Regional-scale hydrogeology of the Upper Devonian–Lower Cretaceous sedimentary succession, south-central Alberta basin, Canada

S. J. Anfort, Stefan Bachu, and L. R. Bentley

ABSTRACT

The flow of formation waters in the Upper Devonian–Lower Cretaceous sedimentary succession in the south-central part of the Alberta basin is controlled mainly by (1) outcrops of Devonian and Mississippian strata at high elevation in the south in Montana, and at low elevation at the Peace River in the north; (2) subcrops of Devonian to Jurassic strata at the sub-Cretaceous unconformity; and (3) deposition of Cretaceous sediments on pre-Cretaceous relief exposed for a long period of time. Weathering of Upper Devonian strata during this long period of subaerial exposure and the concurrent paleokarsting of the Grosmont Formation led to high permeability in these aquifers. As a result, the Grosmont aquifer and the Upper Devonian aquifer system that subcrop at the sub-Cretaceous unconformity form a drainage path in a northward regional-scale flow system in the southern and central parts of the Alberta basin. This long-range flow system is fed by meteoric recharge in the south, by updip flow of connate waters from deep Paleozoic aquifers that subcrop along the western flank of the main system, and by downdip meteoric recharge through Cretaceous strata along the eastern basin edge. A plume of relatively high salinity is formed in the Lower Mannville aquifer in the area where highly saline Devonian waters discharge at the sub-Cretaceous unconformity and mix with fresh water of meteoric origin.

Hydrocarbons generated in Upper Devonian to Lower Cretaceous strata of the deep foreland basin migrated northeastward updip, driven by buoyancy and supported by a concurrent hydrodynamic drive. The great majority of the generated hydrocarbons reached the sub-Cretaceous unconformity, where they were trapped in complex stratigraphic traps in the Lower Mannville Formation. Downward flow of meteoric water along

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the eastern flank of the basin hydrodynamically enhanced the trapping and led to hydrocarbon biodegradation in place into heavy oils and oil sands in the Cold Lake and Athabasca areas.

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INTRODUCTION

The flow of formation waters as a factor during the evolution of sedimentary basins and in the generation and accumulation of energy and mineral resources has long been established. In the last decade, many numerical models and basin studies have shown that the flow of formation waters is driven by various mechanisms, such as compaction, tectonic compression, erosional rebound, topography, and buoyancy (for a review see Bethke and Marshak [1990]). In a mature stage of exploration, the amount of data, collected commonly by the energy industry, allows a detailed analysis of basin hydrogeology and its effects on hydrocarbon generation, migration, and accumulation. This is the case of the Alberta basin, where more than 200,000 wells have been drilled and numerous studies have been performed to date, owing to the availability of data in the public domain through the Alberta Energy and Utilities Board (AEUB). Using this vast amount of information, many hydrogeological studies have been performed in the basin, particularly in the last decade. The basin, however, being very large and complex, has never being analyzed as a whole, but instead has been analyzed in a piecemeal fashion both stratigraphically and geographically. A previously postulated north-northeastward flow in Upper Devonian aquifers along the eastern edge of the Alberta basin (Bachu, 1995a) and its effect on hydrocarbon accumulations in this area have never been fully demonstrated. The flow pattern in this area was mainly inferred from either an extremely limited data base (Hitchon, 1969) or studies that were peripheral to or marginally overlapping with this area, such as the Peace River arch area to the northwest (Hitchon et al., 1989), the Athabasca area to the northeast (Bachu and Underschultz, 1993), and the Mississippian to Cretaceous succession to the west (Bachu and Underschultz, 1995). We present in this article the hydrogeology of the Upper Devonian–Lower Cretaceous succession in the south-central part of the Alberta basin in an area defined by long. 110–115°W, lat. 51°30′–56°N that covers approximately 325,000 km^2 (Figure 1). The results demonstrate indeed the existence of the postulated flow system from the southern part of the basin to northeast Alberta and that the Upper Devonian aquifers that subcrop at the sub-Cretaceous unconformity act as an internal drain. In addition, the hydrogeological analysis presents new insights regarding the accumulation and biodegradation of hydrocarbons into heavy oils and oil sands (bitumen) in the Lloydminster, Cold Lake, and Athabasca areas and the generation of biogenic gas in shallow strata in southern Alberta.

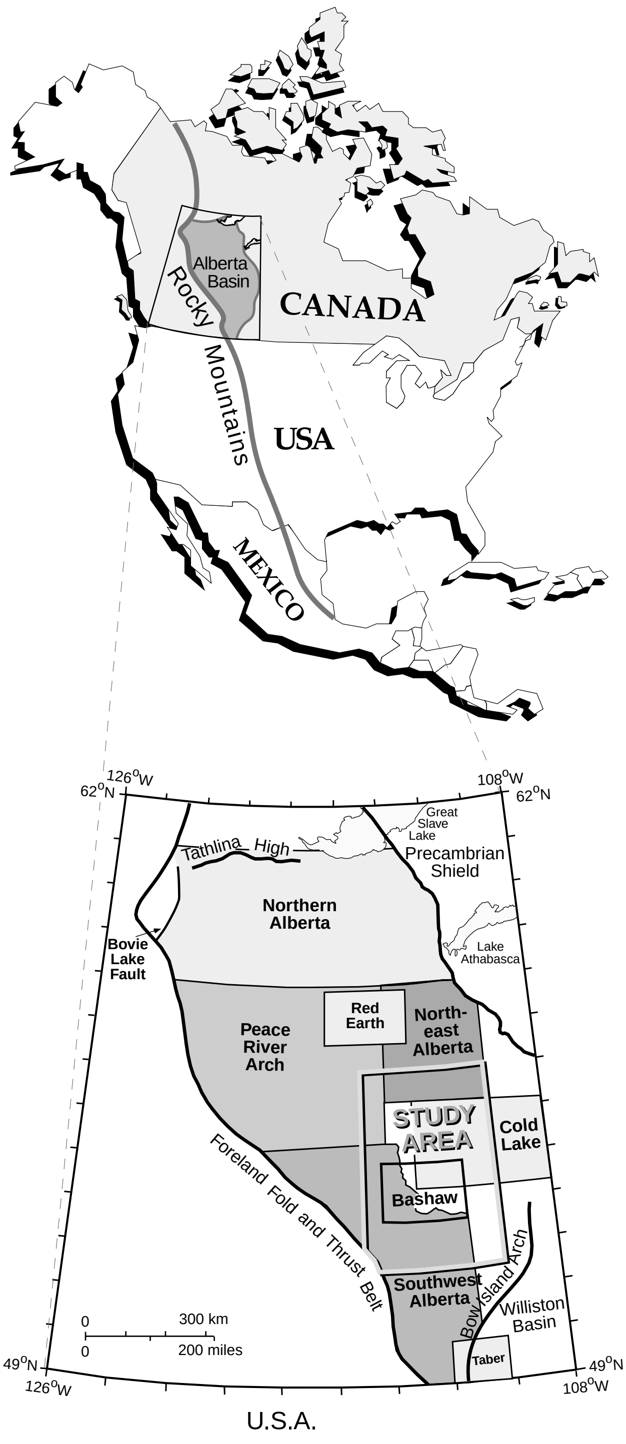


Figure 1. Location of the Alberta basin and of the study area. Previous regional-scale hydrogeological studies in the basin are Red Earth (Toth, 1978); Taber (Toth and Corbet, 1986); Cold Lake (Hitchon et al., 1989); Peace River arch (Hitchon et al., 1990); northeastern Alberta (Bachu and Underschultz, 1993); southwestern Alberta (Bachu and Underschultz, 1995); Bashaw (Rostron and Toth, 1996, 1997); and northern Alberta (Bachu, 1997).

SHORT HISTORICAL REVIEW

The Alberta basin sits on a stable Precambrian platform and is bounded by the Rocky Mountain trench to the west and southwest, the Tathlina high to the north, the Precambrian Canadian shield to the northeast, and the Williston basin to the east and southeast (Figure 1). It comprises a wedge of sedimentary rocks that increases in thickness from zero at the Canadian shield in the northeast to close to 6000 m in the southwest at the fold and thrust belt. The basin was initiated during the late Proterozoic by rifting of the North American craton. At its base it consists of a Middle Cambrian to Middle Jurassic passive-margin succession dominated by carbonates and evaporites that have some intervening shales (Porter et al., 1982). As a result of the accretion of allochthonous terranes to the western margin of the proto–North American continent, a foreland-basin succession follows, which is dominated by clastics, mainly shales. Pre-Cretaceous erosion partially removed older strata that subcrop in the undeformed part of the basin at the unconformity and increase in age from west to east. Tertiary to Holocene erosion has removed up to 3800 m of sediments in the southwest but only up to 1000 m in the north (Nurkowski, 1984; Kalkreuth and McMechan, 1988; Bustin, 1991). The present-day topography of the undeformed part of the basin has a general, basin-scale trend of decreasing elevations from highs in the 1200 m range in the southwest to lows around 200 m in the north-northeast at Great Slave Lake, which is the lowest topographic point in the basin.

Based on a small amount of then-available data, Hitchon (1969) analyzed the hydrogeology of the basin and concluded that the flow of formation waters is at steady state, in equilibrium with and driven from the southwest to the northeast by the present-day topography. Hitchon (1969) was the first to notice very low hydraulic heads in the Devonian Grosmont Formation and postulated that this carbonate aquifer acts as a basin-scale drain, directing the flow of formation waters from the south-southwest to northeast. Many regional-scale hydrogeological studies have been performed in the last two decades for various parts of the Alberta basin, reviewed by Bachu (1995a, 1999), and are not referenced here unless they are specifically relevant to this work. These studies led to a new conceptual model of the basin-scale flow of formation waters (Bachu, 1995a, 1997). According to this model, the flow in deep Cambrian and Middle Devonian strata in the southern and central part of the basin is postulated to be driven by past tectonic compression (Bachu, 1995a; Machel et al., 1996). In studies of the Cold Lake and Peace River arch areas and in northeastern Alberta, Hitchon et al. (1989, 1990) and Bachu and Underschultz (1993) identified the Grosmont aquifer as exerting a drawdown effect on Upper Devonian and Lower Cretaceous flow systems in the central part of the Alberta basin. A study of formation waters in Lower Cretaceous strata in southern Alberta (Cody and Hutcheon, 1994) shows that there is a northward decrease in hydraulic potential concurrent with an increase in salinity and progressive isotopic enrichment, all indicative of aquifer recharge from the south in Montana. Based on these and other studies for southern and southwestern Alberta (Toth and Corbet, 1986; Corbet and Bethke, 1992; Bachu and Underschultz, 1995), Bachu (1995a) postulated that the flow in Upper Devonian to Mississippian strata along the central-eastern basin edge is driven northward by basin-scale topography. The formation waters flow in a long-range system from recharge at outcrop of Devonian and Mississippian strata in northern Montana to discharge in northeastern Alberta at outcrop of Devonian strata at Peace River and near Lake Athabasca (Figure 1). Bachu (1995a) assumed that the main conduit for the flow of formation water in this system is formed by Upper Devonian carbonate aquifers that subcrop along the sub-Cretaceous unconformity and by the Grosmont aquifer. The latter crops out at an elevation of approximately 250 m along Peace River. Bachu (1995a) also postulated that this regional-scale flow system is fed laterally along its western flank by updip flow in Upper Devonian and Mississippian aquifers. Continuing higher up in the sedimentary succession, the flow in Cretaceous strata in southwestern Alberta is driven inward by erosional rebound in thick shales. Finally, near-surface flow is driven by local topography. Cross-formational flow in Devonian strata was identified in places in west-central and northeastern Alberta where carbonate reefs breach through shaly aquitards (Toth, 1978; Bachu and Underschultz, 1993; Rostron and Toth, 1996, 1997).

