RESOURCE ESTIMATES OF INDUSTRIAL MINERALS IN ALBERTA FORMATION WATERS

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by

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PREFACE

This report presents the results of work performed in the third and final year of a project (MDA92-011) funded by the Canada-Alberta Partnership Agreement on Mineral Development regarding the industrial mineral potential of formation waters in Alberta. In the first year the contents of Ca, Mg, K, Li, I and Br in formation waters were characterized throughout the province. Based on elemental concentrations, five stratigraphic intervals in four regions in Alberta were identified as being of potential economic interest. In the second year, potential resources were broadly estimated in the respective regions and stratigraphic intervals. This report presents more realistic resource estimates potentially leading to mineral extraction and plant siting, based on elemental concentrations and more accurate areal and stratigraphic delineation. The latter was obtained from isopachs of the potentially productive strata determined on the basis of rock porosity and permeability which allow extraction of formation waters.

Contents

Figures

Abstract

Formation waters in the Alberta basin contain dissolved minerals in various concentrations. Of these, calcium (Ca), magnesium (Mg), potassium (K), lithium (Li), iodine (I) and bromine (Br) are found in places at concentrations above the corresponding regional and detailed exploration limits. Depending on resource amount and ability to pump formation waters for mineral extraction, the potential exists for the economic exploitation of these minerals from Alberta brines. Specific areas and stratigraphic intervals in Alberta with producibility potential for Ca, Mg, K, Li, I and Br were identified based on elemental concentrations above the respective exploration thresholds, minimum thickness and porosity of the host interval, and minimum rock permeability. The use of these criteria in estimating resources ensures that the respective mineral is found in potentially economic amounts and that it can be extracted from the host formation. The distributions of the various minerals are presented as maps per element, area and stratigraphic interval and are expressed as grams per m^2 of land surface or t/km^2. These maps can be used for exploration drilling, resource extraction and possible plant siting.

Calcium, magnesium, potassium and bromine in high concentrations are found, depending on location, between 1,240 m and 2,600 m depth in lower Elk Point Group strata in two areas in central-eastern Alberta, and in six areas in Beaverhill Lake Group strata in southern Alberta. Resources vary between 25 and 760 kg/m^2 for Ca, 2 and 136 kg/m^2 for Mg, up to 116 kg/m^2 for K and up to 10 kg/m^2 for Br. Lithium in high

concentrations is found between 2,700 m and 4,000 m depth in west-central Alberta in reefal and platform carbonates of the Woodbend and Beaverhill Lake groups. Resources vary between 0.01 and 0.57 kg/m^2. Iodine in concentrations above the regional exploration threshold is found in Viking and Belly River strata in localized areas in south-central Alberta, at depths varying between 650 m and 950 m. Resources vary between 0.2 and 1.8 kg/m^2.

Introduction

Formation waters have been used as sources of industrial minerals since early in the last century. Analyses of formation waters from Alberta have become available since the 1930s through drilling by the oil industry. By the 1970s, the files of the Alberta Energy Resources Conservation Board contained sufficient formation water analyses from stratigraphic units throughout the province to allow searching for specific analyses of interest to industry and performing regional-scale evaluations of the mineral potential of Alberta formation waters. However, there have been no publications on this subject except for a report on Ca and Mg in Alberta brines (Hitchon and Holter, 1971), one on Br, I and B in formation waters (Hitchon et al., 1977), and a confidential report on Li (Hitchon, 1984a). The scope of the work performed under the current Canada-Alberta Mineral Development Agreement and reported here is to identify areas and stratigraphic intervals in Alberta where formation waters contain high concentrations of dissolved industrial minerals and where rock porosity and permeability would allow production.

A geochemical exploration was performed in the first year (Hitchon et al., 1993) by searching a data base of approximately 130,000 formation water analyses from Alberta for Ca, Mg, K, Li, I and Br. By examining the areal distribution of these elements in every hydrostratigraphic unit (aquifer) in the sedimentary succession, five stratigraphic intervals in four regions in Alberta were identified in which elemental concentrations exceed the respective threshold values for regional exploration (Hitchon, 1984b). These values are:

20,000 mg/l for Ca, 3,000 mg/l for Mg, 5,000 mg/l for K, 50 mg/l for Li, 1,000 mg/l for Br and 40 mg/l for I. Detailed exploration threshold values (60,000 mg/l for Ca, 9,000 mg/l for Mg, 10,000 mg/l for K, 75 mg/l for Li, 3,000 mg/l for Br and 100 mg/l for I) were established based on the composition of the commercial brine produced by the Dow Chemical Co., Midland, Michigan, USA, from the Lower Devonian Sylvania Sandstone in the Michigan basin. Calcium, Mg and K concentrations exceed the detailed exploration threshold in Elk Point Group strata in northern Alberta and in Beaverhill Lake Group strata in southern Alberta (Figure 1a). Bromine is also present in high concentrations. In both cases the high Ca, Mg, K and Br concentrations are associated with the presence of evaporites. Beaverhill Lake and Woodbend strata in west-central Alberta (Figure 1b) contain formation waters with Li concentrations above the detailed exploration threshold, which seem to be associated mainly with reefal carbonate build-ups. Formation waters in the Viking and Belly River strata in south-central Alberta (Figure 1b) contain I concentrations near the detailed exploration threshold. However, the regions with high I concentrations in these two units are discontinuous over large areas, and tend to be associated locally with hydrocarbon accumulations. The four regions identified in the first phase and shown in Figure 1 are rather large (between 75,000 km^2 and 210,000 km^2), being selected on the basis of broad concentration distribution and ease of geographic delineation in the Dominion Land Survey (DLS) system of coordinates. As a result, these regions actually cover areas with elemental concentrations both below and above the respective threshold values for exploration.

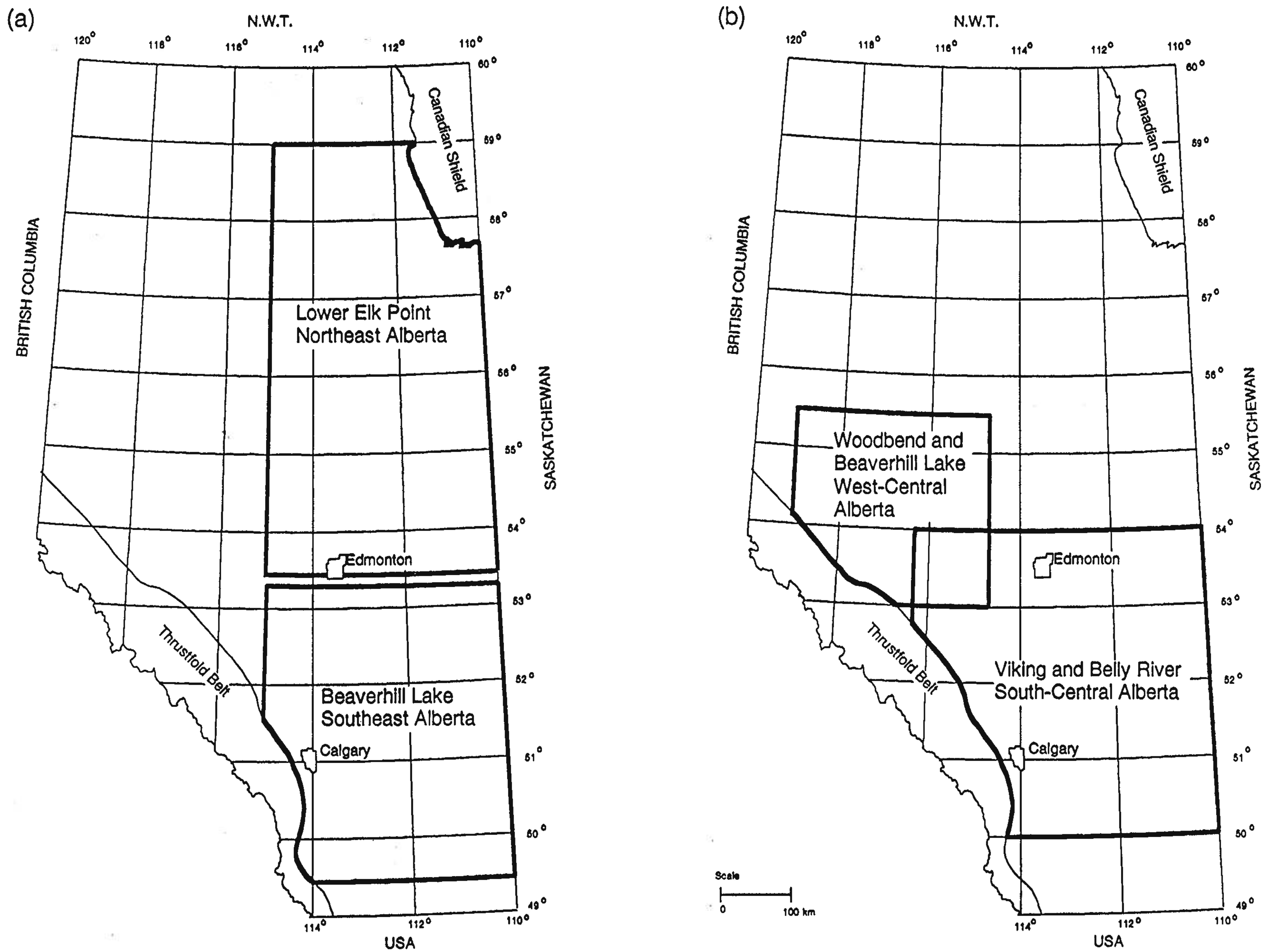

Figure 1. Regions of potentially economic industrial minerals in Alberta formation waters:
(a) mainly for Ca, Mg, K and Br; (b) mainly for Li and I.

In the second year of the study, resources were broadly estimated for each element of interest in the respective stratigraphic interval and area based on concentrations and volumes of formation water in the rock pore space (Underschultz et al., 1994). The resources were actually overestimated because: (1) the regions identified initially cover also areas with elemental concentrations below the respective exploration threshold; (2) the thickness (isopach) of the strata of interest was generally determined based on a coarse, large-scale stratigraphic delineation of the Alberta basin (Mossop and Shetsen, 1994); and (3) the pore space was estimated based on porosity values measured in core plugs, which were generally taken from the more porous portions and, as such, are not necessarily representative of the entire stratigraphic interval. In many cases tight intervals are present within thick sections, thus further reducing the available resource because of the inability to extract economic amounts of formation water from low permeability rocks. Nevertheless, the second year study helped to identify areas of interest in terms of resource amounts (expressed in tonnes per unit area) rather than concentrations.

The work performed in this third and final year of the study has the objective of estimating, as accurately as possible, the potential for extracting industrial minerals from Alberta formations waters. The resource estimates are based on elemental concentrations greater than the detailed threshold values and on the actual thickness of the rocks which have sufficient porosity and permeability to allow the economic production of formation waters. As a result, potential target areas for drilling can be identified, leading to site-specific evaluation and potential plant siting.

Methodology

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

$$R = C \times D \times \phi \tag{1}$$

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

Data sources

Concentrations of the elements of interest are reported in analyses of formation water samples, most of which were collected by the oil industry under provincial regulations. The 'standard' industry analyses are stored in hardcopy with the Alberta Energy Resources Conservation Board (ERCB). They usually report Ca and Mg among other anions and cations, but only occasionally are minor and trace elements like Br, I and Li reported. Besides the ERCB file, which constituted the major source of information, two other sources were used in the regional-scale geochemical exploration phase of the study (Hitchon et al., 1993). The analyses from these additional sources contain more information about trace elements. All the analyses of formation waters were entered into an electronic data base at the Alberta Geological Survey, verified, and culled for incomplete or erroneous analyses according to a set of 15 criteria (Hitchon and Brulotte, 1994). The data base was then searched for Ca, Mg, K, Li, Br and I at or above the respective threshold values. The distributions were mapped at a regional scale, and areas of potential economic interest were identified.

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

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

Data processing

Because of their different nature and representativeness, the concentration, porosity and permeability data have to be processed differently. Drillstem tests are performed and water samples taken usually from a single interval within a stratigraphic unit. It is assumed that within the same hydrostratigraphic unit (aquifer), elemental concentrations do not vary with depth (in the same well), only areally (from well to well). This is particularly the case for thin stratigraphic intervals whose vertical dimension is much smaller than the lateral variability scale. Unlike concentrations, which generally have a smooth variation because of transport processes like diffusion, dispersion and advection, rock porosity and permeability tend to have a high discontinuous variability both vertically and laterally. As an example, Figure 2 shows the vertical porosity variation in Beaverhill Lake Group strata in well 12-13-14-14W4 Mer as estimated from geophysical logs and measured on core plugs. It is obvious from Figure 2 that the zone with high and

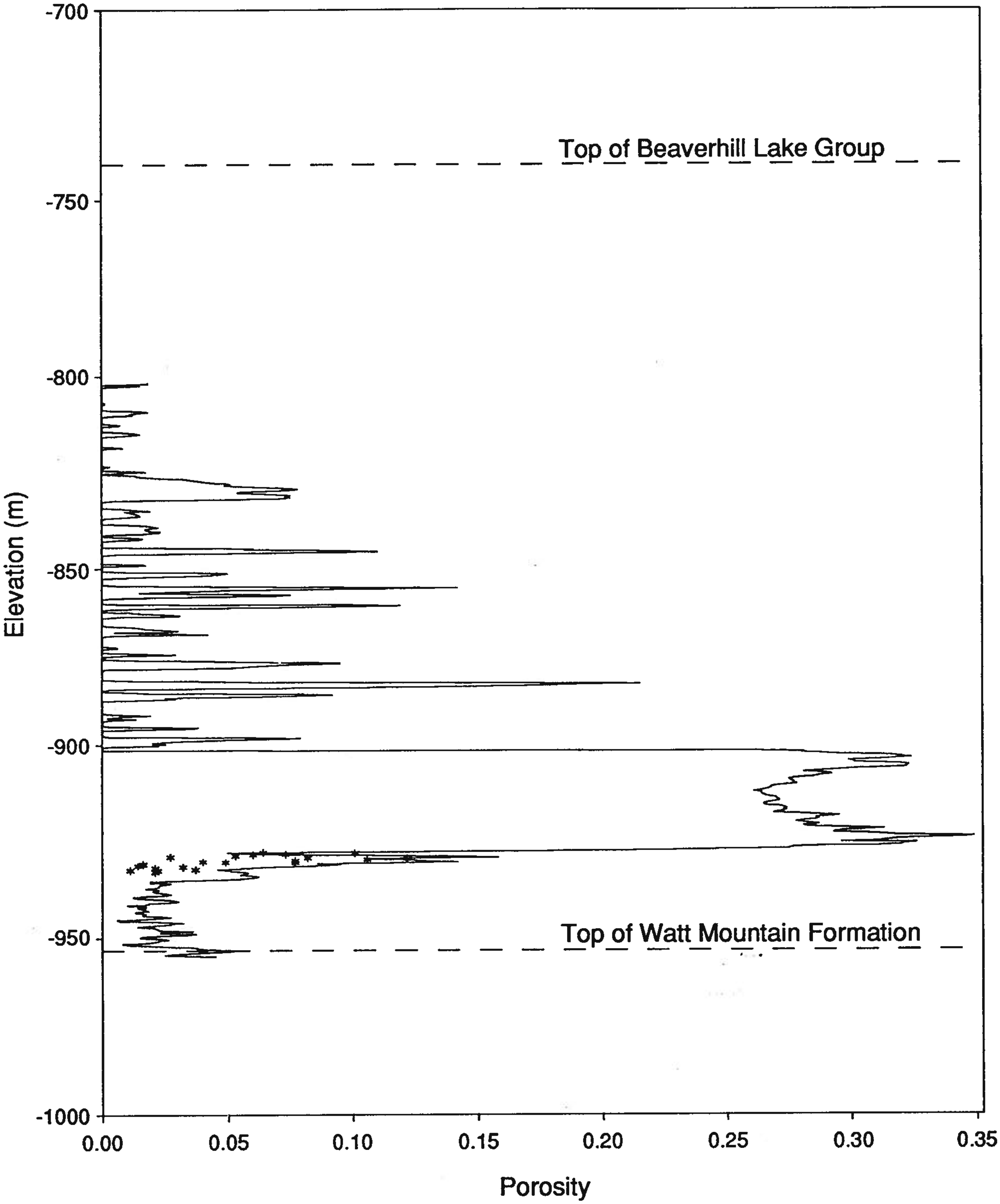

Figure 2. Porosity variation with depth in Beaverhill Lake Group strata in well 12-13-14-14W4 Mer as measured in core (*) and estimated from geophysical logs (—).

continuous porosity is not present throughout the interval shown. Figure 2 also illustrates also the point made previously that core analyses tend to be biased toward the more porous intervals. Because so few wells penetrate the Beaverhill Lake Group strata in southern Alberta and the Elk Point Group strata in northeastern Alberta, not all of which were cored, geophysical logs were used to estimate the porosity variation in 74 and 37 wells in each area, respectively. The porosity variation with depth in each well was used to determine: (1) the actual depth and thickness of the potentially productive interval; and (2) its average porosity and permeability. To use the example well of Figure 2, the thickness and average porosity of the potentially productive interval are 38 m and 26%, respectively, as opposed to 211 m and 5%, respectively, for the entire of Beaverhill Lake Group interval at this location. Because porosity is a scalar (additive) property of porous media, the scaling up from the plug and log-reading scale to the well scale is done by weighted arithmetic averaging of the plug or log scale values (Baveye and Sposito, 1984; Cushman, 1984; Dagan, 1989). The weighting is by the length of the representative interval indicated in core analyses. Porosity values obtained from geophysical logs were read at a constant 0.25 m interval, such that the well-scale value was obtained by straight arithmetic averaging of the digital porosity log values. For the Beaverhill Lake and Elk Point strata in southern and northeastern Alberta, respectively, porosity logs were obtained and used in every well because of the scarcity of wells and core analyses. For other strata and areas of interest only core analyses were used because of data abundance and high cost of digitizing logs, the latter being highly labour intensive. The well-scale porosity values were analyzed both statistically (frequency plots) and areally, in order to identify for each interval of interest zones of high porosity, hence with potential for extraction of formation waters, and areas of tight rocks (low porosity). As an example, Figure 3 shows the frequency distribution of well-scale porosity in the Beaverhill Lake Group strata in southern Alberta in the area delineated in Figure 1a. The average well-scale porosity in this case is close to 9%.

