INDUSTRIAL MINERAL POTENTIAL
OF
ALBERTA FORMATION WATERS

Prepared for

Alberta Energy under Contract M92-04-011
Canada/Alberta Partnership Agreement on Mineral Development

by

Brian Hitchon (Hitchon Geochemical Services Ltd.)

and

J. R. Underschultz and S. Bachu
(Alberta Geological Survey, Alberta Research Council)

ALBERTA RESEARCH COUNCIL
Edmonton, Alberta, Canada

1993-06-01

PREFACE

This report deals with geochemical exploration for industrial minerals in formation waters from Alberta, and was funded under MDA contract M92-04-11. It is the first part of a two-part study, with the second part concerned with a resource evaluation of areas identified as of potential economic interest.

The report is formatted as an Alberta Research Council bulletin, which is intended for release some time in 1993.

Acknowledgements

Special thanks are due Campbell Kidston and Kelly Roberts who did the major portion of the technical manipulation of the data and the computer preparation of the illustrations. The nearly 700 detailed special analyses were prepared for computer manipulation by Kathie J. Skogg. Secretarial duties were ably carried out by Margaret Booth. The manuscript has benefitted from the critical reviews of R. Olson and W. Hamilton.

Contents

Tables

Figures

Appendix

Abstract

An electronic data base of nearly 130,000 analyses of formation waters from Alberta and adjacent areas was searched for elements of potential economic interest. For regional exploration, the elements and threshold values were: Ca (20,000 mg/l), Mg (3,000 mg/l), K (5,000 mg/l), Li (50 mg/l), Br (1,000 mg/l) and I (40 mg/l). Using a variety of culling procedures, element concentration maps, and maps of posted values of individual analyses, areas were identified where these elements exceeded their respective detailed exploration threshold values: Ca (60,000 mg/l), Mg (9,000 mg/l), K (10,000 mg/l), Li (75 mg/l), Br (3,000 mg/l) and I (100 mg/l).

Aquifers and areas identified as justifying further resource evaluation are: (1) Lower Elk Point in northern Alberta associated with the Cold Lake and Lotsberg salts, for Ca, Mg, K and Br; (2) Beaverhill Lake in southern Alberta, for Ca, Mg, K and Br; (3) a high-Li trend associated with the Devonian Windfall-Swan Hills carbonate complexes; and (4) parts of the Viking and Belly River of central and southern Alberta, for I.

Introduction

Historical background

Formation waters have been a source of industrial minerals, *sensu lato*, from prehistoric times. Hanor (1987) has reviewed the development of thought on the origin of saline formation waters and noted that early man in Europe was aware that some groundwaters and springs were salty and took commercial advantage of this fact. Indeed, many towns and cities in central Europe owe their location to saltworks. Doubtless the Indians roaming Alberta were aware of most springs, including the saline ones along the Athabasca River north of Fort McMurray -- whether they used them is not known.

The link between the saline spring and its source was first established in 1670 by a coal prospector in Cheshire, England, who used primitive drilling techniques to discover the presence of rock salt at a depth of 32 m below ground surface (Multhauf, 1978). In the case of the La Saline spring north of Fort McMurray, it took almost another 300 years and modern chemical and isotope techniques to confirm the origin of the dissolved salts as due to dissolution of halite and anhydrite by meteoric water (Hitchon et al., 1969).

We have not been able to establish exactly when formation waters were first used as sources of industrial minerals, in the modern sense, but it was doubtless at least early in the last century. Since that time many of the industrialized countries have used their formation waters for their chemical industry, including Canada -- and specifically Alberta.

Analyses of formation waters from Alberta have become available since the 1930s through drilling by the petroleum industry. Since WW II the Alberta Energy Resources Conservation Board published quarterly reports comprising compilations of formation water analyses, mainly by fields and pools, but also periodic separate compilations of formation waters with Br and I. None of these analyses was specifically identified as being of potential commercial interest, although clearly some were. By the 1970s the Energy Resources Conservation Board files contained sufficient formation water analyses from stratigraphic units throughout the province to justify a search for specific analyses of possible interest to industry and to be fairly certain that no major regional exploration areas would be overlooked. The result was a report on Ca and Mg in Alberta brines (Hitchon and Holter, 1971) and one on Br, I and B in Alberta formation waters (Hitchon et al., 1977). More recently, a confidential report was prepared for an industrial client on Li in Alberta formation waters (Hitchon, 1984b). Apart from these reports, there have been no publications on the regional distribution of elements of potential interest.

Definitions and scope of study

The perceptive reader will have noticed that the terms groundwater, formation water, saline formation water and brine have been used in the previous section to refer to waters found underground. There is no universally recognized classification of underground waters. The terms and definitions used in this open file report are arbitrary and as generic as possible:

groundwater: shallow formation water, commonly potable (salinity generally < 1,000 mg/l)

formation water: preferred generic term for all underground water, regardless of salinity

saline formation water: loosely used for formation water with salinity > 100,000 mg/l

brine: strictly for formation water with salinity > 100,000 mg/l, but saline formation water is the preferred term

In searching for potential resources, information on the geochemistry and origin of formation waters is important, as is an understanding of the regional and local hydrogeology. An exploration program therefore comprises three phases:

1. Geochemical exploration

   Using minimum regional exploration limits for the components of interest, areas are identified within each aquifer where the formation waters exceed the specified threshold values. An understanding of the origin of formation waters can assist in suggesting areas of interest for which there are no data. Within the regional exploration areas may lie smaller areas where the specific thresholds for detailed exploration are exceeded.

2. Resource evaluation

   The hydrogeological characteristics (mainly porosity and permeability) of the aquifer within each detailed exploration area for each component of interest are evaluated with respect to both the aquifer and the contained fluids. The objective is to identify potential target areas for drilling.

3. Site specific evaluation

   Before a well is drilled, all required production parameters need to be identified and provision made for the collection of appropriate data and samples. These include, but are not limited to, drillstem tests, cores, and the collection and proper preservation and analysis of formation water samples.

The scope of the work presented in this open file report is limited to phase 1.

Threshold values

Formation waters are geochemically continuous features, unlike ore bodies which are geochemically discontinuous with their host rocks. Therefore, the concepts of regional threshold values (background), local threshold values (outlining the primary dispersion zone), and anomalies (ore bodies) do not strictly apply to formation waters. Instead, Hitchon (1984a) defined a detailed exploration threshold value for each element of interest based on their current economically producing fields. In order to allow for machine contouring of sparse data and extrapolation into undrilled areas, a lower regional exploration threshold value was also defined for each element of interest. Regions where a particular component is above the specified detailed exploration threshold value may be of potential economic value and would commonly justify phase 2 evaluation.

The threshold values used in this study are based on those given by Hitchon (1984a), together with additional information specific to this study. These values are compared in table 1 with the composition of the commercial brine produced by The Dow Chemical Co., Midland, Michigan, USA, from the Lower Devonian Sylvania Sandstone. The detailed exploration threshold values are rounded numbers generally close to the values in the commercial brine, except for I which is based on commercial values other than the Michigan brine. The regional exploration threshold values are generally about one third the corresponding detailed exploration threshold.

Data base and data processing

Data base

The main source of formation water analyses in Alberta is the Alberta Energy Resources

Table 1. Threshold values for regional and detailed exploration, compared with a commercial brine.

Component sought	Regional exploration threshold value (mg/l)	Detailed exploration threshold value (mg/l)	Commercial brine (ppm)	
			Ref. A	Ref. B
Ca	20,000	60,000	74,800	72,200
Mg	3,000	9,000	9,960	9,200
K	5,000	10,000	9,120	8,000
Li	50	75	70	58
Br	1,000	3,000	2,910	2,790
I	40	100	40	34

A. White et al. (1963, Table 13, No. 8).

B. Egleson and Querio (1969, Table 1, avg. of analyses from 51 wells).

Conservation Board; most of the analyses are of samples collected by the petroleum industry under provincial regulations. The majority of analyses are 'standard' analyses in which sodium (Na) is determined as the difference between the analyzed anions [chloride (Cl), sulphate (SO_4), bicarbonate (HCO_3), carbonate (CO_3)] and cations [calcium (Ca), magnesium (Mg)], therefore including accumulated analytical and other errors; only occasionally are minor and trace elements reported. Although these 'standard' analyses are vital to studies such as that reported here, especially those analyses which include minor and trace elements of interest (Br, I, Li), in general 'standard' analyses are of limited utility for detailed work such as evaluating water-rock reactions and scaling problems. This deficiency becomes rapidly apparent for a phase 3 evaluation at the site specific level.

Two other sources of analytical data were used in this study. The first source comprises published detailed analyses from Hitchon et al. (1971), Hitchon et al. (1989) and Connolly et al. (1990 a, b). The second source is formed of two sets of unpublished detailed analyses in the files of the senior author. The first set, the so-called D-series, are formation waters collected by the senior author in the summer of 1972 from Devonian and pre-Devonian oil and gas fields throughout Alberta and northeastern British Columbia. The samples were collected under optimum conditions with temperature, pH, Eh (redox) and alkalinity determined in the field, and aliquots treated for preservation of minor and trace elements as appropriate. Minor and trace elements of interest include K, Br, I and Li.

The second set, and the majority of the unpublished detailed analyses, comprises the so-called RCAH - series (Research Council of Alberta Hitchon - series). These samples were collected in 1975-1977 through a co-operative project with the Energy Resources Conservation Board. All were from drillstem tests of then currently drilled wells. The produced water was subsampled by the operating company for the Energy Resources Conservation Board and the Alberta Research Council (then Research Council of Alberta). Major components were determined by the Energy Resources Conservation Board and selected minor and trace elements by the Alberta Research Council. The majority of the trace elements were determined by Chemical and Geological Laboratories Ltd. of Edmonton. Analytical techniques used for the D-series and RCAH-series included atomic absorption, inductively coupled plasma and specific ion electrode.

Both the published detailed analyses and the unpublished detailed analyses were entered into the electronic Alberta Geological Survey Well Data Base (AGSWDB) and verified. They were then run through the geochemical computer program SOLMINEQ.88 (Kharaka et al., 1988). In addition to computing the charge balance, either the CO_2 or the mineral dissolution/precipitation option was used until saturation with calcite was obtained at formation temperature. Two thirds of the analyses had charge balances < 5%, and one quarter had charge balances between 5% and 10%. Analyses with charge balances > 15% were removed from the data base. Full details of the manipulations carried out can be found in Hitchon (1993). It is sufficient to note here that 697 detailed analyses were added to AGSWDB following checking with SOLMINEQ.88.

Before using the 'standard' analyses in this study, they were culled using an automatic (electronic) culling program designed to reject obviously erroneous analyses or incomplete analyses. The criteria used are shown in table 2. The final data base used in this studytherefore combined the 'standard' analyses that had passed the automatic culling program with the detailed analyses that had passed the SOLMINEQ.88 program. The data base was then searched for Ca, Mg, K, Li, Br and I at or above the specified threshold values.

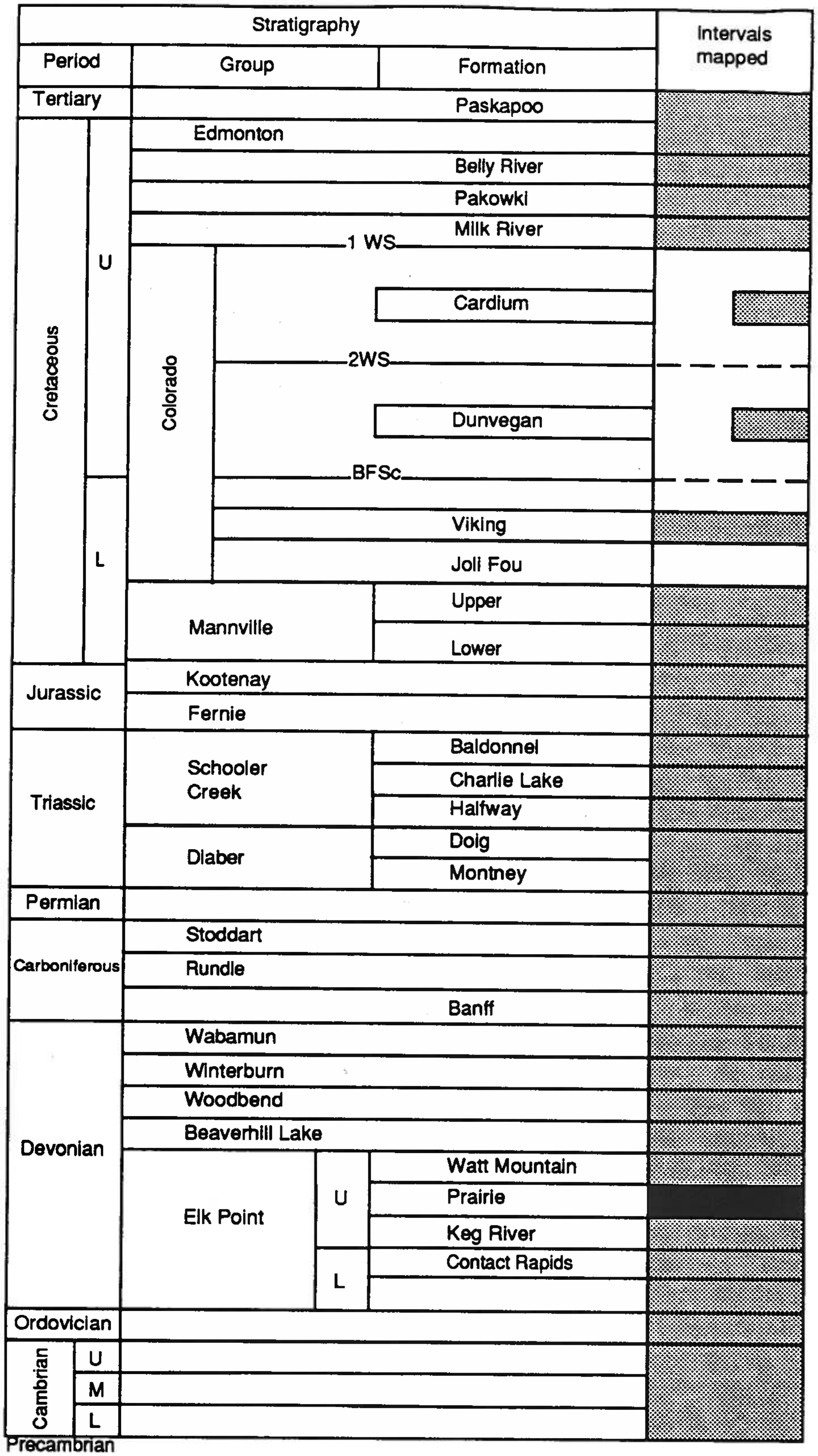
Data processing

The study area was arbitrarily defined as the province of Alberta, plus 2° longitude of western Saskatchewan, 2° longitude of eastern British Columbia and 1° latitude of southern Northwest Territories. This was done to avoid possible edge effects at Alberta boundaries due to automatic contour extrapolation. Only information within Alberta is reported here.

Many of the techniques for use with large hydrogeological data bases as described by Hitchon et al. (1987) and Bachu et al. (1987) were used in this study and will only be noted briefly. The analyses in the formation water data base were automatically assigned to their respective stratigraphic units using preliminary electronic surfaces (grids) from the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1993). Figure 1 shows the specific intervals used in this study. Several are dominantly aquitards

Table 2. Automatic (electronic) culling criteria for 'standard' formation water analyses.

Criteria	Possible causes
OH reported	Wash from cement job; poor analysis
Ca and Mg reported as equivalent Ca	Incomplete analysis; insufficient sample; very low Ca + Mg, hence difficulty in determination
Any of Ca, Mg, Cl, HCO_3 or SO_4 zero, missing, or reported as <or> value	Incomplete analysis; insufficient sample; very low content, hence difficulty in determination
pH <5.0 or> 12.0 (0.0 is considered no pH reported)	Acid wash contamination or wash from cement job, respectively; typing error in decimal point
Mg > Ca	Usually signifies significant loss of CO_2 and precipitation of $CaCO_3$ before analysis; sample not preserved in the field or a long time between sampling and analysis; very low Ca + Mg, hence difficulty in determination
Density < 1.0	Poor determination, organic matter contamination; contamination with alcohol additive to drilling mud
Na (calculated) is negative	Poor analysis
If a drillstem test, more than one test interval is reported	Sample from multiple aquifers



Period		Group		Formation	Intervals mapped
Tertiary				Paskapoo	▨
Cretaceous	U	Edmonton			▨
				Belly River	▨
				Pakowki	▨
				Milk River	▨
		Colorado		1 WS	
				Cardium	▨
				2WS	– – –
				Dunvegan	▨
				BFSc	– – –
	L				
				Viking	▨
				Joli Fou	
		Mannville		Upper	▨
				Lower	▨
Jurassic		Kootenay			▨
		Fernie			▨
Triassic		Schooler Creek		Baldonnel	▨
				Charlie Lake	▨
				Halfway	▨
		Diaber		Doig	▨
				Montney	▨
Permian					▨
Carboniferous		Stoddart			▨
		Rundle			▨
				Banff	▨
Devonian		Wabamun			▨
		Winterburn			▨
		Woodbend			▨
		Beaverhill Lake			▨
		Elk Point	U	Watt Mountain	▨
				Prairie	■
				Keg River	▨
			L	Contact Rapids	▨
					▨
Ordovician					▨
Cambrian	U				▨
	M				▨
	L				▨
Precambrian					

Figure 1. Generalized stratigraphic nomenclature, showing the intervals mapped (stippled). Aquicludes in black; aquitards blank.

and one (Prairie Formation) is an aquiclude; analyses falling within these aquitards or aquiclude were, respectively, from stray aquifers and were considered separately or were in error with respect to depth and were reassigned to the correct interval. Once assigned to their stratigraphic interval, the chemical data were searched for analyses reporting elements exceeding the pertinent threshold values. Due to the coarseness of the atlas grids, considerable manual re-allocation of analyses was required.

Because Ca and Mg were reported in all analyses evaluated, they were treated together and by slightly different methods from the other components. For plotting (mapping) purposes, a content of Ca exceeding 10,000 mg/l or of Mg exceeding 2,000 mg/l triggered inclusion of the analysis in the samples to be studied, rather than the regional exploration threshold values given in table 1. This allowed more reliable plotting of the regional threshold value contours. Preliminary examination of regional maps of Cl, Ca and Mg distribution, together with print-outs of the data, revealed many anomalies due to a variety of causes. These included, but were not limited to: (1) high Ca and low pH, possibly with high Mg, due to acid washes or swabbing; (2) high K due to KCl - mud contamination; (3) high Ca, sometimes also high Mg, together with high Fe, due to evaporation and corrosion within separators or treaters; (4) low Ca and/or low Mg, compared to adjacent analyses, as a result of dilution by fresh water or drilling mud during a drillstem test; (5) high Ca and possibly high Mg due to evaporation in a holding tank (all samples from tanks were discarded, as were all bailed samples); (6) analyses from AOF tests where there was high Ca and Cl as a result of evaporation of formation water in the gas stream;

and (7) anomalously high Ca combined with anomalously low Mg, compared with the Ca + Mg of adjacent samples, indicating possibly a bad analysis -- this was particularly noticeable in some of the pre-1950 analyses. All analyses with Ca > 30,000 mg/l and Mg > 5,000 mg/l (arbitrary values) were checked individually; this was to ensure that there was absolutely no chance for a potential source to be overlooked.

Table 3 shows the total number of formation water analyses with Ca > 10,000 mg/l and/or Mg > 2,000 mg/l by stratigraphic unit. Those culled on the first pass were removed for one of the seven reasons cited above, together with a few which were incorrectly assigned due to the coarseness of the surface grids but then reassigned correctly. In most cases the second set of Cl, Ca and Mg distribution maps, together with print-outs of the data, was sufficient. Stratigraphic units with either many analyses or with regions designated for detailed exploration commonly required a third culling to remove analyses not caught previously, and specifically to remove individual analyses which did not follow the local composition trends in areas of dense data points. The third set of Cl, Ca and Mg distribution maps was that reported here.

Potassium was reported in > 52,350 formation water analyses, of which 92% were below the regional exploration threshold of 5000 mg/l (table 4). Many of the values > 5000 mg/l are the result of contamination by KCl muds. These contaminated samples were removed by an electronic screening process. The Appendix gives the general statistics for the K/Na x 10^3 value in formation waters from 29 stratigraphic units. The

Table 3. Processing of formation waters for Ca and Mg.

Stratigraphic unit	Total analyses	Culled on first pass	Culled (or reassigned) on second pass	Final data set
Cretaceous				
Belly River Fm.	4	4	-	-
Lea Park Fm.	1	1	-	-
Upper Colorado Gp.	10	10	-	-
Dunvegan Fm.	1	1	-	-
BFSc to Viking Fm.	18	18	-	-
Viking Fm.	1	1	-	-
Joli Fou Fm.	14	14	-	-
U. Mannville Gp.	94	42	14	38
L. Mannville Gp.	130	36	18	76
Jurassic				
Kootenay Gp.	73	36	6	31
Fernie Gp.	44	23	-	21
Triassic				
Baldonnel Fm.	7	7	-	-
Charlie Lake Fm.	70	14	6	50
Halfway Fm.	86	21	-	65
Diaber Gp.	15	7	3	5
Permian	9	9	-	-
Carboniferous				
Stoddart Gp.	43	12	-	31
Rundle Gp.	138	86	-	52
Banff Fm.	67	34	-	33
Devonian				
Wabamun Gp.	745	131	62	552
Winterburn Gp.	1267	370	95	802
Woodbend Gp.	1083	152	151	780
Beaverhill Lake Gp.	928	239	97	592
Elk Point Gp.				
Watt Mountain Fm.	640	130	65	445
Keg River Fm.	69	7	-	62
L. Elk Point Gp.	1434	302	108	1024
Ordovician	10	1	-	9
Cambrian	136	41	28	67
Precambrian	9	9	-	-
TOTAL	7146	1758 (24.6%)	653 (9.1%)	4735 (66.3%)

Table 4. Processing of formation waters for K.

Stratigraphic unit	K(mg/l)		No. of samples		
	Min.	Max.	K<5000	K5000-10,000	K>10,000
Tertiary, Wapiti Fm.	0.1	81,900	1,530	83	108
Upper Cretaceous					
Belly River Fm.	0.29	50,830	1,761	80	182
Lea Park Fm.	0.02	40,500	647	23	43
Milk River Fm.	1.0	38,000	292	20	54
Cardium Fm.	0.1	41,900	836	38	98
Dunvegan Fm.	2.0	46,880	215	14	34
Lower Cretaceous					
Viking, Bow Island Fms.	0.1	82,000	7,293	247	287
U.Mannville Gp.	0.3	112,000	10,393	292	344
L.Mannville Gp.	0.4	93,845	8,038	171	321
Jurassic	0.1	83,250	3,423	126	220
Triassic	1.0	93,900	1,924	179	206
Permian	2.0	34,000	263	13	11
Carboniferous					
Stoddard, Rundle Gps.	0.1	65,000	2,171	94	116
Banff Fm.	1.0	78,000	1,322	37	46
Devonian					
Wabamun Gp.	0.4	99,310	1,369	61	49
Winterburn Gp.	0.3	27,800	1,031	150	32
Woodbend Gp.	1.0	32,460	896	103	24
Beaverhill Lake Gp.	0.5	97,500	1,749	42	28
Watt Mountain Fm.	1.0	41,500	1,378	24	16
Keg River Fm.	14.0	9,810	37	6	-
L. Elk Point Gp.	2.0	17,500	1,482	19	3
Ordovician	26.0	1,668	5	-	-
Cambrian	4.0	110,000	63	35	18
Precambrian	14.6	71,200	122	11	5
Total			48,240	1,868	2,245

Table 4. cont.

