ALBERTA RESEARCH COUNCIL

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HYDROCHEMISTRY OF THE PEACE RIVER ARCH AREA, ALBERTA AND BRITISH COLUMBIA

by Hitchon Geochemical Services Ltd.

for Alberta Research Council

October 1990

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Abstract - The Peace River Arch area is defined as 54° to 58°N, and 114°W to the eastern limit of the disturbed belt. More than 30,000 formation water analyses from the area were entered into the Alberta Geological Survey Well Data Base, verified, and subjected to electronic and manual-electronic culling to leave a data base of about 9600 fairly reliable analyses. Following study by means of composition distribution maps, cumulative frequency plots of log Cl, and data compilations, the final data base comprised about 6800 analyses, or just over 22% of the original data base.

Salinity ranges from freshwater to 380,000 mg/l. Salinity distribution maps are of two major types. Pre-Cretaceous aquifers have salinity trends parallel to the structure contours, and show higher salinity with increased depth, hence increased temperature. This pattern may be modified by the presence of halite or high permeability trends within individual aquifers. Both modifications result in relatively higher salinity for comparable depths. Cretaceous aquifers below the Harmon-Joli Fou aquitard show salinity trends unrelated to structure contours and possibly more related to surface topography. However, this association may be spurious when considering relatively shallow aquifers in regions with strongly contrasting surface topography. There are too few aquifers above the Harmon-Joli Fou aquitard to permit general statements.

Distribution patterns for Cl, Ca and Mg closely resemble that for salinity, and as a broad generalization for any specific aquifer, the higher salinity area has a relatively lower HCO_3 content compared to the lower salinity area. Except for the association of SO_4 > 2500 mg/l with anhydrite in the Charlie Lake aquifer, SO_4 generally shows no obvious regional trends. Generally, the salinity distribution map provides a broad indication of the distribution of other components in the aquifer.

The report is illustrated with 36 salinity distribution maps and 4 maps for individual components. Although the data distribution only averages 60 analyses per cubic kilometer the patterns which emerge suggest strong relations among formation water composition, depth, temperature and water-rock reactions. As such the hydrochemical information presented should form a sound basis for future hydrogeological studies in the Peace River Arch area.

INTRODUCTION

The Alberta Research Council and the Institute of Sedimentary and Petroleum Geology (Geological Survey of Canada) agreed to undertake a cooperative evaluation of the Peace River Arch area of Alberta and British Columbia with specific emphasis on the petroleum potential. Part of this study was an overview of the regional subsurface hydrogeology, of which the hydrochemistry is an integral entity, and which is the subject of this report.

The Peace River Arch area (Fig. 1) is defined as 54°N to 58°N, and 114°W to the eastern limit of the disturbed belt. With respect to the Dominion Land Survey this is approximately Tp 58 to Tp 103, and the 5th Mer (114°W) to the eastern limit of the disturbed belt. Formation waters from wells drilled in the disturbed belt were entered into the data base but are not evaluated in this report. The study area is ~200,000 km^2 and the subsurface hydrogeological evaluation is therefore at a basin-scale. *Specific details in local areas should only be sought after reevaluation of the hydrochemical data base at a local scale.*

This report comprises two parts. The first, and shorter, part is essentially a description of the hydrochemical data base held in electronic form at the Alberta Research Council, and of the specific data processing methods used in this study. The second part is a descriptive and illustrated evaluation of the hydrochemistry of the major aquifers in the study area, noting the most important geochemical features. Where pertinent, attention is drawn to other literature on the hydrochemistry or hydrodynamics of the specific aquifer, and to economic aspects such as potentially recoverable minerals.

ELECTRONIC DATA BASE

About 22,000 wells have been drilled in the Peace River Arch study area, data from which form the basis of the regional stratigraphy for this report. The hydrogeological data base comprises ~480,000 core analyses, ~42,000 bottomhole temperatures, >46,000 drillstem tests, and 30,404 formation water analyses. The formation water analyses were obtained from the files of the Alberta Energy Resources Conservation Board (ERCB) and the British Columbia Ministry of Energy, Mines and Petroleum and represent effectively all non-confidential data to the end of 1989.

The analytical and ancillary data were entered into the Alberta Geological

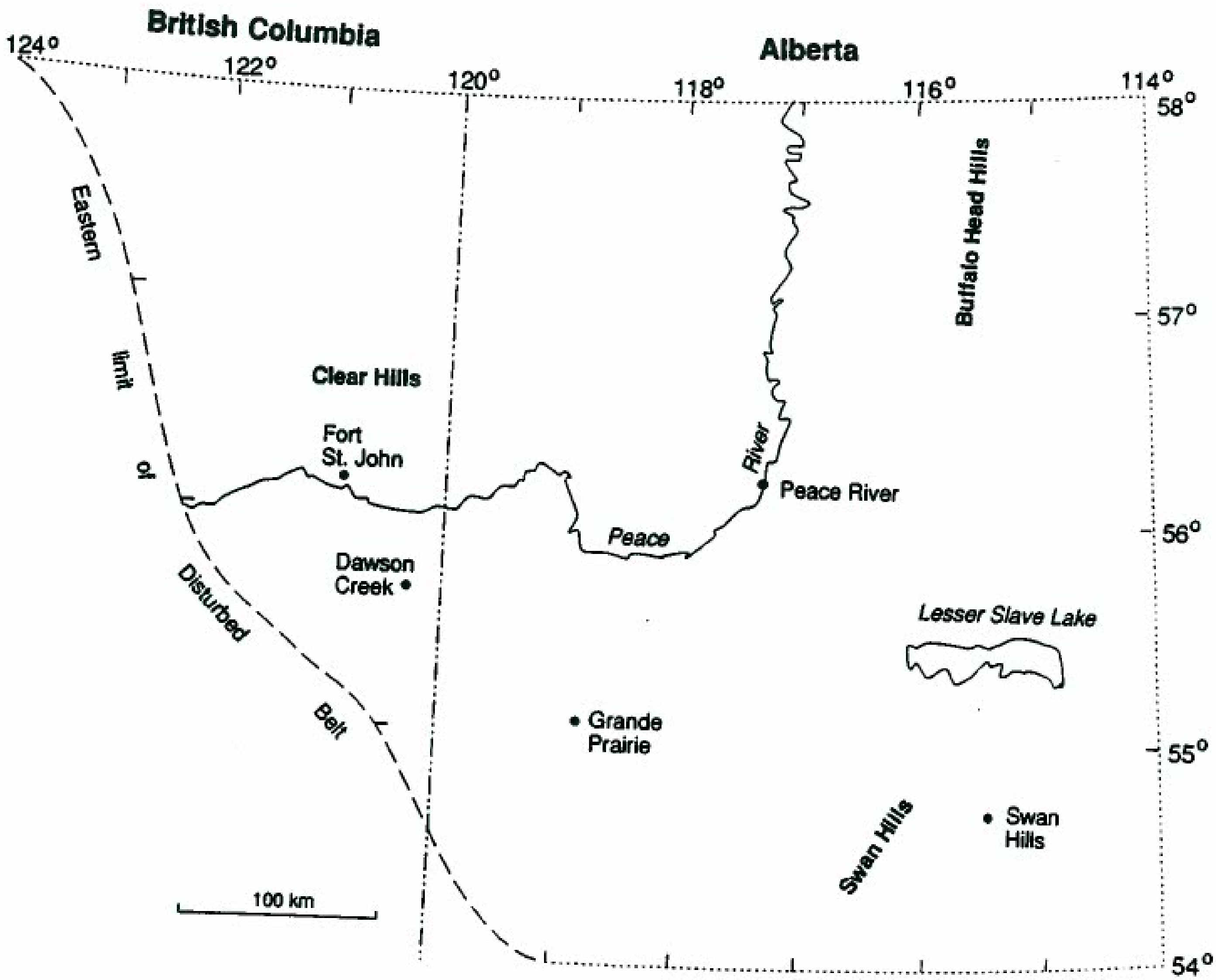

Figure 1. Peace River Arch study area showing the main geographical features.

Survey Well Data Base (AGSWDB), and verified. Data include a unique well site identifier, and electronic links to a pertinent drillstem test, if appropriate. Table 1 shows a typical water analysis report as entered into AGSWDB; not all analytical and ancillary data entered are included in this standard report form. Calculated values include percent milli-equivalents, milli-equivalents per litre, Na (by difference) and total dissolved solids. For more details on the data base see Bachu *et al.* (1987), Hitchon *et al.* (1987), and Bachu *et al.* (1990).

Following data entry and verification, the analyses were first subjected to electronic culling, then assigned to stratigraphic units. Following this they were processed by a mixture of electronic and manual culling before production of final maps, tables and other illustrative material.

For the Alberta portion of the study area, it is important to note that the regional grid used to generate the stratigraphic surfaces, between which the formation waters were interpolated, used the full suite of ERCB stratigraphic data for only five key surfaces (Ground, Nordegg-pre-Cretaceous, Debolt-pre-Cretaceous, Wabamun-pre-Cretaceous and Precambrian). All other surfaces in Alberta and all surfaces in British Columbia were generated from a grid of selected wells at a spacing of one-per-township, with stratigraphic information compiled by geologists at the Alberta Research Council. As a result, the surfaces for Alberta (other than the five key surfaces) are not as precise as if all available data had been used. For British Columbia, stratigraphic information is not in electronic form and so the grid of wells at a spacing of one-per-township is as accurate as time allowed, bearing in mind the basin-wide scale of the study. This situation is brought to the attention of the reader because, for thin aquifers particularly, formation waters are sometimes missassigned. Hence it was felt prudent to report hydrochemical trends only in general terms and to caution, in the Introduction, that local-scale trends should be based on a reevaluation of the data base.

DATA PROCESSING

Electronic culling

The objective of electronic culling is to remove, using computers, all analyses which show clear evidence of contamination, are mixed samples, or are incomplete in some way. This is done immediately after the data are entered and verified, and

Table 1. Typical formation water analysis from the AGWSDB.

AGSWDB WATER ANALYSIS REPORT

AGSWDB Well site identifier (SITID): 95610 Chemistry number: 1
AGSWDB Hard copy number (HRDCPNO): 26274

CHEMICAL & GEOLOGICAL LAB LTD Lab. Sample ID. E11139-2

Well identifier	Well name	KB elev.	Gr. elev
0625082010000	MOBIL OIL GOOSE CREEK 10-20-62-8	776.60	773.00

Interval Sampled from: 2450.59 to: 2463.39 meters KB

Formation Sampled: CAMBRIAN

Sample produced by: DST # 4 Sampling point:BOTTOM DP
DST Recovery
1445.10 M SALT WATER

CATIONS

ION	mg/l	%MEQ	MEQ/L
Ca	36810.	25.001	1836.8
Mg	6448.	7.222	530.6

ANIONS

ION	mg/l	%MEQ	MEQ/L
Cl	176220.	67.655	4970.5
HCO3	75.	0.017	1.2
SO4	372.	0.105	7.7

Hydrogen Sulfide Description:
Organics Description :
Calculated sodium: 60067.
TDS by Evapor. @ 110 C: 318260.
Calculated TDS : 279954.
TDS at Ignition : 279720.

Remarks:

PRIM SALI 52.46; SEC SALI 47.50; SEC ALK .04; CL SALI 99.86; SO4 SALI .14

before any other processing. Table 2 lists the automatic culling criteria and their possible causes; note that this type of culling has been developed (Hitchon, 1990) for use with large data bases of 'standard' formation water analyses and is not necessarily applicable to properly collected and preserved formation water samples. For the Peace River Arch study area 9333 analyses (30.7%) failed to pass the electronic culling, leaving slightly less than 70% for further study. This compares to 65% remaining from a smaller data base (3650 analyses) studied in the Cold Lake area of Alberta (Hitchon *et al.*, 1987). As noted by Hitchon (1990), the criteria listed in Table 2 fail to remove analyses contaminated by water injection, water cushion, mud filtrate or KCl muds; these have to be removed by a mix of manual and electronic culling.

Manual-electronic culling

Following electronic culling the remaining 21,071 analyses were assigned to one of 59 stratigraphic units; the data were subsequently combined into the stratigraphic units reported here. Even the number of remaining analyses is an order of magnitude greater than that processed in the Cold Lake study area (Hitchon *et al.*, 1989a) and so the manual-electronic culling described by Hitchon (1984b), Bachu *et al.* (1987) and Hitchon *et al.* (1987) had to be modified.

The distribution of analyses reported CO_3 was effectively random in most stratigraphic units. These samples were commonly contaminated with water cushion or mud filtrate, and as expected often showed high SO_4 or low Cl, or both, compared to adjacent analyses. In addition to the presence of CO_3, criteria for specific upper limits for SO_4 and lower limits for Cl were set for each stratigraphic unit (Table 3); analyses exceeding these limits were electronically culled. The culling criteria have to be specific for each stratigraphic unit and for the Peace River Arch study area, and depend on both the general salinity of formation waters in that unit as well as on the regional distribution of both the unit and the data points. For example, highly saline formation waters in a restricted portion of the study area may have a high lower limit for Cl, whereas generally similar samples from the deep portion of a stratigraphic unit with wide areal distribution and much less saline waters in its shallower portion would have a much lower lower-limit for Cl. Higher upper limits for SO_4 were set for stratigraphic units containing anhydrite. As a result of this manual-electronic cull there remained 9626 analyses

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

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

Table 3. Manual-electronic culling criteria for formation waters, Peace River Arch study area.

Stratigraphic unit	Number after electronic culling	Criteria for manual-electronic culling: Presence of carbonate	Upper limit for SO_4 (mg/l)	Lower limit for Cl (mg/l)	Number after manual-electronic culling
Other Upper Cretaceous	475	CO_3	1000	1000	141
Wapiabi	82	↑	↑	↑	66
Chinook	18				9
Puskwaskau	29			↓	22
Badheart	27			1000	14
Muskiki	92			2500	52
Cardium	190		↓	↑	41
Kaskapau	94		1000		30
Doe Creek-top	130		2000		19
Doe Creek-base	25		↑		6
Dunvegan	341				122
Shaftsbury	190				114
Paddy	904				459
Harmon	257				105
Spirit River	1285			↓	656
Bluesky	2164			2500	1174
Gething/Cadomin	1283			5000	596
Fernie	572		↓	5000	224
Nordegg	1017		2000	10,000	534
Baldonnel	127		4000	10,000	43
Charlie Lake	1756		4000	25,000	560
Halfway	376		2000	10,000	80
Diaber	942		↑	10,000	381
Belloy	500			10,000	270
Taylor	196			15,000	80
Taylor zone	161		↓	15,000	49
Golata	174		2000	15,000	76
Debolt	1375		1000	5,000	595
Pekisko	121		1500	5,000	64
Banff	32		1500	5,000	11
Middle Banff	47		1250	5,000	16
Lower Banff	47		1250	25,000	17
Wabamun	741		1250	25,000	302
Graminia	71		1500	50,000	28
Blueridge 1	201		2000	10,000	111
Blueridge 2	9		1500	50,000	4
Nisku	145	↓	1500	5,000	91
Carbonate-shale	138	CO_3	1500	40,000	70
Ireton	292	Re-allocated to Leduc or Waterways			-
Grosmont	19	CO_3	4000	10,000	15
L. Ireton	2	↑	2000	10,000	-
Leduc	321		1500	75,000	198
Cooking Lake	27		2000	25,000	16
Waterways	524		↑	50,000	247
Basal carbonate	1190			25,000	643
Fort Vermilion-top	24			50,000	10
Fort Vermilion-base	144			50,000	75
Watt Mountain	24			50,000	17
Gilwood	308			50,000	209
Muskeg	288		↓	50,000	137
Keg River	404		2000	100,000	270
Chinchaga/Contact Rapids	38	↓	4000	50,000	28
Granite Wash	1018	CO_3	2000	50,000	489
Red Beds 1	-				-
Ernestina Lake	-				-
Lotsberg	-				-
Red Beds 2	1	Moved to adjacent unit			-
Cambrian	46	CO_3	2000	75,000	33
Basal Cambrian sandstone	17	CO_3	2000	100,000	7
Disturbed belt	50	Examined individually			-
	21,071				9,626

(31.7% of the original data base) for purely manual processing (together with 50 analyses from the disturbed belt which passed the electronic culling).

Manual culling

This involves examination of individual Cl-distribution maps, cumulative frequency plots of Cl, and tabulated data, and the identification of anomalous analyses. Commonly, it is combinations of items which identify anomalous samples; for example, high Cl and Ca with low pH indicating acid-wash contamination. These are sets of criteria for which it is very difficult to set limits which could be used for electronic culling. The final data set on which the second part of this report is based comprised 6786 analyses, or 22.3% of analyses in the original data set. Figure 2 shows the distribution of the data base of 21,071 formation water analyses which passed the electronic culling. Distribution of the final data set is shown in Fig. 3. Clearly, even though only 22.3% of the original data base remains after the electronic and manual culling, the processing has not affected the general distribution of reliable formation water analyses.

REGIONAL HYDROCHEMISTRY

Introduction

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

Precambrian basement

As noted by Hitchon *et al.* (1989b) in a study of the Swan Hills area, the Precambrian basement is assumed to be an aquiclude, and therefore a zero-flow boundary. Although recent studies have demonstrated the presence of saline formation waters (some >250,000 mg/l at depths >1 km in the exposed Canadian Shield), no work has been done in western Canada which would indicate similar saline formation waters, even at shallower depths, in the covered Precambrian.

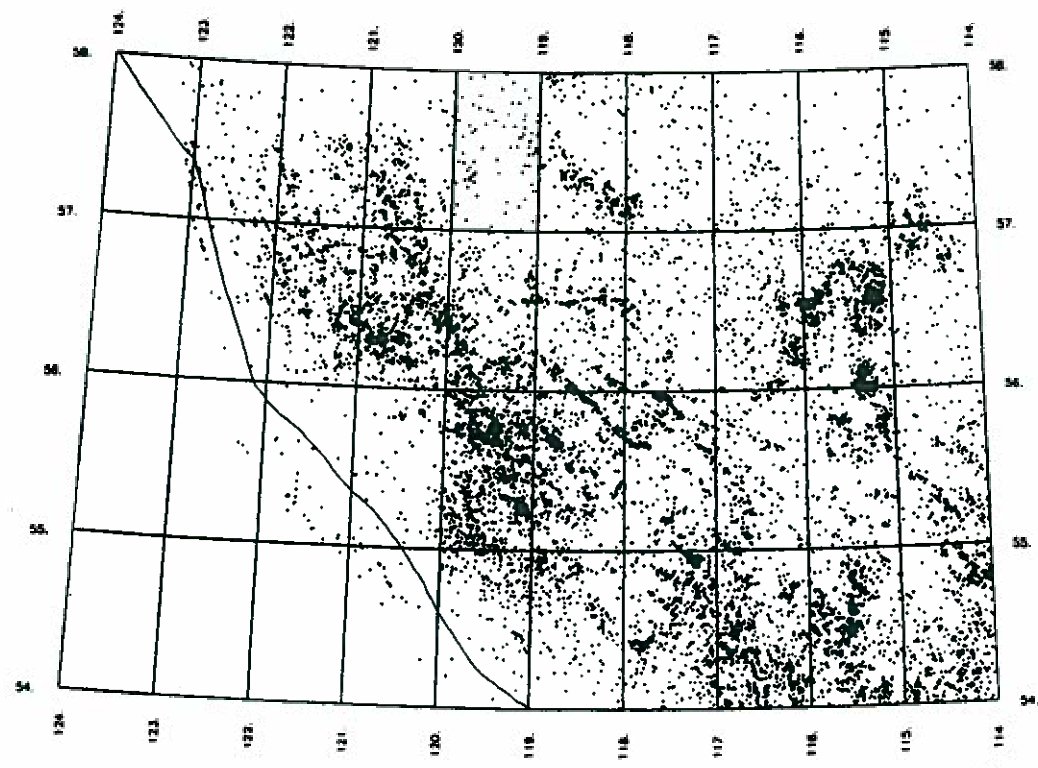

Figure 2. Distribution of the data base of 21,071 formation water analyses which passed the electronic culling, Peace River Arch study area.

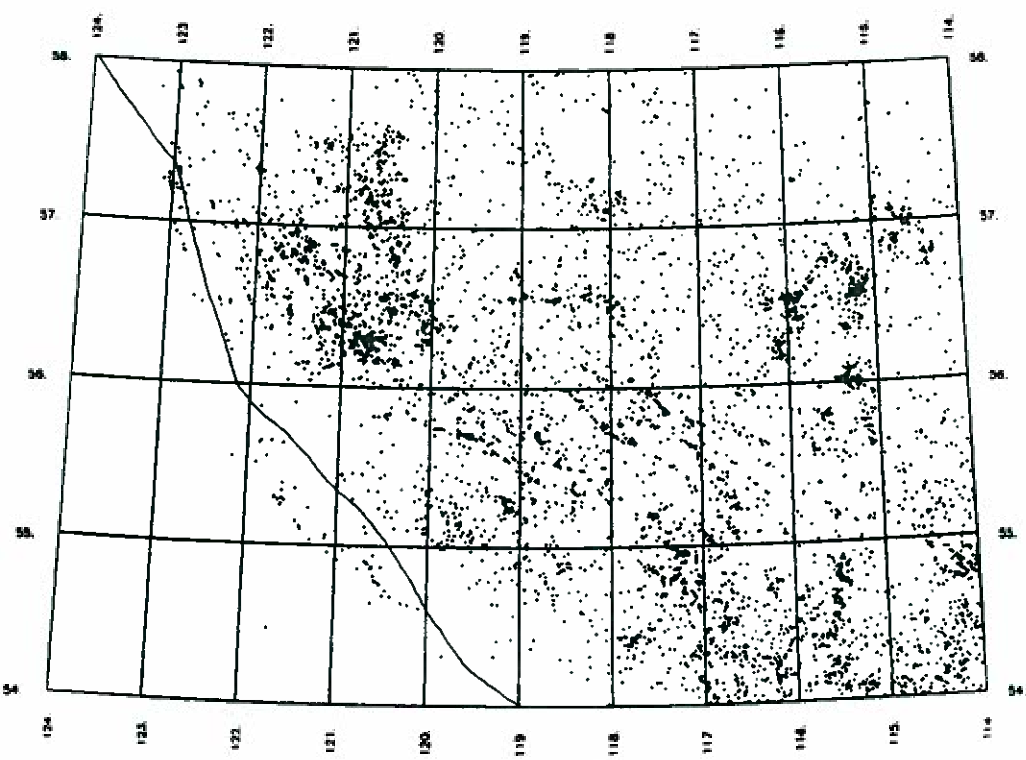

Figure 3. Distribution of the final data set of 6786 formation water analyses, Peace River Arch study area, on which this report is based.

Figure 4 shows the distribution of stratigraphic units immediately overlying the Precambrian basement, together with a generalized indication of salinity.

Cambrian

Middle and Upper Cambrian strata are confined to the southeast corner of the study area, where they range in thickness from zero at the northern erosion edge to >400 m. The final data base contained too few analyses from the Basal Cambrian sandstone for computer plotting so all Cambrian data were combined. This resulted in rather irregular composition distribution maps because, as noted by Hitchon *et al.* (1989b) for the Swan Hills area "as a broad generalization and at any location, salinity and chloride increase with depth in Cambrian aquifers and also increase in the direction of flow and toward the northeast where Cambrian rocks are overlain by Lower Devonian Lower Elk Point Group halite...". Despite this there are some broad regional compositional trends (Fig. 5). The most saline formation waters (>280,000 mg/l) are found where the Cambrian is overlain by the Lower Devonian Lotsberg salt. Where anhydrite of the Middle Devonian Muskeg Formation overlies the Cambrian the salinity is intermediate (200,000-260,000 mg/l). The lowest salinity (<200,000 mg/l) is found where the overlying evaporites are absent and the Cambrian strata are thickest. Again, quoting Hitchon *et al.* (1989b), there is "hydraulic connection between Cambrian aquifers and both the overlying Muskeg Formation anhydrites and the various evaporitic phases of the Lower Elk Point Subgroup...". Chloride, Ca and Mg exhibit generally similar compositional trends to salinity. Both SO_4 and HCO_3 are highly variable in their distribution, without obvious trends; however, the highest SO_4 contents (>400 mg/l) occur in the western part, and not beneath the Muskeg Formation anhydrite.

Granite Wash

This unit extends throughout much of the central part of the study area (Fig. 6), although it is absent where Beaverhill Lake, Leduc and Ireton strata lie directly on Precambrian basement (Fig. 4). In part, it lies directly on Cambrian rocks, and in part is overlain by Chinchaga-Contact Rapids, Keg River and Muskeg strata as these units onlap the ancient Peace River landmass. In the Swan Hills area (Hitchon *et al.*, 1989b) the Upper Cambrian Lynx aquifer, the Granite Wash

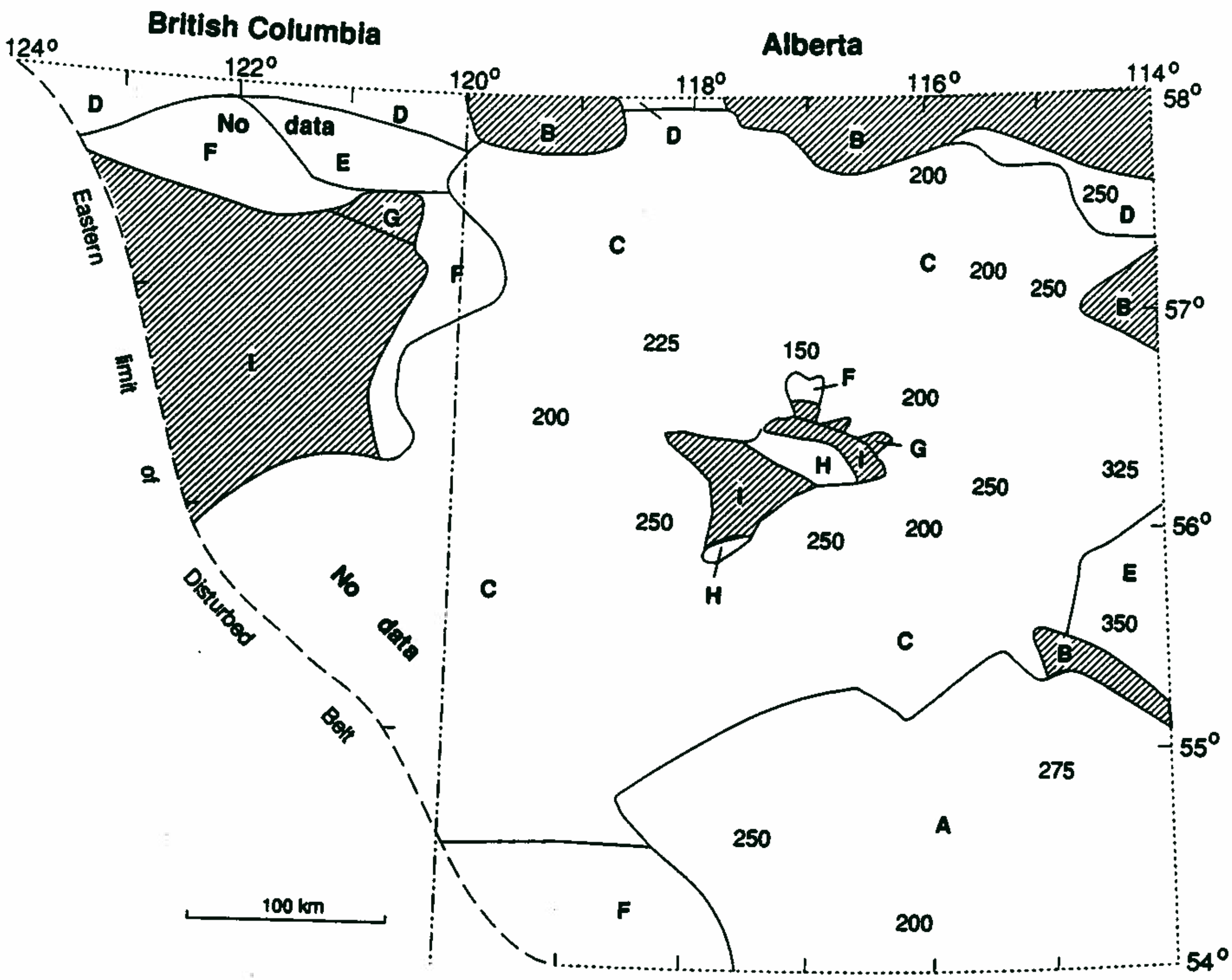

Figure 4. Stratigraphic units immediately overlying the Precambrian basement. A. Cambrian; B. Red Beds 1 and 2; C. Granite Wash; D. Chinchaga-Contact Rapids; E. Keg River; F. Basal Carbonate unit; G. Waterways unit; H. Leduc; I. Ireton. Numbers refer to salinity (mg/lx10^3). Hatched areas effectively aquitards.

