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Alluvial architecture of the Horsefly unit (Basal Quartz) in southern Alberta and northern Montana: influence of accommodation changes and comtemporaneous faulting

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Abstract

The Basal Quartz (Early Cretaceous) consists of a nested succession of mineralogically distinct, unconformity-bounded units. The second oldest of these, the Horsefly sandstone, occupies a broad (28–52 km wide), north–south trending, flat-floored valley (the Taber-Cutbank valley) in northern Montana and southern Alberta (south of Township 15) that has a maximum relief of 50 m. The valley-fill deposits are entirely fluvial in origin. Two internal sequences are recognized. Each begins with a regional erosion surface and sheet sandbody consisting of amalgamated channel sandstones. Contemporaneous overbank sediments (now represented by mudstone-pebble conglomerates) were completely eroded. These sandstones are overlain by mudstone-dominated deposits which consist mainly of red vertisols and contain isolated, ribbon channel sandstones and sheet sandstones formed by crevasse splays. Each sequence accumulated under conditions of continuously increasing accommodation space. Tectonic movements, perhaps in response to episodic thrust loading, are thought to be the major control on accommodation; eustatic fluctuations were probably not important because the study area lay far inland at the time of deposition.

Syndepositional block faulting partially overprinted the regional changes in accommodation, producing constrictions in the valley at the location of cross-valley uplifts; slightly greater uplift of the northern part of the valley caused an overall down-stream narrowing. Local areas of greater subsidence trapped the northward-moving, extrabasinal gravel, accelerating the proximal–distal fining trend. Such areas also tend to display evidence of higher water tables, including the preservation of organic-rich deposits, and to contain a higher number of channel sandstones because the rivers preferentially avoided the subtly uplifted areas. This study shows that the influence of subtle faulting can be significant during times of limited accommodation because it is not masked by rapid sedimentation.

Résumé

Le Quartz de Base (Cretacé inférieur) consiste en une succession nichée d'unités minéralogiquement distinctes et limitées par des discordances. La plus vieille de celles-ci, le grès de Horsefly, occupe une large vallée à fond plat (28–52 km de largeur), d'orientation nord-sud (la vallée de Taber-Cutbank) dans le nord du Montana et le sud de l'Alberta (au sud du Canton 15) qui a au maximum un relief de 50 m. Les dépôts de remplissage de vallée sont entièrement d'origine fluviale. Deux séquences internes sont reconnues. Chacune débute par une surface d'érosion régionale et des nappes de masses de grès composées surtout de grès de chenaux amalgamés. Les sédiments contemporains d'inondation (maintenant représentés par des conglomérats à galet de mudstone) ont été complètement érodés. Ces grès sont recouverts par des sédiments dominés par du mudstone, qui consistent surtout en des vertisols rouges et contiennent des grès isolés de chenaux en ruban et des nappes de grès formées par des crevasses de crues. Chaque séquence s'est accumulée dans des conditions d'espace d'accommodement en croissance continue. Les mouvements tectoniques, possiblement en réponse à la mise en charge tectonique, sont interprétés comme étant le contrôle principal de l'accommodement; les fluctuations eustatiques n'étant probablement pas importantes car la région d'étude était située loin dans les terres au moment de la sédimentation.

Le faillage syndépositionnel par blocs s'est partiellement surimposé aux changements régionaux de l'accommodement, produisant des rétrécissements dans la vallée localisés aux rehaussements transverses aux vallées; un rehaussement légèrement supérieur de la partie nord de la vallée a causé dans l'ensemble un rétrécissement en aval. Des régions locales de plus grande subsidence ont piégé le gravier extrabasinal, qui se déplaçait vers le nord, et accéléré la tendance à l'affinement proximal–distal des sédiments. De telles régions ont aussi tendance à montrer des évidences de hautes nappes phréatiques, incluant la préservation de sédiments riches en matière organique, et à contenir un plus grand nombre de grès de chenal parce que les rivières ont préférentiellement évité les régions à rehaussement subtil. Cette étude montre que l'influence de faillage subtil peut être significative durant les périodes d'accommodement limité parce qu'il n'est pas masqué par la sédimentation rapide.

Traduit par Lynn Gagnon

Introduction

Recently, there has been considerable interest in incised-valley systems, in the Western Canada Sedimentary Basin and elsewhere, because of the significant quantity of hydrocarbons they host. Previous work has concentrated on the seaward part of valleys that experience transgressive, estuarine sedimentation during valley filling (Segments 1 and 2 in the classification of Zaitlin et al., 1994). Significantly less work has been done on valley fills that consist entirely of fluvial deposits. As a result, less is known about the various factors that influence their stratigraphic organization.

The Basal Quartz (Lower Mannville Group; Early Cretaceous; Fig. 1) in southern Alberta and northern Montana provides an ideal opportunity to examine the facies organization and sequence-stratigraphic subdivision of a fluvial, incised-valley system. In this area (Fig. 2), the Basal Quartz consists almost entirely of the unconformity-bounded, mineralogically distinct, Horsefly unit (Zaitlin et al., 1999, 2000, this issue; Arnott et al., 2000), which forms part of a northward-offlapping sequence set (Ardies, 1999; Fig. 3). The Horsefly occupies a broad, north–south oriented valley (the Taber-Cutbank valley; Hayes, 1986; Dolson and Piombino, 1994) that was cut and filled when the Boreal Sea had withdrawn far to the north (Cant, 1989; Cant and Abrahamson, 1996). Thus, the Horsefly valley fill consists exclusively of fluvial deposits over its entire length (Zaitlin et al., this issue; cf. Glaister, 1959; Hayes, 1986; Dolson and Piombino, 1994). This unit is a prolific hydrocarbon producer, including the large Cutbank Field in Montana (Fig. 2), but is still not completely understood, despite several decades of work on the Basal Quartz (summarized in Hayes, 1986; Leckie et al., 1997; Arnott et al., 2000; Zaitlin et al., this issue). Thus, the objectives of this study are to 1) document the nature of these valley-fill deposits and their sequence-stratigraphic organization, 2) describe the spatial variability of the best preserved valley and its fill, and 3) examine the various factors that influenced the characteristics of these deposits.

Stratigraphic Setting and Study Area

The Basal Quartz (BQ) consists of the oldest preserved sediments resting on the sub-Cretaceous unconformity throughout southern Alberta and northern Montana (Hayes et al., 1994; Figs. 1, 3). Prior to the deposition of the BQ, the area was exposed for as long as 17–35 Ma (Leckie and Smith, 1992; Cant and Abrahamson, 1996; Zaitlin et al., this issue), during which time river systems eroded into the underlying Jurassic and Mississippian succession. The A-Sandstones (*sensu* Zaitlin et al., 1999, 2000, this issue) were deposited early in this interval, but were then subjected to renewed erosion, leaving only isolated remnants on topographic highs (Fig. 3). After this episode of erosion, relative sea level rose, perhaps in response to a eustatic rise (Haq et al., 1988), but also because of foreland-basin subsidence associated with thrust loading of the ancestral Rocky Mountain Foreland Fold and Thrust Belt (Ricketts, 1989). In response to the net increase in accommodation, a series of progressively more distal valley-fill units were deposited. The first of these was the Horsefly, which consists entirely of fluvial sediments, followed by the BAT (Bantry–Alderson–Taber) and Ellerslie (Figs. 1, 3), which contain progressively greater proportions of estuarine deposits (Farshori and Hopkins, 1989; Ardies, 1999; Arnott et al., 2000; Ardies et al., 2002). This overall transgressive interval culminated with the deposition of the Ostracod member, which represents the time of maximum marine transgression during Mannville time (Cant and Abrahamson, 1996).

Regional studies by Zaitlin et al. (1999, 2000, this issue) indicate that the Horsefly is preserved mainly in the area south of Township 15 in Canada, and extends southward into Montana. This paper is an examination of the Horsefly throughout this region (Fig. 2; total area more than 13,000 km^2), and combines the work of Lukie (1999), who described the deposits from Township 31N (Ranges 3W–9W) in Montana to Township 6 (Ranges 14W4–22W4) in Alberta, and Ardies (1999), who examined the area from Townships 7–15 (Ranges 14W4–22W4). This study utilized 1800 geophysical well logs, from which 45 cross-sections were constructed, using the Ostracod member as the datum where it is present, or the top of the Upper Mannville elsewhere. One hundred and seventy-five cores were logged, and 125 thin sections were examined. Facies and facies associations were identified using cores that were then correlated to adjacent, uncored wells using geophysical logs.

