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HYDROCHEMISTRY OF PHANEROZOIC STRATA, NORTHEAST ALBERTA

by Hitchon Geochemical Services Ltd.

for Alberta Research Council

December 1991

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Hydrochemistry of Phanerozoic Strata, Northeast Alberta

Report prepared for
Alberta Research Council

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CONTENTS

Abstract - The Northeast Alberta study area is defined as 55° to 58°N, and 110° to 114° W. A total of 2933 formation water analyses from the area were entered into the Alberta Geological Survey Well Data Base, verified, and subjected to a variety of electronic, manual-electronic and manual culling to leave a final data base of 525 analyses on which this study was based.

Salinity ranges from freshwater to 325,000 mg/l, and there are corresponding maximum contents of Cl (200,000 mg/l), Ca (40,000 mg/l) and Mg (8000 mg/l). Nine maps illustrate the distribution of salinity, which is essentially depth (temperature)-related except where there is incursion of fresher waters from overlying aquifers. Sulfate is high (500-5500 mg/l) in aquifers in which anhydrite is present (Elk Point hydrostratigraphic unit -- Prairie Formation; Beaverhill Lake aquifer -- Fort Vermilion Formation; and Grosmont aquifer -- Hondo Formation). Formation waters in the Elk Point hydrostratigraphic unit from near the updip solution edge of the Prairie aquiclude (halite) are similar to those of saline springs in the valley of the Athabasca River, which have been shown to originate from solution of evaporites by meteoric water.

Based on the composition of their formation waters the aquifers can be combined into groups separated by aquitards, as follows: Viking aquifer (weak Joli Fou aquitard); Grand Rapids aquifer (strong, regional Clearwater aquitard); Clearwater, Wabiskaw and McMurray aquifers; Wabamun and Winterburn aquifers (weak Upper Ireton aquitard); Grosmont aquifer (strong Lower Ireton aquitard); Beaverhill Lake aquifer (significant, regional Prairie aquiclude); Elk Point hydrostratigraphic unit (mainly Keg River aquifer); Precambrian aquiclude. In summary, the formation waters of the Northeast Alberta area are an extension of those in the adjacent Peace River Arch area, exhibit similar characteristics, and have similar origins.

INTRODUCTION

This report is part of a more extensive study of the hydrogeology of northeast Alberta presently being carried out by the Alberta Research Council in collaboration with the Conservation and Protection Branch of Environment Canada. The objective of the main hydrogeological study is to evaluate the effects of deep waste injection of produced residual waters from the currently planned commercial-size operation of the Underground Test Facility (UTF) of the Alberta Oil Sands Technology and Research Authority (AOSTRA). The UTF site is located in Sections 7 and 8, Tp 93, R 12, W4 Mer, about 50 km northwest of Fort McMurray and 20 km southwest of Fort McKay. For the purpose of a regional-scale hydrogeological evaluation, the Northeast Alberta study area (Fig. 1) is defined as between latitudes 55°N and 58°N, and longitudes 110°W (4th Mer; Alberta-Saskatchewan border) to 114°W (5th Mer). In DLS coordinates this is Tp 70-103, R 1-26, W4 Mer.

A preliminary report on the regional geology and hydrostratigraphy of northeast Alberta has been submitted to Environment Canada and all references in the present report to the geology of the study area are taken directly from that report (Petroleum Geology and Basin Analysis Group, 1991). The Northeast Alberta study area lies immediately east of the Peace River Arch study area, the hydrochemical aspects of which were described by Hitchon (1990). The regional subsurface hydrogeology of the Peace River Arch study area is summarized in Hitchon et al. (1990). Previous comprehensive hydrogeological studies in the Northeast Alberta study area include the eastern quarter of the Red Earth region (Fig. 1) studied by Toth (1978) and the reports by Hackbarth and Nastasa (1979) and Hackbarth and Brulotte (1981) on the generally near-surface hydrogeology of the Athabasca oil sands area. Other papers dealing less comprehensively with the hydrogeology of the study area will be cited as pertinent.

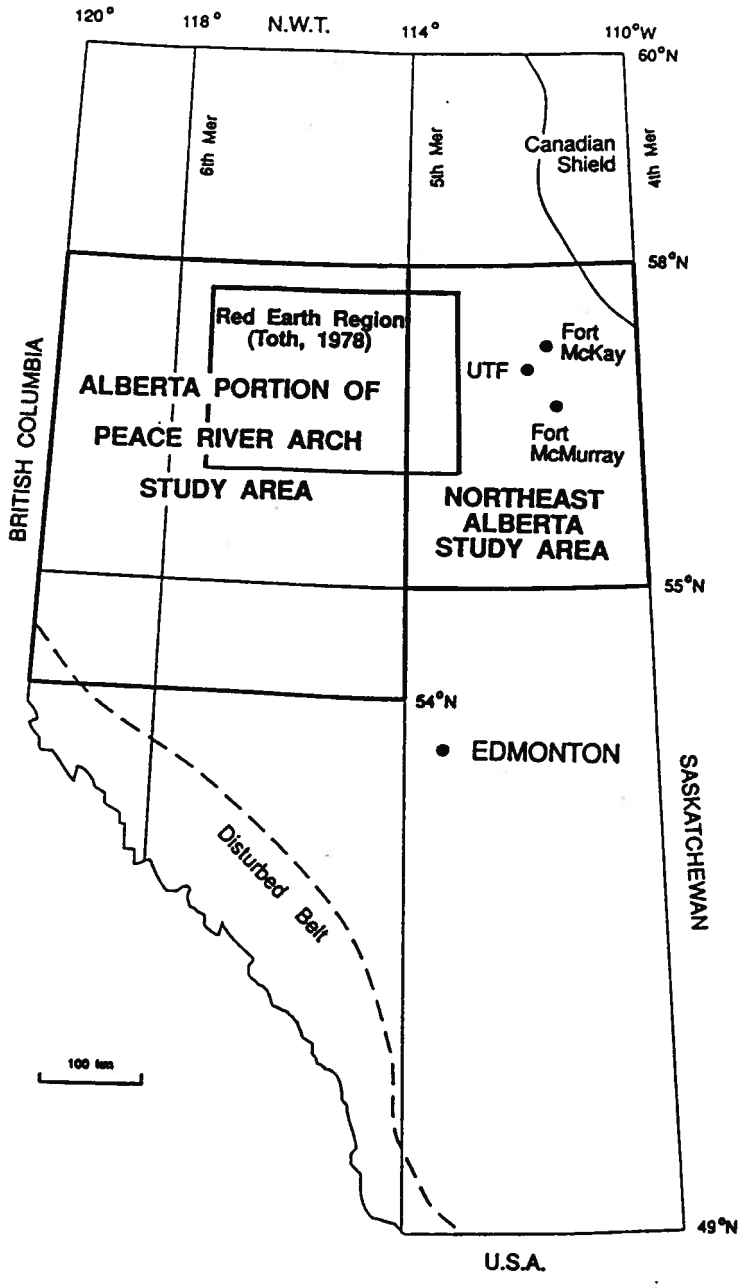

Fig. 1. Location of Northeast Alberta study area.

ELECTRONIC DATA BASE

Close to 12,500 wells have been drilled in the Northeast Alberta study area, with regions of high well density reflecting the location of major oil sands deposits and oil and gas discoveries. Analyses of formation waters recovered from these drilling operations are in the files of the Alberta Energy Resources Conservation Board (ERCB), and these data, together with that from Hackbarth and Brulotte (1981), were entered into the Alberta Geological Survey Well Data Base, and verified. Data include a unique well site identifier, and electronic links to a pertinent drillstem test, if appropriate. For more details of the data base see Bachu et al. (1987), Hitchon et al. (1987), and Bachu et al. (1991).

DATA PROCESSING

Following data entry and verification, the analyses were first subjected to electronic culling, then assigned to stratigraphic units. Following this they were processed by a combination of electronic and manual culling before production of final maps, tables, and other illustrative material. Methods used for the electronic, manual-electronic, and manual culling were the same as those used in the adjacent Peace River Arch study area (see Hitchon, 1990, pp. 7-12).

Of the 2933 formation water analyses in the data base, 1759 (60%) passed the electronic cull. Because of poor areal data distribution and paucity of analyses, the 294 analyses of formation waters from pre-Cretaceous aquifers that passed the electronic cull were all examined manually. Formation water analyses from Cretaceous aquifers (83% of those analyses passing the electronic cull) were subjected to a manual-electronic cull, the criteria for which are given in Table 1.

The final data set on which this report is based comprised 525 analyses, or 17.9% of the original data base, a percentage that is in general conformity with that (22.3%) from the adjacent Peace River Arch study area.

Table 1 Manual-electronic culling criteria for formation waters from Cretaceous aquifers, Northeast Alberta study area

Stratigraphic unit	Number after electronic culling	Criteria for manual-electronic culling			
		Rejected if carbonate present	Rejected if SO_4 exceeds this value (mg/l)	Rejected if Cl less than this value (mg/l)	Number after manual-electronic culling
Upper Cretaceous	135	yes	-	-	129
B.F. Sc.	35	yes	100	-	4 (added to Viking)
Viking	153	yes	100	1000	44
Grand Rapids	409	yes	500	1000	120
Clearwater	147	yes	500	1000	54
Wabiskaw	203	yes	500	1000	98
McMurray	383	yes	500	1000	213

REGIONAL HYDROCHEMISTRY

Introduction

It is not necessary to illustrate here the detailed composition distribution maps for each hydrostratigraphic unit and the various tables and cumulative frequency plots produced during this study. Indeed, the interested reader may well disagree with the various culling criteria used and feel it best to carry out specific and different culling methods. Accordingly, only the most general regional hydrochemical trends are described and illustrated.