No. remaining after electronic culling			No. remaining after manual culling		
K<5000	K5000-10,000	K>10,000	K<5000	K5000-10,000	K>10,000
964	2	2	891	-	-
1,316	-	1	1,318	-	-
512	-	3	492	-	-
218	3	2	211	-	-
679	-	2	668	-	-
166	1	5	162	-	-
6,474	-	3	6,310	-	-
9,266	7	1	9,248	-	-
7,275	2	1	7,253	-	-
3,124	1	-	3,099	-	-
1,753	28	1	1,738	6	-
235	-	1	234	-	-
2,055	9	3	2,037	1	-
1,275	-	-	1,274	-	-
1,312	36	2	1,307	9	-
991	114	2	988	103	-
872	95	2	881	133	-
1,719	26	7	1,713	25	6
1,367	14	-	1,367	7	-
33	1	-	79	7	-
1,472	14	-	1,432	1	-
5	-	-	5	-	-
50	18	-	40	-	-
117	3	-	-	-	-
43,250	374	38	42,747	292	6

analyses were separated in those from producing wells, which were definitely uncontaminated, and those from drillstem tests believed to be free from KCl mud contamination. Bearing in mind the different numbers of samples and areal distribution of samples within each unit, there is effectively no difference between the producing and drillstem test groups. Separate K/Na x 10^3 statistics were prepared for stratigraphic units with high-Ca formation waters. Based on the data in the Appendix, a threshold value of K/Na x 10^3 was set for each major stratigraphic unit (table 5), above which the analysis was rejected. The electronic culling removed about 98% of extreme values (K > 10,000 mg/l), 80% of intermediate values (K 5000 - 10,000 mg/l) and 10% of values below the regional exploration threshold. All remaining analyses reporting K > 5000 mg/l were examined individually. Further culling was accomplished using maps of postings of selected values, and contour maps for some stratigraphic units of potential interest, but no attempt was made to rigorously screen data below the regional exploration threshold. The final data base comprises 298 analyses above the regional exploration threshold, of which only 6 analyses are above the detailed exploration threshold.

Lithium was reported in 708 formation water analyses, of which > 95% were from the unpublished detailed analyses made available for this study. All analyses with Li above the regional exploration threshold (50 mg/l) were from these unpublished analyses, and no culling was necessary because of the rigorous screening and checking prior to entry into the data base. The processing information in table 6 reflects minor re-allocation of

Table 5. Threshold values of K/Na x 10^3 for culling formation waters contaminated by KCl mud.

Stratigraphic unit	**Rejected if K/Na x 10^3 exceeds this value**
Tertiary	50
Upper Cretaceous	50
Lower Cretaceous	100
Jurassic	100
Triassic	100
Permian	100
Carboniferous	200
Devonian	
Wabamun, Winterburn Gps.	200
Woodbend Gp.	250
Beaverhill Lake Gp. (Ca < 60,000 mg/l)	200
(Ca > 60,000 mg/l)	1,000
Elk Point Gp. (Ca < 60,000 mg/l)	200
(Ca > 60,000 mg/l)	1,000
Lower Paleozoic	200

Table 6. Processing of formation waters for Li.

Stratigraphic unit	**Li (mg/l)**		**Final no. of samples**		
	Min.	**Max.**	**Li < 50**	**Li 50-75**	**Li > 75**
Tertiary, Wapiti Fm.	0.01	1.6	14	-	-
Upper Cretaceous					
Belly River Fm.	0.1	2.6	29	-	-
Lea Park Fm.	0.4	1.0	3	-	-
Milk River Fm.	0.3	5.2	4	-	-
Cardium Fm.	0.6	3.0	5	-	-
Dunvegan Fm.	-	-	-	-	-
Lower Cretaceous					
Viking, Bow Island Fms.	0.2	21.0	161	-	-
U. Mannville Gp.	0.3	34.0	118	-	-
L. Mannville Gp.	1.5	48.0	69	-	-
Jurassic	1.6	49.0	35	-	-
Triassic	4.0	68.0	14	10	-
Permian	9.0	40.0	6	-	-
Carboniferous					
Stoddart, Rundle Gps.	1.8	60.0	35	9	-
Banff Fm.	3.0	52.0	12	1	-
Devonian					
Wabamun Gp.	3.7	115.0	27	1	7
Winterburn Gp.	7.6	90.0	16	10	4
Woodbend Gp.	5.3	140.0	8	9	23
Beaverhill Lake Gp.	0.01	130.0	18	-	7
Watt Mountain Fm.	26.0	98.0	14	5	2
Keg River Fm.	32.0	95.0	2	2	3
L. Elk Point Gp.	0.01	71.0	22	2	-
Cambrian	-	81.0	-	-	1
Total			612	49	47

some samples due to coarseness of the electronic stratigraphic grids. The final data base comprises 96 analyses above the regional exploration threshold, of which 47 analyses are above the detailed exploration threshold.

Bromide (the ionic form in which Br occurs in all the formation waters) was reported in nearly 2330 formation water analyses (table 7), with 97% of the values below the regional exploration threshold (1000 mg/l). All analyses with Br > 1000 mg/l were examined individually. Further culling and re-allocation was accomplished using postings of selected values and contour maps for selected stratigraphic units. No attempt was made to screen, rigorously, values below the regional exploration threshold. The final data base comprises 51 analyses above the regional exploration threshold, none of which is above the detailed exploration threshold.

Iodide (the ionic form in which I occurs in all the formation waters) was reported in 3480 formation water analyses (table 8), of which 93% were below the regional exploration threshold (40 mg/l). All analyses with I > 40 mg/l were examined individually. Maps of postings of specific values, and contour maps were used for selected stratigraphic units to cull the data further, but no attempt was made to rigorously screen data below the regional exploration threshold. The final data base comprises 100 analyses above the regional exploration threshold of which only 3 are above the detailed exploration threshold.

Table 7. Processing of formation waters for Br.

Stratigraphic unit	Br (mg/l)		No. of samples			Final data base		
	Min.	Max.	Br<1000	Br1000-3000	Br>3000	Br<1000	Br1000-3000	Br>3000
Tertiary, Wapiti Fm.	0.1	504	61	-	-	55	-	-
Upper Cretaceous								
Belly River Fm.	1.3	200	72	-	-	80	-	-
Lea Park Fm.	1.3	160	20	-	-	5	-	-
Milk River Fm.	5.0	73	5	-	-	5	-	-
Cardium Fm.	0.6	597	22	-	-	19	-	-
Dunvegan Fm.	2.7	80.1	4	-	-	4	-	-
Lower Cretaceous								
Viking, Bow Island Fms.	1.0	73,113	408	2	2	406	-	-
U. Mannville Gp.	0.1	613	332	-	-	324	-	-
L. Mannville Gp.	0.4	2,585	307	1	-	308	-	-
Jurassic	0.3	350	121	-	-	112	-	-
Triassic	1.3	278	40	-	-	40	-	-
Permian	72.0	196	8	-	-	7	-	-
Carboniferous								
Stoddart, Rundle Gps.	1.0	533	104	-	-	107	-	-
Banff Fm.	0.03	590	37	-	-	35	-	-
Devonian								
Wabamun Gp.	0.7	1,068	138	2	-	130	-	-
Winterburn Gp.	3.9	5,728	244	7	1	227	4	-
Woodbend Gp.	10.0	2,115	116	18	-	134	22	-
Beaverhill Lake Gp.	0.25	2,786	93	4	-	88	4	-
Watt Mountain Fm.	8.0	1,180	40	1	-	42	-	-
Keg River Fm.	-	-	-	-	-	6	19	-
L. Elk Point Gps.	9.0	1,360	84	22	-	84	2	-
Ordovician	-	-	-	-	-	-	-	-
Cambrian	44.0	363	2	-	-	2	-	-
Precambrian	328.0	1,530	9	1	-	-	-	-
Total			2,267	58	3	2,220	51	-

Table 8. Processing of formation waters for I.

Stratigraphic unit	I (mg/l)		No. of samples			Final Data Base		
	Min.	Max.	I<40	I40-100	I>100	I<40	I40-100	I>100
Tertiary, Wapiti Fm.	0.01	980	80	5	4	81	-	-
Upper Cretaceous								
Belly River Fm.	1.0	102	114	18	1	128	14	-
Lea Park Fm.	0.3	44	33	3	-	3	-	-
Milk River Fm.	1.0	44	15	1	-	15	-	-
Cardium Fm.	1.0	174	24	8	2	27	3	-
Dunvegan Fm.	4.0	29.4	6	-	-	6	2	-
Lower Cretaceous								
Viking, Bow Island Fms.	0.01	1,279	511	40	5	510	41	1
U. Mannville Gp.	0.05	4,613	549	9	7	550	5	-
L. Mannville Gp.	0.06	4,656	537	9	6	538	-	-
Jurassic	0.05	342	171	8	3	165	-	-
Triassic	1.16	106	66	5	1	68	1	-
Permian	5.0	1,479	9	1	1	8	2	-
Carboniferous								
Stoddart, Rundle Gps.	0.4	47	146	1	-	150	2	-
Banff Fm.	0.01	4,998	74	1	3	71	1	-
Devonian								
Wabamun Gp.	0.27	450	172	6	7	162	-	-
Winterburn Gp.	1.0	1,159	247	5	11	225	-	1
Woodbend Gp.	0.07	520	128	7	7	148	2	-
Beaverhill Lake Gp.	0.25	169.5	131	12	1	127	5	-
Watt Mountain Fm.	0.03	2,200	69	3	2	70	-	-
Keg River Fm.	4.59	36.2	4	-	-	28	18	1
L. Elk Point Gp.	0.03	120	139	30	1	119	1	-
Ordovician	-	3.0	1	-	-	1	-	-
Cambrian	6.0	15.9	3	-	-	3	-	-
Precambrian	1.0	610	11	5	1	-	-	-
Total			3,240	177	63	3203	97	3

Evaluation of potential resources

The industrial mineral potential of Alberta formation waters is treated by stratigraphic units rather than by commodities in this study. This makes sense economically because more than one component may be extracted from a given resource, as is done by The Dow Chemical Co. at Midland, Michigan. Any geochemical deficiencies in this approach will be taken care of in the summary at the end of this section.

Precambrian

Although Frape and Fritz (1987) reported brines from the exposed Canadian Shield at depths of up to 1 km, no analyses from the present data base could be assigned, unequivocally, to the Precambrian, *sensu stricto*. Of the nine analyses reporting Ca and Mg above the threshold vales and assigned to the Precambrian due to the coarseness of the electronic stratigraphic grid (table 3), most were deleted for a variety of reasons, and two reassigned to the overlying Lower Elk Point aquifer. All analyses reporting K (table 4), Br (table 7) and I (table 8) were first culled of erroneous data and then reassigned to overlying stratigraphic units.

Cambrian

Bachu et al. (1986) studied the hydrogeology of the basal Cambrian aquifer in south-central Alberta, and presented a suite of hydrochemical maps. The distribution of Ca (figure 2) and Mg (figure 3) in formation waters from Cambrian aquifers is similar to that found by Bachu et al. (1986), bearing in mind that the present study included aquifers above the basal Cambrian sandstone. Maximum contents of both Ca and Mg are found in deep strata adjacent to the disturbed belt and in the northern part of the region, although only rarely is Ca > 30,000 mg/l and Mg > 4,000 mg/l. The distribution patterns suggest that commercial contents of Ca and Mg will not be found in Cambrian aquifers in Alberta. Potassium was < 3,500 mg/l in 40 analyses (table 4), without any obvious regional trends. One sample from the Upper Cambrian at 15-17-61-15-W5M reported 81 mg/l Li (table 6), a value above the detailed exploration limit. At this location the Upper Cambrian Lynx Formation is overlain by ~ 52 m of Middle Devonian Watt Mountain Formation siliciclastics, and then by the carbonates of the Swan Hills Formation (Beaverhill Lake Group). Formation waters from the Swan Hills aquifer within a few townships have up to 130 mg/l Li. This suggests that formation waters from Upper Cambrian aquifers (particularly the Lynx Formation) beneath the Swan Hills Formation in this region should be analysed for Li. Maximum contents of Br and I in the few formation waters from Cambrian aquifers reporting these elements were 363 mg/l and 15.9 mg/l, respectively.

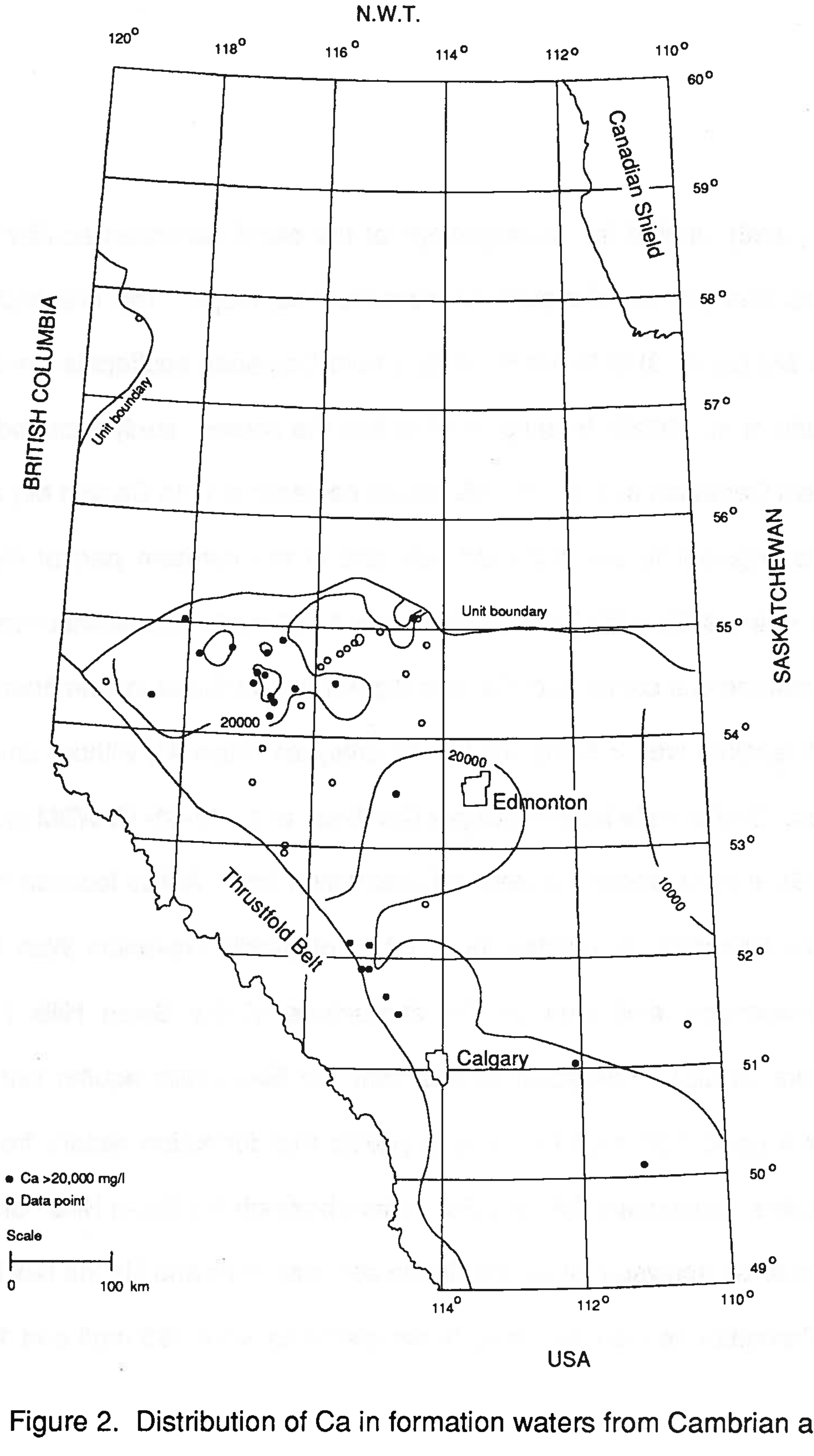


Figure 2. Distribution of Ca in formation waters from Cambrian aquifers.

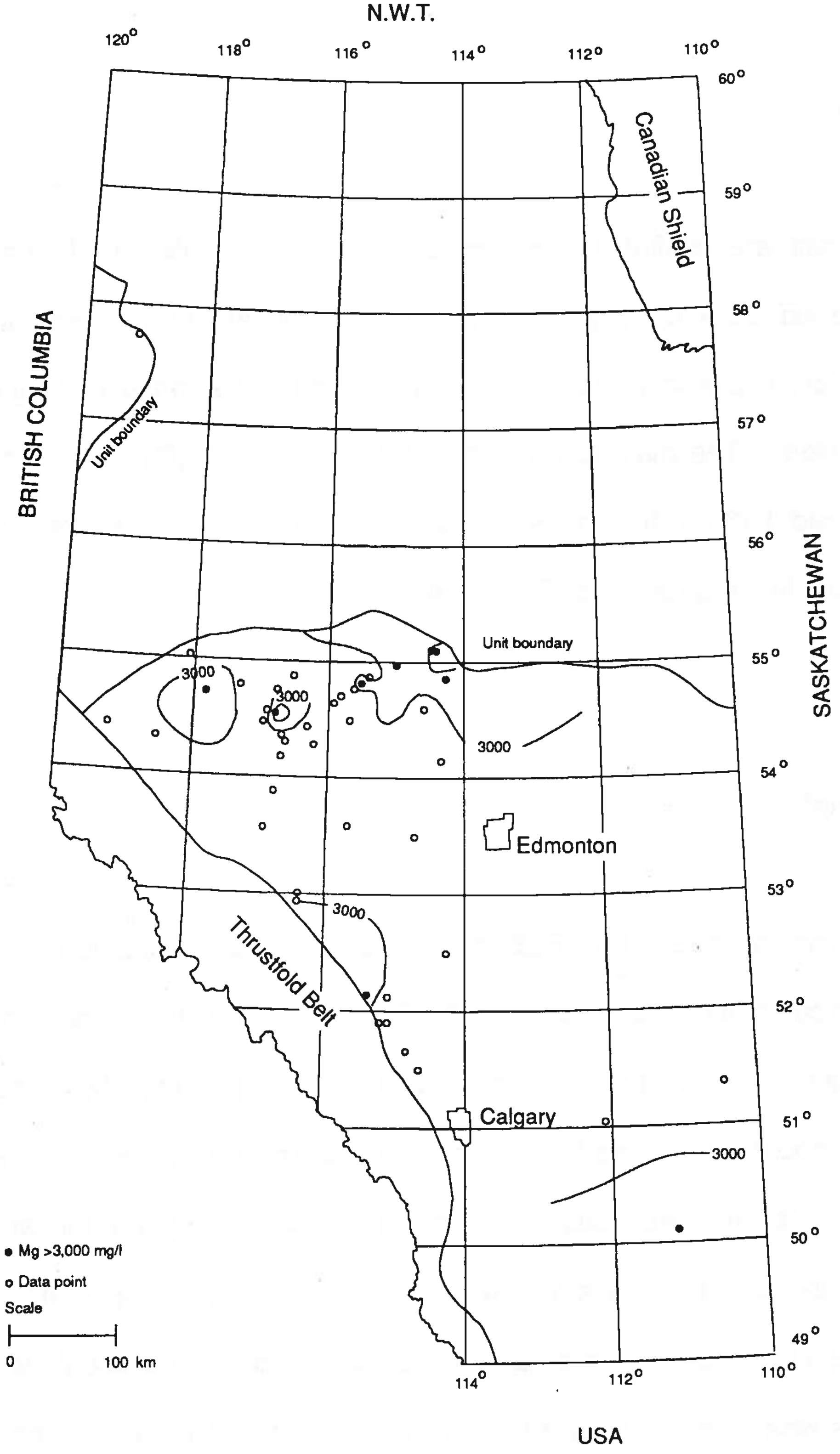


Figure 3. Distribution of Mg in formation waters from Cambrian aquifers.

Ordovician

Ordovician strata are confined to southeastern Alberta. Only four formation water analyses reported Ca and Mg above the regional exploration threshold values. The regional variations in the content of both Ca and Mg are similar to those in the underlying Cambrian aquifers. The maximum content of K was about 1,700 mg/l and only one analysis reported I (3 mg/l). Industrial minerals are unlikely to be recovered from formation waters in Ordovician aquifers in Alberta.

Devonian

Lower Elk Point

This interval comprises aquifers in Middle and Lower Devonian strata below the Keg River Formation, and commonly includes Granite Wash aquifers where these are present above the Precambrian. Most of the formation waters with Ca and Mg above the regional exploration threshold limits come from the northern half of the province. The content of Ca exceeds the detailed exploration threshold value (60,000 mg/l) in eleven analyses (figure 4 and table 9). The content of Mg exceeds the detailed exploration threshold value (9000 mg/l) in all but two of the same eleven analyses (figure 5 and table 9). There are two regions which warrant detailed exploration. The southern region, approximately bounded by the 40,000 mg/l Ca contour, coincides with the western half of the distribution of the Lotsberg salt (Grayston et al., 1964). The northern region, represented by a single

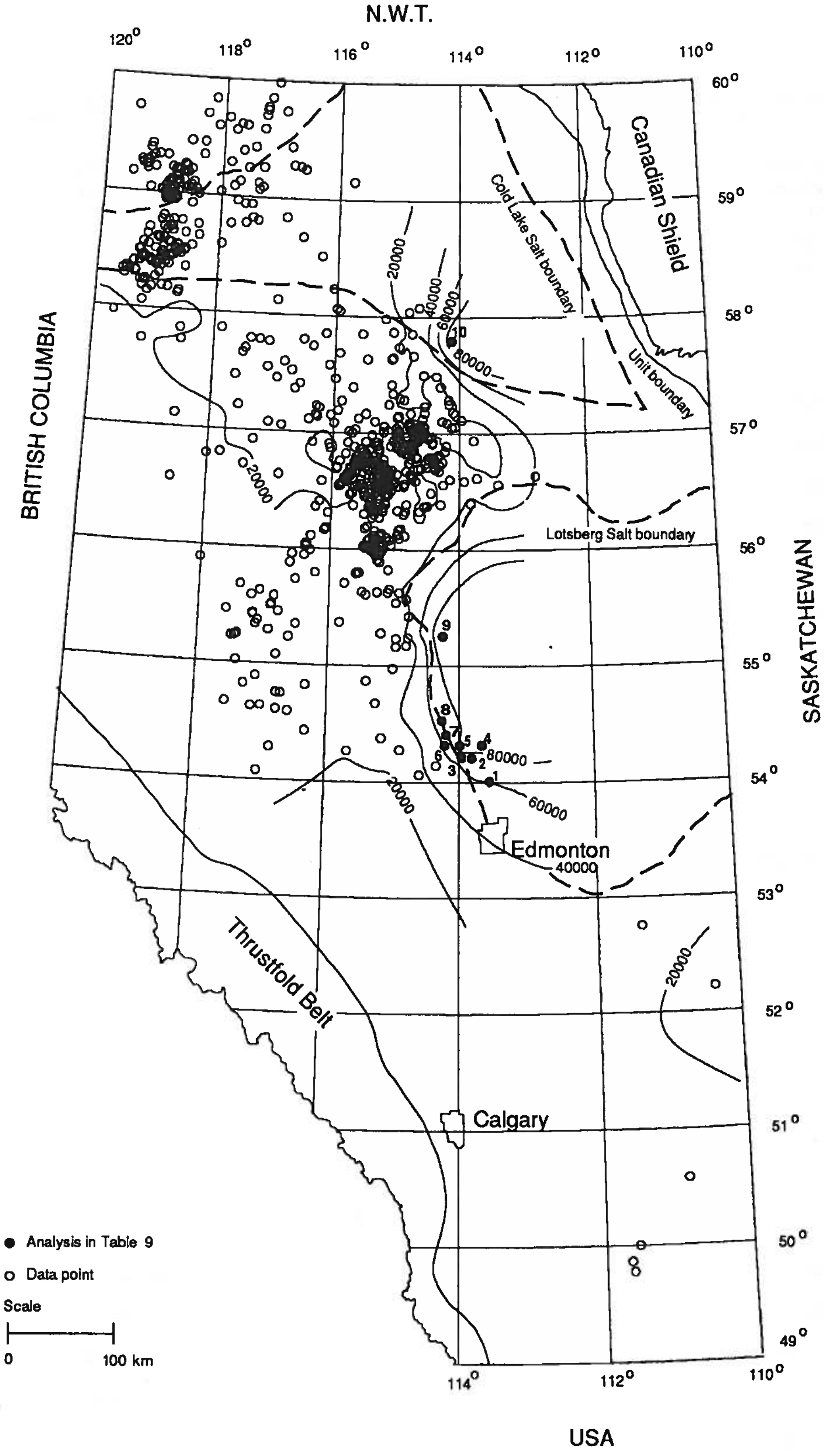


Figure 4. Distribution of Ca in formation waters from the Lower Elk Point aquifer.

