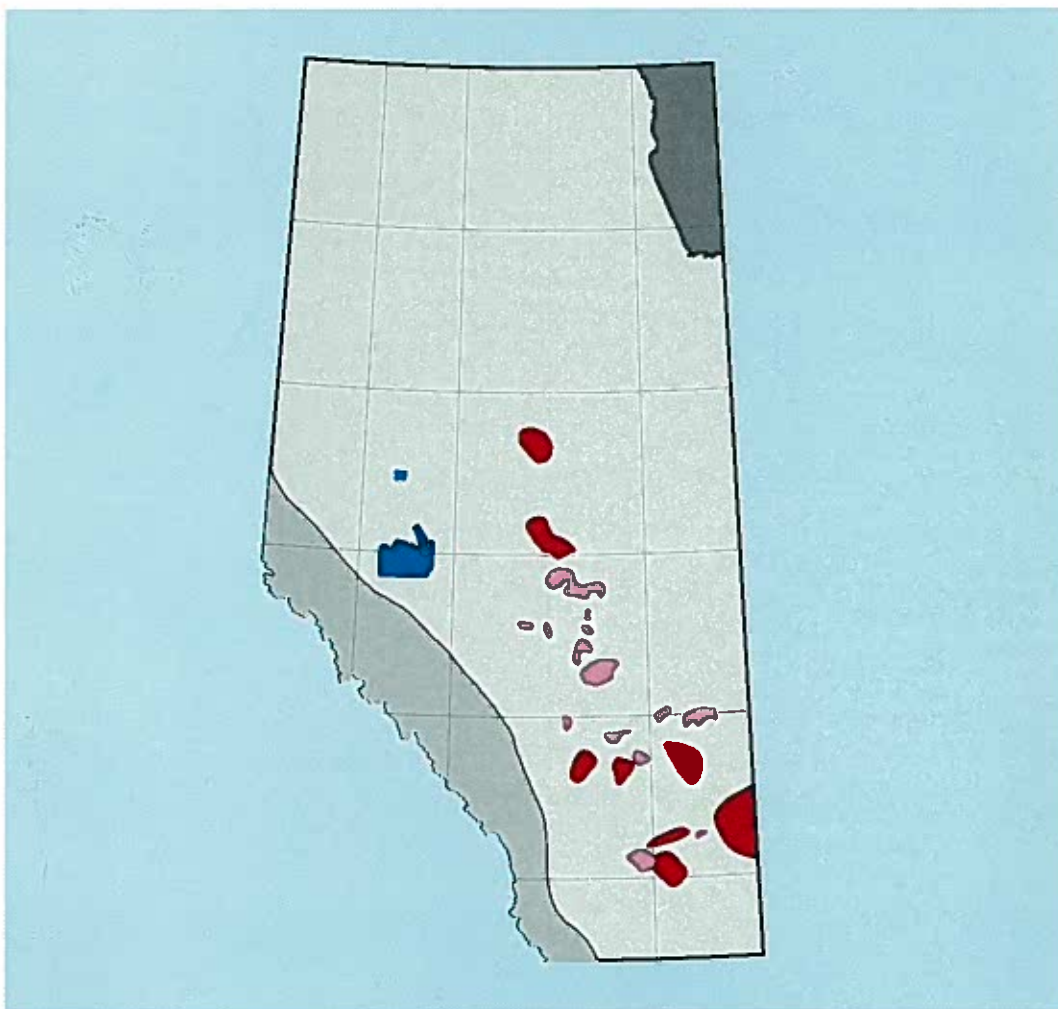# Industrial Mineral Potential of Alberta Formation Waters

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of
Alberta Formation Waters

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Cover:
Resource areas for industrial minerals in
Alberta formation waters: Ca-Mg (Br)
brines — red; Li — blue; I — violet

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Abstract

Nearly 130 000 analyses of formation waters from Alberta and adjacent areas were searched for contents of Ca, Mg, K, Br, I and Li exceeding specified regional exploration thresholds. The 5280 analyses meeting these criteria comprise the formation water industrial mineral data base, of which only 79 show these components exceeding the detailed exploration thresholds (Ca 60 000 mg/l, Mg 9000 mg/l, K 10 000 mg/l, Br 3000 mg/l, I 100 mg/l, Li 75 mg/l). Concentration contour maps and data-point distribution maps identified areas and aquifers for which resource estimation was justified. Using information from well logs, drillstem tests and core analyses, areas were identified in each target aquifer which met the combined criteria of exceeding the detailed exploration threshold for element concentration as well as aquifer thickness (>10 m), porosity (>5%) and permeability (>10^{-14} m^2, 10 millidarcies). Resource estimates were made, and are compiled, for these identified areas and aquifers. The estimates are based on element concentrations and water producibility alone, and indicate only a potential to be of economic interest; no implication with respect to economic recoverability should be construed. In view of the present market conditions, and taking into account comparisons with commercial operations elsewhere in the world, it is suggested that of the element concentrations found in Alberta formation waters only that of Li may be of additional interest at this time because contents are similar to those of the major USA producer. The study recommends that industry continue to analyze formation waters for Ca, Mg, Br, I and Li in selected aquifers and areas.

Introduction

Historical background

Formation waters have been a source of industrial minerals, *sensu lato*, from prehistoric times. Hanor (1987) 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 Aboriginal People of 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. Allan (1920) noted that salt from these springs was "collected and used by the Hudson's Bay Company and also by the Roman Catholic Mission", with "upwards of four tons" collected annually. Wells drilled in the early part of this century penetrated salt and gypsum; indeed, one of the first undertakings of the newly formed Alberta Research Council was to explore and drill for salt in the Fort McMurray area.

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, early drilling (Allan, 1920) and modern chemical and isotope techniques (Hitchon et al., 1969) confirm that the source of the dissolved salts is halite and anhydrite dissolved at depth by meteoric water.

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 Alberta's Energy Resources Conservation Board (ERCB; amalgamated with other provincial agencies in 1994 to form the Alberta Energy and Utilities Board) published quarterly reports that included compilations of formation water analyses, mainly by fields and pools, and also published 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 ERCB 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, Hitchon (1995) has summarized information on the geochemistry of Li in Alberta formation waters. Apart from these reports, there have been no publications on the regional distribution of elements of potential interest. Further, none of the above-cited reports assessed the economic potential of the resources in terms of producibility.

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 bulletin are arbitrary and as generic as possible:

groundwater:	shallow formation water, commonly potable (salinity generally <1000 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 the generic saline formation water is t h e 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 thickness, 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 additional 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 bulletin is limited to phases 1 and 2.

Threshold values

Formation waters are geochemically continuous features, unlike ore bodies which are geochemically discontinuous within 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 (1984) defined a detailed exploration threshold value for each element of interest based on their current economically producing fields. In order to allow for automatic 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 (1984), together with additional information specific to this study. These values are compared in Table 1 with the composition of the commercial brine produced by Dow Chemical Company, 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.

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	3000	9000	9960	9200
K	5000	10 000	9120	8000
Li	50	75	70	58
Br	1000	3000	2910	2790
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).

Formation water data base and data processing

Data base

The main source of formation water analyses in Alberta is the ERCB; 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. (1990a, b). The second source comprises *unpublished* detailed analyses in the files of the senior author. The second source includes the so-called D-series of formation waters, which were 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 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 ERCB; all were from drillstem tests. The produced water was sampled by the operating company for the ERCB and the Alberta Research Council (then Research Council of Alberta). Major components were determined by the ERCB 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 and 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 imbalances <5%, and one quarter had charge imbalances between 5% and 10%. Analyses with charge imbalances >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 (Hitchon and Brulotte, 1994) designed to reject obviously erroneous or incomplete analyses. The final data base used in this study therefore 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 regional-scale study area was arbitrarily defined as the province of Alberta, extended by 2° longitude in western Saskatchewan, 2° longitude in eastern British Columbia and 1° latitude in the southern Northwest Territories. This was done to avoid possible edge effects at Alberta boundaries. 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 electronic surfaces (grids) from the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1994). Figure 1 shows the specific stratigraphic intervals used in this study. Depending on their permeability, sedimentary strata can be classified from a hydrogeological point of view into aquifers, aquitards and aquicludes. Sandstones and carbonate rocks are commonly aquifers, shales usually aquitards, and evaporites are aquicludes. Of the stratigraphic units shown in Figure 1, several are dominantly aquitards, and the Prairie Formation is the main aquiclude; analyses falling within these aquitards or aquicludes 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 and large scale (1:5 000 000) 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 2000 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 printouts of the data,

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

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 >5000 mg/l (arbitrary values) were checked individually; this was to ensure that there was absolutely no chance for a potential source to be overlooked. To ensure that all available data were utilized, the data base was also searched for analyses reporting (Ca + Mg), which is a separate entry in the data base. A threshold value of 23 000 mg/l was used for the regional exploration limit (67 analyses) and 69 000 mg/l (i.e. the combined Ca and Mg detailed exploration threshold values) for the detailed exploration threshold. Only two analyses exceeded the detailed exploration threshold and both were from an area and aquifer with analyses reporting the individual elements.

Table 2 shows the total number of formation water analyses in Alberta, at the time of performing the work, with Ca >10 000 mg/l and/or Mg >2000 mg/l, by stratigraphic unit, and the results of data screening. 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 printouts 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 work reported here is based on the third set of Cl, Ca and Mg distribution maps.

Potassium was reported in >52 350 formation water analyses, of which 92% were below the regional exploration threshold of 5000 mg/l (Table 3). 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 analyses were separated into those from producing wells, which were definitely uncontaminated, and those from drillstem tests known 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 corresponding threshold value of K/Na x 10^3 was set for each major stratigraphic unit (Table 4), 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 screen, rigorously, 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 5 reflects minor re-allocation of 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.

Table 2. Processing of formation waters with Ca >10 000 mg/l and Mg >2000 mg/l.

Stratigraphic unit	Total analyses	Culled on first pass	Culled (or reassigned) on second pass	Final data set
Upper Cretaceous				
Belly River Fm.	4	4	-	-
Lea Park Fm.	1	1	-	-
Upper Colorado Gp.	10	10	-	-
Dunvegan Fm.	1	1	-	-
Lower Cretaceous				
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	653	4735
		(24.6%)	(9.1%)	(66.3%)

Table 3. Processing of formation waters reporting 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	1530	83	108
Upper Cretaceous					
Belly River Fm.	0.29	50 830	1761	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	7293	247	287
U.Mannville Gp.	0.3	112 000	10 393	292	344
L.Mannville Gp.	0.4	93 845	8038	171	321
Jurassic	0.1	83 250	3423	126	220
Triassic	1.0	93 900	1924	179	206
Permian	2.0	34 000	263	13	11
Carboniferous					
Stoddard, Rundle gps.	0.1	65 000	2171	94	116
Banff Fm.	1.0	78 000	1322	37	46
Devonian					
Wabamun Gp.	0.4	99 310	1369	61	49
Winterburn Gp.	0.3	27 800	1031	150	32
Woodbend Gp.	1.0	32 460	896	103	24
Beaverhill Lake Gp.	0.5	97 500	1749	42	28
Elk Point Gp.					
Watt Mountain Fm.	1.0	41 500	1378	24	16
Keg River Fm.	14.0	9810	37	6	-
L. Elk Point Gp.	2.0	17 500	1482	19	3
Ordovician	26.0	1668	5	-	-
Cambrian	4.0	110 000	63	35	18
Precambrian	14.6	71 200	122	11	5
TOTAL			48 240	1868	2245

Table 3. 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	-	-
	1316	-	1	1318	-	-
	512	-	3	492	-	-
	218	3	2	211	-	-
	679	-	2	668	-	-
	166	1	5	162	-	-
	6474	-	3	6310	-	-
	9266	7	1	9248	-	-
	7275	2	1	7253	-	-
	3124	1	-	3099	-	-
	1753	28	1	1738	6	-
	235	-	1	234	-	-
	2055	9	3	2037	1	-
	1275	-	-	1274	-	-
	1312	36	2	1307	9	-
	991	114	2	988	103	-
	872	95	2	881	133	-
	1719	26	7	1713	25	6
	1367	14	-	1367	7	-
	33	1	-	79	7	-
	1472	14	-	1432	1	-
	5	-	-	5	-	-
	50	18	-	40	-	-
	117	3	-	-	-	-
	43 250	374	38	42 747	292	6

Table 4. 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)	1000
Elk Point Gp. (Ca <60 000 mg/l)	200
(Ca >60 000 mg/l)	1000
Lower Paleozoic	200

Bromide (the ionic form in which Br occurs in all the formation waters) was reported in nearly 2330 formation water analyses (Table 6), 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 (1000 mg/l), none of which is above the detailed exploration threshold (3000 mg/l).

Iodide (the ionic form in which I occurs in all the formation waters) was reported in 3480 formation water analyses (Table 7), of which 93% were below the regional exploration threshold (40 mg/l). All analyses with I >40 mg/l were examined individually. Posting maps of specific values, and contour maps were used for selected stratigraphic units to cull the data further, but no attempt was made to screen, rigorously, 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 5. Processing of formation waters reporting 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
Elk Point Gp.					
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

Table 6. Processing of formation waters reporting 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	252	408	2	2	406	-	-
U. Mannville Gp.	0.1	613	332	-	-	324	-	-
L. Mannville Gp.	0.4	2585	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	1068	138	2	-	130	-	-
Winterburn Gp.	3.9	5728	244	7	1	227	4	-
Woodbend Gp.	10.0	2115	116	18	-	134	22	-
Beaverhill Lake Gp.	0.25	2786	93	4	-	88	4	-
Elk Point Gp.								
Watt Mountain Fm.	8.0	1180	40	1	-	42	-	-
Keg River Fm.	-	-	-	-	-	6	19	-
L. Elk Point Gp.	9.0	1360	84	22	-	84	2	-
Ordovician	-	-	-	-	-	-	-	-
Cambrian	44.0	363	2	-	-	2	-	-
Precambrian	328.0	1530	9	1	-	-	-	-
TOTAL			2267	58	3	2220	51	-

Table 7. Processing of formation waters reporting I.

Stratigraphic unit	I (mg/l)		No. of samples			Final Data Base		
	Min.	Max.	I <40	I 40-100	I >100	I <40	I 40-100	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	1279	511	40	5	510	41	1
U. Mannville Gp.	0.05	4613	549	9	7	550	5	-
L. Mannville Gp.	0.06	4656	537	9	6	538	-	-
Jurassic	0.05	342	171	8	3	165	-	-
Triassic	1.16	106	66	5	1	68	1	-
Permian	5.0	1479	9	1	1	8	2	-
Carboniferous								
Stoddart, Rundle gps.	0.4	47	146	1	-	150	2	-
Banff Fm.	0.01	4998	74	1	3	71	1	-
Devonian								
Wabamun Gp.	0.27	450	172	6	7	162	-	-
Winterburn Gp.	1.0	1159	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	-
Elk Point Gp.								
Watt Mountain Fm.	0.03	2200	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			3240	177	63	3203	97	3

Resource estimation methodology

In order to estimate the amount of any given element present in formation water, it is necessary to know the volume of water filling the rock pore space, and the elemental concentration distribution within that volume. The former is given by the void space of the respective stratum in the area of interest. Thus, the amount (resource R) of any element of concentration C contained in a unit area of the host stratum of thickness D and porosity ø is given by the relation:

$$R = C \times D \times ø \qquad (1)$$

If the concentration is expressed in milligrams per litre and the interval thickness in metres, then the calculated resource R has units of g/m^2 or t/km^2. This means that R grams (tonnes) of an element are present in the formation water contained in the pore space of the rock volume represented by 1 m^2 (km^2) in area and D m in thickness of the respective stratigraphic interval. A map showing the areal variation of the resource R presents, at any point location, an estimate of the resource in place in the respective stratigraphic interval. An estimate of the total resource is obtained by integrating (summing) the distribution of R across the area of economic potential. Producibility of formation water is an important factor in establishing the economics of extracting industrial minerals from the water and, therefore, rock permeability plays a significant role in determining the effective thickness and areal extent of the potentially productive stratigraphic interval. Thus, elemental concentrations and rock porosity are "primary" data used directly in estimating resources according to relation (1), while rock porosity and permeability ("secondary" data) are indirectly used in establishing the thickness D and the areal extent of the stratum hosting the resource.

Data sources

Two sources were used to obtain information on the porosity of the strata of interest. Porosity and permeability measurements are routinely performed by the oil industry on plugs taken from core. The data, stored electronically with the ERCB, tend to be biased toward the high-porosity zones of interest to the

petroleum industry, and are not necessarily fully representative for any particular stratigraphic unit. Geophysical logs are another source of information on porosity. Neutron-porosity, density-porosity, sonic and gamma-ray logs were transferred from microfiche to hardcopy, digitized and stored in electronic form. The INTELLOG geophysical log-analysis software was calibrated on the basis of logs and porosity measurements on core plugs from the same well, and used to produce continuous porosity profiles in selected wells for the intervals of interest. Thus, the ERCB data base was augmented for areas and stratigraphic intervals with little or no core porosity information like the Beaverhill Lake Group in southern Alberta and the Elk Point Group in northeastern Alberta.

Permeability data were also obtained from two different sources. Core analyses performed by the oil industry often include plug-scale permeability measurements. ERCB electronic files were used to extract this information for the areas and strata of interest. Beside core analyses, drillstem tests (DSTs) are used by the industry to estimate the formation pressure and permeability. A DST electronic data base was implemented at the Alberta Geological Survey using electronic information acquired from the Canadian Institute of Formation Evaluation (CIFE) and from Digitech Information Services Ltd. Permeability data from this data base were used to augment the data from ERCB files. Nevertheless, the data from the two sources cannot and were not merged because they are representative for different rock volumes being tested. The permeability value measured and reported in core analyses is representative for the plug scale (10^{-2} m) and needs to be scaled up to the well scale. The permeability value calculated on the basis of a drillstem test is representative of the tested interval (10^0 - 10^1 m scale). As with porosity measured in core, permeability determinations tend to be biased toward the more porous and permeable strata.

Data processing

The concentration, porosity and permeability data have to be processed differently because of their

fundamentally different natures. Drillstem tests are performed and water samples taken usually from a single interval within a stratigraphic unit. It is assumed that, in the same hydrostratigraphic unit (aquifer), elemental concentrations do not vary with depth in the same well, only areally (from well to well). This is particularly the case for thin stratigraphic intervals whose vertical dimension is much smaller than their lateral dimension. Unlike concentrations, which generally have a smooth variation because of transport processes (such as diffusion, dispersion and advection), rock porosity and permeability tend to have a high discontinuous variability both vertically and laterally. As an example, Figure 2 shows the vertical porosity variation in the Beaverhill Lake Group in well 12-13-14-14-W4M as estimated from geophysical logs and measured on core plugs. It is obvious from Figure 2 that the zone with high and continuous porosity is not present throughout the interval shown. Figure 2 also illustrates the point made previously that core analyses tend to be biased toward the more porous intervals. For selected wells, the porosity variation with depth in each well was used to determine: (1) the actual depth and thickness of the potentially productive interval; and (2) its average porosity and permeability. To use the example well in Figure 2, the thickness and average porosity of the potentially productive interval are 38 m and 26%, respectively, as opposed to 211 m and 5%, respectively, for the entire Beaverhill Lake Group at this location. Because porosity is a scalar (additive) property of porous media, the scaling up from the plug and log-reading scale to the well scale is done by weighted arithmetic averaging of the plug or log scale values (Baveye and Sposito, 1984; Cushman, 1984; Dagan, 1989). The weighting is by the length of the representative interval indicated in the core analysis. Porosity values obtained from geophysical logs were read at a constant interval of 0.25 m, such that the well-scale value was obtained by straight arithmetic averaging of the digital porosity log values. For selected wells in specific aquifers, porosity logs were obtained and used because of the scarcity of core analyses. For other strata and areas of interest only core analyses were used because of data abundance and the high cost of digital log analysis, the latter being particularly labour intensive. The well-scale porosity values were analyzed both statistically (frequency plots) and areally, in order to identify, for each interval of interest, zones of high porosity, hence with potential for extraction of formation waters, and areas of tight rocks (low porosity). As an example, Figure 3 shows the frequency distribution of well-scale porosity in the Beaverhill Lake Group in southern
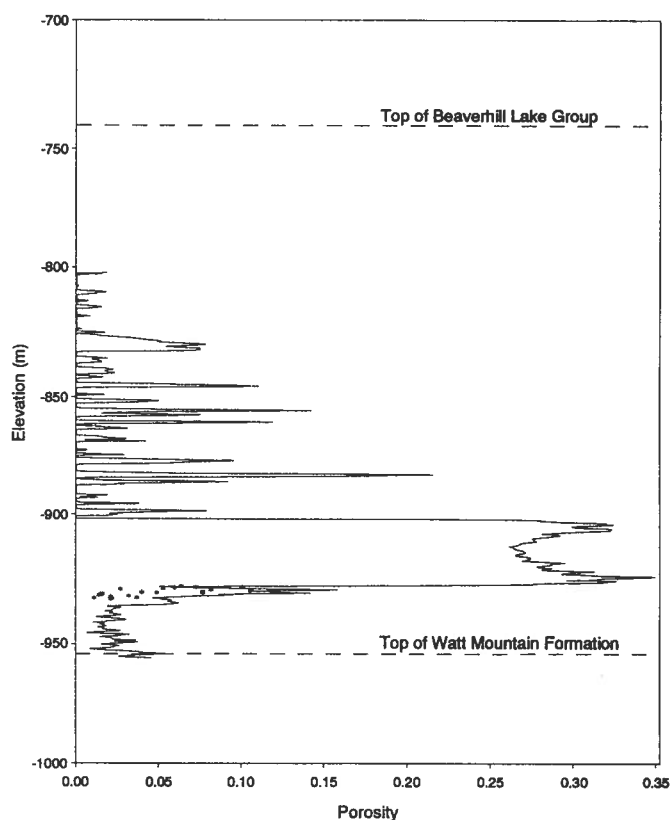
Figure 2. Porosity variation with depth in the Beaverhill Lake Group in well 12-13-14-14-W4M as measured in core (*) and estimated from geophysical logs (—).