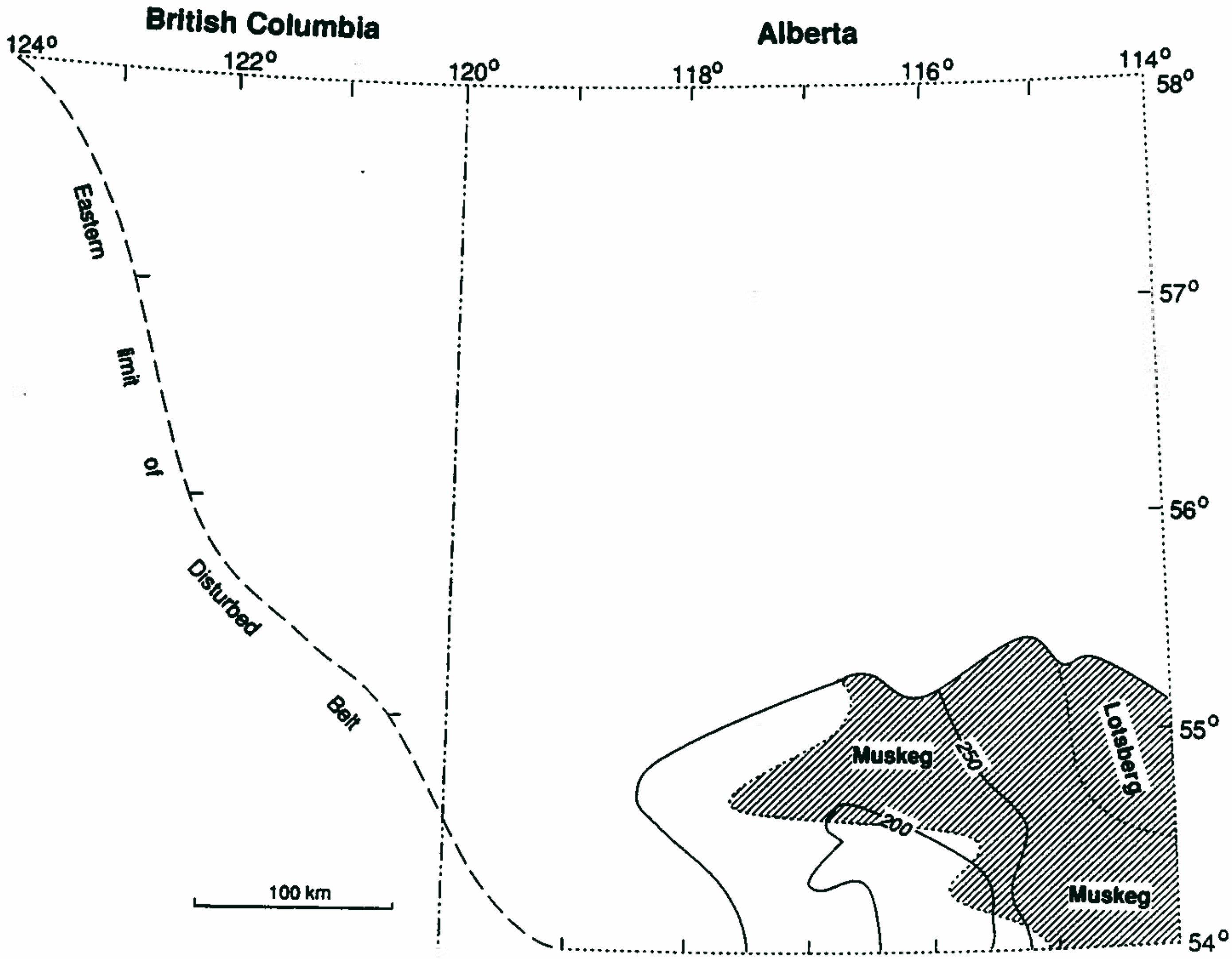

Figure 5. Salinity distribution (mg/lx10^3) in Cambrian strata. Area overlain by Lower and Middle Devonian evaporites is hatched.

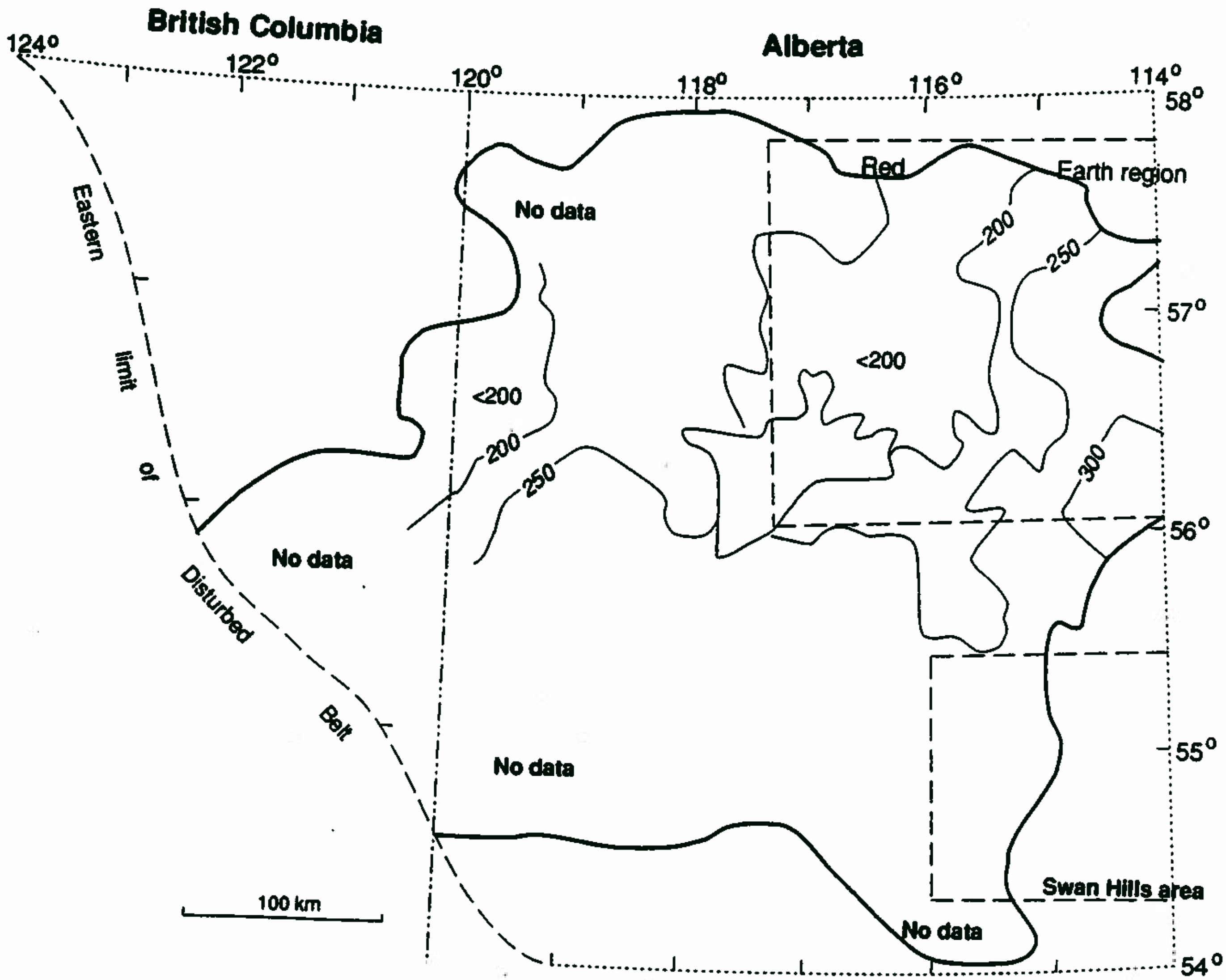

Figure 6. Salinity distribution (mg/lx10³) in the Granite Wash aquifer. The Red Earth region (Toth, 1978) and the Swan Hills area (Hitchon *et al.*, 1989b) are indicated by dashed lines.

overlying the Cambrian (pre-Lower-Middle Devonian) and the Middle Devonian Contact Rapids and Keg River aquifers were designated the Cambro-Devonian aquifer system. In the Red Earth region, Toth (1978) combined the Granite Wash and Keg River aquifers with the Ernestina-Chinchaga aquitard to form the Devonian I hydrostratigraphic unit. Certainly, there are strong similarities in the hydrochemistry of these units, and likely they are part of the same hydrostratigraphic unit outside the Swan Hills area and Red Earth region. The Granite Wash in the Peace River Arch study area varies considerably in thickness, ranging from zero to ~120 m.

The salinity distribution (Fig. 6) in the eastern part of the study area reflects the presence of the overlying Middle Devonian evaporites, with the salinity reaching nearly 330,000 mg/l. Over most of the area south of the arch the salinity of formation waters is in the range 250,000 to 280,000 mg/l, while north of the arch is a region with salinity as low as 160,000 mg/l. There are comparable trends and ranges for Cl (100,000-205,000 mg/l), Ca (10,000-45,000 mg/l) and Mg (1000-10,000 mg/l). There is a general tendency for contents of SO_4 >1000 mg/l to occur only in the region north of the arch with salinity <200,000 mg/l. Bicarbonate shows no obvious regional trends.

Chinchaga-Contact Rapids

The Chinchaga-Contact Rapids aquifer (base of the Middle Devonian) forms part of the Cambro-Devonian aquifer system of Hitchon *et al.* (1989b) and the Devonian I hydrostratigraphic unit of Toth (1978). It occurs in two separate parts of the study area (Fig. 7). The smaller area in the southeast is underlain, in descending order, by Red Beds 1, Ernestina Lake Formation, Lotsberg Formation salt, and Red Beds 2; the western margin is depositional against the ancient Peace River landmass and the unit thickens to ~100 m in places. The larger area along the northern edge of the study area lies north of the ancient Peace River landmass, with a southern depositional boundary; thickness ranges up to ~40 m.

Salinity is generally >300,000 mg/l in the southern area, and ranges up to 335,000 mg/l. In the northern area the salinity decreases northward from ~300,000 mg/l to ~200,000 mg/l. There are no data in the western part of the study area. The close relation of highly saline formation waters and the Lotsberg Formation salt found for formation waters from the Cambrian is evident also in

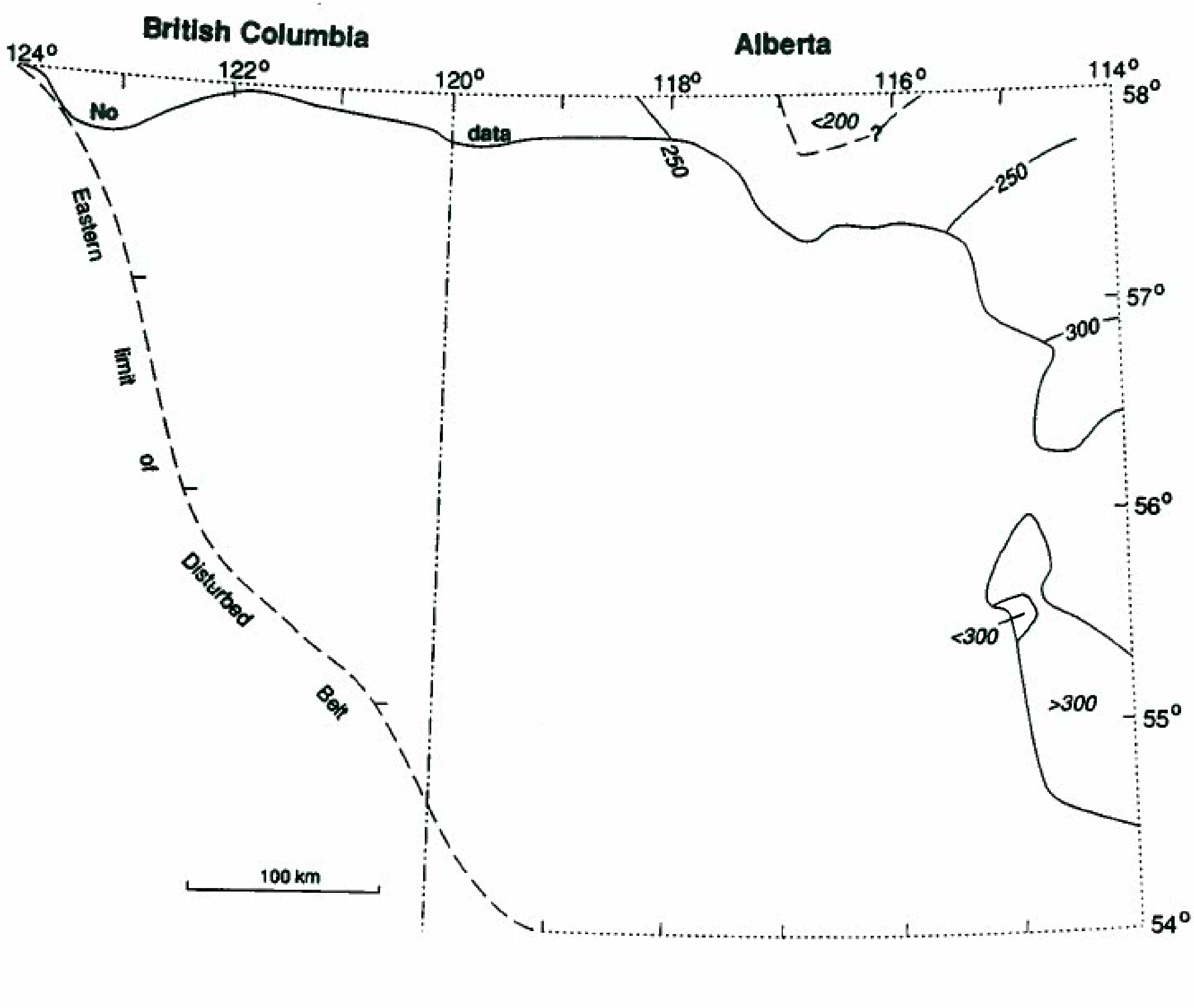

Figure 7. Salinity distribution (mg/lx10³) in the Chinchaga-Contact Rapids aquifer.

formation waters from the Chinchaga-Contact Rapids aquifer. Similar regional distribution trends to salinity occur with respect to Cl, Ca and Mg, with up to ~40,000 mg/l reported for Ca and >8000 mg/l reported for Mg. Neither SO_4 nor HCO_3 show obvious regional compositional trends.

Keg River

Deposition of the Keg River sediments represents continued onlap of the ancient Peace River landmass, and the unit overlaps the underlying Chinchaga-Contact Rapids Formation. The western and southern margins are depositional and thicknesses range up to ~100 m in places, although 40 m is an average thickness for the study area. Both Toth (1978) and Hitchon *et al.* (1989b) grouped the Keg River aquifer and the Chinchaga-Contact Rapids aquifer in the same hydrostratigraphic unit -- together with the Granite Wash aquifer (Devonian I and Cambro-Devonian aquifer system, respectively). Highly saline formation waters (ranging up to 380,000 mg/l) are found in the extreme northeast of the study area and along the eastern margin (Fig. 8). Elsewhere, the salinity decreases toward the depositional edge but is nowhere <170,000 mg/l. Chloride, Ca and Mg exhibit generally similar compositional distributions, with the 300,000 mg/l salinity contour corresponding generally to 200,000 mg/l Cl, 35,000 mg/l Ca and 5000 mg/l Mg. Hitchon and Holter (1971) report one analysis (see Fig. 8) with both Ca and Mg exceeding the minimum detailed exploration limits as defined by Hitchon (1984c). As a general rule, SO_4 is <400 mg/l in the regions with salinity >300,000 mg/l; elsewhere, it ranges up to 2000 mg/l (the upper limit for manual-electronic culling). Bicarbonate exhibits no obvious regional trends.

Muskeg

In his study of the Red Earth region, which extended east of the limits of the Peace River Arch study area, Toth (1978) grouped the Middle Devonian Muskeg Formation and Prairie Formation evaporites into a single regional aquitard, while recognizing that there was local effective porosity in the associated shaley carbonates. In the Swan Hills area, Hitchon *et al.* (1989b) found the Muskeg Formation to be a leaky aquitard, based on pressure head-depth plots and numerical simulations (calculated 2.0×10^{-8} m/d vertical hydraulic conductivity). The Muskeg Formation overlaps the Keg River Formation; the southern and

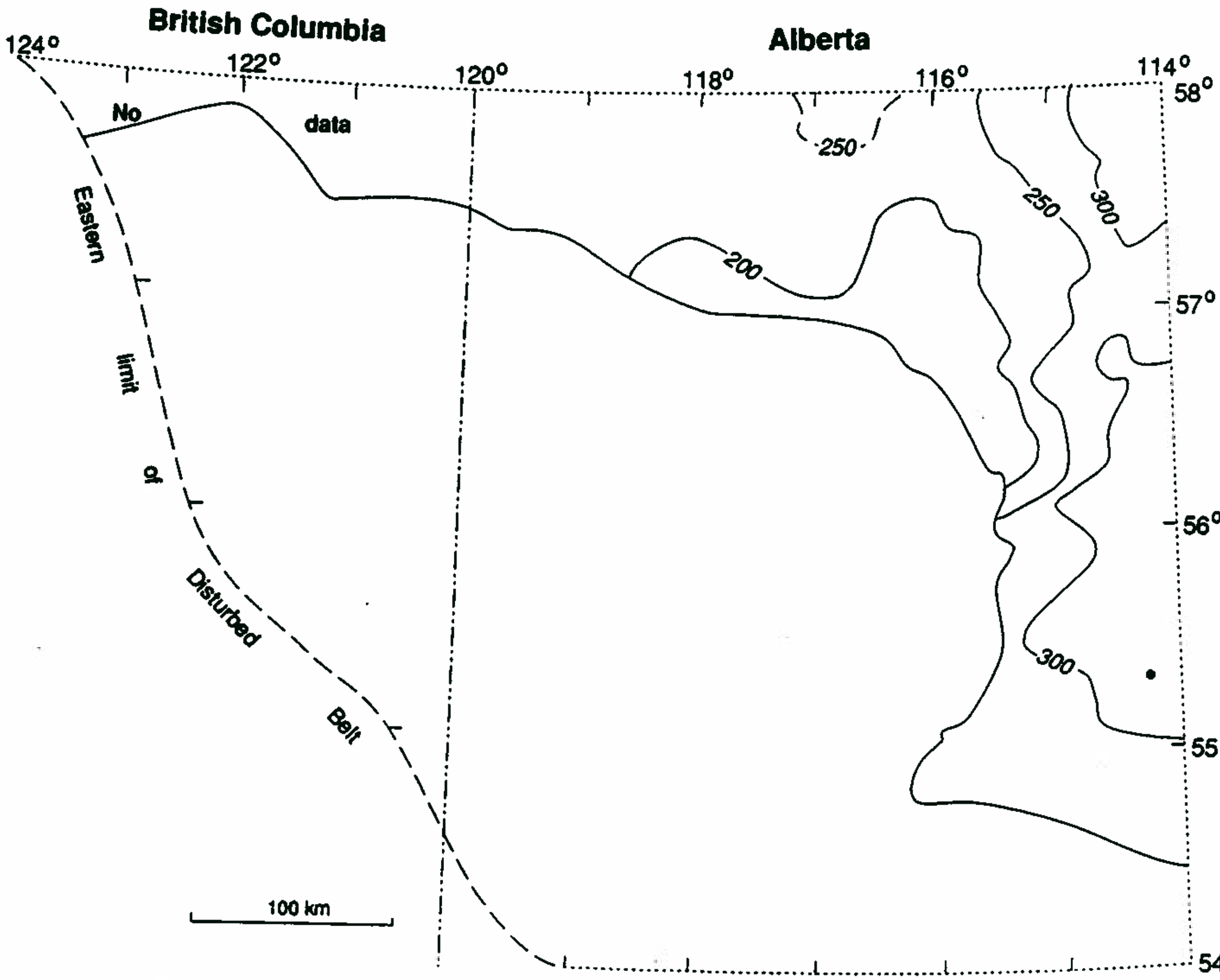

Figure 8. Salinity distribution (mg/l$\times10^3$) in the Keg River aquifer. Solid dot: formation water with both Ca (99,324 mg/l) and Mg (11,865 mg/l) exceeding the minimum detailed exploration limits, as defined by Hitchon (1984c).

western margins are depositional, and the unit is nearly 370 m thick in places along the eastern edge of the study area and >300 m thick in the extreme northeast corner and patchily in the north-central part of the study area. The pattern of salinity distribution (Fig. 9) mirrors that in the underlying Keg River aquifer (Fig. 8), with salinity >300,000 mg/l along the extreme eastern margin of the study area and no salinity <160,000 mg/l. Chloride contents corresponding to the 200,000 mg/l and 250,000 mg/l salinity contours are 120,000 mg/l and 160,000 mg/l, respectively. The composition distribution patterns for Ca and Mg follow those of salinity and Cl only in a very general way, but highest contents of both components occur irregularly distributed in the east-central part of the area, as opposed to being directly associated with salinity >300,000 mg/l. Neither SO_4 nor HCO_3 exhibit any obvious trends.

Gilwood

Sandstones of the Gilwood Member are part of a delta system that drained southward off the ancient Peace River landmass and flowed into a shallow basin of prodelta muds (Watt Mountain Formation). Figure 10 shows both the western depositional margin against the ancient Peace River landmass and the eastern seaward limit of the delta. The Gilwood Member ranges up to ~50 m thick, but averages only 15 m in the study area. In the Red Earth region Toth (1978) combined the Watt Mountain Formation and overlying Slave Point Formation carbonates into a single aquifer (DII), thereby distinguishing the Slave Point aquifer from the overlying Beaverhill Lake (plus Ireton) aquitard (D_B). In contrast, in the Swan Hills area, the Beaverhill Lake Group comprises thick, extensive reefs (Swan Hills Formation). As a result, Hitchon *et al.* (1989b), using pressure head-depth plots and hydraulic-head profiles, were able to show that the Watt Mountain Formation, and the Beaverhill Lake Group and overlying Cooking Lake Formation carbonates could be considered as a single hydrostratigraphic unit (Beaverhill Lake aquifer system) -- within which is the thin (~10 m) Fort Vermilion aquiclude.

In the southern part of the Gilwood area formation water salinity is generally >200,000 mg/l, with salinity >250,000 mg/l adjacent to the depositional margin and at the eastern margin. This distribution is a subdued reflection of that in the underlying Muskeg aquitard (Fig. 9). Regions with salinity >250,000 mg/l have,

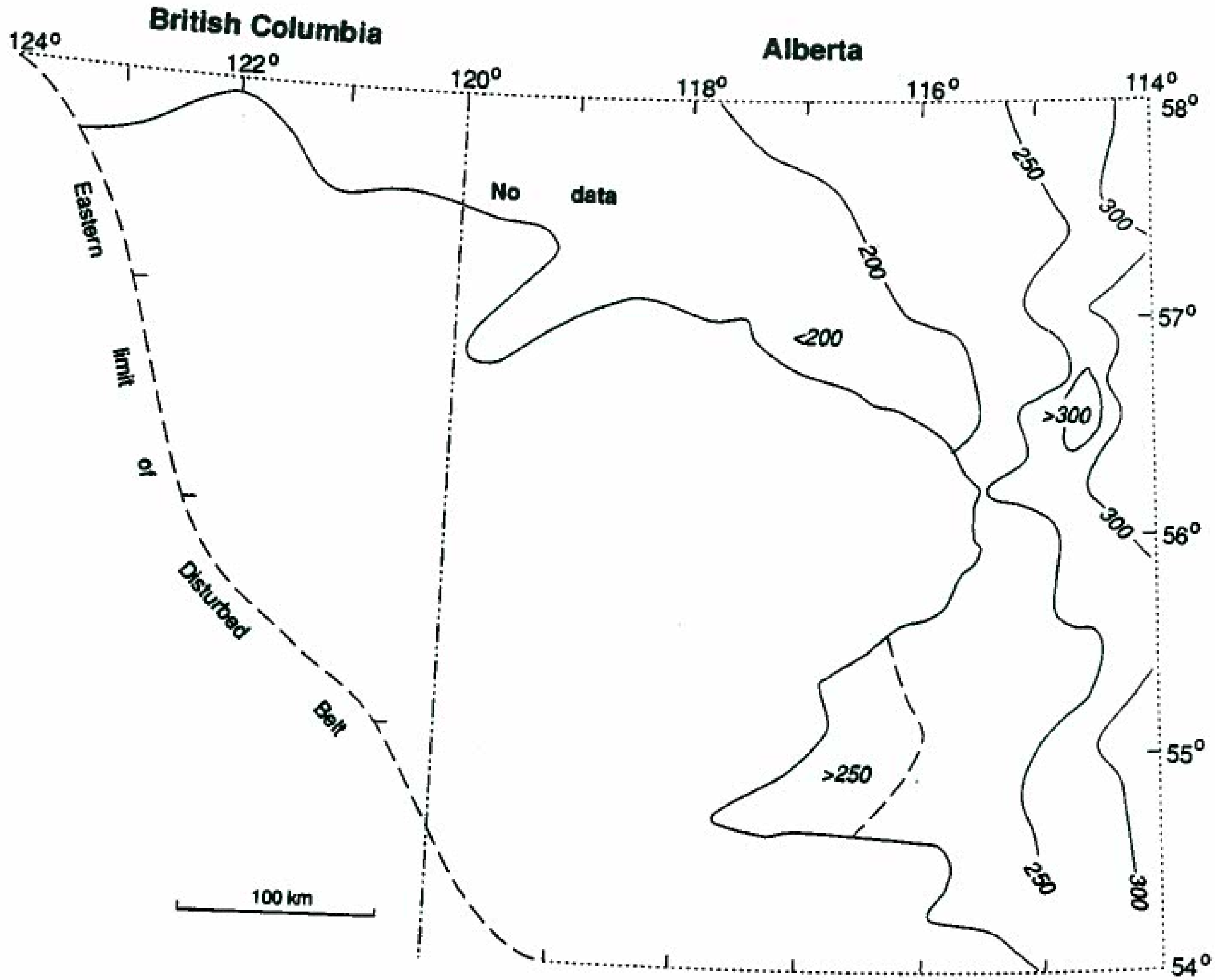

Figure 9. Salinity distribution (mg/lx10³) in the Muskeg aquitard.

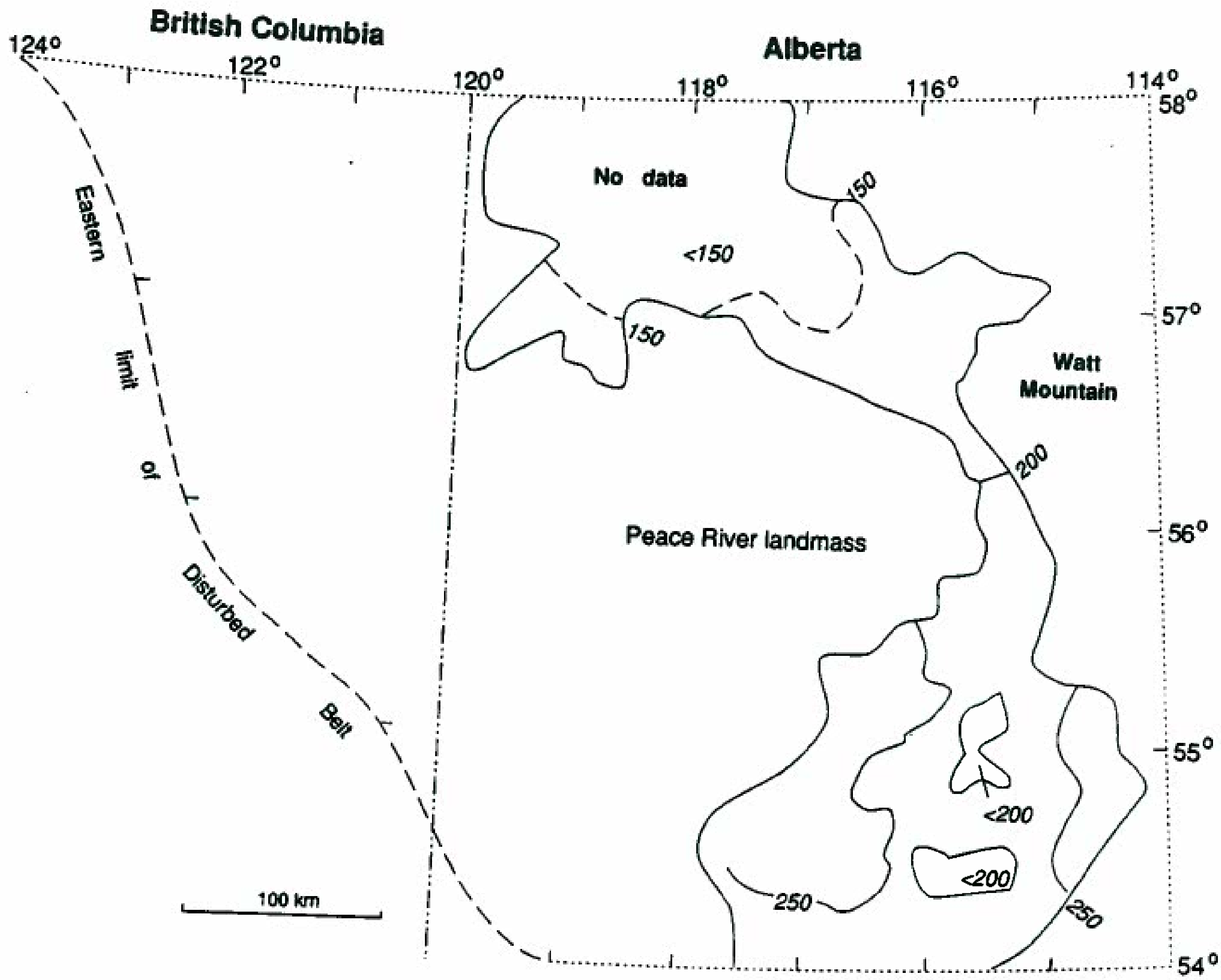

Figure 10. Salinity distribution (mg/l x 10^3) in the Gilwood aquifer.

generally, Cl > 160,000 mg/l, Ca > 25,000 mg/l and Mg > 3000 mg/l. The region between, with salinity ~ 200,000 mg/l, has Cl ~120,000 mg/l, Ca < 20,000 mg/l and Mg < 2000 mg/l. Neither SO_4 nor HCO_3 show obvious regional trends, although SO_4 is commonly < 600 mg/l.