Table 9. Lower Elk Point aquifer: formation waters with Ca > 60,000 mg/l or Mg > 9000 mg/l.

	1	2	3	4	5
Location	8-18-58-24-W4M	1-27-60-26-W4M	10-27-60-27-W4M	10-34-61-25-W4M	10-33-61-27-W4M
Depth (m)	1873.00-1876.35	1871.47-1888.24	1917.19-1969.01	1764.79-1815.08	1886.71-1902.26
Source	DST 7	DST 11	DST 3	DST 1	DST 1
Recovery	877.8 m sw 182.9 m mud	1205.5 m sw (71.6 m above packer)	893.1 m sw 45.7 m mud	464.8 m mc sw	248.7 m sw (128 m above SI tool)
Na (diff.)	24450	40766	41785	38322	35607
Ca	61200	75485	68577	83432	81762
Mg	5530	10663	11518	9467	11713
Cl	161500	227300	219143	234000	233600
HCO_3	140	80	101	210	37
SO_4	680	179	165	214	91
Fe	-	-	88	present	present
TDS (calc.)	253429	354433	341238	365539	362792
pH (lab.)	-	5.80	5.49	5.40 (22°C)	5.10 (23°C)
Density (16°C)	1.1950	1.2580	1.2528	1.2760	1.2650
Resistivity (ohm m)	-	-	0.0540 (23°C)	0.0680 (20°C)	0.0580 (20°C)
Refractive formation index (25°C)	-	-	-	-	1.4070
Estimated formation temp. (°C)	47	49	51	45	48
K/Na x 10^3 (est.)	300	450	400	525	500
Na (est.)	18808	28114	29846	25129	23738
K (est.)	5642	12652	11939	13193	11869
ΔG_{diff} dolomite	1.11	1.48	1.59	1.35	1.47
ΔG_{diff} anhydrite	0.21	-0.52	-0.65	-0.36	-0.90
ΔG_{diff} halite	-1.93	-1.30	-1.32	-1.32	-1.36
pH (formation temp.)	5.57	5.73	5.60	5.34	5.84
Remarks			Assineau ss.		Assineau ss.

- not determined, sw = salt water, mc = mud cut

Table 9. cont.

6A 10-34-61-2-W5M 1978.46-1994.61 DST 3 1573.7 m mc sw (top fluid D.P.)	6B 10-34-61-2-W5M 1978.46-1994.61 DST 3 1573.7 m mc sw (MFE chamber)	7 10-35-62-2-W5M 1955.60-1972.06 DST 2 1195.7 m sw (top of packer)	8 4-16-64-2-W5M 1915.67-1978.15 DST 2 815.3 m sw	9 2-28-72-2-W5M 1652.02-1676.40 DST 1 364.2 m sw 164.6 m swc mud	10 7-29-101-1-W5M 952.20-975.97 DST 1 304.8 m sw 22.9 m wc mud (bottom)
46460	47725	40462	45957	26050	37223
62542	63103	65906	68083	95200	90971
12004	11324	9428	6584	10449	11081
217000	217400	206200	210238	238915	250000
150	130	130	91	100	904
253	1029	255	276	85	137
present	present	much	present	13	present
338333	340645	322315	331182	370748	389856
5.80	6.00	5.30 (23°C)	5.58	5.20	6.20
1.2430	1.2430	1.2170	1.2433	1.2898	1.2780
0.0490 (20°C)	0.0480 (20°C)	0.0610 (20°C)	0.0480 (25°C)	0.0480 (24°C)	0.1040 (20°C)
-	-	1.3985	-	-	1.4072
56	56	55	57	50	35
325	325	350	375	650	600
35064	36019	29972	33423	15788	23264
11396	11706	10490	12534	10262	13959
1.82	1.90	1.63	1.42	1.42	1.13
-0.42	0.51	-0.34	-0.25	-0.82	-0.61
-1.26	-1.24	-1.39	-1.37	-1.64	-1.16
5.47	5.57	5.43	5.60	5.49	4.73
Morse River ss.	Morse River ss.	Morse River ss.	Morse River ss.		

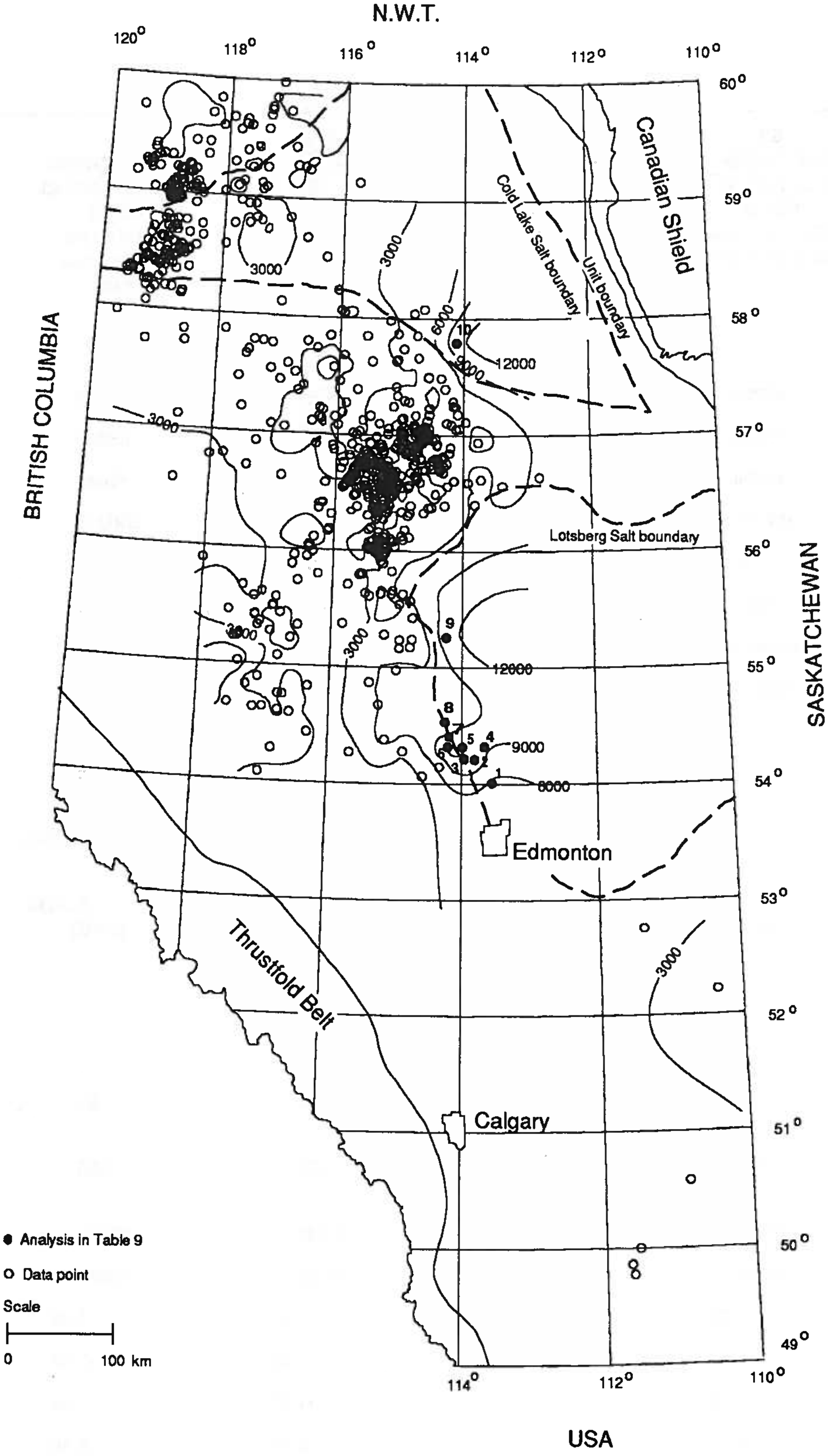


Figure 5. Distribution of Mg in formation waters from the Lower Elk Point aquifer.

point, lies near the southwestern margin of the limit of the Cold Lake salt (Grayston et al., 1964). There are sufficient data in northwestern Alberta to indicate that formation waters in the Lower Elk Point aquifer over most of the area of the northern Cold Lake salt basin have < 20,000 mg/l Ca and < 3000 mg/l Mg. It is therefore only in the northeastern part of the Cold Lake salt basin that detailed exploration should be considered.

None of the analyses in table 9 reports Na and K. The value Na (diff.) is computed so as to reach an ionic balance based on the cations and anions determined. It is in error by the amount of other major and minor ions not analyzed, plus analytical errors. The major missing ions are Na and K, and the following procedure was used to estimate their contents. Because no analyses from this aquifer which have Ca and Mg exceeding the detailed exploration threshold limits also report Na and K, use was made of similar high-salinity analyses in the Beaverhill Lake aquifer. This extrapolation is justified on the basis that (1) both aquifers are carbonate rocks associated with evaporites, and (2) both aquifers are at the same general PT conditions and therefore their associated formation waters have been subjected to similar water-rock reactions. A search showed that there were six analyses with Ca and Mg close to or exceeding the detailed exploration limits (table 10). The ratio K/Na x 10^3 varied in the range 185-703. By contrast, the ratio K/Na x 10^3 in the Slave Point Formation and the Swan Hills Formation of the Beaverhill Lake aquifer, and in southern Alberta were all < 120 (figure 6). Thus the formation waters with high Ca and Mg also have high K/Na ratios. A plot (figure 7) of Ca versus K/Na yielded a least squares line:

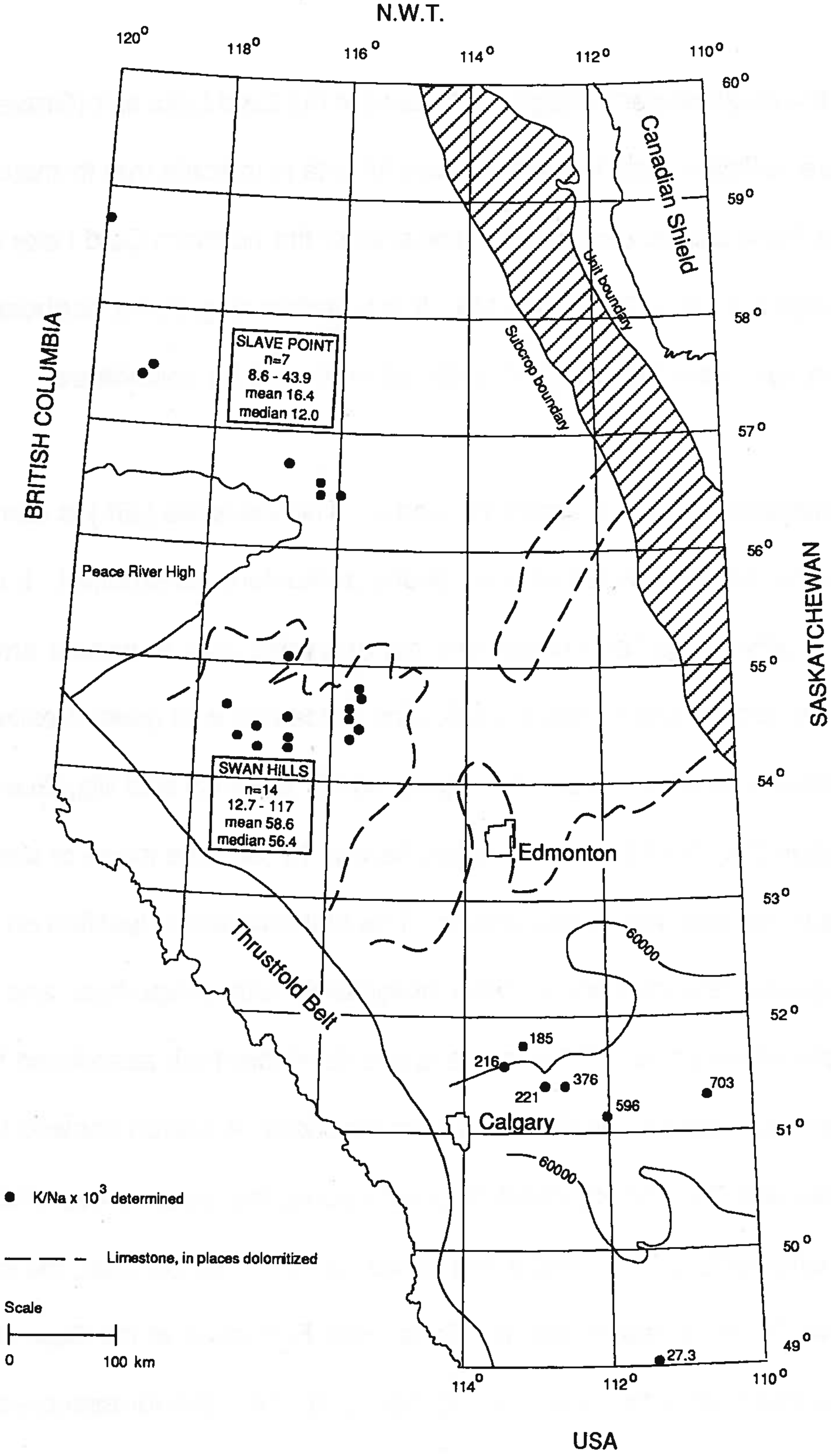


Figure 6. Distribution of K/Na ratio in formation waters from the Beaverhill Lake aquifer. The 60,000 mg/l isoline is for Ca (from figure 9).

Table 10. K/Na ratio of selected formation waters from the Beaverhill Lake aquifer.

	Composition (mg/l)						
Location	**Salinity (calc.)**	**Ca**	**Mg**	**K**	**Na**	**K/Na x 10^3**	**Remarks**
16-29-1-11-W4M	119,514	10,085	3,981	795	29,100	27.3	LP separator
8-24-25-15-W4M	266,221	64,060	9,720	10,560	17,710	596	DST, good rec.
8-23-27-5-W4M	436,856	96,100	13,410	19,160	27,250	703	DST
11-14-28-19-W4M	365,954	78,134	9,602	13,550	36,000	376	DST
6-35-28-21-W4M	317,999	61,220	6,075	8,720	39,370	221	DST, good rec.
16-11-30-25-W4M	304,127	62,766	6,311	8,000	37,000	216	DST, good rec.
10-30-32-23-W4M	256,593	45,222	4,764	7,400	40,000	185	DST, good rec.

rec. = recovery.

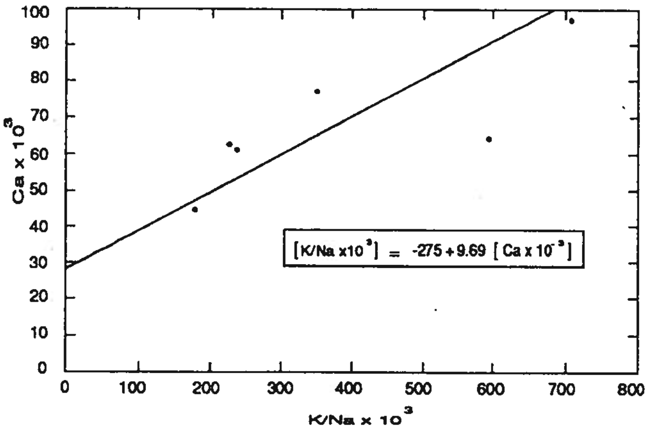


Figure 7. Plot of Ca versus K/NA for selected formation waters from the Beaverhill Lake aquifer.

$$[K/Na \times 10^3] = -275 + 9.69\ [Ca \times 10^{-3}]$$

from which the K/Na ratio can be determined, and hence the individual K and Na values. The estimated K and Na values are reported in table 9 and were input into SOLMINEQ.88 with the rest of the analyses. In order to compensate for the loss of CO_2 on sampling, and to determine the mineral solubility characteristics at formation temperature, two procedures were carried out. First, the formation temperature was calculated from the depth of the drillstem test, and the integral regional geothermal gradient and annual ground temperature from Bachu and Burwash (1993). Second, the CO_2 option or the mineral dissolution/precipitation option in SOLMINEQ.88 was used until the solution was saturated with respect to calcite at formation temperature.

SOLMINEQ.88 reports the saturation of the water sample with respect to a large suite of minerals in terms of the Gibbs free energy difference (ΔG_{diff}) between the actual and equilibrium states of the mineral. A positive value of ΔG_{diff} indicates that the mineral should precipitate from the water; a negative value of ΔG_{diff} indicates that the mineral should dissolve in the water; $\Delta G_{diff} = 0.0$ indicates that the mineral is in equilibrium with the water. The calculation is strictly an equilibrium calculation. If the water is supersaturated with respect to the mineral, the mineral may not precipitate because of kinetic considerations. However, the greater the supersaturation, the more likely it is to precipitate.

At formation temperature, all the brines are oversaturated (ΔG_{diff} > 1.0) with respect to dolomite, effectively at equilibrium with respect to anhydrite (ΔG_{diff} - 0.5 to + 0.5), and undersaturated with respect to halite (ΔG_{diff} > - 1.0). The pH calculated at formation temperature ranges from 4.73 to 5.84, and is generally less than 0.5 pH units lower or higher than the laboratory-determined value.

With one exception (K = 5,340 mg/l), all formation waters on which K was determined had a K content below the regional exploration threshold. The majority of samples were from areas outside the boundaries of the Cold Lake and Lotsberg salts, even the relatively few samples with K in the range of 2,500 mg/l to 5,000 mg/l. Values of K calculated (table 9) for samples with high contents of Ca and Mg are dominantly in the range 10,000 mg/l to 13,000 mg/l, and all these samples are generally within the salt boundaries. Confirmation would rest on the acquisition of more detailed analyses.

Both samples with Li above the regional exploration limit (51 and 71 mg/l, respectively) are from the Granite Wash in the Red Earth region, in an area with several values in the Lower Elk Point aquifer which are < 50 mg/l. The maximum content of Br is 1,530 mg/l (from the Granite Wash aquifer) and of I is 40 mg/l; sample distribution of other analyses reporting these halogens indicated no region of potential economic interest.

In summary, there is considerable potential for the production of formation waters with high contents of Ca, Mg, and possibly K, all three elements being associated with specific regions within the boundaries of the Cold Lake and Lotsberg salts. Samples of formation waters acquired within these regions should be analyzed for Ca, Mg and K, as well as other economically interesting elements such as Br.

Keg River

Formation waters from the Keg River aquifer which exceed the regional exploration threshold limits for Ca and Mg are confined to the northern half of the province. No analyses exceed the detailed exploration thresholds for these elements. Figure 8 shows that the composition of formation waters in the Keg River aquifer in northern Alberta falls into three groups, reflecting two processes causing increased salinity, namely, increased temperature (depth) in the west and the influence of evaporites (underlying Lower Elk Point Group and overlying Prairie Formation) in the east. The deeper formation waters are near the southwestern depositional margin of the Keg River Formation and much higher contents of Ca and Mg are unlikely, especially in view of the fact that the content of these elements are similar in formation waters in the deeper Cambrian aquifers. Where the content of Cl is ~ 200,000 mg/l, the maximum contents of Ca and Mg are 46,000 mg/l and ~ 7000 mg/l, respectively. In view of the regional compositional trends in the underlying Lower Elk Point aquifer, it would be prudent to analyze formation waters from wells penetrating the Keg River aquifer east of the present limit of hydrochemical data, as suggested by Hitchon and Holter (1971). It should be noted that the high contents of Ca and Mg reported in the Keg River aquifer by Hitchon and Holter (1971)

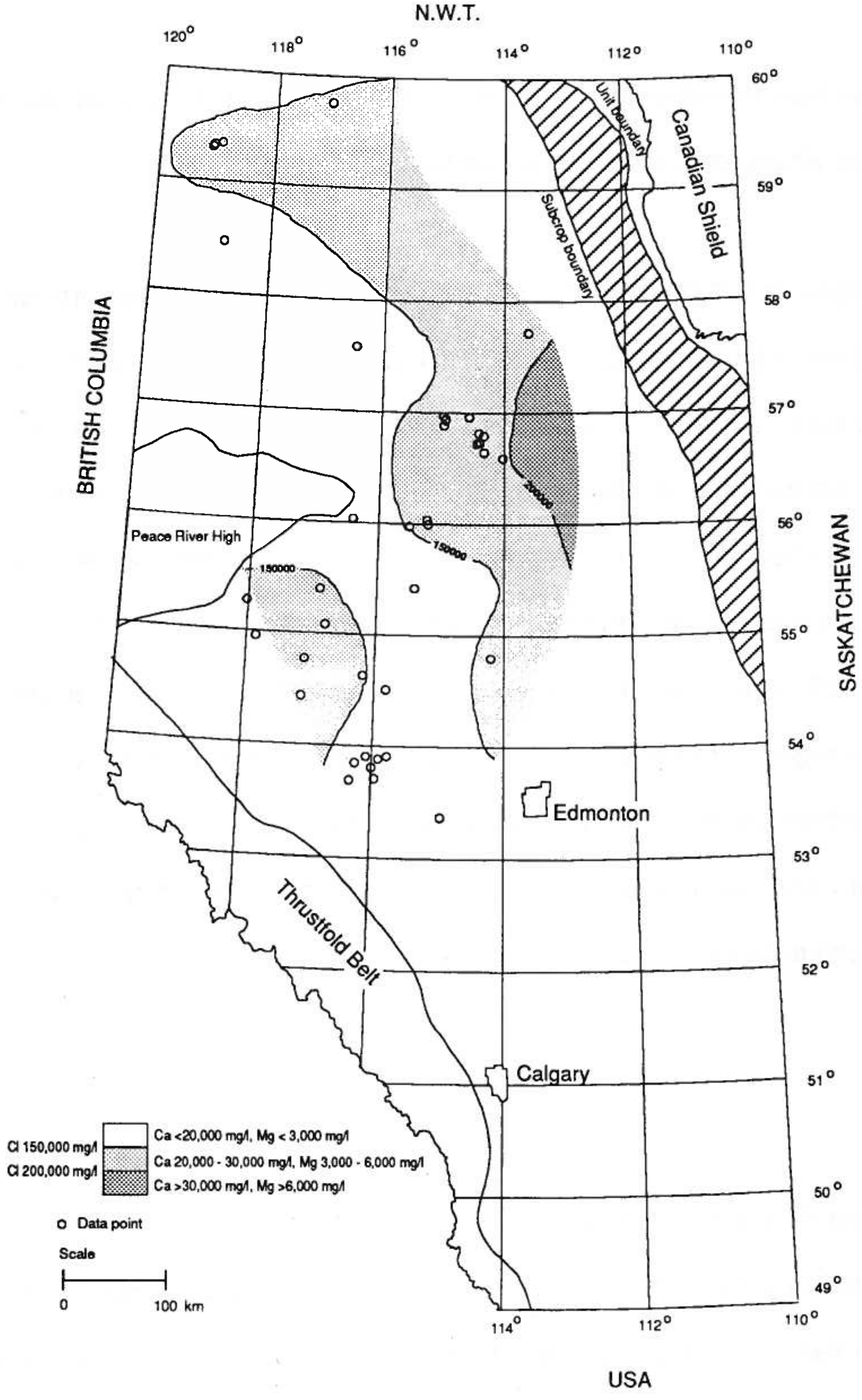


Figure 8. Formation water characteristics, Keg River aquifer.

could equally be from formation waters in the underlying Lower Elk Point aquifer in this region where the stratigraphy was then not so well defined.

