INDUSTRIAL MINERAL RESOURCES
IN
ALBERTA FORMATION WATERS

Prepared for

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

by

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1994-03-31

PREFACE

This report presents the results of work performed in the second year of a three year program funded by the Canada-Alberta Partnership Agreement on Mineral Development (project MDA92-011) regarding the industrial mineral potential of Alberta formation waters. In the first year the contents of Ca, Mg, K, I, Li and Br in formation waters were characterized throughout the province, and four regions and stratigraphic intervals of potential economic interest identified. This report presents maps of resource estimates in terms of $Tx10^3/km^2$ for elements occurring at high concentrations in each of these key regions and stratigraphic intervals.

Acknowledgements

Special thanks are due to Kelly Roberts and Campbell Kidston who did the majority of the data processing and report illustrations. Michel Brulotte provided data base support and Sherry Grolway assisted in the preparation of the manuscript.

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Abstract

Stratigraphic intervals in four regions of Alberta were previously identified as having formation waters with potentially economic concentrations of calcium (Ca), magnesium (Mg), potassium (K), iodide (I), lithium (Li) and bromide (Br). The present study estimates the element resources in each of the four areas and stratigraphic intervals. For each area, maps were produced of the distributions of thickness, porosity and element concentration. Resource distribution maps were then generated in units of thousands of Tonnes per square kilometer for each element of potential economic interest.

Formation waters in Lower Elk Point strata of northeastern Alberta contain high concentrations of Ca, Mg, K and Br, with Ca and Mg concentrations exceeding the detailed exploration threshold. Above the Lotsberg salt deposit, where data control is good, resources of Ca and Mg are of the order of 200 - 600 $Tx10^3/km^2$ and 20 - 60 $Tx10^3/km^2$, respectively. Formation waters in Beaverhill Lake strata of southern Alberta also have high concentrations of Ca, Mg, K and Br, with Ca, Mg and K concentrations exceeding their detailed exploration thresholds. In this region, Ca resources range from 250 - 1250 $Tx10^3/km^2$, Mg resources range from 50 - 200 $Tx10^3/km^2$, and K resources from 5 - 250 $Tx10^3/km^2$. Formation waters in Woodbend and Beaverhill Lake strata of west-central Alberta have a high Li content with resources of about 1 - 2 $Tx10^3/km^2$ where data control is good. Formation waters

in Viking strata across central and southern Alberta have regions of high I concentrations with resource estimates locally as high as 0.6 $Tx10^3/km^2$, but generally of the order of 0.2 $Tx10^3/km^2$. In lower Belly River strata I resources are in the range 10 - 50 $Tx10^3/km^2$. The producibility of the resources characterized for these four regions of Alberta will be examined in the third phase of the study.

Introduction

This report is the second of a three-part series which examines the industrial mineral resources of Alberta formation waters. The first part (Hitchon et al., 1993) presented the mineral potential of Alberta formation waters in terms of element concentrations for Ca, Mg, K, I, Li and Br, and outlined areas of possible economic interest. This report presents estimates of the magnitude of the resource in each of the areas previously identified as being of potential economic interest.

Definitions and scope of study

Although there is no universally recognized classification of underground waters, the terms and definitions used in this report are as generic as possible:

ground water:	shallow formation water, commonly potable (salinity generally <1,000 mg/l);
formation water:	preferred generic term for all underground water, regardless of salinity;
saline formation water:	loosely used for formation water with salinity <100,000 mg/l;
	and
brine:	strictly for formation water with salinity > 100,000 mg/l, but saline formation water is the preferred term

In searching for potential mineral resources, information on the geochemistry and origin of formation waters is important, as is an understanding of the regional and local hydrogeology. An exploration program therefore should have three phases (Hitchon et al., 1993):

1. Geochemical exploration

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

2. Resource evaluation

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

3. Site specific evaluation

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

Hitchon et al. (1993) identified areas and stratigraphic intervals in Alberta where elemental concentrations are above detailed exploration thresholds (phase 1). This report presents work with respect to a portion of the second phase (as identified above), namely, characterization of porosity distribution within the zones of potential economic interest and estimation of the magnitude of the resource. Evaluation of permeability distributions for the areas and zones of potential economic interest is required in order to estimate the producibility of the resource, and this aspect of the second phase will be covered in the third year of the study.

Industrial mineral potential of Alberta formation waters

An electronic data base of nearly 130,000 analyses of formation waters from Alberta and adjacent areas was searched for elements of potential economic interest (Hitchon et al., 1993). For regional exploration, the elements and their respective threshold values were: Ca (20,000 mg/l), Mg (3,000 mg/l), K (5,000 mg/l), Li (50 mg/l), Br (1,000 mg/l) and I (40 mg/l). Using a variety of culling procedures, element concentration maps, and maps of posted values of individual analyses, four areas and stratigraphic intervals were identified where these elements exceed their respective detailed exploration threshold values: Ca (60,000 mg/l), Mg (9,000 mg/l), K (10,000 mg/l), Li (75 mg/l), Br (3,000 mg/l) and I (100 mg/l). The detailed exploration threshold values are comparable to concentrations in formation waters produced commercially by Dow Chemical Co. from the Lower Devonian Sylvania Sandstone in the Michigan Basin at Midland, Michigan, USA.

Table 1 summarizes the vast amount of data examined in terms of the maximum contents of Ca, Mg, K, Li, Br, and I in each of the stratigraphic units examined. For ease of presentation, maximum contents above the detailed exploration thresholds are presented in bold characters. The values where the maximum content is less than the regional exploration threshold are starred. After examining all the available information, Hitchon et al. (1993) outlined four stratigraphic intervals over specific geographic areas (figure 1) where the formation waters contain elements of potentially economic concentrations.

Table 1. Summary of maximum contents (mg/l) of potential industrial minerals in Alberta formation waters (from Hitchon et al., 1993).

Stratigraphic Unit	Ca	Mg	K	Li	Br	I
Tertiary	*	*	*	*	*	*
Cretaceous						
Belly River Formation	*	*	*	*	*	99
Lea Park Fm.	*	*	*	*	*	*
Milk Rover Fm.	*	*	*	*	*	*
Cardium Fm.	*	*	*	*	*	77
Dunvegan Fm.	*	*	*	*	*	62
Viking, Bow Island Fms.	*	*	*	*	*	128
U. Mannville Gp.	*	5000	*	*	*	76
L. Mannville Gp.	*	5000	*	*	*	*
Jurassic						
Kootnay Gp.	28000	4000	*	*	*	*
Fernie Gp.	*	5000	*	*	*	*
Triassic						
Baldonnel Fm.	*	*	*	60	*	*
Charlie Lake Fm.	23000	6000	*	68	*	*
Halfway Fm.	41000	10000	6000	58	*	53
Montney Fm.	20000	5000	*	60	*	*
Permian	*	*	*	*	*	90
Carboniferous						
Stoddart Gp.	22000	4500	*	*	*	*
Rundle Gp.	25000	7000	*	60	*	58
Banff Fm.	25000	5000	*	52	*	43
Denvonian						
Wabamun Gp.	30000	12300	10000	115	*	*
Winterburn Gp.	30000	5000	8500	90	1880	38
Woodbend Gp.	39000	8000	10000	140	2115	53
Beaverhill Lake Gp.	98000	13500	19000	130	2785	50
Watt Mountain Fm.	40000	8000	7000	98	*	*
Keg River Fm.	46000	7000	7000	95	136-	120
L. Elk Point Gp.	95000	12000	5000	71	1530	40
Ordovician	27000	75000	*	*	*	*
Cambrian	30000	7000	*	81	*	*

* = all formation water analyses below respective regional exploration thresholds.

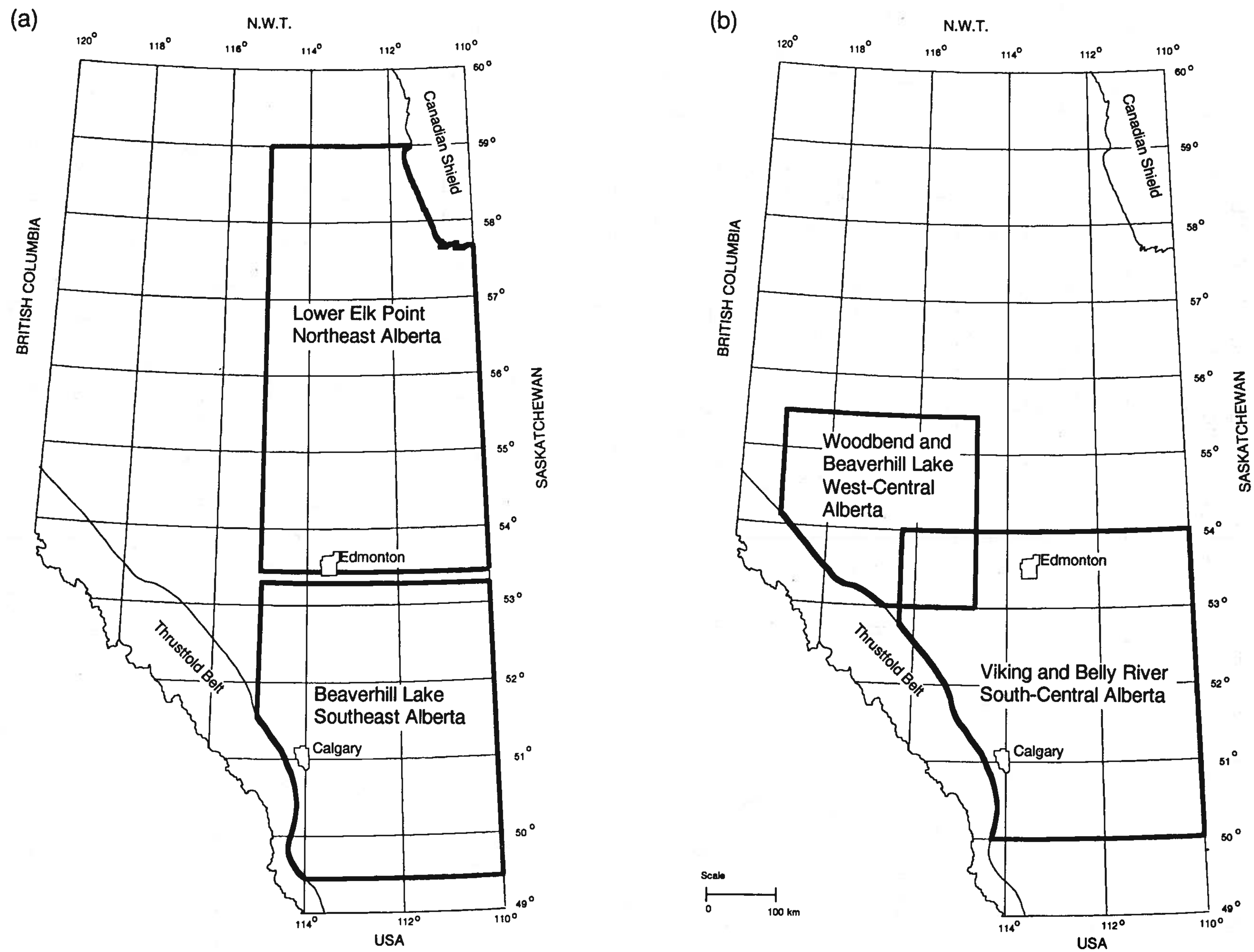


Figure 1. Regions of potentially economic industrial minerals in Alberta formation waters:
(a) mainly for Ca, Mg, K and Br; (b) mainly for Li and I.

Lower Elk Point

Formation waters in Lower Elk Point strata between the top of the Contact Rapids Formation and the top of the first underlying salt bed (Upper Lotsberg, Lower Lotsberg or Cold Lake, depending on the geographic position) in northeastern Alberta contain high concentrations of Ca, Mg, K and Br. The Ca and Mg concentrations are greater than their respective detailed exploration thresholds. Although K and Br concentrations do not reach the detailed exploration threshold, they warrant consideration because they could be byproducts if Ca and Mg were to be produced. The high concentrations of these elements appear to be associated with the distribution of Lower Elk Point Group evaporite deposits. Unfortunately, there are few reliable analyses of formation waters in this region and stratigraphic interval, resulting in a poorly constrained geographic area of potential economic interest. The geographic region for which industrial mineral resources are estimated in this study covers approximately 210,000 km^2, from Tp 53 to Tp 115 and from R 1 W4Mer to R 6 W5Mer (figure 1).

Beaverhill Lake

Formation waters in Beaverhill Lake strata in southern Alberta have concentrations of Ca, Mg and K exceeding their respective detailed exploration threshold value. As in the Lower Elk Point of northeast Alberta, these high concentrations are associated with the presence of an evaporite deposit. The region for which industrial mineral resources are estimated is approximately 170,000 km^2, in the area defined from Tp 7 to Tp 52 and from R 1 W4Mer to R 7 W5Mer (figure 1).

Woodbend and Beaverhill Lake

Woodbend and Beaverhill Lake strata in west-central Alberta contain formation waters with Li concentrations above the detailed exploration limit. The high Li concentrations appear to be associated mainly with carbonate build-ups of the Leduc Formation in the Woodbend Group and the Swan Hills Formation of the Beaverhill Lake Group (figure 2). High values are also recorded in the Cooking Lake Formation of the Woodbend Group, other formations within the Beaverhill Lake Group and even strata as low as the Cambrian. The geographic area for which Li resources are estimated covers approximately 75,000 km^2, from Tp 51 to Tp 76 and from R 4 W5Mer to R 7W6Mer (figure 1).

Viking and Belly River

The Viking and Belly River strata in central and southern Alberta have formation waters which contain I concentrations near the detailed exploration threshold. High I concentrations in these two units tend to be discontinuous over large areas, and are associated locally with hydrocarbon accumulations. The geographic area for which I resources are estimated covers approximately 190,000 km^2, from Tp 12 to Tp 57 and from R 1 W4Mer to R 14W5Mer (figure 1).

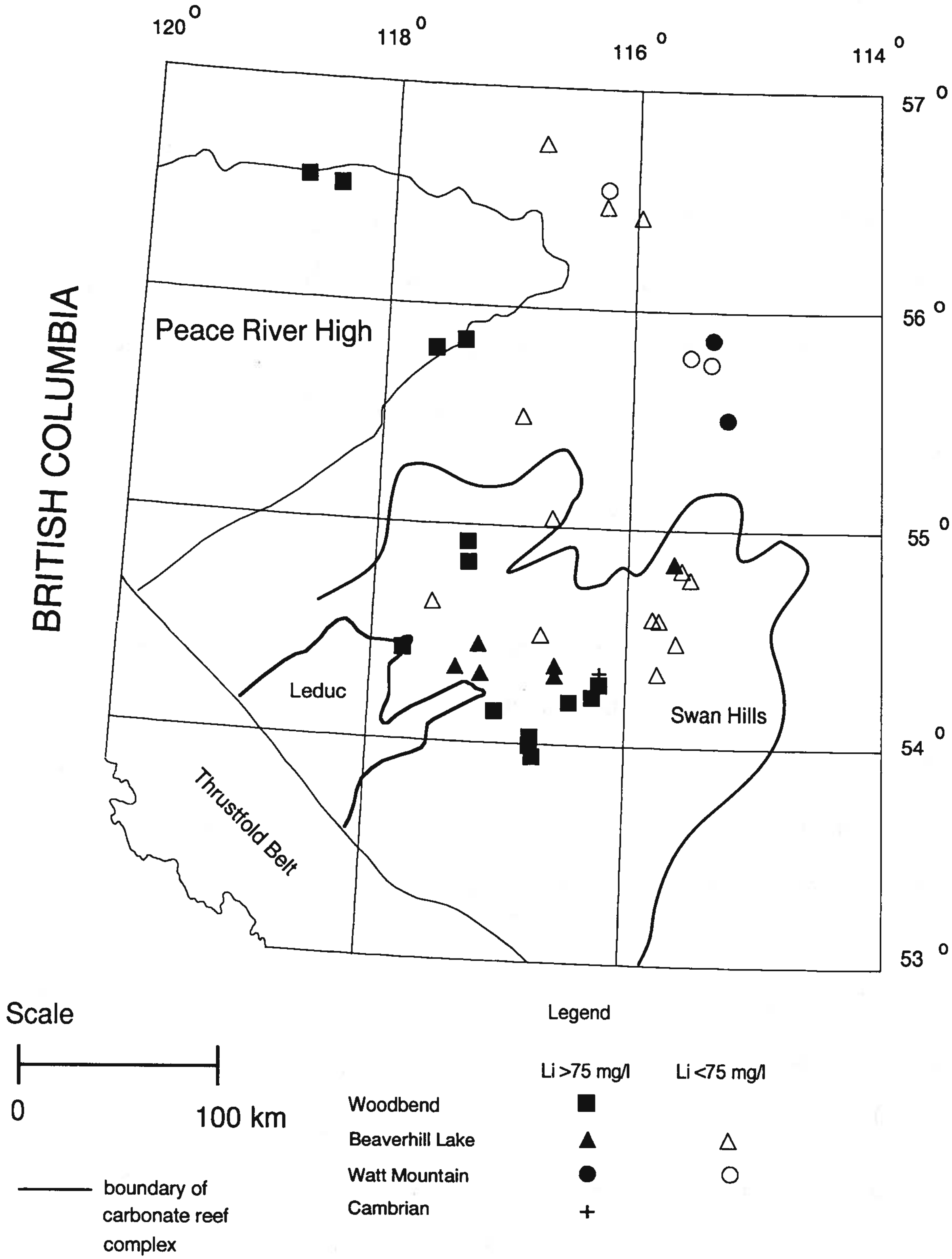


Figure 2. Posting of Li in formation waters, Woodbend and Beaverhill Lake strata, west-centeral Alberta.

Data sources and data processing

Three parameters are required in order to calculate the resources of an element in formation waters within an area of a specific stratigraphic interval: (1) the concentration of the element; (2) the thickness of the unit; and (3) the porosity distribution. The resource can then be estimated according to the relation:

$$(D \times Ø \times C)/1000 = R \qquad (1)$$

where D is thickness in m, Ø is porosity expressed as a fraction, C is concentration in mg/l, and R is the resource per aquifer unit area in kg/m^2. Therefore, a distribution map of R presents, at any location, an estimate of the element resource to be found in that stratigraphic interval. An estimate of the total resource for a stratigraphic interval and area of interest can be calculated by integrating the distribution of R across the region.

Although the thickness, porosity and element concentration data came from separate sources, their distributions were characterized using similar electronic gridding and mapping procedures. Because thickness, porosity, and concentration measurements are seldom available at every location, the resource estimates were calculated from electronic grids (maps) rather than individual data points.

Electronic mapping and contouring

Parameters, such as some of those needed in this study, which have a continuous distribution are most conveniently displayed in the form of contour maps for ease of analysis and understanding. The contour maps are based on electronic grids constructed from the original data. An electronic grid is defined as a mathematical resampling of irregularly spaced data into a regular distribution. The gridding algorithm and the grid spacing can have a significant impact on the resulting grid and the corresponding map.

In an integrated approach, as is the case in this study, it is important to select a gridding algorithm producing grids and maps which meet criteria essential for all aspects of the project. The main criteria for algorithm selection were: (1) the final grid spacing and dimensions must be constant for all data types and stratigraphic units within any given area; (2) where data exist, the resultant grid must accurately represent the observed values; and (3) the gridding must take into account the high variability in data density both areally and with depth. With these constraints in mind, a convergent gridding algorithm from CPS-3 software of Radian Corporation was selected whereby grid-node values are converged upon through several iterations. The value at a given node is estimated by using a distance-weighting technique such that control points closer to the node have a larger effect on the outcome of the value at the node (Graf and Thomas, 1988).

In the convergent gridding process, a series of steps are performed within each iteration. A coarse grid is used in the first iteration. The grid dimensions depend on the size of the study-area and the number of data points. Several surrounding points are considered at each node (8 to 16 depending on the data density). The coarse grid is subsequently smoothed and tied to point values using a biharmonic filter (Graf and Thomas, 1988). There may be up to 10 gridding iterations, and at each successive iteration fewer surrounding point values are considered at each node, and the number of nodes increases. In the last pass, the grid is refined to its final grid spacing and only the closest point value is considered at each node. This iterative process produces a trend-like solution in areas of sparse or no data, and an accurate representation where data exist. During each iteration, the goodness of fit between the grid and the data is monitored to determine if more iterations are necessary (Graf and Thomas, 1988). The final map is generated by contouring the electronic grid produced by the convergent gridding algorithm. A consistent set of grids representing various parameters within a study area allows for inter-grid operations such as the production of a resource map according to relation (1).

Thickness data

Thickness data for the zone of interest within each geographic area were derived from geophysical well logs. The quantity and quality of data varied greatly between the zones and areas of interest. The control data point set from the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1994), which consists of one well per township, was used as an initial data set for each of the areas. Other data sets were used, as appropriate. Once all the available data were checked and culled, thickness data were gridded and mapped.

Lower Elk Point

In the Lower Elk Point strata of northeast Alberta, the interval of interest is from the top of the Contact Rapids Formation to the top of the first underlying salt bed, which may be the Cold Lake, Upper Lotsberg or Lower Lotsberg, depending on the geographic position. Although salt is absent in parts of the study area, these regions correspond to areas where the concentrations of the elements of interest are below the detailed exploration thresholds. Because the control data point set (from Mossop and Shetsen, 1994) does not include picks for these particular stratigraphic horizons, previously culled data sets (Bachu and Underschultz, 1993) containing picks for all wells north of Tp 69 were used. Energy Resources Conservation Board (ERCB) stratigraphic picks were extracted, checked and culled for the area south of Tp 70. These data sets were combined and used as the control set (1047 wells) for gridding and mapping the thickness of the strata of interest in northeast Alberta.