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

$$k_{ef}^{w} = \frac{1}{n} \sum k_i^{w} \tag{2}$$

where n is the number of samples in the distribution and w is an empirical power. Note that the harmonic, geometric and arithmetic averages are retrieved in relation (2) for values of w = -1, w = 0 and w = 1, respectively. For a permeable unit, the well-scale permeability is higher than the geometric average but lower than the arithmetic average. A value of w = 0.8 (Desbarats and Bachu, 1994) was used in this study to estimate the well-scale permeability based on core-plug measurements. In scaling up permeability from plug to well scale, only the potentially productive interval was considered, as determined from porosity and permeability variations in each well. As mentioned previously, permeability estimates from drillstem tests are already at the well scale, and

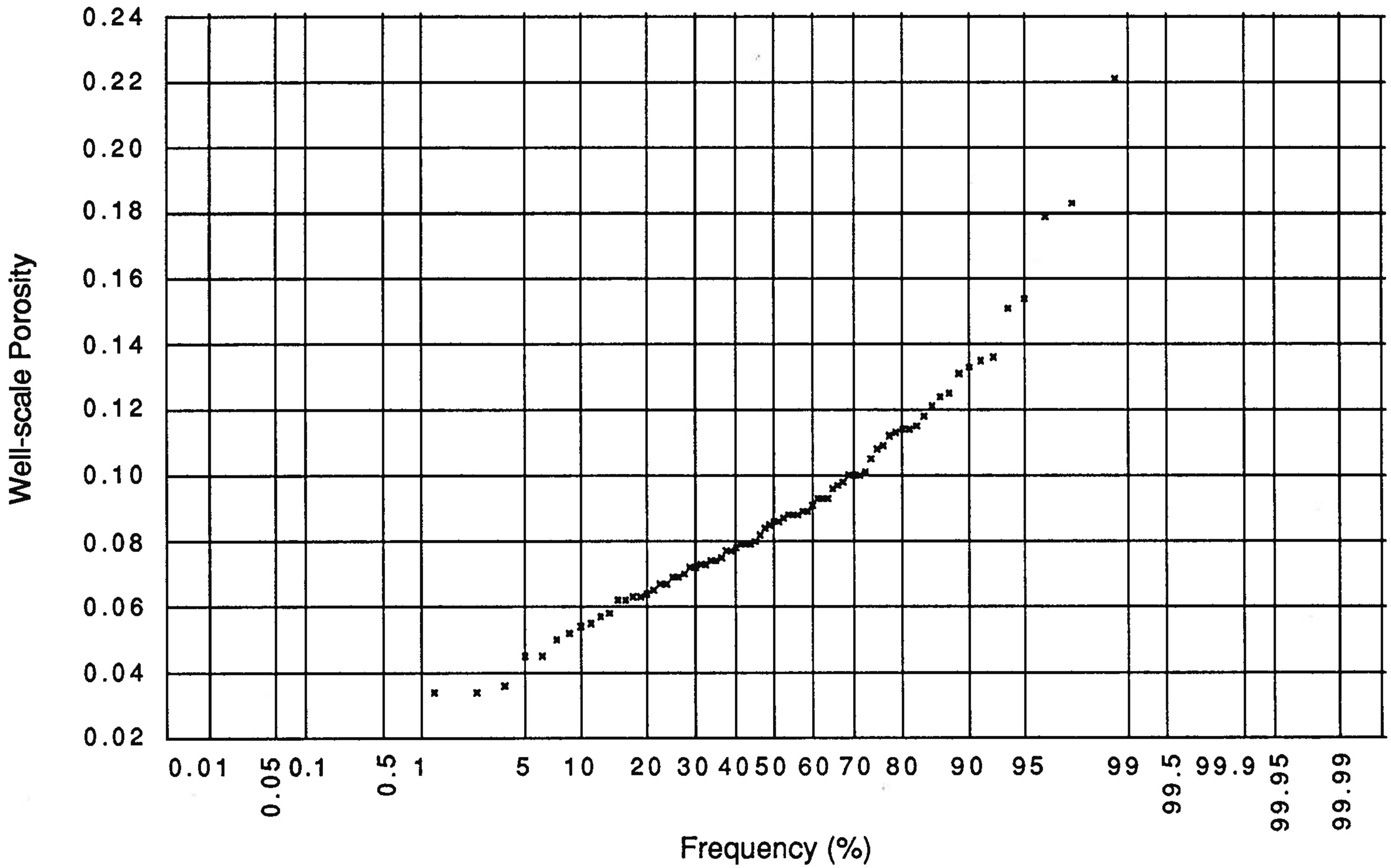

Figure 3. Frequency distribution of well-scale porosity in Beaverhill Lake Group strata, southern Alberta.

as such do not need to be scaled up. To illustrate the above points, Figure 4 presents the permeability variation in a cored interval from Beaverhill Lake strata in well 16-11-20-12W4 Mer, as measured in core plugs and in a drillstem test.

The permeability data obtained from drillstem tests and the well-scale permeability values obtained by scaling-up the plug-scale measurements on core were merged for the statistical and areal analysis of permeability variation in each interval and area of interest. Well scale permeability values vary in a wide range, from less than $10^{-15}m^2$ (1 md) to more than $10^{-12}m^2$ (100 md). As an illustration, Figure 5 shows the frequency distribution of well-scale permeability in the Beaverhill Lake Group strata in southern Alberta in the area delineated in Figure 1a. Generally there are less wells with permeability determinations than with porosity determinations. Statistical analysis of the well-scale porosity and permeability data in the areas of interest has shown that generally the less porous rocks tend also to be less permeable (tight). For illustration, Figure 6 shows the correlation between the well-scale porosity and permeability values in Beaverhill Lake Group strata in southern Alberta, obtained by scaling-up core-plug measurements. Thus, in areas with no permeability measurements, porosity can be used as a rough indicator of rock permeability, hence producibility of formation water for mineral extraction.

Not all data categories (elemental concentrations, porosity, permeability and interval thickness) were available in every well. In order to overcome this shortcoming of the data distributions, rather than estimating resources at each well location according to relation

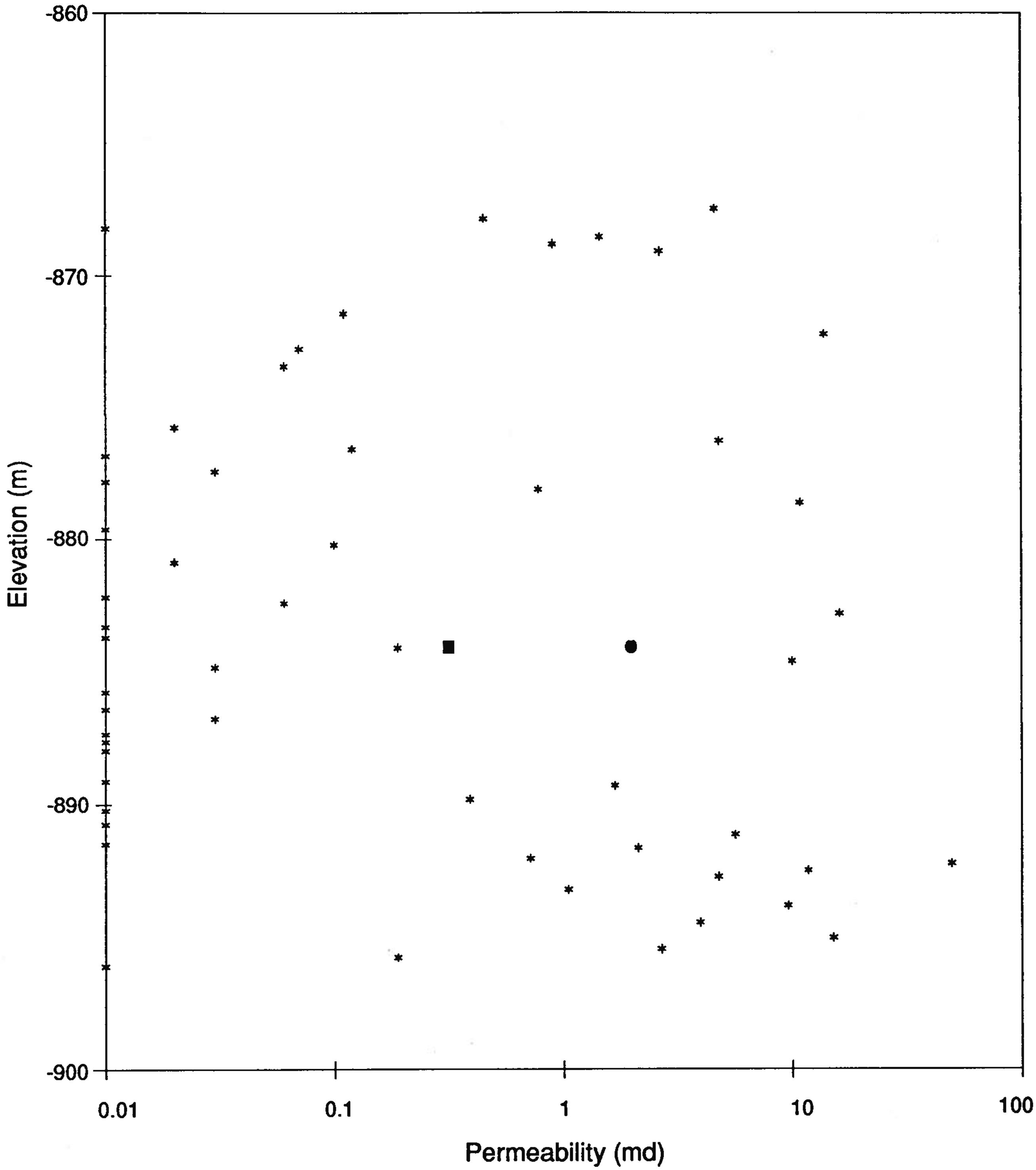

Figure 4. Permeability variation with depth in Beaverhill Lake Group strata in well 16-11-20-12W4 Mer as measured in core plugs (∗), in a drill stem test (■), and well-averaged (●).

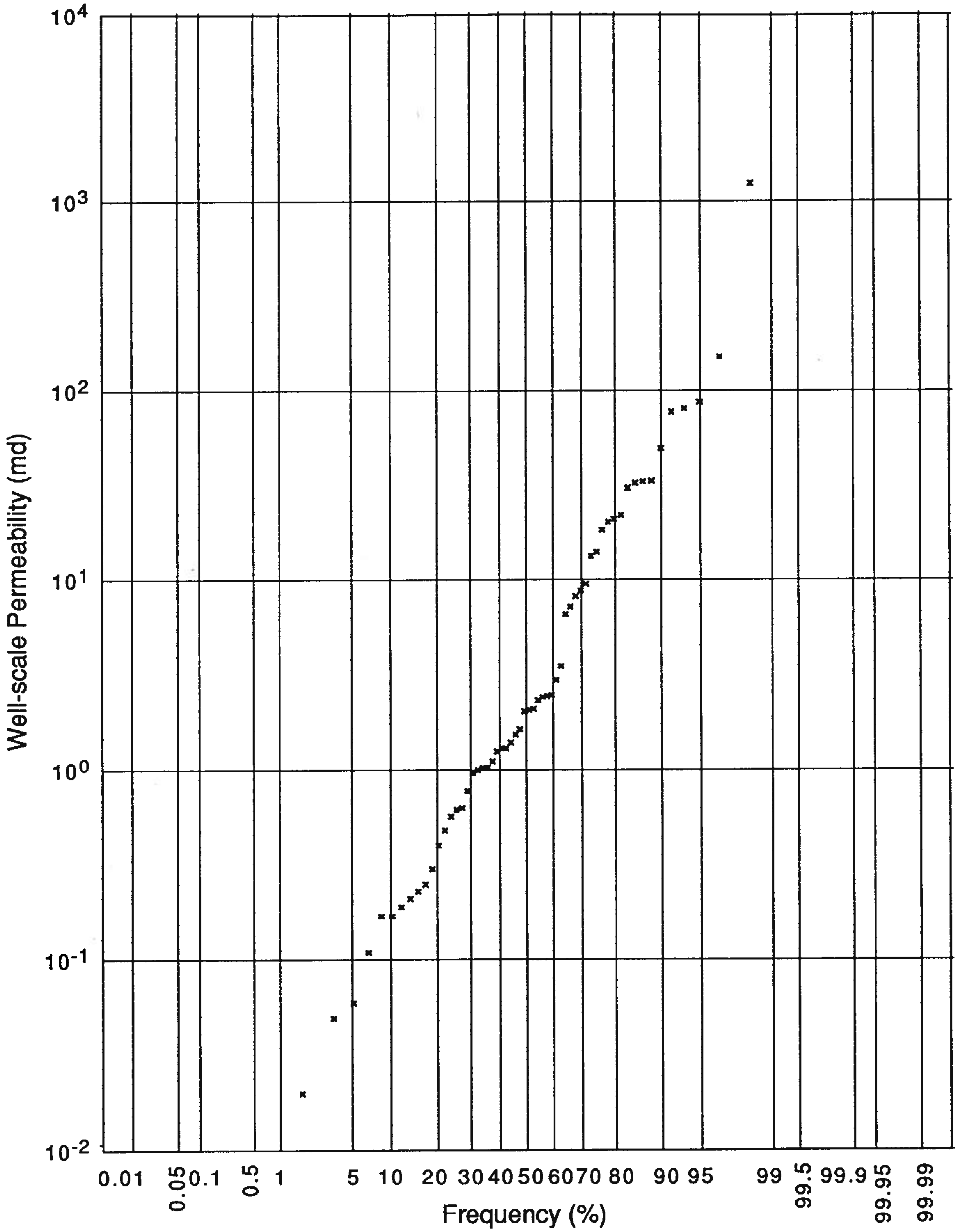

Figure 5. Frequency distribution of well-scale permeability in Beaverhill Lake Group strata, southern Alberta.

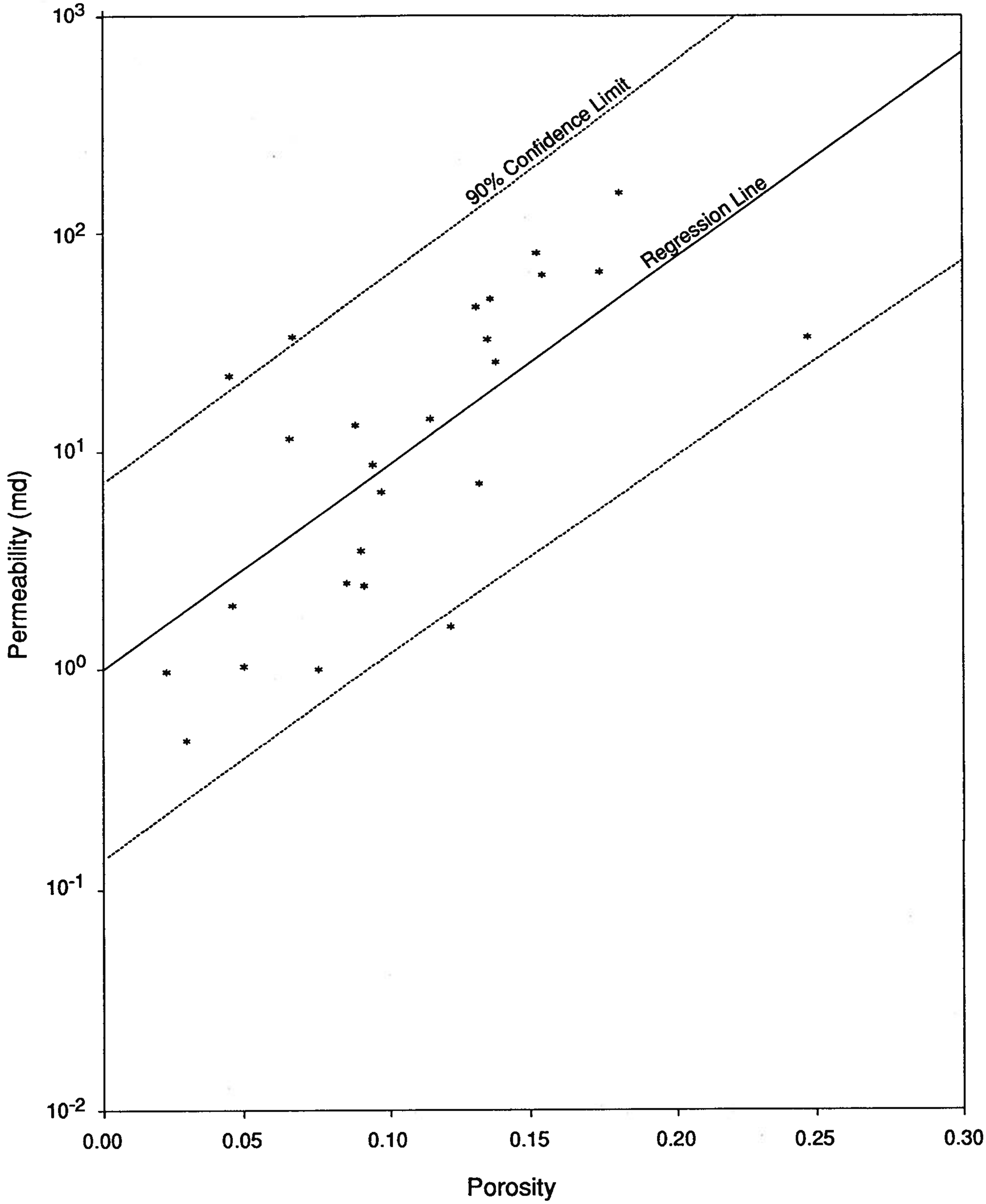

Figure 6. Correlation between well-scale permeability and porosity measured in core plugs from Beaverhill Lake Group strata, southern Alberta.

