



**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.

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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 m² of land surface or t/km². 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/m² for Ca, 2 and 136 kg/m² for Mg, up to 116 kg/m² for K and up to 10 kg/m² 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/m². 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/m².

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 km² and 210,000 km²), 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.

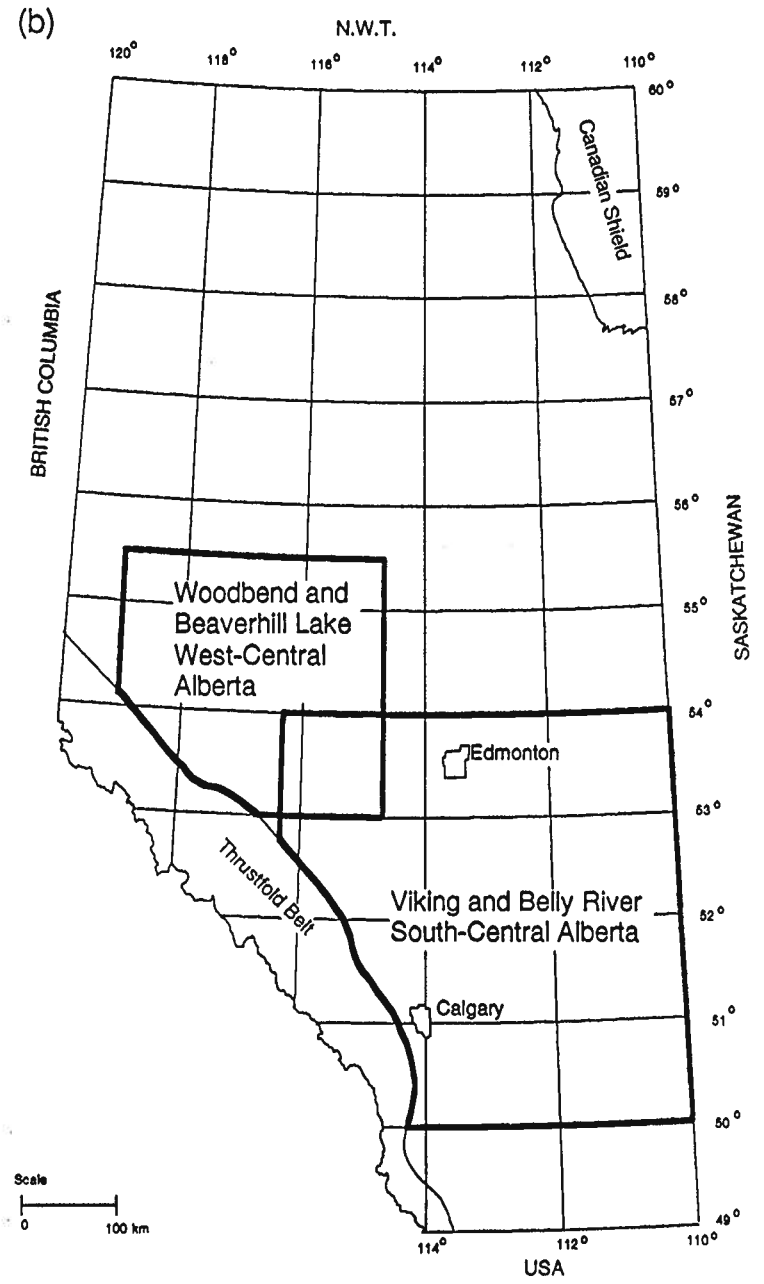
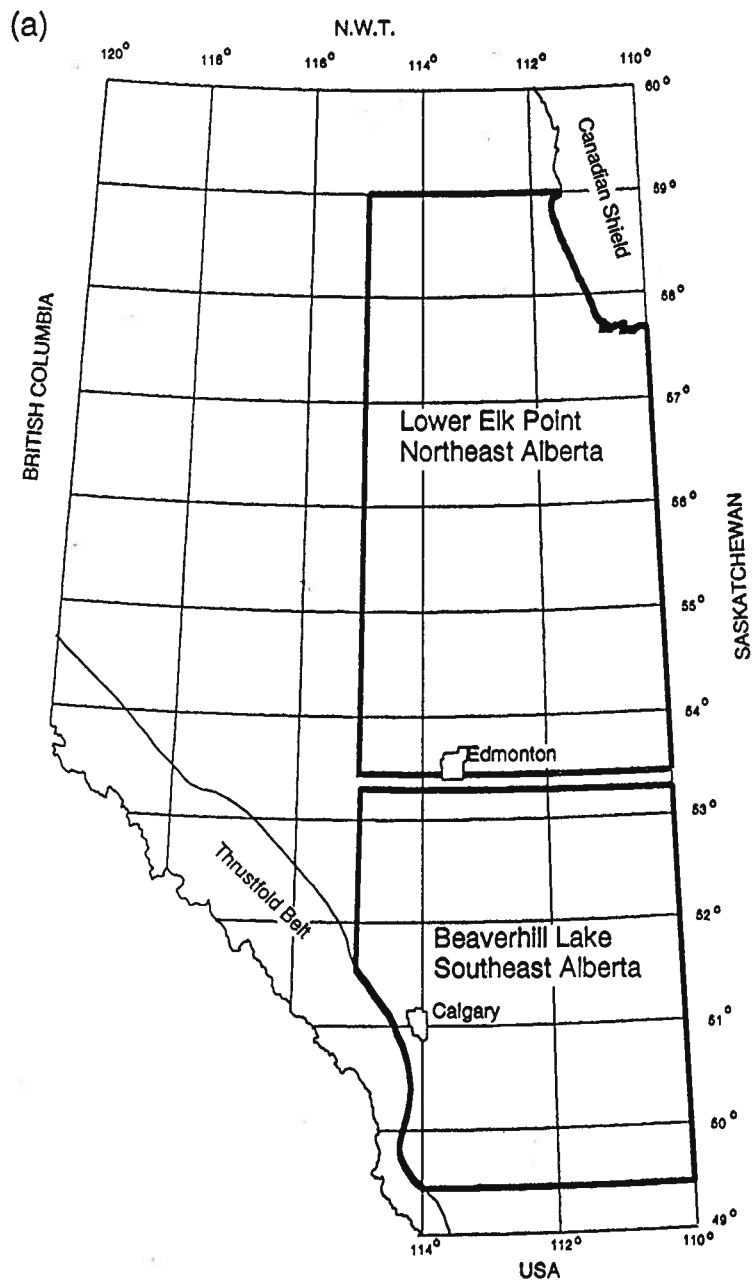


Figure 1. Regions of potentially economic industrial minerals in Alberta formation waters:
 (a) mainly for Ca, Mg, K and Br; (b) mainly for Li and I.