Elk Point hydrostratigraphic unit

Of the 44 formation waters from the Lower and Middle Devonian Elk Point Group that passed the electronic cull, only 19 remained after manual culling, dominantly from the Keg River aquifer. Because most had similar chemical characteristics they were combined into the Elk Point hydrostratigraphic unit; the data are distributed in a wide northwest-southeast trending band across the study area (Fig. 2).

Salinity ranges from ~40,000 mg/l in some places east of the subcrop (solution) edge of the Prairie halite aquiclude to ~325,000 mg/l (Fig. 2). This latter value is the same as that along the adjacent eastern margin of the Peace River Arch study area (Hitchon, 1990, Fig. 8). The corresponding ranges for Cl are 20,000-200,000 mg/l, which are the suggested limits across the study area for use in calculating formation water density at reservoir temperature for use in hydrodynamic studies. The most saline formation waters have the highest contents of Ca (~40,000 mg/l) and Mg (~8,000 mg/l), with the lower limits in the least saline formation waters of the order of 1200 mg/l Ca and 150 mg/l Mg. Neither Ca nor Mg exceed the minimum detailed exploration limits selected by Hitchon (1984). These trends are in sharp contrast to those for SO_4 (Fig. 3) and HCO_3 (Fig. 4), both of which have higher concentrations closer to the solution edge of the Prairie halite.

Hitchon et al. (1969) showed that saline springs discharging into the Athabasca River and the Slave River in northeastern Alberta result from the solution by meteoric water of halite and gypsum in the Elk Point Group. Selected data from the two saline

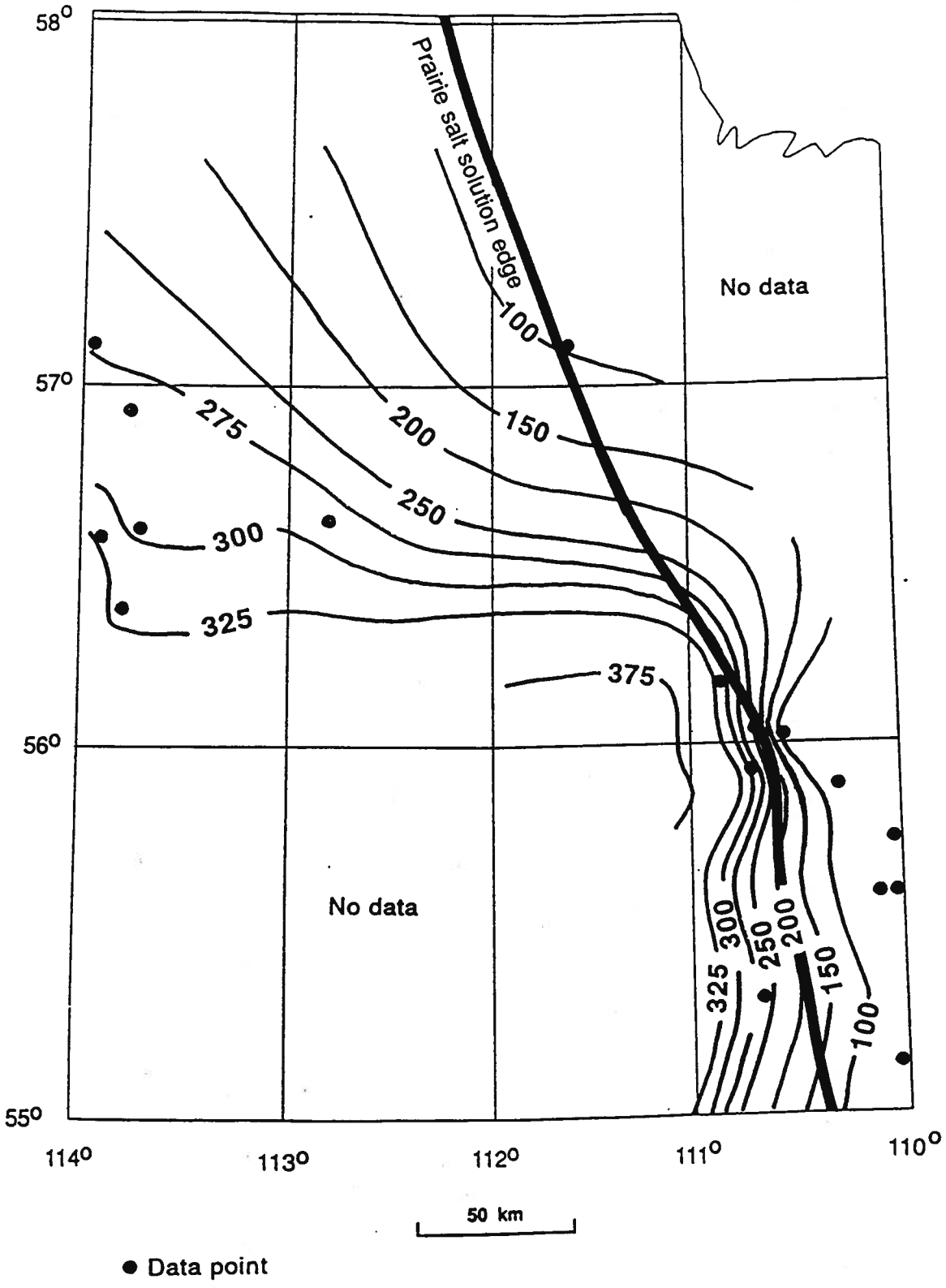

Fig. 2. Salinity distribution (mg/lx10^3) in formation waters from the Elk Point hydrostratigraphic unit (data dominantly from the Keg River aquifer).

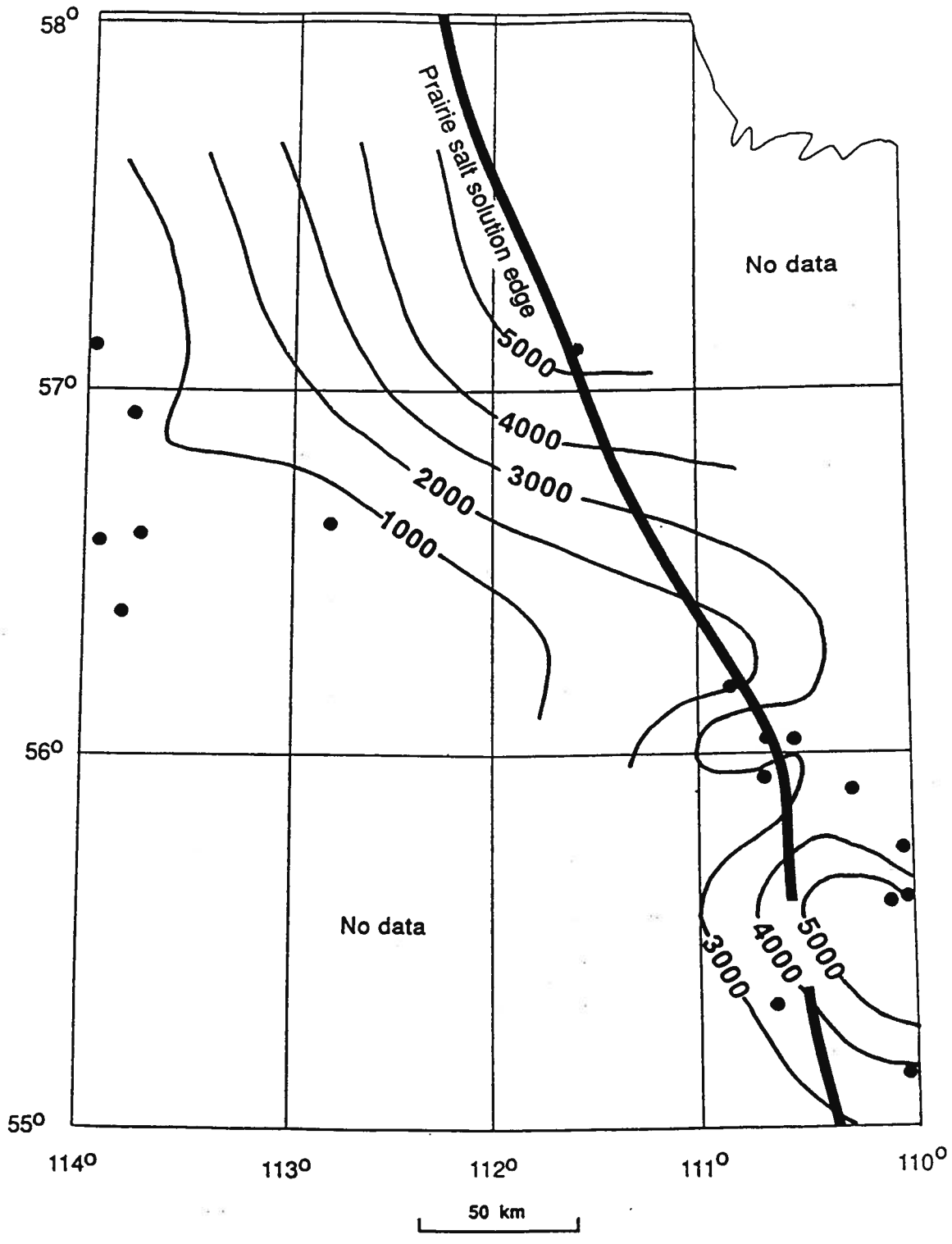

Fig. 3. Sulfate distribution (mg/l) in formation waters from the Elk Point hydrostratigraphic unit (data dominantly from the Keg River aquifer).

