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Preliminary Investigation of Potential, Natural Hydraulic Pathways between the Scollard and Paskapoo Formations in Alberta: Implications for Coalbed Methane Production

Energy Resources Conservation Board

Alberta Geological Survey

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Energy Resources Conservation Board
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Abstract

This report presents the preliminary results of an investigation to assess risk to groundwater in the Paskapoo Formation from potential hazards associated with future coalbed methane (CBM) production in the Ardley Coal Zone of the Scollard Formation. The investigation focused on two key hydrogeological components:

- the degree of hydraulic connectivity between the Ardley coals and the Paskapoo Formation
- the degree of hydraulic connectivity and hydraulic continuity within the Paskapoo Formation itself

Strong local hydraulic connectivity between the Ardley coals and the Paskapoo Formation can occur where Paskapoo sandstone channels have eroded the hydraulically insulating upper Scollard mudstones and rest directly atop the Ardley Coal Zone. Direct sandstone-to-coal contact presumably provides hydraulic connectivity. The evidence for local hydraulic connectivity is the observation that formation pressures and hydraulic heads in the Ardley Coal Zone are similar in magnitude to those measured in the Paskapoo Formation, which relate to depth and position in a gravity-driven regional groundwater-flow system. Where such connectivity does not exist through contact between sandstone and coal, the Scollard Formation, including the Ardley Coal Zone, is strongly underpressured. The limited data allow us to develop this conceptual model and advance it with further investigation, but the probability of connectivity at any given location in the system is presently unknown.

Because the presence of overlying Paskapoo channel sandstones cannot be determined from current information, it is impossible to predict the local connectivity of the Ardley to the Paskapoo prior to drilling, logging and pressure testing. After drilling, however, the local connectivity can be ascertained with relative certainty. If there is no connectivity, there will probably be no more impact on, or hazard to, Paskapoo Formation groundwater from Ardley CBM production than from any gas well.

If there is connectivity between the Ardley Coal Zone and the Paskapoo Formation, the probability of impact on groundwater depends on 1) the degree of regional interconnectivity of the sandstones in the Paskapoo Formation, and 2) the degree of hydraulic continuity between a given Ardley CBM development and users of Paskapoo groundwater over the time scale of that CBM production. We can estimate the degree of regional interconnectivity from sandstone-abundance maps using concepts of percolation theory. Percolation concepts suggest that, when regional sandstone abundances are less than 40%, sandstone bodies in the Paskapoo Formation may be locally connected but probably not regionally connected. When regional sandstone concentrations are greater than 60%, the Paskapoo sandstone bodies probably interconnect at the regional scale as well as the local scale. The threshold marking the change from local-only to local-plus-regional interconnectivity occurs somewhere between 40% and 60% sandstone.

The distribution of natural-gas occurrences in the lower Paskapoo Formation supports this model. Gas occurrences in the Paskapoo Formation with volumes significant enough for commercial production tend to occur where regional sandstone abundances are between 40% and 60%, and structurally lower than areas where regional sandstone abundances are less than 40%. Above 60% sandstone, there are few gas occurrences, suggesting that these zones have little capacity to trap natural gas. There are also few gas occurrences when sandstone abundance is below 40%, suggesting minimal regional capacity to allow migration of gas into the Paskapoo sandstones in these zones.

The nature of hydraulic interconnectivity is important in determining hydraulic continuity and therefore the degree of impact associated with the propagation of pressure disturbances laterally and vertically through the Paskapoo Formation. Hydraulic continuity defines whether a hydraulic or pressure disturbance originating at one point is measurable at a different point. It depends on the distance between the point of origin and the point of observation, the time lag between time of origin and time of

observation, and the hydraulic diffusivity of the rock framework between the point of origin and the point of observation.

The hydraulic diffusivity of a sandstone-mudstone system consisting of discrete sandstone bodies encased in mudstone, such as the Paskapoo Formation (as opposed to a simple layered system), will be dominated by sandstone properties where the sandstone is regionally interconnected and by mudstone properties where it is not. Since we can estimate and map the sandstone abundance and predict regional connectivity using percolation theory, we can identify areas where the sandstone properties will control the regional hydraulic diffusivity and the areas where it will not:

- In areas where sandstone bodies are regionally interconnected, and given the hydraulic properties of Paskapoo sandstones, there is likely to be regional hydraulic continuity between most points of origin and most points of observation after 10 or more years of CBM development, wherever those points are located, so long as the abundance of sandstone is above 60%.
- Where sandstone bodies do not interconnect regionally, and given the hydraulic properties of Paskapoo mudstones, there is not likely to be regional hydraulic continuity between most points of origin and most points of observation after 10 years or more of CBM development, wherever those points are located, so long as the abundance of sandstone is below 40%. In these cases, however, there will still be the possibility of local-scale connectivity and hydraulic continuity, which will decrease as the regional sandstone abundance decreases and the points of origin and observation become farther apart.

As in all geological investigations that rely on sparse data from wells, there is uncertainty in the conceptual model developed in this report. Further studies can reduce but not eliminate this scientific uncertainty. Studies that would probably advance our understanding of the Ardley-Scollard-Paskapoo system include

- investigating the role of fractures at depth;
- investigating the reservoir qualities and internal hydraulic continuity of coal beds in the Ardley Coal Zone; and
- testing the robustness of the conceptual model through more sensitivity analysis of the parameters chosen to map the internal architecture of the Paskapoo Formation, including petrophysical cutoffs and slice-thickness magnitudes and orientations.

1 Introduction

The report of the Multi-Stakeholder Advisory Committee on Coalbed Methane/Natural Gas in Coal (2006) recommended that the processes for CBM development approvals in Alberta recognize and be more stringent in areas where groundwater resources could be at risk.

Risks to groundwater associated with CBM production based on coal-seam depressurization include

- a potential reduction of hydraulic head in aquifers that are in hydraulic communication with the coal seams via natural geological pathways; the resultant declines in static water levels in wells completed in communicating aquifers increase in magnitude with the magnitude and duration of depressurization but decrease in magnitude with increasing distance from the centre of depressurization; and
- the potential escape of fugitive methane gas (i.e., released from depressured coal seams but not captured by production wells) from the CBM reservoirs into shallow aquifers via natural geological pathways.

The purpose of this report is to identify areas within the Ardley-Scollard-Paskapoo hydrogeological system that could have greater or lesser natural tendencies toward hydraulic communication and connectivity between the Ardley Coal Zone and the overlying Paskapoo Formation. The area of study includes all of Alberta underlain by the Paskapoo and Scollard formations (Figure 1). This includes all areas of the Ardley Coal Zone that could be exploited for coalbed methane resources and potentially impact groundwater resources in the Paskapoo Formation.

1.1 Framework for Measuring the Benefits of Groundwater Protection

Raucher (1983) presented a conceptual framework for measuring the societal and economic benefits of groundwater protection (Appendix 1). This framework allows application of knowledge of the Ardley-Scollard-Paskapoo hydrogeological system to policy formulation that would maximize benefits to society through groundwater protection, while helping to minimize costs to Alberta's CBM operators.

In brief, Raucher modelled the benefit of groundwater-protection policies in two ways: 1) through the benefits accrued to society by adoption of policies that reduced the probability of contamination; and 2) through the benefits accrued to society by adoption of policies that increased the probability of detection. In terms of Raucher's framework, an outcome of our study is to identify areas where the probability of contamination or hydraulic impact in the Paskapoo Formation, associated with CBM production from the Ardley Coal Zone (Raucher's *p*, Appendix 1), is naturally very low, so that the costs associated with a policy (Raucher's *Xi*, Appendix 1) can be avoided. The premise of this effort is that, in such areas, if they exist, the expected benefit of additional groundwater protection policies would be negligible, and industry and government resources aimed at groundwater protection (*Xi*) could therefore be better applied elsewhere.

1.2 Structure of this Report

This report has four sections. The first describes the Ardley-Scollard-Paskapoo system in terms of geology, hydrogeology, and gas and water production. The second section describes the system in terms of hydraulic continuity and connectivity, based on the results presented in the first section. The third section proposes a strategy to assess risks associated with CBM development and, based on the findings of the first two sections, identifies areas where risk to groundwater associated with reduction in pressure or fugitive gas migration is relatively low. The last section discusses recommendations for further work to validate some of the interpretations and conclusions of this investigation.

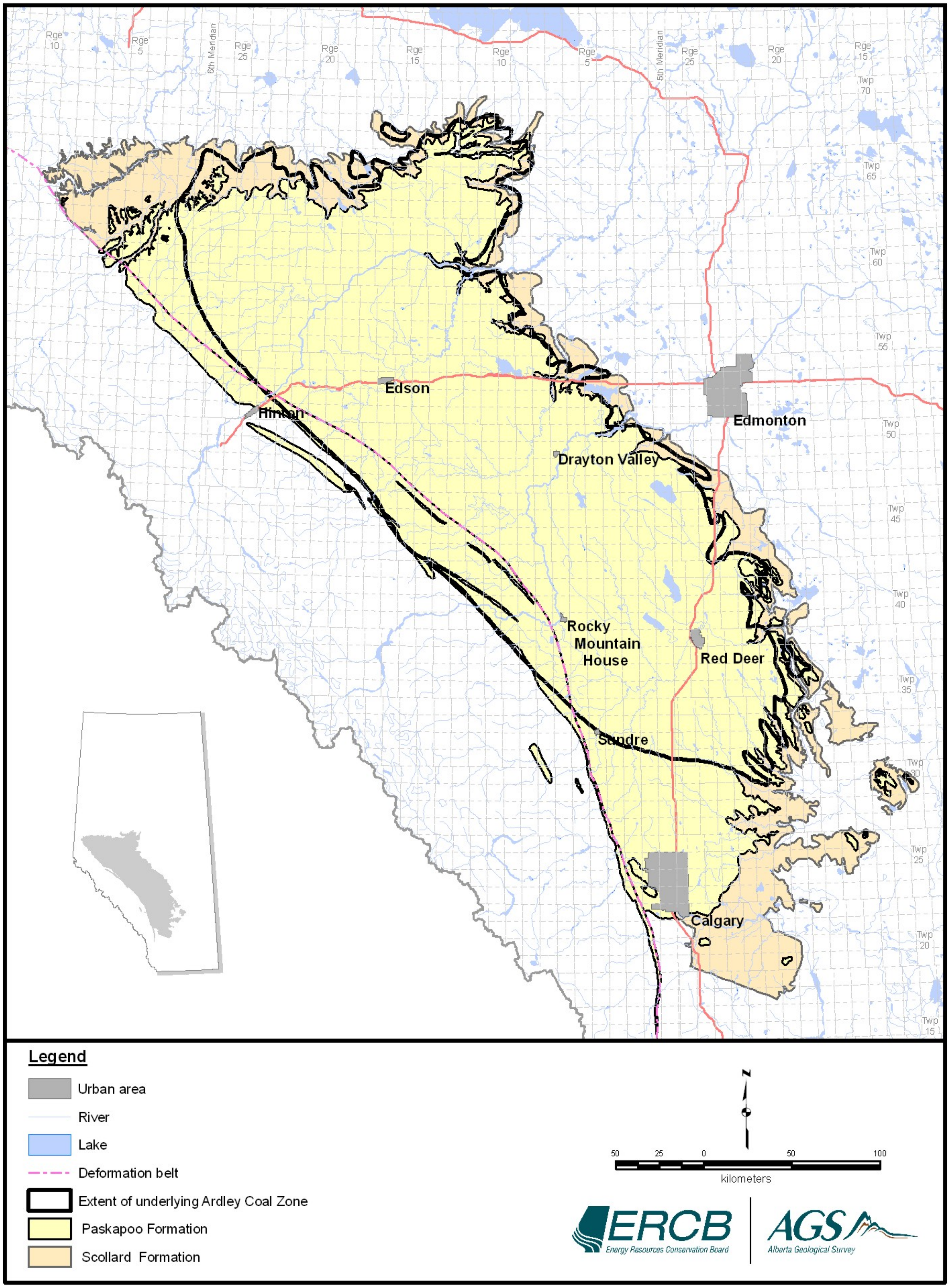

Figure 1. Extent of the Paskapoo and Scollard formations in Alberta.

2 Geology and Hydrogeology of the Ardley-Scollard-Paskapoo System

The area of interest includes the central plains region of Alberta, extending west to the eastern edge of the Rocky Mountain foothills where the mountain-building processes have deformed the rock units. The system of interest includes three bedrock units: the Battle Formation, the Scollard Formation and the Paskapoo Formation (Figure 2). The Scollard Formation contains the Ardley Coal Zone. The Scollard and Paskapoo formations are heterolithic in the sense that they comprise beds of different lithology (rock type) in varied proportions. Areally persistent relative proportions of lithology, combined with the age and genesis, are used to define these formations. Because these formations are defined based on lithology, geologists also refer to them as lithostratigraphic units.

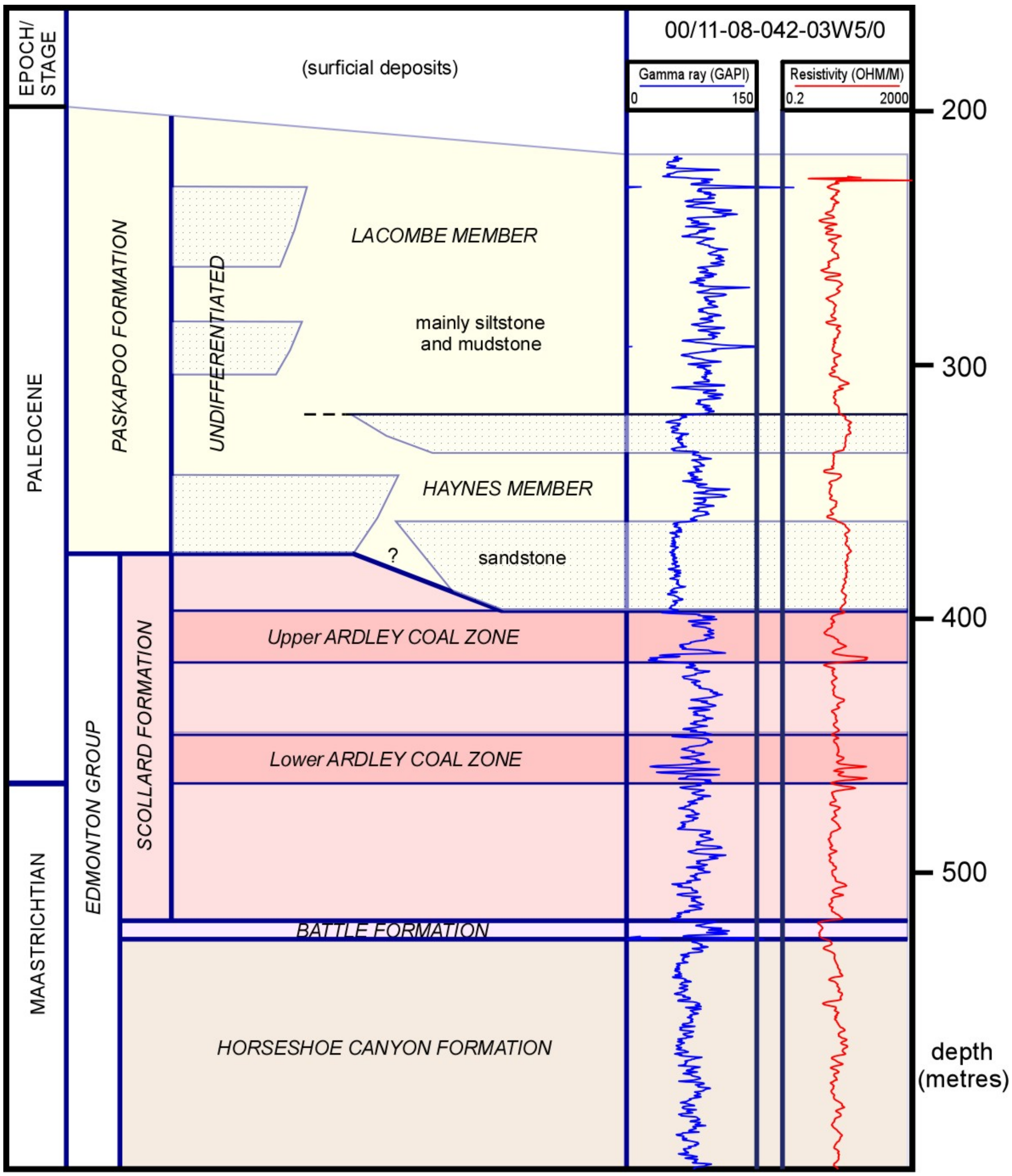

Figure 2. Table of formations for the Ardley-Scollard-Paskapoo system, with representative well log (after Alberta Energy and Utilities Board, 2002).

Figure 3 shows a west-to-east, geological cross-section through these formations. Note that the vertical exaggeration of the cross-section shortens it horizontally while stretching it vertically. The cross-section includes geophysical logs run in petroleum-exploration boreholes. The ‘gap’ in vertical coverage between the tops of most petroleum logs and the land surface represents the interval where surface casing is installed in oil and gas wells for well-control purposes. Surface casing also serves to protect nonsaline groundwater from drilling operations. New regulations (Alberta Energy and Utilities Board, 2006a) have since made logging of this gap mandatory.

The cross-section in Figure 3 highlights the known geological elements of the Ardley-Scollard-Paskapoo system:

- The contact between the Battle and Scollard formations decreases in elevation from east to west. Therefore, the geological units ‘dip’ to the west. The actual direction of maximum dip of strata older than the Paskapoo Formation in west-central Alberta is toward the southwest, perpendicular to the Rocky Mountains.
- The modern ground surface decreases in elevation from west to east away from the mountains. The beds of interest in this report thus form a wedge of rock and sediment that tapers to the northeast.
- The top of the bedrock has an irregular topography due to erosion by glacial ice and rivers. The irregularities can be masked where thick deposits of glacial drift or modern river sediments infill bedrock topographic lows.
- The thickness of both the Scollard and Paskapoo formations increases to the west. To geologists, this indicates that the underlying bedrock was tilting and subsiding during deposition of these formations. In Alberta, this feature correlates to the formation of the Canadian Rocky Mountains: as the mountain sheets piled on from the west, the crust below Alberta warped downwards and formed an elongate trench parallel to the mountain front. Detritus eroded from those same rising mountains both simultaneously and subsequently filled this trench.
- At some point between the deposition of the Scollard Formation and the end of deposition of the Paskapoo Formation, mountain building and subsidence stopped. The trench filled, but deposition from the eroding mountains in the west continued. Over time, sedimentary beds derived from the west no longer dipped to the southwest but gradually flattened and then started to dip down to the northeast, lapping off the Rocky Mountains as a precursor to the modern landscape.
- The base of the Scollard Formation is generally a relatively smooth surface, decreasing in elevation to the southwest in a regular, predictable manner. This regularity indicates substantive areas of little erosion between the end of deposition of the Battle Formation and the beginning of deposition of the overlying Scollard Formation. Locally, however, there are areas where erosion has removed the Battle Formation at the base of the Scollard Formation. Geologists know little about the nature or origin of these areas.
- The top of the Scollard Formation, on the other hand, is irregular in many places. In some places, the Scollard Formation was removed all the way down to the Ardley Coal Zone, and recognizable Paskapoo sandstones are sitting directly on top of Ardley coals. This indicates that there was a time break corresponding to significant localized erosion between the end of Scollard Formation deposition and the beginning of Paskapoo Formation deposition.
- The distribution of the Ardley coals within the Scollard Formation is irregular, although delineation of a regionally persistent and distinct Upper Ardley Coal Zone and Lower Ardley Coal Zone is often locally possible. The irregular distribution partly reflects the environment of deposition of the coals in a channellized environment, where coals were presumably deposited in areally restricted, low-lying areas that may have experienced subsequent erosion or cutoff by downcutting stream channels.

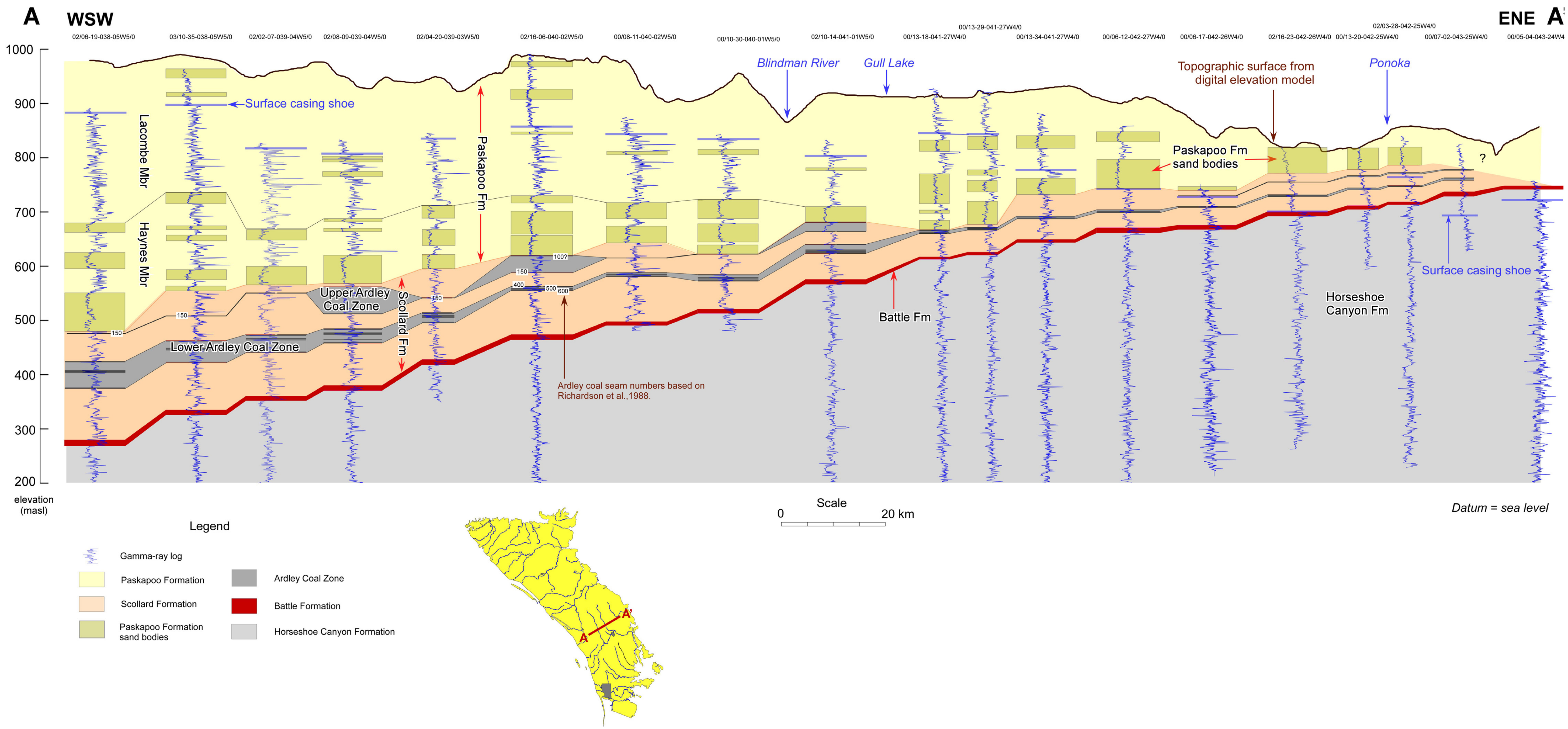

Figure 3. Regional structural cross-section, highlighting the geology of Ardley-Scollard-Paskapoo system.

- There are no regionally persistent marker beds, such as marine shales, bentonites (volcanic ash) or coal zones, within the Paskapoo Formation that we can correlate from well to well over any significant distance. Moreover, the individual sandstone bodies identifiable on well logs generally do not persist from well to well. Nevertheless, one can easily discern from additional cross-sections and mapping (not shown here) that there is more sandstone in the Paskapoo Formation in its lower parts and to the west than in its upper parts and to the east.

Formation-specific observations follow.

2.1 Battle Formation

The Battle Formation is an Upper Cretaceous unit consisting mainly of shale and mudstone (Dawson et al., 1994a). Figure 4 shows the structural elevation of the top of the Battle Formation in map view. We obtained the initial picks used to generate this surface and subsequent surfaces in this report from AGS data holdings and then substantially augmented them with new downhole geophysical log picks to help ensure accuracy and consistency.

The Battle Formation represents a time of relatively stable, subaerial depositional environments with extensive paleosol formation and lacustrine deposition. In west-central Alberta, this period had poor drainage, with numerous lakes ponding on the landscape. Mudstones and siltstones typically deposited into these systems. As one moves toward the mountains, however, the characteristic lithological assemblage of mudstone or shale in the Battle Formation becomes thin and indistinct. In the westernmost part of the study area, the Battle Formation is usually only recognizable on subsurface logs by a change in log pattern that is correlative to the more easily recognized and thicker mudstone units to the east.

Where present in significant thickness (i.e., several metres or more), the Battle Formation is considered to be a regional aquitard because of its mudstone-dominated lithology. The Battle Formation sometimes marks the separation between regionally pervasive, subhydrostatic formation pressures plus westward-flowing groundwater in the underlying Horseshoe Canyon Formation and normal, or nearly hydrostatic, formation pressures plus northeast-flowing groundwater in the overlying Paskapoo Formation (Bachu and Michael, 2002). The strong subhydrostatic pressures in the Horseshoe Canyon Formation are considered to be evidence of elastic rebound due to erosional unloading of relatively low permeability and low connectivity strata (Parks and Toth, 1995), and are known to be regionally extensive across much of the west-central Alberta plains (Bachu and Michael, 2002; Beaton, 2003).