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:

$$R = C \times D \times \phi \quad (1)$$

If concentration is expressed in mg/l and interval thickness in m, then the calculated resource R has units of g/m² or t/km². 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 m² (km²) 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

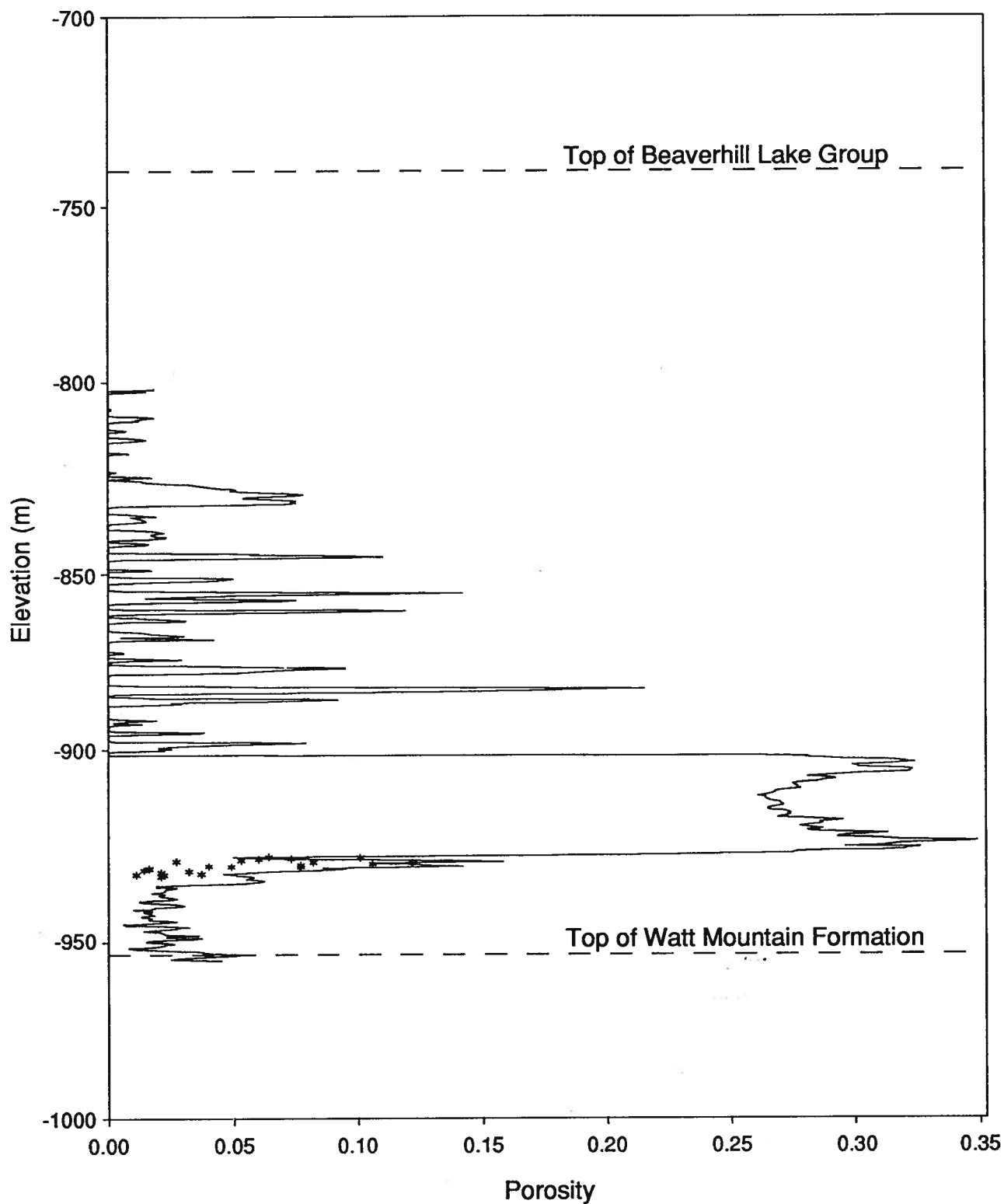


Figure 2. Porosity variation with depth in Beaverhill Lake Group strata in well 12-13-14-14W4 Mer as measured in core (*) and estimated from geophysical logs (—).

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:

