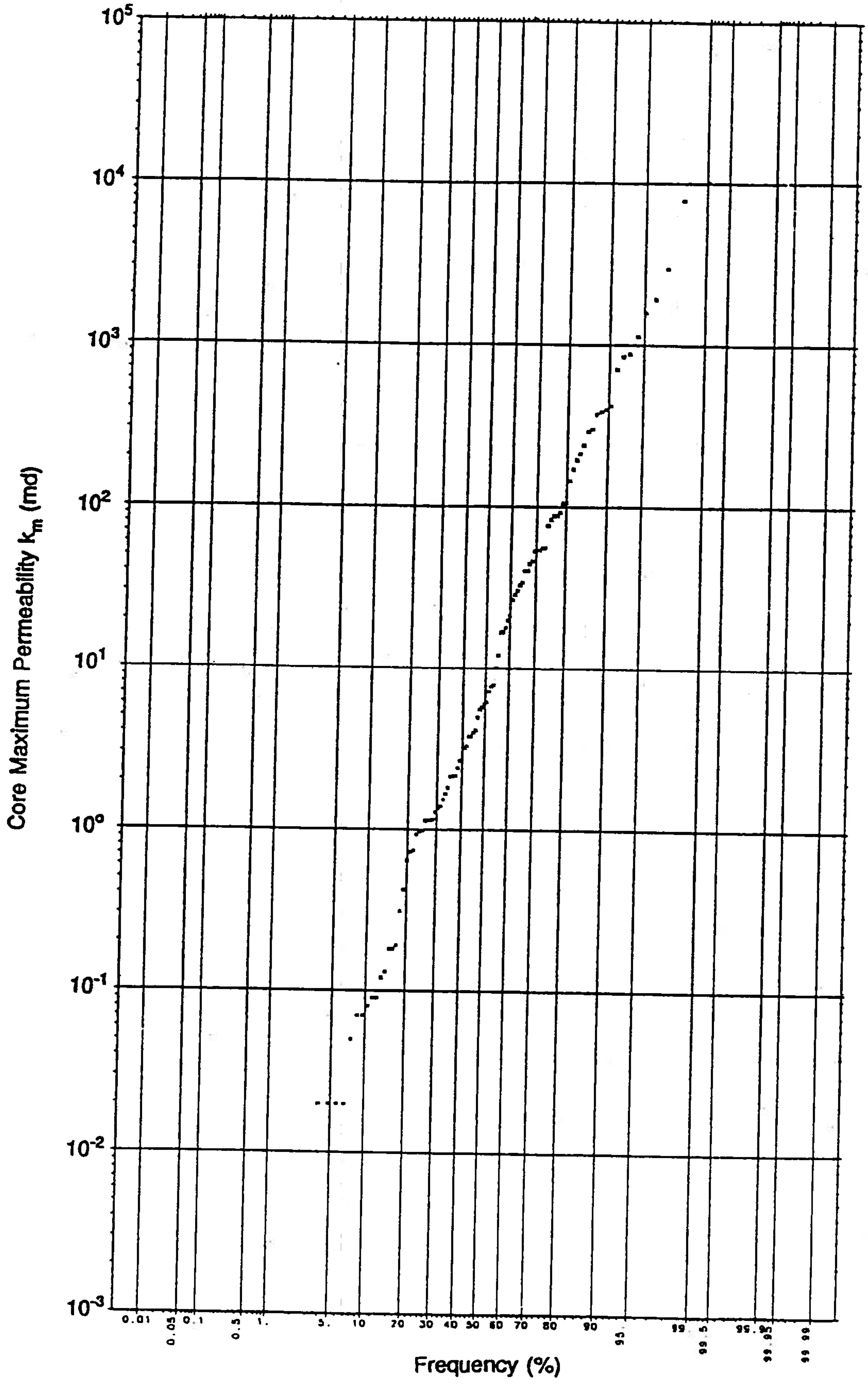


Figure 7. Frequency distribution of core-plug measurements of maximum permeability k_m in a well, Grosmont hydrostratigraphic unit.

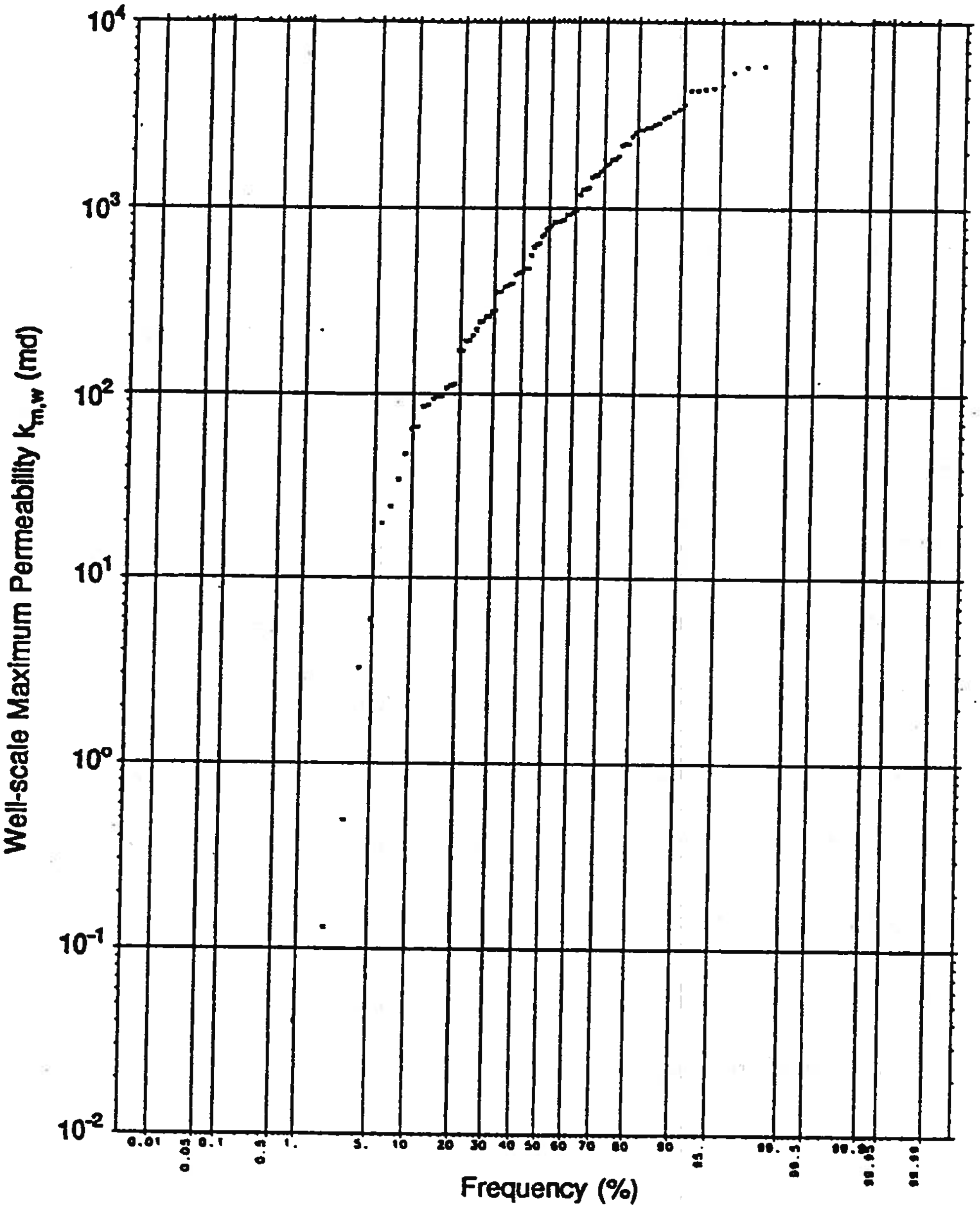


Figure 8. Frequency distribution of well-scale values of maximum permeability k_m for the Grand Rapids hydrostratigraphic unit.

permeability is the geometric average of the well-scale permeability values (Dagan, 1989). Table 7 shows, by hydrostratigraphic unit, the formation (basin) scale characteristic values for maximum permeability k_m and the associated statistics.

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 (see Table 6); 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, the formation (basin) scale 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 8 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 (basin) scale anisotropy values A_H and A_V. As an example, Figures 9 and 10 show graphically the correlation between the maximum permeability k_m and k_{90} and k_v, respectively, for the Wabiskaw aquifer.

Past studies (Hitchon et al., 1989a, b) have shown that in the Western Canada Sedimentary Basin the values of maximum permeability derived from core tend to be

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 7. Characteristic regional-scale values for permeability measurements (md) obtained from core analyses (1 darcy = $0.987\times10^{-12}m^2$).

Hydrostratigraphic Unit	Horizontal Anisotropy			Vertical Anisotropy		
	No. of Samples	R^2	A_H	No. of Data	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 8. Regional-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.

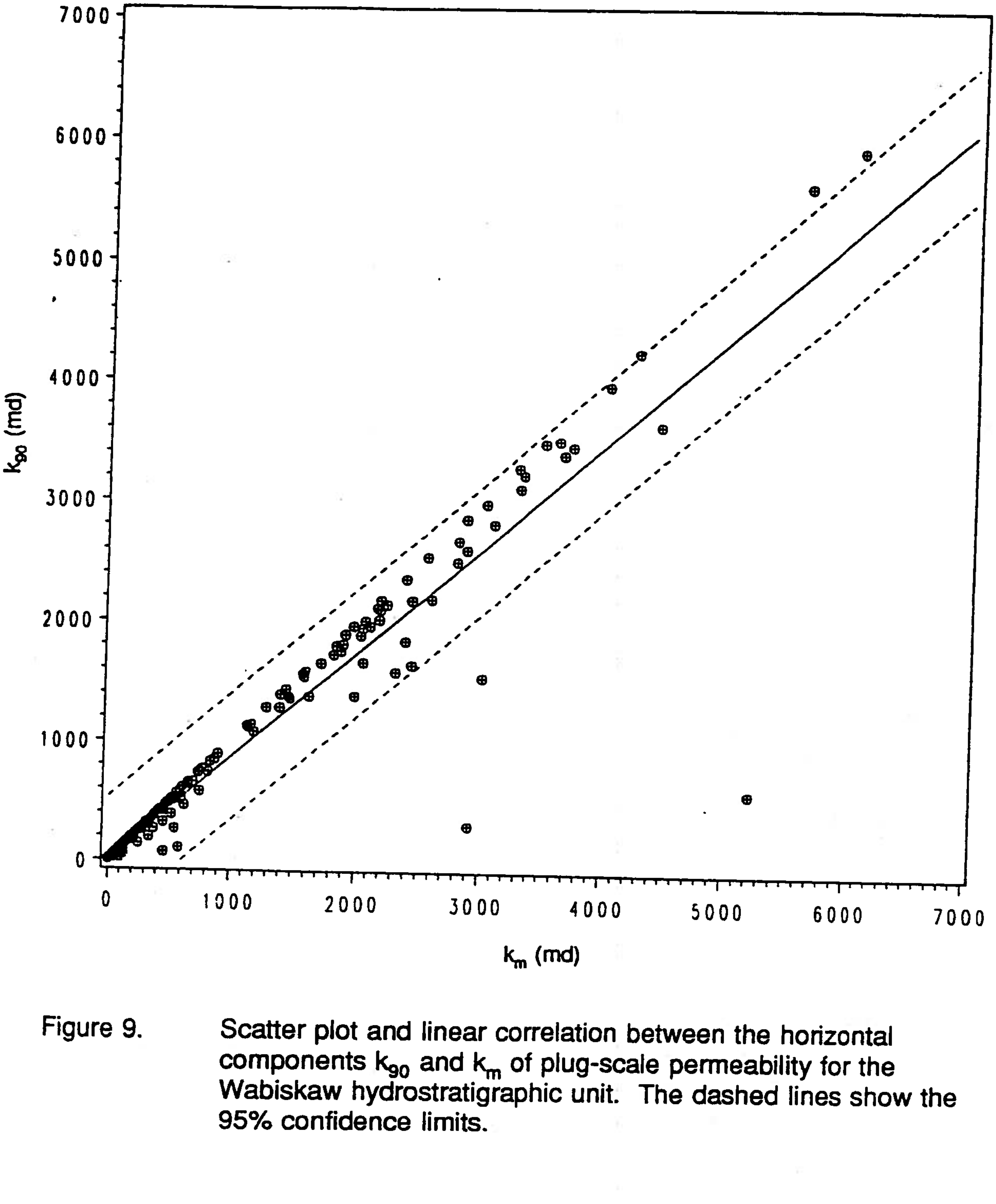


Figure 9. Scatter plot and linear correlation between the horizontal components k_{90} and k_m of plug-scale permeability for the Wabiskaw hydrostratigraphic unit. The dashed lines show the 95% confidence limits.

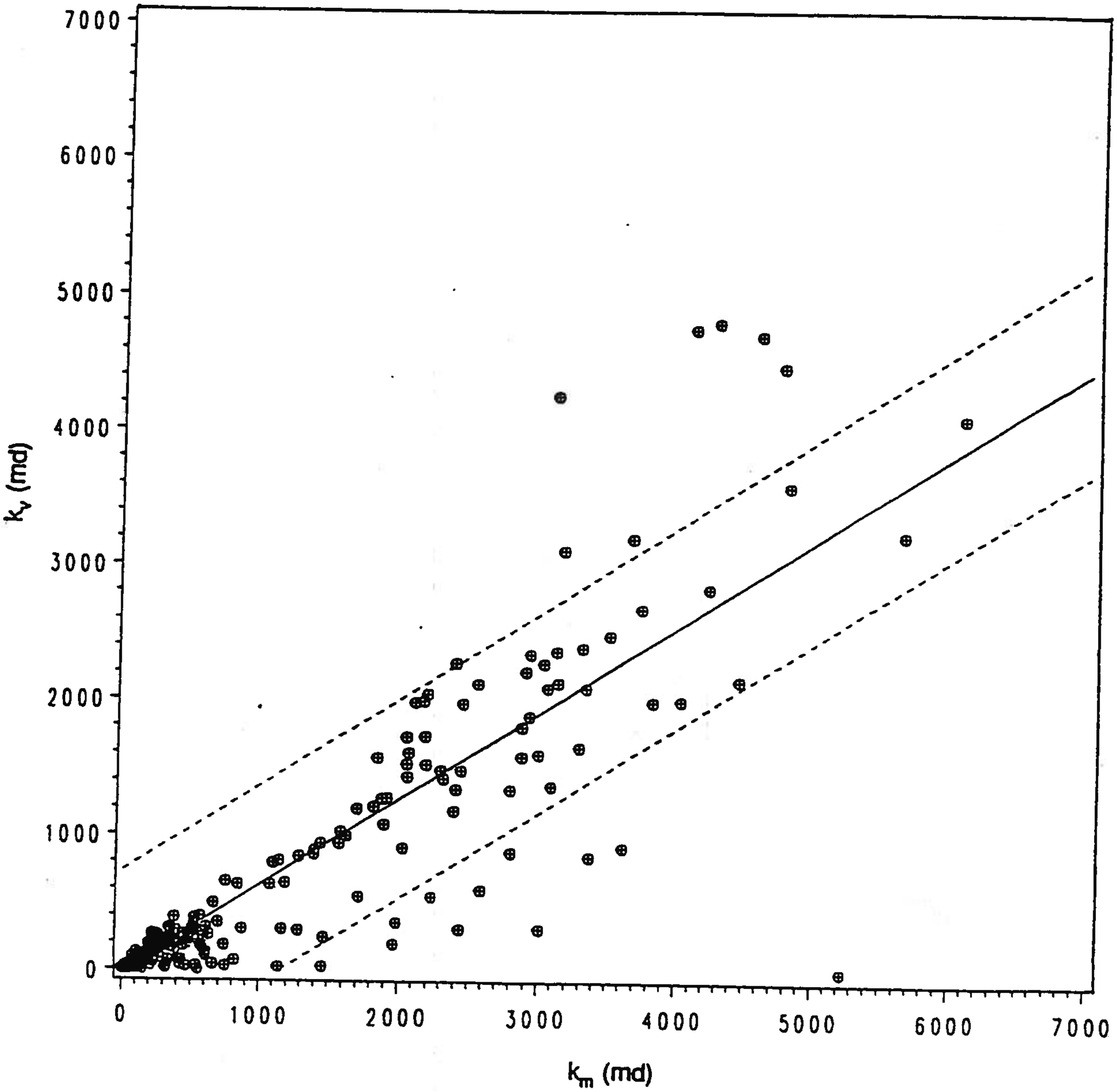


Figure 10. Scatter plot and linear correlation between the vertical and horizontal components k_v and k_m of plug-scale permeability for the Wabiskaw hydrostratigraphic unit. The dashed lines show the 95% confidence limits.

higher than the permeability values obtained from drillstem tests, fact confirmed also by the results of this study. This could be due to the sample size, the sampling procedure, or to the fact that the core has been disturbed and depressured. 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 contribute to the observed difference. There is currently no recognized methodology for reconciling the discrepancy between the two types of measurement.

Porosity, unlike permeability, is a scalar property of the porous media. 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 and it has a much smaller variance than permeability. Figure 11 shows the frequency distribution of porosity measurements from the Wabiskaw hydrostratigraphic unit within an individual well. This non-normal distribution is 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. Figure 12 shows a typical non-normal

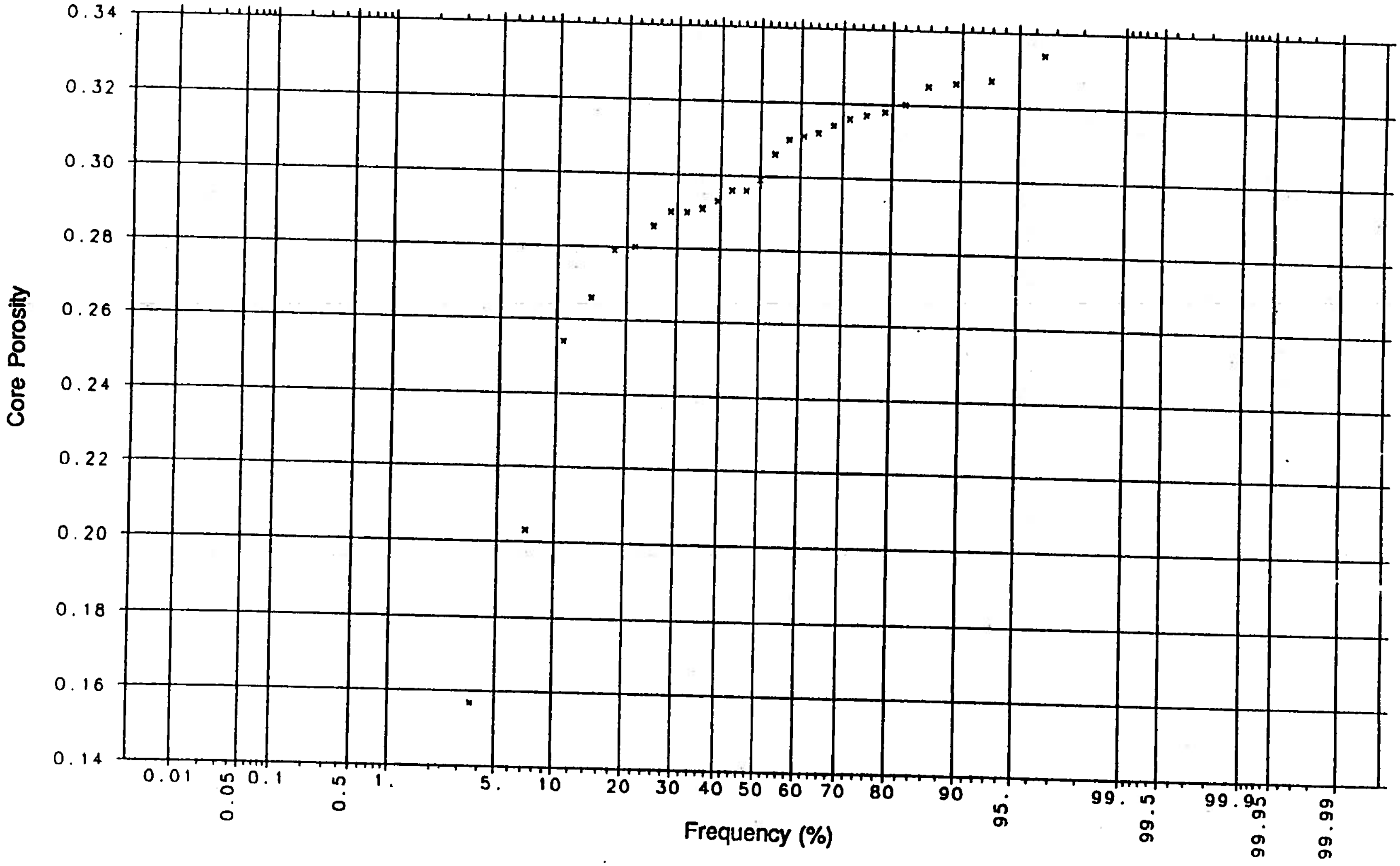


Figure 11. Frequency distribution of core-plug porosity measurements in a well, Wabiskaw hydrostratigraphic unit.

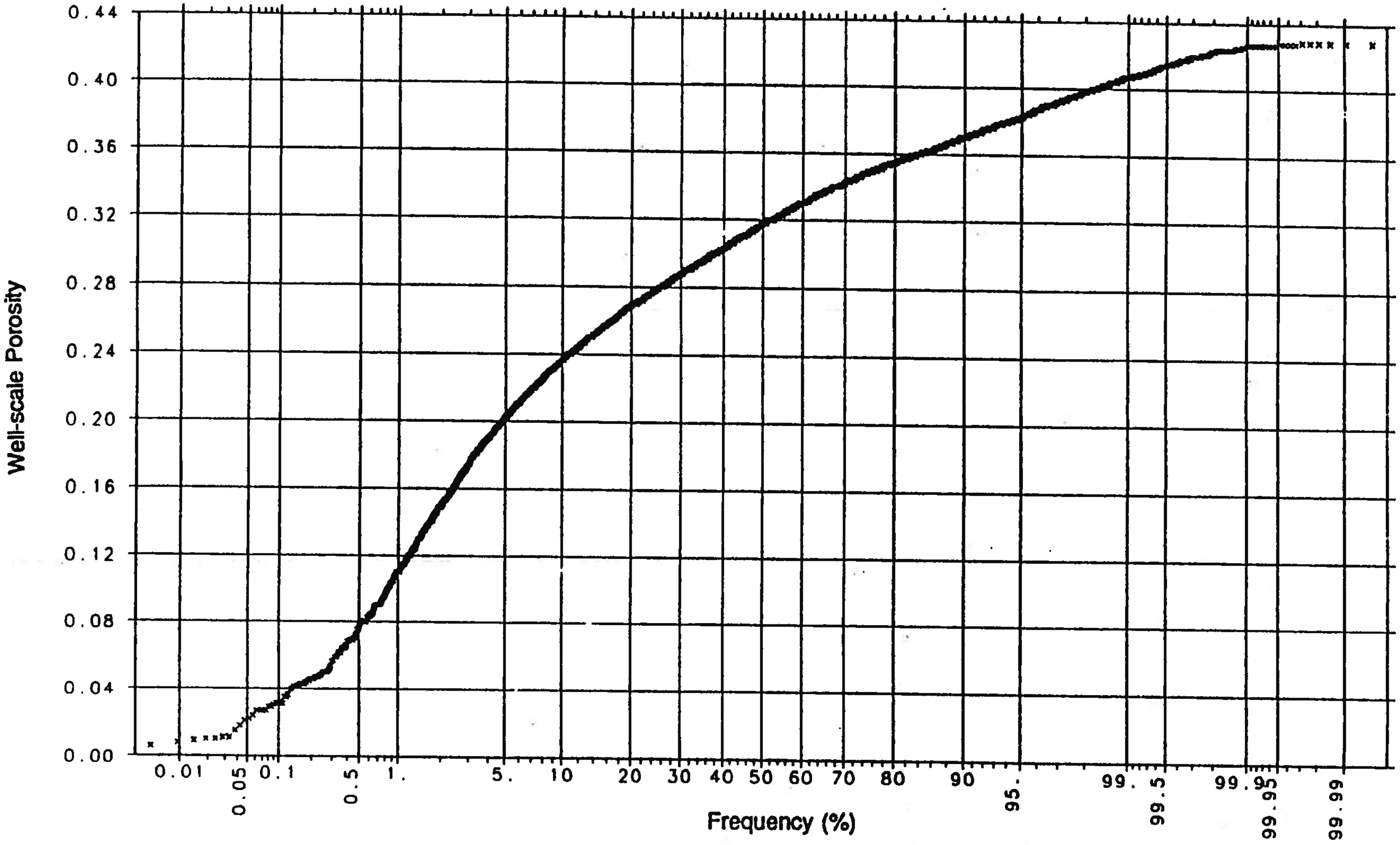


Figure 12. Frequency distribution of well-scale porosity values for the Wabiskaw hydrostratigraphic unit.

frequency distribution of well-scale porosity values. The arithmetic average of therepresentative well-scale values is used for the regional-scale characterization of porosity for each unit. Table 9 shows the representative formation (basin) scale porosity value and associated statistics for each hydrostratigraphic unit.

