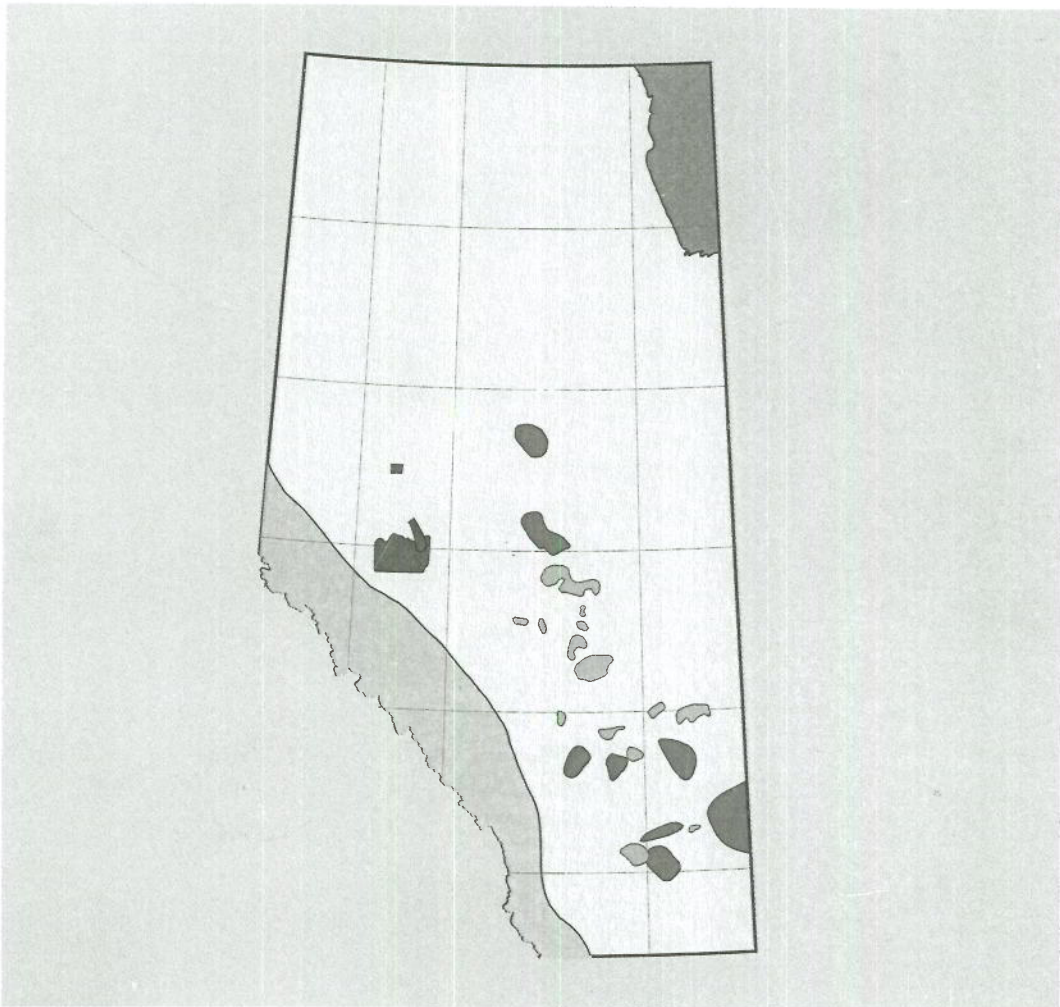


Industrial Mineral Potential of Alberta Formation Waters

Brian Hitchon, Stefan Bachu,
J.R. Underschultz and L.P. Yuan



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Alberta Geological Survey

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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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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} m²; 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} m² (0.07 and 410 md), respectively. Permeability values measured in drillstem tests vary between 3×10^{-16} and 2.6×10^{-12} m² (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} m² (0.3 and 730 md), respectively. Permeability values measured in drillstem tests vary between 10^{-18} and 10^{-12} m² (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.

