BULLETIN OF CANADIAN PETROLEUM GEOLOGY
VOL. 48, NO. 3 (SEPTEMBER, 2000), P. 212-229

Geological controls on reservoir distribution in the Lower Cretaceous Basal Quartz, Chin Coulee–Horsefly Lake area, south-central Alberta

R.W.C. ARNOTT
Department of Earth Sciences and Ottawa-Carleton Geosciences Centre
University of Ottawa
Ottawa, ON
K1N 6N5

B.A. ZAITLIN
PanCanadian Petroleum Ltd.
150-9 Avenue SW
Calgary, AB
T2P 2S5

D.J. POTOCKI
PanCanadian Petroleum Ltd.
150-9 Avenue SW
Calgary, AB
T2P 2S5

ABSTRACT

In much of southern Alberta the Lower Cretaceous Basal Quartz is a complex assemblage of mostly nonmarine sandstone and mudstone. Within the study area, which is centred on Horsefly Lake and Chin Coulee pools (twp. 7-9; rge. 14-17W4), the BQ comprises a minimum of five unconformity-bounded sequences that are differentiated by a unique assemblage of attributes, including mineralogy, micro- and macroscopic sedimentological textures and structures, reservoir-quality characteristics, and production history. In stratigraphic succession, these sequences are informally termed the "A" sandstone, "weathered Horsefly" sandstone, "unweathered Horsefly" sandstone, "old BAT" sandstone, and "young BAT" sandstone.

The oldest strata consist of the "A" and "weathered Horsefly" sandstone. As a result of extensive pedogenic alteration, primary sedimentary characteristics and reservoir quality have been largely destroyed. Reservoir development in these strata is the result of diagenetic leaching, and is limited in areal extent (limited reservoirs). The younger "unweathered Horsefly" sandstone, or simply "Horsefly" sandstone, and "BAT" sandstones form the principal reservoirs in the study area. However, in spite of their different ages, a consistent vertical assemblage of lithofacies exists for each sandstone unit a braided fluvial succession several metres thick (primary reservoir strata) is overlain abruptly by a several-metre-thick meandering fluvial succession. This consistent upward change is interpreted as resulting from repetitive changes in sediment supply and its control on the nature and spatial patterns of sedimentation.

Although the Basal Quartz was deposited over about 18-32 my, it is less than ~ 25 m thick within the Chin Coulee–Horsefly Lake study area. This suggests that Basal Quartz sediment accumulated under highly accommodation-limited conditions, which in turn caused net sedimentation rates to be very low. One of the most significant consequences of this limitation was the development of a particularly complex stratigraphic succession. Because of the limited accommodation space, each unconformity-bounded succession tends to incise from a similar stratigraphic horizon, which therefore requires careful regional mapping to determine relative ages. In additon, younger stratigraphic successions eroded some or most of the commonly extensively pedogenically altered older ones. This resulted in the formation of an extremely complex succession of strata and a highly compartmentalized reservoir system.

RÉSUMÉ

Dans une grande partie du sud de l'Alberta, le Quartz de Base (QB) du Crétacé inférieur est un assemblage complexe composé surtout de grès non-marin et de mudstone. À l'intérieur de la région d'étude, qui est centrée sur les champs du Horsefly Lake et de Chin Coulee (T7-9, R-14-17W4), le QB comprend un minimum de cinq séquences limitées par des discordances qui sont différenciées par un assemblage unique d'attributs, incluant la minéralogie, les textures et structures micro- et macroscopique, les textures et structures sédimentaires, les caractéristiques de qualité de réservoir et l'histoire de production. Dans la succession stratigraphique, ces séquences sont nommées informellement grès "A", grès "Horsefly altéré", grès "Horsefly non-altéré", grès "vieux BAT" et grès "jeune BAT".

Les plus vieilles strates correspondent aux grès "A" et "Horsefly altéré". À la suite d'un altération pédogénique prolongée, les caractéristiques sédimentaires primaires et la qualité de réservoir ont été amplement détruites. Le développement d'un réservoir dans ces strates est le résultat d'un lessivage diagénétique et est limité en étendue (réservoirs limités). Le grès le plus jeune de "Horsefly non-altéré" ou plus simplement le grès "Horsefly" et les grès "BAT" forment les principaux réservoirs de la région d'étude. Toutefois, en dépit de leurs âges différents, un assemblage vertical et consistant de lithofaciès existe pour chacune des unités de grès : une succession fluviale anastomosée de plusieurs mètres d'épaisseur (strates de réservoir primaire) est recouverte abruptement par une succession fluviale à méandre de plusieurs mètres d'épaisseur. Ce changement consistant vers le haut est interprété comme résultant de changements répétés d'espaces d'ajustement et de sédimentation.

Même si le Quartz de Base a été déposé pendant à peu près 18 à 32 m.a., il est de moins de 25 m d'épaisseur à l'intérieur de la région d'étude de Chin Coulee-Horsefly Lake. Ceci suggère que le sédiment du Quartz de Base s'est accumulé sous des conditions d'ajustement très limitées, qui à leur tour ont causé des taux de sédimentation net très bas. Une des conséquences les plus significatives de cette restriction est le développement d'une succession stratigraphique particulièrement complexe. En raison de cet espace d'ajustement restreint, chaque succession limitée par une discordance tend à s'inciser à partir d'un horizon stratigraphique similaire, qui nécessite une cartographie régionale soignée pour déterminer les âges relatifs. De plus, les successions stratigraphiques plus jeunes ont érodé certains ou la plupart des successions plus vieilles communément altérées pédogéniquement de façon étendue. Ceci a eu pour résultat la formation d'une succession extrêmement complexe de strates et un système de réservoir hautement compartimentalisé.

Traduit par Lynn Gagnon

INTRODUCTION

In southern Alberta, the Lower Cretaceous Basal Quartz is a highly complex and presently poorly understood stratigraphic succession. This can be attributed to two major factors. Firstly, a significant part of the Basal Quartz in this area consists of nonmarine strata. Presently, our understanding of the auto- and allocyclical processes that control nonmarine stratigraphy is poor. Secondly, because the stratigraphic record is the manifestation of the interaction between accommodation space and sediment supply, spatial and/or temporal differences in either will profoundly affect stratigraphy. In the case of the Basal Quartz, accommodation space varied significantly throughout different parts of the Early Cretaceous Mannville Basin (Cant and Abrahamson, 1996). One of the results of this difference is that areas of low accommodation space would have accumulated thinner stratal assemblages compared to high accommodation settings. Because of limited net aggradation in low-accommodation systems, younger alluvial systems would have incised and extensively eroded the older ones. The long-term effect would be a complex juxtaposition and cross-cutting of stratal units, which although potentially similar in stratal architecture would be different in age. Moreover, if reservoir quality differed between units, there would possibly be significant local variability in hydrocarbon production. As a result, in order to explore successfully in accommodation-limited basins, or parts of larger basins, it is essential to first develop a highly-resolved stratigraphy that identifies not only the constituent stratal units but also their unique internal geometry and areal distribution. The objective of this paper, therefore, is to illustrate the depositional and diagenetic processes that controlled reservoir distribution in the Lower Cretaceous Basal Quartz sandstone in the Chin Coulee–Horsefly Lake area of southern Alberta (Fig. 1), a stratal succession that accumulated in an accommodation-limited part of the Early Cretaceous Mannville Basin.

REGIONAL GEOLOGY

In the Western Canada Sedimentary Basin (WCSB), strata of the Mannville Group overlie the regional post-Valanginian (or sub-Cretaceous) unconformity, and in turn are unconformably overlain by the Colorado Group (Joli Fou Formation) (Leckie and Smith, 1992). The Mannville was deposited above the Middle to Upper Jurassic Ellis Group that comprises the Detrital, Sawtooth, Rierdon and Swift formations (and their equivalents; Leckie and Smith, 1992), and has been interpreted to represent a third-order, westward-thickening, coarse clastic continental wedge associated with the initiation of the Western Canada Foreland Basin (Cant and Abrahamson, 1996). Although the stratigraphic nomenclature for the Mannville Group (see below) varies across the WCSB, it can be generally subdivided into two units: the Lower and Upper Mannville successions (Glaister, 1959). The Lower Mannville overlies the sub-Cretaceous unconformity and in most places is overlain by the post-Ostracode to pre-Glauconite unconformity, and ranges in age from Tithonian (~148 Ma) to latest Aptian (113 Ma) (Fig. 2). The Upper Mannville succession overlies the Lower and is capped unconformably by the Colorado Group (Middle Albian). Compared to the ~18-32 my represented by the Lower Mannville (Leckie et *al*., 1996; Leckie et *al*., 1997), the Upper Mannville represents only about 10 my of geological time.

The onset of Lower Mannville sedimentation coincided with 1) a major episode of tectonism and uplift related to the Colombian Orogeny and 2) a third-order southward transgression of the (northern) Boreal Sea (Cant and Abrahamson, 1996). Tectonism and uplift rejuvenated several tectonic elements that localized the incision of a number of major, generally northward-trending paleovalley systems termed the Cut Bank, Whitlash and pre-Cantuar incised-valley systems in southern Alberta and southwestern Saskatchewan (Christopher, 1964, 1974, 1980, 1985; Hayes, 1986). Southward transgression of the Boreal Sea, however, drowned parts of many

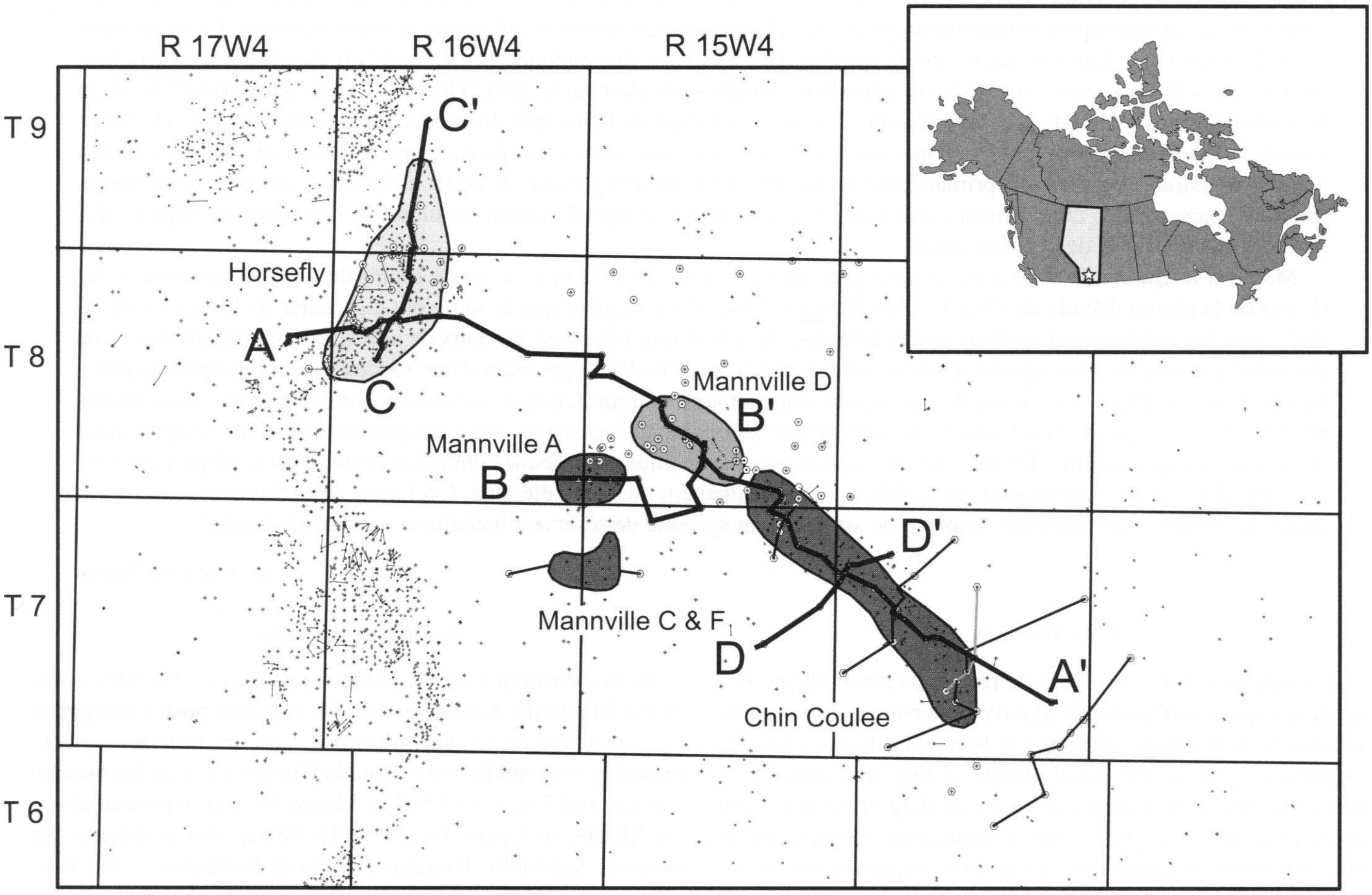

Fig. 1. Location map of the study area in south-central Alberta. Each square represents a 36 mile^2 (92 km^2) area. Names and general outlines of each of the pools discussed in the text are shown. In addition, stratigraphic cross-sections constructed in this study are shown. Those that are labelled (*e.g.* A-A') are presented in Figures 11 and 12. Wells designated with large open dots represent data points for this study; note that not all data points occur on stratigraphic cross-sections.

paleovalleys and filled them with a succession of backstepping estuarine deposits over fluvial deposits as far south as the Canada–United States border (Dolson and Piombino, 1994; Lukie, 1999). Transgression was most probably episodic, resulting in multiple incision events and the stacking of different-aged fluvial-estuarine systems within the major incised-valley systems.