Potassium ranges up to 6,800 mg/l in formation waters from the Keg River aquifer, and all the samples with contents above the regional exploration threshold come from the Rainbow-Zama area. There are no analyses from the region with high Cl (figure 8) and so it would be advisable to analyse for K and Br, in addition to Ca and Mg, in any formation waters recovered from the Keg River aquifer in this region. Three formation waters report Li above the detailed exploration threshold; they are from the Zama (95 mg/l), Utikuma (95 mg/l) and Suffield (76 mg/l) areas. The sparse data preclude indication of any regional trends for Li. The highest contents of both Br and I are in the Kidney area (90-5-W5M), with maximum values of 1,360 mg/l Br and 120 mg/l I. The high contents of I are most unusual, considering the general composition of the rest of the analyses; contamination cannot be ruled out.

Watt Mountain

In the Peace River Arch area the Watt Mountain aquitard was combined with the Muskeg aquitard as the Muskeg-Watt Mountain aquitard system (Hitchon et al., 1990). Within this aquitard system lies the Gilwood aquifer. Both the data distribution and the regional compositional trends of formation waters from the Watt Mountain aquitard (dominantly the Gilwood aquifer) are similar to those in the Keg River aquifer. This is not surprising in view of the facts that (1) both the Muskeg and Watt Mountain aquitards are leaky (Hitchon et al., 1990), (2) in the eastern part of the area the Watt Mountain Formation and the Keg River Formation are separated by the Prairie Formation halite and so salinities of formation waters from these units are correspondingly high, and (3) in the western part of the area the Muskeg aquitard thins against the Peace River Arch and the Gilwood and Keg River aquifers are contiguous and comprise near-shore arenaceous facies. With respect to Ca and Mg in formation waters from the Gilwood aquifer, similar comments apply as for the Keg River aquifer. Maximum contents are Ca 40,000 mg/l and Mg 8000 mg/l. Maximum contents of the other elements are K 6,550 mg/l, Li 98 mg/l, Br 893 mg/l and I 35 mg/l, There is a slight tendancy for the higher contents of K and Li to be found in this aquifer immediately updip of the northeast margin of the overlying Swan Hills aquifer. No trends were discernable for Br or I. Generally, formation waters in this thin aquifer are not likely to be of economic significance.

Beaverhill Lake

Formation waters with Ca and Mg contents exceeding the regional exploration threshold values occur throughout most of the province except in the subcrop region, northwest Alberta, and extreme southern Alberta. The regional trends for Ca (figure 9) and Mg (figure 10) indicate that detailed exploration is only justified in southern Alberta in an area of partly dolomitized limestone with associated evaporites, mainly anhydrite. In this area, twelve analyses have both Ca and Mg exceeding the detailed exploration limits (table 11).

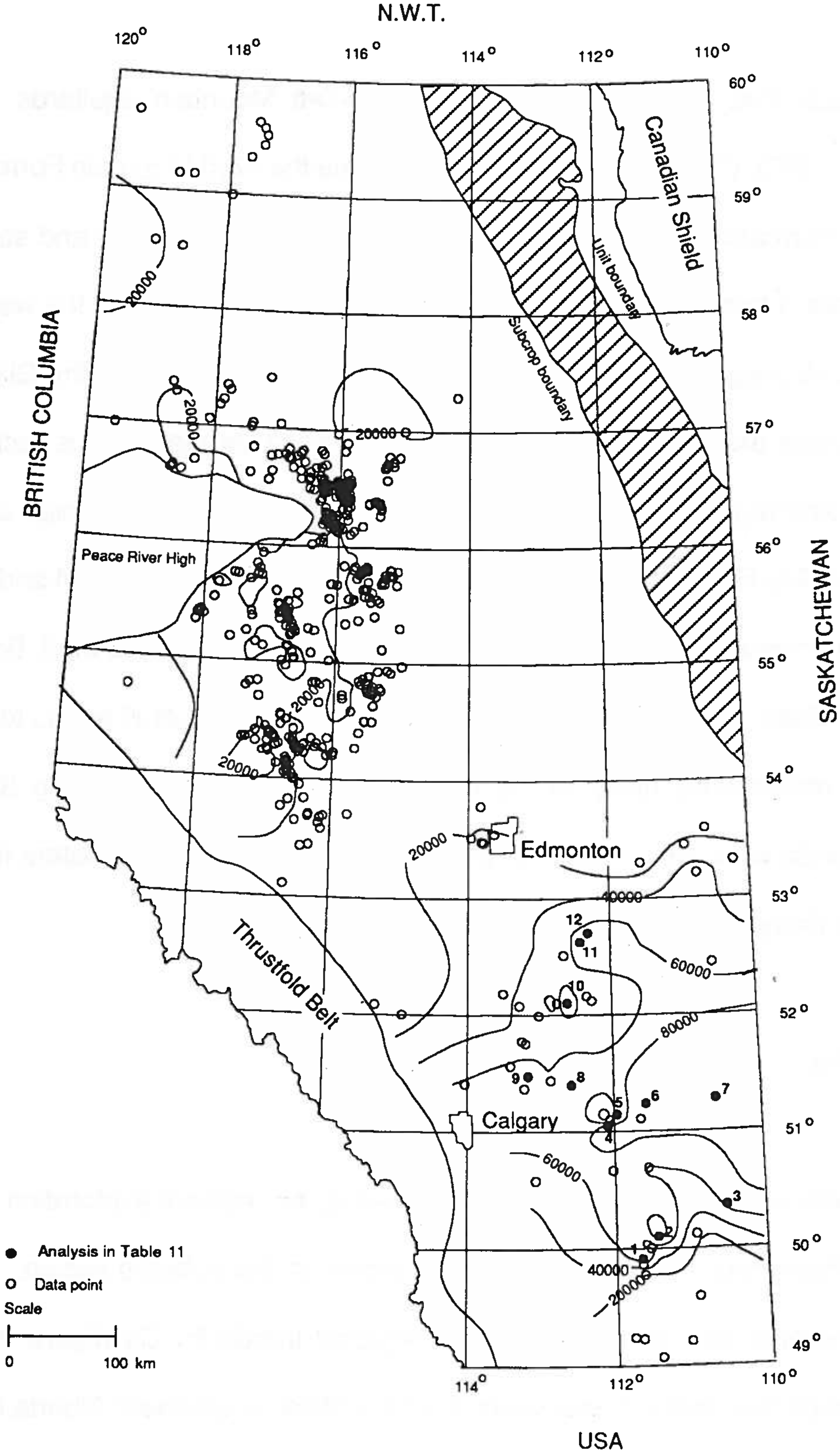


Figure 9. Distribution of Ca in formation waters from the Beaverhill Lake aquifer.

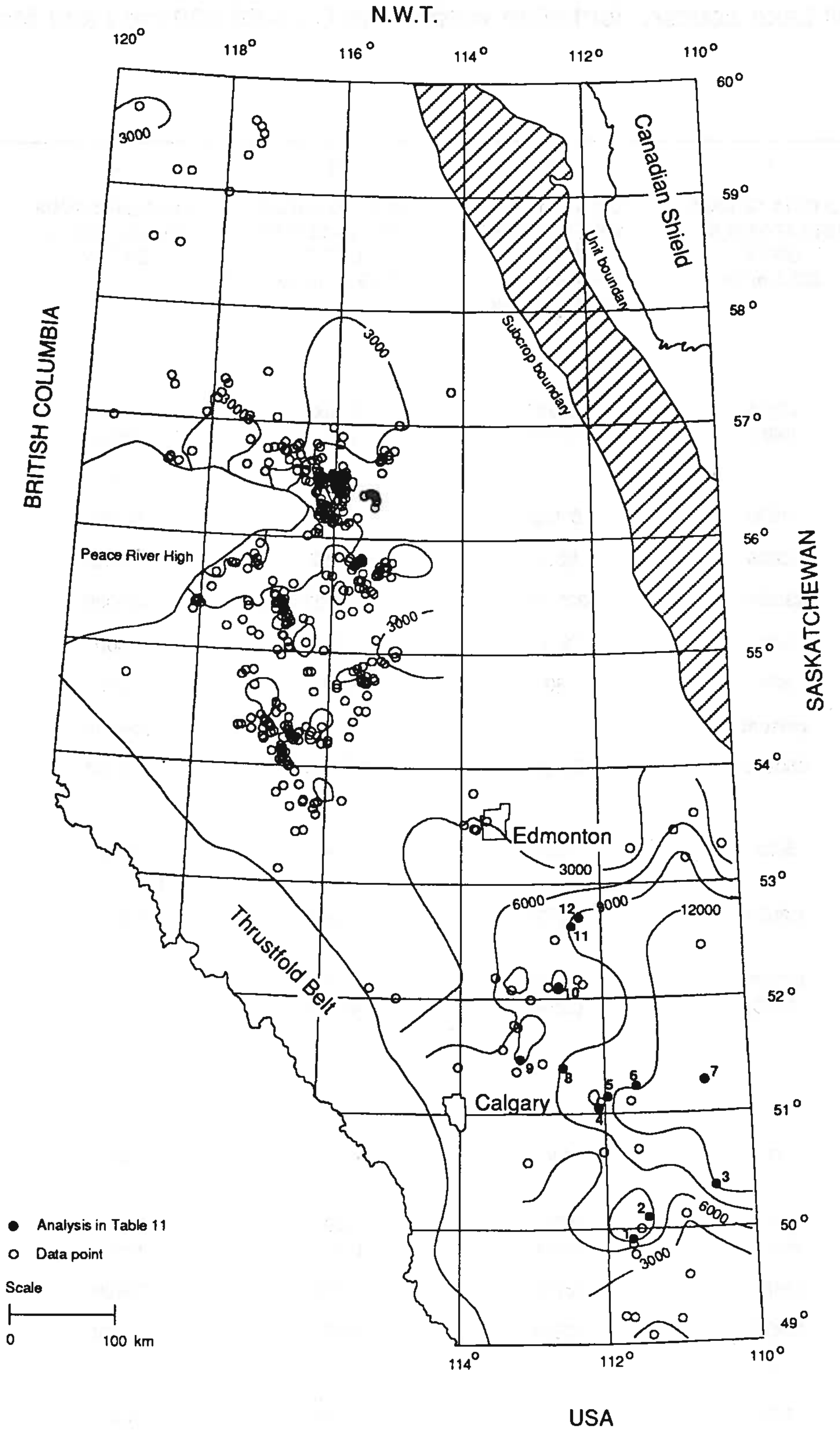


Figure 10. Distribution of Mg in formation waters from the Beaverhill Lake aquifer.

Table 11. Beaverhill Lake aquifer: formation waters with Ca > 60,000 mg/l and Mg > 9000 mg/l.

	1	2	3	4	5
Location	12-13-11-13-W4M	10-21-13-11-W4M	11-20-16-4-W4M	11-18-24-15-W4M	8-24-25-15-W4M
Depth (m)	1610.87-1621.54	1586.48-1592.58	1535.28-1542.90	1796.49-1801.06	1815.00-1855.00
Source	DST 6	DST 7	DST 7	DST 17	DST 3
Recovery	222.5 m sw	48.8 m sw 57.9 m mc sw	82.3 m mc sw	-	116.0 m sw 28.0 m mc sw
Na	47159 (diff.)	28987 (diff.)	51150 (diff.)	39605 (diff.)	17710
K	-	-	-	-	10560
Ca	71970	86030	64180	82802	64060
Mg	10646	9830	12197	11519	9720
Cl	230600	223770	227000	240000	172000
HCO_3	510	817	1480	1400	214
SO_4	234	80	144	424	391
Fe	present	-	-	present	-
TDS (calc.)	360860	351885	355399	375038	266221
pH (laboratory)	5.10	7.60	6.40	6.20	6.00
Density (16°C)	1.2530	1.2730	1.2540	1.2750	1.2080 (25°C)
Resistivity (ohm m)	0.0520 (20°C)	0.0400 (24°C)	0.0470 (20°C)	-	0.0570 (25°C)
Refractive index (25°C)	-	-	-	-	1.3883
Estimated formation temperature (°C)	37	38	40	44	45
K/Na x 10^3	400 (est.)	550 (est.)	350 (est.)	500 (est.)	596
Na (est)	33685	18701	37889	26403	-
K (est)	13474	10286	13261	13202	-
ΔG_{diff} dolomite	1.36	1.10	1.48	1.31	1.43
ΔG_{diff} anhydrite	-1.05	-1.00	-0.86	0.05	-0.18
ΔG_{diff} halite	-0.47	-1.50	-1.03	-1.23	-1.85
pH (formation temp.)	5.06	4.78	4.59	4.48	5.42
Remarks		Br = 2786			

sw = salt water, mc = mud-cut.

Table 11. cont.

6	7	8	9	10	11	12
9-23-26-12-W4M 1673.35-1692.25 DST 13 146.3 m mc sw	8-3-27-5-W4M 1595.00-1605.00 DST 1 75.0 m mc sw 90.0 m mud	11-14-28-19-W4M 1908.00-1940.00 DST 1 - (bottom)	13-10-29-23-W4M 2321.05-2336.90 DST 5 - (middle)	6-23-36-19-W4M 1960.47-1966.87 DST 1 177.7 m sw 15.2 m mud (bottom)	5-20-42-17-W4M 1654.15-1663.29 DST 5 304.8 m sw 134.1 m mc sw	10-18-43-16-W4M 1545.03-1567.28 DST 1 364.2 m sw 61.0 m mc sw (bottom)
30999 (diff.)	27250	36000	49158 (diff.)	32370 (diff.)	29079 (diff.)	30674 (diff.)
-	19160	13550	-	-	-	-
97790	96100	78134	71890	75700	69300	66266
11629	13410	9602	9361	10100	9200	9392
254000	280000	233972	230000	213000	194000	191500
1000	1403	273	215	230	113	212
146	97	43	188	186	250	379
present	-	trace	-	much	-	-
395056	436856	365954	360703	331470	301885	298315
5.10	6.60	5.00	5.20	5.20	5.80	5.6 (28°C)
1.2721 (calc., 25°C)	1.2770 (25°C)	1.2667 (15°C)	1.2460	1.2480	1.2270	1.2190
-	0.0580 (25°C)	0.0400 (25°C)	0.0660 (20°C)	0.0570 (20°C)	0.0530 (21°C)	0.0620 (20°C)
1.4086	1.4057	1.4016 (19°C)	-	1.3982	-	1.3937
40	39	46	57	53	46	44
650 (est.)	703	376	400 (est.)	450 (est.)	400 (est.)	350 (est.)
18787	-	-	35113	22324	20771	22721
12212	-	-	14045	10046	8308	7953
1.31	1.38	1.40	1.68	1.57	1.31	1.39
-0.47	-0.71	-1.43	-0.47	-0.47	-0.39	-0.17
-1.29	-0.87	-1.07	-1.19	-1.57	-1.65	-1.58
4.65	4.48	5.12	5.22	5.23	5.63	5.41

Contents of Ca and Mg are comparable to those in the Lower Elk Point aquifer, but, perhaps characteristically, drillstem test recoveries are generally much lower than in the Lower Elk Point aquifer, suggesting generally lower permeability in the Beaverhill Lake aquifer. The maximum contents are Ca 98,000 mg/l and Mg 13,500 mg/l; although Hitchon and Holter (1971, Appendix B, No. 217) reported a maximum of 15,000 mg/l Mg, the high pH (8.1) of this sample suggests possible contamination, and for the present study no analyses from this well were included.

The twelve formation water analyses in table 11 were treated in a similar manner to those in table 9 with respect to estimating the contents of K and Na, and calculating mineral saturations and pH at formation temperature. All formation waters are oversaturated ($\Delta G_{diff} > 1.0$) with respect to dolomite, at equilibrium (ΔG_{diff} - 0.5 to + 0.5) to undersaturated ($\Delta G_{diff} < - 1.0$) with respect to anhydrite, and generally undersaturated ($\Delta G_{diff} > - 1.0$) with respect to halite. Some laboratory determined pH values are clearly far from the value calculated at formation temperature, which fall in the range 4.48 to 5.63.

Contents of K above the regional exploration threshold are confined to southern Alberta (figure 11) in the region where the formation waters also contain significant amounts of Ca (figure 9) and Mg (figure 10). Further, the distribution pattern for K corresponds closely to the distribution of potash mineralization in the underlying Prairie Formation salt. Six analyses have K contents exceeding the detailed exploration threshold; they are

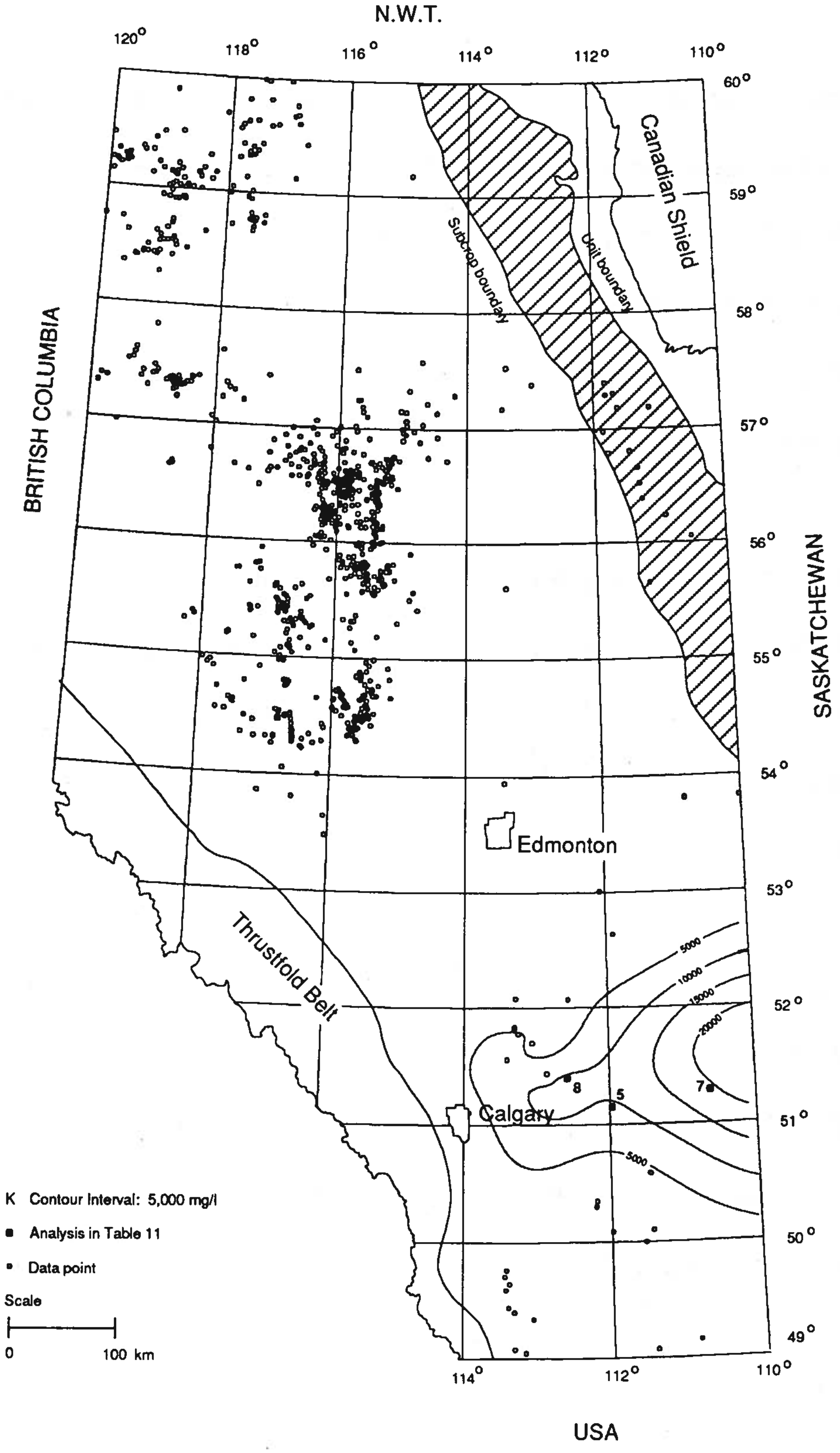


Figure 11. Distribution of K in formation waters from the Beaverhill Lake aquifer.

analyses 5, 7 and 8 in table 11, and duplicate analyses from the same drillstem tests not reported in the table. Only four formation waters report Br > 1,000 mg/l (max. 2,786 mg/l, analysis 2, table 11), two being from drillstem tests in the same well. The distribution of formation waters reporting Br (figure 12) suggests that higher Br contents cannot be ruled out in the same area in which K > 5,000 mg/l because both Br and K accumulate strongly after halite precipitation.

Lithium is above the detailed exploration threshold in seven samples (max. 130 mg/l), all in the Swan Hills aquifer downdip of the high values in the underlying Watt Mountain aquifer. Iodide contents > 40 mg/l (max. 50.3 mg/l) were found in five formation waters distributed widely over the Swan Hills and Slave Point aquifers, without any obvious regional trends.

In summary, the Beaverhill Lake aquifer includes two areas of potential interest. In southern Alberta there are high contents of Ca, Mg and K in the formation waters, and probably also Br. The other area is in the Swan Hills Formation where the content of Li is particularly high; unfortunately other components are generally below (K, Br, I) or sometimes slightly above (Ca, Mg) the regional exploration thresholds.

Woodbend

The Woodbend aquifer comprises individual aquifers in the Grosmont and Leduc

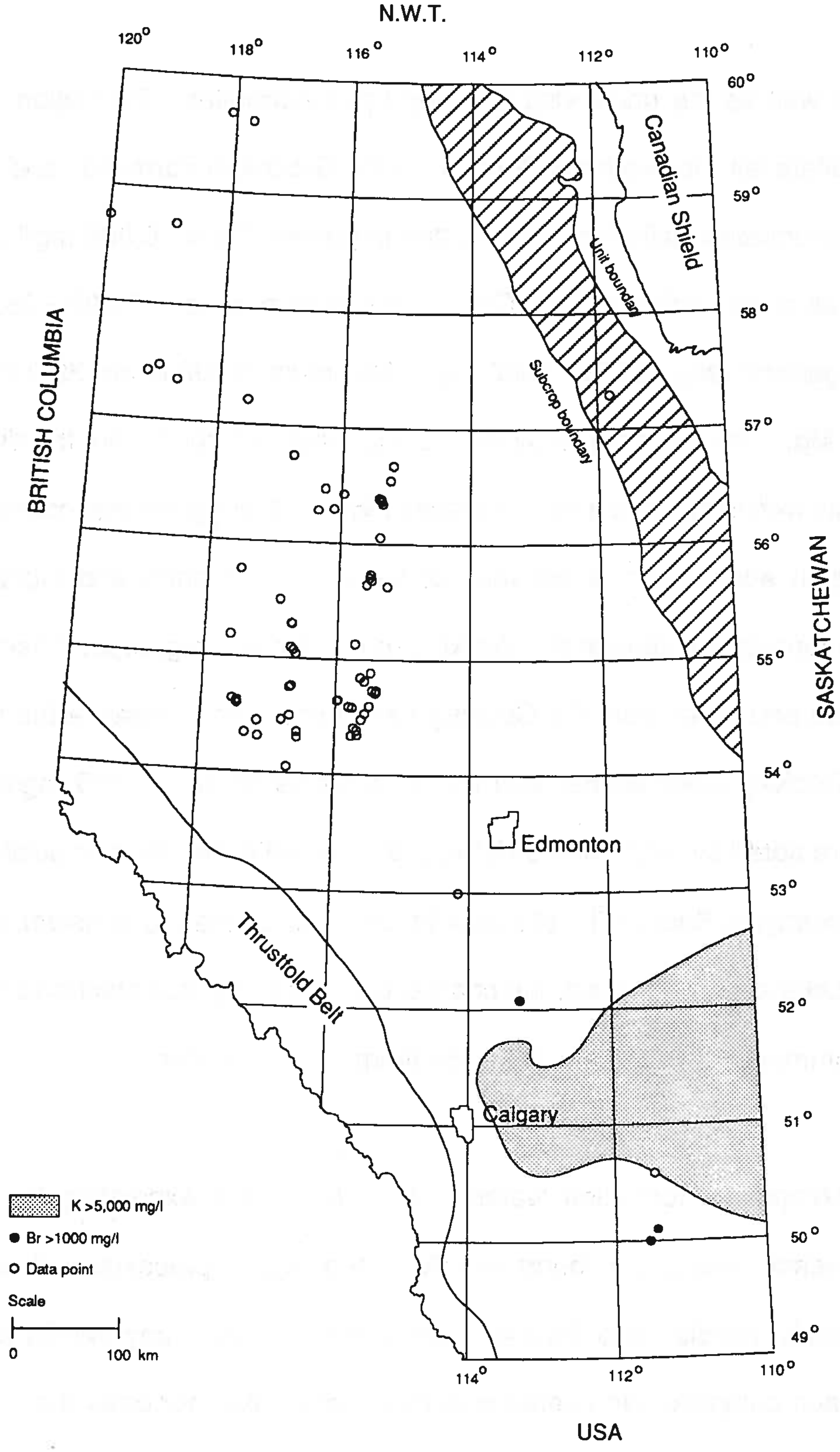


Figure 12. Distribution of formation waters exceeding the regional exploration threshold for Br in the Beaverhill Lake aquifer.