The previous studies cover the entire sedimentary succession in the central, northeastern, northern, and southwestern parts of the basin (Figure 1). In the south-central part, the Devonian succession has not been studied except for the Bashaw and Taber areas. The results we present in this article identify the Upper Devonian aquifers that subcrop at the sub-Cretaceous unconformity as a northward flow path for formation waters and clarify that the Grosmont aquifer acts as a regional-scale, long-range drain. Implications for hydrocarbon accumulations along the eastern flank of the Alberta basin are inferred based on the flow pattern and previous geochemical studies.

DATA SOURCES AND PROCESSING

All the data used in this article were obtained from the Alberta Geological Survey (AGS) of the AEUB. The geological framework of the sedimentary succession in the area of interest was constructed using stratigraphic picks from 23,587 wells drilled in the study area. Based on the concept of control surfaces, the units of interest were mapped either directly from structure tops or indirectly from isopachs using the methodology outlined in Bachu et al. (1987). Accordingly, we used major geological events, stratigraphy, and lithology to identify the major hydrostratigraphic units relevant at the study scale, then we mapped each unit individually, and finally we assured the internal self-consistency of the resulting three-dimensional framework.

In Alberta, test companies report the mechanical success of a drillstem test (DST), therefore the quality of the pressure recorded, using letter codes that signify best quality (A), nearing stabilization (B), possible plugging (C), questionable (D), low permeability and low pressure (E), and low permeability and high pressure (F). The DST report also indicates the nature of the dominant fluid recovered: water, oil, gas, or mud. Formation pressures in the Upper Devonian–Lower Cretaceous succession were calculated only from A and B quality DSTs that recovered formation water. In addition, although the A and B are the highest quality tests, the set was manually culled for erroneous and/or incomplete data recording, very large testing interval ($>$ 100 m) or testing of several aquifers, insufficient shut-in time for pressure stabilization, and pressure-induced drawdown (PID) from adjacent producing wells. The PID culling is based on the time since production started in adjacent wells, the distance between producing and tested wells, and the production rate in producing wells (Toth and Corbet, 1986; Barson, 1993). Permeability values were calculated only from the 811 DSTs that have sufficient data (Bachu et al., 1987) for the carbonate Grosmont, Mississippian, and Wabamun aquifers. Permeability values were not calculated and analyzed for the Lower Mannville aquifer because of the complex nature of its geology, stratigraphy, and lithology.

We used standard formation water analyses collected by the industry and submitted to AEUB and culled them using automatic and manual methods (Hitchon and Brulotte, 1994; Hitchon, 1996; Bachu et al., 1987). We allocated the remaining 5976 formation analyses, the 8335 DSTs that passed culling, and the permeability values into the hydrostratigraphic framework that was constructed previously based on stratigraphic picks and lithology of the respective units. Finally, we mapped the corresponding distributions of hydraulic head (H), permeability, salinity (total dissolved solids), and chloride (Cl) and bicarbonate (HCO_3) concentrations and used these in the analysis and interpretation of the hydrogeological regime of formation waters in the Upper Devonian–Lower Cretaceous succession in south-central Alberta.

GEOLOGY AND HYDROSTRATIGRAPHY OF THE STUDY AREA

The geology of the sedimentary succession described herein for the study area is based on the *Geological Atlas of the Western Canada Sedimentary Basin* (Mossop and Shetsen, 1994). Given the general hydraulic properties (mainly permeability) of various rock types, lithology is a fairly good indicator of hydrostratigraphy. The hydrodynamic and hydrochemical data from DSTs and analyses of formation waters confirmed the initial hydrostratigraphic delineation.

The stratigraphic succession of interest (Figure 2) is underlain by the thick Ireton Formation shales of the Upper Devonian Woodbend Group and overlain by the shales of the Lower Cretaceous Clearwater For-

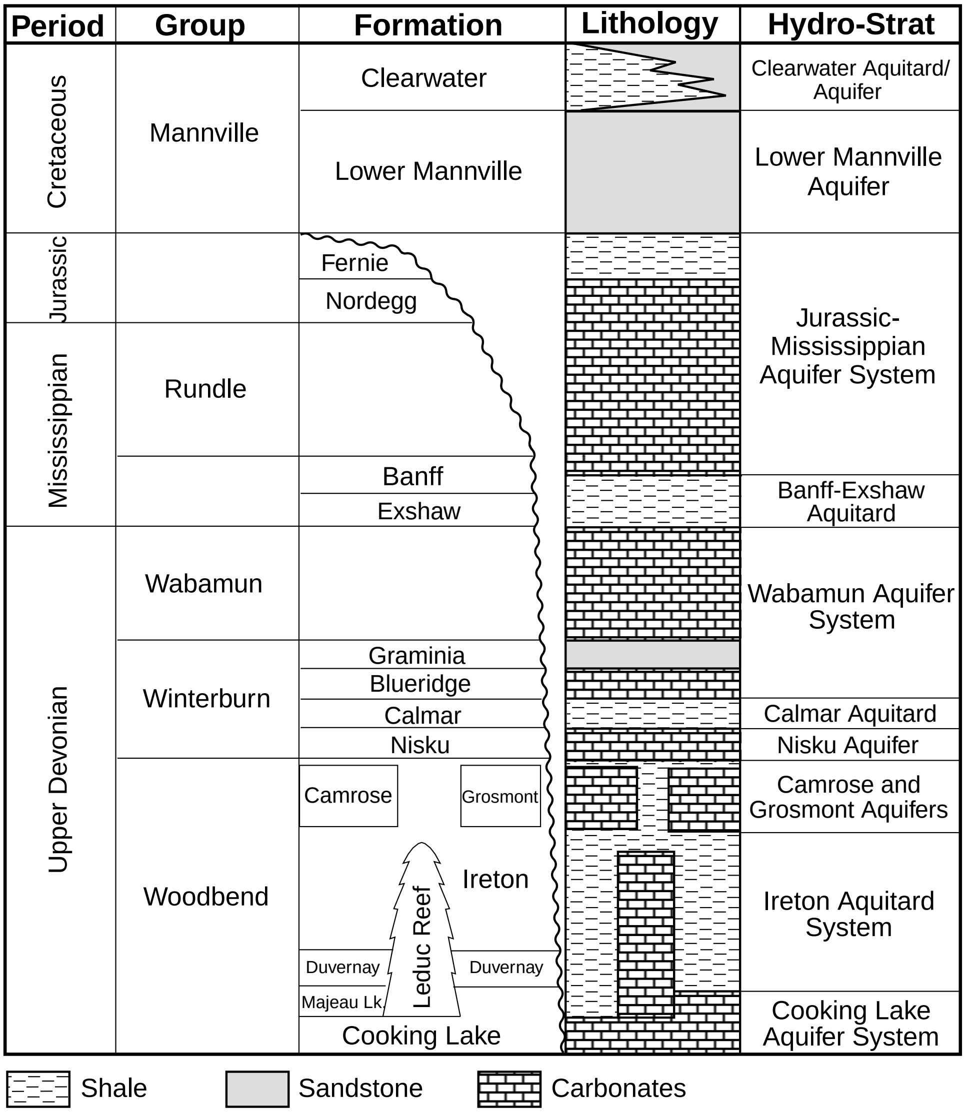


Figure 2. Relevant regional-scale stratigraphic and hydrostratigraphic delineation and nomenclature in the south-central part of the Alberta basin.

mation that both form regional-scale strong aquitards (Hitchon et al., 1989, 1990; Bachu and Underschultz, 1993, 1995). The entire Mannville Group is overlain by shales of the Colorado Group, which form a confining aquitard system in the southern part of the study area where the Clearwater Formation is absent. The Upper Devonian Woodbend Group consists of several formations (Figure 2) that were deposited during a series of transgressive-regressive sea level changes. The transgressive events resulted in the aggradation of shelf carbonates (Cooking Lake, Camrose, and Grosmont formations) and the growth of the Leduc Formation reefs fringing the shelf margin of the Cooking Lake platform (Figure 3a). The Cooking Lake and Leduc carbonates form the Cooking Lake aquifer system. The infill shales of the Majeau Lake, Duvernay, and Ireton formations were deposited during regressive phases and form a single, very thick (up to 300 m) aquitard system (Figure 2). The Camrose and Grosmont dolomitized carbonates are partially present in the southern and northern parts of the study area, respectively, and form isolated aquifers embedded in the Ireton aquitard system. Their boundaries are not well defined, and until this study it was unclear whether they are in hydraulic continuity. An extensive paleokarst system is present in the Grosmont Formation, characterized by dissolution cavities, collapse breccia, sinkholes, and fractures (Dembicki and Machel, 1996). These features enhance the permeability of the Grosmont Formation. The underlying Ireton shales form a strong aquitard, but the Upper Ireton shales overlying the Grosmont aquifer are very thin (up to 10 m) and incompetent, and at some locations they are only a weak aquitard.

The subsequent sea transgression resulted in the deposition of the dolomitized carbonates of the Nisku Formation (Winterburn Group), which range in thickness from 40 m in the southwest to 80 m in the northeast and form a good aquifer. Regionally the Nisku aquifer is separated from the underlying Cooking Lake aquifer system by the thick intervening Ireton aquitard system and from the Grosmont and Camrose aquifers by the thin intervening Upper Ireton shales. The Nisku aquifer is locally in direct hydraulic communication with the Cooking Lake aquifer system in places where pinnacle Leduc Formation reefs breach through the Ireton shales or where the Ireton shales above Leduc reefs are very thin and brecciated (Bachu and Underschultz, 1993; Rostron and Toth, 1996, 1997). In the northern part of the study area, the Grosmont aquifer provides a local communication path between the underlying Cooking Lake–Leduc aquifer system and the Nisku aquifer in isolated places where Leduc reefs breach through the Ireton aquitard and where the Upper Ireton shales are thin to absent (Figure 3c).

The Nisku aquifer is overlain by very thin evaporitic cycles at the top of the formation and by the siltstones and shales of the Calmar Formation. Together they form the thin (5–15 m) Calmar aquitard (Figure 2). The Calmar Formation becomes dolomitic in the area of the Bashaw reef complex, suggesting that, at least locally, the Calmar aquitard is weak. The Calmar Formation is successively overlain by the dolomitized Blueridge Formation and the sandstones interbedded with siltstones of the Graminia Formation. Both are aquifers that have a combined thickness ranging between 20 and 40 m. Renewed transgression at the end of the Devonian led to deposition of the thick carbonates of the Wabamun Group, which range in thickness between 160 and 260 m in the uneroded part of the unit. Owing to the increasing presence of anhydrite in the southeastern part of the study area, the Wabamun Group may exhibit locally an aquitard behavior. As a result of direct contact and hydraulic continuity at the scale of the study area, however, the entire Upper Devonian Blueridge-Wabamun succession exhibits aquifer properties, as demonstrated by distributions of hydraulic head, permeability, and salinity, and forms a single aquifer system called the Wabamun aquifer system (Figure 2).

Mississippian strata, ranging in thickness from 200 m in the southwest to approximately 100 m at the subcrop edge, were deposited unconformably on the Wabamun Group as series of transgressive-regressive cycles. The first cycle deposited the organic-rich, black shales of the Exshaw Formation and the Banff Formation. The Lower Banff is dominated by shales, whereas the Upper Banff is dominated by carbonates. The following cycle resulted in the deposition of the extensively dolomitized platform carbonates of the Rundle Group. The Jurassic platform carbonates of the Nordegg Formation unconformably overlie Mississippian strata and comprise most of the Jurassic sediments preserved in the area, except for a thin wedge (< 40 m) of Fernie shales in the southwest corner of the study area. The Exshaw and Lower Banff shales form the Banff-Exshaw aquitard, whereas the Upper Banff, Rundle Group, and Jurassic strata, which are in hydraulic contact, form the Jurassic–Mississippian aquifer system (Figure 2).