Beaverhill Lake

In southern Alberta, the stratigraphic interval of interest is from the top of the Cooking Lake Formation to the top of the Elk Point Group. This interval comprises the Cooking Lake Formation and the Beaverhill Lake Group. Data from the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1994) were used as a basis against which ERCB picks from all the wells within the area were checked and culled. A final data set of 1379 points was used to constrain the thickness grid and map within the region of interest.

Woodbend and Beaverhill Lake

The stratigraphic interval of interest for the region of formation waters with high Li includes the Leduc and Cooking Lake formations of the Woodbend Group and the underlying Beaverhill Lake Group (Waterways, Swan Hills, Slave Point and Fort Vermilion formations). For these strata, data from the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1994) and stratigraphic picks from a previous study in the Peace River Arch region (Hitchon et al., 1990) were used as a basis of defining the stratigraphy. These data were supplemented by ERCB picks which were checked and culled to be consistent with other data sets. A total of 5586 points were used within the region of interest.

Viking and Belly River

Both the Viking and Belly River formations contain high I concentrations over generally the same region of central and southern Alberta. Data from the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1994) and ERCB data were used to define the stratigraphy of these two formations. Within the region of interest, 10,010 wells record the Viking Formation and 32,431 wells record the Belly River Formation. Within the Belly River Formation, I concentrations exceed the detailed exploration threshold only in the lower third of the unit. Thus, the isopach constructed for the purpose of resource estimation represents only the thickness of the economically-interesting lower portion of the Belly River Formation.

Porosity data

Two data sources were used to obtain information on porosity distribution. Porosity measured on core plugs provided voluminous direct measurements, although this information tends to be biased toward high porosity zones of interest to the petroleum industry. Porosity estimated from geophysical log analysis provided an indirect but continuous measure across the entire interval of interest at any particular geographic location. Because of the different nature of the two types of porosity data, each required separate processing.

Porosity from core plugs

A typical core-plug analysis contains information about the porosity, permeability, grain density, and length of the characteristic interval. Nearly all core plugs are analyzed for porosity, while less than half are measured for permeability. There are commonly several core-plug measurements within each cored interval. Because of the large number of analyses, an automated electronic screening procedure was required to check, first that the analyzed interval contained porosity measurements, and second, that the recorded value was acceptable. Porosity determinations greater than 43% (near the value characteristic for unconsolidated sediment) were considered erroneous and were rejected.

Porosity data obtained from core analyses represent volume-averaged values corresponding to the plug-scale (Baveye and Sposito, 1984). In order to characterize a geological unit at a regional scale, a scaling-up process must be used. Because of the large difference in magnitude between the plug-scale and the regional scale, a sequential scaling-up process is required (Cushman, 1984). Therefore, once the porosity data were located within the unit of interest, they were scaled-up to the well-scale using the same procedure employed by Bachu and Underschultz (1992) in the analysis of porosity and permeability variation in the Peace River Arch area. Porosity is a scalar property of the porous media. It is generally accepted (Dagan, 1989) that the local-scale porosity in uniform sediments and sedimentary rocks can be described by a normal probability density function. The representative well-scale porosity values were calculated as the arithmetic average of the plug-scale values weighted by the length of the representative interval. The formation-scale distributions of well-scale porosity values were analyzed for spatial variability by stratigraphic unit through a gridding and mapping procedure.

Porosity from geophysical logs

For wells with digitized geophysical logs the determination of porosity was conducted using INTELLOG electronic geophysical log-analysis software. Electronic logs were obtained by manually digitizing hard-copy geophysical logs. The INTELLOG-based system uses neutron-porosity, density-porosity and gamma-ray logs, and is calibrated to information from core-plug analyses where these are available. The output from the INTELLOG log analysis is a porosity estimate at a 0.25 m interval. Unlike core-plug data, which tend to be restricted to specific intervals, the log analysis provides an estimate of porosity throughout the entire stratigraphic interval of interest. The porosity values (obtained on a 0.25 m interval) were subsequently scaled-up to characteristic well-scale values using the same procedure described previously for core-plug porosity data. Because obtaining digital geophysical logs is labour intensive, this type of data was used only for units where core plug analyses were felt to be grossly insufficient.

Elk Point strata in northeast Alberta and Beaverhill Lake strata of southern Alberta vary widely in lithology and corresponding rock properties, and are constrained by the fewest core-plug values of the four regions studied. Thus, all wells having the required suite of logs in the specific interval of interest were digitized and calibrated to the available core-plug data. As a result, 15 wells from Elk Point strata of northeast Alberta and 12 wells from the Beaverhill Lake strata of southern Alberta were used to characterize the porosity distributions in the regions. Only the log-derived porosity data were used in producing the porosity distribution maps because the core and log data sets represent different populations and cannot be mixed. Of the two data types, the core data are probably less representative for the purposes of resource estimation.

The Viking and Belly River formations are relatively thin stratigraphic intervals and contain a large number of porosity analyses (2758 and 1315 well-scale values for the Viking and Belly River formations, respectively), distributed rather evenly. Therefore, only core-plug data were used to characterize the spatial variability of porosity in these units. The Woodbend and Beaverhill Lake strata within the high Li area are thick and have a large lithologic variability, therefore, only the 2310 well-scale porosity values derived from core-plug measurements were used to characterize the spatial variability of porosity in the area of interest.

Element concentration data

Element concentration data from the first phase of the study (Hitchon et al., 1993) were extracted from the data base and mapped at a scale and grid spacing consistent with that used for thickness and porosity data. Any small differences between element-concentration distributions shown in this report and equivalent ones shown in the previous regional study (Hitchon et al., 1993) are due to different scales, grid spacing, and data control (e.g. only data falling within the detailed study areas were used here).

Resource estimate maps

Before presenting the resource estimate maps it is extremely important to point out the practical limitations of maps generated through mathematical manipulation. First, for all the stratigraphic units evaluated, the data density for both formation water analyses and porosity is sparse, uneven, and inadequate for all but the type of regional study carried out here. Second, the resource values used to compile the maps are based on average porosity values across the entire stratigraphic interval being evaluated. The maps are therefore estimates, at best, of the total amount of element in formation water at that location, much of which may not be producible, for a wide range of reasons. Third, and apart from economic considerations, producibility relates to permeability (among many other factors) which has not been considered in this phase of the study. In evaluating the producibility, attention must be directed at the high porosity zones, rather than to the total interval over which the present porosity values relate. These caveats to the limitations of the resource estimate maps presented here must be considered in any interpretation of the numbers. In part, these limitations are an effect of attempting to handle huge amounts of information necessary for this type of regional study within a staged, dollar-constrained project.

Evaluation of resources

The industrial mineral resources of Alberta formation waters are estimated for the regions and stratigraphic intervals previously identified (Hitchon et al., 1993) as having concentrations of elements above their respective detailed exploration thresholds. For this reason, mineral resources are evaluated by region and stratigraphic interval rather than by commodity.

Lower Elk Point

In northeast Alberta, the Lower Elk Point strata of interest form a wedge which thickens from 20 m in the northeast to more than 100 m in the southwest (figure 3). Porosity data are from geophysical logs calibrated to core analyses and therefore represent the entire stratigraphic interval. Although the number of well-averaged porosity values is small, some porosity trends are evident (figure 4). Most noticeable is an east-west trending zone of low porosity (<8%) across the area between about Tp 90 and Tp 105. North of this zone, porosity increases to the northwest, while south of the zone porosity increases from west to east. The zone of low porosity approximately corresponds to the region of the Lower Elk Point interval devoid of salt beds. Resource estimates for individual elements were determined from the thickness, porosity, and element concentration grids according to relation (1).

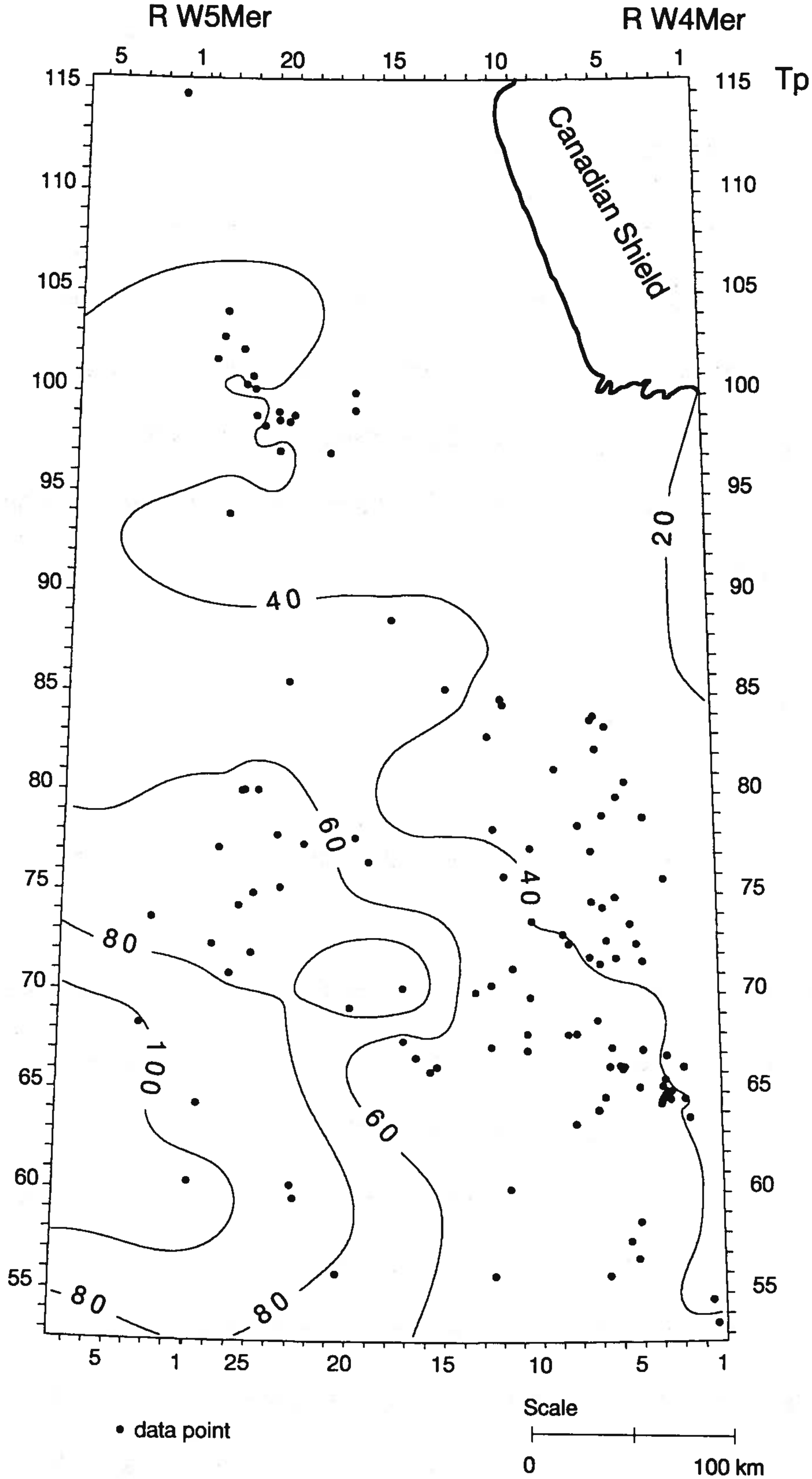


Figure 3. Isopach of Lower Elk Point strata, northeast Alberta (contour interval: 20 m).

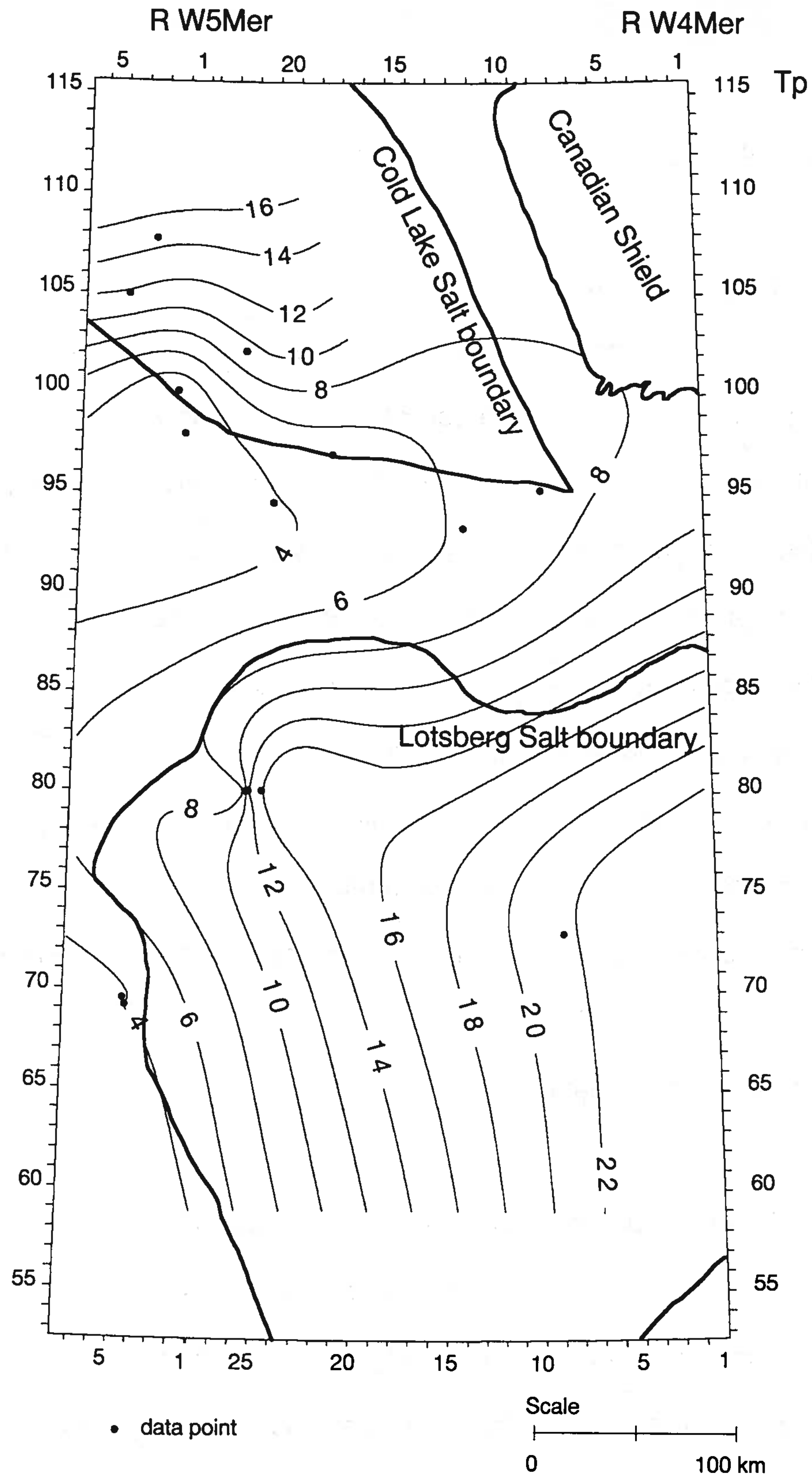


Figure 4. Porosity distribution, Lower Elk Point strata, northeast Alberta (contour interval: 2%).

Calcium resource estimate

Although the distribution of formation water analyses is limited to the western half of the study area, two regions of high Ca concentration (greater than 60,000 mg/l) occur above the Lotsberg and Cold Lake salt deposits in the southeastern and northeastern parts of this area, respectively (figure 5). The highest resource estimate per unit area for Ca is located in the south-central part of the study area (figure 6), coincident with a small region of anomalously thick strata (figure 3). For areas of high Ca, the estimated values are significantly greater in the south than in the north (figure 6) due to a combination of greater thickness, higher porosity and higher Ca concentration. It should be noted that the Ca concentration data are few and poorly distributed (figure 5), resulting in speculative values throughout much of the study area. Reserve estimates should be made only for the area bounded by the dashed line (figure 6).

Magnesium resource estimate

Regions within the study area where Mg exceeds the 9000 mg/l detailed exploration threshold (figure 7) generally correspond to the high-Ca areas noted previously. Figure 8 shows the distribution of the Mg resource within the study area, with the highest values in the southern part of the study area. As in the case of Ca, the most

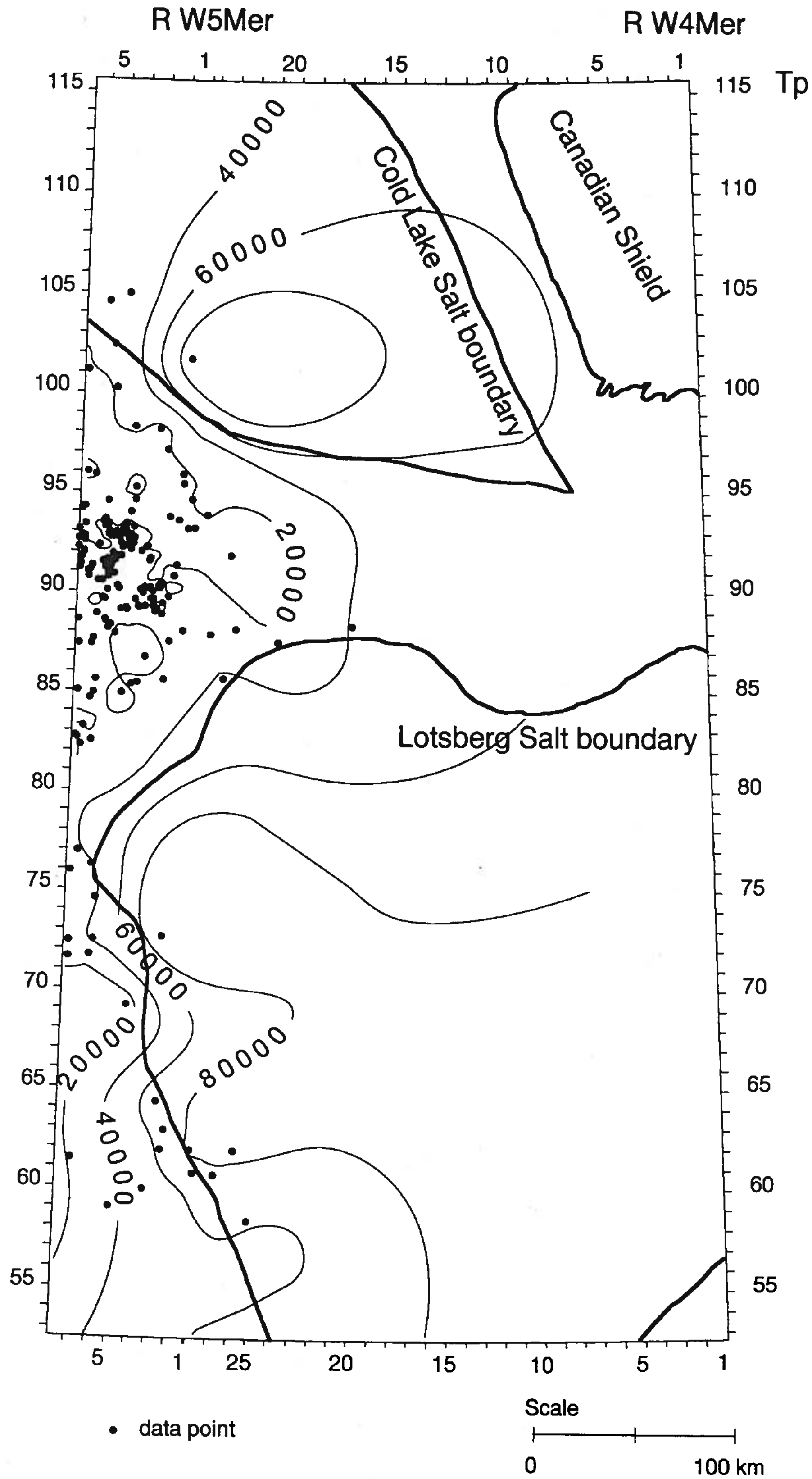


Figure 5. Distribution of Ca in formation water, Lower Elk Point, northeast Alberta (contour interval: 20,000 mg/l).