2.2 Scollard Formation

The Scollard Formation is Cretaceous to Paleogene (early Tertiary) in age. It lies disconformably atop the Battle Formation (Dawson et al., 1994a). Figure 5 shows the structure of the top of the Scollard Formation. A disconformity means that there was a time gap with erosion or nondeposition, but not deformation, between the end of Battle Formation deposition and the deposition of the Scollard Formation. Two informal units are in the Scollard. The lower Scollard unit is generally barren of coal and consists of thin, fining-upward cycles of fine-grained sandstone overlain by mudstone and siltstone. The upper unit is similar to the lower unit in terms of containing sandstone, siltstone and mudstone, but it also contains the Ardley Coal Zone (Beaton, 2003). The Cretaceous–Paleogene (K–T) boundary occurs near the base of the Ardley Coal Zone (Sweet and Braman, 1992).

Figure 6 shows the cumulative thickness of the Ardley Coal Zone. Richardson et al. (1988) and Dawson et al. (1994b) have discussed in detail the regional geology of the Ardley Coal Zone. Future CBM explorers will be attracted to this zone by its coal thickness, coal permeability, gas content and low water-disposal costs.

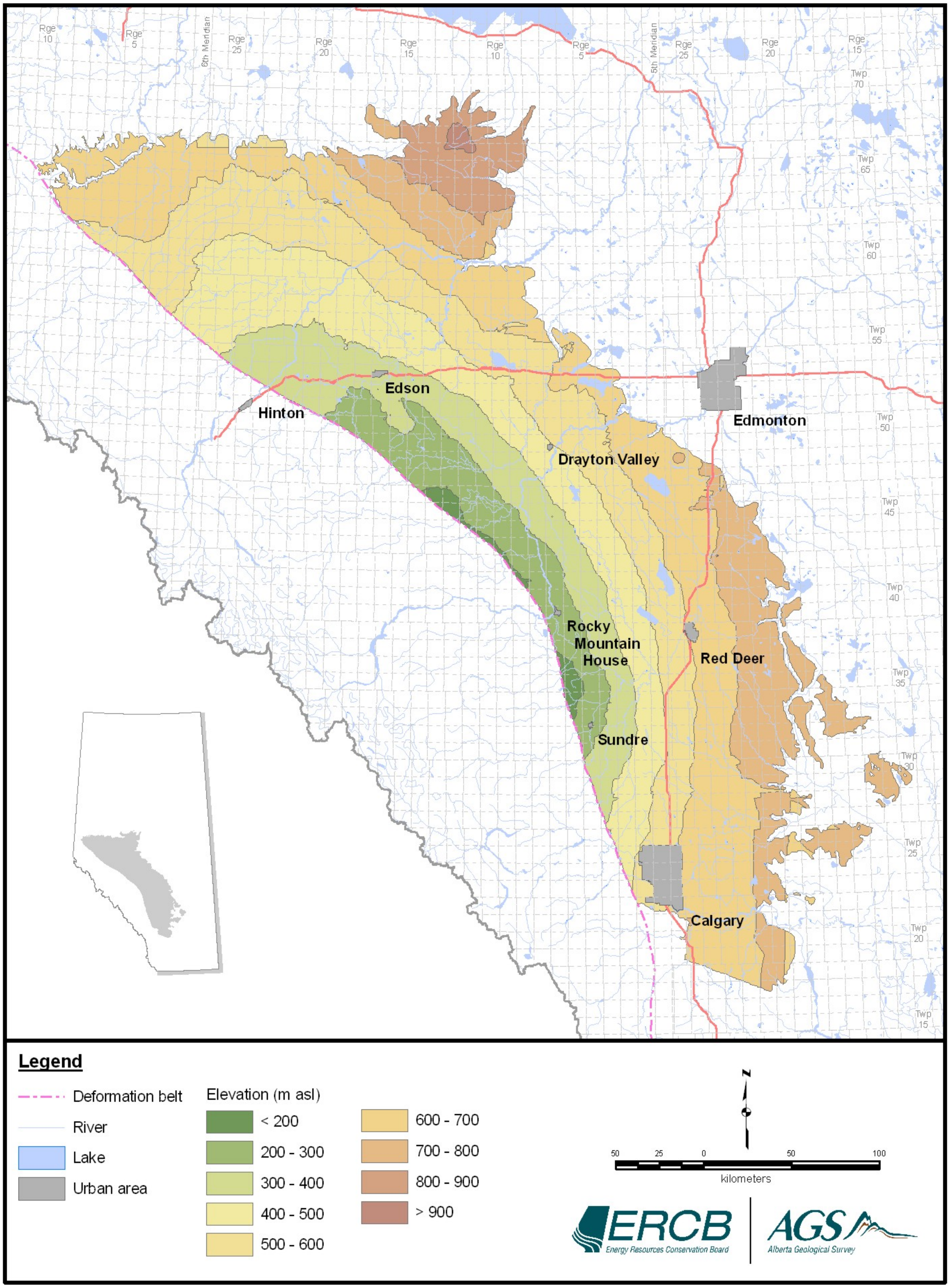

Figure 4. Structural elevation, top of Battle Formation.

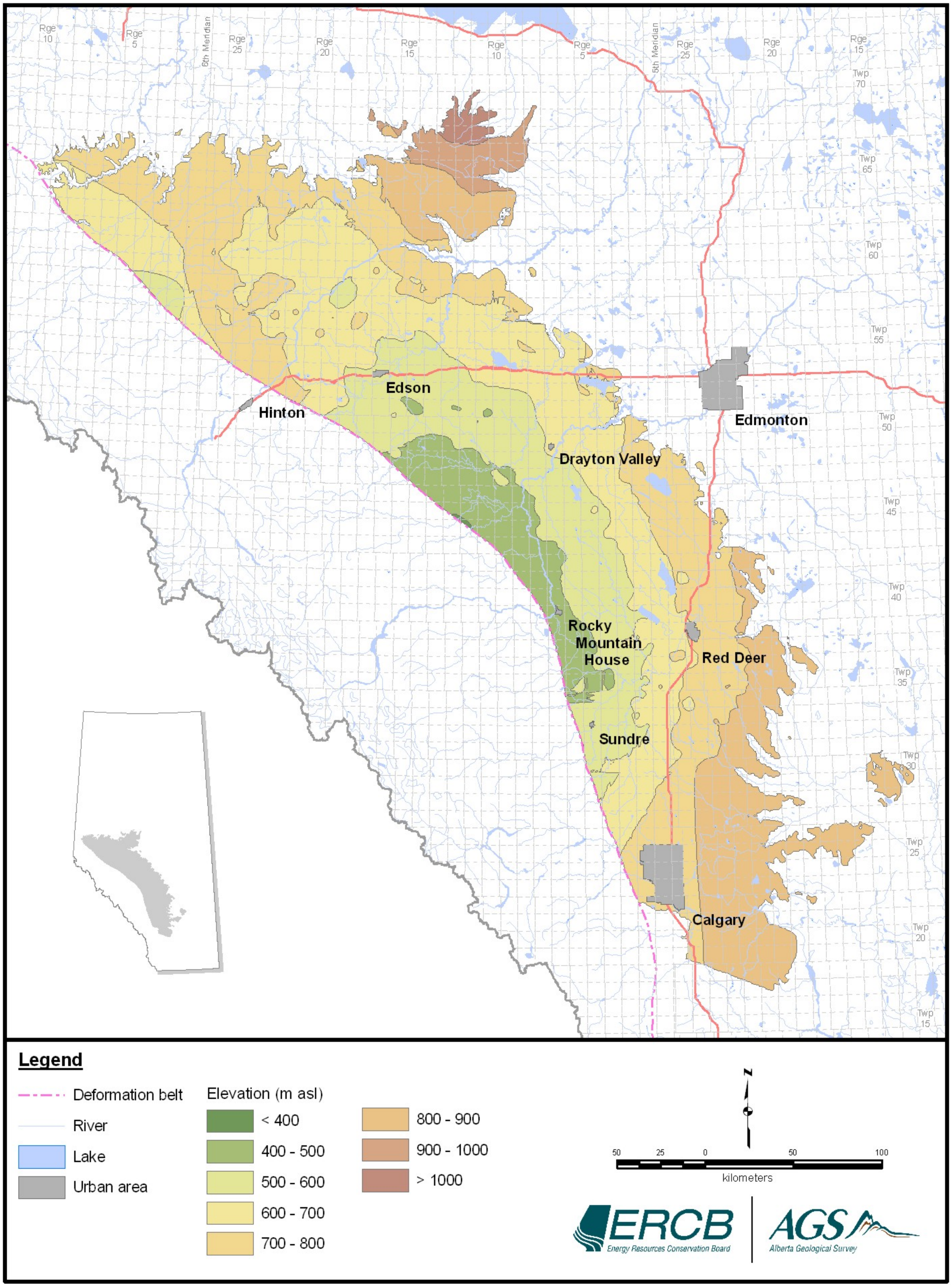

Figure 5. Structural elevation, top of Scollard Formation.

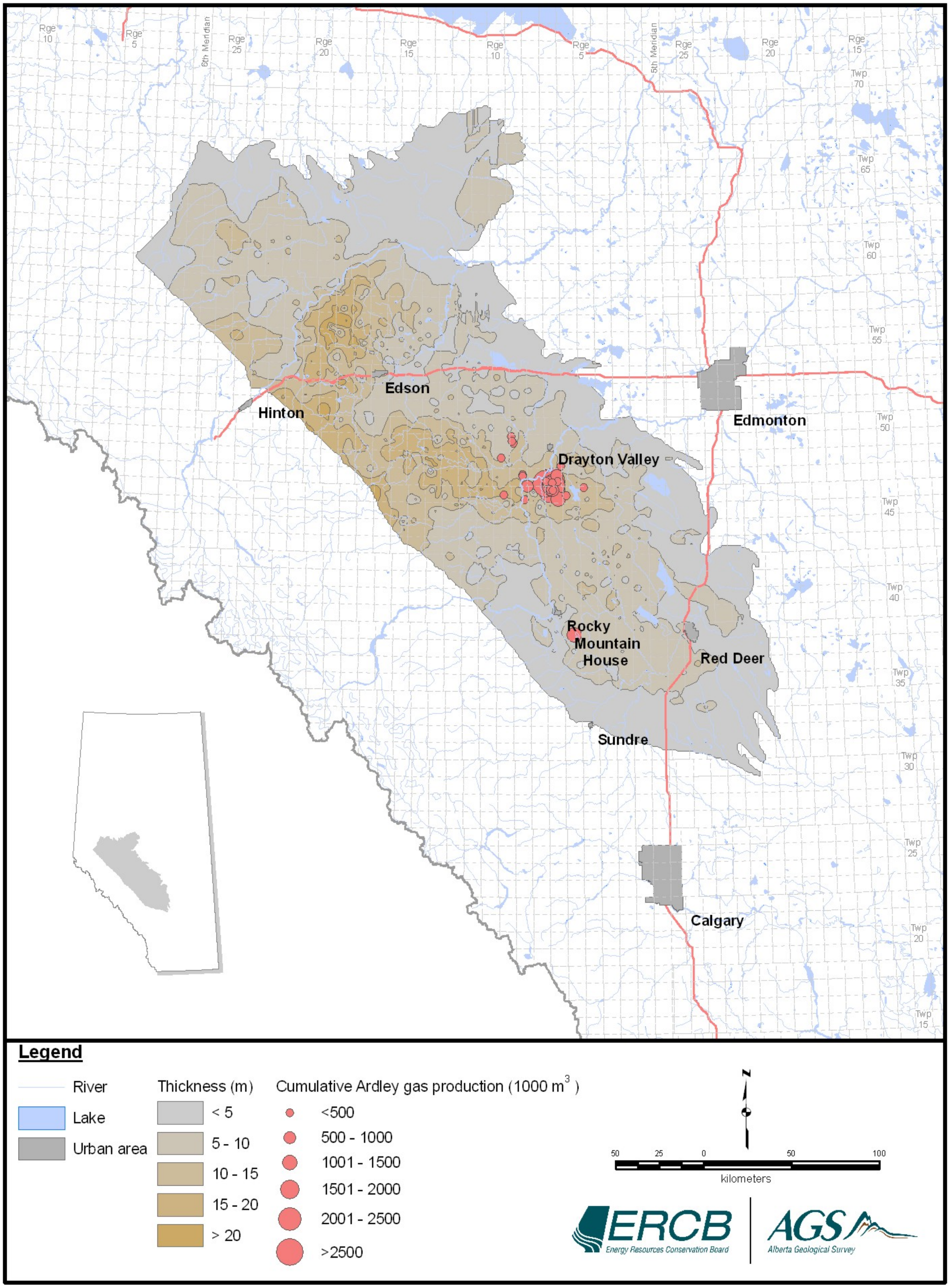

Figure 6. Cumulative thickness of Ardley coals in the Scollard Formation, and Scollard gas production (*from* Beaton, 2003).

The Scollard Formation is heterogeneous in that it contains beds of varied lithology, thickness and areal extent. The heterogeneity has a pattern in the vertical recurrence of the different lithologies as a function of their depositional environment. Although the pattern of heterogeneity is recognizable, it is not predictable in that lithologies observed in boreholes cannot be confidently extrapolated to areas between boreholes in a 'deterministic' (i.e., unquestionable or inherently obvious) way. This lack of interwell correlation means that the length scale of the bedding is likely much less than interwell spacing. One important implication of this observation is that the bulk hydraulic properties of the Scollard Formation at the regional scale can be generalized from knowledge of the lithology and be fairly represented by average numbers (i.e., details of the internal bed architecture are not relevant for predicting regional fluid behaviour).

Geologists know little about the hydrogeology of the Scollard Formation. The nature and heterogeneity of the strata suggest it will act regionally as an aquitard. Locally, however, the Scollard Formation can act as an aquifer or gas reservoir, capable of fluid production to a borehole, depending on the presence of porous and permeable sandstones or coals, and an overlying cap rock. Figure 6 also shows gas production from Scollard/Ardley gas wells. The few drill-stem test (DST) charts that are available for Scollard/Ardley beds indicate moderate permeability, determined qualitatively from reference industry DST response curves, but these data are usually biased toward potential reservoir-quality rock, as poor permeability rock is rarely tested. Bachu and Michael (2002) considered the Scollard to be hydraulically part of the Paskapoo Formation, but Harrison et al. (2005, 2006) differentiated the hydraulic regime of the Scollard into a normal regime with affinity to the overlying Paskapoo Formation (their Type 1) and an underpressured regime with affinity to underlying formations (their Type 2).

Formation pore pressures from drill-stem tests (DSTs) of non-commingled reservoirs in the Scollard Formation were from the Energy Resources Conservation Board (ERCB) and other sources. The formation pore pressures (for DSTs), extrapolated from a Horner (1951) plot, and highest measured reservoir pore pressures (for production tests) are plotted on a pressure-depth diagram in Figure 7.

The pressures are compared on the diagram to a nominal freshwater hydrostatic gradient (9.8 kPa/m). In static systems, freshwater pore pressures will increase with depth along this gradient (or one proportional to the average fluid density). In groundwater-flow systems driven by gravity, pore pressures in descending limbs of regional flow systems below recharge areas will have subhydrostatic pore pressures, whereas pore pressures in ascending limbs of regional flow systems below discharge areas will have superhydrostatic pore pressures. Pore pressures associated with lateral groundwater flow in gravity-driven flow systems will be close to hydrostatic in magnitude. On the other hand, subhydrostatic pore pressures related to rock-framework deformation rather than flow are recognizable by

- the presence of a vertical zone of minimum absolute pore pressures,
- a lack of any corresponding superhydrostatic pore pressures in the system, indicative of return flow to the surface, and
- magnitudes of hydraulic head lower than the elevation of the lowest outcrop in the system (Parks and Toth, 1995).

Inspection of Figure 7 shows that three sample populations are present, as documented in Harrison et al. (2005, 2006). First, there is a group of pore pressures with a close affinity to the nominal hydrostatic gradient value (yellow). Second, there is a group of subhydrostatic pore pressures (green, blue, purple) with no affinity to the nominal hydrostatic gradient, but whose measurement predated any known fluid production in the Ardley within a 10 km radius. Third, there is a group of particularly low subhydrostatic pressure values (blue), but these values were from pressure tests conducted after the gas wells were completed and, therefore, are probably not representative of virgin conditions. A single low-pressure

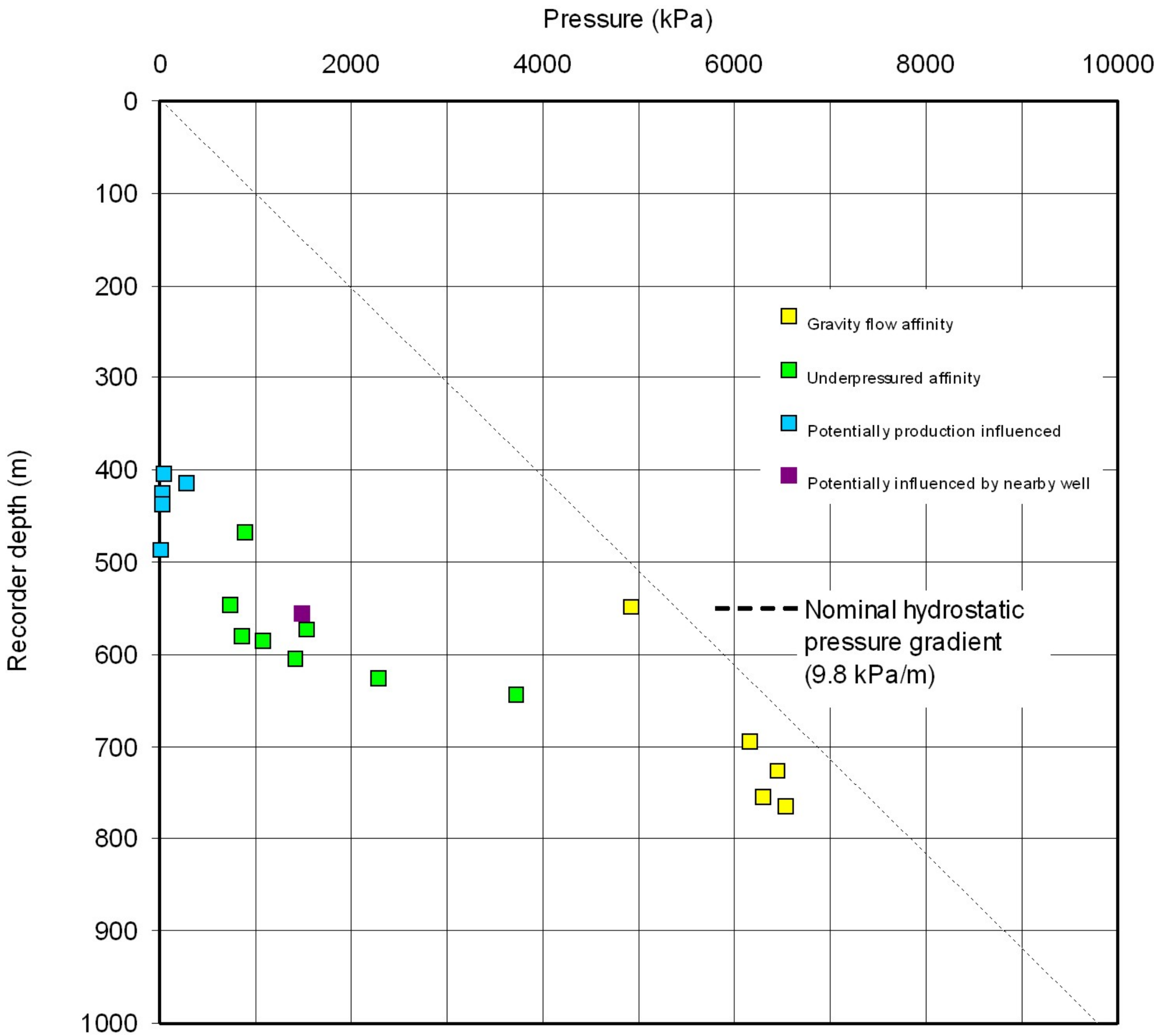

Figure 7. Pressure-depth plot, Scollard Formation; labels indicate location on cross-section (Figure 8).

value (purple) came from a well located within 10 km of a gas well with production prior to the pressure test and, therefore, may also show the influence of gas production.

The available Scollard Formation pressures thus appear to have affinity to both normal pressures associated with regional gravity flow in the Paskapoo Formation (discussed below) and the subhydrostatic pressures associated with the deeper Horseshoe Canyon–Edmonton–Wapiti formations (documented in the references cited herein). The degree to which the Scollard falls into either class is unknown at this point because the data are so sparse.

We inspected geophysical logs from the wells where pore pressures have a preproduction, underpressured affinity for the thickness of Scollard above the Ardley Coal Zone. In all cases, we saw Scollard Formation mudstone facies lying between the highest Ardley coal and the base of the first Paskapoo sandstone. Where Scollard Formation pressures have a gravity-flow affinity, geophysical-log signatures indicate that the Ardley Coal Zone either 1) is directly overlain by an erosionally based Paskapoo channel sandstone rather than the regional mudstone facies of the upper Scollard Formation, or 2) shows evidence of a fining-upward gamma-ray signature that suggests such a sandstone body is nearby (Figure 8). These observations suggest that, in regions where Ardley-Scollard pressures have a gravity-flow affinity, the hydraulically insulating upper Scollard mudstone facies above the Ardley is thin or missing.

2.3 Paskapoo Formation

The Paleogene-age Paskapoo Formation is an eastward-tapering wedge of interbedded nonmarine sandstone, siltstone and mudstone, with minor amounts of coal and bentonite. Its eroded top marks the top of bedrock across its subcrop and outcrop extent (Figure 9).

The base of the Paskapoo Formation is more difficult to define than its top. The base is marked at the bottom of the first thick (>5 m in this study) sandstone lying above the uppermost coal seam of the Ardley Coal Zone (Demchuk and Hills, 1991). The relative vertical position of this lithostratigraphic boundary depends wholly on the distribution of fluvial-channel sandstones in the interval above the Ardley Coal Zone. At some locations, a channel sandstone (and therefore the Paskapoo Formation) will rest directly on the Ardley Coal Zone, but time–equivalent, fine-grained strata elsewhere will be included in the upper Scollard Formation (Figure 8). Therefore, we cannot regard the base of the Paskapoo Formation as a simple, single unconformable surface. A map of the thickness of Scollard above the highest Ardley coal (Figure 10) suggests the erosional nature of the base of the Paskapoo sandstones. This figure shows that there are several areas where the remnant thickness of Scollard above Ardley coal is 10 m or less.

2.3.1 Paskapoo Formation Subdivisions

Demchuk and Hills (1991) divided the Paskapoo Formation into three members based on lithology observed in outcrop and the persistence of these lithological groupings into the subsurface. The members include

- the lowermost Haynes Member, consisting largely of thick, locally conglomeratic, medium- to coarse-grained sandstone that forms prominent cliffs at outcrop;
- the middle Lacombe Member, consisting of interbedded siltstone, mudstone, shale and coal, with subordinate sandstone and conglomerate; and
- in the highest elevations in northwest-central Alberta, the uppermost Dalehurst Member, which is characterized and marked by the occurrence of thick coals.

Demchuk and Hills (1991) noted that the uppermost Lacombe Member may be stratigraphically equivalent to the lowermost Dalehurst Member, but one cannot make the distinction based on lithology without the presence of the Dalehurst Member coalbeds. In a similar vein, Jerzykiewicz (1997) informally divided the Paskapoo into lower and upper members based on relative sandstone content. It is important to note that neither author could define a regionally identifiable or correlatable surface by which their subdivisions could be precisely mapped in the subsurface. Hamblin (2007a–c) published detailed core and outcrop descriptions, and found it useful to adopt the member stratigraphy of Demchuk and Hills (1991) to orient the reader. For similar reasons, we find it useful to adopt the Demchuk and Hills (1991) stratigraphy for the Paskapoo Formation.

2.4 Internal Architecture of the Ardley-Scollard-Paskapoo System

To help understand the internal architecture of the Ardley-Scollard-Paskapoo system, we prepared slice maps showing relative degree of sandiness. Geologists commonly use slice maps to investigate the distribution of rock properties when the stratigraphic framework is poorly defined. In this investigation, we considered slice mapping showing the proportion of sandstone to be of prime importance because hydraulic properties are generally correlated with lithology. Note that the Paskapoo Formation is often observed to be fractured in outcrop. Inspection of water-well license reports during this project suggested that there is evidence of fracturing as deep as 50 m below the top of

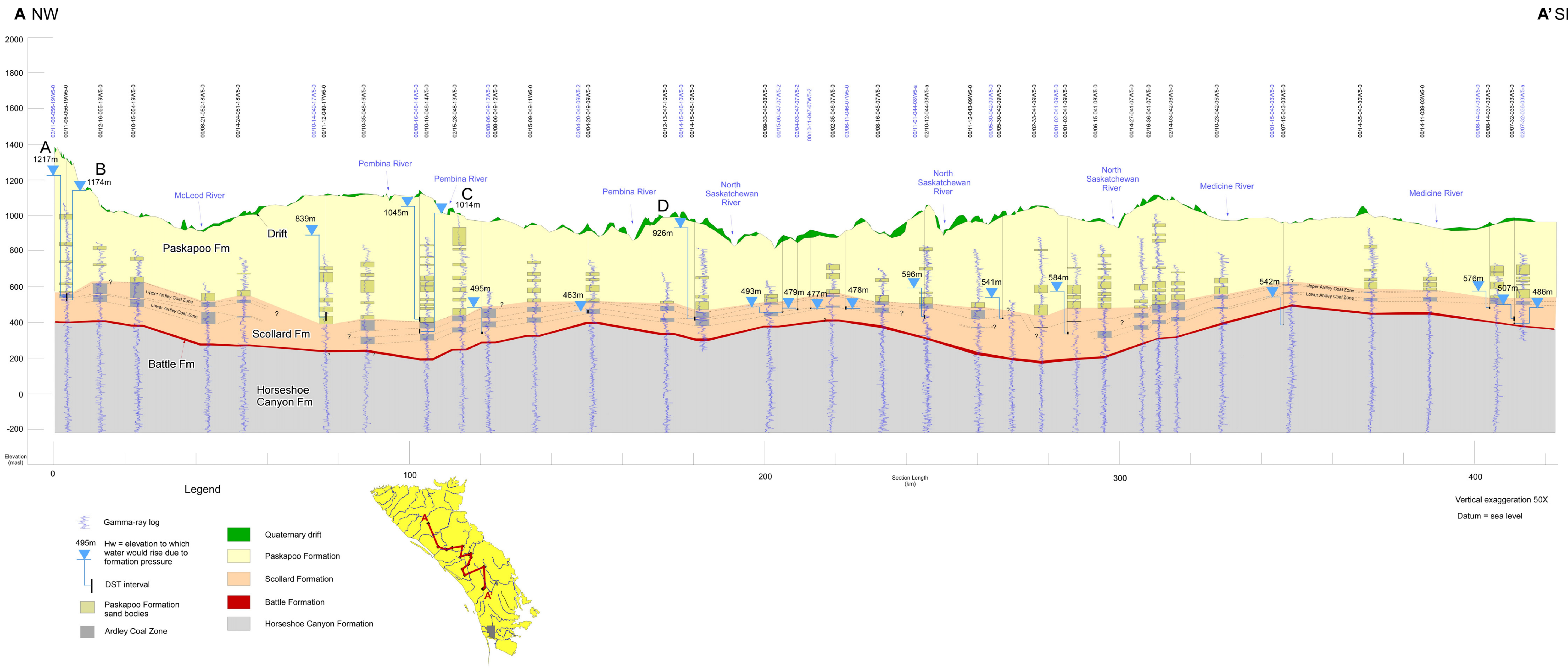

Figure 8. Northwest–southeast cross-section showing generalized geology, including drill-stem test locations, formation head and labels indicating location on pressure-depth plot (Figure 7).