Alberta. The average well-scale porosity in this case is close to 9%. Like porosity, permeability values measured on core plugs have to be scaled up to the well scale; unlike porosity, however, permeability is not additive. Theoretical and numerical studies (e.g. Desbarats and Bachu, 1994) have shown that the effective well-scale permeability k_{ef} is given by a "power-average" of the plug-scale values k_i, which for a discrete distribution is expressed as:

$$k_{ef}^w = \frac{1}{n} \sum k_i^w \qquad (2)$$

where n is the number of samples in the distribution and w is an empirical power. Note that the harmonic, geometric and arithmetic averages are retrieved in relation (2) for values of $w = -1$, $w = 0$ and $w = 1$,
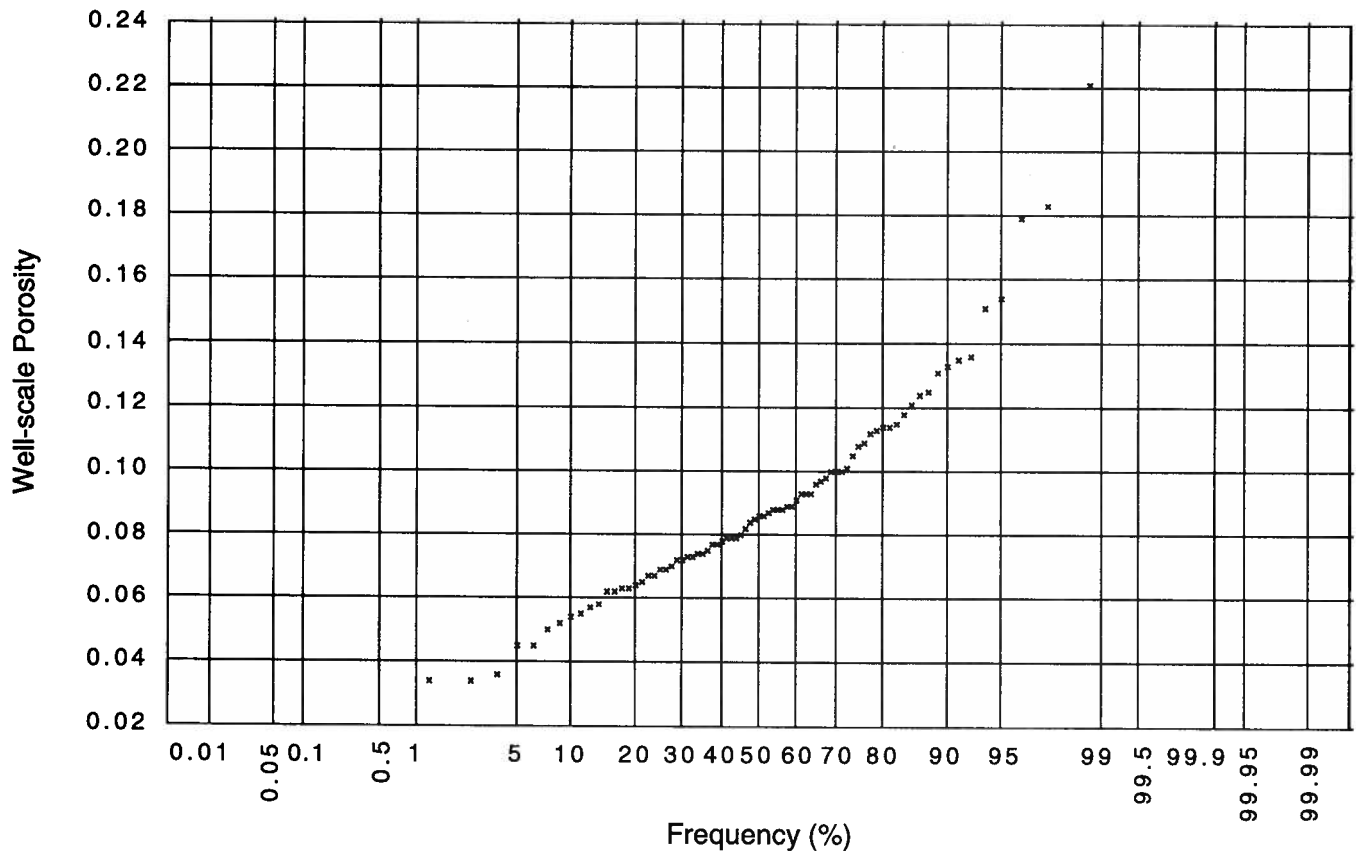
Figure 3. Frequency distribution of well-scale porosity in the Beaverhill Lake Group, southern Alberta.

respectively. For a permeable unit, the well-scale permeability is higher than the geometric average but lower than the arithmetic average. A value of $w = 0.8$ (Desbarats and Bachu, 1994) was used in this study to estimate the well-scale permeability based on core-plug measurements. In scaling up permeability from plug to well scale, only the potentially productive interval was considered, as determined from porosity and permeability variations in each well. As mentioned previously, permeability estimates from drillstem tests are already at the well scale, and as such do not need to be scaled up. To illustrate the above points, Figure 4 presents the permeability variation in a cored interval from the Beaverhill Lake Group in well 16-11-20-12-W4M, as measured in core plugs and in a drillstem test.

The permeability data obtained from drillstem tests and the well-scale permeability values obtained by scaling-

up the plug-scale measurements on core according to relation 2 were merged for the statistical and areal analysis of permeability variation in each interval and area of interest. Well-scale permeability values vary in a wide range, from $<10^{-15}m^2$ (1 md; 1 millidarcy) to $>10^{-12}m^2$ (100 md). As an illustration, Figure 5 shows the frequency distribution of well-scale permeability in the Beaverhill Lake Group in southern Alberta. Generally, there are fewer wells with permeability determinations than with porosity determinations. Statistical analysis of the well-scale porosity and permeability data in the areas of interest shows that, generally, the less porous rocks tend also to be less permeable (tight). For illustration, Figure 6 shows the correlation between the well-scale porosity and permeability values in the Beaverhill Lake Group in southern Alberta, obtained by scaling-up core-plug measurements. Thus, in areas with no permeability

measurements, porosity can be used as a rough indicator of rock permeability, hence producibility of formation water for mineral extraction.

Not all data categories (element concentrations, porosity, permeability and interval thickness) were available for every well. In order to overcome this shortcoming of the data distributions, rather than estimating resources at each well location according to relation (1), the areal variation of each data type was mapped in the regions of interest. Concentrations, isopach, porosity and permeability distribution maps were used to delineate the regions where mineral extraction from formation waters may be potentially economic, based on high element concentrations, water volumes, and water producibility. With respect to

concentrations, the detailed exploration thresholds were used for areal delineation. With respect to the other parameters, the following somewhat arbitrary limiting values were used: interval thickness >10 m; porosity >5%; and permeability >$10^{-14}m^2$ (10 md). Using computer-based methods, distribution maps were produced and superimposed for each region of interest, leading to the identification and delineation of the areas with economic potential. The resources in each area were then automatically calculated from distribution maps according to relation (1). The resulting maps and resources indicate which areas and stratigraphic intervals have the potential for the economic extraction of industrial minerals from formation waters *based on element concentrations and water producibility alone.*

Figure 4. Permeability variation with depth in the Beaverhill Lake Group in well 16-11-20-12-W4M as measured in core plugs (*), in a drillstem test (•), and well-averaged (•).
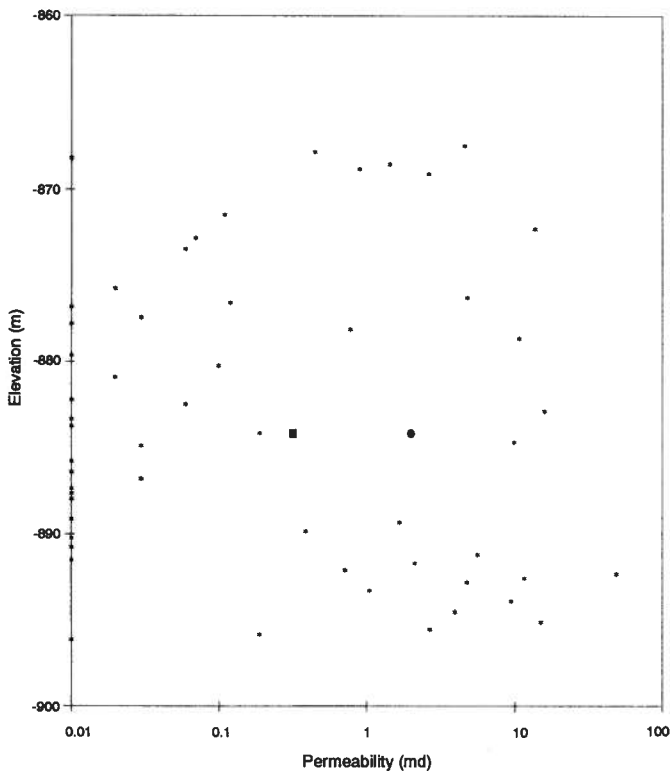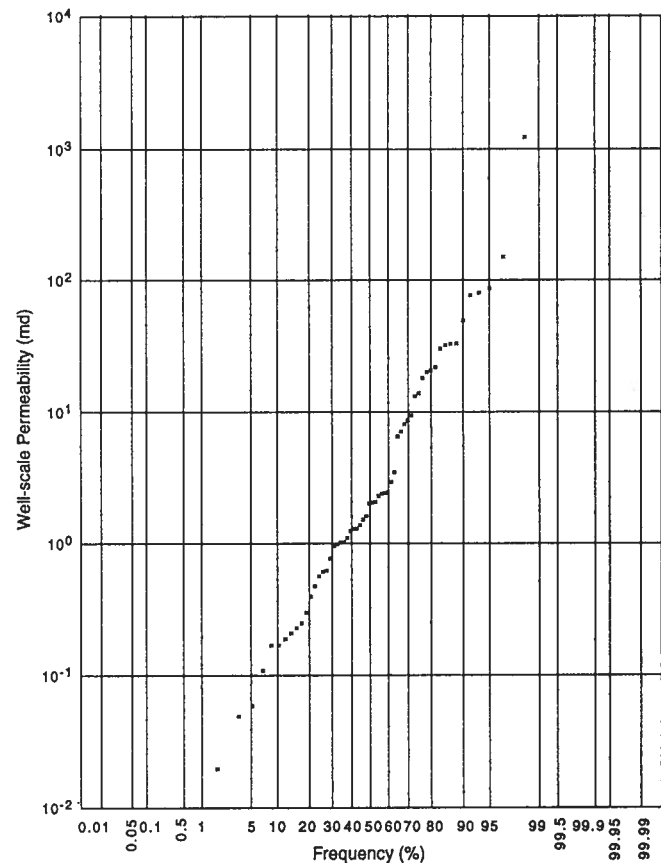

Figure 5. Frequency distribution of well-scale permeability in the Beaverhill Lake Group, southern Alberta.
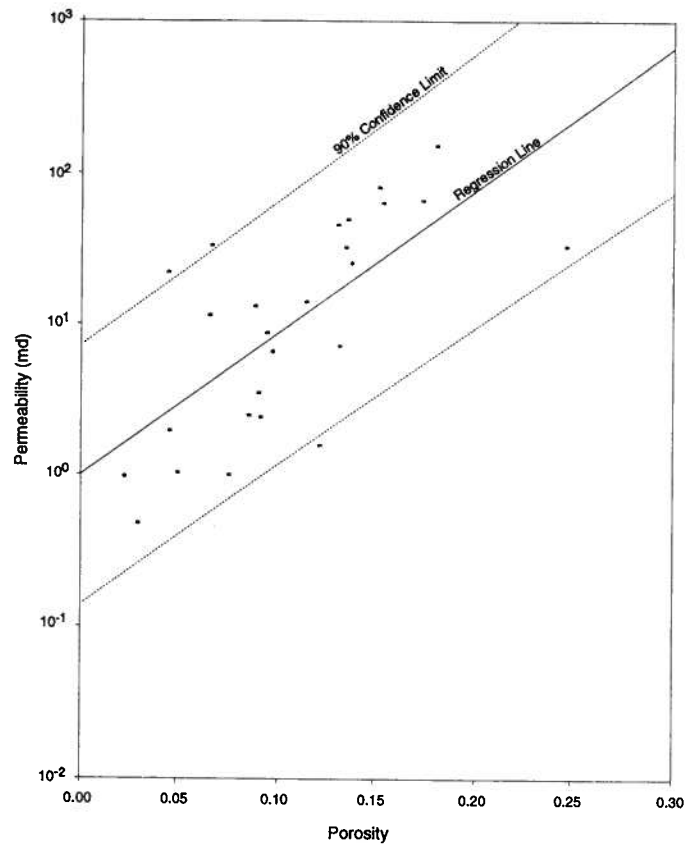
Figure 6. Correlation between well-scale permeability and porosity measured in core plugs from the Beaverhill Lake Group, southern Alberta.

Evaluation of potential resources

The industrial mineral potential of Alberta formation waters is treated by hydrostratigraphic units (aquifers) 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 Dow Chemical Company at Midland, Michigan. Any geochemical deficiencies in this approach are taken care of in the summary at the end of this bulletin.

Regional maps of element concentrations were prepared for all major stratigraphic units shown in Figure 1. Based on the amount of the element and the data distribution, each unit was evaluated with respect to the occurrence of elements that might be extracted for use as industrial minerals (Hitchon et al., 1993). This information is summarized in Table 8. The stratigraphic units and areas (Figure 7) which justified resource estimates are:

Devonian
   1. Elk Point Group, northeast Alberta [Ca, Mg]
   2. Beaverhill Lake Group, southern Alberta [Ca, Mg, K]
   3. Woodbend and Beaverhill Lake groups, west-central Alberta [Li]

Cretaceous
   4. Viking Formation, southern Alberta [I]
   5. Belly River Formation, southern Alberta [I]

The evaluation of these units and areas comprises the main part of this study.

Devonian

Elk Point

For the purpose of this study, the Elk Point aquifer was defined as those aquifers lying between the Prairie aquiclude and the Lotsberg and Cold Lake aquicludes; dominantly the Contact Rapids and Keg River aquifers, and equivalent arenaceous units, together with the Granite Wash aquifers, which overlie the Cambrian and Precambrian erosion surfaces. By far the majority of formation waters with high contents of Ca and Mg in the Elk Point aquifer came from the Contact Rapids and Keg River aquifers.

Most of the formation waters with Ca and Mg above the regional exploration threshold 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 8 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 9 and Table 9). There are two regions which warrant detailed exploration. The southern region, approximately bounded by the 40 000 mg/l Ca contour, seems to coincide with the western half of the distribution of the Lotsberg salt (Grayston et al., 1964). The northern region, represented by a single data point, lies near the southern margin of the Cold Lake salt (Grayston et al., 1964). There are sufficient data in northwestern Alberta to indicate that formation waters in the 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 all ions present but 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 dominantly 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 from the Beaverhill Lake aquifer with Ca and Mg close to or exceeding the detailed exploration limits (Table 10). The ratio $K/Na \times 10^3$ varied in the range 185-703. By contrast, for formation waters with <60,000 mg/l Ca, the ratio $K/Na \times 10^3$ was consistently <120. Thus the formation waters with high Ca and Mg can be predicted also to have high K/Na ratios. A plot (Figure 10) of Ca versus K/Na yielded a least squares regression line:

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

from which the K/Na ratio can be determined, and hence the individual K and Na values can be estimated.

Table 8. 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.	*	*	*	*	*	*
Upper Cretaceous						
Belly River Fm.	*	*	*	*	*	99
Lea Park Fm.	*	*	*	*	*	*
Milk River Fm.	*	*	*	*	*	*
Cardium Fm.	*	*	*	*	*	77
Dunvegan Fm.	*	*	*	*	*	62
Lower Cretaceous						
Viking, Bow Island fms.	*	*	*	*	*	128
U. Mannville Gp.	*	5000	*	*	*	76
L. Mannville Gp.	*	5000	*	*	*	*
Jurassic						
Kootenay Gp.	28 000	4000	*	*	*	*
Fernie Gp.	*	5000	*	*	*	*
Triassic						
Baldonnel Fm.	*	*	*	60	*	*
Charlie Lake Fm.	23 000	6000	*	68	*	*
Halfway Fm.	41 000	10 000	6000	58	*	53
Montney Fm.	20 000	5000	*	60	*	*
Permian	*	*	*	*	*	90
Carboniferous						
Stoddart Gp.	22 000	4500	*	*	*	*
Rundle Gp.	25 000	7000	*	60	*	58
Banff Fm.	25 000	5000	*	52	*	43
Devonian						
Wabamun Gp.	30 000	11 300	10 000	115	*	*
Winterburn Gp.	30 000	5000	8600	90	1880	38
Woodbend Gp.	39 000	8000	10 000	140	2115	53
Beaverhill Lake Gp.	98 000	13 500	19 000	130	2785	50
Elk Point Gp.						
Watt Mountain Fm.	40 000	8000	7000	98	*	*
Keg River Fm.	46 000	7000	7000	95	1360	120
L. Elk Point Gp.	95 000	12 000	5000	71	1530	40
Ordovician	27 000	7500	*	*	*	*
Cambrian	30 000	7000	*	81	*	*

* = all formation water analyses below respective regional exploration thresholds (see Table 1).
From Hitchon et al. (1993, Table 13).
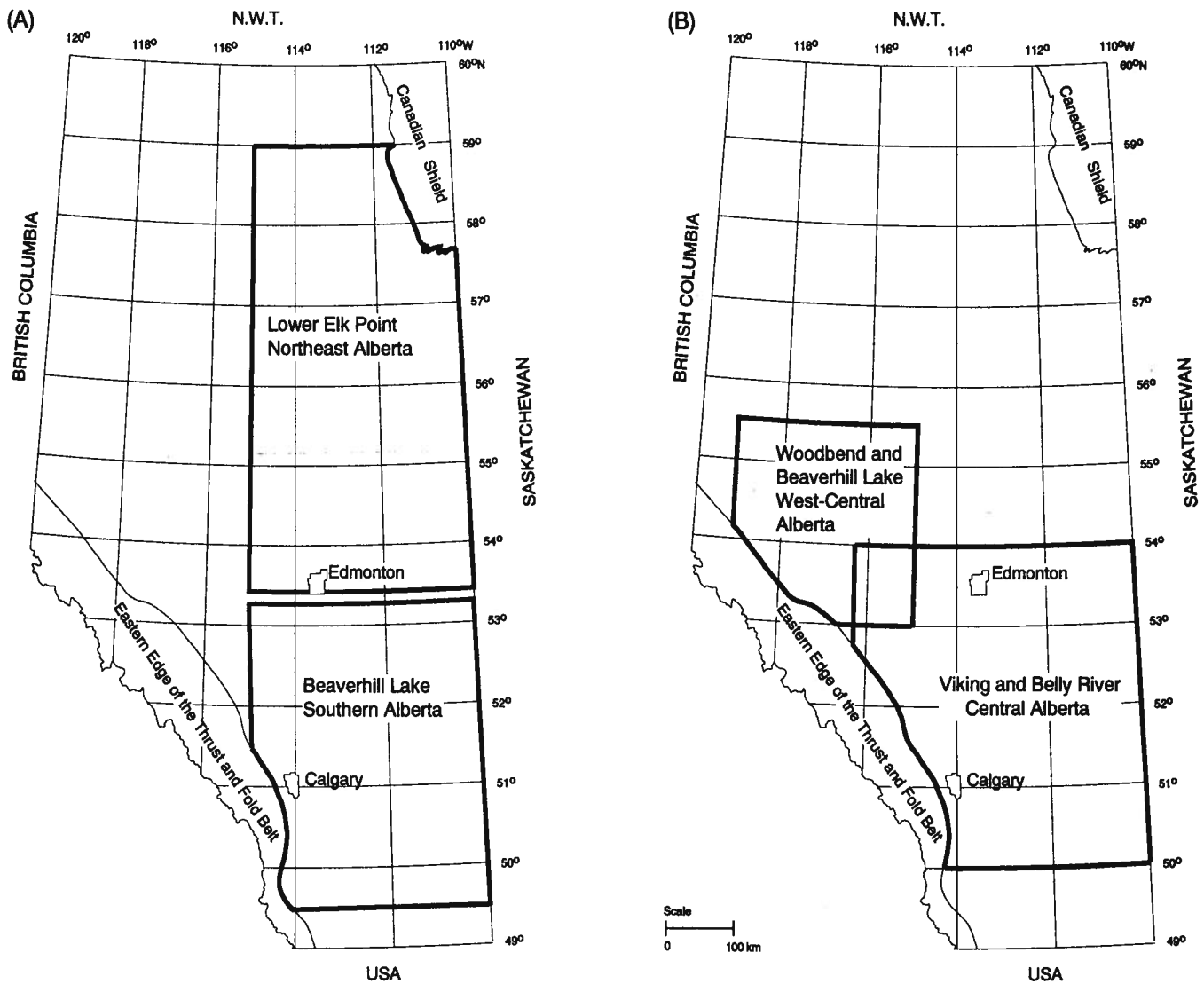
Figure 7. Study areas for detailed evaluation of potentially economic industrial minerals in Alberta formation waters: (A) Ca-Mg (K, Br, I) brines; (B) Li and I.