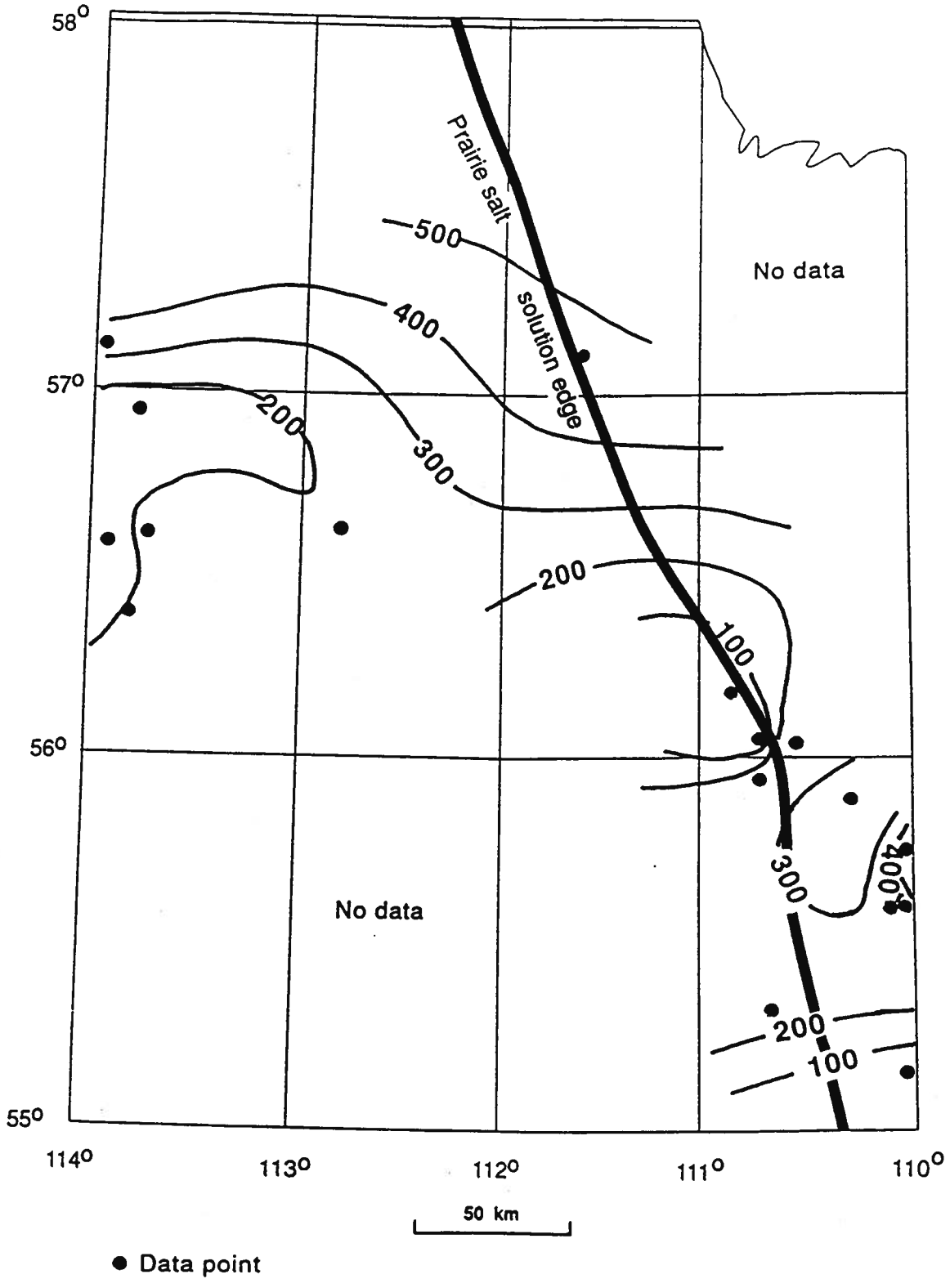

Fig. 4. Bicarbonate distribution (mg/l) in formation waters from the Elk Point hydrostratigraphic unit (data dominantly from the Keg River aquifer).

springs studied by Hitchon et al. (1969) are compared in Table 2 with formation waters from the present study that lie close to the solution edge of the Prairie halite. All have similar characteristics, namely high Na and Cl, high SO_4, and comparably low Ca and Mg, when compared to formation waters of similar salinity elsewhere in the Alberta Basin. Clearly, those formation waters which lie close to the halite solution edge are basically the result of salt solution, and are distinct, particularly in their contents of K (low), Ca (low), Mg (low), SO_4 (high) and HCO_3 (high) from 'true' formation waters of comparable salinity.

Beaverhill Lake aquifer

Preliminary examination of composition distribution maps indicated that formation waters from the Beaverhill Lake and Cooking Lake aquifers should be combined, as was done for the Peace River Arch study area (Hitchon et al., 1990). Figure 5 shows the salinity distribution in this aquifer, which ranges from ~ 20,000 mg/l in the shallower portions to >160,000 mg/l in the southwest corner of the study area. Although the data are sparsely distributed, there is clearly no hydraulic connection with the formation waters in the Elk Point hydrostratigraphic unit, from which the Beaverhill Lake aquifer is separated by the Prairie Formation halite (compare Figs 2 and 5). There are comparable trends for Cl (10,000-95,000 mg/l), Ca (500 to 7500 mg/l) and Mg (250-2000 mg/l). Sulfate is particularly high (1500-5500 mg/l) in these formation waters which probably reflects solution of anhydrite from the immediately underlying Fort Vermilion aquiclude. Bicarbonate is in the range 100 to 700 mg/l without obvious trends. All these observations and trends suggest that the formation waters in the Beaverhill Lake aquifer are distinct from those in the deeper Elk Point hydrostratigraphic unit and have dissolved anhydrite from the underlying Fort Vermilion aquiclude.

Grosmont aquifer

The salinity trends observed in the Grosmont aquifer in the Peace River Arch study area (Hitchon, 1990, Fig. 14) continue into the northeast Alberta study area

Table 2. Comparison of chemical composition (mg/l) and physical properties of formation waters from the Elk Point hydrostratigraphic unit, northeast Alberta, with saline springs studied by Hitchon et al. (1969)

Stratigraphic Unit	Keg River Fm.	Keg River Fm.	Keg River Fm.	-	La Saline (Athabasca River)	Mission Spring (Slave River)
Location	16-13-71-1-W4	11-27-81-4-W4	13-25-81-5-W4	4-32-93-10-W4		
Depth (m)	753.0-761.0	385.0-389.0	488.5	269		
Source	DST1, Bottomhole sampler	DST1, Top of tool	-	Casing, open hole	Surface spring	Surface spring
Recovery	200 m br sw	147 m sw	-	-	-	-
Na	17356	26160	82400	34627 (diff.)	25600	133000
K	48	64	3900	-	64	82
Ca	1298	2410	2065	2015	1830	1020
Mg	483	452	295	559	456	458
Cl	27544	43400	132367	54509	40200	191000
HCO_3	56	361	93	475	475	124
SO_4	3957	3169	3507	5154	4780	3850
TDS (calc.)	50685	75787	222907	97097	73168	329472
pH (laboratory)	6.3	7.4	6.8	6.95	7.51	7.08
Resistivity (ohm, 25°C)	0.168	0.103	0.042	-	0.102	0.0314