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

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

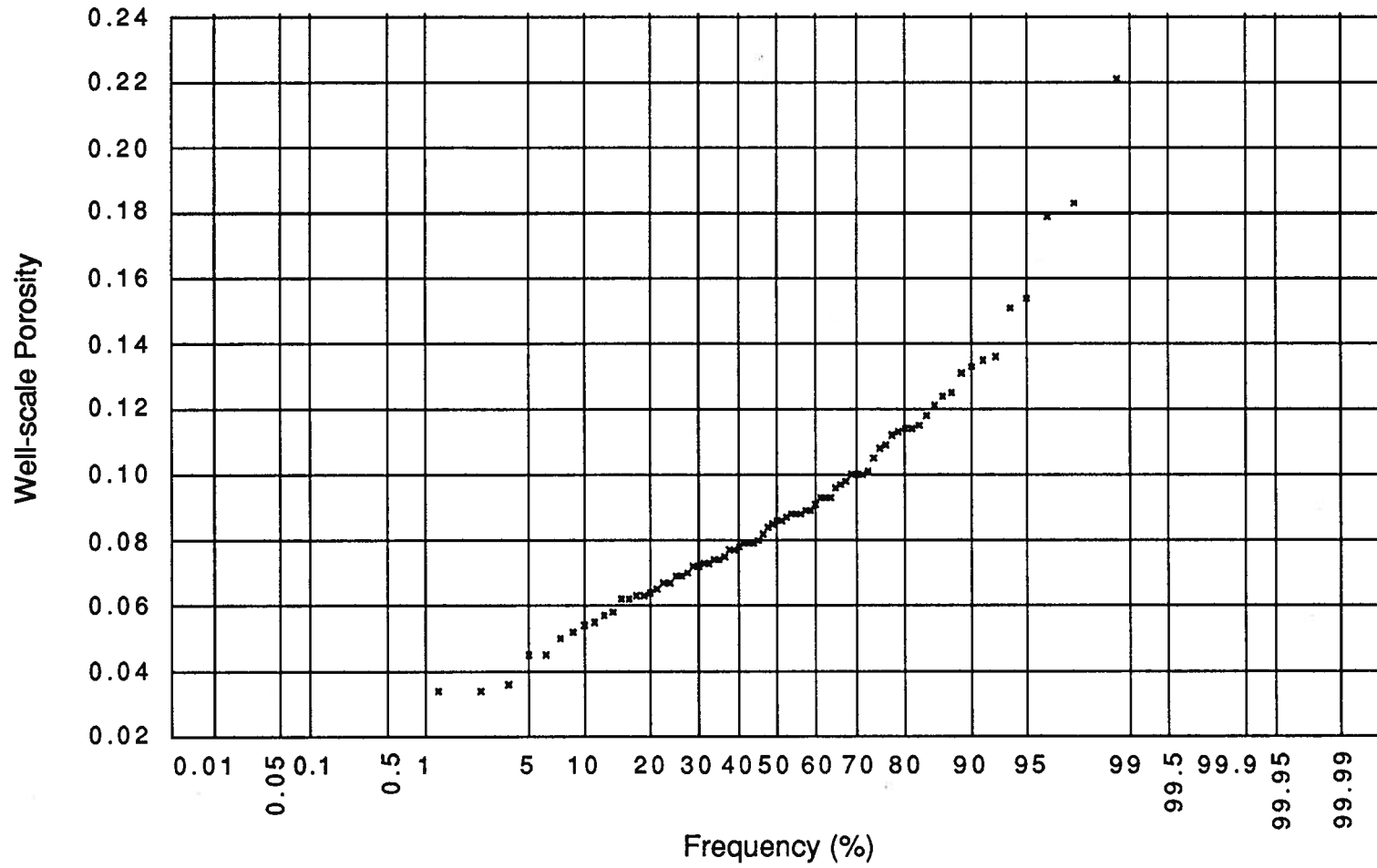


Figure 3. Frequency distribution of well-scale porosity in Beaverhill Lake Group strata, southern Alberta.

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

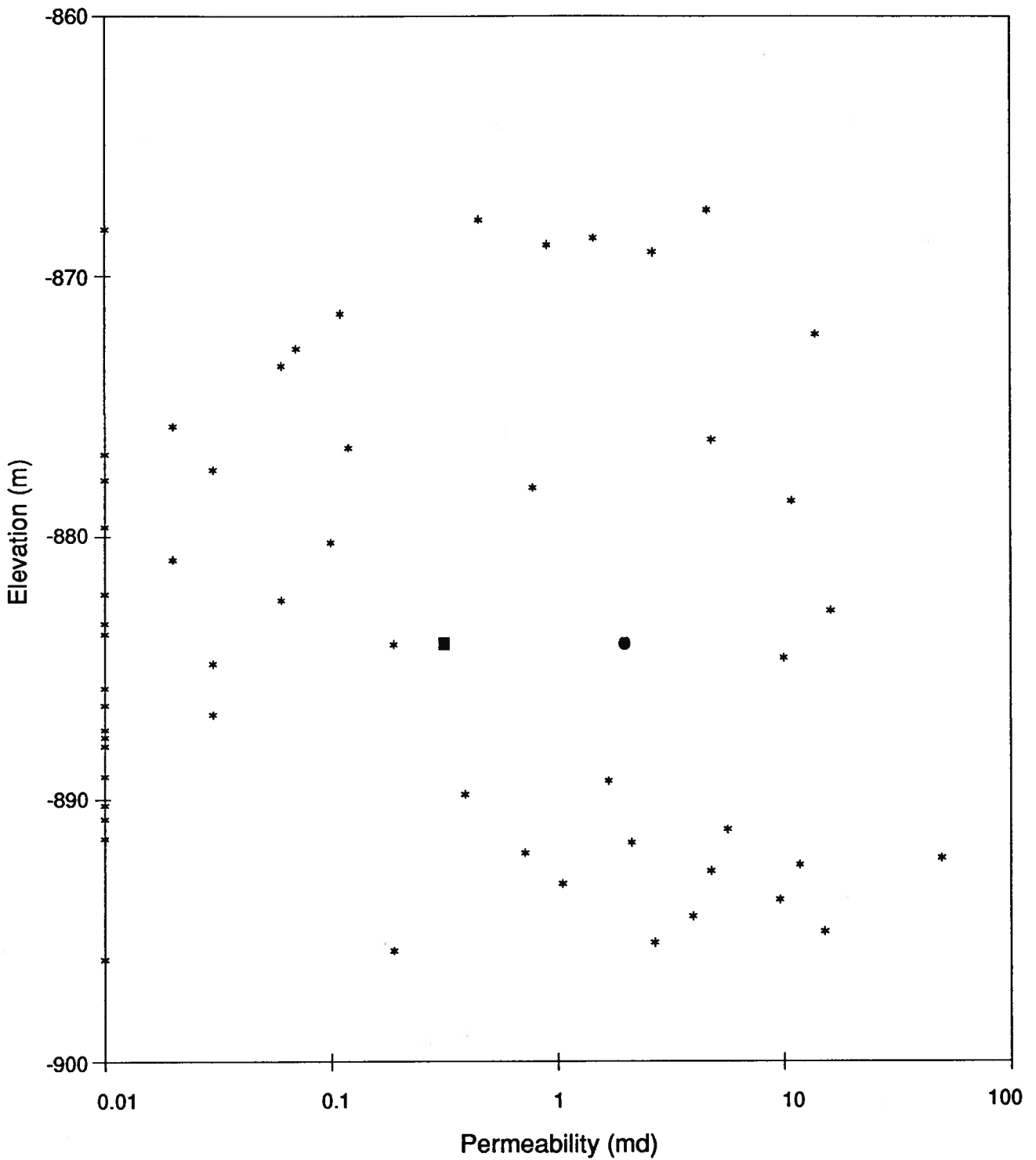


Figure 4. Permeability variation with depth in Beaverhill Lake Group strata in well 16-11-20-12W4 Mer as measured in core plugs (*), in a drill stem test (■), and well-averaged (●).