Formations, as well as the underlying Cooking Lake Formation. Formation waters in Woodbend aquifers fall into two broad groups. In the Grosmont Formation and Southern Alberta Shelf carbonates, salinities are low, and in general Ca < 10,000 mg/l and Mg < 3000 mg/l. In all other Leduc aquifers Ca is in the general range 15,000 - 25,000 mg/l and Mg in the general range 3000 - 5000 mg/l. Maximum contents are 39,000 mg/l Ca and 8000 mg/l Mg. There appear to be few obvious regional trends, but the distribution of the data points within the carbonate complexes (figure 13) suggests that concentrations of Ca and Mg of economic interest will not be found. Hitchon and Holter (1971) considered the formation waters in the Woodbend aquifer in two groups; those from the Leduc Formation and those from the Cooking Lake Formation. Because the formation waters in the Cooking Lake aquifer with higher contents of Ca (63,000 mg/l) and Mg (9000 mg/l) were noted by Hitchon and Holter (1971) as reflecting the composition of the brines in the underlying Beaverhill Lake aquifer, we have chosen to consider them with the Beaverhill Lake aquifer. Indeed, the coarseness of the regional electronic grid used in this study commonly placed them in the Beaverhill Lake aquifer.

With some exceptions, formation waters with a K content exceeding the regional exploration threshold value are found mainly in the higher pressure carbonate reef complexes, namely Windfall and Bashaw, although there are many values below the thresholds in each complex. No overall pattern is discernible, nor does the distribution suggest that values approaching the detailed exploration threshold value will be found in the deep extensions of these reef trends. Lithium ranges up to 140 mg/l in formation

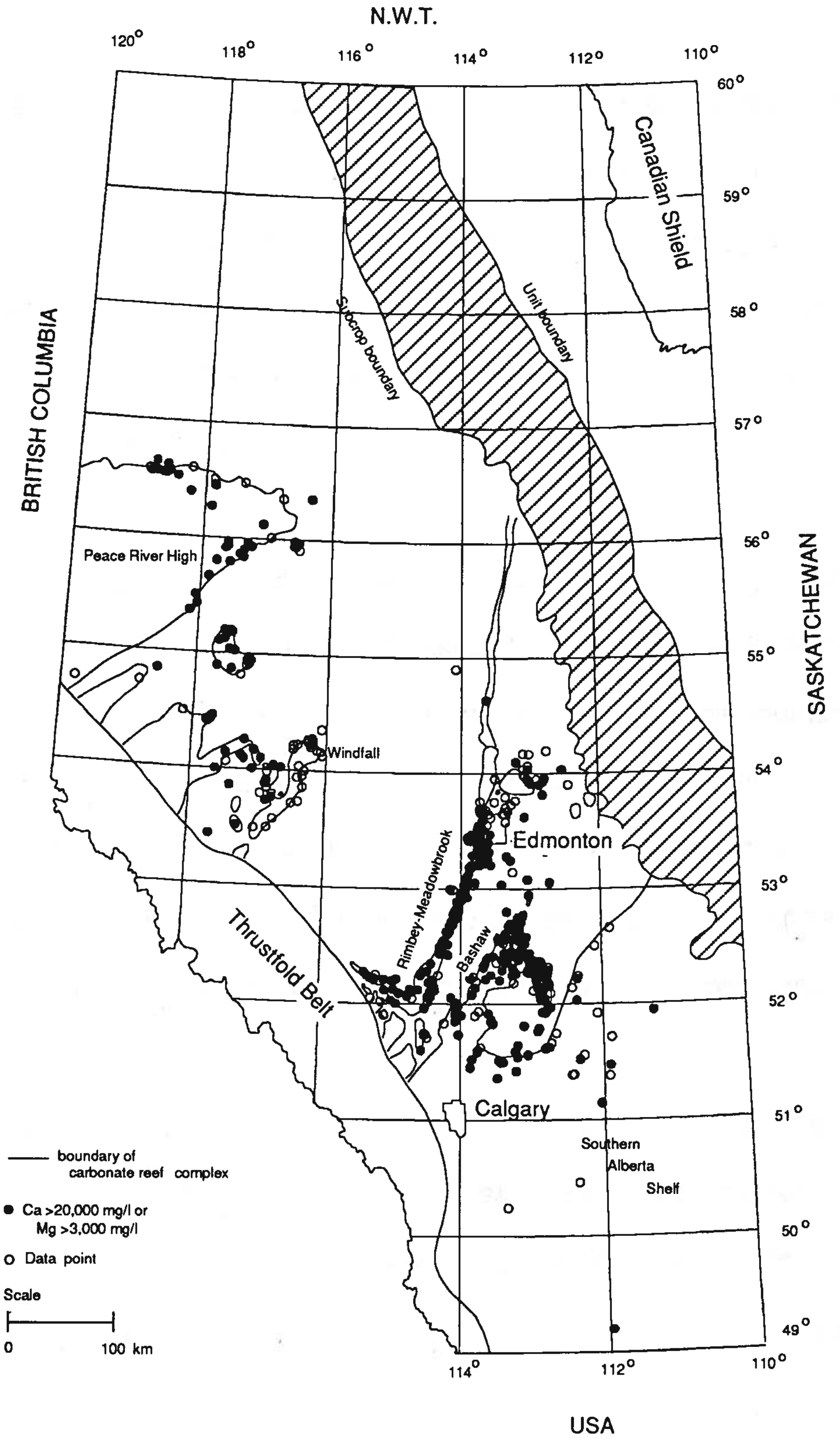


Figure 13. Distribution of formation waters exceeding the regional exploration thresholds for Ca and Mg in Woodbend aquifers.

waters from Woodbend aquifers (found at the Sturgeon Lake South, Bonnie Glen and Homeglen-Rimbey fields). Although there is no clear regional distribution pattern, the data in table 12 suggest that the Windfall reef complex contains formation waters appreciably richer in Li than the other reef complexes, especially compared with the low pressure Rimbey-Meadowbrook trend and its extension to the Grosmont aquifer; the two Cooking Lake samples are from Skaro, also on the low pressure trend.

The content of Br ranges up to ~ 1,500 mg/l. Values were generally < 500 mg/l in the Leduc aquifer at the Peace River Arch, Windfall and Sturgeon Lake carbonate complexes, and in the Grosmont aquifer. The northern end of the Rimbey-Meadbrook carbonate complex has similar values, but the southern portion and the Bashaw and Fenn-Big Valley reef complexes have formation waters with Br generally in the range 500-1,000 mg/l, with the occasional sample at higher values. Iodide showed no clear regional trends, with the majority of contents below the regional exploration threshold (max. 53 mg/l).

Lithium is the only element of potential economic interest in Woodbend aquifers, with particularly high contents being associated with the Windfall-Sturgeon Lake carbonate complex. Other components in the same complex are at or close to the regional exploration threshold (Ca, Mg, K) or considerably below it (Br, I).

Table 12. Summary of Li content of formation waters in Woodbend aquifers.

Unit	No.	Li (mg/l)			
		Minimum	Mean	Median	Maximum
Camrose Tongue	1			7.6	
Grosmont	3	5.3	5.6	5.6	6
Ireton	1			78.1	
Leduc					
Peace River Arch	6	40	73.3	79	100
Windall, Sturgeon Lake	11	82	100	107	140
Rimbey-Meadowbrook	18	11	50.4	42	140
Bashaw	7	50.4	84.5	76	135
Fenn-Big Valley	4	45.5	72.1	56.5	130
West Drumheller	1			52	
Cooking Lake	2	20	31.5	31.5	43

Winterburn

Calcium rarely exceeds 25,000 mg/l (maximum 30,000 mg/l) and Mg 4000 mg/l(maximum 5000 mg/l) in formation waters from the Winterburn aquifer. The distribution of data points (figure 14) indicates that, even in the deepest strata close to the thrustfold belt, the contents of Ca and Mg will not reach the detailed exploration threshold, thus confirming the observation of Hitchon and Holter (1971). Contents of K are highest in Winterburn aquifers over the Windfall-Swan Hills and Fenn-Big Valley carbonate complexes, with a maximum of ~ 8,600 mg/l. Four formation waters report Li above the detailed exploration threshold (max. 90 mg/l), with the higher values generally in the deeper strata along the trends of the underlying Rimbey-Meadowbrook and Bashaw carbonate complexes of the Leduc Formation. Similar characteristics are found for Br (max. 1,880 mg/l) and I (max. 38 mg/l). However, the distribution of data points and the nature of the trends suggest that, even in the deepest strata, contents of these elements will not be of economic interest.

Wabamun

In general terms, the distribution pattern for Ca and Mg in formation waters in the Wabamun aquifer is a subdued replica of that in the Winterburn aquifer. Regions with the occasional sample with Ca > 20,000 mg/l (maximum 30,000 mg/l) or Mg > 3000 mg/l (figure 15) are found over the Leduc Formation reefs in south-central Alberta and over the Swan Hills reef complex in northern Alberta, where Hitchon and Holter (1971)

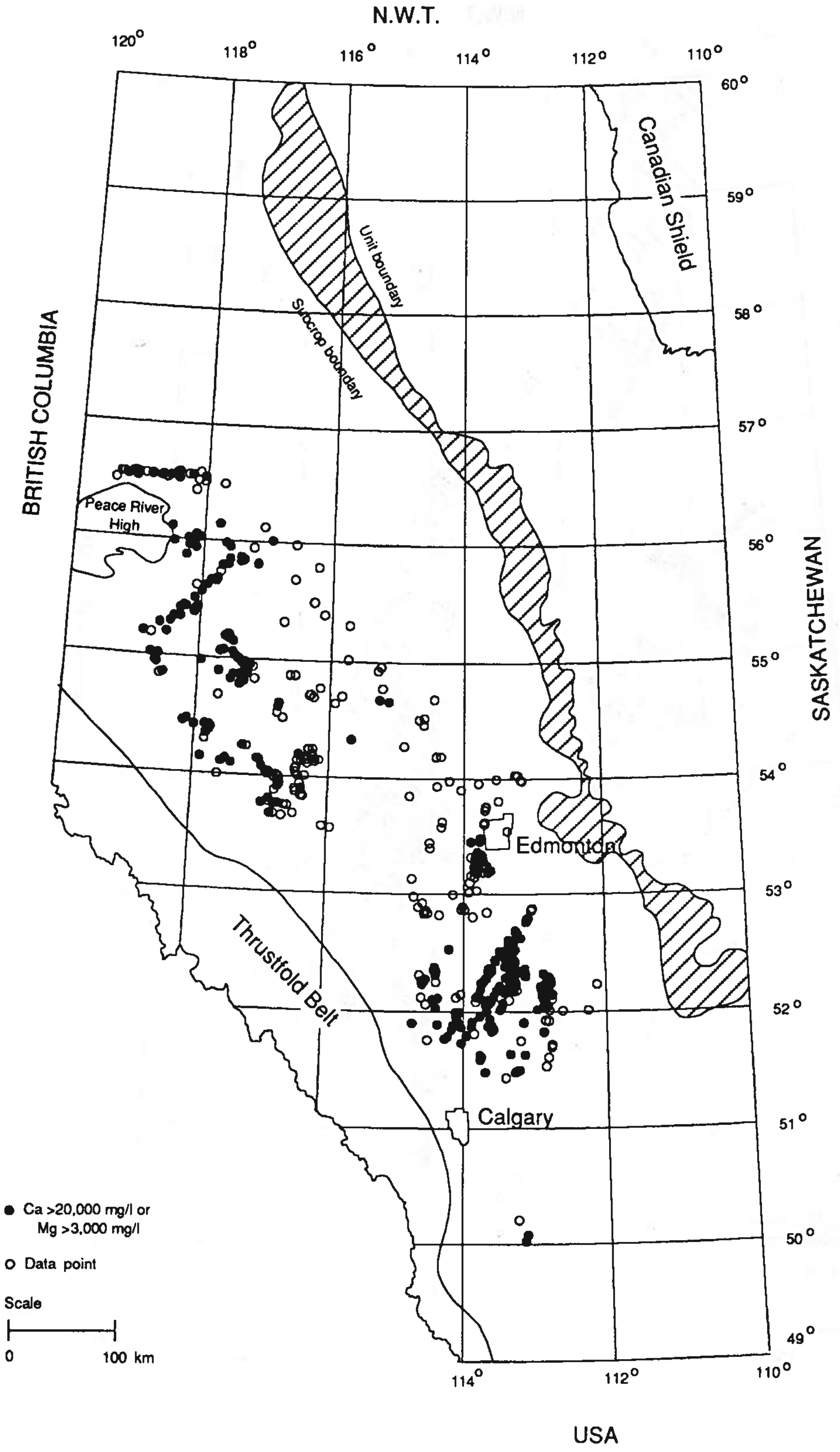


Figure 14. Distribution of formation waters exceeding the regional exploration thresholds for Ca and Mg in the Winterburn aquifer.

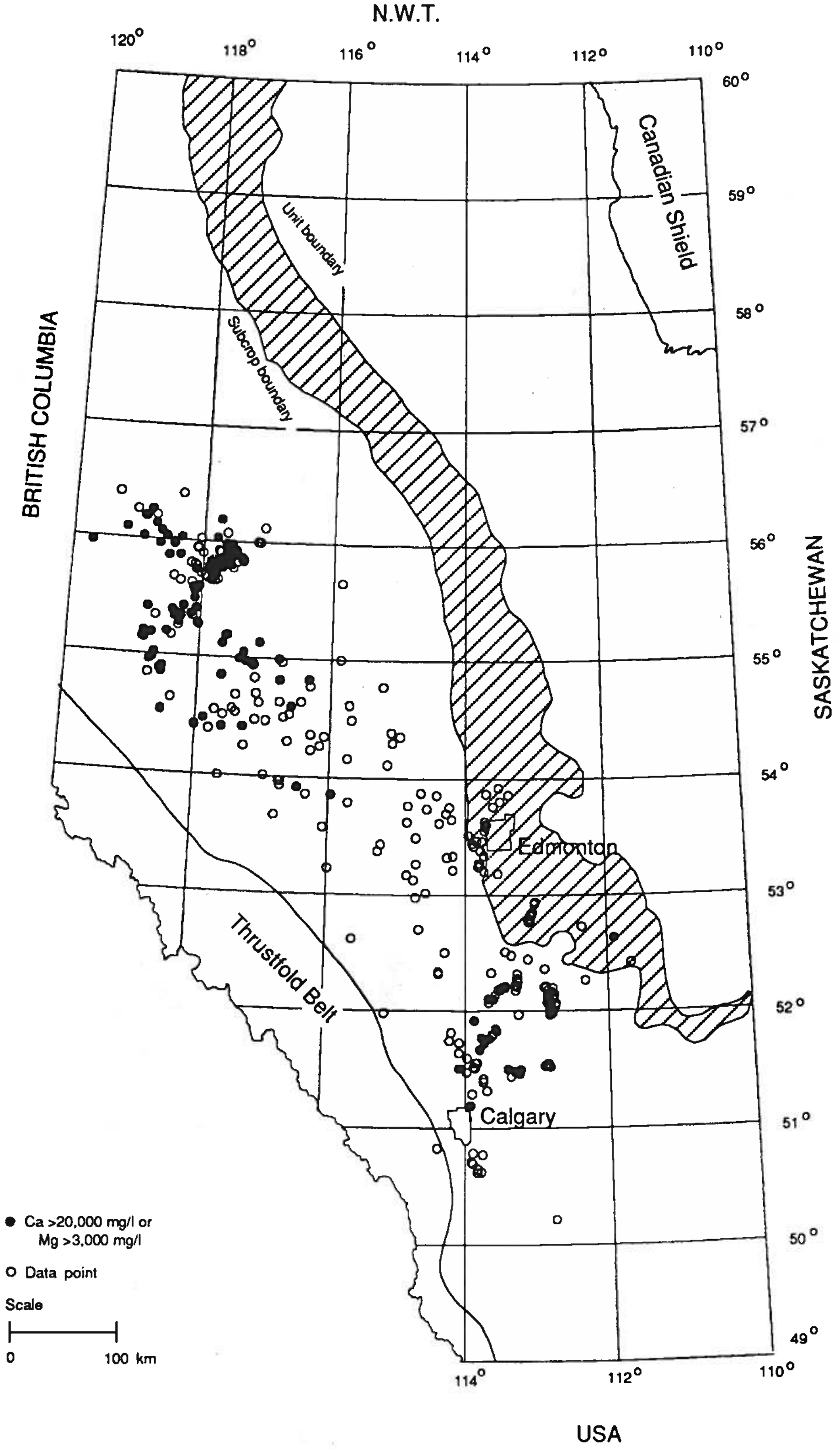


Figure 15. Distribution of formation waters exceeding the regional exploration thresholds for Ca and Mg in the Wabamun aquifer.

reported 11,300 mg/l Mg. These same regions overlie those in the Winterburn aquifer which have the highest numbers of formation waters with Ca and Mg exceeding the regional exploration thresholds. As with the Winterburn aquifer, regions justifying detailed exploration are not likely to be found, even in the deepest strata adjacent to the thrustfold belt, a conclusion in agreement with Hitchon and Holter (1971). Likewise, it is only the occasional formation water in the Wabamun aquifer in which K (max. 9,900 mg/l) and Li (max. 115 mg/l) are above their respective regional exploration threshold, and these are mainly in the Peace River Arch area in the case of Li. Maximum contents of Br (860 mg/l) and I (38 mg/l) are below the respective regional exploration thresholds. The only trend observed is to higher Br contents in deeper strata overlying the Rimbey-Meadowbrook carbonate complex. In general, economic contents of any of these elements are unlikely in the Wabamun aquifer, even in the deepest strata close to the thrustfold belt.

Carboniferous

Formation waters with Ca and Mg exceeding the threshold values were assigned to the Banff, Rundle and Stoddard stratigraphic units. Calcium is always < 25,000 mg/l and Mg < 7000 mg/l. The distribution of data points (figure 16) confirms that higher values for these elements are unlikely even in the deepest strata near the thrustfold belt. Potassium is always below the regional exploration threshold (max. 4,900 mg/l), with the higher values generally in deeper strata; lowest contents occur in northern and southern Alberta.

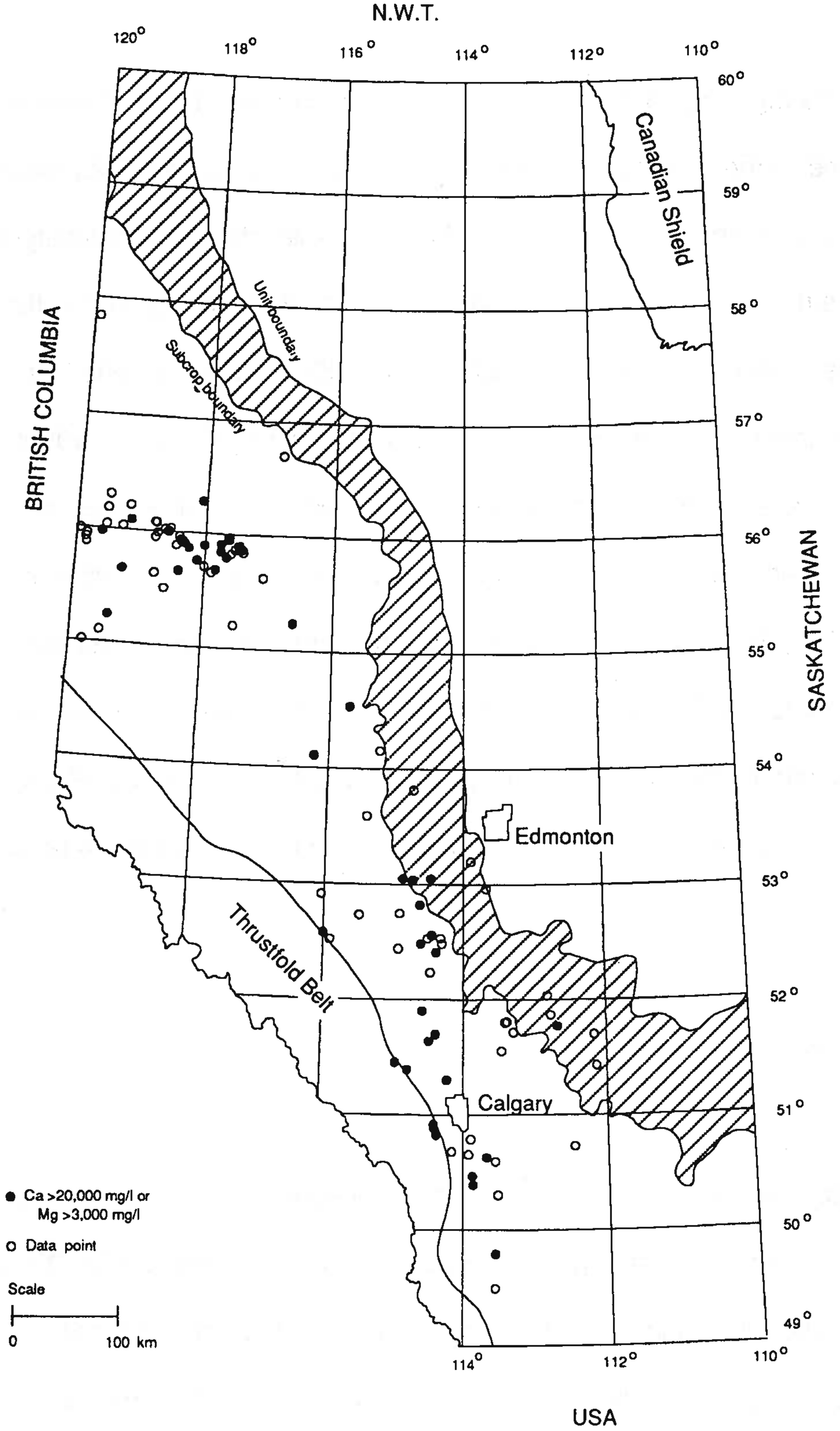


Figure 16. Distribution of formation waters exceeding the regional exploration thresholds for Ca and Mg in the Carboniferous aquifers.

Lithium shows a similar concentration distribution pattern, with a maximum value of 60 mg/l over the Peace River Arch. Bromide is always below the regional exploration threshold (max. 340 mg/l) and with only three exceptions (max. 58 mg/l) so is I. Carboniferous aquifers are thus not of economic interest with respect to these elements in formation waters.

Permian

All formation water analyses reporting Ca and Mg exceeding the regional exploration threshold values were rejected for a variety of reasons. With the exception of two isolated formation waters with I above the regional exploration threshold (max. 90 mg/l), the contents of K (max. 4,625 mg/l), Li (max. 40 mg/l) and Br (max. 193 mg/l) are all below their respective regional exploration thresholds.