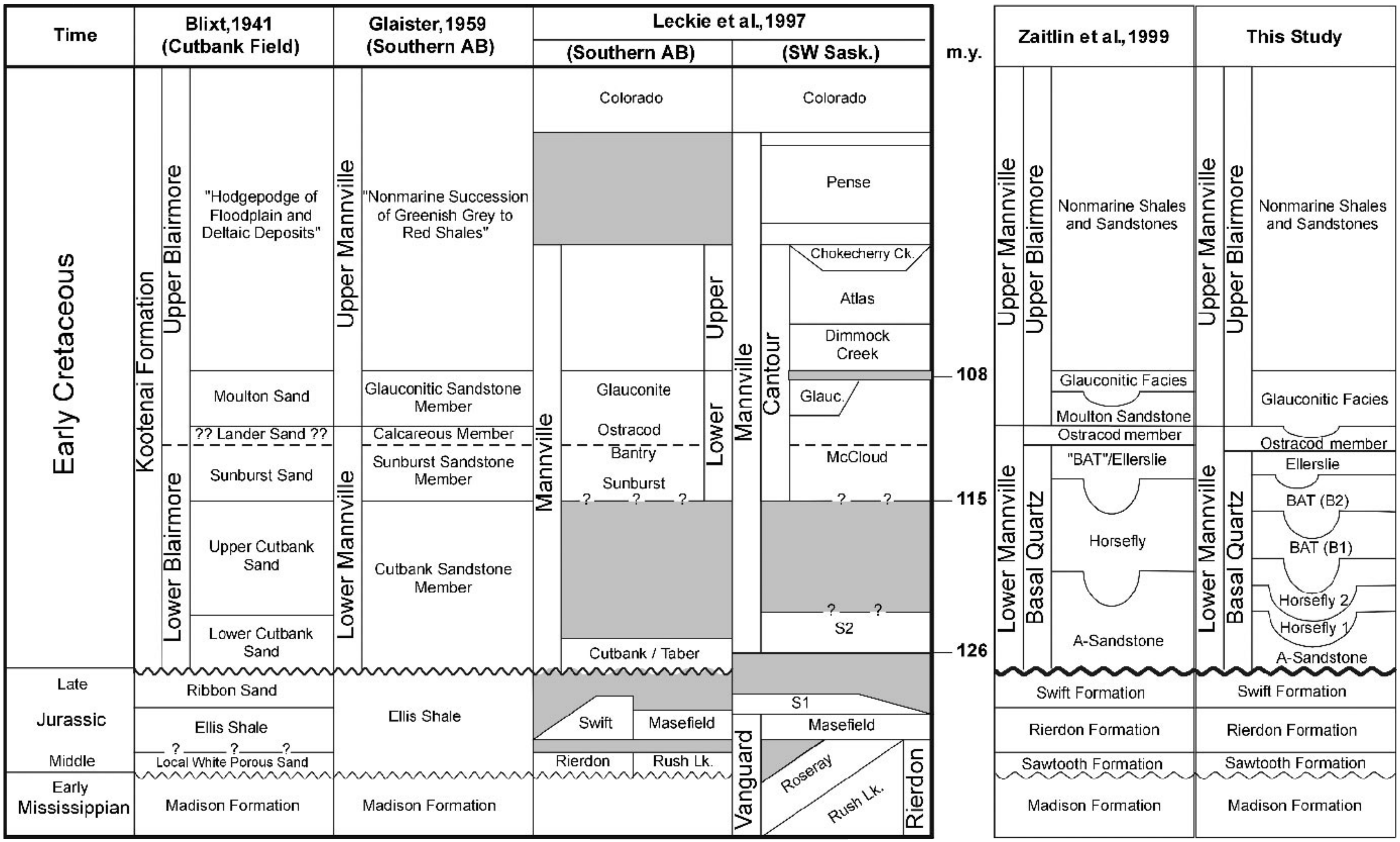

Fig. 1. The stratigraphic framework used in this study (right-hand column), which is a slight elaboration of that first proposed by Zaitlin et al. (1999), compared with previous stratigraphic subdivisions (modified from Ardies et al., 2002; Zaitlin et al., this issue).

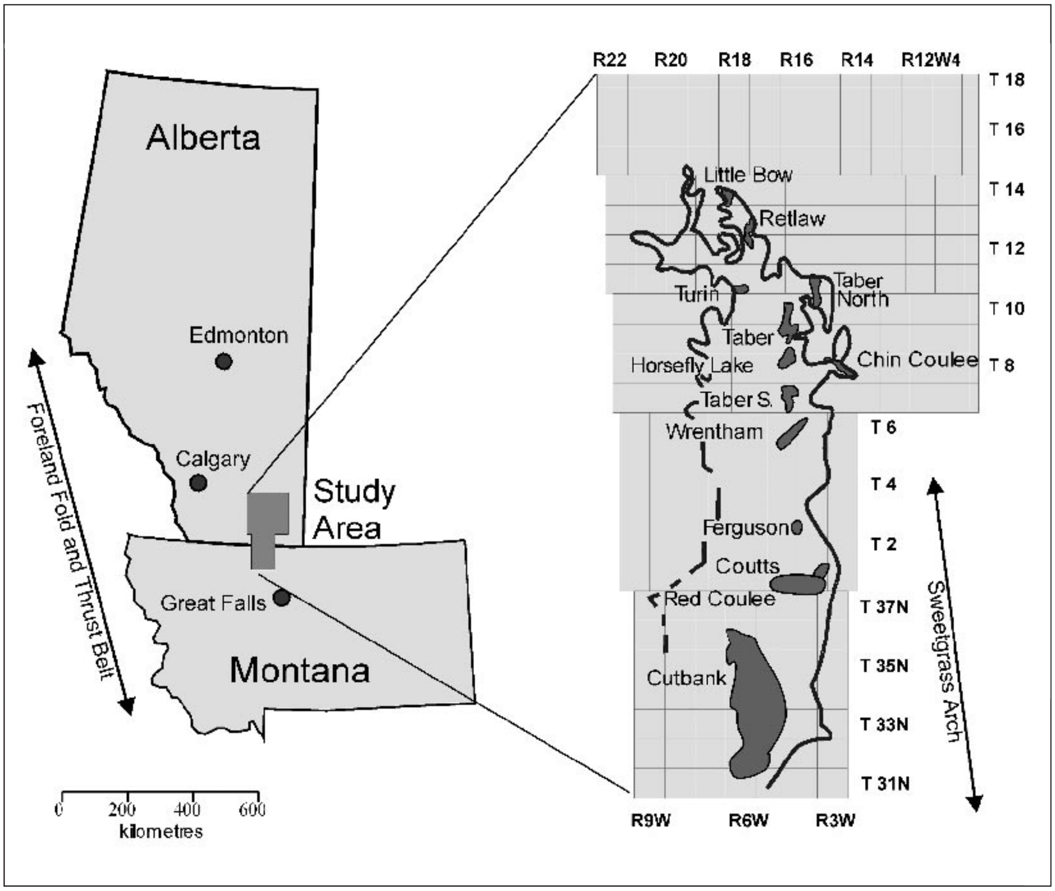

Fig. 2. Location of study area. Detailed map shows the Township (T) and Range (R) grid system (each square is 9.8 km on a side) and the location of notable oil and gas fields (darker shading) within the study area. The U.S.–Canada border lies between T37N in Montana and T1 in Alberta. The solid/dashed line indicates the zero isopach of the Horsefly sandstone, which approximates the margin of the Horsefly (i.e. Taber-Cutbank) valley.