In the northern part of the Gilwood area salinity is < 200,000 mg/l, with minimum values ~ 110,000 mg/l. There are correspondingly lower contents of Cl, Ca and Mg, but SO_4 is seldom < 400 mg/l and ranges up to 1600 mg/l (the upper limit for manual-electronic culling was 2000 mg/l). As a broad generalization, decreasing salinity is accompanied by an increase in HCO_3 (~100 - 400 mg/l, respectively).

Fort Vermilion

Following Watt Mountain time a period of regression and stagnation resulted in the deposition of evaporites and muds (Fort Vermilion Formation) in shallow lagoons and embayments adjacent to the Gilwood delta complex. Alberta Research Council geologists who prepared the stratigraphic grid for the study area tentatively identified a porous unit near the base of the Fort Vermilion Formation and some formation waters were assigned to this unit in the interpolation process. Examination of the analysis sheets shows that most were originally assigned to the Gilwood sandstone or Morse River sandstone. Data are sparse from this unit, but the salinity trends (Fig. 11) generally resemble those in the underlying Gilwood aquifer (Fig. 10) and Muskeg aquitard (Fig. 9), inasmuch as high salinity (>300,000 mg/l) occurs to the east and west of the area with a region of lower salinity (250,000-300,000 mg/l) between, and even lower salinity (200,000-250,000 mg/l) to the north. The similarity of these patterns to those in the underlying units suggests that in the future these formation waters be reallocated to their original units. Note that the three analyses originally assigned to the Morse River sandstone had Ca and Mg concentrations greater than the minimum detailed exploration limits, as defined by Hitchon (1984c).

Basal Carbonate and Waterways

For the purposes of the Peace River Arch study, the equivalent of the Beaverhill Lake Group of central Alberta was divided into a lower Basal Carbonate unit and an upper Waterways unit. The Basal Carbonate unit is approximately

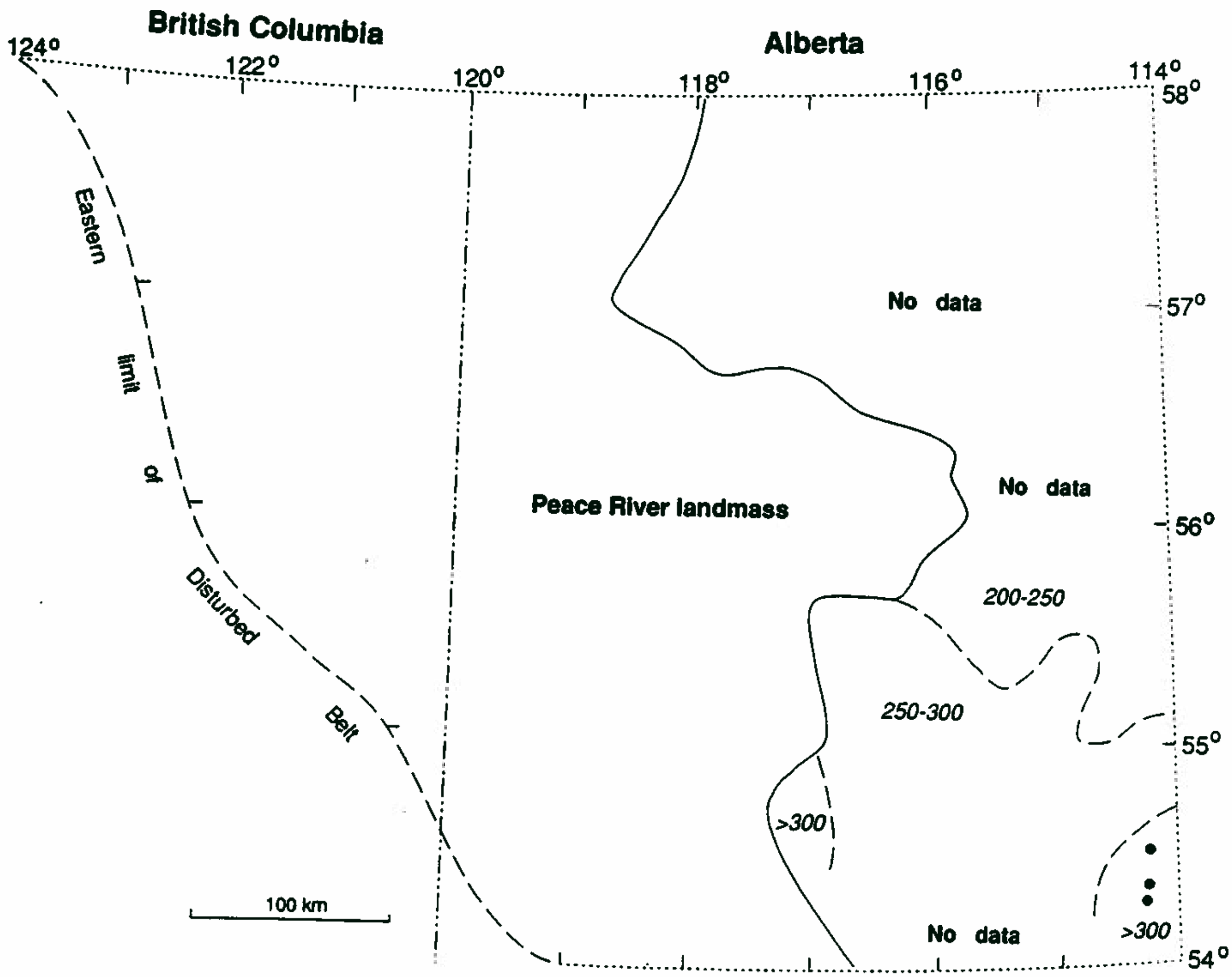

Figure 11. Salinity distribution (mg/lx10³) in the basal portion of the Fort Vermilion aquitard. Solid dots: formation waters originally assigned to the Morse River sandstone with both Ca (62,500-68,000 mg/l) and Mg (6600-12,000 mg/l) exceeding the minimum detailed exploration limits, as defined by Hitchon (1984c).

equivalent to the Slave Point Formation, and in the southeast part of the study area includes the basal carbonates and bank complexes of the reefal Swan Hills Formation. Because the Basal Carbonate unit is generally porous, formation waters have been recovered throughout much of the study area. The Waterways unit comprises mainly shales in the northern and eastern parts of the study area, carbonates close to the ancient Peace River landmass, and the upper portions of the Swan Hills Formation in the southeastern part of the study area. As a result, the distribution of formation water analyses is generally restricted to around the ancient Peace River landmass and in the region of the Swan Hills reefs. The relative distributions of the porous parts of the Basal Carbonate and Waterways units is reflected in the decision of Toth (1978), in the Red Earth region, to classify the "Beaverhill Lake" (Waterways unit in this study) as an aquitard, and to combine the Slave Point Formation and Watt Mountain Formation as aquifer D_{II}, whereas in the Swan Hills area Hitchon *et al.* (1989b) included the Watt Mountain Formation (mainly Gilwood sandstone), Beaverhill Lake Group (dominantly Swan Hills Formation) and Cooking Lake Formation in the Beaverhill Lake aquifer system. These different, but correct, methods of treating the same stratigraphic units point out the difficulty of long-distance correlation of hydrostratigraphic units when major lithological changes are evident.

Salinity distribution in the Basal Carbonate aquifer is shown in Fig. 12, and in the Waterways aquifer in Fig. 13. Maximum salinity (~250,000 mg/l) is found in both aquifers in a small area on the southeast flank of the ancient landmass. To the southeast, in the Swan Hills area, salinity in both units is in the general range 175,000 to 200,000 mg/l. North of the axis of the arch salinity is generally <200,000 mg/l and ranges down to ~100,000 mg/l along parts of the north-central and northeastern portions of the study area. For both aquifers the regional trends for Cl, and to a lesser extent Ca and Mg, tend to follow the salinity trends. Both SO_4 and HCO_3 show no obvious regional trends in either aquifer.

<u>Cooking Lake</u>

Few formation waters were assigned to the Cooking Lake Formation, as defined for the purposes of this study by Alberta Research Council geologists. All were originally classified as Leduc Formation samples and came from the basal portions of carbonate reefs. In future studies they should be included with the Leduc Formation.

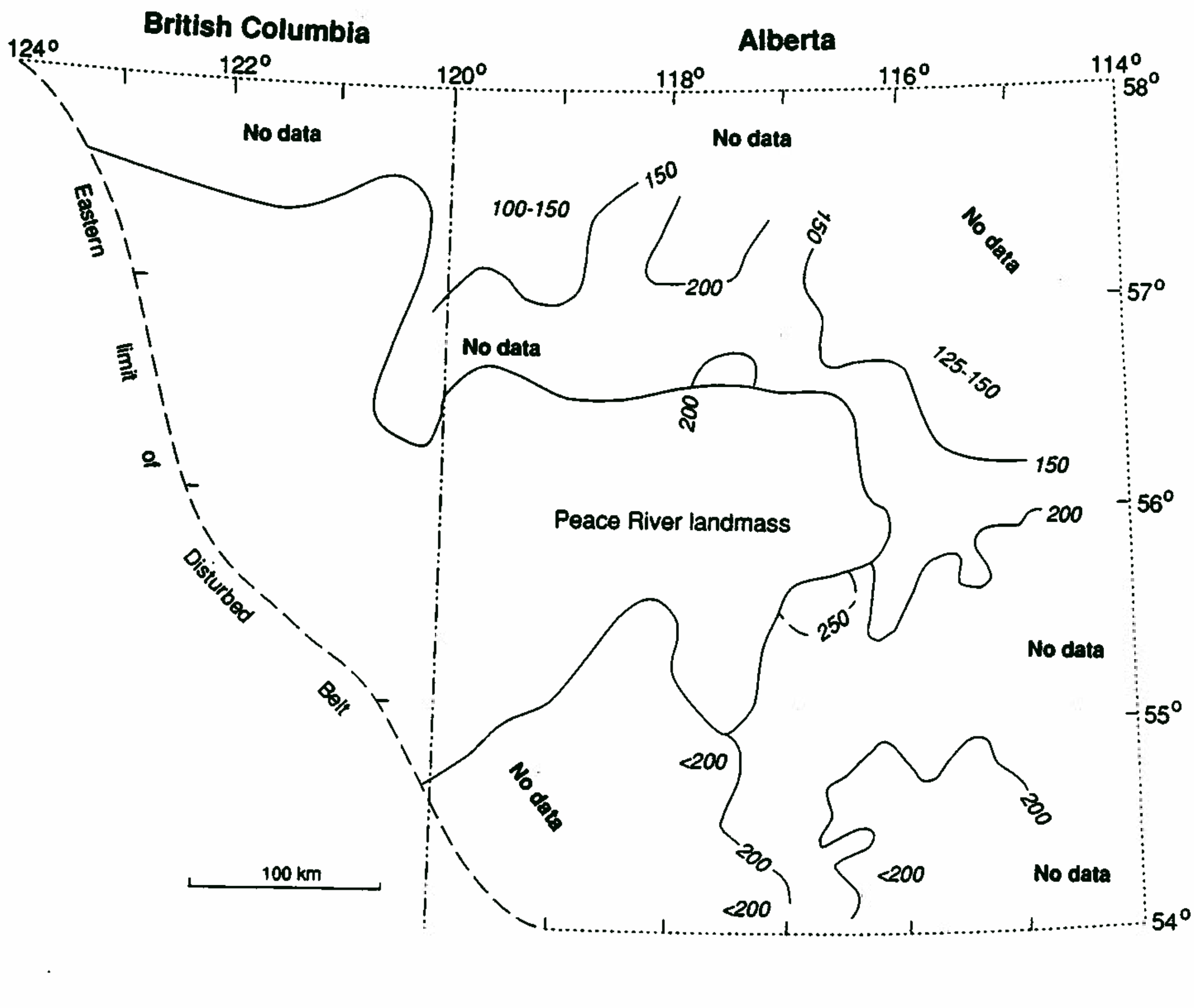

Figure 12. Salinity distribution (mg/lx10³) in the Basal Carbonate unit.

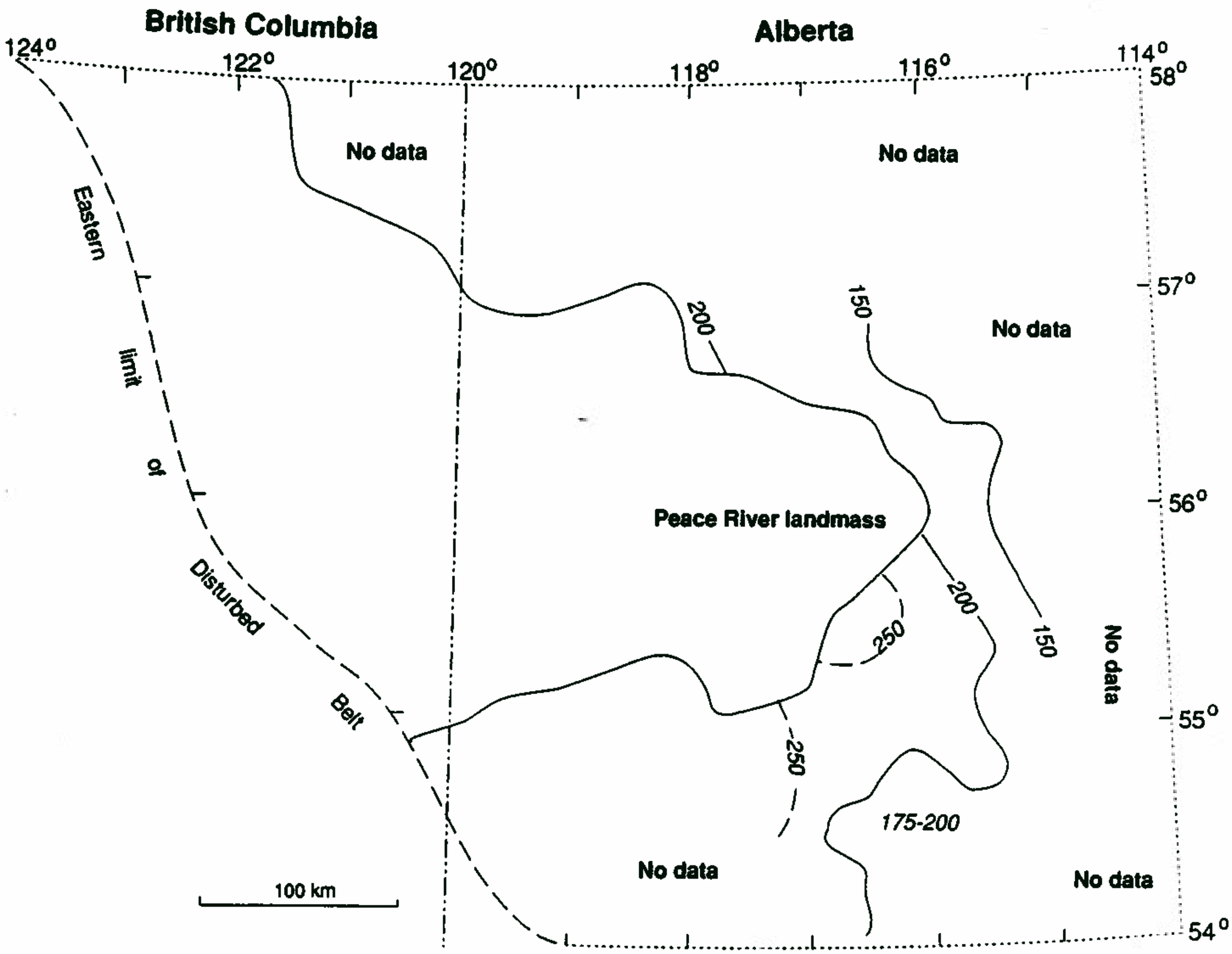

Figure 13. Salinity distribution (mg/l x 10^3) in the Waterways unit.

Leduc and Grosmont

Carbonate reefs, banks and shoals of the Leduc and Grosmont Formations (Fig. 14) were deposited at approximately the same time. The four separate carbonate complexes in the southwestern part of the study area (Sturgeon Lake, Windfall-Pine Creek, Simonette and Gold Creek) lie on Cooking Lake strata, as defined for the purposes of this study. The carbonates of the Peace River complex fringe the ancient Peace River landmass and lie directly on Granite Wash or Precambrian basement. In the study area the carbonates and minor anhydrite (Hondo Formation) of the Grosmont Formation are separated from the Waterways and Basal Carbonate aquifers by ~ 150 m of Lower Ireton Formation shales.

Pressure profiles for fluids in the Windfall-Pine Creek and the underlying Swan Hills carbonate complexes (Hitchon, 1984a), and for these complexes and the Peace River and Sturgeon Lake carbonate complexes (Hitchon, 1969), show that they are all part of the same hydraulic system. In the Swan Hills area, where Leduc carbonate reefs are absent, there is good hydraulic connection between the Swan Hills and Gilwood aquifers; both are part of the Beaverhill Lake aquifer system (Hitchon *et al.*, 1989b). It therefore seems likely that there is hydraulic connection between the four separate carbonate complexes and the Peace River fringing complex, through the underlying Cooking Lake aquifer to the Beaverhill Lake aquifer system. These same hydrodynamic studies (Hitchon, 1969, 1984a; Hitchon *et al.*, 1989b) show that (1) the Grosmont aquifer is hydraulically isolated from the other Leduc aquifers in the study area, (2) it is part of the low pressure Rimbey-Meadowbrook hydraulic system, and (3) the shales of the Ireton Formation effectively isolate the hydrogeological environment of the Beaverhill Lake aquifer system and its connected Leduc aquifers from overlying aquifer systems. Only in areas where the Upper Ireton Formation shales are thin and the unit is a leaky aquitard will the hydraulic isolation of the Leduc aquifers from overlying aquifer systems be breached.

The hydrochemistry reflects the relatively complex hydraulic system in the Leduc and Grosmont aquifers. Each reef complex seems to have its own hydrochemical character; in part, this is an artifact of exploration for petroleum and hence data distribution, but it is also a reflection of depth (and temperature), as the data below illustrates.

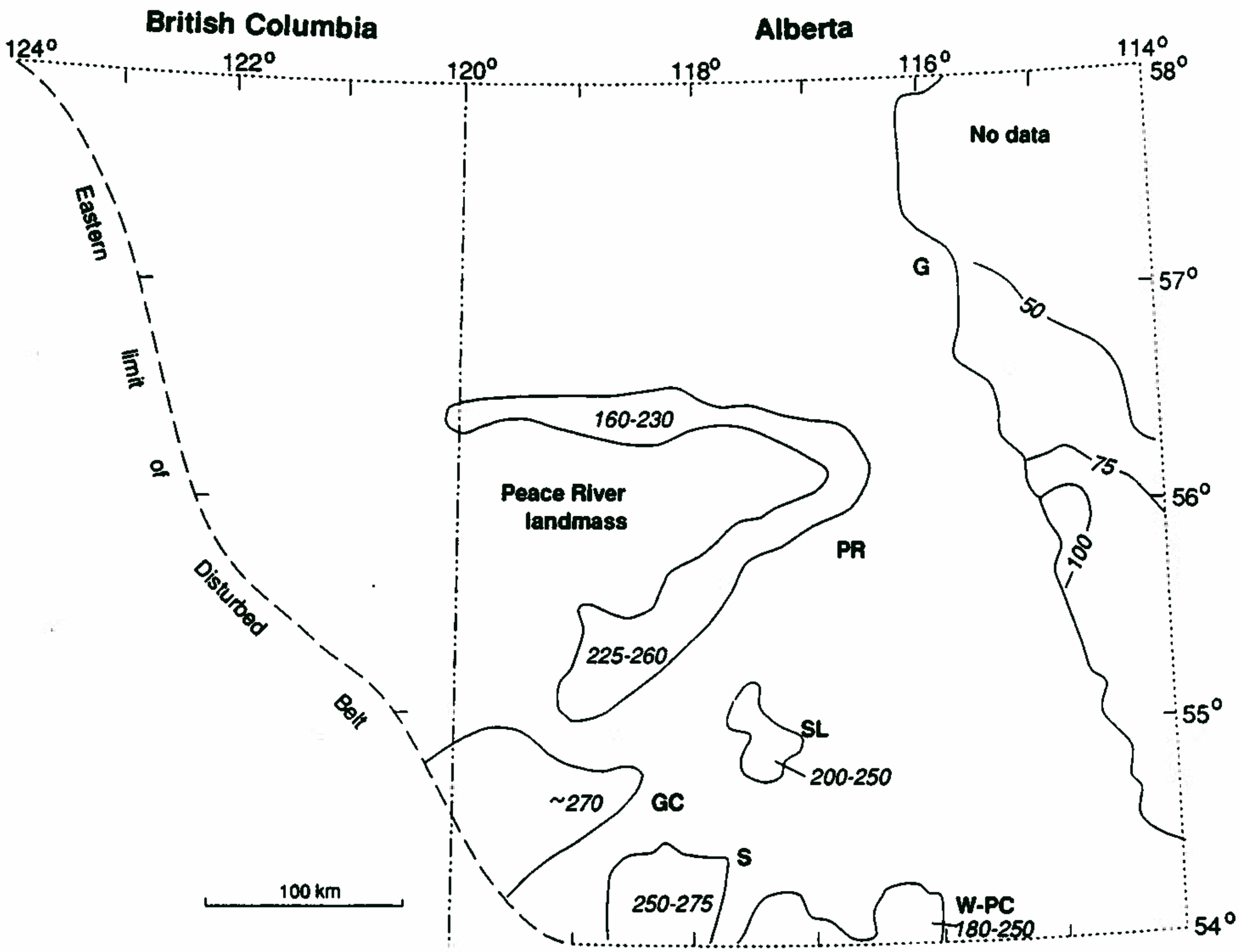

Figure 14. Salinity distribution (mg/lx10³) in the Leduc and Grosmont aquifers. Letters refer to the carbonate complexes; G = Grosmont; PR = Peace River; SL = Sturgeon Lake; GC = Gold Creek; S = Simonette; W-PC = Windfall-Pine Creek.

	Depth (m)	Salinity (mg/l x 10^3)
Grosmont	750 - 1200	40 - 125
Peace River - north	1700 - 2400	160 - 230
Peace River - south	1900 - 2800	225 - 260
Sturgeon Lake	2500 - 2800	200 - 250
Windfall - Pine Creek	2500 - 3800	180 - 250
Gold Creek	~ 3700	~ 270
Simonette	3500 - 3800	250 - 275

Figure 14 shows the salinity range for each carbonate complex. The distribution of data allows contouring only for the Grosmont aquifer.

Carbonate-shale

Shales of the Ireton Formation form the major aquitard in the study area (Toth, 1978; Hitchon *et al.*, 1989b). In the Swan Hills area the calculated vertical hydraulic conductivity is 0.2×10^{-8} m/d, the lowest in the system modelled (Hitchon *et al.*, 1989b). The youngest part of the Ireton Formation includes minor carbonate beds. These represent a transition between the underlying Ireton shale facies, which drowned out the Leduc-Grosmont carbonate complexes, and the carbonates of the overlying new depositional cycle (Winterburn Group). For the purpose of this study the Alberta Research Council geologists who described the stratigraphy termed this transitional succession the Carbonate-shale unit. It is found mainly in the eastern half of the study area (Fig. 15) and although generally thin (~50 m) it does range up to >250 m in isolated places.

Formation waters are confined mainly to the region south of the ancient Peace River landmass and have been variously designated as from the Leduc, Grosmont, Nisku or Ireton Formations on the analysis sheets, as might be anticipated for an arbitrary transition unit. Salinity ranges from ~ 275,000 mg/l on the southern flank of the ancient Peace River landmass to ~90,000 mg/l in the region around the southern margin of the underlying Grosmont aquifer. Comparable trends and ranges for other components are 60,000 to 160,000 mg/l Cl, 4000 to 25,000 mg/l Ca and 1000 to 5000 mg/l Mg. There are no obvious trends for SO_4 (upper limit set at 1500 mg/l), but the highest HCO_3 contents

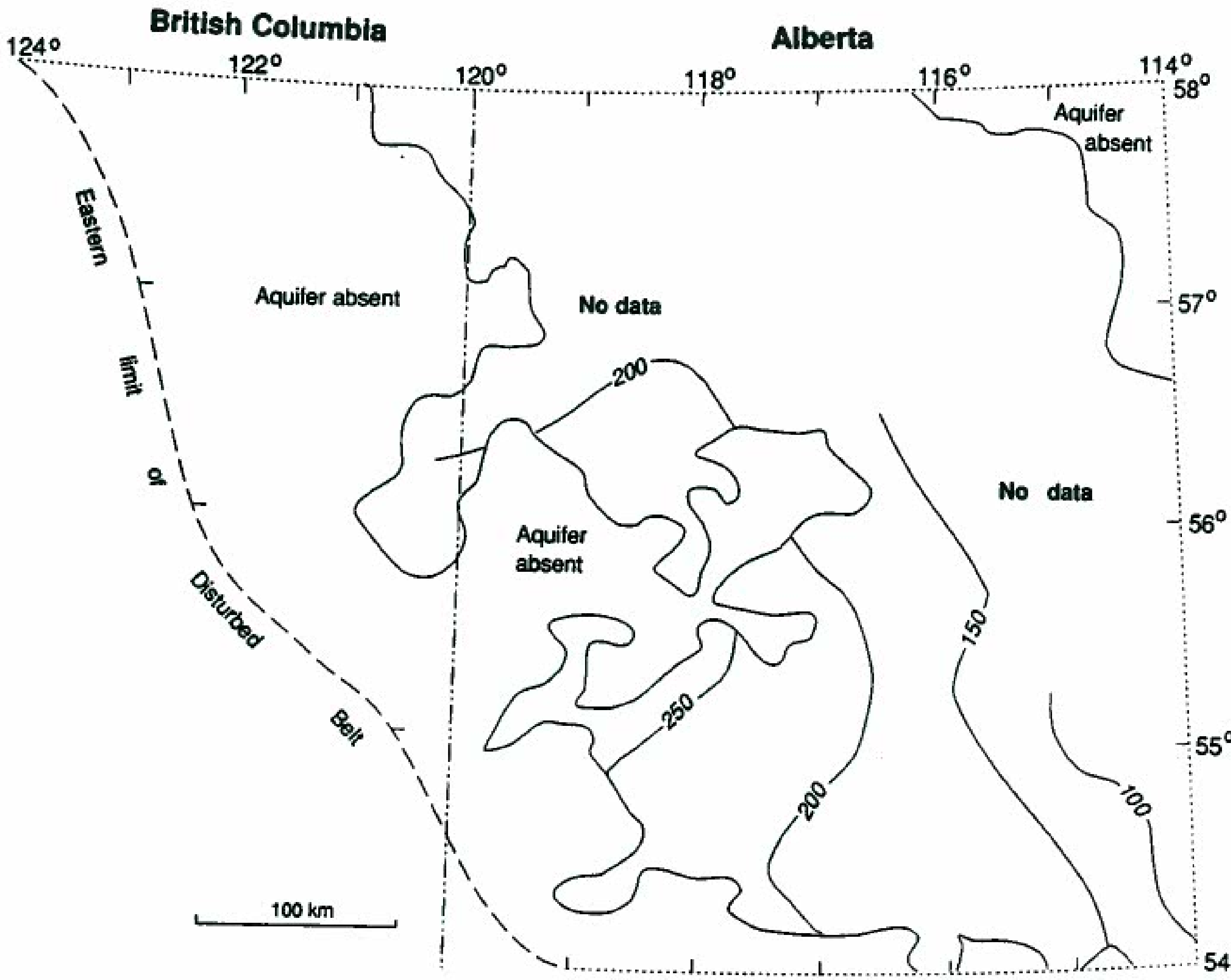

Figure 15. Salinity distribution (mg/lx10³) in the Carbonate-shale aquifer.