Isostatic flexure of the lithosphere during the Columbian orogeny, which started during the middle-late

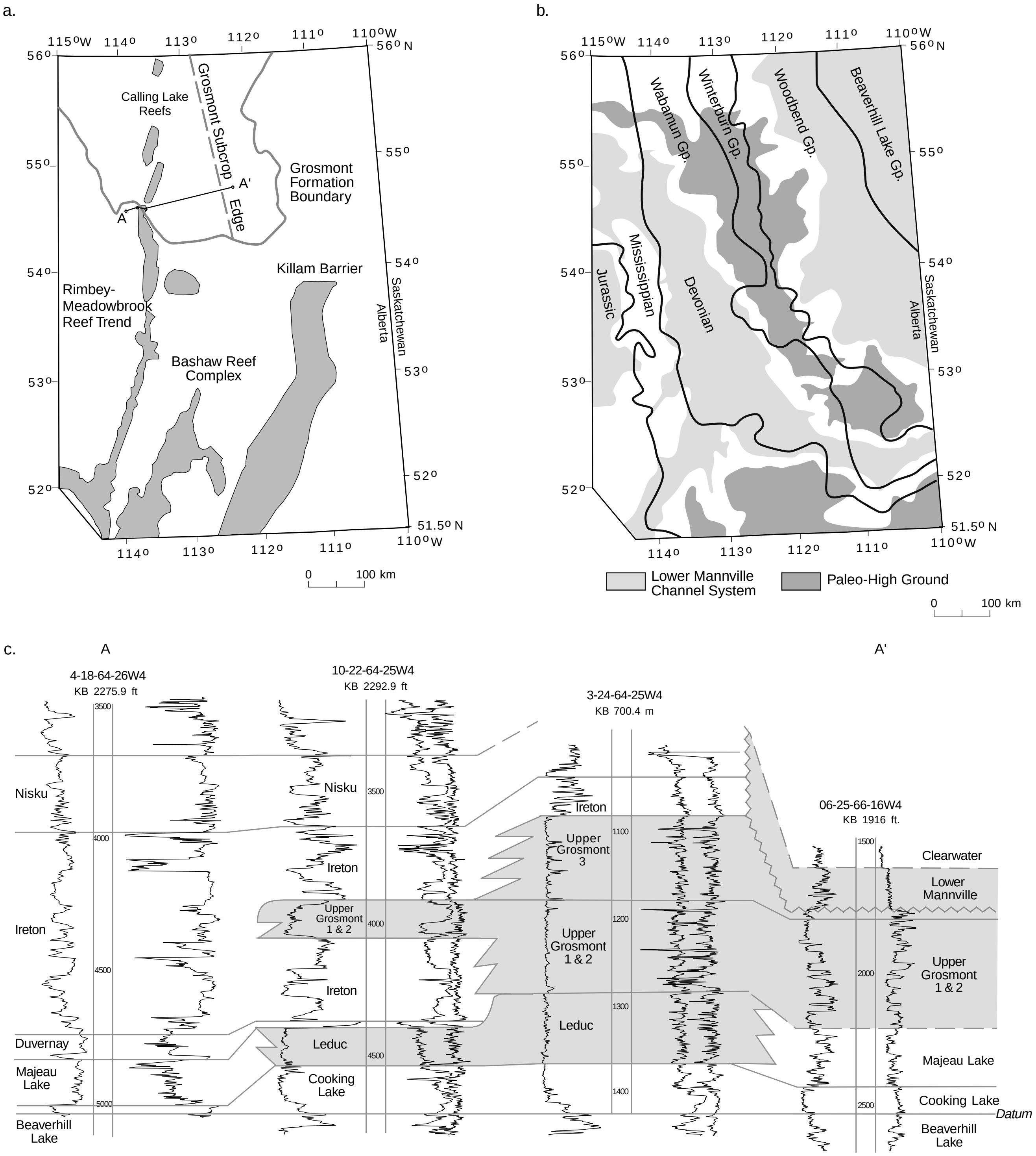


Figure 3. Significant geological features in the study area. (a) Location of the reefs of the Leduc Formation underlying the Upper Devonian–Lower Cretaceous succession of interest. (b) Formations subcropping at, and paleorelief on, the sub-Cretaceous unconformity. (c) Local stratigraphic cross section showing direct hydraulic communication across the entire succession between the underlying Cooking Lake–Leduc aquifer system and the Grosmont, Nisku, and Lower Mannville aquifers, as emphasized by the shaded area.

Jurassic, caused westward dipping and significant pre-Cretaceous erosion that exposed successively older strata from southwest to northeast and created relief and major river valley systems on the unconformity surface (Figure 3b). The following Mannville Group depositional succession consists of alluvial, fluvial, estuarine valley fill, and deltaic sandstones and sheet sands and shales deposited by repeated marine transgressive-regressive events. Lower Mannville strata, comprised mainly of fluvial and deltaic sediments, were deposited on the sub-Cretaceous unconformity surface in a series of northwest-trending drainage systems formed around exposed highlands of Jurassic to Upper Devonian age (Figure 3b) (Jackson, 1984; Pemberton and James, 1997). The channels and the highlands systems coincide with the thickest (up to 150 m) and the thinnest (< 50 m) accumulations, respectively. The Lower Mannville strata form an aquifer overlying the Jurassic to Middle Devonian succession of aquifers and aquitards that subcrop at the sub-Cretaceous unconformity, providing lateral hydraulic communication between aquifers that otherwise are separated by intervening aquitards in the uneroded part of each hydrostratigraphic unit. Continued transgression from the northwest inundated the fluvial system with onlapping sequences of marine sand and shale deposits of the Upper Mannville Clearwater Formation (Jackson, 1984; Pemberton and James, 1997). The shales of the Clearwater Formation form an aquitard that separates the Lower and Upper Mannville aquifers. The sands of the Clearwater Formation are present only along the southern part of the study area, where the entire Mannville Group forms a single aquifer confined by the overlying Colorado Group. The latter corresponds to a lull in tectonic plate convergence and is characterized by a widespread marine transgression and associated deposition of thick shales interspersed with thin sheet sands.

HYDROGEOLOGY

The hydrogeological analysis of the Upper Devonian to Lower Cretaceous strata in southeastern Alberta is based on distribution maps per hydrostratigraphic unit of equivalent freshwater hydraulic head, salinity, and HCO_3. We used formation pressures from DSTs to calculate the equivalent freshwater hydraulic head, H_0:

$$H_0 = p/(\rho_0 g) + z$$

where z is elevation relative to the sea level, p is the formation pressure, $\rho_0 = 1000 \text{ kg/m}^3$ is the density of fresh water, and g is the gravitational constant. The impelling force that acts on a unit mass of a variable-density fluid has a component that derives from a potential field and a component that is the result of density differences, or buoyancy (Hubbert, 1953; Bachu, 1995b). We used the driving force ratio (DFR) between the buoyancy and potential components (Bachu, 1995b) to assess the accuracy of flow directions inferred from the hydraulic head distributions. A low DFR value indicates that the potential flow component dominates and that buoyancy effects are negligible. In this case, the flow field is well represented by hydraulic-head distributions, without significant errors (Bachu, 1995b). A high DFR value indicates that buoyancy effects are important and that their neglect introduces errors in representing the flow pattern by using hydraulic heads alone. Over most of the study area the DFR values are low ($\text{DFR} < 0.5$) as a result of high hydraulic gradients (in recharge zones), mild aquifer slope (in the central and eastern parts of the study area), and low or moderate salinity. Accordingly, flow directions inferred from freshwater hydraulic heads are accurate (Davies, 1987), except at locations shown in Figures 4a, 5a, 6a, 7a, and 8a. The cases where DFR is greater than 0.5 are discussed individually for each aquifer, and the effect of neglecting buoyancy effects in the analysis is discussed in the section on flow synthesis. Hydraulic gradients, which represent the slope of a potentiometric surface (hydraulic head distribution), indicate the flow direction and strength. Closely spaced contours on a potentiometric surface indicate high hydraulic gradients that are commonly the result of high resistance to flow caused by low rock permeability.

Woodbend Group Aquifers

The aquifers in the Woodbend Group are the basal Cooking Lake aquifer system and the Camrose and Grosmont, which are separated by the intervening Ireton aquitard system (Figure 2). Although initially we intended to study only the post-Woodbend to Lower Mannville succession, we found that the Grosmont and Camrose aquifers must be included in the study because of the real or potential hydraulic continuity between these two and the overlying succession.

The Camrose aquifer is present off-center in the eastern-central part of the study area. Hydraulic heads range from between greater than 700 m in the

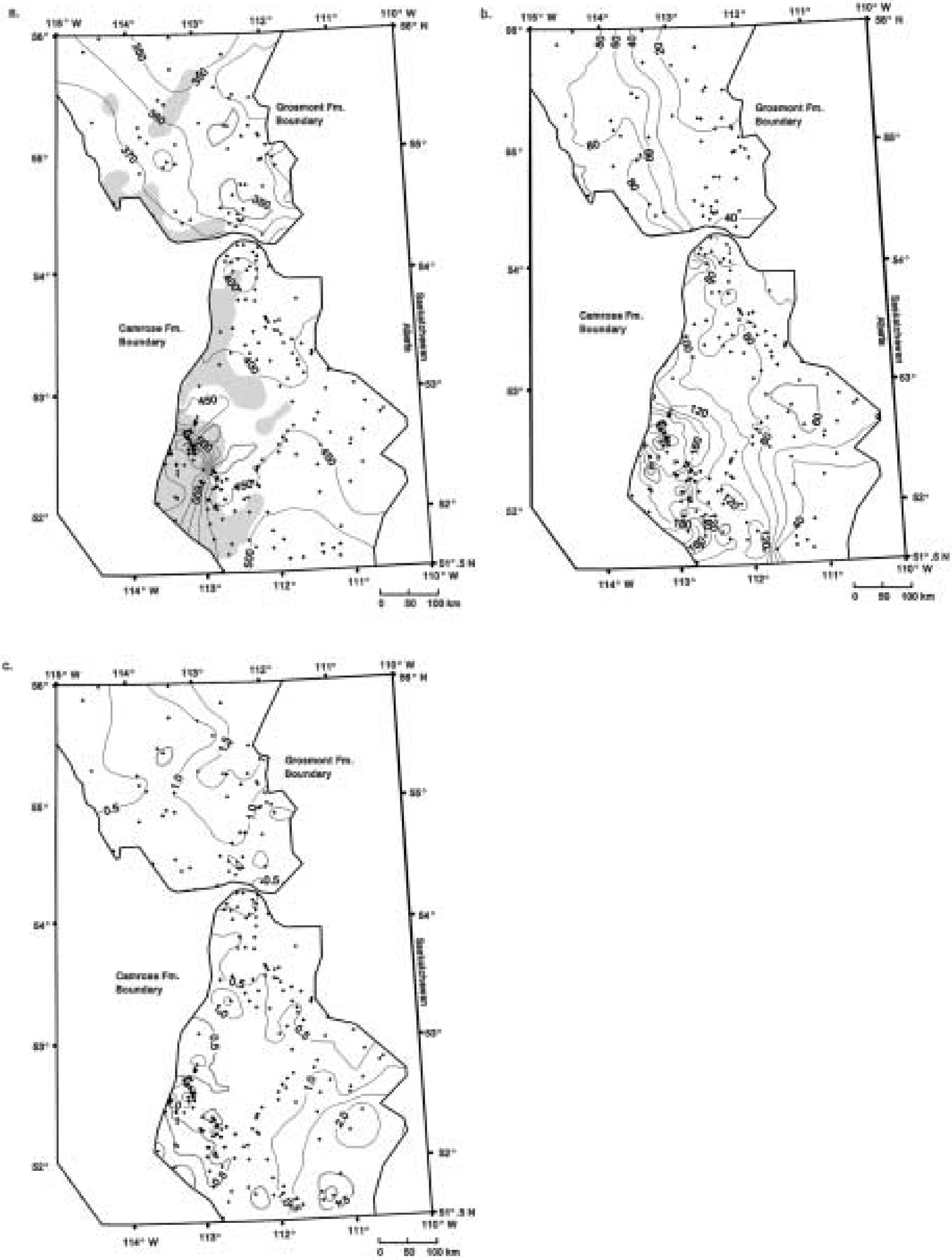


Figure 4. Hydrogeology of the Camrose and Grosmont aquifers. (a) Distribution of hydraulic head (in meters) showing flow toward the low at the northern edge of the study area. The shaded area indicates the region where DFR is greater than 0.5. Note the different contour intervals used for the Grosmont and Camrose aquifers because of vastly different ranges in hydraulic heads. (b) Salinity distributions (g/L) showing an updip, northeastward decrease in concentration. (c) Bicarbonate distribution (g/L) showing relatively high concentrations in the north and in the southeast.