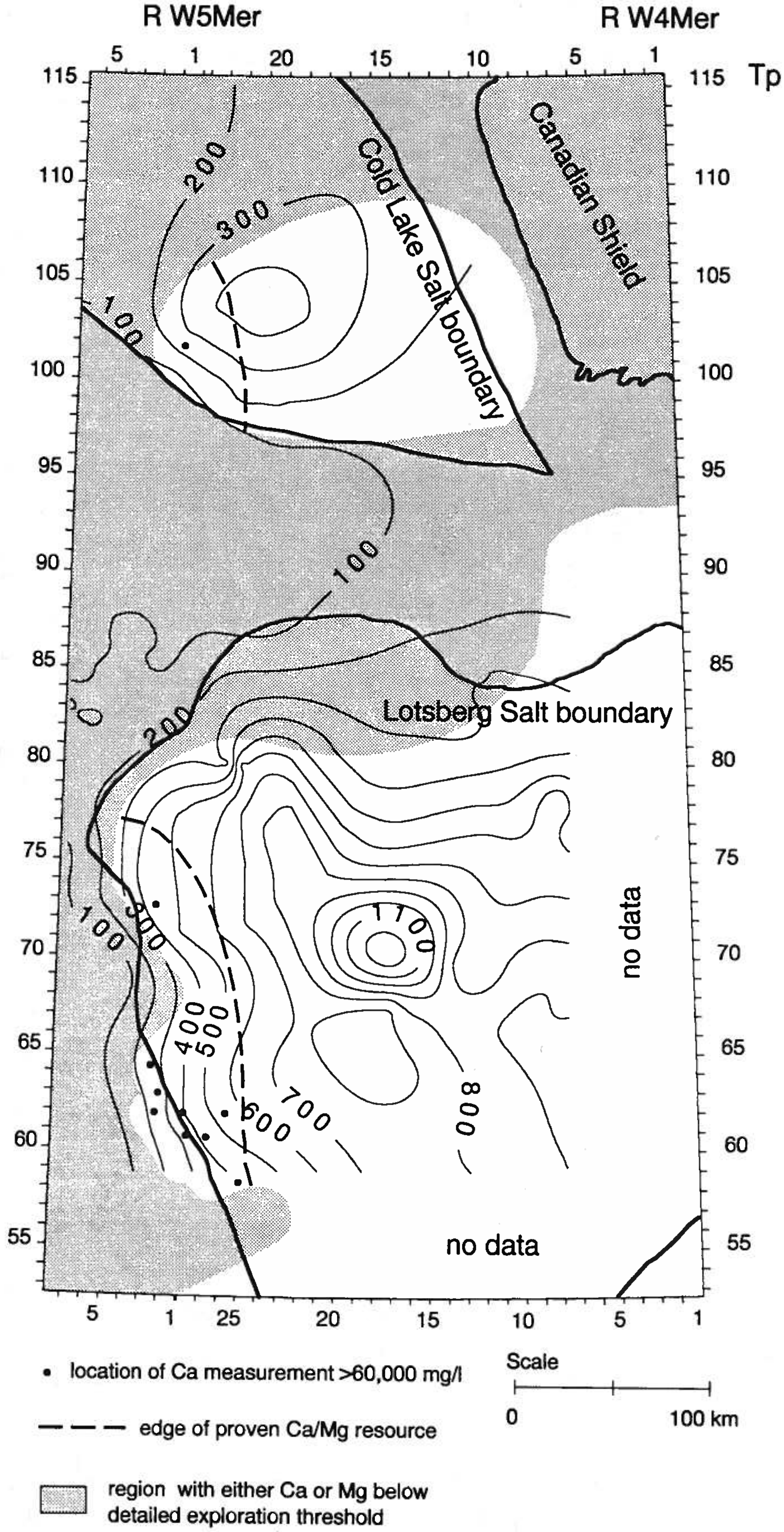


Figure 6. Resource distribution estimate of Ca ($Tx10^3/km^2$) in formation water, Lower Elk Point, northeast Alberta.

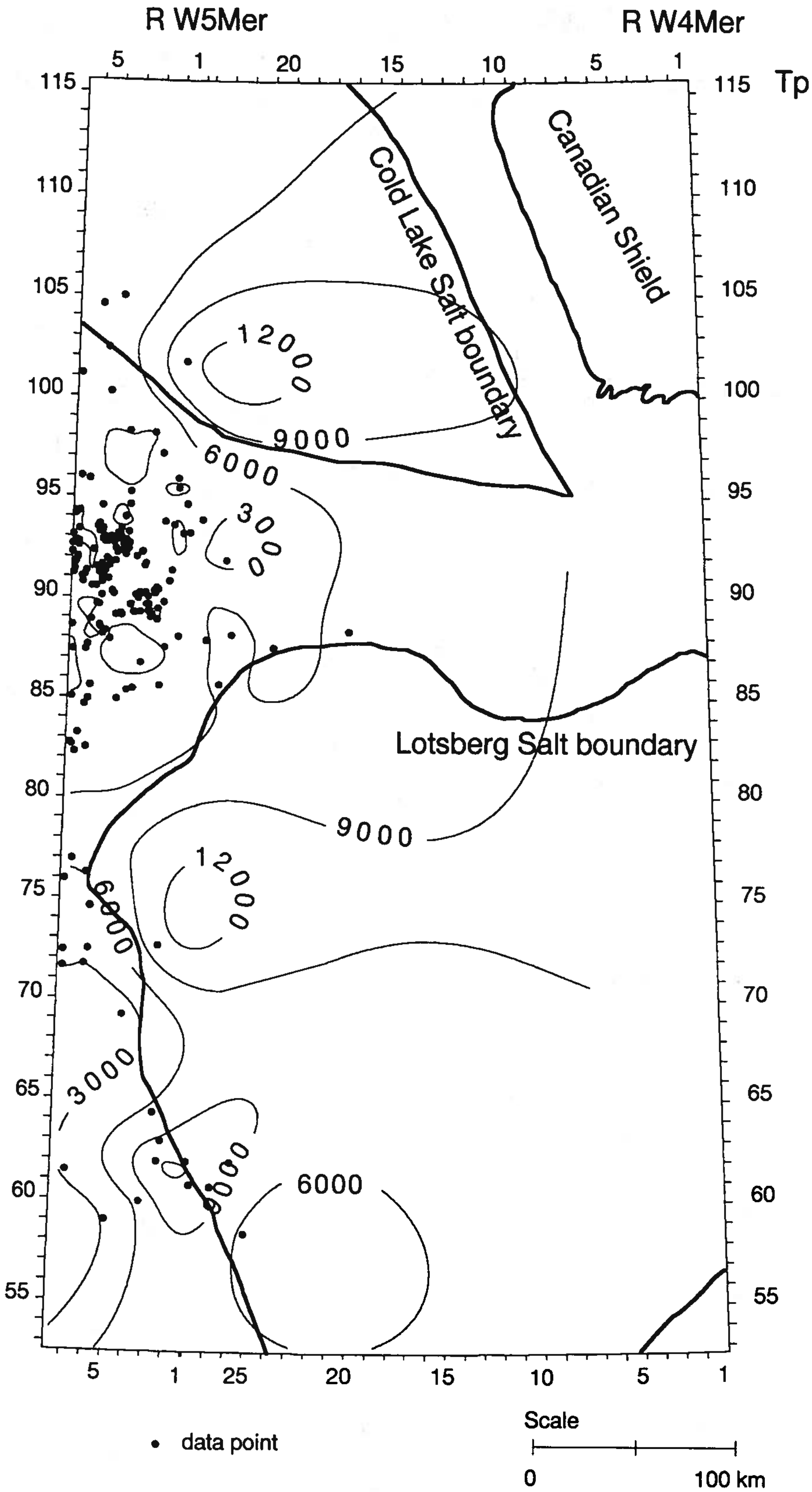


Figure 7. Distribution of Mg in formation water, Lower Elk Point, northeast Alberta (contour interval: 3000 mg/l).

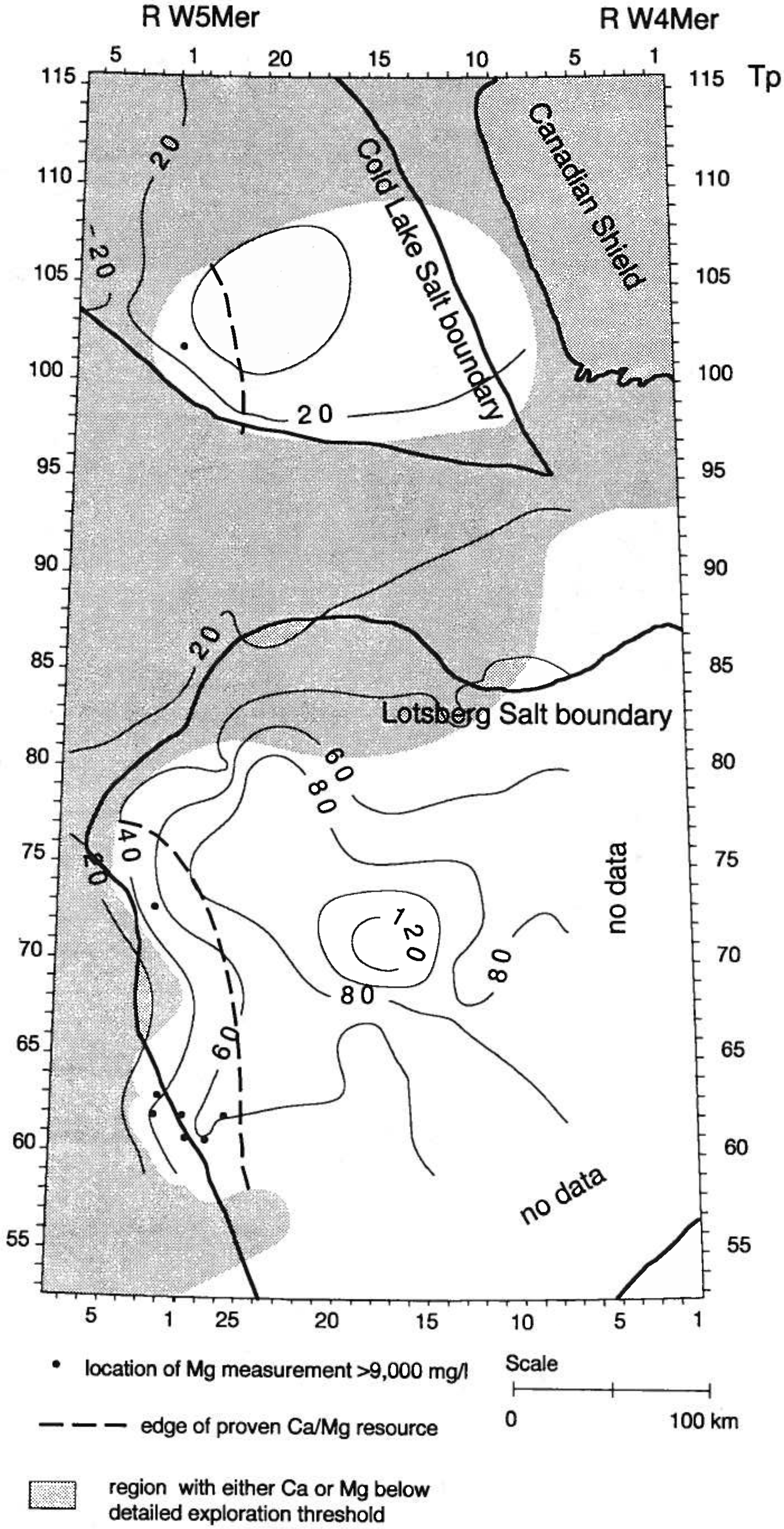


Figure 8. Resource distribution estimate of Mg ($Tx10^3/km^2$) in formation water, Lower Elk Point, northeast Alberta.

Mg per unit area occurs in the south-central part of the area coincident with the anomalously thick part of the stratigraphic section. Again, most of the region with high Mg resource values is poorly constrained and so resource estimates should be made only for the area bounded by the dashed line (figure 8).

Potassium resource estimate

The distribution of K in formation waters (figure 9) shows a different trend from those observed for Ca and Mg. A band of higher K values trends east-west across the area at about Tp 80, with values greater than 3000 mg/l in the extreme east and extreme west. The pattern of highest K resource estimates is generally similar to those for Ca and Mg, with values up to 10^4T/km^2 in the area bounded by the dashed line (figure 10). This suggests that, if Ca and Mg were to be produced in the southern region of interest, K could be considered as a potential byproduct.

Bromide resource estimate

The Br data form a small cluster of values in the west-central part of the study area. Based on a single value, there is a possible trend of increasing Br concentration to the southeast (figure 11). Therefore, the resource estimate map (figure 12), should be treated as purely speculative until more data become available.

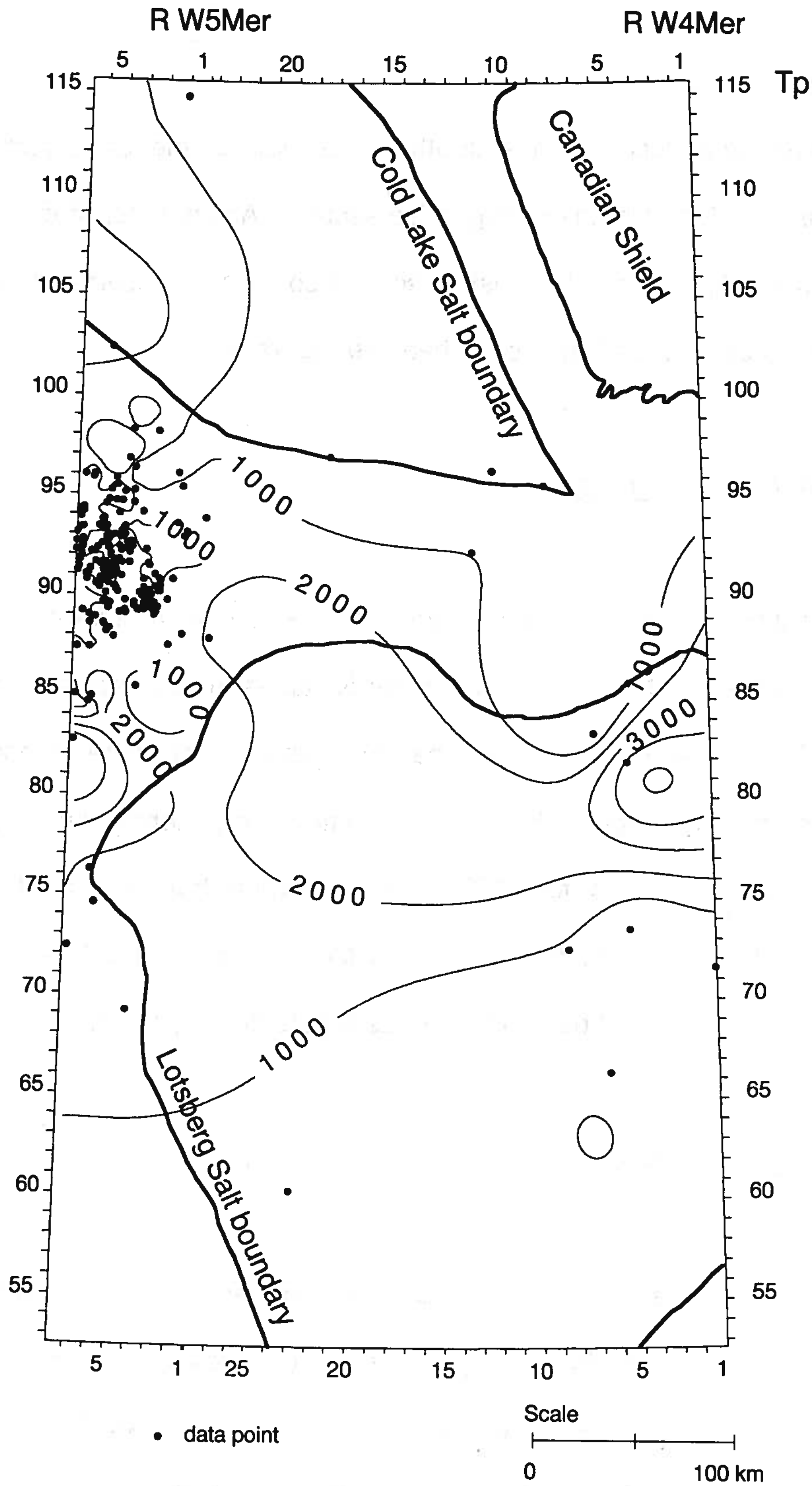
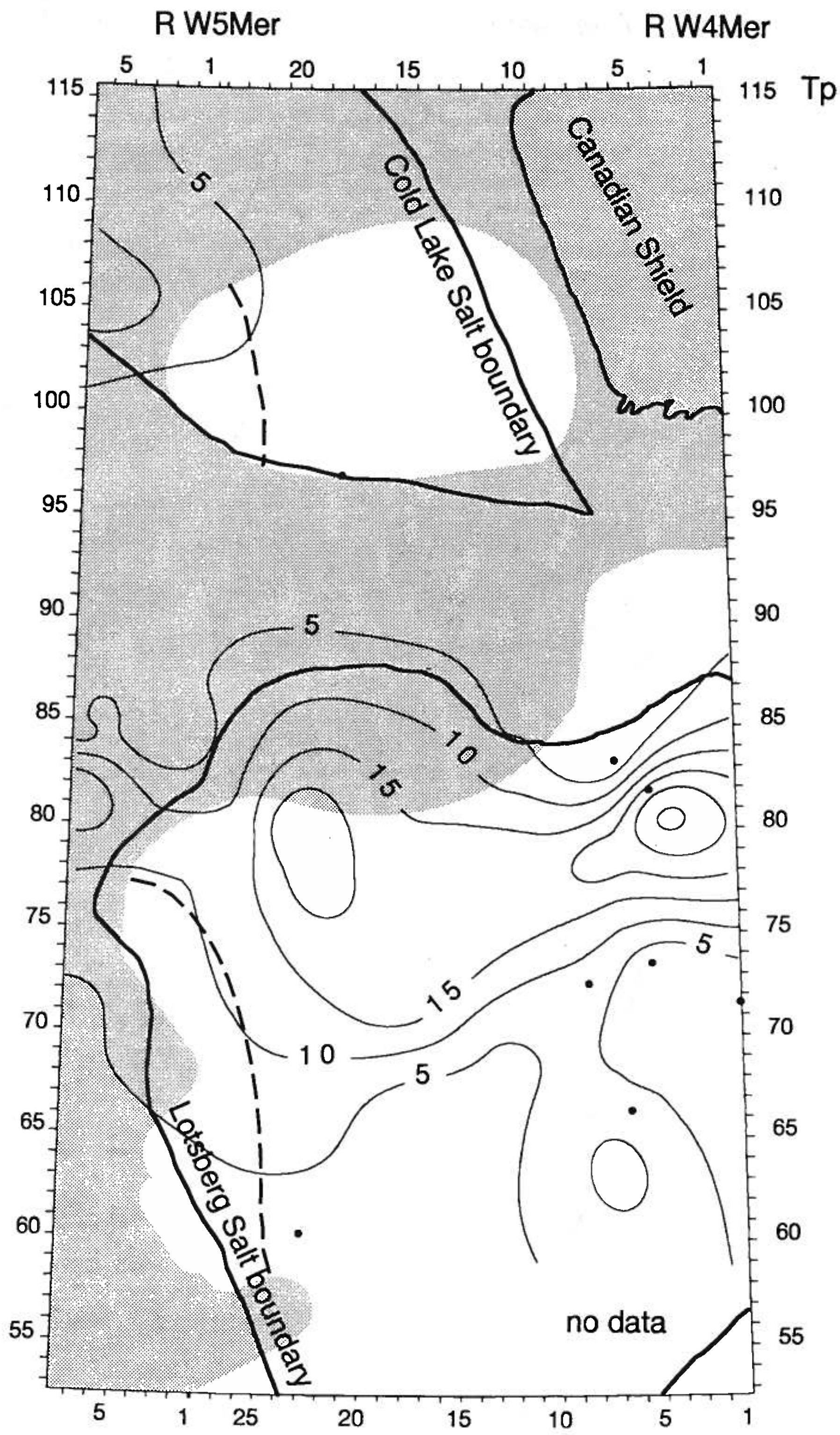


Figure 9. Distribution of K in formation water, Lower Elk Point, northeast Alberta (contour interval: 1000 mg/l).



• location of K measurement in the area of potential economic interest

— — — edge of proven Ca/Mg resource

region with either Ca or Mg below detailed exploration threshold

Figure 10. Resource distribution estimate of K ($Tx10^3/km^2$) in formation water, Lower Elk Point, northeast Alberta.

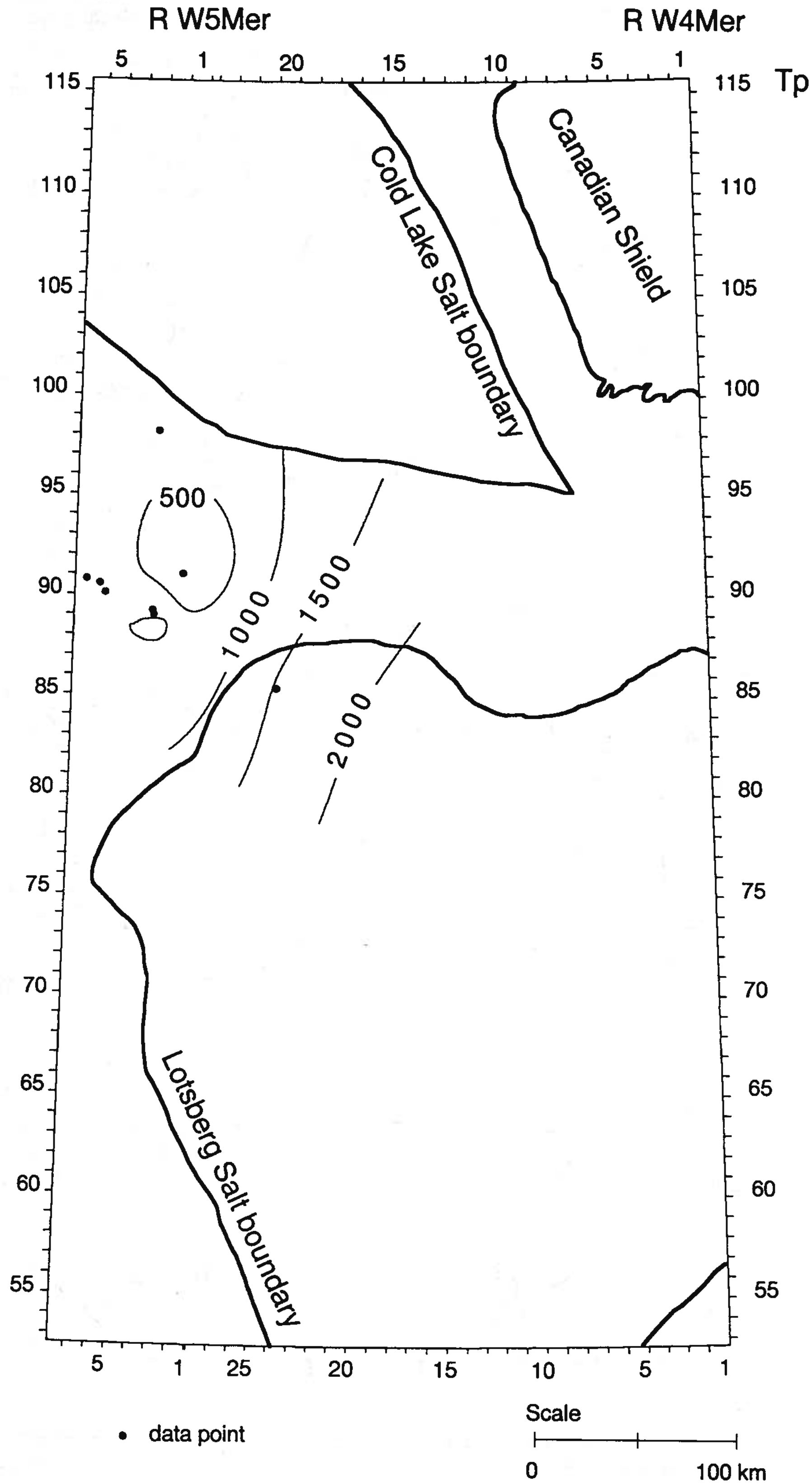


Figure 11. Distribution of Br in formation water, Lower Elk Point, northeast Alberta (contour interval: 500 mg/l).