The estimated K and Na values are reported in Table 9 and were entered 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, the integral regional geothermal gradient, and the annual ground temperature from Bachu and Burwash (1994). 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).
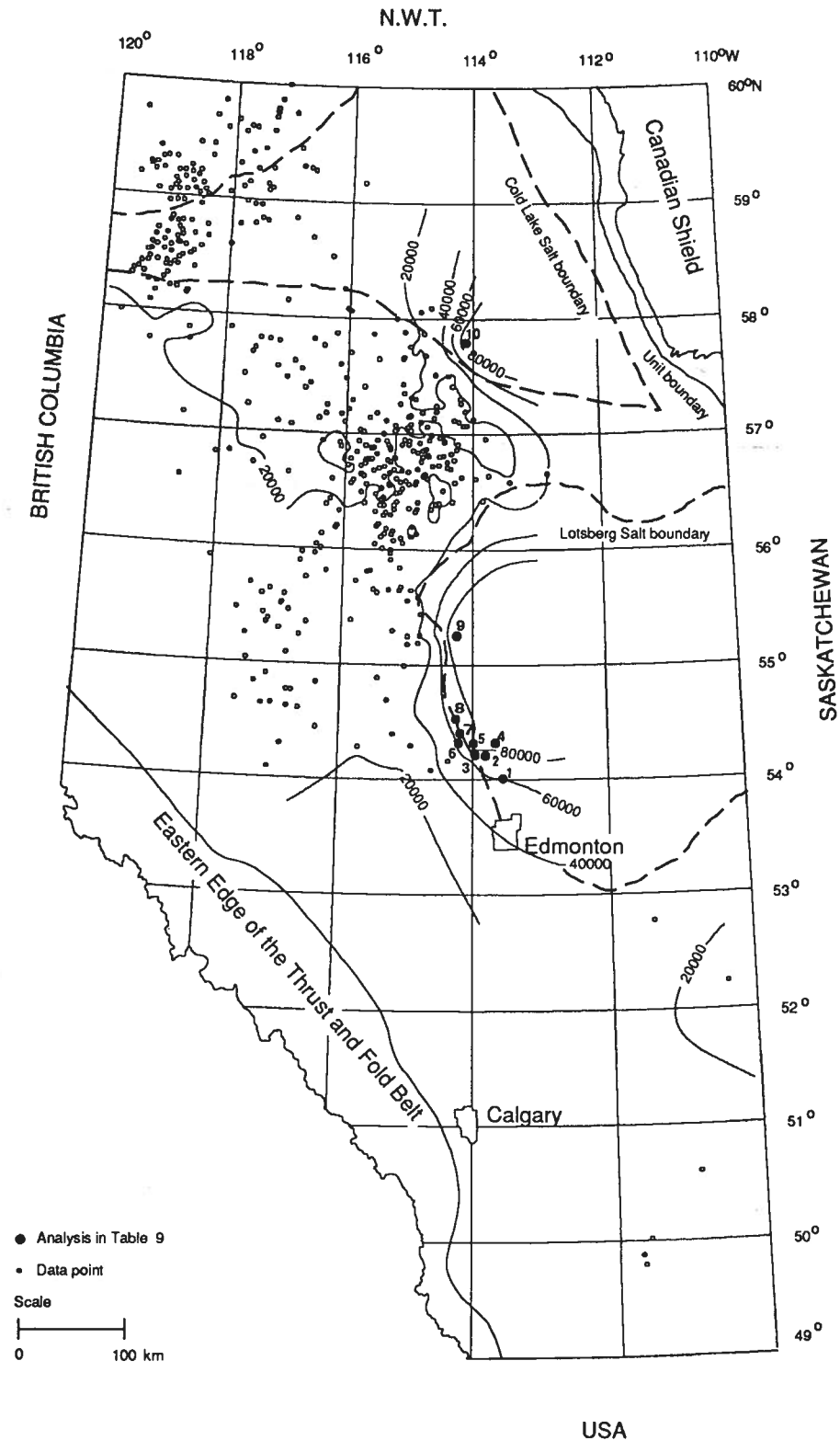
Figure 8. Distribution of Ca in formation waters from the Elk Point aquifer.
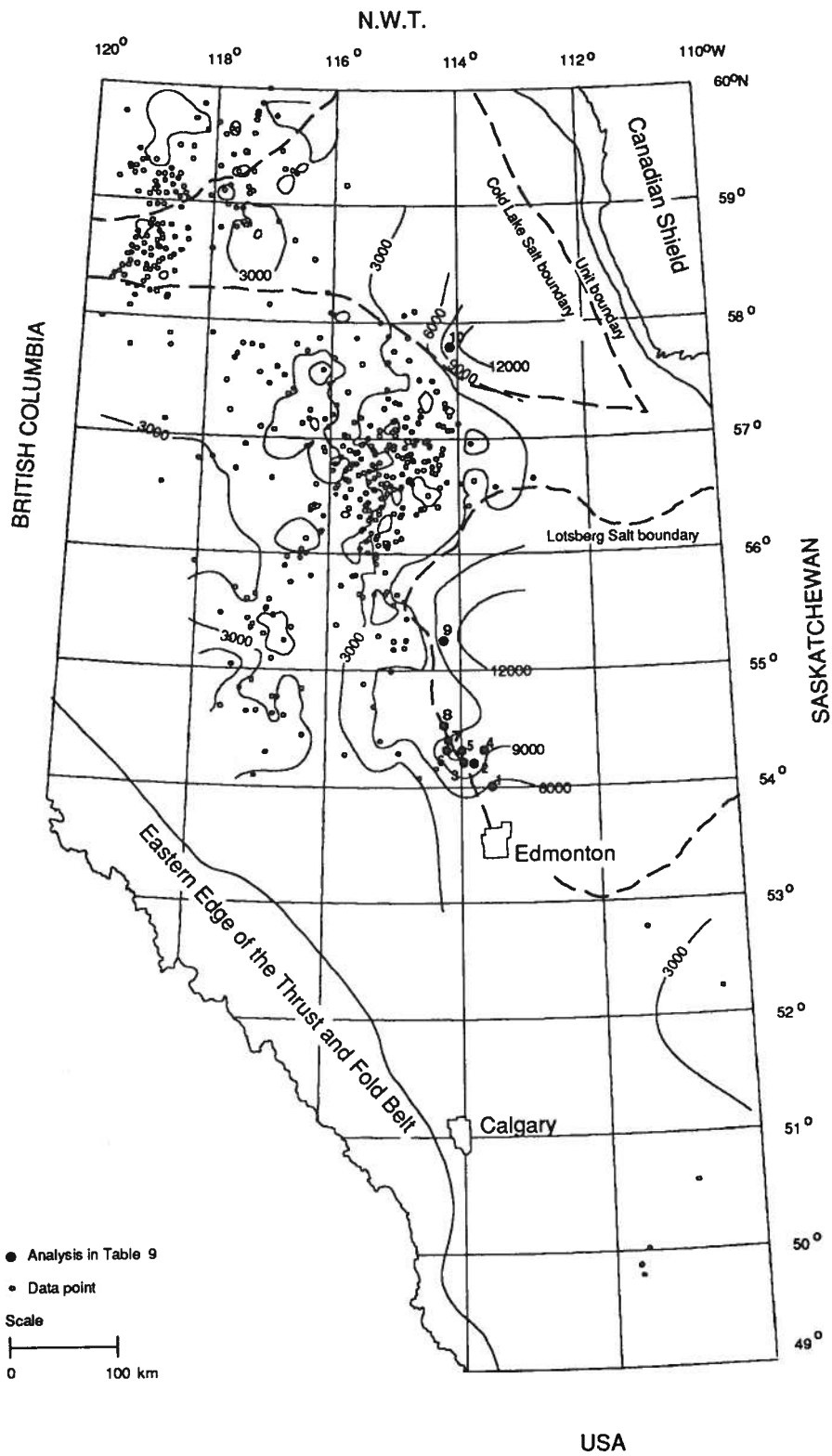
Figure 9. Distribution of Mg in formation waters from the Elk Point aquifer.

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

Sample No.	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	1205.5 m sw	893.1 m sw	464.8 m mc sw	248.7 m sw
	182.9 m mud	(71.6 m above packer)	45.7 m mud		(128 m above SI tool)
Composition (mg/l)					
Na (diff.)	24 450	40 766	41 785	38 322	35 607
Ca	61 200	75 485	68 577	83 432	81 762
Mg	5530	10 663	11 518	9467	11 713
Cl	161 500	227 300	219 143	234 000	233 600
HCO_3	140	80	101	210	37
SO_4	680	179	165	214	91
Fe	-	-	88	present	present
Total dissolved solids (mg/l, calc.)	253 429	354 433	341 238	365 539	362 792
pH (laboratory)	-	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 index (25°C)	-	-	·	-	1.4070
Estimated formation temperature (°C)	47	49	51	45	48
K/Na x 10^3 (est.)	300	450	400	525	500
Na (mg/l, est.)	18 808	28 114	29 846	25 129	23 738
K (mg/l, est.)	5642	12 652	11 939	13 193	11 869
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	5.57	5.73	5.60	5.34	5.84
Remarks			Assineau ss.		Assineau ss.

- = not determined, sw = salt water, mc = mud cut
est.= estimated (see text for discussion)

Table 9. cont.

6A	6B	7	8	9	10
10-34-61-2-W5M 1978.46-1994.61 DST 3 1573.7 m mc sw (top fluid D.P.)	10-34-61-2-W5M 1978.46-1994.61 DST 3 1573.7 m mc sw (MFE chamber)	10-35-62-2-W5M 1955.60-1972.06 DST 2 1195.7 m sw (top of packer)	4-16-64-2-W5M 1915.67-1978.15 DST 2 815.3 m sw	2-28-72-2-W5M 1652.02-1676.40 DST 1 364.2 m sw 164.6 m swc mud	7-29-101-1-W5M 952.20-975.97 DST 1 304.8 m sw 22.9 m wc mud (bottom)
46 460	47 725	40 462	45 957	26 050	37 223
62 542	63 103	65 906	68 083	95 200	90 971
12 004	11 324	9428	6584	10 449	11 081
217 000	217 400	206 200	210 238	238 915	250 000
150	130	130	91	100	904
253	1029	255	276	85	137
present	present	much	present	13	present
338 333	340 645	322 315	331 182	370 748	389 856
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
35 064	36 019	29 972	33 423	15 788	23 264
11 396	11 706	10 490	12 534	10 262	13 959
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.		

Table 10. K/Na x 10^3 ratio of selected formation waters from the Beaverhill Lake aquifer.

| Location	Composition (mg/l)					K/Na x 10^3	Remarks
	Salinity (calc.)	Ca	Mg	K	Na		
8-24-25-15-W4M	266 221	64 060	9720	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	9602	13 550	36 000	376	DST
6-35-28-21-W4M	317 999	61 220	6075	8720	39 370	221	DST, good rec.
16-11-30-25-W4M	304 127	62 766	6311	8000	37 000	216	DST, good rec.
10-30-32-23-W4M	256 593	45 222	4764	7400	40 000	185	DST, good rec.

rec. = recovery.

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.

In the Elk Point aquifer, with one exception (K = 5340 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 2500 mg/l to 5000 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. Ogu and Arnold (1989, Table 1.1) report the Na (12 000 mg/l) and K (7700 mg/l) contents for a formation water from this aquifer within the Lotsberg salt boundary, with a (K/Na) x 10^3 ratio of 642. Because the Cold Lake and Lotsberg salts have yielded very low contents of both K and Br, they have been considered to be salts recycled with fresh water (Wardlaw and Watson, 1966; Holser et al., 1972). Based on the (K/Na) x 10^3 value from Ogu and Arnold (ibid.), this means that the formation waters in this aquifer are influenced not by the Cold Lake and Lotsberg salts, as might appear, but by the overlying Prairie Formation halite, which is a normal marine evaporite deposit. This observation has important implications for industrial minerals in formation waters in this area inasmuch as the Keg River aquifer, lying just below the Prairie Formation, should be an attractive target.

In summary, there is potential for the production of formation waters with high contents of Ca, Mg, and possibly K, all three elements being close to specific regions within the boundaries of the Cold Lake and Lotsberg salts, although apparently influenced geochemically by the overlying Prairie evaporite. Future 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.

The Elk Point aquifer in the northeast Alberta study area (Figure 7A) varies in thickness from <20 m in the northeast to >100 m in the southwest, although the average effective thickness of the potentially productive interval is only 17 m. The well-scale porosity and permeability of this interval vary in the ranges 3 - 11% and 1 x 10^{-16} to 5 x $10^{-14} m^2$ (0.1 - 50 md), respectively. Using the previously defined criteria for

$$[K/Na \times 10^3] = -275 + 9.69 [Ca \times 10^3]$$
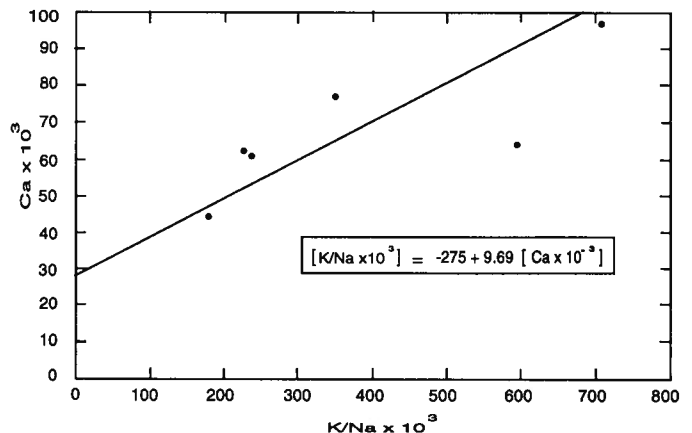
Figure 10. Plot of Ca versus K/Na for selected formation waters from the Beaverhill Lake aquifer.

areal delineation (D >10 m; ø >5%; k >10^{-14}m^2 [10 md]), and considering the poor concentration data distribution in northeastern Alberta (Figures 8 and 9) only two areas were identified in this region (Figure 11) where Ca, Mg, K and Br extraction from formation water in this aquifer might have economic potential. The approximate depth to the potentially productive interval (Figure 12) varies between 1650 m and 2040 m.

The average characteristics of the potentially productive interval are 8% porosity and 18 x 10^{-15}m^2 (18 md) permeability. The two areas cover about 38 townships (3455 km^2). At the time of carrying out this study (1992/1993) the only high-Ca composition data available were those shown in Table 9. Since that time the work of Donald B. Cross and Associates Limited (1993) has indicated a combined (Ca+Mg) content

• Analysis in Table 9
■ Ward Chemicals Ltd.
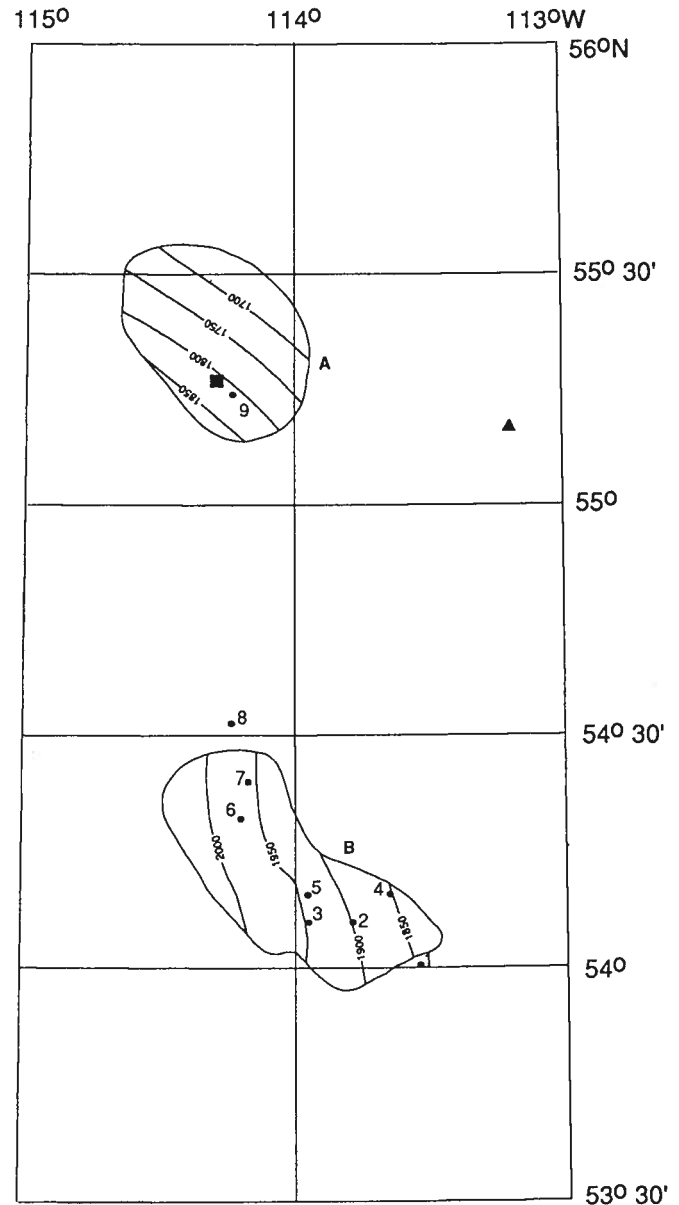▲ Tiger Chemicals Ltd.
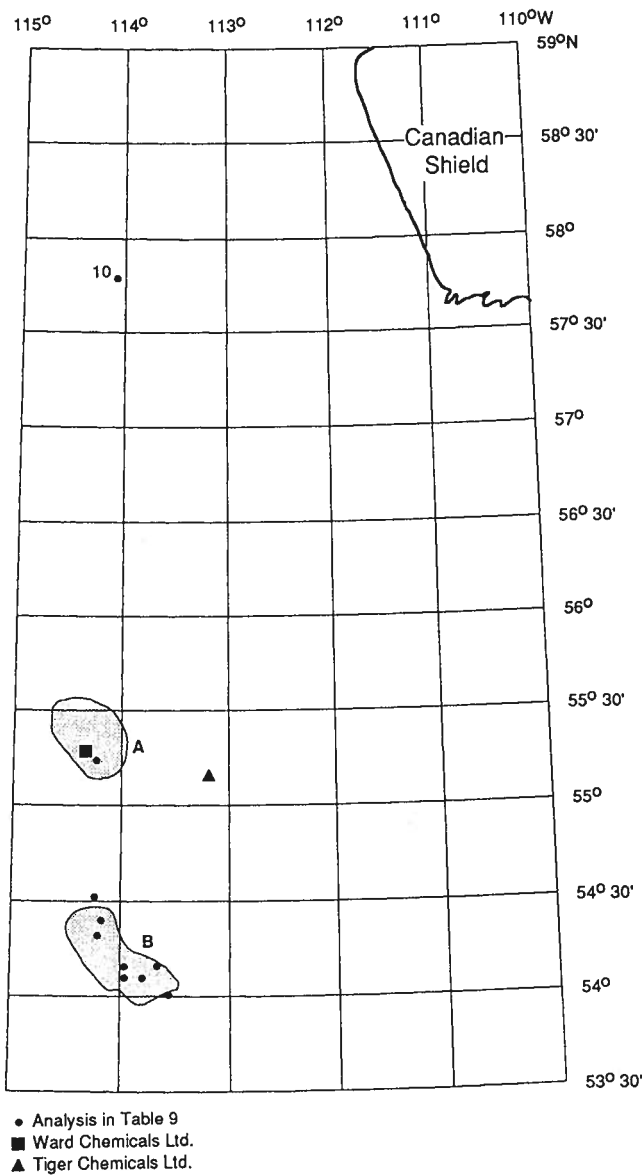
Figure 11. Areas in northern Alberta with producibility potential for Ca, Mg, K and Br from Elk Point aquifer formation waters. The areas have aquifers meeting the combined criteria of:(1) element concentration of formation waters above detailed exploration limit; (2) thickness >10 m; (3) porosity >5%; and (4) permeability >10^{-14} m^2 (10 millidarcies); see text for more details.

• Analysis in Table 9
■Ward Chemicals Ltd.
▲Tiger Chemicals Ltd.

Figure 12. Approximate depth (m) to the stratigraphic interval with producibility potential for Ca, Mg, K and Br in formation waters from the Elk Point aquifer, central-eastern Alberta.

of 122 217 mg/l at the brine well of Tiger Chemicals Ltd. (see more details in Table 15); this is hence the reason why the producing well of Tiger Chemicals Ltd. appears outside any potentially productive area (quite apart from which individual Ca and Mg values are not available at this site).

Calcium, Mg, K and Br resources were estimated (Table 11) for the two areas in the Elk Point aquifer of northeastern Alberta, as well as for the six areas in southern Alberta from the Beaverhill Lake aquifer (discussed below), according to relation (1). Figures 13 to 16 show the regional variations in the resource estimates for Ca, Mg, K and Br, respectively. The southernmost area (B) has slightly higher average porosity and permeability than the northern one (A), and the resource estimates for Ca and Mg are also higher (Figures 13 and 14).
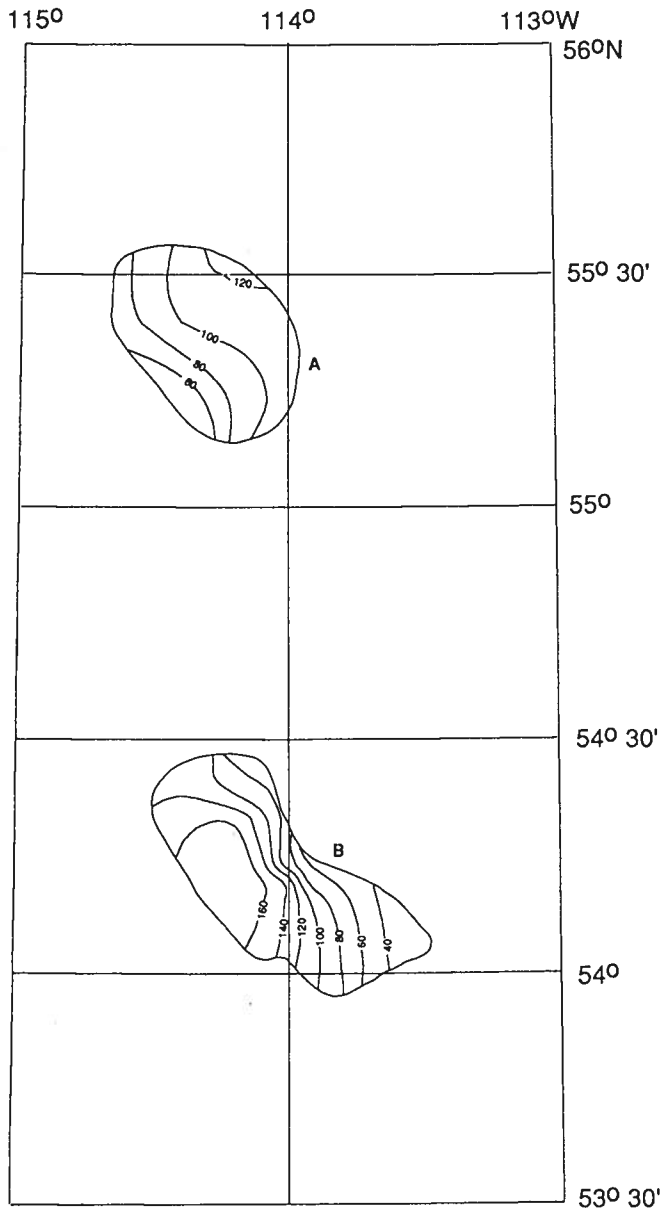
Figure 13. Calcium resource estimates in formation waters in the Elk Point aquifer, central-eastern Alberta(contours in kg/m² or 1000 t/km²).
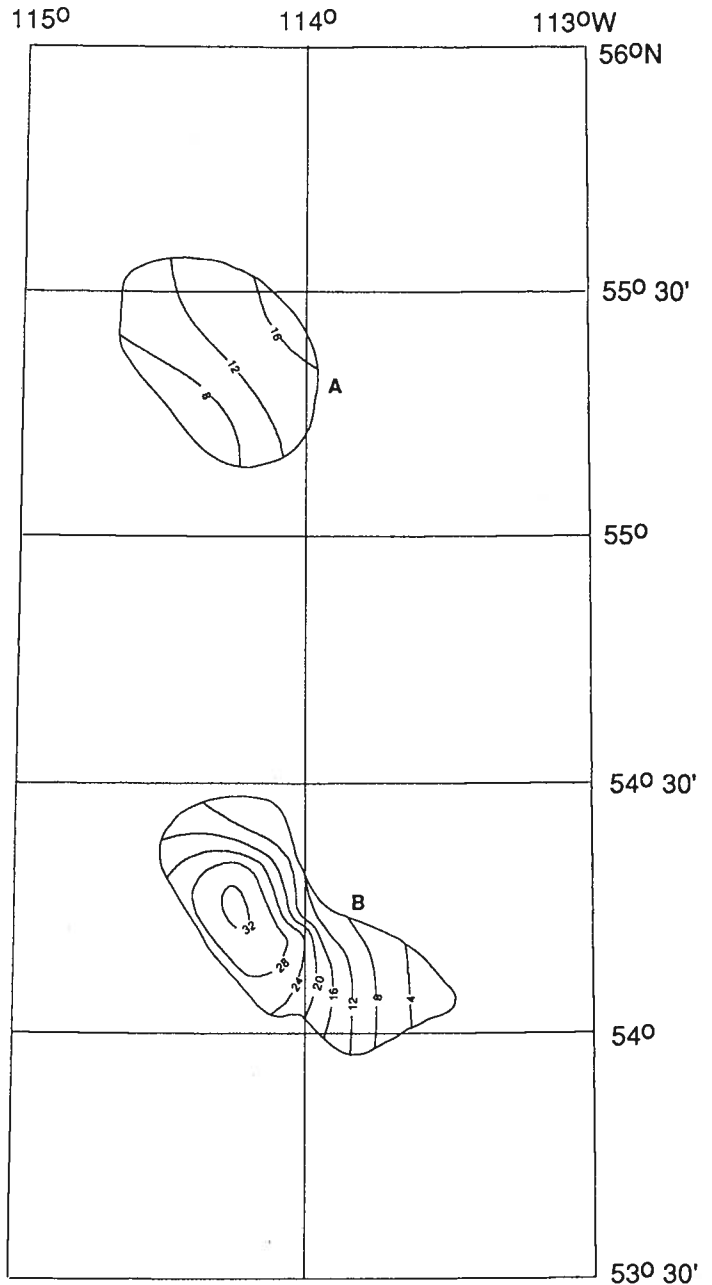
Figure 14. Magnesium resource estimates in formation waters in the Elk Point aquifer, central-eastern Alberta (contours in kg/m² or 1000 t/km²).