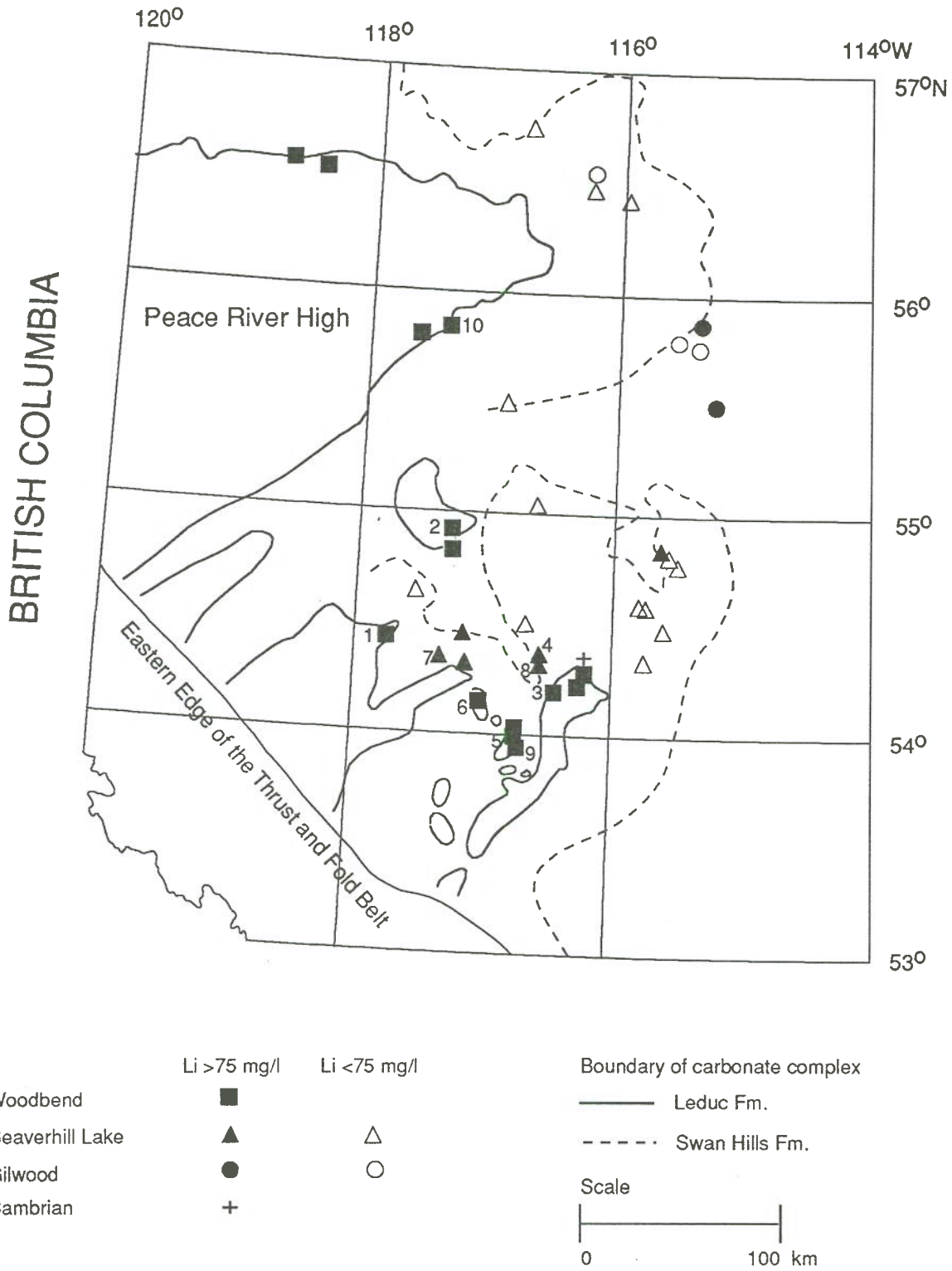


Figure 26. Distribution of Li in formation waters associated with the Windfall-Swan Hills carbonate complex boundaries from Geological Atlas of the Western Canada Sedimentary Basin, Figs. 11.3 and 12.3). Numbered analyses — see Table 13.

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	2	3	4	
	D-31	D-32	RCAH82-475B	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_{eff} 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 [Pine Creek, D-3 pool]	DST 3 271.3 m sw GTS 171000 m ³ /d	DST 1 1484.4 m sw
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

omments:

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 CO₂. No attempt was made to adjust the analyses for H₂S 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 $3.5 \times 10^{-14} \text{ m}^2$ (35 md). The southern Leduc reef aquifer (S) has 25 m average thickness, 6% average porosity, and $2 \times 10^{-14} \text{ m}^2$ (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 $4.3 \times 10^{-14} \text{ m}^2$ (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 platform carbonates. The approximate depth to the potentially productive stratigraphic intervals is shown in Figures 28 and 29.