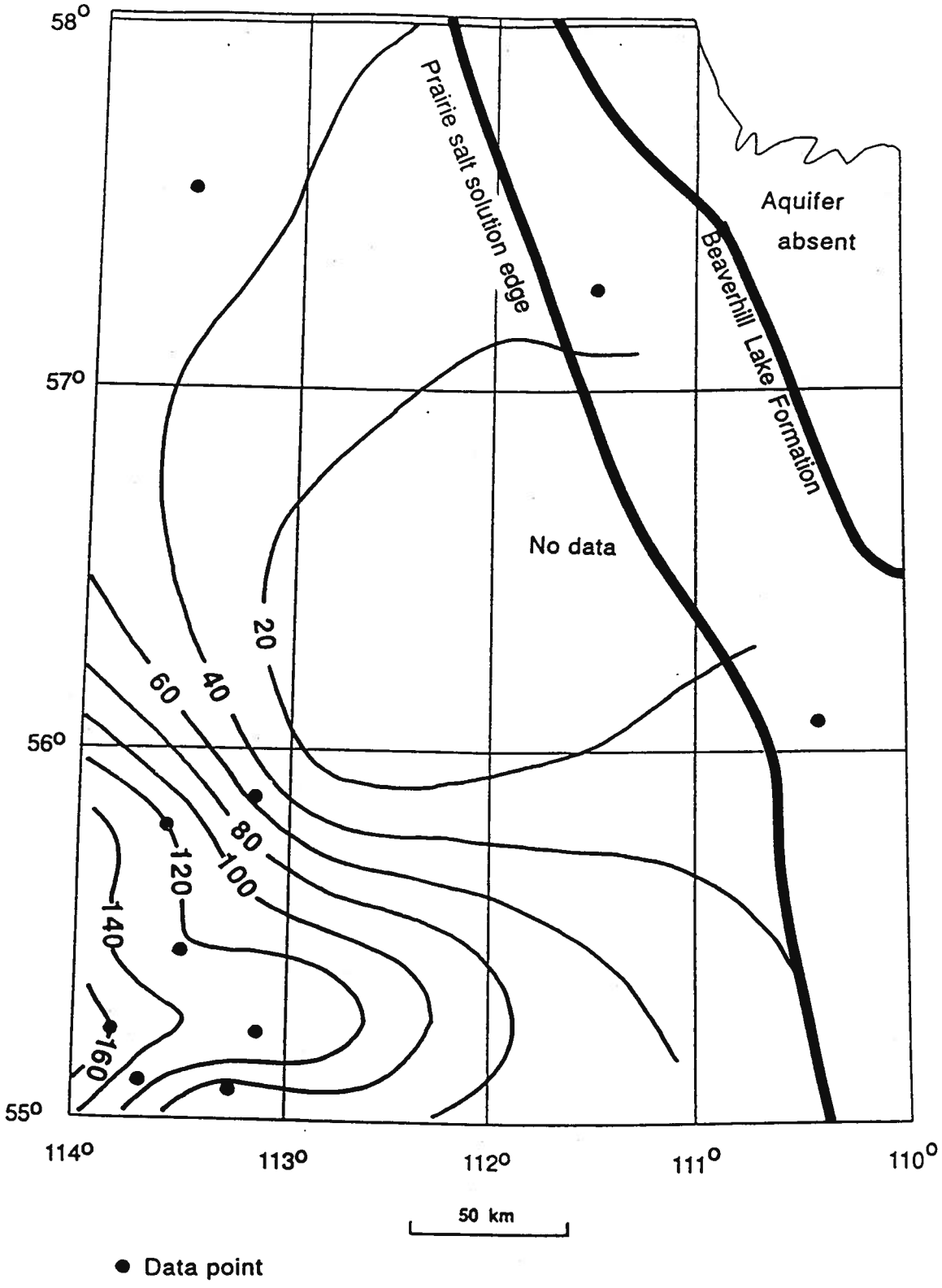

Fig. 5. Salinity distribution (mg/lx10^3) in formation waters from the Beaverhill Lake aquifer.

(Fig. 6), where values as low as 4000 mg/l are found along parts of the eastern subcrop edge; maximum salinity is ~115,000 mg/l. Similar trends and comparable concentrations occur for Cl (1500 to 70,000 mg/l), Ca (<50 to 4500 mg/l), Mg (~10 to 1650 mg/l) and to a major extend SO_4 (a few tens of milligrams per litre in the subcrop region to the range 500-5000 mg/l in the region where salinities are >40,000 mg/l). The trends for HCO_3 are less clear, but contents generally <1250 mg/l occur in the region of more saline formation waters, increasing to slightly >3000 mg/l in parts of the subcrop region.

As a broad generalization, the 50,000 mg/l salinity contour in both the Peace River Arch study area (Hitchon, 1990, Fig. 14) and the northeast Alberta study area (Fig. 6) coincides with the updip eastern margin of the Hondo Formation evaporites(Belyea, 1964, Fig. 6-16). This suggests that the very high SO_4 content of the more saline formation waters in the Grosmont aquifer may be the result of solution of Hondo evaporites, specifically anhydrite.

With respect to salinity, Cl, Ca and Mg, the formation waters in the Grosmont aquifer have similar concentration distributions to those in the Beaverhill Lake aquifer, i.e. very saline in the southwest part of the study area with steep isoconcentration gradients, and a wide area updip with a less saline character. However, salinities are generally at least 40,000 mg/l higher in the deeper aquifer. Bearing in mind the intervening 100-150 m thick Lower Ireton aquitard, this suggests depth (temperature) control of the salinity, Cl, Ca and Mg, as indicated by Hitchon et al. (1990). High SO_4 values are found throughout the Beaverhill Lake aquifer, as are the widespread Fort Vermilion evaporites. In the Grosmont aquifer, where the Hondo evaporites are restricted to the southwestern part of the study area, so are the high-SO_4 formation waters. Thus from comparison of formation waters in these two aquifers it is concluded that salinity, Cl, Ca and Mg are controlled by temperature, SO_4 mainly by solution of interbedded or adjacent evaporites, and HCO_3 by the incursion of fresher water.

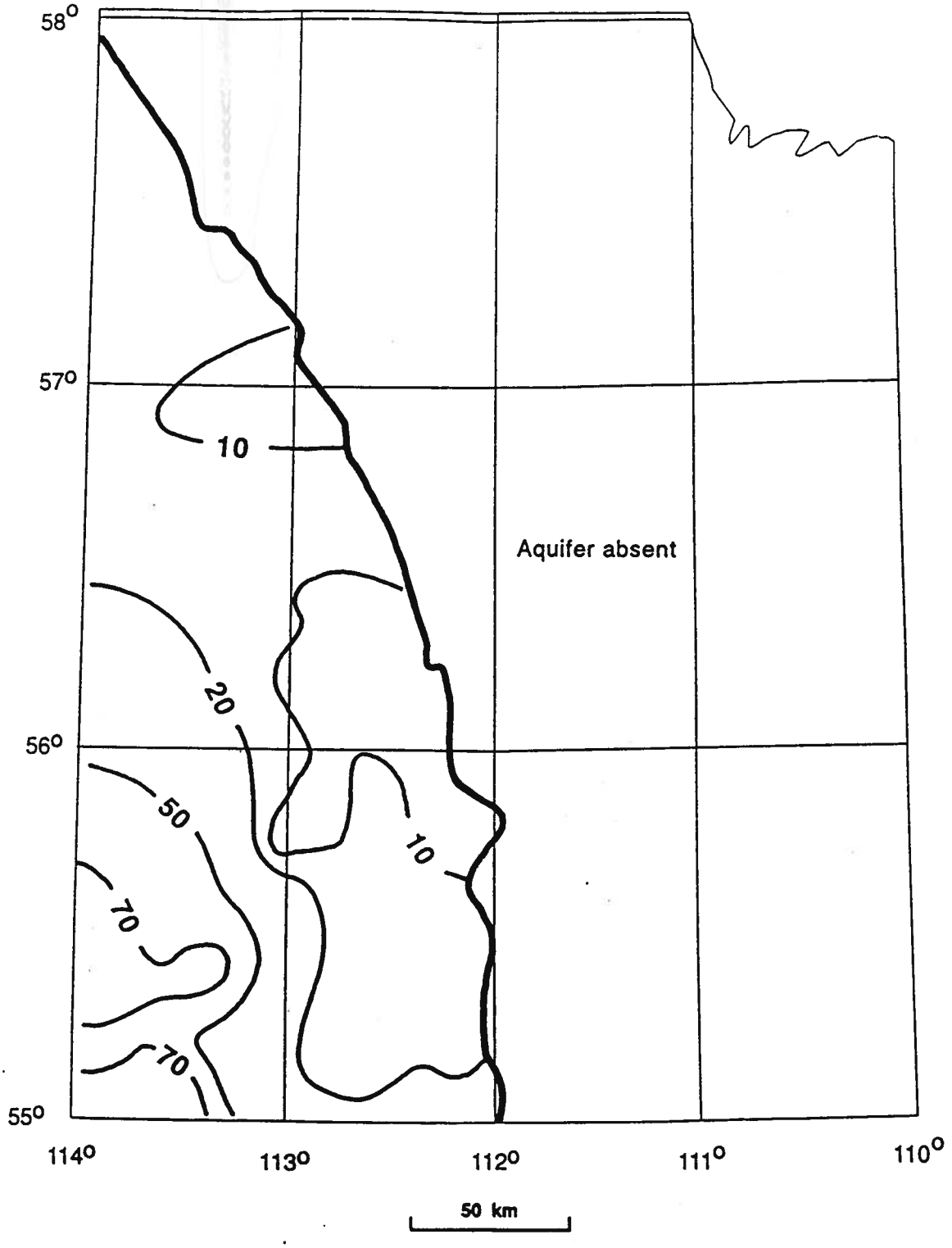

Fig. 6. Salinity distribution (mg/lx10^3) in formation waters from the Grosmont aquifer.

