3D unified geological model of the Milk River Transboundary Aquifer (Alberta, Canada-Montana, USA)

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Abstract

The Milk River Transboundary Aquifer (Canada/USA) has been so intensively used over the twentieth century that concerns have risen about the durability of this resource since the mid-1950s. This aquifer actually corresponds to the middle Virgelle Member of the Upper Cretaceous Milk River Formation (called Eagle Formation in Montana). To assess the conditions needed for a sustainable use of the aquifer, a comprehensive and unified portrait of the aquifer is needed across its international boundary. The stratigraphic framework and geometry of geological units on both sides of the international border were thus unified in a 50 000 km^2 3D geological model. The Virgelle Member is 0 to 60 m thick and it subcrops near the border and along both sides of the Sweetgrass Arch. It dips away from the subcrop areas in a semi-radial pattern. The Medicine Hat gas field hosted by the Alderson Member (Alberta), which is separated from the other members by a regional unconformity, and the Tiger Ridge gas field near the Bears Paw Mountains (Montana) limit the extent of the aquifer. The unified 3D geological model forms the necessary basis for conceptual and numerical hydrogeological models of the Milk River Aquifer.

Résumé

L’aquifère transfrontalier Milk River (Canada/USA) a été intensivement sollicité pendant le 20ème siècle, si bien que des inquiétudes concernant la durabilité de cette ressource sont apparues dès le milieu des années 1950. Cet aquifère correspond en réalité au Membre Virgelle de la Formation Milk River (appelé Formation Eagle au Montana) datant du Crétacé Supérieur. Pour évaluer les conditions nécessaires à un usage durable de l’aquifère, un portrait complet et unifié de l’aquifère est nécessaire à travers sa frontière internationale. Le cadre stratigraphique et la géométrie des unités géologiques des deux côtés de la frontière internationale ont été ainsi unifiés dans un modèle géologique 3D de 50 000 km^2. Le Membre Virgelle a une épaisseur allant de 0 à 60 mètres et sous-affleure près de la frontière et le long des deux côtés de l'arche Sweetgrass. Il plonge depuis les zones de sous-affleurement en suivant une disposition semi-radiale. Le champ de gaz Medicine Hat, contenu par le Membre Alderson (Alberta) qui est séparé de la Formation Milk River par une discordance régionale et le champ de gaz Tiger Ridge près des Montagnes Bears Paw (Montana) délimitent l'aquifère. Ce modèle géologique 3D unifié forme la base indispensable aux modèles hydrogéologiques conceptuel et numérique de l'aquifère Milk River.

Keywords: transboundary aquifer, geological model, hydrostratigraphy, Canada, USA

Introduction

The Milk River Aquifer straddles southern Alberta (Canada) and northern Montana (USA) in a water-short semi-arid region (Government of Alberta, Alberta water for life 2006). This confined sandstone aquifer corresponds more specifically to the Virgelle Member of the Milk River Formation (Eagle Formation in Montana). The extensive use of this resource over the 20th century has led to a major drop in water levels locally, and concerns about the durability of the resources have been raised since the mid-1950s (Meyboom 1960; Borneuf 1976). More recently, AGRA (1998) published a depletion study of the aquifer and made recommendations for the conservation of this resource. A 5-year conservation program in southern Alberta followed this study; however the Milk River Aquifer is still solicited on both sides of the international border in the absence of an agreement between the USA and Canada on the use of this shared resource.

The Milk River Aquifer has been the object of many studies throughout the 20^{th} century; however most of them were limited by the Canada/USA border (Meyboom 1960; Hendry et al. 1991; Alberta Innovates Technology Future 2010), thus preventing a full understanding of the aquifer dynamics. Since geological formations in Alberta and Montana are not defined or named the same way, several stratigraphic charts of the Milk River Formation subdivision have evolved considerably in each country, making transboundary studies challenging. An integrated portrait of the aquifer is, however, necessary to assess the conditions needed for its sustainable shared use.

The objective of this study is to overcome transboundary limitations by providing unified geological and conceptual hydrogeological models of the Milk River Aquifer. The term “unified” means that the study follows the natural limits of the aquifer, not interrupted by the international border. A consistent nomenclature is required to describe the stratigraphic and hydrostratigraphic units across the international boundary. A first component of the conceptual model is the 3D unified geological model of the aquifer presented in this paper (Fig. 1). For this purpose, geological data on both sides of the international border were gathered and assembled consistently in the light of the latest correlation and geological work (Payenberg 2002b; Payenberg et al. 2002; O’Connell 2014). The 3D geological model thus provides a common stratigraphic framework for hydrogeological applications, as done by Ross et al. (2005) and it represents a prerequisite for a representative transboundary hydrogeological numerical model, which in turn will lead to recommendations for the sound management of this shared resource.

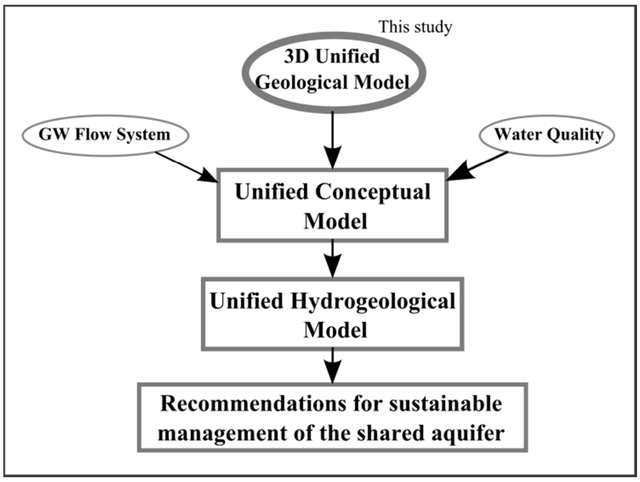


Fig. 1. Successive stages of the Milk River transboundary aquifer study; this paper presents the initial step, the development of a 3D unified geological model.

Study area

The study area extends over about 50 000 km^2 in southern Alberta (Canada) and northern Montana (USA) (Fig. 2). The study area ranges from longitude -110.0° to -113.0° and from latitude 48.2° to 50.3°. The study area is bounded by the edge of the Disturbed Belt (indicated on Fig. 2), on the west, and reaches the Saskatchewan border and the Bears Paw Mountains, on the east. The southern limit is north of the Marias River in Montana. The northern limit is the southern edge of the Medicine Hat gas field in Alberta.

The main structural feature in the study area is the Sweetgrass Arch, composed of the Kevin-Sunburst Dome, the Bow Island Arch and the Sweetgrass Hills. The Sweetgrass Arch in Montana is composed of the Kevin-Sunburst Dome and the South Arch. The South Arch is outside the study area. The Sweetgrass Hills are on the eastern flank of the Sweetgrass Arch. The Sweetgrass

Hills are an ensemble of three buttes (2 100 m altitude) near the Canada/US border. The limits of the model are explained in the section “Geological and Hydrostratigraphic Settings”.

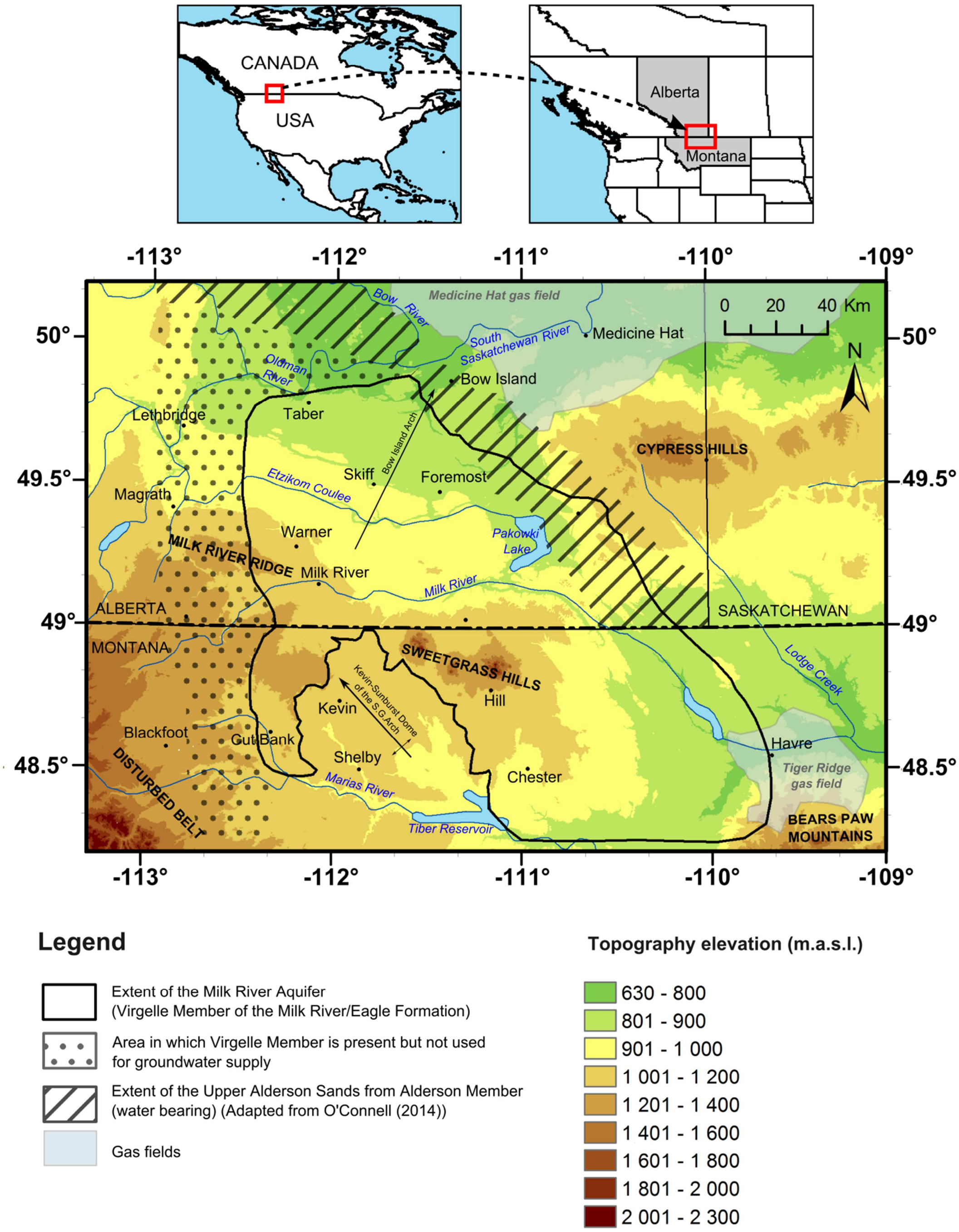


Fig. 2. Study area and extent of the Milk River Aquifer. “S.G. Arch” stands for Sweet Grass Arch.

Correlations

Prior to discussing the geological and hydrogeological contexts of the Milk River Aquifer, it is necessary to establish the correlations between geological units across the international boundary and define the nomenclature that will be used in the remainder of this paper. As the characterization of the Upper Cretaceous Milk River Formation (Eagle Formation in Montana) progressed, the stratigraphic nomenclature evolved significantly during the twentieth century (Fig. 3). The stratigraphic charts not only differ between southern Alberta and northern Montana but also within northern Montana (east and west of the Sweetgrass Arch). As early as 1917, Stebinger (1917b) described the differences between the geologic sections east and west of the 112th meridian in Montana.