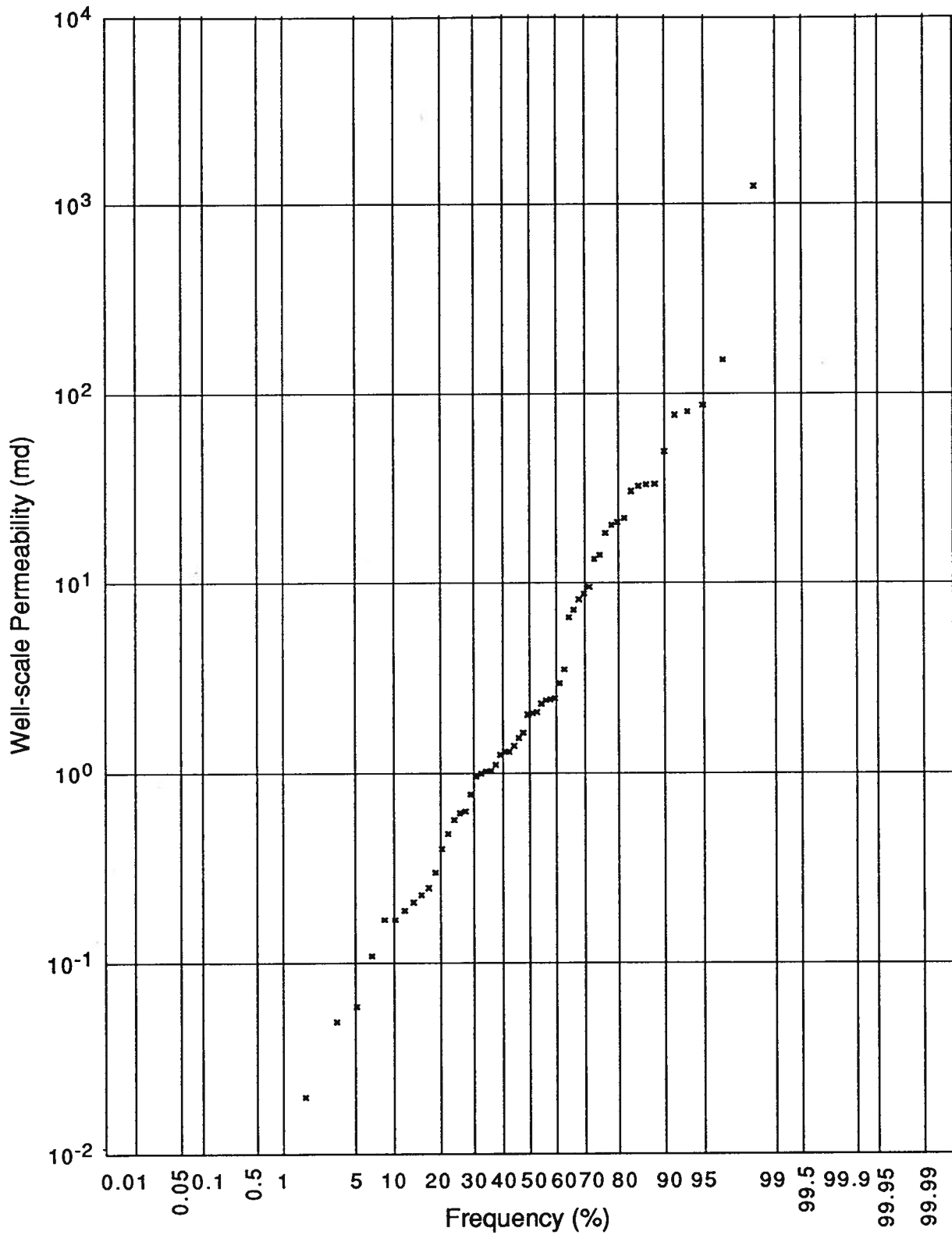


Figure 5. Frequency distribution of well-scale permeability in Beaverhill Lake Group strata, southern Alberta.

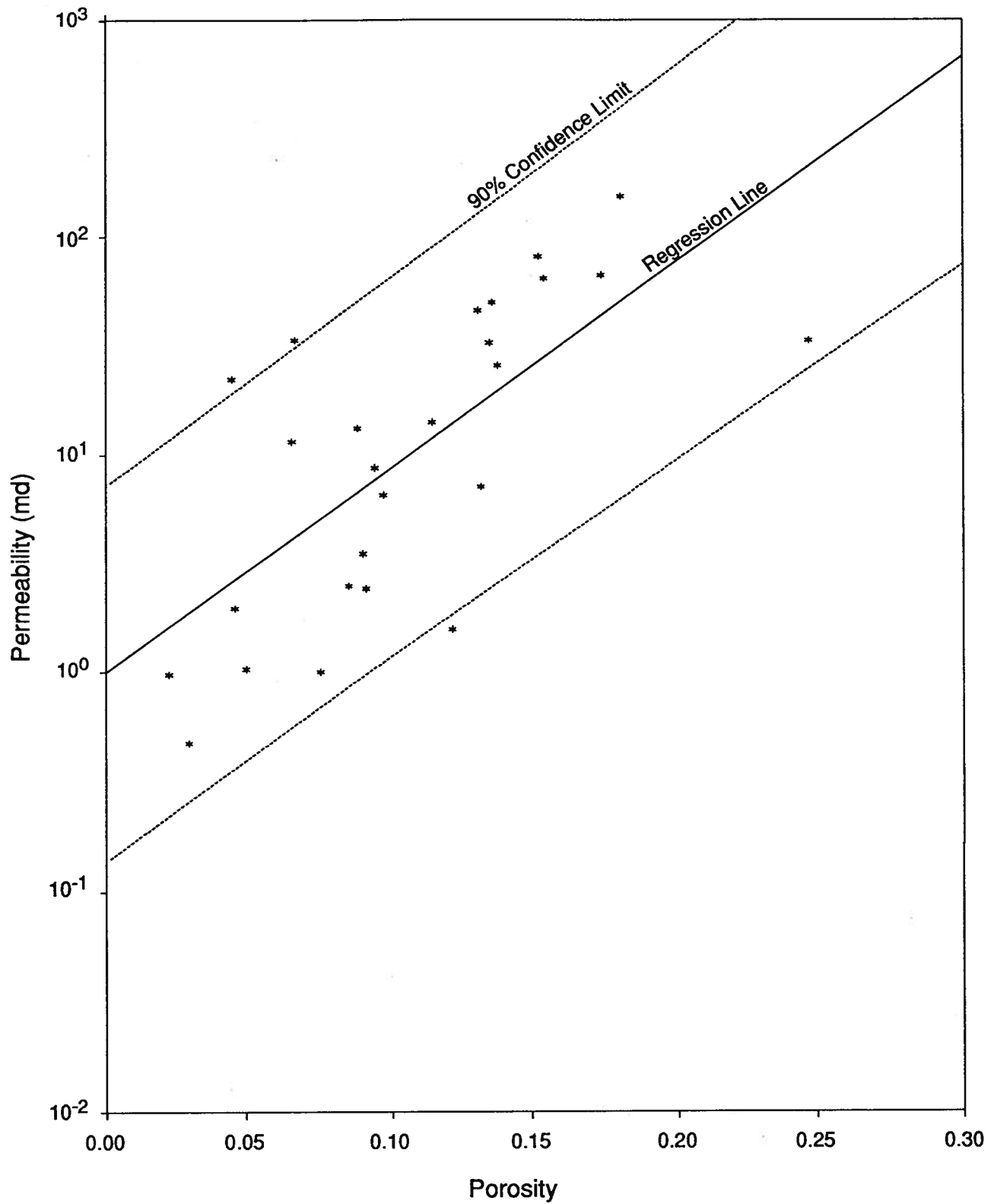


Figure 6. Correlation between well-scale permeability and porosity measured in core plugs from Beaverhill Lake Group strata, southern Alberta.