Triassic

Formation waters with Ca and Mg exceeding the threshold values were assigned to the Diaber, Halfway, Charlie Lake and Baldonnel stratigraphic units. After three passes at culling erroneous data, only a few analyses remained with Ca > 25,000 mg/l or Mg > 4000 mg/l. The data distribution indicates that contents much higher than these values are unlikely, even in the deepest strata near the thrustfold belt or associated with the evaporites of the Charlie Lake Formation. The maximum contents for the other components are K 5,850 mg/l, Li 68 mg/l, Br 278 mg/l and I 53 mg/l. As a general observation, the maximum contents vary little among the four aquifers. However, for Li there appears to be an increased content in formation waters close to the region with > 5% anhydrite in the Charlie Lake Formation (Barss et al., 1964). This is true, to some extent, for adjacent aquifers. However, more data are needed to confirm this observation.

Jurassic

Formation waters with Ca and Mg exceeding the threshold limits were assigned either to the Fernie or Kootenay stratigraphic units. After culling, no analyses had Ca > 28,000 mg/l or Mg > 5000 mg/l. The data distribution indicates that no formation waters from Jurassic aquifers will have Ca or Mg of potential economic interest. The maximum contents for K (~ 3,500 mg/l), Li (49 mg/l), Br (235 mg/l) and I (34 mg/l) are all below their respective regional exploration thresholds.

Cretaceous

Mannville

Although 224 formation water analyses from the Lower and Upper Mannville aquifers have Ca and Mg above the threshold values, following culling, all remaining analyses have Ca < 20,000 mg/l and Mg < 5000 mg/l. The data distribution indicates that no formation waters from Mannville aquifers will have Ca or Mg of potential economic interest. Characteristic of both the Lower and Upper Mannville aquifers is the generally higher contents of K (max. ~ 3,400 mg/l), Li (max. 48 mg/l) and Br (max. 535 mg/l) in central Alberta, compared with southern and northern Alberta. These trends are illustrated in figures 17 to 19, respectively, for the Lower Mannville aquifer and figures 20 to 22, respectively, for the Upper Mannville aquifer. Iodide differs from these trends because K, Li and Br are related to salinity and I to the presence of organic material i.e. crude oil (see discussion in Hitchon and Horn, 1974). Thus plots of I for both the Lower Mannville aquifer (figure 23) and the Upper Mannville aquifer (figure 24) show no areal concentration of high values. However, none of these components are of economic interest.

Viking

Both Ca and Mg are below regional threshold limits in the Viking aquifer. As with the underlying Mannville aquifers, central Alberta contains formation waters with higher contents of K (max. 1,720 mg/l), Li (max. 21 mg/l) and Br (max. 815 mg/l), compared with southern and northern Alberta. These trends are shown in figures 25 to 27, respectively. Note the decreased cut-off value needed to illustrate this feature in going from the Lower Mannville aquifer to the Viking aquifer. Again, I differs from these trends (figure 28) because of its different geochemical characteristics. The acquisition of a much larger data base for I than that used by Hitchon et al. (1977) has resulted in a more obscure

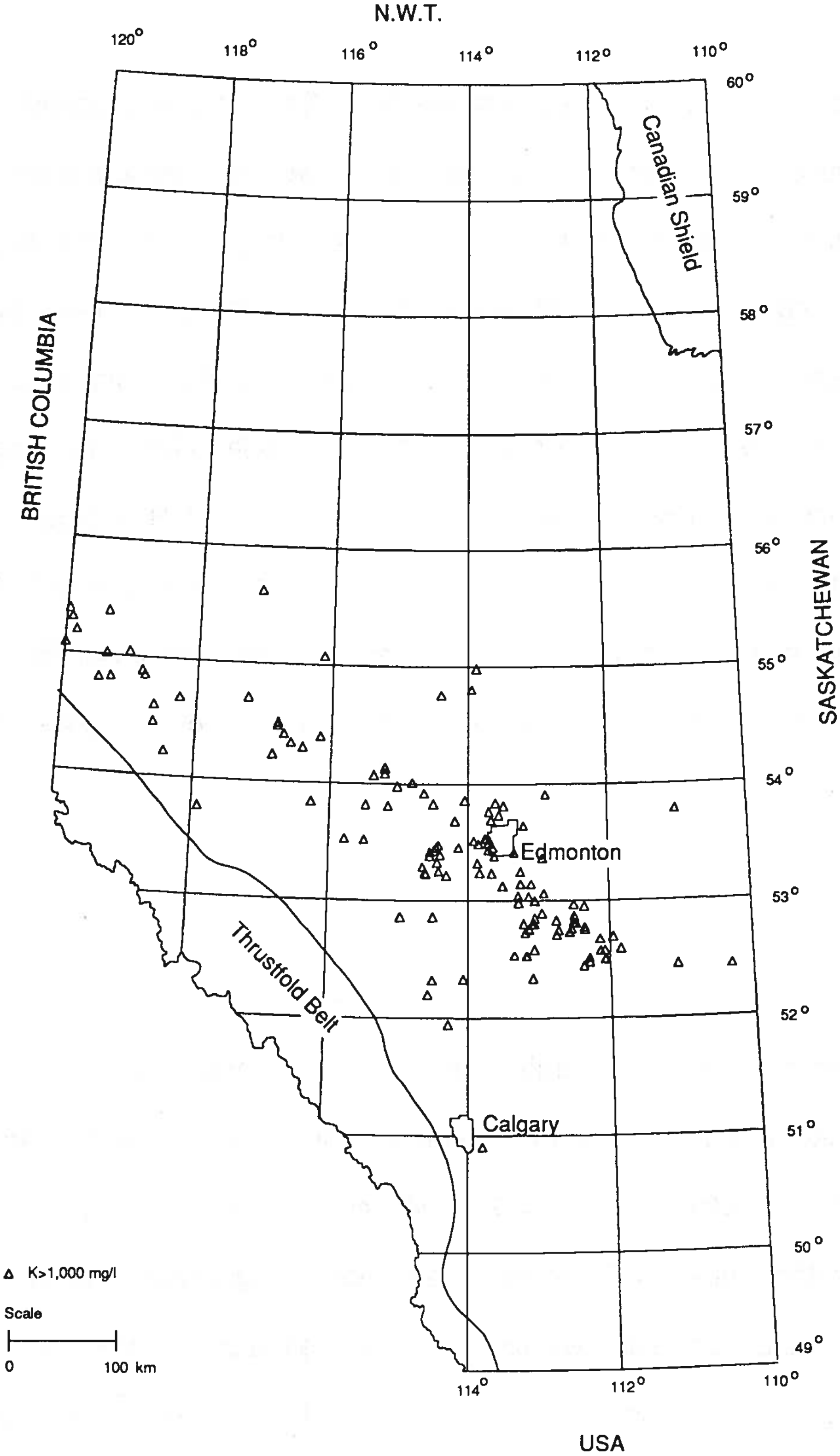


Figure 17. Distribution of K in formation waters from the Lower Mannville aquifer.

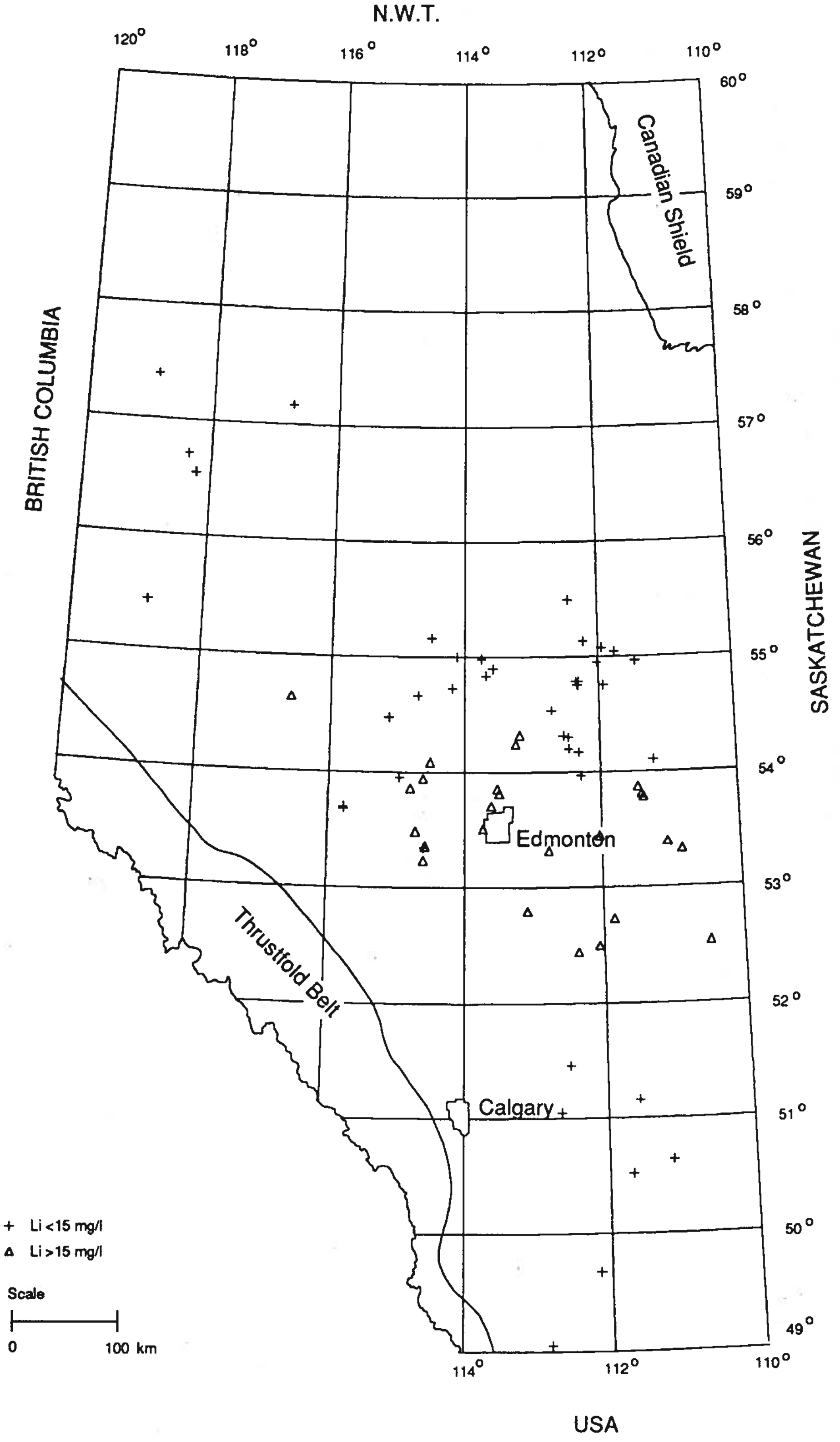


Figure 18. Distribution of Li in formation waters from the Lower Mannville aquifer.

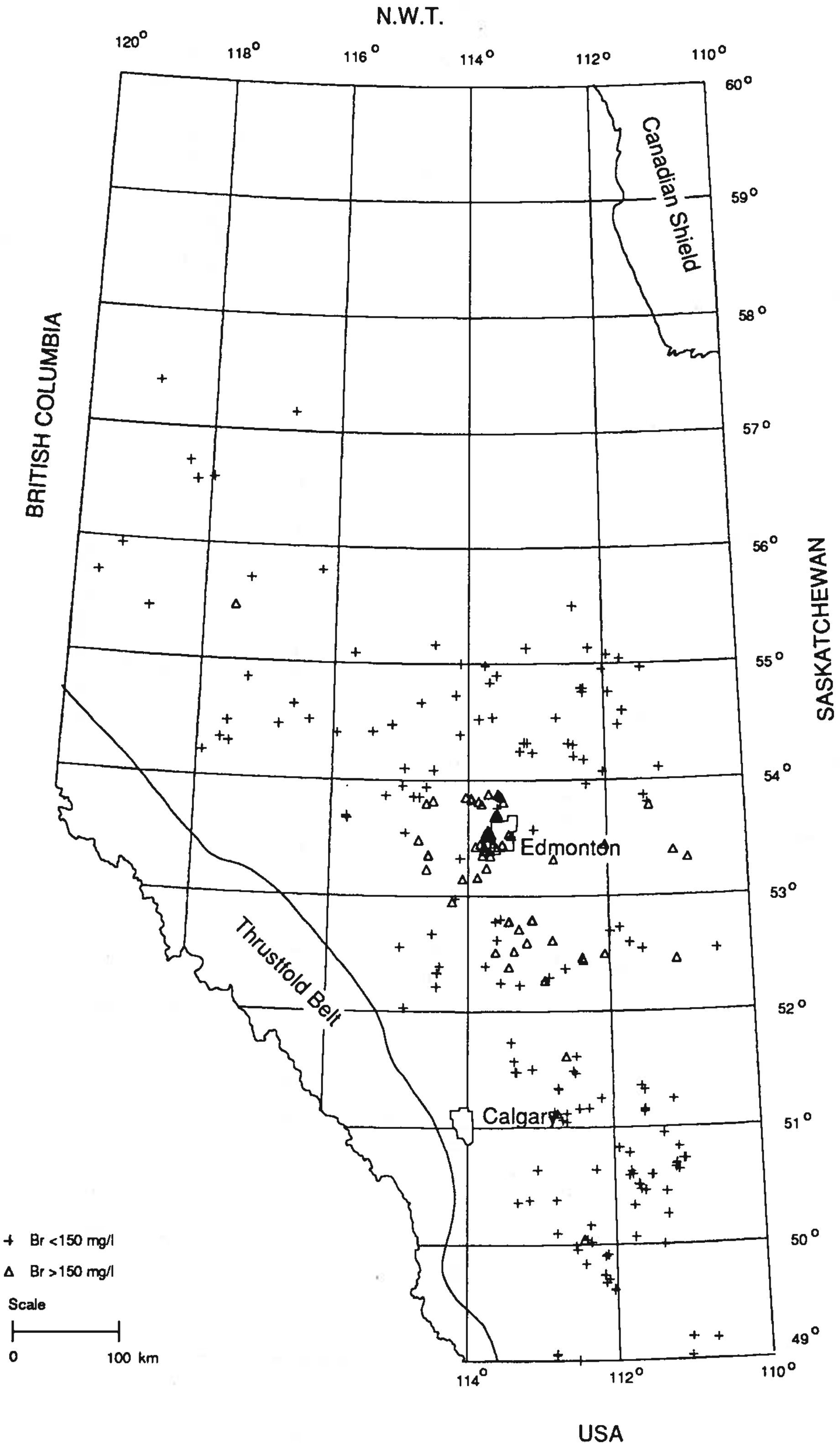


Figure 19. Distribution of Br in formation waters from the Lower Mannville aquifer.

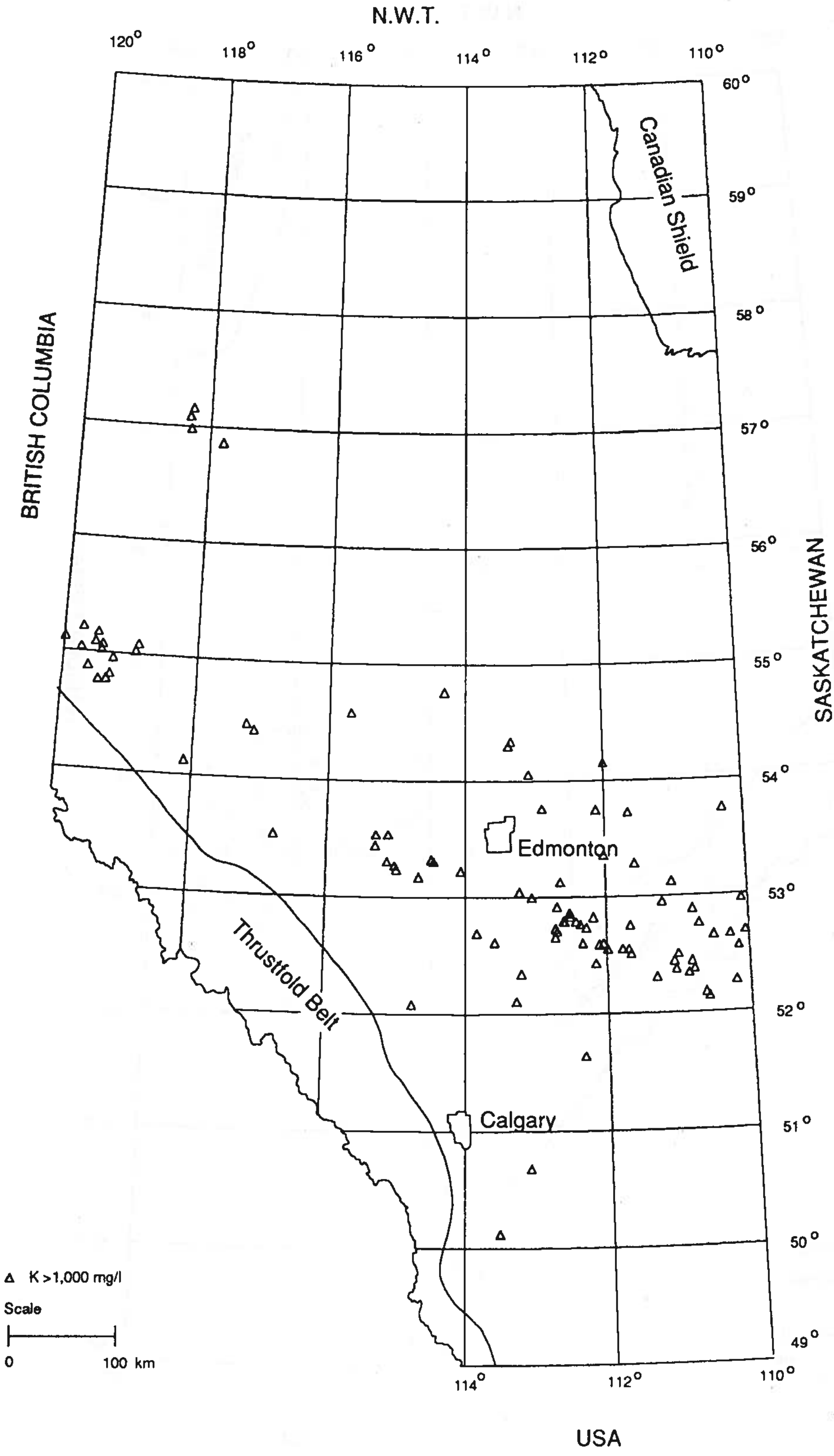


Figure 20. Distribution of K in formation waters from the Upper Mannville aquifer.

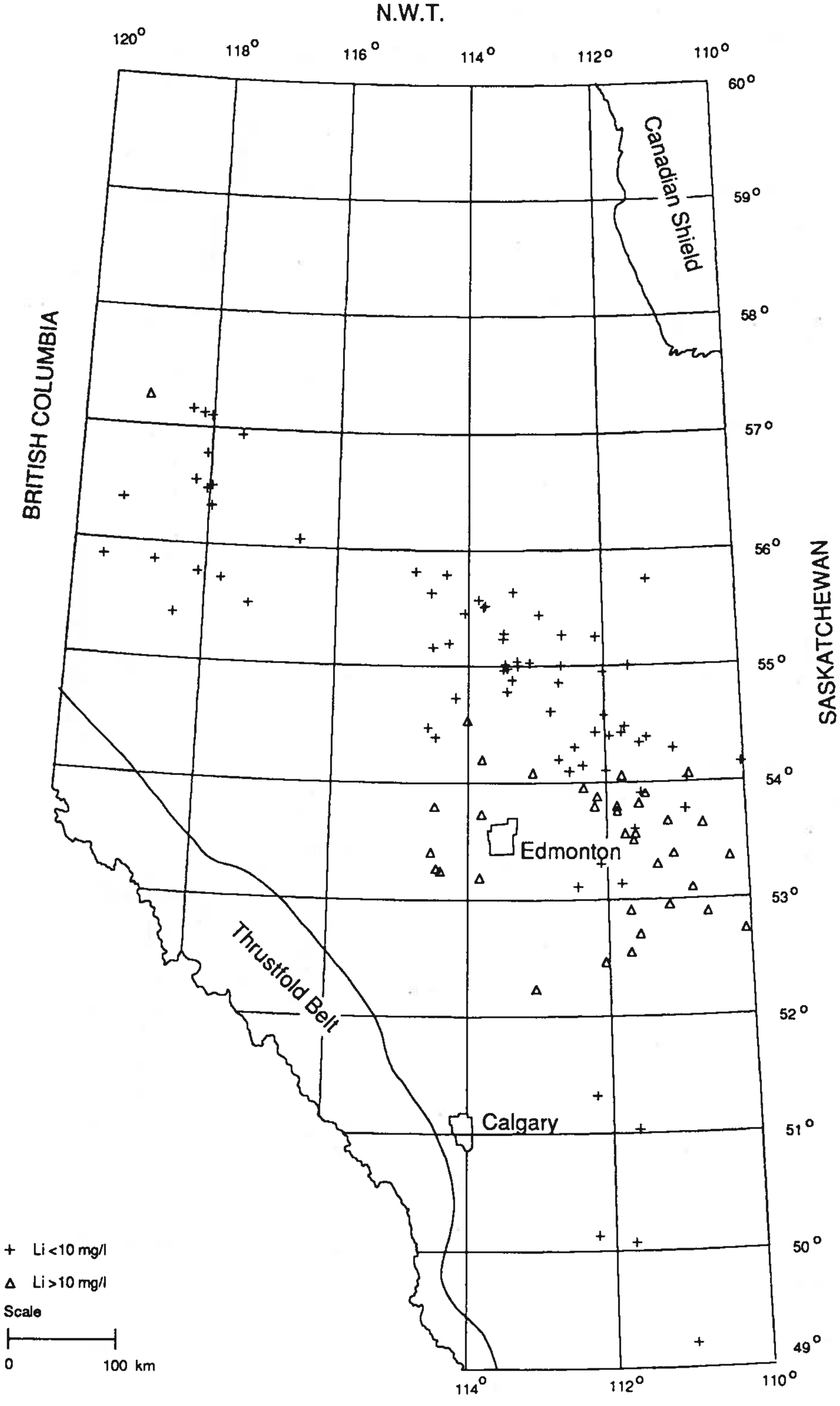


Figure 21. Distribution of Li in formation waters from the Upper Mannville aquifer.

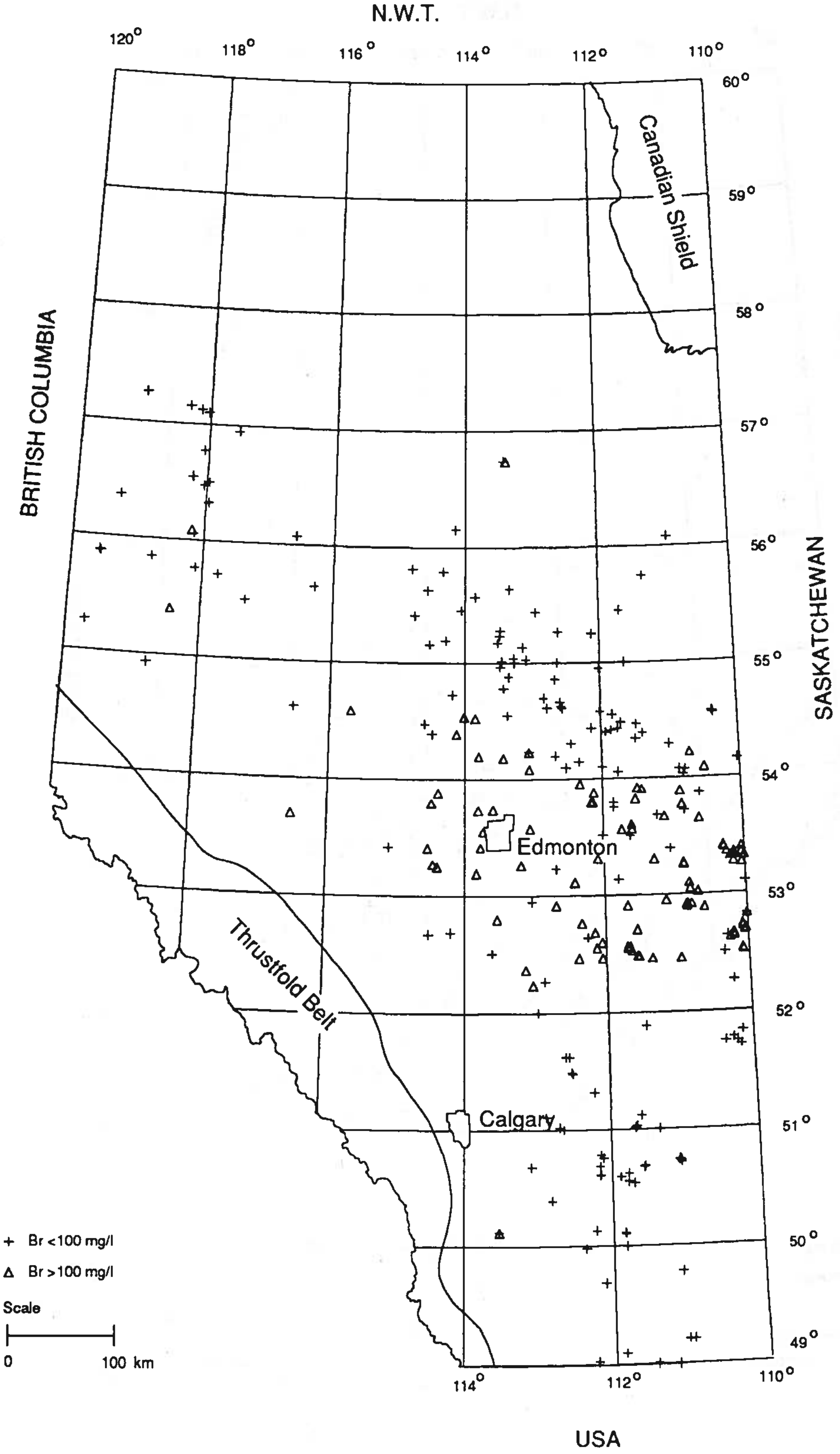


Figure 22. Distribution of Br in formation waters from the Upper Mannville aquifer.