(1), the areal variation of each data type was mapped in the regions of interest. Concentrations, isopach, porosity and permeability distribution maps were used to constrain areally the regions where mineral extraction from formation waters is potentially economic based on high concentrations and volumes, and water producibility. With respect to concentrations, the detailed exploration limits were used for areal delineation. With respect to the other parameters, the following somewhat arbitrary limiting values were used: interval thickness, at least 10 m; porosity, greater than 5%; and permeability greater than $10^{-14}m^2$ (10 md). Using computer-based methods, distribution maps were produced and superimposed for each region of interest, leading to the identification and delineation of the areas with economic potential for the production of industrial minerals from formation waters. The resources in each area were automatically calculated from distribution maps according to relation (1). The resulting maps and resources indicate which areas and stratigraphic intervals in Alberta have the potential for the economic extraction of industrial minerals from formation waters based on concentrations and water producibility alone. No ground surface considerations such as access roads, transportation and construction costs were taken into account. Also, it should be kept in mind that the estimated resources represent the total amount of any mineral of interest dissolved in the water filling the entire rock pore space, and that this volume can not be entirely pumped out. Nevertheless, the resource estimations based on concentrations and producibility should provide valuable information for targeting site-specific evaluations, performing additional testing and economic studies, and, eventually, plant siting.

Resource Estimates

Resources are estimated for calcium (Ca), magnesium (Mg), potassium (K), lithium (Li), bromine (Br) and iodine (I) dissolved in formation waters in Alberta in regions and strata characterized by high concentrations and rock properties (porosity and permeability) which allow water production for mineral extraction. The previous regional-scale review (Hitchon et al., 1993) identified high concentrations of Ca, Mg and K (above the respective detailed exploration thresholds) in Beaverhill Lake Group strata in southern Alberta and in the Elk Point Group strata in northeastern Alberta. The possibility of high Br content in the same formation waters was also identified. High Li concentrations were identified in west-central Alberta in Beaverhill Lake and Leduc carbonate reef complexes. Iodine in high concentrations was identified in Viking and Belly River formations in southern Alberta. Because of the natural grouping, the resource estimates are presented in the same order.

Calcium, Magnesium, Potassium and Bromine

Based on concentration distributions and for ease of data processing and representation, very broad geographic areas and stratigraphic intervals were previously identified as being of potential economic interest (Figure 1). The Beaverhill Lake Group strata in southern Alberta have a gross isopach varying between 160 m in the southwest to more than 300 m in the northeast. However, the net thickness of the potentially productive interval is much less, approximately 30 m on average. The interval is located generally in the lower part of the section. The well-scale porosity and permeability of the interval vary throughout the entire area in the ranges 2 - 22% and 2 x 10^{-17} - 10^{-12}m^2 (0.02 - 1000 md), respectively. Based on threshold concentrations for detailed exploration, on minimum interval thickness of 10 m, and minimum porosity and permeability of 5% and 10^{-14}m^2 (10 md), respectively, six areas were identified in southern Alberta (Figure 7) where Ca, Mg, K and Br extraction from formation waters would potentially be economic based only on elemental concentrations and water producibility. Further exploratory drilling in these areas and other economic considerations should lead to decisions regarding investment and plant siting. The approximate depth to the stratigraphic interval of economic potential (Figure 8) varies between 1,240 m in the east where Beaverhill Lake strata are shallower, and 2,600 m in the west in the deeper part of the basin. The "bull's eye" features apparent in areas B, C and D (Figure 8) may be due to reefal buildup within the Beaverhill Lake carbonate platform. The average characteristics of the potentially productive stratigraphic interval in all these areas are 9% porosity and 55 x 10^{-15}m^2 (55 md) permeability.

In northeastern Alberta, high concentrations of Ca, Mg, K and Br are present in formation water in the lower Elk Point Group. The isopach of the Elk Point Group strata in the initial large area (Figure 1) varies from less than 20 m in the northeast to more than 100 m in the southwest, but the average effective thickness of the potentially productive interval is only 17 m. The well-scale porosity and permeability of this interval vary in the ranges

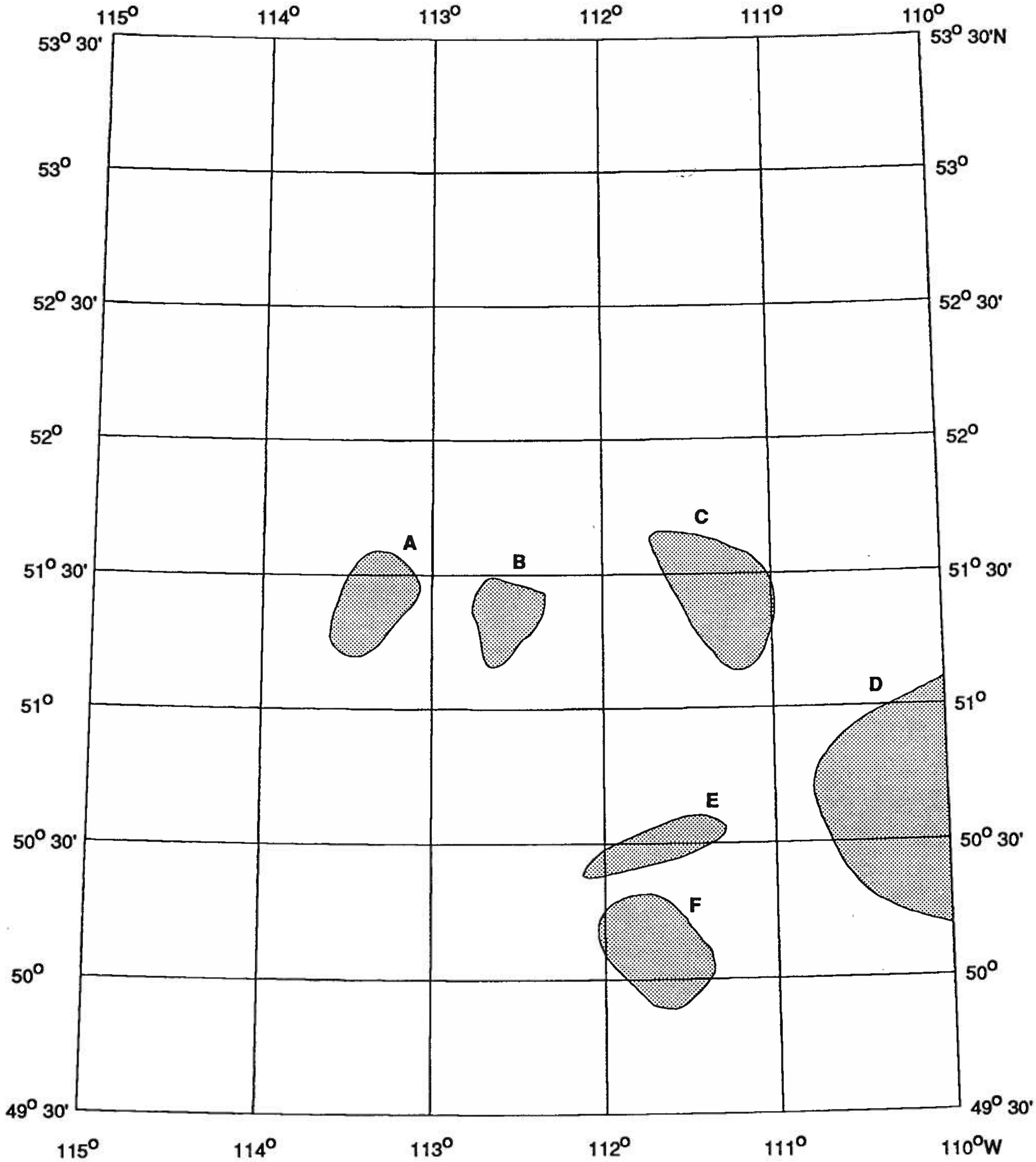

Figure 7. Areas in southern Alberta with producibility potential for Ca, Mg, K and Br from Beaverhill Lake Group formation water.

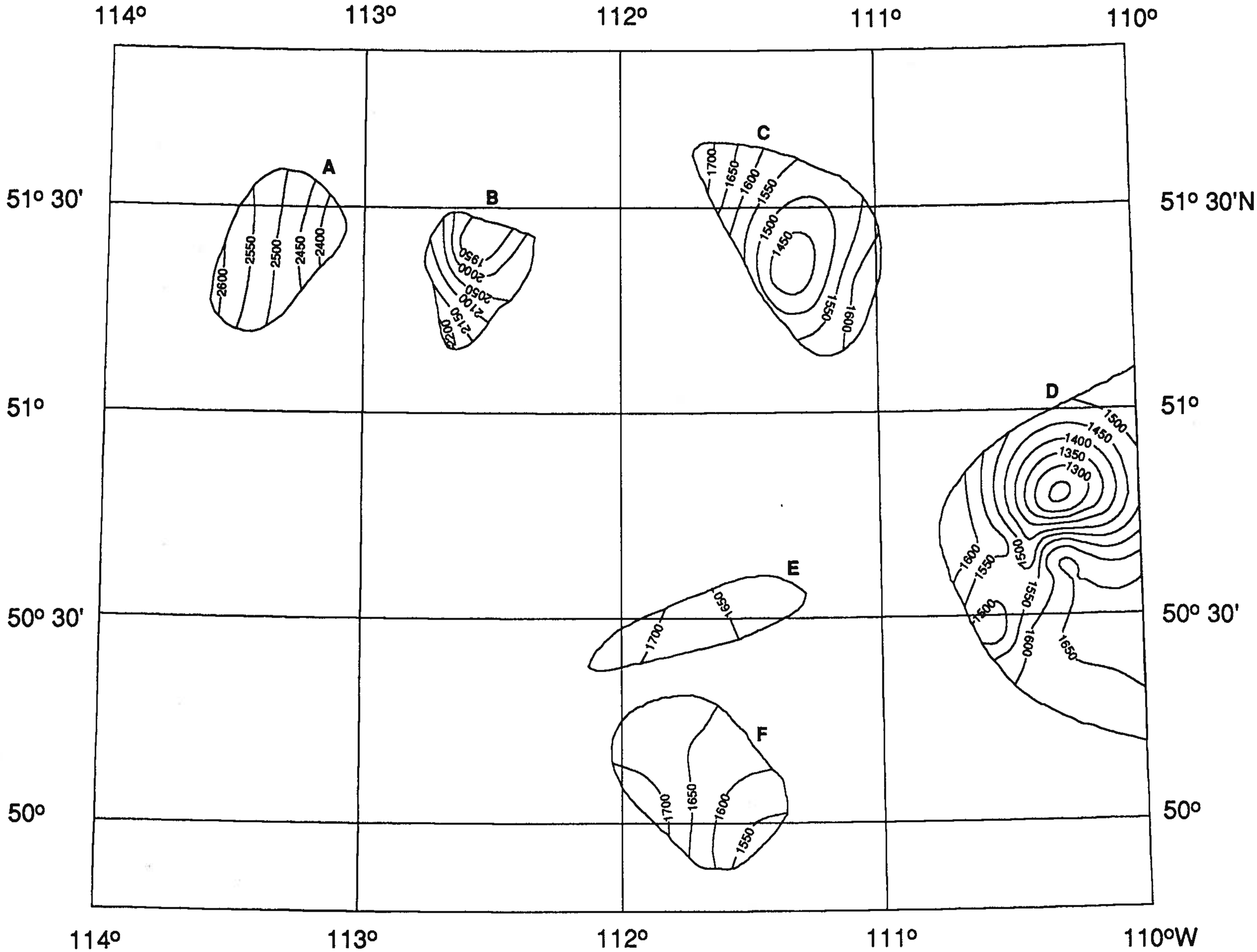

Figure 8. Approximate depth (m) to the stratigraphic interval with producibility potential for Ca, Mg, K and Br in formation water from Beaverhill Lake Group strata, southern Alberta.

3 - 11% and 10^{-16} - 5 x $10^{-14}m^2$ (0.1 - 50 md), respectively. Using the same criteria for areal delineation as for Beaverhill Lake Group strata in southern Alberta, and considering the poor data distribution in northeastern Alberta (Hitchon et al., 1993), only two areas were identified in this region in central-eastern Alberta (Figure 9) where Ca, Mg, K and Br extraction from formation water in this aquifer might have economic potential. The approximate depth to the potentially productive interval (Figure 10) varies between 1,650 m and 2,040 m. Although the Elk Point Group strata are older and stratigraphically deeper than Beaverhill Lake Group strata, the resources in central-eastern Alberta are found at depths comparable with or less than in southern Alberta because the basin becomes shallower to the northeast as it approaches the exposed Precambrian Shield. The average characteristics of the potentially productive interval in central-eastern Alberta are 8% porosity and 18 x $10^{-15}m^2$ (18 md) permeability.

Calcium, Mg, K and Br resources were estimated for the six areas in southern Alberta and two in central-eastern Alberta according to relation (1). Estimates of potentially economic Ca resources in formation water vary between 50 and 760 kg/m^2 in Beaverhill Lake strata in southern Alberta (Figure 11), and between 25 and 180 kg/m^2 in Elk Point strata in central-eastern Alberta (Figure 12). The Mg resource estimates vary between 4 and 136 kg/m^2 in the south (Figure 13), and between 2 and 32 kg/m^2 in central-eastern Alberta (Figure 14). Potassium resource estimates are definitely higher in the south, where they vary between 1 and 116 kg/m^2 (Figure 15), than in the north, where they reach only 2.4 kg/m^2 (Figure 16). Finally, Br resource estimates reach up to 10 kg/m^2 in

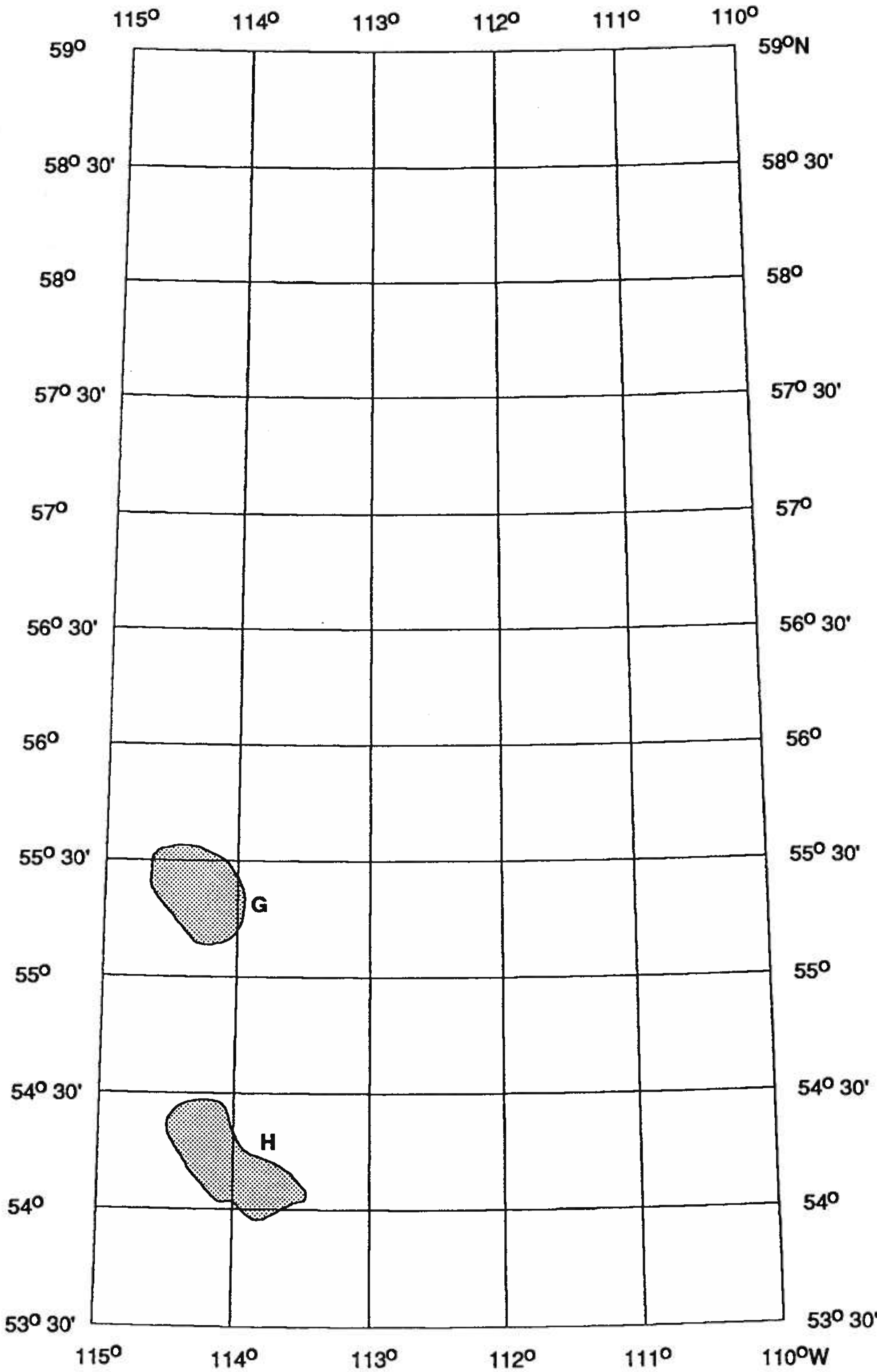

Figure 9. Areas in northern Alberta with producibility potential for Ca, Mg, K and Br from Elk Point Group formation water.