(1000-1500 mg/l) occur along the southern subcrop edge of the unit and decrease to ~100 mg/l to the north; generally, the isoconcentration contours for HCO_3 trend east-west, at right angles to the salinity contours.

Nisku, Blueridge and Graminia

In the Red Earth region Toth (1978) combined the entire succession between the top of the Ireton aquitard and the base of the Mississippian Exshaw Formation into the Devonian III hydrostratigraphic unit. As a unit this was the most continuous, extensive and thickest aquifer system in his study area. It comprised the Nisku and Calmar aquifers (marine clastics and dolomites) separated from the Upper Wabamun aquifer (arenaceous limestones and dolomites) by the Lower Wabamun aquitard (non-porous limestones). In the Swan Hills area, Hitchon *et al.* (1989b) combined the Winterburn Group (Nisku, Calmar and Graminia Formations) and the Wabamun Group into the Wabamun-Winterburn aquifer system. Hydraulic continuity within the aquifer system was confirmed by pressure head-depth plots, although it was recognized that only some zones have high diffusivities. Equally important was the observation of downward flow from the Wabamun-Winterburn aquifer system to the Grosmont aquifer, showing that the thin Upper Ireton aquitard is not an efficient hydraulic barrier in that area.

For the purpose of the study of the Peace River Arch area the Winterburn Group was separated into the Nisku Formation, the Blueridge Member of the Graminia Formation, and the equivalent of the upper silty unit of the Graminia Formation. Because of both the difficulties with the allocation process due to the low density of well coverage through using a well spacing of one-per-township, and the common designation of the formation water analyses as from the Winterburn or D-2 (as opposed to more precise stratigraphic identification), the three maps of salinity distribution in the Nisku (Fig. 16), Blueridge (Fig. 17) and Graminia (Fig. 18) aquifers must be considered in general terms only. The main features are similar for each aquifer, and a composite map of salinity distribution in the Winterburn aquifer is illustrated in Fig. 19. Salinity >250,000 mg/l occurs in deep strata close to the ancient Peace River landmass, and the salinity decreases updip fairly regularly except for a tongue of higher salinity (>200,000 mg/l) lying over the position of the Windfall-Swan Hills carbonate complex. There are similar regional trends for Cl, Ca and Mg. Sulfate shows no definite regional trends. A composite

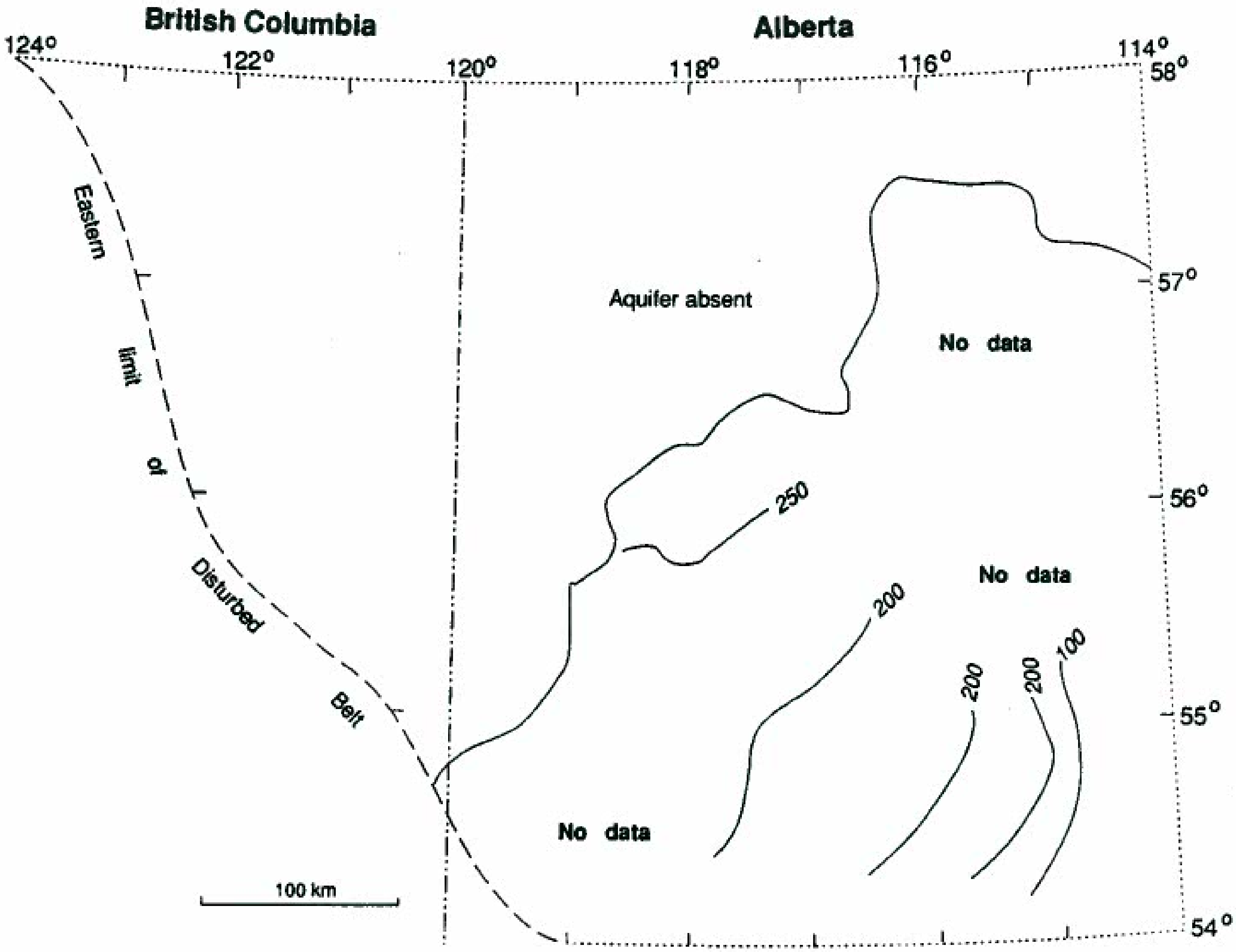

Figure 16. Salinity distribution (mg/lx10³) in the Nisku aquifer.

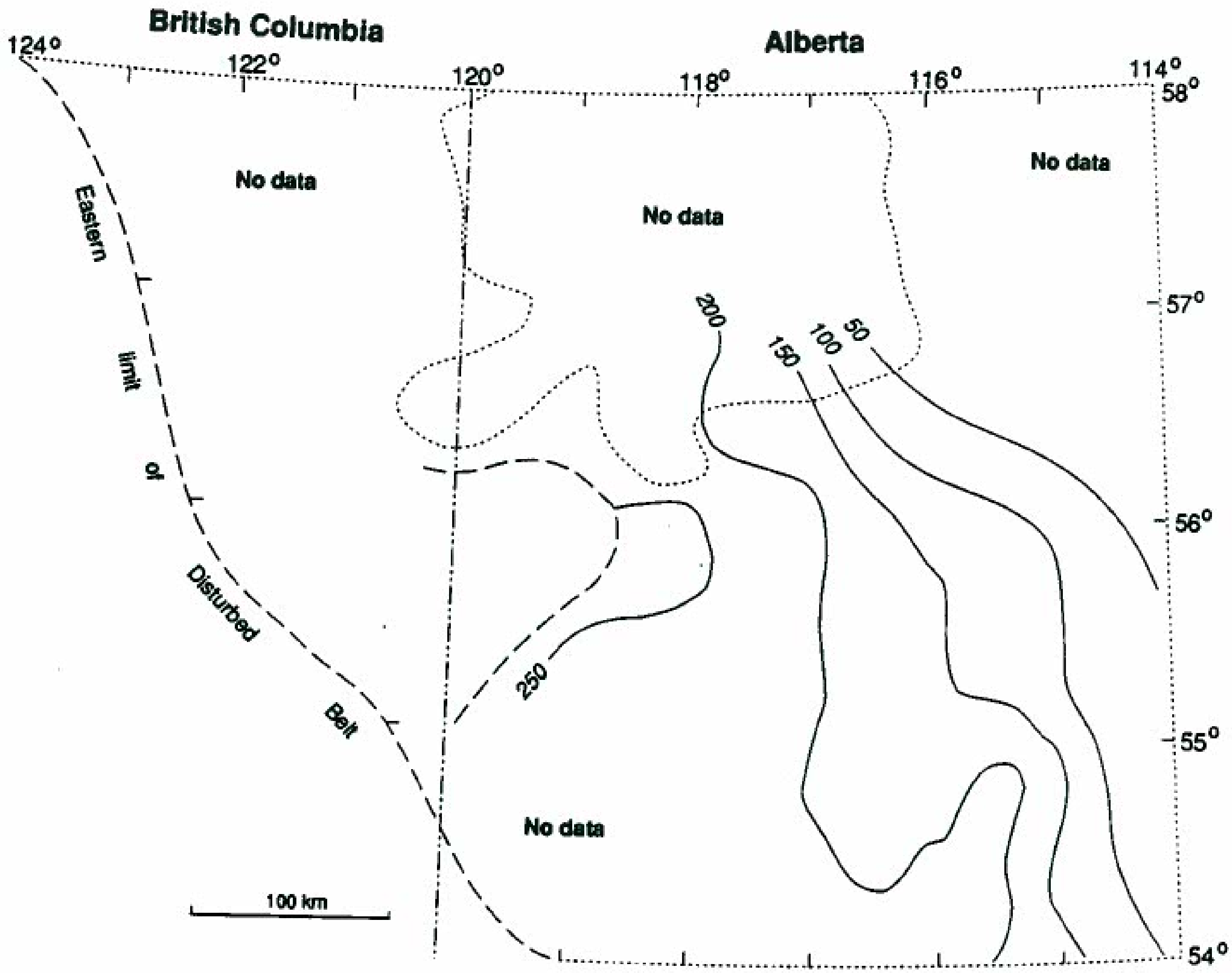

Figure 17. Salinity distribution (mg/lx10³) in the Blueridge aquifer. The short dashes show the distribution of the designated Blueridge 2 aquifer, which was combined with the Blueridge 1 aquifer (depositional limit of the Blueridge 1 aquifer around the ancient Peace River landmass shown in long dashes) because of too few data points for computer contouring.

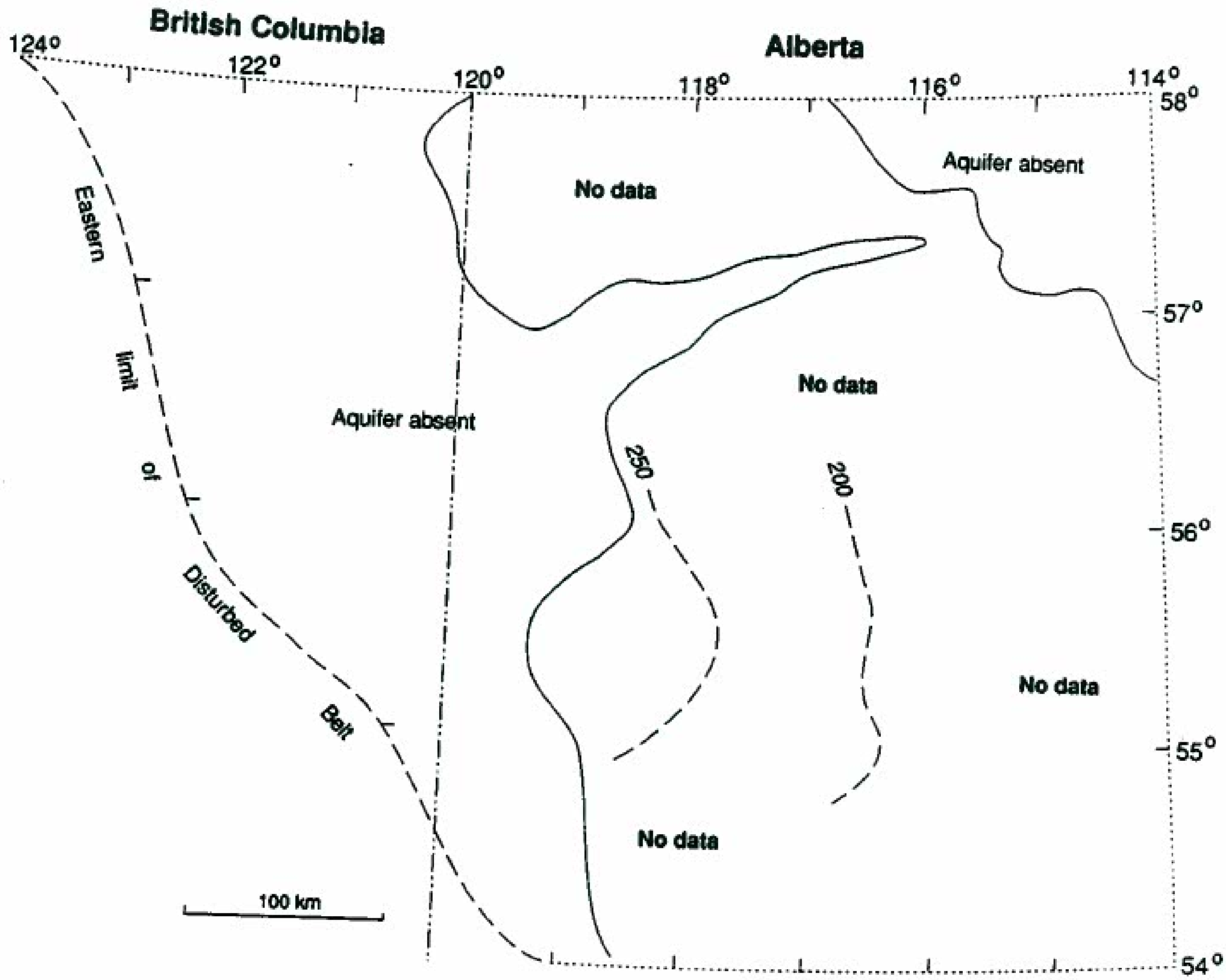

Figure 18. Salinity distribution (mg/lx10³) in the Graminia aquifer.

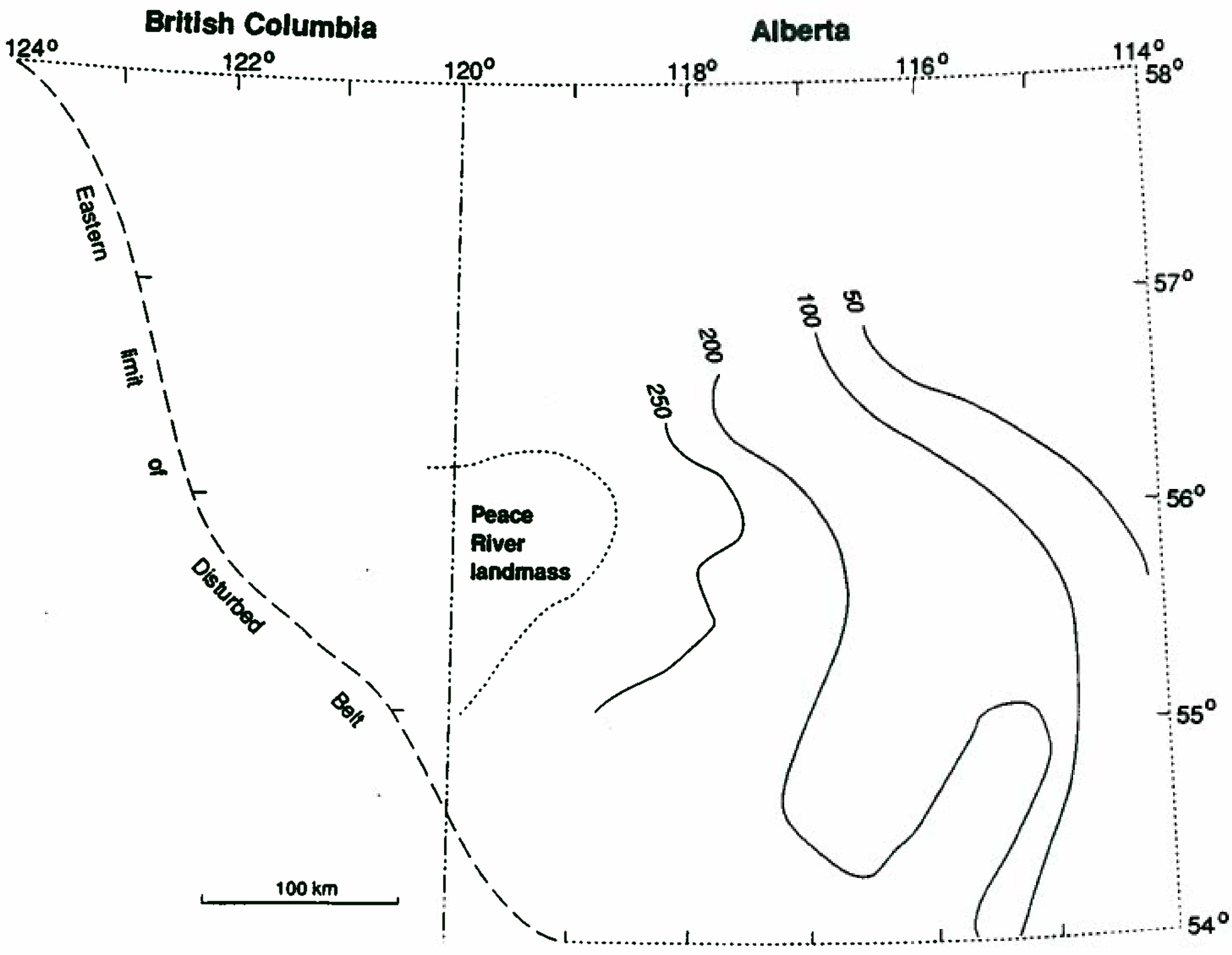

Figure 19. Composite (Figs. 16 to 18) salinity distribution (mg/lx10³) in the Winterburn aquifer. Arbitrary boundary against the Peace River landmass is that of the Blueridge 1 aquifer.

composition distribution map for HCO_3 (Fig. 20) shows contents >1000 mg/l over the general position of the Windfall-Swan Hills carbonate reef complex and the Grosmont aquifer; indeed, as noted by Hitchon *et al.* (1989b), the 500 mg/l HCO_3 contour in the Winterburn aquifer effectively marks the boundary of the underlying Grosmont aquifer. The drain effect of the Grosmont aquifer has resulted in formation waters in the Winterburn aquifer having salinity < ~100,000 mg/l and HCO_3 > 500 mg/l along the eastern border of the study area. The cause for the high salinity (>200,000 mg/l) and high HCO_3 (>1000 mg/l) over the position of the Windfall-Swan Hills carbonate complex must remain unknown until hydrodynamic data are available; the Ireton aquitard is ~300 m thick over the northeastern part of the Windfall-Swan Hills carbonate complex, thins to ~200 m northeast of the Windfall field, but is very much thinner over the southwestern extremity of the complex that lies within the study area.

Wabamun

The final Late Devonian transgression deposited the thick Wabamun Group, which represents a broad carbonate shelf across the now inactive Peace River Arch. The unit is very thin over the centre of the arch but may be up to ~500 m thick in places in the eastern part of the study area where it was protected from pre-Cretaceous erosion by the conformably overlying Mississippian Exshaw Formation. Average thickness is 220 m. The Wabamun Group is not present in the northeast corner of the study area due to pre-Cretaceous erosion (Fig. 21).

Although Toth (1978) and Hitchon *et al.* (1989b) treated the Wabamun Group differently in their respective study areas, no attempt was made in the present study to divide the Wabamun aquifer into parts with greater or lesser transmissivity. Accordingly, Fig. 21 shows the salinity distribution for the entire Wabamun aquifer. Features such as salinity >250,000 mg/l over the general position of the Peace River Arch, the relatively higher salinity bulge just north of the updip edge of the underlying Windfall-Swan Hills reef trend, and salinity <50,000 mg/l in the subcrop region are common to both the Winterburn (Fig. 19) and Wabamun (Fig. 21) aquifers. Trends for HCO_3 in the Wabamun aquifer essentially mirror those in the Winterburn aquifer (Fig. 20). The regional trends for Cl, Ca and Mg are similar to those for salinity. Sulfate shows no obvious regional trends.

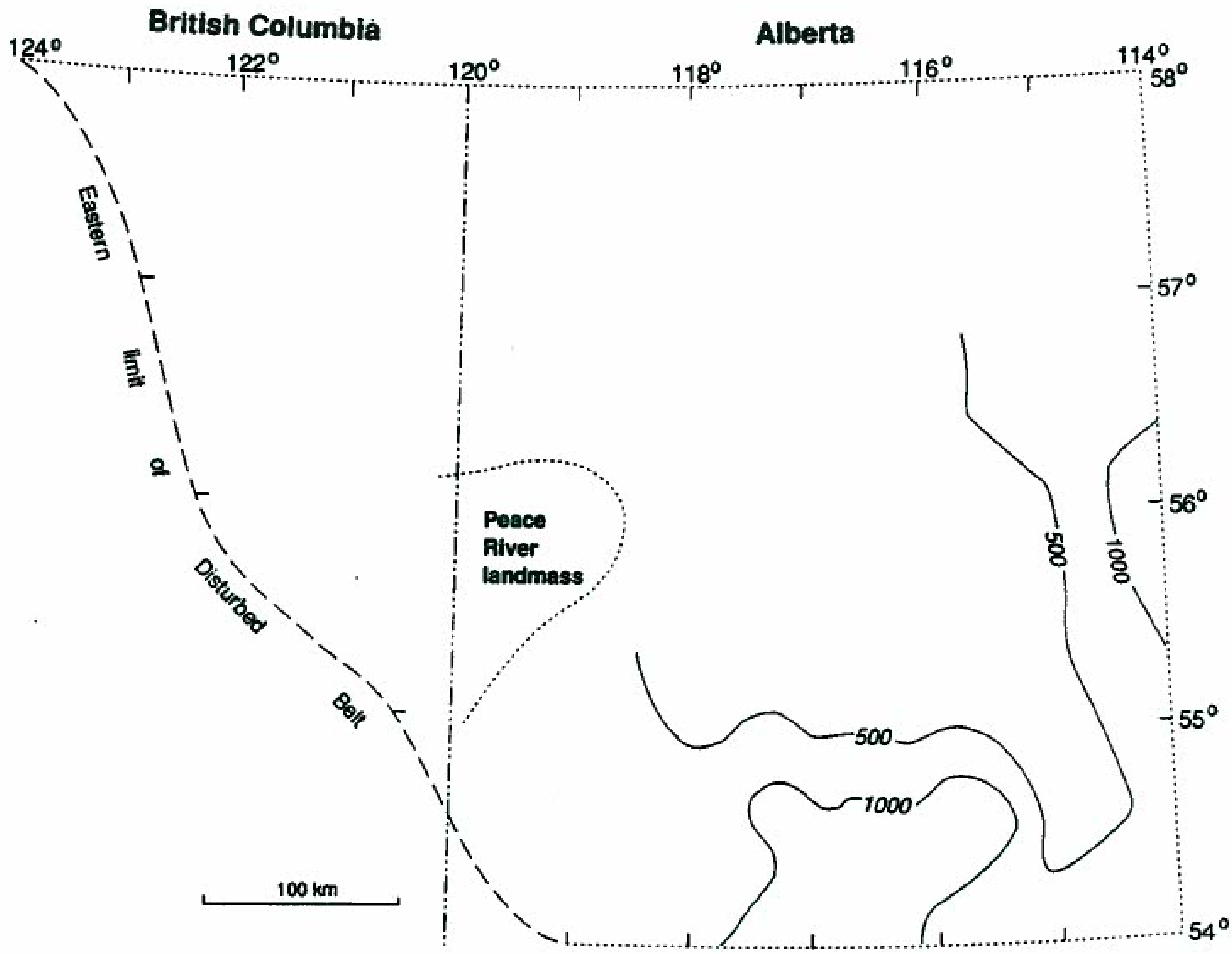

Figure 20. Composite HCO_3 distribution (mg/l) in the Winterburn aquifer.

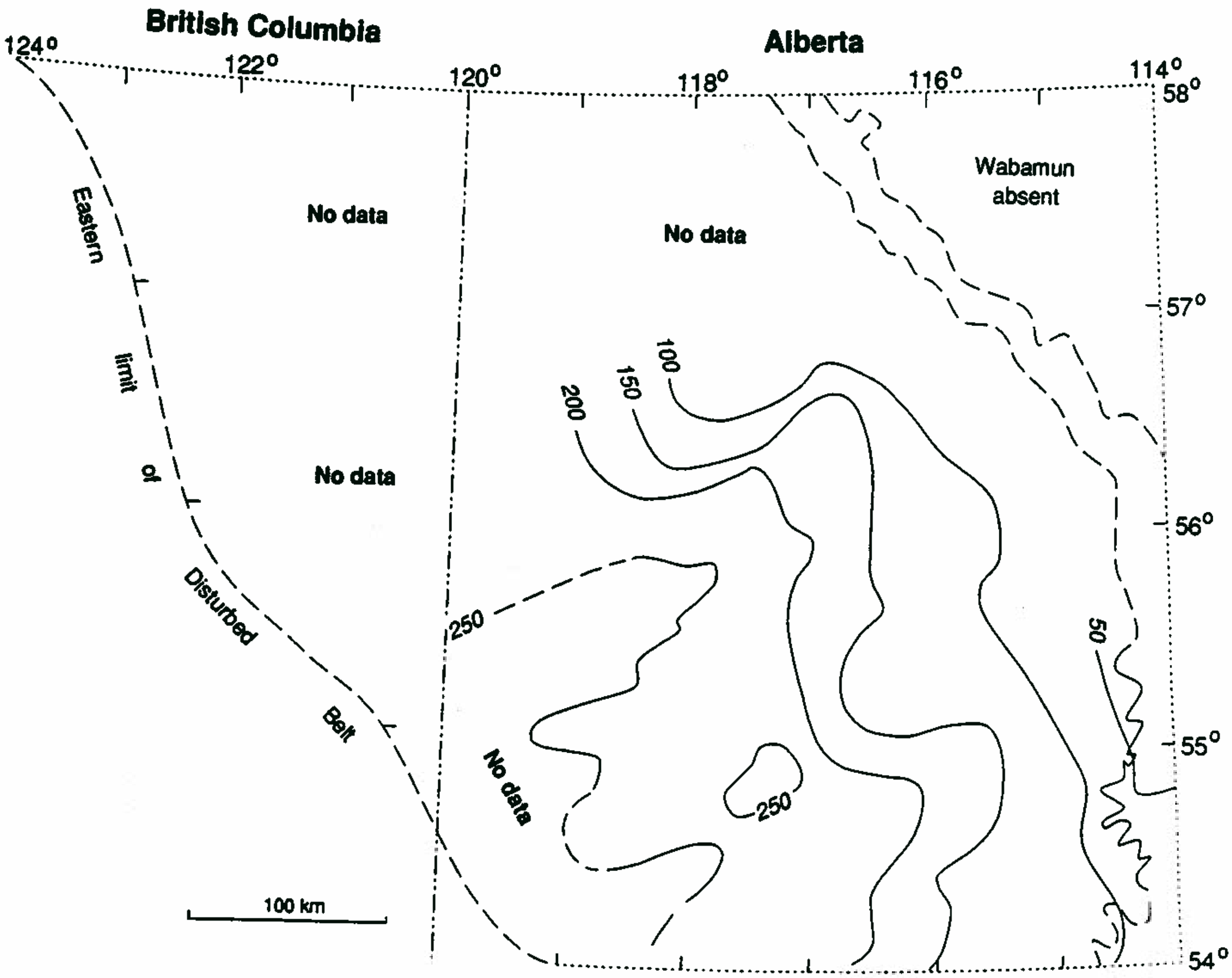

Figure 21. Salinity distribution (mg/lx10³) in the Wabamun aquifer. Detailed eastern subcrop boundary from Hitchon *et al.* (1989b), dashed boundaries from this study.