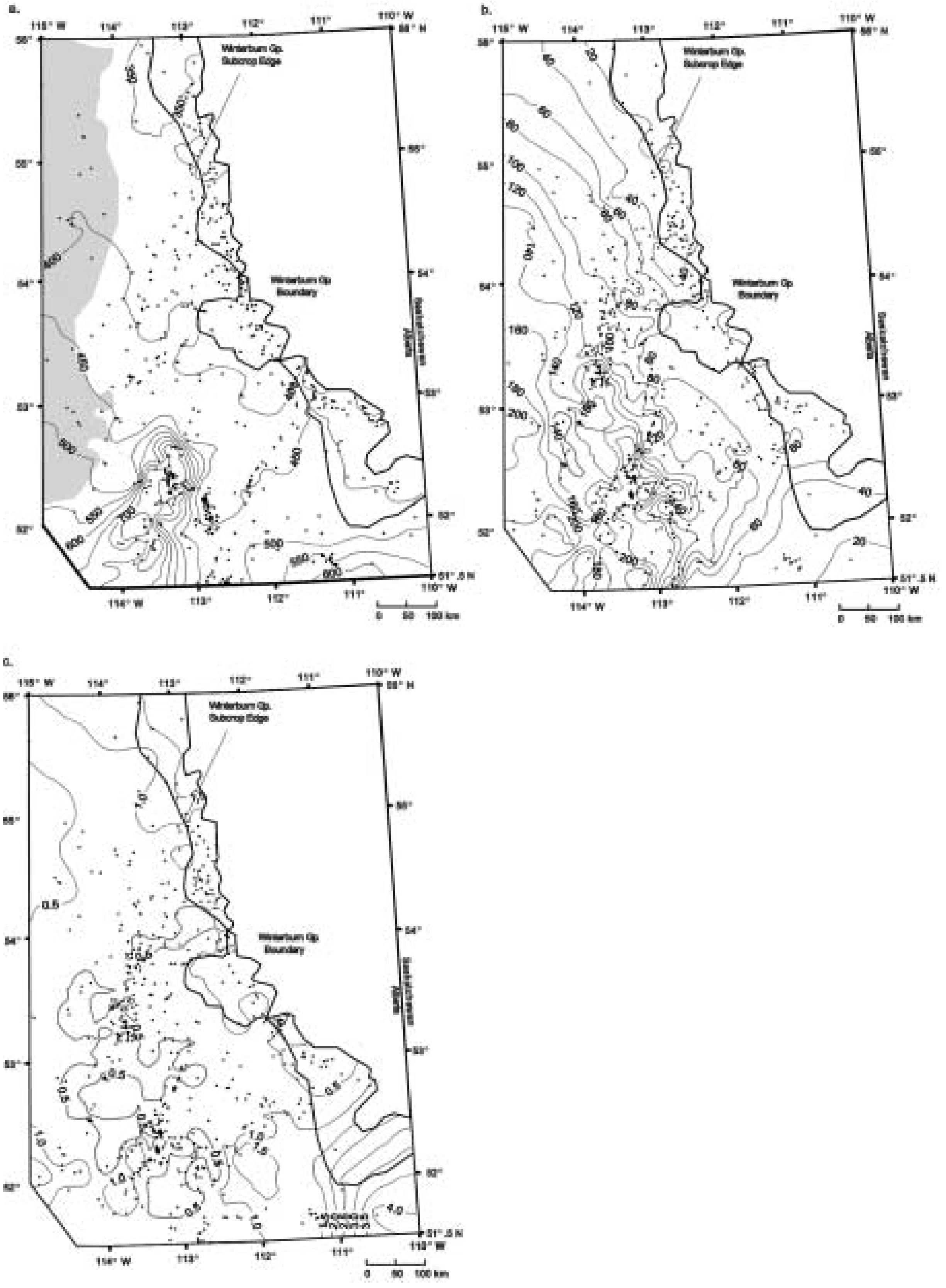


Figure 5. Hydrogeology of the Nisku aquifer. (a) Distribution of hydraulic head (in meters) showing flow from the southeast, southwest, and Bashaw area toward the subcrop area and to the north. The shaded area indicates the region where DFR is greater than 0.5. (b) Salinity distribution (g/L) showing a general updip, northeastward decrease in concentration and low concentrations in the southeast. (c) Bicarbonate distribution (g/L) showing relatively high concentrations in the north and in the southeast.

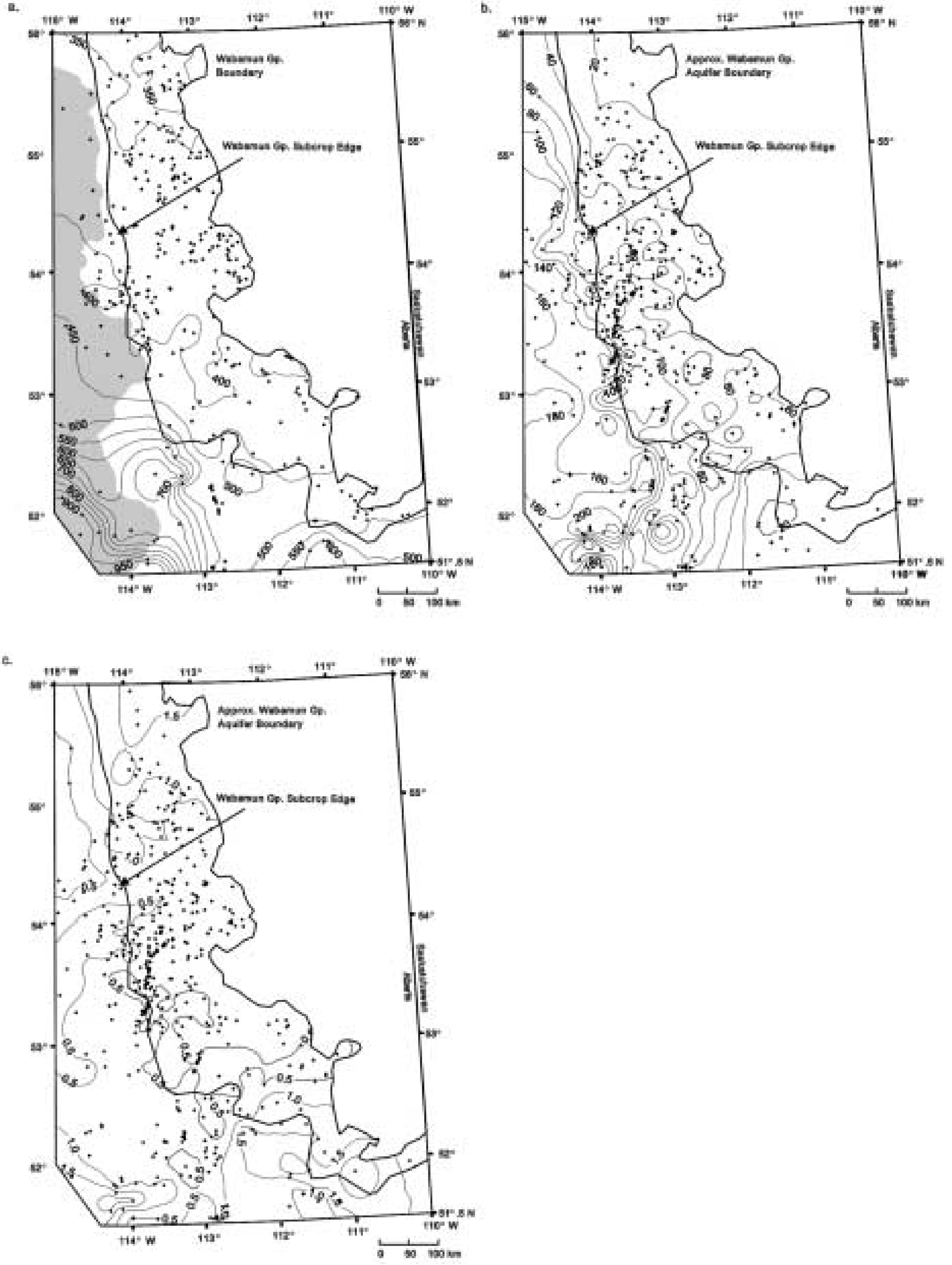


Figure 6. Hydrogeology of the Wabamun aquifer system. (a) Distribution of hydraulic head (in meters) showing flow from the southwest and southeast toward the subcrop area and to the north. The shaded area indicates the region where DFR is greater than 0.5. (b) Salinity distribution (g/L) showing a general updip, northeastward decrease in concentration and low concentrations in the southeast. (c) Bicarbonate distribution (g/L) showing relatively high concentrations in the north and in the southeast.