Table 11. Ranges of resource estimates (kg/m^2) in Ca-Mg brines, Alberta.

Aquifer	Ca	Mg	K	Br
Beaverhill Lake	50-760	4-136	1-116	max 10
Elk Point	25-180	2-32	<0.5-2.4	max 2

Figure 15. Potassium resource estimates in formation waters in the Elk Point aquifer, central-eastern Alberta (contours in kg/m^2 or 1000 t/km^2).

Figure 16. Bromine resource estimates in formation waters in the Elk Point aquifer, central-eastern Alberta (contours in kg/m^2 or 1000 t/km^2).

Beaverhill Lake

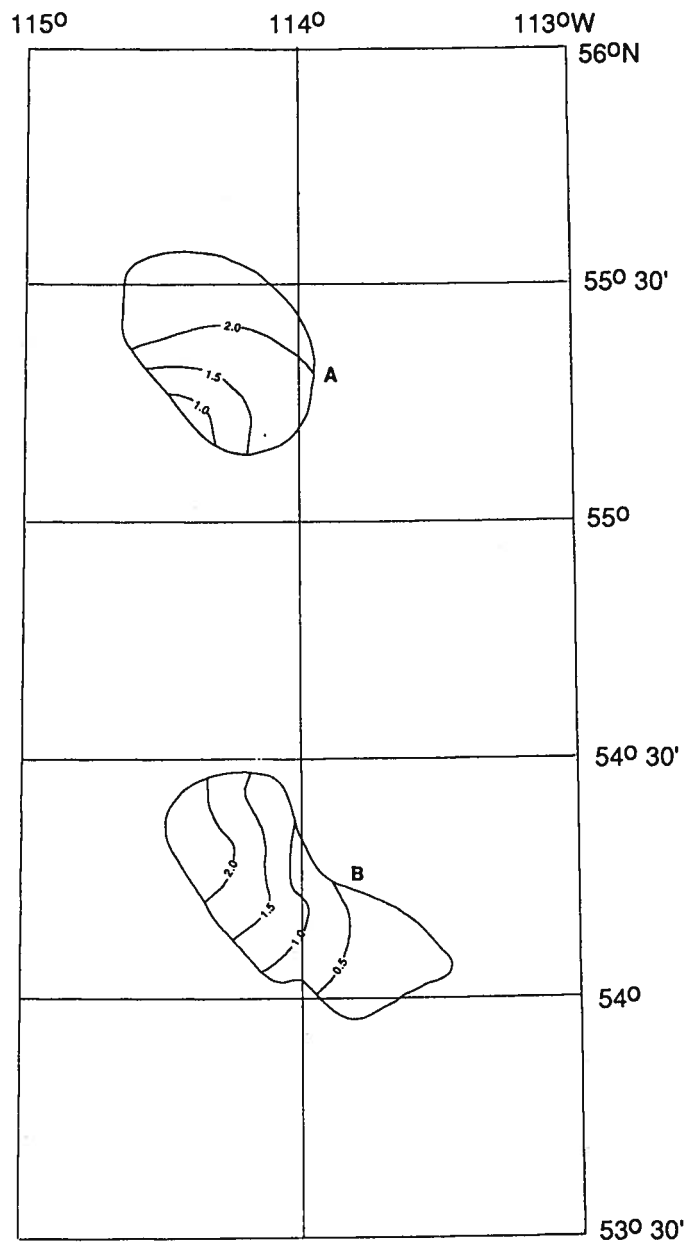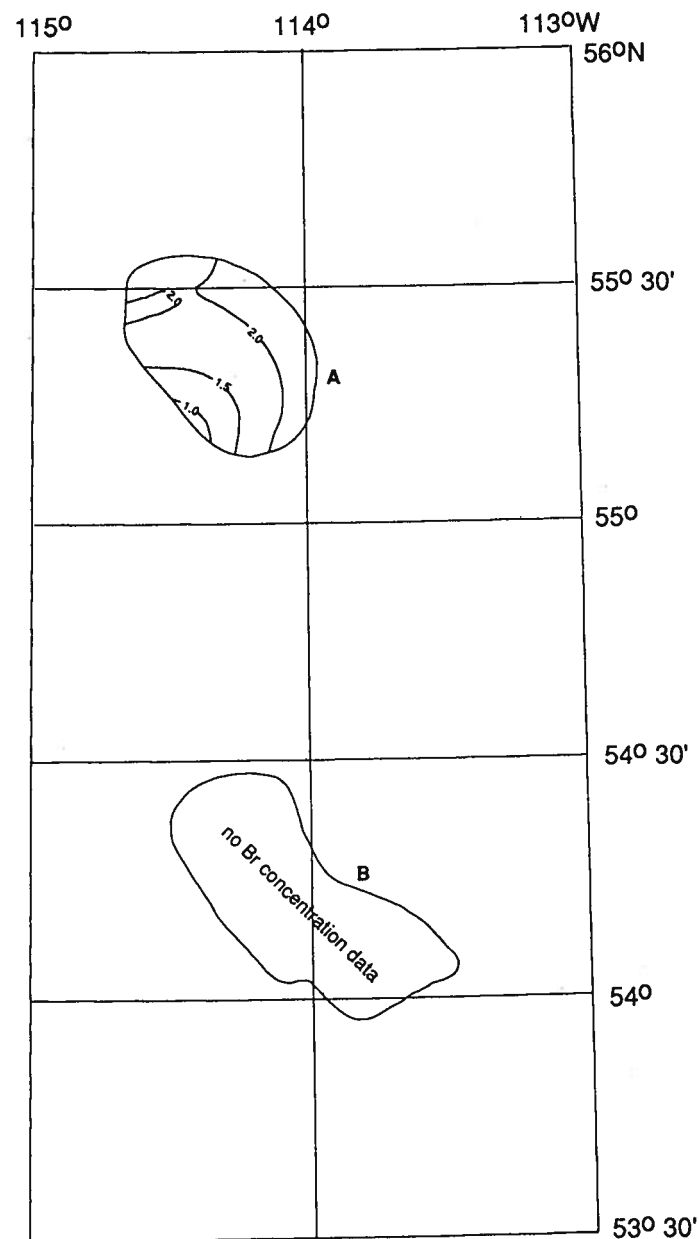Formation waters with Ca and Mg contents exceeding the regional exploration threshold occur in this aquifer throughout most of the province except in the subcrop region, northwest Alberta, and extreme southern Alberta. The regional trends for Ca (Figure 17) and Mg (Figure 18) indicate that detailed exploration is justified only in southern Alberta (see study area, Figure 7A) 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 12). Contents of Ca and Mg are comparable to those in the Elk Point aquifer, but, perhaps characteristically, drillstem test recoveries are generally much lower than in the 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 12 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 (ΔG_{diff} >1.0) with respect to dolomite, at equilibrium (ΔG_{diff} - 0.5 to + 0.5) to undersaturated (ΔG_{diff} <-1.0) with respect to anhydrite, and generally undersaturated (ΔG_{diff} >-1.0) with respect to halite. Some laboratory determined pH values are clearly far from the values 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 19) in the region where the formation waters also contain significant amounts of Ca (Figure 17) and Mg (Figure 18). Six analyses have K contents exceeding the detailed exploration threshold; they are analyses 5, 7 and 8 in Table 12, and duplicate analyses from the same drillstem tests not reported in the table. Only four formation waters report Br >1000 mg/l (max. 2786 mg/l, analysis 2, Table 12), two being from drillstem tests in the same well. The distribution of formation waters reporting Br >1000 mg/l (Figure 19) suggests that higher Br contents cannot be ruled out in the same

area in which K >5000 mg/l because both Br and K accumulate strongly after halite precipitation. Again, the higher K and Br contents suggest influence of the underlying Prairie Formation, a normal marine evaporite.

Another component of interest in formation waters from the Beaverhill Lake aquifer is Li, which 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 Gilwood aquifer. This high-Li aquifer is evaluated below.

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 aquifer 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.

The Beaverhill Lake aquifer in southern Alberta has a gross thickness varying from 160 m in the southwest to >300 m in the northeast. However, the net thickness of the potentially productive interval is much less, about 30 m on average. The interval is located generally in the lower part of the section. The well-scale porosity and permeability of the interval vary throughout the entire area in the ranges 2 - 22% and 2×10^{-17} to $1 \times 10^{-12} m^2$ (0.02 - 1000 md), respectively. Based on threshold element concentrations for detailed exploration, and the aquifer characteristics specified previously, six areas (Figure 20) were identified in the southern Alberta study area (Figure 7A) where Ca, Mg, K and Br extraction from formation waters may be potentially productive based only on elemental concentrations and water producibility. The six areas cover about 105 townships (9800 km²). The approximate depth to the stratigraphic interval of economic interest (Figure 21) varies between 1240 m in the east and 2600 m in the west. The "bull's eye" features apparent in areas B, C and D (Figure 21) may be due to carbonate buildup (= increased aquifer thickness) within the Beaverhill Lake carbonate platform. The average characteristics of the potentially productive aquifer in all these areas are 9% porosity and $55 \times 10^{-15} m^2$ (55 md) permeability.
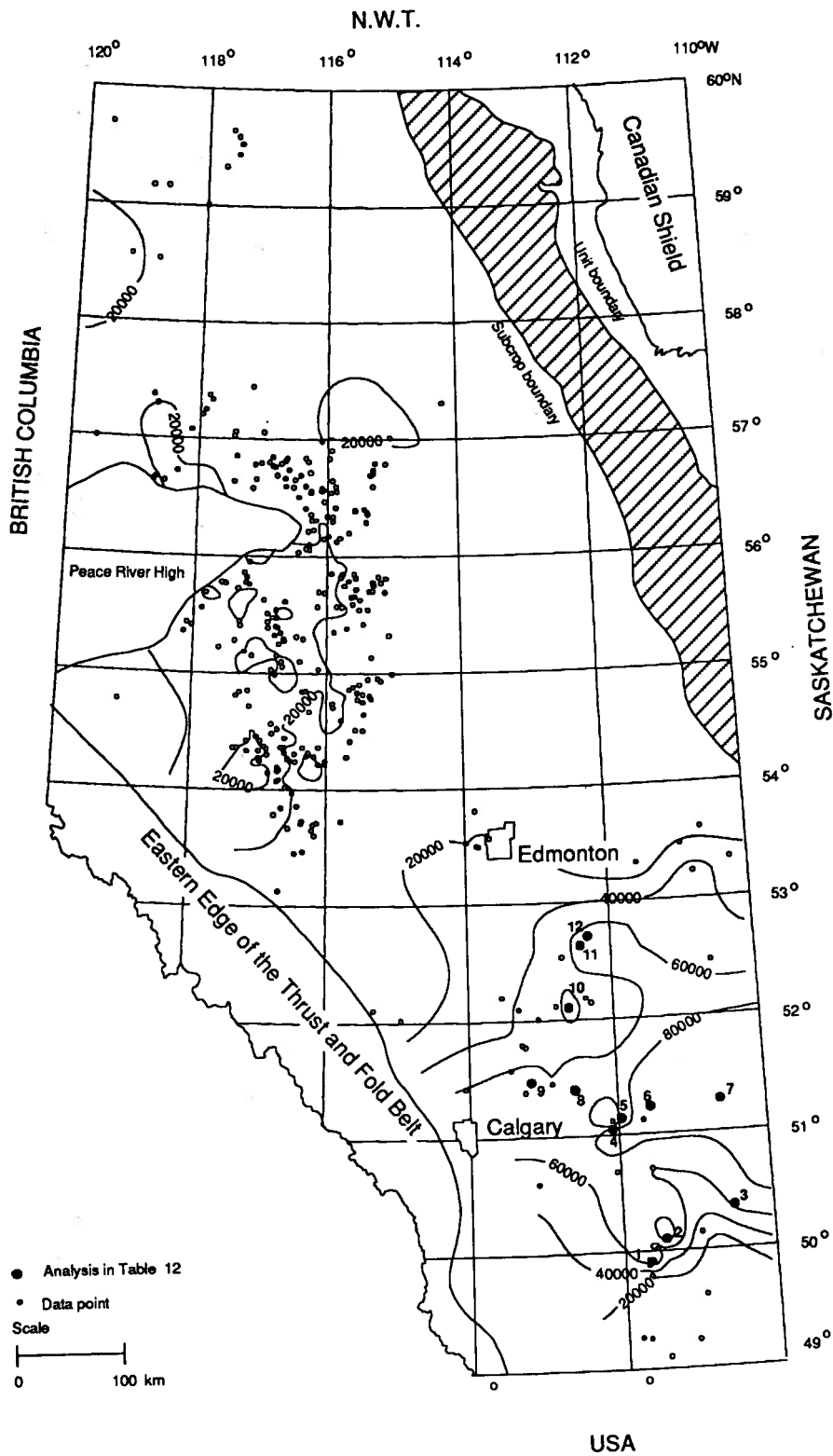
Figure 17. Distribution of Ca in formation waters from the Beaverhill Lake aquifer.

Table 12. Beaverhill Lake aquifer: formation waters with Ca >60 000 mg/l and Mg >9000 mg/l.

Sample no.	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	82.3 m mc sw	-	116.0 m sw
		57.9 m mc sw			28.0 m mc sw
Composition (mg/l)					
Na	47 159 (diff.)	28 987 (diff.)	51 150 (diff.)	39 605 (diff.)	17 710
K	-	-	-	-	10 560
Ca	71 970	86 030	64 180	82 802	64 060
Mg	10 646	9830	12 197	11 519	9720
Cl	230 600	223 770	227 000	240 000	172 000
HCO$_3$	510	817	1480	1400	214
SO$_4$	234	80	144	424	391
Fe	present	-	-	present	-
Total dissolved solids (mg/l, calc.)	360 860	351 885	355 399	375 038	266 221
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 (mg/l, est.)	33 685	18 701	37 889	26 403	-
K (mg/l, est.)	13 474	10 286	13 261	13 202	-
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 temperature)	5.06	4.78	4.59	4.48	5.42
Remarks		Br = 2786			

- = not determined
sw = salt water, mc = mud-cut
est. = estimated (see text for discussion)

Table 12. cont.

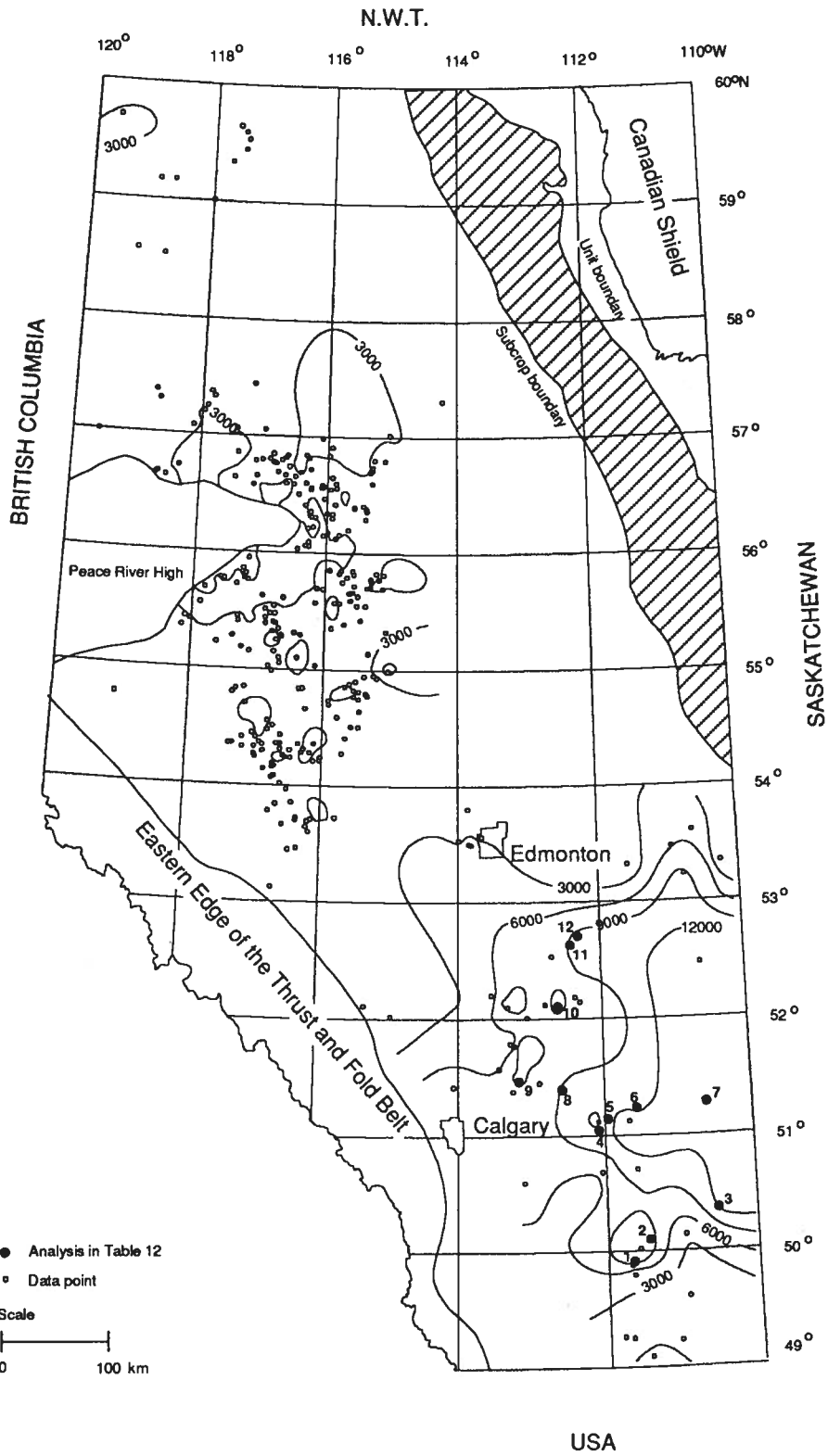| 6	7	8	9	10	11	12
9-23-26-12-W4M 1673.35-1692.25 DST 13 146.3 m mc sw	8-3-27-5-W4M 1595.00-1605.00 DST 1 75.0 m mc sw 90.0 m mud	11-14-28-19-W4M 1908.00-1940.00 DST 1 - (bottom)	13-10-29-23-W4M 2321.05-2336.90 DST 5 - (middle)	6-23-36-19-W4M 1960.47-1966.87 DST 1 177.7 m sw 15.2 m mud (bottom)	5-20-42-17-W4M 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)
30 999 (diff.)	27 250	36 000	49 158 (diff.)	32 370 (diff.)	29 079 (diff.)	30 674 (diff.)
-	19 160	13 550	-	-	-	-
97 790	96 100	78 134	71 890	75 700	69 300	66 266
11 629	13 410	9602	9361	10 100	9200	9392
254 000	280 000	233 972	230 000	213 000	194 000	191 500
1000	1403	273	215	230	113	212
146	97	43	188	186	250	379
present	-	trace	-	much	-	-
395 056	436 856	365 954	360 703	331 470	301 885	298 315
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.)
18 787	-	-	35 113	22 324	20 771	22 721
12 212	-	-	14 045	10 046	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

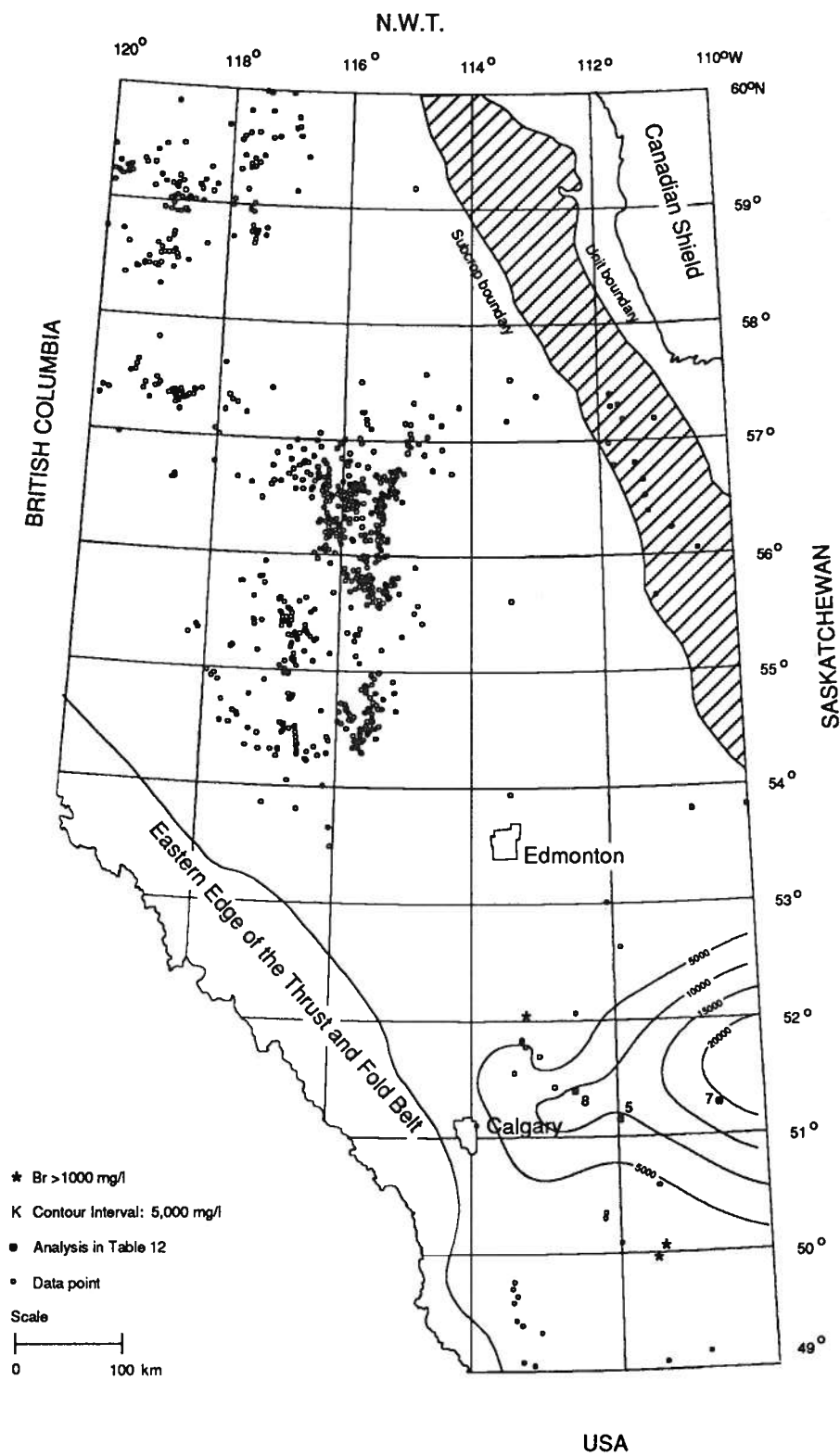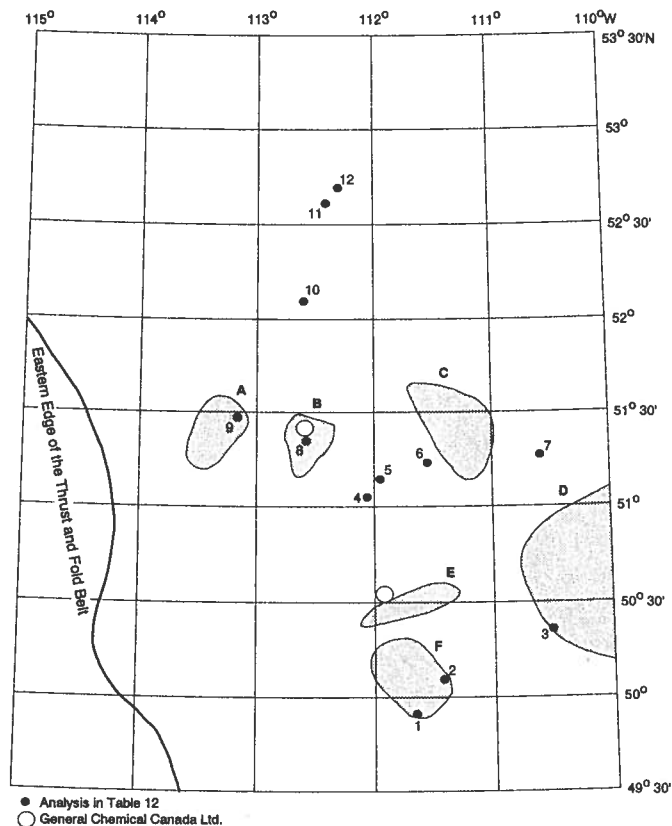**Figure 18.** Distribution of Mg in formation waters from the Beaverhill Lake aquifer.