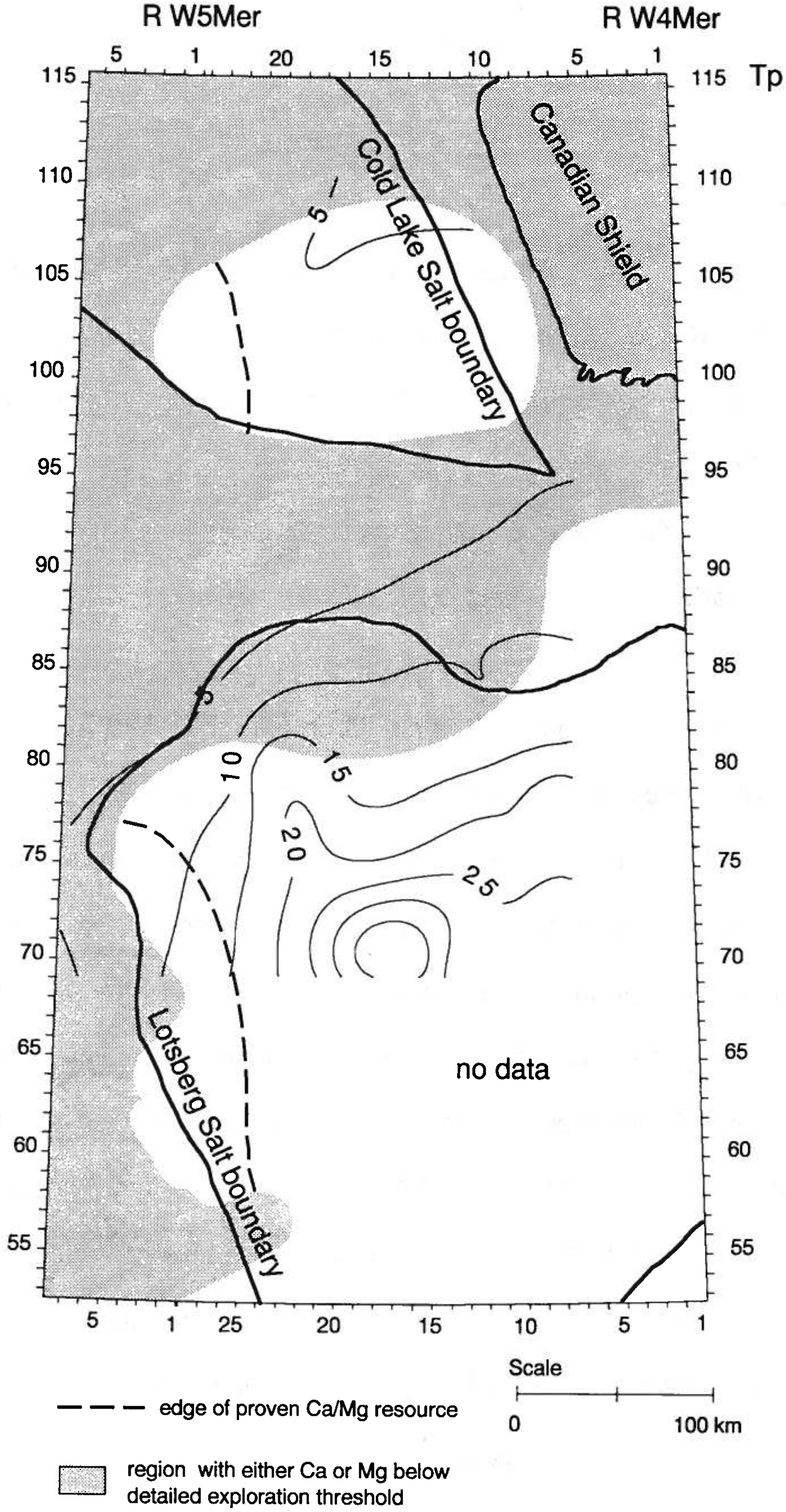


Figure 12. Resource distribution estimate of Br ($Tx10^3/km^2$) in formation water, Lower Elk Point, northeast Alberta.

Beaverhill Lake

Formation waters in Beaverhill Lake strata of southern Alberta contain concentrations of Ca, Mg and K above their respective detailed exploration thresholds. In addition, there are also high concentrations of Br. The isopach map (figure 13) is based on 1379 picks from geophysical logs whose distribution is not shown due to their large number. The unit thickens gradually to the north and northwest, and is generally less than 200 m near the thrustfold belt.

The porosity distribution (figure 14) is based on data from geophysical logs calibrated to core analyses. Because the combined Cooking Lake and Beaverhill Lake interval is thick and of variable lithology, there are large vertical variations in porosity. The log analysis of porosity leads to a well-averaged value across the entire stratigraphic interval. Thus, although the porosity distribution shown in figure 14 indicates generally very low porosity, there are zones of higher porosity within the interval of interest. There is a general southwestward increase in porosity to values about 8%. Because the concentrations of Ca, Mg, K, and Br in formation waters extend throughout the entire stratigraphic interval, these well-averaged values are only appropriate for estimating the gross resources for this region. Producible resources must be calculated using the high-porosity, high-permeability intervals.

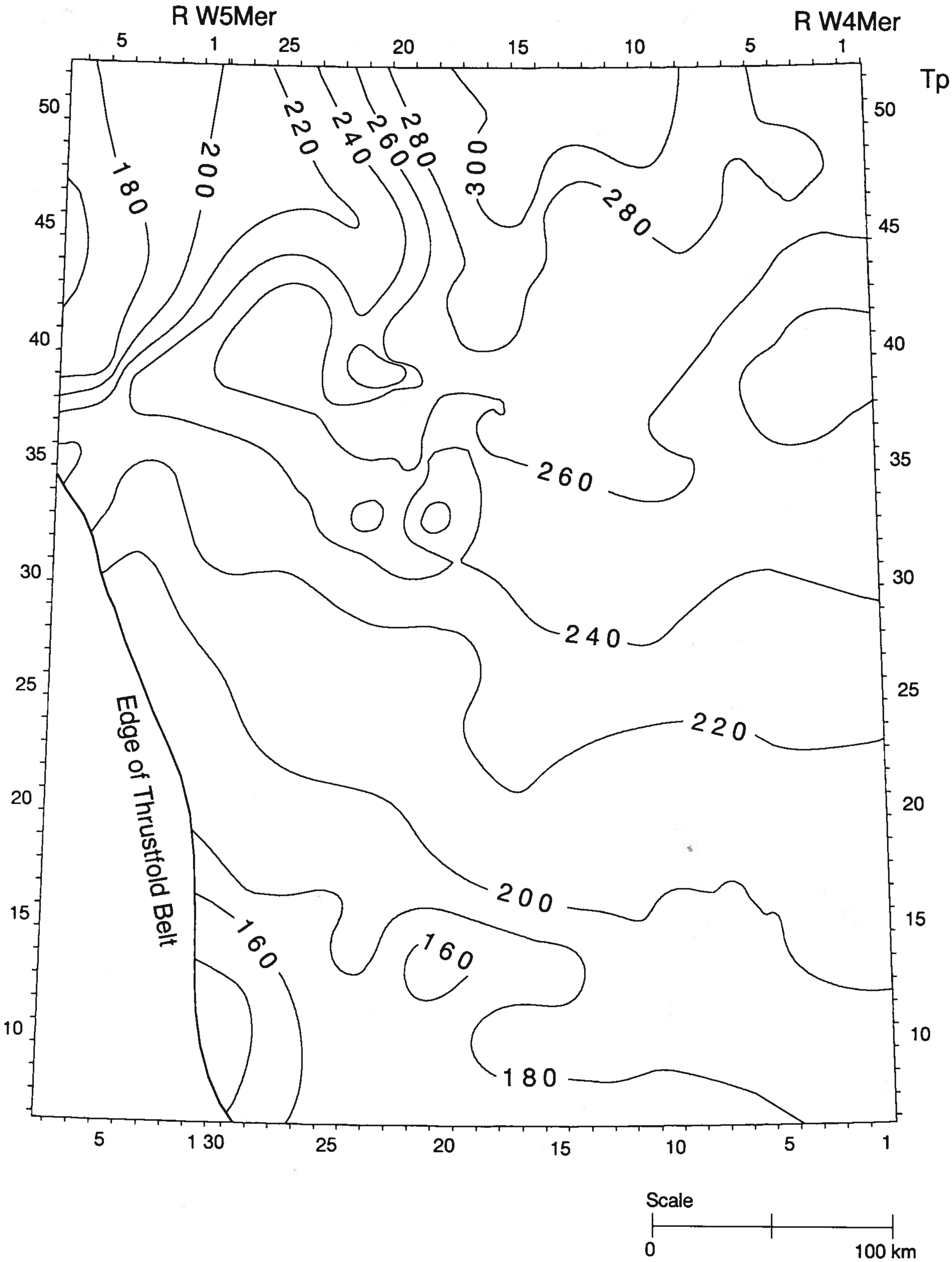


Figure 13. Isopach of Beaverhill Lake strata, southern Alberta
(contour interval: 20 m).

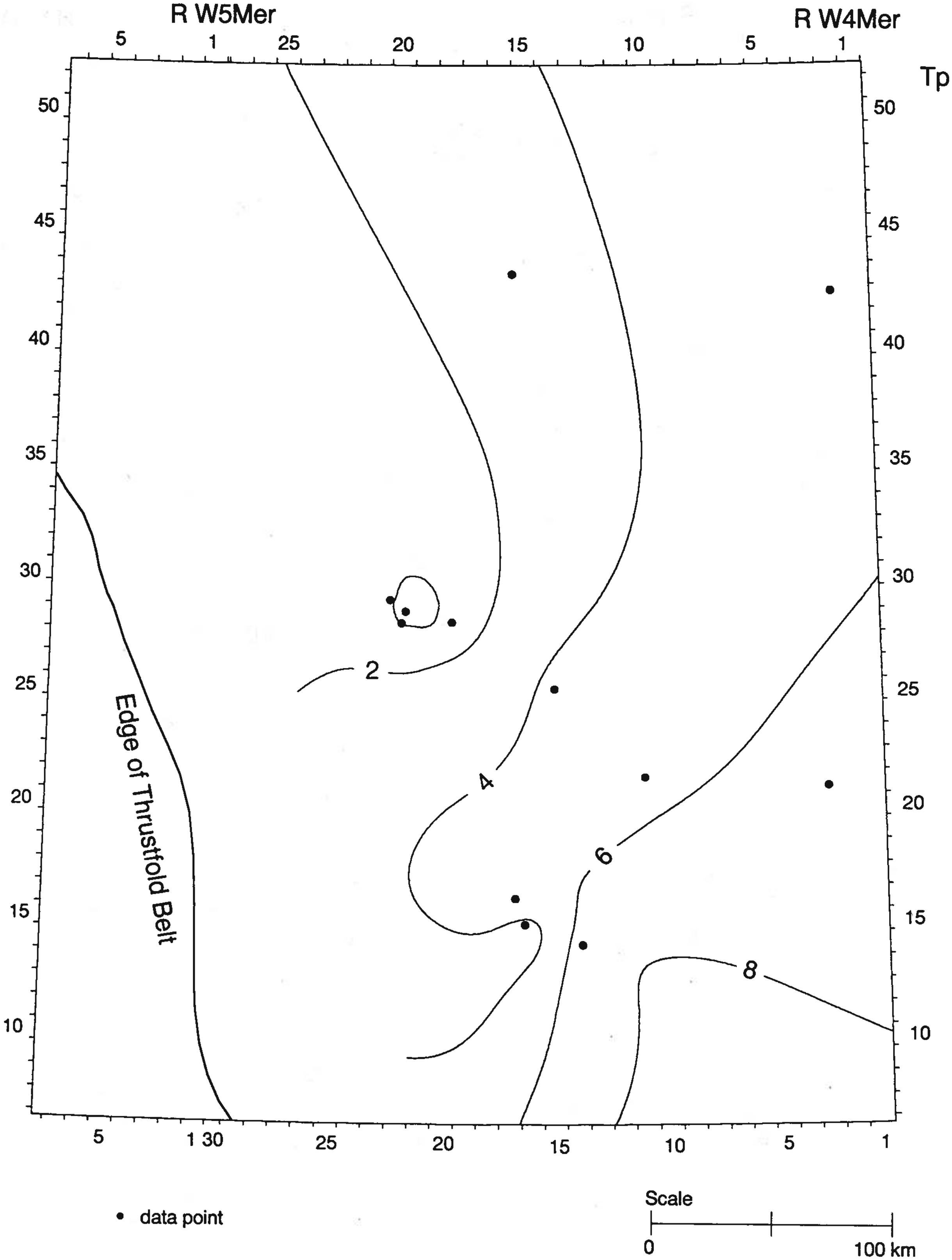


Figure 14. Porosity distribution, Beaverhill Lake strata, southern Alberta (contour interval: 2%).

Calcium resource estimate

The distribution of Ca in formation waters shown in figure 15 is well constrained by a relatively even data distribution. A band of high-Ca formation waters trends east-west in the central part of the study area, with a general increase in Ca content to the east into Saskatchewan. At two locations the concentration of Ca exceeds 100,000 mg/l. The resource map estimate (figure 16) indicates that the southern location with Ca greater than 100,000 mg/l has the highest resource values, due mainly to higher porosity in this region.

Magnesium resource estimate

The distribution of Mg concentration shown in figure 17 defines a broad area of more than 9000 mg/l (the detailed exploration threshold) in the eastern part of the study area, controlled by a relatively even data distribution. The highest value (>18,000 mg/l) occurs in the central part of the area at the same location as the northern location of Ca concentration greater than 100,000 mg/l noted previously. Figure 18 shows the estimated resource distribution. It appears to be mostly controlled by the concentration distribution, showing larger values in the same broad area of high Mg concentrations shown in figure 17.

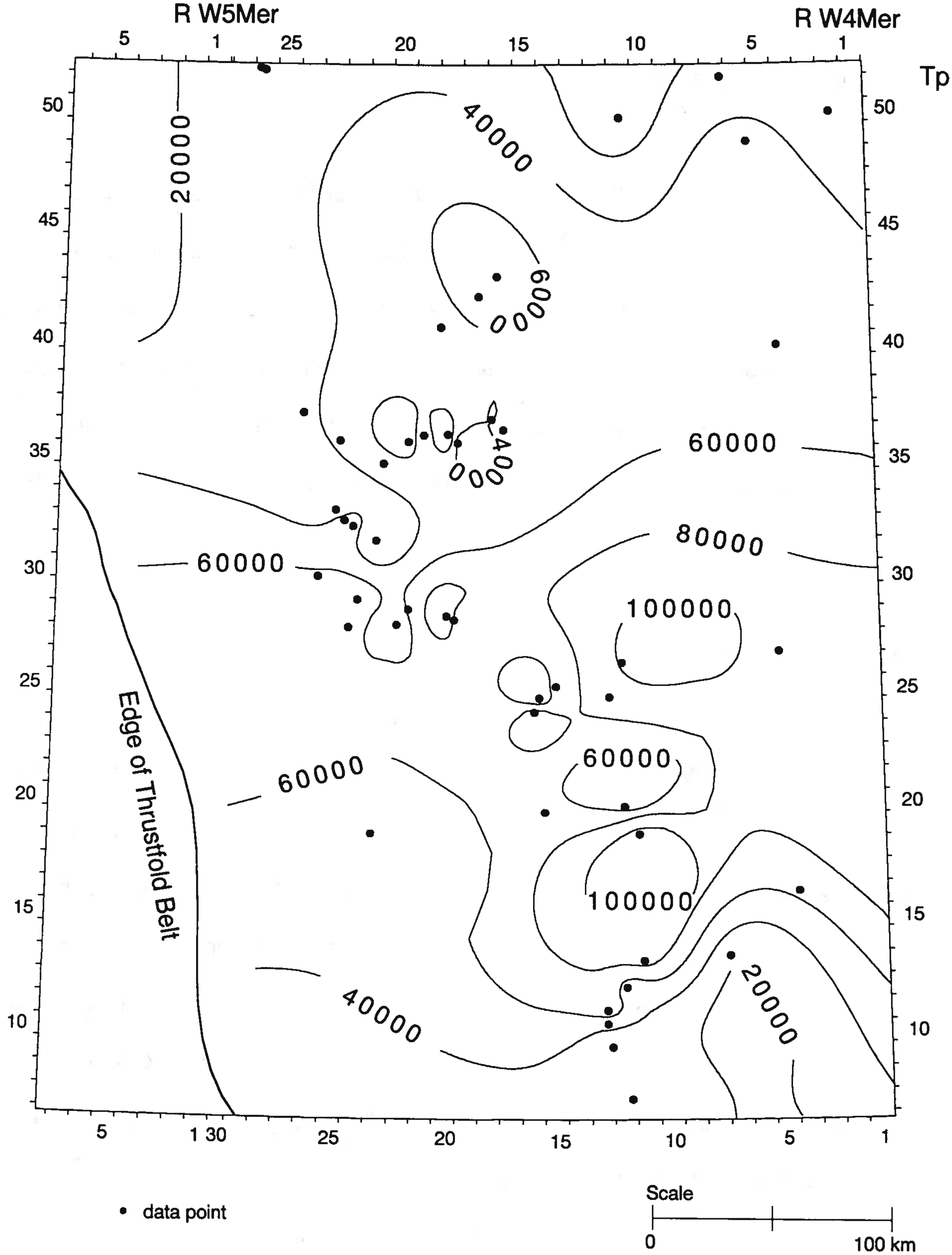
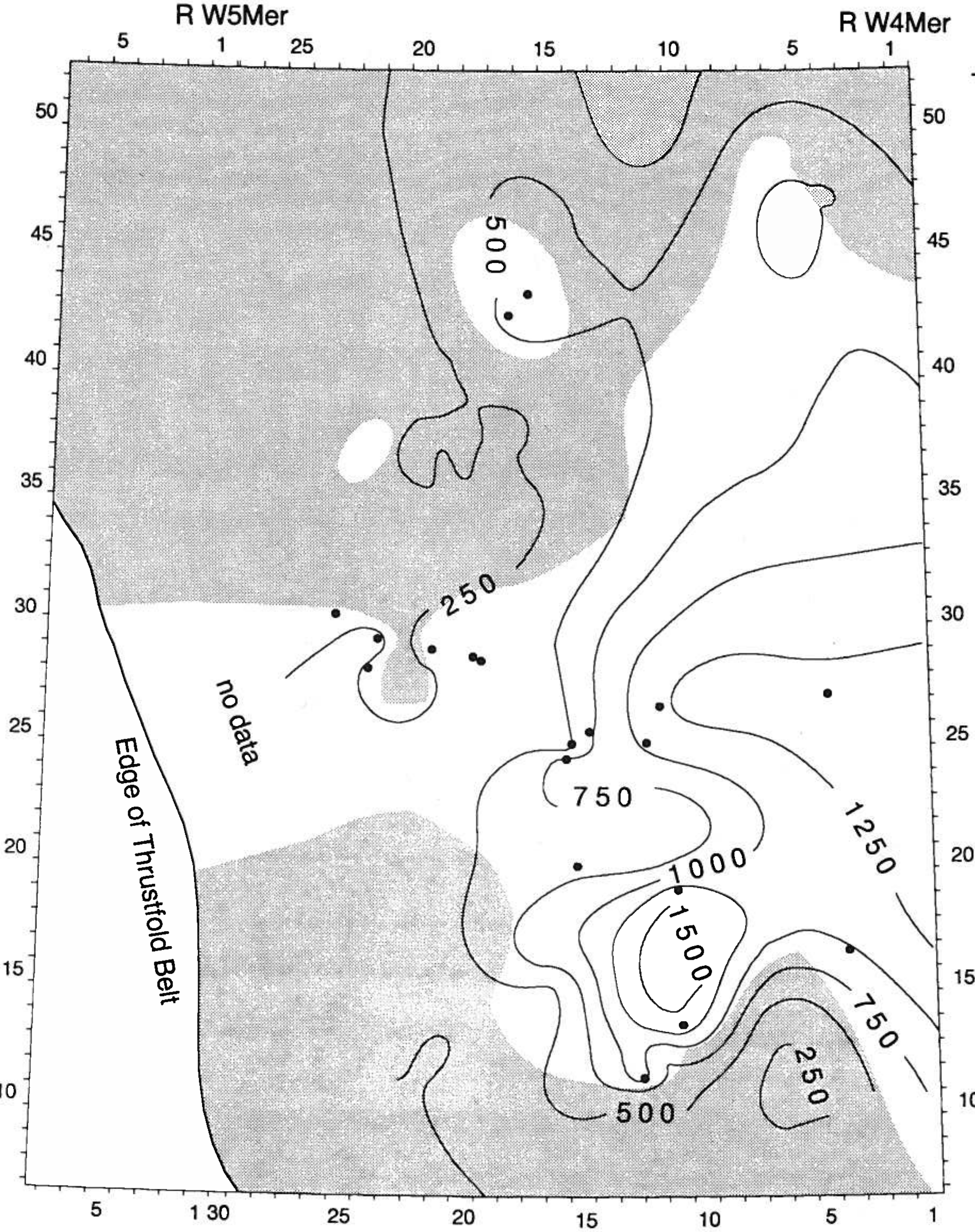


Figure 15. Distribution of Ca in formation water, Beaverhill Lake, southern Alberta (contour interval: 20,000 mg/l).