The existence of a relation between porosity and permeability was tested by regression analysis. Table 10 shows for each hydrostratigraphic unit the number of values, the coefficient of correlation, and the constants of the regression-line fit to the data. Even though the coefficient of correlation for some units appears high, the data are quite scattered. As an example, Figure 13 shows graphically the relation between porosity ϕ and maximum permeability k_m for the Wabiskaw hydrostratigraphic unit. Thus, no good relation between porosity and permeability is apparent for the units within the study area.

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^{-3}
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 9. Characteristic regional-scale values for porosity measurements obtained from core analyses.

Hydrostratigraphic Unit	No. of Values	R^2	a	b
Ground/2nd W.S.S.	31	0.59	4.681	7.654
Viking	84	0.20	-0.188	19.097
Grand Rapids	1581	0.57	-2.267	24.739
Clearwater	664	0.64	-4.104	30.255
Wabiskaw	3888	0.61	-2.806	27.951
McMurray	6249	0.61	-0.963	23.158
Wabamun	586	0.33	-0.336	23.516
Winterburn	614	0.23	-0.836	21.323
Grosmont	9453	0.26	-0.907	23.399
Cooking Lake	226	0.36	-2.632	25.833
Beaverhill Lake	492	0.79	-5.601	35.947
Prairie	98	0.64	-5.016	46.735
Winnipegosis	1968	0.63	-4.059	41.842
Contact Rapids	60	0.44	-4.397	39.746
Basal Red Beds	55	0.60	-0.476	34.288

Table 10. Correlation coefficient and coefficients of the regression line log (k_m) = $a\phi + b$, with k_m expressed in md.

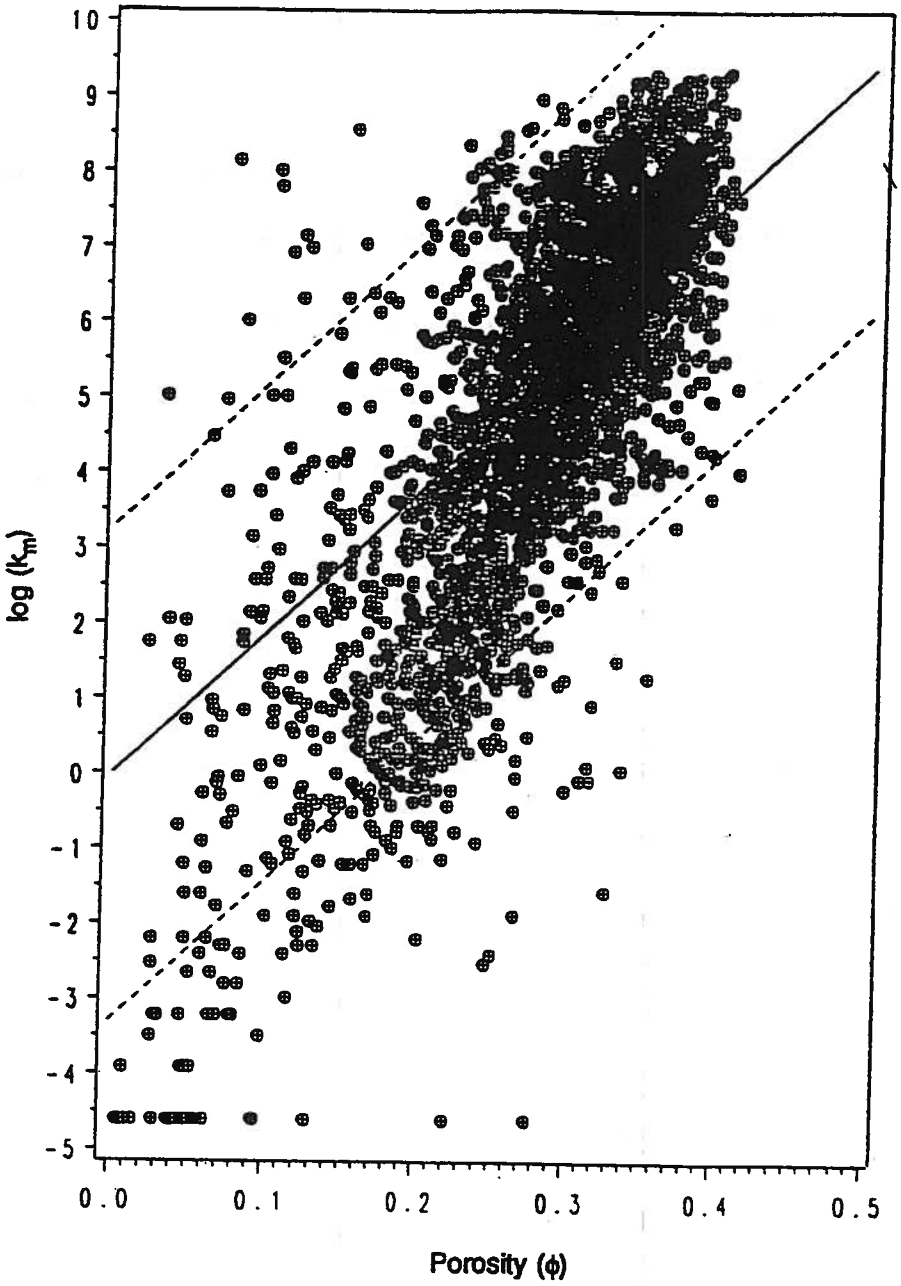


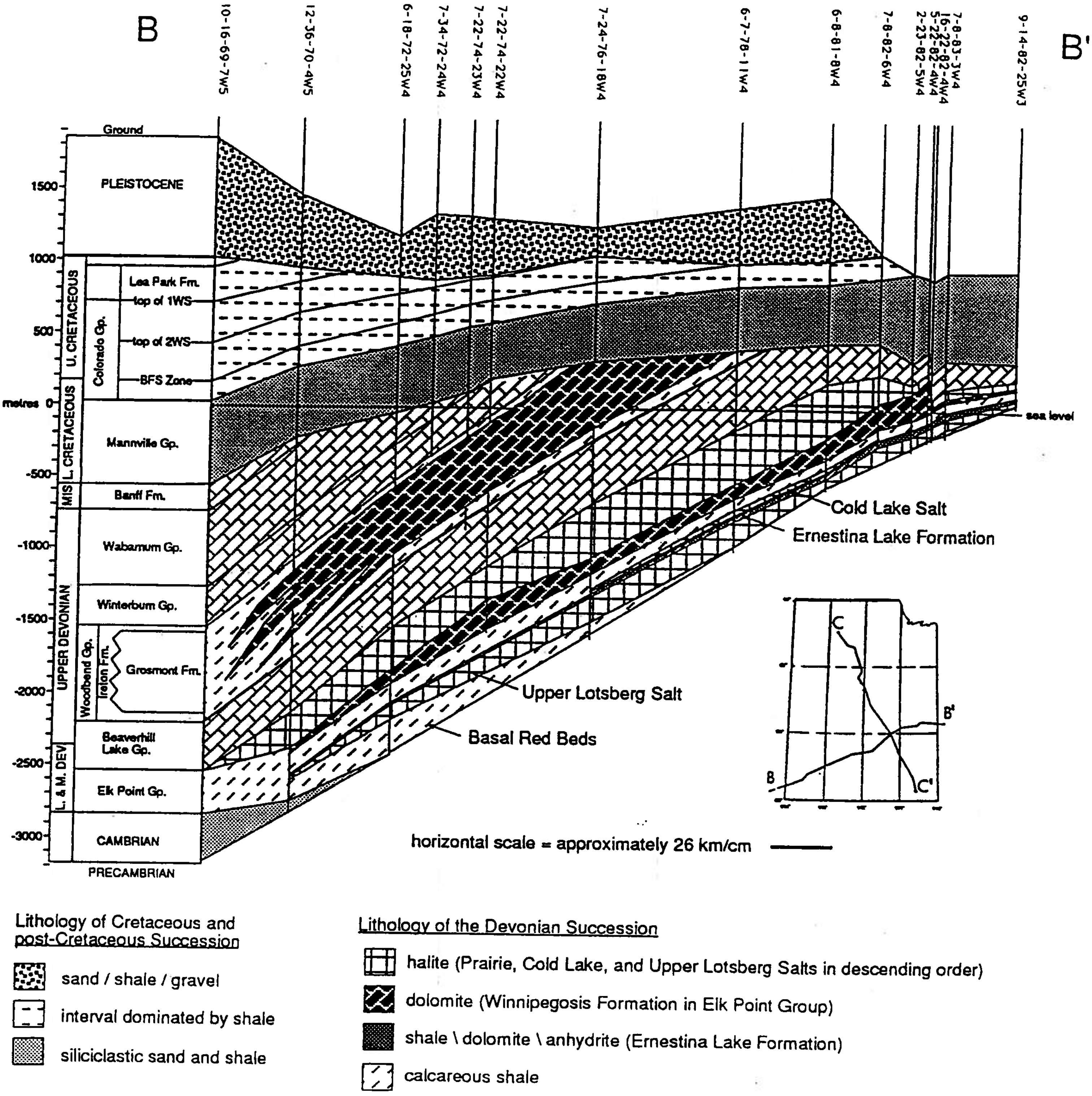
Figure 13. Scatter plot and linear correlation between core-plug maximum permeability, log (k_m), and porosity for the Wabiskaw hydrostratigraphic unit. The dashed lines show the 95% confidence limits.

GEOLOGICAL OVERVIEW

The Alberta Basin comprises a wedge of sedimentary rocks which thicken from a zero edge at the Canadian Shield in the east to more than 6 km at the thrust-fold belt in the west. The basin can be divided into two distinct tectono-sedimentary realms: the passive margin and the foreland basin. The Cambrian to Jurassic passive-margin phase of basin development consisted of dominantly carbonate sedimentation, with periods of clastic and evaporite deposition. Starting in Jurassic time, the western margin of the basin changed to a site of active compressional tectonism, initiating the foreland phase of basin development. The Jurassic to Tertiary foreland basin is dominantly comprised of clastic rocks which were shed from the developing orogenic belt to the west. A more detailed overview of the regional geology in the Western Canada Sedimentary Basin is given by Porter et al. (1982). The northeast Alberta study area is located on the eastern edge of the basin (Figure 2). The stratigraphy within this area (Table 11) can be separated into Paleozoic strata deposited in a passive margin setting and Mesozoic strata deposited in a foreland basin setting. Dip and strike structural cross-sections of the study area (Figures 14 and 15) delineate the wedge geometry of the basin, the angular unconformity separating Cretaceous from Paleozoic strata, and the complex stratigraphy associated with Middle Devonian Elk Point Group strata.

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					
		Devonian	Upper		PreCretaceous Unconformity	5051	1
					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
			Middle		Slave Point		
					Fort Vermilion		
				Elk Point – Upper	Watt Mountain	311	2
					Prairie	152	3
					Winnipegosis (Keg River)	163	3
				Elk Point – Lower (Granite Wash)	Contact Rapids	236	2
			Lower		Cold Lake	34	3
					Ernestina Lake	153	3
					Upper Lotsberg	56	3
					Lower Lotsberg	24	3
					Basal Red Beds	110	4
		Silurian					
		Ordovician					
		Cambrian					
Precambrian						110	1

Table 11. Generalized stratigraphic nomenclature, Northeast Alberta study area.



Lithology of Cretaceous and post-Cretaceous Succession

- ▨ sand / shale / gravel
- ☐ interval dominated by shale
- ▩ siliciclastic sand and shale

Lithology of the Devonian Succession

- ⊞ halite (Prairie, Cold Lake, and Upper Lotsberg Salts in descending order)
- ▨ dolomite (Winnipegosis Formation in Elk Point Group)
- ■ shale \ dolomite \ anhydrite (Ernestina Lake Formation)
- ▧ calcareous shale

Figure 14. Structural dip cross-section of the Phanerozoic succession in northeast Alberta.

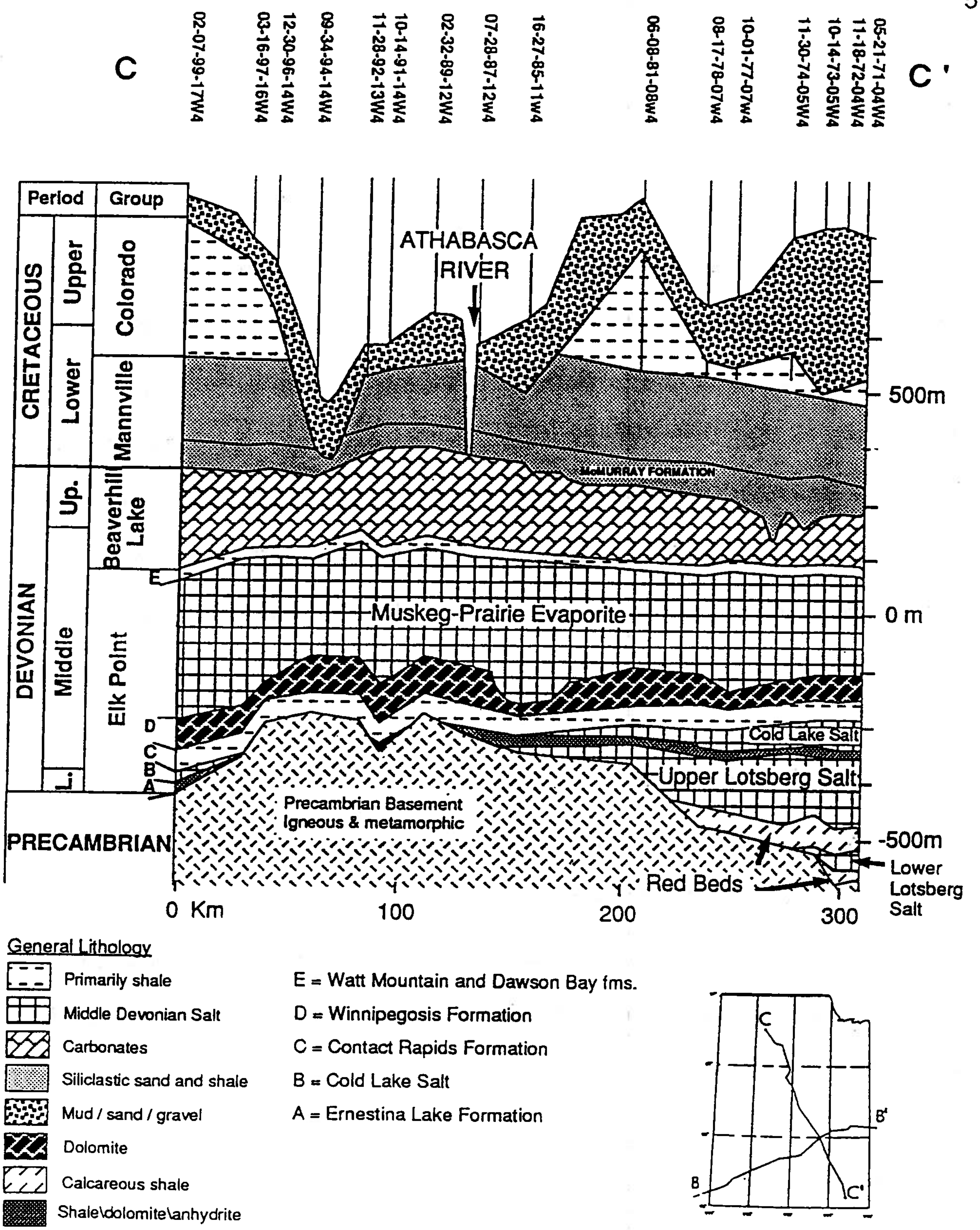


Figure 15. Structural strike cross-section of the Phanerozoic succession in northeast Alberta.

PALEOZOIC GEOLOGY

Paleozoic strata within the northeast Alberta study area lie on the southwest dipping Precambrian basement which is a relatively smooth surface with the exception of a broad low ridge corresponding to the most northeastern extent of the Peace River Arch. The Paleozoic strata can be divided into five successions bounded by disconformities: (1) the Lower Devonian Lotsberg Formation and associated red beds; (2) the Lower Devonian Ernestina Lake and Cold Lake Formations; (3) the Lower and Middle Devonian Upper Elk Point Subgroup; (4) the Middle and Upper Devonian Beaverhill Lake and Woodbend Groups; and (5) the Upper Devonian Winterburn and Wabamun groups.

The Lower Devonian Lotsberg Formation and associated red beds consist of two red bed-halite successions deposited on the Precambrian basement. The strata onlap the basement from the south and form a wedge that is present nearly everywhere in the study area. The succession thins from about 250 m in the south to a thin veneer in the northeast. The halite strata in this succession are confined to the southern half of the study area.

Within the Lower Devonian Ernestina Lake and Cold Lake succession, the Ernestina Lake Formation is a thin (~15 m) regionally extensive unit, which changes from interbedded shale, anhydrite and limestone where it overlies the Lotsberg

Formation evaporite deposits, to a red bed type lithology in the northeast where it becomes difficult to distinguish from the underlying red bed succession. The overlying Cold Lake Formation consists primarily of halite and occurs as two isolated deposits located in the southeast and northwest corners of the study area. The eastern limits of both deposits are thought to be dissolutional while other edges are most likely depositional.

The Lower and Middle Devonian Upper Elk Point Subgroup comprises, in ascending order, the platform carbonates of the Lower Devonian Contact Rapids Formation, and the Middle Devonian platform and reefal carbonates of the Winnipegosis-Keg River Formation, the evaporites of the Prairie Formation and the mainly argillaceous clastics of the Watt Mountain Formation. Carbonate thickness can reach more than 100 m in areas of reef build-up, with sometimes less than 20 m in interreef areas. The areas of reef build up tend to correspond to thin portions of the overlying Prairie evaporite. The Prairie Formation reaches a thickness of more than 200 m in the north and has a sharp eastern edge as a result of salt dissolution. Dissolution of the Prairie Formation and subsequent collapse of overlying strata resulted in a disturbance in the previously smoothly dipping structure. The eastern edge of the dip structural cross-section (Figure 14) shows this complex stratigraphic geometry.

The succession of the Middle-Upper Devonian Beaverhill Lake and Woodbend groups overlies the Watt Mountain Formation. The thick interplatform deposits of the Beaverhill Lake Group consist of a series of alternating calcareous shales and carbonates. These are overlain by the carbonate build-ups, shales and platform carbonates of the Woodbend Group. Carbonate build-ups in the Cooking Lake Formation are followed first by the infilling shales of the Ireton Formation and then by the relatively uniform carbonate platform development of the Grosmont Formation.

The Upper Devonian Winterburn and Wabamun groups present in the southwest corner of the study area represent a progradation of carbonate platforms at the end of Devonian time. Subsequent erosion has removed most of this succession and portions of the preceding Beaverhill Lake and Woodbend groups from the study area.

MESOZOIC GEOLOGY

The Mesozoic in northeast Alberta is represented by Cretaceous strata, which overlie the sub-Cretaceous unconformity, and are themselves overlain unconformably by a thin veneer of Pleistocene deposits. Post-Cretaceous erosion has removed a considerable thickness of strata from the study area, notably along the present-day drainage systems, which has resulted in the exposure of Paleozoic rocks. Generally, the Cretaceous strata within the area can be divided into the Lower Cretaceous Mannville Group and the Lower to Upper Cretaceous Colorado Group.

The Lower Cretaceous Mannville Group consists of a lower non-marine phase, a middle transgressive phase and an upper regressive phase. The non-marine phase is represented by the sand-dominated McMurray Formation which was deposited in the valley systems created by erosion on the sub-Cretaceous unconformity. As a result, the thickness of this unit varies widely. The middle transgressive phase is defined by the Wabiskaw Member, the relatively thin basal sands of the Clearwater Formation. The shales and silts of the Clearwater Formation and the sands of the Grand Rapids Formation form the upper regressive phase. This succession of the upper phase is extremely complex and variable, representing an occasionally time equivalent relation between the Clearwater and Grand Rapids formations.

The Lower to Upper Cretaceous Colorado Group consists of thick successions of shale intercalated with thin sandstones. The only regionally significant sandstone in the study area is the Viking Formation, which grades down into the underlying Joli Fou Formation shales, and up to the overlying Colorado shales. The Viking Formation is thought to represent a short term drop in sea-level which allowed sand to prograde across the shale dominated basin.

Quaternary glacial and post-glacial deposits blanket much of the Cretaceous bedrock. These consist primarily of unconsolidated sands and gravels forming thin sheets, but, occasionally, they may occur locally as glacial channel fill deposits which cut down into the underlying bedrock.

HYDROGEOLOGICAL ANALYSIS

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 units 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 defined in the geological section of this study. The hydrostratigraphic nomenclature is defined as follows: an aquifer is a rock unit which allows the flow of formation waters, an aquitard retards them, and an aquiclude precludes flow. Complex groups of aquifers and/or aquitards exhibiting generally common overall characteristics can be 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.

A preliminary hydrostratigraphic framework was constructed from the stratigraphic geometry and knowledge of the lithology. This was done as part of the regional geological investigation of northeast Alberta. The initial hydrostratigraphic framework was sufficiently detailed to allow the allocation of the formation water chemical analyses, core analyses and drillstem test data, thus grouping them by hydrostratigraphic unit. However, after examining the hydrodynamic data subsequent to their allocation, it became evident that the initial hydrostratigraphic allocation required revision. Pressure data from drillstem tests were the main data used in updating the initial hydrostratigraphic framework.

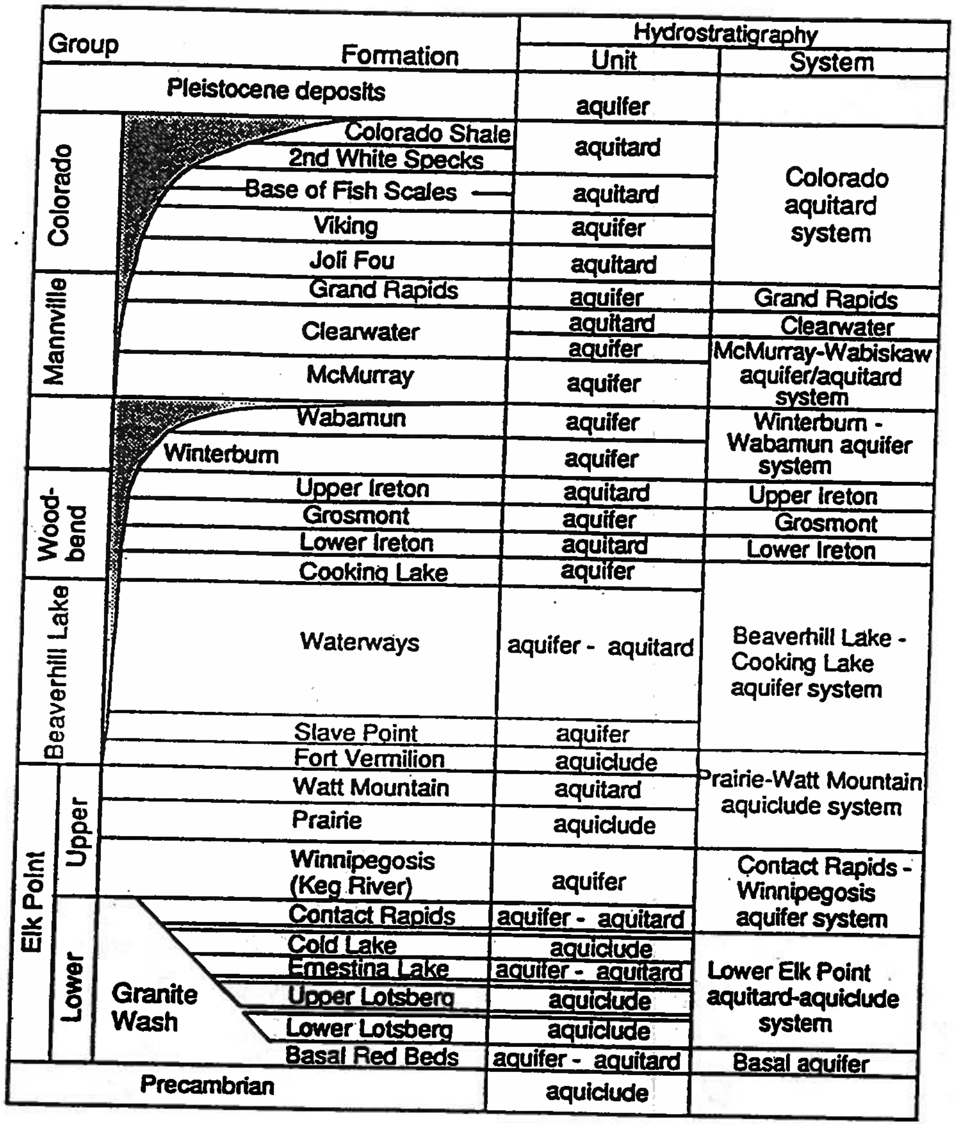
Because, conceptually, it was not expected that any drillstem test would be located within an aquitard or aquiclude, data allocated to this type of hydrostratigraphic unit were examined in detail. First, the drillstem test location and depth were manually checked on geophysical logs to ensure that they 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 show no relation to those in adjacent aquifers, although the drillstem test and core data indicate hydraulic characteristics associated with those of an aquifer. Subsequent detailed stratigraphic analysis showed that the tested zone generally represented a localized, usually discontinuous sandy or carbonaceous interval, completely encased and thus hydraulically isolated by the more regionally extensive aquitard or aquiclude. In these particular cases, the data are included in summaries (Tables 2-10), 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 included these updated thicknesses. The final isopachs of the hydrostratigraphic units presented in this report include these revised thicknesses. Despite the revision, there were no boundary changes, no new units were created and no units were eliminated.