In southern Alberta the "undifferentiated Basal Quartz" forms most of the Lower Mannville succession. It is a purely descriptive lithological term used for the predominantly quartzose sandstone that occurs near the base of the Lower Mannville Group (Glass, 1990). Significant confusion, however, has developed with the use of the term "Basal Quartz" and, regionally, its stratigraphic equivalents (*e.g.* the Detrital, Taber, Cut Bank, and Sunburst successions in southern Alberta). Much of the confusion and consequent proliferation of stratigraphic terms is most probably as a result of 1) earlier use of lithostratigraphic correlation styles in a highly complex stratal succession; 2) attempts to extrapolate local stratigraphic units into other sub-basins as part of the many local to semi-regional studies undertaken over the past 50 years; and 3) the difficulty of differentiating "Basal Quartz" strata from Jurassic sandstone and shale. For these and other reasons, it has been suggested that the term "Basal Quartz" be discarded (Glass, 1990, p. 37), and a new stratigraphic framework be developed.

In order to facilitate a more internally consistent stratigraphic framework, and to limit the confusion in using lithostratigraphic terminology, this paper is the first in a series that presents a revised stratigraphic nomenclature for the "Basal Quartz" (Fig. 2). The informal nomenclature to be presented here ("A" sandstone, "weathered Horsefly" sandstone, "Horsefly" sandstone, and "BAT" sandstone, in addition to other units to be presented in later papers) stems from a series of pool-typing studies of Horsefly Lake, Chin Coulee and Mannville A and D pools. These studies formed part of a larger unpublished regional study undertaken at PanCanadian Petroleum Limited on the "Basal Quartz" between Townships 1-40 and Ranges 1W4 to 5W5. The regional study consisted of the stratigraphic correlation of over 9000 wells in 88 regional and 43 pool-typing cross-sections, incorporating the data from about 1350 described cores and detailed petrographic work. Based on that work, the "A" sandstone is interpreted as

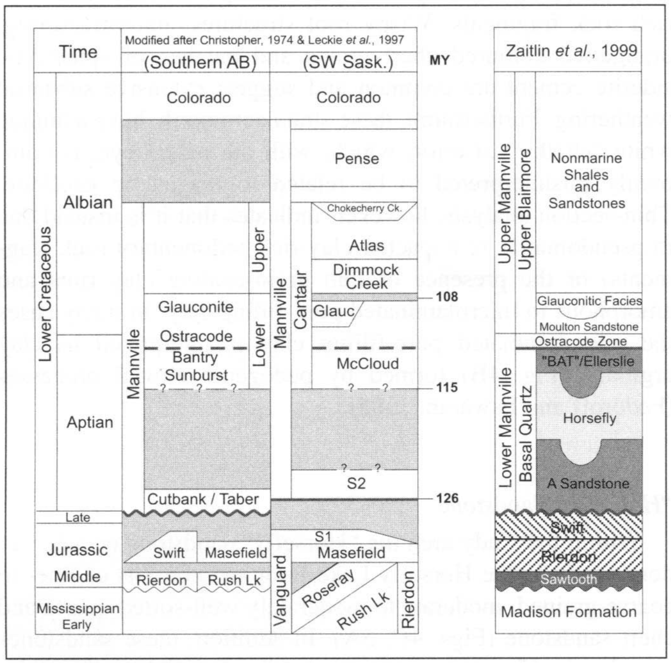

Fig. 2. Stratigraphic framework of Lower Cretaceous strata in southern Alberta and southwestern Saskatchewan modified after Christopher (1974) and Leckie *et al.* (1997) and Zaitlin *et al.* (1999).

representing a complex succession comprising the oldest "Basal Quartz" strata. The Horsefly sandstone, named after its type locality in Horsefly Lake Pool, is an intermediate-aged BQ succession that is succeeded in age by the "BAT" sandstone, an acronym for productive BQ sandstones in the Bantry–Alderson–Taber areas of southern Alberta. From the regional study, it was suggested that the "Basal Quartz" comprises a number of "nested" compound piedmont incised valley systems (sensu Zaitlin et al., 1994) that developed in a variety of low- to high-accommodation settings. In this particular study, the Lower Mannville succession, which represents approximately 18-32 my of geological time (Leckie *et al.*, 1996; Leckie *et al.*, 1997), is generally only of the order of 20-25 m thick. This indicates that "Basal Quartz" strata, hereafter termed BQ, in the Chin Coulee–Horsefly Lake area accumulated in one of the accommodation-limited parts of the Early Cretaceous Mannville Basin.

Study Area and Data Base

The study area is in south-central Alberta and generally is bounded north-south by Townships 6-9 and east-west by Ranges 13-17 west of the fourth meridian (Fig. 1). Structural dip is toward the northwest (Fig. 3) and is related to the fact that the area lies on the northwest limb of the northeast–southwest-trending Sweetgrass Arch (Fig. 1). Within the study area, six pools currently produce primarily from BQ strata. There are the Horsefly Lake, Chin Coulee (termed the Basal Mannville Pool by the EUB, but herein termed Chin Coulee) and Mannville A and D pools. Because two other pools, the Mannville C and F pools, produce from the same stratal succession as the much larger Mannville A Pool, all three are collectively referred to hereafter as Mannville A Pool. A significant observation is that in the Mannville D Pool, a portion of the production in some wells is interpreted to come from strata that overlie the BQ. Production data from these wells are not considered in this study. Although all the producing pools in the study area are close to one another, have similar oil gravity, and produce primarily from the Basal Quartz, important differences exist (Table 1).

Data for the study included detailed bed-by-bed description of 52 cores, petrographic analysis of 75 thin sections, and the construction of 16 wireline log cross-sections covering 157 wells (Fig. 1). Logs were correlated using a regionally extensive horizon consisting of a black fissile shale overlain abruptly by a dense micrite as the stratigraphic datum. In this study, as in Hradsky and Griffin (1984), this horizon is interpreted as marking the base of the Ostracode Zone. This differs from Farshori (1989) and Farshori and Hopkins (1989), who suggest that these strata occur near the base of the Sunburst sheet sandstone — a stratigraphic unit that is not recognized in this study, and also previously questioned by Hayes (1986, 1990). The base of the Ostracode Zone represents a regional flooding surface caused by the long-term southward transgression of the Boreal Sea that flooded much of southern Alberta by the early Albian (Smith, 1994). Although other areally extensive surfaces could have been used, the base of the Ostracode Zone is preferred because it lies in close proximity to the zone of interest, is areally extensive, and can be easily identified in core and on geophysical logs. In addition, aside from a very small number of wells in the Mannville D Pool, all hydrocarbon production in the study area is from strata underlying this horizon.

Table 1. Production characteristics of the three principal pools within the study area that are currently producing from sandstone of the Basal Quartz (Alberta Energy and Utilities Board, 1998).

Pool	Original Oil in Place x10^3 m^3	Recoverable Reserves x10^3 m^3	Recovery Factor 1°	Recovery Factor 2°	Total Area (ha)	Pay (m)	Sw (%)	Porosity (%)	Oil Density (kg/m^3)
Horsefly	7938	2173	<9%	18%	2015	5.20	44	18.5	887 (28 API)
Chin Coulee	3510	1053	10%	20%	1564	2.54	40	19.4	915 (24 API)
Mannville A	1462	292	20%	---	380	3.41	40	20	915 (24 API)

1° – primary production; 2° – secondary production (water-flood pressure support)

BQ SANDSTONE TYPES

PETROGRAPHY

In this study, 75 thin sections from 27 wells were examined. In thin section, mineralogical composition and porosity were quantified through modal point count analysis of 62 thin sections, whereas textural characteristics, specifically grain size, sorting, and packing heterogeneity were estimated visually. Based on these data, BQ sandstones were grouped into four unique assemblages. Most notably, these assemblages were identified based on volume changes in the three major framework components (quartz, chert, clay-rich sedimentary rock fragments), differences in texture, weathering features, and the presence or absence of feldspar. A ternary diagram with quartz, chert and clay-rich grains at the apices proved to be an effective method for partitioning the petrographic data into recognizable populations. These results indicate a generally increasing mineralogical and textural maturity from the "A" sandstone, to the "weathered Horsefly" sandstone, to the (unweathered) "Horsefly" sandstone, and finally the "BAT' sandstone (see below).

"A" Sandstone

"A" sandstone consists commonly of very fine- to coarse-grained, poorly to moderately sorted, matrix-rich sandstone (Fig. 4A). Framework grains consist of quartz, chert and clay-rich rock fragments. Wispy root structures, microfracturing, orange/red coloured chert grains and patches of spherulitic siderite cement are common and suggest extensive subaerial weathering. Furthermore, these strata commonly have a unique white "chalky" exterior, which, with the naked eye, is commonly misinterpreted to be related to diagenetic kaolinite. Thin-section analysis, however, indicates that it is instead due to pseudomatrix (compacted clay-rich sedimentary rock fragments) or the presence of thin grain-coating clay rims and amorphous to microlaminated pore-filling clay. In many cases the microlaminated pore-filling clay is interpreted as clay argillans (Fig. 4B) formed by pedogenic eluvial processes (Fedoroff and Eswaran, 1985).

"Horsefly" Sandstone

Within the study area the "Horsefly" sandstone occurs predominantly in the Horsefly Lake Pool and consists of fine- to coarse-grained, moderate to moderately well-sorted quartz and chert sandstone (Figs. 4C, 5A). In addition, these sandstones contain significant amounts of ductile clay-rich sedimentary and low-grade, schistose, metamorphic rock fragments, and small but comparatively significant amounts of potassium

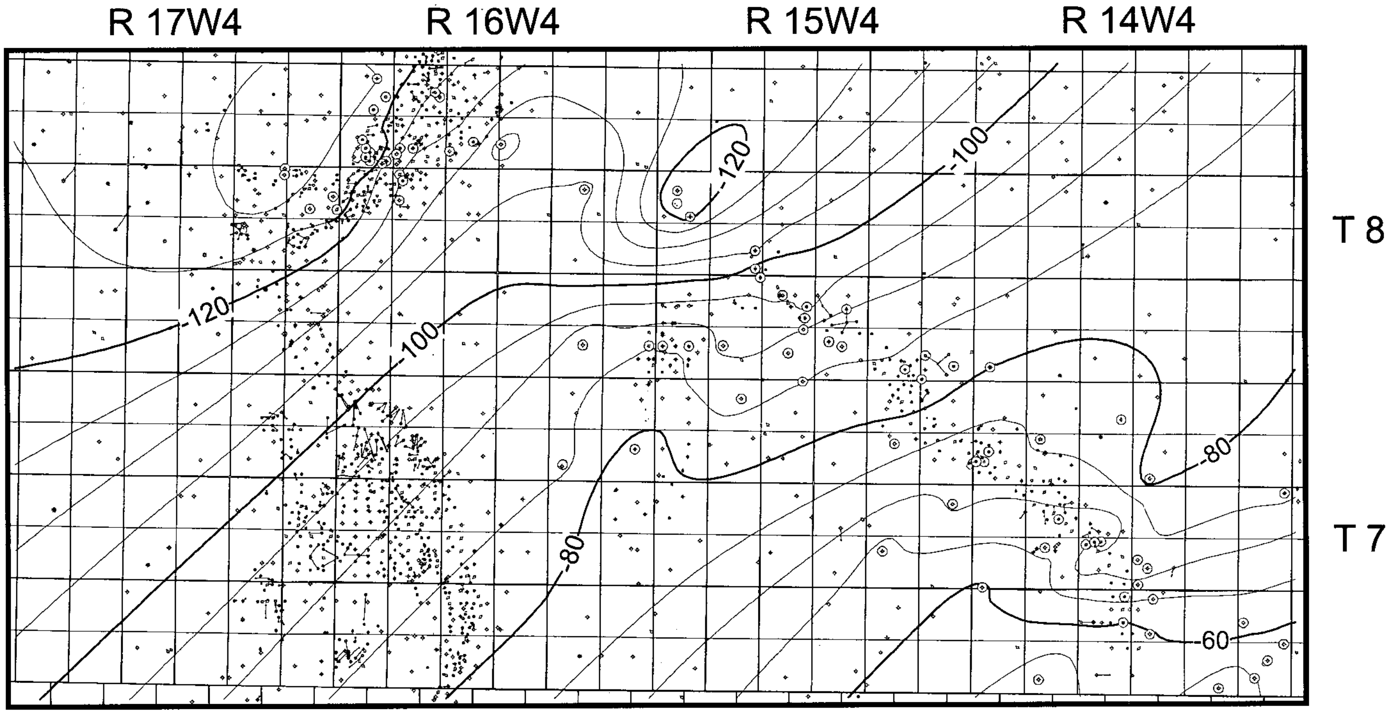

Fig. 3. Structure map on the top of the Lower Cretaceous Basal Quartz stratal succession. Note the consistent northwestward dip of strata, which is related to the area lying on the northwest limb of the Sweetgrass Arch. Contour interval is 5 m.

feldspar. Carbonaceous debris was not observed. It is important to note that framework composition is related in part to grain size; quartz becomes more abundant but chert less abundant with decreasing grain size. Also, the compaction of ductile clay-rich sedimentary rock fragments during burial has formed a widespread pseudomatrix, and consequently has reduced reservoir quality.