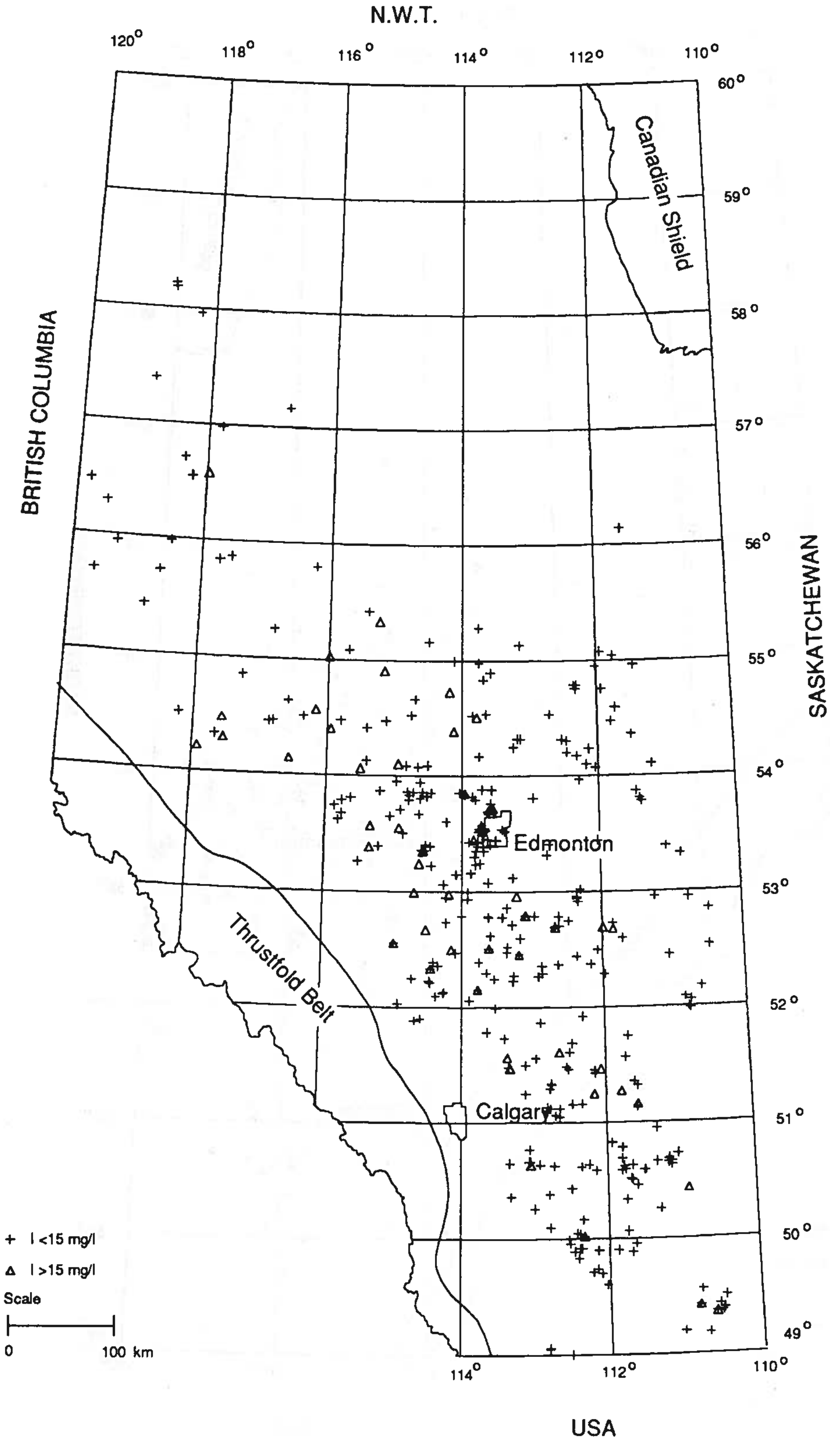


Figure 23. Distribution of I in formation waters from the Lower Mannville aquifer.

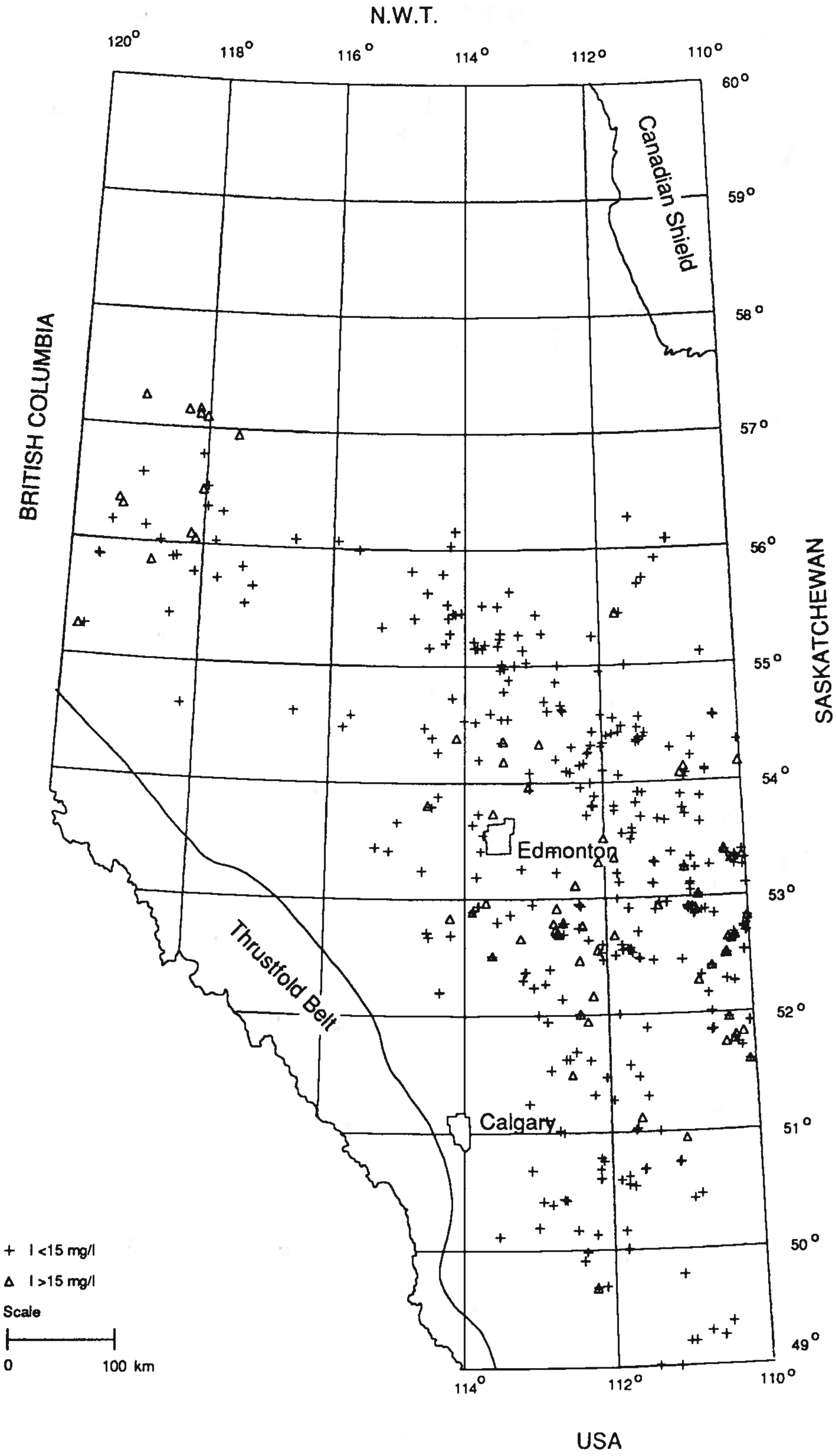


Figure 24. Distribution of I in formation waters from the Upper Mannville aquifer.

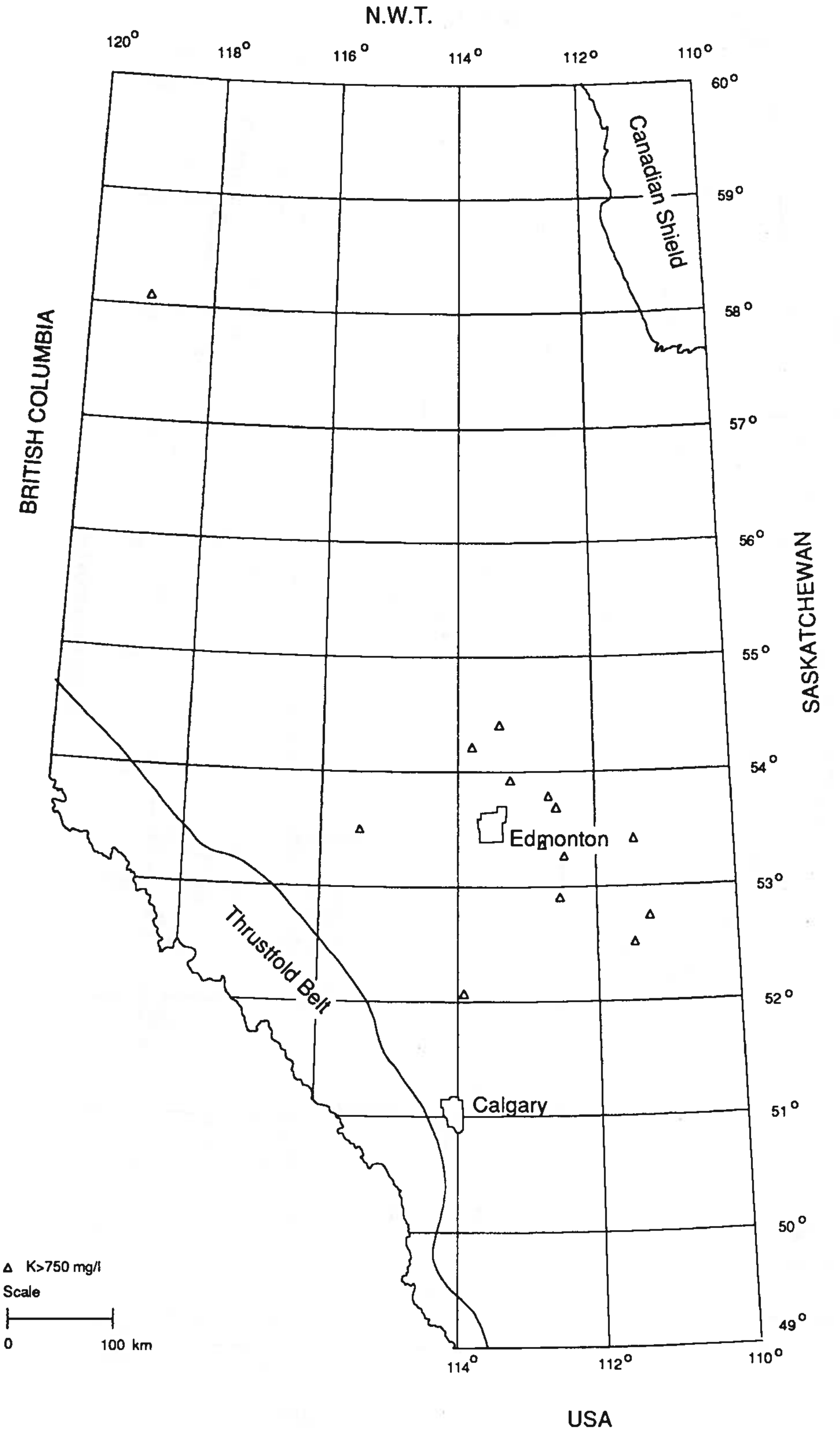


Figure 25. Distribution of K in formation waters from the Viking aquifer.

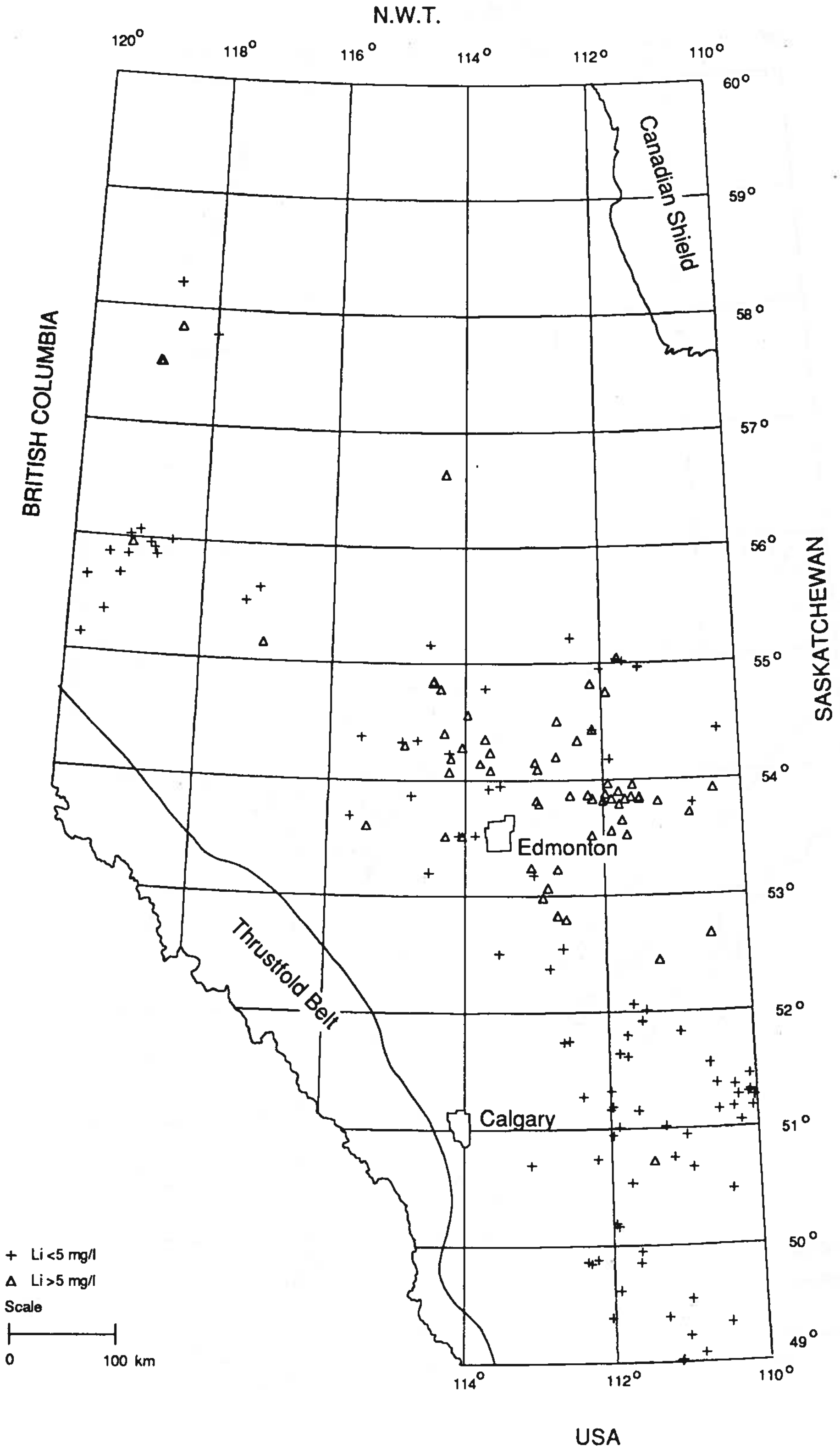


Figure 26. Distribution of Li in formation waters from the Viking aquifer.

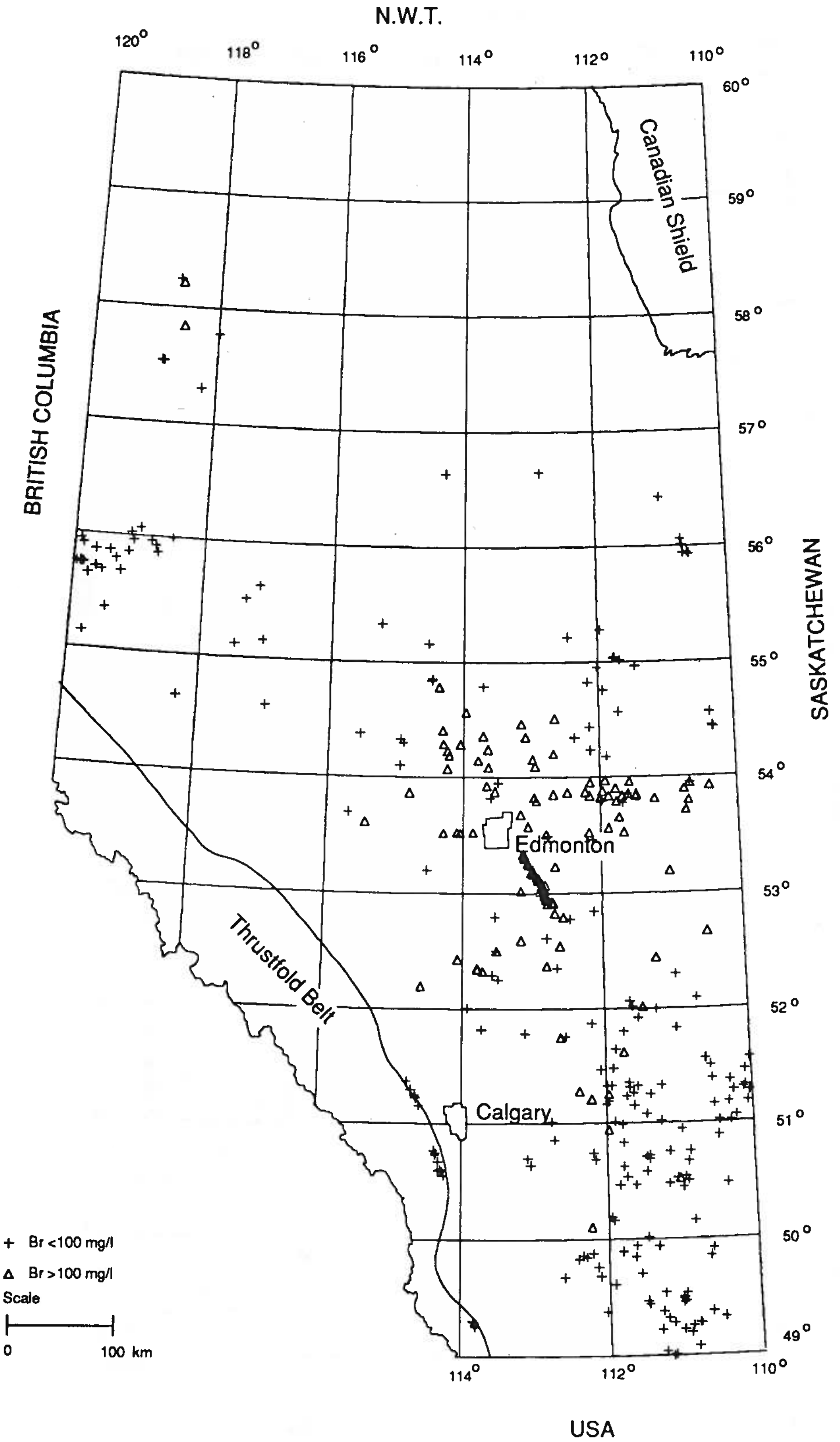


Figure 27. Distribution of Br in formation waters from the Viking aquifer.

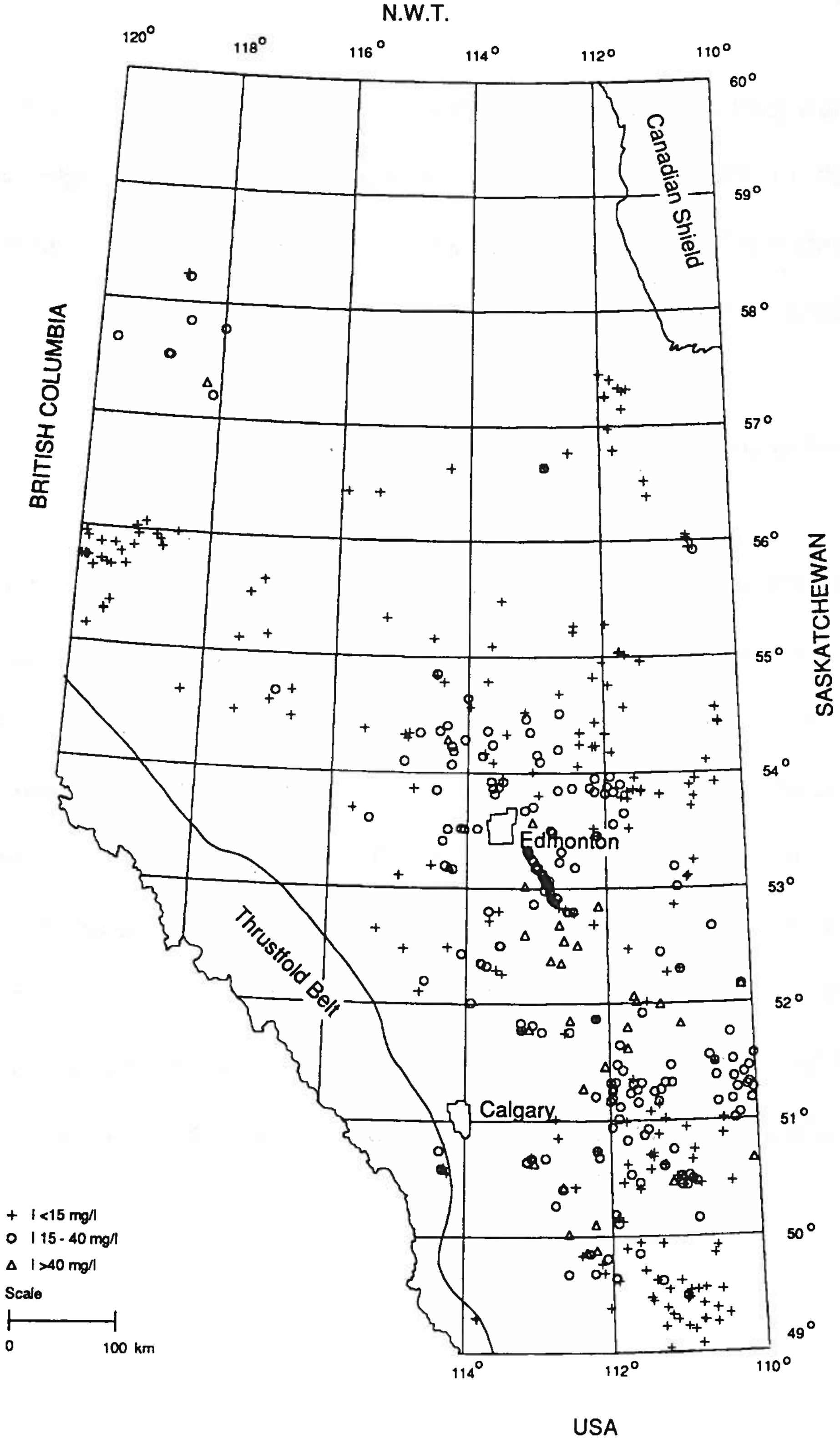


Figure 28. Distribution of I in formation waters from fhe Viking aquifer.

regional variation pattern. Perhaps very detailed contouring would reveal a northwest southeast grain to the isoconcentration contours, which in turn would reflect the sandstone isopachs of Rudkin (1964). Certainly, I contents of potential economic interest occur in the Viking aquifer.