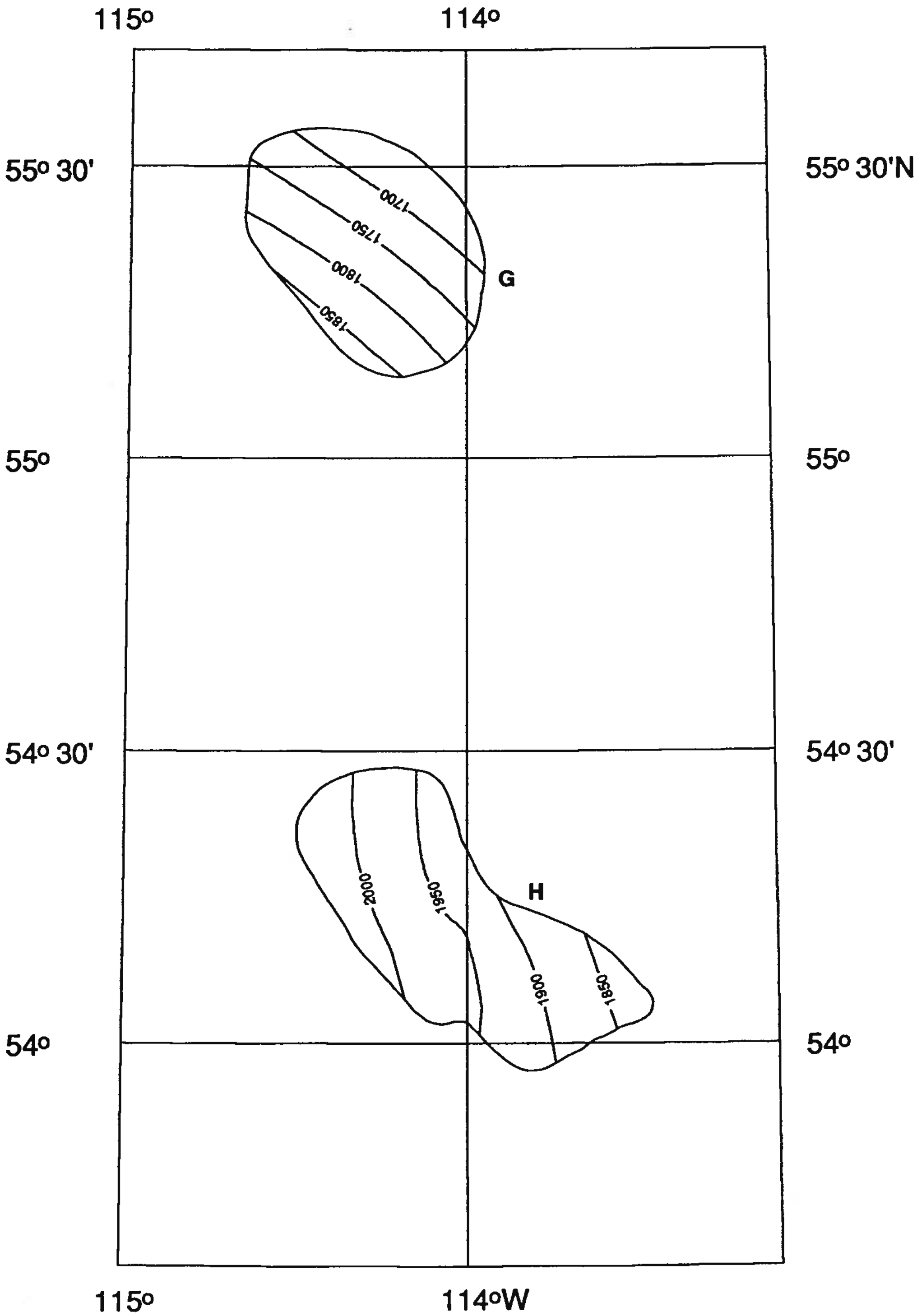

Figure 10. Approximate depth (m) to the stratigraphic interval with producibility potential for Ca, Mg, K and Br in formation water from Elk Point Group strata, central-eastern Alberta.

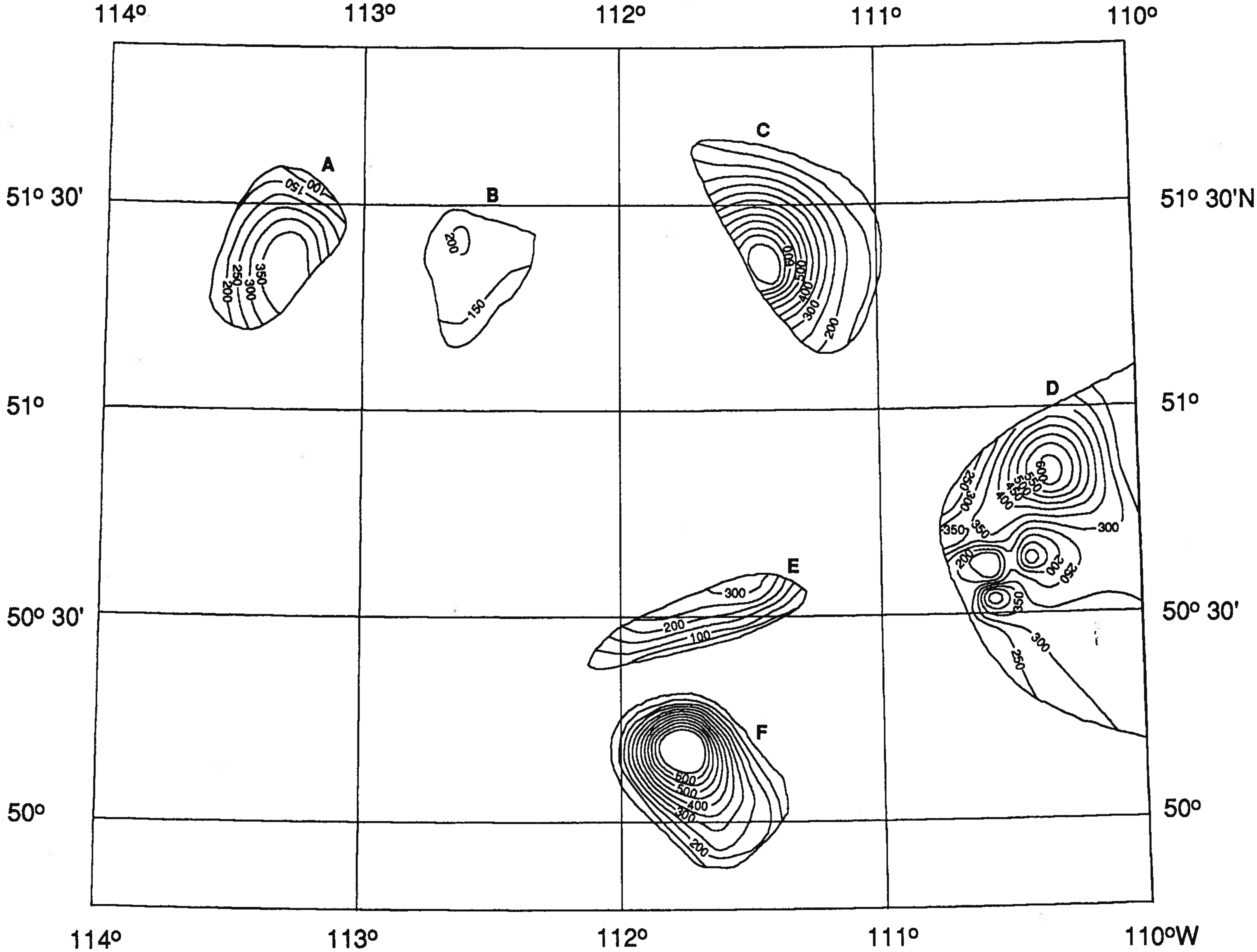

Figure 11. Calcium resource estimates in formation water in Beaverhill Lake Group strata, southern Alberta (contours in kg/m^2 or 1000 t/km^2).

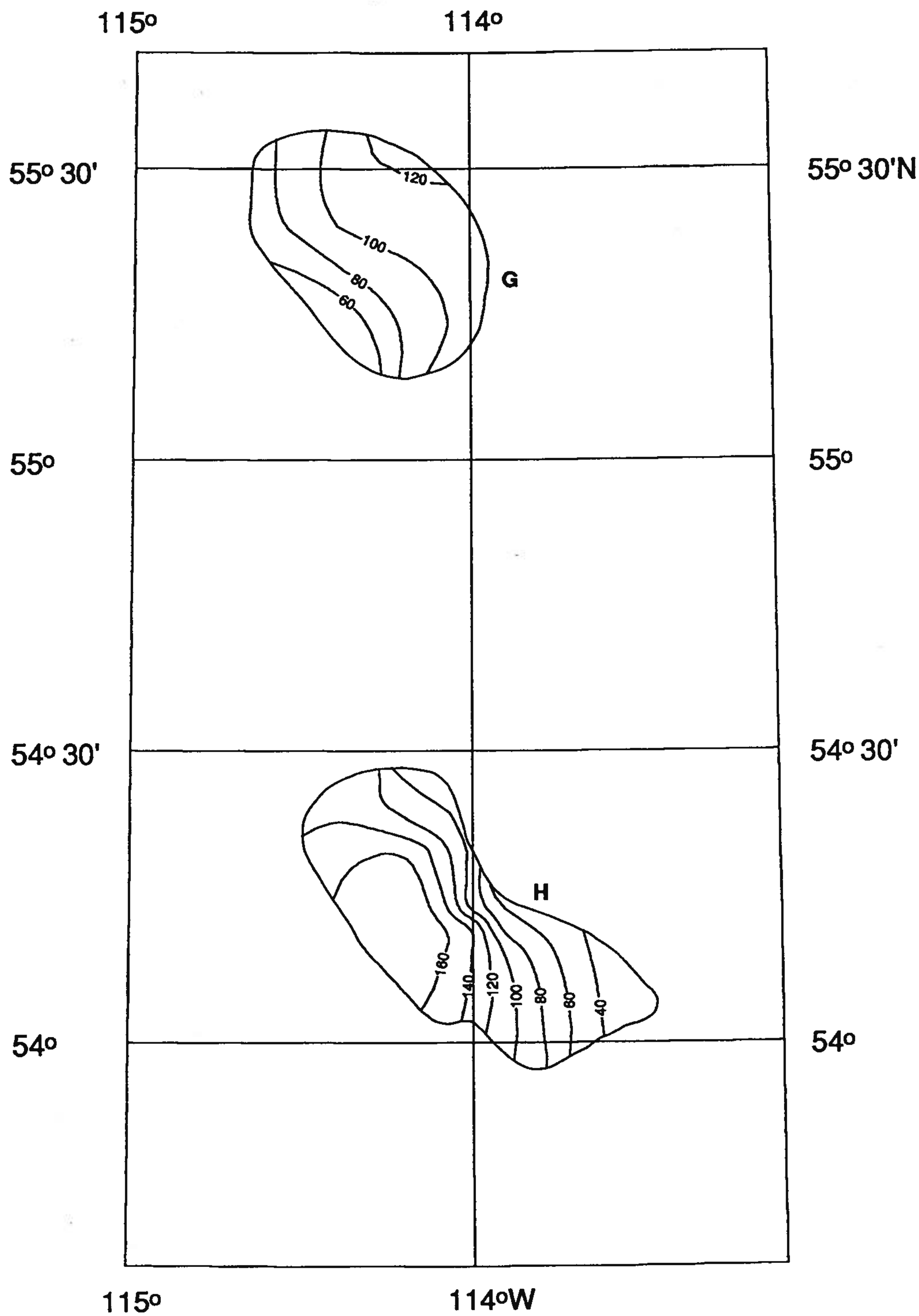

Figure 12. Calcium resource estimates in formation water in Elk Point Group strata, central-eastern Alberta (contours in kg/m2 or 1000 t/km2).

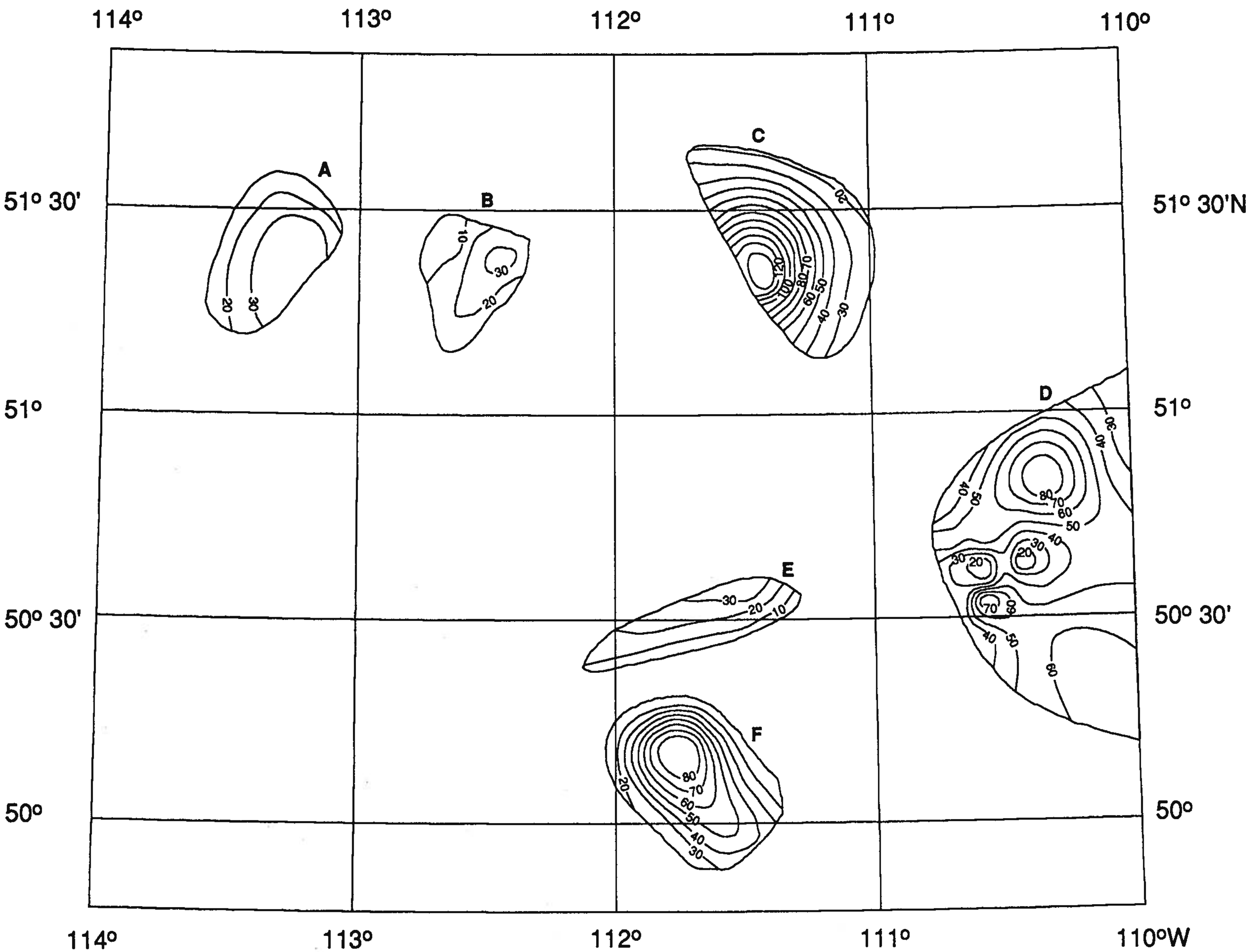

Figure 13. Magnesium resource estimates in formation water in Beaverhill Lake Group strata, southern Alberta (contours in kg/m2 or 1000 t/km2).

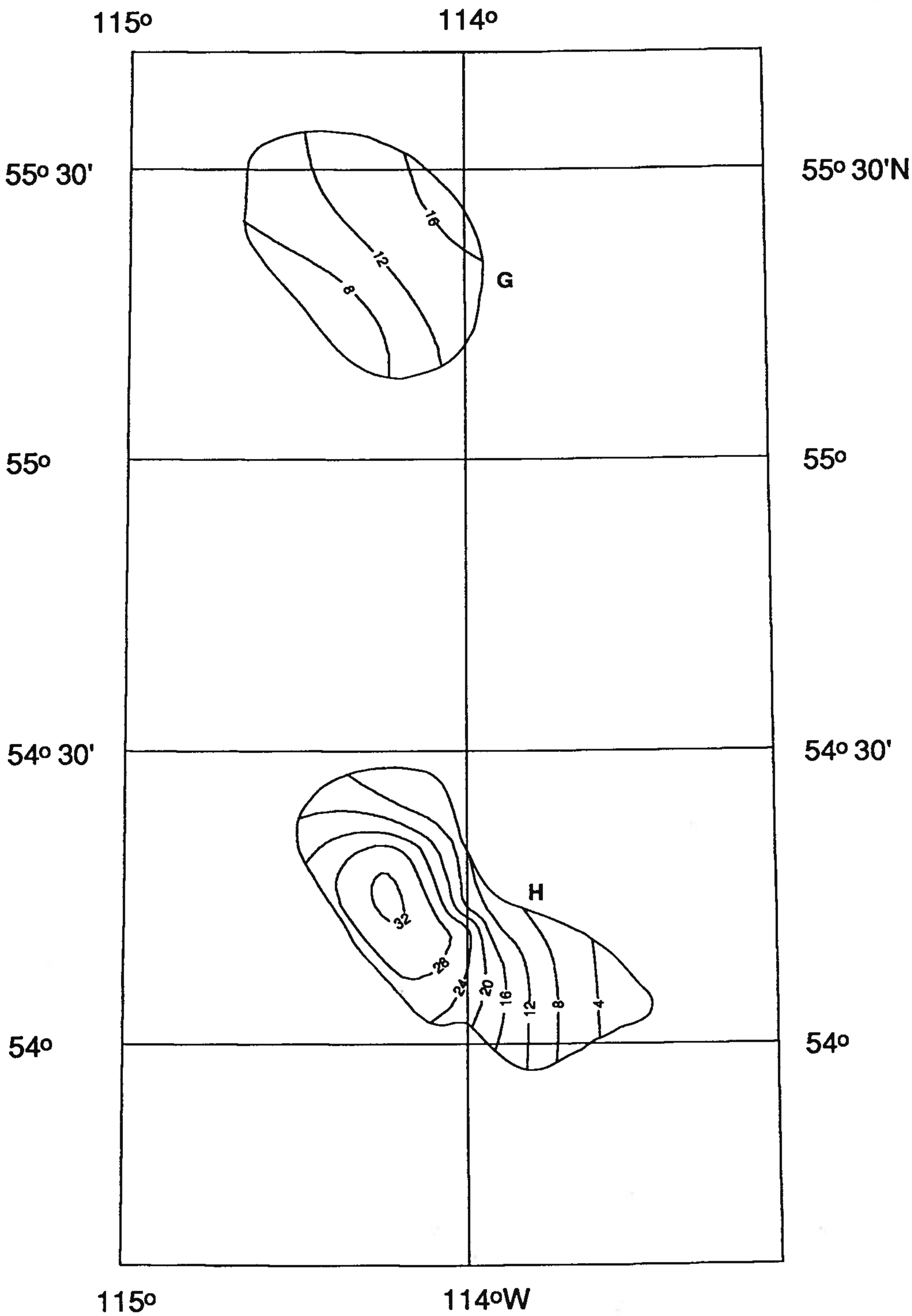

Figure 14. Magnesium resource estimates in formation water in Elk Point Group strata, central-eastern Alberta (contours in kg/m^2 or 1000 t/km^2).