A second major occurrence of "Horsefly" sandstone is present about 9 km to the southeast of Horsefly Lake Pool in the Mannville D Pool. Here, it occurs as an outlier (see later). In

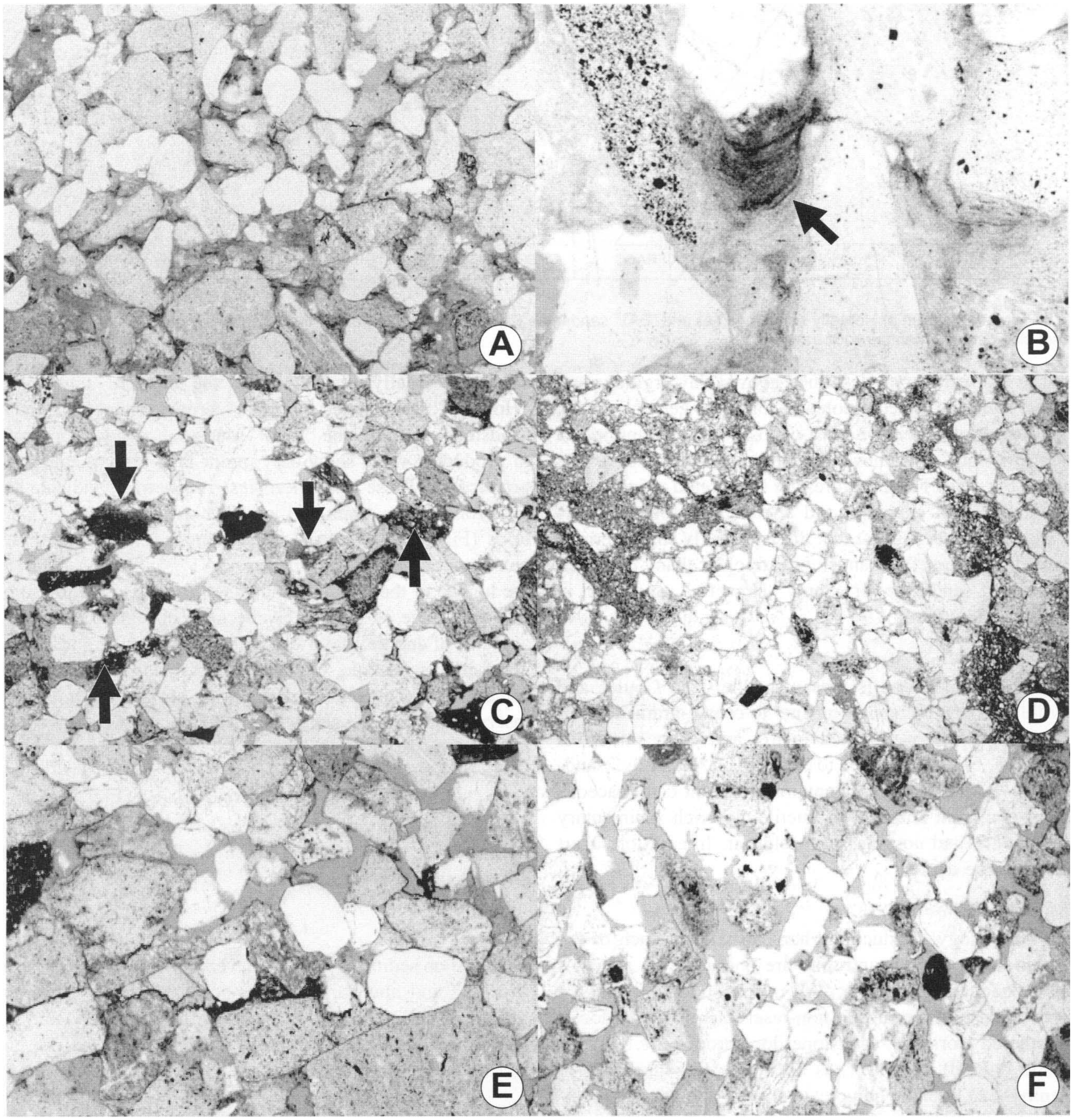

Fig. 4. **(A)** medium-grained "A" sandstone packed with infiltrated clay "matrix" (12-30-7-15W4); **(B)** clay-silt argillan (arrow) in a pedogenically altered "A" sandstone (12-30-7-15W4); **(C)** porous, permeable Horsefly sandstone: note locally developed pseudomatrix formed by deformed sedimentary rock fragments (indicated by arrows) (3-32-8-16W4); **(D)** pedogenically altered weathered Horsefly sandstone (6-9-8-15W4). Locally, the matrix has been completely leached forming porosity, or partly leached (light coloured matrix prevalent in lower centre of the photo); **(E)** BAT sandstone (Chin Coulee Pool): porous and permeable quartz- and chert-rich sandstone (7-35-7-15W4). **(F)** loosely packed, good reservoir quality BAT sandstone similar to those in the Mannville A Pool (4-19-8-15W4). **(B)** is 1mm wide (100 X magnification), **(A)**, **(C)**-**(F)** are 4 mm wide (25 X *magnification*).

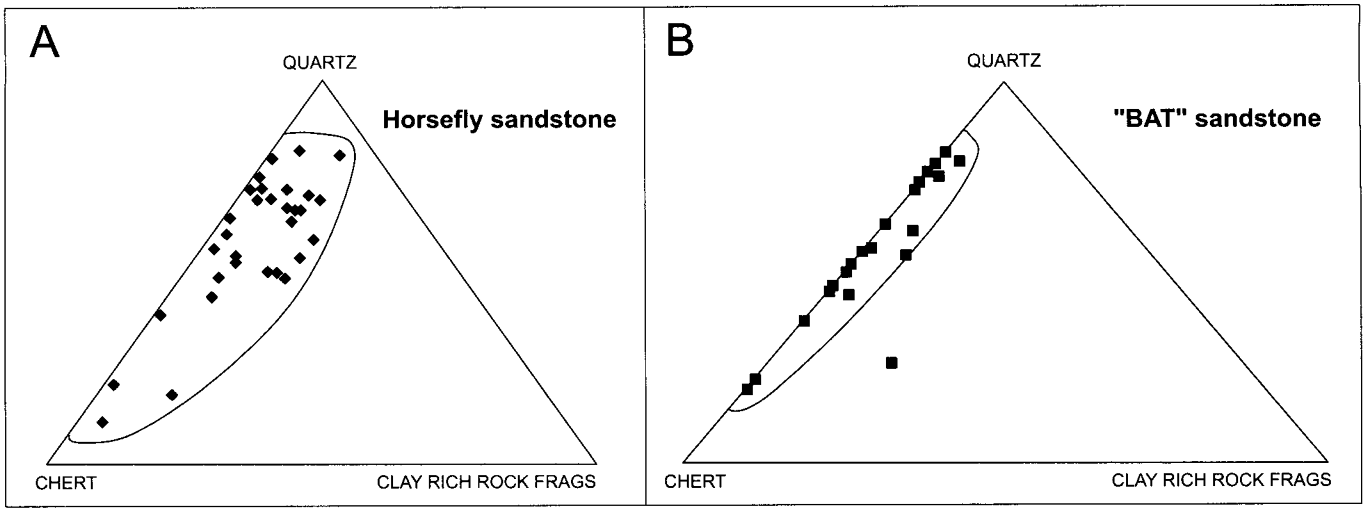

Fig. 5. Ternary diagram of Horsefly sandstone **(A)** and "BAT" sandstone **(B)**. Note the wider field of the Horsefly sandstone resulting from more abundant clay-rich sedimentary rock fragments.

contrast to Horsefly strata described above, clay argillans and authigenic kaolinite are common and sorting is generally poor, with evidence of extensive post-depositional disruption. In addition, evidence of framework-grain and matrix leaching is prevalent (Fig. 4D). These features are interpreted as indicating long-term subaerial exposure and attendant pedogenic alteration, and, therefore, suggest that these Horsefly strata, termed the "weathered Horsefly" sandstone, are older than "unweathered Horsefly" sandstone, or simply "Horsefly" sandstone, in the Horsefly Lake Pool.

"BAT" Sandstone

The "BAT" sandstone is present in the Chin Coulee and Mannville A pools. It consists of fine- to coarse-grained, moderate to moderately well-sorted quartz and chert sandstone (Figs. 4E, 4F, 5B). In contrast to the "A" or "Horsefly" sandstones, the "BAT" sandstone contains abundant carbonaceous debris, insignificant amounts of ductile clay-rich sedimentary rock fragments, and no potassium feldspar. In addition, chert grains tend to be darker.

PRODUCTION CHARACTERISTICS

Like mineralogy, production characteristics of each of the three main kinds of BQ sandstone are unique. As a result of extensive pedogenic alteration, "A" sandstone and "weathered Horsefly" sandstone are mostly non-reservoir. However, locally, "weathered Horsefly" sandstone does produce (*e.g.* in the Mannville D Pool). However, as noted above, some wells in the Mannville D Pool are completed also in strata that immediately overlie the BQ (*i.e.* above the datum). In these wells, *e.g.* the 16-08-8-15w4 well, much of the production is believed to come from these stratigraphically higher strata. In strata beneath the datum in the Mannville D Pool, porosity is the result of (pedogenic) leaching. Oil production in these wells shows rapidly declining trends indicative of limited reservoir conditions (Fig. 6A), which in turn suggests that leaching was similarly areally restricted. In the case of unweathered "Horsefly" sandstone, hereafter termed simply "Horsefly" sandstone, and also the "BAT" sandstone, production profiles of producing wells show only minor long-term changes in oil production. These characteristics, in contrast, indicate good reservoir-quality strata and areally extensive reservoir conditions (Figs. 6B, C, D). However, in spite of this similarity, recovery factors of Horsefly and "BAT" sandstones differ; they are higher in the "BAT" sandstone (Table 1). The reason for this difference is most likely because of significantly higher amounts of ductile, clay-rich sedimentary rock fragments in the "Horsefly" sandstone. As noted earlier, these grains were compacted to form a pseudomatrix during burial, which decreased reservoir quality, as suggested by the much lower hydrocarbon recovery in the Horsefly Lake Pool. Accordingly, the paucity of these grains, and related pseudomatrix in the "BAT" sandstone, has helped preserve good reservoir quality. In addition, and as noted previously by Farshori (1989), the generally higher abundance of clay intraclasts in the Horsefly sandstone has also reduced reservoir quality.

LITHOFACIES

Based on sediment grain size, vertical changes in grain size, and type and abundance of physical sedimentary structures, seven unique lithofacies were identified (Table 2; Figs. 7,8,9). For brevity, only three of the seven lithofacies are presented here.