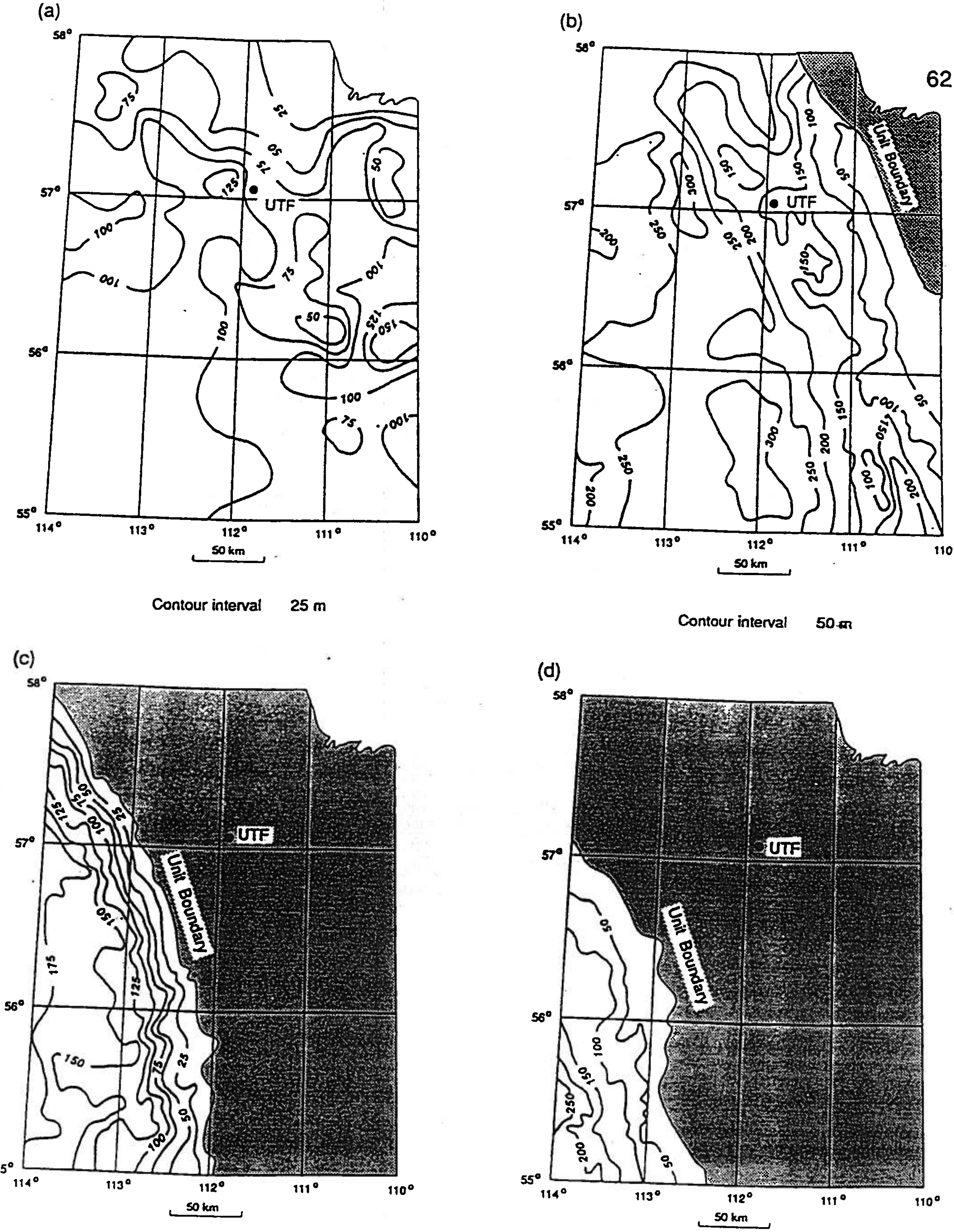
The resulting refined hydrostratigraphic geometry is still only a best approximation of the actual geometry, mainly because of two factors. First, unlike the previously described procedure of using drillstem tests to revise the aquifer thickness in areas of apparent hydraulic continuity, there is no reliable method of determining the aquifer geometry in areas without drillstem test (hydraulic) information. Within the areas without information, 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.

Table 12 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. In addition, the data for the Ernestina Lake aquifer 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 in the initial hydrostratigraphy 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 16a. Similarly, Figure 16b 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



Group		Formation	Hydrostratigraphy Unit	Hydrostratigraphy System
Pleistocene deposits			aquifer	
Colorado		Colorado Shale 2nd White Specks	aquitard	Colorado aquitard system
		Base of Fish Scales	aquitard	
		Viking	aquifer	
		Joli Fou	aquitard	
Mannville		Grand Rapids	aquifer	Grand Rapids
		Clearwater	aquitard	Clearwater
			aquifer	McMurray-Wabiskaw aquifer/aquitard system
		McMurray	aquifer	
		Wabamun	aquifer	Winterburn - Wabamun aquifer system
		Winterburn	aquifer	
Wood-bend		Upper Ireton	aquitard	Upper Ireton
		Grosmont	aquifer	Grosmont
		Lower Ireton	aquitard	Lower Ireton
		Cooking Lake	aquifer	Beaverhill Lake - Cooking Lake aquifer system
Beaverhill Lake		Waterways	aquifer - aquitard	
		Slave Point	aquifer	
		Fort Vermilion	aquiclude	Prairie-Watt Mountain aquiclude system
Elk Point	Upper	Watt Mountain	aquitard	
		Prairie	aquiclude	
		Winnipegosis (Keg River)	aquifer	Contact Rapids - Winnipegosis aquifer system
	Lower	Granite Wash / Contact Rapids	aquifer - aquitard	
		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
Precambrian			aquiclude	

Table 12. Hydrostratigraphic succession and nomenclature, Northeast Alberta study area.



Contour interval 25 m

Contour interval 50 m

Contour interval 25 m

Contour interval 50 m

Figure 16. 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.

the latter. The final isopach of the Grosmont aquifer is thus modified (Figure 16c) in order to incorporate the Lower Ireton data (resulting in a slightly thicker unit than initially defined, but barely noticeable at the 25 m contour interval). 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 aquifers show nearly identical hydraulic characteristics and are considered as a single aquifer whose isopach is shown in Figure 16d.

Within the Cretaceous succession, the McMurray and Wabiskaw aquifers show regionally similar hydraulic characteristics despite the existence locally of bitumen deposits and shaley 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 17a and 17c. The remainder of the Clearwater

Formation comprises the Clearwater aquitard (Figure 17b). The isopach of the Viking aquifer (Figure 17d) required little change from the original stratigraphic geometry.

The hydrostratigraphic nomenclature and geometry, shown in Table 12 and Figures 16 and 17, 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 12479 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.

REGIONAL SUBSURFACE HYDROGEOLOGY

In order to evaluate the lateral flow, each aquifer was examined individually. After the horizontal flow regime within each aquifer was established, the interaction of aquifers, including cross-formational flow, was analyzed by comparing hydraulic head distributions between individual units and using pressure-depth profiles constructed at specific well locations.

The horizontal flow regime was analyzed and characterized by mapping the distributions of formation water salinity and hydraulic head for the individual aquifers or

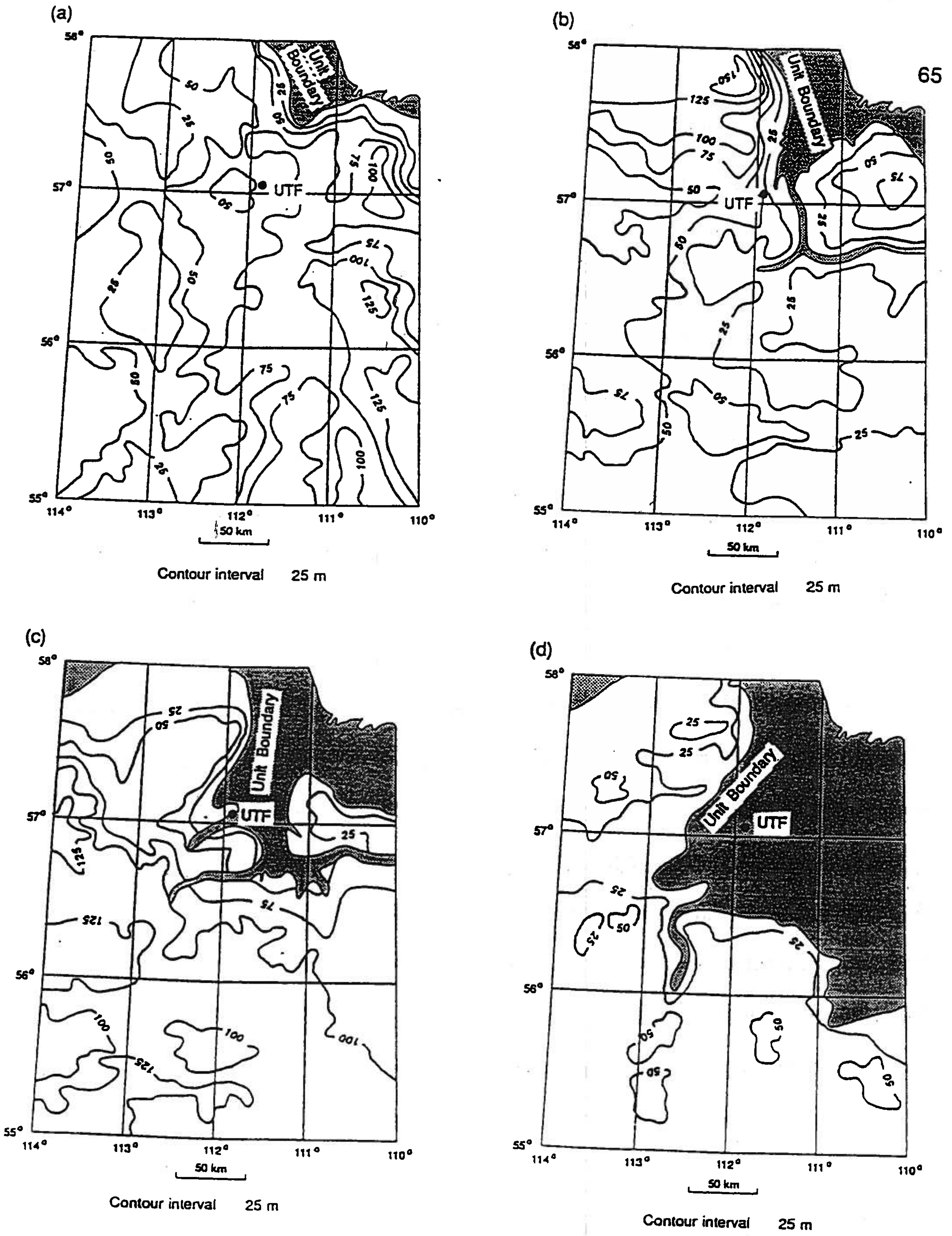


Figure 17. Isopach maps of Cretaceous hydrostratigraphic units in northeast Alberta: (a) McMurray-Wabiskaw aquifer system; (b) Clearwater aquitard; (c) Grand Rapids aquifer; and (d) Viking aquifer.

aquifer systems. The actual computer-generated contour maps of hydraulic head and formation water salinity, with postings of the data distributions, are shown in Appendices A and B, respectively. Interpreted versions of these maps are displayed as figures in this chapter, with arrows indicating the flow direction at various locations. The interpreted versions of the hydraulic head and formation water salinity maps are different from the computer generated maps in areas where poor data distributions and computer extrapolation resulted in unreasonable and artificial features.

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 Deming and Nunn (1991) who showed that a basin would be totally flushed of saline water if the flow of formation waters were strong enough to carry heat by convection. 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 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 the northeast Alberta study area.

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.

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. For this reason, it is important to know the physiography of the region.

Figure 18 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-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 18). 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

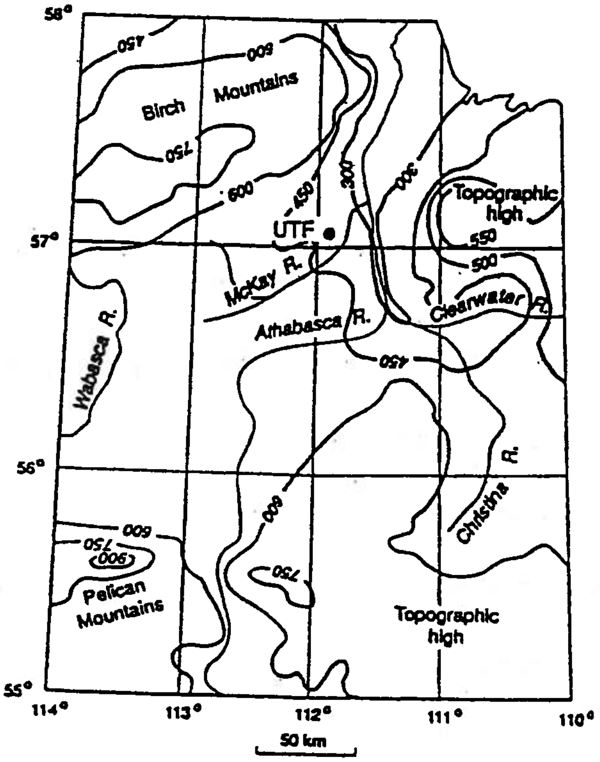


Figure 18. Physiography and major topographic features of the Northeast Alberta study area.

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.

Precambrian Aquiclude

The Precambrian rocks at the base of the Phanerozoic sedimentary strata 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 (Appendix A,

Figure 1) and no reliable analyses of formation water chemistry for this aquifer. The hydraulic head data 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 Contact Rapids-Winnipegosis aquifer system is the oldest flow unit within the study area for which there is a significant amount of hydrodynamic data. Toth (1978) and Hitchon et al. (1989a, 1990) have described the equivalent strata in surrounding areas as being part of a deep aquifer system exhibiting highly saline formation water.

The distribution of formation water salinity (Figure 19a) shows two important features. First, a general increase in salinity to the southwest is evident, opposite to the northeast flow direction (Figure 19b). 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 19a), 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 hydraulic head (Figure 19b) 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. Past the eastern edge of the Prairie aquiclude, local topographic features become the primary controls on the flow directions. In the east, where the aquifer system is close

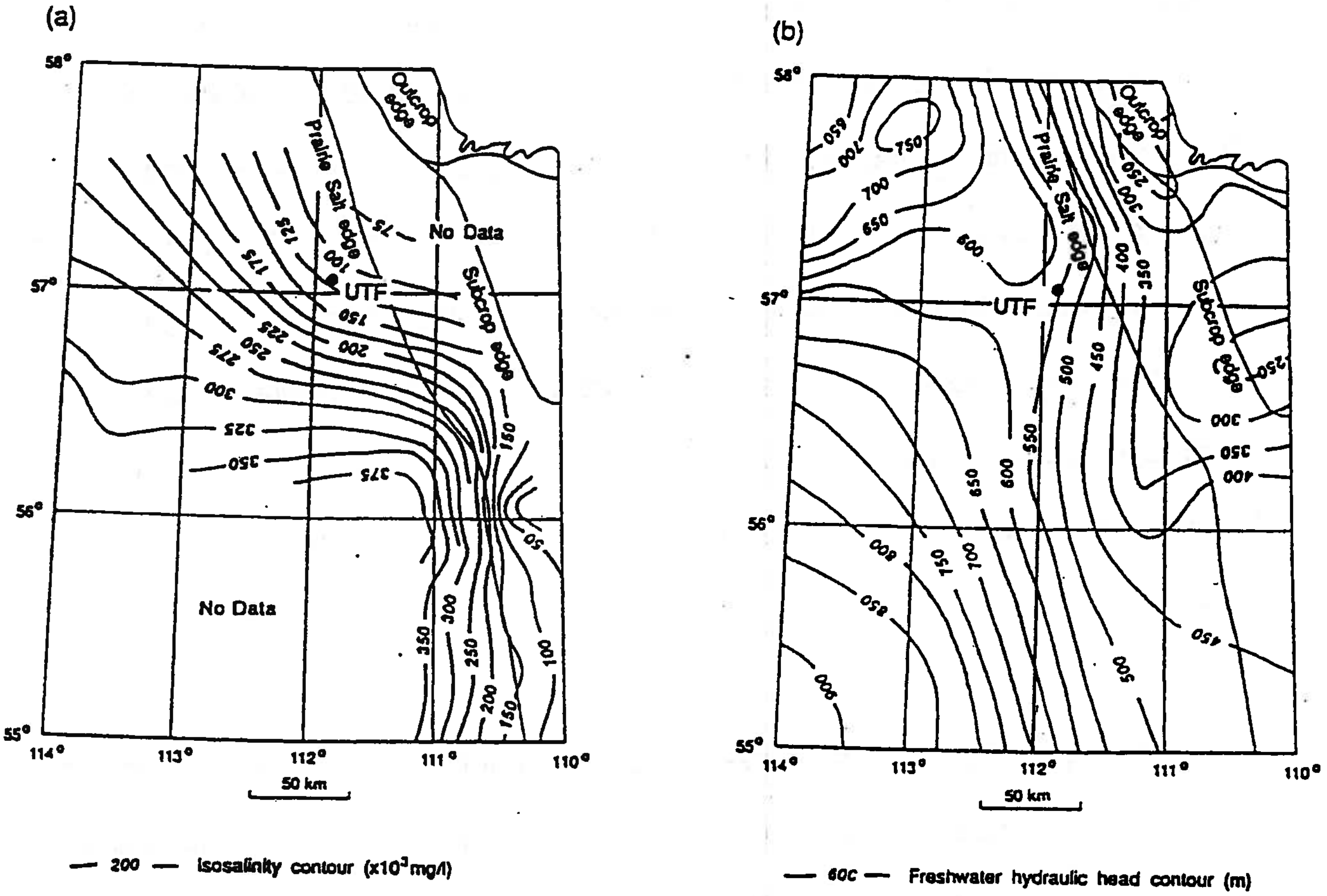


Figure 19. Hydrogeology of the Contact Rapids-Winnipegosis aquifer system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

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. In the northwest, thick Winnipegosis reefs are separated from the overlying Beaverhill Lake-Cooking Lake aquifer system by only a thin layer of Prairie evaporite (Petroleum Geology and Basin Analysis Group, 1991). Locally high hydraulic head values in this area suggest that the overlying thin Prairie aquiclude actually has characteristics similar to those of a weak aquitard, allowing some upward communication between the Contact Rapids-Winnipegosis aquifer system and the Beaverhill Lake-Cooking Lake aquifer system above.

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 must be smaller because of buoyancy forces opposing (retarding) the northeastward gravity-induced flow. The general flow direction is probably correct, however for the intermediate-to-local flow regime in the 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. Both the magnitude and direction of flow are not truly represented because of the interaction between aquifer slope (Figure 16a), density (salinity) gradient and hydraulic gradient (Figure 19). 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. An assessment of the actual magnitude and directions of fluid flow in this aquifer would require numerical modelling of coupled fluid flow, heat transfer and solute transport processes.

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. Where the Prairie evaporite is absent, there are no analyses of formation water chemistry in the adjacent aquifer systems. In areas of thick Prairie evaporite, the analyses and the hydraulic heads 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 (Figure 3), 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) describe 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 carbonate-dominated Cooking Lake Formation make up the Beaverhill Lake-Cooking Lake aquifer system. Although there are few analyses of formation water chemistry, they show a depth (temperature) related trend, with higher values in the southwest and lower values generally to the northeast (Figure 20a). 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

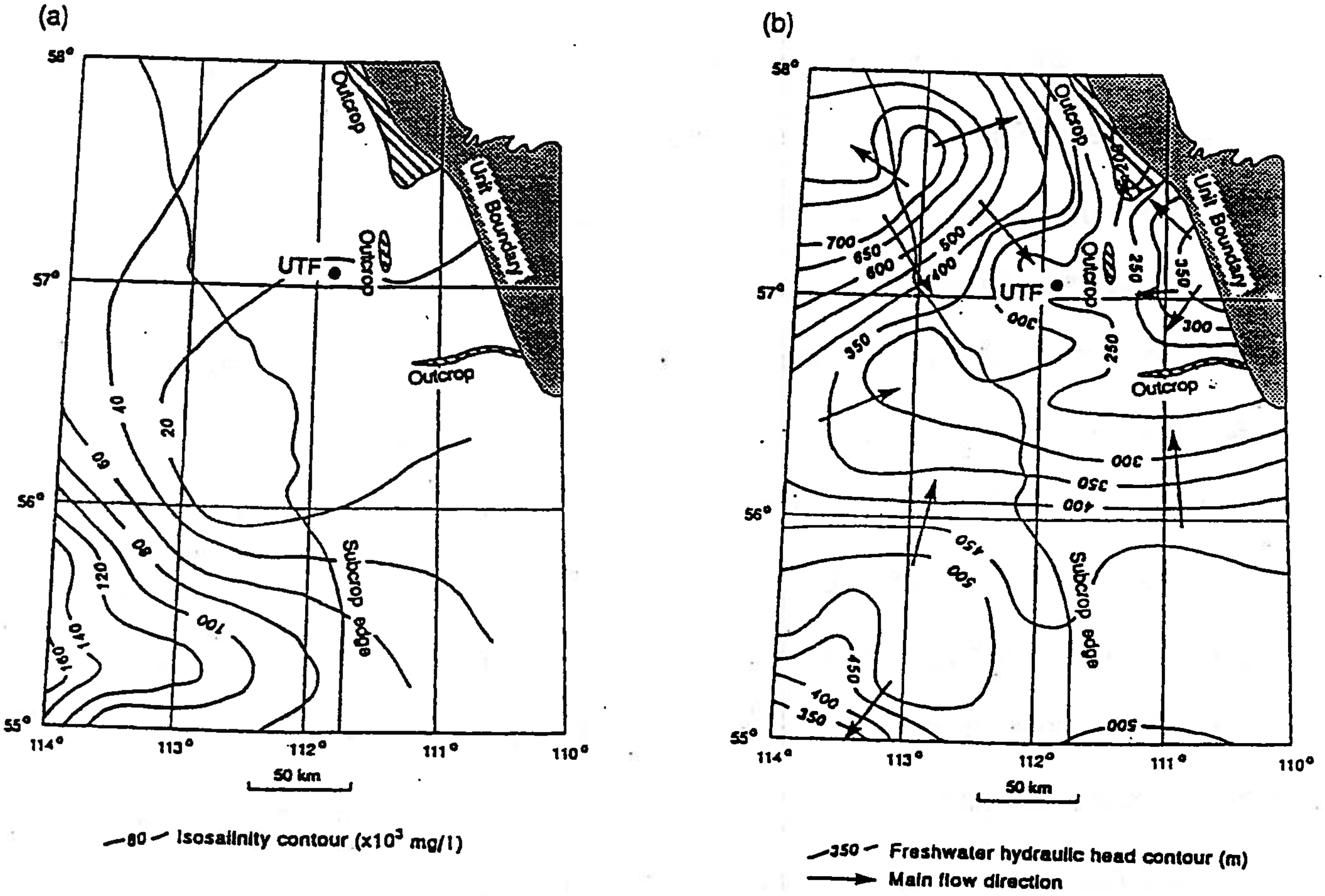


Figure 20. Hydrogeology of the Beaverhill Lake-Cooking Lake aquifer system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

reaching only 140,000 mg/l in the extreme southwest) than in underlying aquifers. Thus, the influence of the Prairie Formation salt is negligible.