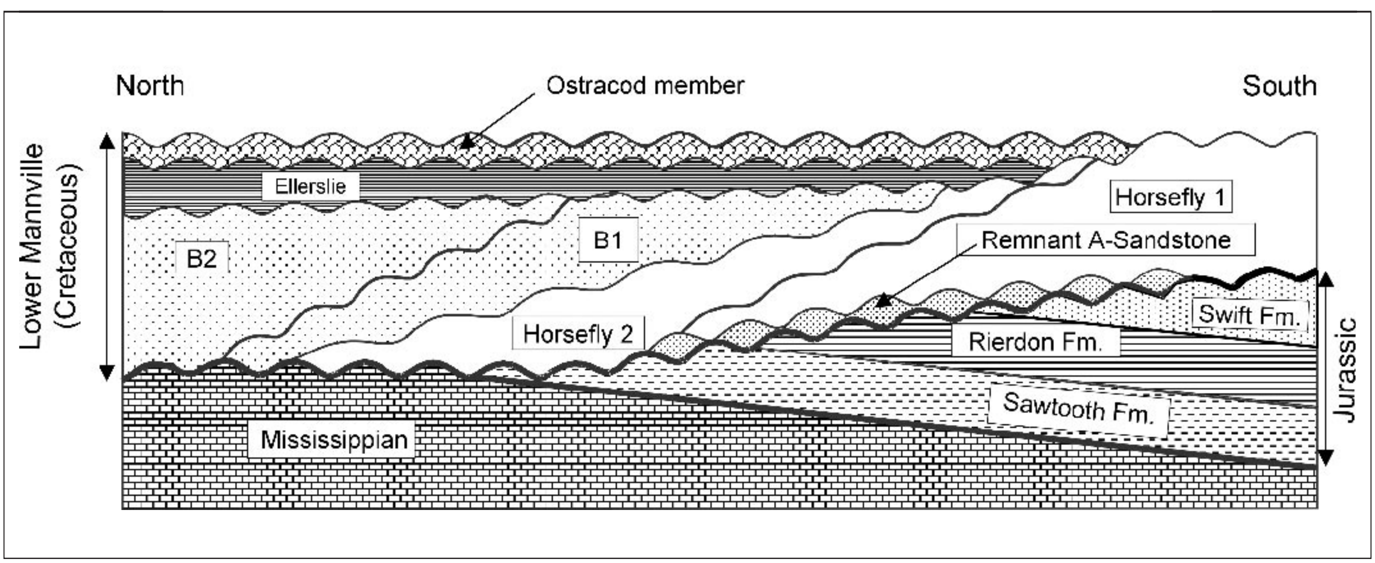

Fig. 3. Schematic north–south section through the Basal Quartz (BQ) in the study area. Traditionally, the BQ includes all deposits between the sub-Cretaceous unconformity (heavy sinuous line) and the base of the Ellerslie Member (i.e. the A-Sandstone, Horsefly 1, Horsefly 2, and BAT units). No scale implied. Modified from Ardies et al. (2002).

Depositional Facies and Facies Associations

The sediments comprising the Horsefly range from conglomerates to mudstones. Based on grain size and sedimentary structures, ten distinct facies have been recognized (Table 1; Fig. 4). With the exception of Facies 7, the conglomerate and sandstone facies (F1–6) were deposited by currents of various intensities and are interpreted to represent channel deposits. In unbroken cores, the crossbedding is almost invariably unidirectional, and rhythmically spaced mudstone drapes are absent, suggesting that tidal action was not present. Thus, these facies are consistent with the fluvial interpretation of the Basal Quartz in the study area (e.g. Hradsky and Griffin, 1984; Hayes, 1986; Farshori, 1989; Dolson and Piombino, 1994; Arnott et al., 2000; Zaitlin et al., this issue). The presence of root traces in Facies 8, 9, and 10 indicate deposition in terrestrial (overbank) environments; the mudstones of Facies 10 are interpreted to represent paleosols of various types (see more below).

These ten facies in turn occur in four, recurring facies associations: 1) sandstones and conglomerates; 2) medium-bedded sandstones in mudstone; 3) heterolithic deposits; and 4) mudstone-dominated deposits.

Facies Association 1: Sandstones and Conglomerates

This facies association (FA) invariably overlies an erosion surface and ranges in thickness from 3 to 8.8 m (Figs. 4A, 5). It generally fines upward, although some occurrences show little or no vertical change in grain size; gamma-ray logs reflect this by showing either an upward increase in gamma-ray values, or a blocky pattern (Fig. 5). Conglomerates (F1 and/or 2; Table 1) are commonly, but not universally, present at the base. They reach a maximum thickness of 2 m, but are more commonly about 0.3–0.5 m thick (Fig. 4A). They are overlain by coarse- to medium-grained, crossbedded sandstones (F3) that pass upward gradually into a variety of finer-grained and thinner-bedded sandstone facies (F4–F8). Mudstone interbeds and root traces were observed commonly in the uppermost portion of the succession, occurring in facies F4 to F8. These deposits may pass upward gradationally into mudstone-dominated sediments of FA 3 (Figs. 4A, B, 5), or be truncated by the erosional base of another unit of FA 1.

Based on these characteristics, we interpret this facies association to consist of river-channel deposits. The lack of extensive bioturbation, rhythmic mudstone drapes, and herringbone crossbedding (i.e. evidence of brackish water and tidal action), indicates that there was no marine influence; rare, meniscate, back-filled burrows observed in Township 11 may have been formed by terrestrial insects (J. MacEachern, pers. comm., 1999).

Facies Association 2: Medium-Bedded Sandstones in Mudstone

This facies association consists of thin- to medium-bedded, sheet sandstones (<3 m thick) encased in heterolithic and/or mudstone-dominated sediments that contain evidence of pedogenesis (FAs 3 and 4; Figs. 4B, 5). These sandstones typically have a sharp to erosional base and generally fine upward from medium sand to silt, passing gradationally upward into heterolithic and/or mudstone-dominated sediments, but some coarsen upward or show no vertical change in grain size. The sandstones contain small crossbeds (generally less than 15–20 cm thick), parallel lamination, and current-ripple bedding. Vertical root traces are present at the top of some examples. Well-log correlations suggest that they have aerial extents of 2 to 3 km^2, with horizontal extent:thickness ratios of the order of 1000:1. These sandstones, which are thinner and contain lower-energy structures than the channel deposits (FA 1), are interpreted as crevasse splays deposited in overbank environments.

Facies Association 3: Heterolithic Deposits

Rocks of this association consist of interbedded sandstone and mudstone, with mudstone contents ranging from about 25–85% by volume, although most examples are mudstone dominated. FA 3 is composed primarily of facies F9 (Table 1), with individual sandstone and mudstone beds ranging from a few millimetres to a maximum thickness of 20 cm (average 8–10 cm thick). Current ripples are the most abundant structures in the sand layers, but some larger crossbeds are also present. Occurrences of this association are generally underlain by channel sandstones (FA 1) and overlain by mudstones of FA 4 with gradational contacts (Figs. 4A, B, 5), and thus show a fining-upward trend.

Two variants of this association occur. Facies Association 3a averages about 1.5 m thick and contains greenish-grey coloured mudstones. Root traces are moderately common, as is soft-sediment deformation. The transition from the underlying channel sandstones is gradual (Fig. 5). Because of this, we interpret this association to represent channel-proximal overbank/levee deposits. The drab colours of the mudstones indicate that the sediment stayed damp. The soft-sediment deformation structures may represent vertebrate trackways.

Facies Association 3b occurs in only two cores where it is 1.5–2 m thick. It differs from FA 3a in that the mudstone component is dark grey to black and root traces are not abundant, which indicate that deposition occurred in the presence of standing water and/or permanently swampy conditions. One occurrence overlies a channel sandstone with a sharp contact, suggesting it formed in an abandoned channel. The other occurrence lies directly on floodplain paleosols and appears to have formed in an overbank setting.

Facies Association 4: Mudstone-Dominated Deposits

This association contains >85% mudstone by volume (Figs. 4A, B, 5); facies F10 (Table 1) dominates these deposits (Figs. 4, 5), but minor amounts of interbedded sandstone, siltstone, and mudstone (F9) and structureless siltstone (F8) are also present. Pedogenic features (stress cutans and slickensides, root traces, rhizoconcretions, and drab haloes) are pervasive. The mudstones are variably coloured (see

Table 1. Descriptions of facies recognized in the Horsefly unit.