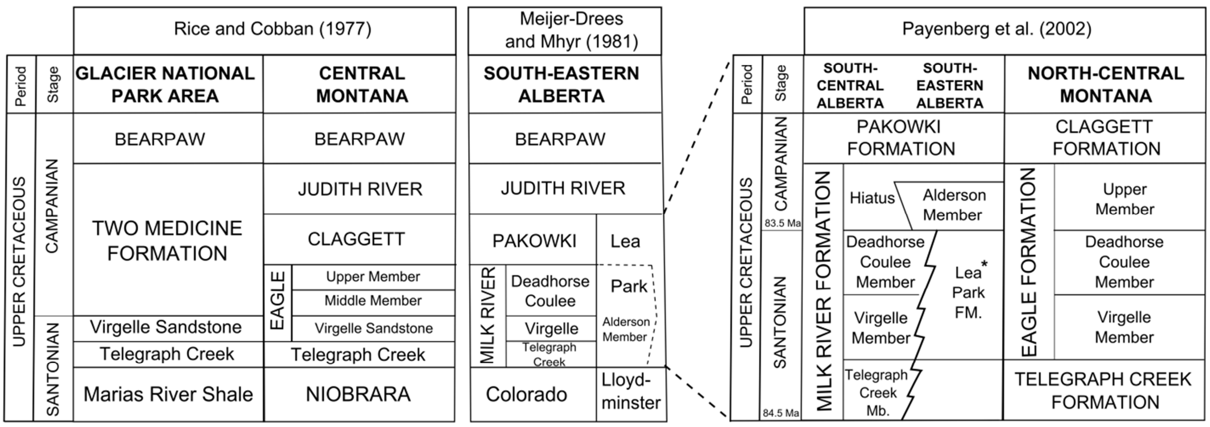


Fig. 3. Comparative stratigraphic nomenclatures existing in the study area (modified from Rice and Cobban 1977; Meijer-Drees and Mhyr 1981 and Payenberg et al. 2002).* The Lea Park Formation may be drawn all the way through the Pakowki Formation, following Meijer-Drees and Mhyr (1981) and Dawson et al. (1994).

The Milk River Formation of southern Alberta was first identified by Dowling (1915, 1917) as the "Milk River Sandstone" in his study of the Southern Plains of Alberta. The Milk River Sandstone consisted then of two parts (lower and upper) bearing successive terminologies (Evans 1931; Russell and Landes 1940). A three-part subdivision of the Milk River Formation was introduced by Tovell (1956), including the Transition beds, Virgelle and Deadhorse Coulee (Tovell 1956, cited by Meijer-Drees and Mhyr 1981). In Montana, the upper and lower parts of the Milk River Sandstone were referred to as Upper Eagle and Virgelle by Williams and Dyer (1930). Meyboom (1960) also equated the lower part of the Milk River Formation to the Virgelle Member of Eagle Sandstone in Montana.

In Montana, Stanton et al. (1905) first described the stratigraphy of Upper Cretaceous rocks in northern and central Montana and in Canada. They defined the Eagle Formation (named by Weed 1899 from Eagle Creek, a tributary of the Missouri River) as massive white sandstone overlain by softer beds consisting of alternating sandstone, shale, and many beds and seams of lignite. They also noticed that small black pebbles occurred at the top. Rice (1980) divided the Eagle Formation into three members: the basal Virgelle Member, and the unnamed middle and upper members. Stanton et al. (1905) established that the overlying Pakowki Shale in Alberta was identical to the Claggett Shale in Montana. They also showed that the Belly River Group that overlies the Pakowki Shale in Alberta was identical to the Judith River in Montana. Payenberg et al. (2002) confirmed that Claggett and Pakowki are of the same age. In the northeastern part of the study area, the stratigraphic equivalent of the Pakowki Formation is the Lea Park Formation (Williams and Dyer 1930).

Meijer-Drees and Mhyr (1981) proposed a stratigraphic nomenclature for southeastern Alberta. They defined the Milk River Formation as the stratigraphic equivalent of the Telegraph Creek Formation and Eagle Sandstone defined by Rice and Cobban (1977). They also defined the Deadhorse Coulee Member in Southeastern Alberta as occupying the same interval as the upper and middle members of the Eagle Sandstone. In the Sweetgrass Hills area, Tuck (1993) named the interval between Virgelle and Claggett the "upper part" of Eagle sandstone. This upper part consisted of interbedded shale, siltstone, sandstone, and coal, and bears close resemblance to the Deadhorse Coulee Member.

Until recently, a clear regional correlation of the Milk River Formation and the Eagle Formation was not possible, due to differences in lithology and time-range (Russell 1970) and the limited and remote exposure of the Eagle Formation within northern Montana (Payenberg et al. 2003). Russell (1970) revealed misunderstandings made in previous stratigraphic correlations. Thirty years after Russell's (1970) attempt at correlating between the Milk River and Eagle Formations, Payenberg (2002b) and Payenberg et al. (2002) reevaluated the lithostratigraphic and chronostratigraphic relationships of Alberta and Montana Upper Cretaceous rocks. They used recent advances in geochronology, magnetostratigraphy, and a paleontological database. The work of Payenberg et al. (2002) provided a clearer litho- and chrono-stratigraphic framework of the study area; it particularly showed that the Telegraph Creek, Virgelle, and Deadhorse Coulee Members are continuous and correlative across the international border (Payenberg 2002a), and also introduced the Alderson Member of the Lea Park Formation in the southern Alberta nomenclature (Fig. 3).

The proposed nomenclature in the present study (Fig. 4) is based on the previous works of Meijer-Drees and Mhyr (1981), Payenberg et al. (2002) and Rice and Cobban (1977). The study area is divided in four zones (Fig. 5a), each with a distinct succession of geological units. These zones are defined as follows:

Zone 1: South-western part of the study area in Alberta, southwest of the Virgelle depositional limit;

Zone 2: North-eastern part of the study area in Alberta, northeast of Virgelle depositional limit;

Zone 3: North-western Montana, west of the Sweetgrass Arch;

Zone 4: Northern Montana, east of the Sweetgrass Arch.

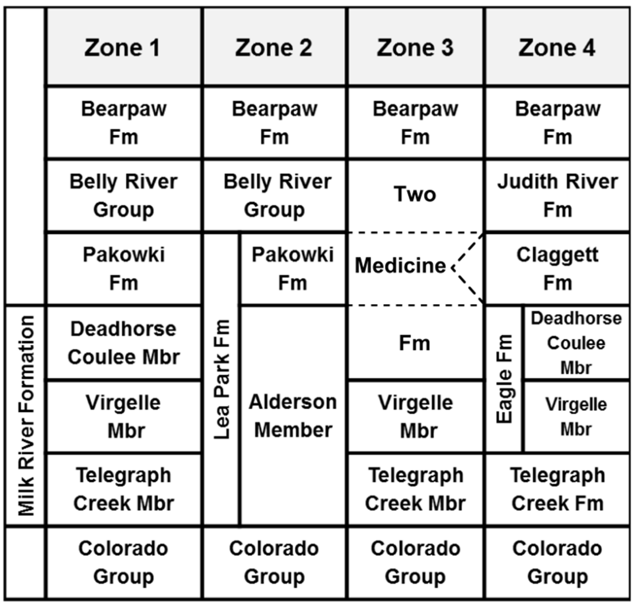
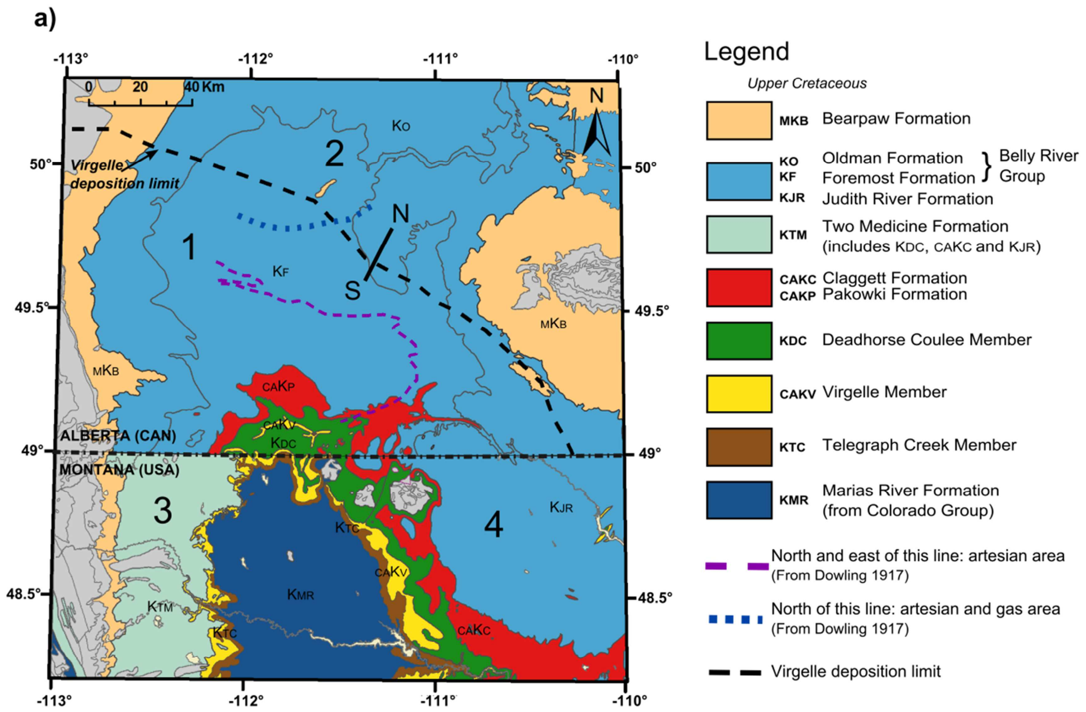


Fig. 4. Proposed stratigraphic nomenclature in the present study and representation of the geological formations described in the 3D geological model (zones shown on Fig. 5a). Note that the Two Medicine Formation has been subdivided into three members (Judith River Formation, Claggett Formation and Deadhorse Coulee Member equivalents). The Bearpaw Formation box also includes the surficial sediments in the 3D model.



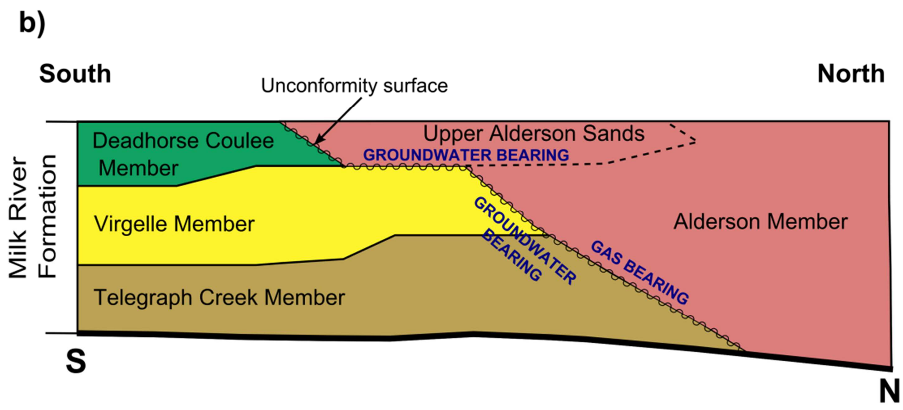


Fig. 5. a) Bedrock geological map of the study area (Adapted from Okulitch et al. 1996). **b)** Cross-section (indicated by "S-N" in Fig. 5a) showing the unconformity surface separating the Alderson Member from the three other members of the Milk River Formation. The encasing units are not represented on this cross section (Adapted from O'Connell 2014).