The distribution map of hydraulic head for the Beaverhill Lake-Cooking Lake aquifer system (Figure 20b) 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 20b). In the northeast, the Clearwater and Athabasca rivers cut down to Paleozoic strata, exposing the Beaverhill Lake-Cooking Lake aquifer system to atmospheric conditions. 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 hydraulic head distribution is strongly influenced by the Athabasca and Clearwater rivers and the local topographic high (Figure 18). 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 20b). 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) which, when extrapolated by computer containing due to poor data control, extends far to the west. Accordingly, the hydraulic head values appear similar to those in the overlying Grosmont aquifer. This appears to be only a coincidence, because the shales of the intervening Lower Ireton aquitard in fact prevent vertical hydraulic continuity. In the northwest portion of the study area, the hydraulic head distribution shows a high potential area (Figure 20b) 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. The distribution of hydraulic heads in the overlying Grosmont aquifer does not show this local high, likely due to its high hydraulic conductivity and other reasons discussed later in this chapter. The Beaverhill Lake-Cooking Lake aquifer system is isolated from the overlying Grosmont aquifer throughout most of this area by the intervening Lower Ireton aquitard; however, to the east of the Lower Ireton subcrop edge (Figure 20b), 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 the Beaverhill Lake-Cooking Lake aquifer system is influenced by the high topography of the Birch Mountains in the northwest portion of the study area, but only east of the Lower Ireton aquitard subcrop edge. This topographic influence on the pressure regime within the Beaverhill Lake aquifer system then propagates to the west below the Lower Ireton aquitard, which affectively isolates it from the overlying Grosmont aquifer.

There is an area of low hydraulic head in the southwest corner of the area, with flow directions to the southwest, opposite to the expected regional trend (Figure 20b). 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 21 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 almost up to the base of the Grosmont Formation carbonates, with only a meter or less of shale separating the two carbonate units. It is speculated and very likely that the existence of several such reefs, which may not all 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 22b). Based on the hydraulic head distributions within the Northeast Alberta

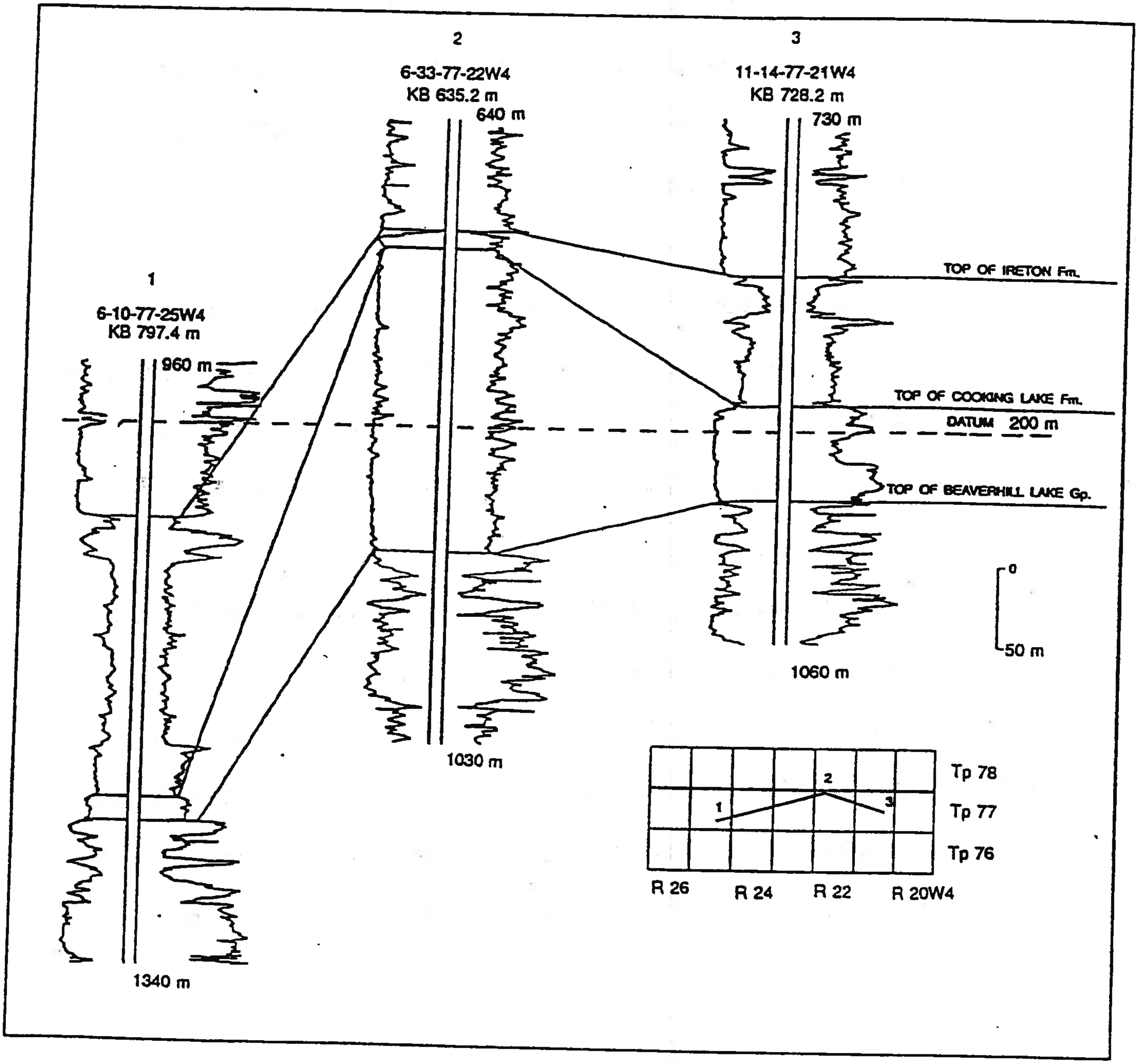


Figure 21. Structural cross-section of the Lower Ireton aquitard showing a Cooking Lake Formation reef.

study area and in surrounding areas (Hitchon et al., 1989b), it is postulated that hydraulic communication and possibly continuity 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.

The southwestern region of the aquifer is in the regional flow regime and the formation waters are characterized by the greatest density (salinity) difference in the aquifer (Figure 20). 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 freshwater hydraulic gradient is locally higher due to local flow systems, resulting in a 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 140,000 mg/l in the latter), a difference caused by the influence of the lower Elk Point Group evaporitic beds on the lower unit.

The distribution of hydraulic heads in Figure 20b generally matches the hydraulic head distribution shown for the Beaverhill Lake-Cooking Lake aquifer system by Hitchon et al. (1989b) in the Cold Lake area to the south. However, it does not match the hydraulic head distribution within the Beaverhill Lake aquifer described by

Hitchon et al. (1990) in the Peace River Arch area to the west. A combination of poor data control along the 5th meridian (Appendix A, Figures 3 and 4) and different stratigraphic definitions for the "Beaverhill Lake aquifer" in these studies, are the probable cause for the mismatch at the boundary between these areas. Caution should therefore be exercised in using the extrapolated hydraulic head distribution for the Beaverhill Lake-Cooking Lake aquifer system along the western edge of the northeast Alberta study area.

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 21). 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 study 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 22a) 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 Hondo 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 throughout the study area (Figure 22b). The Grosmont aquifer and 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.

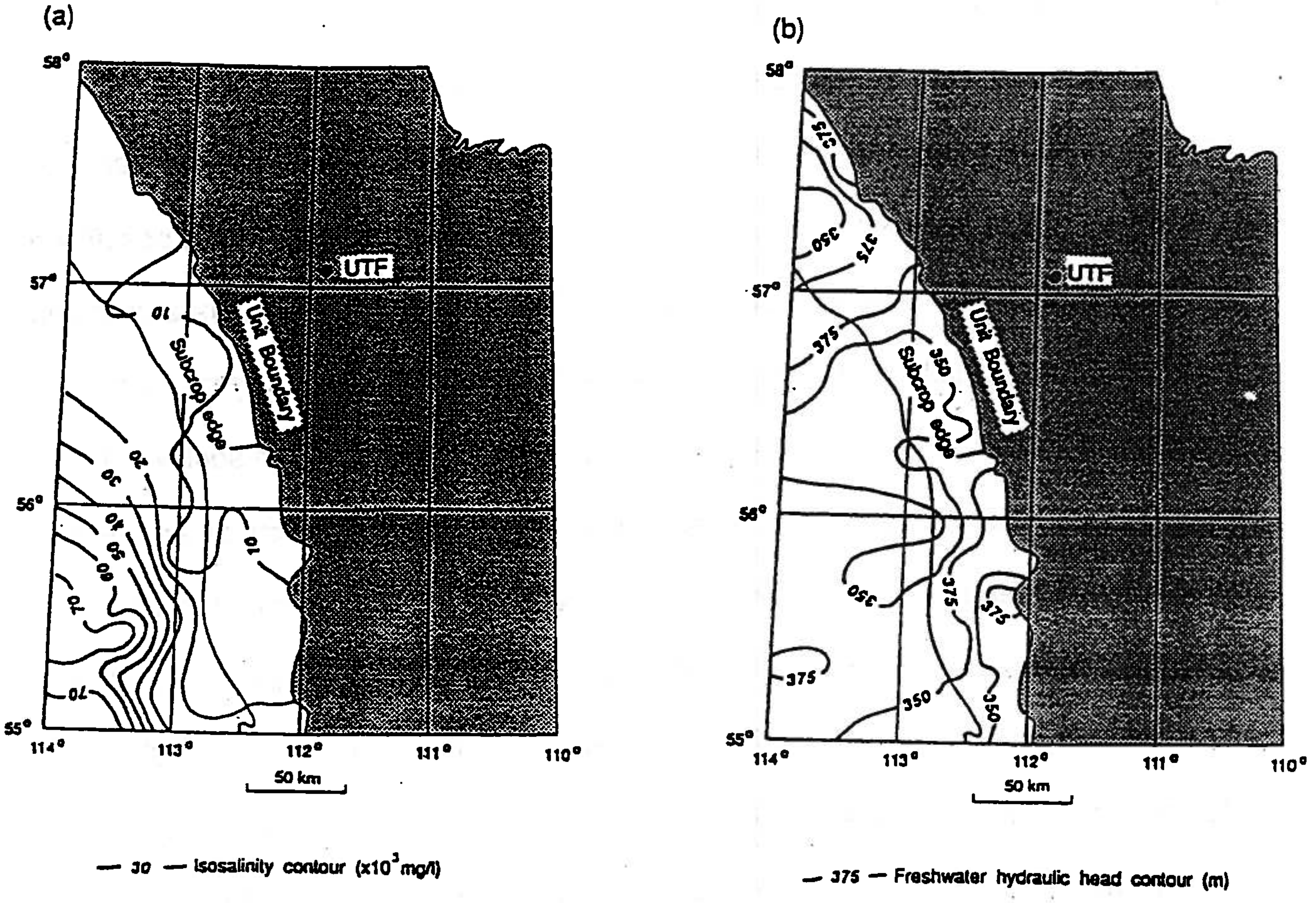


Figure 22. Hydrogeology of the Grosmont aquifer: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

(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 5 and 7), 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 Wabamun-Winterburn 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 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 300 m.

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 22) 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 the Hondo evaporites (Appendix

B, Figures 4 and 5). 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 Hondo 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 (Appendix B, Figure 4).

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 23). 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 22b). This is coincident with the anomalously high salinity in the overlying Winterburn-Wabamun aquifer system (Appendix B, Figure 4). In addition, the Winterburn-Wabamun aquifer system does not have a locally high potential in this area (Figure 23). 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

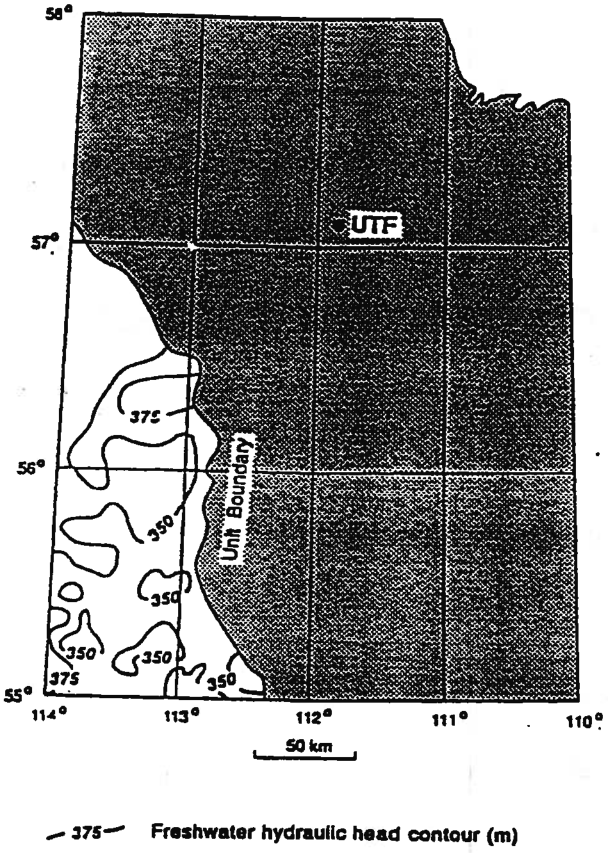


Figure 23. Freshwater hydraulic-head distribution for the Winterburn-Wabamun aquifer system.

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.

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 24a). 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 24b) 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.

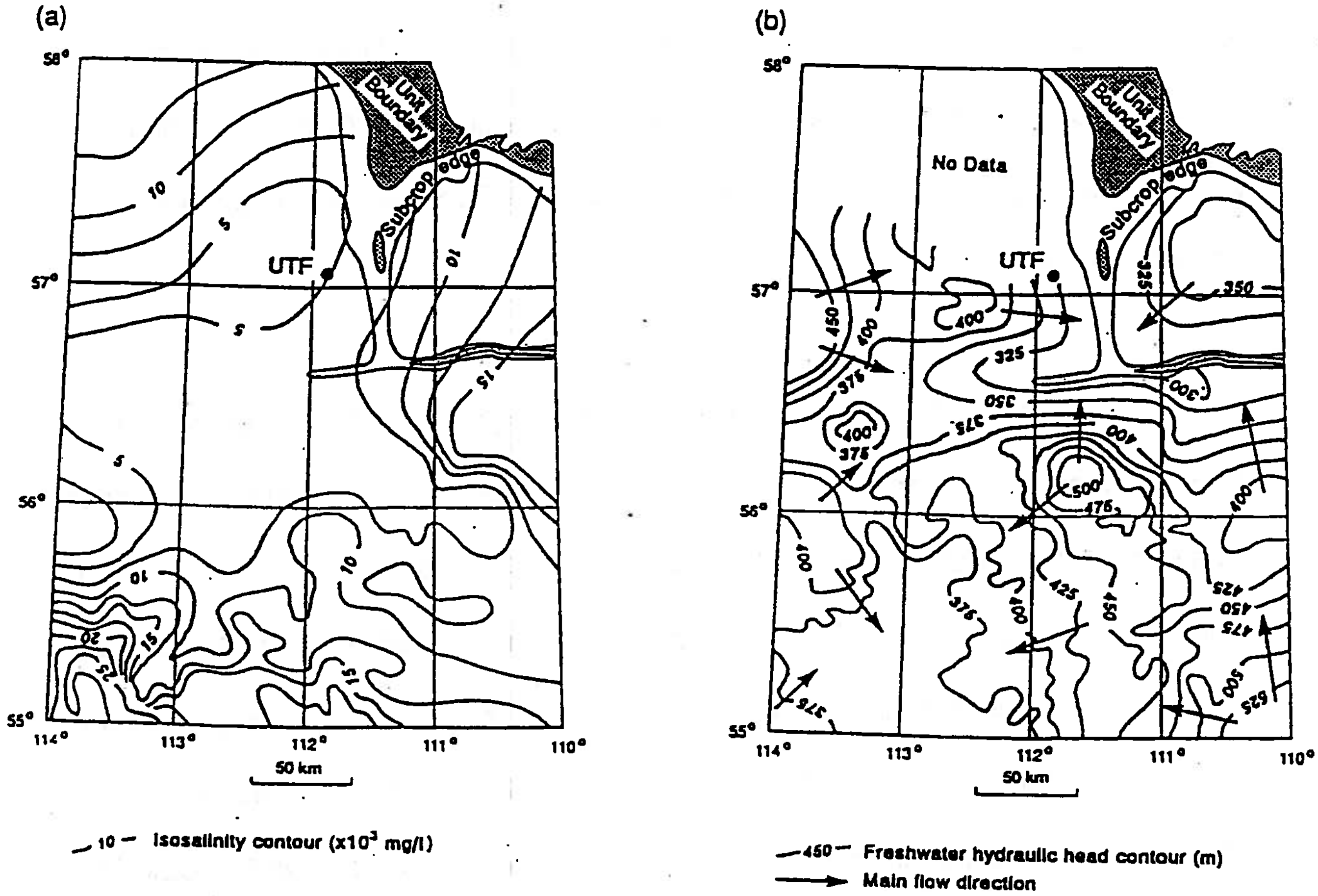


Figure 24. Hydrogeology of the McMurray-Wabiskaw aquifer/aquitard system: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

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

Grand Rapids Aquifer

Geochemical information for 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 25a), with values reaching a maximum of 20,000 mg/l in the extreme southwest. In this region of the study area, the analyses of formation waters suggest that the Clearwater aquitard is a significant barrier to cross-formational flow.

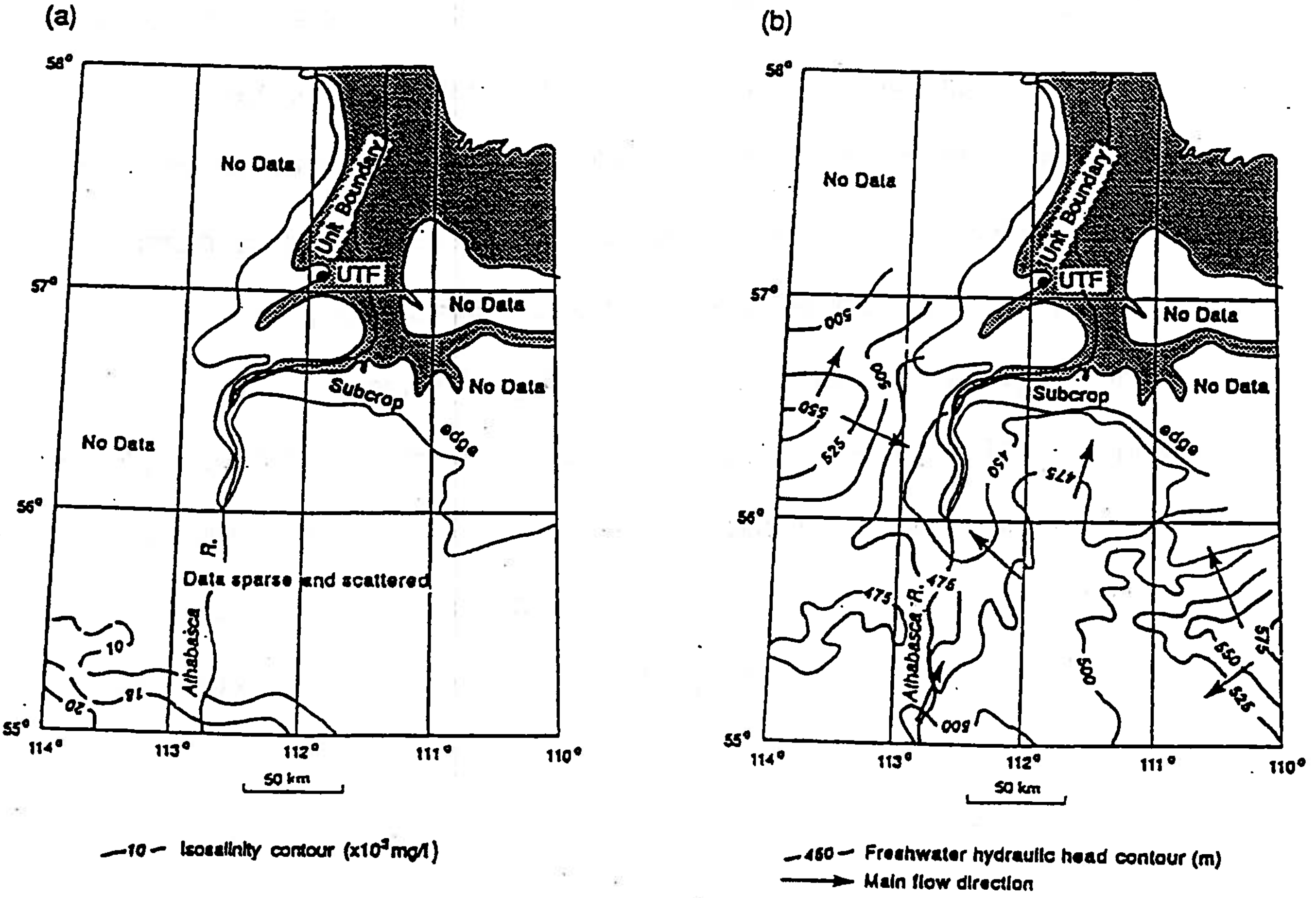


Figure 25. Hydrogeology of the Grand Rapids aquifer: (a) salinity of formation waters; and (b) freshwater hydraulic-head distribution.

The distribution of hydraulic head for the Grand Rapids aquifer is dominated by the effects of the Athabasca River system (Figure 25b), along which the aquifer discharges. The arrows shown in Figure 25b 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 southwest, indicate strong local influence of the Athabasca River (Figure 26). 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 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.

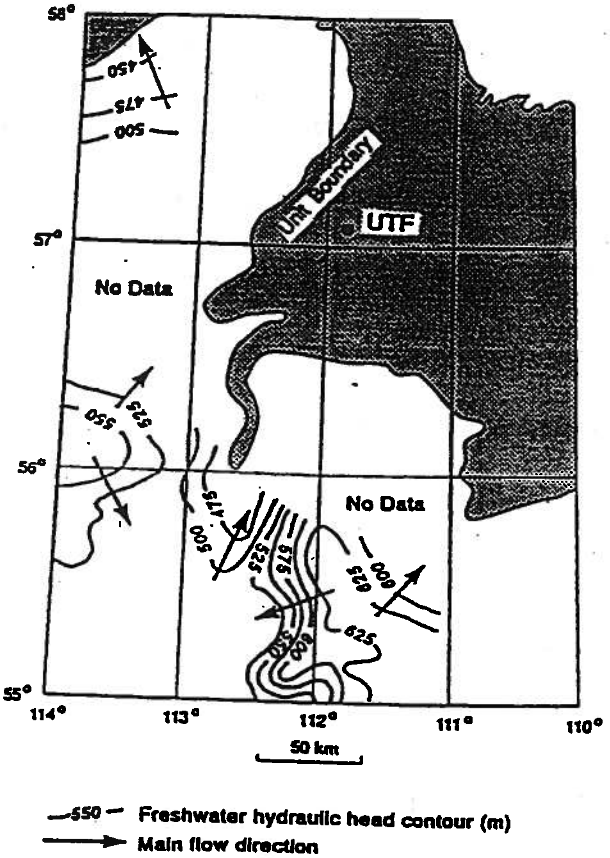


Figure 26. Freshwater hydraulic-head distribution for the Viking aquifer.

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. A dip cross-section of the basin (Wright 1984), whose location is shown in Figure 27, was used to plot the variation of formation water salinity (Figure 28a) and hydraulic head (Figure 28b). In general, regional flow paths are mainly in the plane of section; however, with the local nature of flow in the northeast Alberta study area, a significant flow component is actually directed into and out of the plane of section. Topographically, the cross-section shows 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.

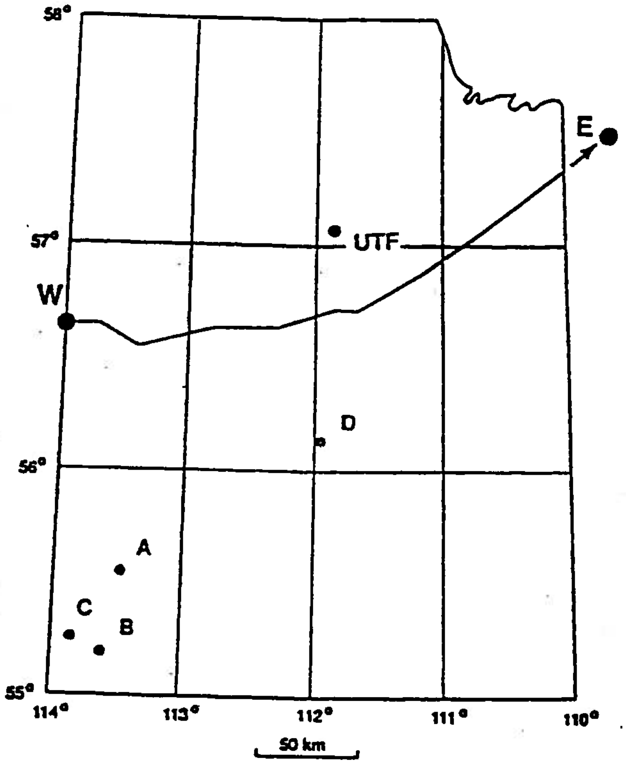


Figure 27. Location of hydrogeological dip cross-section (Figure 28) and of pressure-depth profiles (Figure 29).