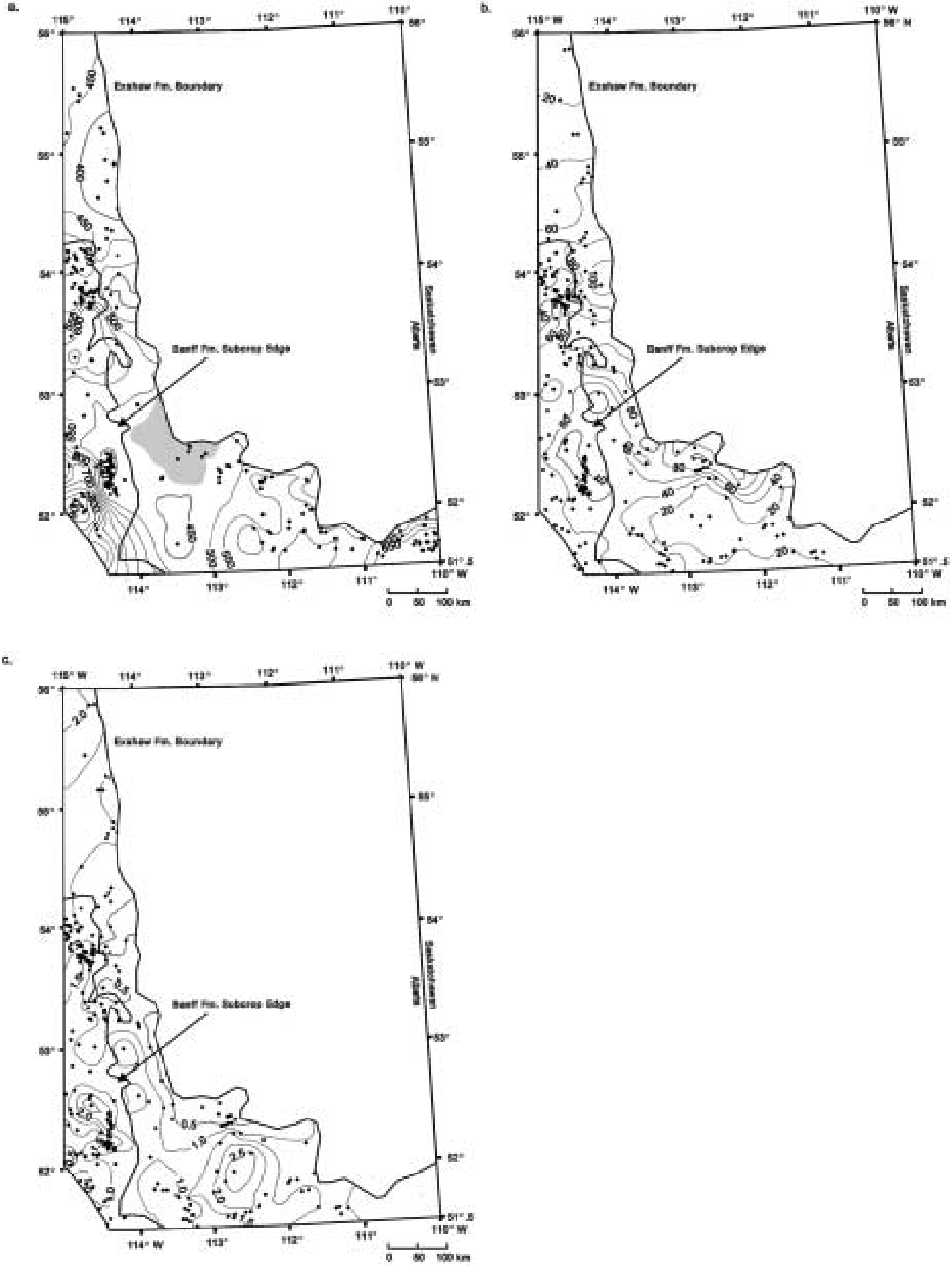


Figure 7. Hydrogeology of the Jurassic–Mississippian aquifer system. (a) Distribution of hydraulic head (in meters) showing flow from the southwest and southeast toward the subcrop area. The shaded area indicates the region where DFR is greater than 0.5. (b) Salinity distribution (g/L) showing a plume of high concentration along the subcrop area in the southwest. (c) Bicarbonate distribution (g/L) showing relatively high concentrations in the south and northwest.

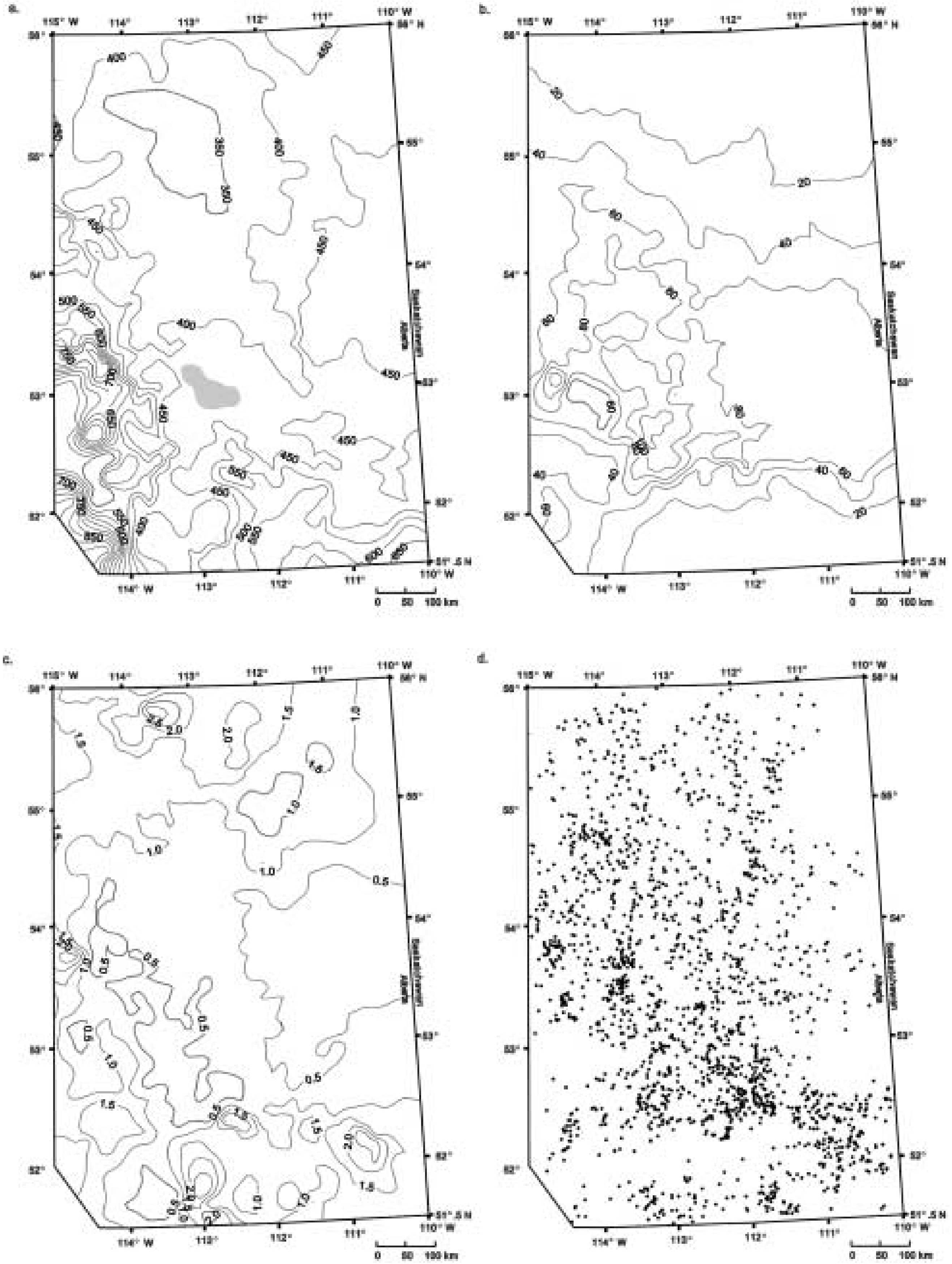
southwestern part of the aquifer and greater than 500 m in the south to slightly less than 400 m at its northern edge, indicating flow directed to the north-northeast (Figure 4a). Salinity ranges from approximately 180 g/L in the southwest, in the area of the Bashaw reef complex of the underlying Cooking Lake aquifer system, to slightly less than 60 g/L at its northern tip and approximately 40 g/L in the southeastern corner of the aquifer (Figure 4b). High hydraulic head and salinity values in the Bashaw reef area in the southwest suggest recharge of this aquifer by connate waters from the underlying Cooking Lake aquifer system through either still unidentified breaching reefs or thin, brecciated thin shales (Rostron et al., 1997). Recharge by fresher, meteoric water in the southeast, originating probably at outcrop regions further to the south in Montana, is indicated by the higher hydraulic head, low salinity, and high HCO_3 values (Figure 4c) in this area. Buoyancy effects are significant ($DFR > 0.5$) along the western edge of the aquifer, where cross-formational flow occurs from the highly saline underlying Cooking Lake aquifer.

The Grosmont aquifer is present in the north-northwestern part of the study area. Hydraulic heads range very narrowly, between slightly more than 370 m in the west and slightly less than 350 m in the north (Figure 4a). Hydraulic gradients are very low, indicating very high permeability most probably due to dolomitization and karstification during the lengthy period of exposure prior to Cretaceous deposition (Dembicki and Machel, 1996). The flow direction is basically north-northeastward, toward discharge further to the north along its outcrop at the Peace River (Bachu and Underschultz, 1993). Salinity ranges between greater than 80 g/L along the western aquifer edge and less than 20 g/L in the northeast (Figure 4b). The salinity distribution generally parallels the aquifer structure, indicating that at least some component is related to depth. The distribution of HCO_3 increases in value from less than 0.5 g/L along the western edge of the aquifer to greater than 1.5 g/L in the northeast, opposite to the salinity trend. The low salinity and high HCO_3 in the northeast indicate recharge by fresh meteoric water from the overlying Lower Mannville aquifer through the intervening thin, weak Upper Ireton aquitard. High salinity in the southwest (Figure 4b) corresponds to similar salinity values in the underlying Cooking Lake aquifer system. Here the two aquifers could be in hydraulic communication through breaching reefs like the ones in the Bashaw area (Rostron and Toth, 1996, 1997) and the one shown in Figure 3c. The large hydraulic-head drop (more than 40 m) and salinity difference (~ 20 g/L) between the northern tip of the Camrose aquifer and the southern tip of the Grosmont aquifer indicate that these two aquifers are not in direct hydraulic contact. The hydrogeological evidence indicates that the two aquifers, whose boundaries are poorly constrained in this area, are separated and that the isolated Camrose aquifer discharges laterally into the Grosmont aquifer through the intervening Ireton aquitard.

Nisku Aquifer

High hydraulic heads (> 750 m) and hydraulic gradients are located in the Nisku aquifer in the southwest (Figure 5a), geographically coincident with the Bashaw reef complex in the Cooking Lake aquifer system, where hydraulic heads are on the order of greater than 800 m (Rostron et al., 1997). Another local high (< 600 m) is situated in the southeast corner. The lowest hydraulic heads (< 350 m) are located in the north (Figure 5a) and coincide geographically with the area of similar hydraulic-head values in the underlying Grosmont aquifer (Figure 4a). On a broad regional scale, the main flow direction is northward. In the southeast the flow direction is directly northward, whereas in the southwest the flow is oriented generally updip northeastward. Except for the Bashaw area in the southwest, hydraulic gradients are low, indicating high permeability.

Salinity values range between 200 g/L near the fold and thrust belt in the southwest, where the aquifer is at its deepest, and less than 20 g/L both in the southeast and in the north, having values around 40–60 g/L in between along the subcrop area (Figure 5b). In the north, the salinity is lower than in the same area in the underlying Grosmont aquifer (Figures 4b, 5b). The general salinity trend mimics the aquifer structure, suggesting that a component of the salinity pattern is strongly related to depth. The HCO_3 distribution is generally in the 0.5–1.0 g/L range, except in the southeast corner, where it reaches values greater than 2 g/L (Figure 5c). Also, values around 1.5 g/L are found in the north, distributed similarly as in the underlying Grosmont aquifer. The areas that have the lowest HCO_3 content (~ 0.5 g/L) correspond generally to the Bashaw region and to the deep parts of the aquifer, except for the extreme southwest at the fold and thrust belt, where HCO_3 concentration reaches up to 1.5 g/L.


a.
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Saskatchewan
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40
60
80
0.5
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The high hydraulic heads and salinity and low HCO_3 in the Bashaw area are due to hydraulic communication and upward flow through the breaching Leduc reefs of connate formation water from the Cooking Lake aquifer system into the Nisku aquifer, as shown by Rostron and Toth (1996, 1997). The slightly elevated HCO_3 concentration in the extreme southwest hints at possible local recharge by meteoric water from the fold and thrust belt, although this interpretation is only speculative at this stage and contrary to previous findings for areas located slightly to the north (Wilkinson, 1995). The high hydraulic head, low salinity, and high HCO_3 values in the southeast indicate recharge by fresh meteoric water originating farther to the south at outcrops of Devonian strata in northern Montana. Low values of hydraulic head and salinity and relatively higher amounts of HCO_3 in the north are distributed similarly in the Grosmont and Nisku aquifers, indicating that the two are in hydraulic communication both directly and across the intervening thin, weak Upper Ireton aquitard (Figure 3c). Buoyancy effects are important along the western edge of the study area (Figure 5a).