Facies	Lithology	Grain Size	Bed/Set Thickness	Sedimentary Structures	Other	Inferred Origin	Occurrence
F1 Conglomerate/ pebble-rich sandstone (extraformational and extrabasinal)	Quartz, chert, shale, and ductile green-clay clasts with sand matrix	Granules to pebbles (most commonly 1–3 cm); medium to coarse sand matrix	5–60 cm	Conglomerates structureless or with vague horizontal bedding; pebble-rich sandstones may be cross bedded	Clasts rounded; ductile green-clay pebbles swell when wetted; minor oil stain	Bedload deposition; dunes present in sandy sediments; clasts derived from beneath and outside the area of deposition	Lower part of Facies Association 1; extrabasinal type not present in northern part of study area
F2 Shale-clast conglomerate (intraformational)	Black shale clasts with sand matrix	Granules to pebbles (most commonly 1–4 cm); medium sand matrix	Generally about 15 cm, but can reach 70 cm	Conglomerates structureless or with vague horizontal bedding; sandier variants cross bedded	Clasts angular to subangular, and flattened by compaction; no oil staining	Bedload deposition; dunes present in sandy sediments; clasts derived from contemporaneous overbank deposits	Lower part of Facies Association 1
F3 Crossbedded sandstones	Quartz-rich sandstones with significant chert content; lithic grains abundant locally	Coarse to fine sand	5–110 cm sets	Trough and/or tabular crossbeds (distinction difficult to impossible in core)	Segregation of quartz and chert define lamination; wood fragments present locally; mud drapes absent; oil staining abundant	Migration of dunes in lower flow regime current	Facies Associations 1 and 2
F4 Massive sandstones	See F3	Coarse to fine sand	30 cm to 1 m beds	No structures visible	locally oil stained	Quick deposition because of rapid decrease in current speed	Facies Associations 1 and 2
F5 Planar-bedded sandstones	See F3	Fine to very fine sand	0–60 cm beds	Planar beds recognized by the alternation of light (quartz-rich) and dark (chert-rich) layers	Oil staining minor; generally overlain by F6	Upper-flow-regime plane-bed transport	Facies Associations 1 and 2
F6 Current-rippled sandstones	See F3	Medium to very fine sand	10–50 cm beds	Current-ripple cross lamination; climbing ripples	Commonly associated with F3; oil staining minor	Deposition in relatively weak currents; climbing-ripples indicate high rates of aggradation	Upper part of Facies Associations 1 and 2

Table 1. Continued.

Facies	Lithology	Grain Size	Bed/Set Thickness	Sedimentary Structures	Other	Inferred Origin	Occurrence
F7 Wave-rippled and wavy-bedded sandstones	See F3	Medium to fine sand	5–15 cm beds	Wave ripples or wavy bedding (poorly developed wave ripples)	Oil staining minor to nil	Oscillatory wave action	Upper part of Facies Association 1
F8 Massive siltstones	Quartz-rich siltstones with minor chert	Silt	0 cm to 2 m beds	No structures visible; rootlets present locally	No oil staining	?? – Aeolian (loess) deposition, with homogenization by soil-forming processes	Near top of Facies Association 1, in transition to Facies Association 3
F9 Interbedded sandstones, siltstones, and mudstones (sandstone: mudstone ratios 60:40 to 15:85)	See F3 and F8; mudstones are mixture of silt and clay (smectite/illite mixed-layer clay, illite, and minor kaolinite)	Fine to very fine sand, silt, and mud	50 cm to 2.4 m packages; beds with interlaminated sand and mud 1–10 cm	Sandstones contain current ripples, parallel lamination, or are structureless; siltstones usually structureless; mudstones may contain planar laminae; rare rootlets; convolute lamination and soft-sediment micro-faults present locally	Colour typically greenish grey (5 R 3/4); siderite blebs and pyrite nodules common; typically overlain by F11; no oil staining	Episodic higher-speed currents in an overall low-energy environment; periodic exposure and rooting; deformation caused by rapid deposition and loading, slumping, and/or vertebrate foot prints	Facies Association 3, in transition from Facies Association 1 to Facies Association 4
F10 Mudstones	Silty- to sandy-mudstones and mudstones; see F9	Silt to clay, minor sand	0.5–20 m units	Typically structureless; minor sand beds; siderite blebs and pyrite nodules; rootlets (some have rhyzoconcretions, others have drab-haloes) and slickensides (stress cutans) and desiccation cracks rare to common; soil horizons not visible	Uniform coloration or mottled; colours (in decreasing abundance)- dark reddish brown (10 R 3/4) to dusky red (5 R 3/4), greenish grey (5 G 6/1), olive brown (5 Y 4/4), brownish grey (5 YR 4/1), and black; organic material absent, except in rare cases	Slow, intermittent aggradation of muddy sediment; exposure and pedogenesis	Facies Association 4

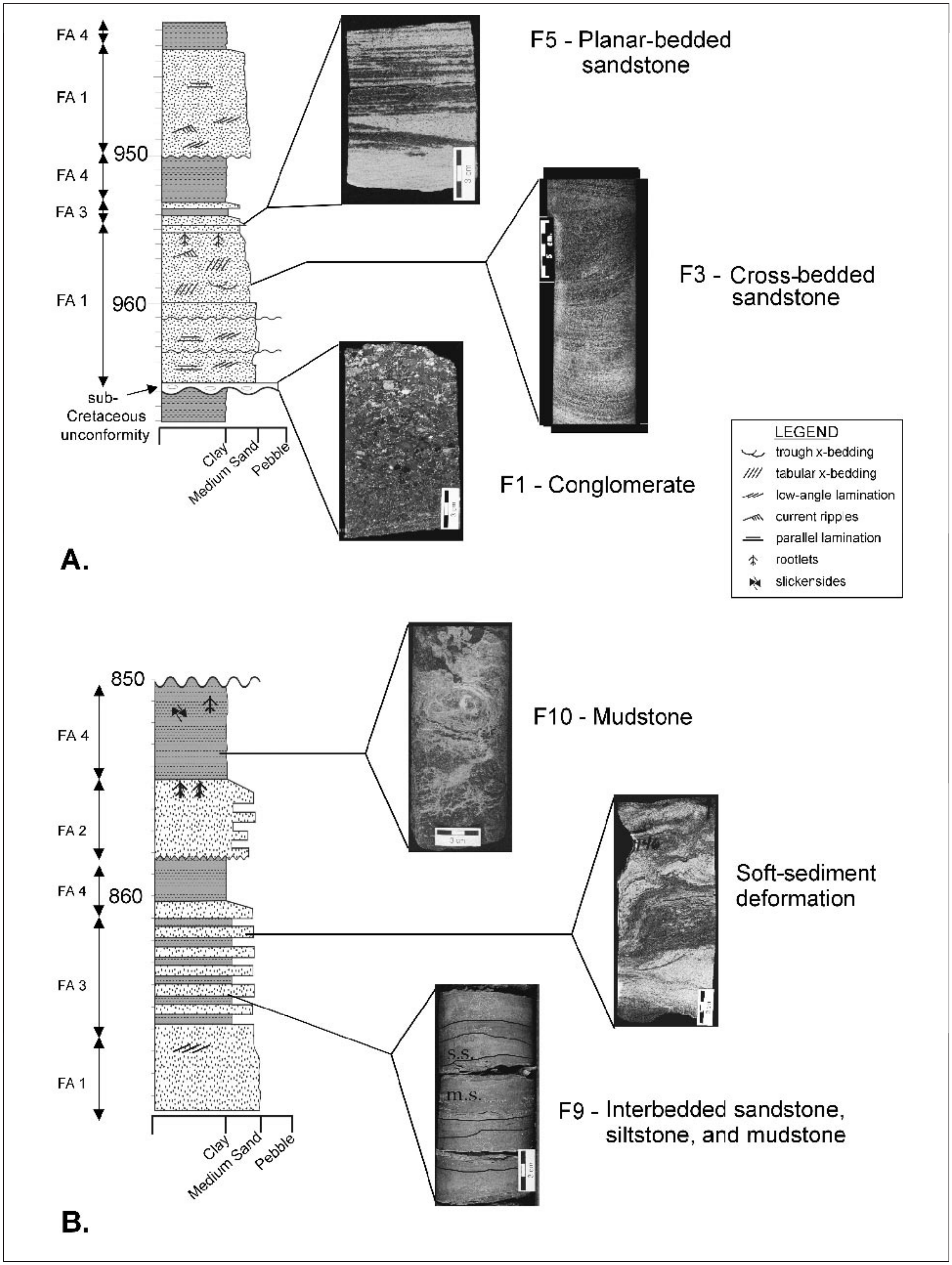

Fig. 4. Core logs showing representative examples of important facies and typical vertical stacking of facies associations (FAs), H1 sequence: **A**. Well NE-NW-1-31N-6W, southern end of the Cutbank Field, Montana. **B**. Well 4-10-1-17W4, Coutts Field, southern Alberta. The lower fluvial-channel sandstone (FA 1) in each core, together with the heterolithic deposits of FA 3 in A, is part of the basal sheet sandbody; the remainder of each core lies in the upper mudstone-dominated interval. Core depths are in metres.