Geological and Hydrostratigraphic Settings

The geology of the study area can be described as a succession of marine and continental sediments that were deposited as the Upper Cretaceous Interior Sea level fluctuated (Russell 1970). The Upper Cretaceous strata are briefly described below and represented on the bedrock geological map in Fig. 5a. Their hydrostratigraphic role is indicated in Fig. 6 and briefly described in the present section.

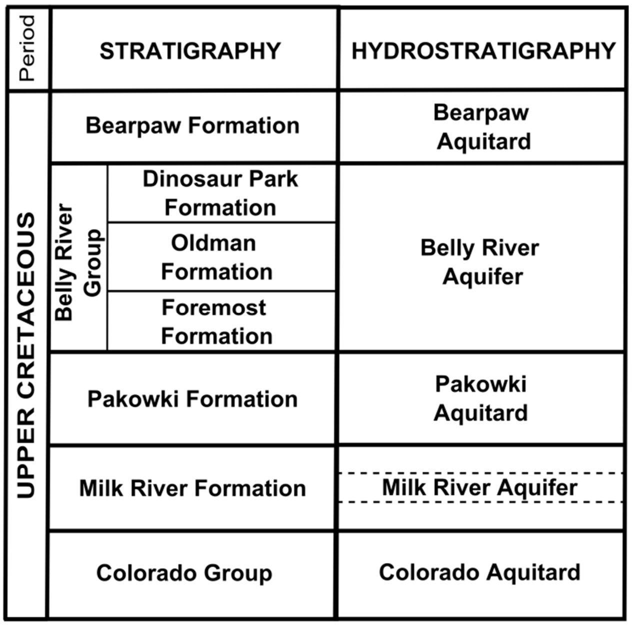


Fig. 6. Stratigraphy and hydrostratigraphy of the main geological units of the study area.

Colorado Group

The Colorado Group (middle Albian to Santonian) underlies the entire study area (Fig. 4). It was deposited during marine conditions in a moderate-depth sea environment. The Colorado Group consists mainly of dark grey to black bentonitic marine shale. It ranges in thickness from 500 to

600 m in southern Alberta and from 450 to 500 m in north central Montana (Hendry et al. 1991; Cobban et al. 1976). The upper boundary of the Colorado Group is commonly taken at the First White Speckled Shales (Meyboom 1960). The Colorado Group is not exposed in southern Alberta (Dyer and Williams 1930) but it outcrops widely over 5 counties in northern Montana, from the Sweetgrass Hills to Great Falls (Cobban et al. 1976). It constitutes a regional aquitard in the study area (Fig. 6) with a hydraulic conductivity ranging from 10^{-14} to 10^{-10} m/s (Hendry and Schwartz 1988). The Colorado Group is overlain by the Milk River Formation and thus the interface between these units constitutes the datum plane of the present regional study.

Milk River/Eagle Formation

The Milk River Formation (Eagle Sandstone in Montana) is a regressive clastic wedge deposited during the Late Cretaceous (Rice 1980; Payenberg et al. 2001). The Milk River Formation has been traditionally subdivided into three members: the basal Telegraph Creek Member, the middle Virgelle Member and the upper Deadhorse Coulee Member.

The Milk River Formation is 150 m thick in the southwest corner of the Canadian part of the study area and thins towards the northeast (O'Connell 2014). It subcrops in an area of 14 townships in southern Alberta near the border, in rings around the Sweetgrass Hills and along both sides of the Sweetgrass Arch. According to Russell (1970): "There is little difference between the western and eastern developments." The Milk River Formation dips gently to the north, east and west, from the subcrop areas following a radial or "fan-like" pattern (Meyboom 1960; Schwartz and Muehlenbachs 1979; Toth and Corbet 1986). The Milk River Formation is confined below and above by the low-permeability shales of the Colorado Group and Pakowki/Claggett Formations, respectively.

The Milk River Aquifer is within the Milk River Formation. The middle Virgelle Member is the most important aquifer within the formation. The Milk River Aquifer is a confined and inclined aquifer, which locally shows flowing artesian conditions. About 200 flowing artesian wells were inventoried in the 1960s in southern Alberta (Meyboom, 1960). In Montana, flowing artesian water occurs in much of the area of Cut Bank, Montana due to the westward dip of the formation (Zimmerman 1967). Tuck (1993) also highlighted some flowing artesian wells in the Sweetgrass Hills area. However, many wells have lost their artesian flow because of the intensive use of this resource. Nowadays, the flowing artesian areas are located in the vicinity of Pakowki Lake and north of the study area, which is still consistent with the flowing artesian limit drawn by Dowling (1917) (Fig. 5a).

Meyboom (1960) showed that the recharge areas of the aquifer were located mainly in the concentric outcrops around the Sweetgrass Hills and to a lesser extent at the subcrop area near the international border. The main discharge areas are located at the pumping or flowing wells of the study area, with small natural discharge (Meyboom 1960).

Groundwater flow in the Milk River Aquifer follows the regional dip of the Milk River/Eagle Formation. In Alberta the general flow is semi-radial from the topographic highs of the Sweetgrass Hills to the north, west and east (Hendry and Schwartz, 1988). In Montana, groundwater flows from the Sweetgrass Hills to the east and south-east and also from the subcrop areas west of the Sweetgrass arch to the west and south (Zimmerman 1967; Levings 1982). Therefore, there are two transboundary flow paths in the study area: 1) from the Sweetgrass Hills to the north, and 2) from north of the Cut Bank, Montana, area to the north (Zimmerman 1967; Tuck 1993).

In southern Alberta, the Alderson Member of Lea Park Formation (Meijer-Drees and Mhyr (1981) unconformably overlays the Milk River Formation in the north, northeast and east of the study area (Fig. 5b). The Alderson Member is a lateral sandy shale equivalent to the Milk River Formation and some authors (Hendry et al 1991) described the relation between the units as a facies change. The Alderson Member has also been included in the Milk River Formation as a fourth member (Payenberg et al. 2002; O'Connell 2014). However, it is much younger than the other three members, is separated from them by a regional unconformity surface and is not present in Montana (Payenberg et al. 2003; O'Connell 2014). In the framework of the present study, the decision was made to include the Alderson Member as a member of the Lea Park Formation as also done by other authors (e.g. Meijer-Drees and Mhyr 1981). The Alderson Member is gas-bearing; it contains the Milk River gas field (or Medicine Hat gas field, Fig. 2), a natural limit of the 3D geological model. Another natural limit is imposed by the Tiger Ridge gas field in Montana, hosted by the Eagle Sandstone in the Bears Paw Mountains area (Fig. 2) (Gautier and Rice 1982), and constitutes another natural boundary for the present 3D geological model.

Telegraph Creek Member/Formation

The Telegraph Creek Member is a transitional unit between the shale of the Colorado Group and the massive sandstone of the Virgelle Member of the Milk River Formation. It is interpreted as deposits of an offshore to shore-face transition (Payenberg 2002a). The Telegraph Creek Member consists of thinly interbedded sandy shale, siltstone and fine-grained shaly sandstone. The Telegraph Creek is 36 to 52 m thick in the Cut Bank, Montana, area where it has formation status (Cobban 1950; Payenberg et al. 2001) and it is 30 to 52 m thick near the Sweetgrass Hills

(Zimmerman 1967; Tuck 1993). The Telegraph Creek transition zone was originally included in the Virgelle Sandstone in north-central and northwestern Montana by Stebinger (1915, 1917a).

Virgelle Member

The Virgelle Member gradationally overlies the Telegraph Creek Member (Meijer-Drees and Mhyr 1981). It consists of grey to buff, thick bedded, fine to medium grained sandstone with thinly bedded siltstone (Tuck 1993). The Virgelle Member was deposited during a regression sequence and is interpreted as a shore-face to foreshore sandstone (Rice 1980). It is up to 69 m thick in southern Alberta and varies from 15 to 60 m thick on the west side of the Sweetgrass Arch (Lorenz 1981; O'Connell 2014). The Virgelle Member is not present in southwestern Saskatchewan or central Alberta because it is truncated by the regional unconformity surface separating the Milk River Formation and the Alderson Member. The Virgelle outcrops along the Milk River in southern Alberta over approximately 25 km in Township 1 and 2, Ranges 12 to 15 (Meyboom 1960). It also outcrops on both sides of the Sweetgrass Arch, in continuous and narrow belts (Fig. 5a).

The Virgelle Member massive sandstone is the most important aquifer part of the Milk River Formation and therefore constitutes the Milk River Aquifer. The hydraulic conductivity of the Virgelle sandstone in southern Alberta ranges from 10^{-8} to 10^{-6} m/s (Persram 1992 unpublished, cited by AGRA 1998). South-east of the town of Milk River, the hydraulic conductivity of the Virgelle is 1.8×10^{-7} m/s (Robertson 1988). The limits of the Milk River Aquifer are shown on Fig. 2. They correspond to the area in which the Virgelle Member exists and is exploited. However the 3D geological model extends farther west, to longitude -113°, where the Virgelle Member continues in the subsurface but is too deep (> 400 m) to be used for groundwater supply

(Stantec 2002). In the framework of the present 3D geological model, the internal stratigraphy, lithofacies, and depositional environment of the Virgelle Member are not further discussed. However, these aspects were studied by Rice (1976; 1980) in northern Montana and Meyer (1998) as well as Meyer and Krause (2006) in southern Alberta.

Deadhorse Coulee Member

The Deadhorse Coulee Member (DHC) represents the upper part of the Milk River Formation as named by Tovell (1956). It is a non-marine unit deposited in the coastal plain environments landward of the Virgelle shore-faces (O'Connell 2014). This well-defined unit consists predominantly of interbedded shale, siltstone and fine grained sandstone with coal seams (Payenberg 2002). The Deadhorse Coulee has a maximum thickness of 60 m in southern Alberta and thins northeastward to approximately 10 m east of the zero edge (from T1 R5 W4 to T13 R22 W4) (O'Connell 2014). In northern Montana, the Deadhorse Coulee equivalent is the unnamed middle member of Eagle Formation (Payenberg et al. 2001). The contact between Deadhorse Coulee and the overlying Pakowki /Claggett Formation is marked by a thin (but laterally continuous) bed of dark grey to black polished chert pebbles, which is interpreted as a transgressive lag overlying a regional unconformity surface (Russell 1970; O'Connell 2014). The Deadhorse Coulee Member constitutes a low permeability unit that overlies the Virgelle Member (O'Connell 2014).

Alderson Member

The Alderson Member was originally considered the lower member of the Lea Park Formation and a stratigraphic equivalent to the Milk River Formation (Meijer-Drees and Mhyr 1981)(Fig. 3). It was entirely deposited in proximal to distal offshore marine environments (O'Connell

2014). In southern Alberta, the Alderson Member is present just northeast of the depositional limit of the Virgelle sandstone (Meijer-Drees and Mhyr 1981). The lithology of the Alderson Member consists of interbedded very fine-grained sand, silt and mud (O'Connell 2014). The sand content increases in the upper part (Meijer-Drees and Mhyr 1981). O'Connell (2014) includes the Alderson Member as the youngest member of the Milk River Formation which is 100 m thick in the northeast corner of the study area. The Alderson Member is younger than the Telegraph Creek, Virgelle and Deadhorse Coulee Members of the Milk River Formation and is separated from them by a regional unconformity representing a large time-gap (O'Connell 2014; Payenberg 2003). It therefore physically overlies and overlaps the erosional edges of the other three members. The Alderson Member is about 85 m thick in southeastern Alberta (Meijer-Drees and Mhyr 1981).