Exshaw-Banff

The end of Devonian time saw subsidence of the Peace River Arch and the accumulation of uniformly developed depositional systems over wide areas of the Alberta shelf during Mississippian time. The basal Exshaw Formation is a thin, upward-coarsening bituminous shale deposited under poorly oxygenated, probably standstill conditions. The overlying Banff Formation is an interbedded shale-to-carbonate succession which indicates continued transgression and greater shelf circulation.

In the Red Earth region Toth (1978) did not evaluate the Mississippian to Permian units in detail, but classified the Exshaw Formation and the shaley Lower Banff Formation as an aquitard. Similarly, Hitchon *et al.* (1989b), in the Swan Hills area, termed the same units the Exshaw-Lower Banff aquitard, which has only very weak sealing properties (calculated vertical hydraulic conductivity 1.5×10^{-8} m/d), with respect to its acting as an impermeable cover for deep waste injection in the underlying Wabamun-Winterburn aquifer system. In the Peace River Arch study area the Exshaw-Lower Banff aquitard ranges up to ~200 m in places but averages 65 m.

All formation waters recovered from the Banff Formation come from the Upper Banff Formation. Figure 22 shows salinity decreasing from ~200,000 mg/l to as low as 12,000 mg/l close to the subcrop margin; however, data are confined to the eastern part of the Banff aquifer. There are similar trends and comparable ranges for Cl (6000-120,000 mg/l), Ca (<200-10,000 mg/l) and Mg (<100-3000 mg/l). Sulfate shows a very irregular distribution. Formation waters with HCO_3 > 1000 mg/l are only found very close to the subcrop margin; elsewhere, HCO_3 may be as low as 180 mg/l.

Pekisko

The open shelf circulation in evidence in Late Banff time, and represented by the limestones of the Upper Banff aquifer, continued for much of the remainder of Mississippian time as shown by the mostly limestone succession of the overlying Rundle Group (Pekisko, Shunda and Debolt Formations). In the Red Earth region Toth (1978) classified the combined Pekisko and Shunda Formations as an aquitard, and the overlying Debolt Formation was included with the Permian Belloy Formation as an aquifer. Based on hydraulic head profiles and pressure

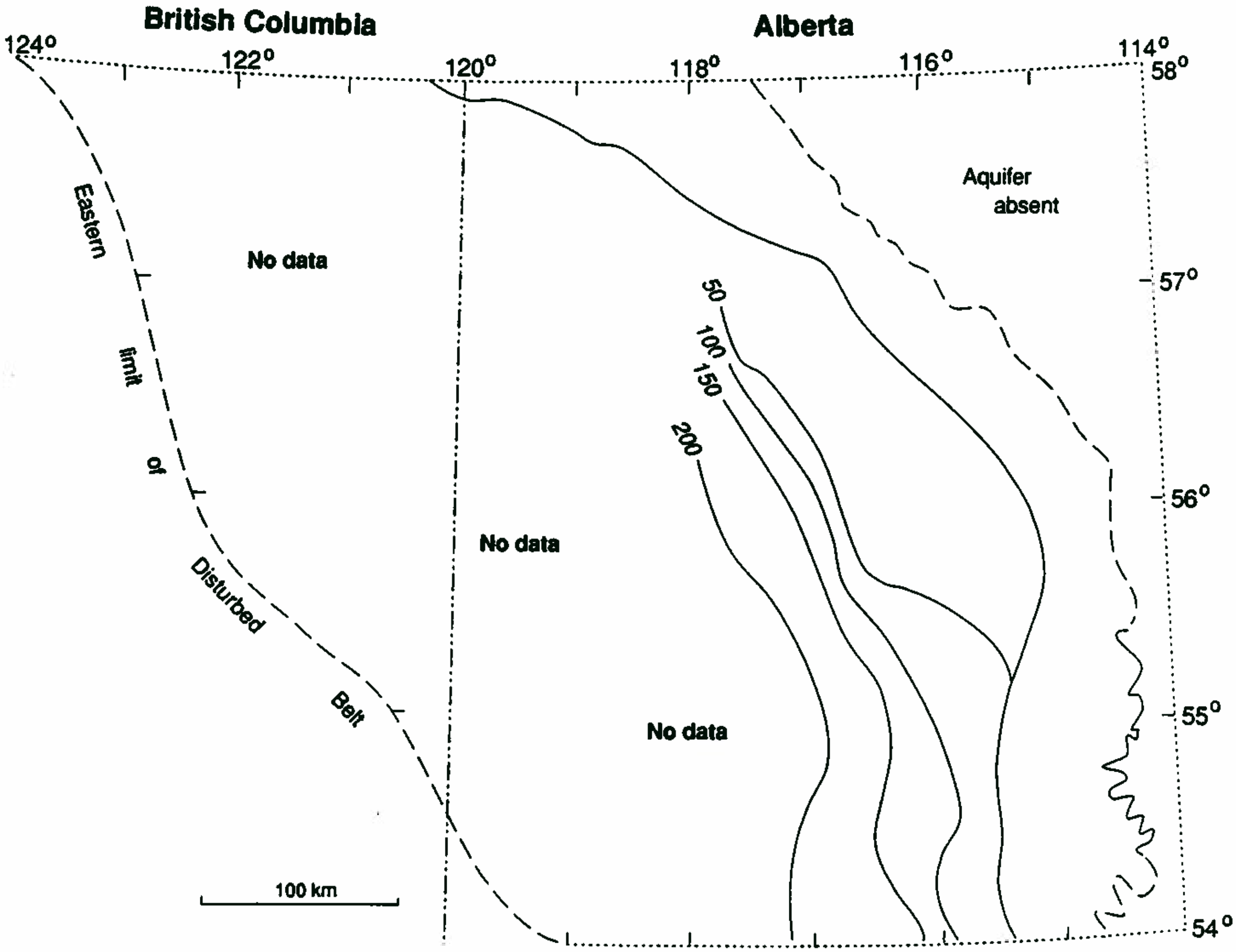

Figure 22. Salinity distribution (mg/l x 10^3) in the Upper Banff aquifer. Detailed eastern subcrop boundary from Hitchon *et al.* (1989b), other boundaries from this study.

head-depth plots, Hitchon *et al.* (1989b) showed that the Upper Banff, Rundle and Lower Mannville aquifers were part of one hydrogeological system, which they called the Lower Mannville-Rundle aquifer system. However, for the purpose of this report the individual aquifers will be treated separately.

The Pekisko Formation is found throughout the study area except along the northern and eastern borders; the latter boundary is due to pre-Cretaceous erosion. The unit is very uniform in thickness (average 50 m) and includes a shaley, 50 m-thick upper portion in the northern part of the region (Fig. 23). Formation water data are mainly confined to the subcrop and adjacent areas where salinity is always <50,000 mg/l. Maximum salinity found was 197,000 mg/l at 2200 m. The regional trends are similar for Cl (up to 120,000 mg/l), Ca (up to ~9000 mg/l) and Mg (up to ~1500 mg/l). Trends for SO_4 are irregular, but HCO_3 is generally >2000 mg/l where salinity is <50,000 mg/l, and ranges down to ~200 mg/l in the most saline formation waters.

Debolt

Debolt limestones occur throughout the study area except where removed by pre-Cretaceous erosion (Fig. 24). Maximum thickness is 1240 m over the central part of the Peace River Arch. In the subcrop region salinity of formation water may be as low as 25,000 mg/l but is generally in the range 25,000 to 50,000 mg/l. A tongue of high salinity (150,000-175,000 mg/l) formation water occurs over the central part of the Peace River Arch. There are comparable trends and concentration ranges for Cl (15,000-115,000 mg/l), Ca (commonly <5000 mg/l) and Mg (commonly <1000 mg/l). Sulfate shows no obvious regional trends. Maximum HCO_3 contents (>4000 mg/l) are found where salinity is <~30,000 mg/l, and as a general rule formation waters with salinity >75,000 mg/l have HCO_3 <1000 mg/l.

Golata and Taylor

Uppermost Mississippian and Lower Pennsylvanian rocks in the Peace River area comprise a dominantly clastic (sandstones and siltstones) succession with minor carbonates deposited in a marine or regressive continental environment. The units were severely truncated by Late Pennsylvanian erosion, and by later erosional episodes. The succession comprises, in ascending order, the Golata, Kiskatinaw and Taylor Flat Formations. Golata strata are thin (average 40 m) but

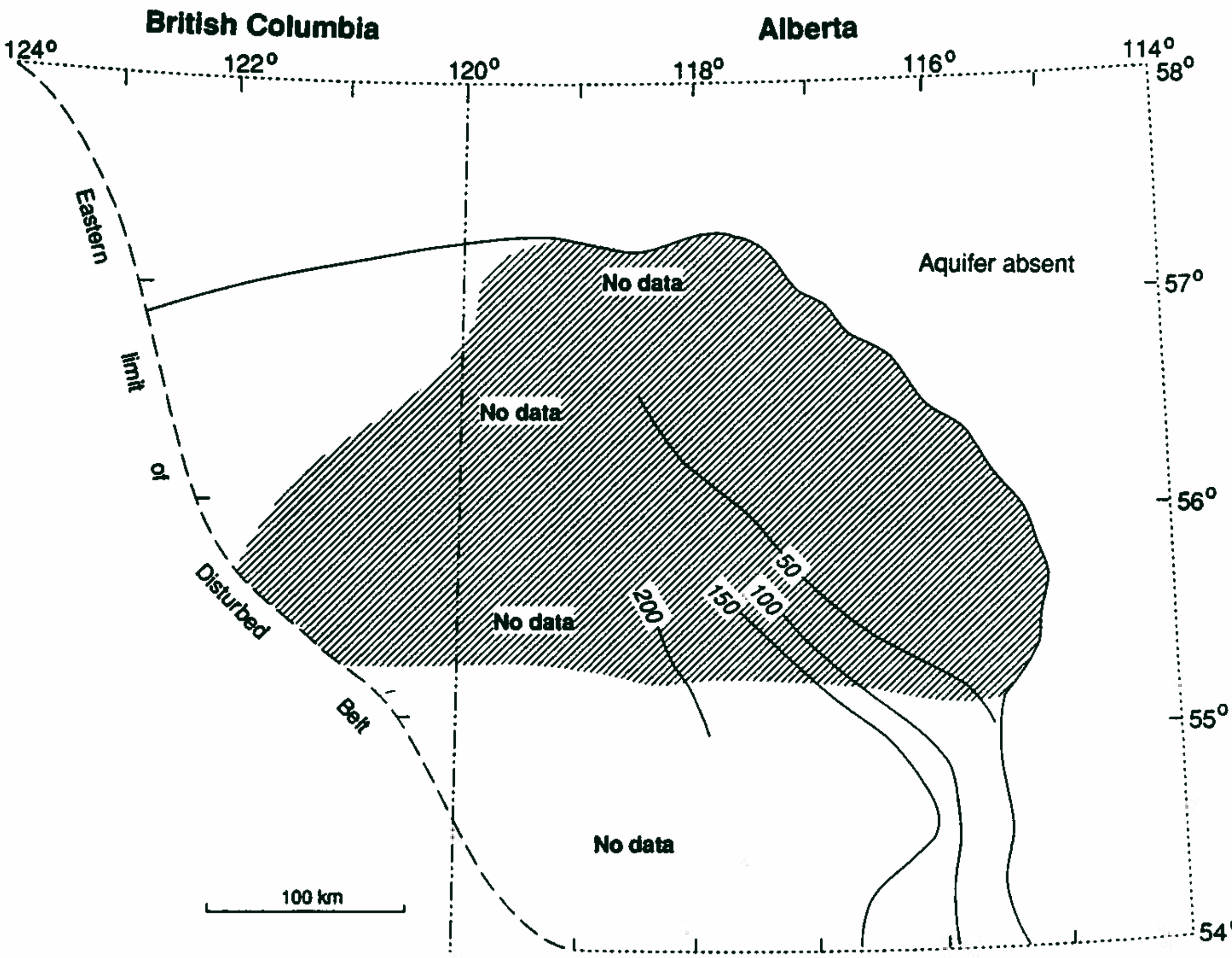

Figure 23. Salinity distribution (mg/lx10³) in the Pekisko aquifer. Screening shows the limits of the shaley upper part of the Pekisko Formation.

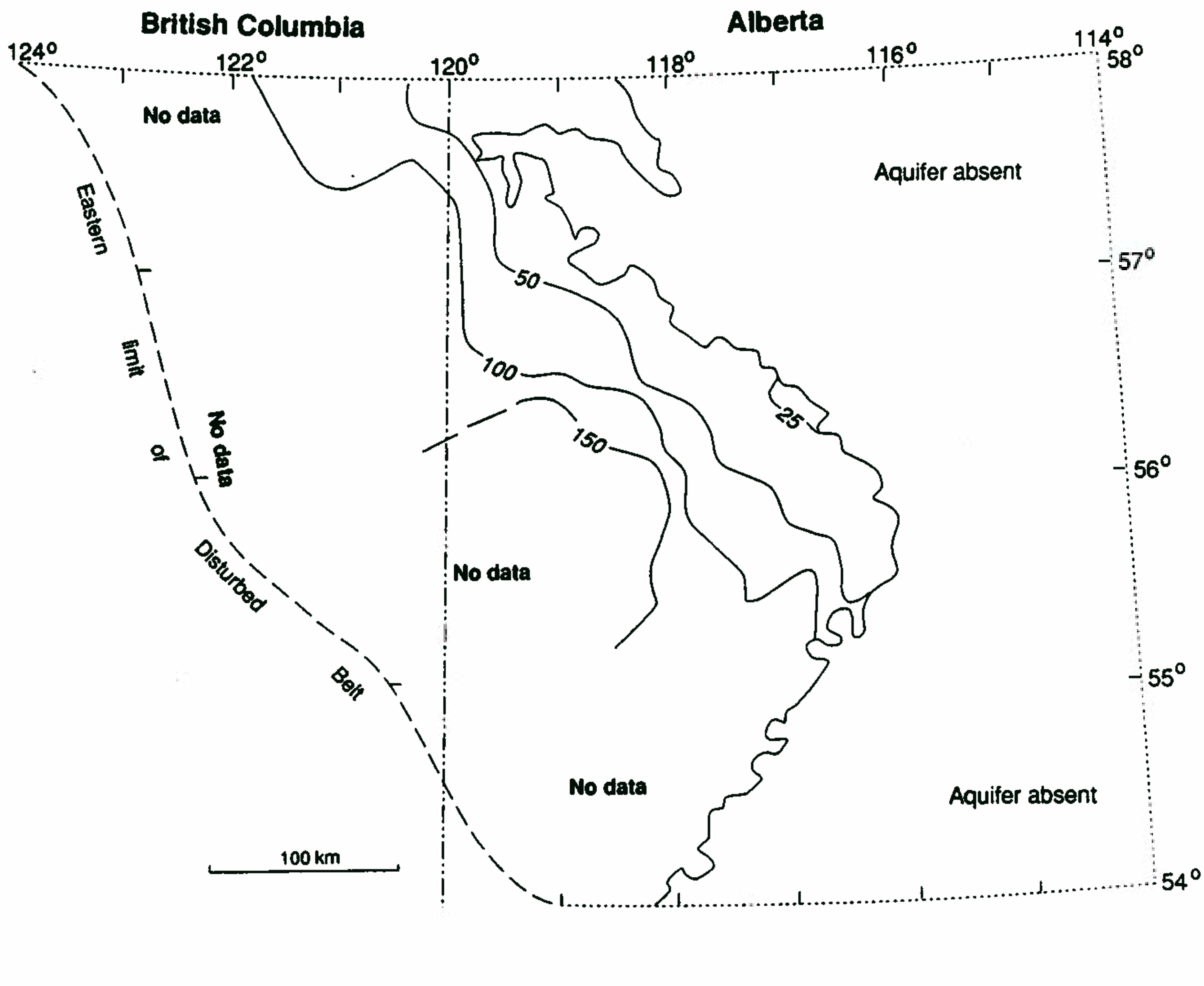

Figure 24. Salinity distribution (mg/lx10³) in the Debolt aquifer.

include many small areas where the thickness ranges up to nearly 400 m. No formation waters were assigned to the Kiskatinaw Formation. The overlying Taylor Flat Formation was originally divided into the porous Taylor Zone and an upper unit, but similarity of salinity trends suggested they be combined into a single Taylor aquifer; maximum thickness of the Taylor aquifer is 1000 m, with an average thickness of ~200 m.

Salinity in the Golata aquifer (Fig. 25) varies rather uniformly from ~175,000 mg/l in the deepest sample recovered to <50,000 mg/l in the shallowest strata near the subcrop margin. There are comparable ranges and trends for Cl (20,000-100,000 mg/l), Ca (<100-~8000 mg/l) and Mg (<100-~2000 mg/l). Sulfate shows no obvious regional trends; HCO_3 varies from <100 mg/l in deeper strata to >1000 mg/l in the shallowest beds, with a trend that is generally similar to that for salinity.

Salinity in the Taylor aquifer (Fig. 26) is very similar to that in the Golata aquifer; maximum salinity is ~180,000 mg/l and decreases to <40,000 mg/l in the shallowest part of the aquifer. The trends and ranges for Cl, Ca and Mg mirror those for salinity and for the same components in the underlying Golata aquifer. Sulfate shows no obvious trends. In the shallowest part of the aquifer where salinity is <75,000 mg/l contents of HCO_3 are >1000 mg/l and, differing from the underlying Golata aquifer, some of the deeper formation waters also have HCO_3 > 1000 mg/l; this may be an artifact of data distribution or lack of sample preservation in the field leading to CO_2 loss before analysis.

<u>Belloy</u>

Late Pennsylvanian was a period of erosion (pre-Absaroka unconformity), and it was not until middle Early Permian time that sedimentation began again in the study area. The Permian Belloy Formation consists mainly of interbedded sandstones, siltstones, porous dolomites, bedded cherts and occasional limestones. For convenience it was included within the Lower Mannville-Rundle aquifer system in the Swan Hills area (Hitchon *et al.*, 1989b) because there were so few data, but reevaluation is required for the Peace River Arch study area, where it is widespread although thin (average 30 m).

Salinity trends are quite uniform (Fig. 27), ranging from 40,000 to 180,000 mg/l; there are similar trends and contents for Cl (20,000-100,000 mg/l) and

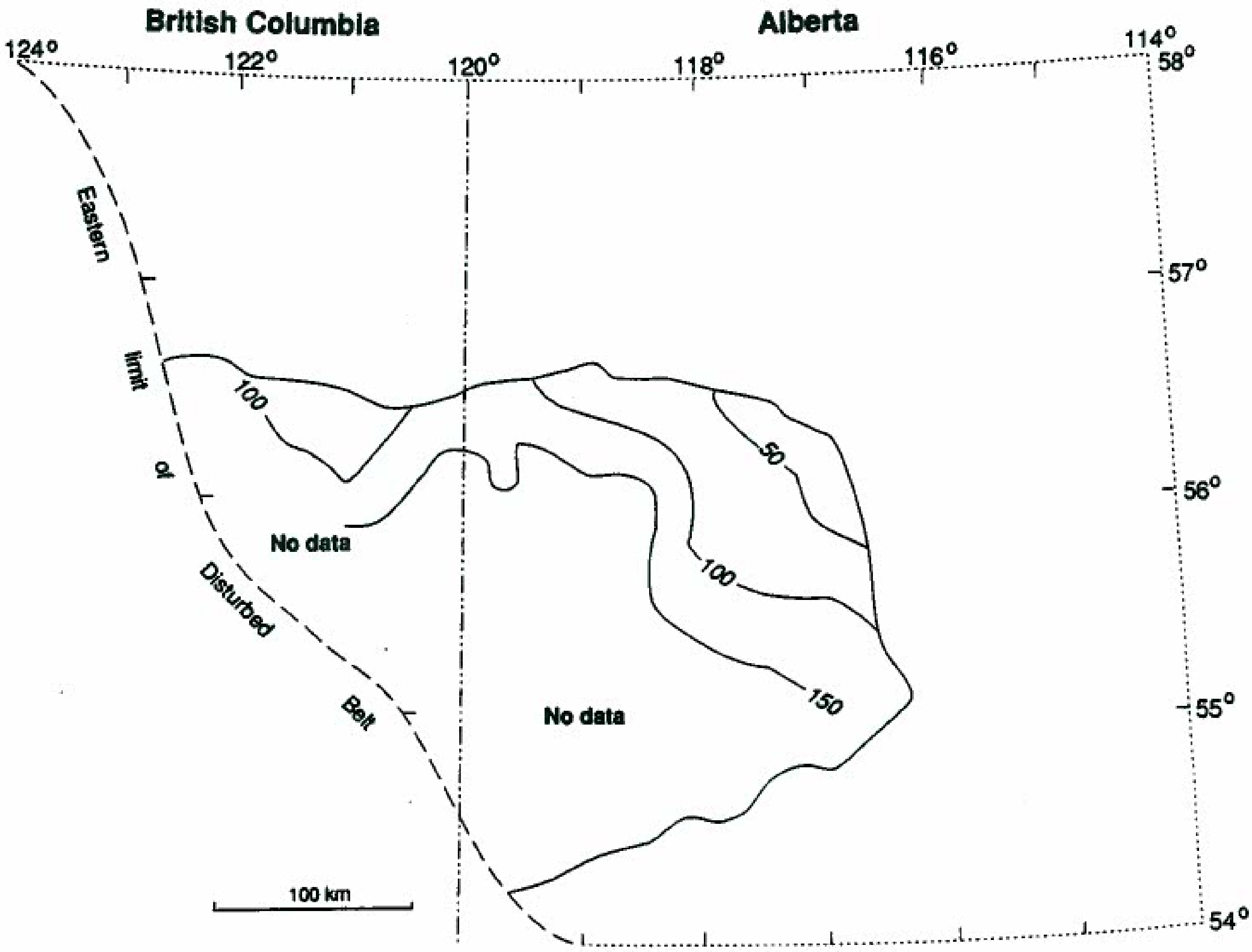

Figure 25. Salinity distribution (mg/lx10³) in the Golata aquifer.

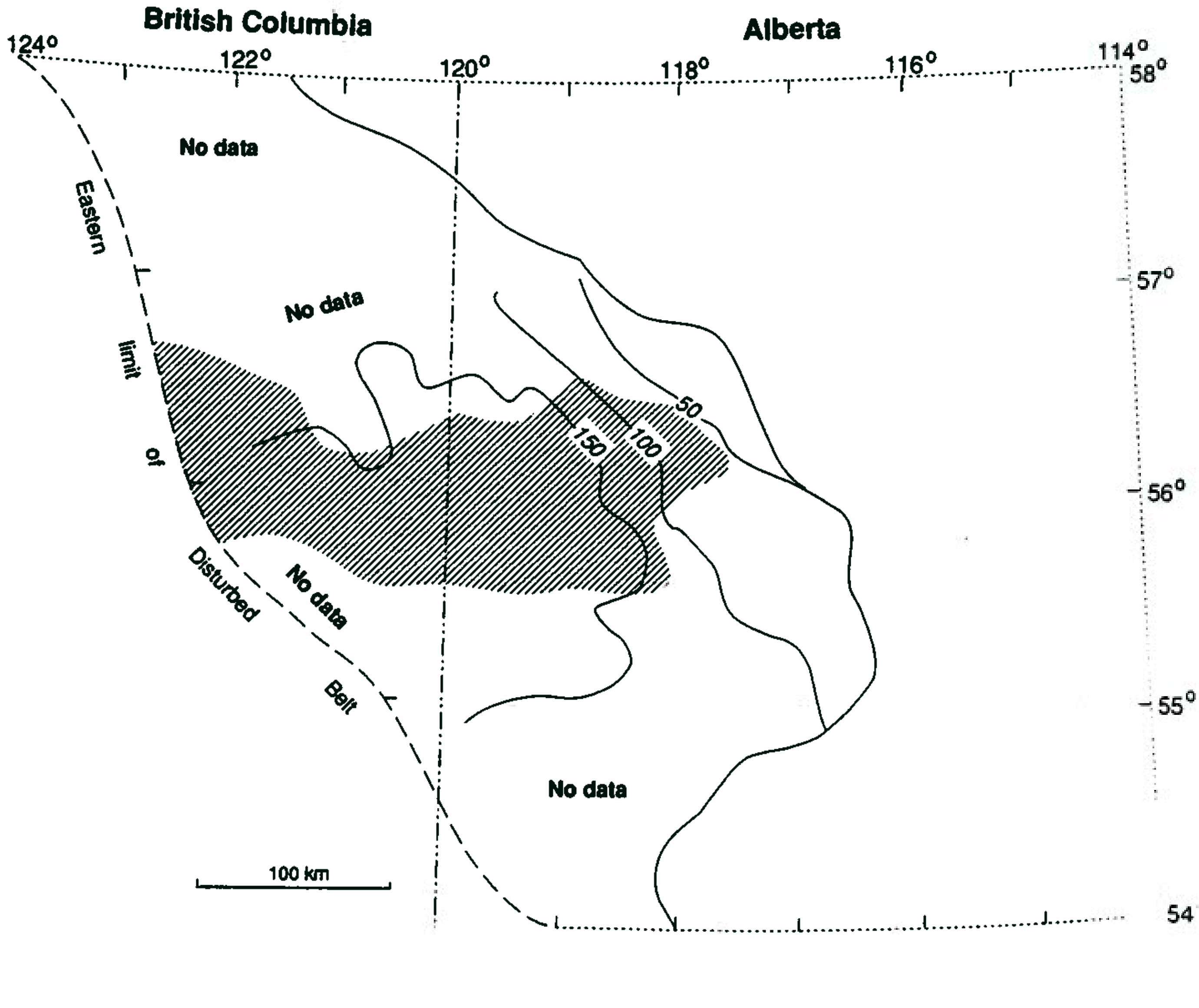

Figure 26. Salinity distribution (mg/lx10³) in the Taylor aquifer. Screened area shows the limits of the Taylor Zone.

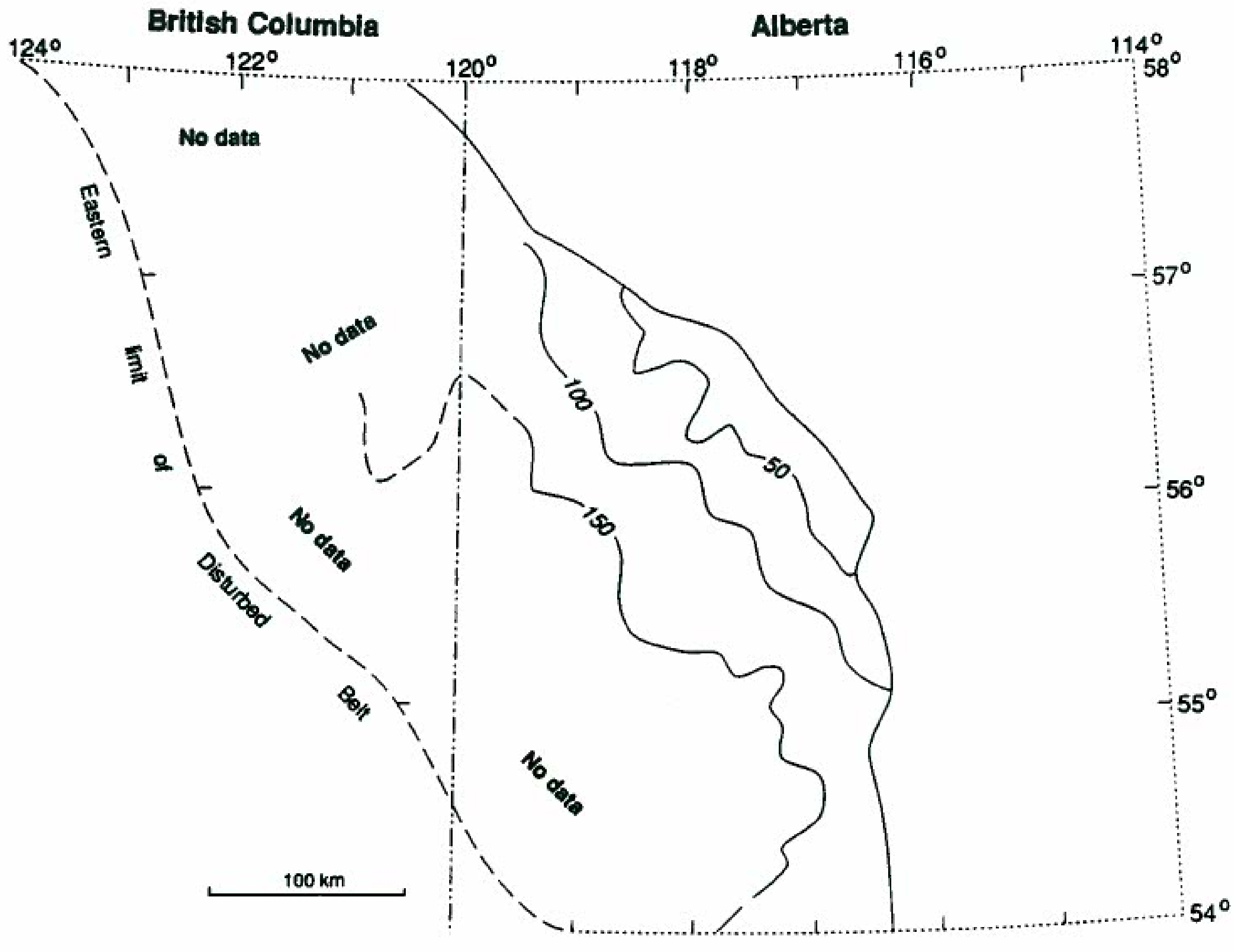

Figure 27. Salinity distribution (mg/l x 10³) in the Belloy aquifer.