(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 $2 \times 10^{-17} - 10^{-12} \text{m}^2$ (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 $55 \times 10^{-15} \text{m}^2$ (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

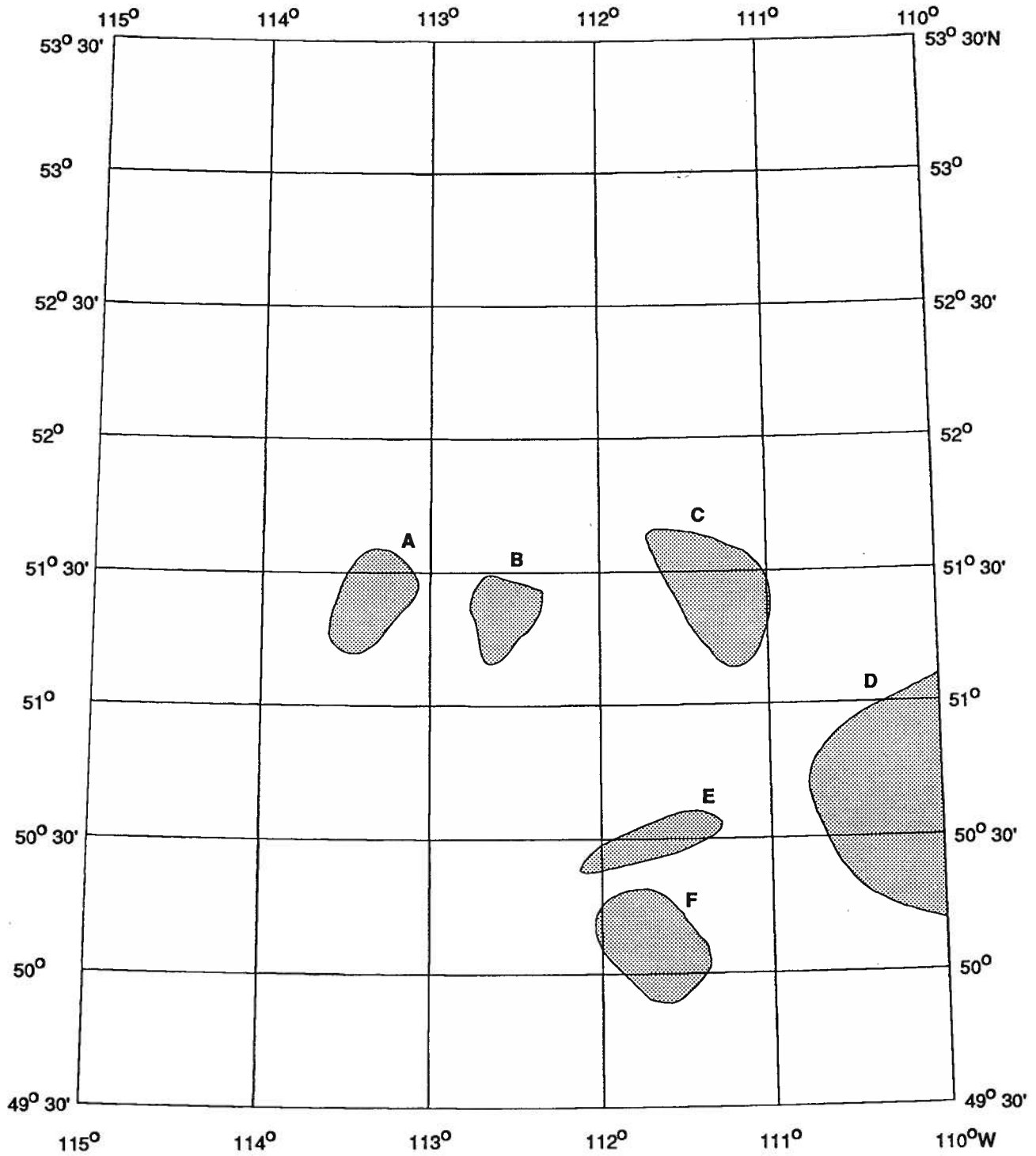


Figure 7. Areas in southern Alberta with productivity potential for Ca, Mg, K and Br from Beaverhill Lake Group formation water.

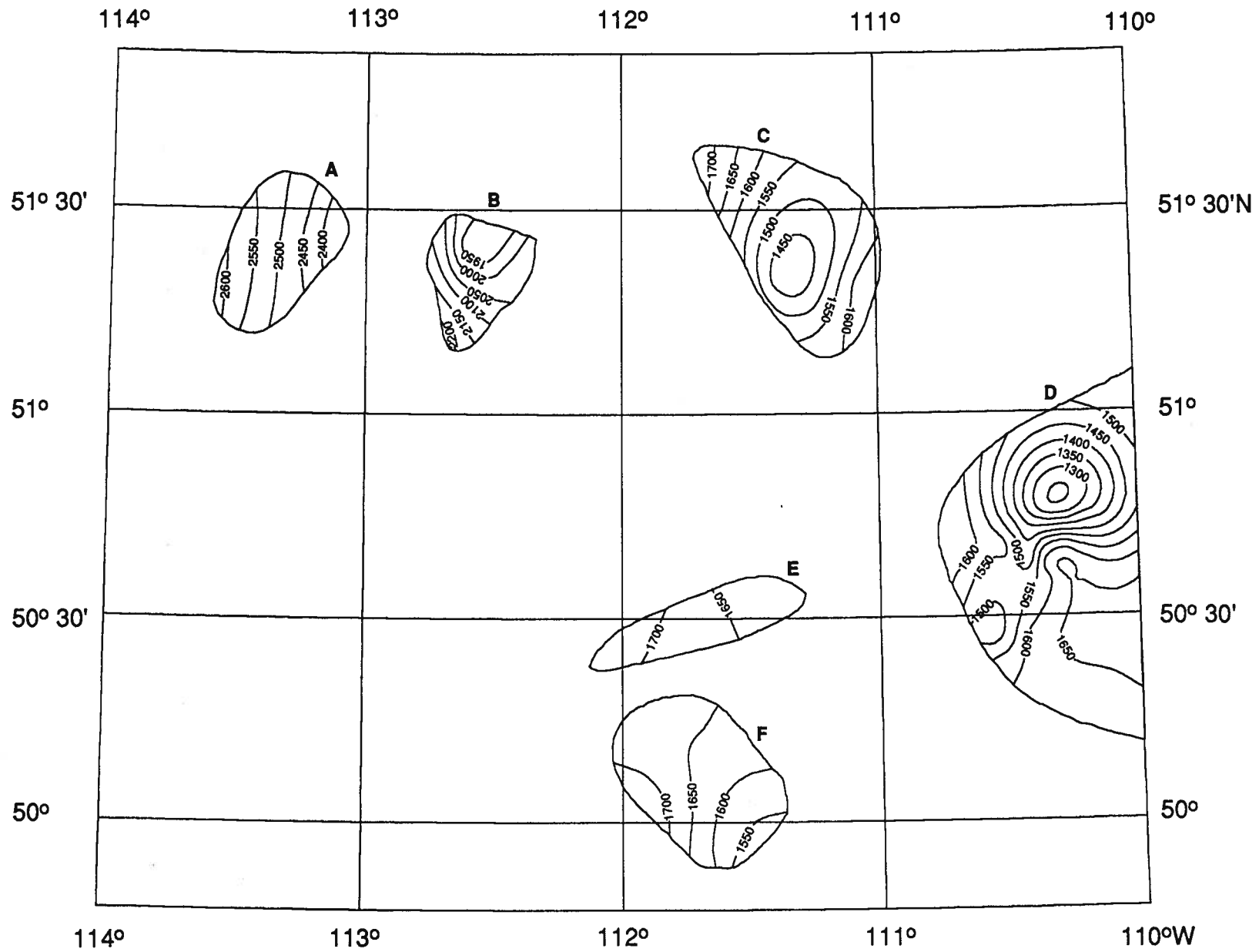


Figure 8. Approximate depth (m) to the stratigraphic interval with producibility potential for Ca, Mg, K and Br in formation water from Beaverhill Lake Group strata, southern Alberta.