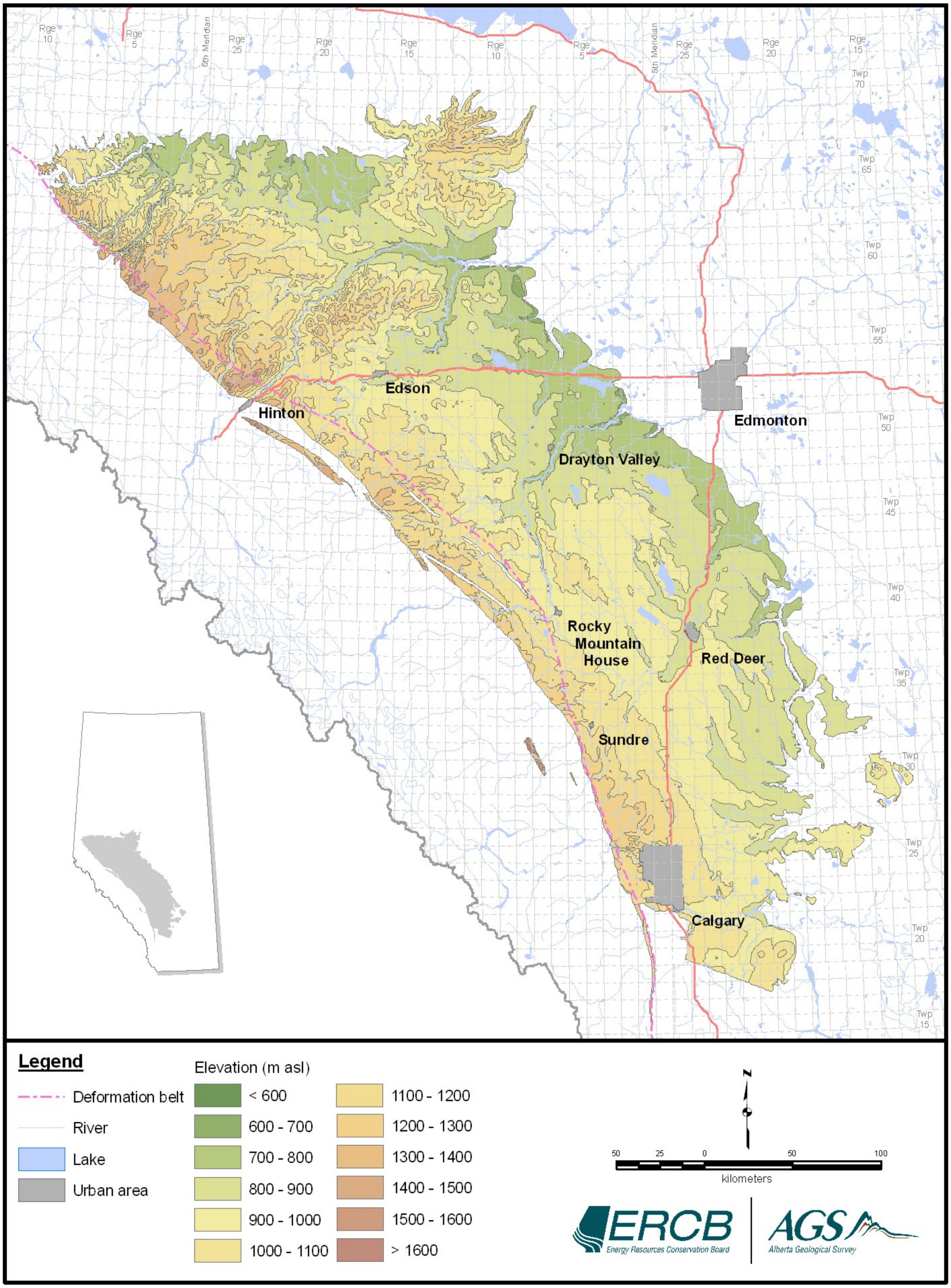

Figure 9. Structural elevation, top of Paskapoo Formation.

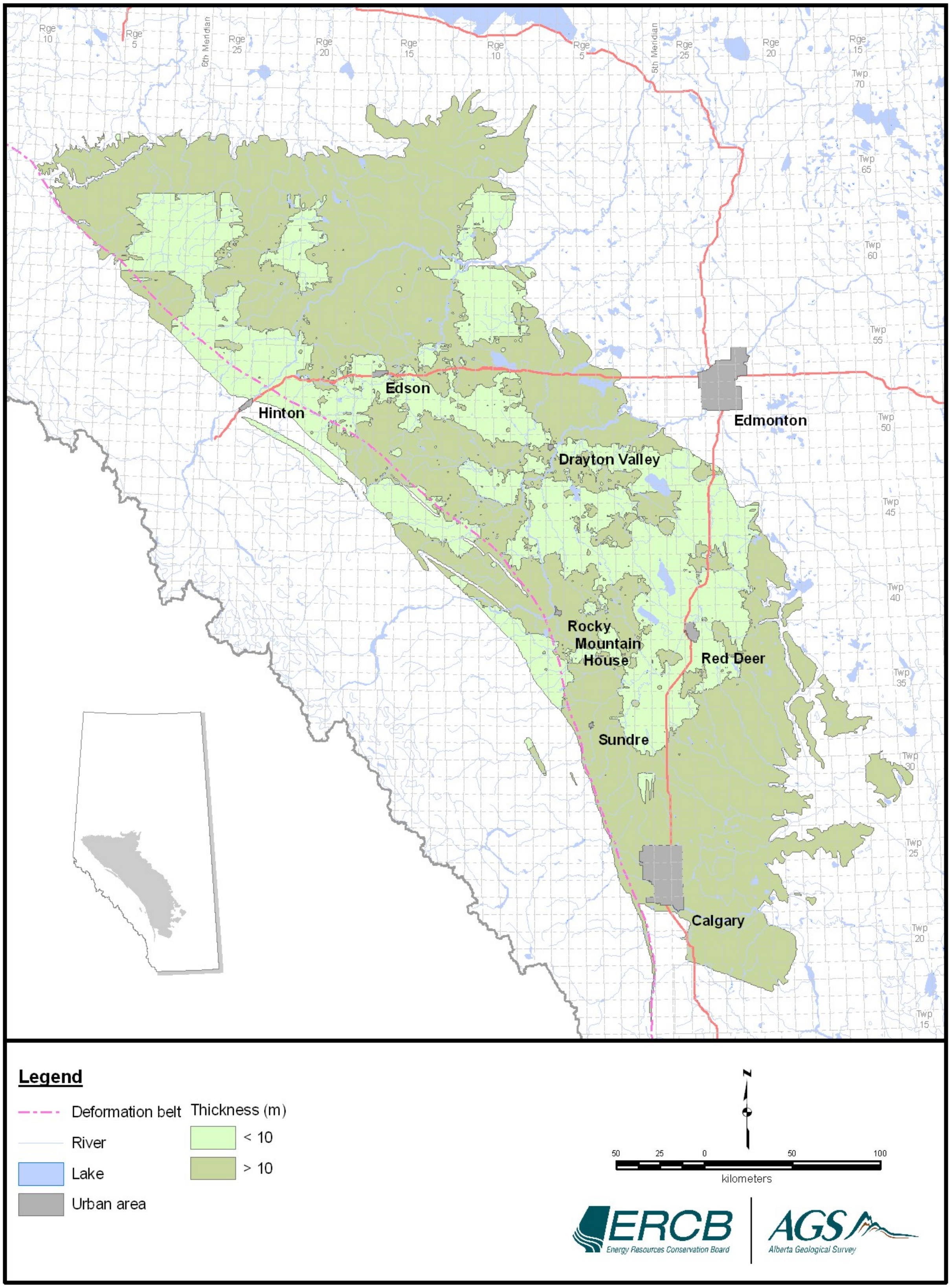

Figure 10. Isopach of the Scollard Formation above the highest Ardley coal, emphasizing areas greater than and less than 10 m thickness.

bedrock, but further study is needed to ascertain the nature and distribution of interconnected fractures at depth.

The maps were prepared in 50 m slices parallel to the top of the Battle Formation. We recognized that this choice builds in a bias by encouraging the assumption that the Paskapoo Formation beds were deposited parallel to the top of the Battle Formation, which is only strictly true for the lowest and oldest beds of the Scollard Formation. We therefore investigated alternative slicing arrangements, including constant elevation, constant depth and proportional thickness, but the slices parallel to the Battle Formation were most informative in this study, despite the known bias. We chose the 50 m slice thickness to be greater than the thickness of most single or multistorey sandstone bodies recognizable on well logs. In this way, the impacts of single sandstone bodies will be averaged out to reveal regionally persistent trends. We also prepared slice maps of 100 m thickness, but the 50 m slices were more revealing in terms of coherent and therefore mappable trends in sandiness.

We calculated the degree of sandiness in each slice (abundance) from the natural gamma response measured in downhole geophysical logs from oil and gas boreholes. This part of the study used more than 40 000 gamma-ray (GR) logs covering part or all of the Paskapoo Formation. For each log, we summed the thickness of every sand body with a gamma-ray value equal to or less than 75 API (American Petroleum Institute standard unit of measure for gamma response) and expressed that total as a percentage of the 50 m thick slice. We did not do these calculations for those sections of a log that did not span the entire 50 m slice interval. Beds with coal and limestone may also have GR values of <75 API, but they are not distinguished from sandstone in this study. These kinds of beds are known to be minor components of the Paskapoo Formation, and we assume that they do not contribute substantially to the overall sums.

A distribution plot of air-permeability values (Kmax) measured in core samples of Paskapoo sandstone with a gamma-ray response of 75 API or less (Figure 11) shows that core-scale hydraulic conductivities with this magnitude of gamma-ray response range from 10^{-9} to 10^{-5} m/s (0.1–1000 millidarcies [mD]). These values fall in the typical range of permeability of sandstones to groundwater flow (Freeze and Cherry, 1979, p. 29). Transmissivity values calculated from aquifer test results in Paskapoo aquifers on file with Alberta Environment (AENV) show values at the higher end of this range, typically in the order of 2×10^{-4} m^2/s. The observation that higher values are in the aquifer tests reflects a known bias of aquifer tests toward the more permeable parts of formations.

Trial maps using 60, 75 and 90 API cutoffs also showed that the resulting maps best matched sandstone accumulations as interpreted by AGS geologists on cross-sections when a 75 API cutoff was used. We investigated the need for rescaling the available gamma-ray logs to reflect baseline shifts between logging companies (e.g., Shier, 2004) and deemed rescaling unimportant for this study, as only logs that postdated 1985 were used. Quality-control steps included corrections for factors such as gamma-ray readings through casing, missing intervals where no gamma-ray measurements were collected, mislabelled log curves in source files, and the presence of placeholder numerical values indicating absence of data in third-party data files.

Figures 12–24 are slice maps showing relative sandstone abundance in every 50 m slice from the Battle Formation top to 600 m above the Battle Formation top. Note that the slice maps are bounded on their eastern side by their intersection with the subcrop top of either the Scollard Formation or the Paskapoo Formation, and on their western side by the western limit of the Rocky Mountain deformation front.

The following is a summary of the salient features of the slice mapping, starting from the Battle Formation and moving upwards:

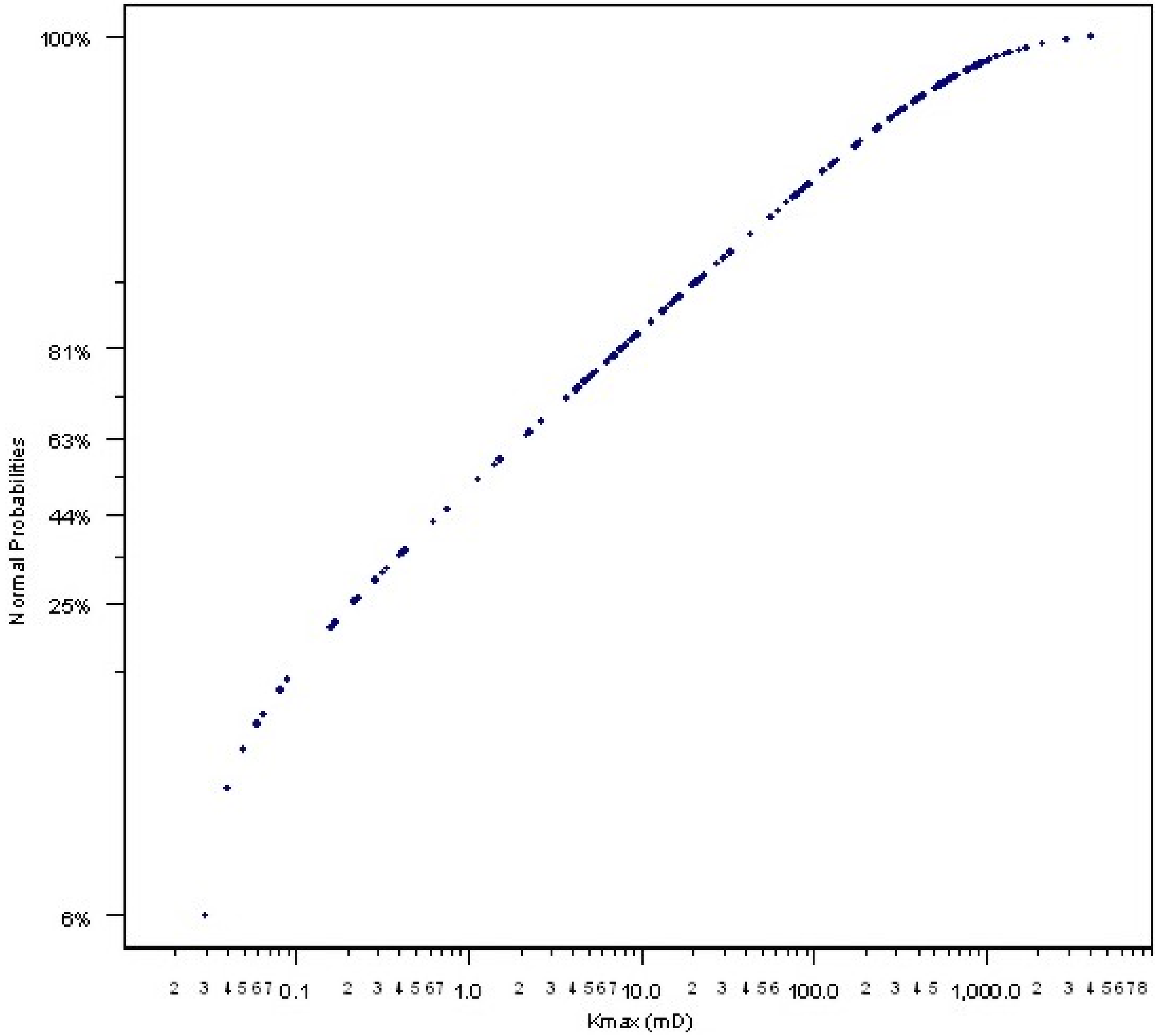

Figure 11. Probability plot of permeabilities (Kmax) from cores of Paskapoo sandstone with natural gamma-ray values of <75 API.

Battle Formation plus 0–50 m (Figure 12): As the Scollard Formation is generally about 40–60 m thick throughout most of the study area, this slice consists mostly of Scollard Formation. Most of this slice has a vertically averaged sandstone content of less than 40%. In the westernmost part of the study area, the Scollard Formation thickens to well over 100 m and so will be represented, at least in part, by subsequent slices.

Battle Formation plus 50–100 m to Battle Formation plus 250–300 m (Figures 13–17): These slices have elongate trends of areally continuous sandstone accumulations greater than 40% running subparallel to the mountain front, with substantial areas of sandstone accumulations in excess of 60%. The peak sandstone abundances overlap in subsequent slices, suggesting that there is one main sandstone body. More detailed geological analysis will be needed to characterize the geometry and origin of this significant sandstone trend.

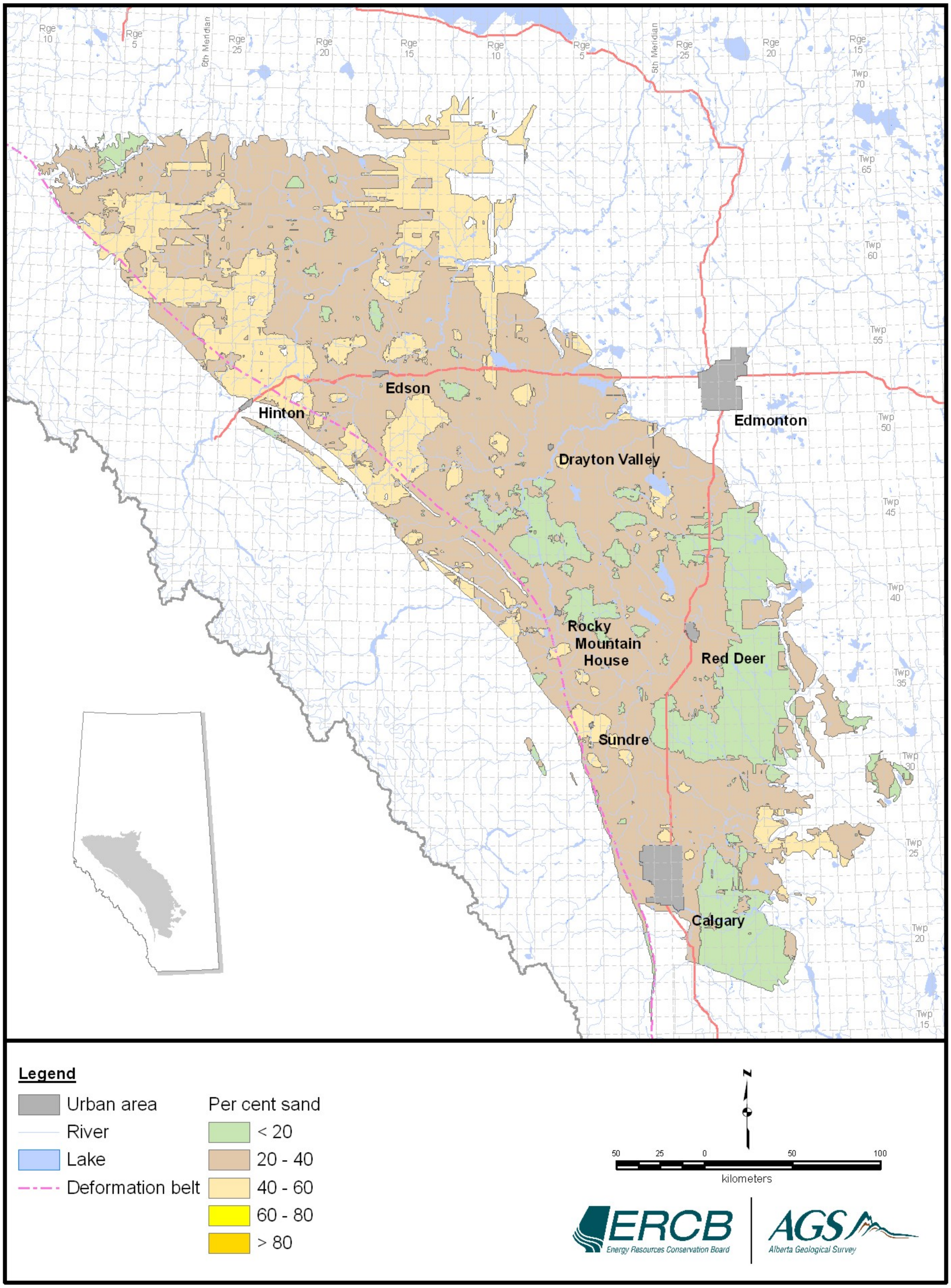

Figure 12. Vertically averaged gamma-ray–derived sandstone abundance, slice from 0 to 50 m above the Battle Formation.

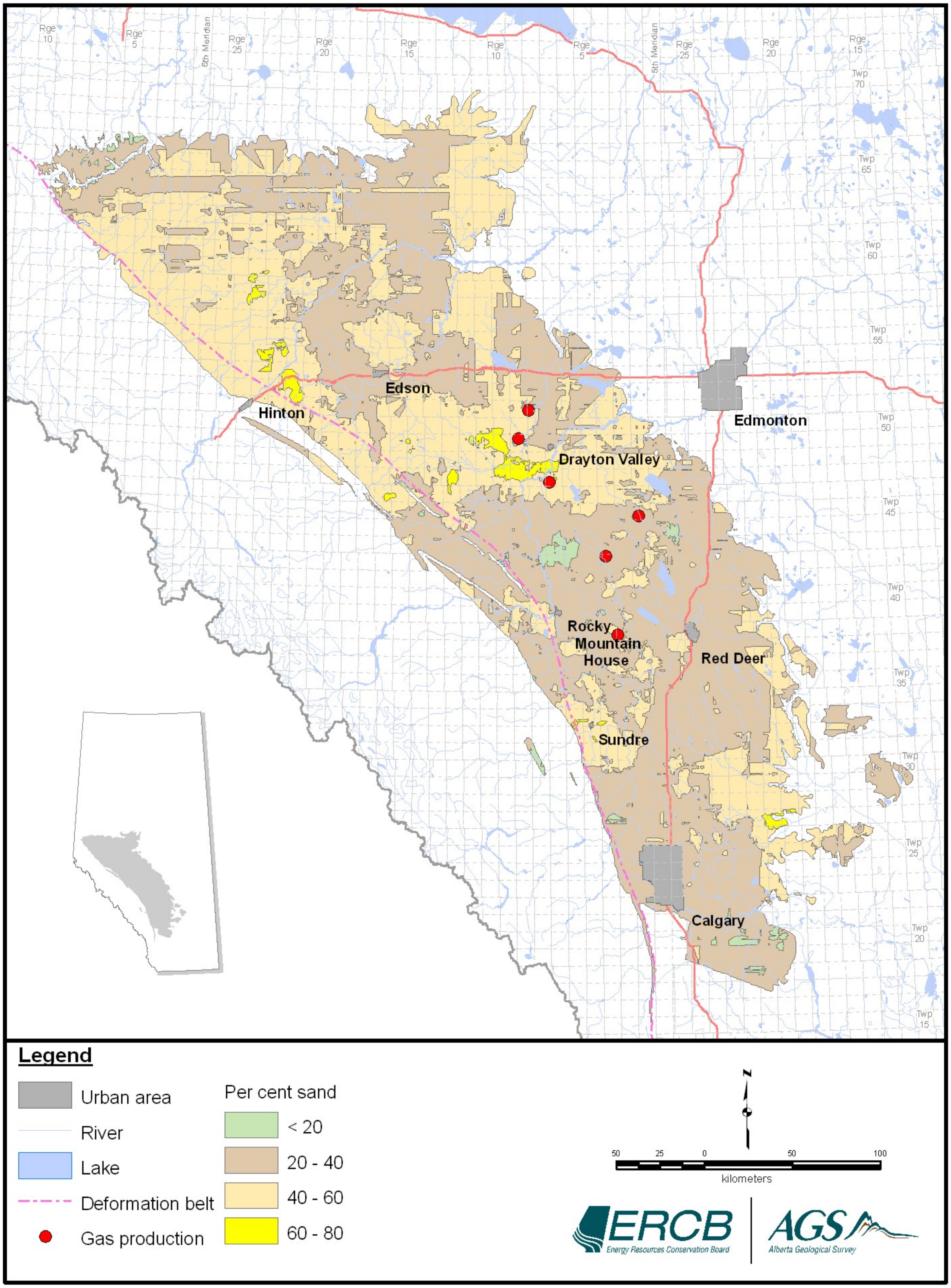

Figure 13. Vertically averaged gamma-ray–derived sandstone abundance, slice from 50 to 100 m above the Battle Formation.