• location of Ca measurement >60,000 mg/l

region with either Ca or Mg below detailed exploration threshold

Figure 16. Resource distribution estimate of Ca ($Tx10^3/km^2$) in formation water, Beaverhill Lake, southern Alberta.

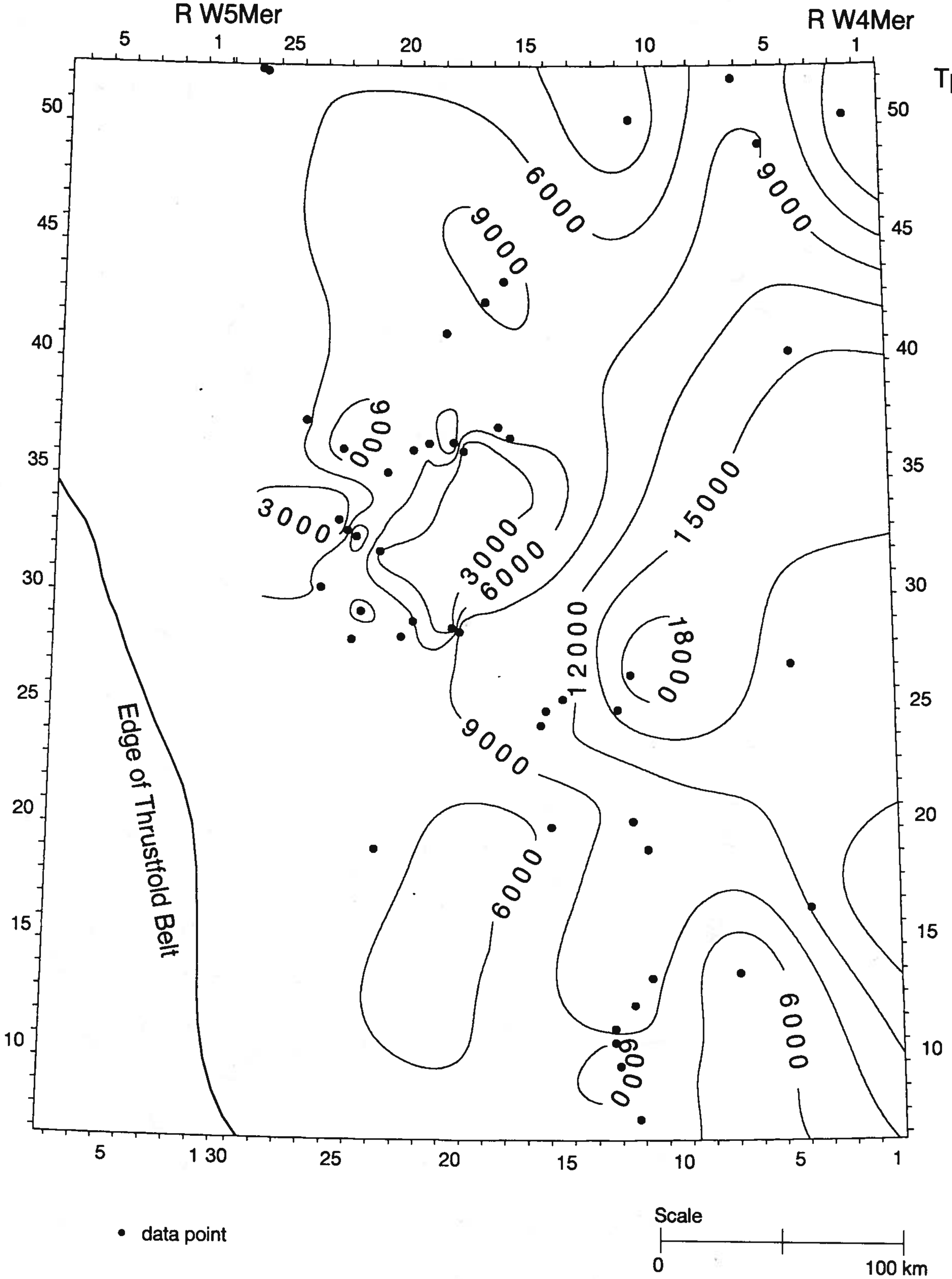


Figure 17. Distribution of Mg in formation water, Beaverhill Lake, southern Alberta (contour interval: 3000 mg/l).

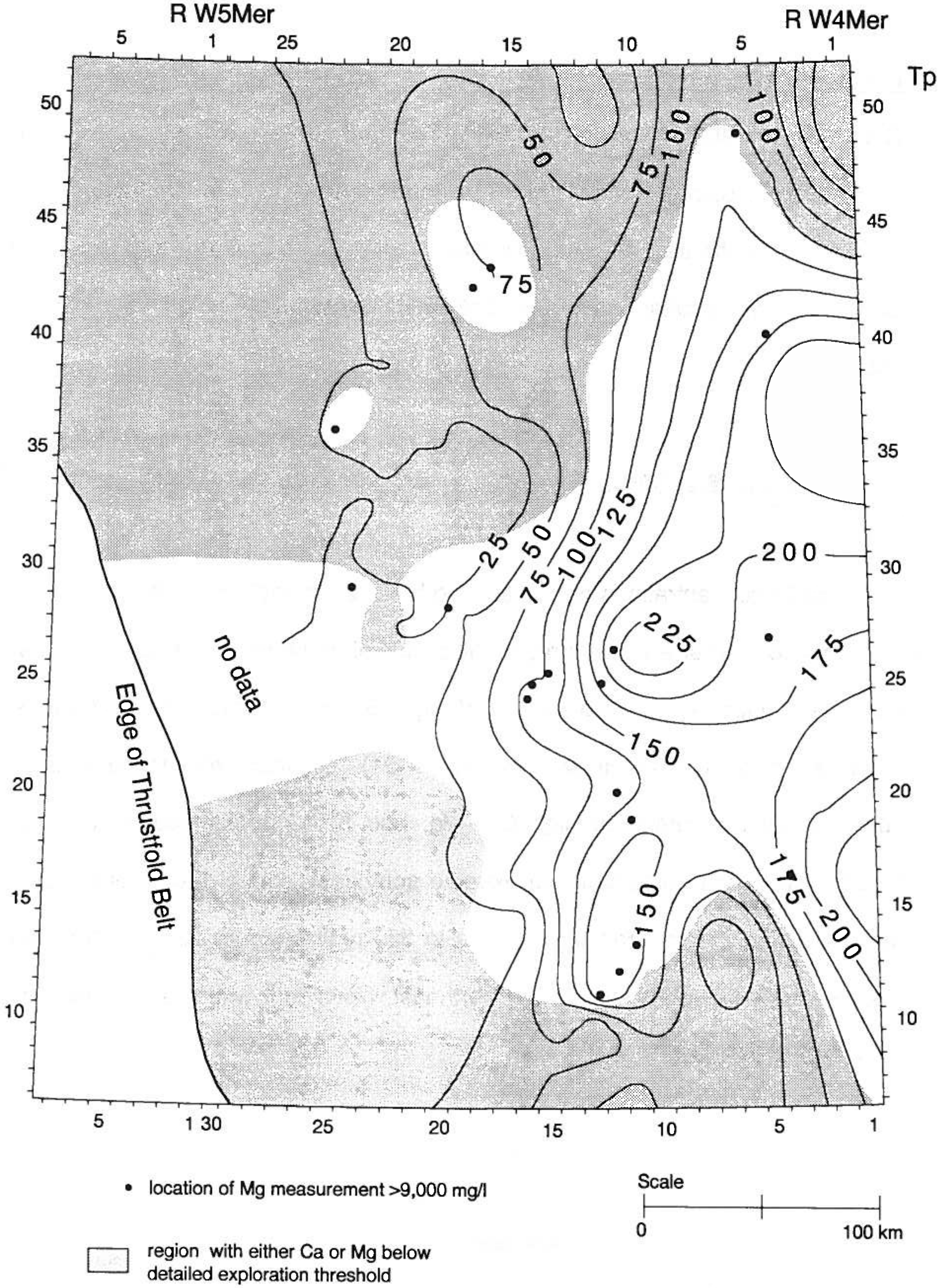


Figure 18. Resource distribution estimate of Mg ($Tx10^3/km^2$) in formation water, Beaverhill Lake, southern Alberta.

Potassium resource estimate

Only one formation water analysis within the study area has a K concentration above the detailed exploration threshold. The general distribution of K concentration shows an increase to the east into Saskatchewan (figure 19). This concentration distribution dominates the resultant resource distribution (figure 20), where a similar trend is observed.

Bromide resource estimate

Although Br concentrations do not exceed its detailed exploration threshold, significant concentrations exist within the region and interval of interest. Based on a very limited data distribution, there is a region of high Br in the northwest and the extreme southeast parts of the study area (figure 21). Unfortunately, these areas do not coincide with the areas of high Ca, Mg, and K. The high concentrations of Br, together with high porosity in the extreme southeast, control the resource distribution map, resulting in large resource values in this region (figure 22). Another region of high resource values occurs in the northeast, coincident with the thickest part of the stratigraphic interval.

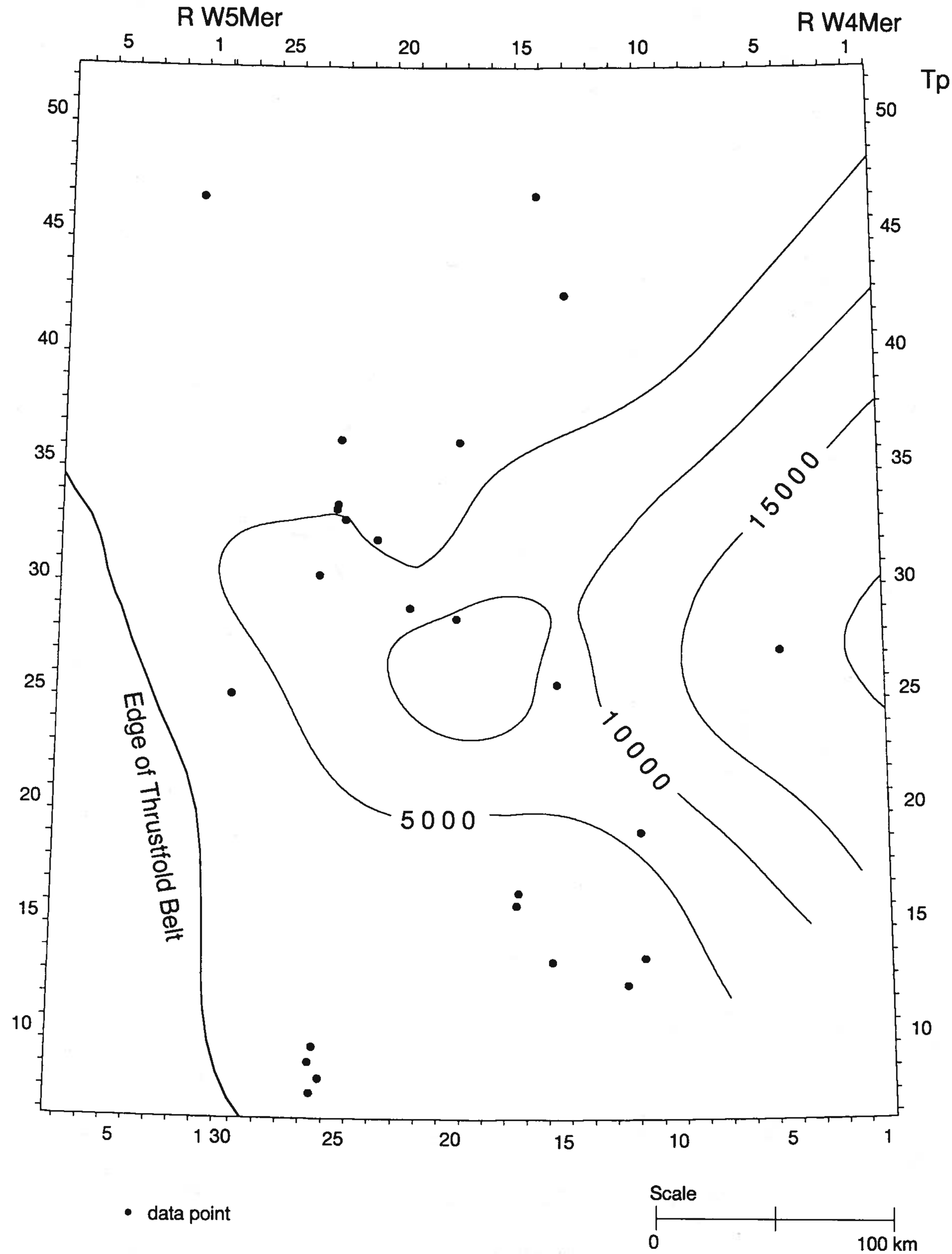
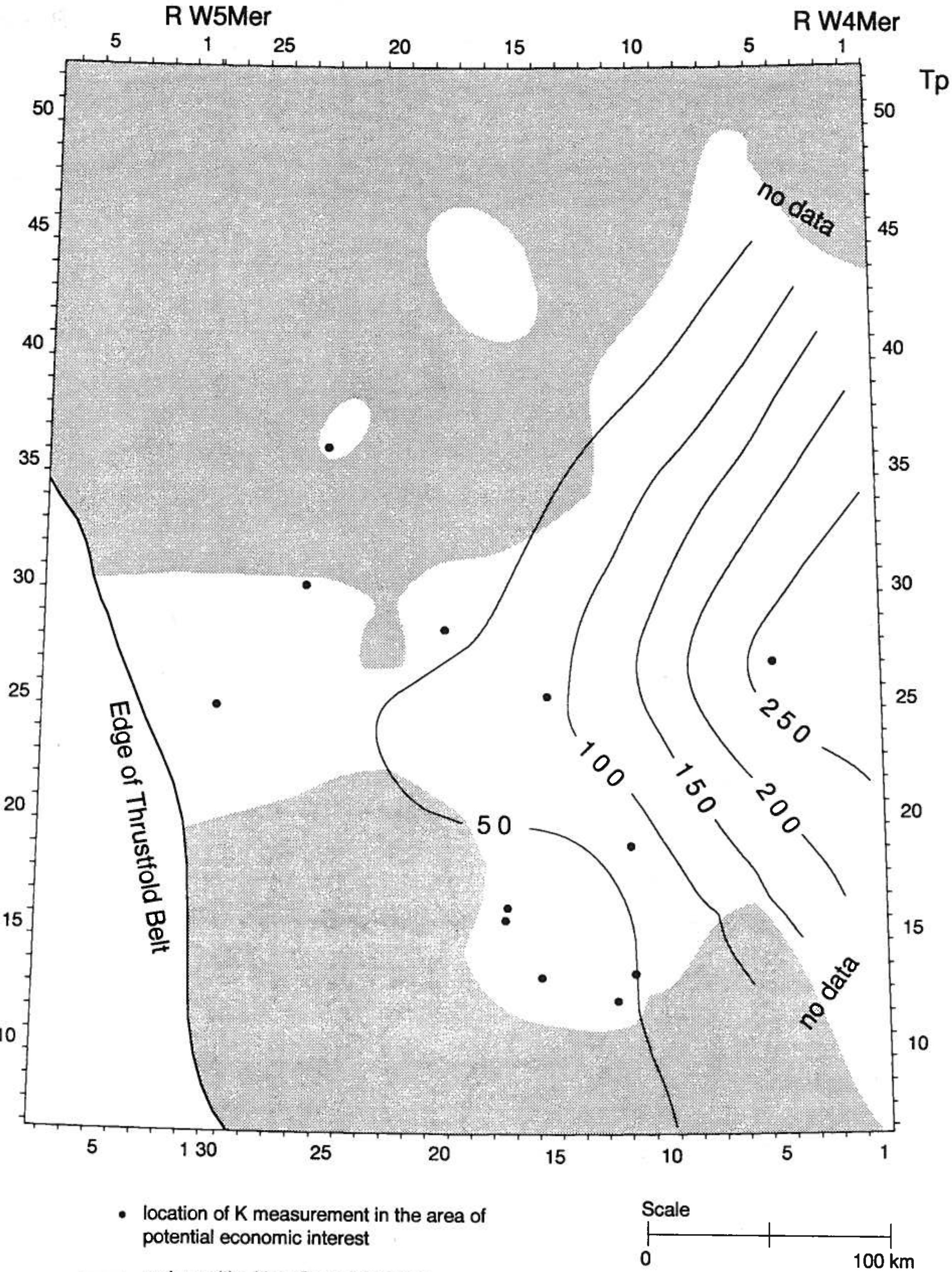


Figure 19. Distribution of K in formation water, Beaverhill Lake, southern Alberta (contour interval: 5000 mg/l).



• location of K measurement in the area of potential economic interest

region with either Ca or Mg below detailed exploration threshold

Figure 20. Resource distribution estimate of K ($Tx10^3/km^2$) in formation water, Beaverhill Lake, southern Alberta.

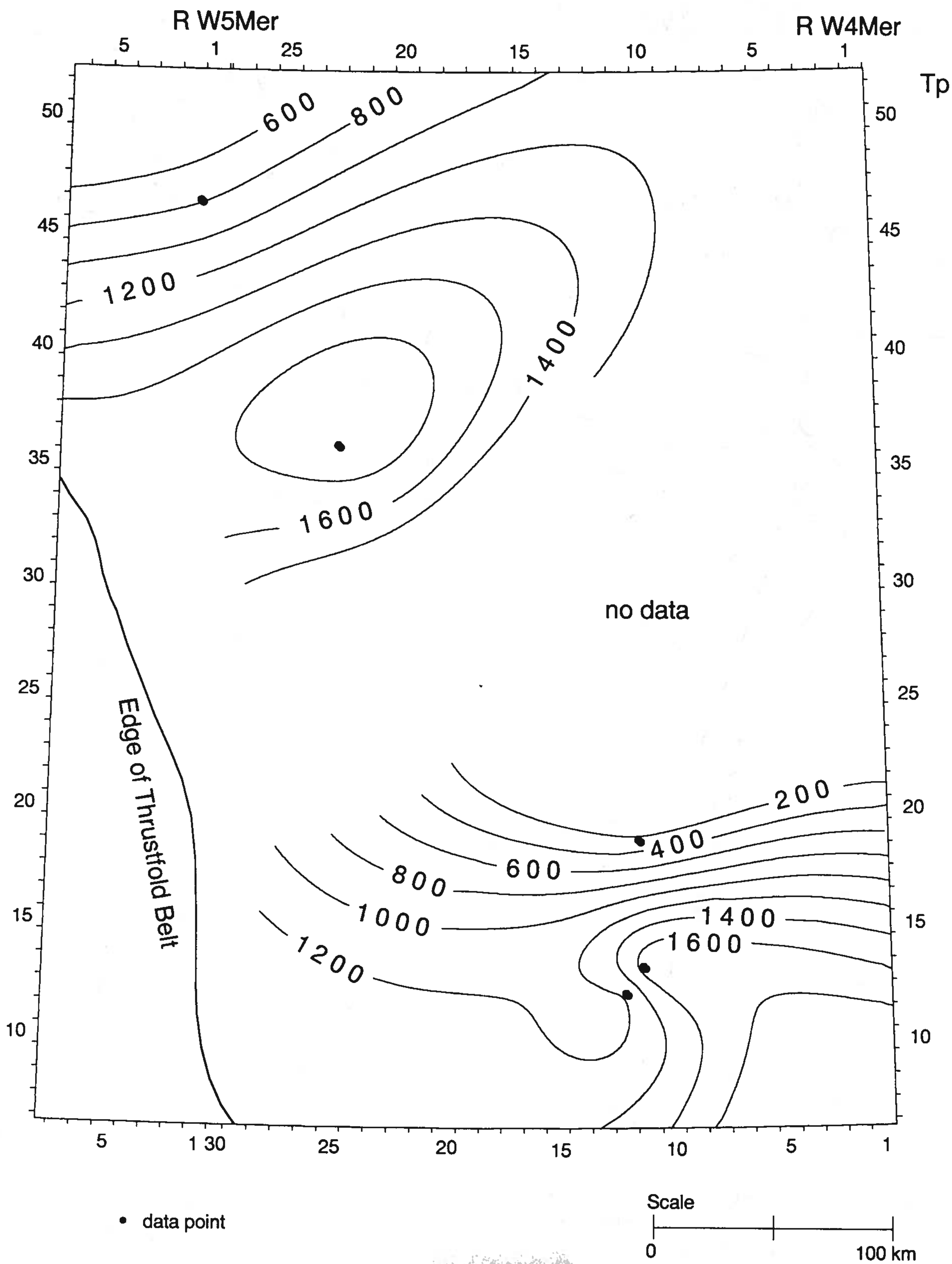
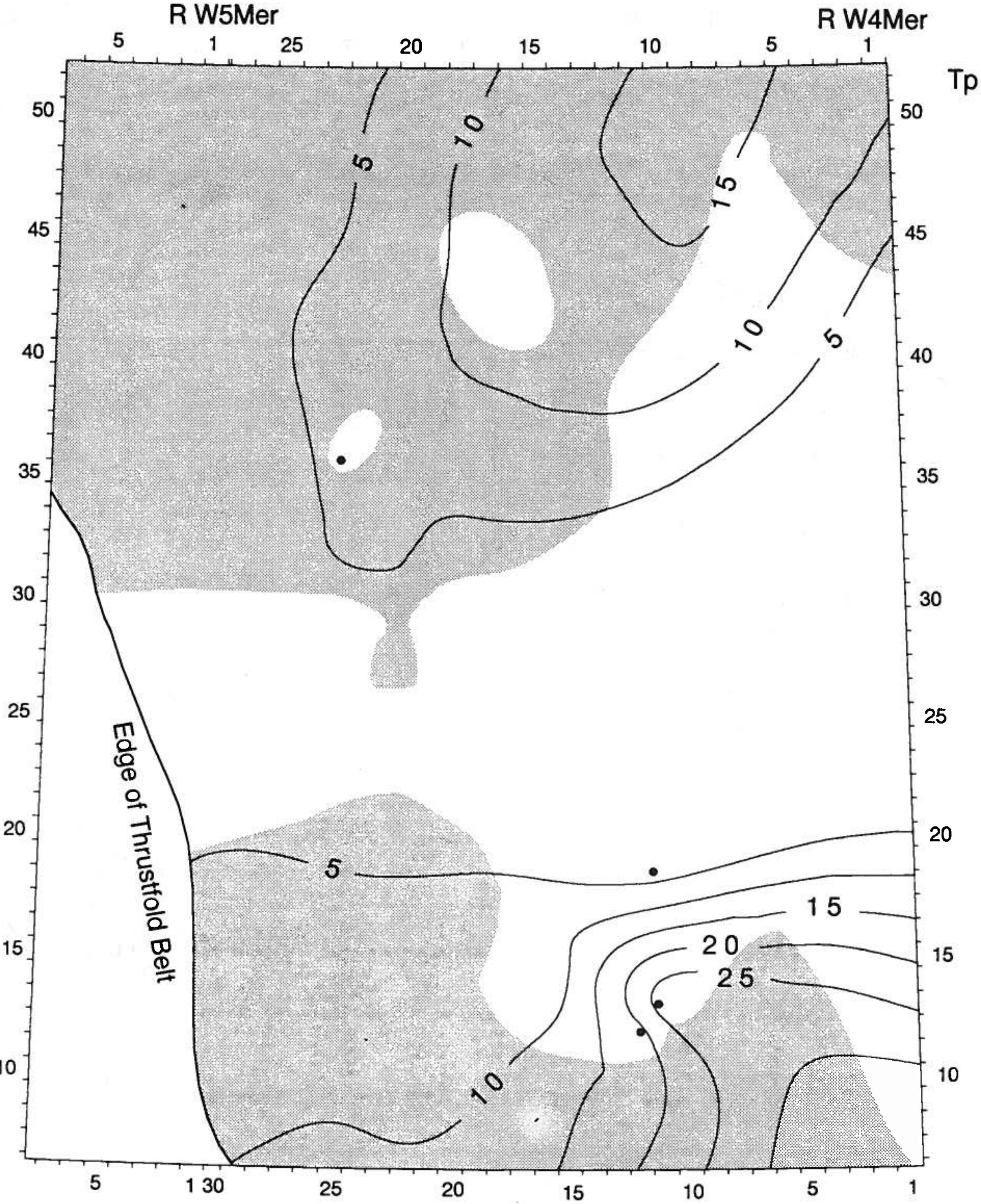


Figure 21. Distribution of Br in formation water, Beaverhill Lake, southern Alberta (contour interval: 200 mg/l).