The Alderson Member hosts the Medicine Hat gas field (Hamblin and Lee 1997; Fig. 2). However, the upper part of the Alderson Member contains two distinct large sand bodies which form a regional aquifer in southern Alberta. This unit is named the Upper Alderson Sands by O'Connell (2014). It covers an area of 74 townships and has a NW-SE trend (Fig. 2). The Upper Alderson Sands forms small lobate sand bodies. According to O'Connell (2014): "The Virgelle and Upper Alderson aquifers are separated from each other by muddy sediments of the Alderson and Deadhorse Coulee members, but they are locally in contact at the Virgelle erosional edge and water flow between the two aquifers is likely."

Pakowki Formation/ Claggett Shale

The Milk River Formation is overlain by a thick unit of marine shales, the Pakowki Formation (Claggett Shale equivalent in Montana). The Pakowki and Claggett Formations consist of thinly bedded, black marine shales, with few sandstone beds (Tovell 1956 cited by Payenberg et al. 2003). The Pakowki Formation is 98 m thick at Bow Island, 65 m at Lethbridge, Alberta, and up to 130 m in the Sweetgrass Hills area (Williams and Dyer 1930; Tuck 1993). A thin horizon of chert pebbles is present at the base of the unit. The formation was deposited during an extensive Late Cretaceous transgression episode; however the sea invasion did not reach the western part of the Sweetgrass Arch (Stebinger 1917b; Williams and Dyer 1930). Therefore, the tongue of marine shale progressively thins to zero westward. Where the Claggett/Pakowki Formations pinch out, the Milk River Formation is directly overlain by the Judith River Formation/Belly River Group. The top of the Pakowki Formation is equivalent to the top of the Lea Park Formation in central Alberta (Williams and Dyer 1930; Meijer-Drees and Mhyr 1981; Dawson et al 1994). The Pakowki/Claggett Formation effectively constitutes a regional aquitard (Fig. 6); the hydraulic conductivity of the Pakowki/Claggett Formation is in the order of 10^{-11} m/s (Toth and Corbet 1986; Anna 2011).

Two Medicine Formation

The non-marine Two Medicine Formation of Late Cretaceous age outcrops in northwestern Montana. This unit consists of mudstones and sandstones and is about 600 m thick (Lorenz 1981). West of the Sweetgrass Arch, the Two Medicine Formation includes the equivalent upper part of Eagle Formation (i.e. Deadhorse Coulee Member equivalent), the poorly recognizable Claggett Shale and the Judith River Formation (Pierce and Hunt 1937; Zimmerman 1967; Gill and Cobban 1973; Fig. 4). The Two Medicine Formation overlies the well-defined Virgelle Member. It is 152 m thick in the Cut Bank, Montana, area (Zimmerman 1967).

Belly River/Judith River

The Belly River Group (or equivalent Judith River Formation in Montana) outcrops in a large part of the study area (Fig. 5a). It represents the sequence of continental beds above the Pakowki Formation and below the Bearpaw Formation. The Belly River includes the Dinosaur Park Formation (upper part), the Oldman Formation (middle part) and Foremost Formation (lower part) (Eberth and Hamblin 1993; Hamblin 1997) . However, the upper part is only present in a limited part of the study area, covering of about 12 townships, near the Saskatchewan border (Hamblin 1997). Fig. 5a is adapted from the geological map from Okulitch (1996) in which the Dinosaur Park Formation is not represented.

The dark shale, sandstone and coal seams of the Foremost Formation are overlain by massive yellow and grey sandstone of the Oldman Formation and thick sandstones and siltstones of the Dinosaur Park Formation. The Belly River Group/Judith River Formation is 320 m thick at Lethbridge, and is less than 182 m in northern Montana (Williams and Dyer 1930; Pierce and Hunt 1937). The Belly River Group/Judith River Formation constitutes an aquifer with a hydraulic conductivity ranging from $9x10^{-8}$ m/s to $8.8x10^{-7}$ m/s (Anna 2011).

Bearpaw Formation

The Bearpaw Formation overlies the Belly River Group/Judith River Formation (or the Two Medicine Formation, west of the Sweetgrass Arch in Montana) and is made up of dark grey shale (Russell 1970). These marine strata were deposited during a subsequent Late Cretaceous transgression episode and are lithologically similar to the Pakowki Formation. In the western part of the study area, the Bearpaw Formation outcrops along a narrow north-south band, and around the Cypress Hills in south-eastern Alberta. The Bearpaw Formation is about 70 m thick in the north-western part of the study area and constitutes a regional aquitard (Tokarsky 1974) (Fig. 6).

Available data and Methods

Data collection

Geological data from five sources were gathered. In Alberta, the first source of geological data was from O'Connell (2014). Of the 2170 total borehole data, only the non-deviated wells were selected to develop the 3D geological model (2070 borehole data). These data from non-deviated wells contain the depth of the tops of the Alderson Member and the geological formations included in the Milk River Formation: Deadhorse Coulee Member, Virgelle Member and Telegraph Creek Member. The extent of the data is from 49° to 50.3° north latitude and from longitude -110° to -113°. Amongst the data provided by O'Connell (2014), there is an area of about 14 townships close to the border with no subsurface data for the Milk River Formation. This area is the structural crest of the Sweetgrass Arch, in which the Milk River Formation is too shallow to be covered by geophysical logs from hydrocarbon exploration boreholes.

The geological data of the units above the Milk River Formation were obtained from the Alberta Geological Survey/Alberta Energy Regulator. The elevations of the tops of Lea Park Formation (Milk River and Pakowki Formations equivalents) (unpublished data), Belly River Group (Glombick 2010) and the bedrock topography (Atkinson and Lyster 2010) in southern Alberta were added to the model.

In Montana, three sources of geological data were used: Feltis et al. (1981), described the elevation of the tops of each geological formation in north central Montana, from Jurassic to Quaternary. The geological formations in the Colorado Group to the Judith River Formation were selected. The 190 resulting wells range from 48.2° to 49° north latitude and from longitude -109.6° to -112.5°.

The second source of geological information consists of well logs of the area, provided by the Montana Geological Society (Montana Geological Society 2013). 103 scanned logs (mostly from the 1950's) located in Glacier, Toole, Liberty and Hill Counties were selected. They were digitized and converted into elevation format to be integrated to the data set. These logs contain the description of all the members that compose the Eagle Sandstone.

About 10 control wells with altitude of the top of Judith River Aquifer in northern Montana were retrieved from a map produced by Noble et al. (1982). This map was scanned, georeferenced and converted from feet into meters.

The top of the geological model is ground level, represented by a Digital Elevation Model (DEM) of the study area. The DEM in Alberta is from the National Topographic Data Base (NTDB) and the DEM of northern Montana is from USGS Earth Explorer. They are both at 1:50 000 scale (or 1 arc second).

The last source of data used in this study consisted of hydrogeological cross sections of the study area from Borneuf (1974), Tokarsky (1974) and a transboundary map of the bedrock geology from Okulitch et al. (1996).

These various geological data required several steps of conversion and transformation in order to use them consistently in the building of the 3D geological model.

Method: Data processing and unification of the geological data

The geological data collected for this regional and transboundary study presented various formats and several spatial and stratigraphic references. Data processing was needed to obtain a consistent file containing the coordinates of a well and the associated elevations of each geological formation.

The main steps of data processing were: the conversion from feet to meters and from spatial reference NAD 27 to NAD 83, the transition from Township/Range system to latitude/longitude coordinates and the transition from depth to elevation data (the reference is the mean sea level). Additionally, the two available DEM files were merged to obtain a unique DEM covering the study area.

The various sets of geological data on both sides of the border are now homogeneous (same format, same spatial reference and same units). The next stage was to unify these data, since the main goal of the 3D geological model is to represent the geology of the study area in a unified way. Thus the geological data corresponding to equivalent layers in Alberta and Montana needed to be merged. In particular, specific work on the equivalent members of the Milk River Formation was needed to represent the Milk River Aquifer (i.e. Virgelle Member) in its entirety.

The collected data did not always present the same degree of information everywhere in the study area. In order to assemble the data sets for each geological unit, some working hypotheses had to be made following the 4 zones of the study area (Fig. 5a and Fig. 6).

O'Connell (2014) described every member of the Milk River Formation in Alberta (i.e. Telegraph Creek, Virgelle and Deadhorse Coulee Members in zone 1 and the Alderson Member in zone 2). Feltis et al. (1981) only represented the "Eagle Sandstone" which is the Milk River Formation equivalent in northern Montana (zones 3 and 4). The constituting members of the Eagle Sandstone are not described individually. Considering these two sources of data, the degree of geological information on the Milk River Formation is higher in Alberta than in Montana. Yet, we want to represent the 3 members of the Milk River Formation in the entire study area. Consequently, the "Eagle Sandstone" layer from Feltis et al. (1981) was subdivided in 3 parts, using the detailed logs from the Montana Geological Society (2013). In zone 3, the constitutive members of the Two Medicine Formation were also described individually on the basis of the detailed logs from the Montana Geological Society (2013).

Some of the wells from Feltis et al. (1981) were also part of the set of scanned logs from the Montana Geological Society (2013). The comparison of these wells clearly showed that what Feltis et al. (1981) called "Eagle Sandstone" actually included Telegraph Creek and Virgelle Members west of the Sweetgrass Arch (zone 3). East of the Sweetgrass Arch (zone 4), the comparison of the logs shows that an upper part (30 to 35 m thick) overlying the Virgelle Member was also included in the "Eagle Sandstone" layer. This upper part would equate to the "middle member" of Eagle, as defined by Payenberg et al. (2002), i.e. the Deadhorse Coulee member equivalent in Alberta.

Based on these observations, it was assumed that east of the Sweetgrass Arch (zone 4), the top of the Eagle Sandstone described by Feltis et al. (1981) corresponds to the top of the Deadhorse

Coulee Member whereas, west of the Sweetgrass Arch (zone 3), it corresponds to the top of the Virgelle Member.

West of the Sweetgrass Arch, the upper part of Eagle is included within the Two Medicine Formation and is not described. Therefore the question of how much of the lower part of the Two Medicine Formation is actually equivalent to the Deadhorse Coulee Member was raised. Reexamination of detailed boreholes from the Montana Geological Society (2013) west of the Sweetgrass Arch allowed the identification of the transgressive chert pebble lag surface, which represents the top of the Deadhorse Coulee. Too few descriptions delineated the chert pebbles marker bed, so eventually it was decided to designate the lower 75 m of the Two Medicine Formation as the Deadhorse Coulee equivalent. This value was based on the Lexicon definition of the Two Medicine Formation (WEBLEX Canada 2013), which mentions coarse sandstone beds in the lower 75 m interpreted to represent the fluvial channel sandstones of the Deadhorse Coulee. Rice and Cobban (1977) supported this value, citing Cobban (1955): “the sandstone is mainly in the basal 76 m, which is more or less equivalent to the middle and upper members of the Eagle Sandstone”. A dummy data point set representing the top of the Deadhorse Coulee west of the Sweetgrass arch was therefore added. Close to the international border, the thickness of the Deadhorse Coulee Member was reduced at 60 m to be consistent with the data of O’Connell (2014) in southern Alberta.