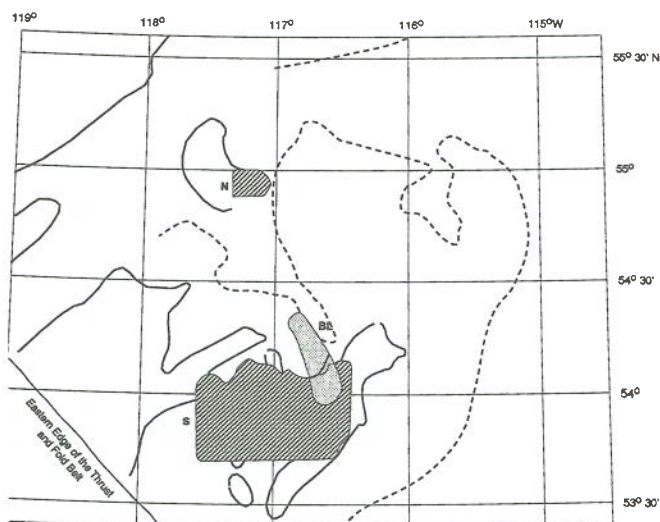


Figure 27. Areas in west-central Alberta with producibility potential for Li from formation waters in the Leduc (N and S) and Beaverhill Lake (BL) aquifers. Stratigraphic boundaries as in Figure 26. The areas have aquifers meeting the combined criteria of: (1) element concentration of formation waters 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.

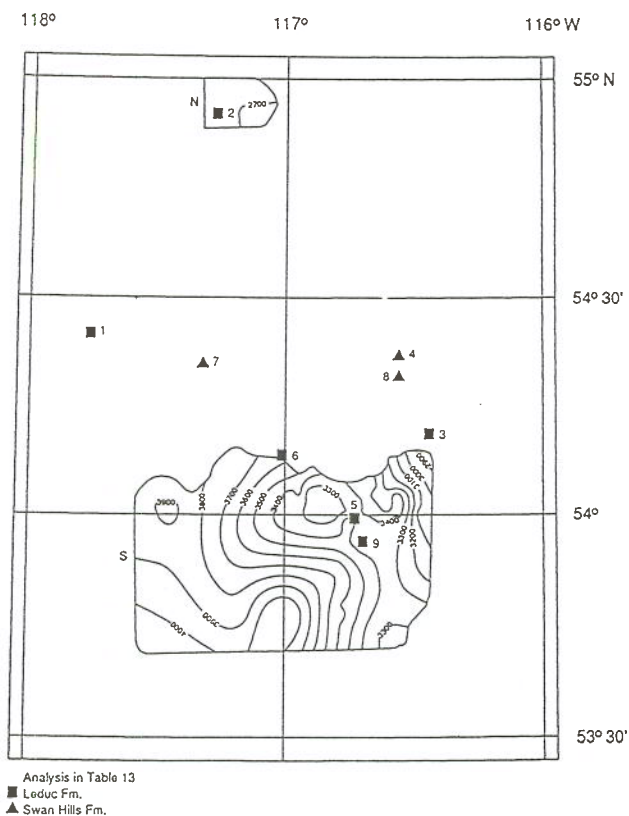


Figure 28. Approximate depth (m) to the stratigraphic interval with producibility potential for Li in formation waters from the Leduc aquifer, west-central Alberta.