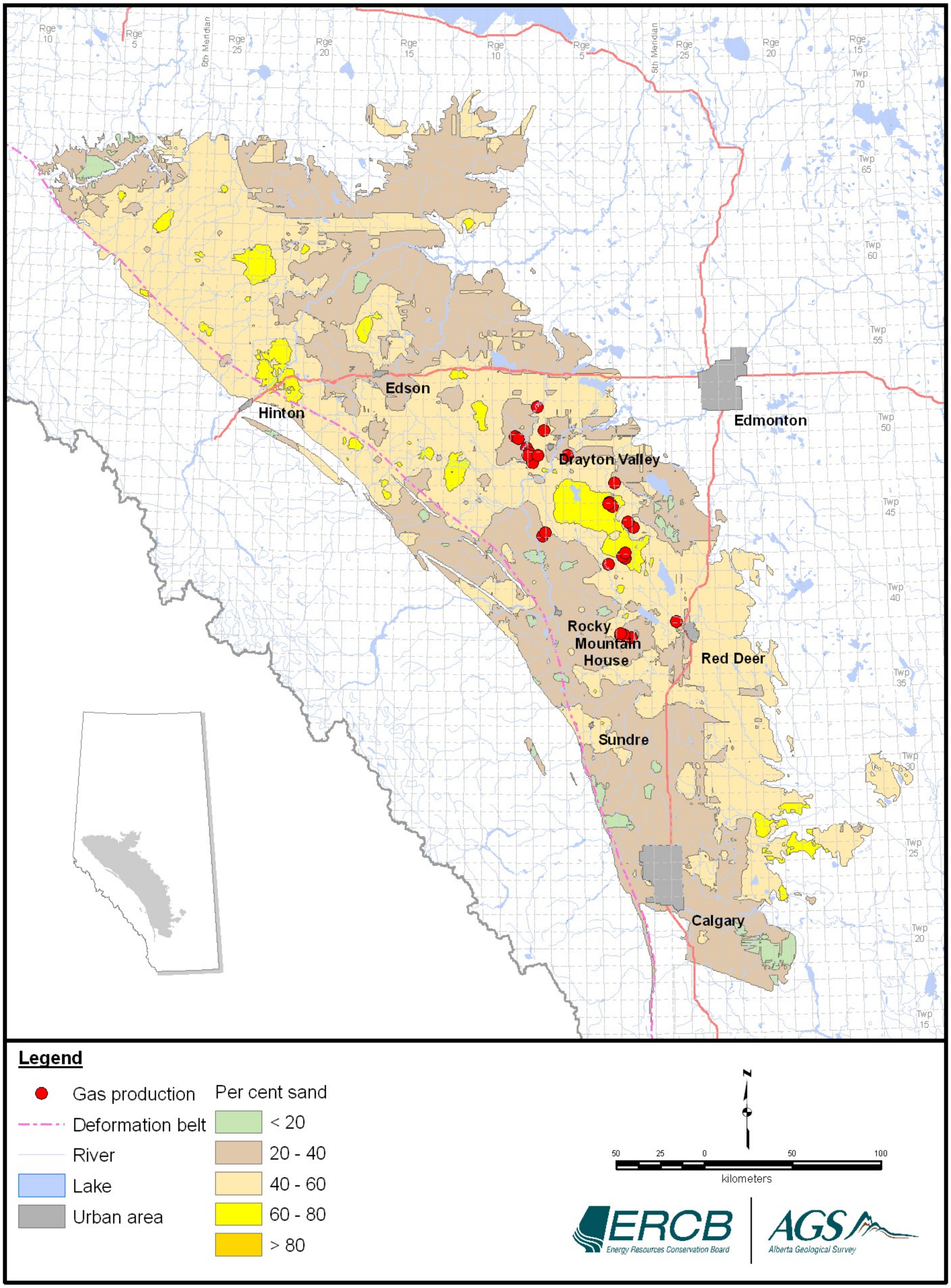

Figure 14. Vertically averaged gamma-ray–derived sandstone abundance, slice from 100 to 150 m above the Battle Formation.

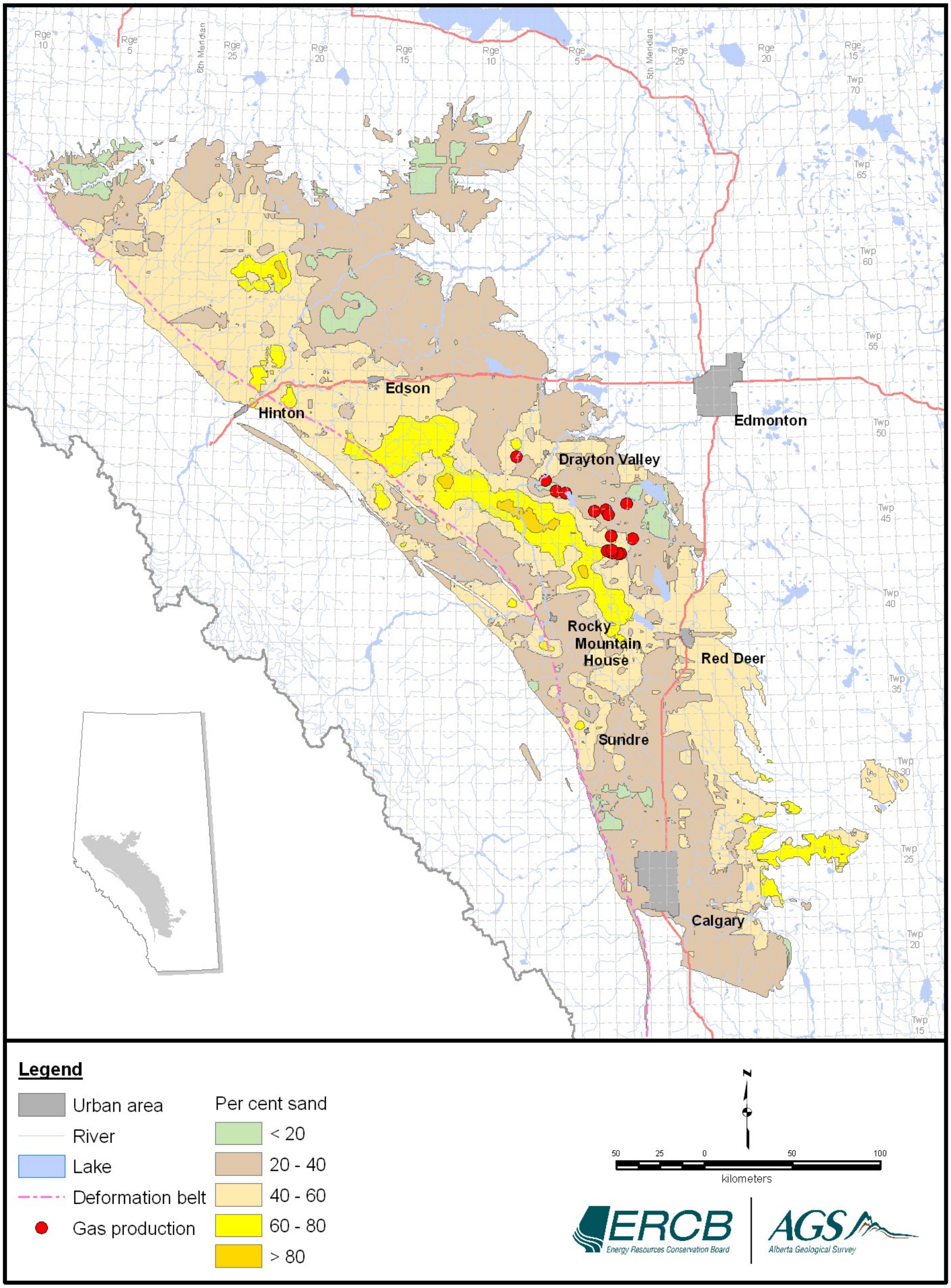

Figure 15. Vertically averaged gamma-ray–derived sandstone abundance, slice from 150 to 200 m above the Battle Formation.

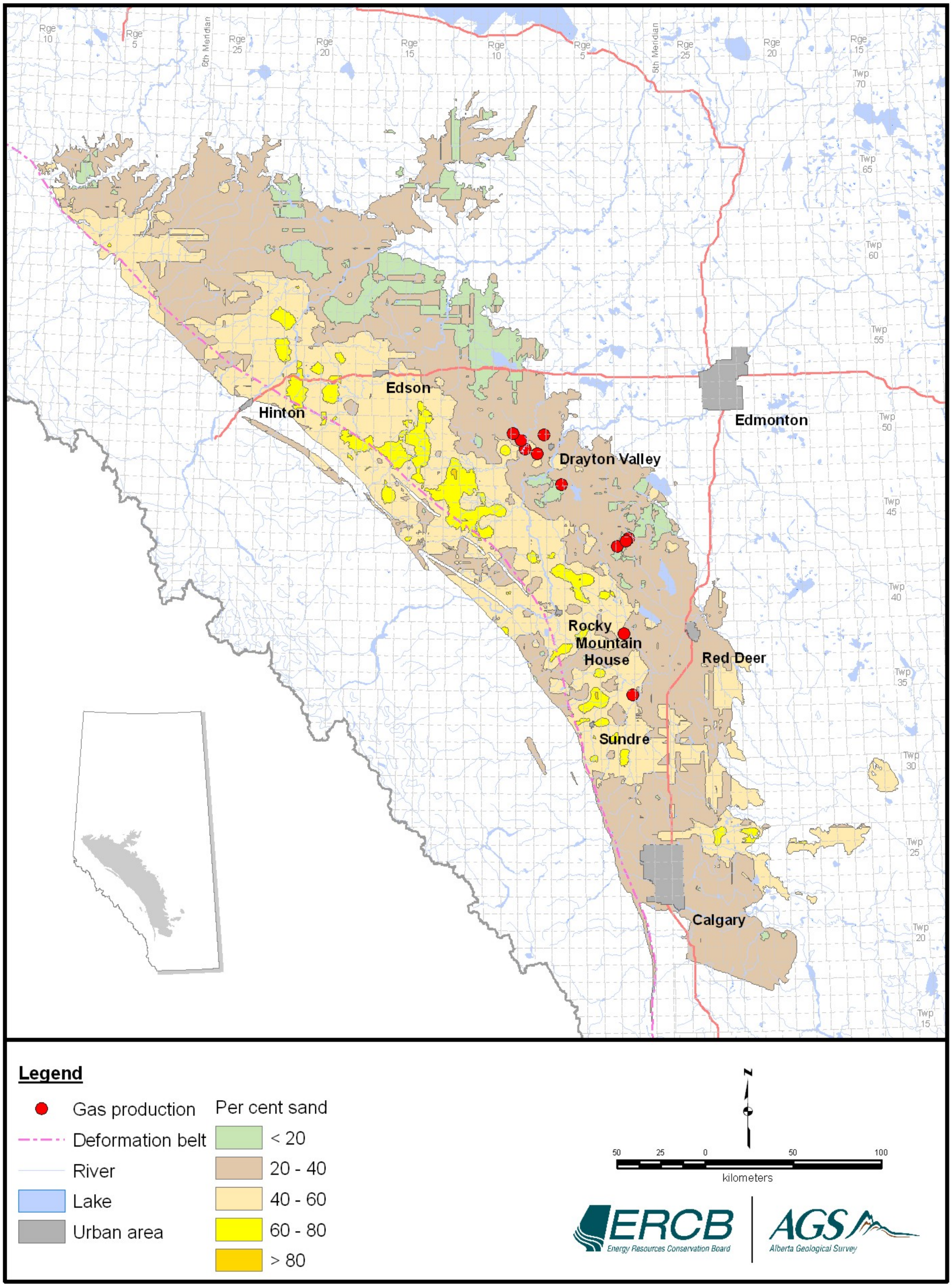

Figure 16. Vertically averaged gamma-ray–derived sandstone abundance, slice from 200 to 250 m above the Battle Formation.

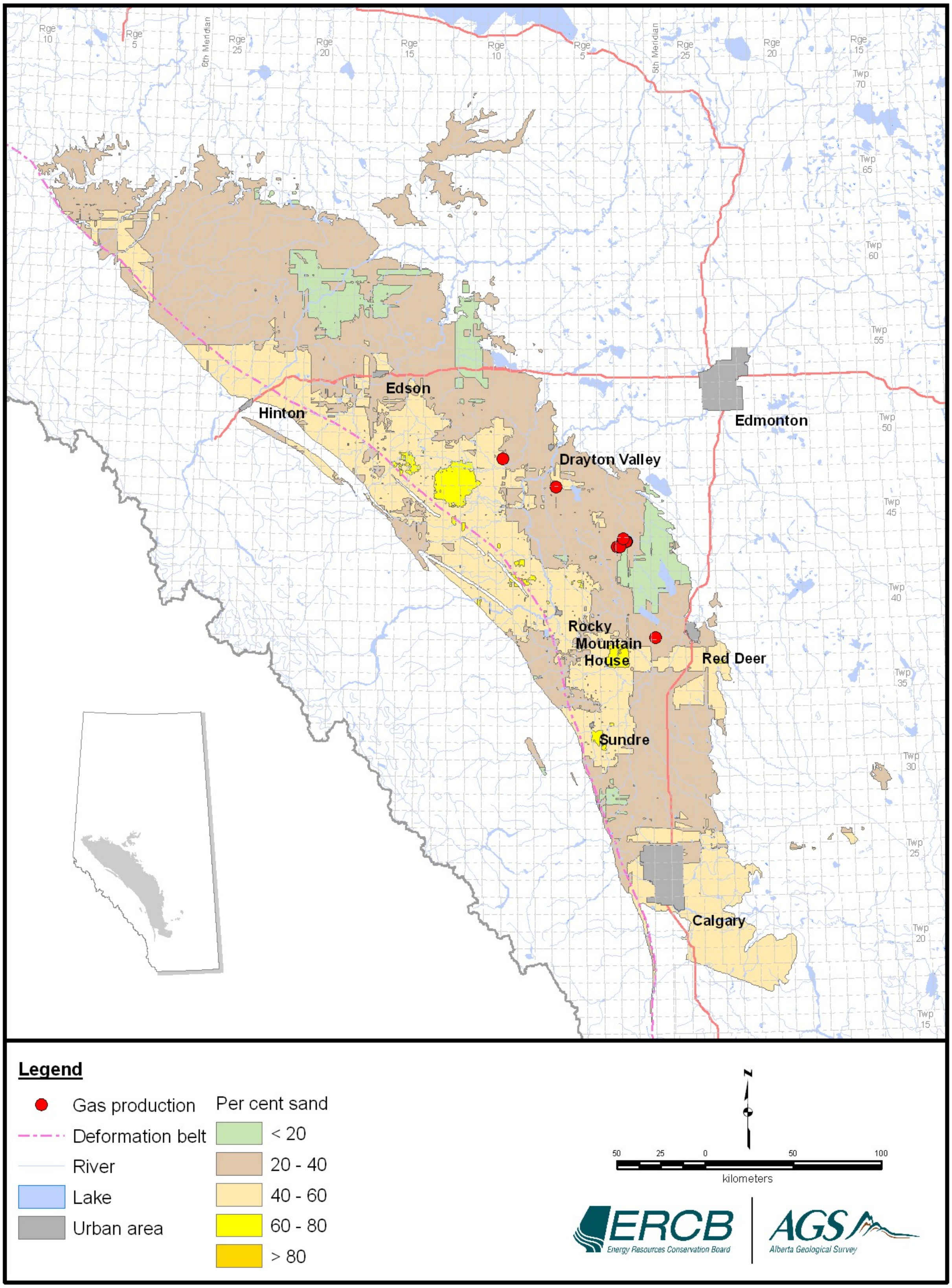

Figure 17. Vertically averaged gamma-ray–derived sandstone abundance, slice from 250 to 300 m above the Battle Formation.

Battle Formation plus 300–350 m to Battle Formation plus 550–600 m (Figures 19–24): The areas with vertically averaged sandstone content greater than 40% in these slices are relatively small, lie farther west in each successively shallower slice, and tend to stack atop one another in the west-central part of the Paskapoo Formation. This means that most of the Paskapoo strata in these slices have vertically averaged sandstone abundances of less than 40%–60%. This pattern suggests that most of the volume in these slice maps should be considered as part of the Lacombe Member of Demchuk and Hills (1991).

Commercial gas shows in the Paskapoo Formation, some with sustained production, are present in the slices shown in Figures 13–17. The amount of gas produced is small compared to deeper conventional gas production. Most of these gas shows occur on the updip side of the significant sand accumulations, particularly where sand abundances are between 40% and 60% (Figure 18). Some gas shows do occur in both sandier and muddier zones, but the bulk of gas occurs in zones of this range. Few commercial gas shows occur above the 300–350 m slice above the Battle Formation. We discuss further the significance of this lack of commercial gas shows in the next section. Note that there are recorded observations of gas in water wells completed in the shallowest parts of the Paskapoo Formation, but we presumed these to be unrelated to these deeper gas shows, being locally sourced by bacteria in wells or near-surface aquifers (Lemay, 2003).

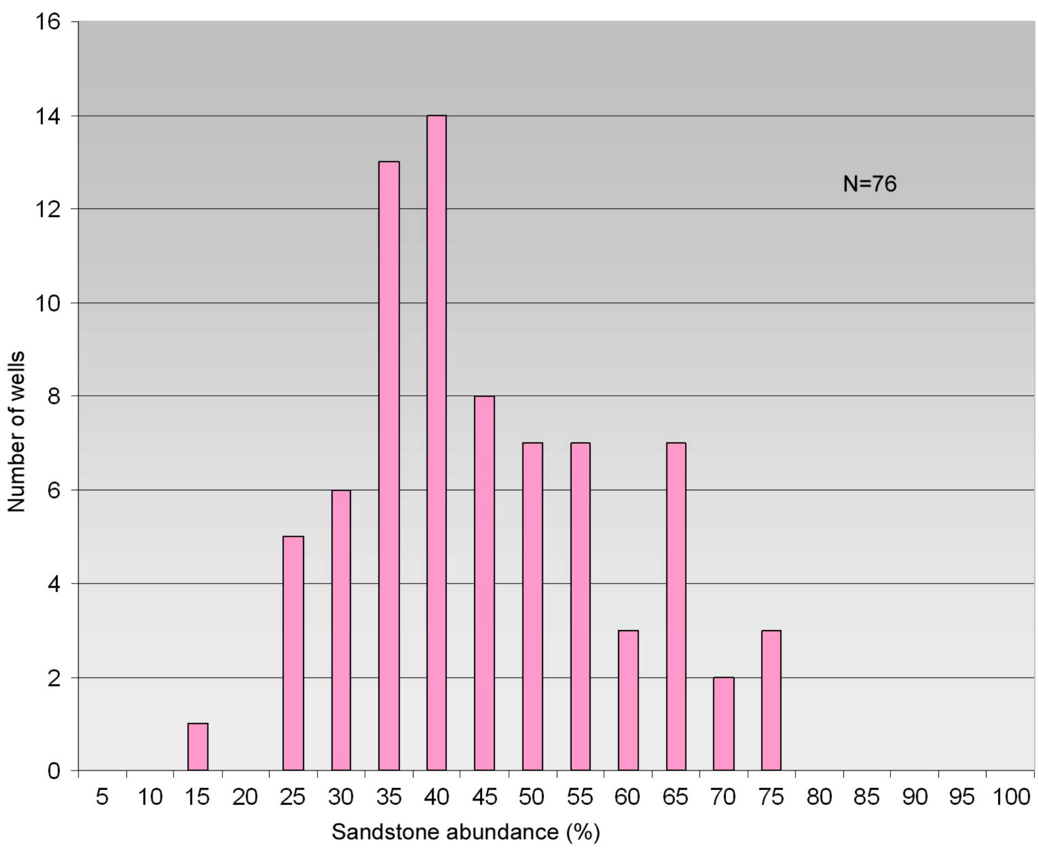

Figure 18. Histogram showing sandstone abundance of the 50 m slice in which the Paskapoo gas well was completed.

Battle Formation plus 600–650 m to Battle Formation plus 900–950 m (not shown): There are very few wells in these slices and they tend to fall close to the disturbed belt of the Rocky Mountain Foothills, parallel to the western edge of the undeformed Paskapoo Formation. The vertically averaged sandstone abundances are particularly high in some of these wells. This may be the subsurface expression of the Dalehurst Member of Demchuk and Hills (1991).

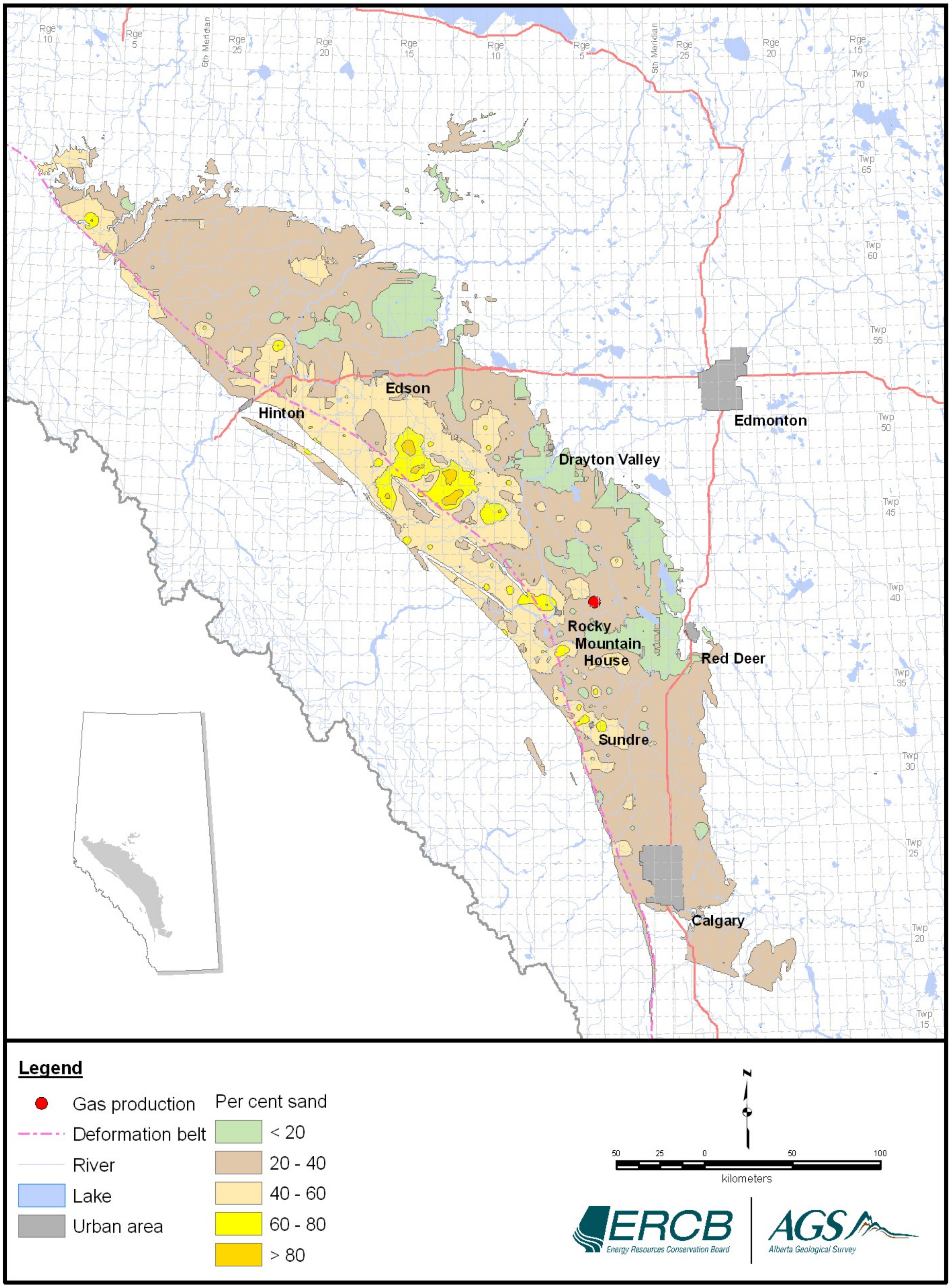

Figure 19. Vertically averaged gamma-ray–derived sandstone abundance, slice from 300 to 350 m above the Battle Formation.

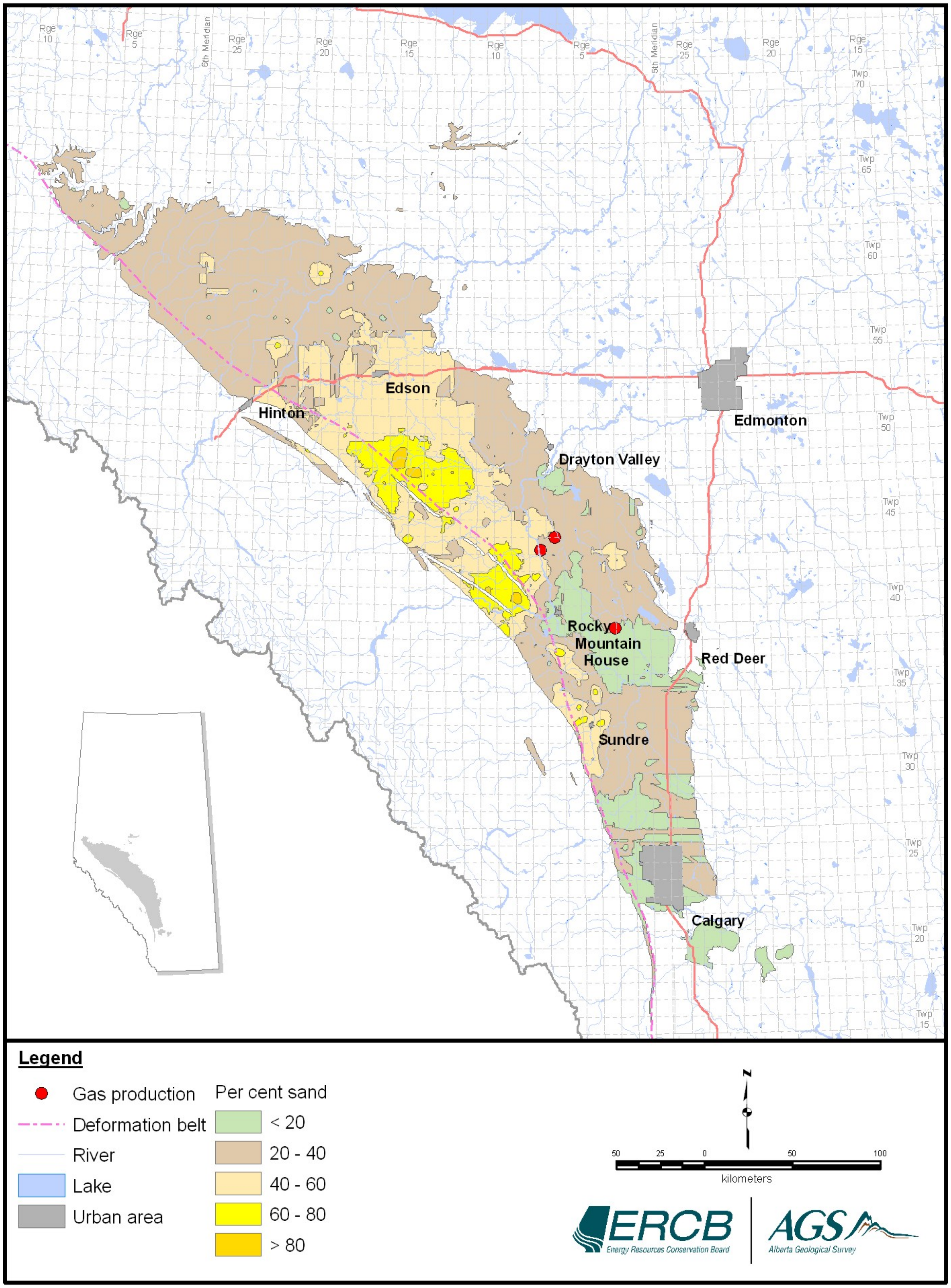

Figure 20. Vertically averaged gamma-ray–derived sandstone abundance, slice from 350 to 400 m above the Battle Formation.