Wabamun Aquifer System

Hydraulic heads in the Wabamun aquifer system (Figure 6a) range between greater than 900 m in the southwest at the edge of the fold and thrust belt and less than 350 m in the north where hydraulic-head values are similar to those of the underlying Nisku and Grosmont aquifers. The regional-scale flow in the Wabamun aquifer system is to the north and is similar to the flow direction in the underlying Nisku aquifer. A local hydraulic-head high in the 600 m range is present along the southern boundary between long. 111 and 112°W. A local, subdued hydraulic-head high is still present in the Bashaw area in the southwest where the Calmar aquitard is weak. The hydraulic gradients in the subcrop region at the sub-Cretaceous unconformity are much lower than in the uneroded part of the aquifer in the southwest, indicating higher permeability in the subcrop area. Permeability values calculated from 396 DSTs range between 2.5×10^{-17} and 3.95×10^{-11} m^2 (0.03 md and 40 d), having a geometric average of 1.05×10^{-14} m^2 (11 md).

Salinity in the Wabamun aquifer system ranges between 200 g/L at its deepest in the southwest and 20 g/L in the southeast, as well as in the north at its most shallow depth (Figure 6b). The salinity distribution shows a depth-related trend similar to other Devonian aquifers. The inflection of contour lines along the subcrop boundary (Figure 6b) indicates the influence of the northward flow along the subcrop. The HCO_3 distribution (Figure 6c) is similar to the one in the Nisku aquifer, although the variation range is not as wide. Concentrations around 0.5 g/L are basically present everywhere in the aquifer, except for the extreme southwest at the fold and thrust belt, in the southeast, and in the north, where concentrations reach greater than 1.5 g/L. The distributions of hydraulic head, TDS, and HCO_3 in the Wabamun aquifer system indicate northward flow along the subcrop area that eventually discharges into the Grosmont aquifer. This system is recharged with connate water from the west-southwest, although a plume of fresher water in the extreme southwest may indicate local meteoric water recharge from the fold and thrust belt. Fresher water in the southeast is most probably due to meteoric water recharge from outcrops of Devonian strata in Montana. Buoyancy effects are significant along the western edge of the study area (Figure 6a). The similarity between the Nisku aquifer and the Wabamun aquifer system with respect to hydraulic head, TDS, and HCO_3 distributions suggests that the intervening thin Calmar aquitard is weak.

Jurassic–Mississippian Aquifer System

This aquifer system is present only in a narrow band along the western and southern margins of the study area (Figure 3b), being absent everywhere else as a result of pre-Cretaceous erosion. Hydraulic heads range between approximately 900 m in the southwest at the fold and thrust belt and less than 400 m in the north (Figure 7a). In the south-southeast, hydraulic heads are

Figure 8. Hydrogeology of the Lower Mannville aquifer. (a) Distribution of hydraulic head (in meters) showing flow from all directions toward the hydraulic sink located around long. 113°W, lat. 55°N. The shaded area indicates the region where DFR is greater than 0.5. (b) Salinity distribution (g/L) showing a plume of high salinity located around long. 113°W, lat. 53°N, decreasing concentrations northeastward updip, and low concentrations in the southeast. (c) Bicarbonate distribution (g/L) showing relatively high concentrations in the north and in the southeast. (d) The data distribution is shown separately because of the extremely high density.

in the 600–650 m range. Unlike the Devonian aquifers, hydraulic heads in the Bashaw region are less than 500 m, having a closed low less than 450 m (Figure 7a). Regional-scale flow directions are northward in the south and eastward along the western part of the aquifer, toward the Wabamun-Winterburn subcrop area. Hydraulic heads drop abruptly in the uneroded part of the aquifer, and only slightly in the subcrop area, indicating higher permeability in the latter. Permeability values calculated from 393 DSTs range between 10^{-17} and 2.09×10^{-12} m^2 (0.01 md and 2 d), having a geometric average of 5.9×10^{-15} m^2 (6 md).

The salinity of formation waters has a completely different pattern and overall is significantly lower than in the underlying Devonian aquifers (Figure 7b). Salinity is relatively low in the south-southeast and in the extreme north (~ 20 g/L), moderate in the deeper part in the southwest near the fold and thrust belt (~ 60 mg/L) and high (> 80 mg/L) at the aquifer's eastern boundary along the subcrop edge of the Wabamun aquifer system. Bicarbonate is high (> 1.5–2 g/L) in the south, southwest, and northwest and low (~ 0.5 g/L) along the aquifer edge (Figure 7c).

The flow is basically drawn from the west and southeast toward the Wabamun aquifer system at the center of the study area. The moderately high salinity values in the southwest and low values in the southeast and north indicate a general dependence on depth. The high salinity along the aquifer boundary near the subcrop edge of the Wabamun aquifer system is most probably due to more saline formation water originating in the latter that is driven by buoyancy downdip, along the sub-Cretaceous unconformity, into the Jurassic–Mississippian aquifer system. Unlike the Devonian aquifers, buoyancy effects are significant only in a small area near the aquifer edge in the southwest (Figure 7a), where hydraulic heads are low and salinity is high as a result of mixing with more saline waters in Devonian aquifers that subcrop immediately east of this aquifer's eastern boundary. In this area the flow is probably directed downdip, southwestward, from the subcrop of the underlying Wabamun aquifer system toward the closed hydraulic low centered around long. 113.5°W, lat. 51.7–52°N, driven by both buoyancy and the sink effect of the low potential. The differences between the distributions of hydraulic head, TDS, and HCO_3 in the Jurassic–Mississippian aquifer system and those in the Upper Devonian aquifers indicate that the Banff-Exshaw aquitard is strong.

Lower Mannville Aquifer

The Lower Mannville aquifer covers the entire study area and may provide possible communication paths between aquifers otherwise separated by aquitards, allowing flow to bypass the aquitards around their erosional edges. The hydraulic head distribution (Figure 8a) is based on pressure measurements in 4128 different wells. (The data distribution is shown separately in Figure 8d because of the extremely high density.) Hydraulic heads range between 950 m in the southwest corner at the fold and thrust belt, 650 m in the southeast corner, and less than 350 m in a large closed hydraulic-head low near the northern edge of the study area (Figure 8a). Hydraulic heads drop abruptly to around 500 m in the southwest, indicating lower permeability than in the rest of the area, where hydraulic gradients are quite low. The hydraulic head distribution is convoluted in places, most likely due to permeability variations related to changes in lithology; however, a general trend is evident. The flow converges from all directions toward the large, closed hydraulic-head low located in the north (centered on long. 113°W, lat. 55°N) and defined by the 400 m contour line (Figure 8a). From the southwest and along the western margin the flow is oriented northeastward, updip from the deeper part of the aquifer. From the southeast, the flow is almost along strike toward northwest. Along the shallower eastern part of the aquifer and from the northeast the flow is downdip, toward the closed hydraulic low. The flow pattern in the south and along the western margin of the study area closely resembles the flow pattern in the underlying Jurassic–Mississippian aquifer system, consistent with the two being in contact. The flow pattern in the central and northern parts of the aquifer generally is similar to the pattern in the underlying Devonian aquifers, again indicating hydraulic contact. The flow pattern along the eastern edge and in the northeast shows a newly identified feature in the hydrostratigraphic succession. In this area, Upper Devonian aquifers are absent owing to pre-Cretaceous erosion, and the Lower Mannville aquifer is underlain by the Ireton and Waterways aquitards.

Two local, much smaller closed hydraulic-head lows are present in the south-southwest, around long. 113–114°W, lat. 51.5–52°N and long. 114.5°W, lat. 52.3°N, and have values reaching less than 400 m (Figure 8a). These local lows are well defined by many pressure data and are not the result of production. The southernmost low corresponds to the local low observed in the Jurassic–Mississippian aquifer system.

There, hydraulic heads are slightly less than 450 m, indicating upward flow from the Jurassic–Mississippian aquifer into the Lower Mannville aquifer.

Salinity ranges in the Lower Mannville aquifer from greater than 100g/L southwest of the center of the study area, to 60 g/L and less in deeper parts of the aquifer in the southwest, and to less than 20 g/L in the south-southeast and in the north-northeast (Figure 8b). The salinity distribution along the western and southern margins of the aquifer has a similar pattern and range of values as the salinity in the underlying Jurassic–Mississippian aquifer system, again indicating hydraulic continuity. The area of high salinity in the lower Mannville aquifer actually corresponds to the erosional edge of the Jurassic–Mississippian aquifer system and the subcrop edge of the underlying Wabamun aquifer system, whose formation waters are characterized by higher salinity in the same 100 g/L range (Figure 6b). This feature was previously identified by Rostron and Toth (1997). Similarly, the sharp salinity increase from less than 20 g/L to greater than 60 g/L in the south corresponds largely to the subcrop edge of the Wabamun aquifer system. In the subcrop area of the Wabamun aquifer system, the salinity distributions in the Lower Mannville aquifer and the Wabamun aquifer are almost identical (Figures 6b, 8b), again indicating hydraulic contact and continuity between the two aquifers. Because of high salinity and low hydraulic heads, DFR is greater than 0.5 in a small area centered around long. 113°W, lat. 53°N (Figure 8a). In that area, where highly saline Devonian water discharges into the Lower Mannville aquifer, the flow may be actually stagnant as a result of the interplay between a strong buoyancy and a weak potential drive. Bicarbonate values range from 0.5 g/L in the central part of the aquifer to between 1.5 and 2.5 g/L along the southern, western, and northern margins of the study area (Figure 8c).

The distributions of hydraulic head, TDS, and HCO_3 in the Lower Mannville aquifer suggest the following flow pattern. On a regional scale, formation waters are drawn from all directions toward discharge in the area of the closed hydraulic head in the northern part of the study area. This sink is geographically centered on a Devonian highland (Figure 3b) that is an erosional feature of exposed Devonian-age rocks on the sub-Cretaceous unconformity surface (Jackson, 1984) over which the Lower Mannville aquifer is very thin (Hayes et al., 1994). Water is directed toward the underlying highly permeable Grosmont aquifer. Thick, highly permeable channel sandstones of the Lower Mannville, which are peripheral to this highland (Figure 3b), are the main flow paths toward this sink. Recharge by basin waters occurs updip from the southwest and west. The underlying Devonian aquifers come in contact with the Lower Mannville aquifer in the area where they subcrop at the sub-Cretaceous unconformity. Recharge from these aquifers, however, is probably minimal or absent, because the Devonian waters are more saline (hence buoyancy would impede upward flow) and the flow in both Devonian and Lower Mannville aquifers is directed northward in the subcrop area, toward the Grosmont aquifer. Nevertheless, the effect of the Devonian aquifers that subcrop underneath the Lower Mannville aquifer is seen in the plume of relatively high salinity water and low HCO_3 observed southwest of the center of the study area, around long. 113.5°W, lat. 53°N, as noted previously by Rostron and Toth (1997). Recharge by fresh, meteoric water in the Lower Mannville aquifer occurs from the southeast, consistent with the pattern seen previously in underlying aquifers, and from the northeast, where Cretaceous strata thin out toward the edge of the basin at the Precambrian shield.

Exceptions that do not affect the regional-scale flow pattern are in the southwest, where flow is locally directed toward two closed hydraulic-head lows. These local sinks form a hydrodynamic barrier to flow from the extreme southwest corner of the study area, at the fold and thrust belt, toward the regional flow system. Here the Clearwater Formation is sandy and the entire Mannville Group forms a single aquifer underlain by the Fernie aquitard and overlain by the thick Colorado aquitard system (Bachu, 1995a). In the same region, the flow from the underlying Jurassic–Mississippian aquifer system is directed upward, as indicated by higher hydraulic heads in the Jurassic–Mississippian aquifer system than in the Lower Mannville aquifer (Figures 7a, 8a). A probable explanation for these local features is that the immediately overlying Joli Fou aquitard of the Colorado Group is thin and weak in these places. Thus, the effect of erosional rebound of the thick shales of the Colorado Group observed in the overlying Viking aquifer (Hitchon, 1969; Bachu and Underschultz, 1995) propagates downward across the weak Joli Fou aquitard into the Mannville aquifer, leading to underpressuring and upward flow. This hypothesis, which still must be verified by local studies, is plausible because in this area Tertiary to Holocene erosion has removed greater than 3 km of sediments (Bustin, 1991).