CHALKY-WHITE SANDSTONE AND MUDSTONE (LITHOFACIES 2)

Strata of this lithofacies have only been observed in a small number of cores within the study area. Generally, they are non-reservoir, but locally form limited reservoirs (Mannville D Pool). In core, strata have a distinctive salt-and-pepper texture; the light-coloured sediment has a distinctive white, chalky appearance and the dark material is mostly dispersed black chert grains, commonly up to coarse-sand size (Figs. 7B, C). In addition, these strata are petrographically unique and consist of "A" sandstone and "weathered Horsefly" sandstone. Throughout the study area these strata abruptly overlie shale of the Rierdon Formation and consist of interstratified sandstone and sandy/silty mudstone units several metres thick. Sandstone units are generally massive, although rarely, a poorly defined upward-fining trend can be detected.

Reservoir quality is generally poor, with core-measured porosity and permeability of the order of 6-12% and 0.01 mD, respectively. However, less commonly cores have excellent porosity and permeability (20-24% and >1D, respectively). Petrographic analyses indicates that the apparent excellent reservoir quality is the result of extensive leaching of framework grains and/or matrix (see Fig. 4D). Sandy mudstone units are massive, and, although large sand-filled root moulds are common, carbonaceous debris is absent (absent also in sandstone strata). Dispersed sphaerosiderite nodules, ranging up to several millimetres in diameter, are common but are more abundant in mudstone strata. In addition, large sand-filled fractures and ductile deformation are common, particularly in finer-grained strata (Fig. 7C).

Interpretation

The distinctive white colour and generally poor reservoir quality of these strata is interpreted as the result of extensive pedogenic alteration. For example, the interstitial clay argillans observed in strata from the 12-30-7-15W5 well (Fig. 4B) are formed by vertical vadose-zone flushing (eluviation) (Fedoroff and Eswaran, 1985). Furthermore, the lack of carbonaceous debris but abundance of sphaerosiderite is suggestive of extensive pedogenic alteration (iron-carbonate precipitation might have been mediated by soil bacteria and their influence on local geochemical conditions). These strata, therefore, are interpreted as the remnants of ("Basal Quartz") alluvial deposits that were subaerially exposed and extensively pedogenically altered before and during deposition of reservoir sandstone in the study area. Also, extensive pedogenic alteration has destroyed the reservoir quality of these strata. However, locally, reservoir quality of Lithofacies 2 strata is excellent and is the

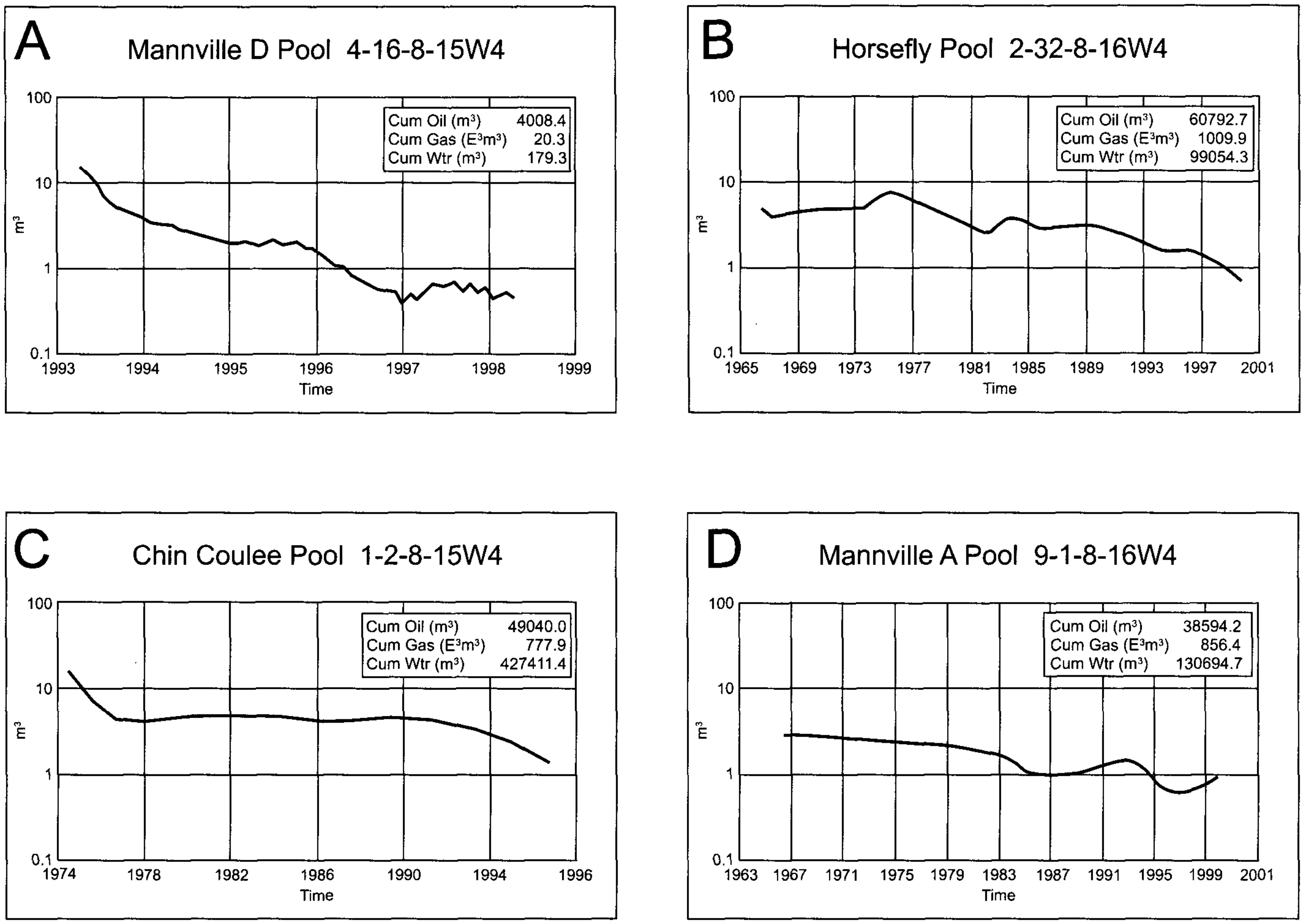

Fig. 6. Production profiles (average daily oil production versus time) of each of the four major pools in the study area **(A)** Mannville D Pool (weathered Horsefly sandstone); **(B)** Horsefly Lake Pool (Horsefly sandstone); **(C)** Chin Coulee Pool (BAT sandstone); **(D)** Mannville A Pool (BAT sandstone). In all but the Mannville D Pool, average daily oil production shows only minor long-term decline. Also shown is the cumulative oil, gas and water production from each well (data provided by Accumap EnerData).

Table 2. Lithofacies, their distinguishing characteristics and depositional interpretation. *See text for detailed description of Lithofacies 2, 3 and 4. Present/absent indicates that the characteristic is or is not present, which as outlined in the text depends on the sandstone unit present (e.g. "Horsefly" sandstone, "BAT" sandstone etc.).*

Lithofacies	Lithofacies Interpretation	Physical Sedimentary Structures	Trace Fossils	Evidence of Weathering	Carbonaceous material	Porosity (%)	Permeability (mD)	Reservoir Quality
1	regolith (Fig. 7A)	poorly bedded matrix- and clast-supported conglomerate with interbedded sandstone	absent	present	present/absent	variable, generally low	variable, generally low	variable, generally poor
2	weathered alluvial strata (Figs. 7B, C)	massive sandstone, siltstone, mudstone	absent	extensive	absent	variable, generally low	variable, generally low	variable, generally poor
3	braided fluvial (Fig. 7D)	medium-scale cross-stratified sandstone	absent	absent	present/absent	18-24	100's - 1000's	good
4	meandering fluvial (Figs. 8A, B, C)	upward fining succession; medium- to small-scale cross-stratified sandstone to massive silt-/mudstone	absent	absent	present/absent	15-23 (basal) 8-14 (upper)	100's (base) 1-10's (upper)	good (base) poor (upper)
5	lacustrine (Fig. 9A)	planar and small-/medium-scale, low-angle cross-stratification	absent	absent	absent	13-17	<10	poor
6	floodplain (Fig. 9B)	interstratified siltstone/ sandstone fining upward to mudstone	uncommon *Planolites*	present/absent	absent	--	--	poor
7	tidal channels and tidal-flat strata (Fig. 9C)	medium-scale cross-stratified sandstone fining upward to interstratified sandstone/mudstone	low to moderate bioturbation: *Planolites*, *Arenicolites*, *Skolithos*	absent	present	17-21	100's - 1000's	good (base) poor (upper)

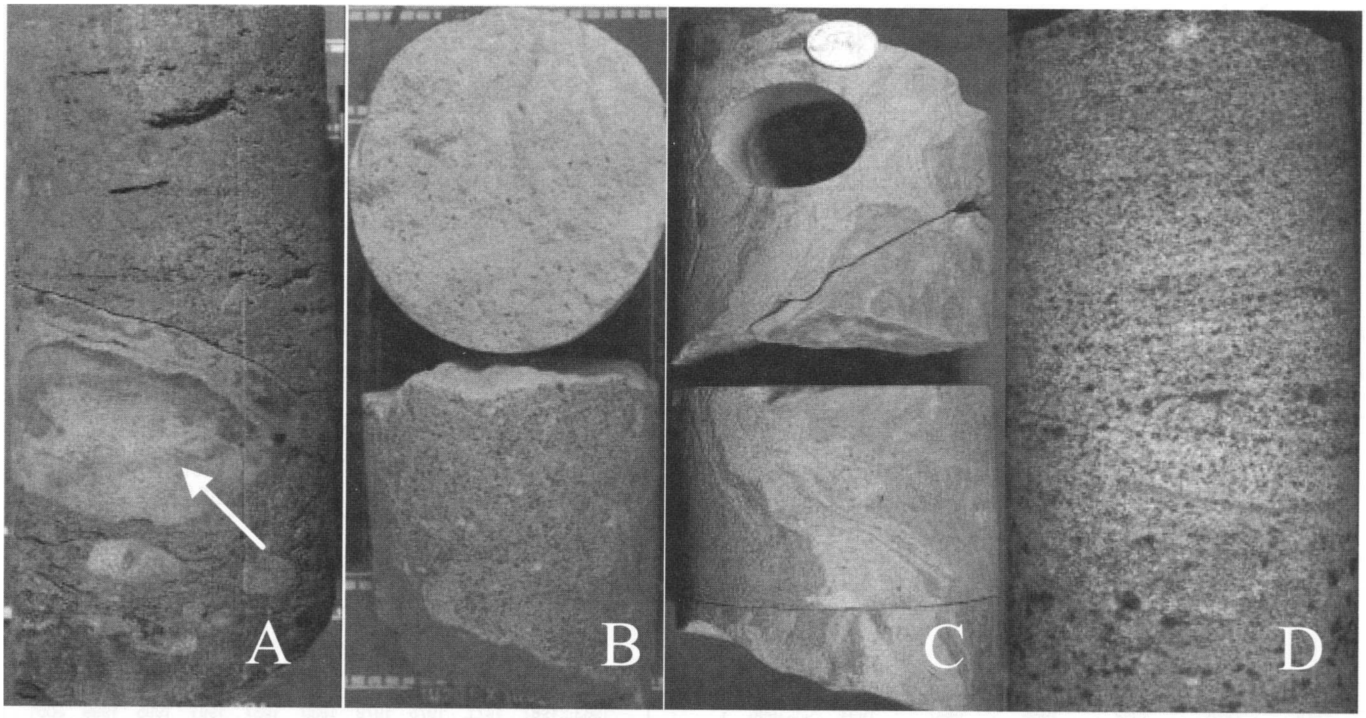

Fig. 7. (A) Disorganized, poorly sorted regolith (Lithofacies 1). Abundant sandstone/siltstone intraclasts eroded from older Basal Quartz strata occur in the lower part of the core (arrow). Tabular holes in upper part of the core are the weathered-out remnants of Jurassic Rierdon Shale clasts (3-5-9-16W4); **(B)** Matrix-rich, salt-and-pepper sandstone (Lithofacies 2); dark grains are mostly black chert (12-30-8-16W4); **(C)** Pedogenically deformed sandstone/mudstone of Lithofacies 2 (8-17-8-15W4); **(D)** Medium-scale cross-stratified sandstone deposited in a braided fluvial system (Lithofacies 3). These strata make up the primary reservoir unit in the study area. Dark spots are remnant oil staining (3-5-9-16W4). All cores are 10 cm in diameter.

result of extensive pedogenic leaching, but reservoirs are areally and volumetrically limited.