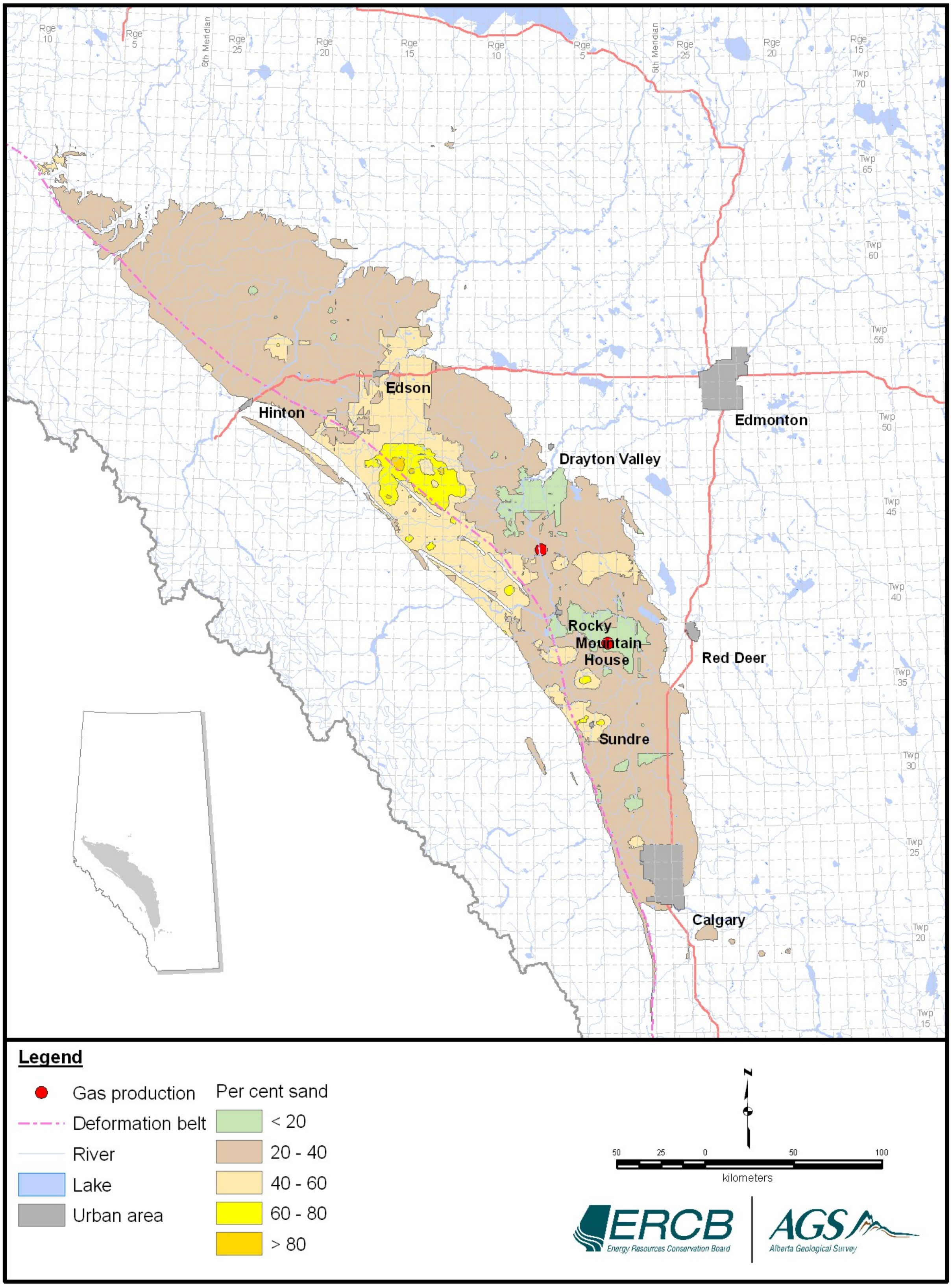

Figure 21. Vertically averaged gamma-ray–derived sandstone abundance, slice from 400 to 450 m above the Battle Formation.

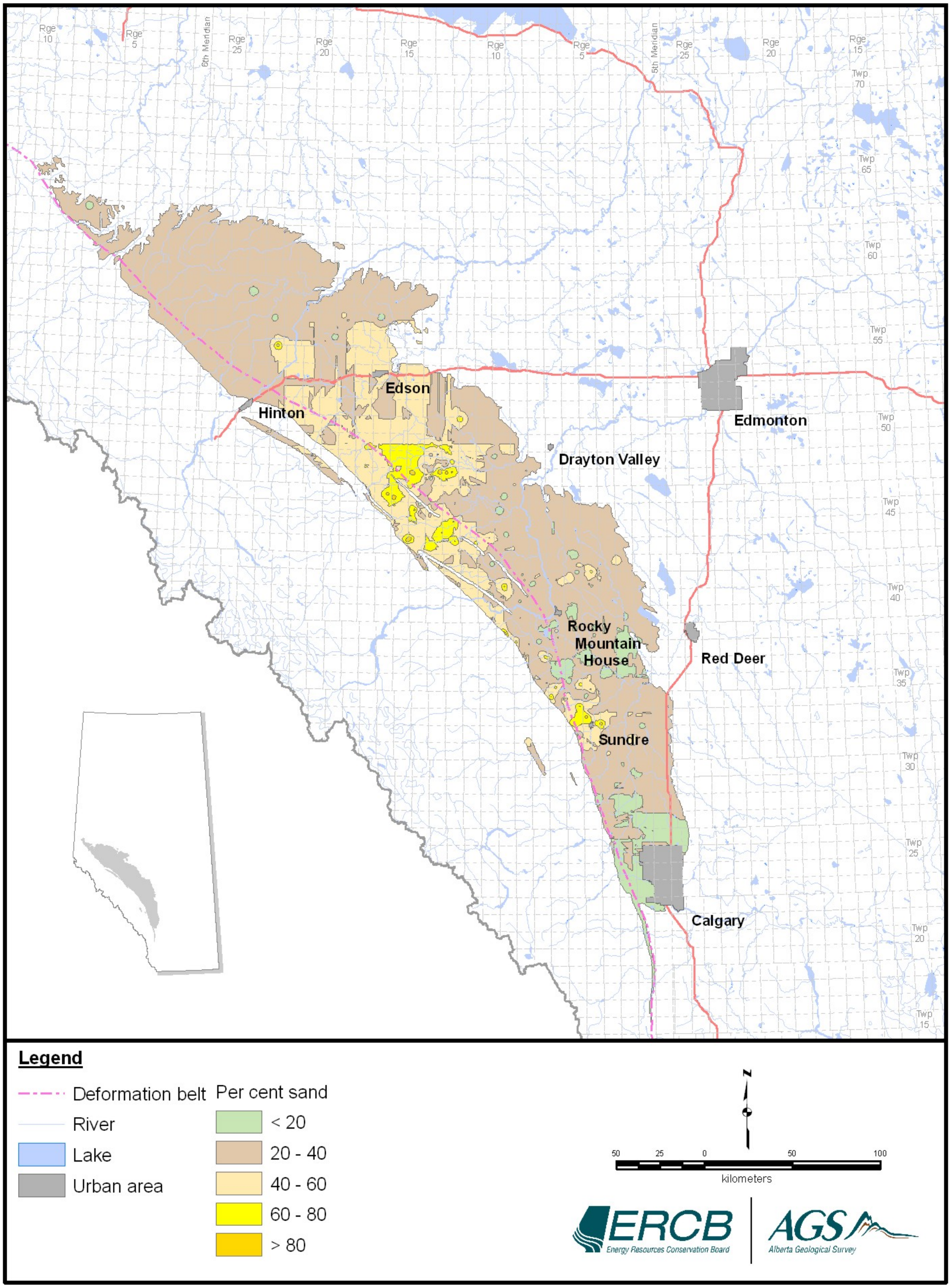

Figure 22. Vertically averaged gamma-ray–derived sandstone abundance, slice from 450 to 500 m above the Battle Formation.

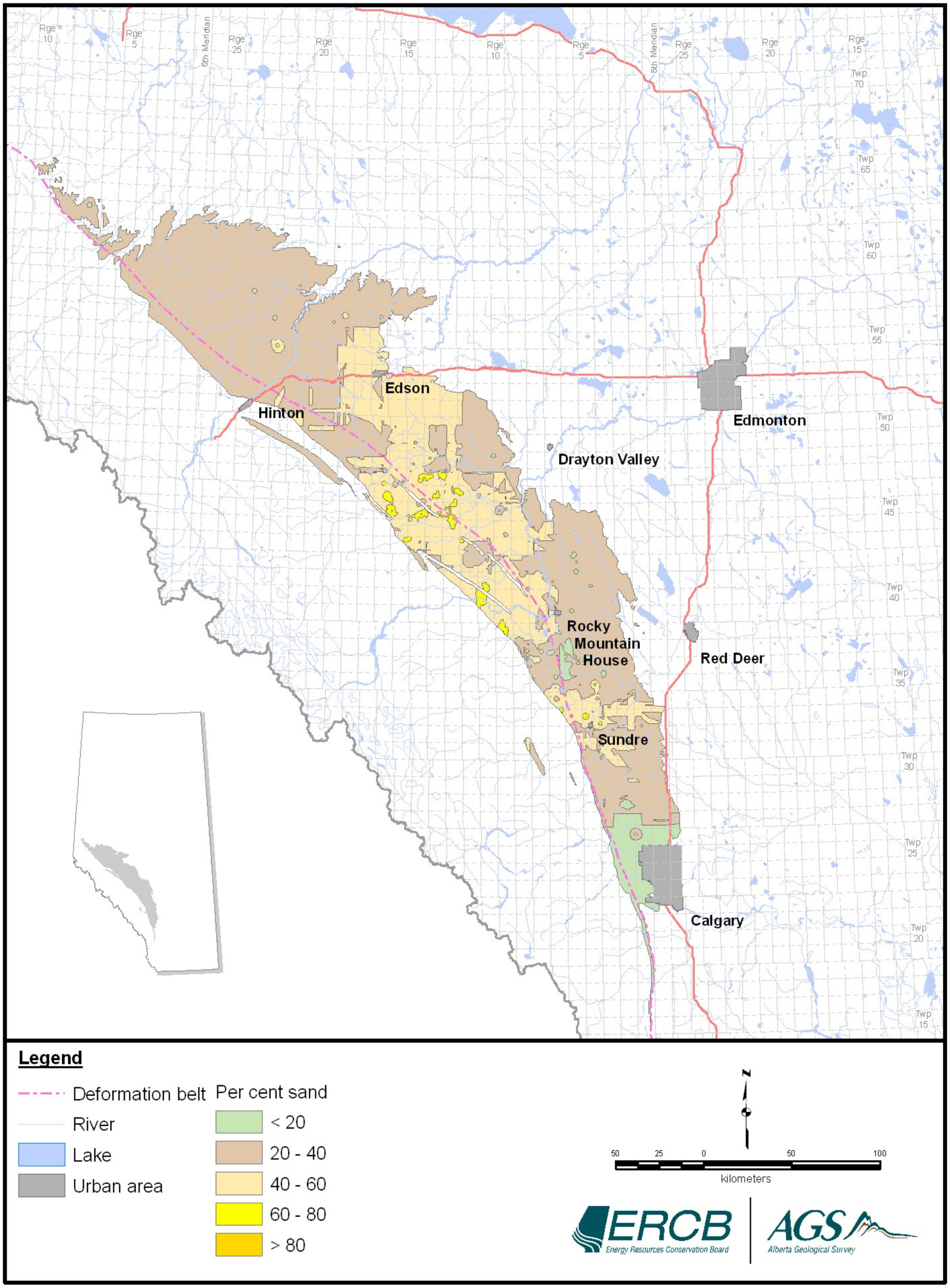

Figure 23. Vertically averaged gamma-ray–derived sandstone abundance, slice from 500 to 550 m above the Battle Formation

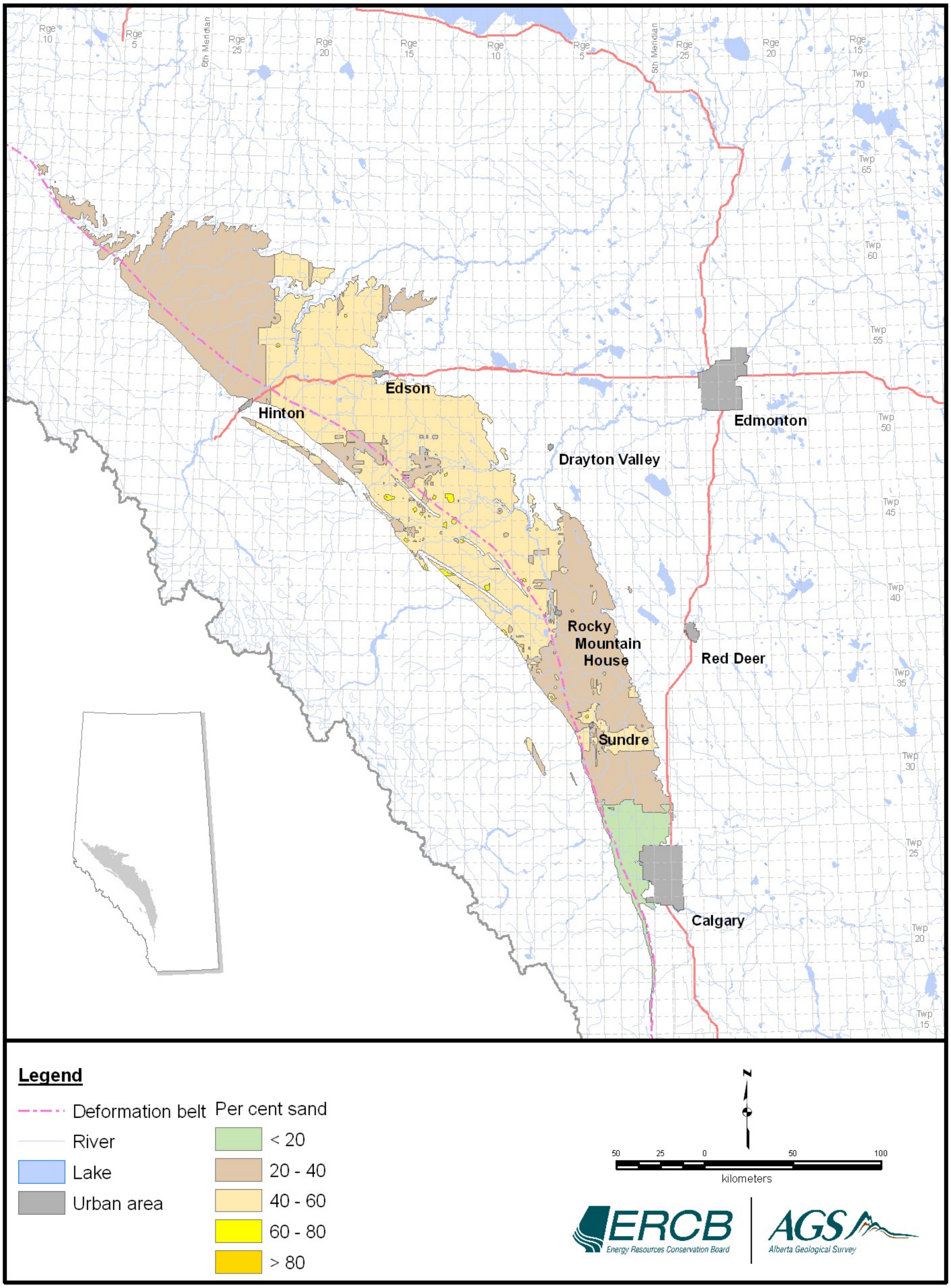

Figure 24. Vertically averaged gamma-ray–derived sandstone abundance, slice form 550 to 600 m above the Battle Formation.

2.4.1 Regional Groundwater Flow

Regional hydraulic heads, calculated from DST-derived formation pressures and from static water levels in water wells, were used to create hydraulic-head maps for the lower part (Haynes Member) and the upper part (Lacombe Member to Dalehurst Member) of the Paskapoo Formation. These are in Figures 25 and 26, respectively.

These hydraulic-head maps suggest that there is a composite gravity-driven groundwater-flow system (*after* Toth, 1995) in the lower Paskapoo Formation, consisting of 1) a deep northeast-flowing system in the west controlled by regional topography (recognized by Bachu and Michael, 2002), and 2) numerous shallow systems in the east controlled by the local topography. These systems have not been studied in terms of fluxes, water balances or groundwater residency times. Some work of this type has been reported for the area of Paskapoo bedrock near Calgary (e.g., Grasby et al., 2008), but their observations and conclusions should be regarded as preliminary in the context of Paskapoo hydrogeology.

It is reasonable to expect that off-channel mudstone facies of the lower Paskapoo could be underpressured like the mudstone facies of the Scollard Formation, if they are sufficiently isolated from the sandstone facies. However, no significantly underpressured Paskapoo beds have been identified from DST data, either in this study or in any of the water-well reports we have reviewed.

Little is known about the regional hydraulic heads of the mudstone-dominated beds of the Lacombe Member of the Paskapoo Formation that lie between the deepest domestic water wells and the oil and gas wells of the lower Paskapoo Formation because there are no data. We presume that the flow will be dominantly vertical and characterized by falling hydraulic heads with depth, consistent with theories of gravity-driven cross-formational flow of meteoric water. Although there is no way to verify this at present, planned geochemical sampling of lower Paskapoo groundwater by AGS may help validate this presumption.

3 Hydraulic Continuity and Hydraulic Connectivity

This section describes the Ardley-Scollard-Paskapoo system in terms of its hydraulic continuity and connectivity. Hydraulic continuity is a concept that relates the time it takes to propagate a pressure disturbance through a porous medium to the time and location of an observer. Hydraulic connectivity is a physical property of the porous medium that captures the ease with which a pressure disturbance can propagate through a porous medium or with which a substance can travel through the medium.

For there to be off-seam changes in water levels in aquifers due to CBM development, there needs to be hydraulic continuity between the point of origin and the point of observation over the time scale of development. Hydraulic continuity is not solely a physical property of a porous medium; it is dependent on the relative time and position of a pressure change and the point of observation. Hydraulic continuity is not synonymous with impact. Impact is a function of the magnitude of the disturbance, which will increase with time and with proximity to the disturbance, and of the change in social, economic or other values associated with that magnitude.

Similarly, for there to be an off-seam impact of gas migration from any given CBM development, there needs to be

- sufficient hydraulic connectivity to allow migration of gas from the point of liberation to the point of detection,
- sufficient size and longevity of a source to overcome natural attenuation effects en route, and
- favourable driving forces oriented in such a way as to drive migration from the source to the point of detection.

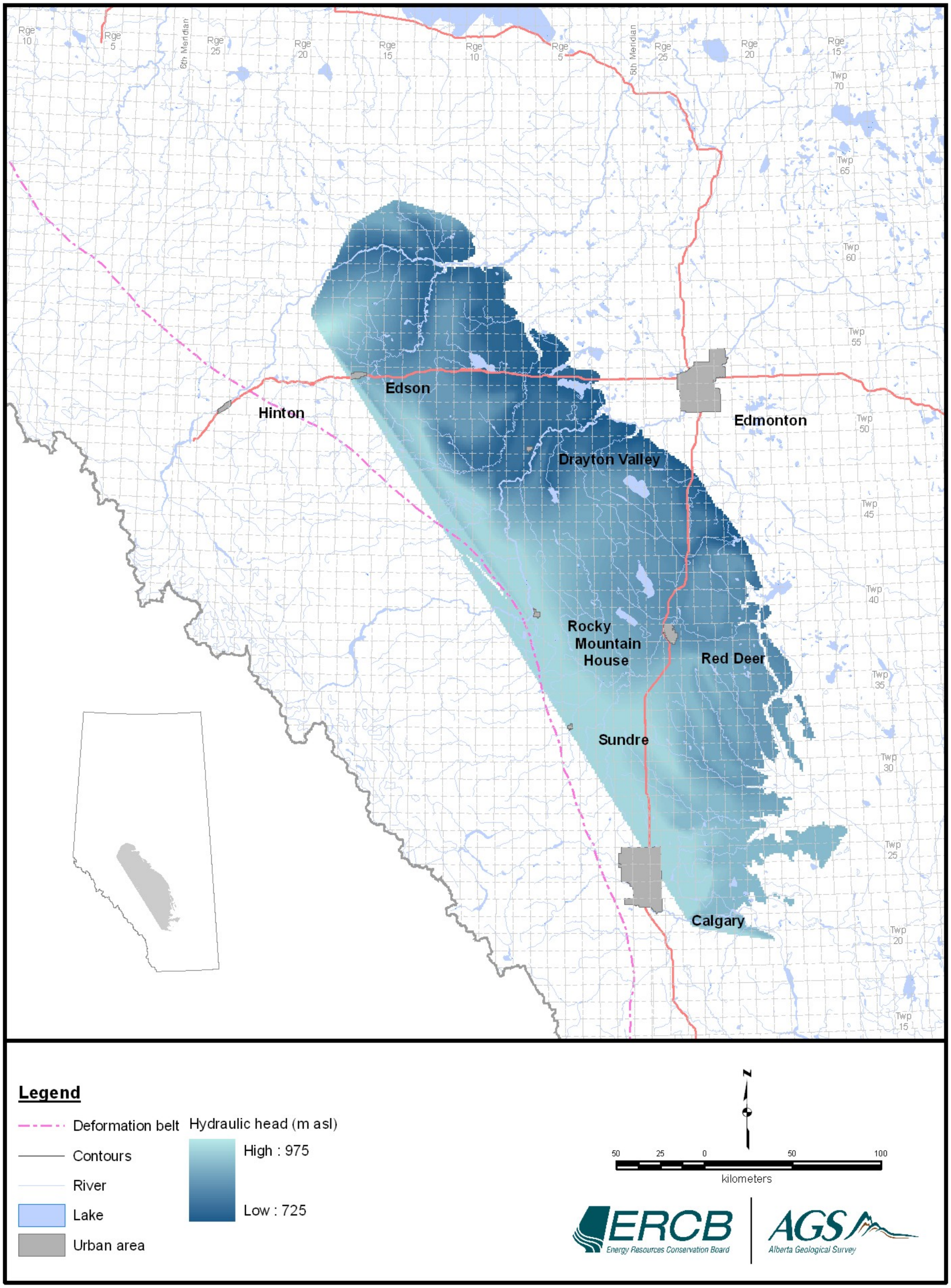

Figure 25. Hydraulic head, lower Paskapoo Formation.

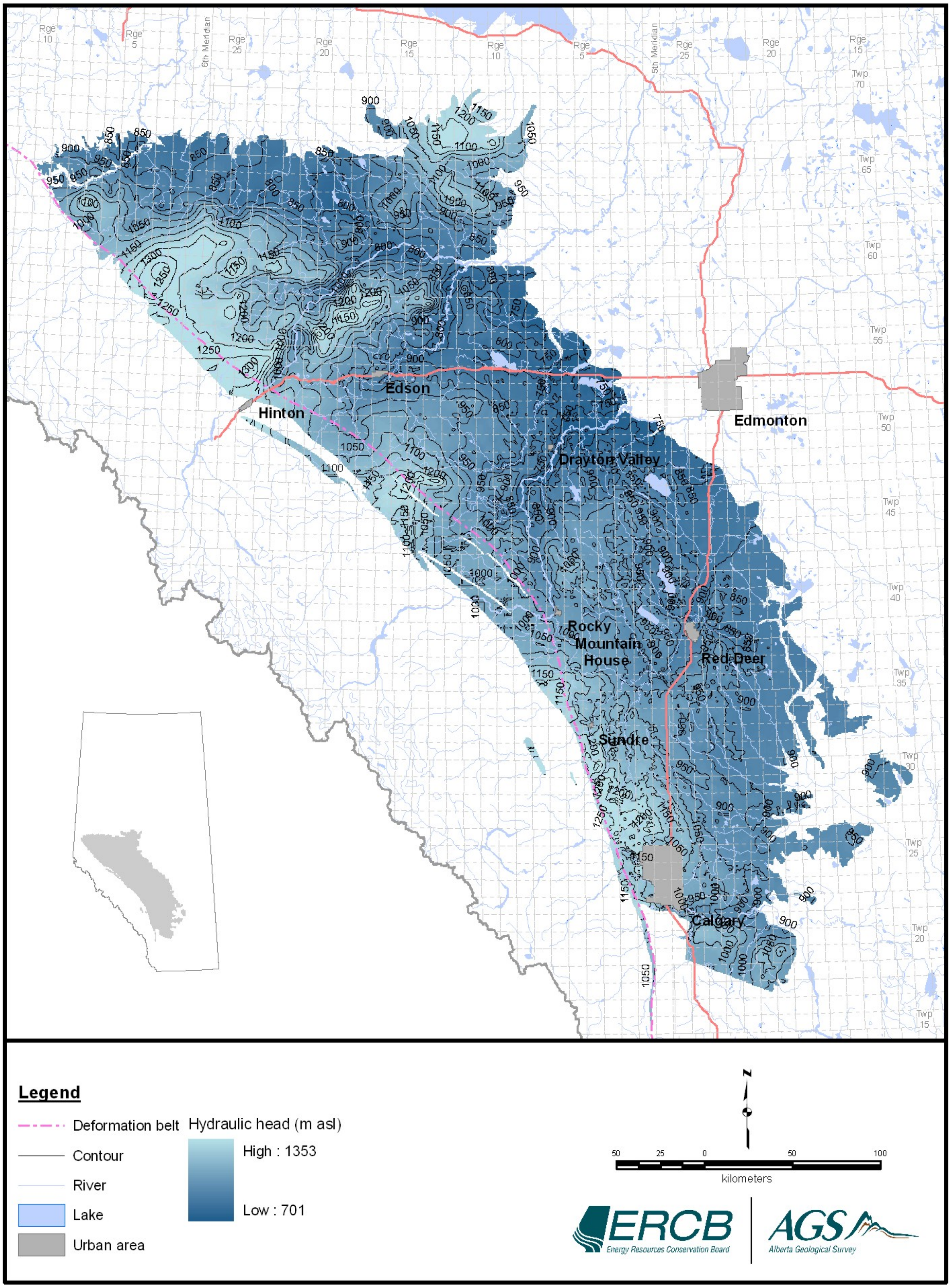

Figure 26. Hydraulic head, upper Paskapoo Formation.