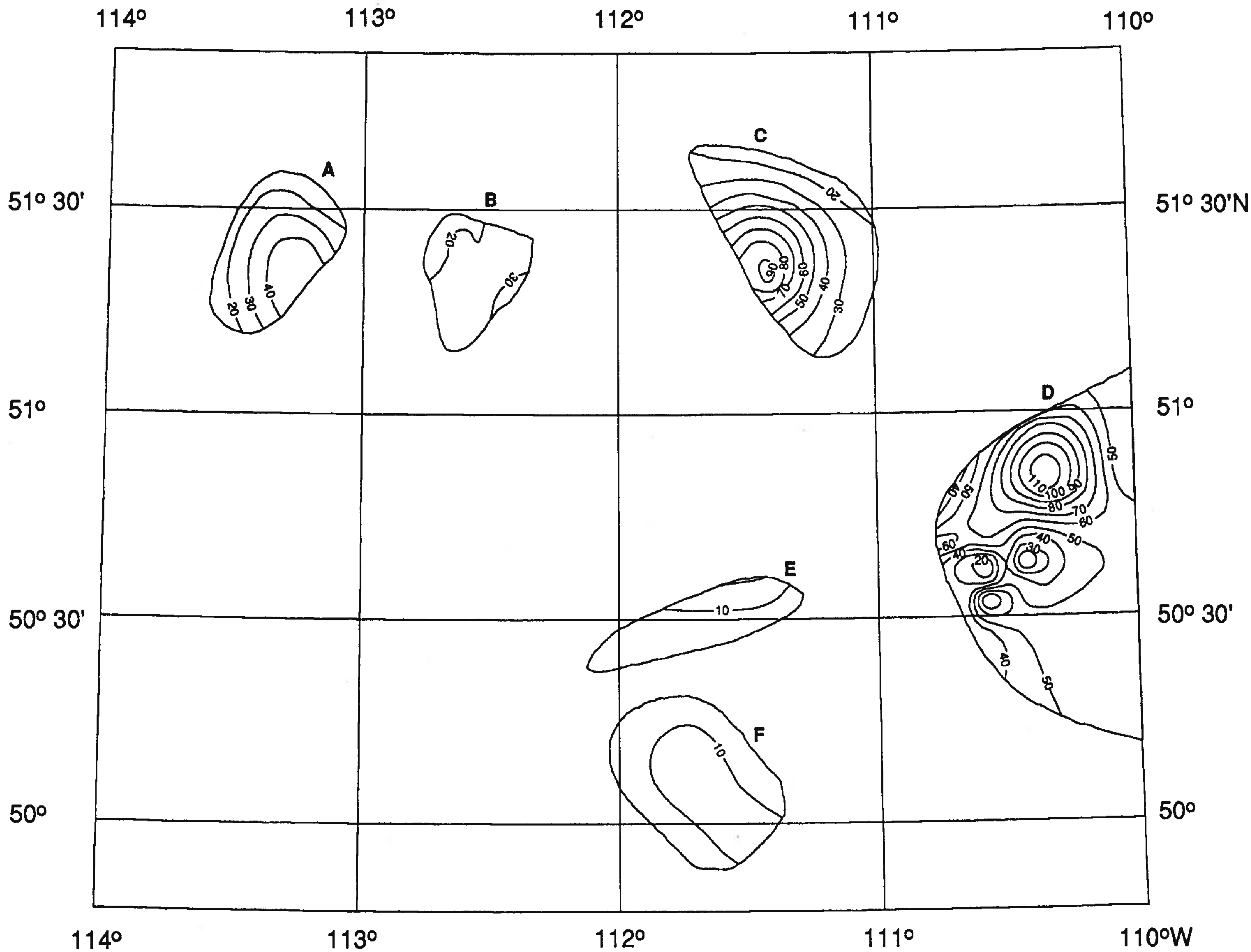

Figure 15. Potassium resource estimates in formation water in Beaverhill Lake Group strata, southern Alberta (contours in kg/m^2 or 1000 t/km^2).

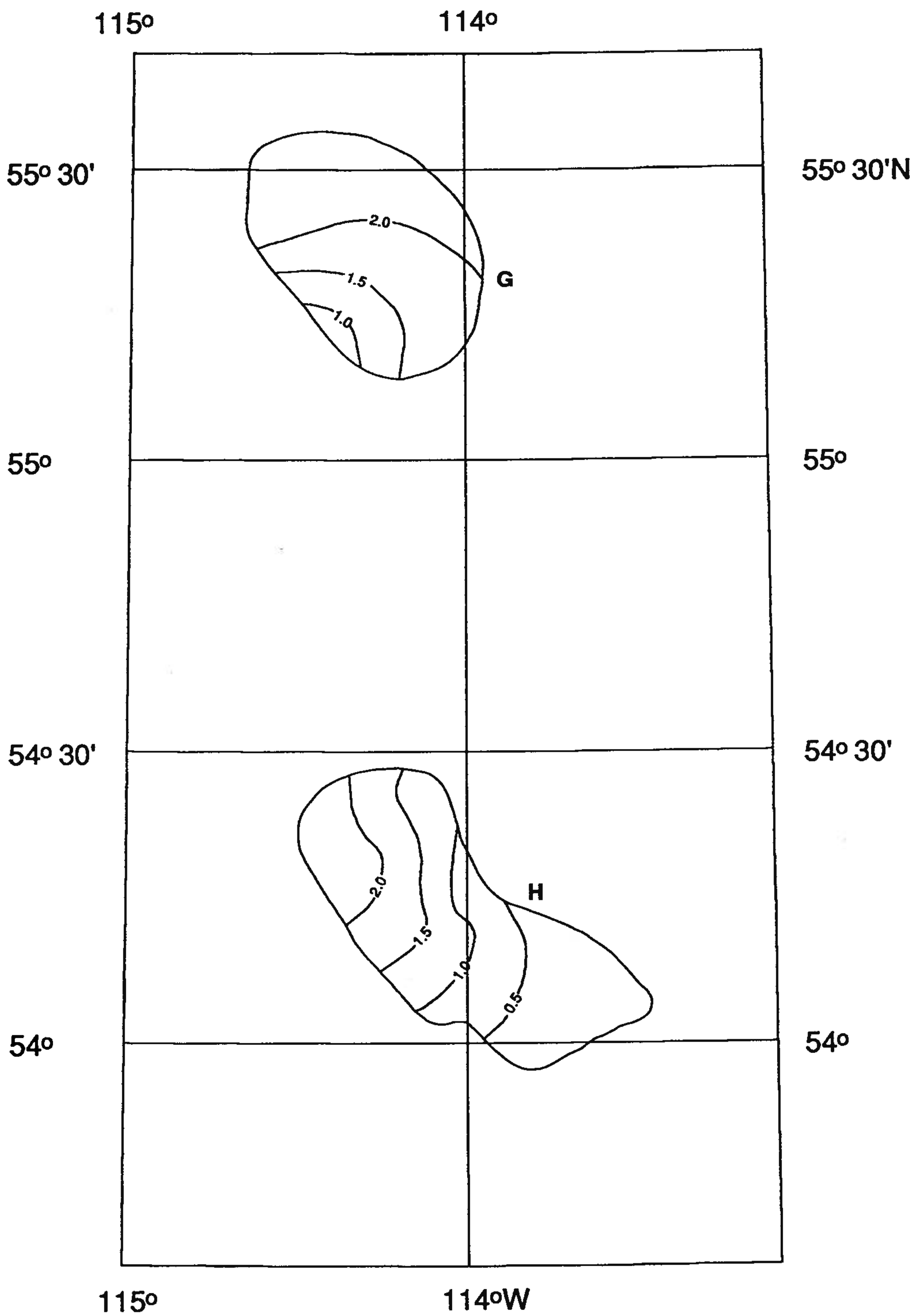

Figure 16. Potassium resource estimates in formation water in Elk Point Group strata, central-eastern Alberta (contours in kg/m² or 1000 t/km²).

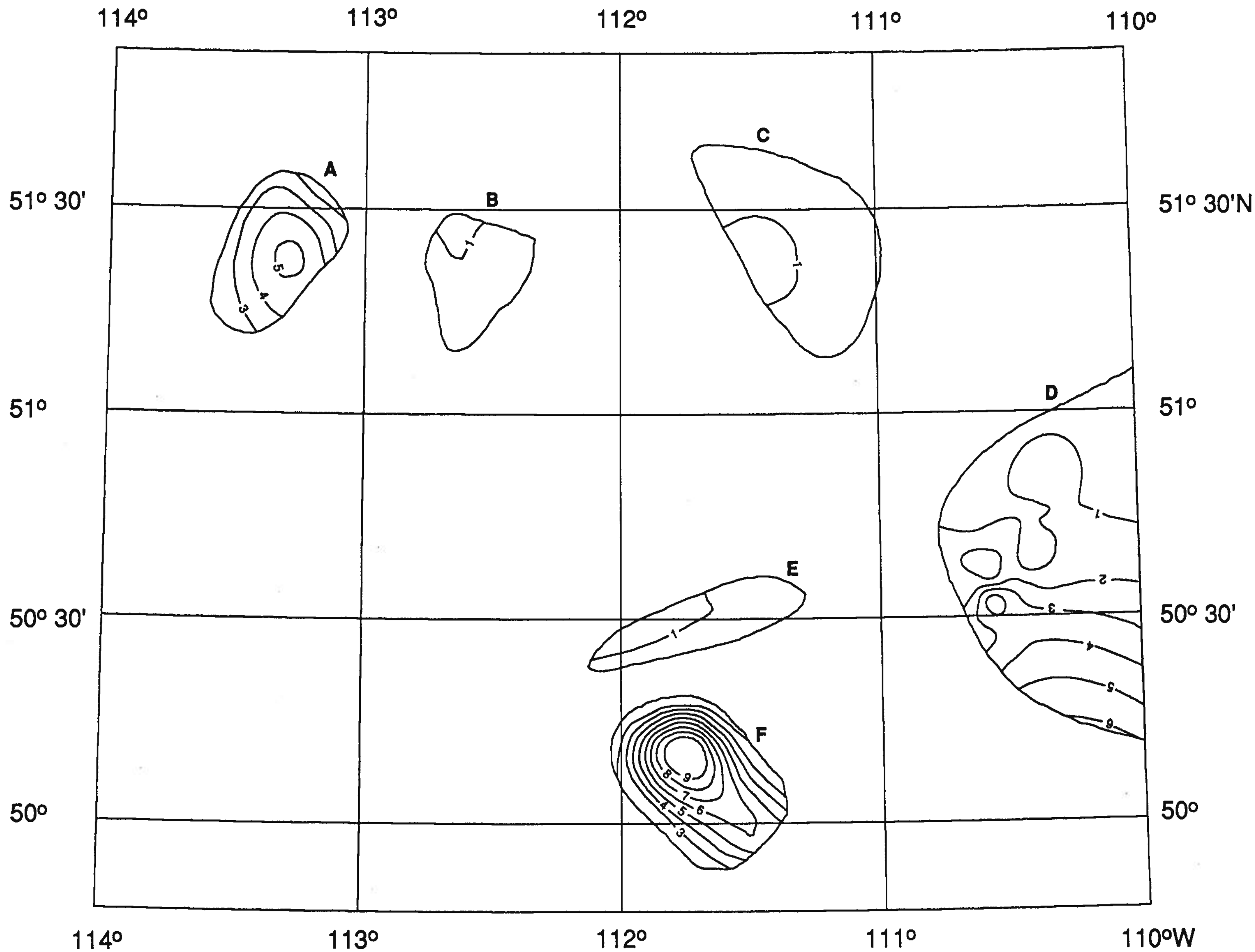

Figure 17. Bromine resource estimates in formation water in Beaverhill Lake Group strata, southern Alberta (contours in kg/m^2 or 1000 t/km^2).

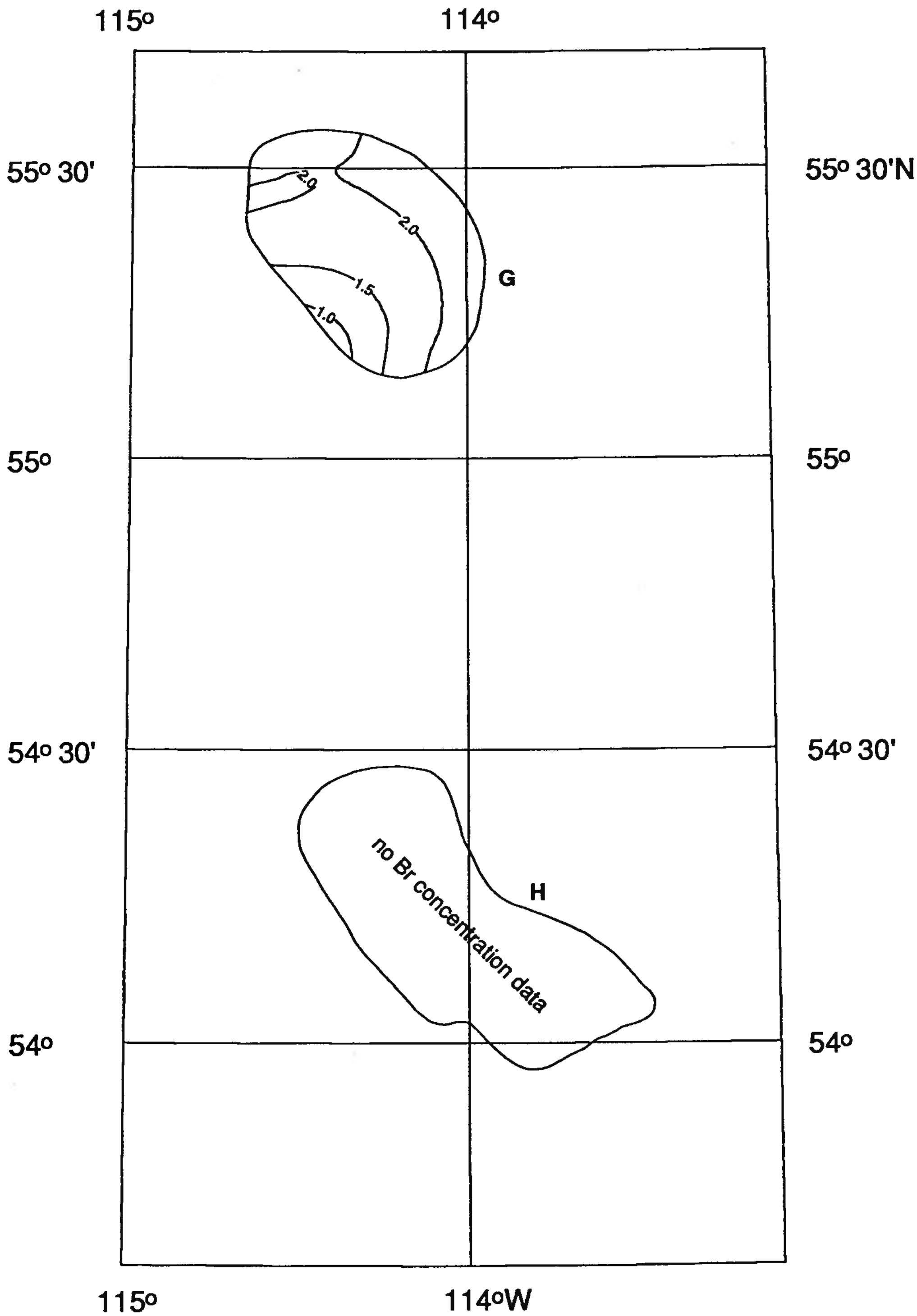

Figure 18. Bromine resource estimates in formation water in Elk Point Group strata, central-eastern Alberta (contours in kg/m^2 or 1000 t/km^2).

southern Alberta (Figure 17), but only 2 kg/m^2 in central-eastern Alberta (Figure 18). The obvious trend of higher resource estimates for Beaverhill Lake strata in southern Alberta than for Elk Point strata in central-eastern Alberta is mainly due to thicker and slightly more porous potentially-productive strata in the south than in the north. Also, elemental concentrations are generally higher in Beaverhill Lake strata than in Elk Point strata (Hitchon et al., 1993). The large variability in resource estimates in southern Alberta (Figures 11, 13, 15 and 17) is also due mainly to variations in the thickness and porosity of the potentially productive stratigraphic interval. Particularly, the consistent pattern of "bull's eyes" in resource distributions in southern Alberta (Figures 11, 13, 15 and 17) is caused by variations in thickness of the stratigraphic interval with productive potential, variations most probably due to reefal buildup within the Beaverhill Lake carbonate platform. Of the six areas identified in southern Alberta, areas C and D have the best production potential because of relatively shallow depth, high average porosity (10%) and permeability (9×10^{-14}m^2 or 90 md), and generally high resource potential per unit area. Areas A and B have also high average porosity (9%), but lower average permeability (2.5 - 10^{-14}m^2 or 25 md) and the potentially productive interval is at a greater depth (more than 2,000 m). The two southernmost areas (E and F) are generally characterized by lower average porosity and permeability (approximately 7% and 10^{-14}m^2 or 10 md, respectively). In central-eastern Alberta, the southernmost area (H) has slightly higher average porosity and permeability than the northern one (G), and the resource estimates for Ca and Mg are also higher (Figures 12 and 14).

The total resource estimates of industrial minerals contained in formation waters in southern and central-eastern Alberta are: 3,171.7 x 10^6 t of Ca, 471.1 x 10^6 t of Mg, 359.5 x 10^6 t of K and 270.0 x 10^6 t of Br. These amounts appear to be huge, but one should keep in mind that they are distributed in the pore space of approximately 300 x 10^9 m^3 of sedimentary rock covering an area of 13,260 km^2 (some 144 townships) in Alberta, with a total weight of the order of 700 x 10^9 t. Thus, the estimated resources represent together approximately 0.6% of the mass of the host rock. Another important consideration to be kept in mind is that only a small fraction of this resource is producible, in the sense that, although the volume of formation water containing these minerals is correspondingly huge, only a relatively very small fraction can be pumped out.