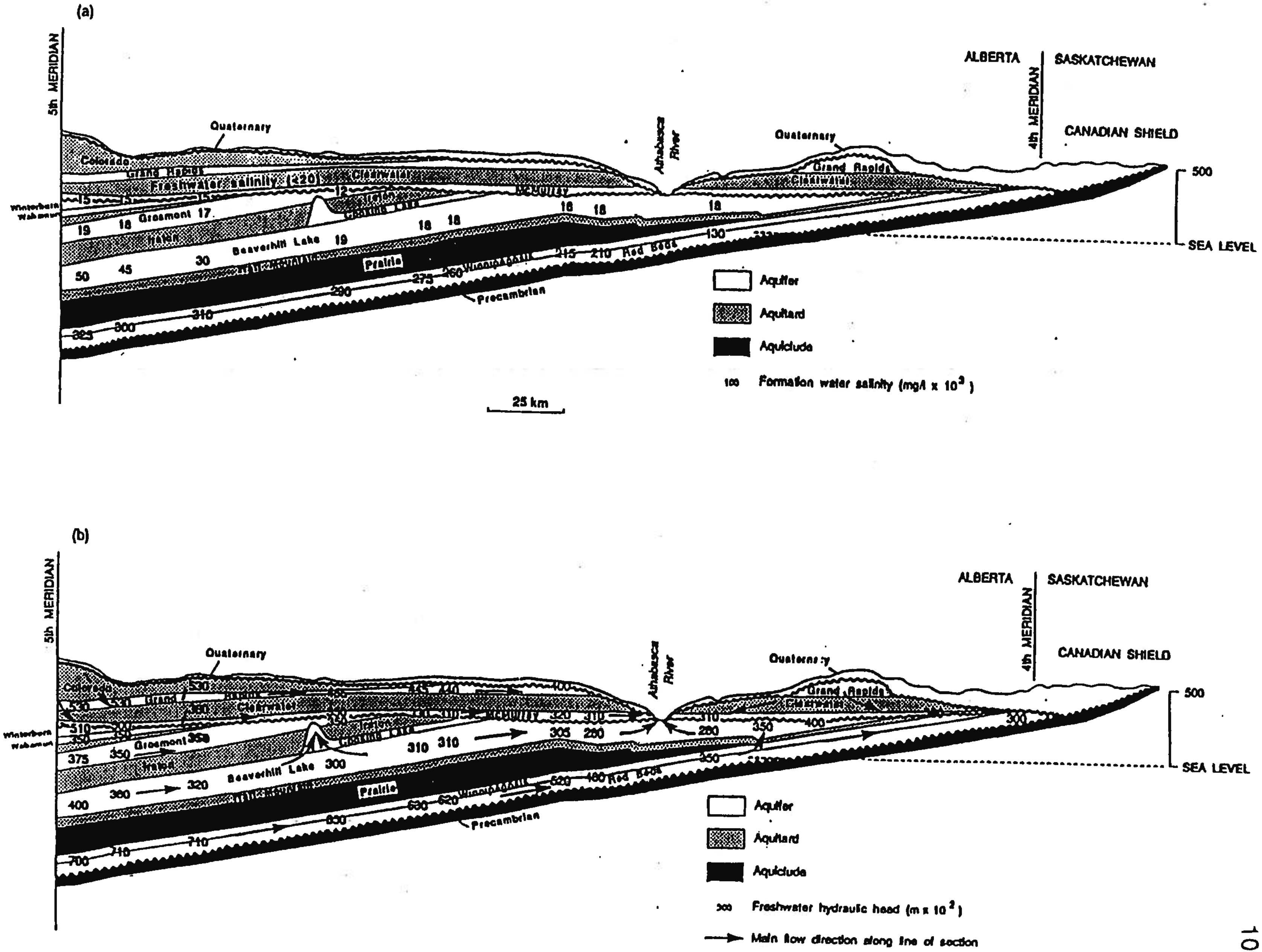


Figure 28. Hydrogeological dip cross-section showing distributions of: (a) salinity of formation waters; and (b) hydraulic head. Cross-section location is shown in Figure 27 (cross-section from Wright, 1984).

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REGIONAL FLOW REGIME

From examination of the regional hydrogeological cross-sections (Figures 28a and b) 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 28b). These aquifers show depth (temperature) related salinity distributions, with generally high values is the vicinity of the Elk Point evaporitic units (Figure 28a). Buoyancy effects are probably important, inducing a downdip flow component opposed to the updip gravity-driven flow, with the net effect of retarding the flow of formation waters. Past the eastern edge of the Prairie aquiclude, the formation waters in these aquifers are subjected to dilution by fresher meteoric waters and modification of the flow regime by intermediate to local flow systems.

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 generally shows updip flow toward the northeast, and depth (temperature) dependent salinity. This pattern is interrupted locally by Cooking Lake reefs which "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 28b). 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 20b) and poor data control to the west. The Cooking Lake Formation reef depicted here is speculative, and without well control. Based on the hydraulic head distributions in the Beaverhill Lake-Cooking Lake aquifer system and the Grosmont aquifer (Figures 20b and 22b, respectively), hydraulic continuity between the two flow units, possibly facilitated by Cooking Lake Formation reefs such as the one shown in Figure 21, 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 28b) 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 gravity driven.

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 28b). The formation water salinity within Cretaceous aquifers is extremely low, confirming the influence of meteoric waters being introduced by topographically controlled local flow systems (Figure 28a). 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. Within a continuous hydrostratigraphic (hydrodynamic) system, the formation pressure increases with depth at a constant rate. If the system is hydrostatic or if only lateral (horizontal) flow occurs, the rate of pressure increase with depth is 10 kPa/m. Therefore, if the formation pressure increases at a constant rate even across an aquitard, it indicates that the aquitard is not an effective barrier to flow (there is hydraulic communication and sometimes even continuity). A change in the variation of pressure with depth after crossing an aquitard indicates that the intervening aquitard is an effective barrier

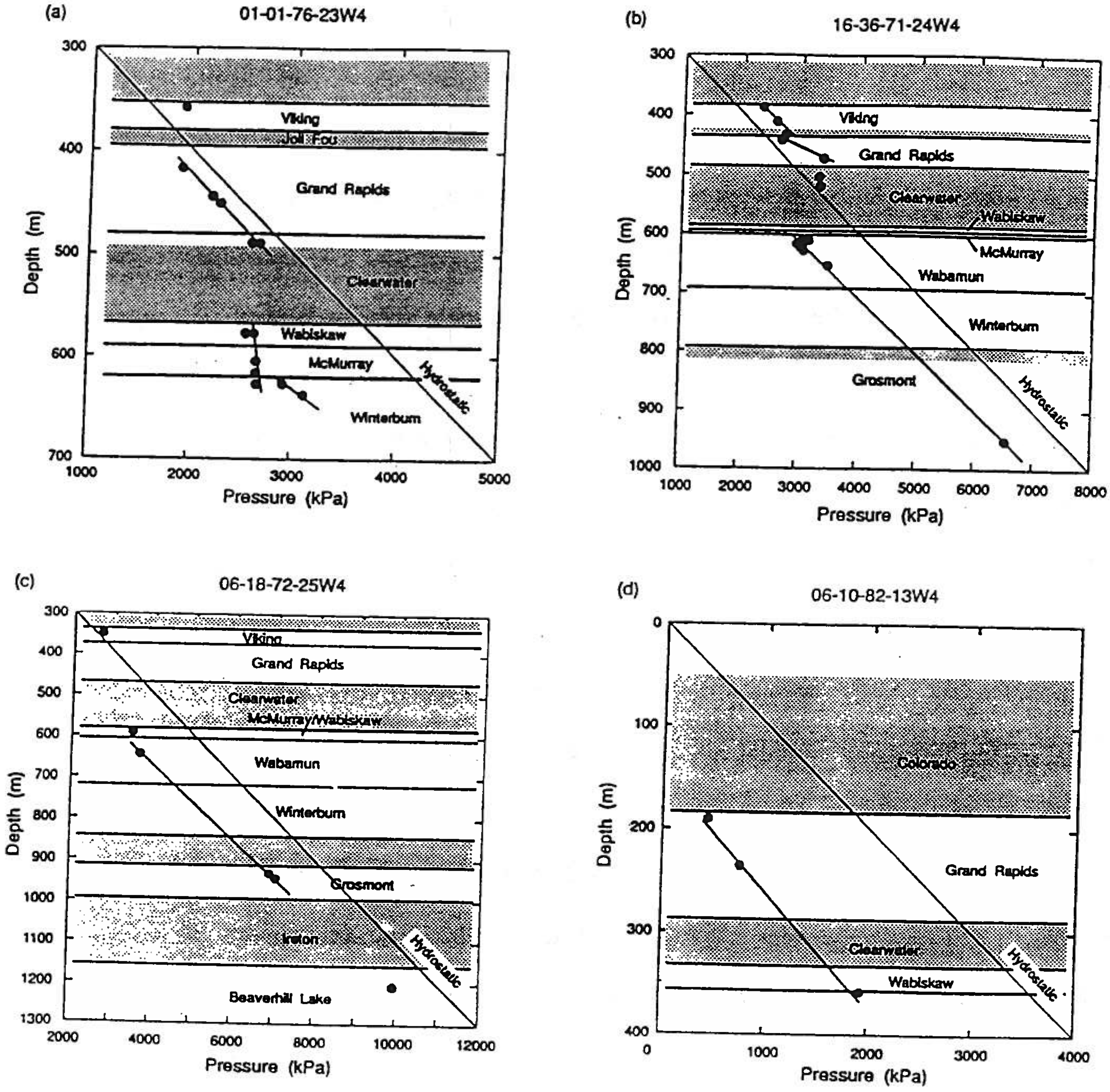

Figure 29. Variation of pressure with depth in selected wells (locations shown in Figure 27).

slight downward component.

Figure 29b 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 29a are also present here. Pressure measurements in the Viking aquifer have a constant slope, indicating a slight downward 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 flow barrier in this area. The slope of the pressure distribution in the Grand Rapids aquifer indicates a strong downward flow component in contrast to the slight upward flow component displayed by the data in Figure 29a. 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 barrier to flow because there is a significant change 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 29a. 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 29a, the McMurray-Wabiskaw unit exhibits aquitard characteristics. The pressure increase with depth in the Wabamun aquifer connects on a straight line with a pressure measurement in the Grosmont aquifer below. This indicates hydraulic communication (close to continuity) 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 06-18-072-25W4Mer is shown in Figure 29c. 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 a significant barrier 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 29a 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 continuity as shown in Figure 29b, then the slope of pressure increase with depth at this location indicates a slight upward 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 distributions in the Beaverhill Lake-Cooking Lake aquifer system (Figure 20b) and the Grosmont aquifer (Figure 22b). 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 above and below the aquitard (Figures 23 and 22b, 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

SUMMARY AND CONCLUSIONS

The regional subsurface hydrogeology of northeast Alberta has been characterized by considering all the available stratigraphic and hydrogeological data. The strata have been divided into aquifer, aquitard and aquiclude systems based on their lithostratigraphic and hydraulic nature (Table 12). Characteristic hydraulic parameters and rock properties for individual hydrostratigraphic units are based on core plug analyses and drillstem test measurements, presented in Tables 5, 7, 8 and 9.

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. Despite these stratigraphic and hydrodynamic complexities, several general hydraulic characteristics can be observed, many of which are displayed in hydraulic cross-section in Figure 28b. 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) and Hitchon et al. (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 regimes 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 (temperature) 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 gravity induced flow of formation waters. In the northeastern region 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 hydraulic characteristics consistent with an intermediate-to-local flow regime. Formation water salinity is lower than that observed for Elk Point aquifers, indicating a lack of hydraulic communication with Elk Point Group evaporites across the Watt Mountain aquitard. 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 anomalous southwest flow directions.

GROSMONT-TO-WABAMUN AQUIFERS

The Grosmont aquifer together with the overlying Winterburn-Wabamun aquifer system is 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 (temperature) related trends noticeable in the southwest.

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APPENDIX A

DISTRIBUTIONS OF FRESHWATER HYDRAULIC HEAD

Figure 1. Freshwater hydraulic head values (m) for the Basal aquifer.

Figure 2. Distributions of freshwater hydraulic head (m) and data for the Contact Rapids-Winnipegosis aquifer system.

Figure 3. Distributions of freshwater hydraulic head (m) and data for the Beaverhill Lake aquifer.

Figure 4. Distributions of freshwater hydraulic head (m) and data for the Cooking Lake aquifer.

Figure 5. Distribution of freshwater hydraulic head (m) for the Beaverhill Lake-Cooking Lake aquifer system.

Figure 6. Distributions of freshwater hydraulic head (m) and data for the Grosmont aquifer.

Figure 7. Distributions of freshwater hydraulic head (m) and data for the Winterburn aquifer.

Figure 8. Distributions of freshwater hydraulic head (m) and data for the Wabamun aquifer.

Figure 9. Distribution of freshwater hydraulic head (m) for the Winterburn-Wabamun aquifer system.

Figure 10. Distributions of freshwater hydraulic head (m) and data for the McMurray aquifer.

Figure 11. Distributions of freshwater hydraulic head (m) and data for the Wabiskaw aquifer.

Figure 12. Distribution of freshwater hydraulic head (m) for the McMurray-Wabiskaw aquifer/aquitard system.

Figure 13. Distributions of freshwater hydraulic head (m) and data for the Grand Rapids aquifer.

Figure 14. Distributions of freshwater hydraulic head (m) and data for the Viking aquifer.

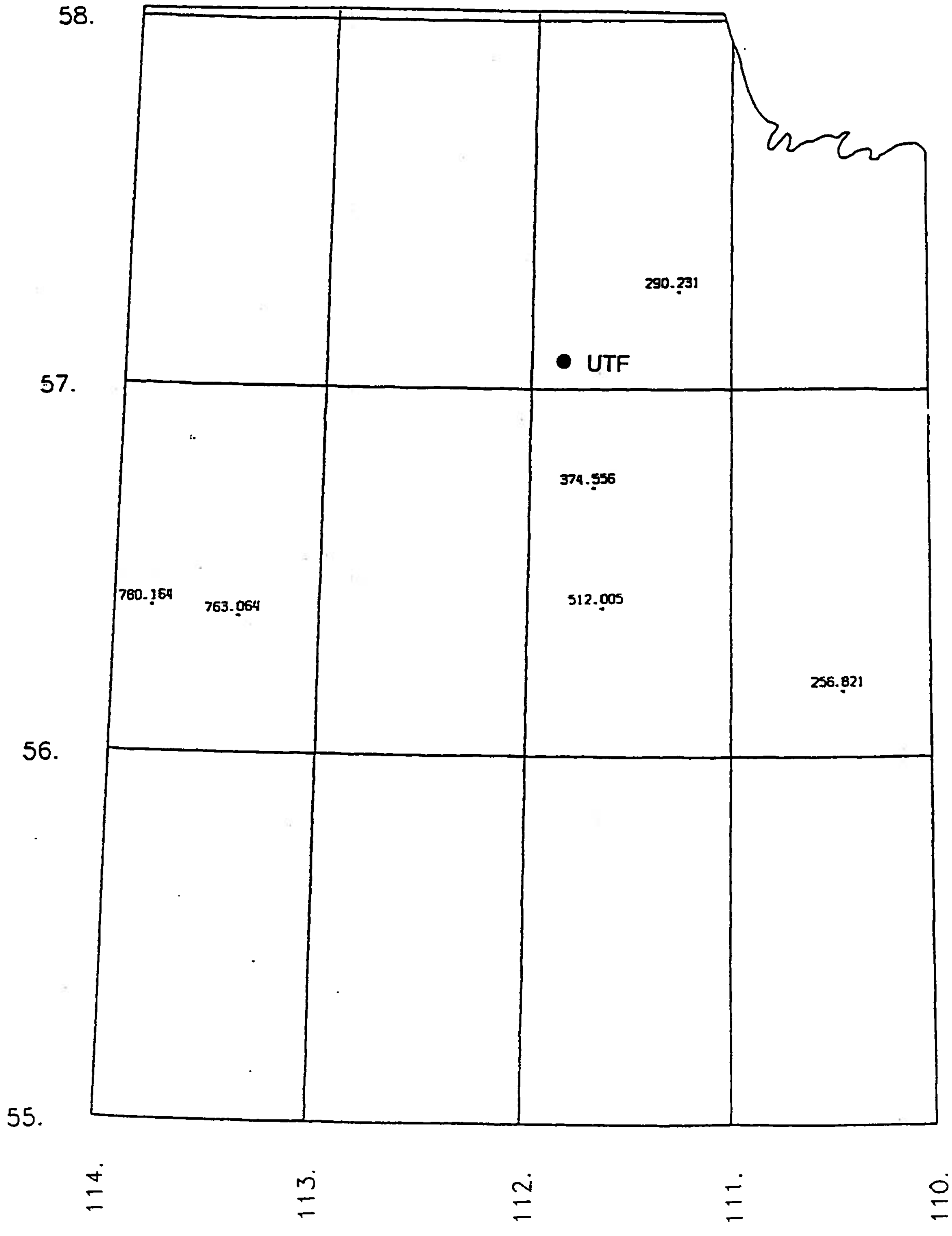


Figure 1. Freshwater hydraulic head values (m) for the Basal aquifer.

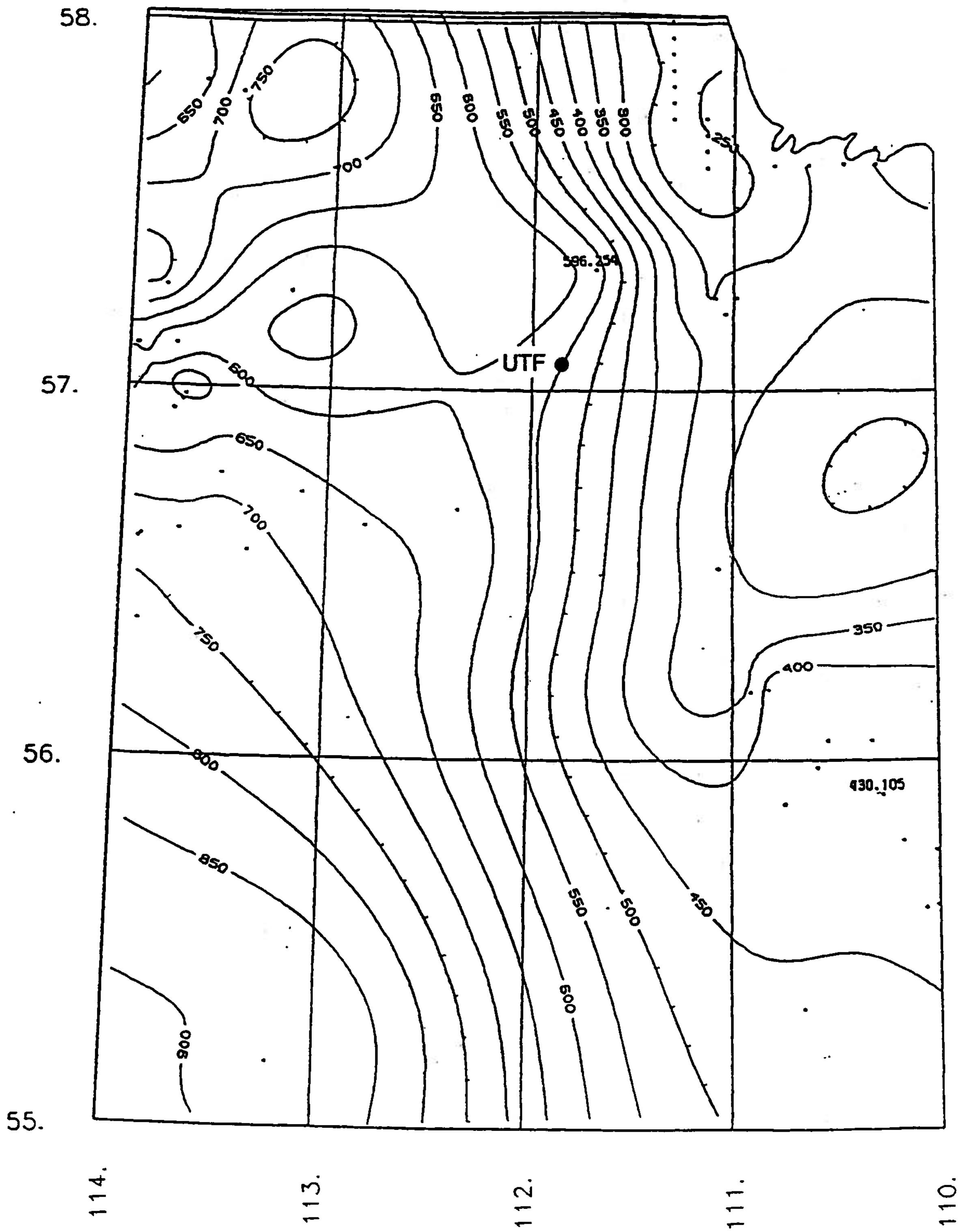


Figure 2. Distributions of freshwater hydraulic head (m) and data for the Contact Rapids-Winnipegosis aquifer system.

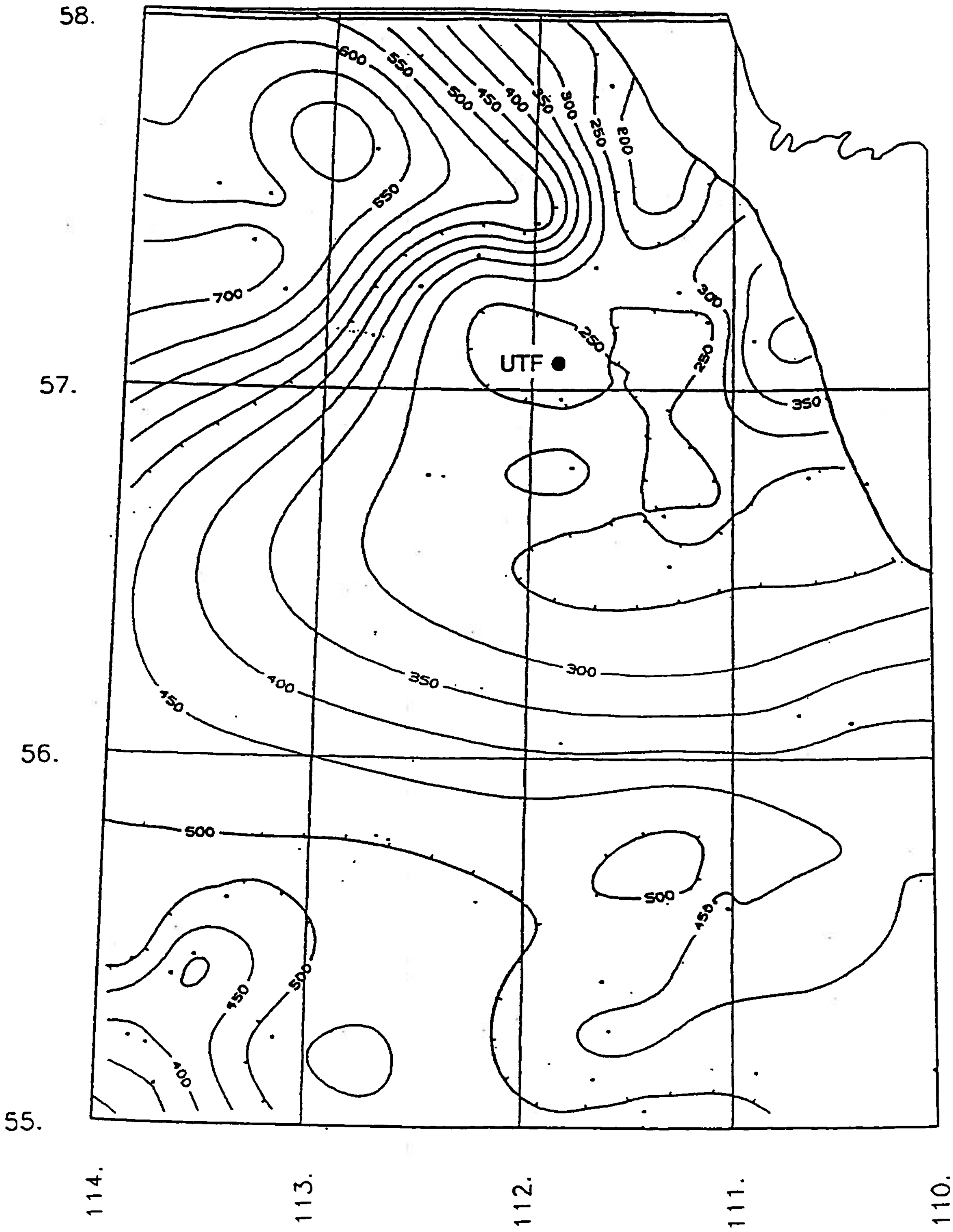


Figure 3. Distributions of freshwater hydraulic head (m) and data for the Beaverhill Lake aquifer.