Decimetre-Thick Upward-Fining Sandstone (Lithofacies 3)

These strata abruptly overlie grey-green shale of the Rierdon Formation or a thin regolith. Within the study area they constitute the primary reservoir and consist of units several metres thick comprising stacked, erosively based upward-fining sandstone. Each succession is generally <1 m thick, rarely up to 2 m, and grades upward from coarse/upper medium sandstone, commonly with dispersed chert pebbles and grey-green tabular shale clasts, to lower medium/upper fine sandstone. Grain size changes gradationally or abruptly. Sandstone is pervasively stratified by medium-scale, planar-tabular and less common trough cross-stratification (Fig. 7D). Carbonaceous debris and coal fragments are common in all Lithofacies 3 sandstones except from the Horsefly Lake Pool. Core-measured porosity is 18-24% and permeability commonly ranges from several hundreds to thousands of mD. Significantly, strata less than about 1 m above the Rierdon unconformity are commonly cemented with pore-filling calcite, and as a result reservoir quality is poor (core measured porosity is 5% and permeability is <0.01 mD).

Interpretation

Strata of Lithofacies 3 are interpreted as having been deposited in a sand-dominated braided fluvial system. Stacked, upward-fining sandstone successions represent the superposition of shallow braided-fluvial channel fills. Sand formed most of the bed load sediment and was transported through the system mostly by two-dimensional and less commonly in three-dimensional subaqueous dunes and bars. Common grey-green shale clasts were most probably eroded from exposed Rierdon Shale (cf. Farshori, 1989). Dunes and bars formed the ubiquitous medium-scale, planar-tabular and trough cross-stratification, respectively. The predominance of two-dimensional

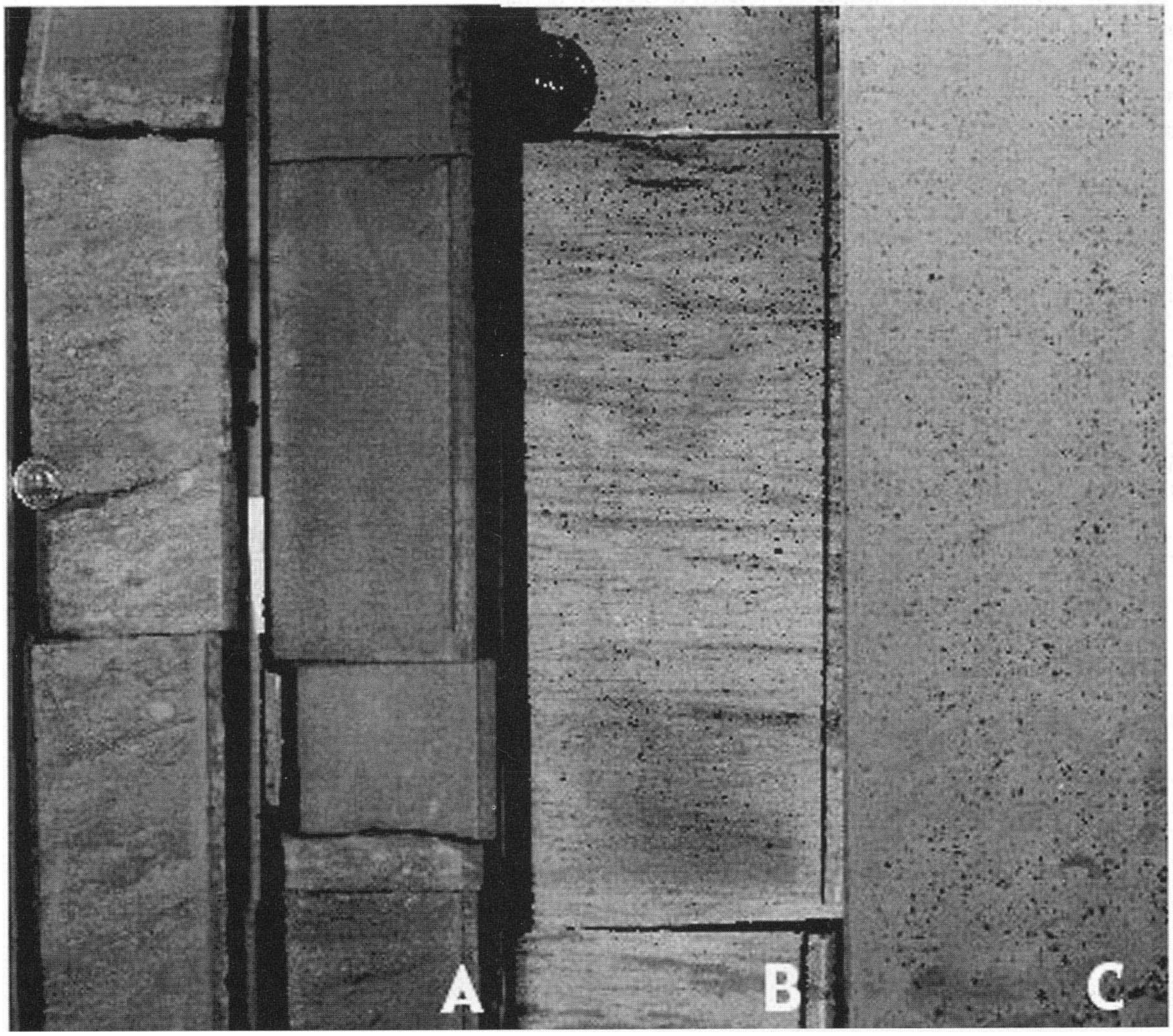

Fig. 8. Upward-fining meandering fluvial point-bar succession (Lithofacies 4) (02/06-29-8-16W4). **(A)** Medium-scale cross-stratified (dunes), upper medium to lower coarse sandstone with abundant dispersed mudstone clast, overlain gradationally by **(B)** small-scale cross-stratified (current ripples) fine sandstone, in turn gradationally overlain by **(C)** massive muddy siltstone (floodplain). In **(B)** and **(C)** the abundant dark coloured blebs are authigenic sphaerosiderite. All cores are 10 cm in diameter.

dunes and bars, forming planar-tabular cross-stratification, are common in sandy bedload braided fluvial systems (for example, Cant, 1982; Martinsen *et al.*, 1999). However, longitudinal bars, as previously reported by Farshori (1989), were not recognized in this study. These bars are more common in gravel braided fluvial systems (cf. Hein and Walker, 1977), and represent bedload sheets formed in poorly sorted, coarse-grained bedloads (Whiting *et al.*, 1988). The general lack of siltstone or mudstone strata, on the other hand, is probably related to the extensive lateral migration of the braided channels in this limited accommodation setting (see later). Fine-grained sediment that was deposited on topographically high features, *e.g.* bar tops, was preferentially remobilized and flushed downflow during a subsequent high discharge event that most probably coincided with flood. As a result, reservoir quality is generally good in these strata, except where destroyed by authigenic cement. The preferential cementation of strata in close proximity to the Rierdon unconformity is most likely related to diversion of formation fluids through the porous sandstone immediately above the unconformity and/or early diagenetic mixing of formation fluids derived from the Paleozoic and overlying Cretaceous successions.

METRE-SCALE UPWARD-FINING SANDSTONE (LITHOFACIES 4)

These strata abruptly overlie the decimetre-thick upward-fining sandstone succession and in places deeply incise it, *e.g.* in the Chin Coulee Pool. Typically, this stratal unit consists of a single, upward-fining succession, up to 10 m thick, although locally it may comprise two stacked units, several metres thick. In the basal <0.5 m, strata consist of poorly sorted matrix-supported conglomerate with a medium to lower very coarse sandstone matrix (Fig. 8A). Clasts are subrounded and several centimetres in diameter and composed mostly of sandstone and silty mudstone. This basal unit is abruptly overlain by medium-scale cross-stratified upper medium to lower coarse sandstone a few metres thick (Fig. 8A), which is gradationally overlain by massive or small-scale cross-stratified fine sandstone a few metres thick (Fig. 8B), in turn gradationally overlain by massive siltstone and/or silty mudstone (Fig. 8C). In addition, dispersed carbonaceous debris is common in Lithofacies 4 strata in the "BAT" sandstone, but is absent in the "Horsefly" sandstone.

Within each upward-fining succession, reservoir quality varies but generally decreases upward. In the lower conglomeratic unit, core-measured porosity and permeability are low, although both vary considerably. In contrast, the overlying

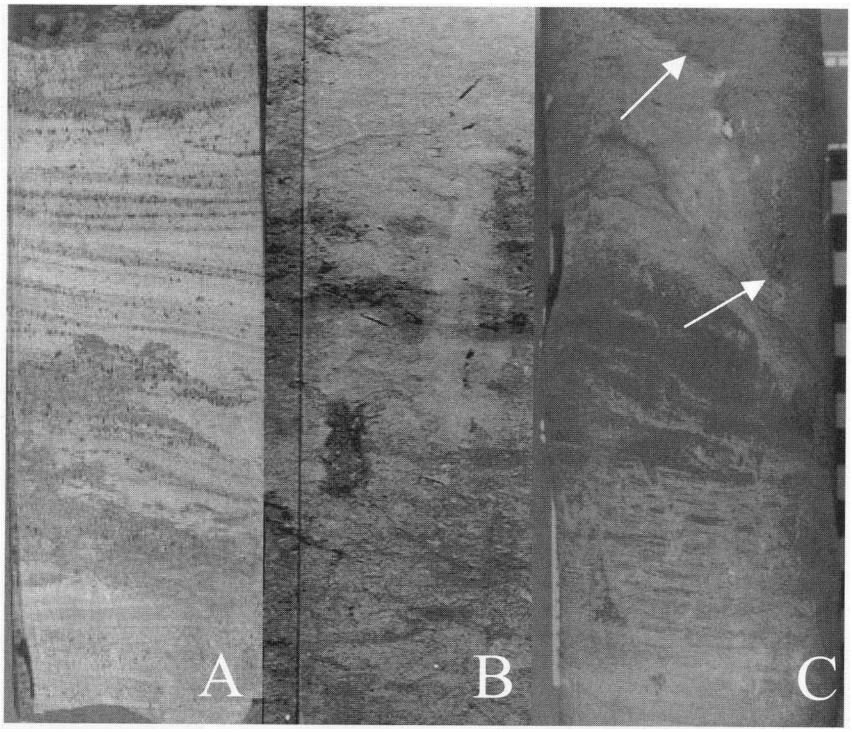

Fig. 9. **(A)** Well-sorted, low-angle cross-stratified very fine sandstone (Lithofacies 5: lacustrine deposits). Dispersed black-coloured blebs are diagenetic sphaerosiderite (3-5-9-16W4); **(B)** Bioturbated mud-rich siltstone with abundant carbonaceous rootlets interpreted as floodplain deposits (Lithofacies 6) (10-35-7-15W4); **(C)** Bioturbated (mostly by inclined *Arenicolites* burrows), inclined interstratified fine sandstone and mudstone deposited near the top of a tidal-channel fill (Lithofacies 7). This unit is then erosively overlain (arrows) by medium sandstone at the base of a younger tidal-channel fill (11-19-8-15W4). All cores are 10 cm wide.

medium-scale cross-stratified unit has good reservoir quality (porosity is 15-23% and permeability is several hundred mD). In the uppermost fine sandstone reservoir quality is poor (porosity is 18-24% and permeability is 1-10 mD). In successions that consist of stacked upward-fining units, much of the lower unit is commonly calcite cemented.

Interpretation

These strata are interpreted to represent meandering fluvial channel fills (point-bar deposits). The poorly sorted, matrix-supported conglomerate that occurs commonly at the base of the succession represents a channel lag. The typically variable, although generally poor, reservoir quality of this unit is the result of locally abundant silty-mudstone clasts that were most probably sourced from bank collapse of floodplain deposits along the channel's cutbank margin. These deposits were then buried by medium-scale cross-stratified sandstone emplaced by two- and three-dimensional subaqueous dunes. In turn these strata are gradationally overlain by small-scale cross-stratified fine sandstone deposited by current ripples that migrated along the lower energy, upper reaches of the point bar.

Stratigraphically upward, the progressive decrease in reservoir quality is the result of decreasing grain size and concomitant decrease of preserved intergranular pore volume.

Basal Quartz Paleovalley Fills In The Chin Coulee–Horsefly Lake Area

Relative Timing of Valley Fills

The BQ is predominantly a sandstone, siltstone and mudstone succession that in many places unconformably overlies grey-green shale of the Rierdon Formation, and in turn is overlain by black fissile shale/micrite at the base of the Ostracode Zone. Correlation within the study area suggests that the BQ is made up of a complex succession of different-aged incised valley and valley-fill deposits. Within the Chin Coulee–Horsefly Lake study area, cross-cutting channel relationships indicate five episodes of valley cut and subsequent fill (Figs. 10A-B, 11) (note that in this study area, cross-cutting relationships for the "Horsefly" sandstone cannot be proven unequivocally. However, the recent regional work of Zaitlin *et al.* (1999) and also Ardies (1999) shows it to be older than the "BAT" sandstone). Valleys were eroded into Rierdon Shale or previously deposited Basal Quartz sediment, and in most cases were subsequently filled with non-marine deposits. Each valley fill commonly consists of a unique mineralogical assemblage and reservoir quality. Valleys were eroded into Rierdon Shale or previously deposited BQ sediment, and in most cases were subsequently filled with nonmarine deposits.