Lithium

Lithium in concentrations above the detailed exploration threshold (75 mg/l) is found in west-central Alberta in formation waters of the Beaverhill Lake and Woodbend groups. In this area, the carbonate platform of the Cooking Lake Formation and the reefs of the Leduc Formation (both of the Woodbend Group) overlie the Beaverhill Lake Group carbonates, such that it is sometimes difficult to differentiate between the various formation waters. The area of interest as defined in the regional-scale reconnaissance study (Hitchon et al., 1993) is quite large (Figure 1). Actually, there are no Li concentration data west of 118° W (W6Mer), and very low concentrations east of 115° W. The Leduc Formation reefs, found in the western part of the study area

(Figure 19), reach thicknesses of more than 300 m in places, while the Beaverhill Lake carbonate platform varies in thickness from more than 150 m in the south to around 50 m in the northwest. Eighty-eight wells with 3,768 core analyses and 29 permeability measurements in drillstem tests penetrate the Leduc Formation reefs, and 183 wells with 18,256 core analyses and 32 permeability measurements in drillstem tests penetrate the Beaverhill Lake Group. However, the well distribution is uneven, with a great density in the reef area, and sparser outside it. Because of the abundance of core and DST data, no well logs were used in the analysis. Plug-scale porosity and permeability values measured in core vary over a very wide range (1 to 20 %, and 10^{-17} to 10^{-11} m^2 or 10^{-2} to 10^4 md, respectively). The well-scale porosity and permeability values for the Beaverhill Lake Group vary between 1 and 11 %, and between 7×10^{-17} and 4.1×10^{-13} m^2 (0.07 and 410 md), respectively. Permeability values measured in drillstem tests vary between 3×10^{-16} and 2.6×10^{-12} m^2 (0.3 to 2600 md). For the Leduc Formation reefs, the well-scale porosity and permeability values vary between 1 and 13 % , and between 3×10^{-16} and 7.3×10^{-13} m^2 (0.3 and 730 md), respectively. Permeability values measured in drillstem tests vary between 10^{-18} and 10^{-12} m^2 (0.001 and 1000 md). This extremely large range of variation in rock properties at the core and well scales indicates that, in this region, the Leduc Formation and Beaverhill Lake Group strata are very heterogeneous both areally and with depth, with significant zones of tight rocks from which production of formation water would be quite uneconomic.

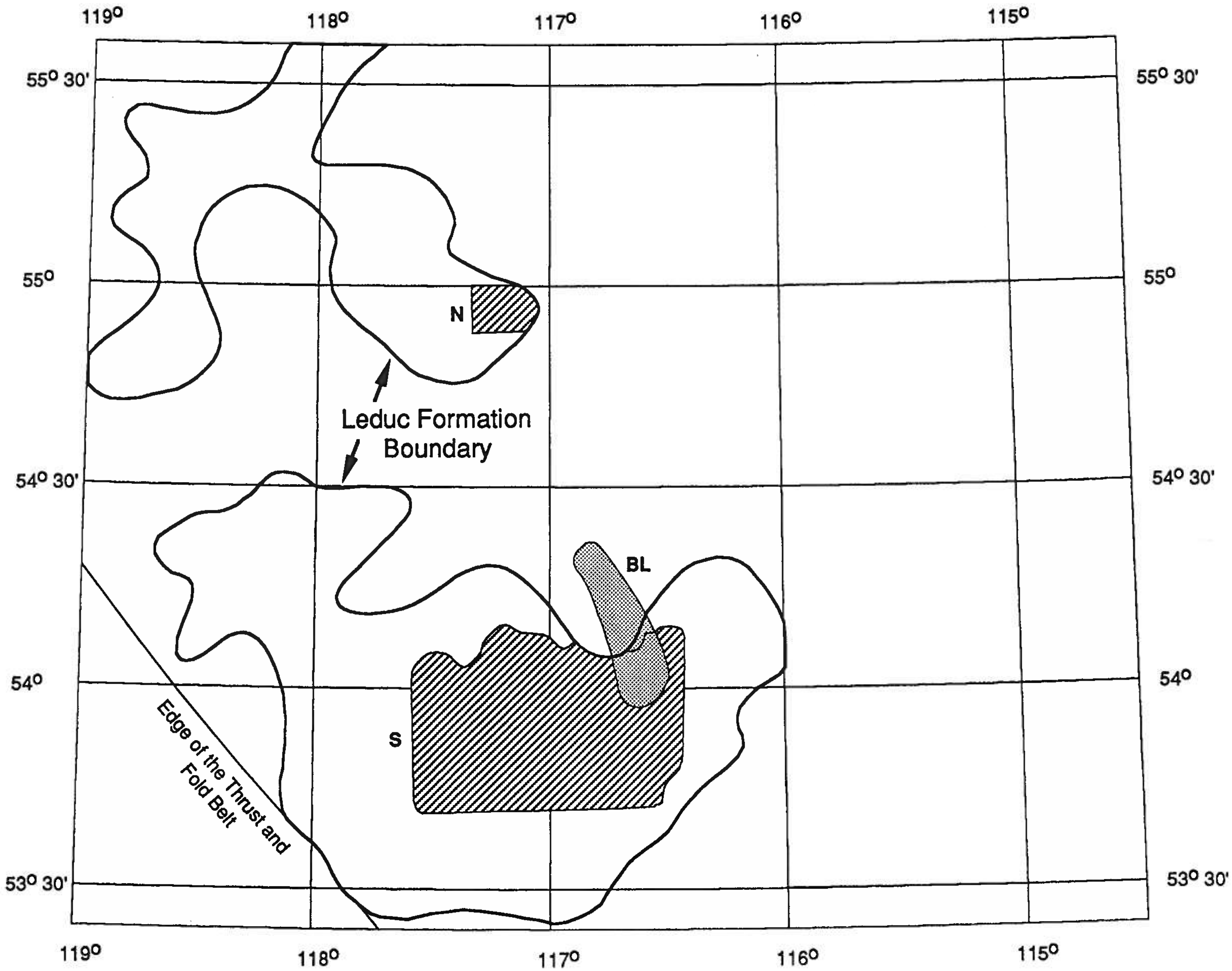

Figure 19. Areas in west-central Alberta with producibility potential for Li from formation water in Leduc Formation (N and S) and Beaverhill Lake Group (BL) strata.

Using Li concentration and rock properties data, three areas with potential for formation water production and economic Li extraction were identified (Figure 19), one in the northern Leduc reef (N), one in the southern Leduc reef (S), and one in Beaverhill Lake Group strata (BL). There is some overlap between the southern Leduc Formation area (S) and the Beaverhill Lake Group area (BL) (Figure 19). There are still some intervals of relatively low permeability within the identified stratigraphic intervals, but, overall, they are characterized by favourable rock properties. The potentially productive stratigraphic interval in the northern Leduc reef (N) has an average thickness of 12 m, an average porosity of 6% and an average permeability of 3.5×10^{-14} m^2 (35 md). The southern Leduc reef interval (S) has 25 m average thickness, 6 % average porosity and 2×10^{-14} m^2 (20 md) average permeability. The potentially productive interval in Beaverhill Lake Group strata (BL) has an average thickness of 46 m, an average porosity of 7 %, and an average permeability of 4.3×10^{-14} m^2 (43 md). Two observations are significant with respect to the Beaverhill Lake interval: (1) 113 wells with 14,800 core analyses are concentrated in this small area, compared with 183 wells for the entire initial study area; and (2) porosity and permeability are on average higher than for the Leduc Formation reefs, although locally higher values are found in the latter. The small areal extent and the relatively high porosity and permeability characterizing the rocks in this area lead to the hypothesis that this is most probably a reefal feature embedded in the Beaverhill Lake carbonate platform. The approximate depth to the potentially productive stratigraphic intervals is shown in Figures 20 and 21.

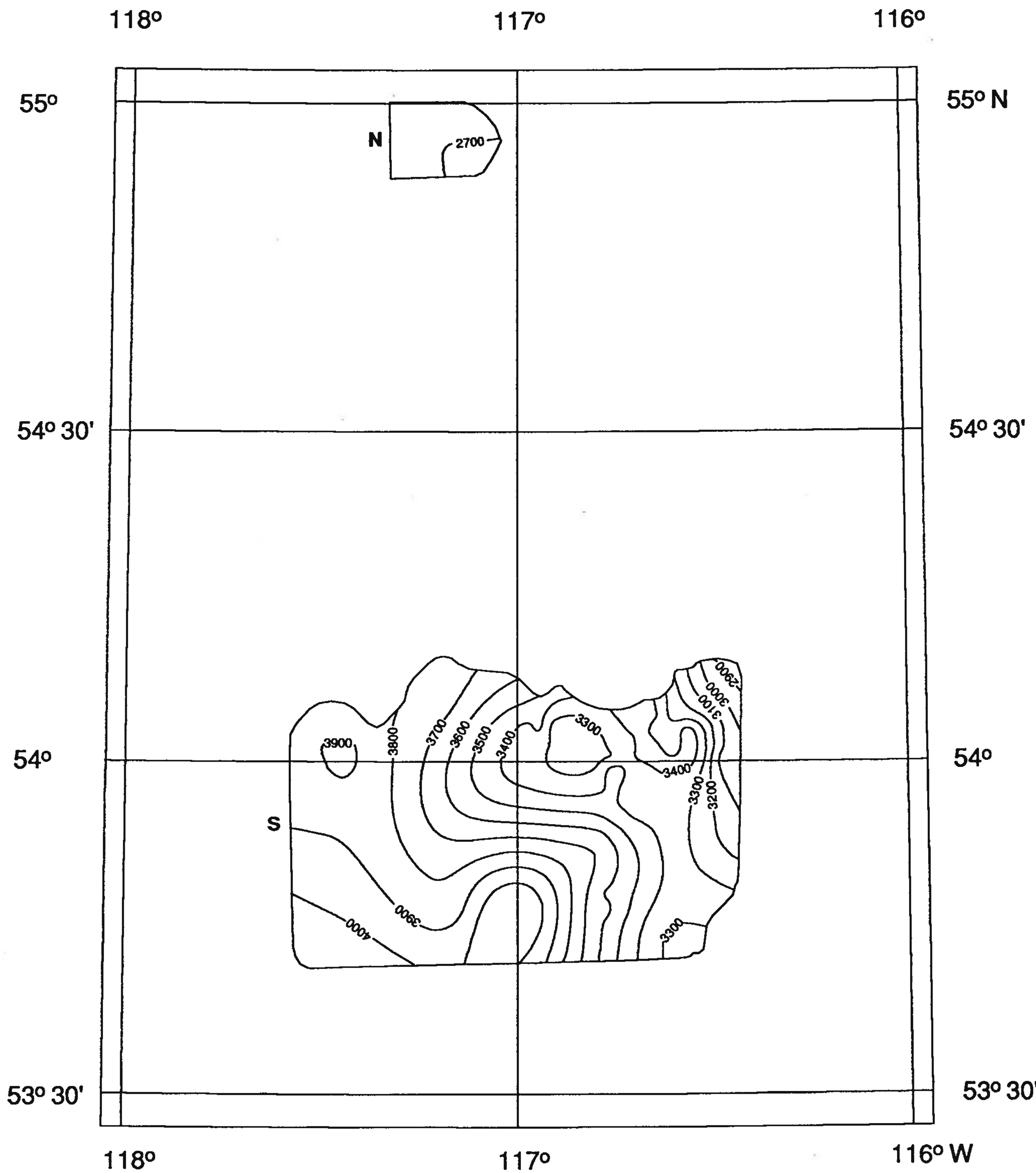

Figure 20. Approximate depth (m) to the stratigraphic interval with producibility potential for Li in formation water from the Leduc Formation reefs, west-central Alberta.

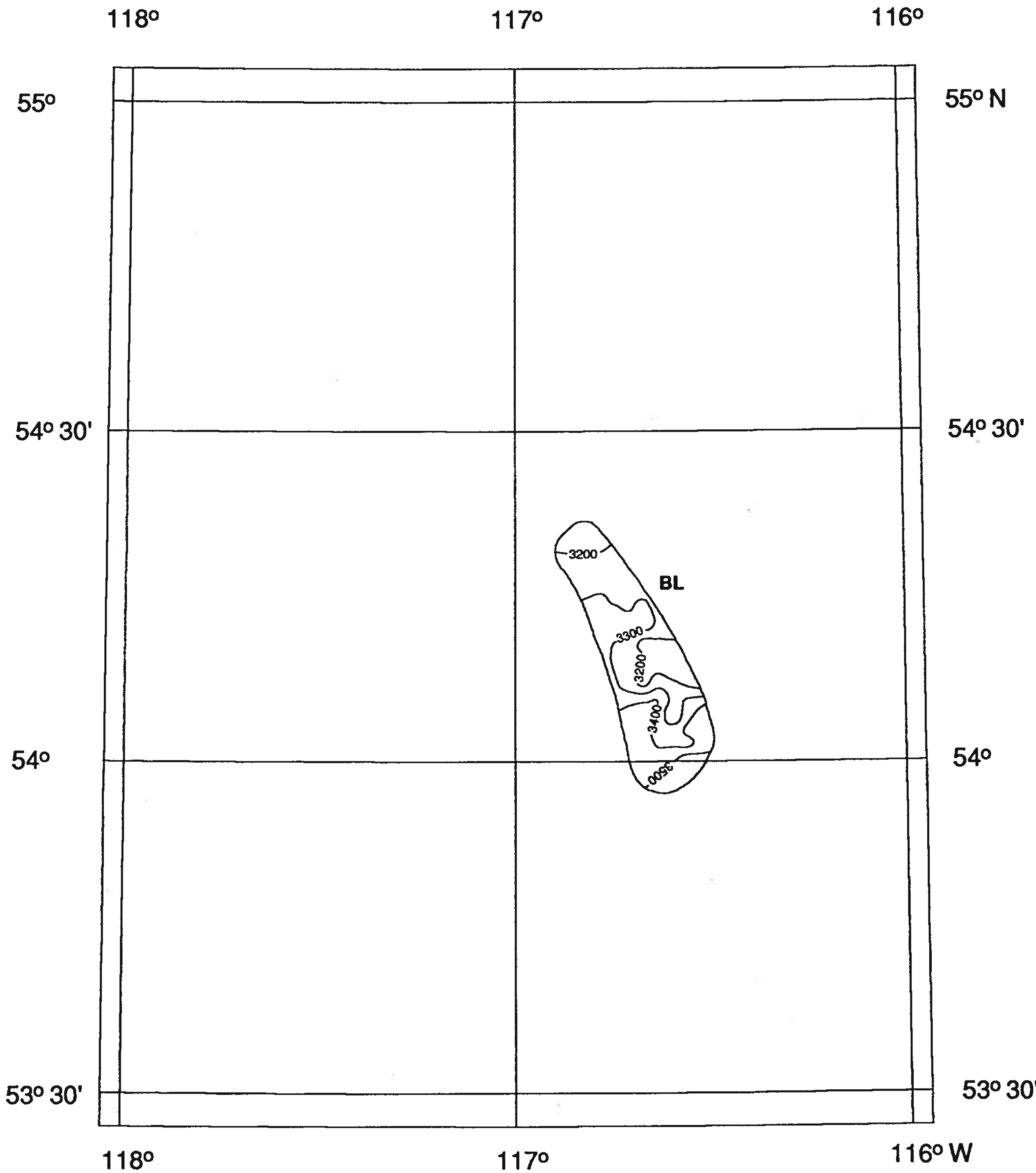

Figure 21. Approximate depth (m) to the stratigraphic interval with producibility potential for Li in formation water from the Beaverhill Lake Group strata, west-central Alberta.

Estimates of potentially economic Li in formation water in Leduc reefs vary between 10 and 570 g/m^2 (t/km^2) in the southern area, and between 34 and 340 g/m^2 (t/km^2) in the northern area (Figure 22). Resource estimates for Li in Beaverhill Lake formation water vary between 11 and 918 g/m^2 (t/km^2) (Figure 23). The highly variable resource distribution in all these areas is due to high variability in the porosity and thickness of the potentially productive interval, which is characteristic of reef complexes. The total resource estimate for potentially economic Li present in Leduc and Beaverhill Lake formation waters in west-central Alberta is 0.515 x 10^6 t, distributed over a cumulative area of 3,980 km^2 (approximately 43 townships) and representing about 2 x 10^{-6} of the host rock mass.

Iodine

The highest iodine concentrations in Alberta formation waters are found in the Viking and Belly River formations in south-central Alberta. Concentrations reach values higher than the regional exploration limit (40 mg/l), but they are below the detailed exploration threshold of 100 mg/l (Hitchon et al., 1993). A very broad area (Figure 1) was initially identified as having economic interest (Hitchon et al., 1993); however, I concentrations within this area vary in a wide range in both formations, from less than 10 mg/l to more than 60 mg/l. In order to identify exploration targets with producibility potential, the current analysis was restricted only to those areas (disjoint) where the I concentration in formation water was found to be greater than the regional exploration limit (40 mg/l).