Figure 19. Distribution of K and Br >1000 mg/l in formation waters from the Beaverhill Lake aquifer.
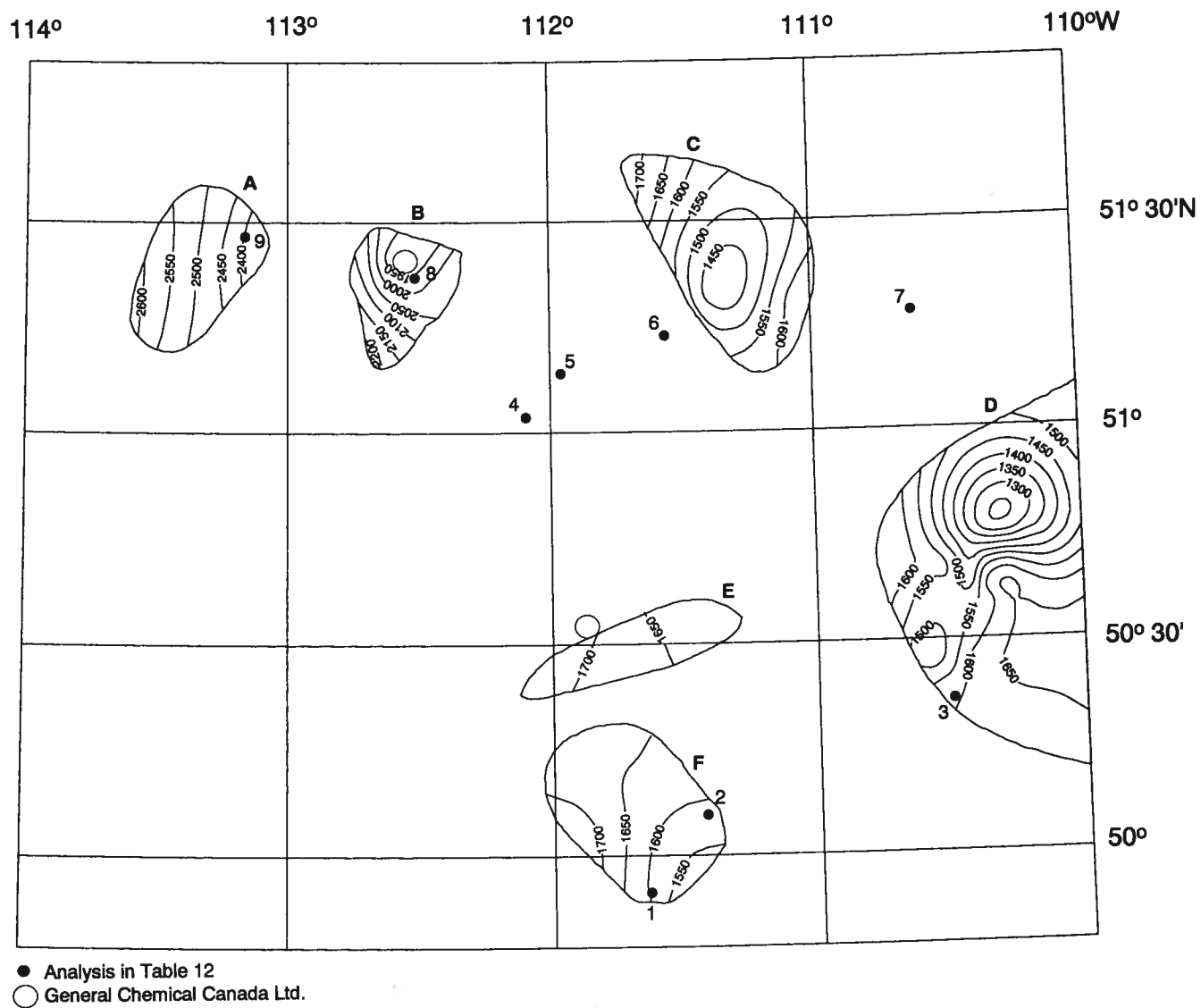
Figure 20. Areas in southern Alberta with producibility potential for Ca, Mg, K and Br from Beaverhill Lake aquifer formation waters. The areas have aquifers meeting the combined criteria of: (1) element concentration of formation waters above detailed exploration limit; (2) thickness >10 m; (3) porosity >5%; and (4) permeability >10^{-14} m^2 (10 millidarcies); see text for more details

The ranges of resource estimates are given in Table 11, and the regional variations in these estimates in each of the six areas of interest, are shown in Figures 22 to 25 for Ca, Mg, K and Br, respectively. The obvious trend of higher resource estimates for the Beaverhill Lake aquifer in southern Alberta than for the Elk Point aquifer in northeastern Alberta is mainly due to thicker and slightly more porous potentially-productive strata in the south than in the north. Also, elemental concentrations are generally higher in the Beaverhill Lake aquifer than in the Elk Point aquifer. The large variability in resource estimates in southern Alberta (Figures 22 to 25) is also due mainly to variations in the thickness and porosity of the aquifer. Particularly, the consistent pattern of "bull's eyes" in resource distributions in southern Alberta (Figures 22 to 25) is caused by variations in aquifer thickness. Of the six areas identified in southern Alberta, areas C and D have the best production potential because of relatively shallow depth, high average porosity (10%) and permeability (9 x 10^{-14}m^2; 90 md), and generally high resource potential per unit area. Areas A and B also have high average porosity (9%), but lower average permeability (2.5 x 10^{-14}m^2; 25 md) and the potentially productive interval is at a greater depth (>2000 m). The two southernmost areas (E and F) are generally characterized by lower average porosity and permeability (approximately 7% and 10^{-14}m^2; 10 md, respectively).

Figure 21. Approximate depth (m) to the stratigraphic interval with producibility potential for Ca, Mg, K and Br in formation waters from the Beaverhill Lake aquifer, southern Alberta.
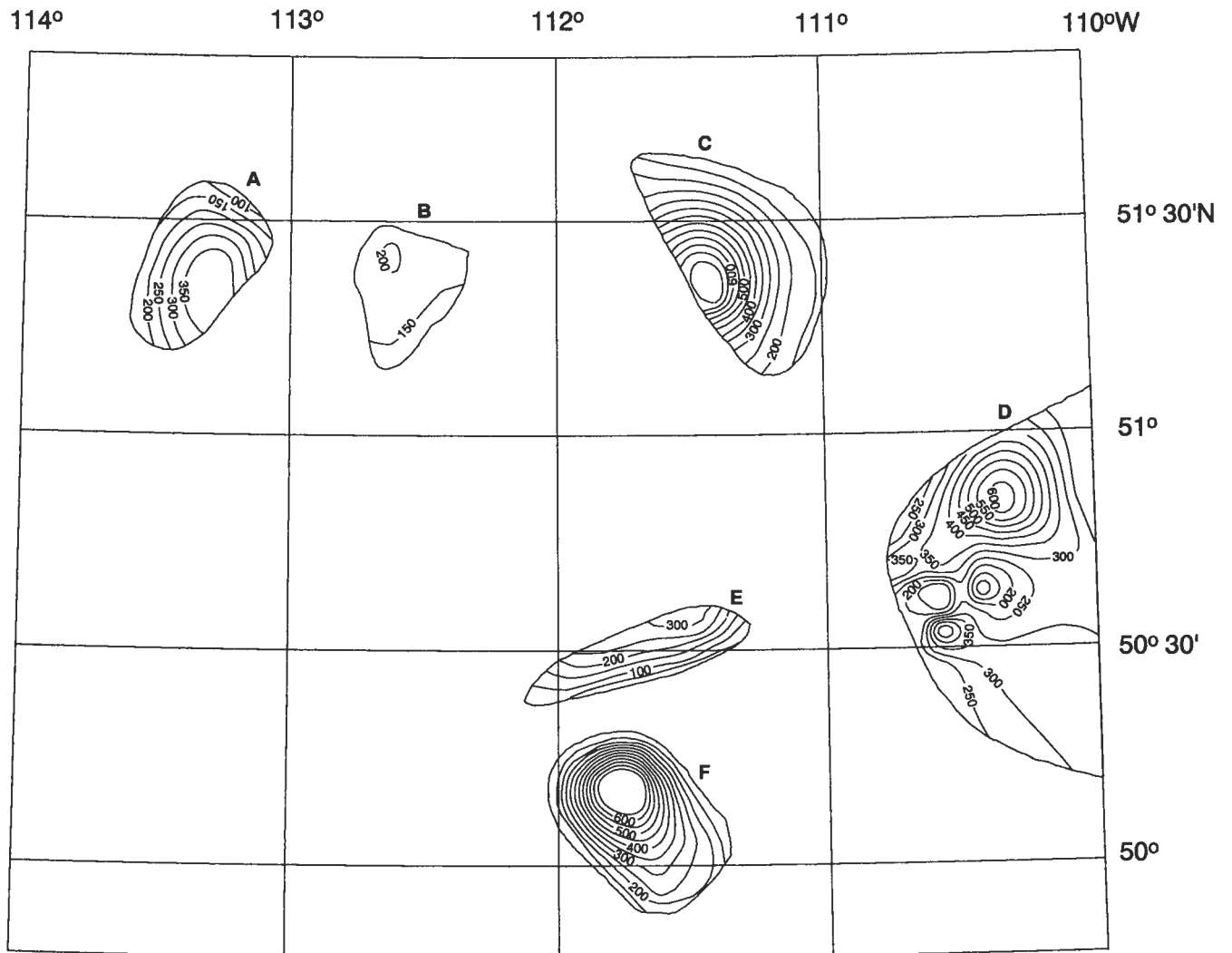
Figure 22. Calcium resource estimates in formation waters in the Beaverhill Lake aquifer, southern Alberta (contours in kg/m² or 1000 t/km²).
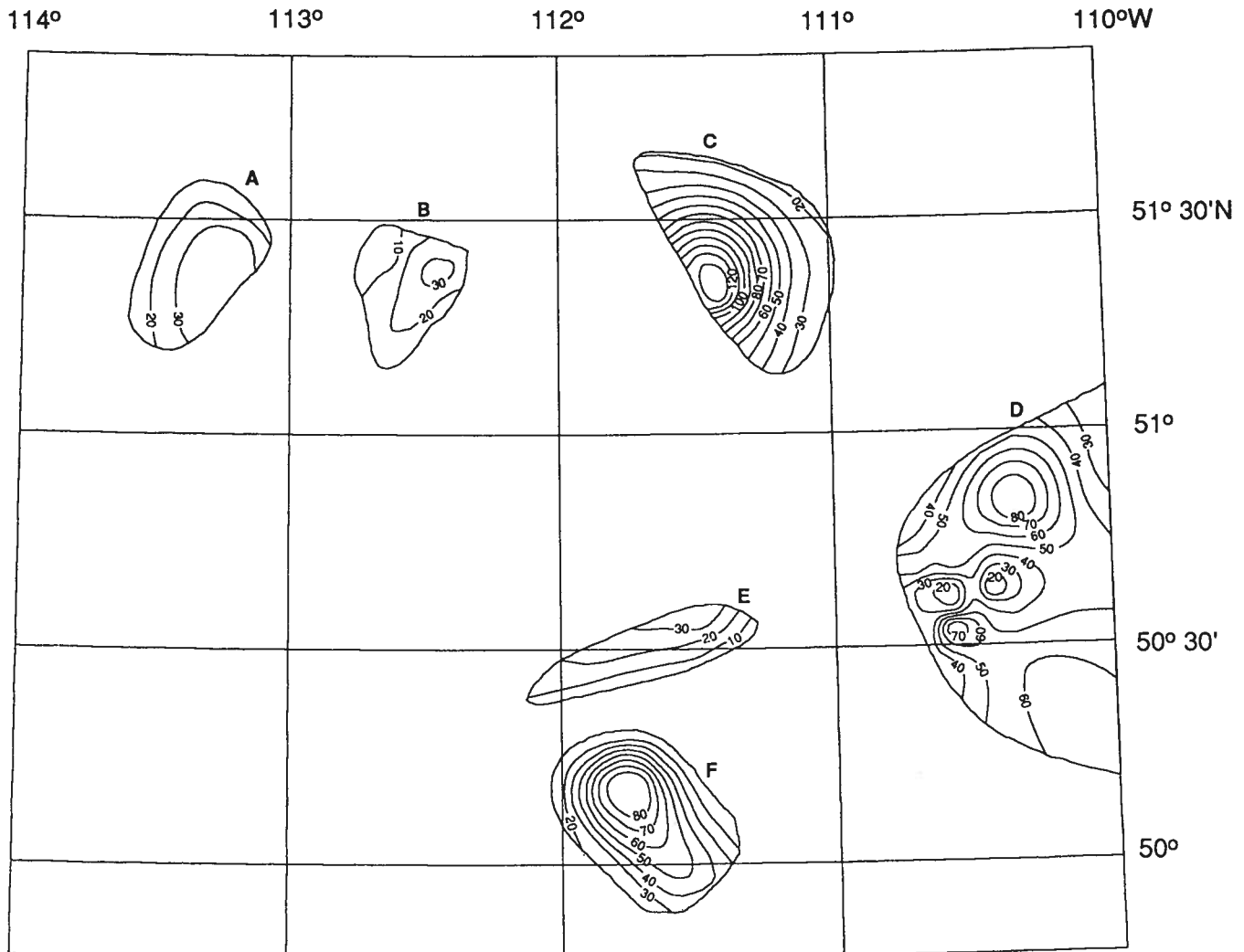
Figure 23. Magnesium resource estimates in formation waters in the Beaverhill Lake aquifer, southern Alberta (contours in kg/m² or 1000 t/km²).
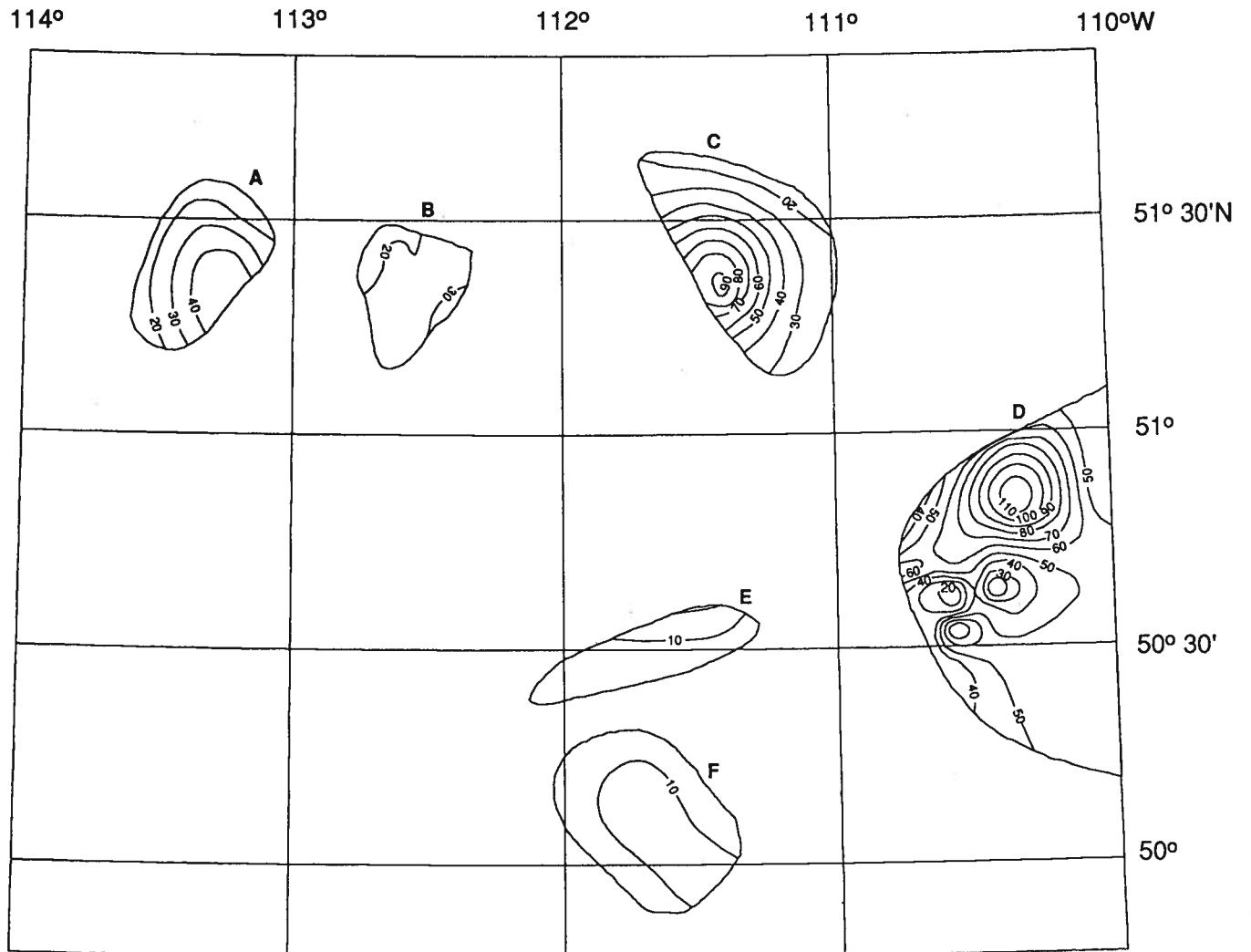
Figure 24. Potassium resource estimates in formation waters in the Beaverhill Lake aquifer, southern Alberta (contours in kg/m² or 1000 t/km²).
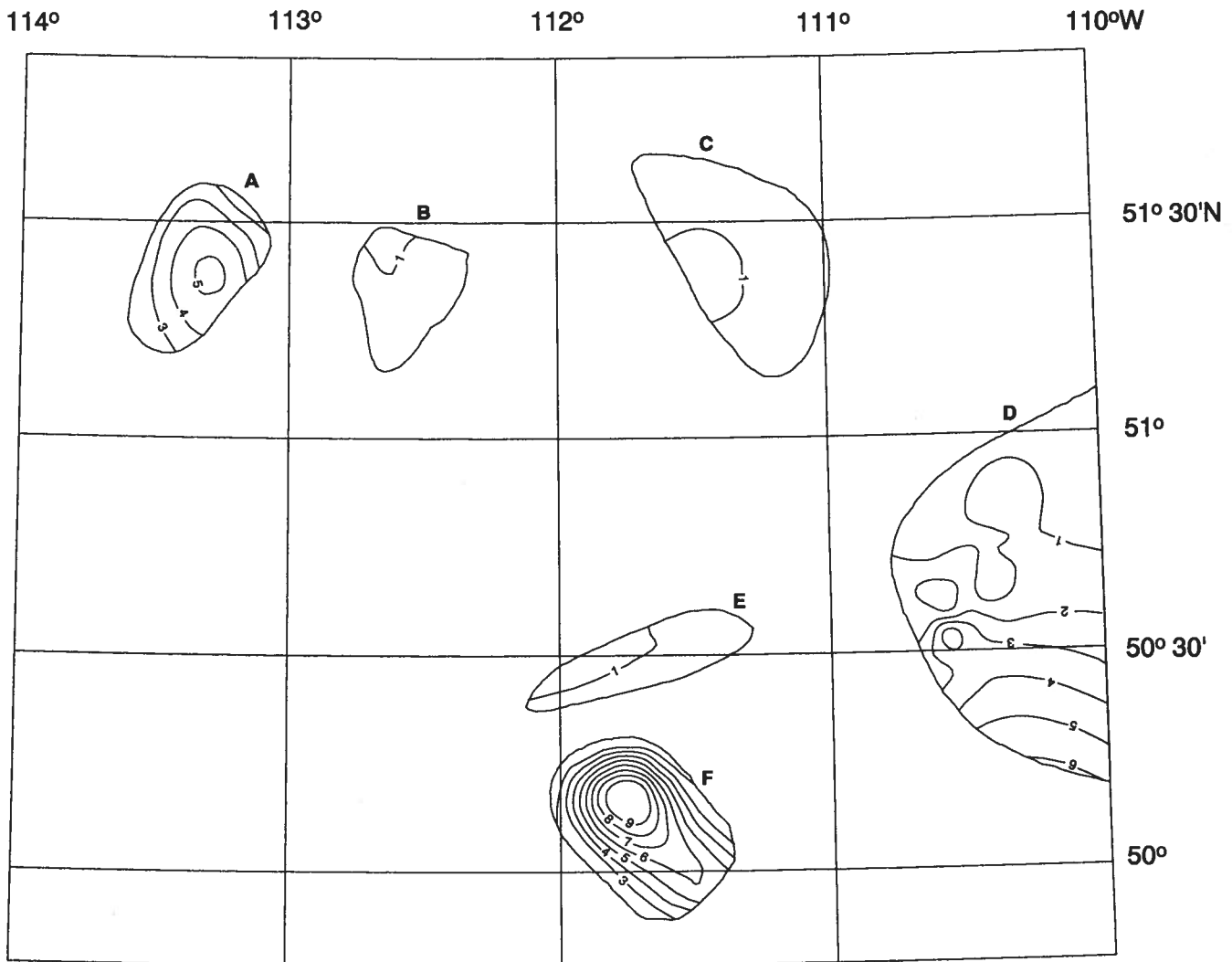
Figure 25. Bromine resource estimates in formation waters in the Beaverhill Lake aquifer, southern Alberta (contours in kg/m² or 1000 t/km²).