FLOW SYNTHESIS

Figure 9 shows diagrammatically the main characteristics of the flow of formation waters in the Upper Devonian–Lower Cretaceous strata that subcrop at and overlie the sub-Cretaceous unconformity in the south-central part of the Alberta basin. The most striking feature is the convergence of flow from all directions toward the area in the north where the Grosmont aquifer is present. The analysis indicates the existence of a large-scale flow system across multiple units, characterized by several features. The main flow system is directed in a south-southeast to north-northwest direction across the entire study area, along the subcrop region of the aquifers in the Upper Devonian Winterburn and Wabamun groups. The flow in this system is driven by present-day basin-scale topography. It probably originates in Montana, where Cambrian to Cretaceous strata crop out at the Big Snowy anticlinorium, a topographic high in the range of approximately 1000 m elevation (Mallory, 1972). The Upper Devonian, Mississippian, Jurassic, and Lower Cretaceous aquifers are recharged there by fresh meteoric water. In the study area, this recharge is seen in the south-southeast in all the aquifers in the Upper Devonian–Lower Cretaceous succession. In this region hydraulic heads are in the range of 600 m; salinity is low, in the 20 g/L range; and HCO_3 concentrations are greater than 2 g/L. The discharge of this large-scale flow system is north of the study area, where the underlying Grosmont aquifer crops out at the Peace River at an elevation of approximately 250 m (Bachu and Underschultz, 1993). No aquifers in the succession of interest discharge to the northeast of the study area. There the pre-Cretaceous aquifers are absent because of erosion, although the Lower Mannville strata that crop out along the Athabasca River in the northeast have aquitard characteristics in this region (Bachu and Underschultz, 1993) because they are saturated with bitumen (Athabasca oil sands deposits). Thus, no other discharge point exists within this system. Moreover, the Grosmont aquifer acts as a hydraulic drain because of its generally high permeability caused by paleokarst processes (Dembicki and Machel, 1996). The main flow conduit between recharge in the south-southeast and discharge in the north-northwest is comprised of the subcrop areas of the Upper Devonian Nisku aquifer and Wabamun aquifer system. In this region, hydraulic heads are low, ranging from 600 to 350 m over a long distance (> 650 km). The corresponding low hydraulic gradients are indicative of high permeability in the sub-

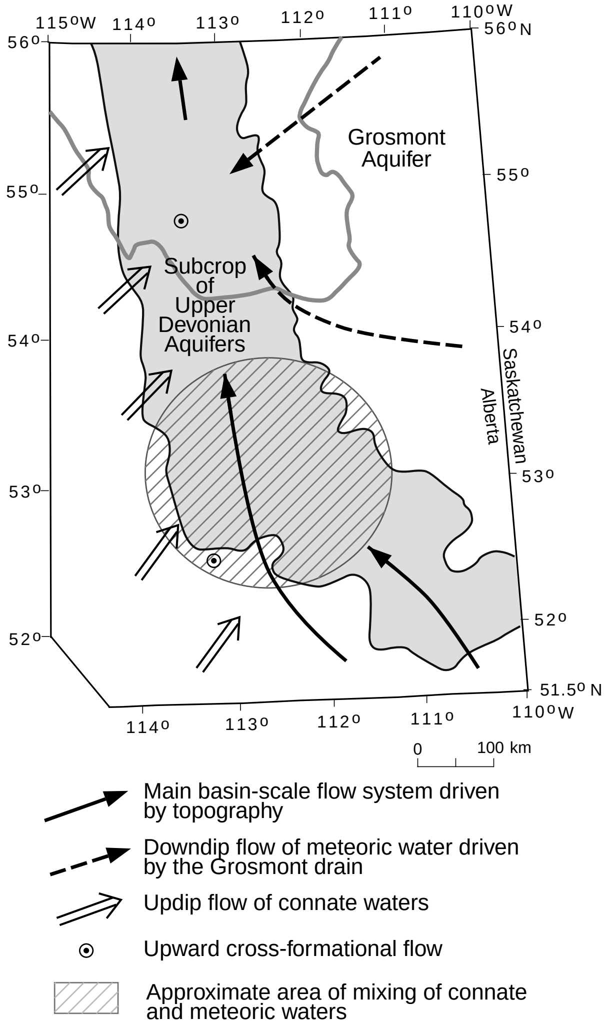

Figure 9. Diagrammatic representation of the flow of formation waters in the Upper Devonian–Lower Cretaceous strata in the southeastern part of the Alberta basin. The flow is mainly northward along the drain created by weathered Devonian carbonates that subcrop below the Cretaceous Mannville Group strata and by the paleokarsted Grosmont aquifer (shaded area). Recharge by connate waters occurs mainly from the southwest and west, updip along aquifer bedding, and through local breaching of the Ireton aquitard by underlying reefs of the Cooking Lake–Leduc aquifer system. Recharge by fresh meteoric water probably occurs at the outcrop of Devonian and Mississippian aquifers further to the south at the Big Snowy anticlinorium in Montana and downdip from the northeast in the Lower Mannville aquifer. A zone of mixing exists at the sub-Cretaceous unconformity at the confluence of deep brines of connate origin and of fresh meteoric water (approximate location indicated by hatched area).

crop area, caused most probably by weathering of the exposed Upper Devonian strata during the long hiatus prior to Cretaceous deposition. The propagation far upstream of low hydraulic heads is characteristic of flow systems that have downstream high-permeability environments (Belitz and Bredehoeft, 1988). The almost identical hydraulic head and salinity distributions in the Wabamun aquifer system and Nisku and Grosmont aquifers suggest that the intervening thin Calmar and Upper Ireton aquitards are very weak. Basically, the entire Grosmont to Wabamun succession acts as a single major hydrostratigraphic unit, thereby called the Upper Devonian aquifer system, which is the path for the long-range flow system originating in Montana and discharging at the Peace River. In addition, this long-range flow system is fed within the study area by formation waters from three different sources.

The first feeder into the main system is updip, northeastward flow from the southwest and west in all the aquifers in the succession. In the uneroded parts of the Nisku aquifer and Wabamun aquifer system, hydraulic heads are high (up to > 900 m at the fold and thrust belt), dropping abruptly to approximately 550 m, and salinity is also significantly higher (up to 200 g/L in the southwest). The corresponding high hydraulic gradients are indicative of lower permeability than in the subcrop areas, consistent with the hypothesis that the higher permeability in the latter is due to weathering during subaerial exposure. Although the hydraulic-head distribution is already an indicator, the permeability variation between the eroded and uneroded parts of these aquifers requires further study. The intervening Calmar aquitard seems to be weak, based on the similarity of hydrogeological characteristics between the Nisku aquifer and the Wabamun aquifer system, reinforcing the concept of a single Upper Devonian aquifer system (Bachu, 1995a). The similarity in the distributions of hydraulic head and salinity in the Jurassic–Mississippian aquifer system and the Lower Mannville aquifer is due to the absence of a continuous intervening aquitard (the Fernie shales are thin and spotty), as identified previously west of the study area (Bachu and Underschultz, 1995). The marked differences in distributions of hydraulic head and salinity between the Upper Devonian and the Jurassic–Mississippian aquifer systems, however, indicate that the intervening Banff-Exshaw aquitard is strong. Salinity along the western margin of the study area shows a consistent increase with depth, both within the same hydrostratigraphic unit and between them. Bicarbonate concentration in all the aquifers in the western part of the study area is low, in the 0.5 g/L range, indicative of deep connate waters. Small plumes of relatively lower salinity and higher HCO_3 water near the fold and thrust belt in the southwest corner of the study area are possibly due to local recharge by fresh meteoric water through faults or along thrust sheets. Buoyancy effects are significant in the Devonian aquifers along the western edge of the study area, except for the Bashaw area in the southwest, where hydraulic gradients are high (Figures 4a, 5a, 6a). In the area of significant buoyancy effects, the Devonian aquifers dip southwestward and have a higher slope than in the shallower central and eastern parts of the study area, and the salinity of formation waters is also higher. Thus, the errors introduced by the use of hydraulic heads only in assessing flow direction and strength in this zone start to become significant (Davies, 1987).The flow directions, however, are most probably correct, because hydraulic gradients and buoyancy (as indicated by salinity gradients) act in opposite directions along dip (southwest to northeast). The flow strength in this zone is actually less than that indicated by hydraulic gradients because of buoyancy that opposes (retards) the hydraulic drive. The presence and direction of flow are nevertheless correct, as indicated by the plume of highly saline water present in the Lower Mannville aquifer and that spills back into the Jurassic–Mississippian aquifer system in the center-southwest. In these small areas buoyancy effects are significant in these aquifers (Figures 7a, 8a). In the Lower Mannville aquifer the formation water is probably stagnant in this small area and has flow around it, similar to the much larger scale flow pattern observed in the Williston basin (Bachu and Hitchon, 1996). In the case of the Jurassic–Mississippian aquifer system, the flow in the area of strong buoyancy is probably reversed toward a hydraulic sink located downdip. At the scale of the study area, the errors in assessing the flow strength in the areas of strong buoyancy do not affect the main findings and conclusions of this article regarding the flow in the Upper Devonian aquifers along the pre-Cretaceous unconformity, the factor of the Grosmont drain, and general flow directions.

The main flow system is fed also from the east and northeast by fresh meteoric water that recharges along the eastern basin edge and descends downdip in the Lower Mannville aquifer. The flow is driven not by local surface topographic features, because ground elevations decrease eastward, but by the hydraulic drop between the recharge elevation at surface and the Upper Devonian drainage system. In this area the Lower Mannville aquifer is underlain by the thick, competent

Ireton and Waterways aquitards, and the only possible flow direction is toward the drain formed by the Upper Devonian aquifer system. The salinity of formation waters is low, having high HCO_3 content, indicative of water of meteoric origin. The pattern of flow in the Lower Mannville aquifer, that has recharge from the south, west, east, and north, thus becomes one of a definite large sink into the Upper Devonian aquifer system. The hydraulic sink into the Upper Devonian drain corresponds to a paleotopographic highland of exposed Devonian strata that developed during the formation of the sub-Cretaceous unconformity (Jackson, 1984). The recharge by fresh meteoric water descending from the Lower Mannville aquifer in the northeast explains the low salinity ($\sim$ 20 g/L) and high HCO_3 ($>$ 1.5 g/L) in the Upper Devonian aquifer system in the paleotopographic highland area.

Finally, the main, long-range Upper Devonian flow system is fed locally from underlying Woodbend aquifers. Upward cross-formational flow of highly saline waters ($\sim$ 200 g/L) occurs in the Bashaw reef area from the underlying Cooking Lake aquifer system through breaching Leduc Formation reefs across the Ireton aquitard into the Upper Devonian aquifer system (Rostron and Toth, 1996, 1997). After vertical cross-formational flow, these waters migrate laterally updip until they reach the subcrop drainage area. This area is coincident with the plume of high salinity and mixing between connate and meteoric waters observed in the Lower Mannville aquifer. Similarly, upward cross-formational flow through breaching Leduc reefs across the Ireton aquitard occurs to the north directly into the Grosmont aquifer in the area of the Rimbey-Meadowbrook reef trend (Figure 3c) and further to the north in the Athabasca area (Bachu and Underschultz, 1993). Potential for lateral cross-formational flow exists within the Woodbend Group from the isolated Camrose aquifer, also recharged from the south, into the Grosmont aquifer, across a relatively narrow band of the Ireton aquitard separating the two aquifers.