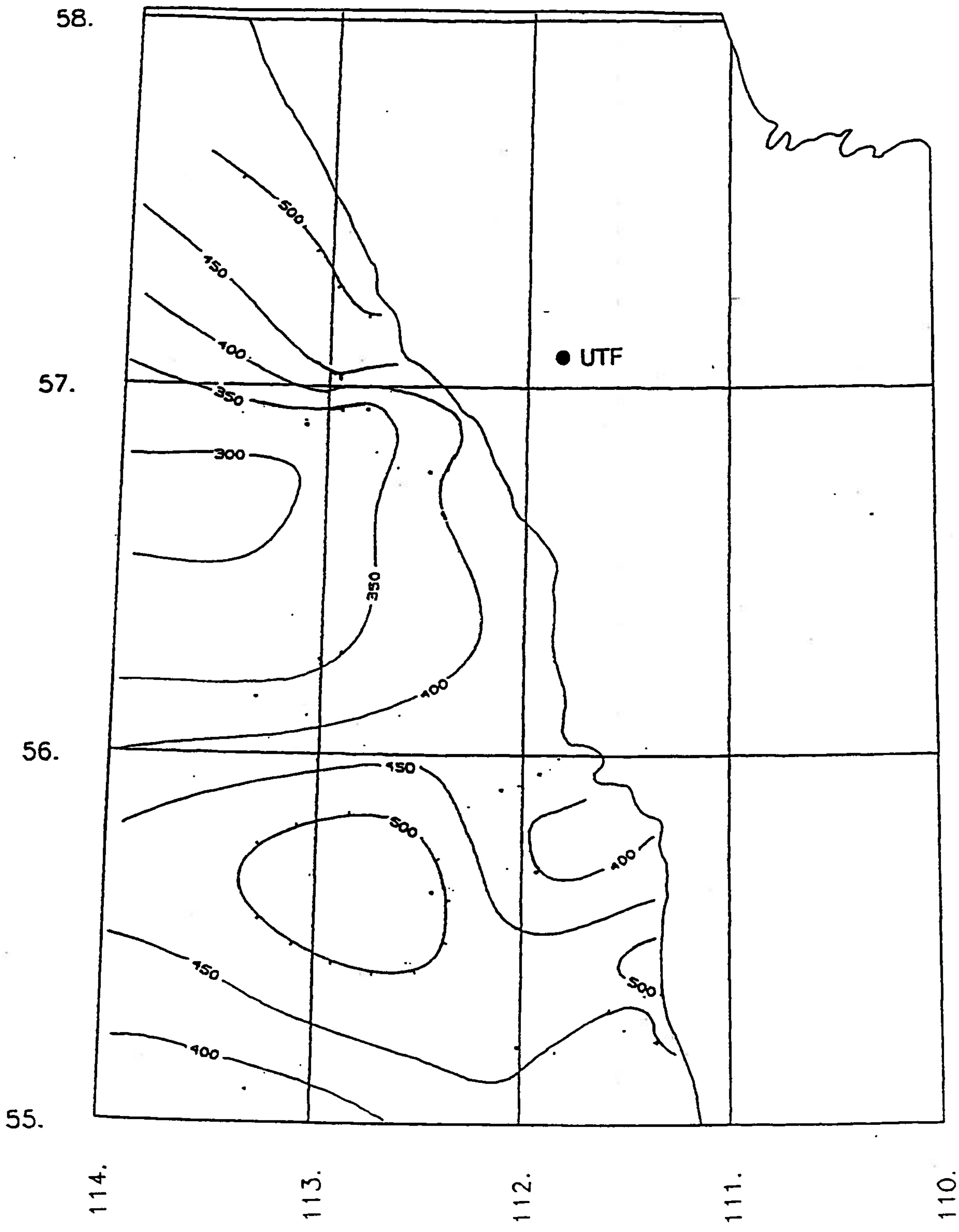


Figure 4. Distributions of freshwater hydraulic head (m) and data for the Cooking Lake aquifer.

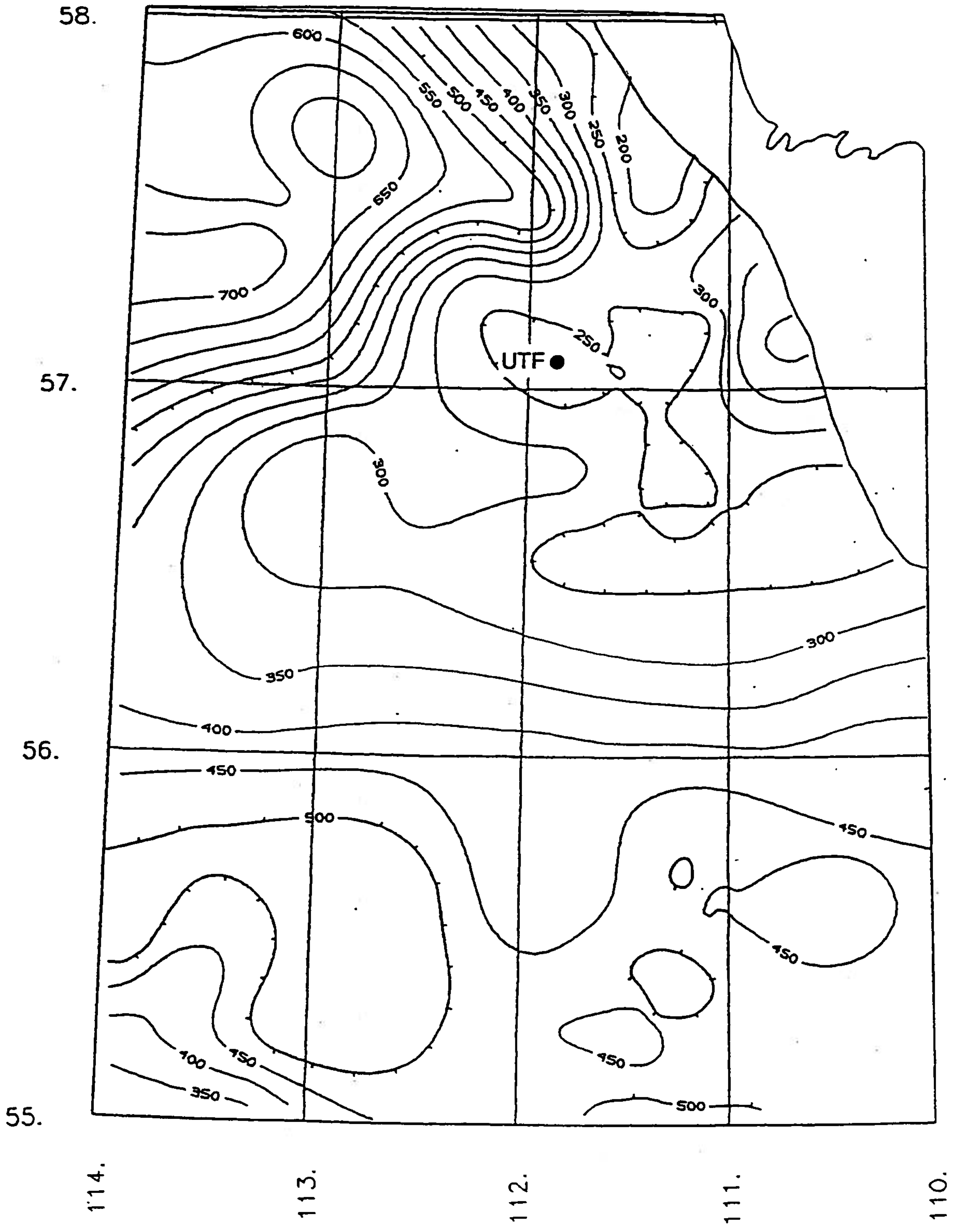


Figure 5. Distribution of freshwater hydraulic head (m) for the Beaverhill Lake-Cooking Lake aquifer system.

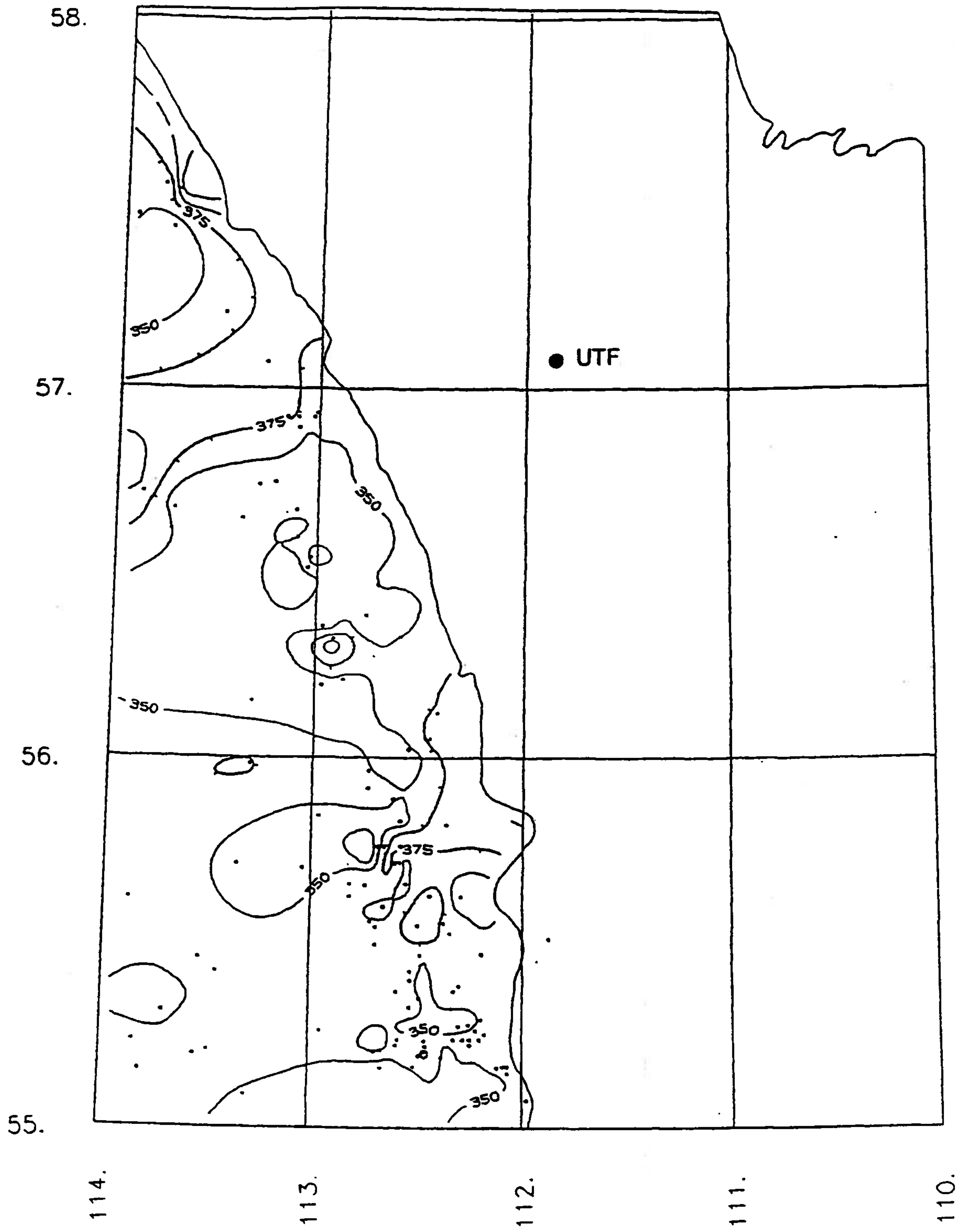


Figure 6. Distributions of freshwater hydraulic head (m) and data for the Grosmont aquifer.

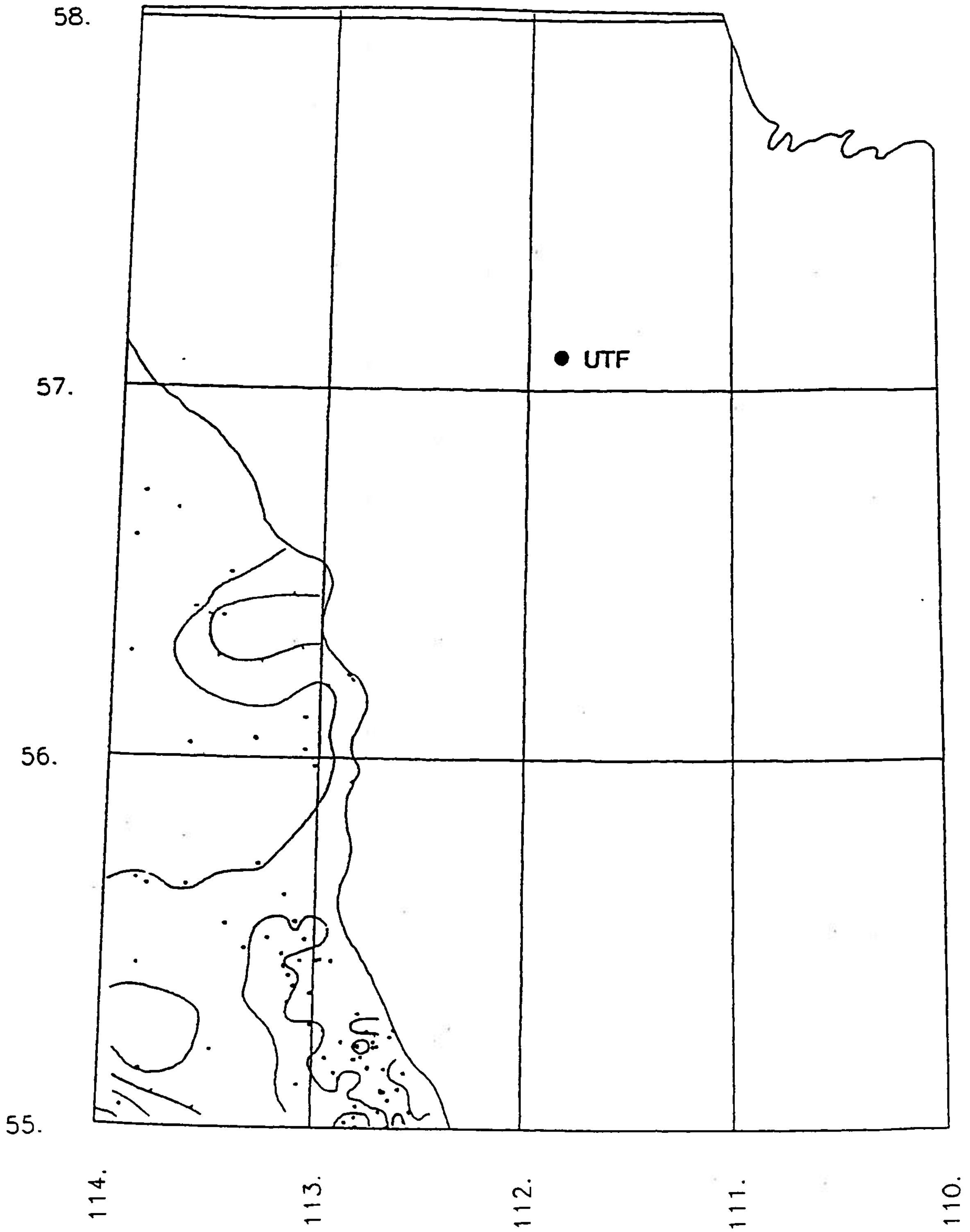


Figure 7. Distributions of freshwater hydraulic head (m) and data for the Winterburn aquifer.

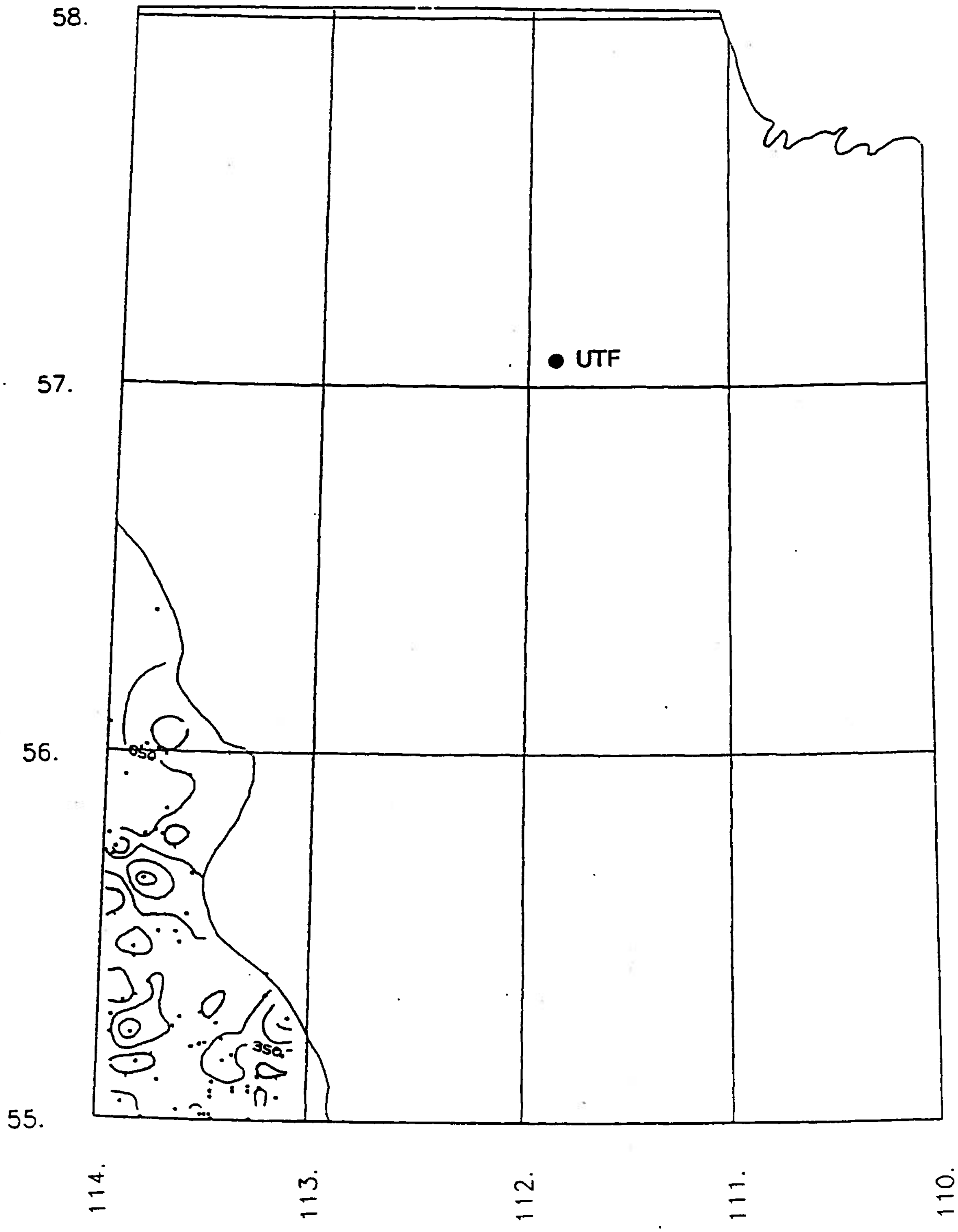


Figure 8. Distributions of freshwater hydraulic head (m) and data for the Wabamun aquifer.

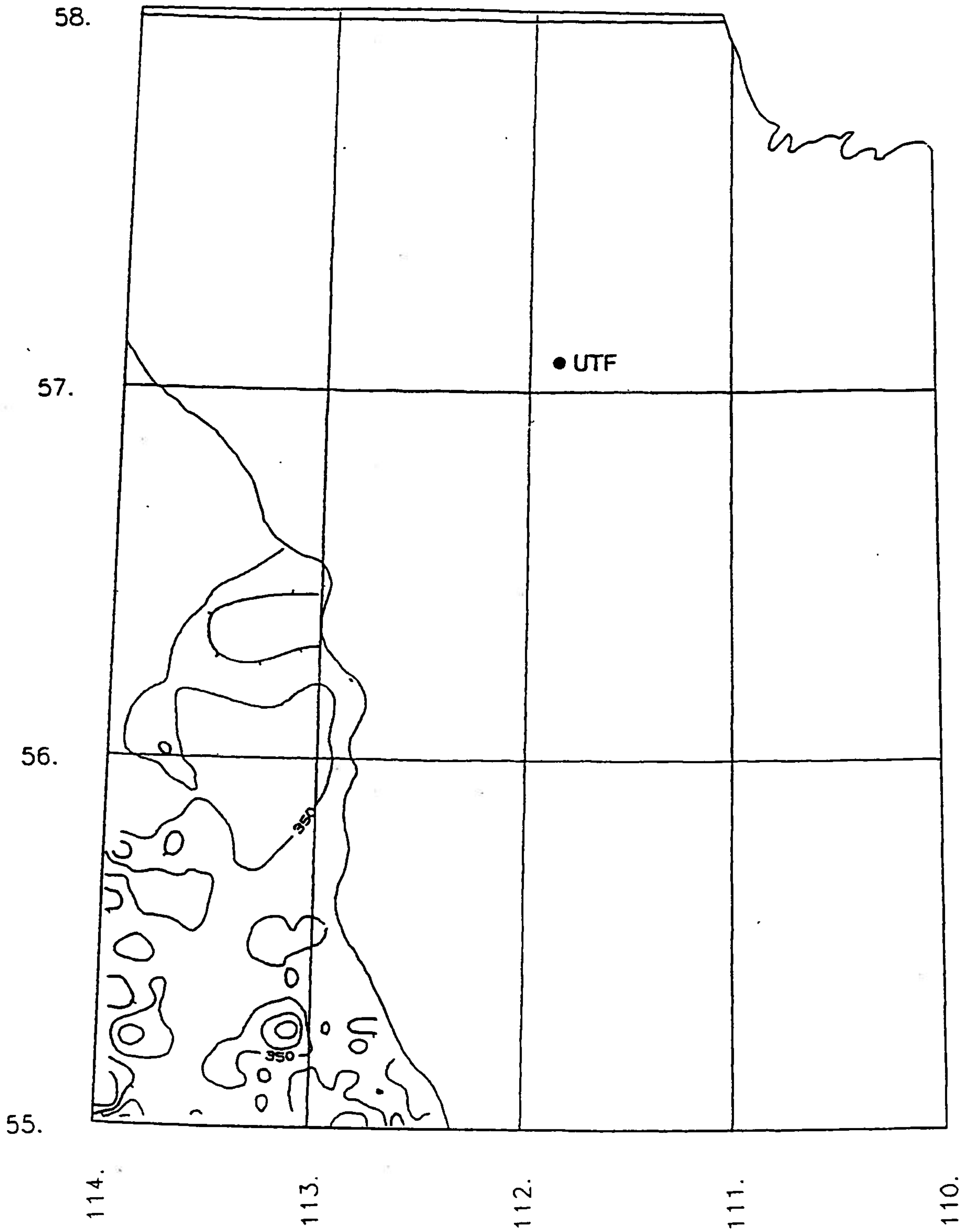


Figure 9. Distribution of freshwater hydraulic head (m) for the Winterburn-Wabamun aquifer system.