Woodbend-Beaverhill Lake carbonate complex

Three stratigraphic units contain formation waters with contents of Li >100 mg/l. These high-Li samples are from the Wabamun Group (one sample), Leduc Formation (Woodbend Group) and Swan Hills Formation (Beaverhill Lake Group), all in the region adjacent to and south of the Peace River High (Figure 26). This same region also contains other aquifers with formation waters with contents of Li greater than the detailed exploration threshold (75 mg/l). Included is one sample from the Upper Cambrian at 15-17-61-15-W5M reporting 81 mg/l Li. At this location the Upper Cambrian Lynx Formation is overlain by ~52 m of Middle Devonian Watt Mountain Formation, including the Gilwood Sandstone, and then by the carbonates of the Swan Hills Formation. Formation waters from the Swan Hills aquifer a few townships away 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. Additional formation water samples with Li >75 mg/l occur in the Gilwood Sandstone updip of the northeast margin of the Swan Hills carbonate complex.

Detailed analyses of formation waters with Li >100 mg/l from the Windfall-Swan Hills carbonate complexes shown in Figure 26 are compiled in Table 13. Note that while the content of Li exceeds the detailed exploration threshold value, Ca (13 600-27 500 mg/l), Mg (976-3260 mg/l), K (2000-7600), Br (243-518 mg/l) and I (5-21 mg/l) are all consistently below their respective detailed exploration thresholds. All the formation waters are saturated with respect to dolomite and quartz, and undersaturated with respect to halite. Anhydrite shows undersaturation in most samples, but is effectively at saturation in some. The ΔG_{diff} values for some possible well scales are given for information; values for barite indicate effective saturation at reservoir conditions. The analyses in Table 13 are of samples taken at the wellhead or during drillstem tests.

As such the analyses are an indication of the composition of the formation water but more carefully collected production samples and additional geochemical modelling are recommended if further evaluation of this potential resource is contemplated.

The Leduc Formation reefs, found in the western part of the study area (Figure 7B; Figure 26), reach thicknesses >300 m in places, while the Beaverhill Lake carbonate platform varies in thickness from >150 m in the south to around 50 m in the northwest. Eighty-eight wells with 3768 core analyses and 29 permeability measurements in drillstem tests penetrate the Leduc Formation reefs, and 183 wells with 18 256 core analyses and 32 permeability measurements in drillstem tests penetrate the Beaverhill Lake Group. However, the well distribution is uneven, with a high density in the reef area, and sparser outside it. Because of the abundance of core and DST data, no well logs were used in the analysis. Plug-scale porosity and permeability values measured in core vary over a very wide range (1 to 20%, and 10^{-17} to 10^{-11} m^2; 10^{-2} to 10^4 md, respectively). The well-scale porosity and permeability values for the Beaverhill Lake Group vary between 1 and 11%, and between 7×10^{-17} and 4.1×10^{-13} m^2 (0.07 and 410 md), respectively. Permeability values measured in drillstem tests vary between 3×10^{-16} and 2.6×10^{-12} m^2 (0.3 to 2600 md). For the Leduc Formation reefs, the well-scale porosity and permeability values vary between 1 and 13%, and between 3×10^{-16} and 7.3×10^{-13} m^2 (0.3 and 730 md), respectively. Permeability values measured in drillstem tests vary between 10^{-18} and 10^{-12} m^2 (0.001 and 1000 md). This extremely large range of variation in rock properties at the core and well scales indicates that, in this region, the Leduc Formation and Beaverhill Lake Group are very heterogeneous both areally and with depth, with significant zones of low-permeability rocks from which production of formation water would be limited.
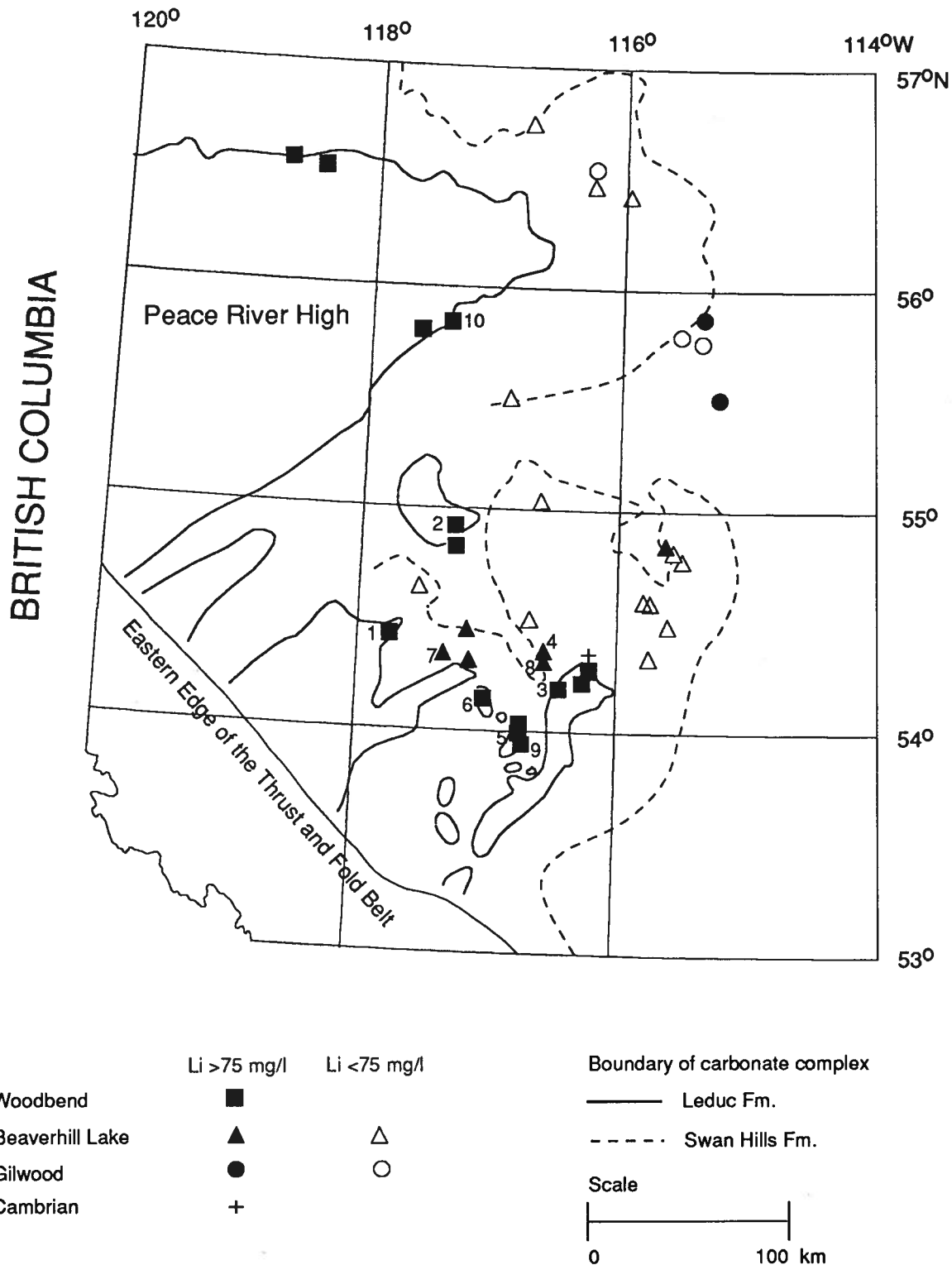
Figure 26. Distribution of Li in formation waters associated with the Windfall-Swan Hills carbonate complex (boundaries from Geological Atlas of the Western Canada Sedimentary Basin, Figs. 11.3 and 12.3). Numbered analyses — see Table13.

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Table 13. Chemical composition (mg/l), physical properties and production data for formation waters with Li >100 mg/l in the Windfall-Swan Hills carbonate complex.

Sample number		1 D-31	2 D-32	3 RCAH82-475B	4 RCAH111-676A
Stratigraphic unit		Leduc Fm.	Leduc Fm.	Leduc Fm.	Swan Hills Fm.
Location		11-6-63-25-W5M	13-27-68-22-W5M	14-14-60-17-W5M	10-13-62-18-W5M
Depth (m)		avg. 3533.5	2605.4-2611.5	2657.2-2665.5	3077.0-3104.4
Formation temp. (°C)		102	88	64	79
Source		Y Battery separator [Simonette, D-3 pool]	Separator [Sturgeon Lake South, D-3 pool]	DST 1 2063.5 m sw	DST 2 1563.6 m sw 1163.7 m wc
Composition (mg/l)					
Li		140	140	130	130
Na		61 000	60 000	43 200	54 000
K		3900	4300	7500	5100
Mg		2000	2890	1610	2010
Ca		22 800	27 000	18 000	15 900
Sr		660	670	725	630
Ba		18	5.3	5.7	19
Cu		1.0	1.7	*	0.49
Zn		*	*	*	5.9
Pb		5.8	11	8.5	3.3
Ag		2.4	4.4	*	1.3
Fe		2.8	2.4	*	0.85
Mn		0.62	0.61	14	14
V		1.6	2.5	*	0.8
As		*	*	*	*
B		110	110	2709	260
PO$_4$		48	58	76	24
NH$_3$		297	347	558	637
SiO$_2$		57	49	54	43
F		-	-	6.7	6.2
Cl		145 000	154 000	117 000	125 100
Br		436	413	430	426
I		15	18	14	18
SO$_4$		224	373	389	155
HCO$_3$		790	194	365	232
Total dissolved solids (mg/l, calc.)		238 030	251 118	191 630	205 945
Balance (%)		0.3	0.2	2.9	1.0
pH (field)		6.70	6.52	-	-
pH (laboratory)		7.85	6.90	7.15	6.76
pH (calc., formation temperature)		4.66	5.23	5.19	5.39
Density (15.56°C)		1.1560	1.1691	1.1413	1.1368
Refractive index (25°C)		1.3765	1.3802	1.3680	1.3668
ΔF$_{diff}$ values					
anhydrite	CaSO$_4$	-0.70	-0.42	-0.77	-1.44
barite	BaSO$_4$	0.16	-0.21	0.30	0.22
celestite	SrSO$_4$	-1.33	-0.94	-0.76	-1.57
cerussite	PbCO$_3$	-8.18	-7.25	-5.13	-6.62
dolomite	CaMg(CO$_3$)$_2$	2.32	2.17	1.35	2.01
fluorite	CaF$_2$	-	-	1.63	0.56
halite	NaCl	-1.62	-1.51	-1.90	-1.77
quartz	SiO$_2$	0.74	0.86	1.24	0.87
rhodochrosite	MnCO$_3$	-7.18	-7.04	-3.18	-3.56
siderite	FeCO$_3$	-3.79	-3.79	-	-3.90
smithsonite	ZnCO$_3$	-	-	-	-8.59
strontianite	SrCO$_3$	-2.28	-2.24	-1.79	-1.88

- = no determined
* = below detection
+ = Sr >500 mg/l by ICP, following dilution (sample not re-analyzed)
sw = salt water
wc = water cushion

Additional determinations (mg/l):
D-31 (Co 1.2, Cr 2.4, Ni 2.7, Ti 0.9)
D-32 (Co 1.9, Cr 3.5, Ni 3.4, Ti 1.4)

RCAH82-475B (Co 2.5, Cr 3.1)
RCAH111-676A (Co 0.54, Cr 1.5, Ti 0.6)
D-44 (Co 0.67, Cr 1.3, Ni 1.2, Ti 0.6)
RCAH26-574A (Cr 0.71)
RCAH37-576B (Cr 3.4, Mo 5.0, Ni 4.3, Ti 1.4)
RCAH110-676A (Cr 0.55, Mo 0.65, Ni 0.42, Ti 0.2)
W-80 (Rb 15.4); reported in Hitchon et al. (1971, Table 2, sample no. 80, p. 576)
D-38 (Co 1.5, Cr 2.7, Ni 3.0, Ti 1.1)

Table 13. cont.

Sample number		5 D-44	6 RCAH26-574A	7 RCAH37-576B
Stratigraphic unit		Leduc Fm.	Leduc Fm.	Swan Hills Fm.
Location		2-10-58-19-W5M	11-36-59-21-W5M	7-11-62-23-W5M
Depth (m)		3456.4-3485.7	3325.4-3372.6	3624.1-3638.7
Formation temp. (°C)		113	79	96
Source		Sale gas meter	DST 3	DST 1
		[Pine Creek, D-3	271.3 m sw	1484.4 m sw
		pool]	GTS 171000 m³/d	
Composition (mg/l)				
Li		120	120	118
Na		42 400	37 500	69 600
K		5000	5660	4600
Mg		979	976	2250
Ca		27 500	18 000	24 370
Sr		615	660	845
Ba		4.7	1.4	2.2
Cu		0.57	*	1.2
Zn		*	3.3	*
Pb		4.0	42	13
Ag		1.5	*	*
Fe		0.89	*	2.5
Mn		0.38	0.73	2.0
V		0.9	*	2.7
As		*	*	35
B		180	180	129
PO_4		23	11	38
NH_3		551	-	166
SiO_2		88	34	28
F		-	-	8.8
Cl		123 700	98 500	147 400
Br		317	243	462
I		18	11	6
SO_4		239	1130	213
HCO_3		1110	1890	460
Total dissolved solids (mg/l, calc.)		203 703	166 112	251 387
Balance (%)		0.9	0.6	4.6
pH (field)		-	-	-
pH (laboratory)		8.10	8.65	7.50
pH (calc., formation temperature)		4.37	4.48	4.89
Density (15.56°C)		1.1341	1.1146	1.1687
Refractive index (25°C)		1.3710	1.3606	1.3747
ΔF_{diff} values				
anhydrite	$CaSO_4$	-0.19	0.15	-0.83
barite	$BaSO_4$	-0.82	-0.17	-1.41
celestite	$SrSO_4$	-1.24	-0.10	-1.23
cerussite	$PbCO_3$	-8.80	-4.25	-7.32
dolomite	$CaMg(CO_3)_2$	1.71	1.36	2.29
fluorite	CaF_2	-	-	0.52
halite	NaCl	-2.12	-2.24	-1.46
quartz	SiO_2	0.86	0.66	0.33
rhodochrosite	$MnCO_3$	-7.66	-5.08	-6.19
siderite	$FeCO_3$	-4.89	-	-3.81
smithsonite	$ZnCO_3$	-	-8.35	-
strontianite	$SrCO_3$	-2.68	-2.01	-2.05

Comments:

The D-Series samples were preserved in the field; the other samples were analyzed as soon as possible after collection. All analyses were examined using SOLMINEQ.88 (Kharaka et al., 1988), and the analysis adjusted for calcite saturation at formation temperature by the addition of CO_2. No attempt was made to adjust the analyses for H_2S lost on sampling. The total dissolved solids and ionic balance are based on SOLMINEQ.88 results, with an additional adjustment for Br and I (not included in the input to SOLMINEQ.88); no account has been taken of the additional determinations (at right) in calculating either the total dissolved solids or the ionic balance.

Table 13. cont.

| Sample number		8 RCAH110-676A	9 W-80	10 D-38
Stratigraphic unit		Swan Hills Fm.	Leduc Fm.	Leduc Fm.
Location		7-36-61-18-W5M	10-23-57-19-W5M	1-16-79-22-W5M
Depth.(m)		3095.9-3109.0	3397.3-3417.7	2040.9-2095.9
Formation temp. (°C)		76	118	66
Source		DST 2 1066.8 m sw	Separator [Pine Creek, D-3 pool]	Wellhead [Normandville, D-3A pool]
Composition (mg/l)				
Li		115	100	100
Na		39 800	50 200	66 900
K		4300	7600	2000
Mg		1630	1590	3260
Ca		13 600	17 600	22 600
Sr		+	1060	580
Ba		1.7	-	5.2
Cu		0.27	0.06	1.2
Zn		1.9	0.19	*
Pb		10	-	9.1
Ag		0.92	-	3.0
Fe		0.36	0.04	2.4
Mn		9.0	0.1	1.2
V		0.28	-	1.9
As		*	-	*
B		190	178	43
PO_4		16	-	49
NH_3		381	-	119
SiO_2		19	-	40
F		4.7	-	-
Cl		94 160	11 900	155 000
Br		329	319	518
I		5	21	12
SO_4		778	120	348
HCO_3		316	1100	149
Total dissolved solids (mg/l, calc.)		156 567	199 729	251 953
Balance (%)		0.2	0.7	0.05
pH (field)		-	-	6.81
pH (laboratory)		7.34	7.31	6.50
pH (calc., formation temperature)		5.29	4.45	5.57
Density (15.56°C)		1.1112	1.1352	1.1716
Refractive index (25°C)		1.3600	1.3665	1.3805
ΔF_{diff} values				
anhydrite	$CaSO_4$	-0.34	-1.02	-0.84
barite	$BaSO_4$	-0.21	-	0.01
celestite	$SrSO_4$	-	-1.41	-1.11
cerussite	$PbCO_3$	-4.77	-	-6.15
dolomite	$CaMg(CO_3)_2$	1.90	2.49	1.84
fluorite	CaF_2	0.09	-	-
halite	NaCl	-2.23	-2.07	-1.32
quartz	SiO_2	0.29	-	1.08
rhodochrosite	$MnCO_3$	-2.93	-8.41	-5.84
siderite	$FeCO_3$	-4.24	-7.02	-3.27
smithsonite	$ZnCO_3$	-8.43	-10.99	-
strontianite	$SrCO_3$	-	-2.01	-2.05

Using Li concentration and rock property data, three areas with potential for formation water production and Li extraction were identified (Figure 27), one in the northern Leduc reef (N), one in the southern Leduc reef (S), and one in the Beaverhill Lake aquifer (BL). There is some overlap between the southern Leduc aquifer area (S) and the Beaverhill Lake aquifer area (BL) (Figure 27). There are still some intervals of relatively low permeability within the identified aquifers but overall they are characterized by favourable rock properties. The potentially productive aquifer in the northern Leduc reef (N) has an average thickness of 12 m, an average porosity of 6%, and an average permeability of 3.5×10^{-14} m^2 (35 md). The southern Leduc reef aquifer (S) has 25 m average thickness, 6% average porosity, and 2×10^{-14} m^2 (20 md) average
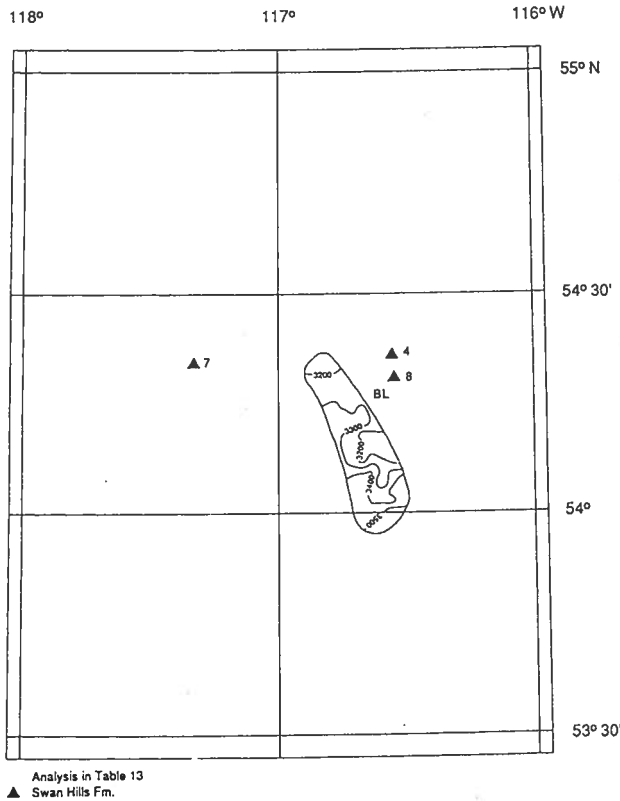
permeability. The Beaverhill Lake aquifer (BL) has an average thickness of 46 m, an average porosity of 7%, and an average permeability of 4.3×10^{-14} m^2 (43 md). Two observations are significant with respect to the Beaverhill Lake aquifer: (1) 113 wells with 14 800 core analyses are concentrated in this small area, compared with 183 wells for the entire initial study area; and (2) porosity and permeability are on average higher than for the Leduc reefs, although locally higher values are found in the latter. The small areal extent and the relatively high porosity and permeability characterizing the rocks in this area indicate local carbonate buildups within the Beaverhill Lake platformal carbonates. The approximate depth to the potentially productive stratigraphic intervals is shown in Figures 28 and 29.
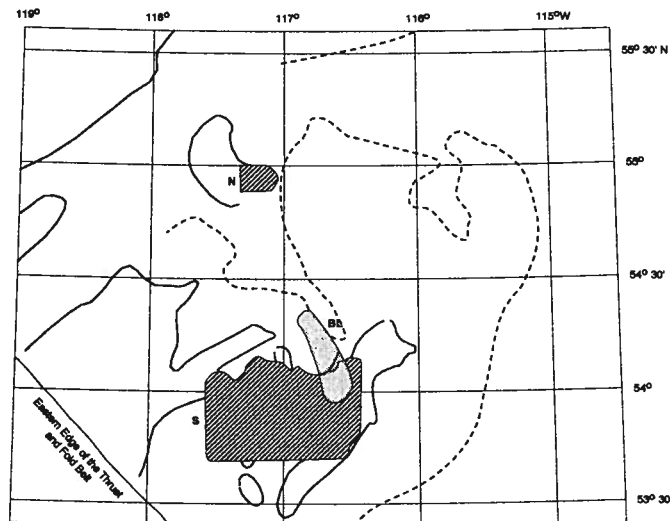
Figure 27. Areas in west-central Alberta with producibility potential for Li from formation waters in the Leduc (N and S) and Beaverhill Lake (BL) aquifers. Stratigraphic boundaries as in Figure 26. The areas have aquifers meeting the combined criteria of: (1) element concentration of formation waters above detailed exploration limit; (2) thickness >10 m; (3) porosity >5%; and (4) permeability >10^{-14} m^2 (10 millidarcies); see text for more details.

Analysis in Table 13
■ Leduc Fm.
▲ Swan Hills Fm.
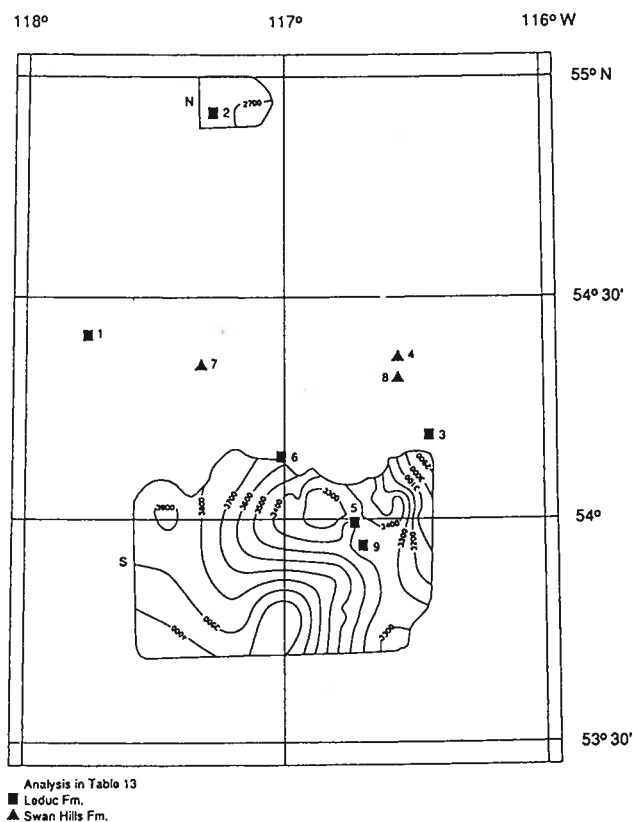
Figure 28. Approximate depth (m) to the stratigraphic interval with producibility potential for Li in formation waters from the Leduc aquifer, west-central Alberta.