Table 1). Red colours predominate in the south, whereas green to grey colours are more common in the north. In some cores from the area south of Township 6, up to three alternations between red and green mudstones are present, with the amount of red mudstone increasing up-core. In one core, FA 4 overlies FA 3b and consists of a black mudstone lacking pedogenic features. It in turn grades up into green and grey mudstones, and ultimately into brownish grey mudstone containing pedogenic slickensides.

The mudstones comprising this association accumulated in overbank (floodplain) settings and represent paleosols of various types. The green mudstones are interpreted as gleyed paleosols (*sensu* Mack et al., 1993) that accumulated where the sediments were poorly drained, while the red mudstones are interpreted as vertisols (*sensu* Mack et al., 1993). The abundant carbonate rhyzoconcretions and pedogenic slickensides in these red mudstones indicate that the climate was semiarid and the sediment was subjected to alternating wet and dry conditions, forming incipient calcretes. The structureless, rooted siltstones of facies F8 may be loessite (cf. Johnson, 1989; Chan, 1999).

The lack of distinct soil horizons indicates that the area experienced continual, but slow, aggradation. The scarcity of sandstone, relative to FA 3a, suggests that FA 4 was deposited at greater distances from the coeval channel. The vertical alternations between red and green paleosols seen in the southern part of the study area could be interpreted to reflect changes in climate (drier versus wetter, respectively). However, the colour bands cannot be correlated for more than a few kilometres, something that might be expected if they were the result of regional climatic variations. Instead, they are believed to result from local changes in flood-plain drainage, perhaps because of changing distances from the nearest channel. Thus, the green paleosols may have formed when the river was closer, causing the water table to be higher, while the red paleosols formed when the channel was farther away and the sediment was drier. Indeed, the green paleosols contain more sandstone, on average, than the red paleosols, an observation that is consistent with this interpretation.

The rare black to dark grey, organic-rich mudstones in this facies association overlies a thin channel deposit (FA 1; 1.5 m

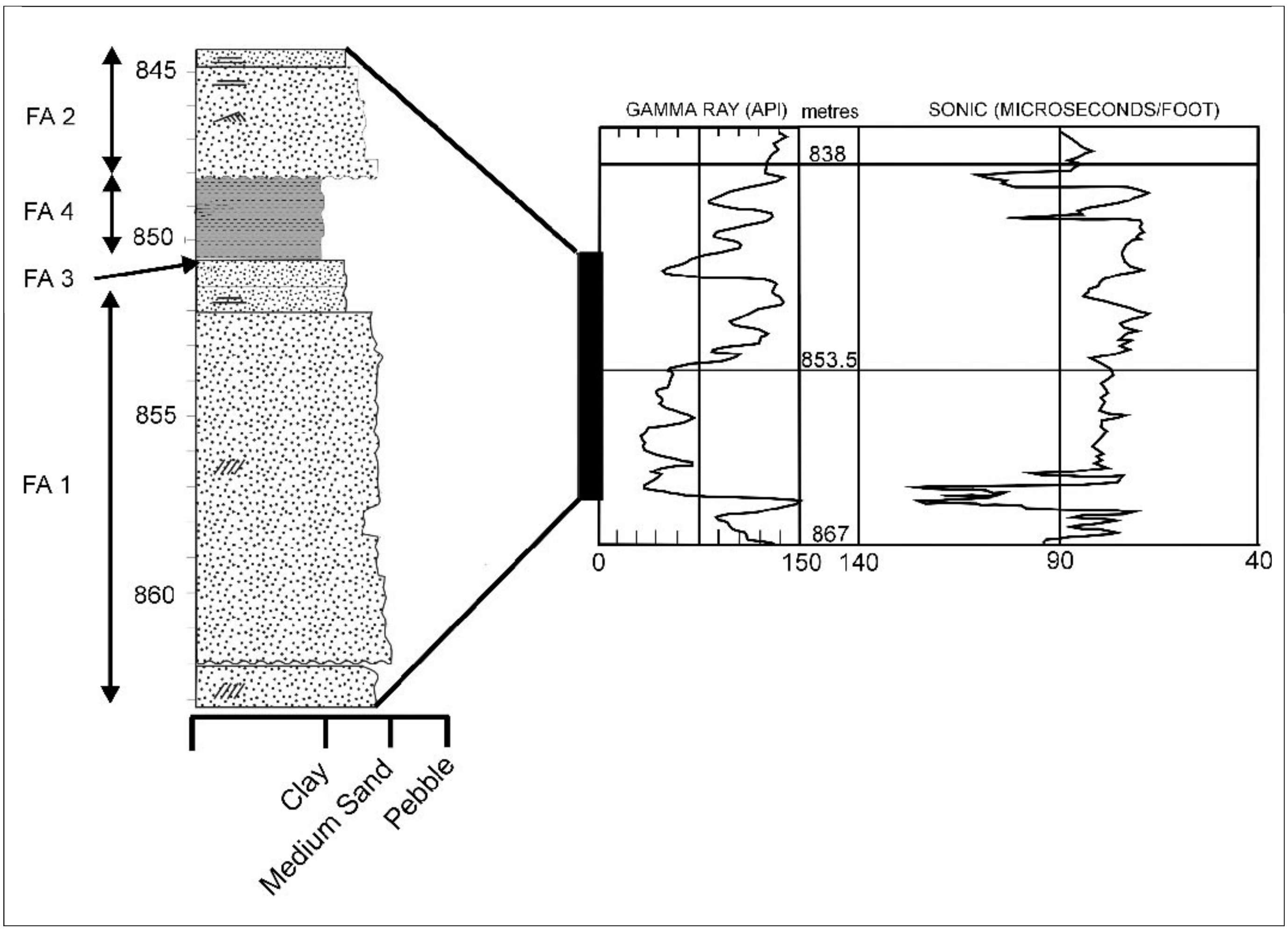

Fig. 5. Core log and corresponding geophysical logs from the H1 sequence, southern Alberta (Well 7-4-1-17W4), showing representative vertical succession of facies associations. FAs 1 and 3 form part of the basal sheet sandstone; FAs 2 and 4 are part of the upper, mudstone-dominated interval. Core depths are in metres. See Figure 4 for legend.

thick) and a package of interbedded sandstone and mudstone (FA 3b; 1.5 m thick). Thus, they may represent deposition in a perennially wet, abandoned channel where organic material was protected from oxidation. The upward passage into greenish-grey pedogenically altered mudstones presumably reflects filling of the channel.

Sequence-Stratigraphic Subdivision

The above facies associations are themselves organized into a larger-scale, erosionally based, fining-upward succession with an average thickness of 25–35 m. It consists of two parts (Fig. 6): 1) a lower part composed almost entirely of amalgamated channel sandstones (FA 1) that form a sheet-like sandbody; and 2) an upper part dominated by overbank mudstones (FAs 3 and 4) that contain isolated, fluvial-channel and crevasse-splay sandstones (FAs 1 and 2).

Basal Sandbody

This sandbody consists of fluvial-channel sandstones and conglomerates (FA 1) that generally lack intervening, fine-grained overbank deposits. Numerous erosion surfaces are present in the lower part of this sandbody (Figs. 4A, 5), separating truncated and amalgamated, fining-upward channel deposits. Extraformational and extrabasinal conglomerates (F1) and pebbly sandstones are only present in the lower 5 m, with the thickest conglomerates (up to 1.8 m) occurring at the very base (Fig. 4A). Above this, the sediments fine upward overall through the composite sandbody, from coarse and medium sandstone in lower channels, to fine sandstone in higher ones. The sediments within each channel deposit also fine upward, but bar-top facies (F8 and F9) and overbank sediments (FAs 2, 3, and 4) are not present, except in the topmost channel (Figs. 4A, 5). However, the presence of intraformational conglomerates (F2) at many of the individual channel bases indicates that overbank deposits were originally present, but have been completely removed by channel erosion.