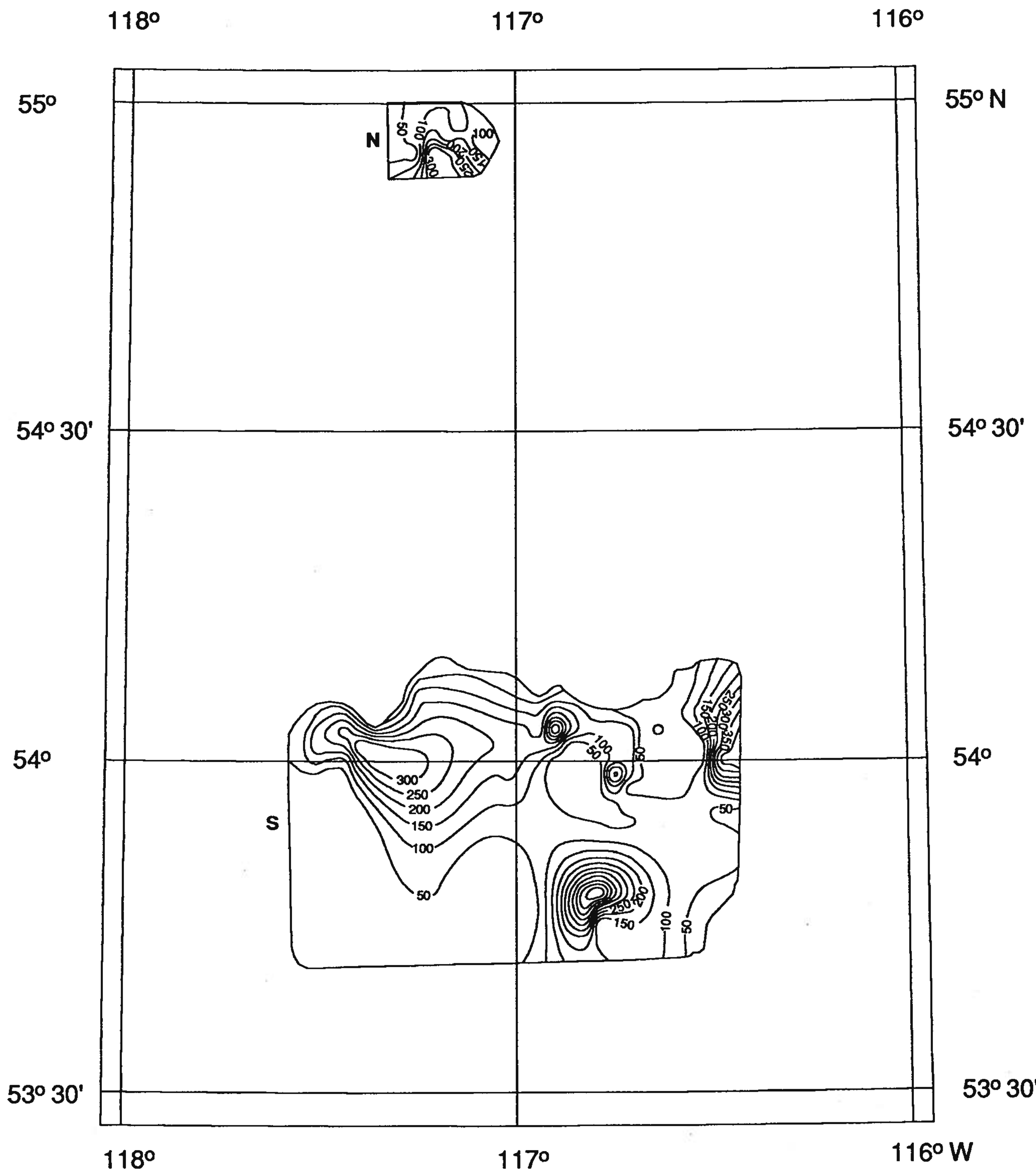

Figure 22. Lithium resource estimates in formation water in Leduc Formation reefs, west-central Alberta (contours in t/km2).

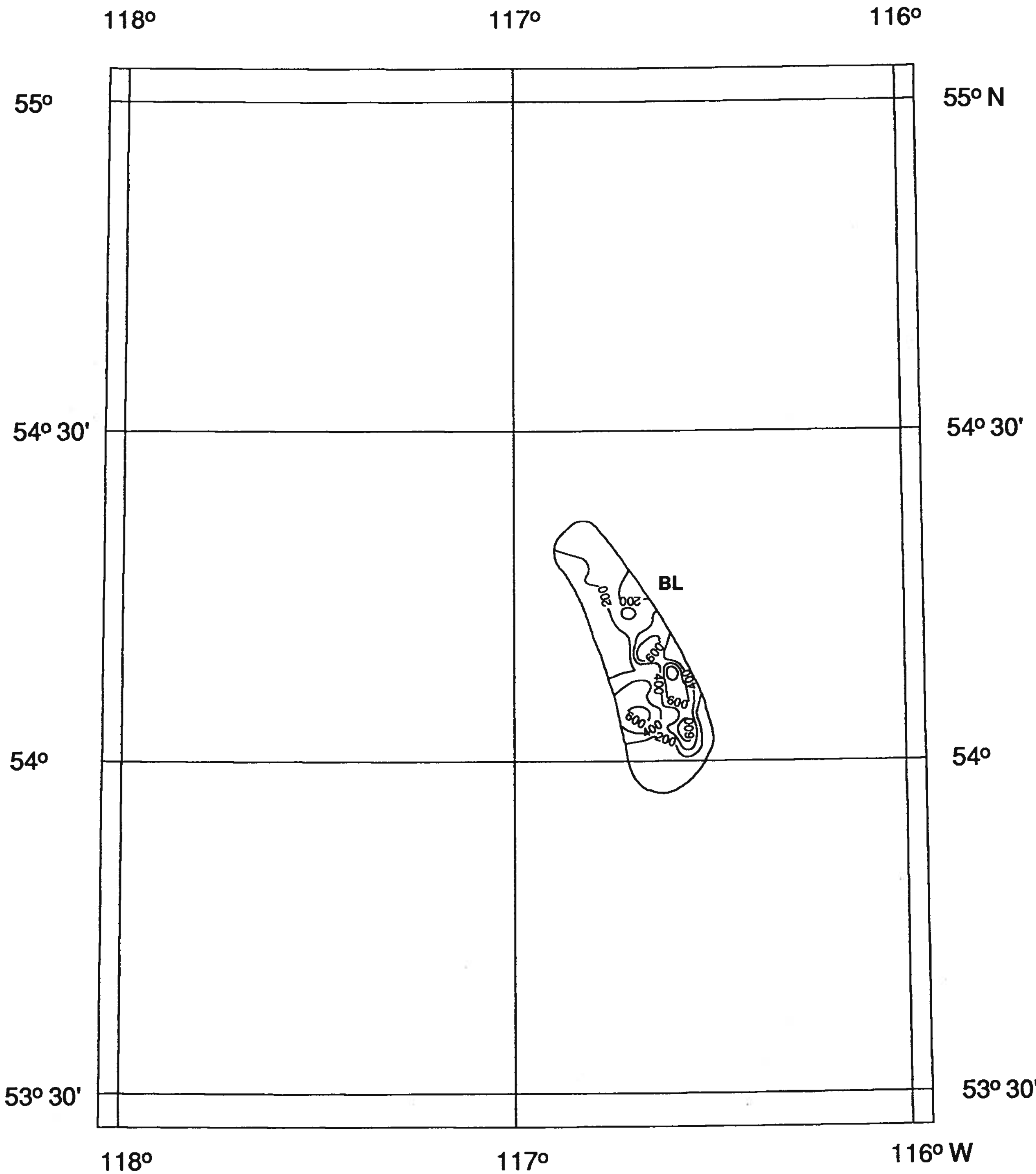

Figure 23. Lithium resource estimates in formation water in Beaverhill Lake Group, west-central Alberta (contours in t/km^2).

Three hundred and eighty nine wells with 8,110 core analyses penetrate the Viking Formation in the areas with I concentrations of interest. For the Belly River Formation, 412 wells record 13,827 plug-scale porosity and permeability analyses in the stratigraphic interval and areas where I concentration is greater than 40 mg/l. Given the abundance of core data, no additional well logs were used in the analysis. Rock porosity and permeability vary in a very wide range in the areas of interest. Well-scale porosity and permeability in the Viking Formation vary between 6% and 19%, and between 8 x 10^{-17} and 1.4 x $10^{-12}m^2$ (0.08 and 1400 md), respectively. For the Belly River Formation, the well-scale petrophysical properties vary between 7% and 27% for porosity and between 5 x 10^{-12} and 0.5 x $10^{-12}m^2$ (0.05 and 500 md) for permeability. Applying resource producibility criteria of minimum 10% porosity and $10^{-14}m^2$ (10 md) permeability, the areas with potential for I production were reduced further (Figure 24). Nine areas of interest were identified in the Viking Formation (marked V_1 to V_9) and five areas in the Belly River Formation (marked B_1 to B_5). The Viking Formation is characterized in these areas by 4,288 core analyses in 135 wells and by 20 drillstem tests, while the Belly River Formation is characterized by 4,650 core analyses in core from 246 wells and by 50 drillstem tests. The approximate depth to the potentially productive intervals in the Viking and Belly River formations varies between 650 m and 950 m (Figures 25 and 26). Although the Viking Formation is older and stratigraphically deeper than the Belly River Formation, the depth range is similar because the areas of interest in the Belly River Formation are situated generally to the west of the areas of interest in the Viking Formation, in the direction of general stratigraphic downdip and increased topographic

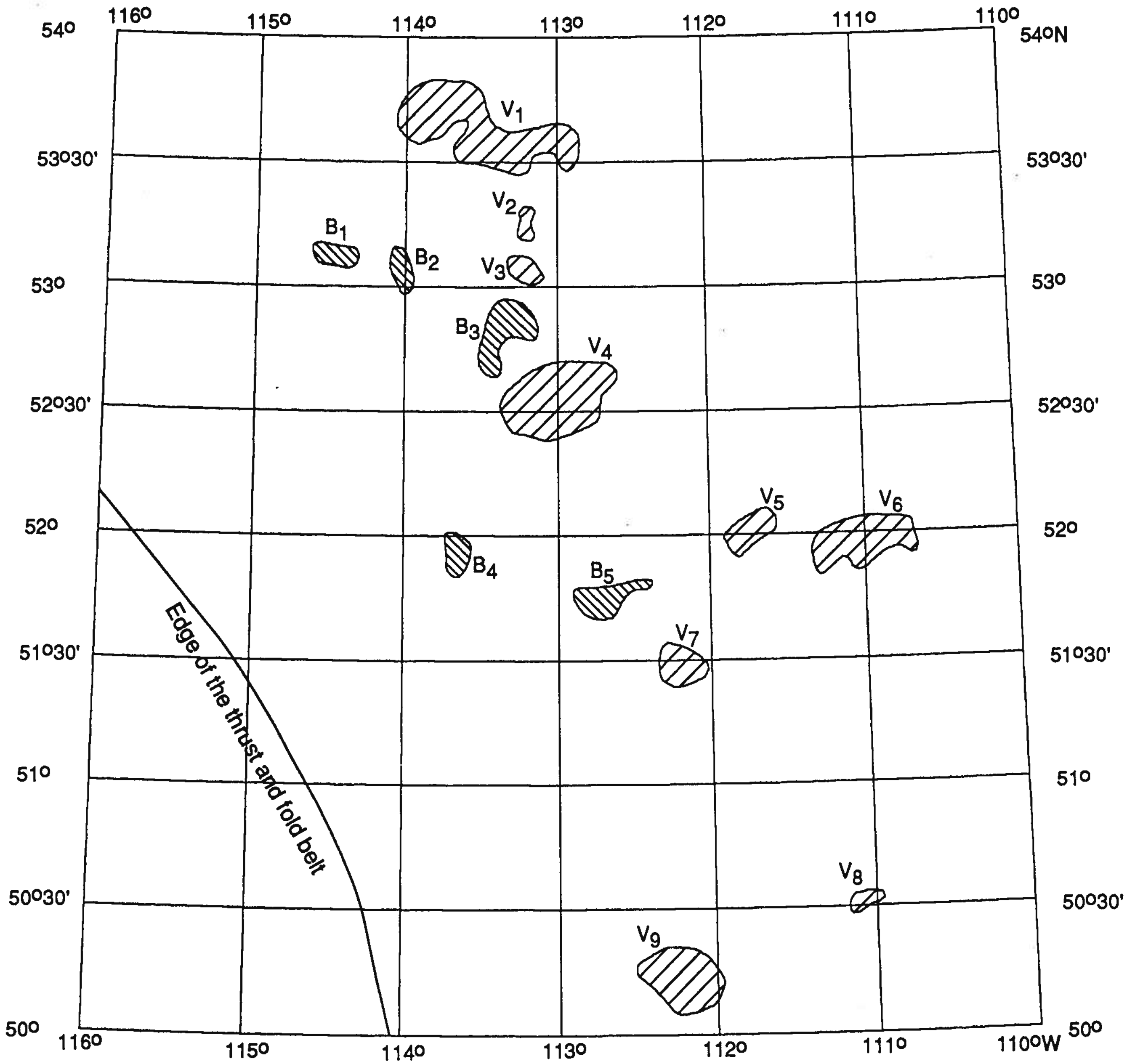

Figure 24. Areas in south-central Alberta with producibility potential for I from formation water in Viking and Belly River formation strata ($V_1 \ldots V_9$ and $B_1 \ldots B_5$, respectively).

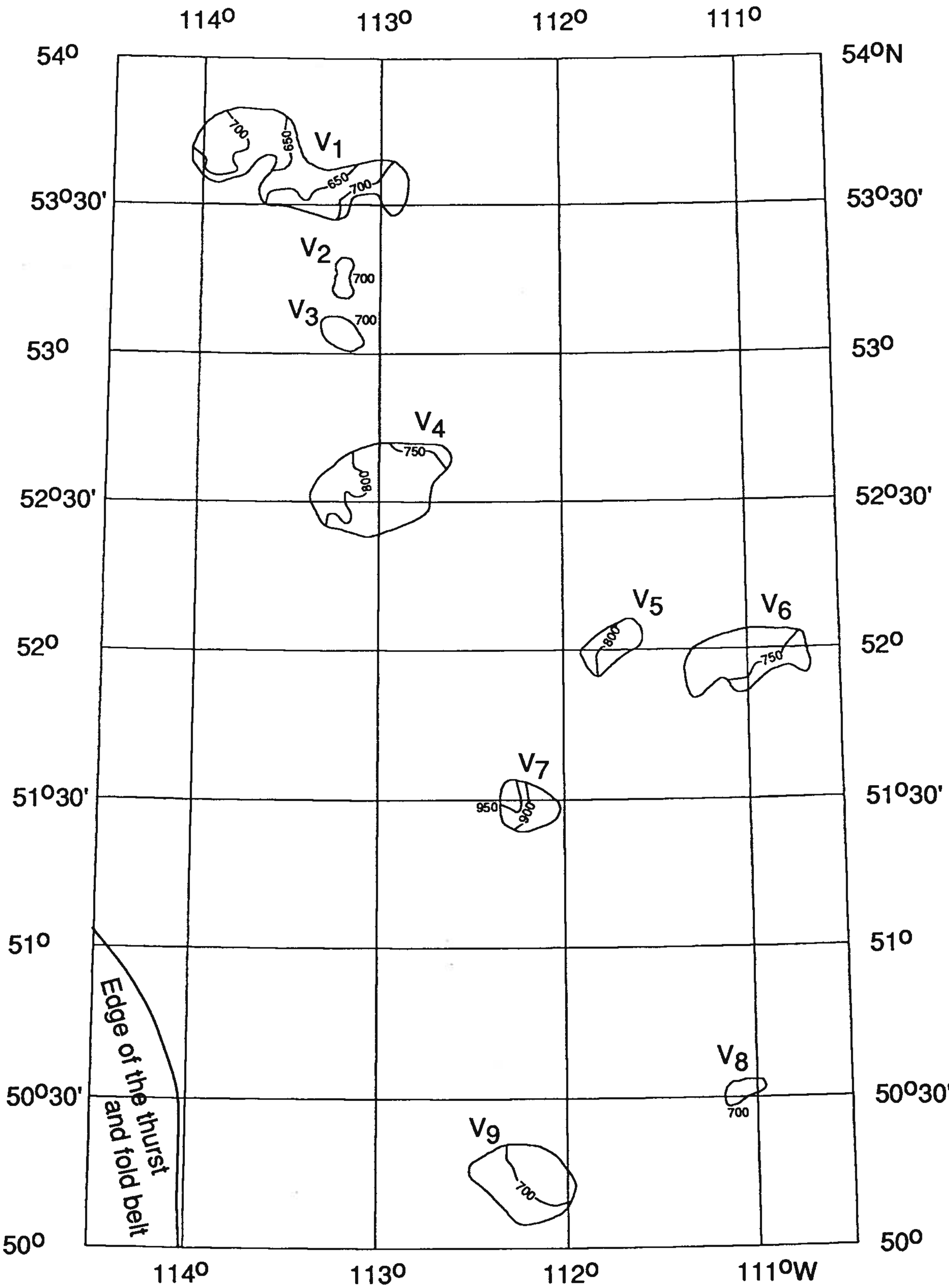

Figure 25. Approximate depth (m) to the stratigraphic interval with producibility potential for I in formation water from the Viking Formation, south-central Alberta.

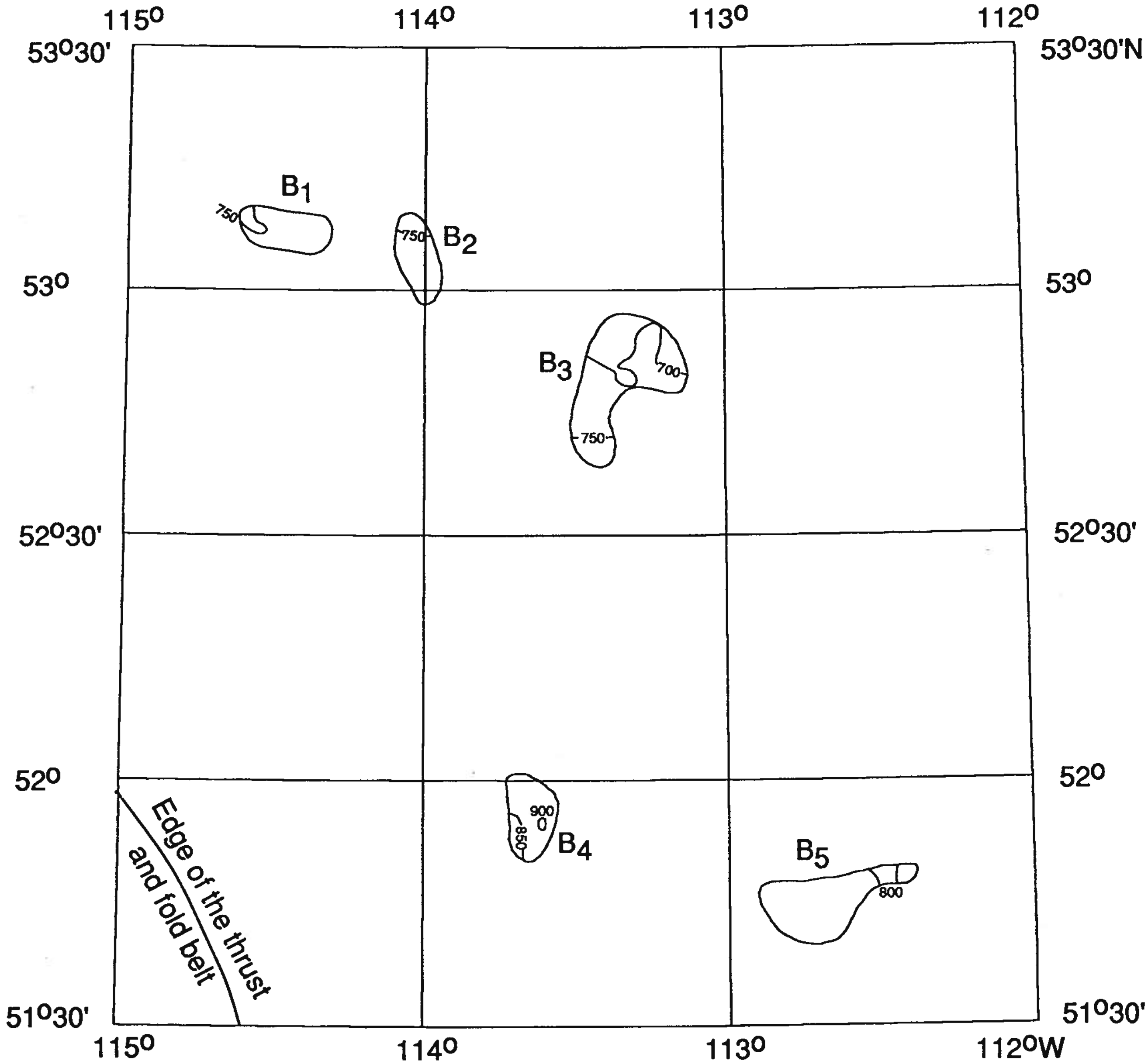

Figure 26. Approximate depth (m) to the stratigraphic interval with producibility potential for I in formation water from the Belly River Formation, south-central Alberta.

elevation. The thickness of the Viking strata in the areas of interest varies from less than 30 m in the north to more than 60 m in the south, with an average of 45 m. The average thickness of the Belly River strata of interest is 73 m. The average porosity is 17% and 20% for Viking and Belly River strata, respectively.