Ca (400-9000 mg/l). There were no obvious trends for Mg or SO_4. The distribution of HCO_3 was as expected, with contents of 1000 to 2000 mg/l where formation water salinity is <50,000 mg/l, and generally <1000 mg/l elsewhere.

Diaber

There was a brief period of subaerial erosion in Late Permian and very Early Triassic time, following which there was a rapid eastward marine transgression and deposition of the Diaber Group. This consists of dark shales and siltstones in the west and deltaic strata and coquina banks along an eastern shoreline. As a result formation waters are recovered mainly in the updip, eastern half of the region. The Diaber Group reaches thickness of 500 m over the central part of the Peace River Arch, although the average thickness is only 200 m.

Salinity shows a fairly uniform decrease updip, from ~250,000 mg/l at 3300 m to <40,000 mg/l in the shallowest part of the subcrop region (Fig. 28). There are comparable trends and ranges for Cl (~20,000-150,000 mg/l), Ca (<1000-8000 mg/l) and Mg (<500-~3000 mg/l). Neither SO_4 nor HCO_3 show clear regional trends.

Halfway

The Halfway Formation is a fine-grained quartzose sandstone with varying amounts of silt and carbonate cement. It lies conformably on the Diaber Group in the west of the study area but in the east represents an erosional interval. It is thin (average 35 m; maximum ~200 m). Few formation waters have been recovered and their salinity varies from ~125,000 mg/l to just over 250,000 mg/l (Fig. 29); the trends are very general because of relatively sparse data. Comparable trends and ranges occur for Cl (75,000-160,000 mg/l), Ca (<1500-~10,000 mg/l) and Mg (500-3000 mg/l). Contents of SO_4 tend to be higher than in the underlying Diaber aquifer (650-1950 mg/l; average 1210 mg/l), but without any clear regional trends. Bicarbonate shows no obvious regional trends.

Charlie Lake

During Charlie Lake time a barrier lay to the west of the study area, behind which evaporitic sediments of the Charlie Lake Formation accumulated; they comprised anhydrite, gypsum, carbonates, silts and muds. Against the disturbed

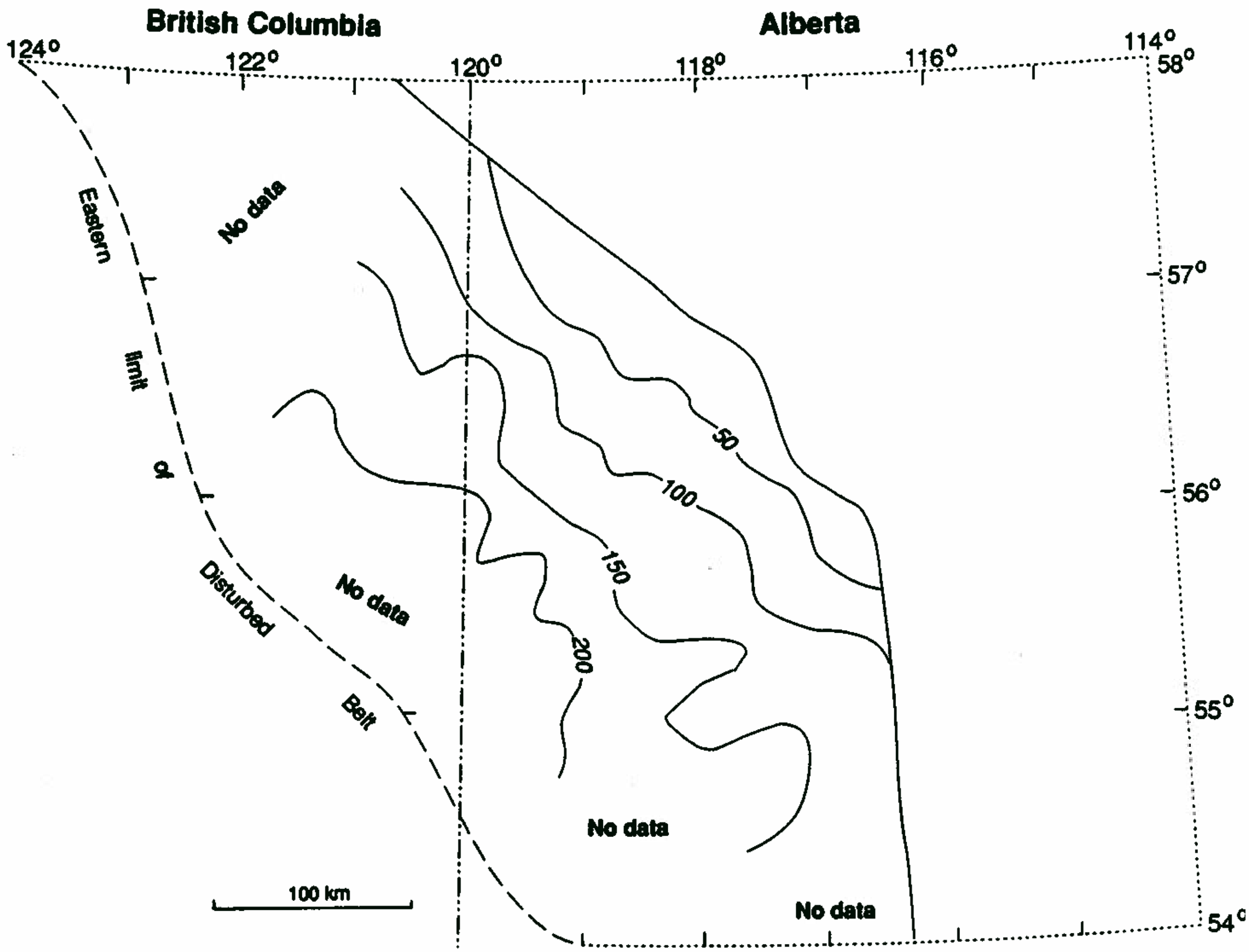

Figure 28. Salinity distribution (mg/lx10³) in the Diaber aquifer.

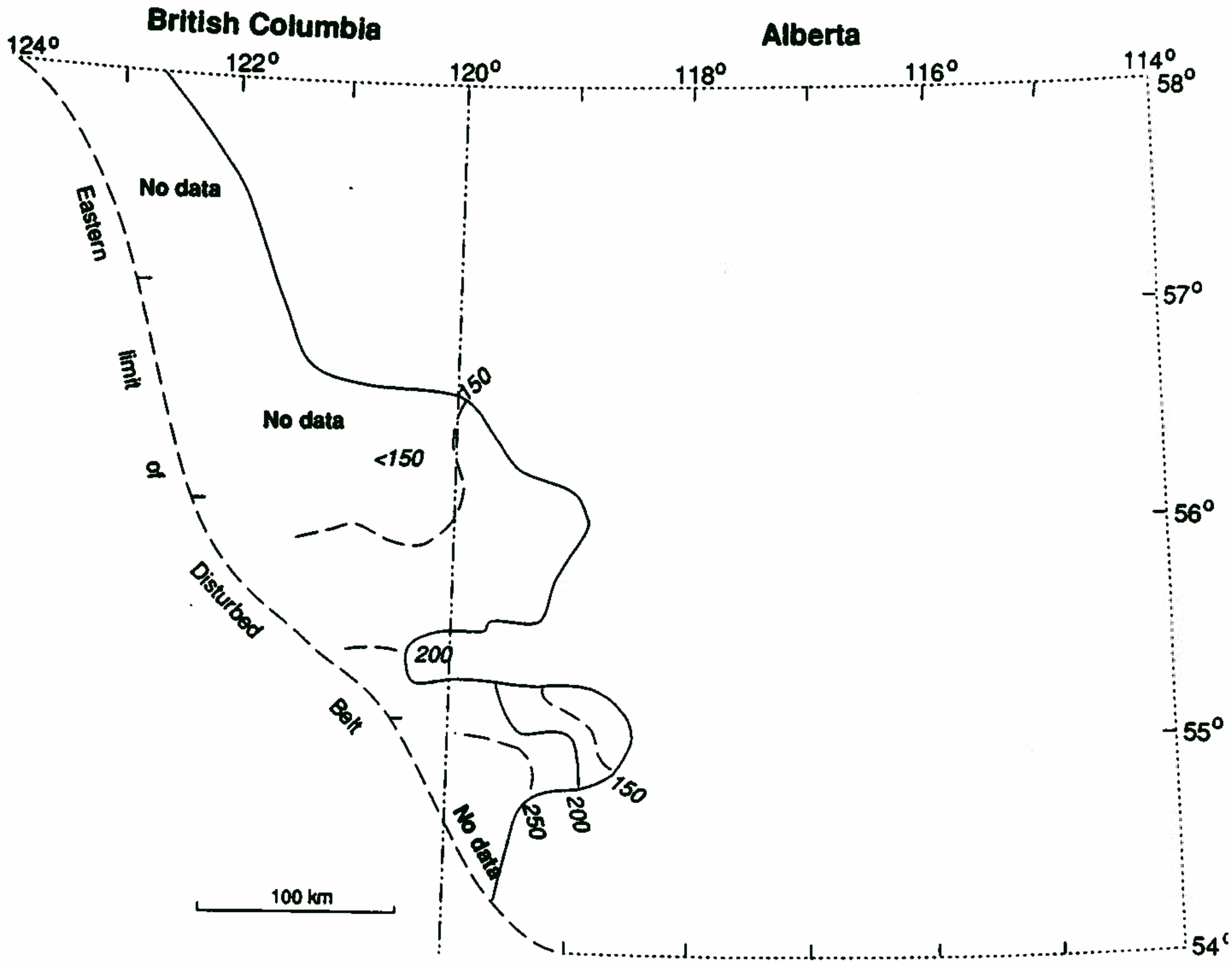

Figure 29. Salinity distribution (mg/lx10³) in the Halfway aquifer.

belt the thickness of the unit reaches 500 m, though the average is 175 m.

Maximum salinity (~225,000 mg/l) is found in deep strata close to the disturbed belt, and the salinity decreases updip to ~75,000 mg/l at places along the subcrop edge (Fig. 30). There are similar trends for Cl, and less obviously for Ca and Mg. No obvious regional trends can be discerned for HCO_3, but there is a tendency for maximum SO_4 to be found in regions with the thickest evaporite section (Fig. 31).

Baldonnel

The Baldonnel Formation represents one of the last major transgressive carbonate units of the Triassic and lies conformably on the Charlie Lake Formation evaporitic rocks. Uplift in the Late Triassic and subsequent erosion in pre-Sinemurian Jurassic and pre-Aptian Cretaceous times reduced the subcrop region considerably; maximum thickness is 78 m.

Salinity data are restricted to the shallower eastern part of this aquifer where values are in the range 50,000 to 75,000 mg/l, and are one-third to half that in the underlying Charlie Lake aquifer. There were insufficient data to produce reliable contour maps but two characteristics can be noted; first, the region with SO_4 > 2500 mg/l lies over part of the high-SO_4 area of the Charlie Lake aquifer (Fig. 32) and second, the content of HCO_3 is considerably greater than in the Charlie Lake aquifer.

Jurassic

The Peace River Arch area was emergent from Late Triassic (Rhaetian) to Early Jurassic (earliest Sinemurian) time, and throughout the remainder of the Jurassic there were several intervals of non-deposition. Aquifers within the Jurassic include the Lower Jurassic calcareous shales and thin cherty sandstones of the Nordegg Member, minor sandstones of the Middle Jurassic Rock Creek Member, and arenaceous units of the Upper Jurassic Nikanassin and Kootenay Formations.

For the purpose of this report all formation waters from Jurassic aquifers are included in the salinity distribution map in Fig. 33, although the majority are from the Nordegg Member. Data are confined to the shallower, eastern half of the Jurassic area, and the salinity ranges from close to 160,000 mg/l to ~40,000 mg/l,

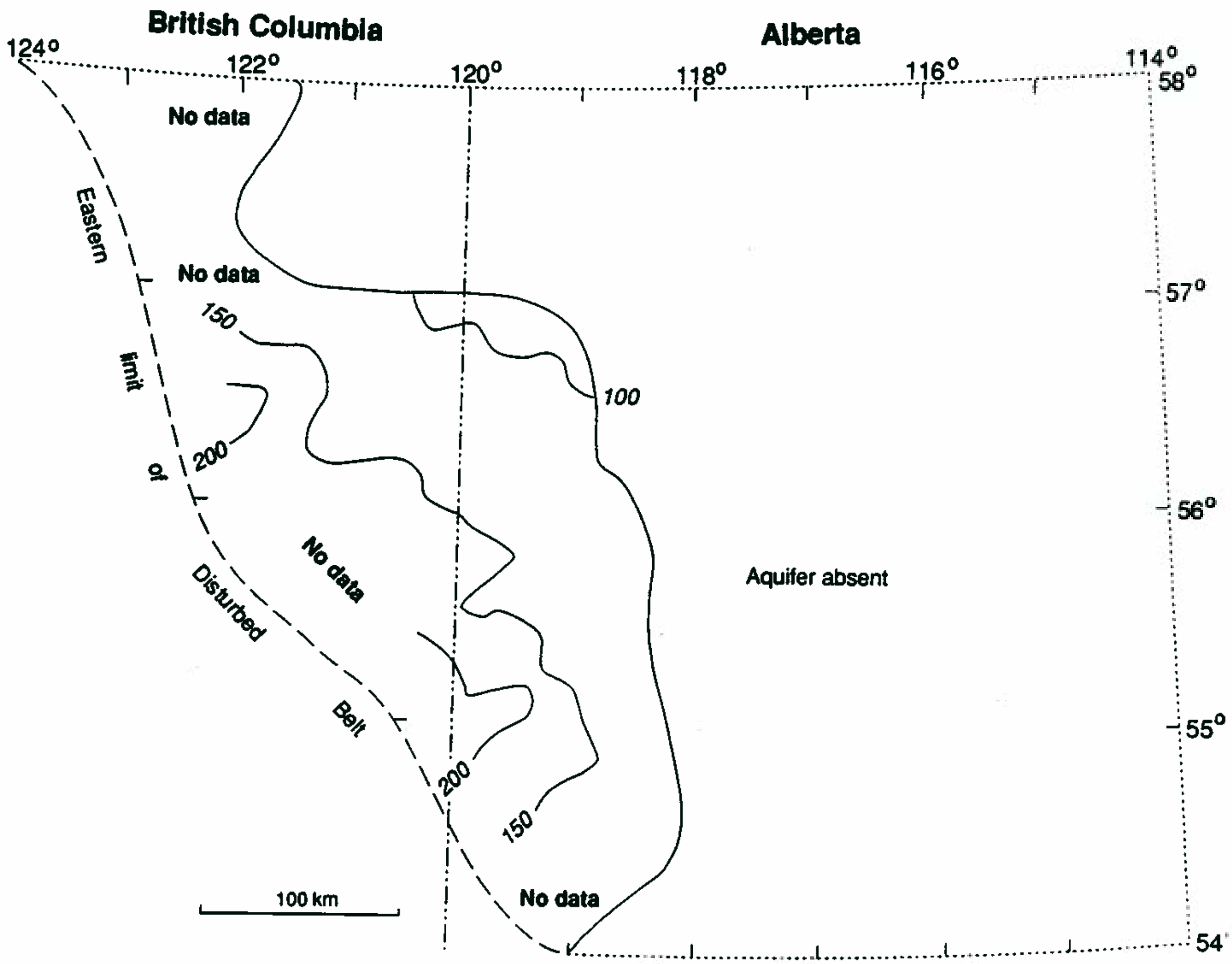

Figure 30. Salinity distribution (mg/l x 10^3) in the Charlie Lake aquifer.

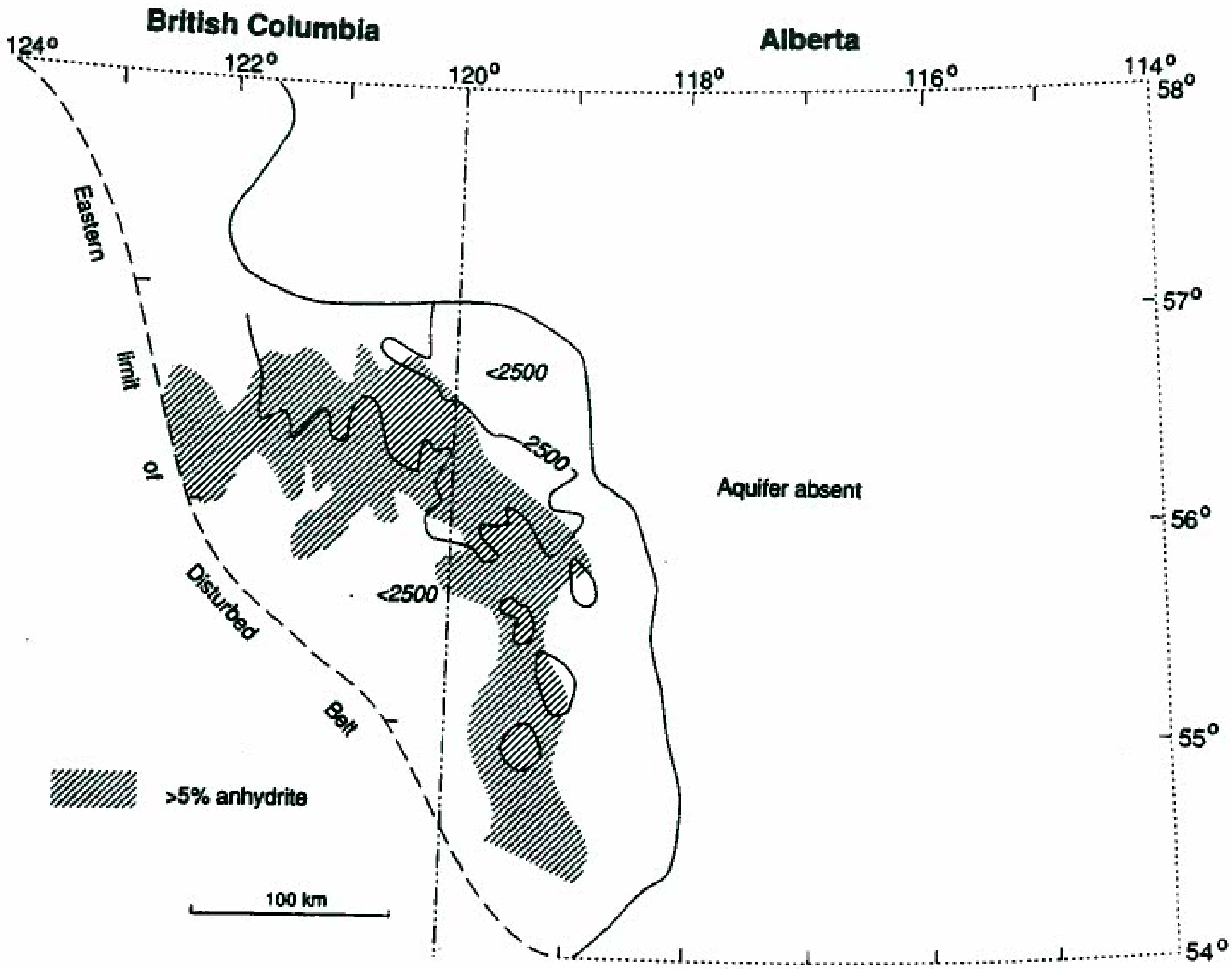

Figure 31. Relation of formation waters with SO_4>2500 mg/l to the main evaporite trend in the Charlie Lake aquifer; region of >5% anhydrite from Barss *et al.* (1964).

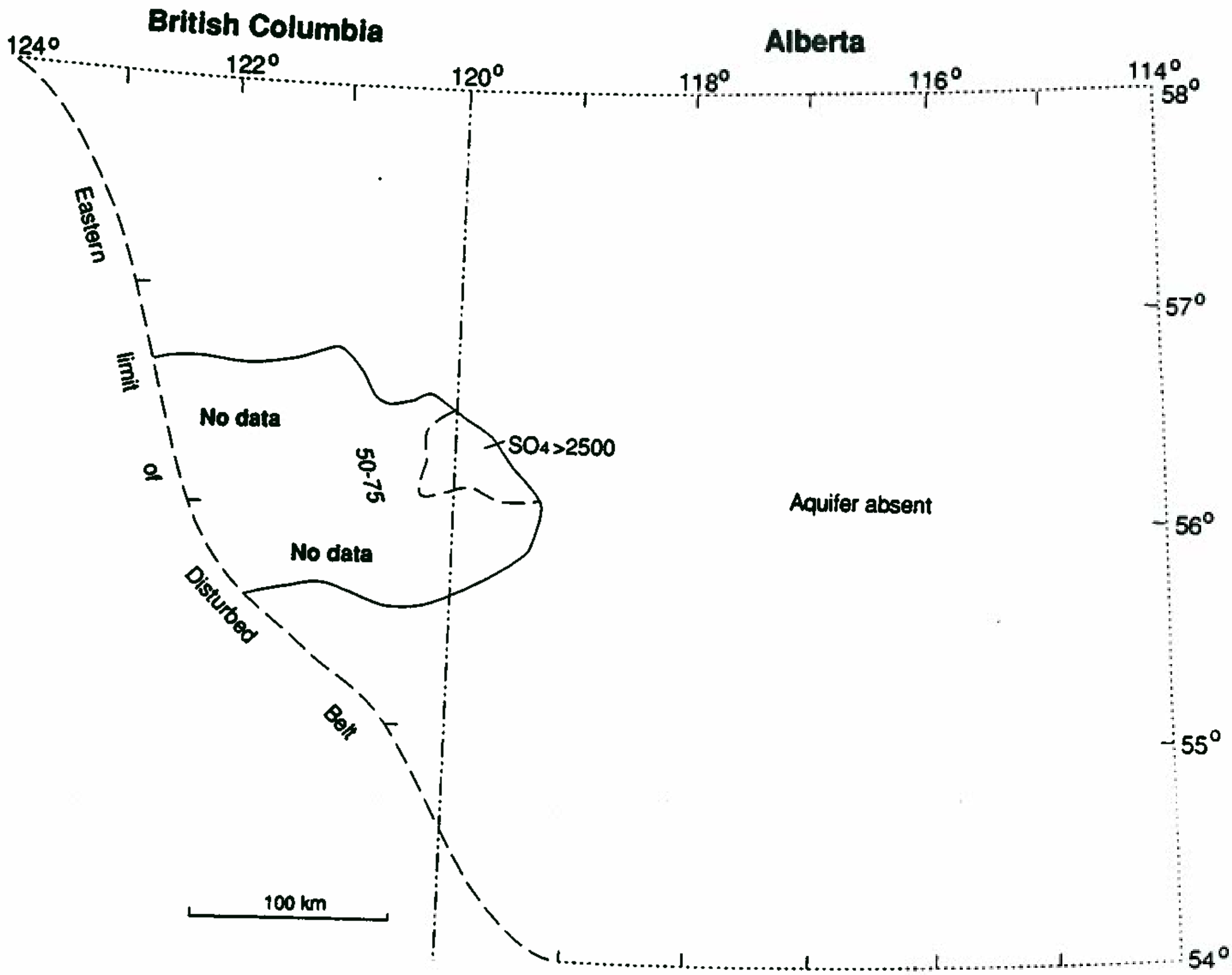

Figure 32. Baldonnel aquifer showing the range in salinity (mg/lx10³) and the area with SO_4>2500 mg/l.

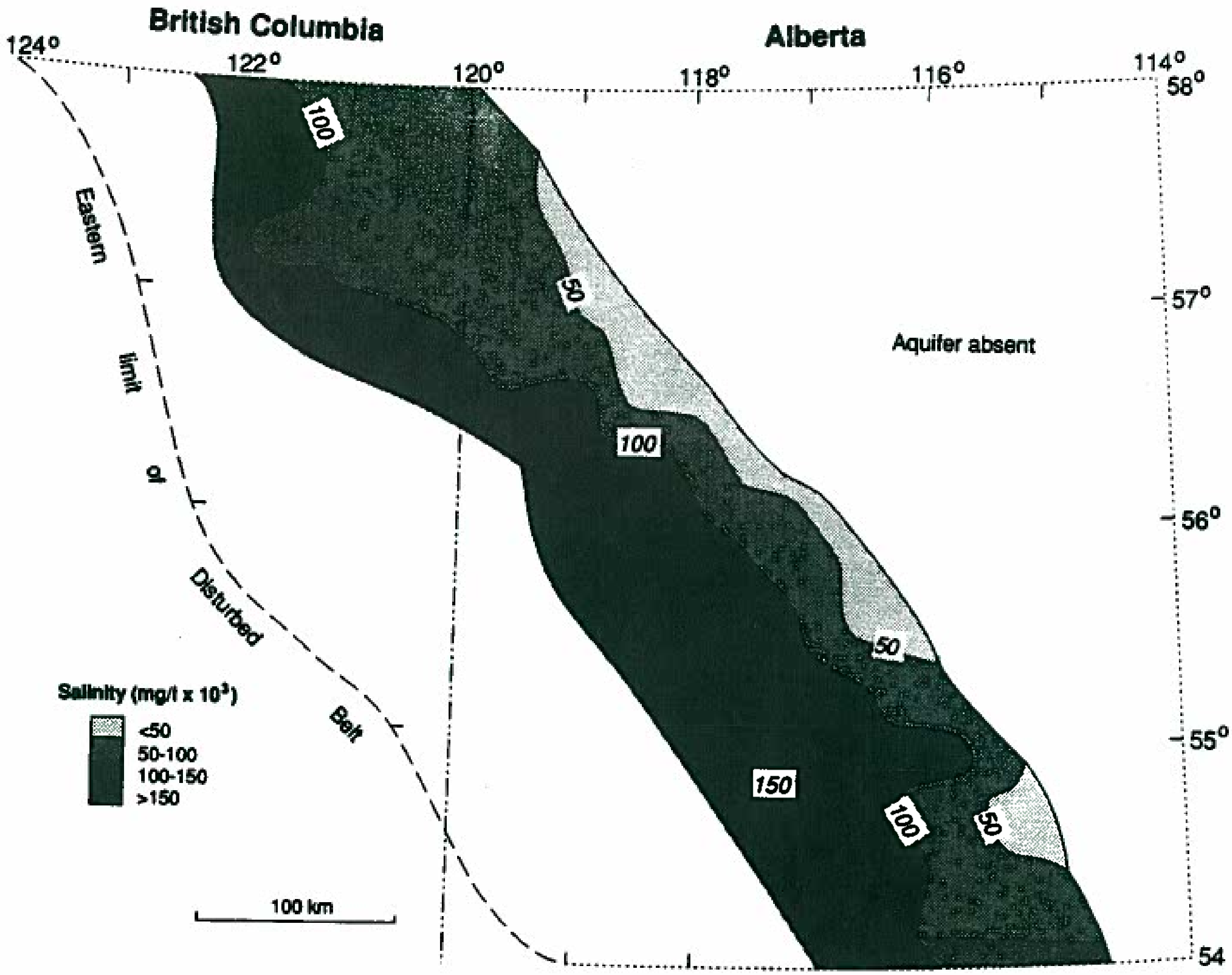

Figure 33. Salinity distribution (mg/lx10³) in combined Jurassic aquifers.

with a very uniform salinity gradient. If a composite map is constructed of the salinity distribution in aquifers immediately below the Jurassic (Fig. 34) it is seen that there is a close correspondence between this map and the salinity distribution in Jurassic aquifers (Fig. 33). This suggests good hydraulic continuity between the basal Jurassic aquifers and the underlying aquifers. Note that in Fig. 34 the salinity distribution in the Charlie Lake aquifer (see Fig. 30) is indicated "through" that in the Baldonnel aquifer (see Fig. 32). The formation waters in the Baldonnel aquifer appear to have anomalously low salinity compared to those in the Charlie Lake aquifer and closer affinities with the salinity distribution in the Gething-Cadomin aquifer (Fig. 35) which lies above the Jurassic -- at the location of the Baldonnel Formation the Jurassic is dominantly shaley.