• location of Br measurement in the area of potential economic interest

region with either Ca or Mg below detailed exploration threshold

Scale

0 100 km

Figure 22. Resource distribution estimate of Br ($Tx10^3/km^2$) in formation water, Beaverhill Lake, southern Alberta.

Woodbend and Beaverhill Lake

The Woodbend and Beaverhill Lake strata of west-central Alberta host formation waters with concentrations of Li above the detailed exploration threshold (75 mg/l). The stratigraphic interval of interest is complex, consisting of the Leduc and Cooking Lake formations of the Woodbend Group, and the underlying Beaverhill Lake Group. Because of the large variation in rock properties, the Leduc Formation is characterized in terms of thickness and porosity separately from the remainder of the interval of interest. The Li concentration and Li resource estimate distributions are presented for the entire interval.

The isopach map in figure 23 comprises the thick carbonate buildups of the Leduc Formation and the carbonates of the underlying Cooking Lake Formation. Even though the Cooking Lake Formation extends over much of the study area, these strata are included in the isopach only where the overlying Leduc Formation is present. The Leduc Formation carbonate complexes tend to have high porosity, and the porosity distribution (figure 24) is based on 114 well-averaged values derived from core-plug analyses. Porosity is in the range 6 to 8% throughout much of the area, reaching 10% in places.

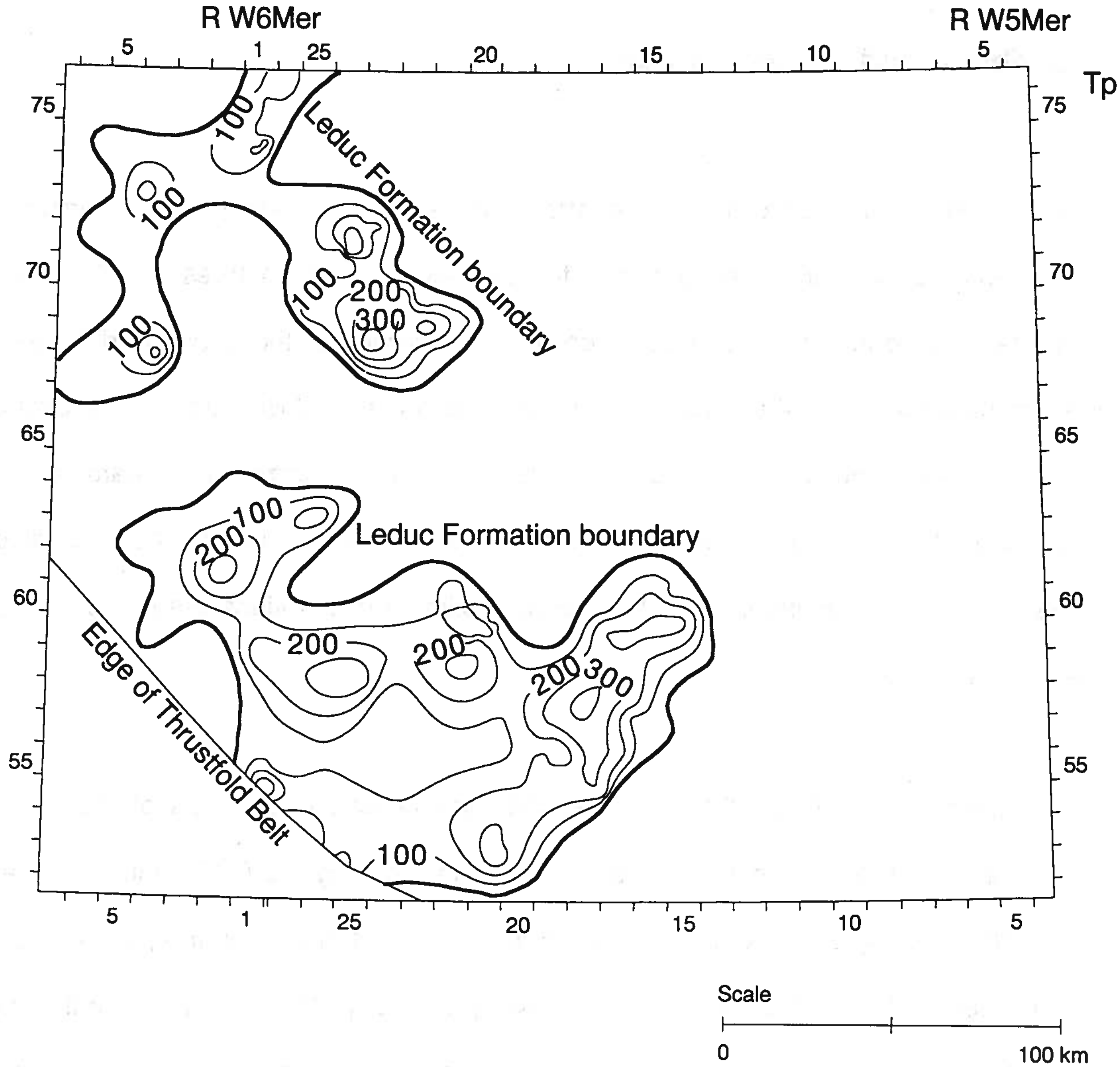


Figure 23. Isopach of Leduc strata, west-central Alberta (contour interval: 100 m).

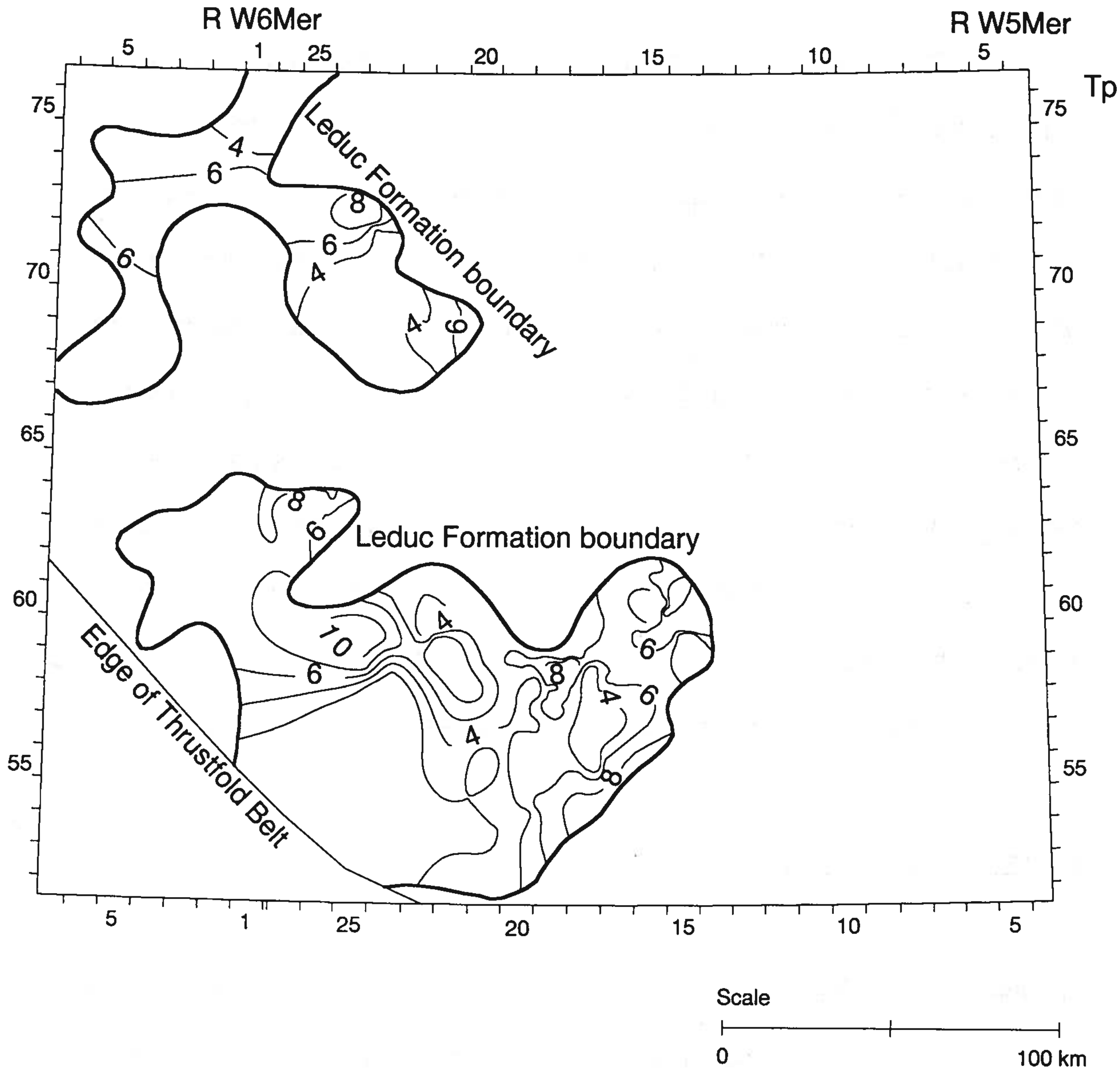


Figure 24. Porosity distribution, Leduc strata, west-central Alberta (contour interval: 2%).

The Beaverhill Lake isopach has an overall wedge-shaped geometry, thickening from 50 m in the northwest to more than 150 m in the eastern part of the study area (figure 25). The porosity distribution (figure 26) shows no obvious trend and, although there are a few areas with values greater than 8%, the values generally tend to be lower than those observed for the Leduc Formation. The porosity distribution is constrained by 2215 well-averaged values derived from core-plug analyses. Because the Beaverhill Lake interval is extremely variable in both lithology and associated rock properties, the characterization shown here and used for estimating Li resources is far from precise. The core analyses tend to be from porous and permeable zones of interest to the petroleum industry. Because no geophysical log analyses were used for this area, the resource estimates probably represent an upper limit.

Lithium resource estimate

For the Woodbend and Beaverhill Lake strata in west-central Alberta, Li concentrations in the formation waters have values above the detailed exploration threshold only in isolated areas. The distribution of Li within the study area (figure 27) shows three areas of high Li: in the northwest, northeast, and southwest. The resource distribution map (figure 28), however, shows that only the northwest and southwest areas contain significant resources. These two areas correspond to locations where Leduc strata contribute significantly to the total thickness of the overall interval being characterized and where the Li concentration distribution is poorly constrained.

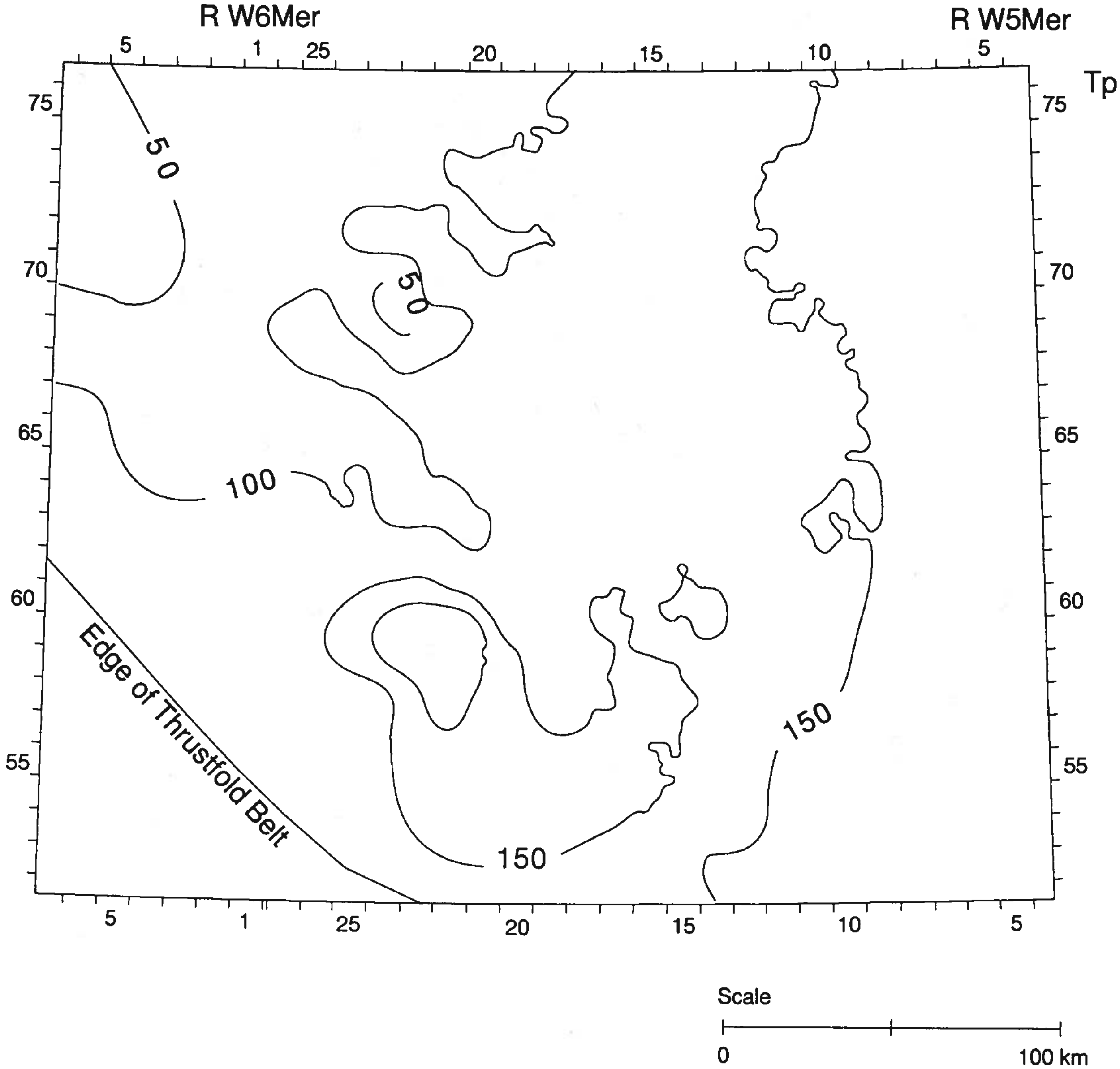


Figure 25. Isopach of Beaverhill Lake strata, west-central Alberta (contour interval: 50 m).

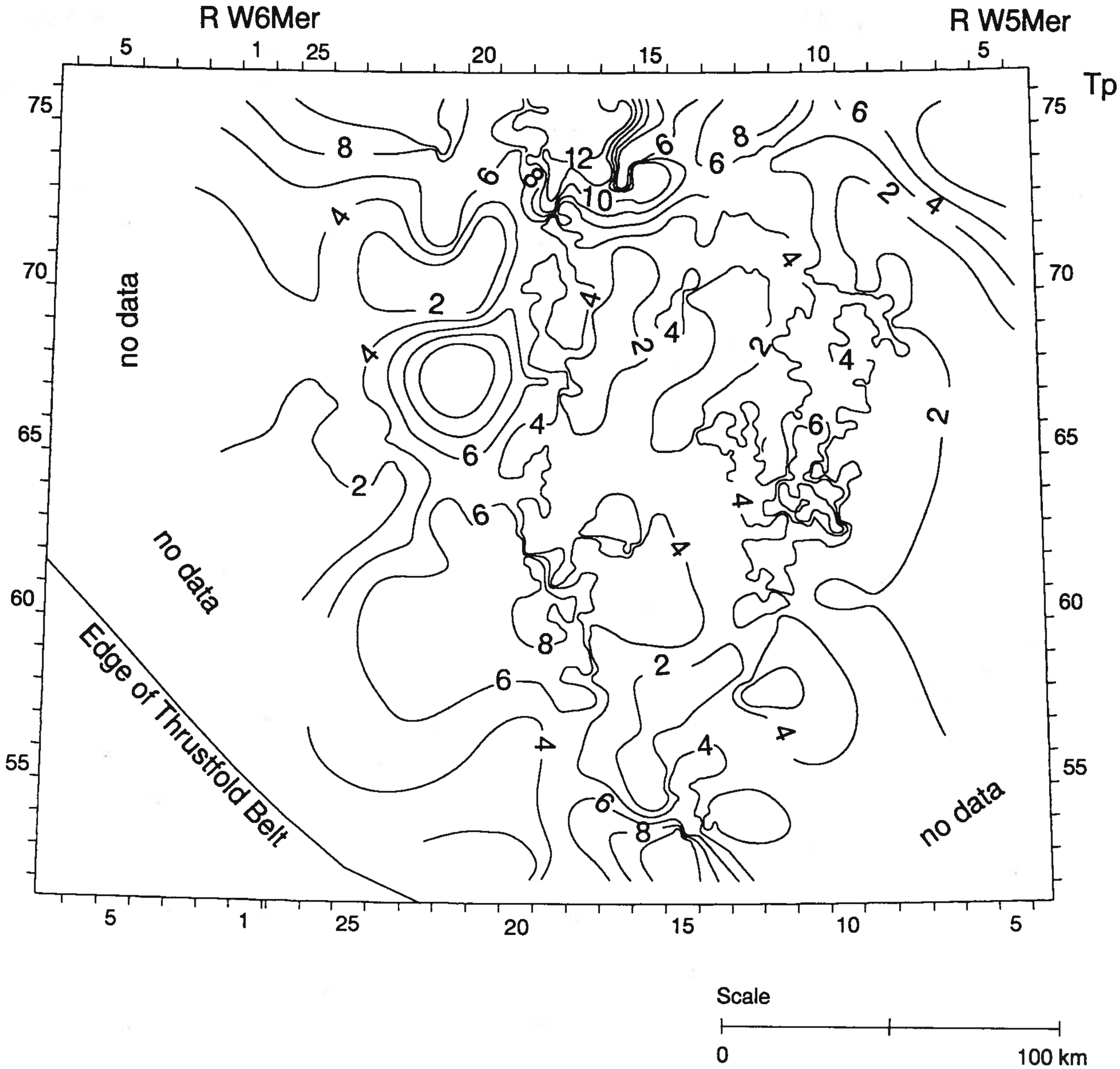


Figure 26. Porosity distribution, Beaverhill Lake strata, west-central Alberta (contour interval: 2%).