Estimates of potentially economic I in Viking Formation water (Figure 27) vary from less than 200 g/m^2 (t/km^2) to more than 1800 g/m^2 (t/km^2). Resources estimates for the Belly River Formation (Figure 28) vary between less than 300 g/m^2 and more than 1000 g/m^2 (t/km^2). The variability in resource distribution is due to variations in I concentration and porosity and thickness of the host stratigraphic interval. The total resource estimate for I dissolved in Viking and Belly River strata with economic and producibility potential in south-central Alberta is 2.82×10^6 t distributed over a cumulative area of 5,960 km^2 (approximately 64 townships) and representing about 4×10^{-6} of the host rock mass.

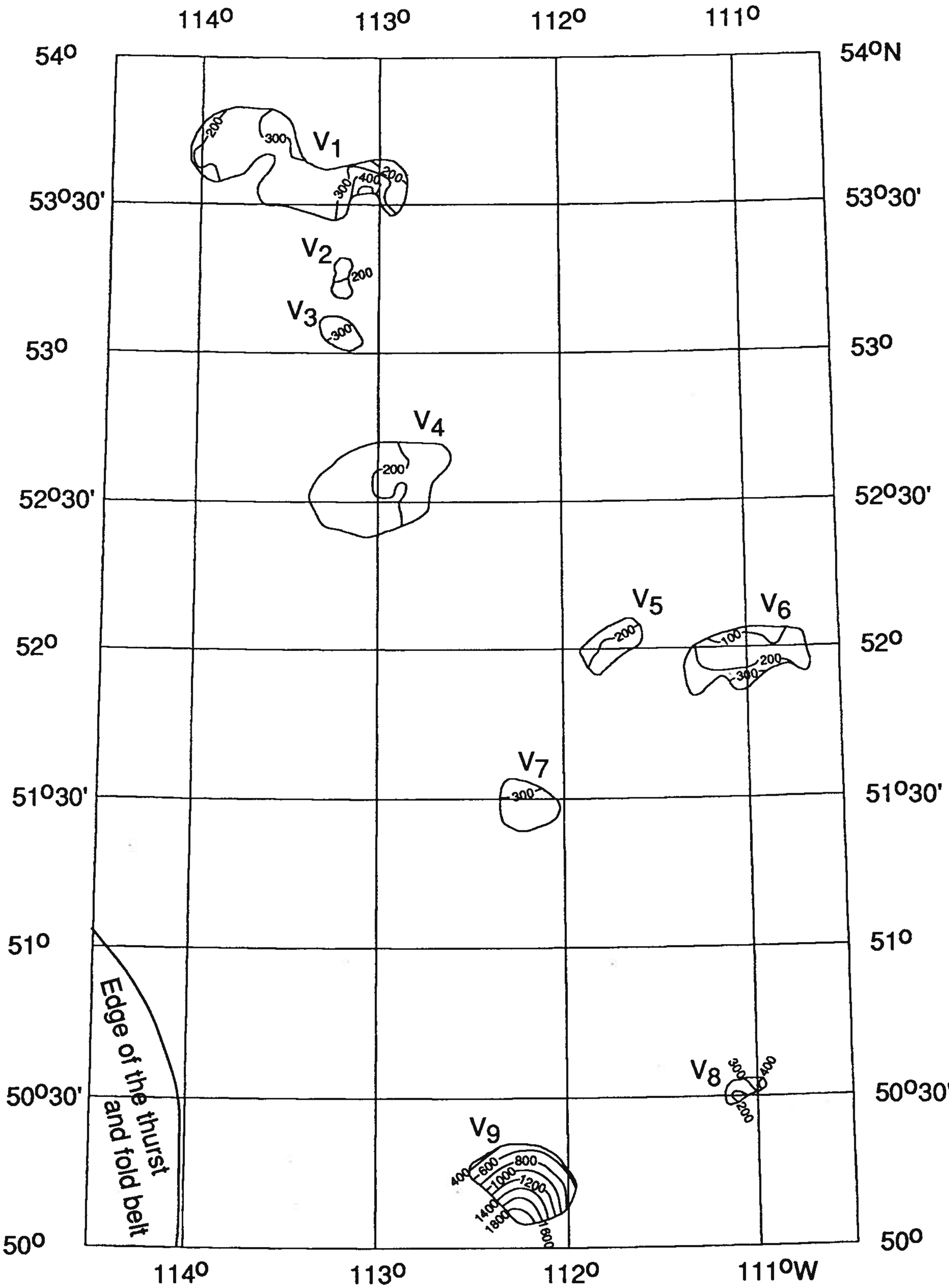

Figure 27. Iodine resource estimates in formation water in Viking Formation, south-central Alberta (contours in t/km^2).

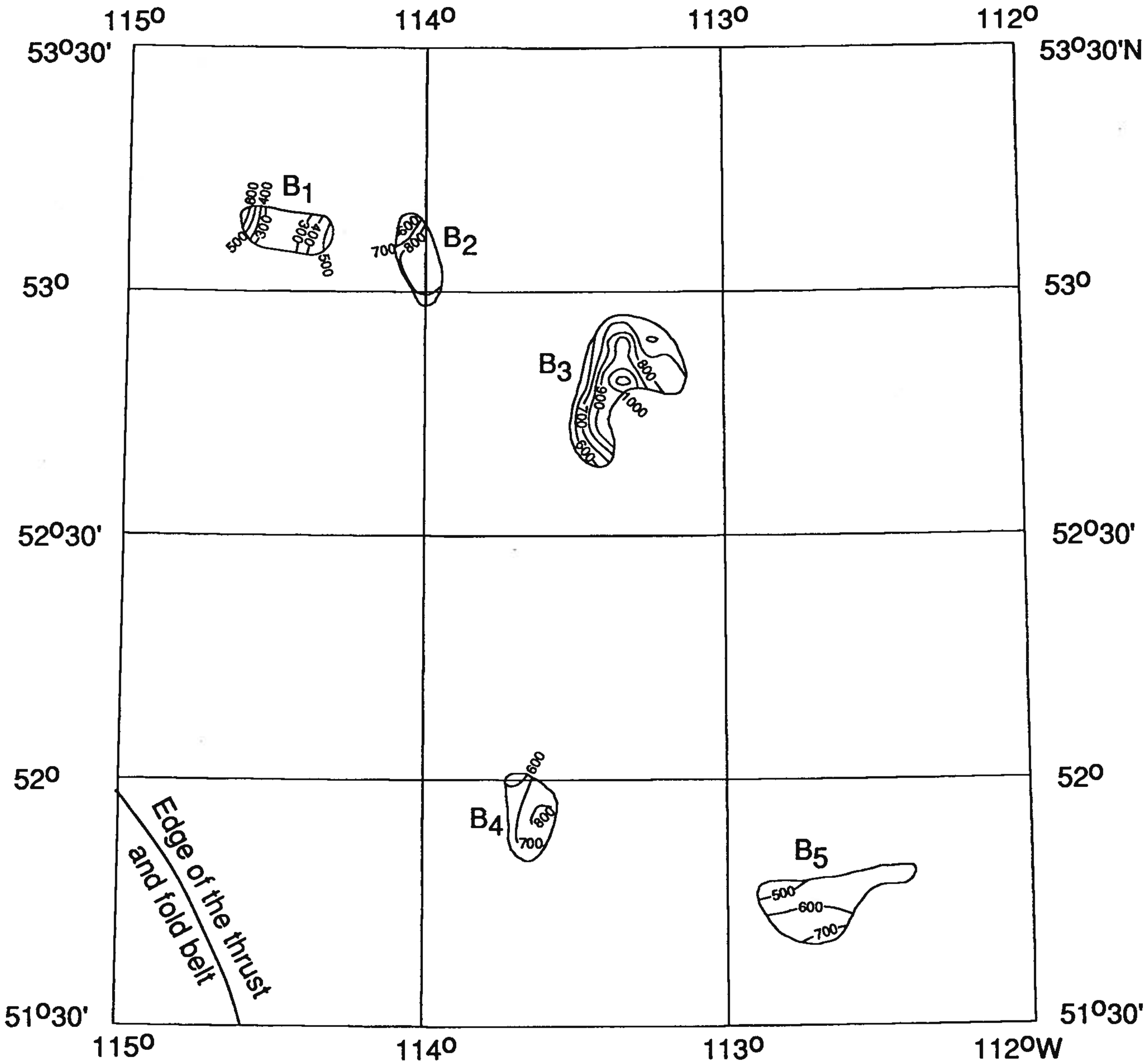

Figure 28. Iodine resource estimate in formation water in Belly River Formation, south-central Alberta (contours in t/km^2).

Summary

This report presents the results of work perfromed in the last year of a three-year program funded by the Canada-Alberta Partnership Agreement on Mineral Development (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 for the entire sedimentary succession throughout Alberta. Four broad regions and five stratigraphic intervals of potential economic interest were identified: Beaverhill Lake Group strata in southern Alberta and lower Elk Point Group strata in northeastern Alberta with Ca, Mg, K and Br concentrations in places above the detailed exploration limit; Beaverhill Lake and Woodbend strata in west-central Alberta with Li concentrations above the detailed exploration limit; and Viking and Belly River strata in south-central Alberta with I concentrations above the regional exploration threshold but less than the detailed exploration limit. In the second year, resources of Ca, Mg, K, Li, I and Br were broadly estimated for the regional-scale areas and stratigraphic intervals of interest, based on gross isopach and rock porosity. The estimates and resource distributions obtained in the second year of the study were, however, too broad to allow identification of exploration targets and possible plant siting. The work in the last year of the study focused on refining the resource estimates and on local-scale identification of specific areas and stratigraphic intervals with producibility potential. These were defined based on the following four criteria which had to be simultaneously satisfied: (1) concentrations of Ca, Mg, K, Li, I or Br in formation water greater than the detailed exploration limit, or

at least greater than the regional exploration threshold; (2) rock porosity greater than 5-10%; (3) rock permeability of at least $10^{-14}m^2$ (10 md); and (4) interval thickness of at least 10 m. Satisfying these conditions ensures that sufficient volumes of formation water with high elemental concentrations can be pumped from the respective sedimentary intervals in order to justify an economic analysis of mineral extraction and potential plant siting. A summary of mineral resource estimates in Alberta formation waters (Figure 29) is given in the following by stratigraphic unit and geographic location.

Lower Elk Point Group

Lower Elk Point Group strata in 2 areas in central-eastern Alberta contain formation water with high concentrations of Ca, Mg, K and Br. The strata, found at depths varying between 1,650 and 2,040 m, are characterized by an average permeability of $18 \times 10^{-15}m^2$ (18 md). Resources vary, respectively, between 25 and 180 kg/m^2 for Ca, 2 and 32 kg/m^2 for Mg, up to 2.4 kg/m^2 for K, and up to 2 kg/m^2 for Br.

Beaverhill Lake Group

Beaverhill Lake Group strata in six areas in southern Alberta contain formation water with high Ca, Mg, K and Br concentrations. The depth to the producible interval varies between 1,240 in the east and 2,600 m in the west. The average characteristics of the potentially producible interval are: 30 m thickness, 9% porosity and $55 \times 10^{-15}m^2$ (55 md)

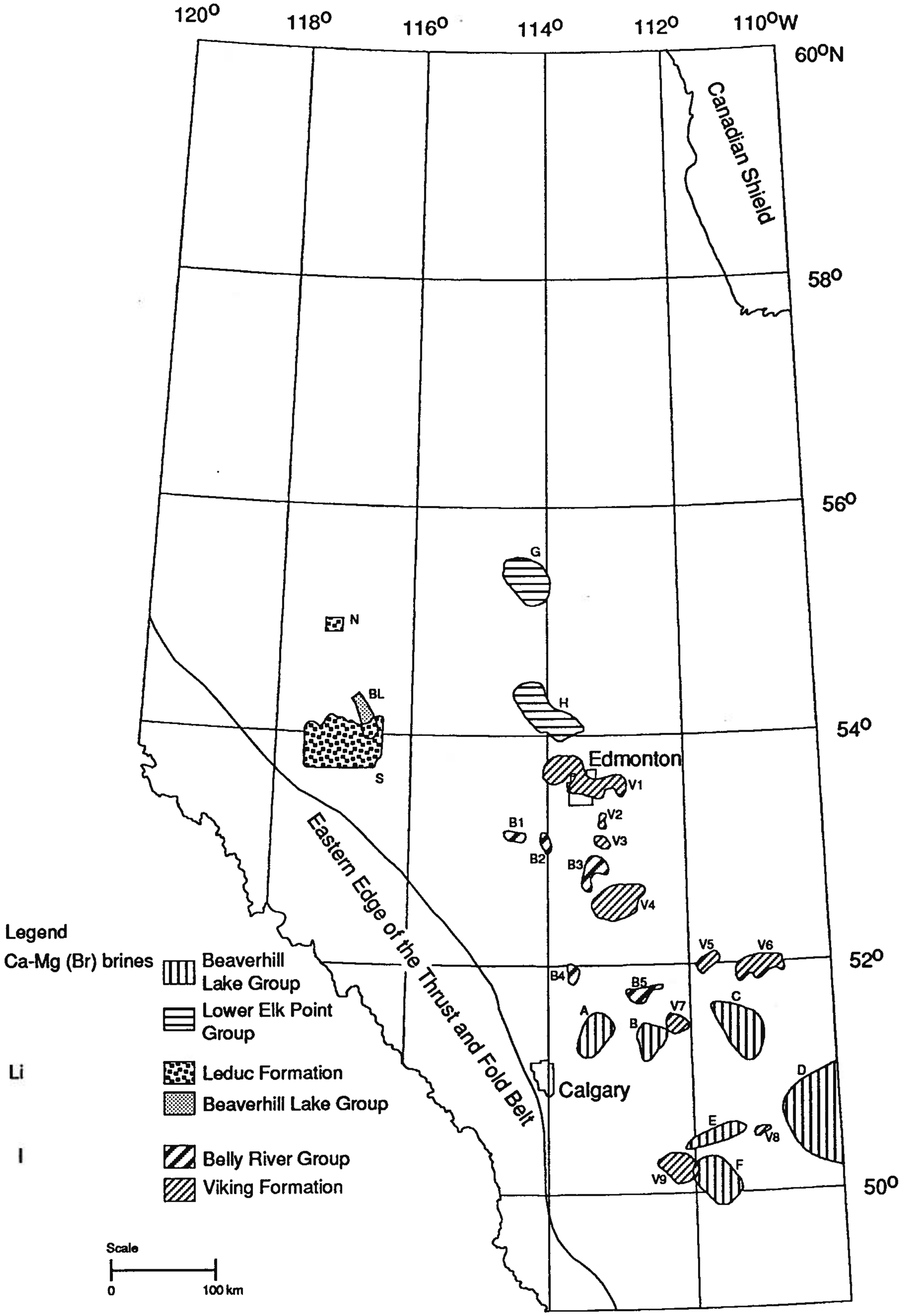

Figure 29. Resource areas for industrial minerals in Alberta formation waters.

permeability. Resources vary between 50 and 760 kg/m^2 for Ca, 4 and 136 kg/m^2 for Mg, up to 116 kg/m^2 for K, and up to 10 kg/m^2 for Br. Generally, Beaverhill Lake Group strata in southern Alberta have greater economic potential than lower Elk Point Group strata in central-eastern Alberta.

Woodbend and Beaverhill Lake Groups

Lithium in high concentrations is found in formation water contained in platform and reefal carbonates of the Woodbend and Beaverhill Lake groups in west-central Alberta. Because of the westward, downdip location, the approximate depth to the strata with producibility potential varies between 2,700 and 4,000 m. Depending on area, the strata are characterized by average thickness varying between 12 m and 46 m, average porosity of 6-7% and average permeability varying between 35 and 43 x 10^{-15}m^2 (35 and 43d md). Lithium resources vary between 0.01 and 0.57 kg/m^2.

Viking and Belly River Formations

Both Viking and Belly River strata in south-central Alberta contain in localized areas formation water with I concentrations higher than the regional exploration threshold, but lower than the detailed exploration limit. The approximate depth to the strata with producibility potential varies, depending on location, between 650 m and 950 m. The strata are characterized by an average thickness of 45 m for Viking Formation and 73 m for Belly River Formation, and by an average porosity of the order of 17-20%. Iodine resources vary between 0.2 and 1.8 kg/m^2 for the Viking strata, and between 0.3 and 1 kg/m^2 for the Belly River strata.

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