Cross-cutting channel relationships and also the degree of pedogenic alteration indicate that the two oldest valley fills consist of "A" sandstone and then younger "weathered Horsefly" sandstone (Lithofacies 2) (Figs. 11, 12A). Following deposition, these strata were eroded extensively by younger valley systems, leaving erosional remnants as mesas between valleys or terraces along valley walls. In addition, because of prolonged subaerial exposure and pedogenic alteration, these strata are largely nonreservoir. The younger Horsefly Lake Pool is made up of the "Horsefly" sandstone, which most probably was deposited in a sand-dominated system that developed within the major northward-trending Cut Bank paleovalley. Here, the "Horsefly" sandstone is bounded only to the east where it onlaps the Rierdon Shale (which forms the local updip hydrocarbon trap), and locally to the south where it has been incised by a younger (Upper Mannville), mud-filled valley (Figs. 11, 12C). Although the "Horsefly" sandstone extends outward from the Horsefly Lake Pool, it commonly occurs at a lower structural elevation and consequently is "wet". Also, in comparison to the older "A" sandstone, and also the younger "BAT" sandstone (see next), the mineralogy of the Horsefly is unique. Most notably is the presence of a small, but significant, amount of feldspar and the abundance of clay-rich, low-grade metamorphic rock fragments. These observations are interpreted as indicating a major change in sediment provenance, and hence the occurrence of a major unconformity at the base and top of the "Horsefly" sandstone. Also, the abundance of sphaerosiderite in the upper part of the "Horsefly" sandstone suggests subaerial exposure and attendent pedogenic iron-carbonate precipitation (see Molgat, 2000; Molgat and Arnott; 2000).

The youngest valley fills in the study area consist of "BAT" sandstone and form the Chin Coulee and Mannville A pools (Figs. 11, 12A, C). In contrast to all other strata, "BAT" sandstones contain no feldspar and uncommon clay-rich sedimentary rock fragments. This suggests another important change in sediment provenance during deposition of the BQ, and an unconformity, at least at the base of the "BAT" sandstone. In addition, the "BAT" sandstone contains abundant carbonaceous debris and no sphaerosiderite. It is also important to note that Lithofacies 7 occurs exclusively in some "BAT" sandstone, *e.g.* Mannville A pool. Lithofacies 7 consists of tidal channel and tidal-flat deposits, and, therefore, is the first direct sedimentological evidence of marine influence on BQ sedimentation (Figs. 11, 12A). This is consistent with the ongoing southward transgression of the Boreal Sea during BQ deposition, and suggests that these "BAT" strata, termed the "young BAT", are the youngest BQ strata in the study area. Moreover, the lack of these strata in the Chin Coulee Pool suggests that sandstones in that area represent an older "BAT" succession, and herein are termed the "old BAT" sandstone.

Valley-Fill Stratal Architecture

Although of different age, the three youngest valley fills, represented by the Horsefly Lake, Chin Coulee and Mannville A pools, consist of a generally similar vertical succession of lithofacies (Fig. 13). This similarity is interpreted as the result of repetitive but consistent changes of the alluvial plain system, in particular fluvial channels, to changes of sediment supply. (Accommodation space, which at this time was severely limited [see below], most probably had a negligible effect on local Basal Quartz stratigraphy.)

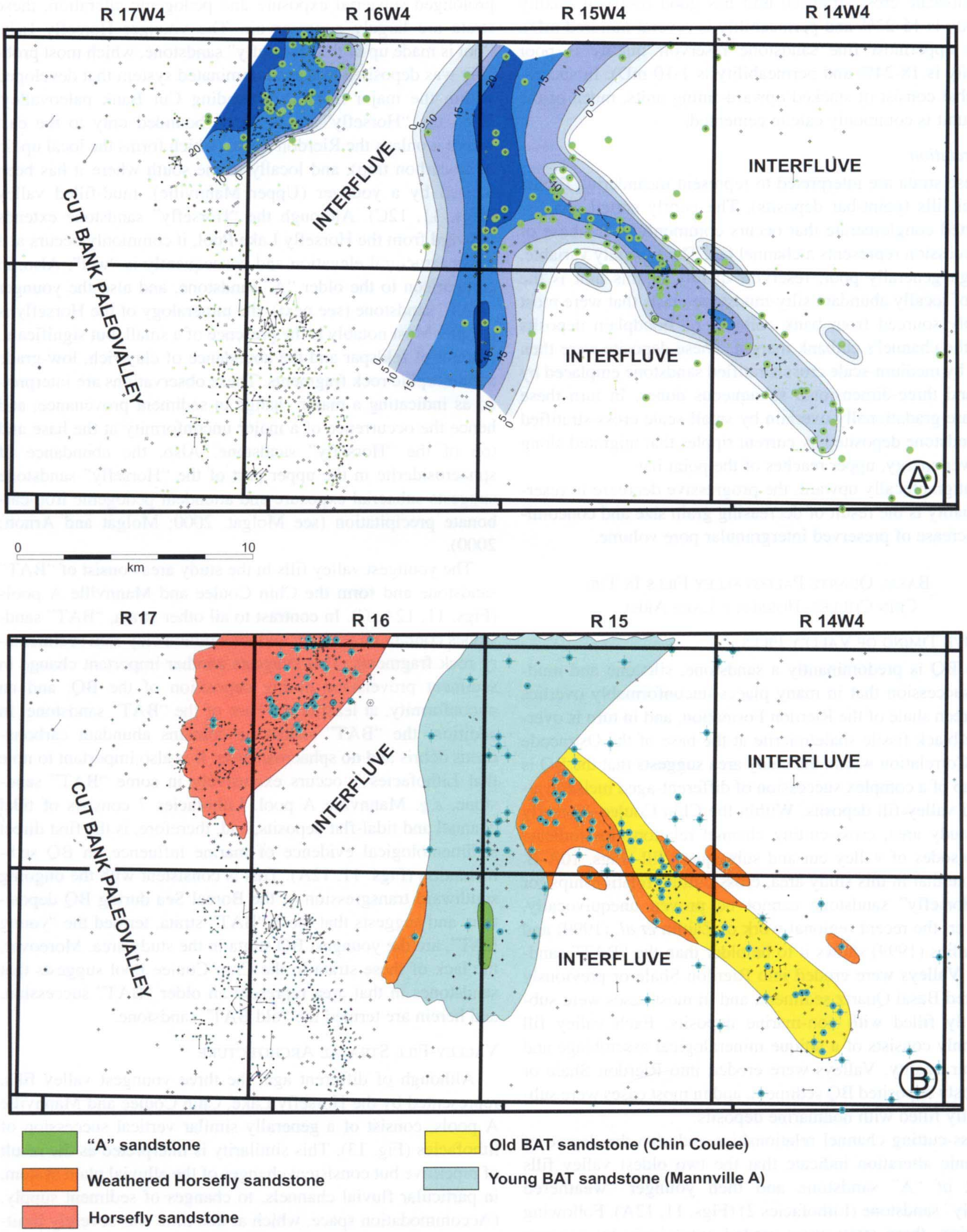

Fig. 10. (A) Isopach map of undifferentiated Basal Quartz strata (large green dots indicate data points). These strata infill eroded depressions that are bounded on most sides by shale of the Jurassic Rierdon Formation (interfluve). Contour interval is 5 m. **(B)** Map of differentiated Basal Quartz strata, which shows that within the study area the Basal Quartz succession consists of parts of five incised valley fills that are bounded on most sides by Rierdon Shale (interfluve).

The two oldest valley fills in the study area consist of the "A", and "weathered Horsefly" sandstones. However, because of extensive pedogenic alteration, sedimentological characteristics of these strata have been largely obliterated, and therefore are excluded from the following discussion. In addition, reservoir quality in most cases has been destroyed. In the other, younger valley fills, the basal part consists of a braided fluvial succession several metres thick (Lithofacies 3), which is the primary reservoir unit in the study area (see below). Locally, this unit overlies a thin, disorganized, coarse-grained regolith (Lithofacies 1). In most places the braided-fluvial succession is then overlain abruptly by meandering fluvial deposits of Lithofacies 4. Channel margin (levée) and floodplain deposits consist typically of siltstone/mudstone strata of Lithofacies 6 and gradationally overlie meandering fluvial channel deposits. In addition, lacustrine deposits (Lithofacies 5) form rare, thick interbeds within the meandering-fluvial succession.

Although similar, strata in the Mannville A Pool differ only in the fact that tidally influenced strata overlie the basal braided fluvial unit. As noted above, this observation is consistent with the long-term, southward transgression of the Boreal Sea.

Reservoir Distribution

Within the study area the entire BQ succession is only about 20-25 m thick, but represents approximately 18-32 my of geological time (Leckie *et al.*, 1996; Leckie *et al.*, 1997). This indicates net sedimentation rate was extremely low, estimated to be on the order of 1m/my (although it is well understood that local sedimentation rates were temporarily significantly higher). Such a low sedimentation rate, and consequent slow upbuilding of the sedimentary record, caused each unconformity-bounded succession to incise from a similar stratigraphic horizon. This, in turn, added to the development of a complex stratigraphy consisting of different-aged, cross-cutting incised valleys and valley fills. As noted above, because of long-term exposure and attendant extensive pedogenic alteration, strata of the two oldest valley fills, consisting respectively of "A" sandstone and "weathered Horsefly" sandstone, are mostly nonreservoir. Presently, these strata form terraces along the margins of younger reservoir paleovalley fills, or as mesas between them (Fig. 14). These inferred depositional relationships have resulted in a complex local stratigraphy, and also reservoir distribution. To date, the use of seismic to differentiate older, nonreservoir strata from younger, reservoir sandstones, particularly in areas near the margins of the younger paleovalleys, has not been effective (in large part because of their similar acoustical properties). Detailed geological mapping, therefore, is still the most effective tool to delineate the units and reduce exploration risk.

In the three youngest valley fills, represented by the Horsefly Lake, Chin Coulee and Mannville A pools, the best reservoir strata occurs consistently in the basal parts of the valley fill. These strata consist of a several-metre-thick braided-fluvial succession composed typically of upper-fine to lower-medium sandstone. Mudstone is rare and occurs as thin interbeds or as small, dispersed intraclasts. Porosity and permeability of the reservoir sandstone are high; porosity ranges from 18-24% and permeability from hundreds to thousands of mD. Notwithstanding, it is important to note that in the lowermost part of the succession, reservoir quality has been significantly reduced by pore-filling, authigenic calcite.

In most places the braided-fluvial succession is then overlain abruptly by meandering fluvial deposits of Lithofacies 4. Typically the contact shows little relief, but locally in the Chin Coulee Pool meandering fluvial channels incise deeply into the underlying braided fluvial succession and as a result significantly reduced the thickness of the primary reservoir. In the

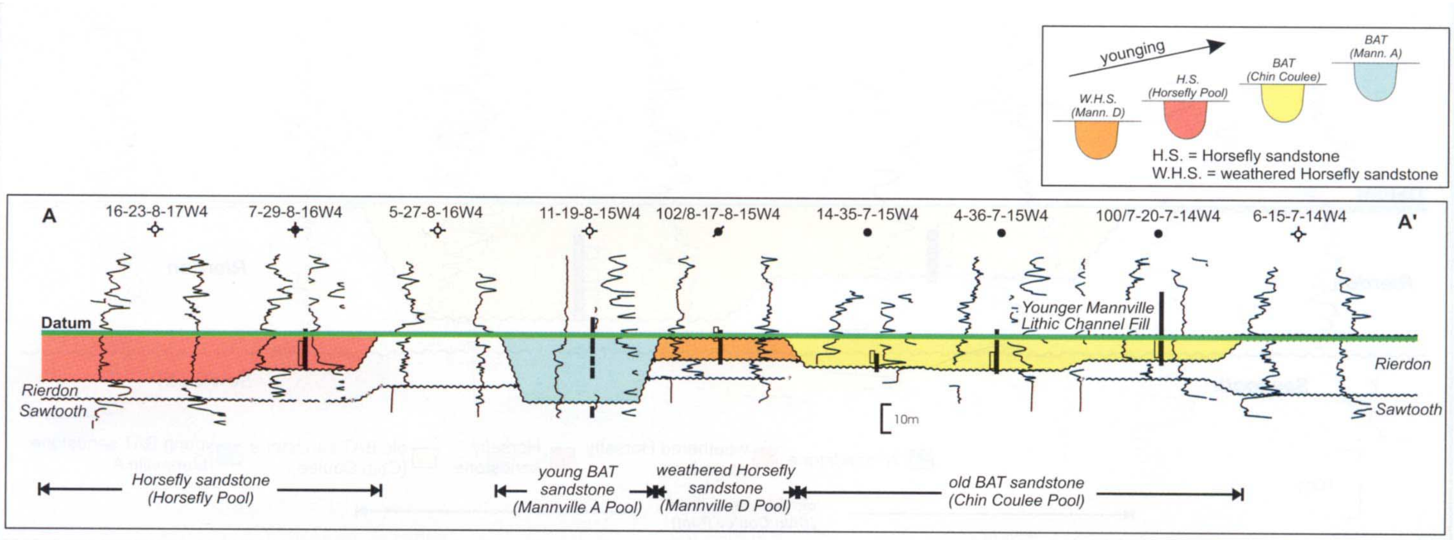

Fig. 11. Stratigraphic cross-section (A-A') using gamma-ray and resistivity well logs (in each well the left- and right-hand trace, respectively). Solid vertical bars indicate cored intervals; open rectangles indicate perforated intervals. In this cross-section, four of the five valley-fill successions are encountered. See Figure 1 for location of cross-section. Schematically illustrated in the inset is the relative age of the four incised valleys encountered in the cross-section.