The geological layers overlying the Eagle Sandstone in Montana (Claggett Shale and Judith River Formation) are only described east of the Sweetgrass Arch by Feltis et al. (1981) and the Montana Geological Society (2013). West of the Sweetgrass Arch, both of these geological layers are included in the Two Medicine Formation, which is not represented in the report of Feltis et al.

(1981), but is well described within the logs from the Montana Geological Society (2013). The Two Medicine Formation is equivalent to the upper part of Eagle, Claggett Shale and Judith River Formation (Zimmerman 1967). Thus, the top of the Two Medicine Formation was identified as the top of the Judith River Formation in zone 3.

The top of the Pakowki Formation was assimilated into the top of Lea Park Formation in Alberta (Williams and Dyer 1930; Meijer-Drees and Mhyr 1981; Dawson et al 1994; Fig. 4). In northern Montana, the Claggett Shale is well described within the Montana Geological Society (2013) well logs and some of the wells of Feltis et al. (1981). However, there are no data describing the Claggett Shale west of Sweetgrass Arch since the marine invasion during which the Claggett/Pakowki was deposited did not extend far beyond the Arch. The Claggett Shale wedges out west of the Sweetgrass Arch, and where it pinches out, the Judith River(Belly River) strata rest on the Deadhorse Coulee Member equivalent.

It is assumed that the top of the Belly River Group in southern Alberta (i.e. top of Oldman Formation or Dinosaur Park Formation, where present) is the stratigraphic equivalent to the top of the Judith River Formation in Montana (Russell 1970). The constitutive layers of the Belly River in Alberta are not represented in the model since the contact between the Oldman and Foremost Formations is difficult to identify (Williams and Dyer 1930).

In Alberta, the top of the Colorado Group was considered to be the bottom of the Telegraph Creek Formation in zone 1, and the bottom of the Alderson Member in zone 2.

As mentioned previously, because of the lack of well logs in the southern Alberta outcrop area, the data in O'Connell (2014) was supplemented by creating a file describing the bedrock topography. The bedrock topography file was built by subtracting the thickness of surficial sediments from the topography of the study area; it was then assumed that the top of the bedrock corresponds to the top of the Deadhorse Coulee Formation where Deadhorse Coulee outcrops. The same assumption was made for the Pakowki and Belly River outcrop areas, following the geological map of Okulitch et al. (1996). Some manual editing was required to represent these outcrop areas with more details. For that purpose, the bedrock geological map (Okulitch et al. 1996) was superimposed on the model as a reference.

The regional unconformity between the Milk River Formation and the Alderson Member is also represented in the 3D model. In the north, northeast and east of the study area, the Telegraph Creek, Virgelle and Deadhorse Coulee members are progressively overlapped by the Alderson Member. An overlapping area is represented, based on the isopach maps of O'Connell (2014). The two sand bodies which make up the upper part of the Alderson Member (Upper Alderson Sands, Fig. 2) are not represented separately but they are included in the Alderson Member.

Finally, it was decided that the Bearpaw Formation and the surficial sediments would be grouped in one layer in the geological model, between the top of the Belly River/Judith River and the ground level. With the geological data on both sides of the border harmonized and the stratigraphy unified, the 3D geological model could be built.

Construction of the 3D unified geological model

The software chosen to build the 3D geological model is Leapfrog Hydro® (Leapfrog Hydro 2013). The approach to build the 3D geological model was to use location data (x, y, z) representing the top of the geological units. Contact surfaces were first created from these data. Then, volumes were obtained from the surfaces for which a chronology had been first determined. Leapfrog Hydro is a recent software and it was chosen mostly for its interoperability with FEFLOW (Finite Element subsurface Flow) (Diersch 2014). The 3D geological unified model will form the basis of a 3D numerical hydrogeological model of the Milk River Aquifer using FEFLOW.

An initial geological model was built as a reference and for the purpose of comparison before and after unification of the geological datasets from both sides of the international boundary. The reference model contains the data from O'Connell (2014) and Feltis et al. (1981) before the harmonization of the geological units. A south-north transboundary cross-section A-A' from this reference model is shown in Fig. 7. This section shows that the level of information was higher in southern Alberta (where Telegraph Creek, Virgelle and Deadhorse Coulee Members were represented) than in northern Montana (where the Eagle Sandstone was solely represented). The two datasets are simply placed alongside in this reference model, so the geological layers are obviously abruptly separated at the international border. The same cross-section A-A' will be shown as unified in the Results section below (Fig. 9b).

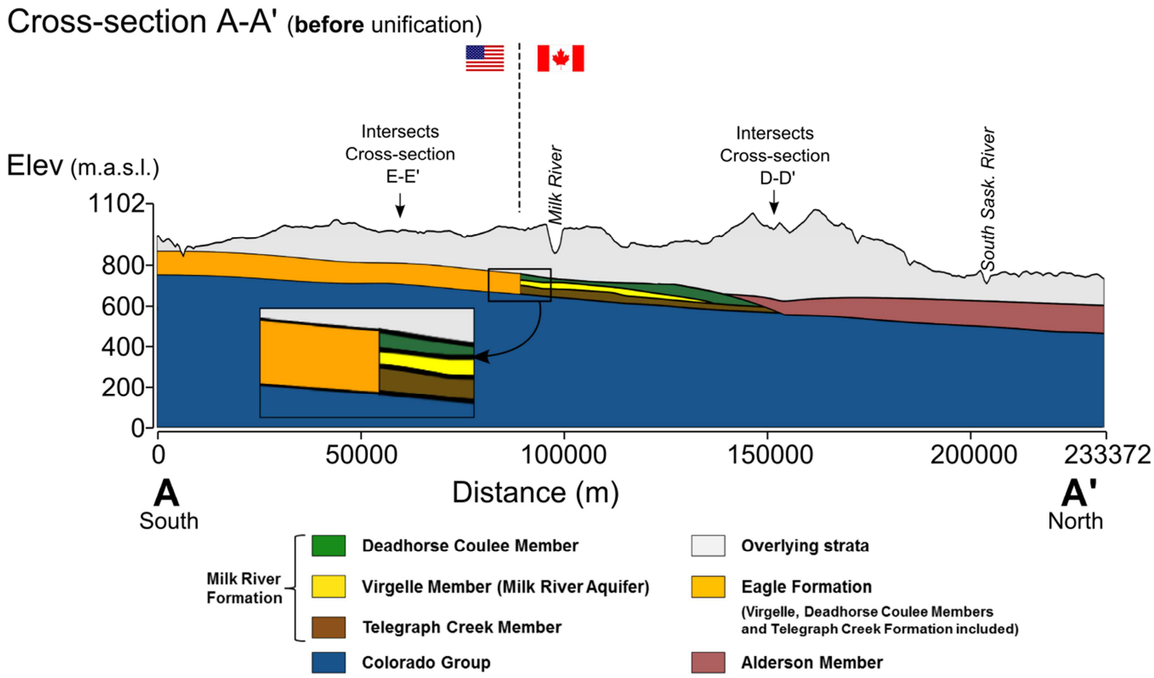


Fig. 7. Transboundary cross-section (south-north) before the unification of the Milk River/Eagle Formation. The geological units above the Milk River/Eagle Formation are not represented in this section. The location of the cross-section is shown in Fig. 9a.

In a subsequent geological model, the integration of detailed logs from Montana Geological Society (2013) and the formulation of working hypothesis on the equivalent layers (described above) allowed the building of the unified 3D geological model of the study area and the separation of the Eagle Formation into three members. The datasets in the 4 zones of the study area (Fig. 5a; Fig. 6) were finally merged to represent each geological unit.

Furthermore, the model was adjusted with the help of cross-sections existing for the study area. About 15 cross-sections (Borneuf 1974; Tokarsky 1974) in Alberta were georeferenced and included in the geological model. The cross sections serve as a guide and allow adjustments of the geological surfaces by manual editing within Leapfrog Hydro® (Fig. 8)

The construction of a sloping surface was needed to represent the regional unconformity between the Milk River Formation and the Alderson Member. This surface was built by selecting points from the Alderson Member dataset, which make up a plateau overlapping Virgelle and Deadhorse Coulee Member.

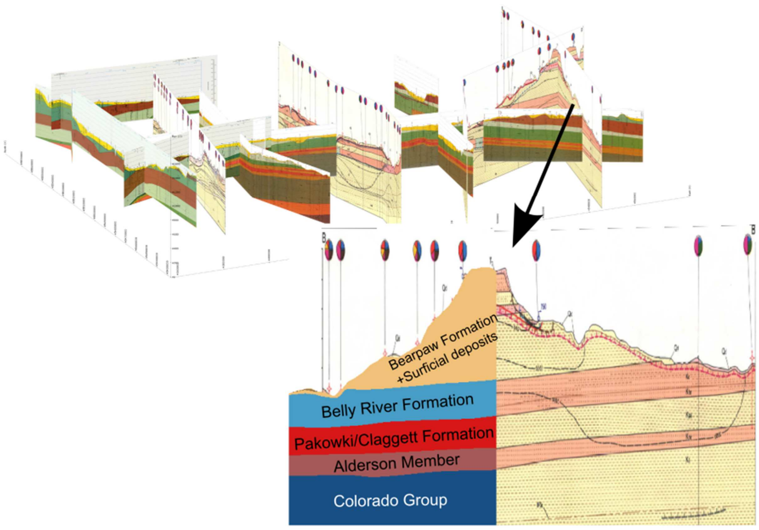
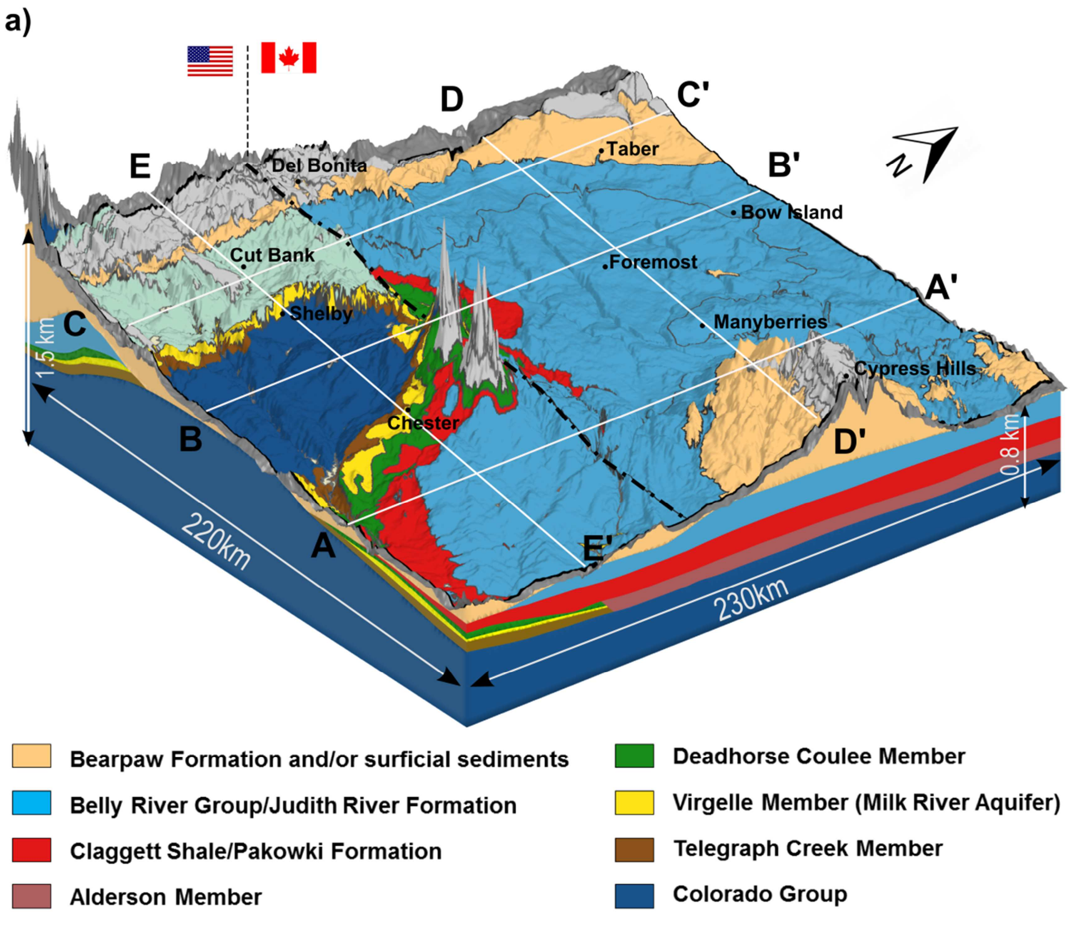


Fig. 8. Examples of geo-referenced cross-sections included in the 3D geological model.