Upper Cretaceous and Tertiary

Both Ca and Mg are below regional threshold limits in all Upper Cretaceous and Tertiary aquifers. Maximum contents of K decrease from ~ 500 mg/l in the Cardium aquifer to < 100 mg/l in Tertiary aquifers. Lithium is generally < 3 mg/l in all Upper Cretaceous and Tertiary aquifers, and Br generally < 125 mg/l (max. 165 mg/l in the Belly River aquifer). Iodide ranges up to nearly 100 mg/l in the Belly River aquifer. The larger I data base, compared with that available to Hitchon et al. (1977), tends to obscure the rather simple contours shown in the earlier study. But, figure 29 still shows a diffuse northwest-southeast trend to the band of I contents > 40 mg/l. A detailed evaluation of the I content of individual sandstones or groups of sandstones could be used in clarifying these trends.

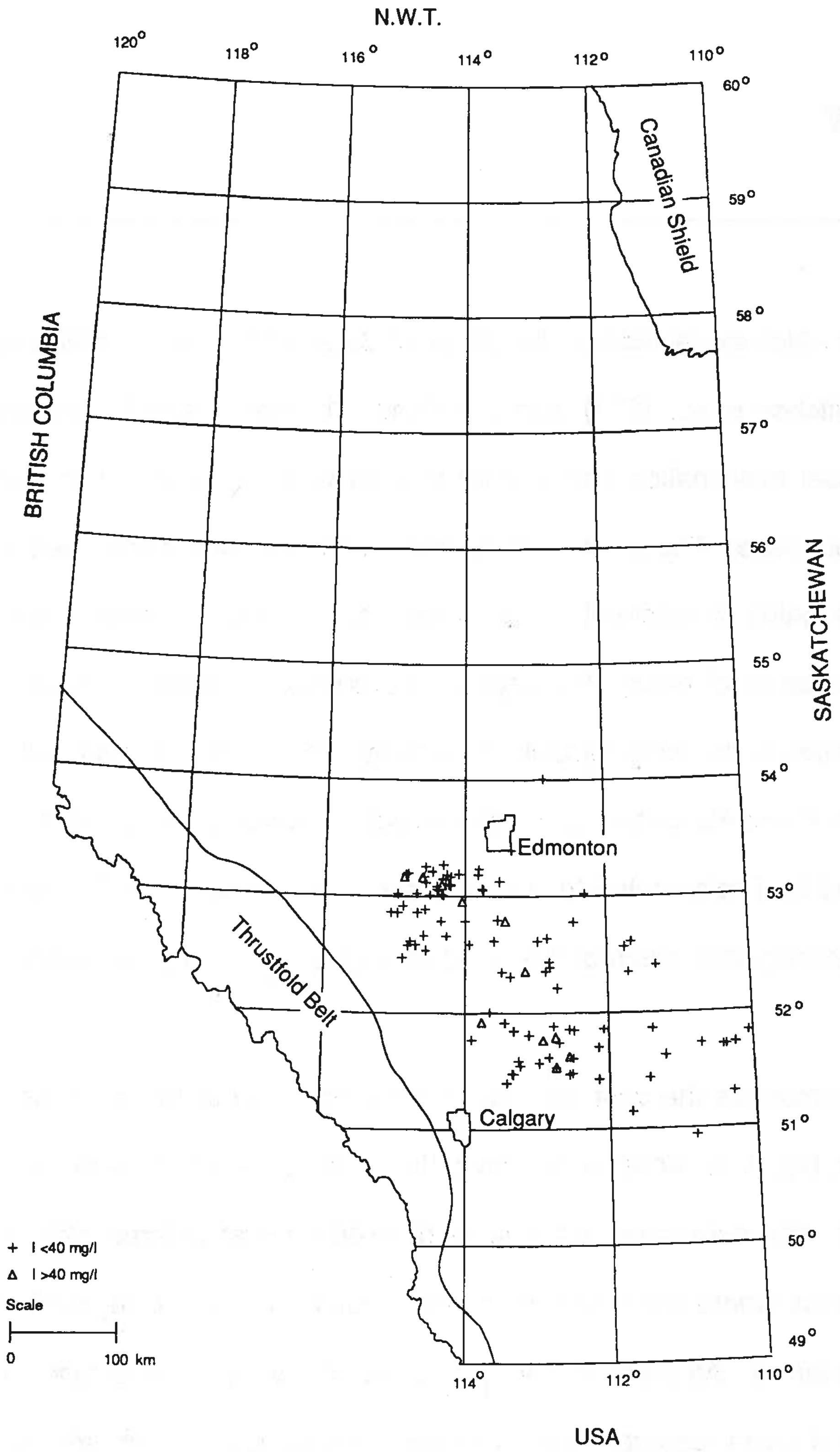


Figure 29. Distribution of I in formation waters from the Belly River aquifer.

Summary

Earlier studies which examined the distribution of Ca and Mg (Hitchon and Holter, 1971), Br, I and B (Hitchon et al., 1977), and Li (Hitchon, 1984b) in Alberta formation waters relied on manual examination and plotting of what was then a much smaller, but still substantial, data base. The present study could not have been undertaken without the analytical data being in electronic form suitable for computer manipulation. Further, advantage was taken of nearly 700 unpublished detailed analyses. These included a significant addition to the existing bank of information on Li, Br and I, as well as reliable values for both K and Na so that an electronic screening program based on the K/Na x 10^3 value could be implemented to cull analyses contaminated by KCl muds. Finally, computer contouring took much of the personal bias out of map presentation.

Table 13 summarizes the vast amount of data examined in terms of the maximum contents of Ca, Mg, K, Li, Br and I in each of the stratigraphic units examined. For ease of presentation, maximum contents above the detailed exploration thresholds (table 1) are in bold, and those where the maximum content was less than the regional exploration threshold are starred. As noted in the introduction, more than one component may be extracted from a given resource; table 13 makes it quite clear which are the preferred units for any given element, and which other elements could be co-produced. However, the element distribution maps must be consulted to ensure that all the maximum contents

Table 13. Summary of maximum contents (mg/l) of potential industrial minerals in Alberta formation waters.

Stratigraphic unit	Ca	Mg	K	Li	Br	I
Tertiary, Wapiti Fm.	*	*	*	*	*	*
Cretaceous						
Belly River Fm.	*	*	*	*	*	99
Lea Park Fm.	*	*	*	*	*	*
Milk River Fm.	*	*	*	*	*	*
Cardium Fm.	*	*	*	*	*	77
Dunvegan Fm.	*	*	*	*	*	62
Viking, Bow Island Fms.	*	*	*	*	*	**128**
U. Mannville Gp.	*	5000	*	*	*	76
L. Mannville Gp.	*	5000	*	*	*	*
Jurassic						
Kootenay Gp.	28000	4000	*	*	*	*
Fernie Gp.	*	5000	*	*	*	*
Triassic						
Baldonnel Fm.	*	*	*	60	*	*
Charlie Lake Fm.	23000	6000	*	68	*	*
Halfway Fm.	41000	**10000**	6000	58	*	53
Montney Fm.	20000	5000	*	60	*	*
Permian	*	*	*	*	*	90
Carboniferous						
Stoddart Gp.	22000	4500	*	*	*	*
Rundle Gp.	25000	7000	*	60	*	58
Banff Fm.	25000	5000	*	52	*	43
Devonian						
Wabamun Gp.	30000	**11300**	**10000**	**115**	*	*
Winterburn Gp.	30000	5000	8600	**90**	1880	38
Woodbend Gp.	39000	8000	**10000**	**140**	2115	53
Beaverhill Lake Gp.	**98000**	**13500**	**19000**	**130**	2785	50
Watt Mountain Fm.	40000	8000	7000	**98**	*	*
Keg River Fm.	46000	7000	7000	**95**	1360	**120**
L. Elk Point Gp.	**95000**	**12000**	5000	71	1530	40
Ordovician	27000	7500	*	*	*	*
Cambrian	30000	7000	*	**81**	*	*

* = all formation water analyses below respective regional exploration thresholds (see table 1).

are in the same area of the province. Areas and aquifers which justify Phase 2 resource evaluation are as follows:

Lower Elk Point

Area:	two, in northern Alberta, associated with the Cold Lake and Lotsberg salts, respectively.
Elements:	detailed exploration thresholds exceeded for Ca (figure 4) and Mg (figure 5); calculated values for K (table 9) also exceed the detailed exploration threshold. There is a possibility of high Br contents.
Exploration:	two aspects need to be considered. First, any formation waters recovered from this aquifer, or from the underlying Granite Wash aquifer or overlying Keg River aquifer in the same area, need complete analyses determined. Second, there were no formation water analyses in the updip portion of the aquifer and so the eastern boundary of the detailed exploration area is open.

Beaverhill Lake

Area: southern Alberta, generally associated with an area of evaporites.

Elements: detailed exploration thresholds exceeded for Ca (figure 9), Mg (figure 10) and K (figure 11); the distribution of Br (figure 12) indicates a high probability of high contents in the same area.

Exploration: two aspects need to be considered. First, any formation waters recovered from this aquifer in this area should have a complete analysis performed. Second, the southwestern boundary of the detailed exploration area is open, but depths to the aquifer will be greater; further, the eastern boundary of the area lies in Saskatchewan, where even higher contents of these elements are possible.

Woodbend

Area: part of northwest Alberta, south of the Peace River High, and associated with the Windfall-Swan Hills carbonate reef complexes (figure 30).

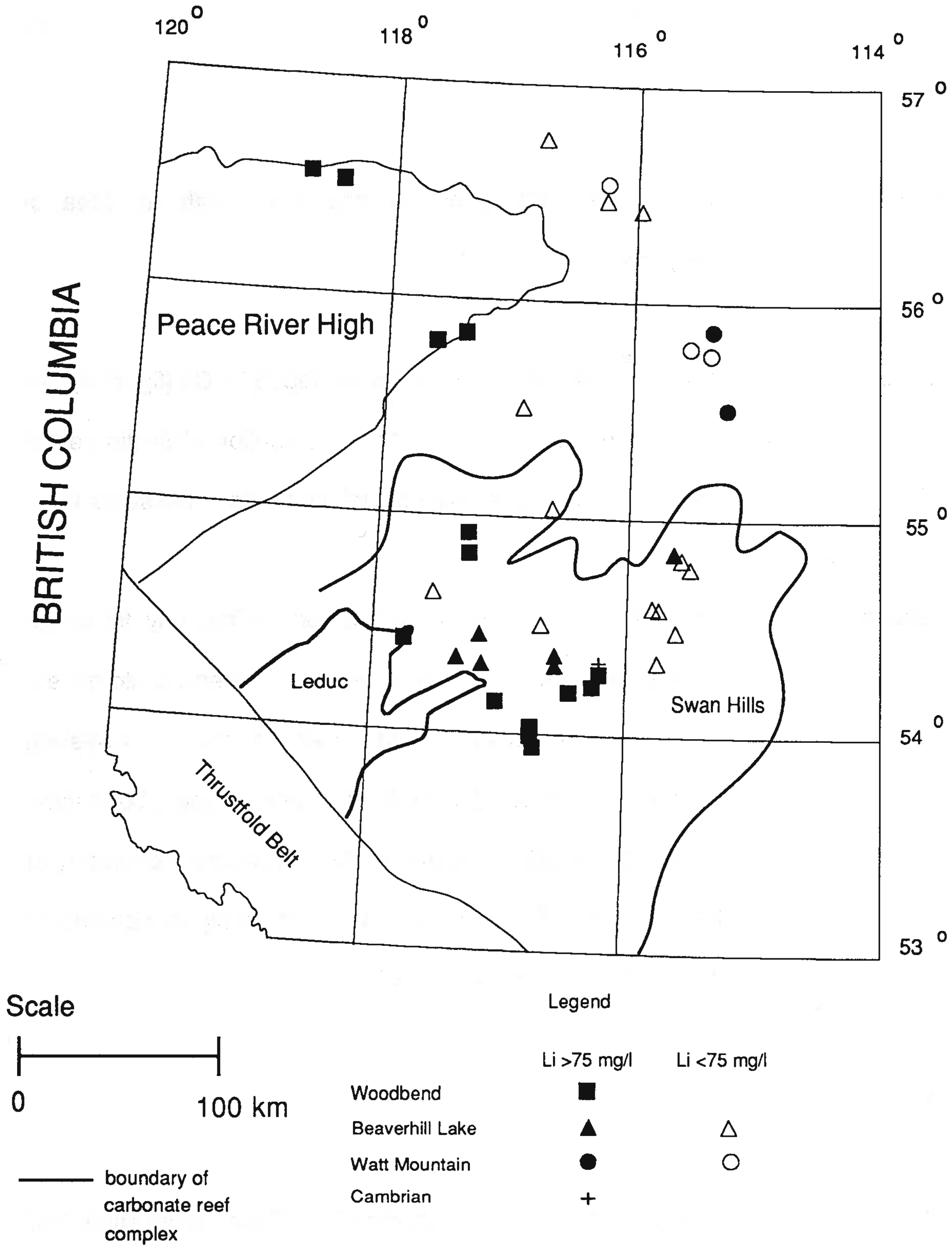


Figure 30. Distribution of Li in formation waters associated with the Windfall-Swan Hills carbonate complex.

Elements: only Li is of potential interest, and it occurs in strata ranging from the Cambrian to the Leduc Formation (Woodbend Group).

Exploration: although perhaps only of academic interest, nevertheless it would be of interest and value to analyze for Li in any formation waters recovered from the deeper portions of these aquifers.

<u>Viking and Belly River</u>

Areas: for both aquifers, central and southern Alberta.

Elements: only I is of potential interest.

Exploration: the different geochemical characteristics of I, compared with the other elements considered, together with the very large data base, have obscured the rather simplistic high-I areas shown by Hitchon et al. (1977). A detailed study is needed of the distribution of I in each of these aquifers, with specific emphasis on the relation of high I contents with producing wells.

References

Bachu, S. and R.A. Burwash (1993): The geothermal regime of the Western Canada Sedimentary Basin; *in* Geological Atlas of the Western Canada Sedimentary Basin. (compiled by G.D. Mossop and I. Shetsen). Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council (*in press*).

Bachu, S., B. Hitchon and P. Mortensen (1986): Preliminary analysis of transport processes in the Basal Cambrian aquifer of south-central Alberta; in Proceedings of Third Canadian/American Conference on Hydrogeology: Hydrogeology of Sedimentary Basins -- Application to Exploration and Exploitation (B. Hitchon, S. Bachu and C.M. Sauveplane, editors), pp. 118-126; National Water Well Association, Dublin, Ohio.

Bachu, S., C.M. Sauveplane, A.T. Lytviak and B. Hitchon (1987): Analysis of fluid and heat regimes in sedimentary basins: Techniques for use with large data bases; American Association of Petroleum Geologists Bulletin, v. 71, no. 7, pp. 822-843.

Barss, D.L., E.W. Best and N. Meyers (1964): Triassic; *in* Geological history of Western Canada (R.G. McCrossan and R.P. Glaister, editors), pp. 113-136; Calgary, Alberta Society of Petroleum Geologists.

Connolly, C.A., L.M. Walter, H. Baadsgaard and F.J. Longstaffe (1990a): Origin and evolution of formation waters, Alberta Basin, Western Canada Sedimentary Basin. I. Chemistry; Applied Geochemistry, v. 5, no. 4, pp. 375-395.

Connolly, C.A., L.M. Walter, H. Baadsgaard and F.J. Longstaffe (1990b): Origin and evolution of formation waters, Alberta Basin, Western Canada Sedimentary Basin.

II. Isotope systematics and water mixing; Applied Geochemistry, v. 5, no. 4, pp. 397-413,

Egleson, G.C. and C.W. Querio (1969): Variation in the composition of brine from the Sylvania Formation near Midland, Michigan; Environmental Science and Technology, v. 3, pp. 367-371.

Frape, S.K. and P. Fritz (1987): Geochemical trends for groundwaters from the Canadian Shield; *in* Saline Water and Gases in Crystalline Rocks (P. Fritz and S.K. Frape, editors), pp. 19-38; Geological Association of Canada Special Paper 33.

Grayston, L.D., D.F. Sherwin and J.F. Allan (1964): Middle Devonian; *in* Geological history of Western Canada (R.G. McCrossan and R.P. Glaister, editors), pp. 49-59; Calgary, Alberta Society of Petroleum Geologists.

Hanor, J.S. (1987): Origin and migration of subsurface sedimentary brines; Lecture Notes for Short Course No. 21, Society of Economic Paleontologists and Mineralogists, 247 pp.

Hitchon, B. (1984a): Formation waters as a source of industrial minerals in Alberta; *in* The Geology of Industrial Minerals in Canada (G.R. Guillet and W. Martin, editors), pp. 247-249; Canadian Institute of Mining and Metallurgy, Special Volume 29.

Hitchon, B. (1984b): Lithium in Alberta formation waters; Confidential Report prepared for an industrial client.

Hitchon, B. (1993): Geochemistry of formation waters, northern Alberta, Canada: their relation to the Pine Point ore deposit; Open File Report 1993-14; Edmonton, Alberta Research Council.

Hitchon, B., S. Bachu, C.M. Sauveplane and A.T. Lytviak (1987): Dynamic basin analysis: an integrated approach with large data bases; *in* Fluid Flow in Sedimentary Basins and Aquifers (J.C. Goff and B.P.J. Williams, editors), pp. 31-44; Geological Society Special Publication No. 34.

Hitchon, B., S. Bachu and J.R. Underschultz (1990): Regional subsurface hydrogeology, Peace River Arch area, Alberta and British Columbia; Bulletin of Canadian Petroleum Geology, v. 38A, pp. 196-217.

Hitchon, B., G.K. Billings and J.E. Klovan (1971): Geochemistry and origin of formation waters in the western Canada sedimentary basin -- III. Factors controlling chemical composition; Geochimica et Cosmochimica Acta, v. 35, pp. 567-598.

Hitchon, B. and M.E. Holter (1971): Calcium and magnesium in Alberta brines; Economic Geology Report No. 1; Edmonton, Alberta Research Council.

Hitchon, B. and M.K. Horn (1974): Petroleum indicators in formation waters from Alberta, Canada; American Association of Petroleum Geologists Bulletin, v. 58, no. 3, pp. 464-473.

Hitchon, B., A.A. Levinson and M.K. Horn (1977): Bromide, iodide, and boron in Alberta formation waters; Economic Geology Report No. 5; Edmonton, Alberta Research Council.

Hitchon, B., A.A. Levinson and S.W. Reeder (1969): Regional variations of river water composition resulting from halite solution, Mackenzie River drainage basin, Canada; Water Resources Research, v. 5, no. 6, pp. 1395-1403.

Hitchon, B., C.M. Sauveplane, S. Bachu, E.H. Koster and A.T. Lytviak (1989): Hydrogeology of the Swan Hills area, Alberta: Evaluation for deep waste injection; Bulletin 58; Edmonton, Alberta Research Council.

Kharaka, Y.K., W.D Gunter, P.K. Aggarwal, E.H. Perkins and J.D. DeBraal (1988): SOLMINEQ.88: A computer program for geochemical modelling of water-rock interactions; U.S. Geological Survey Water-Resources Investigations Report 88-4227.

Mossop, G.D. and I. Shetson (compilers) (1993): Geological Atlas of the Western Canada Sedimentary Basin; Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council.

Multhauf, R.P. (1978): Neptune's gift, a history of common salt; The Johns Hopkins University Press, 325 pp.

Rudkin, R.A. (1964): Lower Cretaceous; *in* Geological history of Western Canada (R.G. McCrossan and R.P. Glaister, editors), pp. 156-168; Calgary, Alberta Society of Petroleum Geologists.

White, D.E., J.D. Hem and G.A. Waring (1963): Chemical composition of subsurface waters; *in* Data on Geochemistry, sixth edition, U.S. Geological Survey Professional Paper 400.

Appendix. Summary of K/Na ratios in Alberta formation waters.

This Appendix presents statistics on the K/Na x 10^3 value in Alberta formation waters from producing wells and from drillstem tests (RCAH- and D- series) believed to be free of KCl mud contamination. From this information, the K/Na x 10^3 values were selected for culling formation water analyses contaminated by KCl mud.

Table A1. Statistics on K/Na x 10^3 value in Alberta formation waters.

Stratigraphic unit	Production samples				Drillstem test samples			
	No.	Min.	Mean	Max.	No.	Min.	Mean	Max.
UPPER CRETACEOUS								
Belly River Fm.	3	3.9	4.6	5.0	12	2.3	5.5	7.8
Basal Belly River Gp.	4	5.5	8.5	12.6	16	4.0	8.4	17.3
Milk River Fm.	-				3	5.1	6.3	8.2
Cardium Fm.	4	2.8	7.2	11.4	1		7.4	
Doe Creek Fm.	1		3.7		-			
Dunvegan Fm.	-				1		26.7	
LOWER CRETACEOUS								
Viking, Bow Island Fms.	13	2.3	5.2	10.9	126	1.9	6.4	81.2
U. Mannville Gp.	2	5.2	16.1	27.0	62	3.2	7.8	21.5
Clearwater Fm.	-				5	4.5	8.2	16.5
L. Mannville Gp.	19	8.4	22.6	47.4	85	2.2	12.1	68.0
JURASSIC	9	14.0	30.3	93.2	8	12.4	19.4	41.0
TRIASSIC	3	21.6	28.7	33.5	24	9.6	27.3	59.8
PERMIAN	-				5	17.2	20.3	28.7
CARBONIFEROUS								
Stoddart, Rundle Gps.	8	8.5	40.7	137	52	3.9	33.3	150
Banff Fm.	3	21.2	25.7	30.8	13	5.7	28.1	153
DEVONIAN								
Wabamun Gp.	7	21.5	44.8	78.6	27	8.0	31.5	128
Winterburn Gp.	20	13.3	82.4	172	22	9.5	37.9	98.2
Ireton Fm.	1		160		-			
Leduc, Grosmont Fms.	37	9.3	91.7	217	16	10.1	81.3	174
Cooking Lake Fm.	2	12.7	15.3	17.8	-			
Beaverhill Lake								
Swan Hills Fm.	4	15.9	23.7	33.6	10	12.9	72.6	117
Slave Point Fm.	2	88.3	105	122	8	8.6	20.3	47.4
High-Ca brines	-				6	185	300	703
Watt Mountain Fm.	1		17.2		4	13.5	19.2	25.5
Sulphur Point Fm.	-				8	36.6	50.0	59.1
Muskeg Fm.	1		59.5		2	20.1	41.2	62.3
Keg River Fm.	2	19.4	44.2	69.0	25	5.2	34.5	91.1
GRANITE WASH	3	13.2	18.9	27.9	7	10.7	15.9	27.9
CAMBRIAN	-				1		98.0	