Winterburn aquifer

Salinity distribution in formation waters from the Winterburn aquifer (Fig. 7) decreases from the range 35,000 to 55,000 mg/l against the western edge of the study area to as low as 7000 mg/l in places within the subcrop area. There are similar distribution patterns and comparable composition ranges for Cl (4000 to 30,000 mg/l), Ca (~100 to 900 mg/l) and Mg (50 to 300 mg/l). Salinities <25,000 mg/l have HCO_3 contents generally >1250 mg/l. Sulfate is >500 mg/l in the two samples north of 56°N, but elsewhere is commonly <100 mg/l; there is no obvious explanation for the high values in the north. The trends observed in the Northeast Alberta study area (Fig. 7) are contiguous with those in the adjacent Peace River Arch study area (Hitchon, 1990, Fig. 19).

Wabamun aquifer

Although the Wabamun aquifer only occurs in the extreme southwest corner of the study area, sufficient formation water analyses passed the various culling criteria to have confidence in the composition distribution trends, which are similar to those in the underlying Winterburn aquifer -- with which it is in hydraulic continuity (see Hitchon et al., 1990). The ranges for salinity (~9000 to >35,000 mg/l; Fig. 8), Cl (5000 to 22,000 mg/l), Ca (~50 to 600 mg/l) and Mg (25 to 300 mg/l) are as expected, compared to the trends in the adjacent Peace River Arch study area (Hitchon, 1990). Neither SO_4 nor HCO_3 show significant trends.

McMurray aquifer

In the Peace River Arch study area most aquifers between the Prairie aquiclude and the sub-Cretaceous unconformity showed strong depth (temperature)-related salinity and composition (Cl, Ca, Mg) gradients (Hitchon, 1990; Hitchon et al., 1990). Only in Lower Cretaceous aquifers is this pattern changed to one in which the higher salinities occur mainly in the deeper strata adjacent to the disturbed belt and in an irregular band along the southern margin of the study area. In the generally shallower Cretaceous aquifers of the Northeast Alberta study area the McMurray aquifer is the

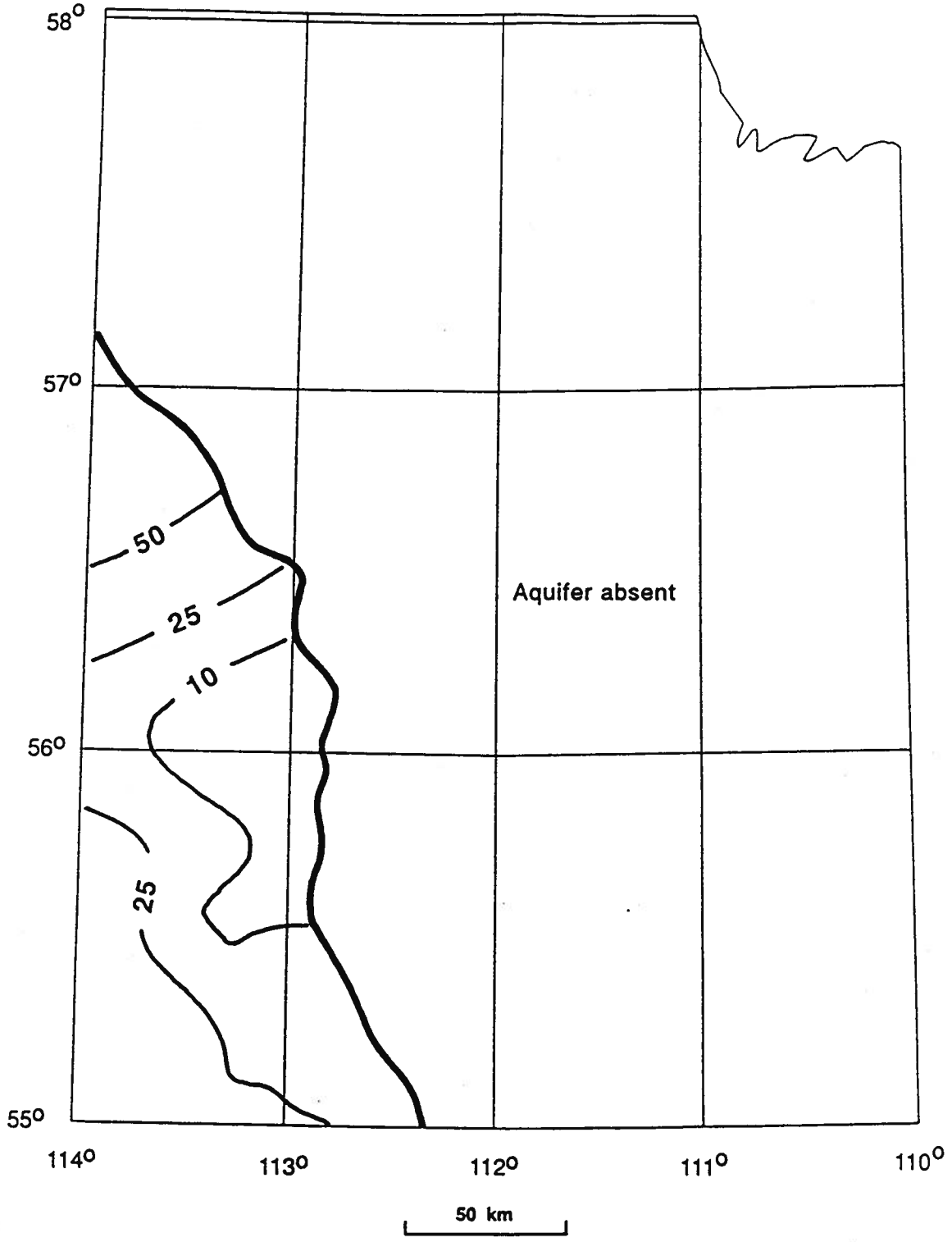

Fig. 7. Salinity distribution (mg/lx10^3) in formation waters from the Winterburn aquifer.

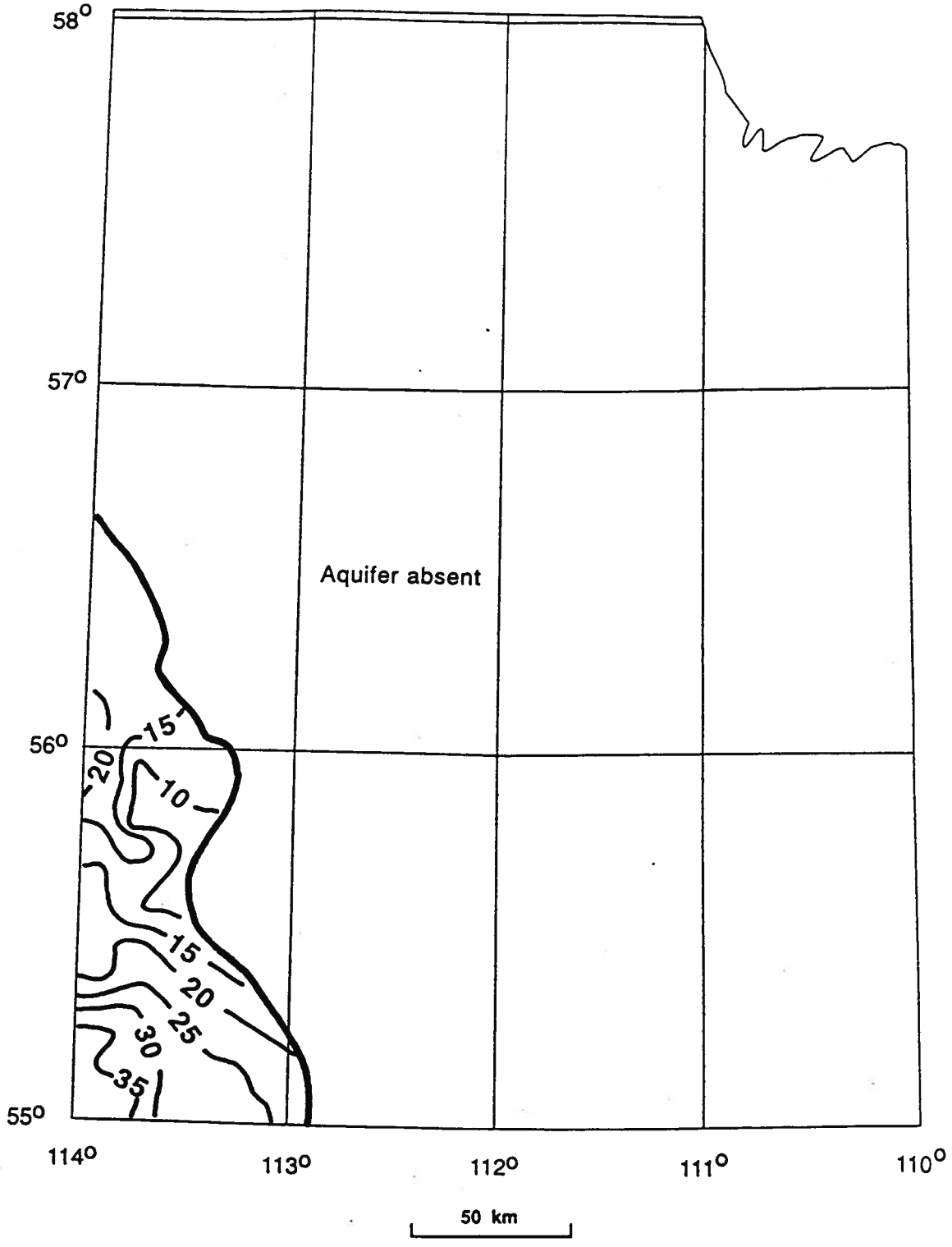

Fig. 8. Salinity distribution (mg/lx10^3) in formation waters from the Wabamun aquifer.

first to show this feature (Fig. 9). Isoconcentration contours south of 56°N are reliable because of the abundant and wide distribution of the data but north of this latitude the contours are tentative due to paucity of data. Maximum values are 33,000 mg/l for salinity, with corresponding values for Cl (20,000 mg/l), Ca (800 mg/l) and Mg (300 mg/l). There are no obvious trends for SO_4 or HCO_3.