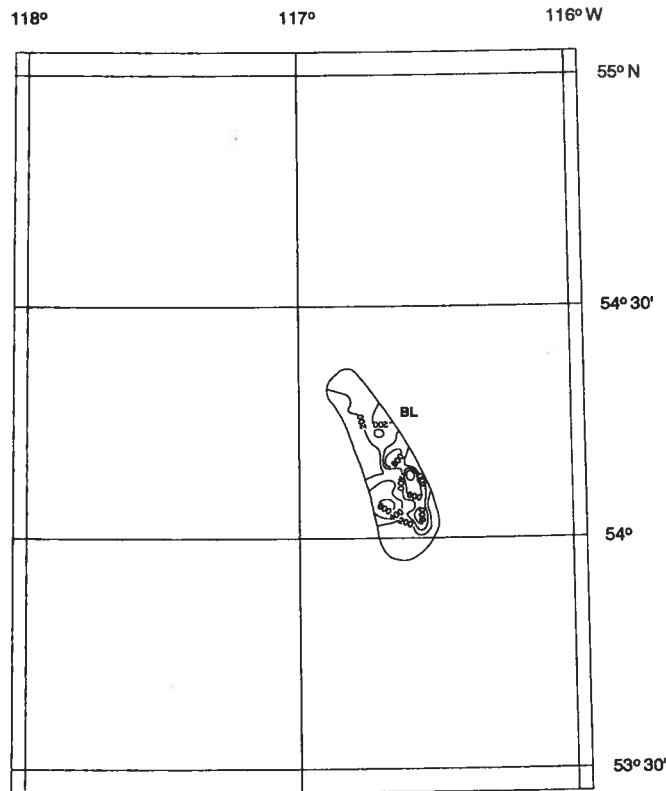**Figure 29.** Approximate depth (m) to the stratigraphic interval with producibility potential for Li in formation waters from the Beaverhill Lake aquifer, west-central Alberta.
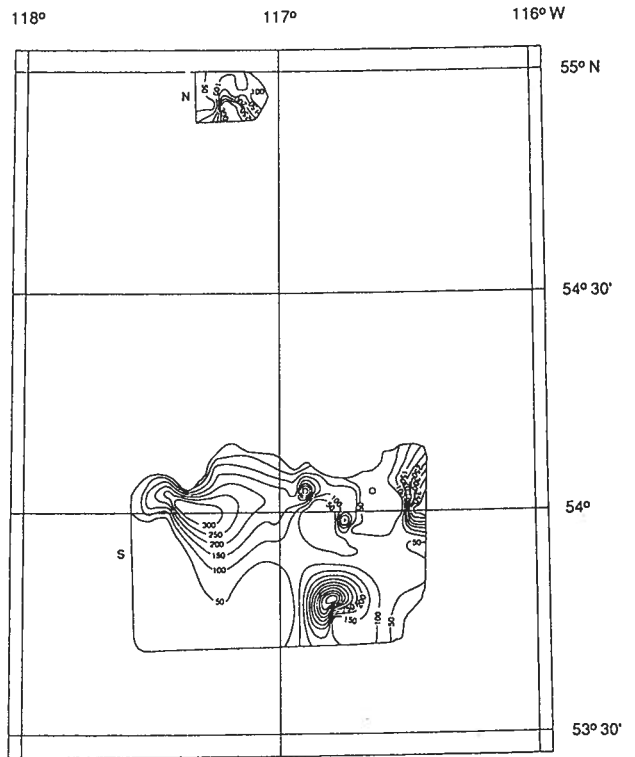
Figure 30. Lithium resource estimates in formation waters in the Leduc aquifer, west-central Alberta (contours in t/km²).

Resource distribution estimates for Li in formation water in Leduc aquifers vary between 10 and 570 g/m² (t/km²) in the southern area, and between 34 and 340 g/m² (t/km²) in the northern area (Figure 30). Resource distribution estimates for Li in the Beaverhill Lake aquifer vary between 11 and 918 g/m² (t/km²) (Figure 31). The highly variable resource distribution in all these areas is due to high variability in the porosity and thickness of the potentially productive interval, which is characteristic of reef complexes. The total resource estimate for Li in formation waters in the Leduc and Beaverhill Lake aquifers is 0.515×10^6 t, distributed over a cumulative area of 3980 km² (approximately 43 townships).

Figure 31. Lithium resource estimates in formation waters in the Beaverhill Lake aquifer, west-central Alberta (contours in t/km²).

Cretaceous: Viking and Belly River

The data in Table 8 indicate that I is the only potentially economic component in formation waters from Cretaceous aquifers, with the Viking and Belly River formations as targets. For the Viking Formation, the acquisition of a much larger data base for I than that used by Hitchon et al. (1977) has resulted in a more obscure regional variation pattern (Figure 32). 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 formation waters in the Viking Formation.

Iodide ranges up to nearly 100 mg/l in formation waters from the Belly River Formation. 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. However, Figure 33 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 perhaps clarify these trends. The distribution patterns in Figures 32 and 33 make assessment of the potential resource very difficult. Attention was directed, therefore, at isolated areas with I contents greater than the regional exploration limit (40 mg/l) because only rarely do I contents exceed or even closely approach the detailed exploration threshold (100 mg/l). Analyses of selected formation waters with I >60 mg/l can be found in Table 14.

Three hundred and eighty nine wells with 8110 core analyses penetrate the Viking Formation in the areas with I concentrations of interest. For the Belly River Formation, 412 wells record 13 827 plug-scale porosity and permeability analyses in the stratigraphic interval and areas where I concentration is >40 mg/l. Given the abundance of core data, no additional well logs were used in the analysis. Rock porosity and permeability vary in a very wide range in the areas of interest. Well-scale porosity and permeability in the Viking Formation vary between 6 and 19%, and between 8×10^{-17} and

$1.4 \times 10^{-12} m^2$ (0.08 and 1400 md), respectively. For the Belly River Formation, the well-scale petrophysical properties vary between 7 and 27% for porosity and between 5×10^{-12} and $0.5 \times 10^{-12} m^2$ (0.05 and 500 md) for permeability. Applying resource producibility criteria of minimum 10% porosity and $10^{-14} m^2$ (10 md) permeability, the areas with potential for I production were reduced further (Figure 34). Nine areas (cumulative area of 47 townships; 4655 km^2) of interest were identified in the Viking Formation (marked V_1 to V_9) and five areas (cumulative area of 13 townships; 1310 km^2) in the Belly River Formation (marked B_1 to B_5). The Viking Formation is characterized in these areas by 4288 core analyses in 135 wells and by 20 drillstem tests, while the Belly River Formation is characterized by 4650 core analyses from 246 wells and by 50 drillstem tests. The approximate depth to the potentially productive intervals in the Viking and Belly River formations varies between 650 and 950 m (Figures 35 and 36). Although the Viking Formation is older and stratigraphically deeper than the Belly River Formation, the depth range is similar because the areas of interest in the Belly River Formation are situated generally to the west of the areas of interest in the Viking Formation, in the downdip direction and toward higher topographic elevations. The thickness of the Viking aquifer in the areas of interest varies from <30 m in the north to >60 m in the south, with an average of 45 m. The average thickness of the Belly River aquifer is 73 m. The average porosity for Viking and Belly River aquifers is 17% and 20%, respectively.

Resource estimates for I in formation waters from the Viking aquifers (Figure 37) vary from <200 g/m^2 (t/km^2) to >1800 g/m^2 (t/km^2). Resources estimates for the Belly River aquifer (Figure 38) vary between <300 g/m^2 and >1000 g/m^2 (t/km^2). The variability in resource distribution is due to variations in I concentration and porosity and thickness of the host aquifer. The total resource estimate for I in formation waters from Viking and Belly River aquifers with producibility potential in south-central Alberta is 2.82×10^6 t.
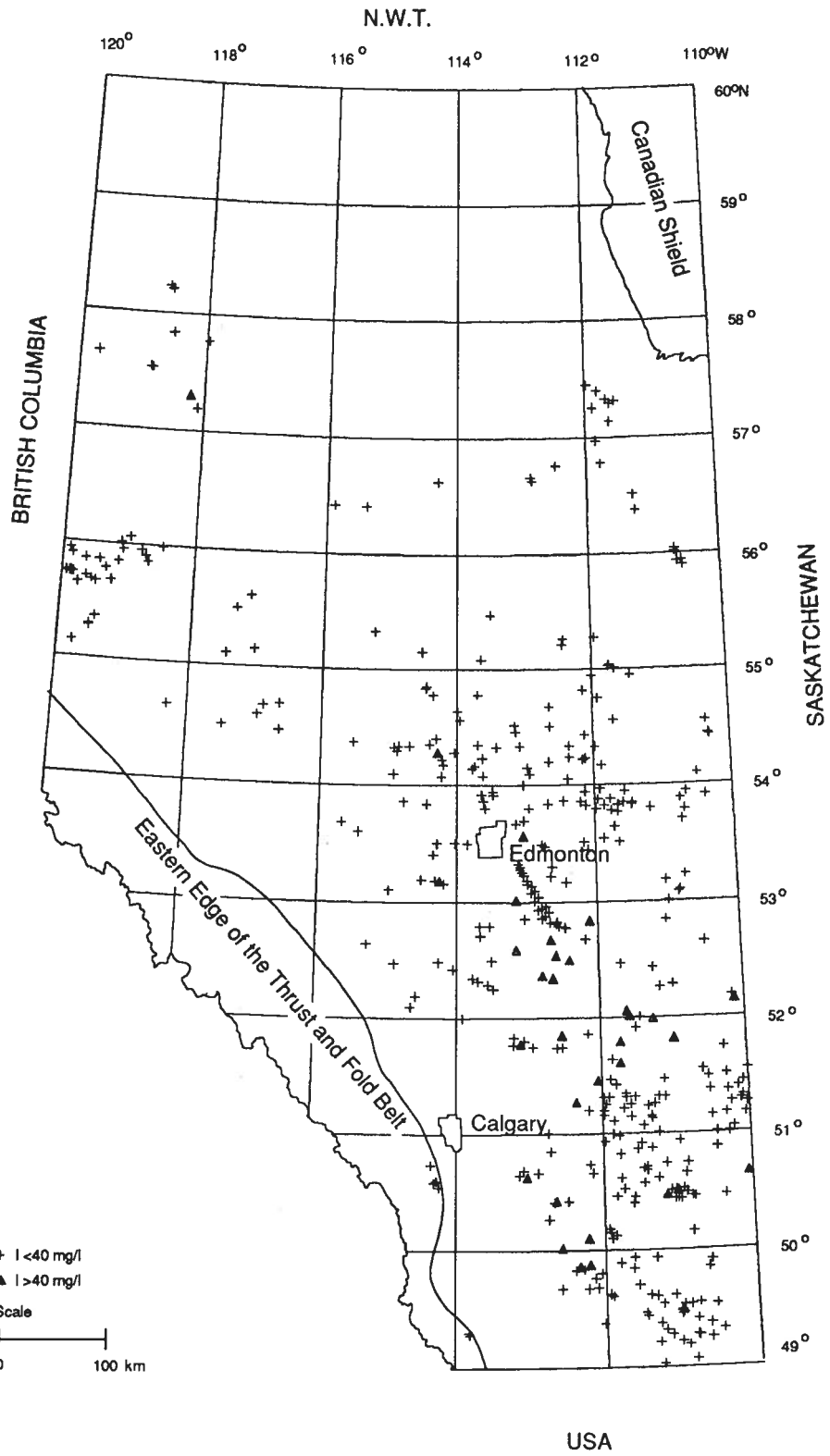
Figure 32. Distribution of I in formation waters from the Viking aquifer.

N.W.T.

120°   118°   116°   114°   112°   110°W   60°N

Canadian Shield

BRITISH COLUMBIA

SASKATCHEWAN

Eastern Edge of the Thrust and Fold Belt

+Edmonton

Calgary

+   I <40 mg/l

▲   I >40 mg/l

Scale

0   100 km

USA
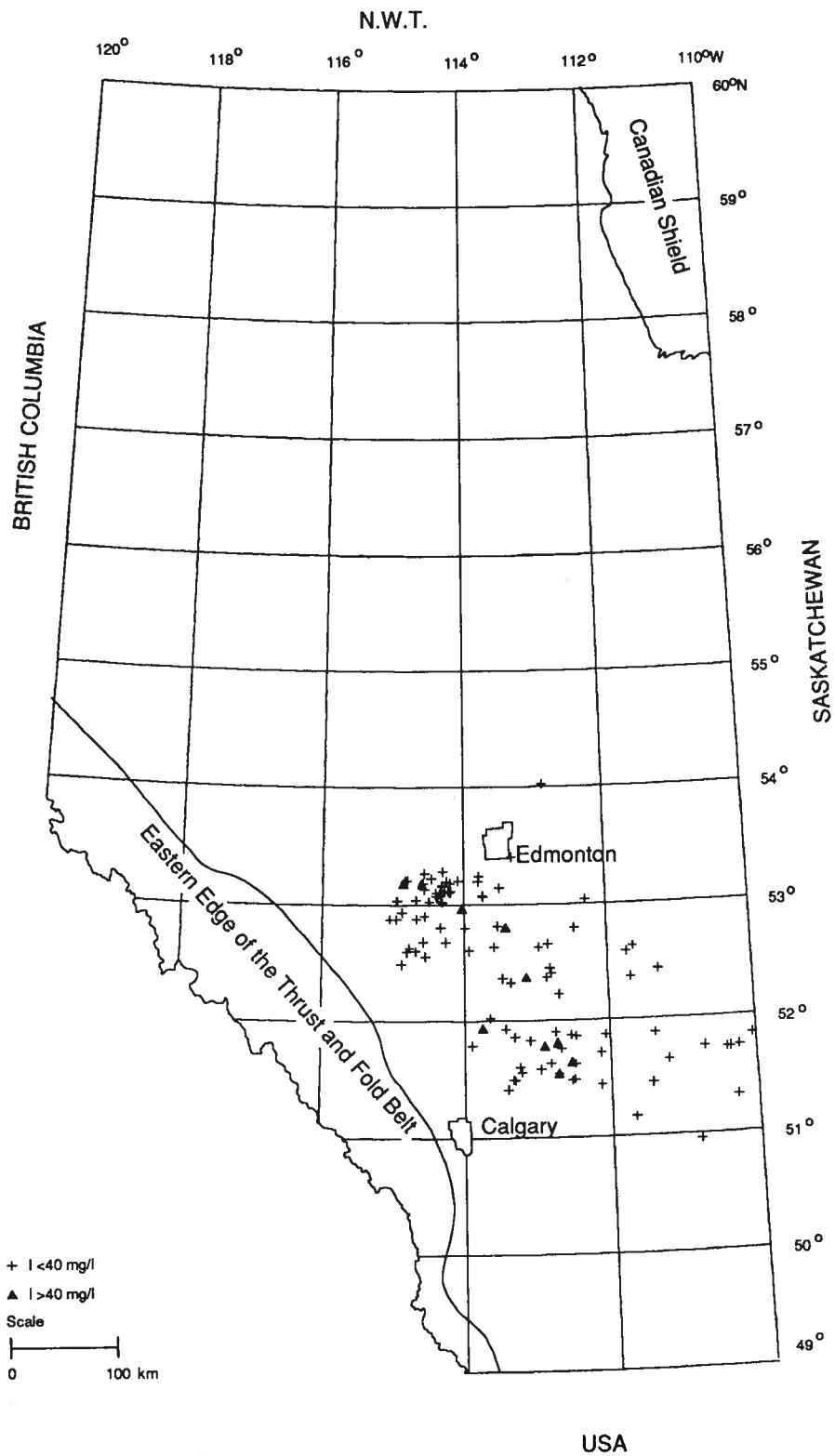
Figure 33. Distribution of I in formation waters from the Belly River aquifer.

Table 14. Viking and Belly River aquifers: selected formation waters with I >60 mg/l.

Sample number	1	2	3
Location	7-30-12-19-W4M	14-23-13-17-W4M	7-15-18-8-W4M
Aquifer	Viking	Viking	Viking
Depth (m)	821.44-854.96	230.22-230.58	772.50-777.50
Source	DST 3	Separator	DST 2
Recovery	222.5 m sw		540.0 m sw
	178.3 m gsy wc mud		
	GTS 198.2 m³/d		
Composition (mg/l)			
Na	7700	4530	4580
K	40	187	115
Ca	248	47	110
Mg	15	17	16
Cl	12 500	7430	7180
Br	118	252	156
I	63	128	87
SO_4	45	5	9
$HCO_3[+CO_3]$	410	592	729
Total dissolved solids (mg/l, calc.)	21 206	13 223	12 754
pH (laboratory)	7.75	7.90	8.00
Density (16°C)	1.0178	1.0050	1.0050
Resistivity (ohm m)	-	0.540	0.550
Refractive index (25°C)	1.3371	1.3430	1.3470
Estimated formation temperature (°C)	23	-	-

- = not determined, sw = salt water, wc = water cut, gsy = gassy, mdy = muddy

Table 14. cont.

Sample number	4	5	6	7
Location	10-34-30-13-W4M	7-13-33-8-W4M	6-15-39-19-W4M	6-16-44-24-W4M
Aquifer	Viking	Viking	Viking	Belly River
Depth (m)	969.26-978.41	874.78-899.16	1105.50	714.45-722.38
Source	DST 6	DST 1	Separator	DST 1
Recovery	213.4 m sw	98.1 m sw		365.8 m mdy sw
		27.4 m mud		
Composition (mg/l)				
Na	5920	4420	7640	4600
K	22	20	453	23
Ca	74	65	605	54
Mg	32	23	127	36
Cl	8293	6105	11 300	6264
Br	117	88	100	95
I	66	64	76	64
SO_4	59	26	43	18
$HCO_3[+CO_3]$	852	707	2070	1369
Total dissolved solids (mg/l, calc.)	14 687	10 876	20 506	11 700
pH (laboratory)	8.82	8.25	7.40	7.54
Density (16°C)	1.0156	1.0122	1.0160	1.0085
Resistivity (ohm m)	-	-	0.350	-
Refractive index (25°C)	1.3357	1.3352	1.3430	1.3353
Estimated formation temperature (°C)	27	24	-	23

54
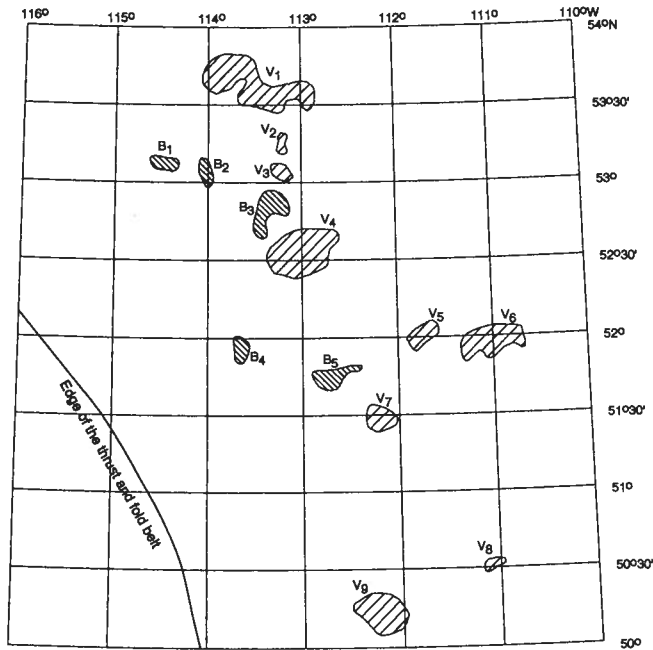
Figure 34. Areas in south-central Alberta with producibility potential for I from formation waters in Viking and Belly River aquifers ($V_1...V_9$ and $B_1...B_5$, respectively). The areas have aquifers meeting the combined criteria of: (1) element concentration of formation waters above regional exploration limit; (2) thickness >10 m; (3) porosity >5%; and (4) permeability >10^{-14} m² (10 millidarcies); see text for more
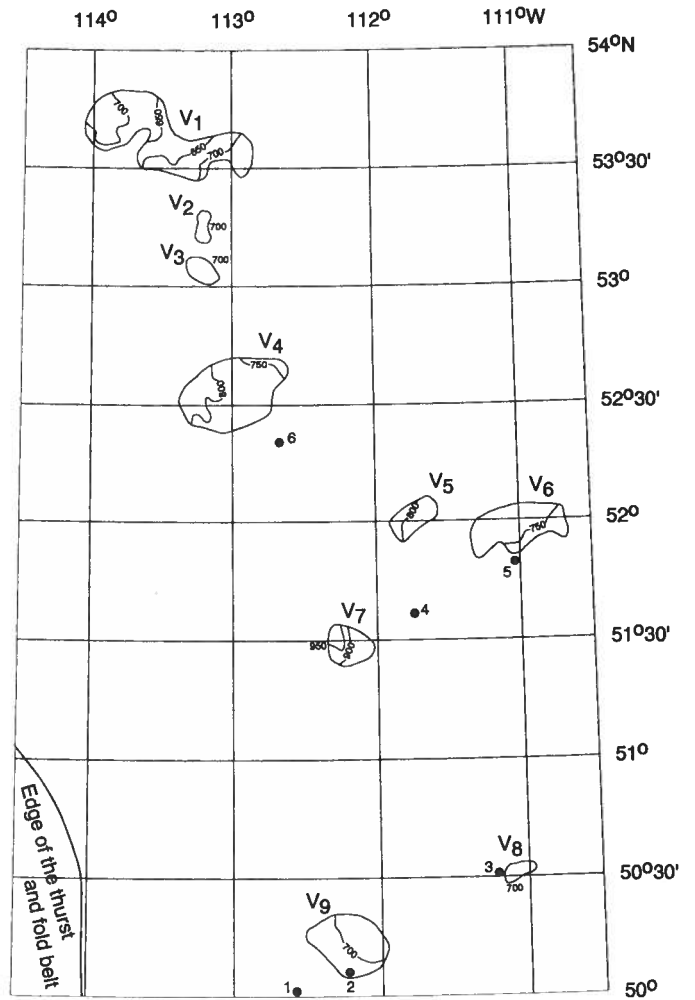
● Analysis in Table 14