Gething-Cadomin

Between Middle Jurassic and Early Cretaceous time, ocean-to-continent collision along the Pacific rim compressed the outer part of the Paleozoic craton-margin sedimentary pile and resulted in its eastward displacement as thrust slices. This thickened crust resulted in a major drainage divide and isostatic downwarp of the new foreland basin. Sediments were accumulated on vast plains and in shallow epicontinental seas in the Western Interior Seaway, which at times stretched from the Arctic Ocean to the Gulf of Mexico. There are numerous aquifers within the Cretaceous of the study area, some of which have been severely truncated by Tertiary erosion. The earliest comprises the sandstones and conglomerates of the Gething and Cadomin Formations. The combined formations form a wedge up to 660 m thick close to the foothills, which thins rapidly eastward, so that over most of the study area the aquifer is <50 m (average 60 m). The eastern limit is depositional against a Paleozoic ridge, which became completely covered by Spirit River time.

Maximum salinity (>80,000 mg/l) occurs essentially in the deepest strata in the southwest corner of the study area (Fig. 35). As a broad generalization, salinity in the range 40,000 to 80,000 mg/l forms a broad band across the southern third of the study area and in an isolated patch stretching northwest-southeast across the Alberta-British Columbia border at about 57°N. Elsewhere salinity as low as 15,000 mg/l has been found close to the town of Peace River where Hitchon (1974, Figs. 13-11 and 13-12), has shown that meteoric water recharge is evident

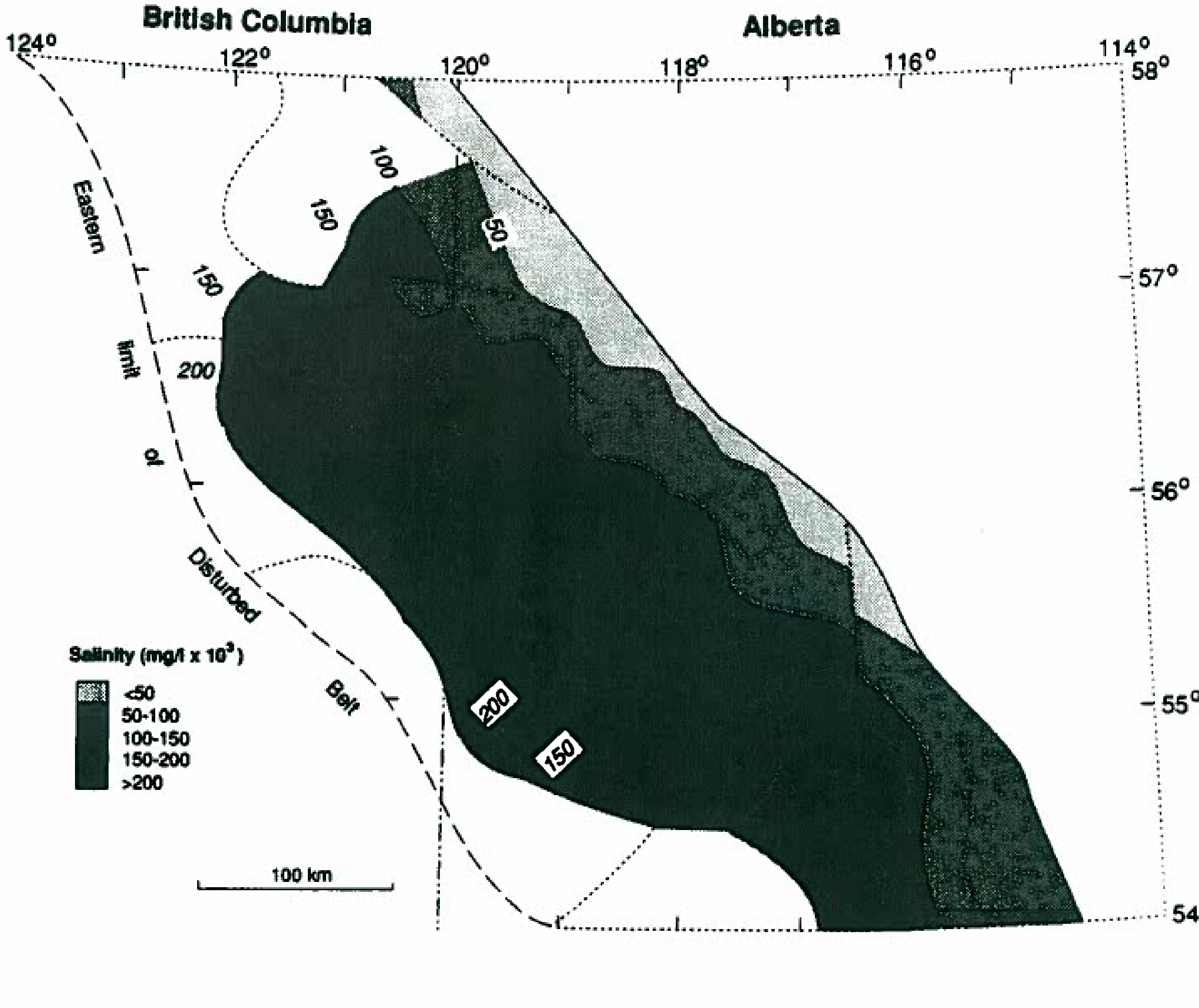

Figure 34. Composite map of salinity distribution (mg/lx10³) in aquifers immediately below the Jurassic.

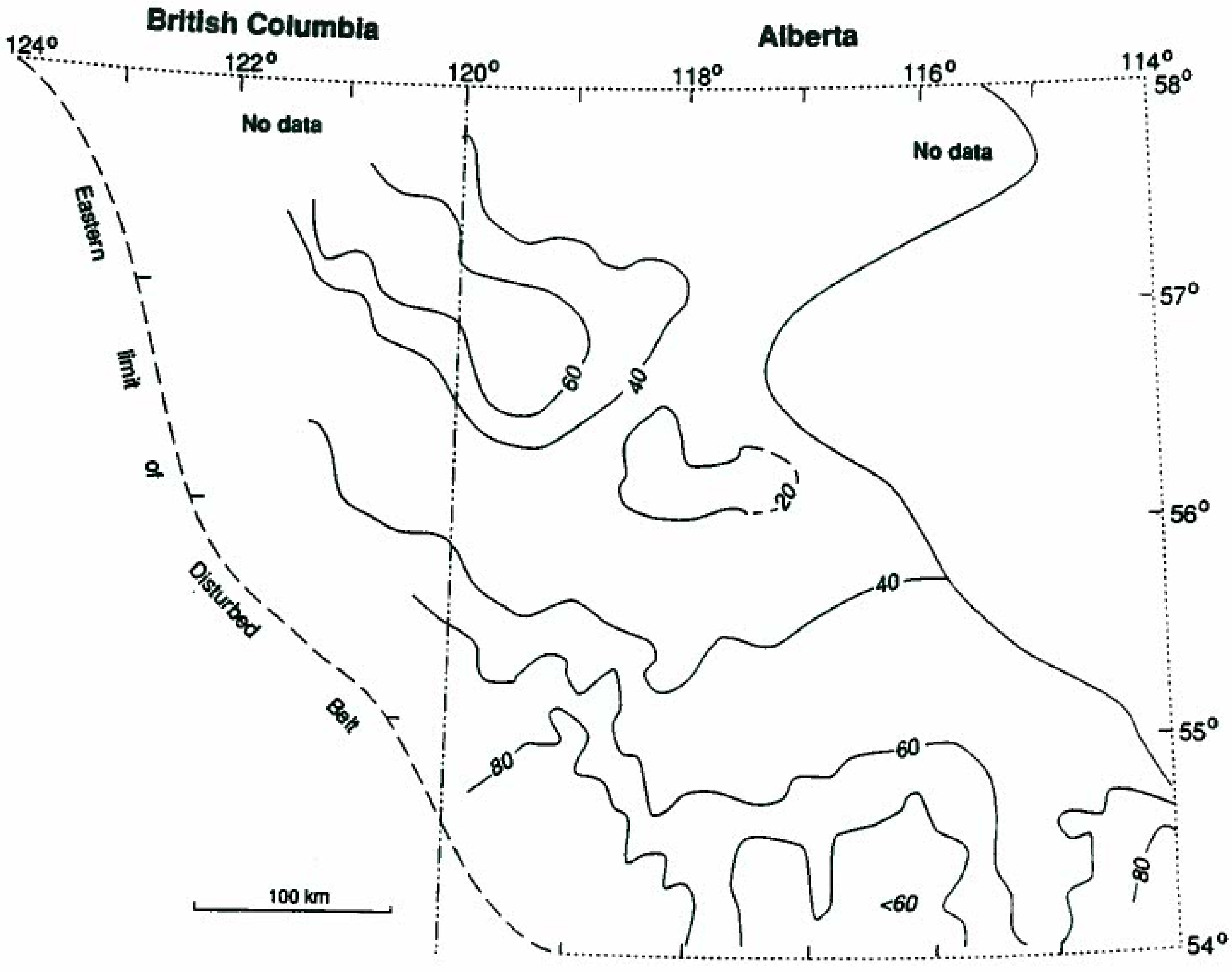

Figure 35. Salinity distribution ($mg/l \times 10^3$) in the Gething-Cadomin aquifer.

in a hydraulic head and salinity cross section through the nearby Peace River oil sand deposit. There are broadly similar trends and comparable contents for Cl (maximum ~50,000 mg/l), Ca (rarely >2000 mg/l) and Mg (rarely >800 mg/l). Bicarbonate is usually <2000 mg/l but in the small area around the town of Peace River with salinity <20,000 mg/l HCO_3 may be >6000 mg/l (Fig. 36). There are no obvious regional trends for SO_4.

Bluesky

The Bluesky Formation lies conformably on the Gething Formation and extends eastward of the depositional margin of the Gething Formation where it covers the Paleozoic ridge. The thickness is ~100 m in the southwest part of the study area but generally the Bluesky aquifer is thin (average 60 m). In the Swan Hills area, Hitchon *et al.* (1989b) grouped the Bluesky aquifer with the Gething and Cadomin aquifers as the Lower Mannville aquifer on the basis of pressure head-depth plots and hydraulic-head profiles. In the Red Earth region, Toth (1978) also combined the stratigraphic equivalents (Bullhead Group and Wabasca Member of the Clearwater Formation) into a single aquifer. It is not surprising, therefore, that the salinity (Fig. 37), Cl, Ca, Mg and, to a lesser extent HCO_3 (Fig. 38) trends resemble those in the Gething-Cadomin aquifer except that the formation waters in the Bluesky aquifer are slightly less saline than those from the immediately underlying Gething-Cadomin aquifer. As usual, there are no obvious regional trends for SO_4.

Spirit River

The Lower Mannville Group (Cadomin, Gething and Bluesky Formations) is overlain conformably by the Upper Mannville Group, which in the Peace River Arch study area comprises the Spirit River Formation (Wilrich, Falher and Notikewin Members, in ascending order). In the Swan Hills area, the Lower Mannville aquifer is overlain by the Clearwater-Wilrich aquitard (Hitchon *et al.*, 1989b), while in the Red Earth region Toth (1978) combined the Wilrich and Falher Members into the Cretaceous A aquitard. To the west and southwest, respectively, of these two areas, however, the Falher and Notikewin Members contain abundant sandstones. As a result, the Wilrich Member, and its correlative the Clearwater Formation, is an aquitard throughout the study area, whereas the Falher and Notikewin Members

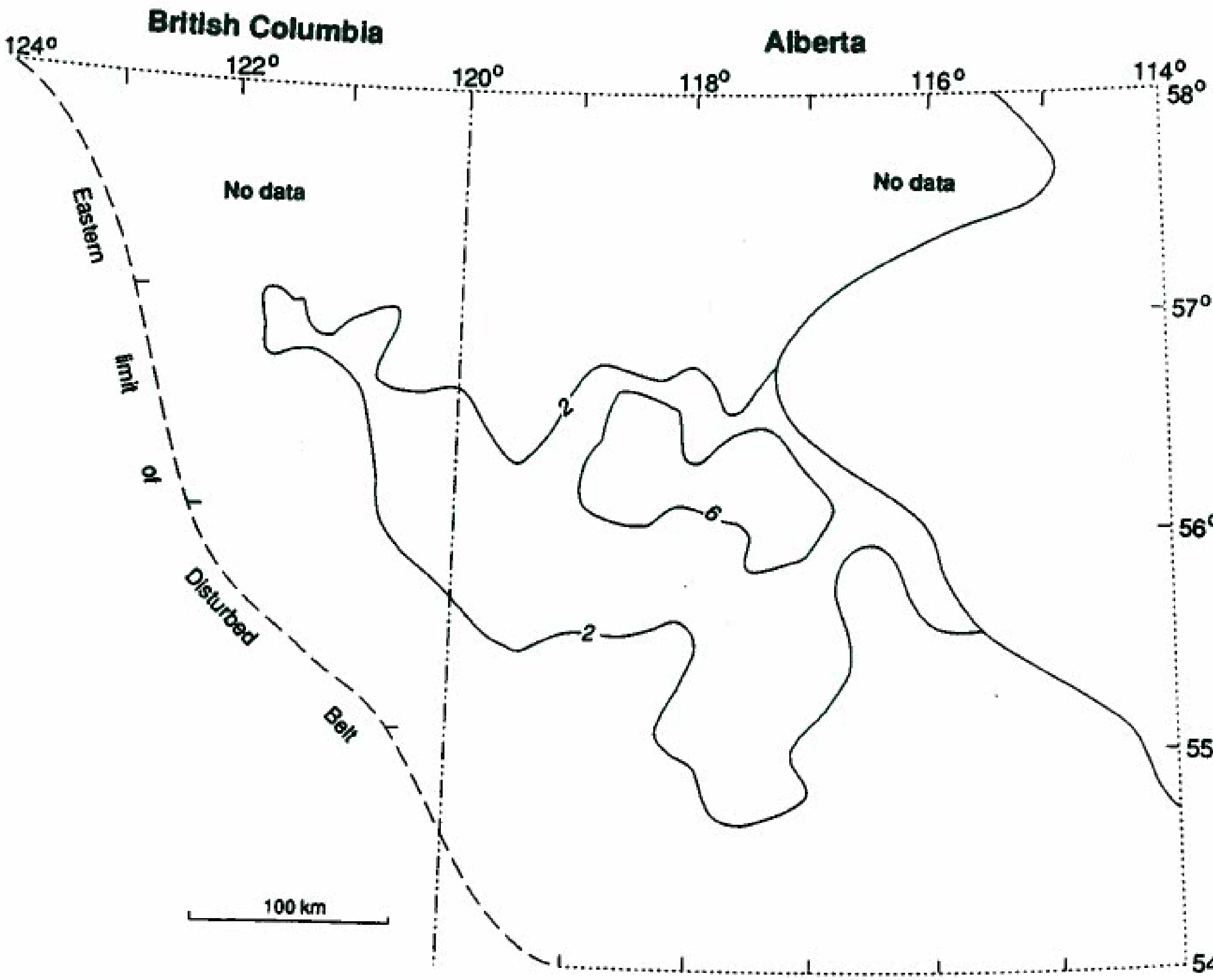

Figure 36. Distribution of HCO_3 (mg/lx10^3) in the Gething-Cadomin aquifer.

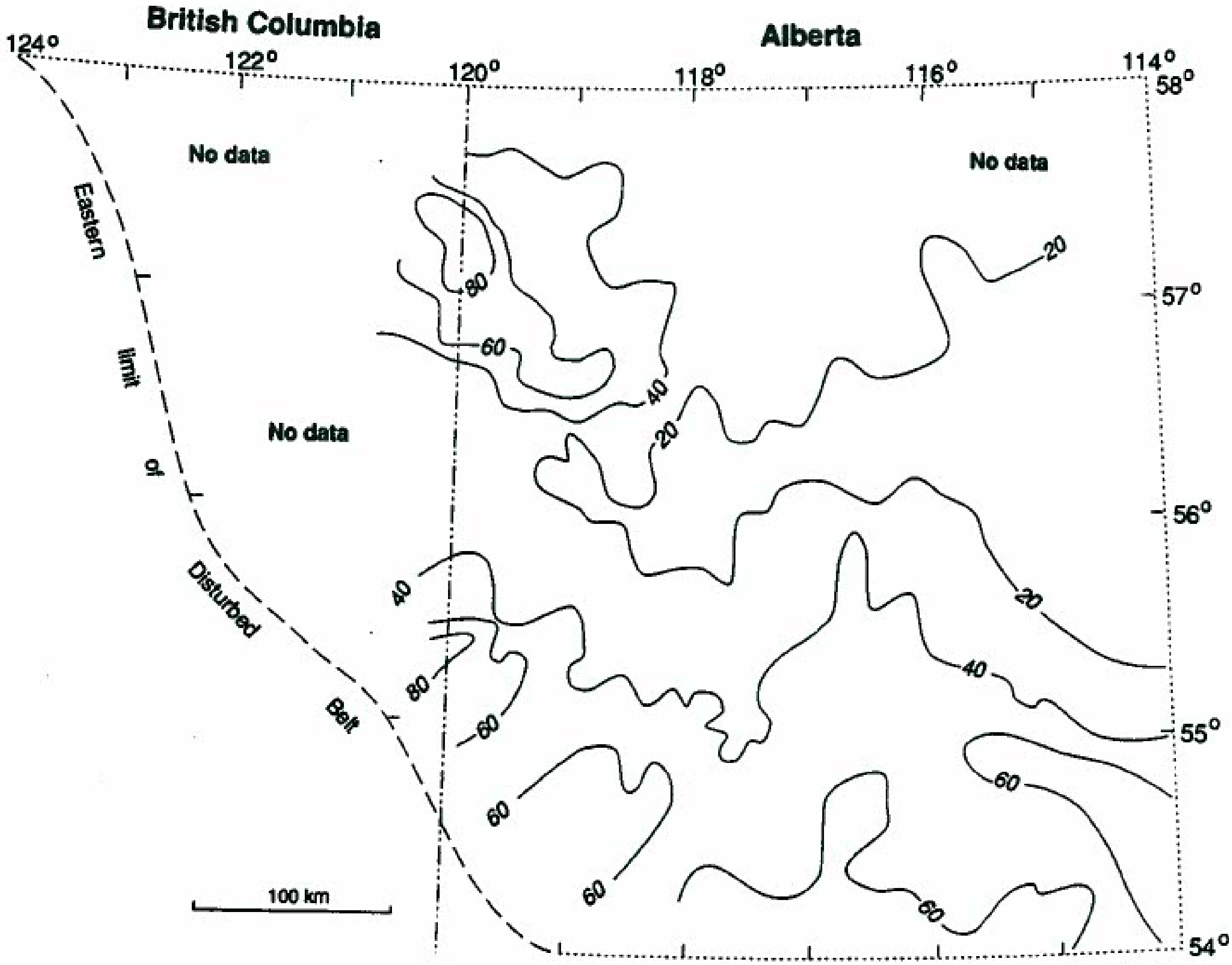

Figure 37. Salinity distribution (mg/lx10³) in the Bluesky aquifer.

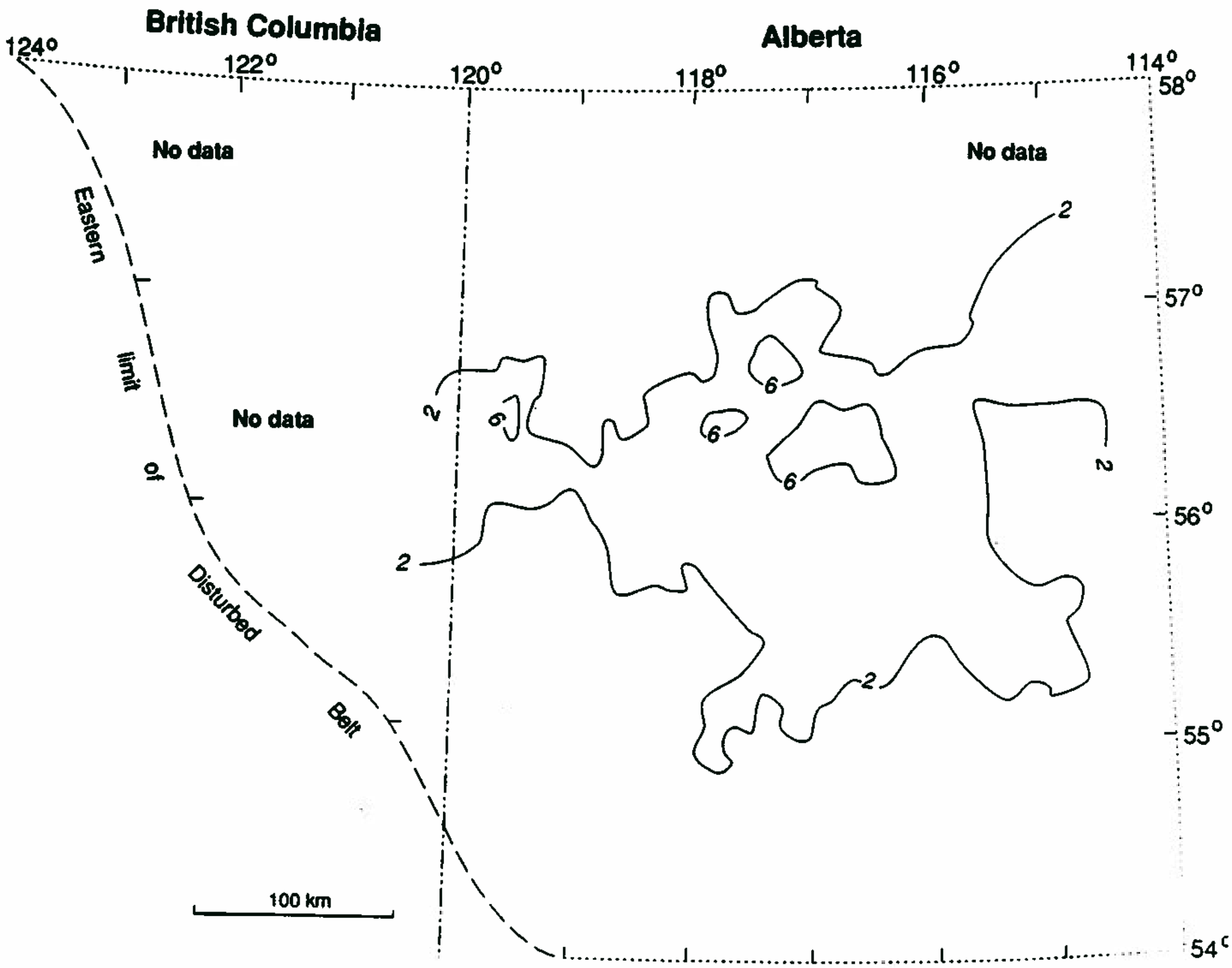

Figure 38. Distribution of HCO_3 ($mg/l \times 10^3$) in the Bluesky aquifer

are aquifers in the southwestern part of the study area but in the north and east the Falher Member is an aquitard. Figure 39 shows the southern and eastern limits of the 0.5 sandstone/shale ratio for the Spirit River Formation (Rudkin, 1964). In the study area the lower shale unit (Wilrich aquitard) is thin but from pressure head-depth plots in the Swan Hills area it is known to be an effective aquitard. Indeed, both the flow pattern and salinity distribution in the Lower and Upper Mannville aquifers in the Swan Hills area are distinctly different, confirming its efficiency as an aquitard. The Spirit River aquifer has an average thickness of 225 m, and is seldom >300 m (maximum 400 m).

The salinity distribution trends (Fig. 39) resemble those in the Bluesky aquifer (Fig. 37), except that the salinity is lower in the Spirit River aquifer. This suggests that, at the scale of the study area, the Clearwater-Wilrich aquitard may not be as effective as the study in the Swan Hills area indicates. Indeed, as will be seen later, the salinity distribution patterns in the Gething-Cadomin, Bluesky and Spirit River aquifers all differ from that in the Paddy aquifer (Fig. 40) which is separated from these three aquifers by the Harmon (Joli Fou) aquitard. Only a detailed study of the hydrodynamics of this suite of hydrostratigraphic units will clarify the relative importance of the Clearwater-Wilrich and Harmon-Joli Fou aquitards as effective regional water-retarding units. The composition distribution patterns for Cl, Ca and Mg resemble that for salinity; the HCO_3 distribution pattern has only a general similarity to that in the underlying Bluesky aquifer (Fig. 38). Sulfate shows no obvious regional trends.

Harmon

Overlying the Spirit River Formation is the Peace River Formation, which comprises a lower Harmon Member and an upper Paddy Member. The Harmon Member is equivalent to the Joli Fou Formation and the Paddy Member to the Viking Formation in central Alberta. The shales of the Harmon Member are thin (average 15 m), and in the Swan Hills area are a rather ineffective aquitard -- termed the Joli Fou aquitard in the report of Hitchon *et al.* (1989b). Toth (1978) did not distinguish the Harmon aquitard in the Red Earth region but included the entire Peace River Formation with the Notikewin Member (Spirit River Formation) as a separate aquifer (K_{II}). A few formation waters were assigned to the Harmon Member but most were from sandy beds transitional to the underlying Notikewin

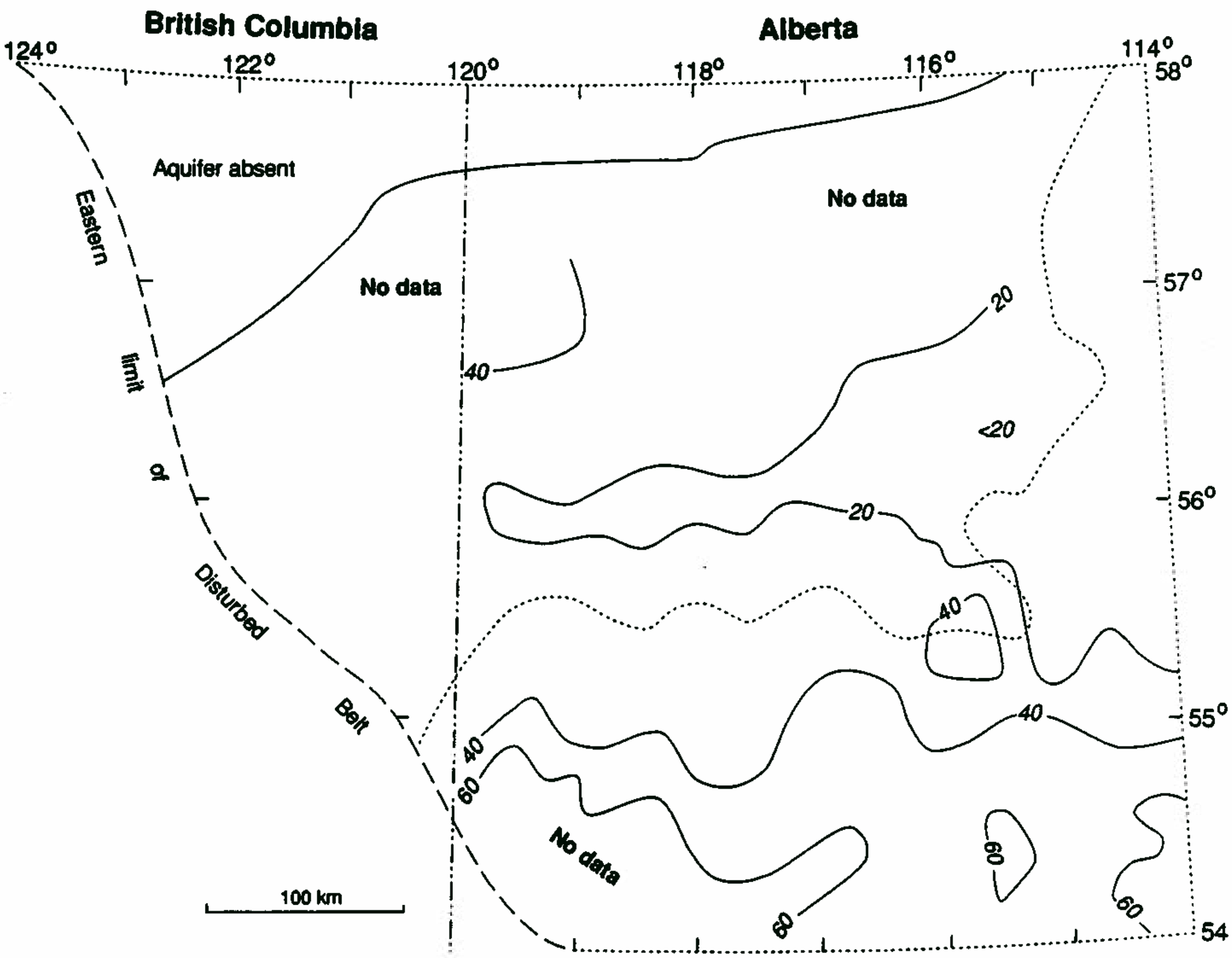

Figure 39. Salinity distribution (mg/lx10³) in the Spirit River aquifer. Line of short dots is 0.5 sandstone/shale ratio (from Rudkin, 1964).