In the southwestern portion of the study area, where there are abundant data in both the McMurray aquifer and the immediately underlying aquifers, there is very little difference in salinity between formation waters in the McMurray and sub-Cretaceous aquifers (Fig. 10). For example, regions in the Wabamun and Grosmont aquifers with salinity >20,000 mg/l coincide in a general way with the two regions with salinity >20,000 mg/l in the McMurray aquifer. Likewise, the 10,000 mg/l salinity contour in the McMurray aquifer at about 55°30'N is reflected by the southern margin of the area across the Wabamun, Winterburn and Grosmont aquifers with salinity <10,000 mg/l. Paucity of data north of latitude 56°N makes comparisons speculative. These salinity and compositional similarities suggest good hydraulic continuity across the sub-Cretaceous unconformity in the study area, at least south of 56°N.

Wabiskaw aquifer

There are abundant data on formation waters in the Wabiskaw aquifer only from the extreme southwest corner of the study area; elsewhere the data are sparse and scattered. Figure 11 shows the salinity distribution in this aquifer. As a broad generalization, and where the data are sufficient to allow interpretation, salinity and composition are very similar to those in the underlying McMurray aquifer.

Clearwater aquifer

Data are effectively confined to the extreme southwest corner of the study area, where the salinity isoconcentration contours (Fig. 12) indicate a distribution pattern effectively similar to that in the underlying Wabiskaw and McMurray aquifers.

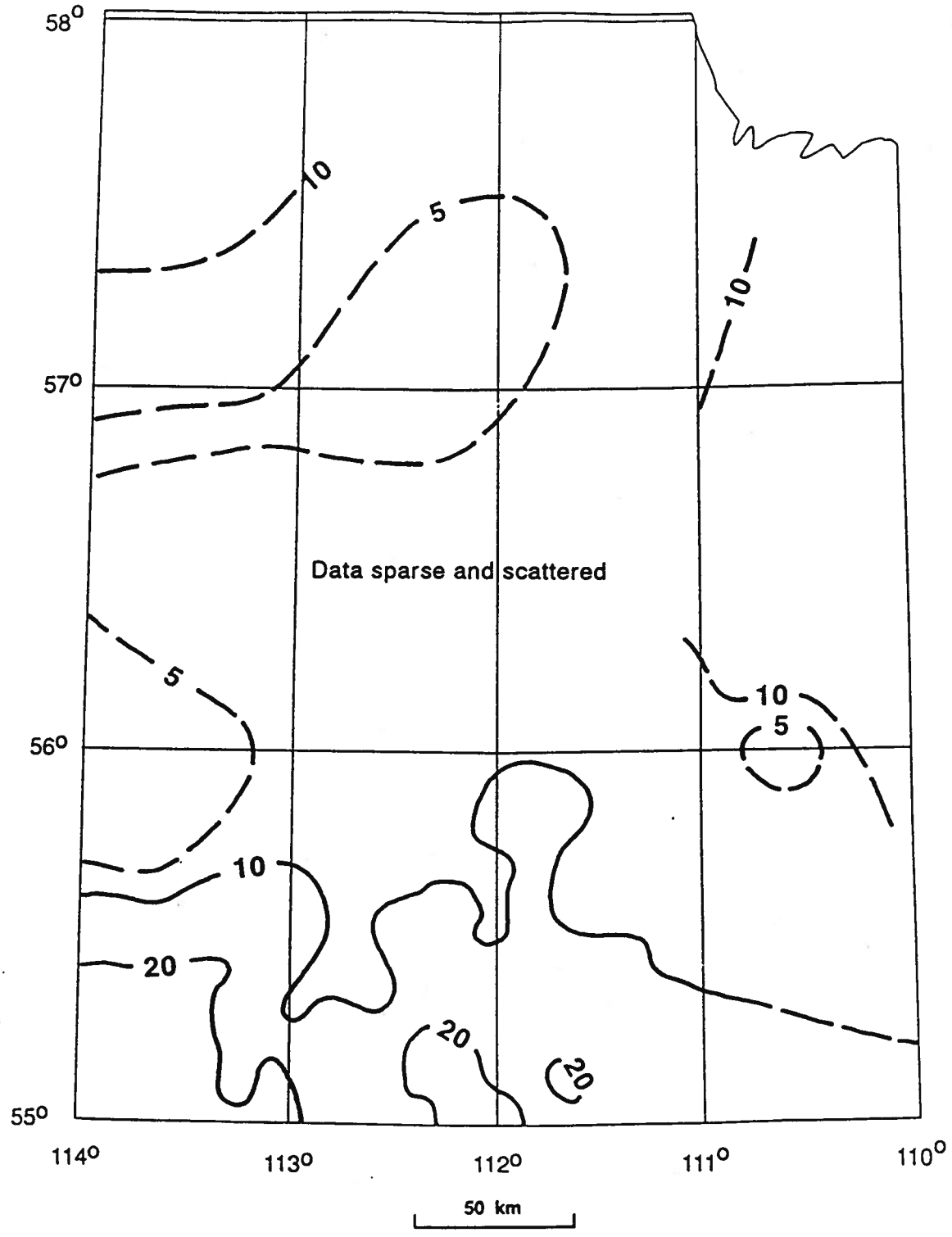

Fig. 9. Salinity distribution (mg/lx10^3) in formation waters from the McMurray aquifer.

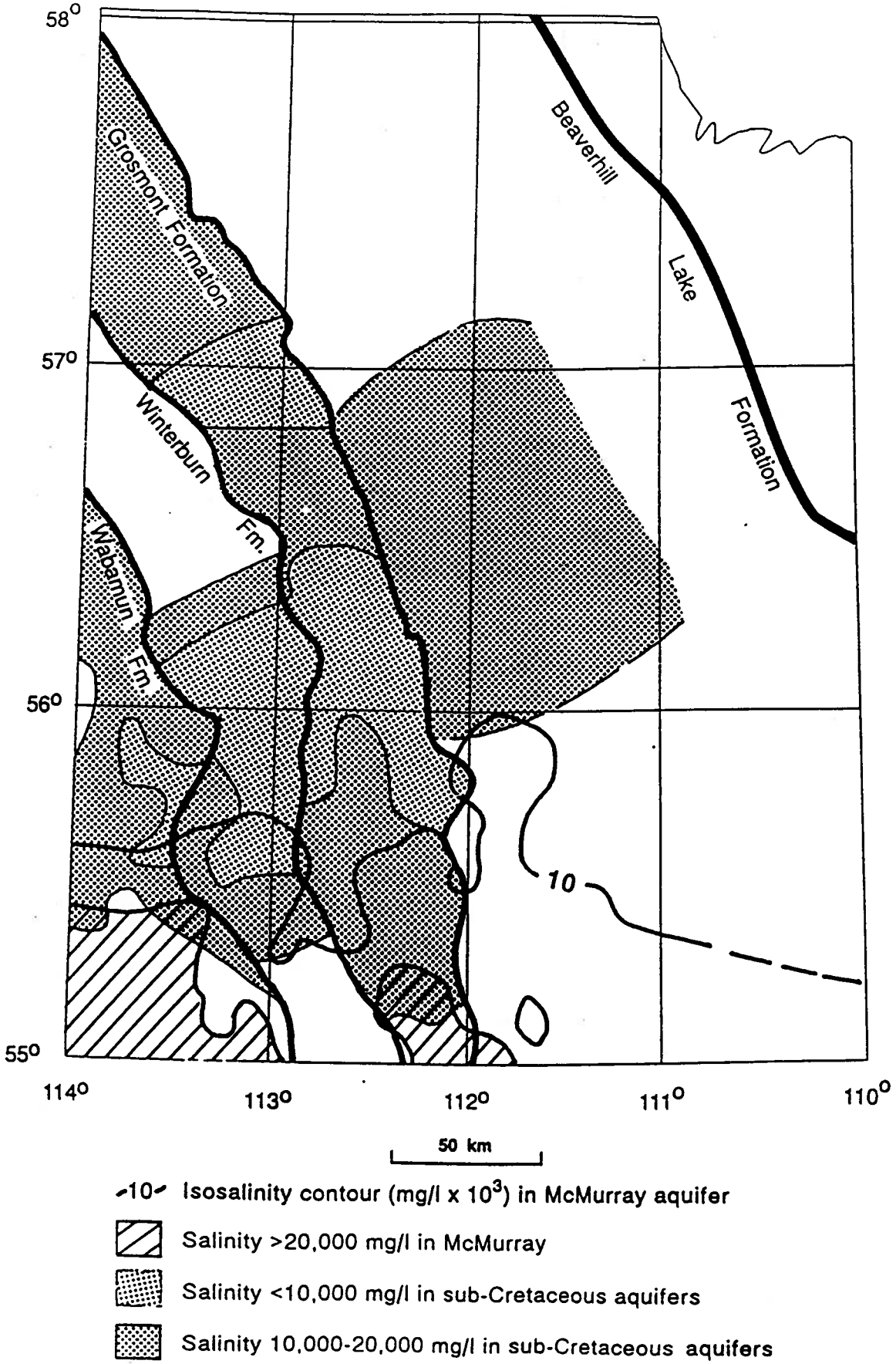

Fig. 10. Comparison of formation water salinity distribution in aquifers above and below the sub-Cretaceous unconformity.