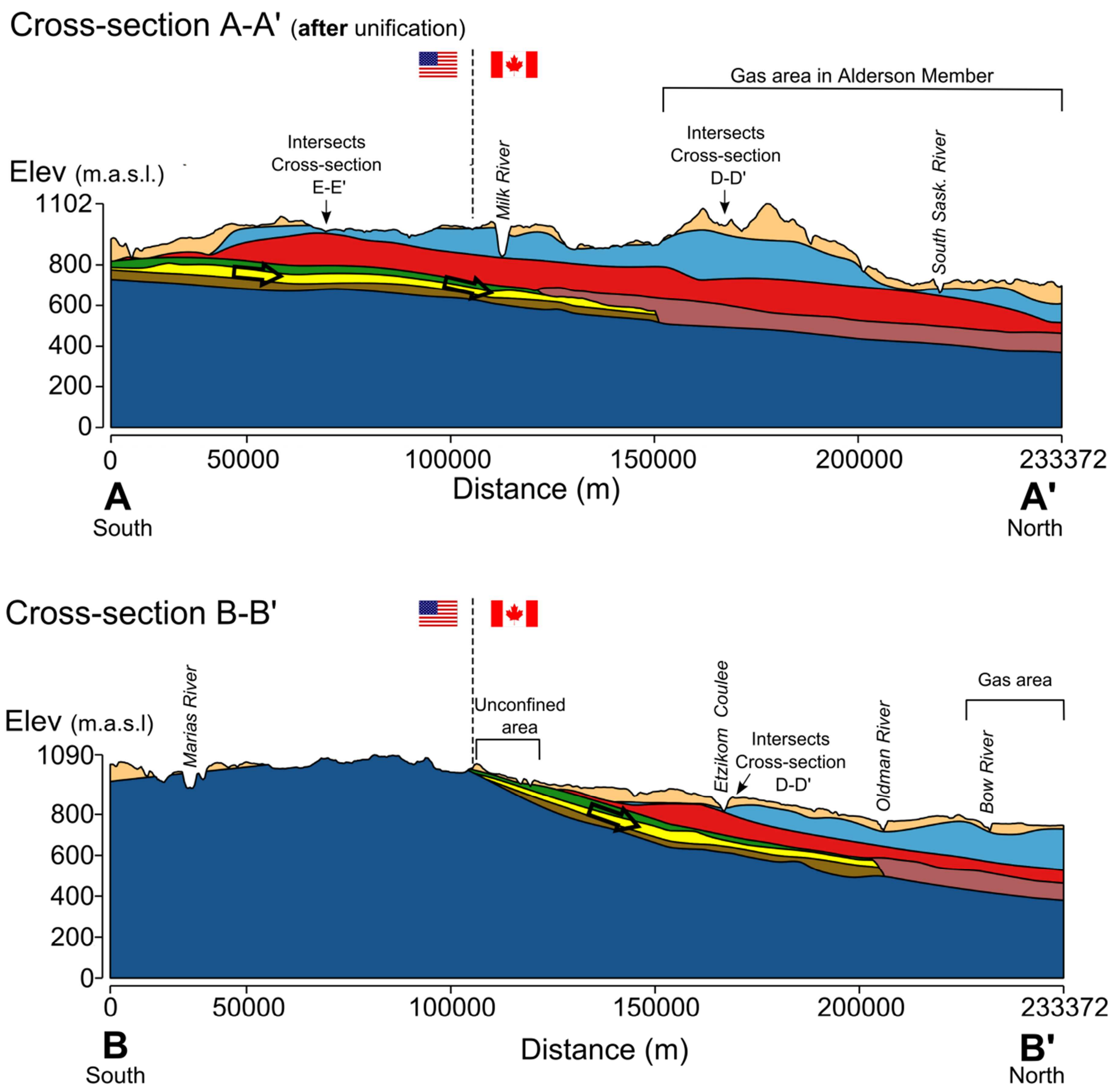
Results

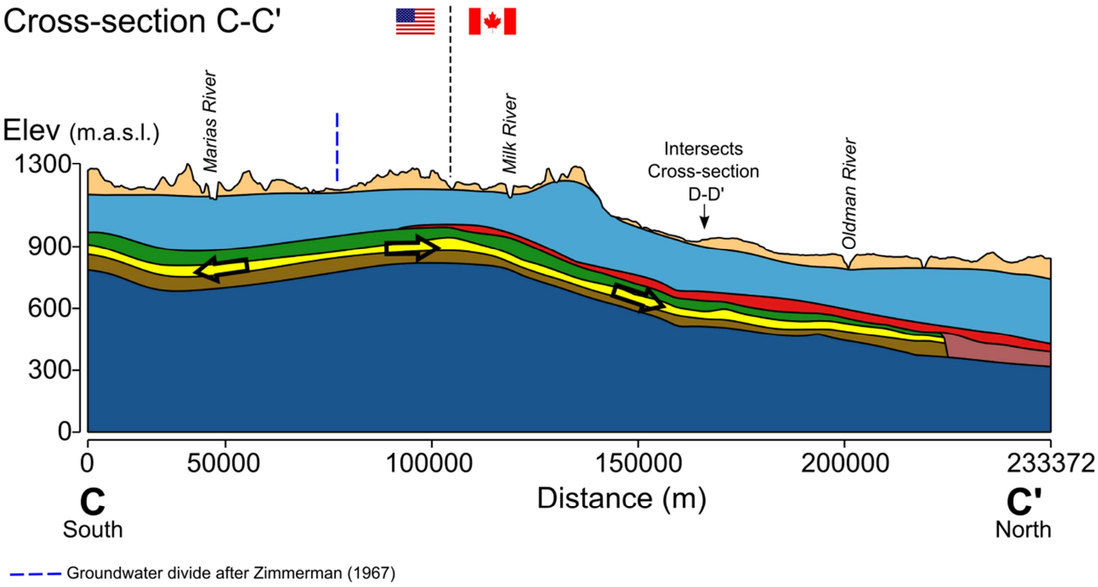
The unified 3D geological model covers 50 000 km^2. The geological units represented in the model are (in ascending order): Colorado Group, Telegraph Creek Member, Virgelle Member, Deadhorse Coulee Member, Alderson Member, Claggett Shale/Pakowki Formation, Belly River Group/Judith River Formation, Bearpaw Formation and surficial sediments (undivided) (Fig. 9).

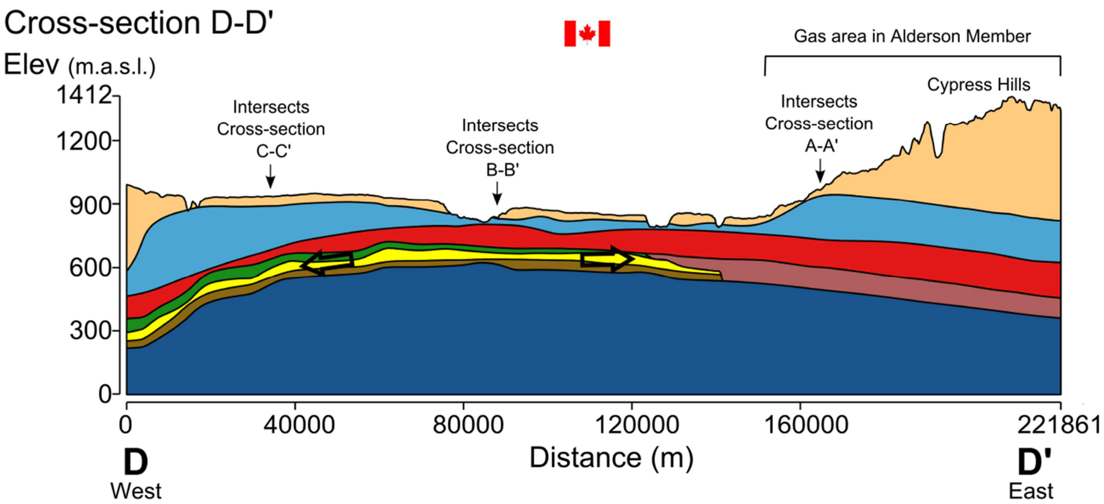
The locations of sections through the geological model are shown on Fig. 9a and these sections are illustrated in Fig. 9b. The general groundwater flow direction is indicated on the cross-sections, based on previous work (Meyboom 1960; Zimmerman 1967; Levings 1982; Tuck 1993; AGRA Earth and Environmental Limited 1998). The area in which the Alderson Member is no longer water-bearing but gas-bearing is indicated on the cross-sections A-A', B-B' and D-D'. The bedrock geological map is superimposed on the model (Fig. 9a). Note that the Two Medicine Formation is shown on the geological map; however the 3D model details all the constitutive members of this formation, especially as shown on cross-section E-E'.



b)


Cross-section A-A' (after unification)
Gas area in Alderson Member
Intersects Cross-section E-E'
Milk River
Intersects Cross-section D-D'
South Sask. River
Elev (m.a.s.l.)
1102
800
600
400
200
0
0
50000
100000
150000
200000
233372
Distance (m)
A
South
A'
North
Cross-section B-B'
Marias River
Unconfined area
Etzikom Coulee
Intersects Cross-section D-D'
Oldman River
Gas area
Bow River
Elev (m.a.s.l)
1090
800
600
400
200
0
0
50000
100000
150000
200000
233372
Distance (m)
B
South
B'
North


Cross-section C-C'
Elev (m.a.s.l.)
1300
900
600
300
0
Marias River
Milk River
Intersects
Cross-section
D-D'
Oldman River
0
50000
100000
150000
200000
233372
Distance (m)
C
South
C'
North
Groundwater divide after Zimmerman (1967)


Cross-section D-D'
Elev (m.a.s.l.)
Gas area in Alderson Member
1412
1200
900
600
300
0
Intersects
Cross-section
C-C'
Intersects
Cross-section
B-B'
Intersects
Cross-section
A-A'
Cypress Hills
0
40000
80000
120000
160000
221861
Distance (m)
D
West
D'
East