Previous workers (e.g. Hradsky and Griffin, 1984; Hayes, 1986; Farshori, 1989; Arnott et al., 2000) have consistently interpreted these sediments as braided-river deposits because of the absence of overbank mudstones. However, there is abundant evidence of channel amalgamation, so it is also possible that these basal sandbodies were created by coarse-grained

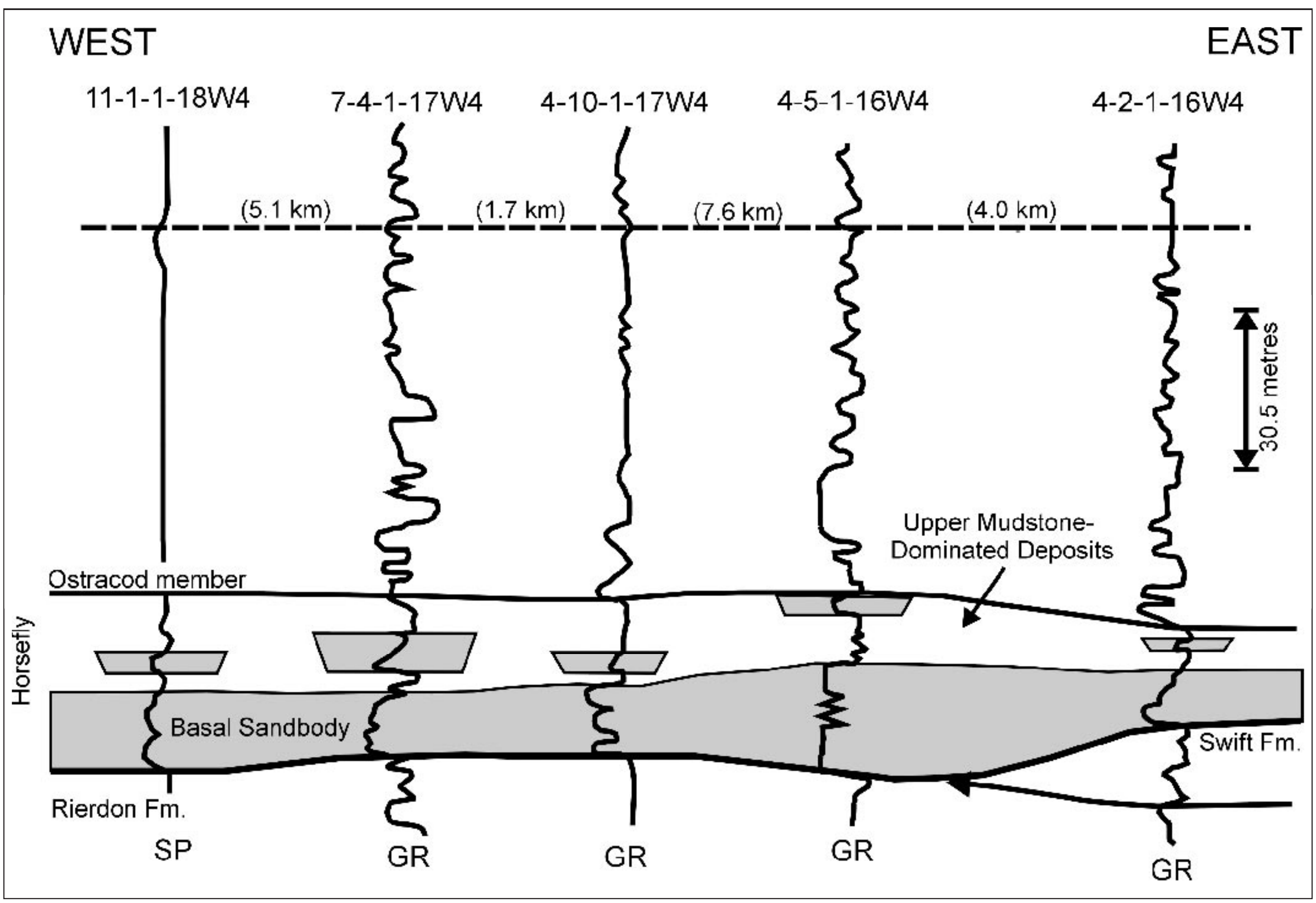

Fig. 6. East–west cross-section through Township 1, southern Alberta, showing the typical two-part subdivision of the Horsefly unit (sequence H1). A sheet-like sandbody comprises the base of the succession, whereas the upper part consists of overbank mudstones that contain isolated, ribbon sandbodies. Note truncation of the Swift Formation along the eastern valley wall, and the flat valley floor. Numbers in brackets between logs are the distances between wells. Cross-section is hung on the top of the Upper Mannville.

meandering rivers in a setting with slow net aggradation and extensive cannibalization of overbank deposits (cf. Wright and Marriott, 1993; Shanley and McCabe, 1994).

Upper Mudstone-Dominated Deposits

The basal sandbody is gradationally overlain by a mudstone-dominated deposit (Fig. 6) that onlaps the walls of the valley and extends more widely than the basal sandstone. Facies Associations 3 and 4 are volumetrically dominant (Fig. 7). However, channel sandstones (FA 1) and crevasse splays (FA 2) are also present (Figs. 4–7), but typically constitute less than 50% of the interval and become less abundant upward. The channel sandstones average approximately 5 m thick (maximum 11 m) and are typically surrounded by finer-grained overbank deposits; amalgamation is rare and is restricted to the lower part of the mudstone-dominated deposits. Based on well-log correlations of individual channel sandstones and Collinson's (1978) relationship between meander-belt width (Wm) and maximum channel depth (h, assumed to equal sandbody thickness), $Wm = 64.6h^{1.54}$, the lateral (i.e. east–west) extent of channel-sandstone bodies is estimated to be 0.5–3 km. They are inferred to be continuous in a north–south direction and thus to have a ribbon-shaped geometry. Unlike the basal sandbody, extraformational conglomerates (Facies 1) are not present. Because the ribbon sandbodies display pronounced fining-upward successions and are isolated within overbank sediments that contain crevasse-splay sandstones (FA 3; Fig. 7), they are interpreted to be the product of coarse-grained meandering rivers.

Most wells intersect one or more channel and/or crevasse-splay sandstones, such that unbroken mudstone intervals are typically less than 10 m thick (Figs. 4–6). In isolated locations, however, much thicker paleosol successions are encountered; in some instances, such paleosols reach 30 m thick and comprise the entire thickness of the upper, mudstone-dominated interval (e.g. Fig. 7). These anomalously thick mudstones are less than a few kilometres in maximum extent and represent areas that were never occupied by a fluvial channel. We refer to these as "paleosol islands."

Sequence Organization

The upward decrease in channel amalgamation from the basal sandbody into the overlying mudstone-dominated deposits suggests that there is a progressive increase in accommodation during deposition of this succession. This is consistent with the fact that extrabasinal conglomerates (i.e. those containing clasts that could not be derived directly from underlying units) occur only near the very base of the succession: the upward increase in accommodation leads to trapping of extrabasinal clasts in more proximal areas. Thus, we interpret the succession as an unconformity-bounded sequence, in which the basal amalgamated sandbody is equivalent to the "lowstand" (low accommodation) systems tract of the alluvial sequence models of Wright and Marriott (1993) and Shanley and McCabe (1994), while the upper mudstone-dominated deposits represent the "transgressive" (high accommodation) systems tract.

A single such sequence (the H1 sequence) comprises the entire thickness of the Horsefly throughout most of the study area, but in Townships 6–15 a second sequence (the H2 sequence) overlies the first (Figs. 8, 9, 10, 11; Ardies, 1999; Arnott et al., 2000). The deposits at the base of the H2 sequence (Fig. 8, Well 8-11-9-18W4) contain extrabasinal conglomerates that locally overlie mudstone-dominated deposits in the upper part of the H1 sequence. Thus, the H2 sandstones are not a local channelized feature in the upper part of H1.