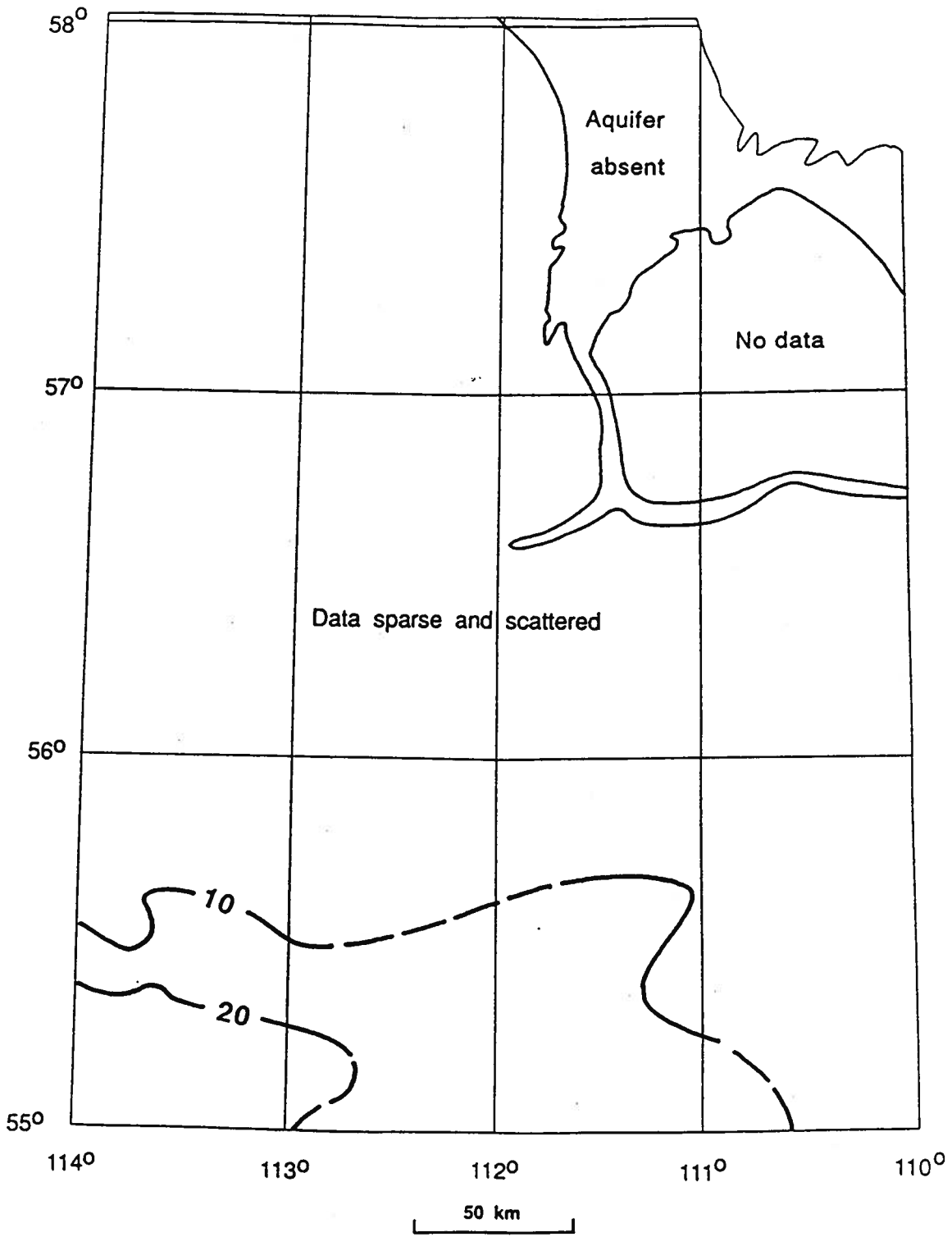

Fig. 11. Salinity distribution (mg/lx10^3) in formation waters from the Wabiskaw aquifer.

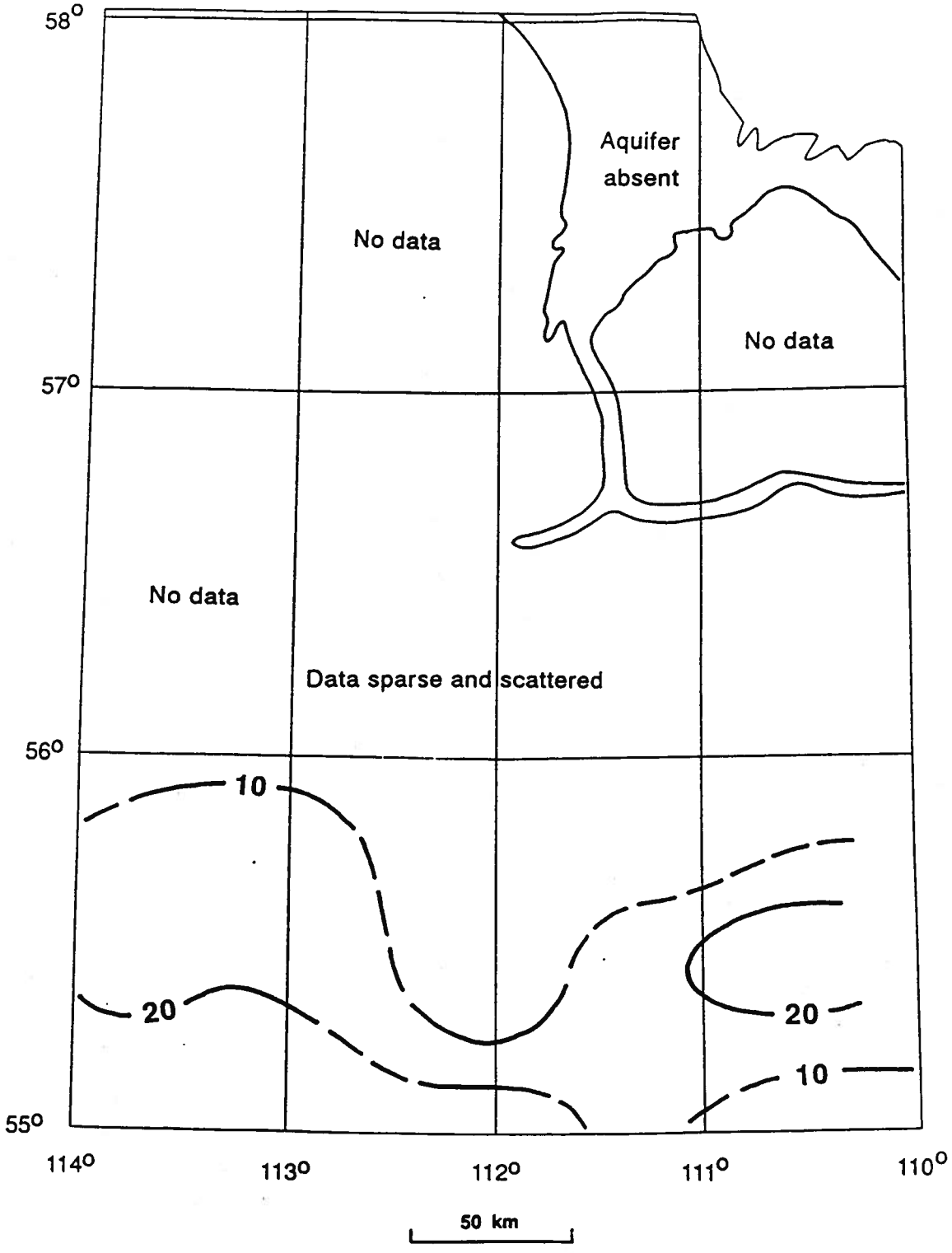

Fig. 12. Salinity distribution (mg/lx10^3) in formation waters from the Clearwater aquifer.

Grand Rapids aquifer

The Grand Rapids aquifer is separated from the underlying Clearwater aquifer by the Clearwater aquitard, which in the adjacent Peace River Arch study area was a significant regional aquitard (Hitchon, 1990; Hitchon et al., 1990). It is not surprising, therefore, that there is a considerable contrast in salinity (Fig. 13) and composition (Cl, Ca, Mg) with the underlying Clearwater, Wabiskaw and McMurray aquifers. As a broad generalization, salinity is half that in the underlying aquifers.

Viking aquifer

Data on formation waters from the Viking aquifer are effectively confined to Tp 70-73 across the western half of the study area. Contour maps show salinity trends similar to those in the Mannville aquifer, which is tentatively interpreted as meaning that the Joli Fou aquitard is a weak aquitard, as it was in the Peace River Arch study area.