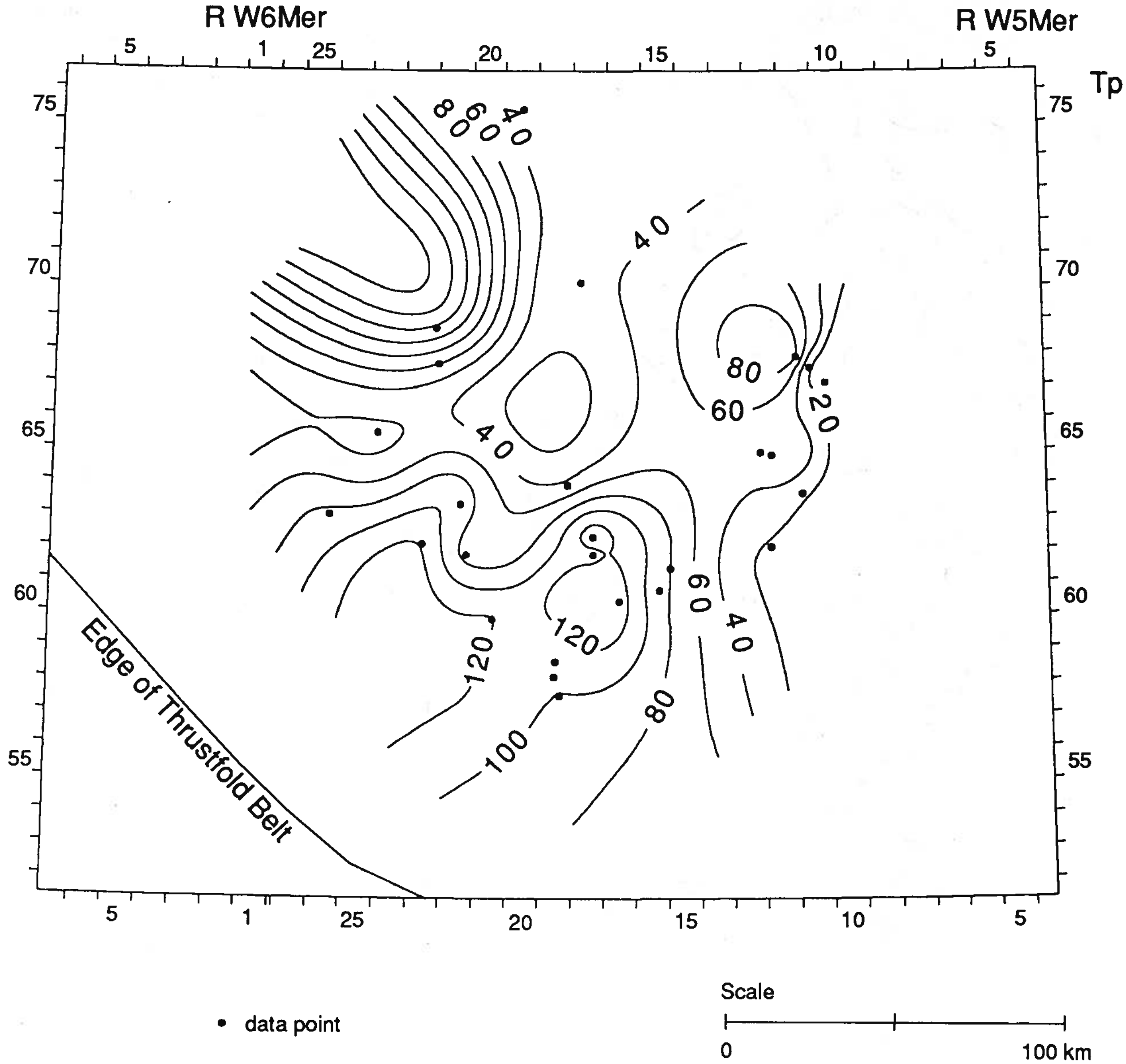
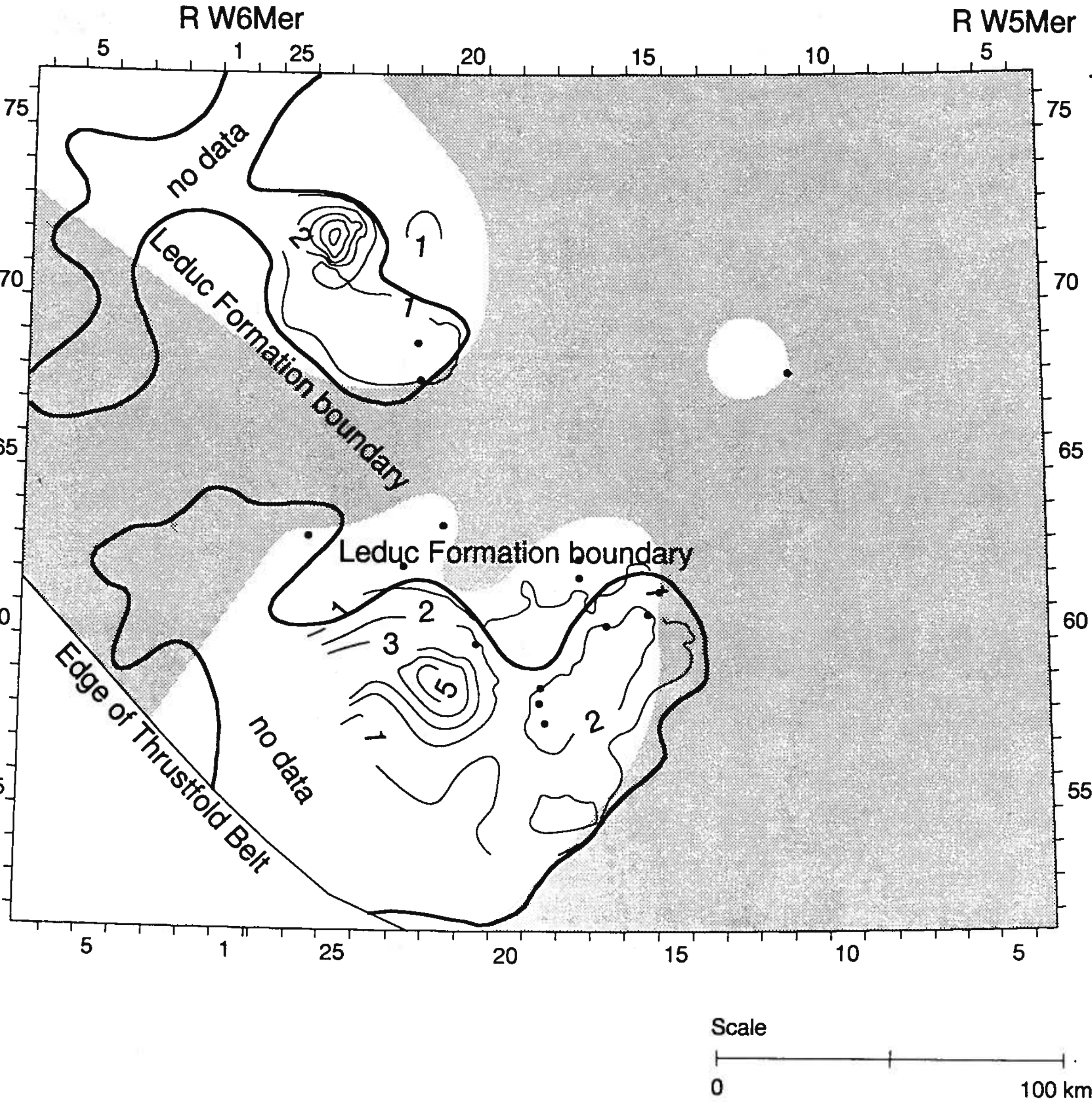


Figure 27. Distribution of Li in formation water, Woodbend and Beaverhill Lake, west-central Alberta (contour interval: 20 mg/l).



• location of Li measurement >70 mg/l

region with Li below detailed exploration threshold

Figure 28. Resource distribution estimate of Li (Tx10^3/km^2) in formation water, Woodbend and Beaverhill Lake, west-central Alberta.

Viking and Belly River

The Viking and Belly River formations in south-central Alberta contain formation waters with high I contents. Although I concentrations are generally below the detailed exploration threshold (100 mg/l), they represent some of the highest contents in Alberta formation waters.

The Viking Formation is about 20 m thick in the northern part of the study area and thickens to more than 80 m in the south, with a thinner region in the extreme southwest (figure 29). The Viking isopach map is based on 10,010 picks from geophysical logs, mostly obtained from the ERCB data set. Porosity generally decreases toward the thrustfold belt, with values about 5% in the southwest and 25% in the northeast, although the trend is not smooth (figure 30). Bachu and Underschultz (1992) suggested that the general decrease toward the thrustfold belt may be the result of increased overburden at the time of maximum burial. The porosity distribution is controlled by 2758 well-averaged values obtained from core plug analyses.

Hitchon et al. (1972) noted that high contents of I in formation waters from Belly River strata were found only in the lower portion of the unit. Contents of I in formation waters ranged up to 50 mg/l in lower Belly River strata, and only up to 30 mg/l in upper Belly River strata. Similar distributions were observed in the present study,

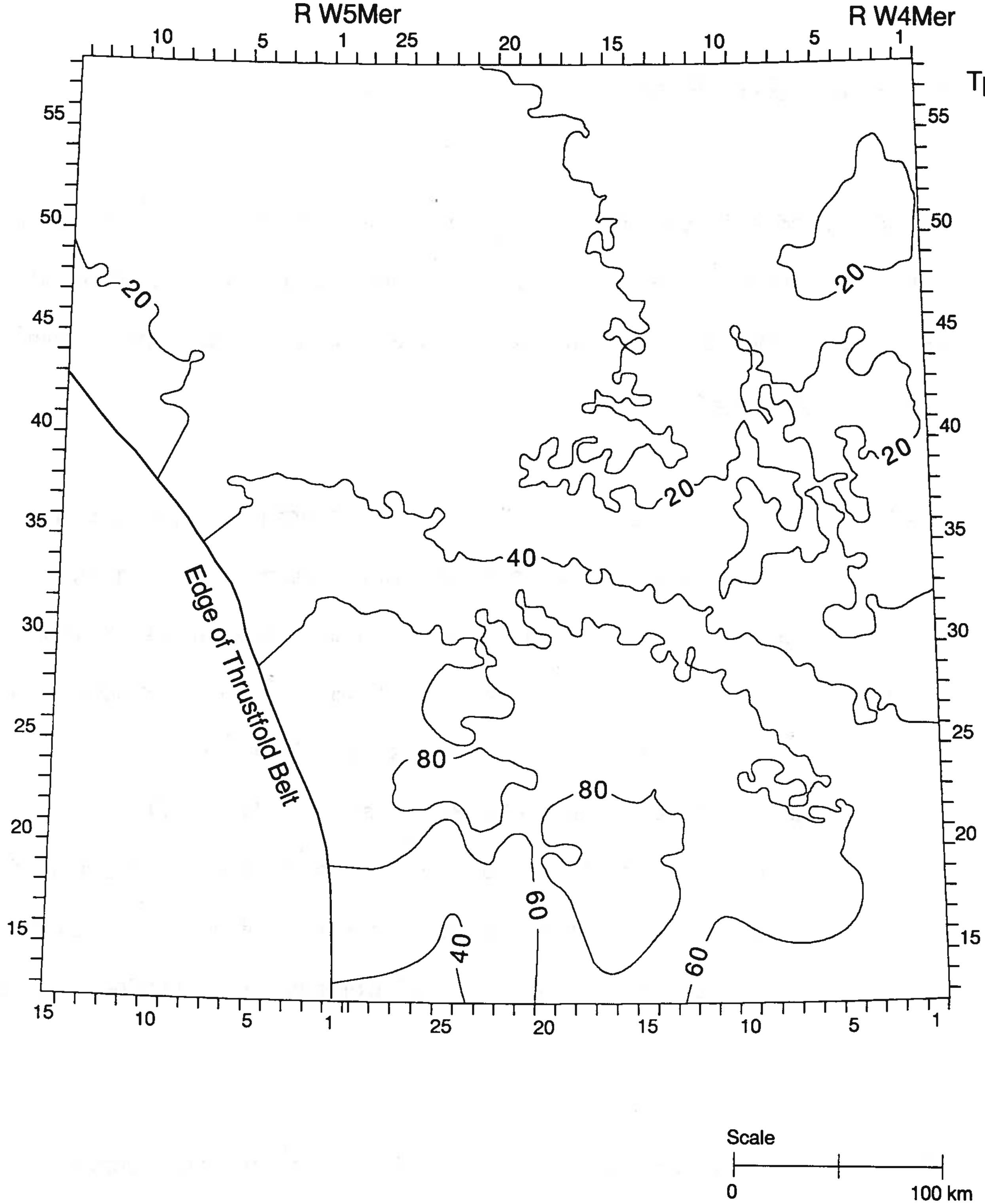


Figure 29. Isopach of Viking strata, south-central Alberta (contour interval: 20 m).

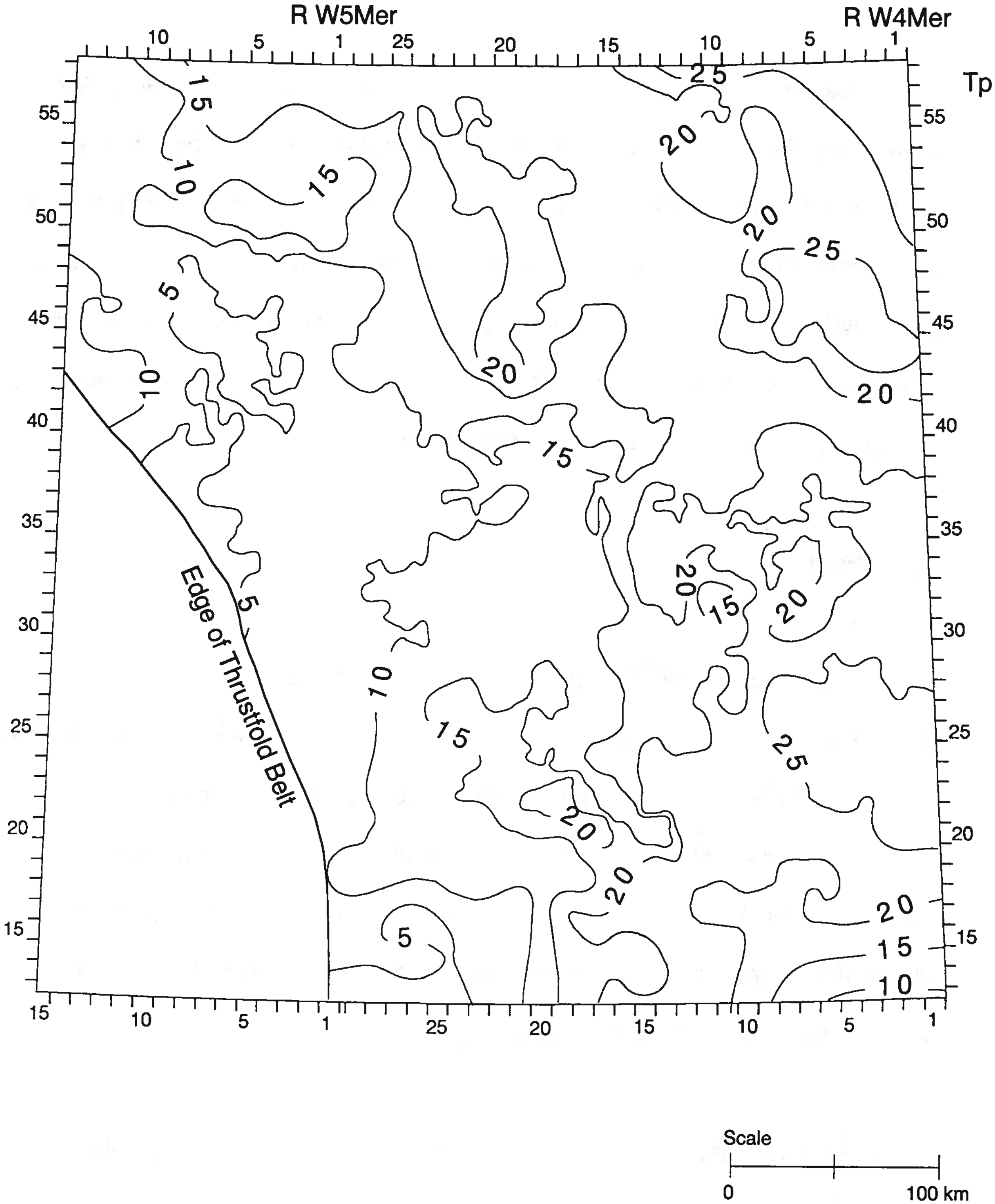


Figure 30. Porosity distribution, Viking strata, south-central Alberta (contour interval: 5%).

with a maximum content of 64 mg/l in formation water from lower Belly River strata. Lower Belly River strata form a wedge which thickens from 20 m in the east to more than 80 m in the west along the thrustfold belt (figure 31). The corresponding porosity distribution (figure 32) shows the highest porosity values (22%) in the east-central areas, with lower values of about 8% along the thrustfold belt in the west and in the southern part of the study area. The porosity distribution map is constrained by 1315 well-averaged values based on core-plug analyses.

Iodide resource estimate

A relatively large and evenly distributed I concentration data set exists within the study area. The I distribution shows a zone of concentrations greater than 40 mg/l through the middle of the study area, trending parallel to the thrustfold belt (figure 33). Hitchon et al. (1977) suggested that the orientation of the high I region may be related to depositional aspects of the Viking Formation. A high value in the extreme southern part of the study area may be anomalous, although the respective formation water analysis seems to be of acceptable quality.

The I resource map for the Viking Formation (figure 34) reflects the northwest-southeast trending zone of high I concentration noted previously. The largest resource estimates occur generally in the southern part of the study area, including the anomalous value on the southern edge.

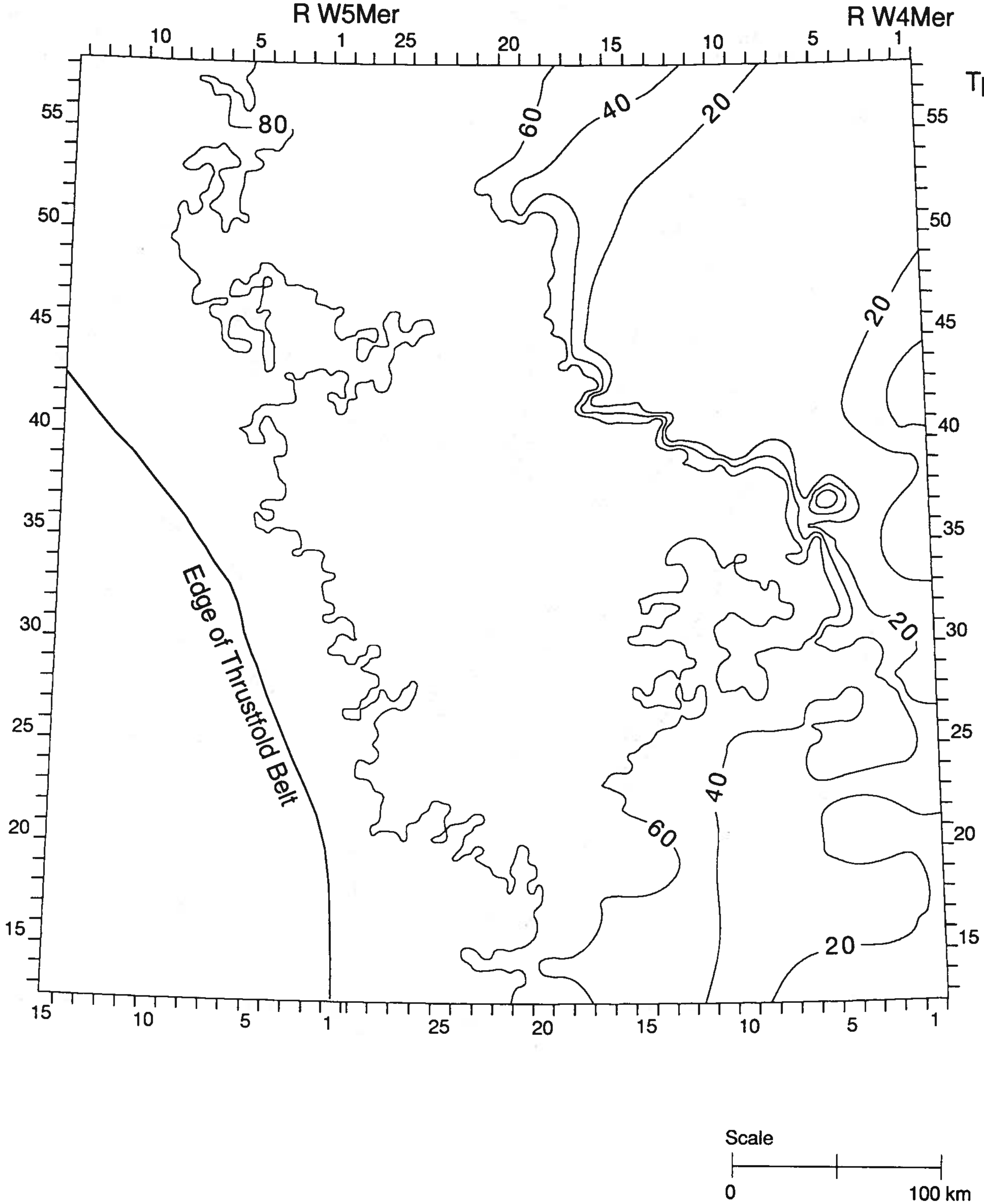


Figure 31. Ispoach of lower Belly River strata, south-central Alberta (contour interval: 20 m).