Hydraulic connectivity is a physical property of a porous medium, but it depends on the spatial structure of the connected pathways and the scale of observation.

The geological and hydrogeological observations reported in the previous section provide considerable insight into the natural local and regional hydraulic continuity and connectivity of the Ardley-Scollard-Paskapoo system. This section of the report elucidates this insight and uses it to develop a strategy for assessing probability of impact via natural pathways in Section 4.

3.1 Regional Hydraulic Continuity and Natural Pressure-Change Propagation in the Ardley-Scollard-Paskapoo System

Toth (1995) characterized hydraulic continuity as the ratio of an inducing change in hydraulic head or pore pressure (such as would accompany the dewatering of a deep coal seam for CBM production) to an induced change in off-seam hydraulic head elsewhere (such as a change in water level in a shallow well measurably distinct from seasonal, barometric or locally induced forcings).

Hydraulic continuity depends on the

- distance between the points of origin and observation of the disturbance,
- hydraulic diffusivity of the rock-fluid system between the points of origin and observation, and
- time of observation.

Hydraulic diffusivity is directly proportional to hydraulic conductivity, which is directly related to the permeability of the porous rock system and inversely proportional to the specific storage of the rock-fluid system. Specific storage relates to the compressibility and elasticity of the rock and the pore-filling fluid. Because pore-pressure changes travel at a finite speed through a rock-fluid system, hydraulic continuity will be a function of the scale of both time and space. Rocks that appear impervious to local transmission of a pressure change over a human time scale can transmit pressure changes over geological time scales. In Toth's (1995) words:

> "[A] subsurface rock body is considered hydraulically continuous on a given time scale if a change in hydraulic head at any one of its points causes a head change at any other point, within a time interval that is measurable on the specified time scale. Large contrasts in permeability of contiguous rock bodies may make the less permeable ones appear impervious from conventional types of observations. Pore-pressure responses at various points in the flow region to a pressure change elsewhere may take longer than the time span of observation, thus rendering the rock body, or parts of it, to appear impermeable."

Understanding hydraulic continuity as a function of space and time scales is important when considering potential changes associated with pore-pressure transmission. For example, if regional hydraulic continuity in the Ardley-Scollard-Paskapoo system only manifests itself over geological time scales because of the hydraulic diffusivity of the rock-fluid system or the distances involved, then the hazard to shallow groundwater associated with deep CBM development on the human time scale may be negligible.

The results shown in the previous section indicate that regional hydraulic continuity exists between the modern land surface, the entire Paskapoo Formation and some parts of the Scollard Formation. Regional hydraulic continuity with the modern land surface does not exist for other parts of the Scollard Formation, the underlying Battle Formation or deeper rock units in the study area.

The Paskapoo Formation can be deemed regionally hydraulically continuous with the modern land surface at some time scale because we are able to map gravity-driven flow systems that are in equilibrium with the modern land surface down to the top of the Scollard Formation.

We base this conclusion on

- the magnitude of pore pressures being comparable to hydrostatic pressure, and
- the degree of correlation between the configuration of the Paskapoo potentiometric surfaces and the modern land-surface topography.

Since the modern land surface in Alberta is on the order of 10 000 years old (the order-of-magnitude date for the last widespread deglaciation, which occurred about 12 500 years ago in central Alberta), it stands to reason that the Paskapoo Formation as a whole could be hydraulically continuous, at least on this time scale. This means that pressure changes from any of the boundaries of the formation or from inside the formation will take approximately 10 000 years or less to propagate throughout the system and for the system to re-equilibrate to that change. Although it is important to understand hydraulic continuity on human time scales for the purpose of risk management, this order-of-magnitude number gives us an upper limit on the time scale involved.

It also stands to reason that, where observed formation pressures and heads of the Scollard Formation are similar to Paskapoo pressures, the Scollard Formation is also hydraulically continuous with the land surface on a time scale of 10 000 years or less. As discussed in the previous section, the contact between Paskapoo Formation channel-sandstone bodies and Scollard rocks of reservoir quality could provide the local hydraulic connectivity in these cases (e.g., Ardley Coal Zone).

The subhydrostatic pore pressures observed in the Scollard Formation and deeper formations are not in hydraulic equilibrium with the land surface, neither being hydrostatic in magnitude nor conforming to a systematic variation from hydrostatic pressure associated with gravity-driven flow. This means that these rocks are not hydraulically continuous with the modern land surface on a time scale of 10 000 years or less. Any sandy intervals within the Scollard must be lenticular with limited lateral continuity to allow isolated yet still permeable areas of underpressure to exist. Since the Paskapoo Formation is regionally hydraulically continuous with the land surface and the Scollard Formation is generally not, this also tells us that the mudstone facies forming the upper Scollard Formation above the Ardley coal, as well as the entire lower Scollard Formation, have very low vertical permeability. It is low enough to retard vertical propagation of modern land-surface boundary conditions through it for the last 10 000 years and thereby assists in maintaining the underpressures within and below. This effect will also work in reverse: pressure disturbances within the Ardley coal underlying the regional Scollard Formation mudstone facies will probably not have any impact at the land surface or in the gravity-flow system over time scales of less than 10 000 years.

The presence of underpressures in the Ardley Coal Zone along with normal pressures (e.g., where Paskapoo sandstones rest directly on the Ardley Coal Zone) also tells us that the Ardley Coal Zone is not laterally hydraulically continuous on the regional scale (a few kilometres or more) over time scales in the order of 10 000 years or less. If it were, there would be hydrostatic or gravity-flow–related pressures encountered in the Ardley where Paskapoo sandstones are neither directly observed nor locally suspected. This appears not to be the case, based on limited available data. Therefore, we can conclude that whatever cleats, fractures or coarse-grained interbeds may provide in terms of local permeability to wells in the Ardley Coal Zone, they are not laterally connected enough for normal pressures to propagate laterally over significant regional distances along bedding in the Ardley Coal Zone over time scales of 10 000 years or less. Nevertheless, the one instance where we saw evidence of pressure drawdown in an Ardley DST from offsetting fluid production (Figure 7) means that long-distance pressure propagation in the Ardley may occur, so we need to remain cautious about generalizations in such a complex system as this one.

Where there is hydraulic communication between the Ardley Coal Zone and the Paskapoo Formation via Paskapoo channel sandstones, there is the possibility for hydraulic continuity and therefore observable pressure changes in the Paskapoo Formation from CBM development over human time scales (i.e., much less than 10 000 years). In this case, the hydraulic-conductivity and specific-storage properties of the Paskapoo Formation can be used to estimate the extent of hydraulic continuity between the Ardley Coal Zone and domestic water wells completed in the Paskapoo Formation as a function of location, distance and time. Section 4 discusses this in more detail.

3.2 Regional Hydraulic Connectivity and Naturally Occurring Gas Migration in the Ardley-Scollard-Paskapoo System

Methane gas forms naturally from

- bacterial degradation of organic matter incorporated in sediment at shallow depths;
- coalification of peats at moderate burial depths; and
- thermal alteration of organic matter derived from terrestrial plants, algal material or plankton trapped in sedimentary rock buried for long periods of geological time at depths sufficient to create the proper pressure-temperature regime for pyrolysis-type chemical reactions to occur.

The Paskapoo Formation has natural gas occurrences in shallow water wells that are usually attributed to shallow bacterial processes acting in water wells or shallow aquifers (Lemay, 2003). The Paskapoo Formation also has natural gas occurrences at greater depths that oil and gas companies exploit, as discussed in the previous section. These latter occurrences are important in this study. Since the Paskapoo Formation includes no extensive coals or source rock, these occurrences are usually attributed to vertical migration from a deeper coal source (e.g., the Ardley Coal Zone) or an even deeper conventional source rock that has produced thermogenic gas. If we accept for simplicity that the gas occurrences in the deep Paskapoo Formation are naturally sourced from the Ardley Coal Zone, then we can draw some conclusions about both the connectivity of the Ardley Coal Zone to the Paskapoo Formation and the internal connectivity of the Paskapoo Formation itself.

If the Ardley Coal Zone is the source of the natural gas in the Paskapoo Formation, then there needs to be direct hydraulic connectivity between the Paskapoo sandstones and the source beds of the Ardley Coal Zone. The most likely connection is via Paskapoo channel sandstones in contact with the Ardley Coal Zone and with each other. There are three lines of argument to support this conclusion:

- There is evidence from logs and pressure measurements that direct hydraulic connections between Ardley coals and Paskapoo channel sandstones exist that provide pressure continuity over time scales of 10 000 years or less. Pressure continuity is necessary, but not sufficient evidence of hydraulic connectivity for Ardley gas migration via Paskapoo channel sandstones.
- The interbedded sandstone-siltstone-mudstone facies of the upper Scollard Formation, which overlies the Ardley, has low vertical permeability based on the discussion above regarding regional hydraulic continuity. A regionally extensive facies that retards pressure transmission could also act as an effective barrier to gas migration. Gas would therefore not easily escape from the Ardley Coal Zone through the upper Scollard Formation without the upper Scollard mudstone being removed by erosion, if it had been deposited at all.
- There is a spatial association of gas occurrences in the Paskapoo Formation with underlying and/or nearby downdip areas where the thickness of upper Scollard atop the Ardley Coal Zone is less than 10 m (Figure 27). The association of gas occurrences with areas of higher probability of the presence of Paskapoo Formation channel sandstone bodies is consistent with the hypothesis that Ardley connectivity to the Paskapoo Formation is preferentially via Paskapoo channel sandstones.

The actual locations of the gas occurrences in the Paskapoo Formation are important in understanding hydraulic connectivity within the Paskapoo Formation and thereby the risk of unwanted gas migration from CBM activity.

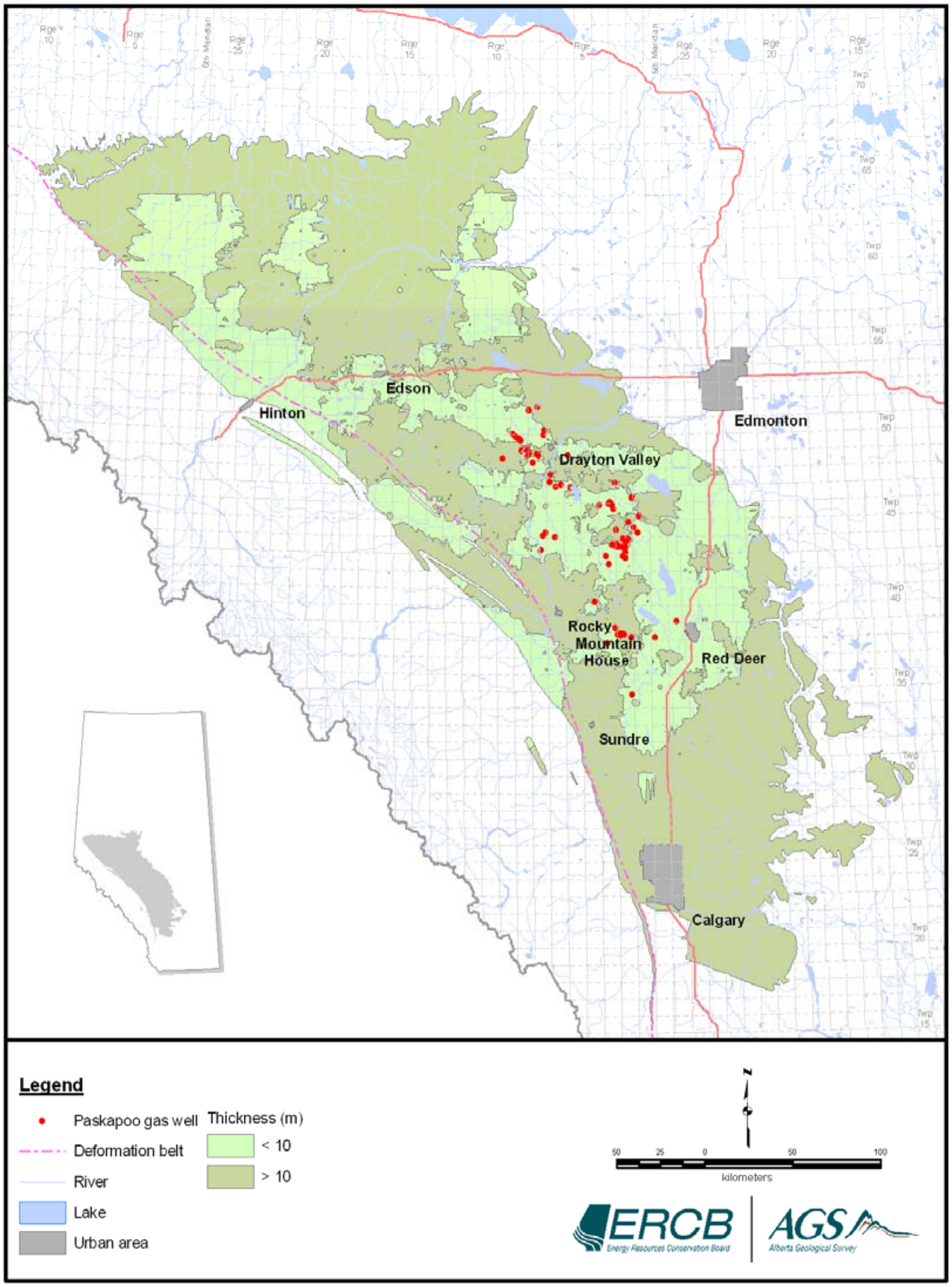

Figure 27. Locations of Paskapoo gas wells relative to thickness of the Scollard Formation above the Ardley Coal Zone.

In general, the locations of gas occurrences large enough to attract industry attention are concentrated in clusters on the updip side of regional sandstone accumulations where the sandstone abundance in any given 50 m slice is commonly between 40% and 60% (*see* Figures 13–17). Likewise, the sandstone abundance in the parts of 50 m slice maps atop these gas occurrences tends to be 40% or less, implying the development of a hydrocarbon seal.

The preferential appearance of gas concentrations on the updip side of the Paskapoo sandstone trends is partly attributable to simple buoyancy of gas in a dipping, water-saturated system, perhaps abetted by northeast regional groundwater flow in the lower Paskapoo Formation, as shown in Figure 25. However, the lack of gas occurrences updip or above areas where the Paskapoo sandstone abundance falls below 40%, even though there are reservoir-quality sandstone bodies present, suggests that there could be a percolation-type phenomenon at work that limits the lateral and vertical migration of gas within the Paskapoo Formation. If true, this phenomenon can help us predict the relative risk of both free gas migration and the propagation of pressure disturbances associated with Ardley CBM production.

Percolation theory is the study of how the properties of interconnected networks change as a function of the probabilities of sites being connected and the scale of observation. It has been successfully applied to problems in reservoir engineering and porous-media hydraulics. In brief, percolation theory uses simplified mathematical models of interconnected networks to discover universal behaviours that, under the proper circumstances, one can use to predict the flow and transport inside heterogeneous geological materials (Stauffer and Aharony, 1994).

The simplest percolation networks are modelled as regular two-dimensional (2-D) or three-dimensional (3-D) lattices. The nodes of the lattice are considered either open or closed to flow from adjacent nodes with some probability. If the probability of any node being open to flow is low, the lattice will have very few open nodes and very many closed nodes; flow across the lattice will not occur. As the probability of any node being open to flow increases, small clusters of open nodes begin to occur, as well as isolated open nodes. Within such clusters, local flow can occur within the lattice but is restricted between the clusters. If the probability of any node being open increases yet again, the average size of the local percolation clusters increases until, at some critical probability, there will be at least one connected path across the entire lattice (and therefore flow), even if the lattice is essentially infinite in size relative to the nodal spacing.

For a given geometric dimension and configuration of nodes, the percolation threshold will be a universal constant. For infinite 2-D square lattices, the critical percolation threshold occurs when the probability of any node being open to flow reaches 0.5927. For infinite 3-D cubic lattices, the critical percolation-threshold probability is 0.3116. Other kinds of lattices will have different percolation thresholds (Stauffer and Aharony, 1994).

Other universal behaviours that derive from percolation experiments include

- the probability that any open node belongs to the so-called infinite cluster that appears above the percolation threshold,
- the probability that two sites some distance apart are connected to each other in a small cluster if they are not part of the infinite cluster, and
- the magnitude of expected conductivity as a function of probability above the percolation threshold.

Although these concepts originated in idealized experimental conditions (summarized in Stauffer and Aharony, 1994), they have been successfully applied to understanding hydraulic conductivity and averaging behaviours in heterogeneous porous media representative of geological materials (e.g., Berkowitz and Balberg, 1993; Hunt, 2005), spatially correlated systems (Silliman and Wright, 1988) and sand-shale systems (King, 1990).

Percolation concepts are applicable to the Paskapoo Formation because, at some level of generalization, the formation comprises randomly distributed, discrete sandstone-channel bodies encased in mudstone-dominated regional facies. The concepts are particularly useful to help us understand the nature of gas trapping in the Paskapoo Formation. Most conventional gas reservoirs form when buoyant gas migration in a permeable bed stops below the cap rock against a sealing discontinuity, such as a cemented fault plane, or against a facies change where reservoir-quality rock decreases rapidly in grain size to become seal-quality rock. Regional gas entrapment within the Paskapoo Formation does not fit the standard model because there are reservoir-quality sandstone bodies above and updip of the edge of the known gas occurrences.

Applying principles of percolation theory frees us from this paradox. Although reservoir-quality rocks are present updip from and above where Paskapoo gas is found, what is apparently missing (in the absence of through-going, pervasive and open fractures) is a sufficiently pervasive network of sandstone body-to-body contacts needed for regional gas migration. This is missing because the sandstone abundance has fallen below a critical percolation threshold, resulting in a lack of sufficient connectivity. The fact that the gas occurrences are present where sandstone abundance on our slice maps tend to be, at most, in the 40%–60% range is quite congruent with the predictions from percolation theory. Consider that, in idealized infinite 2-D networks, the universal percolation threshold is around 0.6. When spatial correlation is added, percolation thresholds will be lower than for uncorrelated networks (Silliman and Wright, 1988). For 2-D geological systems comprising uncorrelated rock bodies that are small compared to the scale of investigation, theoretical results suggest that, at sandstone abundances less than 0.6, regional connectivity dominated by sandstone interconnectivity has a low probability of occurrence and gas migration will become restricted.

Similarly, the probability that sandstone bodies are vertically connected will decline as sandstone abundance declines, until some percolation threshold is crossed. This helps explain why gas is trapped in slices of higher sandstone abundance lying below slices with low sandstone abundance, even though sandstones exist throughout the formation.

The congruency between sandstone abundances and behaviours following theoretical 2-D models of percolation rather than 3-D models seems to indicate that there is not a true 3-D sandstone network in the Paskapoo Formation and that spatial correlation length is present but small relative to the scale of investigation supported by well control. The former would be associated with successions of beds wherein the occurrence of channelling has little to do with underlying landscape (e.g., Bridge and Leeder, 1979). This might suggest highly erosional and erratic channelling events with little competent bedrock or bank-stabilizing vegetation, although this hypothesis is speculative at this point. The latter can explain why the observed abundances related to gas entrapment are lower than theoretical 2-D thresholds but not so significant that percolation concepts fail to apply.

Once the sandstone abundance falls below the percolation threshold (whether 2-D or 3-D) in a sandstone-mudstone system like the Paskapoo Formation, the system’s bulk hydraulic properties will be dominated by the Paskapoo mudstone facies, even though localized clusters of interconnected sandstone bodies will still persist. We can therefore use our sandstone abundance maps to help assess hydraulic continuity inside the Paskapoo Formation: where regional sandstone abundances are above the regional percolation threshold, we should use sandstone hydraulic conductivity values to characterize regional formation transmissivity; where regional sandstone abundances are below the regional percolation threshold, we should use mudstone hydraulic conductivity values to characterize formation transmissivity.

Specifically, we can expect regional-scale sandstone interconnectivity to occur in the Paskapoo Formation where the vertically averaged sandstone abundances in 2-D slices are above 60%. Sandstone interconnectivity does not occur where the vertically averaged sandstone abundances fall somewhere below 40%. There is a threshold between vertically averaged sandstone abundances of this sub-40% and

60%, but our understanding of the Paskapoo Formation is not sufficient to do more than bracket its value somewhere in this range. Not surprisingly, these values are comparable to thresholds needed to regionally trap gas reported for sandstone-shale sequences in the Gulf of Mexico (Glezen and Lerche, 1985).

It is important to add that, within areas where regional sandstone abundances fall below the threshold needed for regional connectivity, there will still be local clusters of interconnected sandstone bodies. One can predict the size distribution of these clusters for simple geometries as a function of sandiness below the threshold value (Berkowitz and Balberg, 1993). As well, the probability that two boreholes that intersect sandstone bodies would be interconnected can be estimated as a function of distance and sandiness (King, 1990) for idealized conditions. The presence of local clusters in percolation systems means that local aquifers, even some of significant size, composed of locally interconnected but regionally disconnected sandstone bodies may exist throughout the system. This may also partially explain why there are many domestic water wells completed in sandstone beds of the Lacombe Member of the Paskapoo Formation, even though it is regionally dominated by mudstone beds.

Note that fracture permeability is also suspected to be an important parameter controlling water-well productivity in the shallowest Paskapoo Formation. These fractures are presumed to be associated with weathering and erosional unroofing. The penetration and connectivity of fractures at depth is unknown; if present, they would add another dimension of local complexity to the conceptual model of hydraulic continuity and connectivity presented here, but would not change the substance of this conceptual model. Indeed, if open and interconnected fractures were present at depths in the subsurface but more strongly associated with brittle sandstone than ductile shale, there would be little change in the conclusions of this study. If, on the other hand, there were regionally pervasive, open and interconnected fractures from surface down to the Scollard Formation with a spatial distribution independent of lithology, then the underpressures observed below the Paskapoo should not exist and known gas traps would be harder to explain. Nevertheless, we should not disregard the potential role of fractures in any model of hydraulic connectivity and continuity. This topic should remain a subject of ongoing observation and study.

4 Assessing Impacts of CBM Production on the Paskapoo Groundwater System

This report examines the regional geology and hydrogeology of the Ardley-Scollard-Paskapoo system to identify areas where the probability of impact from off-seam pressure disturbances or off-seam gas migration may be naturally low. These would be areas where one can drill CBM wells with little risk to groundwater.

The resource presently protected is the nonsaline groundwater found above Alberta’s base of groundwater protection (Alberta Energy and Utilities Board, 2007). Although the resource has not been quantified or extensively mapped, water-well locations determined from water-well licenses and water-well drillers’ reports on file with AENV show its minimum areal extent (Figures 28 and 29). Water-well records do not assign formation names to the production interval. The water wells were assigned to the Paskapoo Formation for this project based on comparison of the elevation of the screen or perforated interval (if recorded) or depth of well (if not) with the geological surfaces defining the top of the Paskapoo and the top of the lower Paskapoo (Haynes Member) from AGS regional maps discussed in the first part of this report.