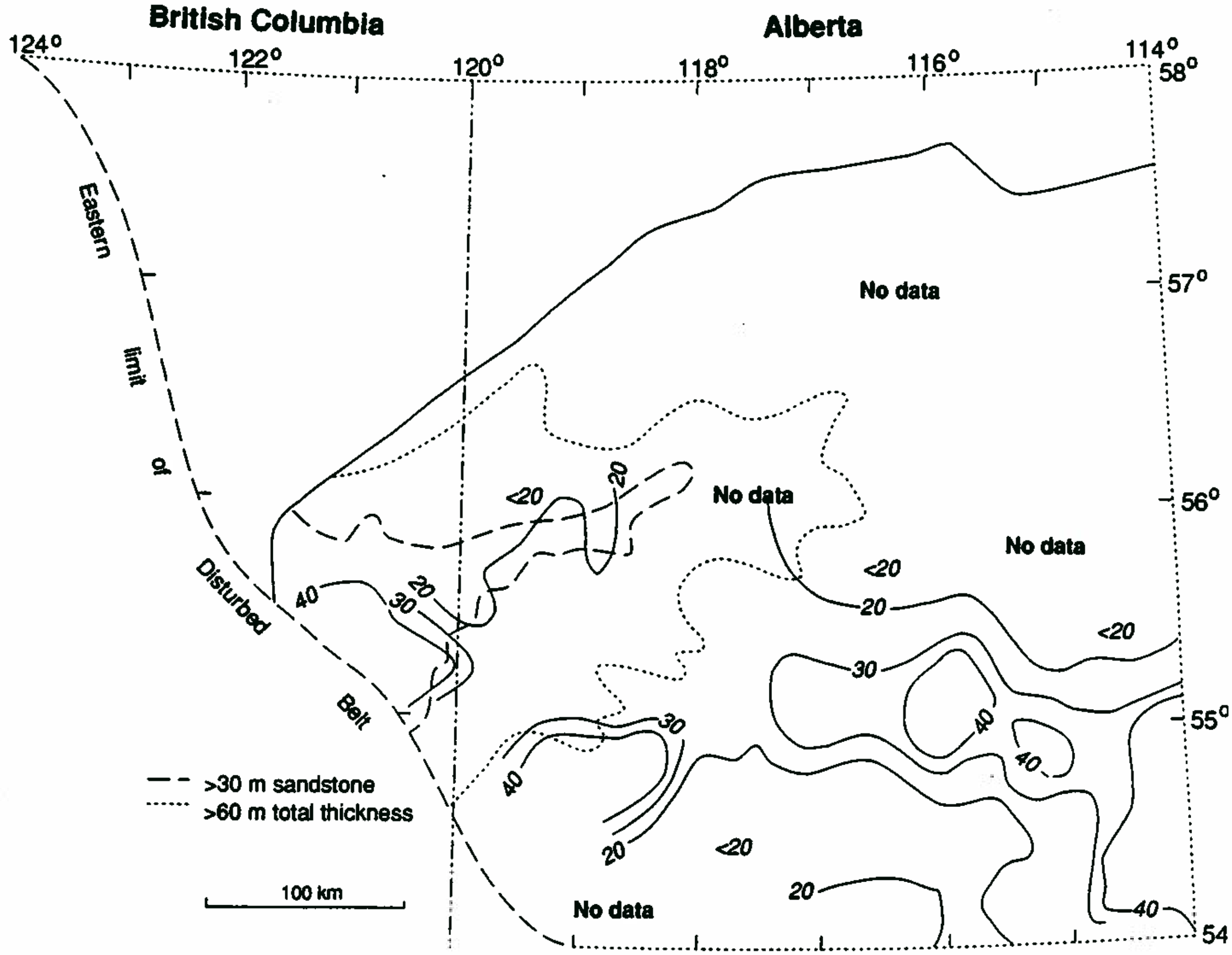

Figure 40. Salinity distribution (mg/lx10³) in the Paddy aquifer.

aquifer or the overlying Paddy aquifer. The northern limit of the Harmon aquitard coincides with the northern limit of the Paddy aquifer (see Fig. 40).

Paddy

The Paddy aquifer averages ~30 m in the Peace River Arch study area, but reaches 110 m in a sandstone-rich band (>100 ft, >30 m; Rudkin, 1964) stretching east-west through the central part of the area (Fig. 40). Salinity distribution (Fig. 40) is complex, with salinity >30,000 mg/l being found in two isolated areas close to the disturbed belt (one in the centre of the sandstone-rich band) and in a generally northwest-southeast trending zone in the southeast quarter of the study area. This particular zone of relatively high salinity formation water coincides with a zone of lower sandstone content (<25 ft, ~7.6 m) within an area of higher sandstone content (25-50 ft, 7.6-15.2 m) identified on an isopach-lithofacies map compiled by Rudkin (1964).

On a basin-wide scale the salinity pattern in the Viking aquifer of central Alberta exhibits a strong northwest-southeast orientation (Hitchon, 1964, Fig. 15-36). Basin-wide hydraulic head distribution in the Viking aquifer is complicated by a closed hydraulic head low in central Alberta (Hitchon, 1969). Clearly, some salinity trends in the Paddy aquifer of the study area may be related to lithology but others are equally clearly unrelated. What is uncertain is the degree to which the closed hydraulic head low and nearsurface meteoric water recharge have affected the salinity pattern distribution. In the Swan Hills area Hitchon *et al.*(1989b) noted both a possible effect of the very northern part of the central Alberta closed hydraulic head low on the Viking aquifer in that area, and also that there was no clear reflection of the effect of recharge at the Swan Hills on the salinity distribution. This is unlikely true for the Peace River Arch study area as a whole because the Paddy aquifer is exposed along part of the valley of the Peace River.

The three high-salinity areas have corresponding high contents of Cl (>20,000 mg/l) and Mg (>100 mg/l), and generally low contents of HCO_3 (<500 mg/l). There were no obvious trends for Ca or SO_4.

Shaftsbury

The Shaftsbury Formation is effectively defined on the basis of the eastern limit of the overlying Dunvegan Formation (Fig. 41). East of the designated boundary, where the Dunvegan aquifer is absent, there is a continuous shale unit (Labiche Formation) from the top of the Paddy aquifer (and equivalent Viking aquifer) to the surface. The Shaftsbury and Labiche Formations include within them the Lower Cretaceous-Upper Cretaceous boundary, marked by the Base of Fish Scales zone. The Shaftsbury Formation is <100 m in the southeast but thickens gradually to 1150 m in the northern part of the study area.

Toth (1978) recognized the Shaftsbury Formation as a major aquitard in the Red Earth region, noting that it was sandy locally. In the Swan Hills area all strata younger than the Viking Formation were classified as the Colorado aquitard system, including all post-Viking aquifers (Hitchon *et al.*, 1989b). Formation water was recovered from the Base of Fish Scales zone at six localities (Fig. 41); salinity was 22,000 mg/l at the western and northern occurrences and 45,000 to 60,000 mg/l at the four eastern occurrences.

Dunvegan

The Dunvegan Formation consists of a series of individual, generally quartzose sandstones with interbedded siltstones and shales. In the south it is <50 m but thickens to 150 to 200 m in the central area; nowhere does it exceed 340 m. Formation water was recovered at several localities in the southern half of the area but the data were insufficient to allow computer contouring. Salinity was in the narrow range 6000 to 20,000 mg/l (Fig. 42), with comparable contents of other components (Cl 2600-11,200 mg/l; Ca ~50-2000 mg/l; Mg < ~100 mg/l; SO_4 1-1000 mg/l; HCO_3 475-4000 mg/l).

Kaskapau and Doe Creek

The thick succession of shales and thin sandstones above the Dunvegan Formation belong to the Smoky Group. In ascending order they include the argillaceous Kaskapau Formation, the Cardium Formation, the shales of the thin Muskiki Formation, the Badheart Formation, and finally the argillaceous Puskwaskau Formation. Within the Kaskapau aquitard are a series of thin sandstones of which only the Doe Creek in the lower part of the aquitard has been

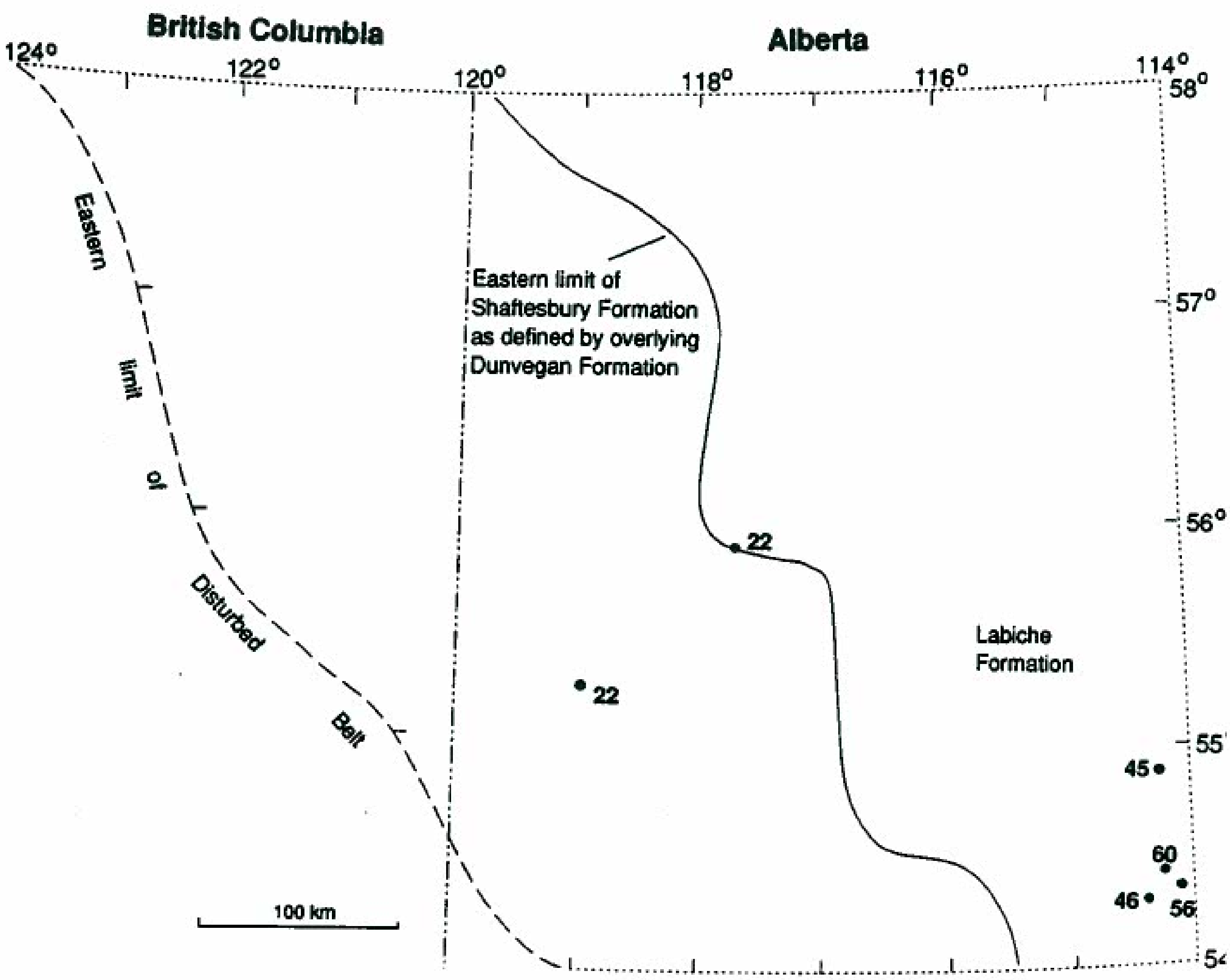

Figure 41. Location and salinity (mg/lx10³) of formation waters recovered from the Base of Fish Scales zone within the Shaftbury and Labiche aquitards.

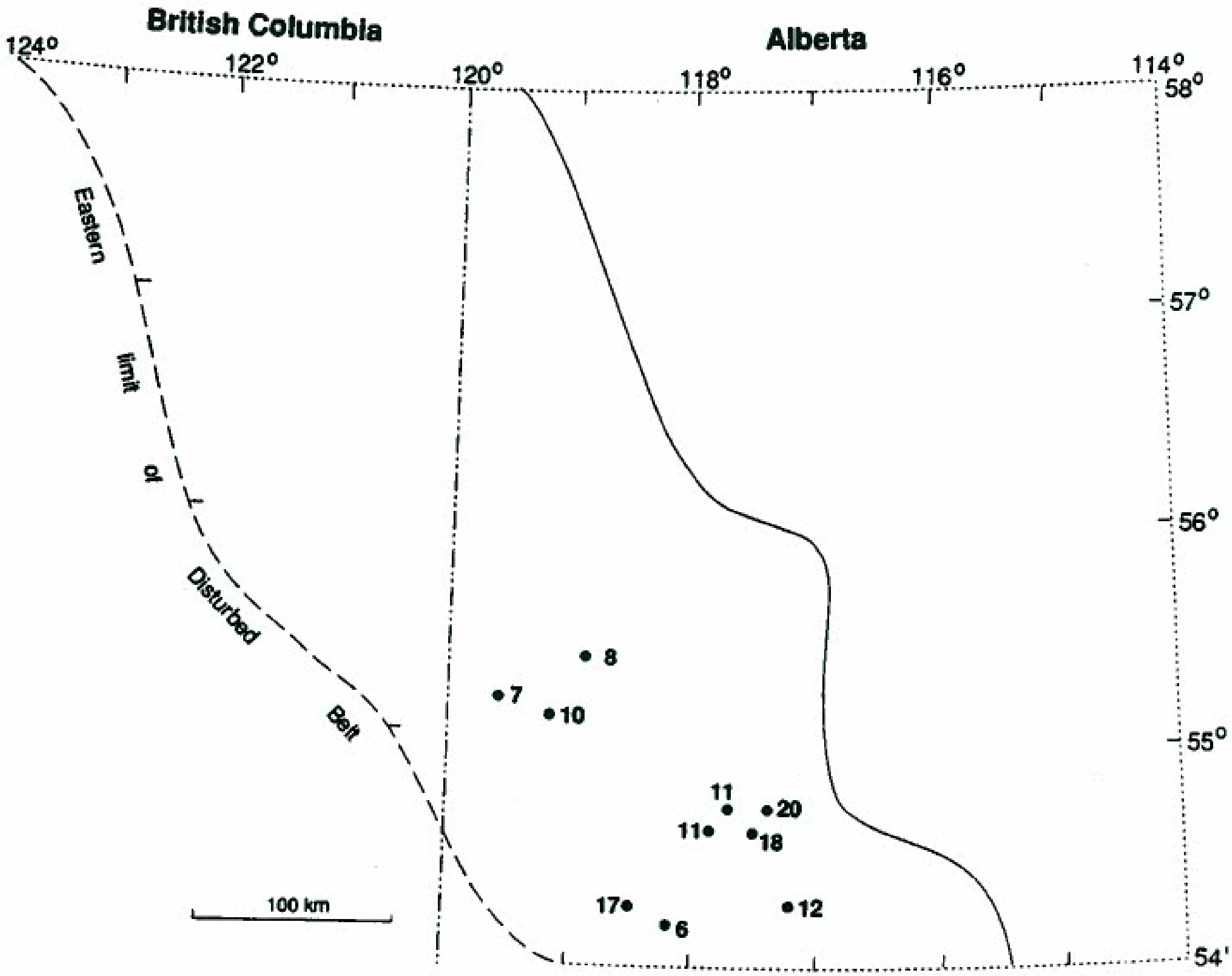

Figure 42. Salinity (mg/lx10³) of formation waters from the Dunvegan aquifer.

distinguished in this study. The Doe Creek aquifer is thin (maximum 120 m, average 20 m) and is found only in the south of the region. Two analyses of formation waters are reported from the Second White Speckled shale (which lies within the Kaskapau Formation) but little can be said other than their salinities were 8000 and 61,700 mg/l.

Cardium

The Cardium aquifer is confined to the south of the study area and lies between the Kaskapau and Muskiki aquitards. Its eastern boundary is depositional and it thickens westward, reaching nearly 140 m in places close to the disturbed belt. Where the Cardium aquifer is present the underlying Kaskapau aquitard ranges from ~175 m in the east to nearly 690 m close to the disturbed belt. Salinity of formation waters (Fig. 43) is in a rather narrow range (7000-~20,000 mg/l), with comparable trends and ranges for the other components.

Badheart

The Badheart aquifer stretches across the southern third of the study area and lies between the Muskiki and Puskwaskau aquitards. The aquifer is generally <10 m thick (maximum 60 m). Where the Badheart aquifer is present the underlying Muskiki aquitard ranges from ~40 m in the east to 175 m close to the disturbed belt in the southwest. All of the formation water analyses originally assigned to this aquifer were from other aquifers.

Chinook

The top unit of the Smoky Group is the Puskwaskau Formation, which for the purposes of this study was distinguished only in the area where it is overlain by the Chinook aquifer. The Puskwaskau aquitard exhibits quite variable thickness, but generally increases to the southwest to a maximum of 245 m close to the disturbed belt. Sandstones identified as belonging to the Chinook aquifer range up to 105 m thick but are generally much thinner (average 23 m); there was no obvious regional trend. A few analyses of formation water were from units variously identified as Chinook sandstone or Lea Park (the equivalent of the Puskwaskau Formation in central Alberta) but none was uncontaminated.

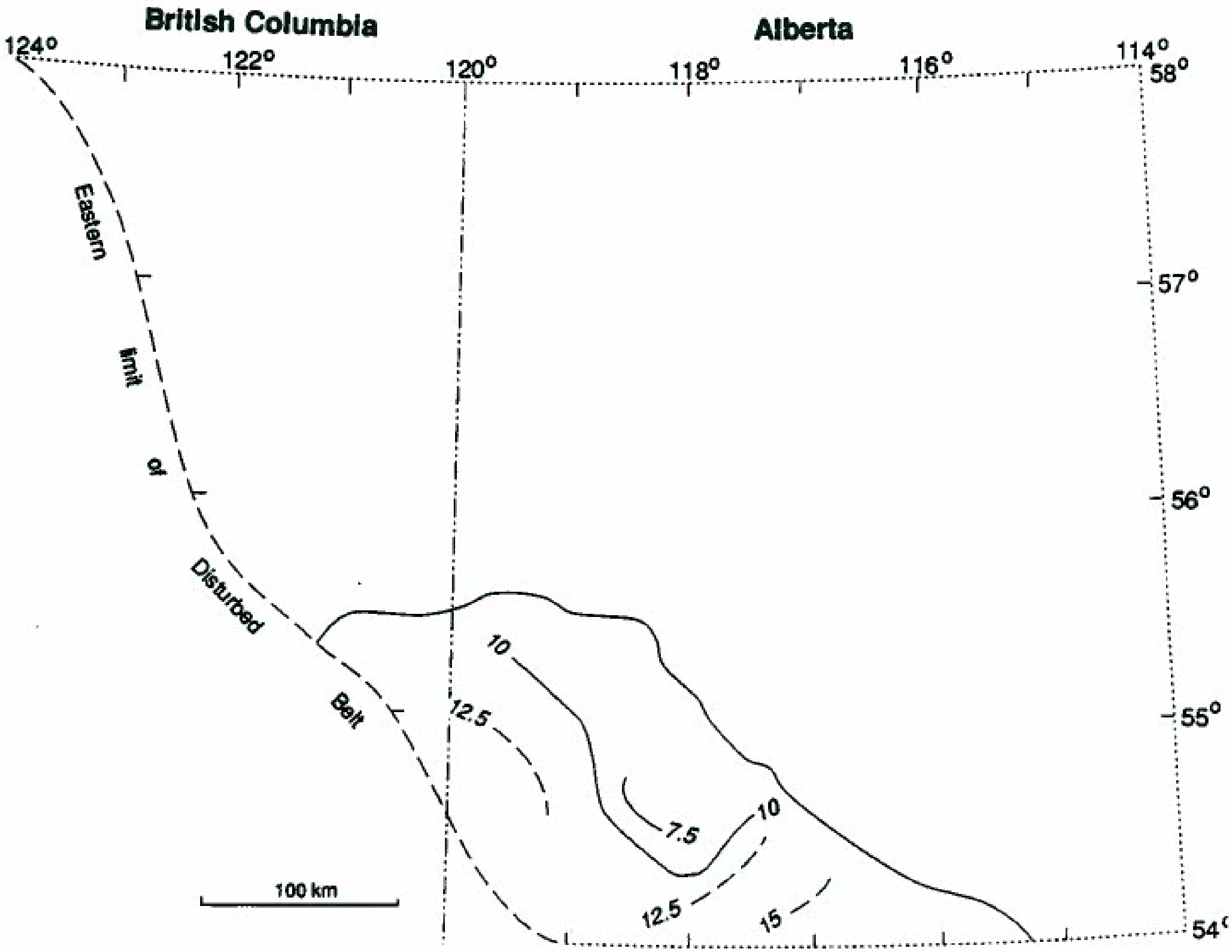

Figure 43. Salinity distribution (mg/lx10³) in the Cardium aquifer.

Wapiabi

The youngest Cretaceous unit is the Wapiabi Formation, which has been subjected to considerable pre-Tertiary and Recent erosion and is now confined to the southern third of the study area. It is capped by the Tertiary Paskapoo Formation in the Swan Hills and along the southern boundary of the study area. Maximum thickness is 225 m. Analyses of formation waters from the Belly River Group in the extreme southeast corner of the study area are from the approximate stratigraphic equivalent of the Wapiabi Formation. Sample depths range from 210 to 600 m, but most are around 400 m. They are mostly freshwater, with salinity in the range 2500 to ~10,000 mg/l, and corresponding ranges for Cl (1500-6000 mg/l), Ca (15-160 mg/l), Mg (5-50 mg/l), HCO_3 (150-400 mg/l) and SO_4 (commonly <100 mg/l).

Tertiary and Quaternary

There were no analyses of formation waters from Tertiary aquifers on file, and no attempt was made to collect or summarize information from shallow Quaternary aquifers held in various groundwater data bases.

SUMMARY

More than 30,000 formation water analyses from the Peace River Arch area were entered into the Alberta Geological Survey Well Data Base, verified, and subjected to a variety of electronic and manual-electronic culling procedures to leave a data base of about 9600 fairly reliable analyses. Subsequent manual culling resulted in a final data base of about 6800 formation water analyses reported here. The coarseness of the stratigraphic grid resulted in a considerable number of misallocations, most of which were corrected in the final set of salinity maps produced for this study. The reader is cautioned, however, to reevaluate the hydrochemical data base at a local scale for specific details in local areas. With this background and caveat in mind, the following general observations can be made on the hydrochemistry of the study area.

Salinity ranges from freshwater to 380,000 mg/l, with the usual regional increase in salinity with depth. This regional salinity increase with depth is also a function of generally decreased permeability with depth (hence slower water movement) and increased temperature (hence increased water-rock reaction). Overlaid on the salinity-depth relation is additional salinity due to the presence of evaporites, especially halite. This results in reversals of the regional salinity-depth relation, for example in aquifers adjacent to the Lower Devonian Lotsberg Formation halite; see salinity distribution maps for the Granite Wash (Fig. 6), Chinchaga-Contact Rapids (Fig. 7), Keg River (Fig. 8), Muskeg (Fig. 9) and Fort Vermilion (Fig. 11) aquifers. Indeed, within the limits of the data distribution, salinity >300,000 mg/l is confined to those aquifers in contact with the Lotsberg Formation halite.

The broad regional salinity distribution patterns for effectively all pre-Cretaceous aquifers, except as modified by the presence of halite, show salinity concentration contours which trend northwest-southeast, parallel to the structure contours. This feature is particularly well seen in aquifers without major internal differences in lithology, and hence transmissivity e.g. Upper Banff (Fig. 22), Belloy (Fig. 27) and Diaber (Fig. 28) aquifers. For aquifers such as the Nisku (Fig. 16), Blueridge (Fig. 17), combined Winterburn (Fig. 19) and to some extent the Wabamun (Fig. 21) there is a high-salinity tongue extending updip to generally shallower depths in the general position of the underlying Leduc and Swan Hills aquifers of the Windfall-Swan Hills reef complex; this tongue is

superimposed on the broad regional salinity distribution pattern and like many similar features probably has an origin in the access of deeper saline water to shallower parts of the aquifer along high-permeability zones. It is interesting that this same feature is associated with higher HCO_3 contents in both the Winterburn (Fig. 20) and Wabamun aquifers, a feature normally associated with hydrodynamic drain effects such as are associated wit the Grosmont aquifer.

For the Gething-Cadomin (Fig. 35), Bluesky (Fig. 37) and Spirit River (Fig. 39) aquifers the salinity distribution pattern shows two major higher salinity (>50,000 mg/l) regions, one along the entire southern boundary of the study area and stretching about one-third of the way northward across the area, and the other a band stretching northwest from about the location of the Clear Hills. These higher salinity regions are unrelated to the structure contours. They appear more related to the regional topography, with the southern region coinciding with topographic elevations >1000 m, which curve in a crescent from Swan Hills to the disturbed belt. The region with salinity <20,000 mg/l and HCO_3 >6000 mg/l (Gething-Cadomin aquifer, Fig. 36; Bluesky aquifer, Fig. 38) is associated with topographic elevations <600 m along the valley of the Peace River. The salinity distribution for the Paddy aquifer (Fig. 40) appears unrelated to either structure contours or surface topography.

With respect to salinity distribution, there are thus two major groups. Pre-Cretaceous aquifers show higher salinity related to increased depth, hence increased temperature, with modifications due to increased salinity associated with Lower Devonian halite and higher permeability trends within individual aquifers. For Cretaceous aquifers below the Harmon-Joli Fou aquitard, the salinity distribution is unrelated to the structure contours and appears more related to surface topographic features. However, this association may be more apparent than real for relatively shallow aquifers in regions with strongly contrasting surface topography. Aquifers above the Harmon-Joli Fou aquitard are too few to make general statements. The resolution of the different salinity distribution patterns must await detailed hydrodynamic evaluation.

The relations of the other components to salinity is usually quite clear. The distribution patterns for Cl, Ca and Mg tend to closely resemble that for salinity. For any specific aquifer, and as a broad generalization, the higher salinity regions have relatively lower HCO_3 contents compared to the lower salinity regions.

Hence for some aquifers (e.g. Grosmont) the HCO_3 distribution map indicates regions of drainage, based on confirming hydrodynamic studies. Sulfate usually shows no obvious regional trends, but in at least the case of the Charlie Lake aquifer (Fig. 31) SO_4 >2500 mg/l is associated with anhydrite. Generally, the salinity distribution map provides a broad indication of the distribution of other components in the aquifer.

This study of the hydrochemistry of the Peace River Arch area is based on about 6800 standard formation water analyses. They are irregularly distributed among many aquifers, which themselves are separated by sometimes considerable thicknesses of aquitards, and occasionally aquicludes. Within a volume of sedimentary rock of about 400,000 km^3, this averages 60 analyses per cubic kilometer. Thus any conclusions drawn can only be of a regional, basin-wide nature. Despite this limitation certain patterns emerge which suggest strong relations among formation water composition, depth, temperature, water-rock reactions and fluid flow. The hydrochemical information presented in this report should form a sound basis for future hydrogeological studies in the Peace River Arch area.

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