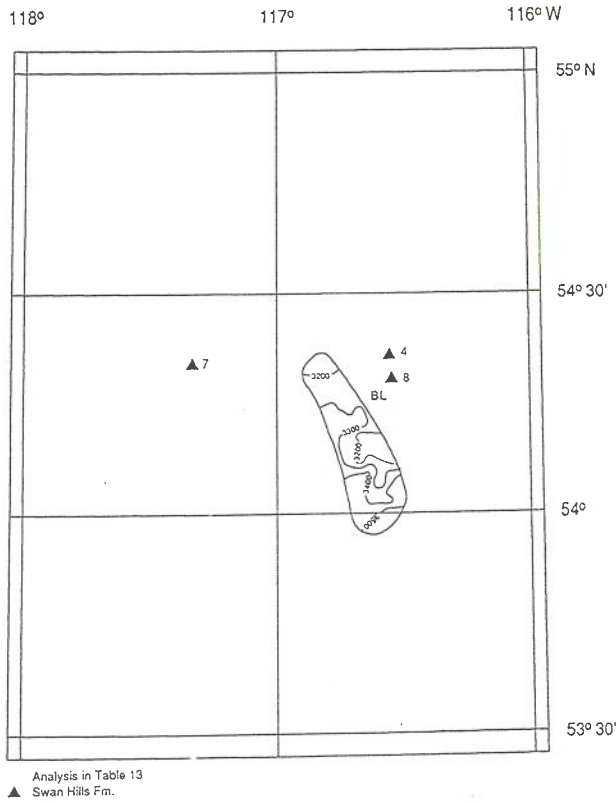


Figure 29. Approximate depth (m) to the stratigraphic interval with producibility potential for Li in formation waters from the Beaverhill Lake aquifer, west-central Alberta.

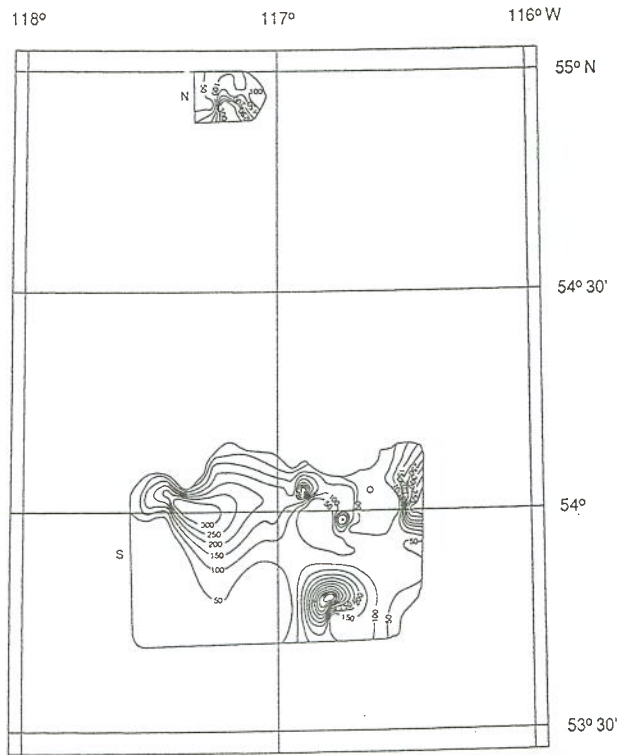
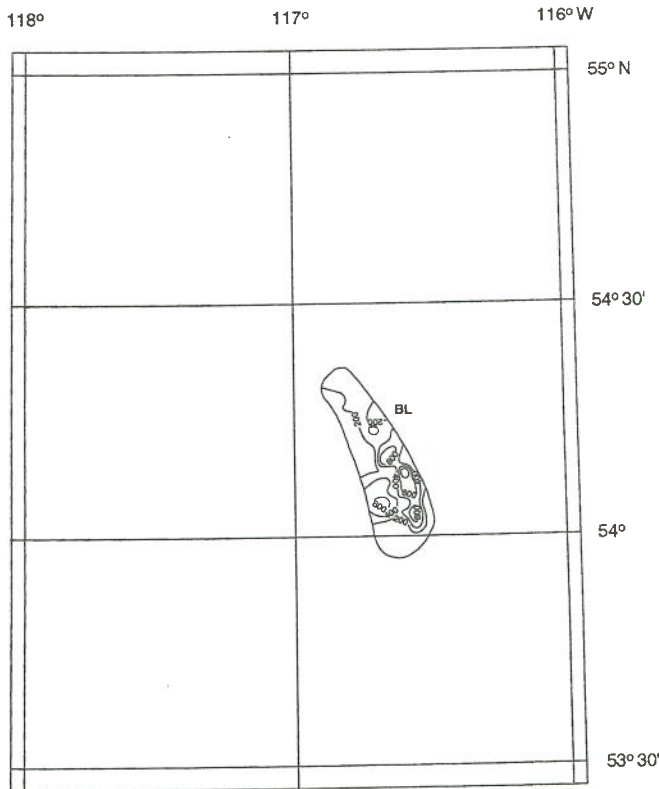


Figure 30. Lithium resource estimates in formation waters in the Leduc aquifer, west-central Alberta (contours in t/km²).



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 x 10⁶ 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).