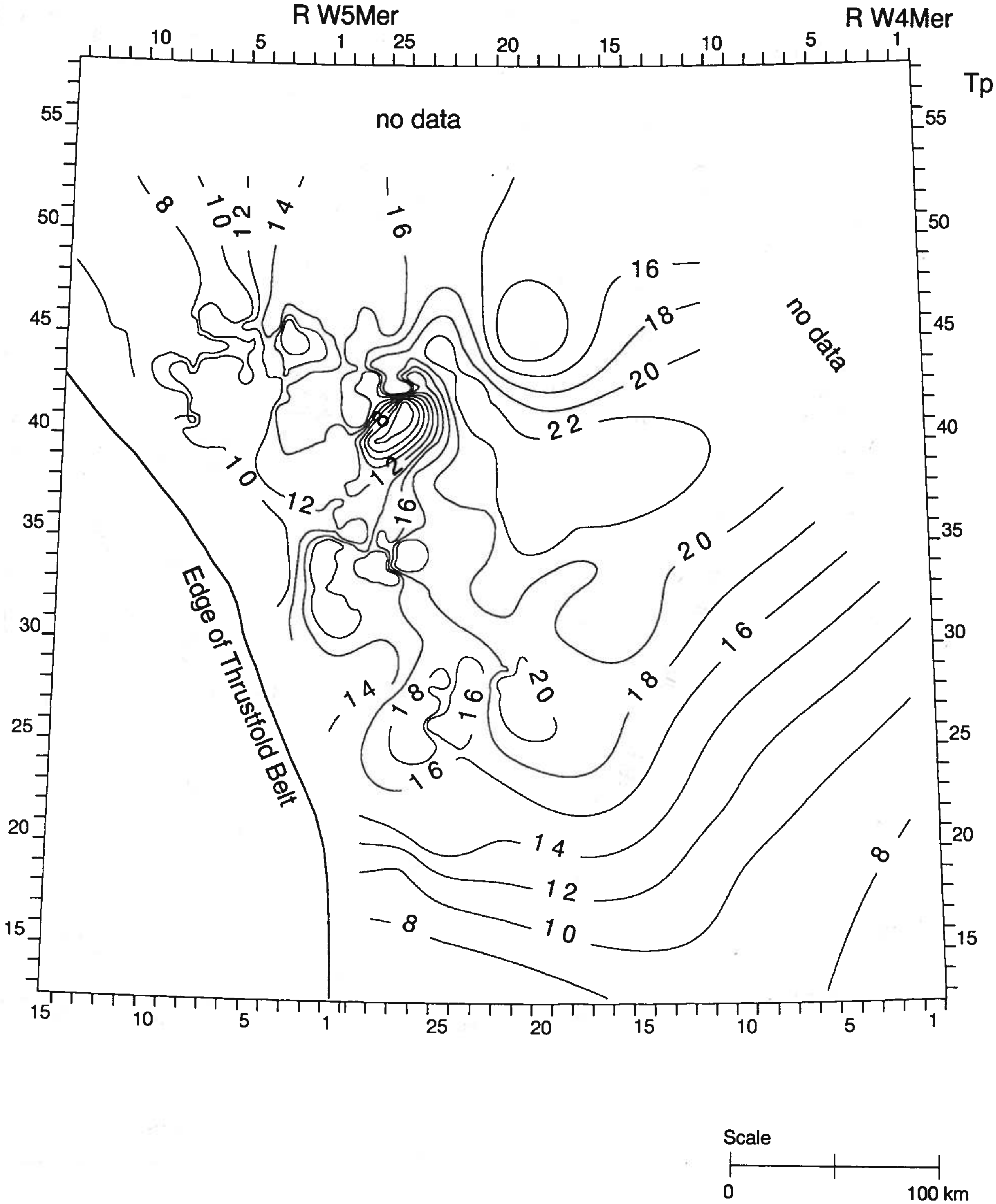


Figure 32. Porosity distribution, lower Belly River strata, south-central Alberta (contour interval: 2%).

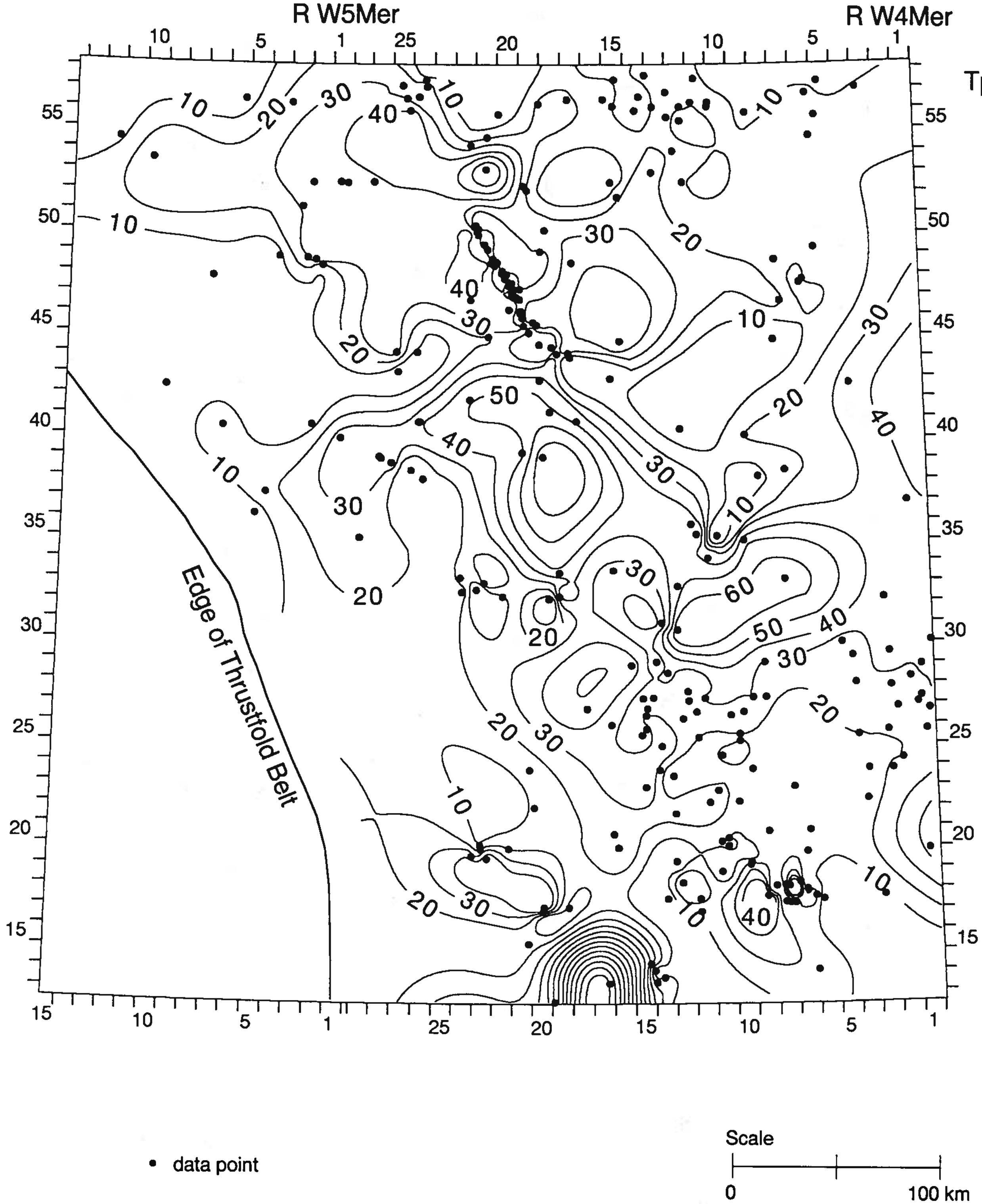


Figure 33. Distribution of I in formation water, Viking, south-central Alberta (contour interval: 10 mg/l).

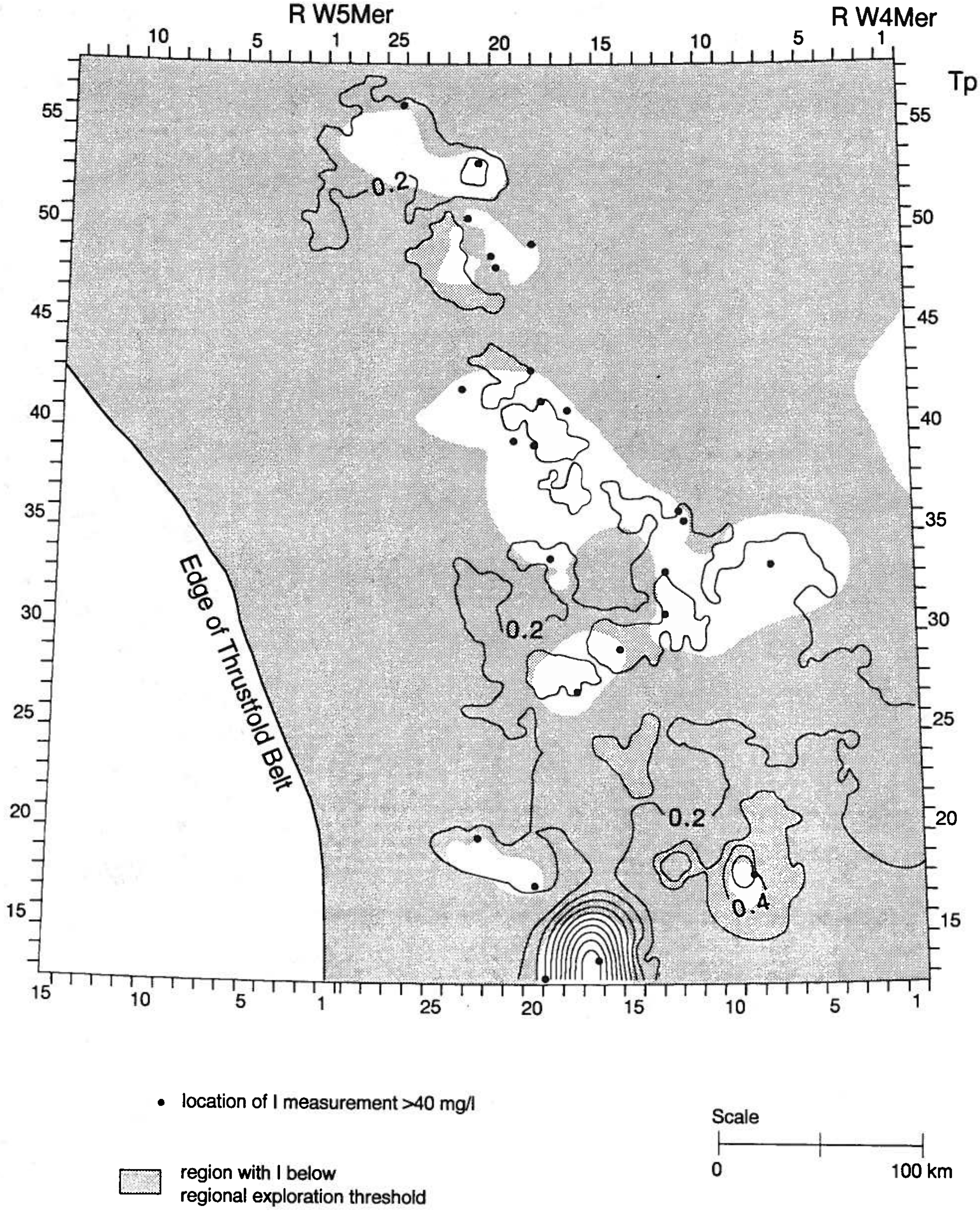


Figure 34. Resource distribution estimate for I ($Tx10^3/km^2$) in formation water, Viking, south-central Alberta.

The distribution of I concentrations in formation waters of lower Belly River strata is shown in figure 35. Only a few areas show concentrations over 40 mg/l, and there is no significant trend to the data. Areas with high I concentrations may be associated with hydrocarbon accumulations (Hitchon et al., 1993). The distribution of the estimated I resource (figure 36) shows two small areas of high values which coincide with the two areas of highest I concentration shown in figure 35.

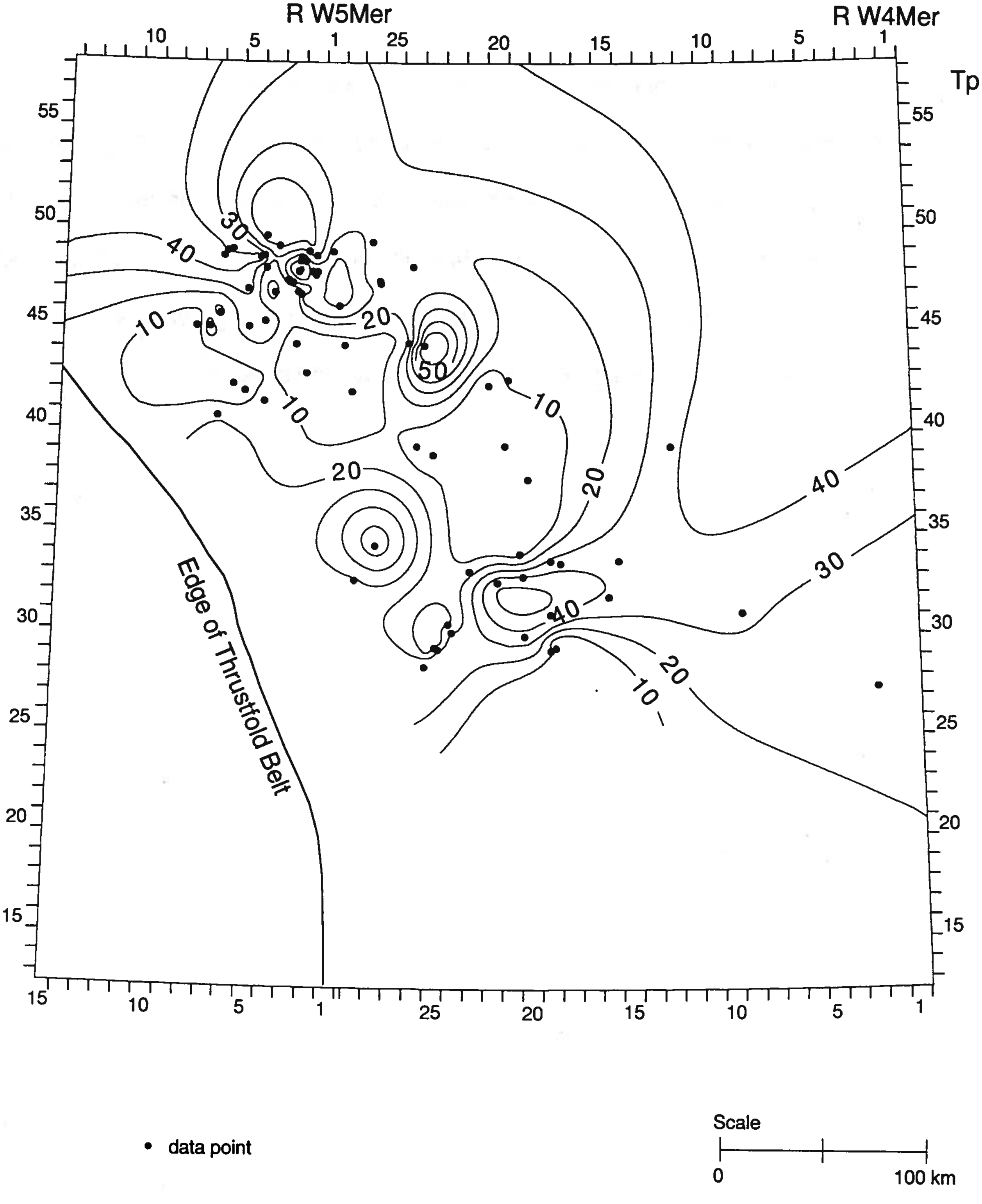


Figure 35. Distribution of I in formation water, lower Belly River, south-central Alberta (contour interval: 10 mg/l).

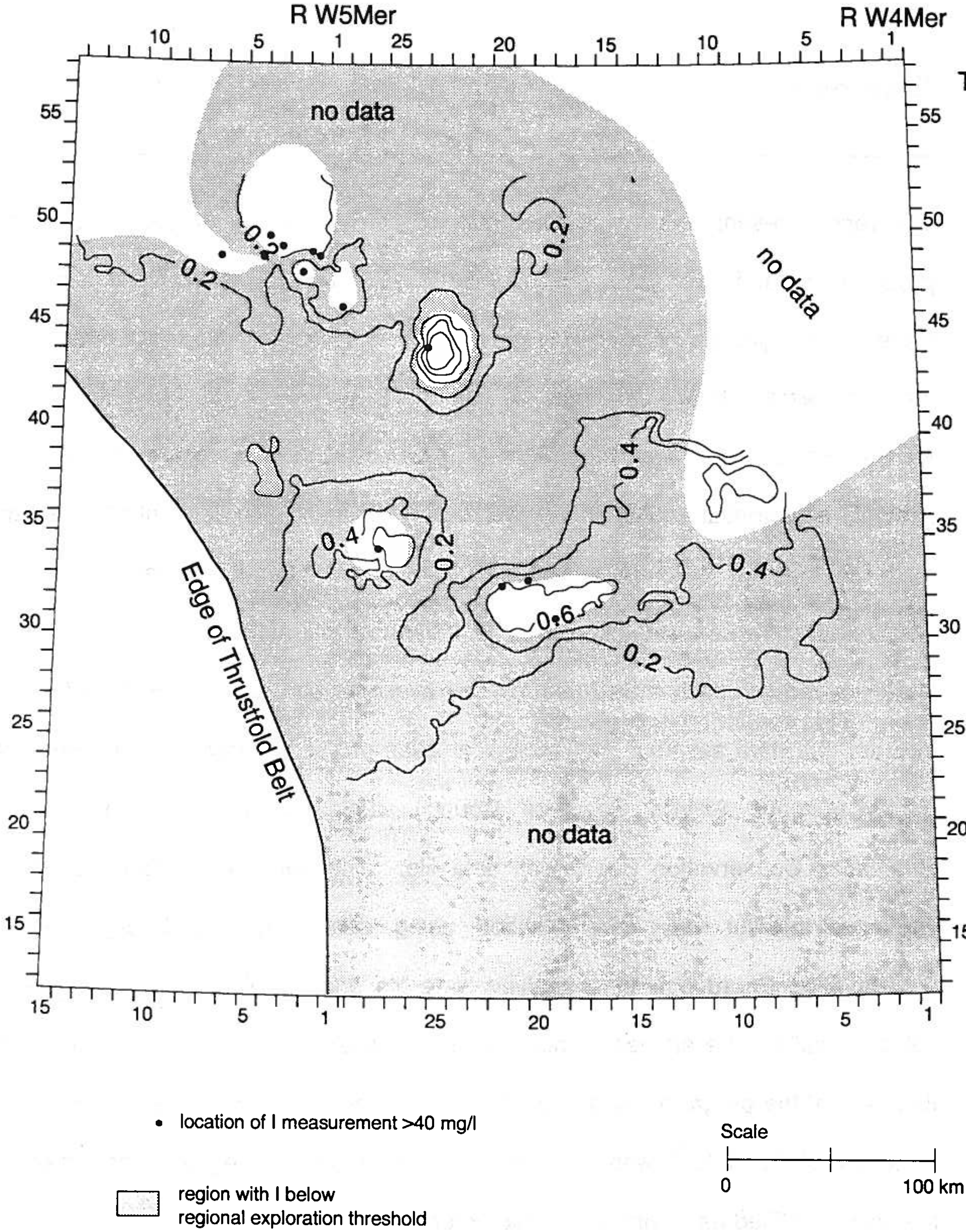


Figure 36. Resource distribution estimate for I ($Tx10^3/km^2$) in formation water, lower Belly River, south-central Alberta.

Summary

This report presents the results of work performed in the second year of a three year program funded by the Canada-Alberta Partnership Agreement on Mineral Development (project MDA92-011) regarding the industrial mineral potential of Alberta formation waters. In the first year, the contents of Ca, Mg, K, Li, I and Br in formation waters were characterized throughout the province, and four regions and stratigraphic intervals of potential economic interest were identified. The present study examines each of these four regions and stratigraphic intervals in detail in order to estimate the magnitude of these potential resources. Each stratigraphic interval of interest was characterized for each area based on all available stratigraphic picks data. These included the data set from the Geological Atlas of the Western Canada Sedimentary Basin, previous Alberta Research Council studies, and data from the Energy Resources Conservation Board well data file. The porosity distributions within the strata of interest were characterized using data from the Energy Resources Conservation Board core-plug analysis data file and geophysical log analyses from selected wells. The element concentrations were obtained from data compiled in the first year of the program. Based on this information, estimates of resource magnitude in terms of $Tx10^3/km^2$ were calculated for each of the regions and stratigraphic intervals identified as having economic potential.

Lower Elk Point in northeast Alberta

Formation waters in Lowewr Elk Point strata of northeast-Alberta contain high contents of Ca, Mg, K and Br, with Ca and Mg concentrations greater than their respective detailed exploration limits. The regions of high element content tend to be associated with underlying salt-deposits of the Lotsberg and Cold Lake formations. In the areas with formation water composition data the resource estimates for Ca and Mg are in the range 200 - 600 $Tx10^3/km^2$ and 20 - 60 $Tx10^3/km^2$, respectively. Comparable extrapolated estimates for K are about 5 $Tx10^3/km^2$ and for Br about 10 $Tx10^3/km^2$, although no formation water analyses reporting high contents of Ca and Mg also report K and Br.

Beaverhill Lake in southern Alberta

Contents of Ca, Mg and K in formation waters in Beaverhill Lake strata in southern Alberta exceed their respective detailed exploration thresholds. Resource estimates are in the broad range 250 - 1250 $Tx10^3/km^2$ for Ca, 50 - 200 $Tx10^3/km^2$ for Mg, and 50 - 250 $Tx10^3/km^2$ for K. There are few determinations of Br in these formation waters, and extrapolated estimates are in the order of only 5 $Tx10^3/km^2$.

Woodbend and Beaverhill Lake in west-central Alberta

Formation waters with contents of Li above the detailed exploration threshold (75 mg/l) occur sporadically in the Leduc and Beaverhill Lake strata, with resource estimates about 1 - 2 $Tx10^3/km^2$.

Viking and lower Belly River in south-central Alberta

Both Viking and lower Belly River strata contain localized areas of formation waters with I contents greater than 40 mg/l. Within these localized areas, resource estimates are of the order of 0.2 $Tx10^3/km^2$ in Viking strata and in the range 10 - 50 $Tx10^3/km^2$ in lower Belly River strata.

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