3 - 11% and 10^{-16} - $5 \times 10^{-14} \text{m}^2$ (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 $18 \times 10^{-15} \text{m}^2$ (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

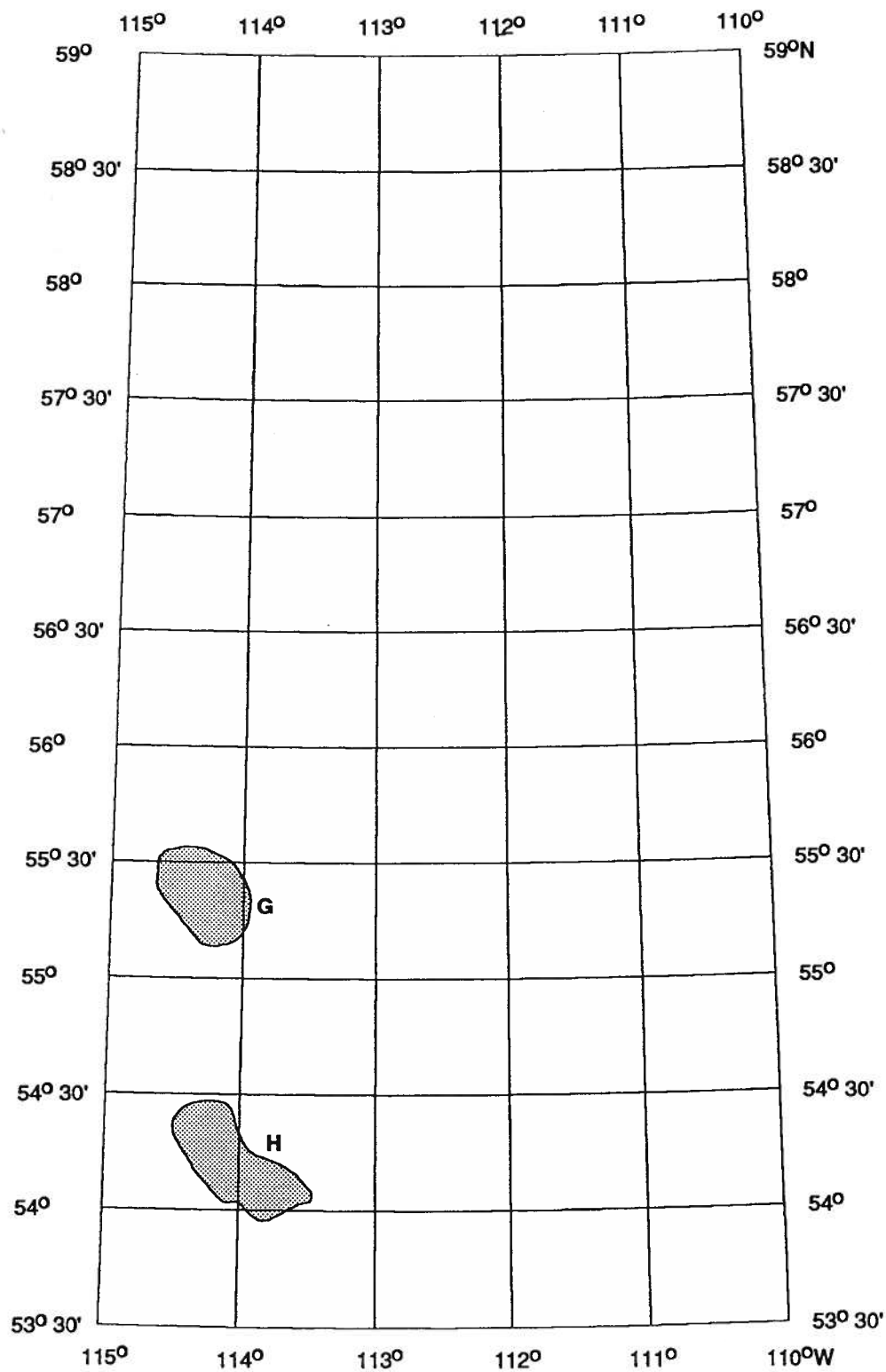


Figure 9. Areas in northern Alberta with producibility potential for Ca, Mg, K and Br from Elk Point Group formation water.