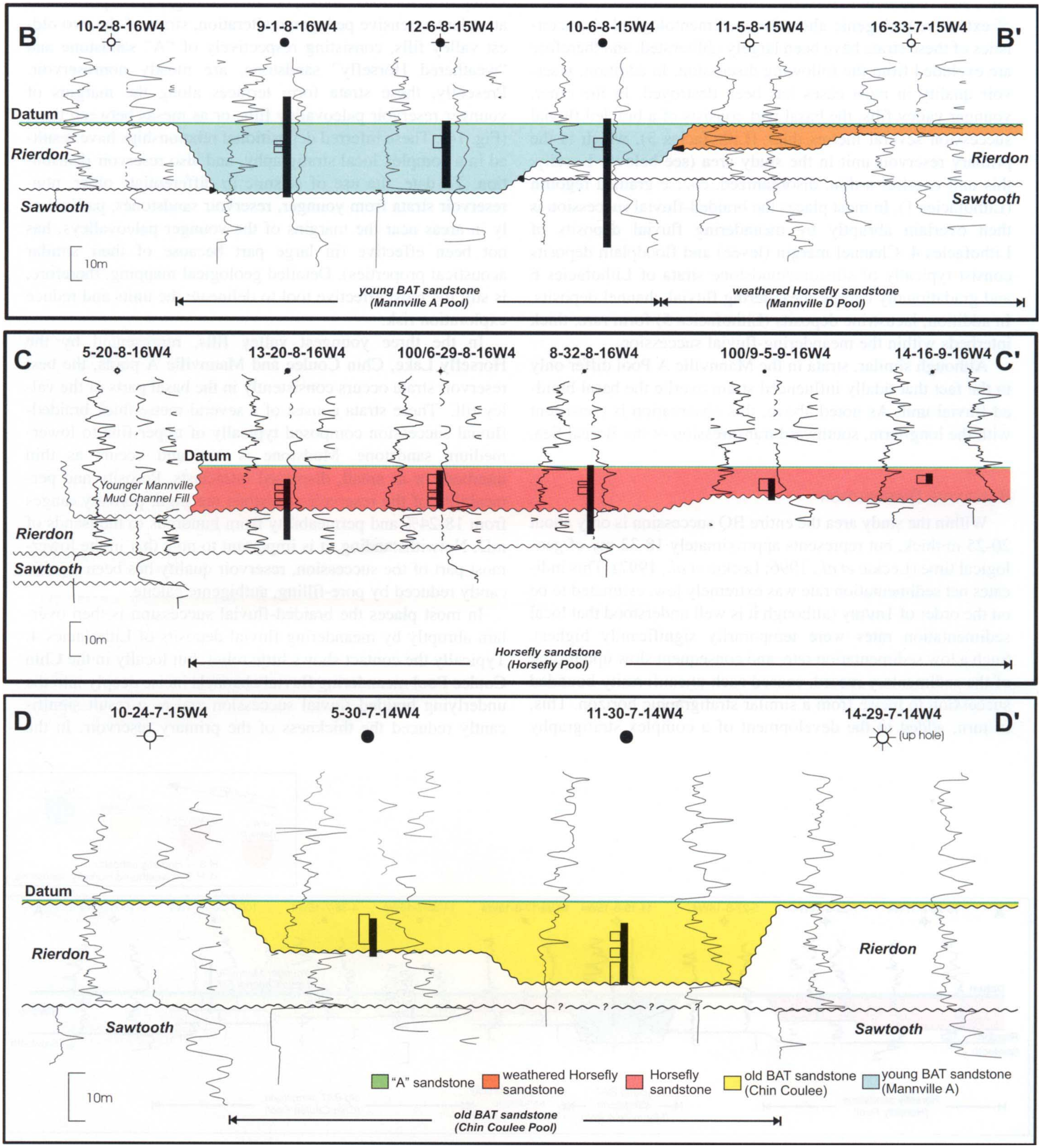

Fig. 12. A-C. Stratigraphic cross-sections using gamma-ray and resistivity well logs (in each well the left- and right-hand trace, respectively). The stratigraphic datum is the base of the Ostracode Zone, which marks the top of the Basal Quartz succession. Vertical bars indicate cored intervals and open rectangles indicate perforated intervals. See Figure 1 for location of wells and lines of cross-section. Note that each unconformity-bounded succession incises from the same stratigraphic level, which is interpreted as a stratigraphic response to sedimentation in an accommodation-limited basin (see text for details).

meandering fluvial succession reservoir development is generally confined to the lower, coarser-grained part of the upward-fining channel fill (point bar deposit). Here, sandstone porosity and permeability are typically of the order of 15-23% and 100's mD, respectively. Significantly, these strata commonly contain abundant mudstone clasts, most probably sourced from bank collapse along the channel's cut-bank margin. These non-porous clasts, which are particularly abundant in Horsefly Lake Pool ("Horsefly" sandstone), not only reduce total porosity in the reservoir, but also form local impediments to the flow of both *in situ* hydrocarbons and fluids being injected for reservoir pressure support. Finer-grained deposits at the top of the point-bar succession gradationally overlie these strata. Because of their finer grain size and concomitant lower intergranular porosity, these strata are general of poorer reservoir quality than those at the base of the succession. In these strata porosity and permeability range from 8-14% and 1-10's mD, respectively. The meandering-channel-fill succession is gradationally overlain by non-reservoir channel margin (levee) and floodplain siltstone/mudstone strata (Lithofacies 6).

Although similar, strata in the Mannville A Pool differ only in the fact that tidally-influenced strata overlie the basal braided fluvial unit. In these strata, reservoir quality is generally very good in the basal part of tidal-channel fills, but is poor in the more mud-prone upper parts of these channel fills and adjacent tidal flat strata. Porosity and permeability in the lower part

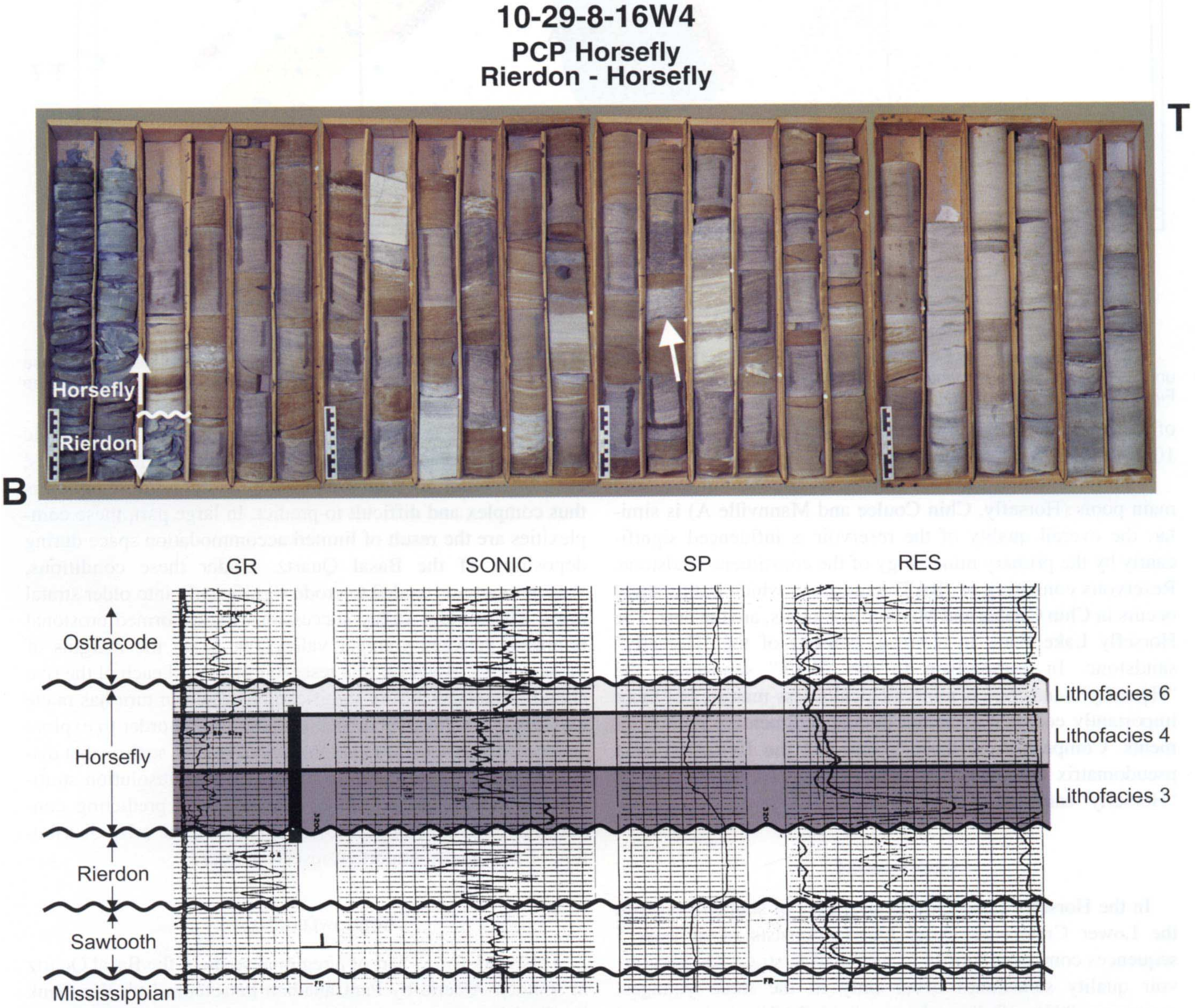

Fig. 13. Core and representative geophysical log from the Horsefly Lake Pool (10-29-8-16W4) illustrating the characteristics of a typical valley-fill succession. In this example, the Horsefly sandstone unconformably overlies the Rierdon Shale and in turn is unconformably overlain by the Ostracode Zone. Stratigraphically upward the valley fill consists of a lower unit of braided-fluvial strata (Lithofacies 3), which is calcite cemented at its base. These strata are the principal reservoir strata in the study area. This unit is then overlain abruptly (indicated by arrow) by a several-metre-thick meandering-fluvial succession (Lithofacies 4 and 6). This succession is then disconformably overlain by the Ostracode Zone.