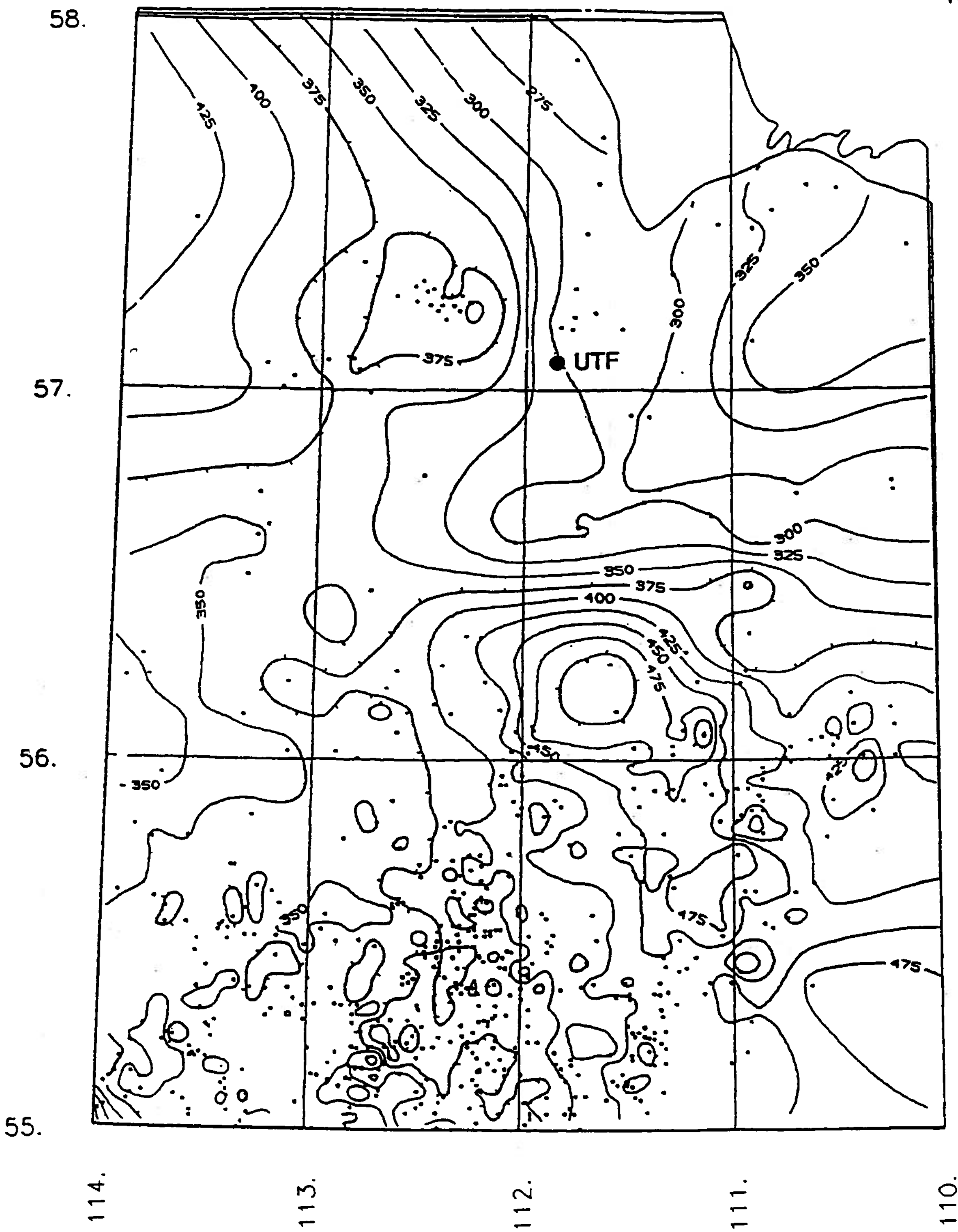


Figure 10. Distributions of freshwater hydraulic head (m) and data for the McMurray aquifer.

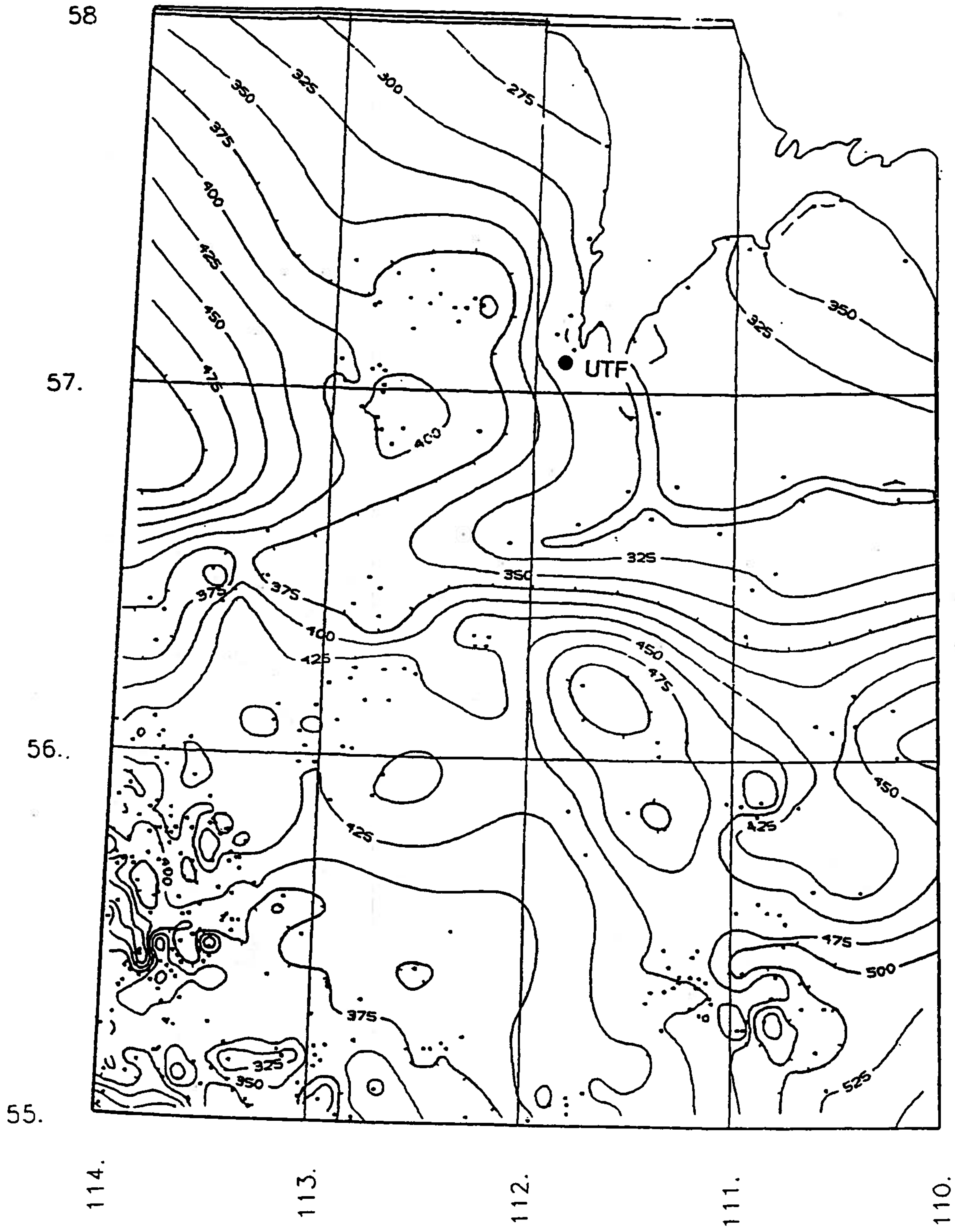


Figure 11. Distributions of freshwater hydraulic head (m) and data for the Wabiskaw aquifer.

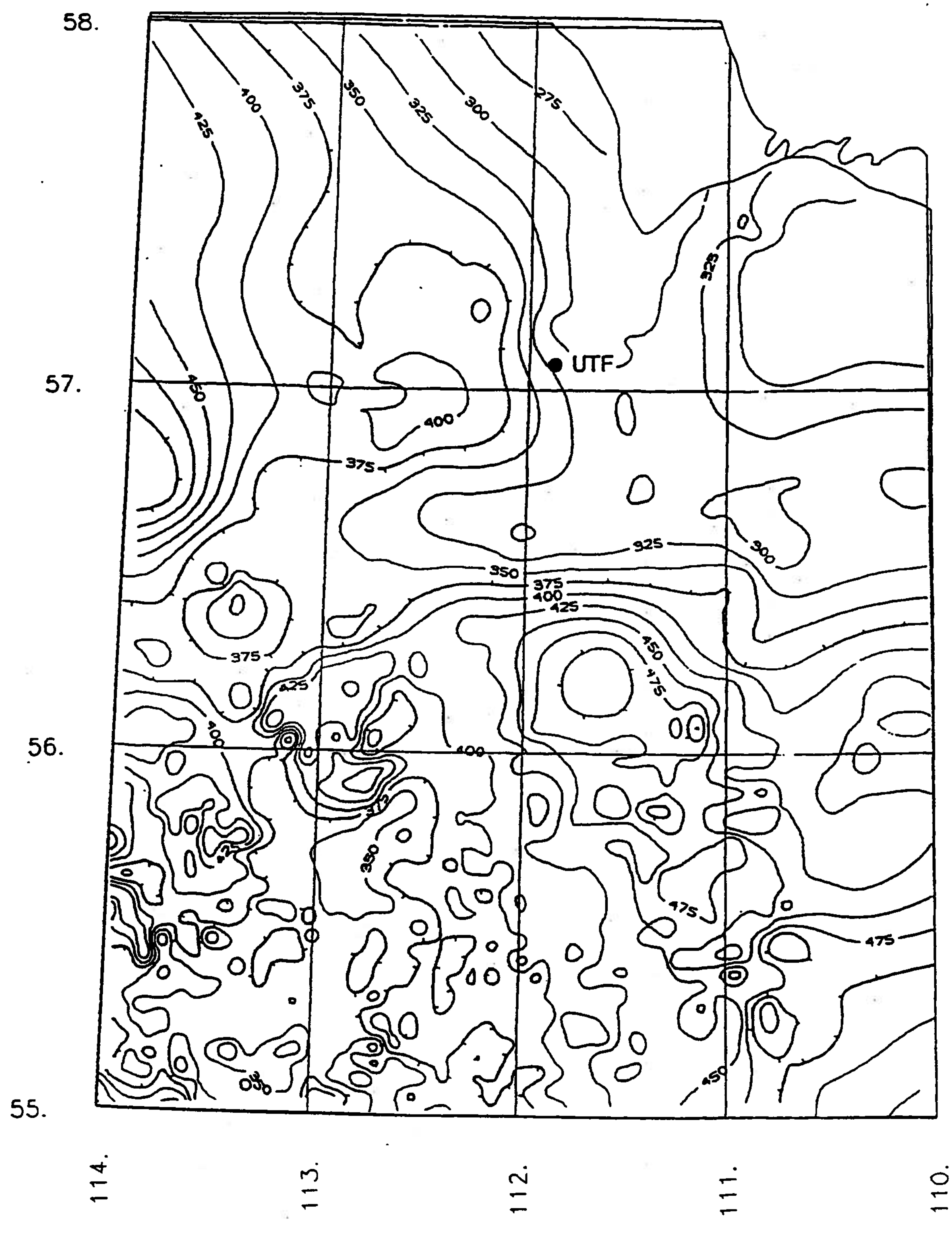


Figure 12. Distribution of freshwater hydraulic head (m) for the McMurray-Wabiskaw aquifer/aquitard system.

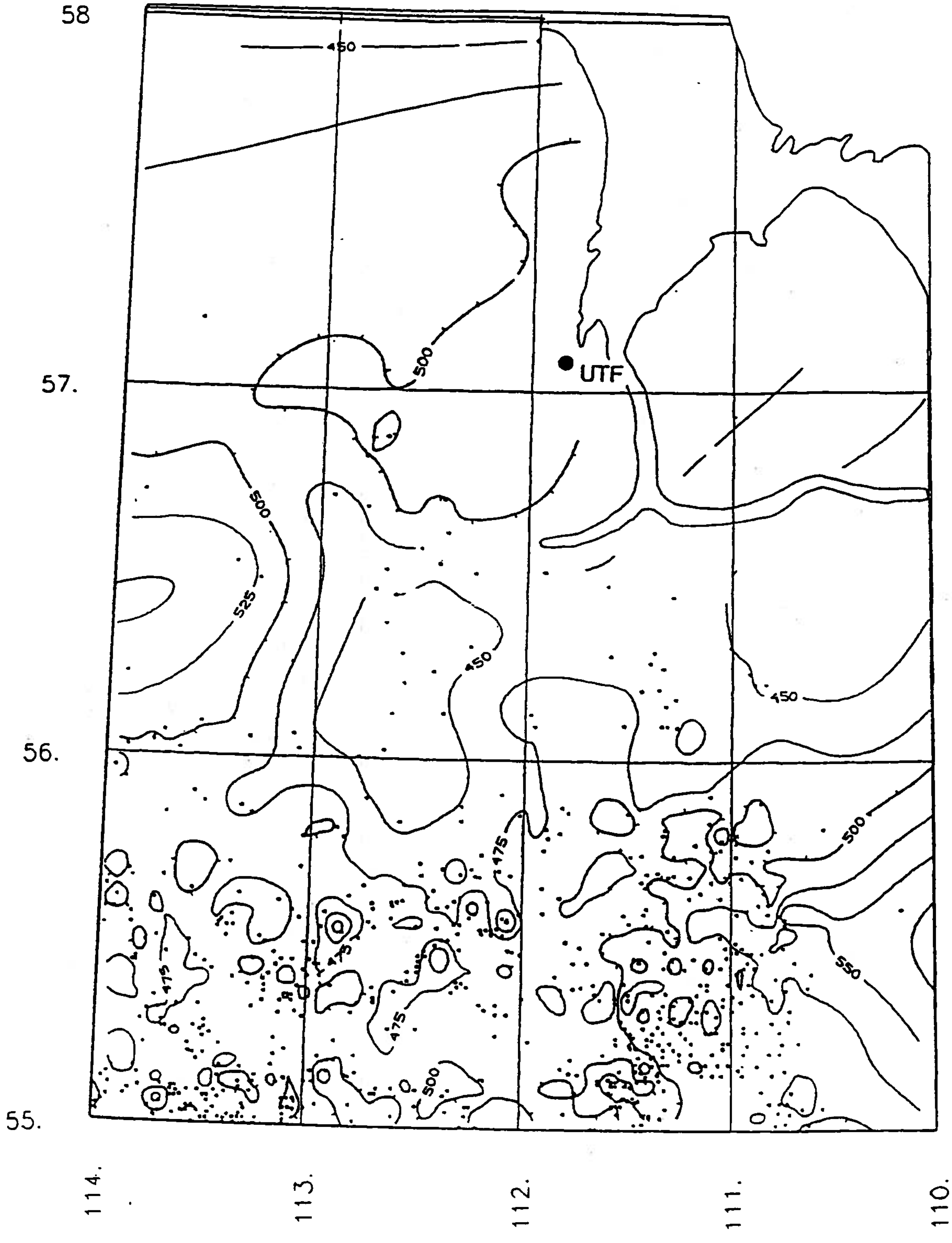


Figure 13. Distributions of freshwater hydraulic head (m) and data for the Grand Rapids aquifer.

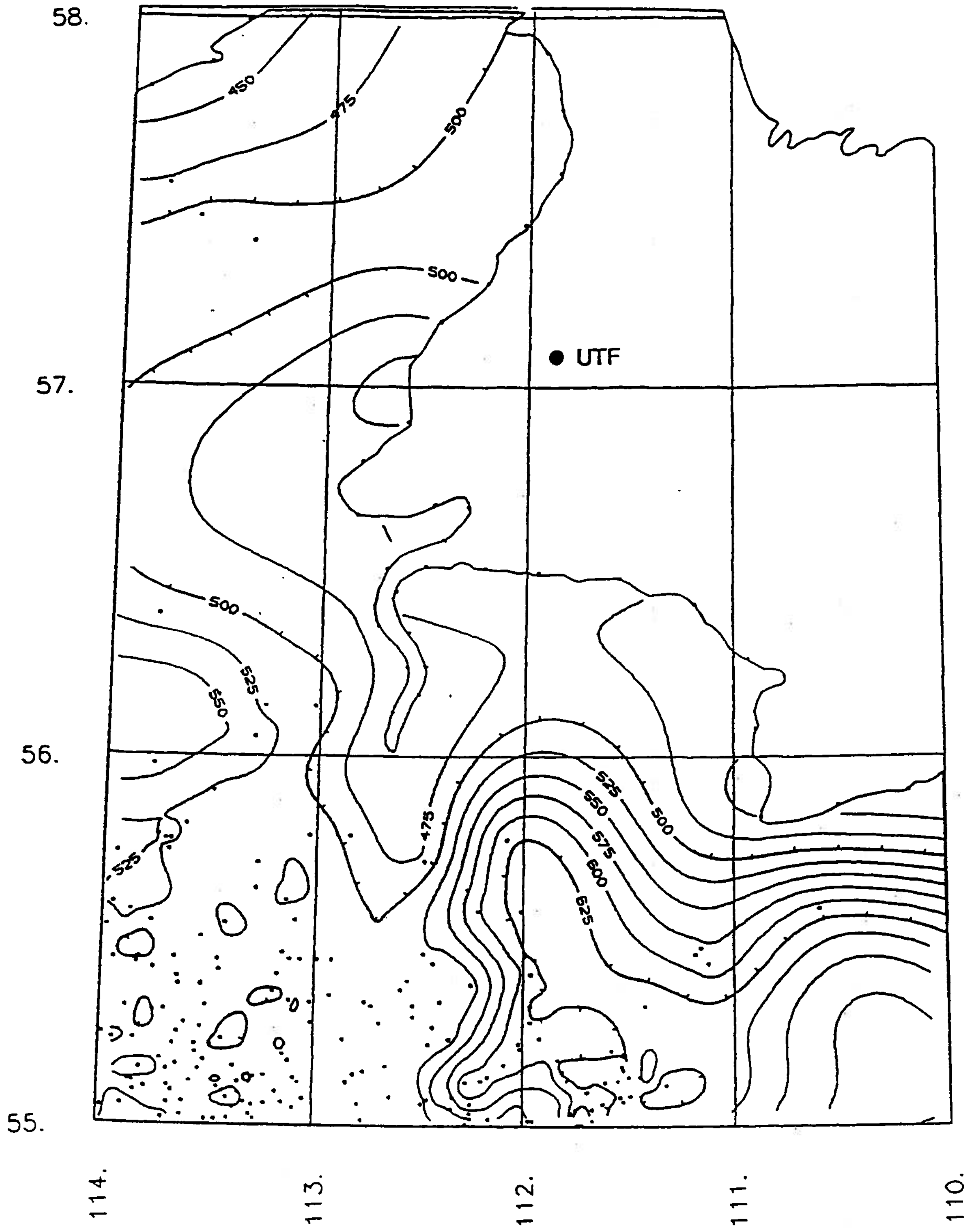


Figure 14. Distributions of freshwater hydraulic head (m) and data for the Viking aquifer.

APPENDIX B

DISTRIBUTIONS OF FORMATION WATER SALINITY

Figure 1.	Salinity of formation waters (mg/l) and data distribution for the Contact Rapids-Winnipegosis aquifer system.
Figure 2.	Salinity of formation waters (mg/l) and data distribution for the Beaverhill Lake-Cooking Lake aquifer system.
Figure 3.	Salinity of formation waters (mg/l) and data distribution for the Grosmont aquifer.
Figure 4.	Salinity of formation waters (mg/l) and data distribution for the Winterburn aquifer.
Figure 5.	Salinity of formation waters (mg/l) and data distribution for the Wabamun aquifer.
Figure 6.	Salinity of formation waters (mg/l) and data distribution for the McMurray aquifer.

Figure 7. Salinity of formation waters (mg/l) and data distribution for the Wabiskaw aquifer.

Figure 8. Salinity of formation waters (mg/l) and data distribution for the Grand Rapids aquifer.

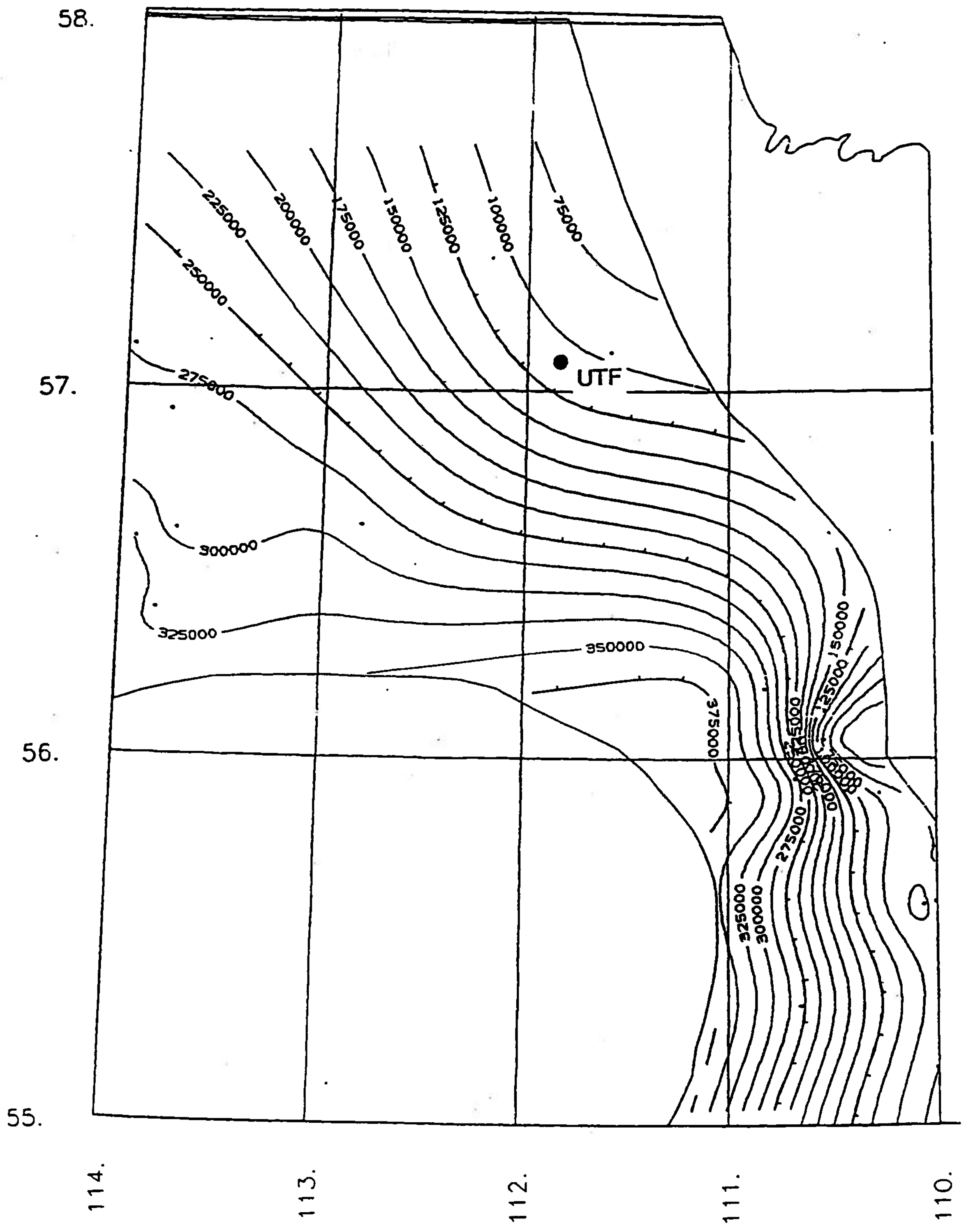


Figure 1. Salinity of formation waters (mg/l) and data distribution for the Contact Rapids-Winnipegosis aquifer system.