Figure 35. Approximate depth (m) to the stratigraphic interval with producibility potential for I in formation waters from the Viking aquifer, south-central Alberta.
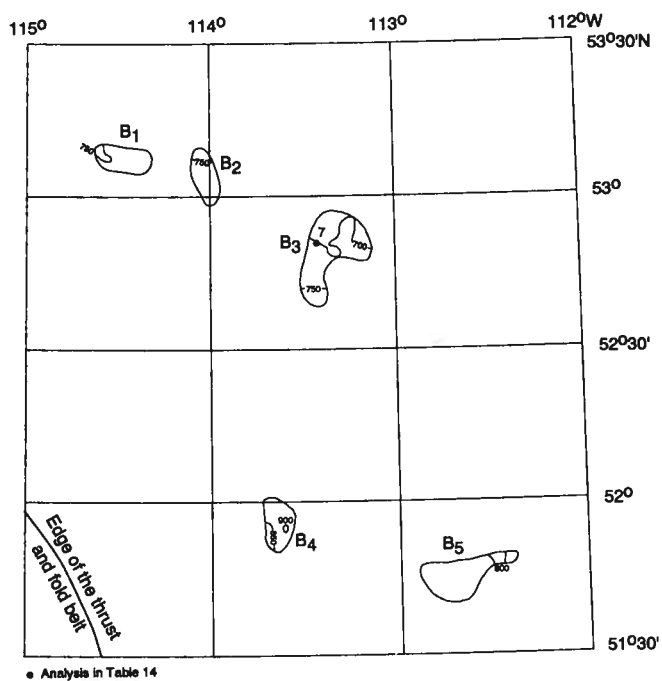
Figure 36. Approximate depth (m) to the stratigraphic interval with producibility potential for I in formation waters from the Belly River aquifer, south-central Alberta.
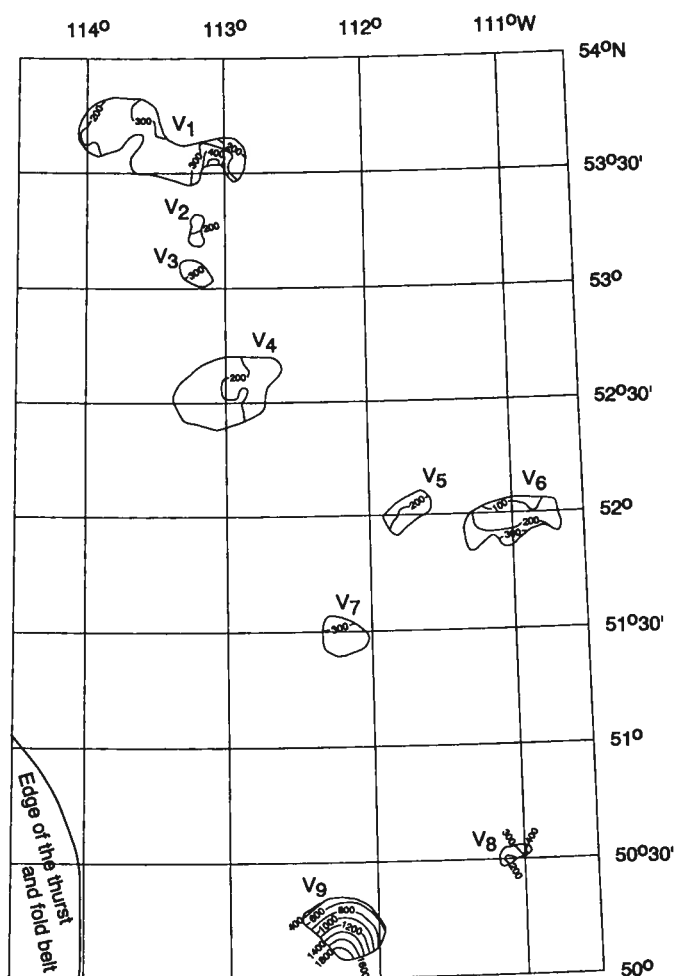
Figure 37. Iodine resource estimates in formation waters in the Viking aquifer, south-central Alberta (contours in t/km²).
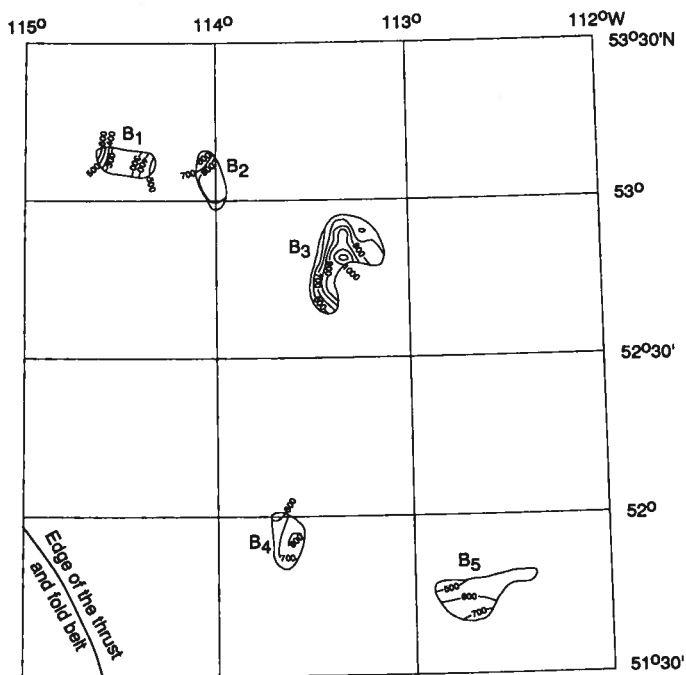
Figure 38. Iodine resource estimates in formation waters in the Belly River aquifer, south-central Alberta (contours in t/km²).

Discussion

This bulletin is concerned with identifying, describing and quantifying the geological and geochemical attributes and resources of potential industrial minerals in formation waters from Alberta. Geochemically, the study had been limited to Ca, Mg, K, Br, I and Li because these elements are believed to be of most immediate interest to those seeking to exploit this resource. It is important to stress that the findings of this study indicate only a potential to be of economic interest. No statement has been made, or should be implied, that the quantities found are economically recoverable. Determination of economic viability must rest with other investigators and the market place. This said, it is nevertheless of interest to compare the findings of this study with economic production of the same components elsewhere in the world.

Ca-Mg (K, Br, I) brines

Brines rich in Ca and Mg are most commonly exploited for calcium chloride and magnesium chloride, though Br and I have sometimes been extracted as byproducts. The production of calcium chloride in North America is dominated by one company (Dow Chemical Company), with 63% of US production capacity coming from brine wells in Michigan; the majority of the remaining capacity is synthetic calcium chloride produced by reacting hydrochloric acid with limestone. About 70% of North American production capacity of magnesium metal and magnesium compounds (including magnesium chloride) comes from brines in Michigan. In Canada, production capacity for calcium chloride is about 68% synthetic calcium chloride (General Chemical Canada Ltd. [formerly Allied Chemical Canada], Amherstburg, Ontario), and the balance from Alberta, including four brine wells. As far as can be ascertained, magnesium chloride from brines is not produced, as such, in Canada. The foregoing production information, and much more, came from Donald B. Cross and Associates Limited (1993), in a report dealing with an economic analysis of extracting calcium chloride and magnesium chloride from Alberta brines. The consultancy concluded that the market for calcium chloride and magnesium chloride in Canada and the USA is mature and shows no signs of significant growth in the near term. Production capacity of all plants for both products is under utilized because of an over supply of product in each market. They note that upgrading of brine feedstocks must be achieved, either by employing solar evaporation or by discovering richer natural brines. The latter may be addressed by studies of the present type.

Table 15 provides details, from a variety of sources, of Ca-Mg brine wells in Alberta. Nearly all the product is calcium chloride solution, within the concentration range 25 to 42% (Donald B. Cross and Associates Limited, 1993). Economic calculations (ibid.) suggest an operating loss per tonne for calcium chloride and an operating profit per tonne for magnesium chloride. This suggests that a high-Mg brine may be of interest. In the Elk Point aquifer the highest recorded Mg content is slightly more than 12 000 mg/l (Table 9, No. 6A), with nearly 10 450 mg/l at a well very close to the producing well of Tiger Chemicals Ltd. (Table 15). Several formation waters from the Beaverhill Lake aquifer in southern Alberta contain >12 000 mg/l Mg (Figure 18, Table 12), with a maximum of 13 410 mg/l. Again, wells penetrating the Beaverhill Lake aquifer in this part of Alberta should be tested for potentially economic brines.

The cause(s) for the enrichment of divalent cations (Ca,Mg) in brines is still the subject of debate. Possible scenarios for the Michigan Basin brines are reviewed by Wilson and Long (1993). Of particular interest to the present discussion is the reason for Mg enrichment. In the Michigan Basin the most likely route seems to be from diagenesis and/or dissolution of Salina A-1 potash salts, in association with dolomitization. The potash salts in Michigan are sylvinite, a mixture of halite and sylvite (KCl). Sylvite can originate during the burial metamorphism of carnallite, as follows:

$$K\,MgCl_3.6H_2O = KCl_{(s)} + MgCl_{2(aq)} + 6H_2O$$
[carnallite]   [sylvite]
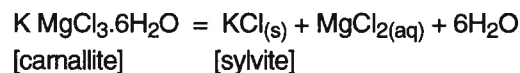
In the Western Canada Sedimentary Basin potash salts (sylvite, carnallite) are confined to the Prairie Formation in Saskatchewan. A recent survey of formation waters in the Williston Basin (Bachu and Hitchon, 1995) indicated few formation water analyses with Mg contents >10 000 mg/l. Contents of Mg up to 76 400 mg/l, however, are reported by the Potash Corporation of Saskatchewan (see Ogu and Arnold, 1989, Table 1.1). Finally, it should be observed that: (1) production of K from a Ca-Mg brine is unlikely in view of the abundant potash salts in Saskatchewan; (2) although Br and I may be produced commercially in Michigan in long-established operations, new sources

Table 15. Details of Ca-Mg brine wells in Alberta.

Operating company[1]	General Chemical	General Chemical	Tiger Chemicals	Ward Chemicals
Well location[1,2]	11-29-18-14-W4M	11-14-28-19-W4M	14-30-72-2-W5M	7-30-71-21-W4M
Producing unit[1]	Beaverhill Lake	Beaverhill Lake	Keg River	Keg River
Depth (m)	1712.8-1795.8[3]	1917.4-1938.9[3]	1685.5-1693 (perfs.)[2]	1373.0-1398.0 (perfs.)[2]
Pressure (kPa)	18 400	21 300	21 140	16 880
Temperature (°C)	46 (BHT)[2]	46[6]	48 est.	40 est.
Porosity[4]	5	9.8	-	-
Permeability (md)[5]	11.5	1.54	19.03	-
Composition (mg/l)				
Ca	70 000[9]	78 134[6]	{ 122 217[8]	126 000[7]
Mg	6000	9602		13 000
Na		36 000	39 745	12 000
K		13 550	-	7700
Cl		233 972	277 438	289 000
SO$_4$		43	0	-
HCO$_3$		273	61	-
Density (16°C)		1.2667	-	1.32
Production capacity (t/a)[8]	4500	4500	50 000	75 000
Product[1]	CaCl$_2$ liquid	CaCl$_2$ liquid	CaCl$_2$ liquid CaCl$_2$ flake	Mainly for dust control on unpaved roads

Sources:

1. Alberta Geological Survey "Alberta Mineral Deposits/Occurrences File"
2. Well Information Services Ltd. "Well File Cards"
3. This study, using logs and the specified selection criteria with respect to interval, porosity and permeability
4. This study, using procedures described in text
5. Permeability (in millidarcies) from drillstem test
6. Table 12, No. 8 (from DST straddling indicated interval)
7. Ogu and Arnold (1989, Table 1.1)
8. Donald B. Cross and Associates Limited (1993)
9. Computer extrapolation of element concentration maps

- = not determined

of these elements elsewhere in the world would seem to preclude their production from Alberta brines. Therefore, with respect to Ca-Mg (K, Br, I) brines in Alberta, it seems likely that only production of Ca and Mg may be of economic interest.

Bromine

Commercial sources, reserves and production of Br have been evaluated thoroughly by Wilhelm and Williams (1994). Although Br is commercially recovered from sea water (60-65 mg/l Br) in France, Japan and the United Kingdom, the higher Br contents in formation waters and in some surface brines continue to be the most economic and preferred sources of production. The Dead Sea (5000 mg/l Br) and Arkansas (5000 mg/l Br) are the two largest commercial production sources today, the latter being brines in the Smackover Formation. Potash is produced from the Dead Sea brines, and Br is extracted from a concentrated (12 000 ppm) effluent stream from that production. With a maximum content of 2786 mg/l Br in a single formation water from the Beaverhill Lake aquifer (Table 12, No. 2), it would certainly be prudent to analyze for Br in all formation waters recovered from this aquifer in southern Alberta. As noted by Wilson and

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Long (1993), few, if any, processes are known which remove Br from solution (they found up to 3340 mg/l Br in some of the samples they studied from the Michigan Basin). Therefore, the highest Br contents might generally be expected associated with the potash deposits of Saskatchewan. Values of Br up to 6800 mg/l are reported by the Potash Corporation of Saskatchewan (Ogu and Arnold, 1989, Table 1.1), but as with the high Mg content noted previously, the source and production details are lacking. Continued analysis for Br in appropriate formation waters in Alberta seems justified.

Iodine

Although I (34-40 mg/l) and Br (2790-2910 mg/l) were once recovered from Michigan brines by Dow Chemical Company, the wells were plugged and abandoned in 1987 (Johnson, 1994). The major international producers are now Japan (47.5%), Chile (25%), former U.S.S.R. (12.5%) and USA (12%) (ibid.). Japanese formation waters are co-produced with natural gas from Miocene, Pliocene and Pleistocene sands and silts; maximum I content is about 160 mg/l. Production in Chile is associated with nitrate ores in the Atacama Desert of northern Chile. Iodine production in the USA now comes totally from I-rich (300 mg/l I) brines in the basal Pennsylvanian sandstones on the north flank of the Anadarko Basin, Oklahoma. The source of Russian production is not known with certainty (ibid.). It seems unlikely that formation waters in Alberta will contain sufficient I to be commercial. Although some older analyses show I >100 mg/l, there is doubt as to their reliability because either: (1) Br was not reported and the high value could have been Br + I, incorrectly reported as only I; or (2) there was the possibility of a source of I from organic matter associated with co-produced mud. The I distribution maps (Figures 32 and 33) indicate that formation waters with I greater than the regional exploration threshold (40 mg/l) are scattered among many waters with much lower contents of I. Only one analysis (Table 14) exceeds the detailed exploration threshold (100 mg/l). Thus, while determination of I in formation waters from Viking and Belly River aquifers may not yield values of interest

to the I-extraction industry, I may be important as a petroleum indicator in some stratigraphic units in Alberta (Hitchon and Horn, 1974).

Lithium

Lithium resources have been evaluated recently by Kunasz (1994). Pegmatites have been the traditional source of lithium minerals, and continue to be a commercial source of Li, but, today, two brine deposits satisfy nearly one-half of the free-world demand for lithium chemicals. The brine deposits are located in shallow Quaternary sediments at Clayton Valley, Nevada, and at the Salar de Atacama, which straddles the Tropic of Capricorn in Chile, and where contents of Li as high as 7000 mg/l have been recorded, although the average is 1350 mg/l. Other surface brine deposits are actively being investigated even though presently identified reserves and production capacity are sufficient to satisfy the conventional market growth of lithium (Kunasz, 1994).

Apart from surface brine deposits, formation waters have not been used as a commercial source of Li, probably because the contents were generally too low. The values reported in this study (Table 13) are some of the highest recorded for formation waters and similar to those at Clayton Valley. Kunasz (1994) notes that the Clayton Valley brine is chemically simple, being a concentrated Na-Cl solution containing subordinate amounts of K and minor amounts of Mg and Ca. The Li concentration is variable (100-300 mg/l) and shows a decrease in concentration as a function of pumping. The Li resources, to a depth of 300 m, are estimated at 115 000 t Li; recent exploration has resulted in increased reserves and increased average Li content pumped to the evaporation pond system. These numbers compare with the 515 000 t Li reported in the Windfall-Swan Hills carbonate complex, using the prescribed criteria for interval thickness, porosity and permeability. It is recommended that Li be analyzed in all formation waters recovered from the carbonate rocks of the Windfall-Swan Hills complex, including formation waters from deeper aquifers.

Summary

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. Using a variety of culling procedures, a formation water industrial mineral data base was compiled, based on specific regional and detailed exploration thresholds (Table 16). Aquifers and areas identified as justifying resource evaluation were:

(1) Elk Point in northern Alberta (Ca, Mg, K, Br);
(2) Beaverhill Lake in southern Alberta (Ca, Mg, K, Br);
(3) Leduc-Beaverhill Lake in the Windfall-Swan Hills carbonate complex (Li);
(4) Cretaceous Viking and Belly River, central and southern Alberta (I).

Using a data base of electronic information on drillstem tests and core analyses, supplemented by selected well log interpretations, and with combined specified thresholds for aquifer thickness (10 m), porosity (5%) and permeability (10^{-14} m^2; 10 md), areas were identified in each of the target aquifers which met the concentration and reservoir thresholds such that the resource, R, could be calculated using the relation:

$$R = C \times D \times \varnothing$$

where the concentration, C, is expressed in milligrams per litre, the aquifer thickness, D, in meters, and porosity, $\varnothing$, as a percentage. The resource unit, in the above, is in g/m^2 or t/km^2. Selected resource results are set out in Table 17 and the areas indicated in Figure 39. The numbers are large, and must be used with caution, and in the context of the criteria and conditions set out in this bulletin. Further, not all of the resource is recoverable through pumping. Despite the size of the resource the amounts are generally <0.5% of the respective rock mass in the areas evaluated.

Comparison with commercial operations elsewhere in the world indicates that: (1) the market for calcium chloride and magnesium chloride in North America is mature and shows no sign of significant growth in the near term; (2) formation waters with high contents of Br, and some surface brines, are the most economic and preferred source of production for Br; (3) the market for I is from sources in Japan, Chile and USA with considerably higher contents of I than found in Alberta; and (4) although the presently identified reserves and production capacity are sufficient to satisfy the conventional market growth for Li, the higher quantities found in some Alberta formation waters are similar to those of the major USA producer.

At this time, and based on the present information, it is recommended that industry continue to analyze formation waters, in selected aquifers and areas, for Ca, Mg, Br and Li. Iodide should probably also be determined, but for purposes other than potential industrial mineral production.

Table 16. Formation water industrial mineral data base.

Element	Regional exploration		Detailed exploration	
	Threshold	No. of analyses	Threshold (mg/l)	No. of analyses
Ca	20 000	{ 4712	60 000	{ 23
Mg	3000		9000	
K	5000	292	10 000	6
Br	1000	51	3000	-
I	40	97	100	3
Li	50	49	75	47

Table 17. Selected resources of industrial minerals in formation waters, Alberta.

Aquifer	Resource (tonnes)		
Elk Point (northern Alberta, area B)	$CaCl_2$ 0.6 x 10^9t	$MgCl_2$ 0.1 x 10^9t	Br -
Beaverhill Lake (southern Alberta)	$CaCl_2$ 8.8 x 10^9t	$MgCl_2$ 1.8 x 10^9t	Br 0.27 x 10^9t
Windfall-Swan Hills carbonate complex	Li 0.5 x 10^6t		
Viking and Belly River (central and southern Alberta)	I 2.8 x 10^6t		

- = no data
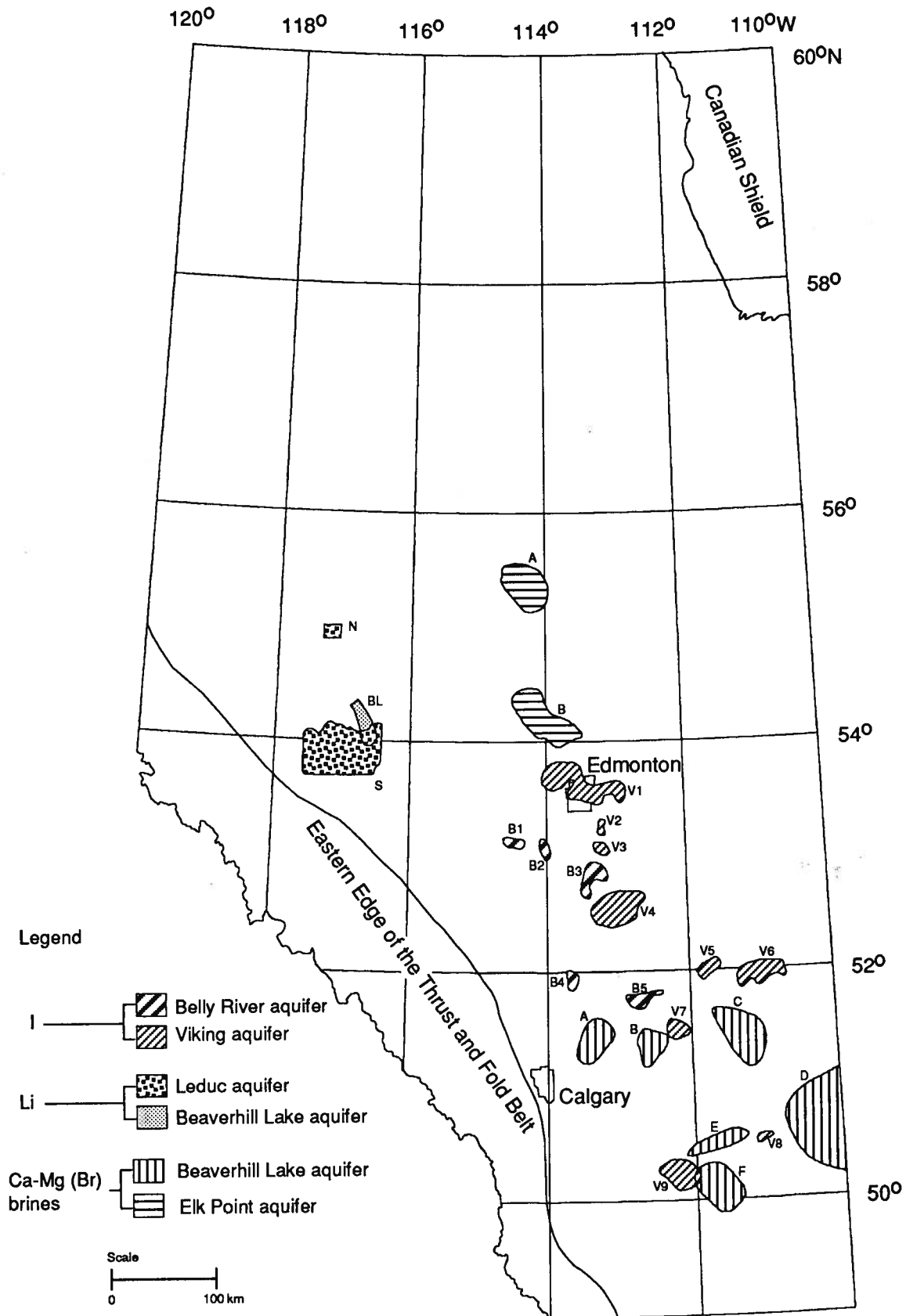
Figure 39. Resource areas for industrial minerals in Alberta formation waters.

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Appendix. Summary of K/Na x 10³ ratios in Alberta formation waters.

This Appendix presents statistics on the K/Na x 10³ value in Alberta formation waters from producing wells and from drillstem tests (RCAH- and D- series) that were free of KCl mud contamination. From this information, the K/Na x 10³ values were selected for culling formation water analyses contaminated by KCl mud.

Table A1. Statistics on K/Na x 10³ 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 Fm.	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 Gp.								
Swan Hills Fm.	4	15.9	23.7	33.6	10	12.9	72.6	117
Slave Point Fm.[low-Ca]	2	88.3	105	122	8	8.6	20.3	47.4
[high-Ca]	-				6	185	300	703
Elk Point Gp.								
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	