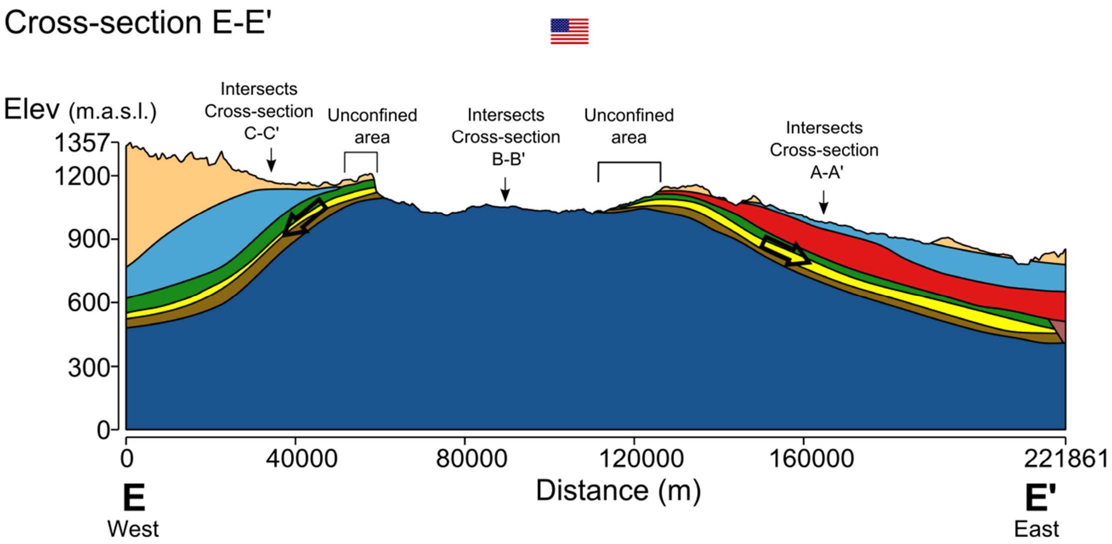


Fig. 9. 3D unified geological model of the Milk River Aquifer and other geological units. **a)** 3D unified block showing the locations of cross-sections. Vertical exaggeration factor is 50. Cross-sections A-A’, B-B’ and C-C’ are transboundary, cross-section D-D’ is located in southern Alberta and cross-section E-E’ is located in northern Montana. **b)** Cross-sections through the 3D geological model. The black arrows represent the general groundwater flow directions. Legend for block diagram (Fig. 9a) and cross-sections (Fig. 9b).

Cross section A-A’ shows that the Milk River Formation is represented on both sides of the border with the same degree of information in the unified model (Fig. 9b). The three members composing the Milk River Formation, especially the Milk River Aquifer (i.e. Virgelle Member), are continuously represented from southern Alberta to north-central Montana. In Montana, the Eagle Formation was divided in three members on the basis of detailed well logs and the working hypothesis described previously. The Milk River Formation dips continuously from northern Montana to southern Alberta. It does not subcrop in this section. The regional unconformity between the traditional 3 members of the Milk River Formation and the Alderson Member is represented as an area of overlap. Groundwater flow is directed to the north, from northern Montana to Alberta. The overlapping area of the Alderson Member corresponds to the Upper Alderson Sands. This part is still water-bearing. However, farther north, the Alderson Member is gas-bearing.

Cross-section B-B’ (Fig. 9b) shows a steeper slope of the Milk River Formation from the international border to the north. The Colorado Group outcrops in northern Montana. A subcrop/outcrop area of the Milk River Formation at the border indicates unconfined conditions of the aquifer corresponding to a recharge area.

West of the Sweetgrass Arch, cross-section C-C’ (Fig. 9b) shows that the Claggett(Pakowki) Formation pinches out in northwestern Montana. In Alberta, the Milk River Formation is overlain by the Pakowki (Claggett) Formation and the thick Belly River Group (Judith River Formation), whereas in Montana the Judith River Formation directly overlies the Milk River Formation equivalents. The Milk River Aquifer is confined and the general groundwater flow is from south to north, except in the vicinity of Cut Bank (Fig. 5a) where it is directed to the south.

Cross-section D-D’ (Fig. 9b) is located in Alberta; it shows the gentle antiformal geometry of the Milk River strata dipping eastward and westward as well as the overlap of the Alderson Member to the east. The Milk River Formation is overlain by 20 to 160 m of Pakowki(Claggett) Formation and 20 to 200 m of Belly River Group (Judith River Formation). Groundwater flows to the north (perpendicular to the cross-section plan), as well as to the east and west following the aquifer elevation.

Cross-section E-E' (Fig. 9b) is located in northern Montana in the vicinity of the Sweetgrass Arch axis. The large outcrop of the Colorado Group is represented. The Milk River Formation equivalents dip to the east and to the west on both sides of the Sweetgrass Arch. The Claggett (Pakowki) Formation is not present west of the Sweetgrass Arch, but it overlies the Eagle Formation in the east. There are two subcrop areas of the Milk River Formation equivalents which correspond to the east and west outcrop bands described above in the bedrock geological map (Fig. 5a) and the Geological Section. Therefore, the Milk River Aquifer is under unconfined conditions in these areas that represent recharge zones. Groundwater flow is directed to the south (perpendicular to the cross-section plan), as well as west and east from the subcrop areas.

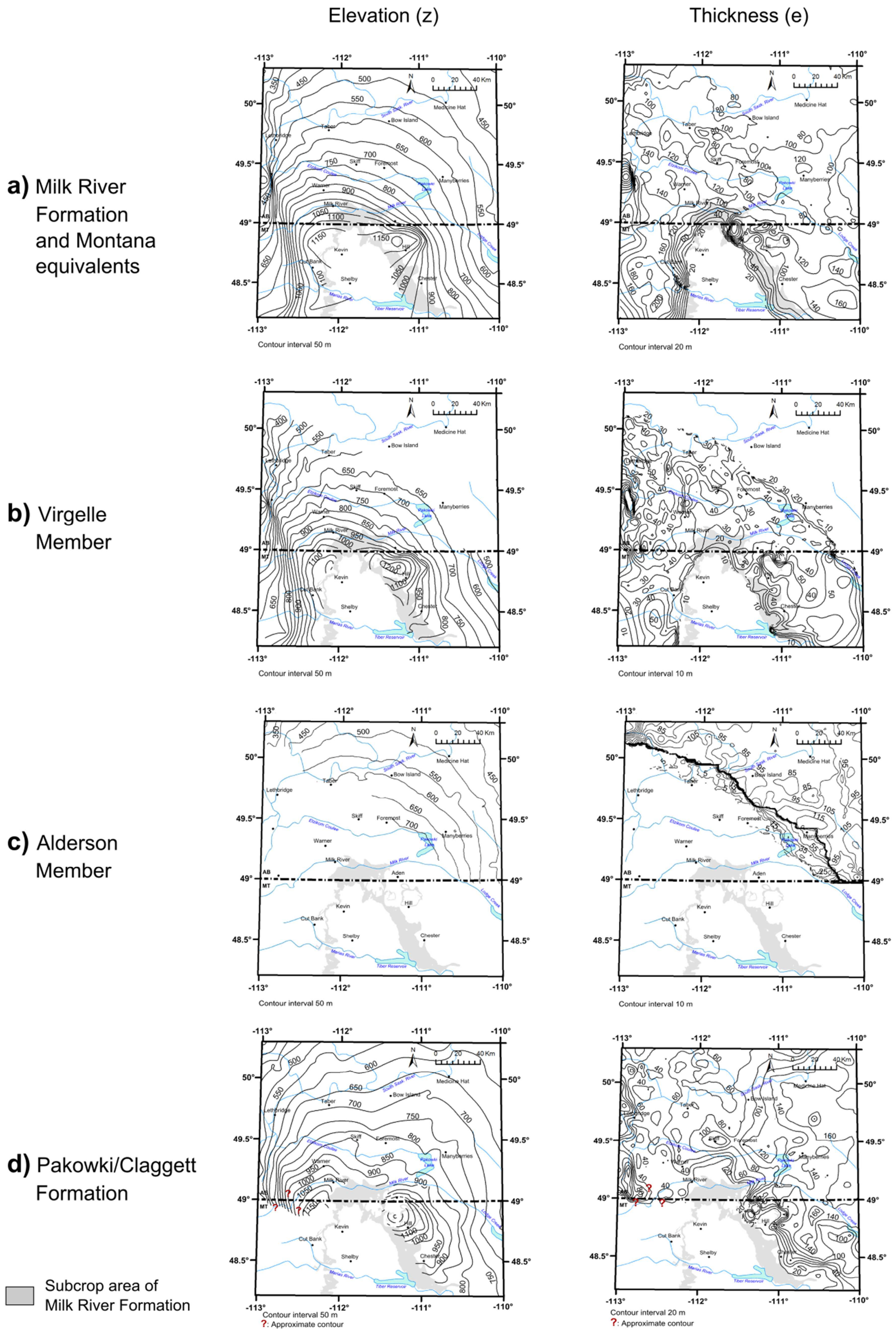
The illustration of the 3D unified geological model is complemented by several elevation and isopach maps of some of the key geological units (Fig. 10).These maps are derived from the 3D geological model which comes from the various sources previously described in the "Data Collection" section. The elevation of the top of the Milk River Formation (including Telegraph Creek, Virgelle, Deadhorse Coulee and Alderson Members) is shown in Fig. 10a. The Milk River Formation dips to the north, east and west from the outcrop area near the international border following a semi-radial pattern. This pattern is continuous through the international border as the Milk River formation dips to the east, south-east and north from the Sweetgrass Hills and to the west, in the area west of the Sweetgrass Arch. The top of the Milk River Formation reaches about 1100 m at the border and decreases to 500 m in the northern part of the study area, about 130 km north of the border. Therefore, the average slope is around 4.7 m/km. In Montana, the dip of the

Milk River Formation equivalents is more pronounced; the top of the formation attains 1100 m around the Sweetgrass Hills and drops to 550 m in the eastern part of the study area, the average slope is therefore 9 m/km. West of the Sweetgrass Arch, the top of the Milk River Formation equivalents drops from 1150 m to 600 m in less than 50 km, so the mean slope is around 13 m/km. The thickness of the Milk River Formation ranges from 0 to 140 m in Alberta and from 0 to 200 m in Montana. In the subcrop areas, the formation is 0 to 60 m thick.

The elevation of the Virgelle Member top is shown in Fig. 10b. As the middle member of the Milk River Formation, it follows the same dipping configuration. The unit thickness ranges between 0 to 60 m in the study area. The Virgelle Member thins towards the deposition limit, which extends from the northwest corner of the study area to the east, near the international border. The extent of the Alderson and Virgelle Members (Fig. 10c) are mutually exclusive except for an overlapping area in the vicinity of the deposition limit of Virgelle where the Alderson Member is 0 to 15 m thick. The Alderson Member thickens to the north and east and reaches a thickness of 95 m in the northeast corner of the study area.

The Milk River Formation is confined by the overlying Pakowki/Claggett Formation which follows the general semi-radial dip of the Milk River Formation (Fig. 10d). The elevation of the top of the Pakowki/Claggett Formation is about 900 m north of the subcrop area of the Milk River Formation. It reaches an elevation of 550 m approximately 120 km farther north. The thickness of this unit ranges from 0 to 160 m; the unit thins from east to west.

The Claggett Shale is not present west of the Sweetgrass arch; it might not be present in the south-west area close to the border in Alberta. Due to the lack of data in the area where Claggett wedges out, the contours are approximate.