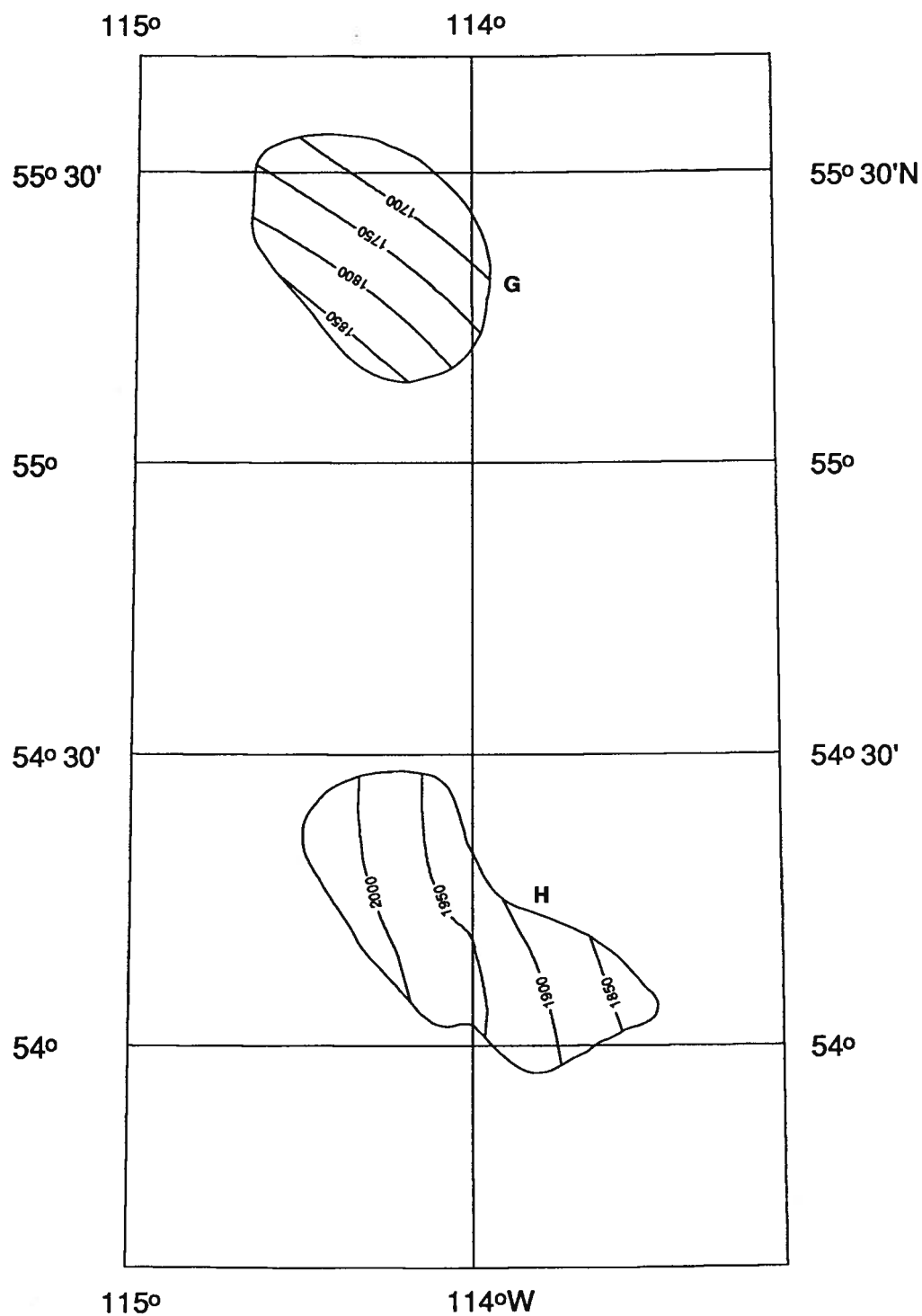


Figure 10. Approximate depth (m) to the stratigraphic interval with producibility potential for Ca, Mg, K and Br in formation water from Elk Point Group strata, central-eastern Alberta.

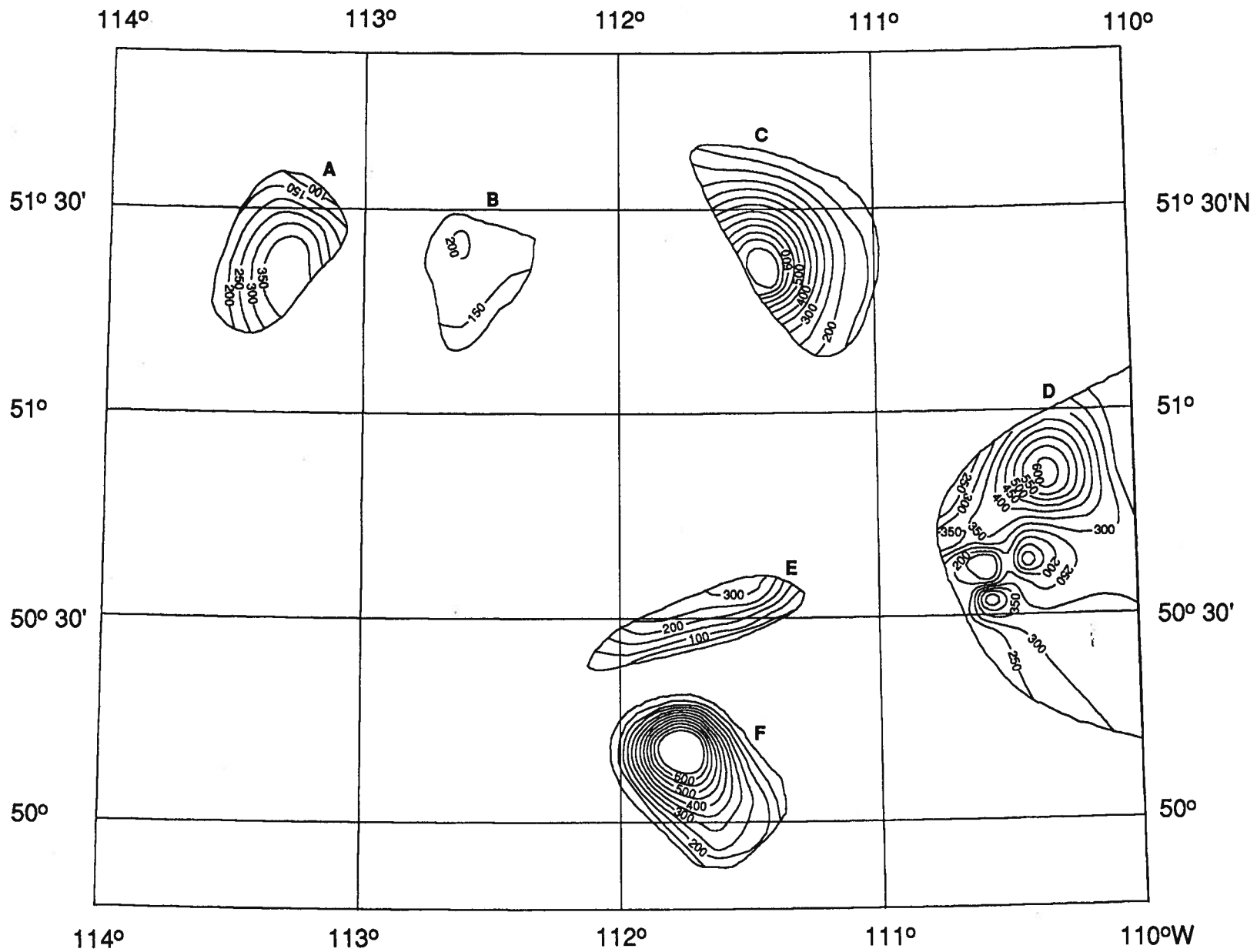


Figure 11. Calcium resource estimates in formation water in Beaverhill Lake Group strata, southern Alberta (contours in kg/m² or 1000 t/km²).