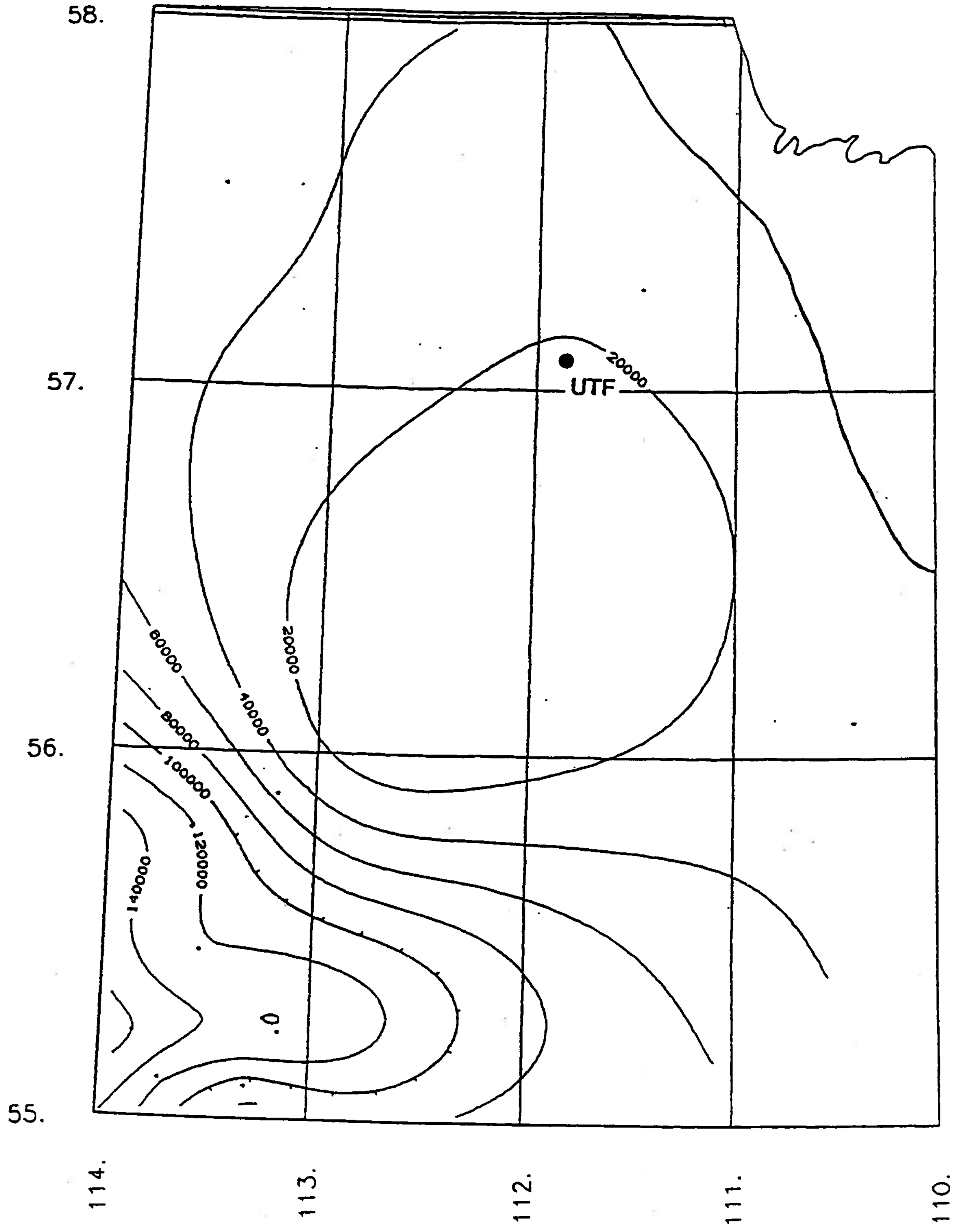


Figure 2. Salinity of formation waters (mg/l) and data distribution for the Beaverhill Lake-Cooking Lake aquifer system.

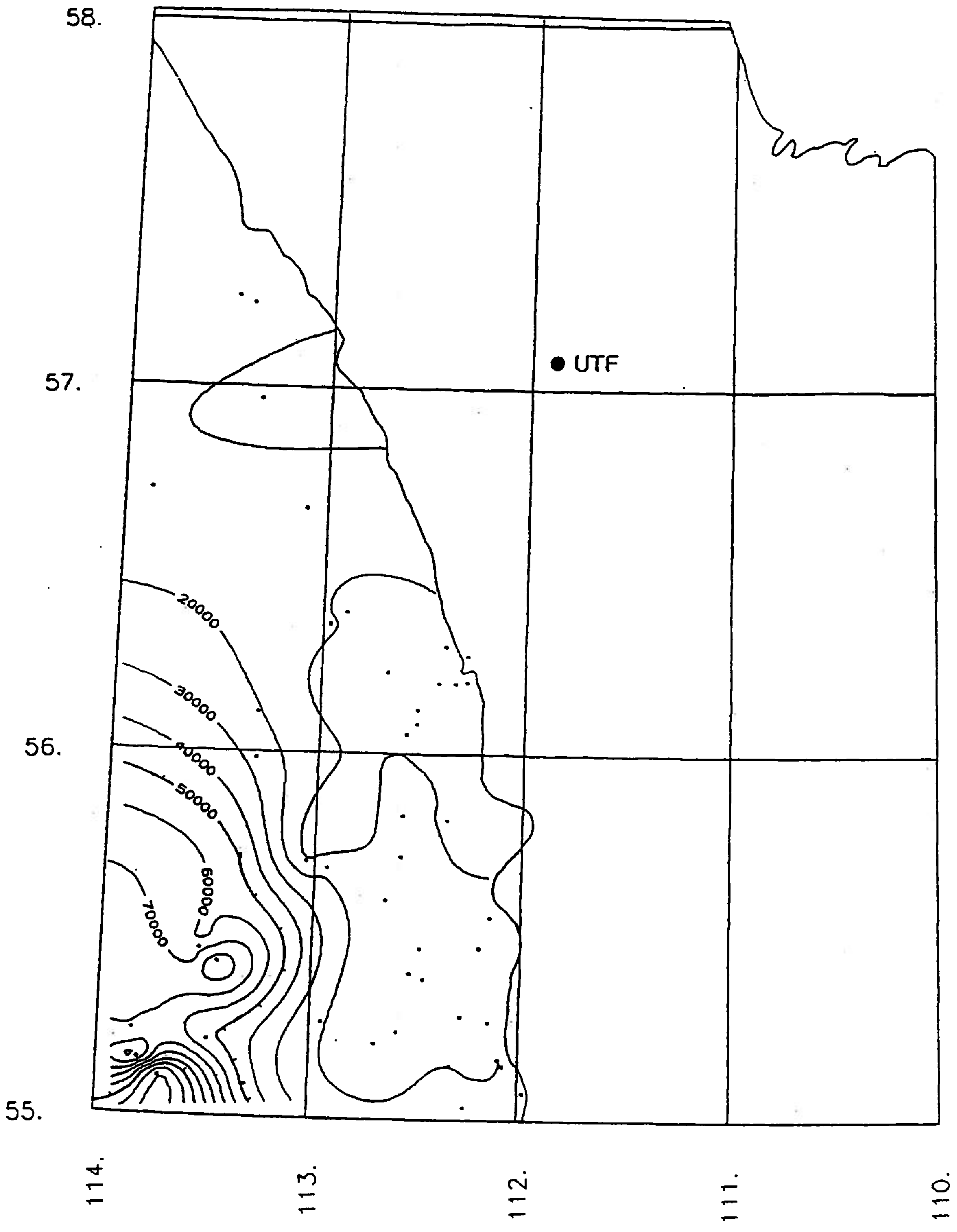


Figure 3. Salinity of formation waters (mg/l) and data distribution for the Grosmont aquifer.

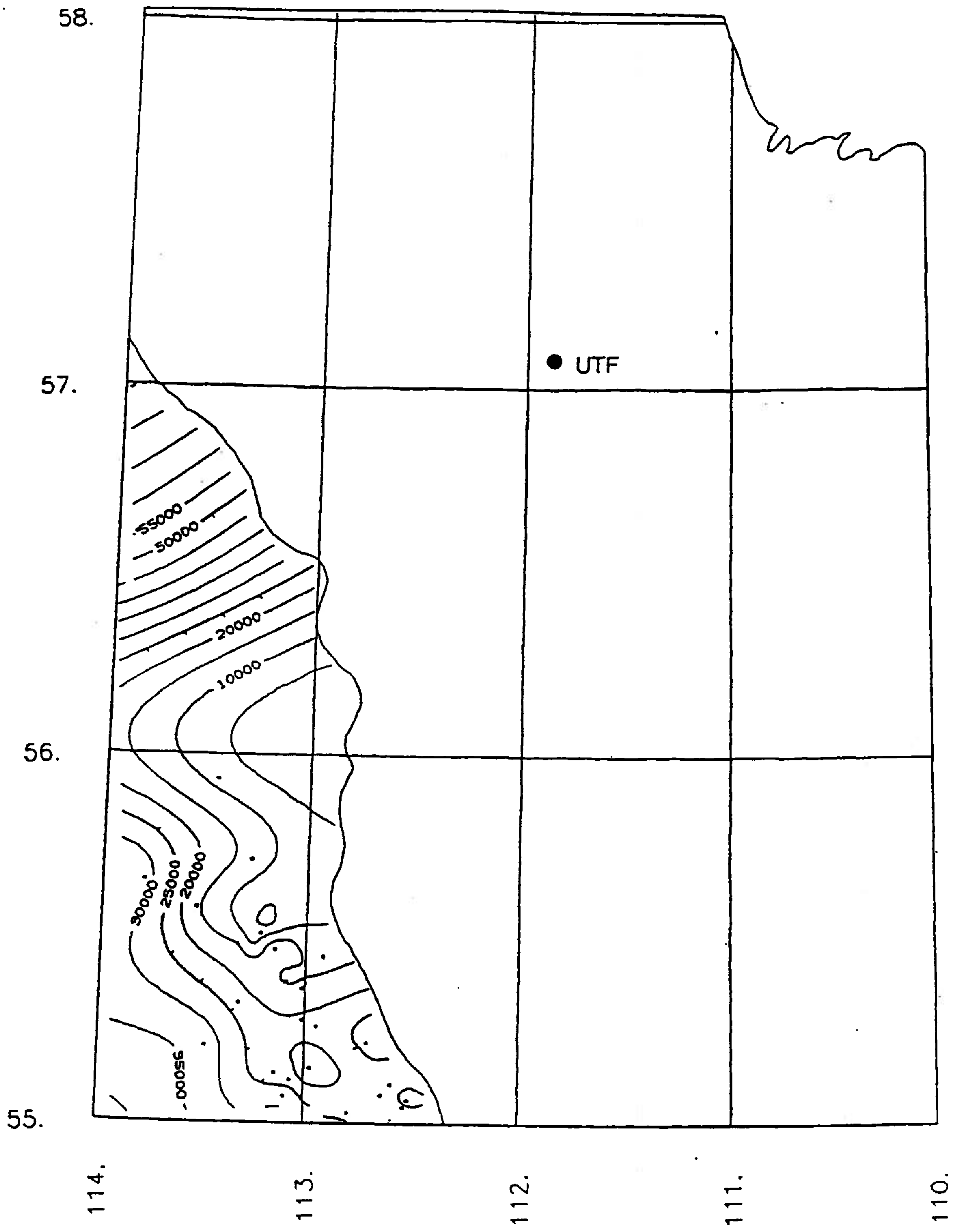


Figure 4. Salinity of formation waters (mg/l) and data distribution for the Winterburn aquifer.

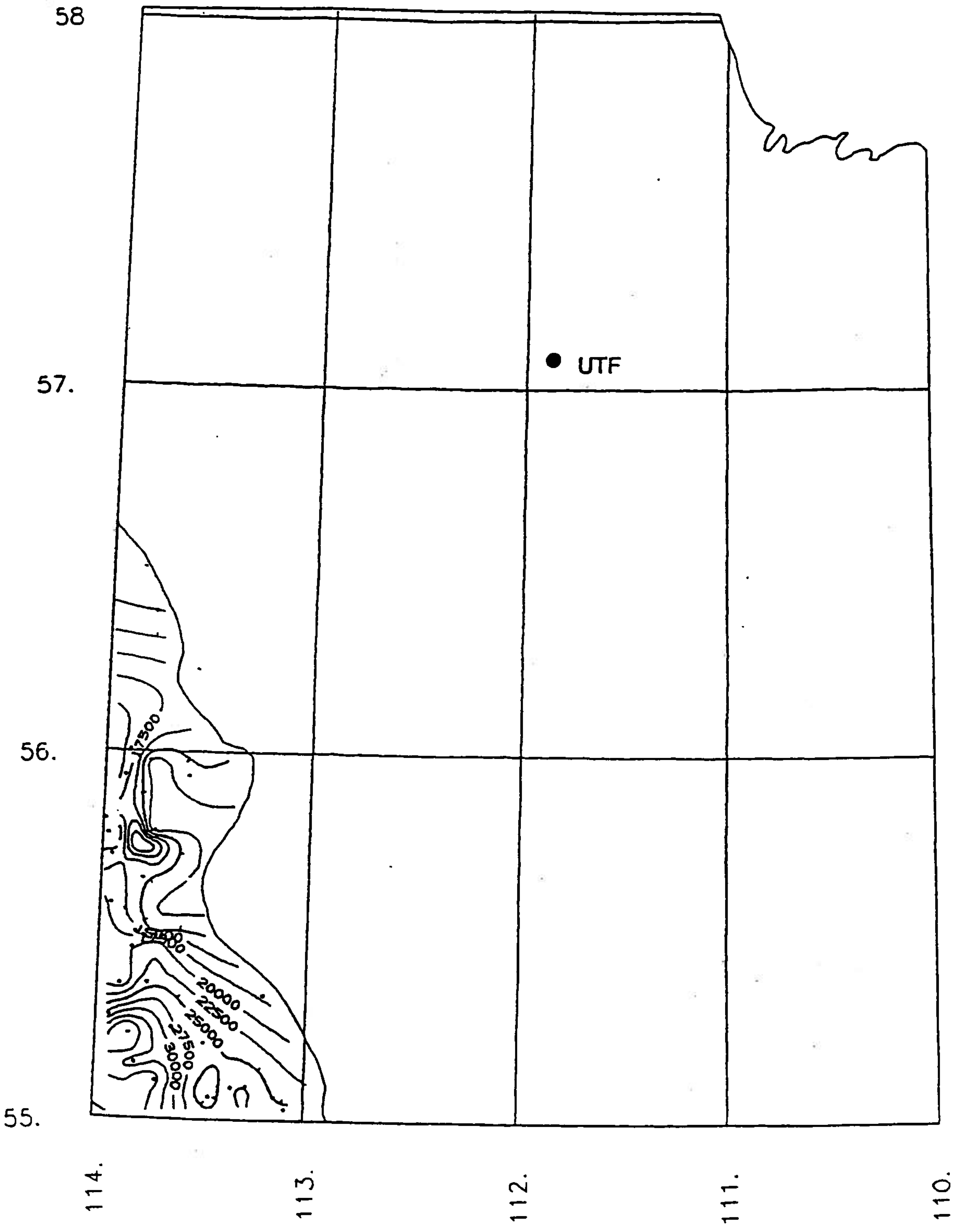


Figure 5. Salinity of formation waters (mg/l) and data distribution for the Wabamun aquifer.

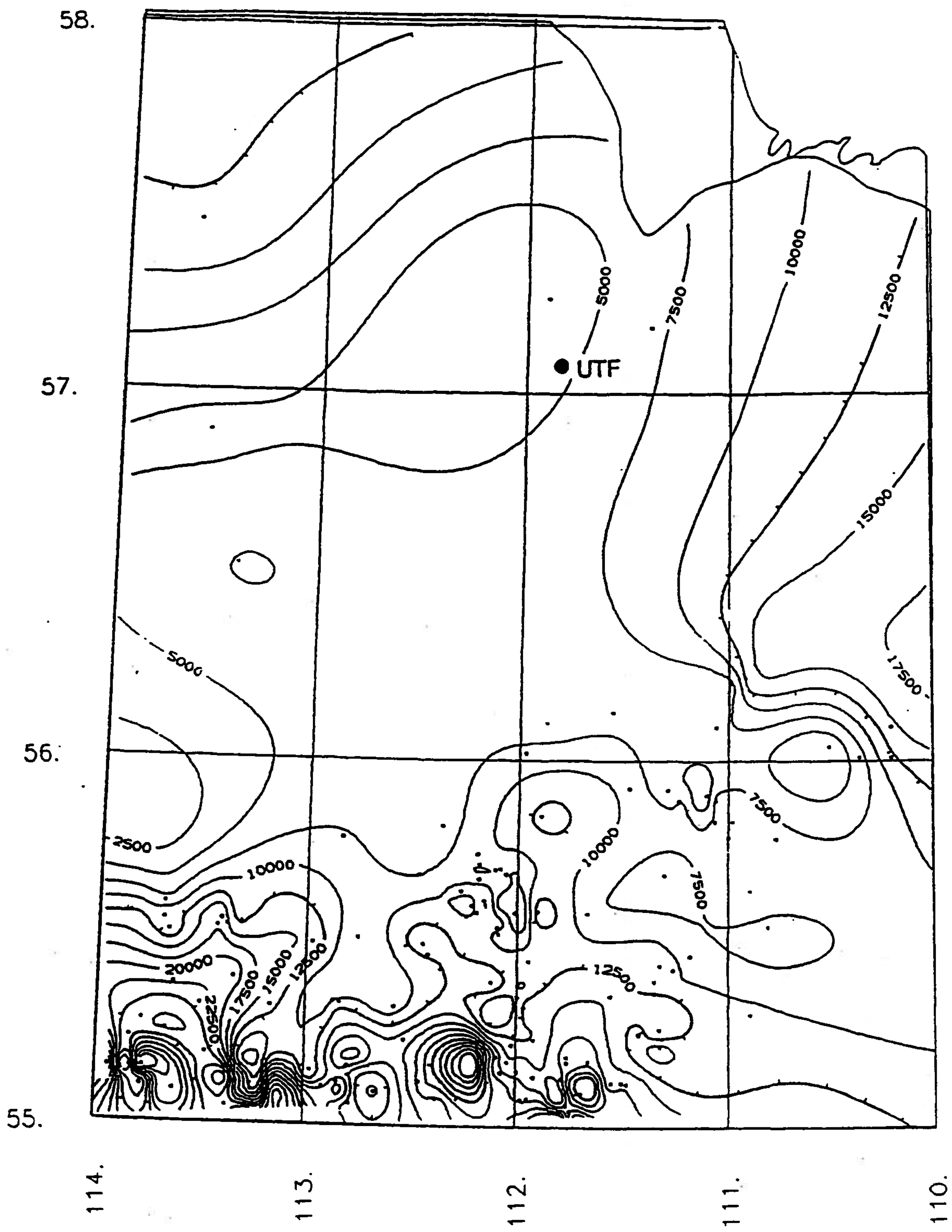
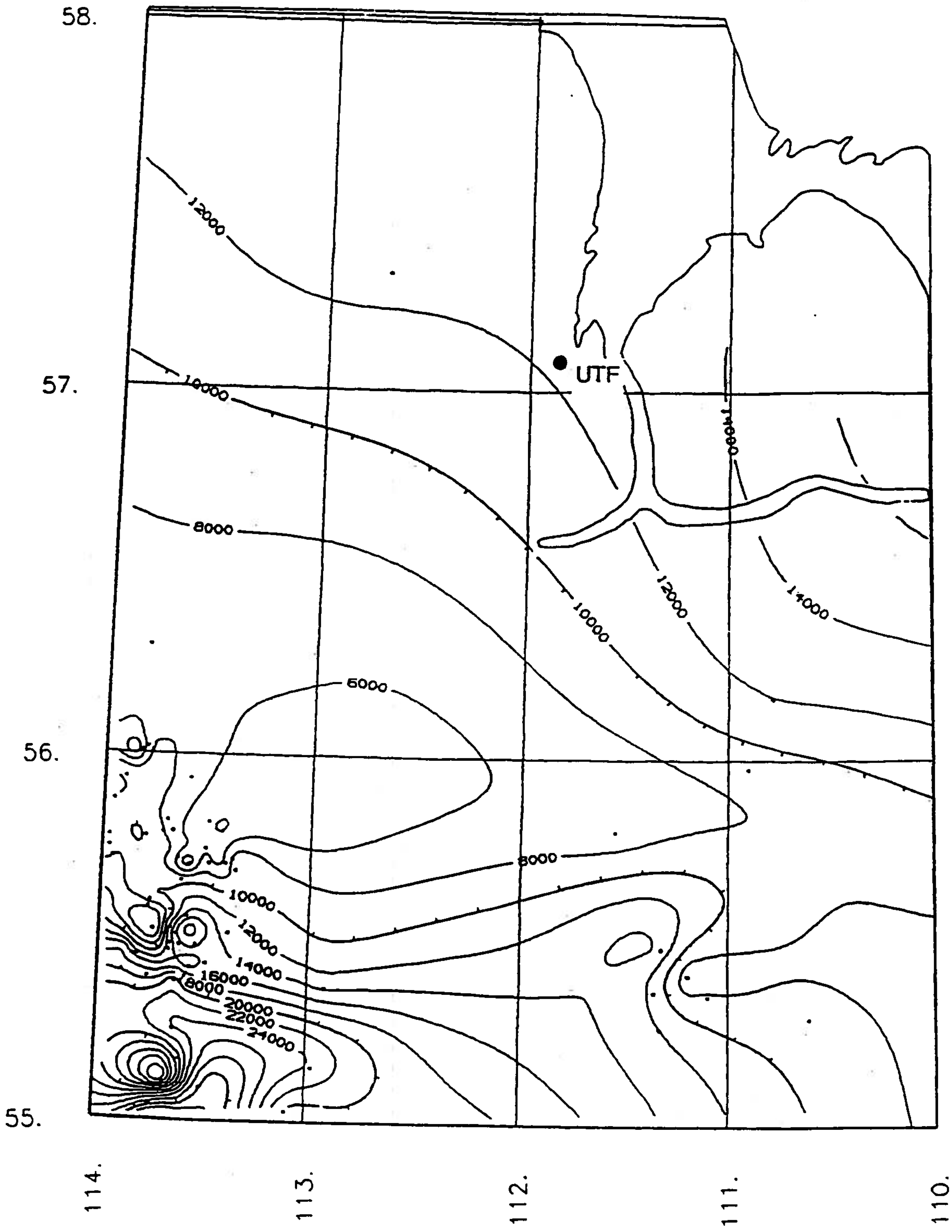


Figure 6. Salinity of formation waters (mg/l) and data distribution for the McMurray aquifer.



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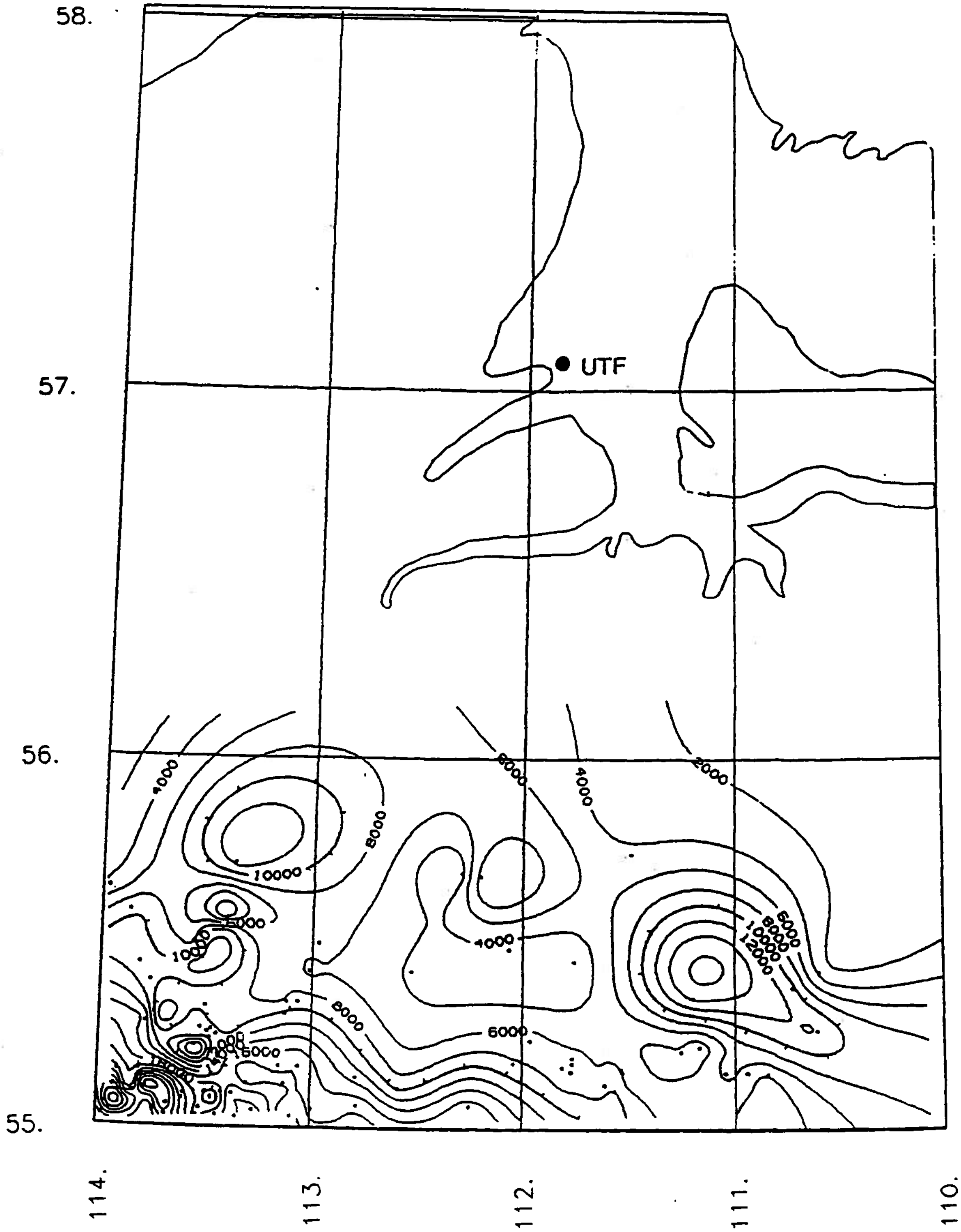

Figure 8. Salinity of formation waters (mg/l) and data distribution for the Grand Rapids aquifer.