Elevation (z)
Thickness (e)
a) Milk River Formation and Montana equivalents
b) Virgelle Member
c) Alderson Member
d) Pakowki/Claggett Formation
Subcrop area of Milk River Formation
Contour interval 50 m
Contour interval 20 m
Contour interval 10 m
?: Approximate contour

Fig. 10. Unified elevation contours of the top of several geological units (left) and isopach maps (right). The elevation reference is the mean sea level and the thickness is in meters. These maps are derived from the 3D geological model which comes from the various sources previously described in the "Data Collection" section. **a)** Elevation and thickness of the Milk River Formation (including Telegraph Creek, Virgelle, Deadhorse Coulee and Alderson Members). **b)** Elevation and thickness of the Virgelle Member. **c)** Elevation and thickness of the Alderson Member. **d)** Elevation and thickness of the Pakowki/Claggett Formation.

Discussion

Changes and confirmations in the geological context

The cross-sections (Fig. 9) and the elevation and isopach maps (Fig. 10) corroborate previous studies of the Milk River Aquifer. In particular, the semi-radial pattern of the elevation of the Milk River Formation top shown in Fig. 10a is in agreement with Meyboom (1960) and others in southern Alberta. Besides, the unified 3D geological model completes this observation by showing that the semi-radial pattern continues into northern Montana.

The 3D geological model represents the subcrop areas of the Milk River Formation near the Sweetgrass Hills and near the international border, which are also traditionally well-documented. However, the model also indicates two additional subcrop areas on both sides of the Sweetgrass Arch in Montana.

This study represents the Alderson Member distinctly from the other three members of the Milk River Formation, separated by a regional unconformity. Previously, the interpreted gradual facies change of the Milk River Formation was only conceptually represented but it was not included in a 3D geological model.

Furthermore, the 3D unified geological model includes the area west of the Sweetgrass Arch in Montana (zone 3). This area was little documented in previous Milk River Aquifer studies. Yet, this is an important area since it hosts the southwestern part of the Milk River Aquifer. Thus, consideration of this zone allows a complete geological representation of the aquifer. The originality of the present work also lies in the representation of the three members of the Milk River Formation continuously across the international border (especially the middle Virgelle Member which is the Milk River Aquifer), as well as the overlying and underlying strata. The 3D geological model thus represents the natural limits of the Milk River Aquifer, not influenced by jurisdictional boundaries.

Hydrogeological implications of the geological model

The elevation contour maps and cross-sections provide a better appreciation of the confined conditions of the aquifer. The Milk River Formation dips to the north from the outcrop areas in the Sweetgrass Hills and near the border in southern Alberta (zones 1 and 2). It dips to the south and east in zone 3 and to the south and west in zone 4. The Milk River Aquifer is therefore confined throughout most of the study area by the overlying Pakowki/Claggett Formations. The recharge areas of the Milk River aquifer have been traditionally identified as the outcrop areas near the border in southern Alberta and around the Sweetgrass Hills in Montana. However, the

Milk River Formation and most importantly the Virgelle Member, subcrop also along both sides of the Sweetgrass Arch in Montana (Fig. 4a; Fig. 9a), which could also represent recharge areas.

The Milk River Aquifer is limited to the north, north-east, and east by the erosional unconformity surface which is overlapped by its lateral equivalent the Alderson Member. Since Alderson Member is included in the Milk River Formation (O'Connell 2014; Payenberg et al. 2003) and its upper part (Upper Alderson Sand) is water-bearing, it has been included in the delineation of the Milk River Aquifer in Southern Alberta by Printz (2004). However, Printz (2004) did not mention the presence of the Alderson Member, unconformably incised into the older members of the Milk River Formation. O'Connell (2014) considered that the Milk River Aquifer consists of two regional sand units within the Milk River Formation: the Virgelle Sand and the Upper Alderson Sands. However, Alderson Member is much younger than the three other members of the Milk River Formation (Payenberg et al. 2002). In addition, unlike the Virgelle Member which is transboundary and continuous through the international border, the Alderson member is not present in Montana where its chronostratigraphic equivalent is located south of the study area (Payenberg et al. 2003). These differences lead us to consider the Alderson Member as distinct from the other members of the Milk River Formation. Thus, the present study limits the Milk River transboundary aquifer to the transboundary Virgelle Member only.

The Milk River Aquifer is limited by the Medicine Hat (Milk River) gas field hosted by the Alderson Member, north, north-east and east of the study area in Alberta. The Tiger Ridge gas field located near the city of Havre (near the Bears Paw Mountains in Montana) represents the south-eastern boundary of the aquifer. In Alberta, the Alderson Member represented in the 3D model, overlaps the lower members of the Milk River Formation. There is no equivalent relationship for the Eagle Formation which hosts the Bearpaw gas field in Montana. For the purpose of the 3D geological model, the Marias River is used as the southern limit of the Aquifer in Montana. Although the Milk River/Eagle Formation extends farther south in Montana, the Marias River physiographic limit has been chosen with respect to the future hydrogeological model and considering the available data. The western limit of the aquifer corresponds to the westernmost area in which water wells have been completed in the Virgelle Member. However, the 3D geological model shows that Virgelle Member exists farther west around the longitude -113° (Fig. 2). No water well is completed in this unit beyond the proposed limit because the aquifer is too deep (Stantec 2002). Thus, the western limit of the aquifer was based on the extent of Virgelle Member water wells.

This work provides a comprehensive geological framework supporting the development of a conceptual model of the Milk River Aquifer. However, other components of the conceptual model still need to be assessed (groundwater-surface water interaction, discharge areas, quantification of transboundary fluxes, geochemistry, etc). Further work will address these components through the development of a unified hydrogeological numerical model of the aquifer.

Model limitations

The amount of available data in Alberta is much higher than in Montana. In order to improve the quality of the 3D geological model, collecting more well log descriptions within northern Montana would be necessary. Regarding the overall resolution of the regional model, the density of geological data is less than 1 datum per km^2. According to the classification of geological models of Culshaw (2005), the geological model would thus be of the “Overview” type.

Simplifications were made concerning the Pakowki/Claggett volume in zone 4. Previous studies described that the transgressive strata did not reach the 112th meridian or wedges out in the vicinity of Cut Bank (Stebinger 1917a; Russell 1970). The volume was not represented west of the Sweetgrass Arch. A rough slimming of the volume was manually edited from the outcrop area of Pakowki in southern Alberta in zone 1 towards the south in zone 3, just north of the Virgelle outcrop. More geological data are needed in the northern part of zone 3 in order to represent the Pakowki equivalent and its disappearance in a more realistic way. Another simplification was made in considering that the interval between the top of the Belly River Group/Judith River Formation and land surface included the Bearpaw Formation (when present) and surficial sediments.

The effort for unification of the Milk River Formation across the international border implied identifying its 3 constitutive members in zones 3 and 4 in Montana, where these members had not previously been defined. This could be done more easily in zone 4 than in zone 3 thanks to the correlation work of Payenberg et al. (2002). The Eagle Sandstone described by Feltis et al. (1981) included the basal Telegraph Creek, Virgelle Member and an upper part, just below the Claggett Shale, which was equated to the Deadhorse Coulee (or middle member of Eagle, following the nomenclature of Payenberg et al. 2002). The upper member of Eagle described in Choteau and Fergus Counties, Montana, does not exist in the study area, according to its depositional area map (Payenberg et al. 2003).

In zone 3, the absence of the Claggett/Pakowki Formation makes the unification work more complex. The Telegraph Creek and Virgelle Members were positively described in well logs. However, the overlying layers were included in the Two Medicine Formation. Given the lack of data in that zone, it was decided to consider the lower 75 m of the Two Medicine Formation as the Deadhorse Coulee equivalent in zone 3, following the description of the Lexicon (WEBLEX Canada 2013). However, isopach maps from O'Connell (2014) indicated that the thickness of the Deadhorse Coulee was about 60 m at the border. The thickness of the dummy Deadhorse Coulee in zone 3 was thus reduced to 60 m close to the border (about 10 km north of the border) to be consistent and continuous with O'Connell's data (2014). The default thickness of 75 m was applied in the remaining area of the geological model. This default value is approximate and might not reflect reality in all of zone 3. However this is considered as an acceptable hypothesis in this regional geological framework study.

The integration of georeferenced cross-sections in the geological model was valuable. It allows verification of how representative the collected geological data were, and the manual editing of geological surfaces based on georeferenced cross-sections compensates for the lack of data encountered in some places (Fig. 8). This technique was particularly useful for the Claggett/Pakowki and Belly River/Judith River surfaces. Cross-sections also show that the hypothesis of equating the tops of Belly River, Pakowki or Deadhorse Coulee to the bedrock topography, where these formations outcropped, was valid. However, there is no cross-section included in the model on the USA side. Cross-sections from the geological maps of the Sweetgrass Hills and Cutbank 30′x60′ quadrangles (Lopez 2001; Berg 2002) did not show a sufficient vertical exaggeration. Thus, the quality of these cross-sections in northern Montana did not allow their use for the development of the 3D geological model.

The Upper Alderson Sands which form small lobate sand bodies was not represented in the model, due to the limitation of the modeling software. However, this unit will be represented in the future hydrogeological FEFLOW model of the aquifer, with distinct hydrogeological properties from the Alderson Member.

Leapfrog Hydro® was chosen mostly for its interoperability with FEFLOW. When using data of various formats in Leapfrog Hydro®, the geological model results in several geological models, each with a specific data format, that are assembled to make up the whole model. Yet, when exporting the model from Leapfrog Hydro® to FEFLOW, only one geological model can be selected for transfer into FEFLOW. This implies the use of data of the same format (locations file with X, Y, Z coordinates).

The area where the Alderson Member overlaps the lower members of the Milk River Formation was difficult to represent with Leapfrog Hydro because many operations and manual editing were necessary. Other software (such as Gocad) could have provided more flexibility for that particular task. The geological model is dynamic; new data or editing of surfaces could be added in an iterative model improvement process.

Conclusion and Perspectives

Geological data on both sides of the Canada/USA border were gathered and processed in order to build a unified three-dimensional geological model of the Milk River Aquifer.

The main contributions of this paper are:

-Our work allowed the unification of the stratigraphic framework of the Milk River Transboundary Aquifer on both sides of the Canada/USA border.

-There is a more rigorous delineation of the extent of the Milk River Transboundary Aquifer, and a better description of its characteristics (thickness, geometry) following its natural boundaries (not the jurisdictional boundaries).

-The 3D geological model provides a representation of the three members of the Milk River Formation (especially the Virgelle Member (Milk River Aquifer) and encasing units continuously through the border.

-The 3D geological model also provides a description of the geological boundaries of the Milk River Aquifer, imposed by the regional structure, the regional unconformity in southern Alberta, and the sealing effects of the adjacent gas fields.

-The 3D geological model also includes the representation of the gas-bearing Alderson Member and the regional unconformity surface which separates it from the lower members of the Milk River Formation.

-The implications of the geological model on the hydrogeological conditions of the aquifer have been highlighted. The hydrostratigraphic role (aquifer or aquitard) of each geological unit has been shown.

This 3D unified geological model is a major component of a unified conceptual hydrogeological model of the Milk River Aquifer. It will form the basis for the future development of a numerical model of the Milk River Aquifer. The next stage in this study will be to propose a unified hydrogeological conceptual model of the Milk River aquifer, including boundary conditions, groundwater flow systems, and groundwater quality. The final stage will be to transfer the geological model into FEFLOW that will be used to develop a numerical groundwater flow model. This transfer of the geological model will allow hydrogeological properties to be assigned to each geological layer.

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