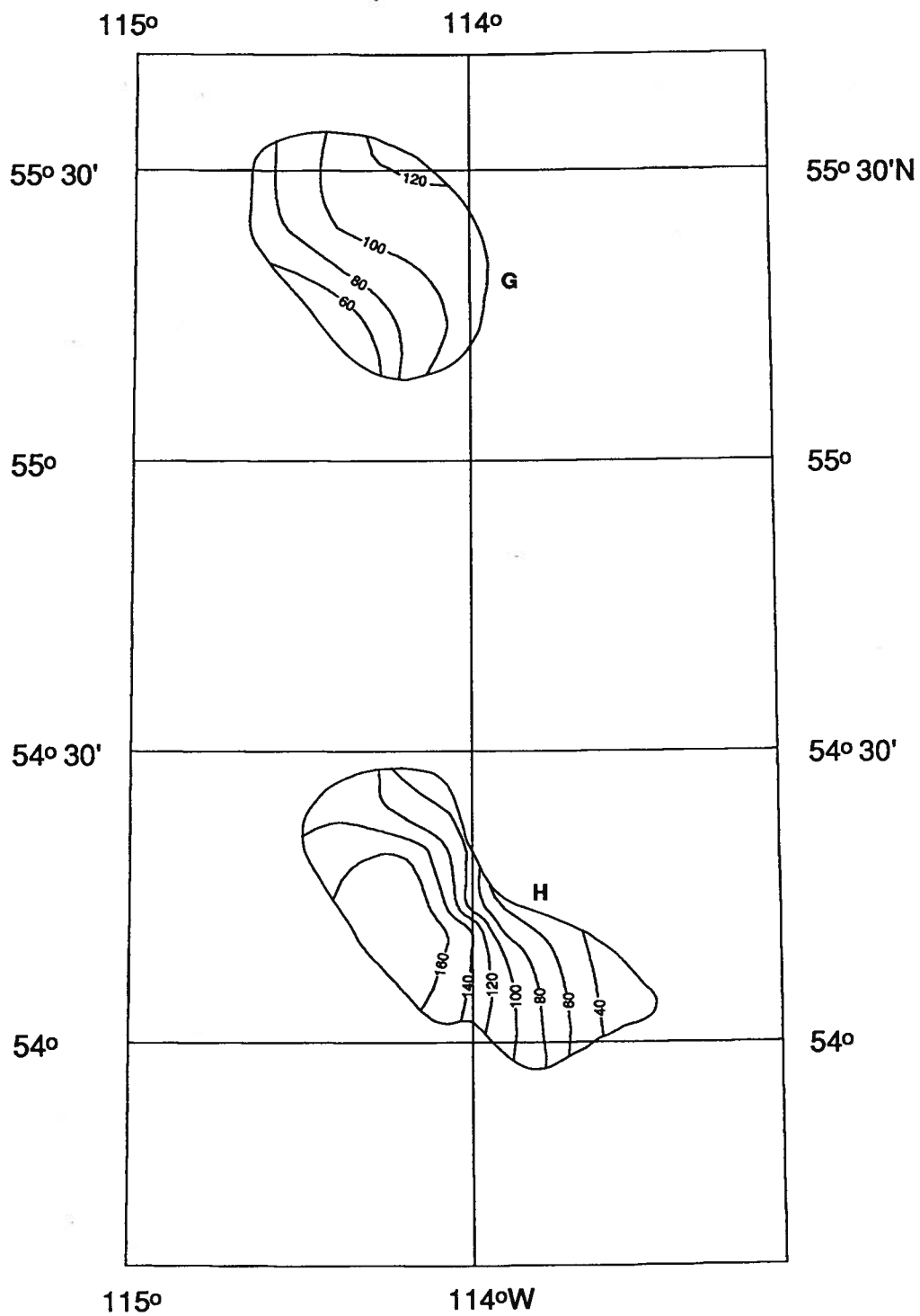


Figure 12. Calcium resource estimates in formation water in Elk Point Group strata, central-eastern Alberta (contours in kg/m^2 or $1000 \text{ t}/\text{km}^2$).

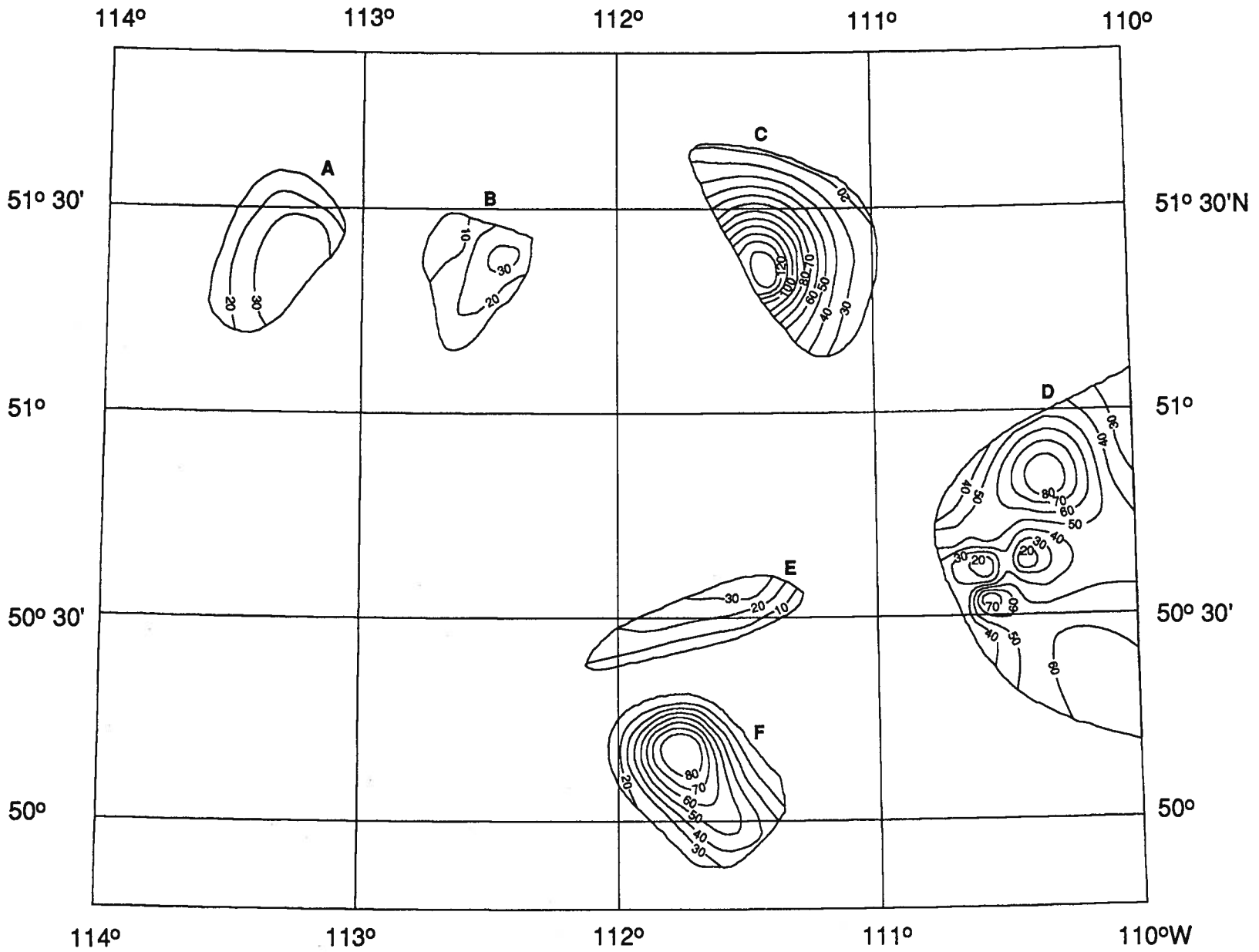


Figure 13. Magnesium resource estimates in formation water in Beaverhill Lake Group strata, southern Alberta (contours in kg/m² or 1000 t/km²).