Spatial Variability of Valley Forms and Valley-Fill Deposits

General Valley Morphology

The isopach map of the older Horsefly (H1) sequence (Fig. 10A), combined with cross-sections demonstrating truncation of Jurassic and Mississippian units (Figs. 6, 8), shows that the H1 sequence occupies a broad (about 28–52 km wide), north–south trending valley that extends as far north as Township 14, where it is erosionally truncated by younger, H2 and BAT valley systems (cf. Figs. 1, 3; Ardies, 1999; Ardies et al., 2002; Zaitlin et

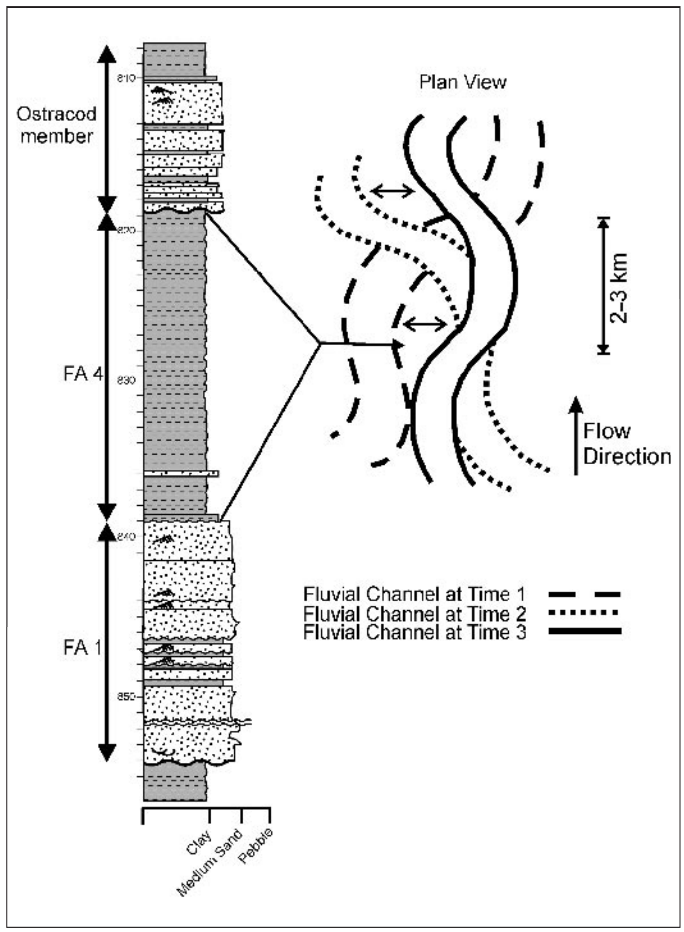

Fig. 7. Core log (Well 2-4-1-17W4) showing anomalous, 20 metre-thick interval of overbank mudstones (FA 4) in the upper part of the H1 sequence. Schematic map shows how such successions are interpreted to form. Core depths are in metres. See Figure 4 for legend.

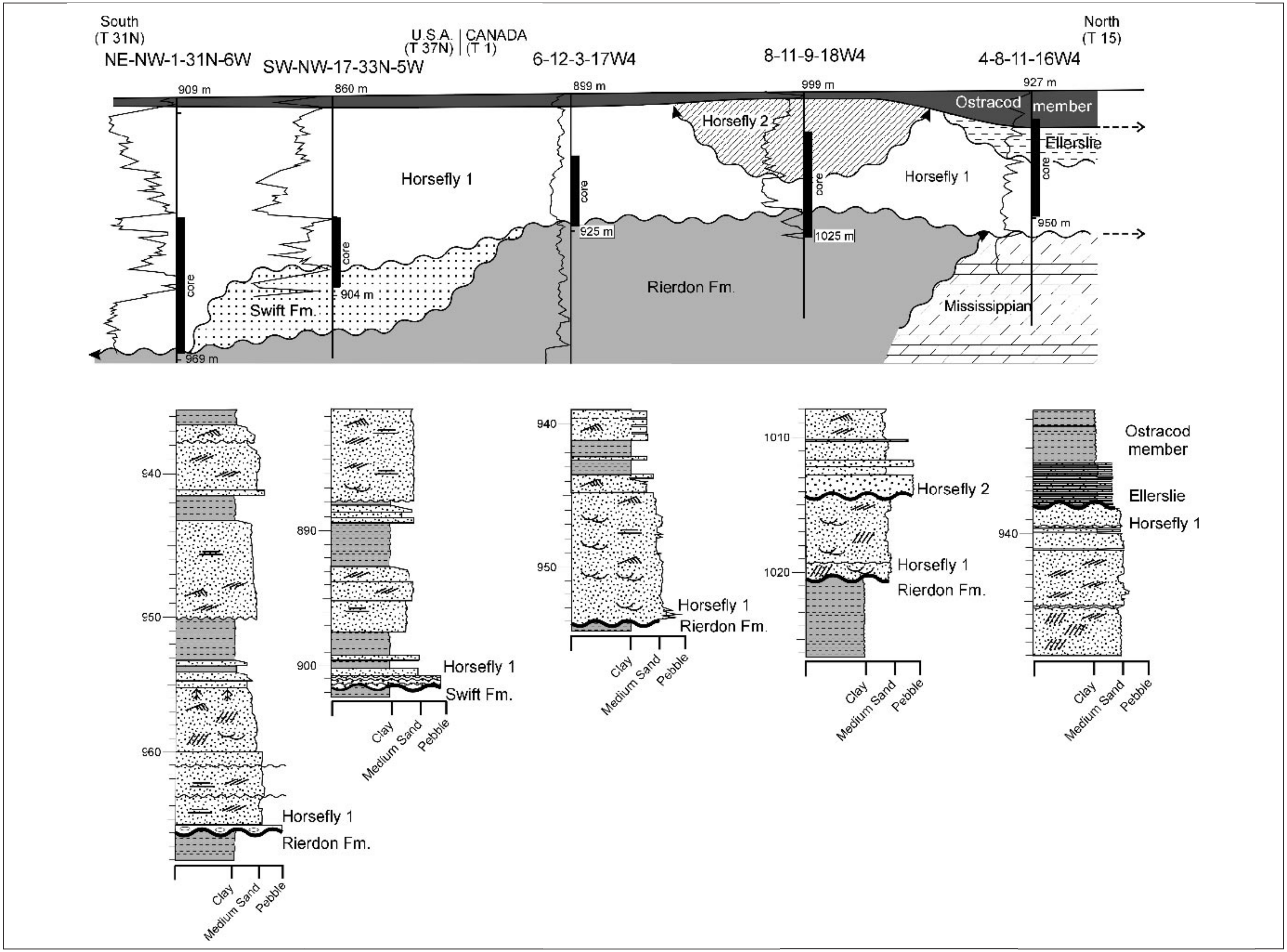

Fig. 8. North–south cross-section along the axis of the Taber-Cutbank (Horsefly) valley showing the stratigraphic organization of the study interval. Note the presence of two unconformity-bounded sequences within the Horsefly, the truncation of older units beneath the Horsefly 1 sequence, and the overall northward thinning of the entire Horsefly.

al., this issue). Cross-sections hung on various overlying markers all show that the base of this valley is relatively flat (Fig. 6), although there are exceptions (see more below), and that the thickness of the H1 unit (average 30 m; maximum 60 m; Fig. 10A) is equal to, or somewhat less than, the relief of the valley. The younger H2 sequence occurs only in Townships 6–15 (Fig. 11) and is typically confined within the H1 valley (compare Figs. 10A and 11). The average width (15 km) and thickness (mean 9 m; maximum 18 m; Fig. 11) of this sequence are both less than corresponding values for the H1 sequence. The basal erosion surface is also not as flat, with more evidence of localized scour. Both valleys display only small tributaries in the form of short, narrow (about 2–5 km wide and up to 10 km long), finger-like projections (Figs. 10A, 11) along their margins.

Spatial Variability within the H1 Sequence

Description

Because of the considerable length over which the H1 sequence has been mapped (Fig. 10), it is possible to examine local and regional changes in the nature of the valley and its fill. Except in the area north of Township 6 in Alberta where later valleys have dissected the H1 sequence, there appears to be limited differential erosion of its upper part. Thus, the preserved isopach distribution of the H1 sequence (Fig. 10A) is assumed to approximate the geometry of the valley floor.