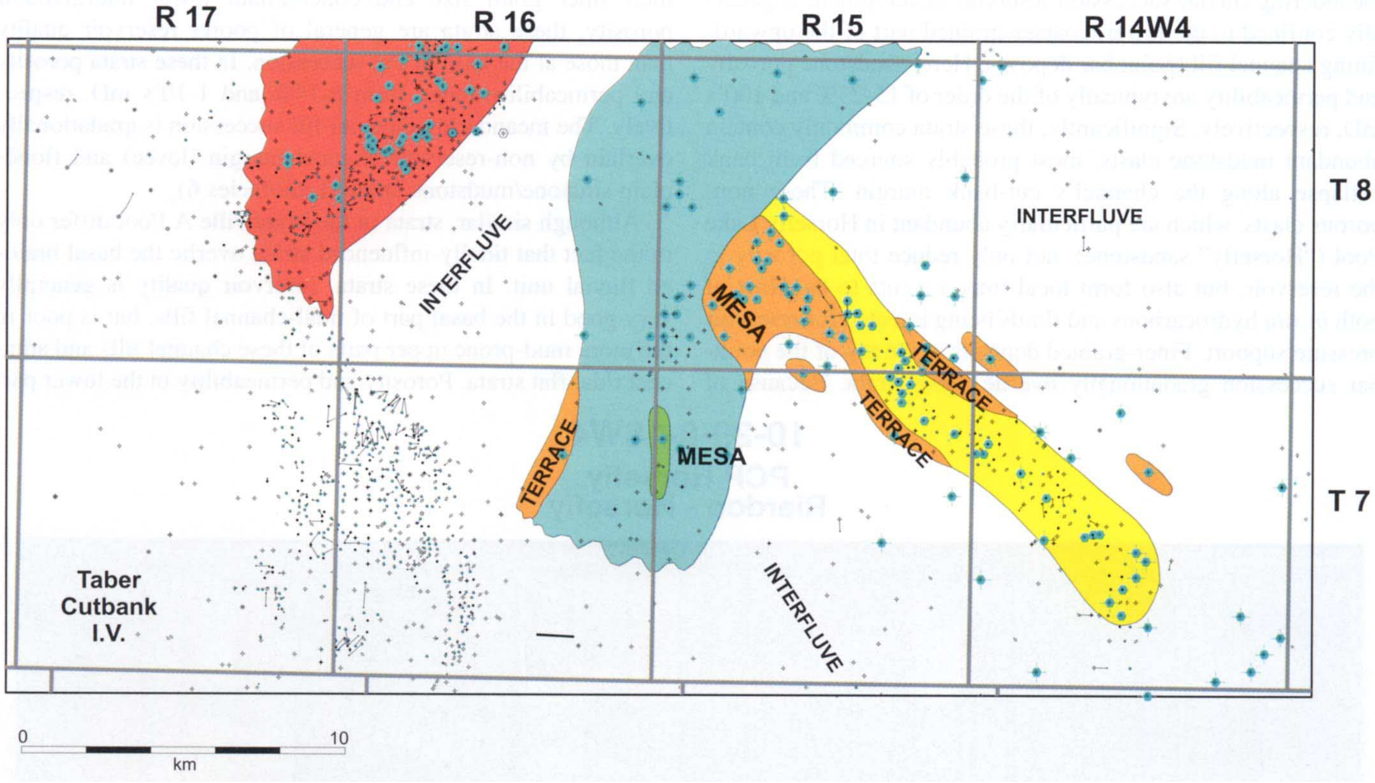

Fig. 14. Map illustrating the location of mesa and valley terrace strata in the study area. In accommodation-limited, non-marine basins, these units, which represent erosional remnants of older strata, are probably common and result in a very complex regional and local stratigraphy (see Fig. 12 for colour code of stratigraphy).

of a tidal-channel fill are generally of the order of 17-21% and 100's to ~1300 mD, respectively.

Finally, although the stratigraphic architecture of the three main pools (Horsefly, Chin Coulee and Mannville A) is similar, the overall quality of the reservoir is influenced significantly by the primary mineralogy of the constituent sandstone. Reservoirs consisting of "BAT" sandstone, which in this study occurs in Chin Coulee and Mannville A pools, are the best. The Horsefly Lake Pool, in contrast, consists of the "Horsefly" sandstone. In comparison to the "BAT" sandstone, the "Horsefly" sandstone is mineralogically less mature, but more importantly contains abundant ductile sedimentary rock fragments. Compaction of these grains and the formation of a pseudomatrix comparatively reduces the reservoir quality of "Horsefly" sandstone.

CONCLUSIONS

In the Horsefly Lake/Chin Coulee area of southern Alberta the Lower Cretaceous Basal Quartz consists of at least 5 sequences composed mostly of non-marine strata. Good reservoir quality sandstones occur only in the three youngest sequences ("Horsefly" sandstone, "old BAT" sandstone and "young BAT" sandstone). Because of extensive pedogenic alteration, the two oldest sequences ("A" and "weathered Horsefly" sandstones) are non-reservoir units. Within the study area, these five sequences form a highly complex stratigraphic succession characterized by profound lithological changes, even over short horizontal distances. Reservoir distribution is thus complex and difficult to predict. In large part, these complexities are the result of limited accommodation space during deposition of the Basal Quartz. Under these conditions, younger systems tended to erode significantly into older stratal units. These older valley successions likely formed erosional remnants between younger valleys, or along the margins of those valleys. However, the reservoir quality of each of the five stratal sequences differs significantly, which in turn has made exploration in this area difficult. Therefore, in order to explore successfully in accommodation-limited basins, such as that discussed here, it is essential to develop a high resolution stratigraphic model that is effective at not only predicting constituent stratal units, but also demonstrating the areal distribution of potentially important reservoir units.

ACKNOWLEDGMENTS

This work forms part of a regional study of the Basal Quartz in southern Alberta by PanCanadian Petroleum Ltd. We thank PanCanadian for permission to published these data and also the many members of the BQ Task Force, in particular Alma Eamer, Don Keith, Jeff Peterson and Matt Woofter, for their help and support throughout the project. Associate Editor Doug

Cant, an anonymous reviewer, and especially Brad Hayes, are thanked for their critical comments and constructive criticism on an earlier version of this paper. We also thank Ron Boyd, Bob Dalrymple and Dale Leckie for fruitful discussions during the project, and in particular, Lorne Rosenthal for sharing his insight and knowledge of BQ stratigraphy. Carolyn and Stavros Michailides and Ennio Trevisanut are thanked for their patience and expertise in drafting the figures. Also, B. Arnott acknowledges the Natural Sciences and Engineering Research Council of Canada for its continued support of his research.

REFERENCES

Alberta Energy and Utilities Board. 1998. Reserve Report Statistical Series, 99-18, 583 p.

Ardies, G.W. 1999. Sedimentology, depositional environments, and high-resolution stratigraphy of the Horsefly, BAT and Ellerslie (Basal Quartz) incised valleys, south-central Alberta, Canada. Unpublished M.Sc. thesis, Queens University, 359 p.

Cant, D.J. 1982. Fluvial facies models and their application. *In:* Sandstone Depositional Environments. P.A. Scholle and D. Spearing (eds.). American Association of Petroleum Geologists, Memoir 31, p. 115-137.

______ and Abrahamson, B. 1996. Regional distribution and internal stratigraphy of the Lower Mannville. Bulletin of Canadian Petroleum Geology, v. 44, p. 508-529.

Christopher, J.E. 1964. The Middle Jurassic Shaunovan Formation of southwestern Saskatchewan. Saskatchewan Geological Survey, Department of Mineral Resources, Report No. 95, 96 p.

______ 1974. The Upper Jurassic Vanguard and Lower Cretaceous Mannville Groups. Saskatchewan Geological Survey, Department of Mineral Resources, Report No. 151, 349 p.

______ 1980. The Lower Cretaceous Mannville group of Saskatchewan – a tectonic overview. *In:* Geology of Mannville Hydrocarbon Reservoirs. L.S. Beck, J.E. Chritopher and D. M. Kent (eds.). Saskatchewn Geological Society Special Publication, No. 5, p. 3-32

______ 1985. The Lower Cretaceous Mannville Group, Northern Williston Basin Region, Canada. *In:* The Mesozoic of Middle North America. D.F. Stott and D.J.Glass (eds.). Canadian Society of Petroleum Geologists, Memoir 9, p. 109-126.

Dolson, J.C. and Piombino, J. 1994. Giant proximal foreland basin non-marine wedge trap: Lower Cretaceous Cutbank Sandstone, Montana. *In:* Unconformity-Related Hydrocarbons in Sedimentary Sequences. J.C. Dolson, M.L. Hendricks and W.A. Wescott (eds.). Rocky Mountain Association of Geologists, p.135-148.

Farshori, M.Z. 1989. Fluvial facies and reservor heterogeneity, Cutbank Sandstone (Lower Cretaceous), Horsefly Lake Pool, southern Alberta. *In:* Geology and Reservoir Heterogeneity. P.G. Aukes (Chairman), Canadian Society of Petroleum Geologists, Core Conference, p. 8.1-8.33.

______ and Hopkins, J.C. 1989. Sedimentology and petroleum geology of fluvial and shoreline deposits of the Lower Cretaceous Sunburst sandstone member, Mannville Group, southern Alberta. Bulletin of Canadian Petroleum Geology, v. 37, p. 371-388.

Fedoroff, N. and Eswaran, H. 1985. Micromorphology of Ultisols. *In:* Soil Micromorphology and Soil Classification. L.A. Douglas and M.L. Thompson (eds.). Soil Society of America, Special Publication No. 15, p. 145-164.

Glaister, R.P. 1959. Lower Cretaceous of southern Alberta and adjoining areas. American Association of Petroleum Geologists Bulletin, v. 58, p. 2227-2244.

Glass, D.J., 1990 (ed.). Lexicon of Canadian Stratigraphy, Volume 4, Canadian Society of Petroleum Geologists, Calgary, Alberta, 772 p.

Hayes, B.J.R. 1986. Stratigraphy of the basal Cretaceous Lower Mannville Formation, southern Alberta and north-central Alberta. Bulletin of Canadian Petroleum Geology, v. 34, p. 30-48.

______ 1990. A perspective on the Sunburst Member of southern Alberta. Bulletin of Canadian Petroleum Geology, v. 38, p. 483-484.

Hein, F.J. and Walker, R.G. 1977. Bar evolution and development of stratification in the gravelly, braided Kicking Horse River, British Columbia. Canadian Journal of Earth Sciences, v. 14, p. 562-570.

Leckie, D.A. and Smith, D.G. 1992. Regional setting, evolution and depositional cycles of the Western Canada Foreland Basin. *In:* Foreland Basins and Fold Belts. R.W. Macqueen and D.A. Leckie (eds.). American Association of Petroleum Geologists, Memoir 55, p. 9-46.

______, Rosenthal, L. and James, D.P. 1996. Sedimentology of clastic reservoirs in southern Alberta: the Blairmore-Mannville Groups and bounding strata. Geological Survey of Canada Open File 3322, 108 p.

______, Vanbeselaere, N.A. and James, D.P. 1997. Regional sedimentology, sequence stratigraphy and petroleum geology of the Mannville Group, southwestern Saskatchewan. *In:* Petroleum Geology of the Cretaceous Mannville Group, Western Canada. S.G. Pemberton and D.P. James (eds.). Canadian Society of Petroleum Geologists, Memoir 18, p. 211-262.

Lukie, T.D. 1999. A study of the sedimentology, geochemistry, and stratigraphic organization of the Lower Cretaceous Horsefly (Basal Quartz) Valley (Taber-Cutbank), southern Alberta and northern Montana. Unpublished M.Sc. thesis, Queens University, 290 p.

Martinsen, O.J., Ryseth, A., Helland-Hansen, W., Flesche, H., Torkildsen, G. and Idil, S. 1999. Stratigraphic base level and fluvial architecture: Ericson Sandstone (Campanian), Rock Springs Uplift, SW Wyoming, USA. Sedimentology, v. 46, p. 235-260.

Molgat, M. 2000. Sedimentology, stratigraphy, and shallow burial alteration of the Upper Jurassic Swift Formation, southeastern Alberta. Unpublished M.Sc. thesis, University of Ottawa, 252 p.

______ and Arnott, R.W.C. 2000. The geochemical and stratigraphic anatomy of an Upper Jurassic-Lower Cretaceous paleosol, southeastern Alberta. Geocanada 2000 millenium Geoscience Summit, Conference C.D.

Smith, D.G. 1994. Paleogeographic evolution of the Western Canadian Foreland Basin. *In:* Geological Atlas of the Western Canadian Sedimentary Basin. G. Mossop and I. Shetsen (comps). Canadian Society of Petroleum Geologists and Alberta Research Council, p. 272-316.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. and Rahmanian, V.D. 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops. American Association of Petroleum Geologists, Methods in Exploration Series 7, 55 p.

Whiting, P. J., Dietrich, W. E., Leopold, L. B., Drake, T. G. and Shreve, R. L. 1988. Bedload sheets in heterogeneous sediment. Geology, v. 16, p. 105-108.

Zaitlin, B.A., Dalrymple, R.W. and Boyd, R. 1994. The stratigraphic organization of incised-valley systems associated with relative sea-level change. *In:* Incised-Valley Systems: Origin and Sedimentary Sequences. R.W. Dalrymple, R. Boyd and B.A. Zaitlin (eds.). Society of Economic Mineralogists and Paleontologists, Special Publication 51, p. 45-60.

______, Potocki, D., Warren, M.J. and Boyd, R. 1999. Sequence stratigraphy in low accommodation foreland basins: an example from the Lower Cretaceous "Basal Quartz" Formation of southern Alberta. Reservoir, v. 26, p. 12-13.

Manuscript received: September 14, 1999

Revised manuscript accepted: February 29, 2000