The following process could explain the high salinity of formation waters in the Jurassic–Mississippian aquifer system along the subcrop edge in the southwest. All pre–Middle Jurassic strata were deposited during the passive-margin stage of basin evolution and were subjected to the same pre-Cretaceous erosional and downwarping processes during the Columbian orogeny, resulting in similar tilting and pre-Cretaceous exposure from west to east of successively older strata. Thus, the Upper Devonian aquifer system subcrops at structurally higher elevation than the stratigraphically overlying Jurassic–Mississippian aquifer system that is characterized by less saline waters. As a result, the higher salinity, hence denser, Upper Devonian waters spill back, driven by buoyancy, into the Jurassic–Mississippian aquifer system through the Lower Mannville aquifer and past the Banff-Exshaw aquitard. This buoyancy-driven backspill flow, combined with hydrodynamic dispersion, could explain the relatively higher salinity waters along the subcrop edge than in the rest of the Jurassic–Mississippian aquifer system. Because of a much smaller dip angle of the Lower Mannville aquifer, a similar backspill of high-salinity water is not observed in it. The high-salinity connate Devonian waters reaching the subcrop area, however, affect the salinity of formation waters in the Lower Mannville aquifer through mixing. As a result, a plume of relatively high salinity (up to 80 g/L) and low HCO_3 ($\sim$ 0.5 g/L) is present in the Lower Mannville aquifer southwest of the center of the study area, along the subcrop edge of the Wabamun aquifer, as noted previously for the Bashaw area by Rostron and Toth (1997).

HYDROCARBON GENERATION, MIGRATION, AND ACCUMULATION

The strata in the southwestern part of the Alberta basin entered the oil and gas generation window after the passive-margin stage of basin evolution, mainly during the Laramide orogeny. The strata in the southeastern part of the basin, along the eastern part of the study area, never reached the oil window, even at the peak of the Laramide orogeny, because of shallow burial and corresponding low maturation of organic material (Creaney et al., 1994).The Lower Mannville strata in the study area, however, are very rich in hydrocarbons that range from internally sourced oil and gas in the west to bacterial gas and biodegraded oils of various origins in the east (Allan and Creaney, 1991; Creaney et al., 1994).

One of the major sources of hydrocarbons in the Alberta basin are the organic rich shales of the Majeau Lake and Duvernay formations of the Woodbend Group (Duvernay petroleum system) (Creaney et al., 1994). After primary expulsion from the source rock into the underlying Cooking Lake and adjacent Leduc aquifers, these hydrocarbons migrated updip, northeastward, along the underlying Cooking Lake aquifer, driven by buoyancy and supported by a concurrent hydrodynamic drive. During migration, hydrocarbons accumulated in the stratigraphic traps formed by the Bashaw and Rimbey-Meadowbrook reefs (Figure 3a) (Li et al., 1998). The reefs in the south filled up to the spill point, in what constitute the major oil and gas pools of the Woodbend Group in south-central Alberta. Where these reefs breach through the Ireton aquitard, particularly in the Bashaw area, hydrocarbons migrated straight upward from the underlying Leduc reefs into the overlying Nisku aquifer (Li et al., 1998), supported again by the concurrent flow of formation waters (Rostron and Toth, 1997). This explains why oil pools in the Nisku aquifer are found in stratigraphic traps generally coincident with Leduc reefs. Oils that did not accumulate in stratigraphic traps continued their updip, northeastward migration in the Nisku aquifer, driven by buoyancy and the concurrent flow of formation waters, until they reached the subcrop area underneath immature Lower Mannville strata (Figure 5a).

Another major source of hydrocarbons in the Alberta basin is the organic-rich Exshaw shales (Exshaw, or Upper Devonian–Mississippian, petroleum system) (Creaney et al., 1994). After primary expulsion, hydrocarbons originating in the southwest in the mature Exshaw shales migrated updip in the adjacent Wabamun and Jurassic–Mississippian aquifer systems, supported by the updip flow of formation waters. Gas pools primarily are found in these units in stratigraphic traps along the western and southern edges of the study area. Because the Upper Devonian and Mississippian aquifers and petroleum systems are open where they subcrop at the sub-Cretaceous unconformity, hydrocarbons sourced in the southwest in the Exshaw shales that were not trapped before reaching the subcrop areas migrated into the immature overlying Lower Mannville strata of southern Alberta (Creaney et al., 1994; Karavas et al., 1998). Hydrocarbons originating in the deep, mature strata of the Mannville Group in the southwest migrated northeastward updip (the Mannville petroleum system of Creaney et al. [1994]; Karavas et al. [1998]; Riediger et al. [1999]).

All the Devonian to Lower Mannville hydrocarbons that reached the Devonian–Mississippian subcrop region in southern Alberta were trapped in the complex Mannville channel system of fluvio-deltaic origin and by the overlying Clearwater aquitard. Some were trapped in local stratigraphic traps (Karavas et al., 1998). Others, particularly the lighter ones, migrated northeastward along dip, driven by buoyancy, until they either accumulated in stratigraphic traps along the eastern flank of the basin (Riediger et al., 1999) or reached the basin edge. Most of the hydrocarbons, particularly the heavier ones, however, migrated north-northeastward, entrained by the northward concurrent flow of formation waters (Figures 9, 10) in the regional-scale flow of formation waters that originates in the south in Montana and ends in the Athabasca–Peace River area in the north. There they contributed to the hydrocarbon reservoirs in the Cold Lake and Athabasca areas (Creaney et al., 1994). The northward hydrodynamic migration of these hydrocarbons explains the geochemically identified contribution of Mississippian Exshaw source rocks to the Cold Lake and Athabasca oil sand deposits (Creaney et al., 1994).

The south-north flow path along the Upper Devonian carbonates that subcrop at the sub-Cretaceous unconformity and into the Grosmont drain contributed significantly to the migration of hydrocarbons in the Alberta basin toward the Athabasca, Wabasca, Cold Lake, and Peace River areas, which

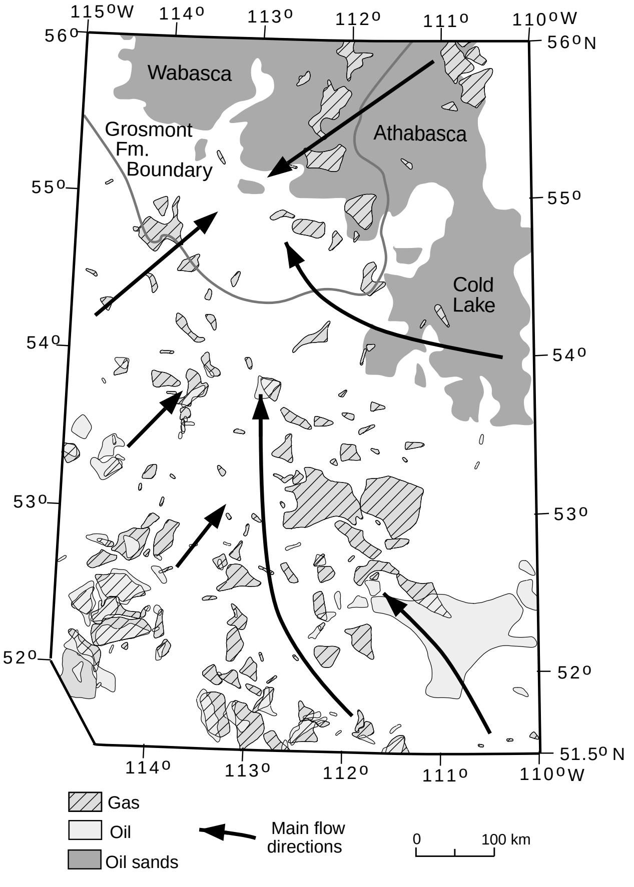

Figure 10. Location of oil sands, oil, and gas deposits in the Lower Mannville strata in the study area, in relation to the main directions of the flow of formation waters.

contain an estimated 1.7 trillion bbl of bitumen in place (AEUB, 1998) that account for 40% of the world's bitumen resource. In addition, hydrodynamic trapping by the downdip, southeastward flow of meteoric water within the Mannville Group along the eastern flank of the basin toward the drainage system formed by the Upper Devonian aquifer system (Figure 10) enhanced other trapping mechanisms. The hydrocarbons of Upper Devonian (Exshaw)–Lower Cretaceous (Lower Mannville) origin that accumulated in shallow Lower Mannville reservoirs along the central-eastern and northeastern flank of the basin lost their volatile components and were biodegraded in place by bacteria carried by the meteoric water descending toward the same northward flow system that drains into the Grosmont aquifer. This process explains the Devonian to Mannville origin of heavy-oil reservoirs in east-central Alberta and the Athabasca and Cold Lake oil sands deposits and the fact that the bitumen is more altered at the base of these deposits than at the top (Allan and Creaney, 1991).

CONCLUSIONS

The flow of formation waters in the Upper Devonian–Lower Cretaceous sedimentary succession in the south-central part of the Alberta basin is fairly complex. Geologically, the flow pattern is controlled by

- Outcrops of Devonian and Mississippian strata at high elevation in the south at the Big Snowy anticlinorium in Montana, outside of the study area
- Outcrops of the Upper Devonian Grosmont Formation at low elevation in the north at the Peace River, outside of the study area
- Subcrops of Devonian to Jurassic strata at the sub-Cretaceous unconformity
- Deposition of Cretaceous sediments on weathered and paleokarsted pre-Cretaceous relief
- Regional-scale shales
- Breaches in places of Ireton shales by reefs of the Woodbend Group

Because of weathering of Upper Devonian strata during a long period of subaerial exposure prior to Cretaceous deposition, and of the concurrent paleokarsting of the Grosmont Formation, these aquifers have high permeability. As a result, the Grosmont aquifer and the Upper Devonian aquifer system subcropping at the sub-Cretaceous unconformity form a drainage path in a northward regional-scale flow system in the southern and central parts of the Alberta basin. This long-range flow system is the result of (1) the topographic drive from recharge in Montana to discharge at the Peace River and (2) hydraulic continuity along a series of aquifers in direct contact or separated by thin, weak aquitards like the Upper Ireton and Calmar.

This flow system is fed by direct meteoric recharge in the south, by connate water from deep Paleozoic aquifers that subcrop along the western flank of the main system, and by meteoric recharge through Cretaceous strata along the eastern basin edge. Cross-formational flow occurs in places where Woodbend Group reefs breach through the otherwise strong and competent Ireton aquitard. The Banff-Exshaw aquitard is strong, separating the respectively overlying and underlying Jurassic–Mississippian and Upper Devonian aquifer systems. A plume of relatively high salinity is formed in the central part of the Lower Mannville aquifer where highly saline Devonian waters discharge at the sub-Cretaceous unconformity and mix with fresh water of meteoric origin.

Hydrocarbons generated in Devonian strata migrated northeastward updip, driven mainly by buoyancy. The secondary migration took place along bedding in aquifers overlain by regional aquitards and upward across the Ireton aquitard through reefal breaches. These hydrocarbons were trapped along the way in the Woodbend Group reefs and other Devonian stratigraphic traps until they reached the sub-Cretaceous unconformity and contributed to oil pools in Lower Mannville reservoirs along the eastern flank of the basin. Hydrocarbons generated in the deep basin in Mississippian to Lower Cretaceous strata in the southwest migrated northeastward updip, driven by buoyancy and supported by a concurrent hydrodynamic drive. Once in the shallower eastern part of the basin, they migrated north and northeastward along the sub-Cretaceous unconformity, supported by the hydrodynamic drive of the main basin-scale flow system. These hydrocarbons were trapped in the complex fluvio-deltaic system of channels of the Lower Mannville Formation that is overlain by the regional-scale Clearwater aquitard. Downward flow of meteoric water along the eastern flank of the basin hydrodynamically enhanced the trapping and led to hydrocarbon biodegradation in place into heavy oils and oil sands in the Cold Lake and Athabasca areas.

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