The distribution of licensed water wells shows that most, but not all, of the Haynes Member (lower Paskapoo) water wells are in the eastern part of the Paskapoo Formation. This is because the Haynes Member is closest to the ground surface along the eastern edge of the formation due to the westward dip

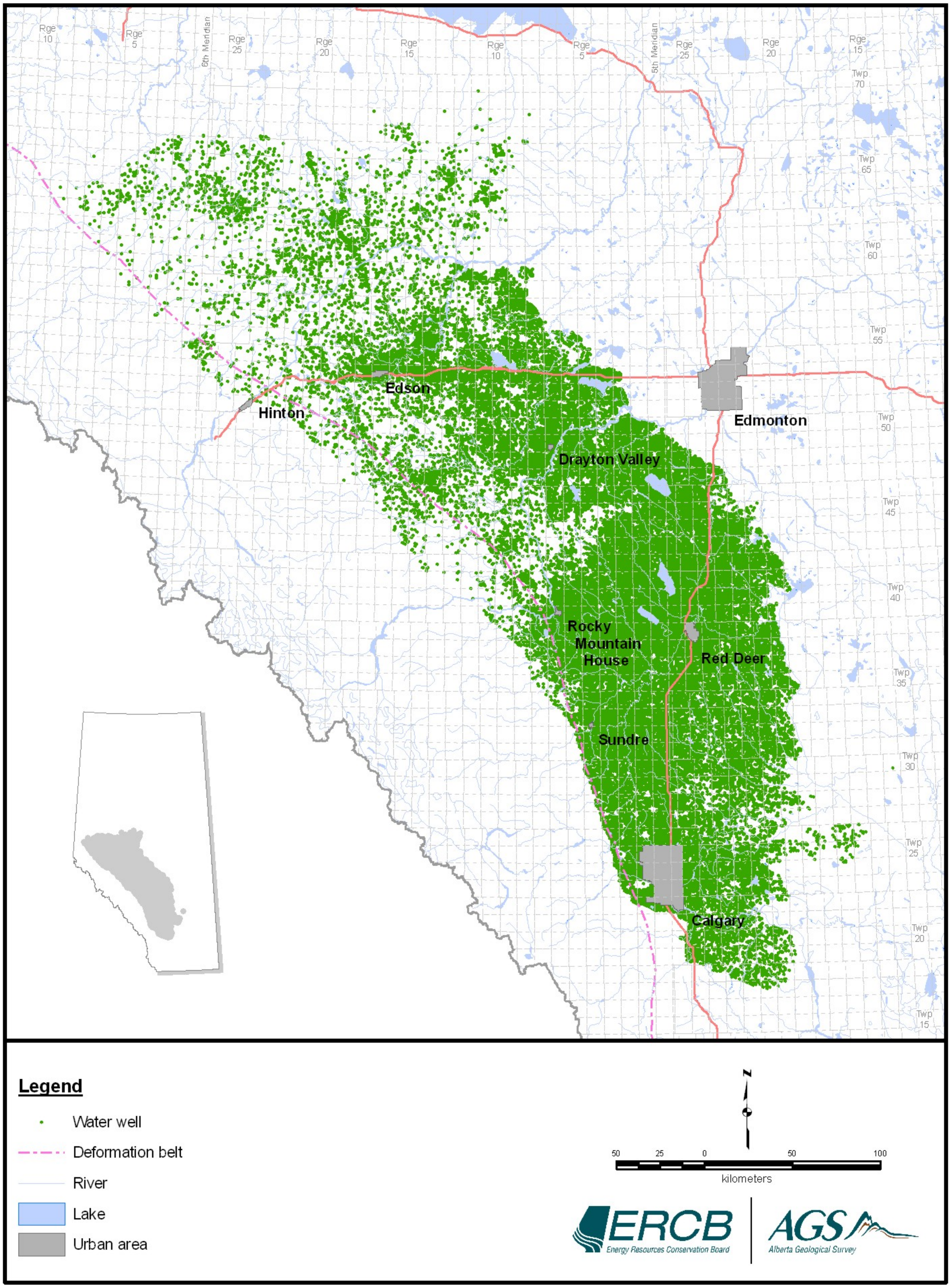

Figure 28. Water wells completed in the Paskapoo Formation, from drillers' reports on file with Alberta Environment.

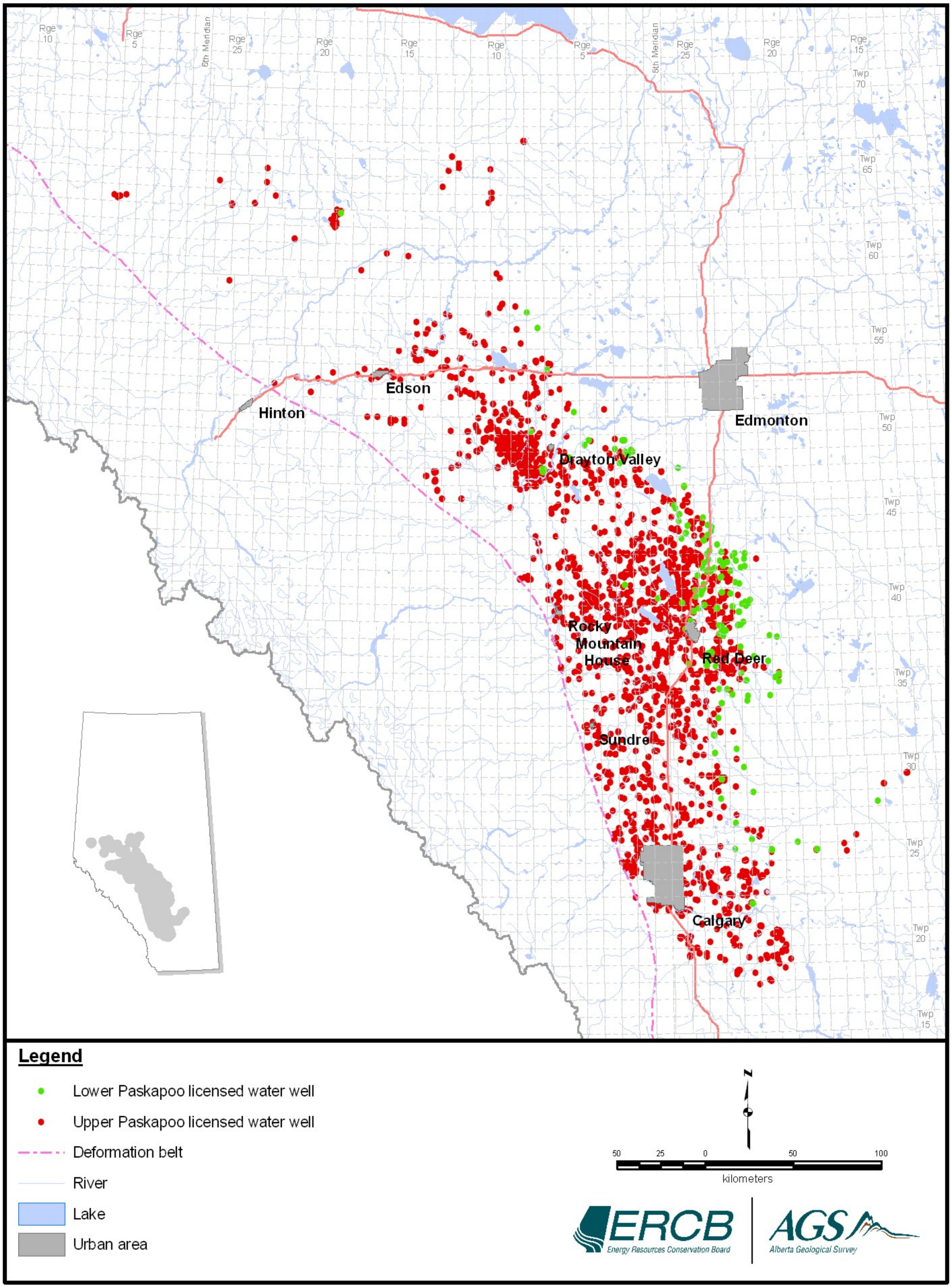

Figure 29. Alberta Environment licensed water wells completed in the Paskapoo Formation.

of the beds. The exceptions are deeper wells, which are mostly industrial supply wells. The water wells completed in the Lacombe Member (upper Paskapoo) are to the west where the shallower Lacombe Member is at surface.

Alberta presently has a policy for managing risk to groundwater for the Lower Ardley Coal Zone. Under ERCB Directive 044 (Alberta Energy and Utilities Board, 2006b), industry is allowed to commingle and coproduce Lower Ardley CBM with deeper zones within the designated Development Entity No. 1 area (Alberta Energy and Utilities Board, 2006c), provided that the total commingled well does not produce more than 5 m^3/month of water per well. These zones were defined by examining the occurrence of dry gas production reported from the Lower Ardley and defining areas where no 'wet' production had yet occurred. If water production above 5 m^3/month per well is reported from those areas, then an investigation into the source of the water production must be conducted and the appropriate remedial action taken in consultation with the ERCB and AENV.

The groundwater-protection policy embedded in the use of development entities and Directive 044 are fairly conservative. The following risk-assessment approach may actually accommodate higher water production from the Ardley Coal Zone, even where it is in hydraulic connection with the Paskapoo Formation.

4.1 Strategy to Assess Risks of CBM Activity to Groundwater in the Paskapoo Formation

The conclusions presented in the previous sections of this report are based on a number of assumptions and interpretations regarding the nature of the geology and hydrogeology, many of which have yet to be rigorously tested.

For example, we have not evaluated or discussed the role of fluid and pressure migration along potentially deep-seated fractures. As well, there is insufficient information to characterize the rock properties to determine local ranges of permeability in sandstones and coarse-grained interbeds in mudstones, or the role of cleats in coal permeability. Likewise, the most appropriate method for selecting cut-off values on gamma logs to generate sand-slice maps, and the appropriateness of establishing the Battle Formation surface to establish sand-slice surfaces, have not been rigorously tested, nor has there been rigorous testing of the modelling algorithms to map the subsurface distributions of sand abundances. Furthermore, we have introduced percolation theory to explain the likelihood of subsurface networks of highly permeable rock units, but this analysis is based on sand-slice mapping methodologies that have yet to be validated.

Notwithstanding these underlying assumptions and uncertainties, a sequential risk-assessment strategy is presented here based on the findings in this report. Maps showing zones where the different aspects of this framework apply, based primarily on geological and hydrogeological criteria, are included below. Their purpose is to illustrate regional concepts and they should not be used for site-specific evaluations or analysis. The actual areas of the zones will depend on regulatory and policy choices regarding uncertainty in sandstone abundance thresholds for vertical and lateral interconnectivity, and choices regarding the time horizon and head-change tolerance for lateral hydraulic continuity. The areas where these zones overlap ERCB-designated Development Entity No. 1 may require additional review. Recommendations for testing and validating aspects of the interpretations and conclusions leading to this strategy are discussed in Section 5.

4.1.1 Sequential Assessment of Risk

1) The critical step in the application of this risk-assessment strategy is determination of reservoir pressure after drilling. The reservoir pressure establishes whether the CBM reservoir is likely connected to the Paskapoo groundwater system via overlying sandstone channels. This information, plus location, determine if the CBM well needs increased scrutiny with respect to groundwater

protection compared to a standard gas well in Alberta. The available pressure and water-production data do not show any spatial predictability regarding the connectivity of the Ardley Coal Zone to the Paskapoo Formation that would be helpful in assessing the likelihood of connectivity before drilling (Figure 30). This is the case even though we can regionally associate areas of thinner Scollard atop the Ardley Coal Zone with gas shows, suggesting more chance of connectivity there (Figure 27). This means the appropriate degree of investigation cannot be determined prior to drilling and pressure measurement in a new Ardley CBM reservoir.

2) If the CBM target zone is known *a priori* or proven after drilling to be substantially underpressured relative to the modern land surface, there is probably no hydraulic connectivity locally between the Ardley Coal Zone and the Paskapoo Formation. Furthermore, there is probably no hydraulic continuity over human time scales at these localities between the CBM reservoir and the Paskapoo Formation. This situation can occur anywhere in the study area.

3) We discussed previously that, although Ardley coals are not laterally connected enough for normal pressures to propagate laterally over significant regional distances, the cleats, fractures or coarse-grained interbeds may provide local permeability to water wells completed in the Ardley Coal Zone. A water well can be drilled to a depth of 150 m without ERCB approval and, in the eastern part of the study area where the Ardley Coal Zone lies less than 150 m from surface, a water well can conceivably be completed in coal if the zone produces sufficient water. This area is marked as Zone I in Figure 31. A strategy to assess potential impact by CBM wells completed in the Ardley Coal Zone at a depth of less than 150 m might therefore consider implementing a preliminary groundwater assessment prior to drilling because the target zone could be used as an aquifer. Discussion of the design and implementation of such a local assessment is beyond the scope of this report.

4) The area where the lower Paskapoo Formation (defined as the top of Battle Formation plus 200 m) has any potential to be used for domestic water wells 150 m deep or less is shown in Figure 31 as Zone II. Within this area, the entire lower Paskapoo Formation and any other formation it is connected with by sandstone interconnectivity and/or fractures will be within the range of domestic water-well drillers. As most water wells in Alberta are 100 m deep or less, Zone II has a built-in safety factor of 30% on depth. As a precaution, however, a strategy to assess potential impact by CBM wells located in Zone II might consider implementing a preliminary groundwater assessment prior to drilling.

5) The western edge of Zone II is referred to hereafter as the ‘domestic water-well line’ for the Haynes Member. Water wells are still found west of this line in the Lacombe Member (upper Paskapoo), but those in the Haynes Member (lower Paskapoo) are presently limited to oil-industry water-source wells. Deep wells (>150 m) must have ERCB licenses and need special drilling techniques, so they are not feasible for the typical domestic water-well owner.

6) If measured formation pressures in the Ardley Coal Zone are close in magnitude to hydrostatic pressure or close to values derived from hydraulic-head maps of the lower Paskapoo Formation (e.g., Figure 25), then this can be an indicator that the CBM reservoir is in hydraulic continuity with the Paskapoo Formation. A Paskapoo channel sandstone, or other indicators of a channel environment, will likely be found in the well logs of that hole. However, it is always possible that no geological indicators of channelling are evident but that a downcutting channel sandstone is near enough to bring the tested zone into hydraulic communication. In any case, there is a possibility of off-seam impacts. If the CBM well is west of the domestic water-well line for the lower Paskapoo Formation, the type of groundwater protection measures applied will depend on where the well is located, as discussed in the next section.

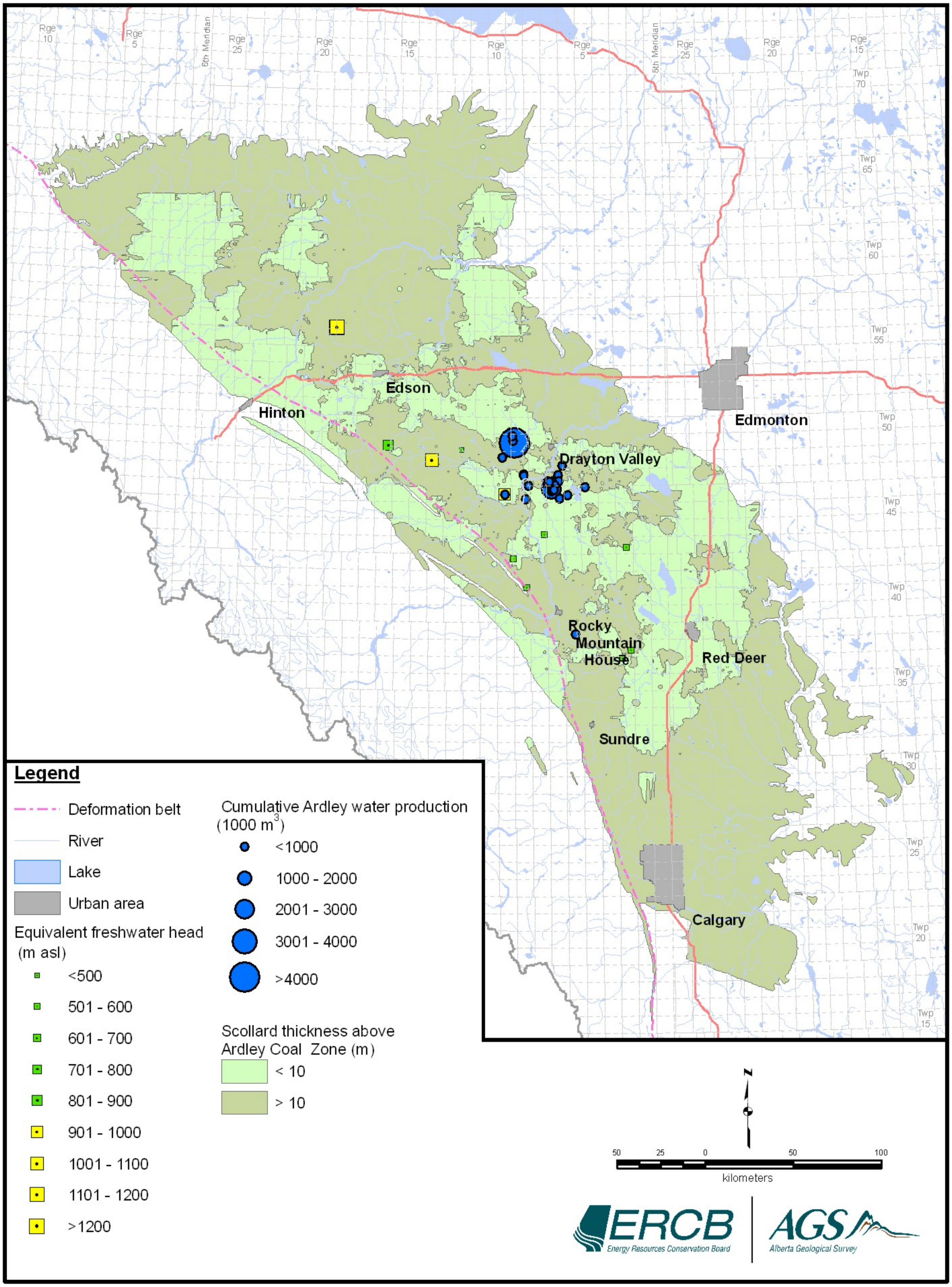

Figure 30. Pressures and water production in the Ardley Coal Zone, showing no predictable association with the thickness of the overlying Scollard Formation.

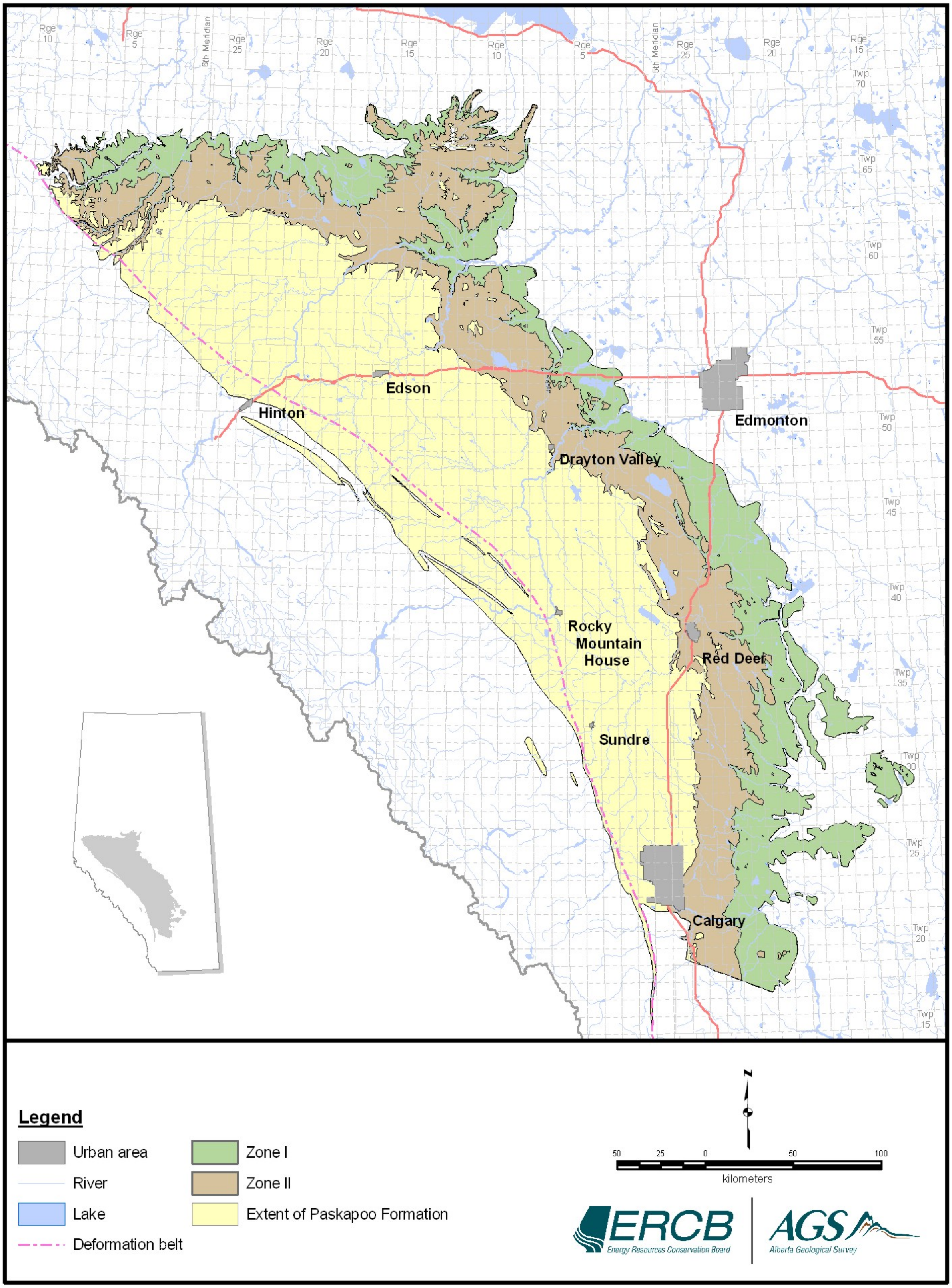

Figure 31. Areas where water wells up to 150 m deep can intersect the top of the Battle Formation (Zone I) and therefore the entire Scollard Formation, as well as areas where water wells up to 150 m deep can intersect the top of the lower Paskapoo Formation, defined as the top of the Battle Formation plus 200 m (Zone II).

7) For there to be impacts from fugitive gas migration of concern to domestic water wells via natural pathways west of the domestic water-well line, there needs to be sufficient hydraulic connectivity between the CBM well and the domestic wells to permit gas migration. The analysis presented in Section 3.2 showed that, if the vertically averaged sandstone abundance is less than 40% (taken over 50 m vertical slices), there is unlikely to be regional sandstone connectivity. Of course, local connectivity is still possible over small distances, but those areas separated from the domestic water-well line through stacked slices of Paskapoo Formation with less than 40% sandstone are generally not interconnected enough to pose any significant risk of long-distance gas migration. These areas are marked as Zone III in Figure 32.

8) The analysis in the previous section showed that, above the Haynes Member (lower Paskapoo), there is not sufficient vertical connectivity to permit gas migration through the Haynes Member into the Lacombe Member (upper Paskapoo). Therefore, there is little regional risk to shallow water wells completed in the Lacombe Member from migrating fugitive gas from Ardley CBM wells west of the domestic water-well line.

   Similarly, if the sandstone abundance is below 40%, then the bulk formation hydraulic properties will be dominated by the mudstone facies. There are no estimates of mudstone permeability available, but there are reports on file with AENV where monitoring wells were set across Paskapoo mudstone/shale intervals above and adjacent to water-production wells. Monitoring results indicate that these types of beds do not transmit pore-pressure disturbances vertically on the human time scale (although they probably transmit pressure disturbances over time scales of 10 000 years; otherwise, the Paskapoo Formation would not be in hydraulic equilibrium with the modern land surface). This means that areas of low regional sandstone connectivity already identified as Zone III (Figure 32) are not likely to be hydraulically continuous on the human time scale. Therefore, regional propagation of off-seam pressure disturbances from these areas is unlikely, even if there is local connectivity between the Ardley Coal Zone and the Paskapoo Formation.

9) If Ardley Coal Zone pressures indicate connectivity with the Paskapoo Formation and the sandstone abundance maps indicate laterally continuous, vertically averaged sandstone abundances greater than 40% (to be conservative) between the CBM development and the domestic water-well line, then there is a possibility of lateral connectivity and therefore regional migration of fugitive gas emissions. A strategy to mitigate this should ensure that developments in these areas have sufficiently close well spacing to ensure that no fugitive gas emissions are likely. These areas are marked as Zone IV on Figure 32.

10) If Ardley Coal Zone pressures indicate connectivity with the Paskapoo Formation and the sandstone abundance maps indicate laterally continuous, vertically averaged sandstone accumulations greater than 40% (to be conservative) anywhere within the Haynes Member (lower Paskapoo) between the CBM development and the domestic water-well line, then there is a possibility of hydraulic continuity and therefore a reduction of pore pressure or water level in water wells. Since hydraulic continuity is time dependent, one can define a time-dependent buffer zone that mitigates this kind of impact. A first-order buffer distance can be estimated using Equation 1 (*after* Bear, 1972, p. 410). This formula represents the change in hydraulic head over time in a 2-D, semi-infinite, isotropic and homogeneous horizontal aquifer where the hydraulic head drops instantaneously to zero at one boundary. This is analogous to initiation of CBM production where formation pore pressure is dropped to near zero at the formation face to induce fluid flow and coal-seam depressurization.

$$h(x,t) = H_o erf\left(\frac{Sx^2}{4Tt}\right)^{\frac{1}{2}}$$

Equation 1

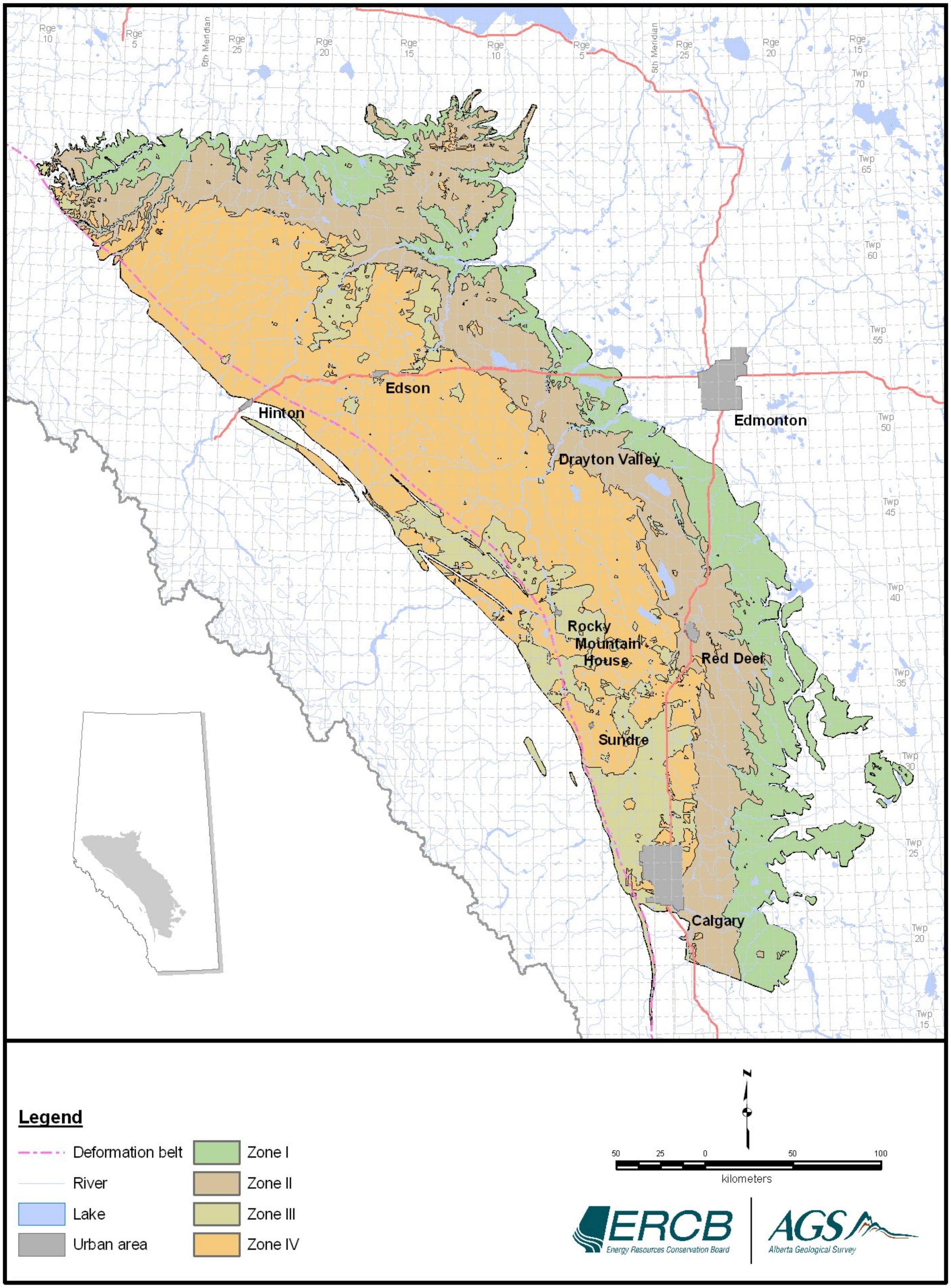

Figure 32. Areas where lower Paskapoo Formation (Haynes Member) has sandstone abundances less than 40% (Zone III) and greater than 40% (Zone IV) west of the domestic water well line.

where:

$h(x,t)$ = the head at t at a radial distance x from an instantaneous head drop from H_0 to 0 (m)
H_0 = initial head (m)
S = storativity (dimensionless)
T = transmissivity (m^2/s)
t = time (s)
x = distance (m)
erf = the error function

Similar equations quantify the time for a pressure pulse to be transmitted through an aquifer (e.g., Gelhar and Wilson, 1974; Domenico and Schwartz, 1990, p. 201; Erskine and Papaioannou, 1997). These are all similar in that they include the hydraulic diffusivity (T/S) or its inverse and will give comparable results. In future, the best answers for this kind of work would be obtained by numerical simulation, using fictitious wells to impart a change in head at all locations and calculating the response times versus distance, given the complex geological and hydrogeological conditions discussed in this report.