Post-Viking aquifers

Data on formation waters from post-Viking aquifers are essentially from near-surface wells drilled for a variety of purposes. The data have not been interpreted in the present study.

Near-surface waters

Although all shallow water data available to the Alberta Geological Survey at the time were entered and verified (total 174 analyses, of which 101 (58%) passed the electronic culling), no attempt was made to interpret them (or their distribution) in the present study.

SUMMARY

A total of 2933 formation water analyses from the Northeast Alberta study area were entered into the Alberta Geological Survey Well Data Base, verified, and

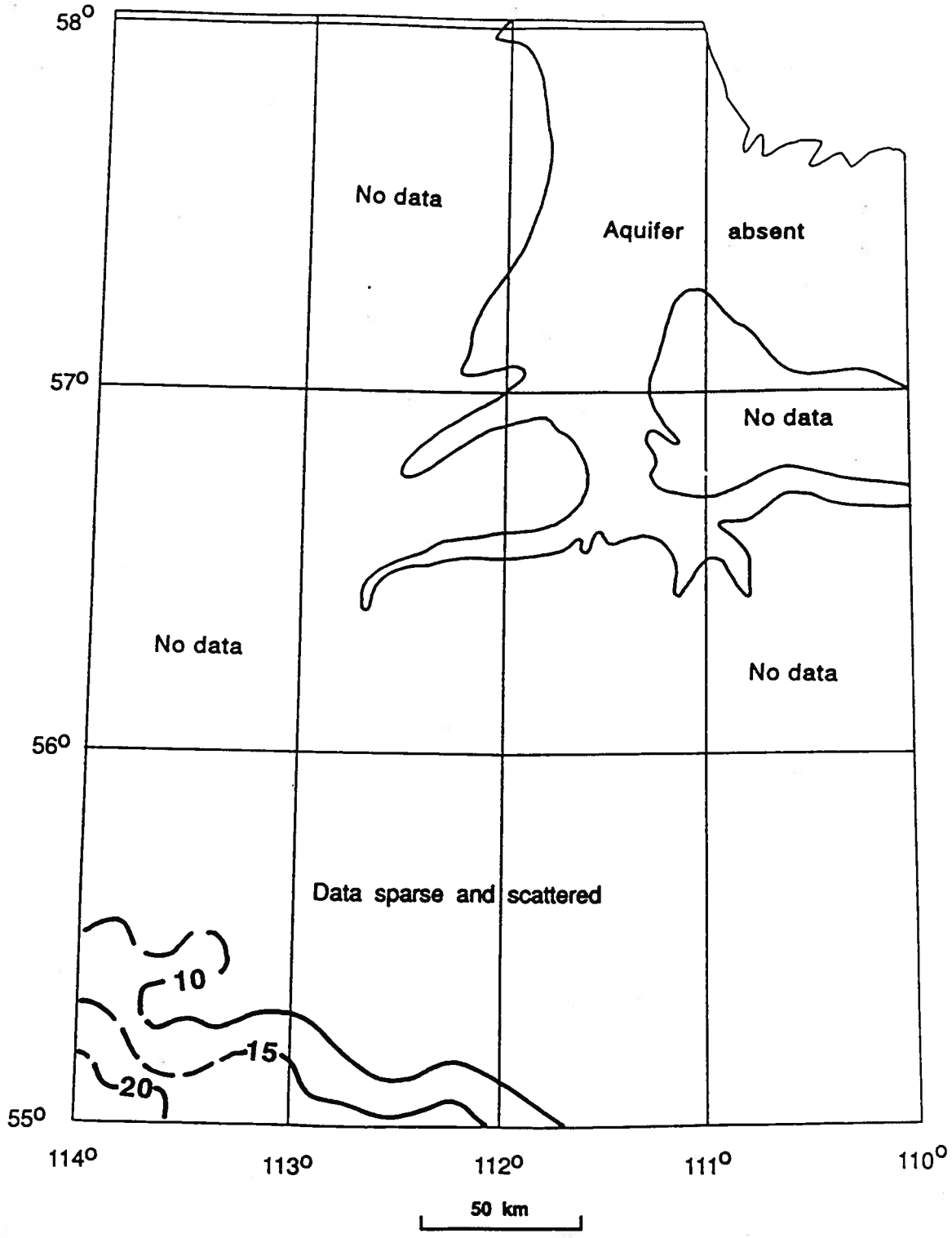

Fig. 13. Salinity distribution (mg/lx10^3) in formation waters from the Grand Rapids aquifer.

subjected to a variety of electronic and manual-electronic culling procedures to leave a data base of about 950 fairly reliable analyses. Subsequent manual culling resulted in a final data base of about 525 formation water analyses on which this report is based.

Salinity distribution maps are shown for nine aquifers, together with information on the contents of Cl, Ca, Mg, SO_4 and HCO_3. The aquifers can be combined into several groups which have similar formation water characteristics and are separated by aquitards. The main groups are as follows:

Viking aquifer

Joli Fou aquitard (weak)

Grand Rapids aquifer

Clearwater aquitard (strong, regional)

Clearwater, Wabiskaw and McMurray aquifers

Sub-Cretaceous unconfirmity (good hydraulic conduit)

Wabamun and Winterburn aquifers

Upper Ireton aquitard (weak)

Grosmont aquifer

Lower Ireton aquitard (strong)

Beaverhill Lake aquifer

Prairie aquiclude

Elk Point hydrostratigraphic unit (mainly Keg River aquifer)

Precambrian aquiclude

In addition to distinguishing these major hydrostratigraphic groups the regional trends for salinity, Cl, Ca and Mg are clearly depth-related and therefore temperature controlled probably because of the low velocity of subsurface waters. There is strong evidence for solution of evaporites in the trends for SO_4 in the Elk Point hydrostratigraphic unit (updip Prairie aquiclude solution edge), Beaverhill Lake aquifer (Fort Vermilion aquiclude, regionally) and Grosmont aquifer (Hondo evaporites, locally). Low salinities and high HCO_3 contents suggest incursion of formation water from overlying aquifers in the Upper Devonian aquifers. Finally, because formation

water composition is similar in aquifers across the sub-Cretaceous unconformity, it is not a barrier to flow.

In summary, the formation waters in the Northeast Alberta area are an extension of those in the adjacent Peace River Arch area and exhibit similar characteristics, namely, salinity mainly controlled by temperature, with high SO_4 if there are associated evaporites, and solution of evaporites due to downward moving meteoric water.

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REFERENCES

Bachu S., Lytviak A.T. and Hitchon B. (1991) Regional hydrogeology of large sedimentary basins: An integrated approach. In Proceedings of the International Conference on "Groundwater in Large Sedimentary Basins", Perth, Australia. Australian Water Resources Council, Conference Series No. 20, pp.464-475.

Bachu S., Sauveplane C.M., Lytviak A.T. and Hitchon B. (1987) Analysis of fluid and heat regimes in sedimentary basins: Techniques for use with large data bases. Bull. Amer. Assoc. Petrol. Geol. 71, 822-843.

Belyea H.R. (1964) Woodbend, Winterburn and Wabamun Groups. In Geological History of Western Canada (eds. R.G. McCrossan and R.P. Glaister), pp. 66-88. Alberta Society of Petroleum Geologists, Calgary.

Hackbarth D. and Brulotte M. (1981) Groundwater observation well network: Athabasca oil sands area. Alberta Research Council Info. Ser. 69.

Hackbarth D. and Nastasa N. (1979) The hydrogeology of the Athabasca oil sands area, Alberta. Alberta Research Council Bull. 38.

Hitchon B. (1990) Hydrochemistry of the Peace River Arch area, Alberta and British Columbia. Alberta Research Council, Open File Report 1990-18.

Hitchon B. (1984) Formation waters as a source of industrial minerals in Alberta. In The Geology of Industrial Minerals in Canada (eds. G.R. Guillet and W. Martin), pp. 247-249. Canadian Inst. of Mining and Metallurgy Spec. Vol. 29.

Hitchon B., Bachu S. and Underschultz J.R. (1990) Regional subsurface hydrogeology, Peace River Arch area, Alberta and British Columbia. Bull. Canadian Petrol. Geol. 38A, 196-217.

Hitchon B., Bachu S., Sauveplane C.M. and Lytviak A.T. (1987) Dynamic basin analysis: An integrated approach with large data bases. In Fluid Flow in Sedimentary Basins and Aquifers (eds. J.C. Goff and B.P.J. Williams), pp. 31-44. Geol. Soc. London Spec. Pub. 34.

Hitchon B., Levinson A.A. and Reeder S.W. (1969) Regional variations of river water composition resulting from halite solution, Mackenzie River drainage basin, Canada. Water Resour. Res. 5, 1395-1403.

Petroleum Geology and Basin Analysis Group (1991) Regional geology and hydrostratigraphy in northeast Alberta. Contract report prepared by the Alberta Research Council for Conservation and Protection, Environment Canada, 1991-08-01.

Toth J. (1978) Gravity-induced cross-formational flow of formation fluids, Red Earth region, Alberta, Canada: Analysis, patterns, and evolution. Water Resour. Res. 14, 805-843.