Aquifer tests in the Paskapoo indicate that a typical value of T is 2×10-4 m^2/s and S is 10^{-4}. The head distribution at any time as a function of distance can be calculated and plotted using Equation 1. As an arbitrary example using these typical values for T and S, the relative head plotted versus distance after 10 years and after 50 years, following a head drop equal to Ho at the boundary of a semi-infinite aquifer, is shown in Figure 33. For the sake of discussion, if one decides that the regulatory timeframe should be 10 years and the social tolerance and/or detection limit for head drop due to this kind of disturbance is 5% of the original head at a point of observation, then the 10-year buffer zone is about

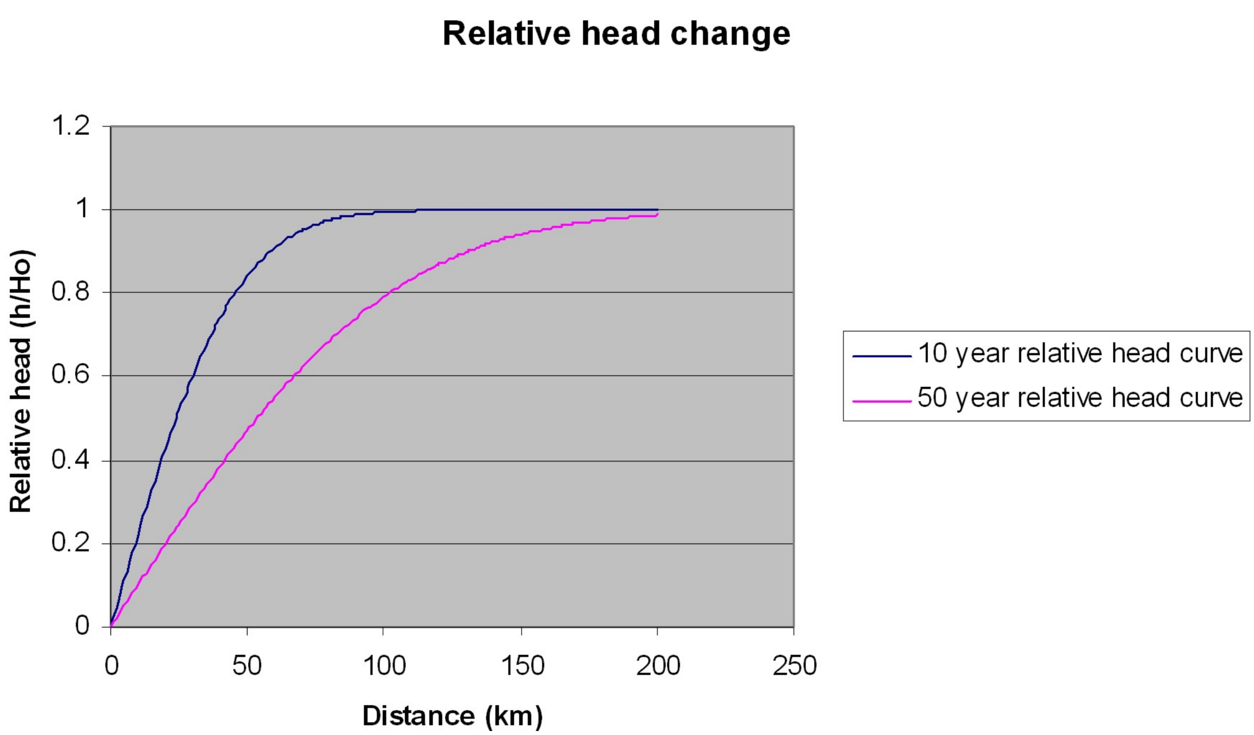

Figure 33. The buffer zone shown on Figure 34 as Zone IV is a 10-year buffer zone for a 5% tolerance on head change, as measured from the line where the lower Paskapoo Formation sandstones within a vertical distance of 200 m of the top of the Battle Formation are within 150 m of the ground surface.

70 km, or 7 townships from the point of disturbance. Areas greater than about 100 km, or 10 townships, are essentially unaffected and therefore are not considered to be in hydraulic continuity with the disturbance after 10 years. However, if the regulatory time horizon was instead 50 years, then the buffer zone is about 156 km, or almost 16 townships. Similar results are obtained by calculating distance-drawdown and time-drawdown graphs for radial flow to fictitious wells.

These calculations are made for demonstration only. If this approach were to be adopted, the estimations would need to be done using a range of possible values for T and S, as a minimum. A superior approach would employ a stochastic method, wherein the entire system is varied within the bounds of geological and hydrogeological uncertainty to assess the sensitivity of the pressure-response travel time and therefore hydraulic continuity within the system. This would highlight areas where hydraulic-continuity estimates are highly certain, as well as those areas where they are uncertain. These values could be cross-referenced with the consequences of undetected but undesired effects, and the costs of monitoring areas where nothing is likely to occur in terms of Raucher's (1983) economic framework, to guide final policy for groundwater protection.

Figure 34 shows, as Zone V, the area of the lower Paskapoo Formation west of the domestic water-well line where sandstone abundance is greater than 40% and the distance from the domestic water-well line is 70 km or less. This covers most of the Paskapoo Formation and thus may be overly conservative. If we instead identify only those parts of the lower Paskapoo with sandstone abundance of 60% or greater plus connectivity with the domestic water-well line, the resultant area is much smaller (Zone VI on Figure 35). In this case, the areas previously identified as Zones IV and V should be treated like Zone III because we would be saying that only sandstone abundances greater than 60% provide regional connectivity and continuity.

If a CBM reservoir underlies these areas and has reservoir pressure comparable in magnitude to the overlying lower Paskapoo Formation, then a preliminary groundwater assessment could help forecast the impact, if any, of CBM development on groundwater in aquifers in these areas and the contiguous parts of Zone II.

11) The areas marked as Zone VI on Figure 35 are likely significant aquifers inside the lower Paskapoo Formation west of the domestic water-well line. There are several areas where sandstone abundance is greater than 60% in the lower Paskapoo Formation west of the domestic water-well line but are separated from that line by areas of less than 60% sandstone abundance. These areas are marked as Zone VII on Figure 36. If a CBM reservoir underlies these aquifers and has reservoir pressure comparable in magnitude to the overlying lower Paskapoo Formation, then a preliminary groundwater assessment could help to forecast the impact, if any, of CBM development on groundwater in these aquifers within their mapped extents.

5 Reducing Uncertainty: Recommendations for Additional Work

Previous sections of the report have alluded to shortcomings in our understanding of the hydrogeological properties and internal architecture of the Paskapoo Formation, and the nature of its hydraulic connection with the Ardley Coal Zone. We recognize that these uncertainties are inherent in some of the core arguments for the strategy proposed for assessing risks from CBM development. The following issues require further work to reduce the uncertainties and increase confidence about risk assessment and management:

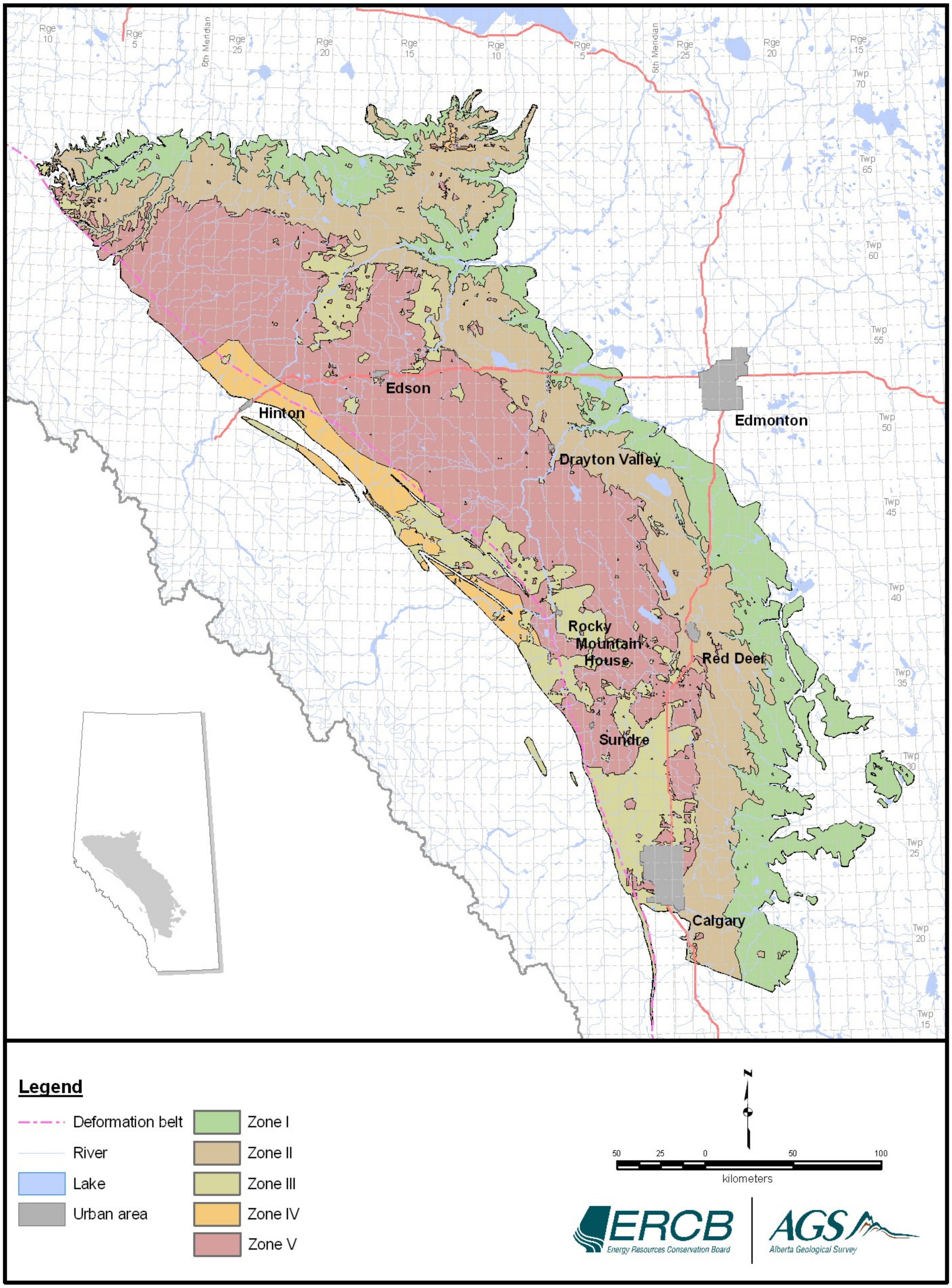

Figure 34. Areas included in a 70 km buffer zone based on 10-year hydraulic continuity where lower Paskapoo Formation (Haynes Member) sandstone abundance is greater than 40% west of the domestic water-well line (Zone V), plus all other zones.

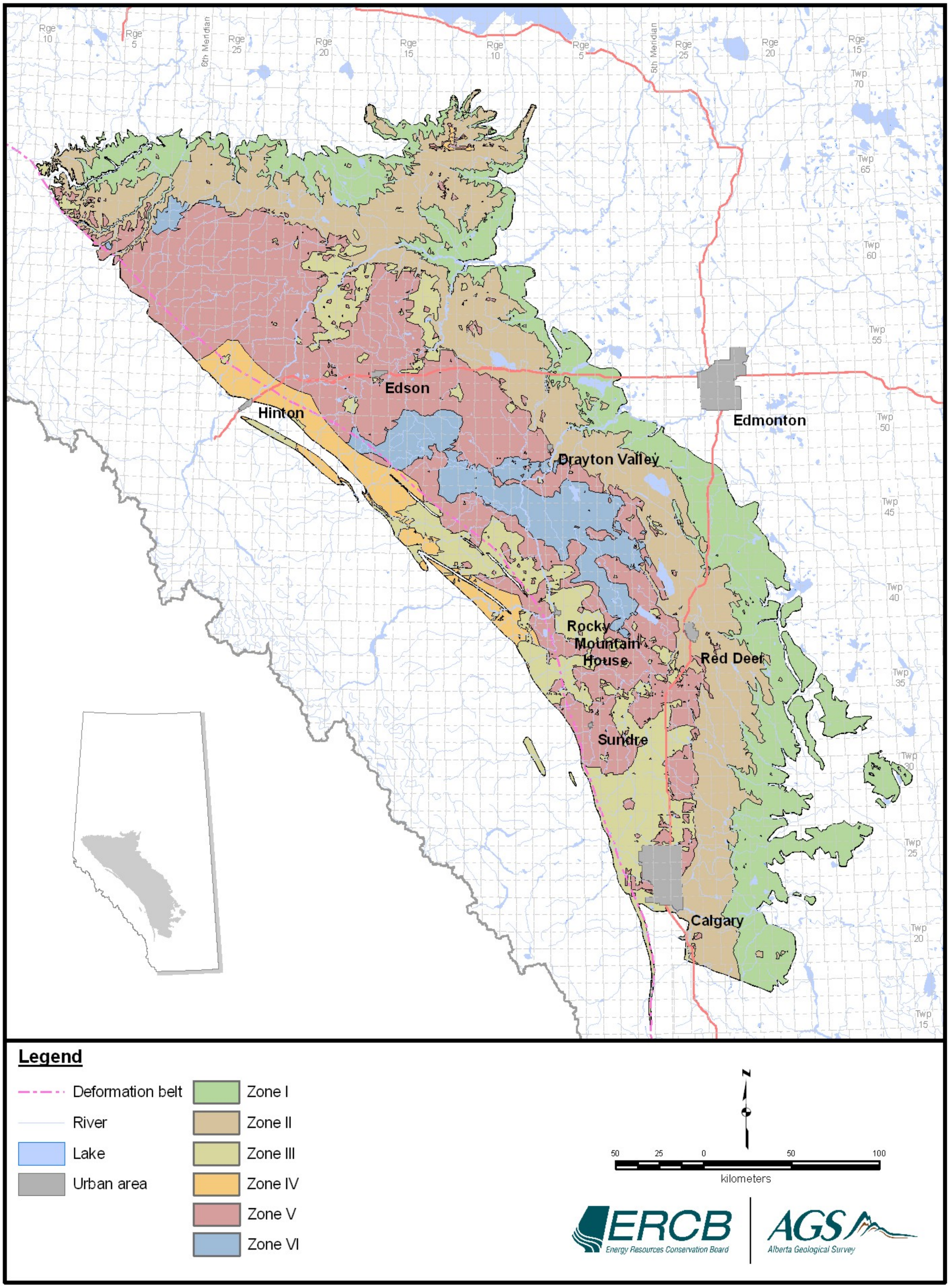

Figure 35. Areas where lower Paskapoo (Haynes Member) sandstone abundance is greater than 60% and contiguous with the domestic water-well line, and within the 10-year hydraulic continuity buffer zone based on 60% sandstone abundance (Zone VI), plus all other zones.

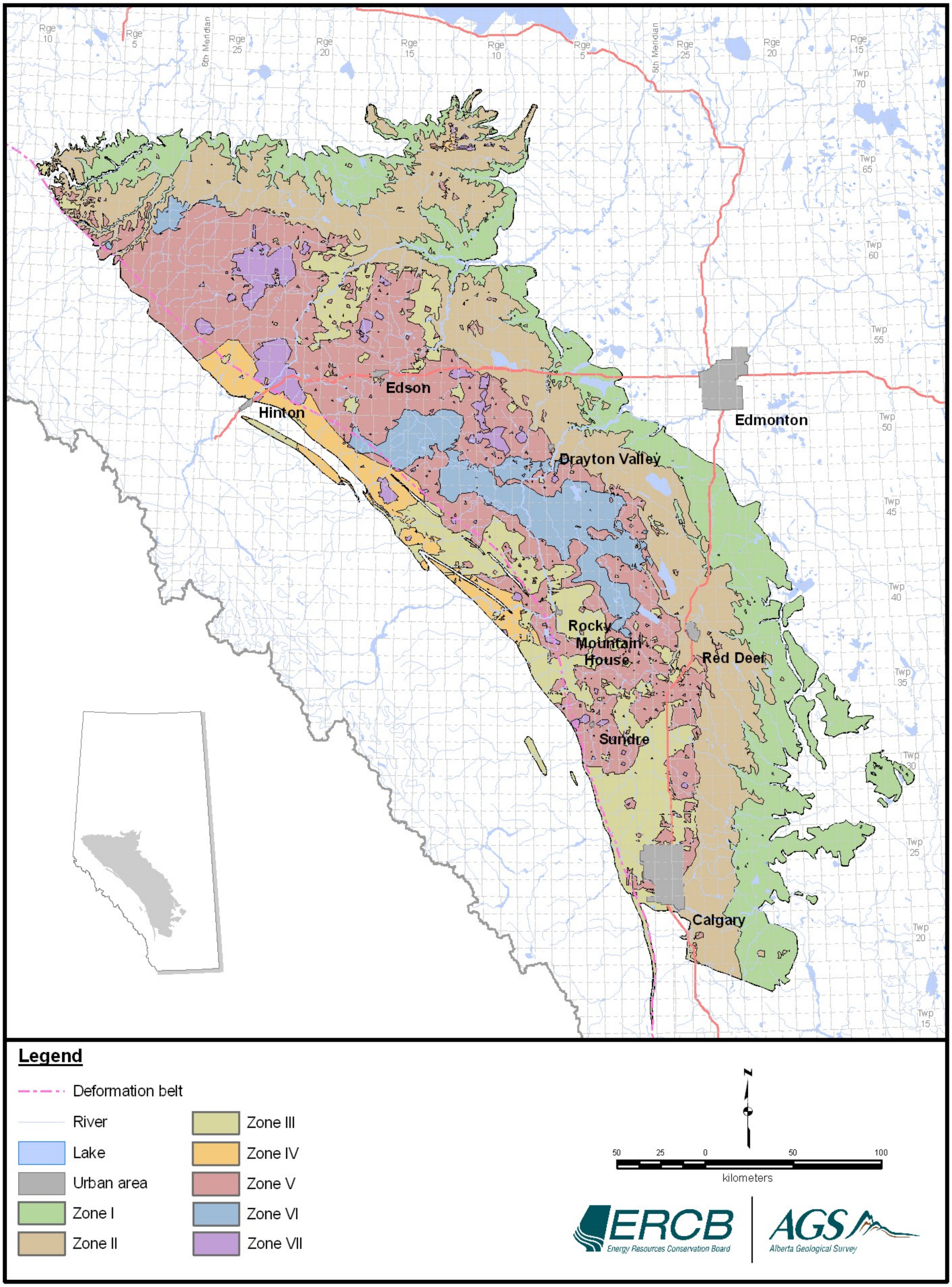

Figure 36. Areas where lower Paskapoo (Haynes Member) sandstone abundance is greater than 60% but not contiguous with the domestic water-well line (Zone VII), plus all other zones.

- The potential role of fractures in any model of hydraulic connectivity and continuity of the Paskapoo Formation needs to be evaluated, as fractures can be the foci for enhanced fluid flow and pressure migration several orders of magnitude greater than flow in porous, permeable media. Further study is needed to ascertain the nature and regional distribution of fractures and the influence they may have on groundwater flow, particularly in propagating pressures through mudstone-dominated rocks within the Paskapoo Formation.

- Current information indicates that whatever cleats, fractures or coarse-grained interbeds are present in the Ardley Coal Zone are not laterally connected enough for normal pressures to propagate laterally over significant regional distances over time scales of 10 000 years or less. In the case where Paskapoo Formation sandstone channels intersect Ardley coals and where formation pressures in the Ardley coals are at hydrostatic pressure, information is needed to establish estimates of the distance at which permeable beds in the coal zone cease to be hydraulically connected to Paskapoo sandstones. As well, the amount of water produced from those permeable zones needs to be evaluated to determine if the Ardley Coal Zone can supply water to local domestic users.

- Cross-plots of gamma-ray response and core-measured permeability showed that sandstones in core with gamma-ray response of 75 API units or less were reasonably permeable ($k > 0.1$ mD; Figure 11). Trial maps using 60, 75, and 90 API cutoffs also showed that the resulting maps best matched sandstone abundances as interpreted by AGS geologists on cross-sections when a 75 API cutoff was used. As this cutoff value is crucial to the construction of sand-abundance maps, additional work is needed to demonstrate that 75 API is the most suitable value for calculating sand abundance from digital gamma-ray logs.

- A refined sandstone-mudstone architecture is crucial when applying percolation theory to understand permeable interconnections and networks in the Paskapoo Formation. The conclusions stemming from our application of percolation theory assume hydraulic connectivity, or separation, based solely on the percentage of sand within 50 m thick slices on sand abundance maps. Following experimentation with different sand-slice mapping approaches, we chose to construct 50 m thick slices parallel to a structural datum (in this case, the top of the Battle Formation). We recognized that this choice builds in a bias by encouraging the assumption that the Paskapoo Formation beds were deposited parallel to the top of the Battle Formation. The progressive westward shift of sand abundances in the lower Paskapoo Formation with increasing slice thickness above the Battle Formation surface could indicate that the sandstone body is more horizontal than the slice-map framework used here, and that the westward shift is more likely an artifact of the slice-map framework than a characteristic of this sandstone body. Evaluation of other sand-slice mapping methods, possibly invoking geostatistical mapping approaches, and more detailed geological analysis are needed to characterize the geometry and origin these sandstone trends. The robustness of the sandstone-abundance thresholds controlling gas occurrences needs to be tested within different map frameworks.

- Improved estimation of uncertainty would allow consideration of policy alternatives in the cost-benefit framework of Raucher (1983), allowing more confidence for stakeholders that the efforts made to protect groundwater from presumed risks associated with CBM development are both sufficient and worthwhile.

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Appendix 1 — Raucher's (1983) Conceptual Framework for Measuring the Benefits of Groundwater Protection

The expected net benefits of an activity that would enhance groundwater protection are stated as

$$E(B_i)_{NET} = E(B_i) - X_i \qquad \text{(Equation A1)}$$

where

$E(B_i)$ = the expected social benefits B of protection strategy i; and
X_i = the social costs associated with implementation of that protection strategy.

The expected damages that may occur in the event of contamination are expressed as

$$E(D) = p(qC_r + (1-q)C_u) \qquad \text{(Equation A2)}$$

where

$E(D)$ = the expected cost of damages D to society due to contamination;
p = the probability in the absence of policy i that contamination will occur;
q = the probability that contamination will be detected before tainted water is used;
C_r = the expense of the most economically efficient response to contamination ($Cr > 0$); and
C_u = the cost incurred if contaminated water were used in the same manner as prior to the incident ($C_u > C_r$).

A policy i that reduces the probability that contamination will occur will increase the expected benefits of the protection strategy by

$$d(EB_i) = \frac{-dE(D)}{dp(i)} = -dp(i)[qC_r + (1-q)C_u] \qquad \text{(Equation A3)}$$

A policy j that increases the probability that contamination is detected will increase the expected benefit of the protection strategy by

$$d(EB_j) = -\frac{dE(D)}{dq(j)} = -dq(j)[p(C_u - C_r)]. \qquad \text{(Equation A4)}$$

Raucher (1983) derived these equations and provided an economic-analysis framework whereby groundwater-protection policy alternatives can be weighed in terms of net benefits to society.