In general terms, the valley width and fill thickness are reasonably uniform throughout the study area, although the valley tends to become slightly narrower to the north (discounting tributaries). Also, the nature of the fill is regionally consistent, with both the basal sandbody and upper mudstone-dominated deposits occurring in all areas, except where local erosion has removed the upper part of the succession. However, when examined in more detail, there are a number of abrupt changes in the nature of the valley and its fill.

South of Township 36N in Montana, the valley fill displays a relatively uniform width and thickness (i.e. the isopach contours on either side of the valley are nearly parallel; Fig. 10A). The basal sandstone is also relatively uniform in thickness (Fig. 10B; average 5–10 m), largely because of the absence of significant large-scale relief on the valley floor. However, in Township 1, the valley width decreases markedly. In particular, all of the isopach contours along the eastern margin are deflected sharply to the west at this point; the contours along the western side of the valley are more poorly constrained, but appear to be deflected eastward at the same latitude (Fig. 10A). The lateral extent of areas with more than 10 m of basal sandstone (Fig. 10B) also decreases abruptly at the northern border of Township 1.

Accompanying these changes, the average, total thickness tends to be less in Townships 2–5 than to the south (Fig. 10A) and the thinnest basal sandstone occurs in Township 1 (Fig. 10B). By contrast, the mudstone-dominated upper part of the valley fill is thickest immediately south of the border (Townships 34N–37N) and contains anomalous occurrences of greyish-black, organic-rich mudstones; elsewhere, the Horsefly is notable for the absence of organic debris. The most northerly occurrences of extrabasinal, gravel-sized clasts are also found in this area, a fact that contributes to the overall northward decrease in average grain size of the basal sandbody. By contrast, intraformational conglomerates (F2) are present throughout the entire extent of the H1 sequence. Within the mudstone deposits, the paleosol types change northward, from dominantly red vertisols in Montana, to greenish-grey gleysols in Canada.

Additional abrupt changes occur in Township 7 where the average thickness of both the entire H1 sequence (Fig. 10A) and the basal sandbody (Fig. 10B) decrease abruptly to less than 10 m. Significant facies changes do not accompany this abrupt thinning, with the exception that "paleosol islands" are not seen north of Township 7.

At a smaller spatial scale, numerous "bulls-eye" anomalies are evident in Figures 10A and B. These localized areas (about 2–10 km in extent) commonly involve abrupt changes in thickness, frequently by a factor of two or more, over distances as short as 200 m. In some instances, the mudstones show an abrupt change from vertisols to gleysols, or even organic-rich mudstones, that coincides with the thickness change. Detailed well-log sections (Fig. 12) reveal that the base of the Horsefly (i.e. the sub-Cretaceous unconformity) and any visible markers in the underlying succession are offset by 5–30 m along the margins of the anomalous areas. These offsets are interpreted to be faults that appear to have been active during Horsefly time. Our relatively sparse well control does not allow the detailed mapping of these faults throughout the entire study area (Fig. 10B shows their mapped locations and orientations), but detailed, in-house studies at PanCanadian Petroleum Ltd. confirm their presence.

Discussion

We believe that the rivers that deposited the H1 sequence flowed from south to north (cf., Jackson, 1985; Banerjee,

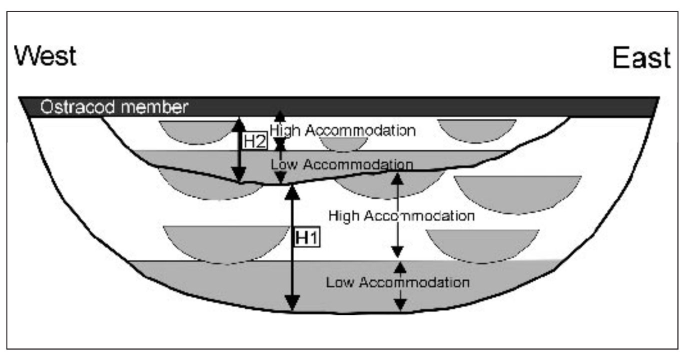

Fig. 9. Schematic, east–west (cross-valley) section showing the stratigraphic organization of the two sequences comprising the Horsefly in the northern part of the study area. The basal sheet sandstone in both valleys formed under conditions of low accommodation, whereas the overlying mudstones with isolated channel sandstones formed when accommodation was relatively high. The valleys are capped by the Ostracod member except where incised by younger valleys of the BAT, Ellerslie, and Glauconitic units.

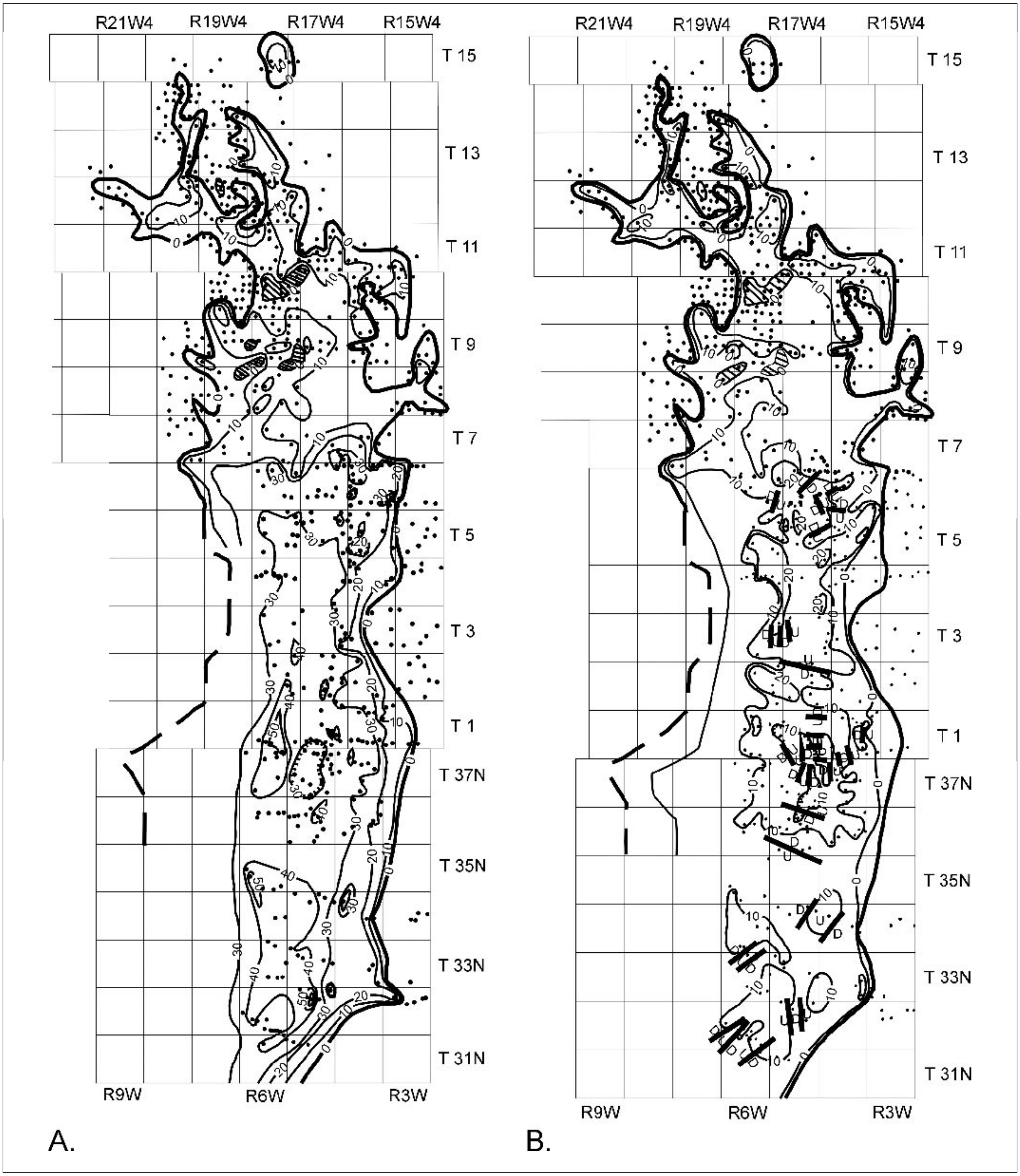

Fig. 10. A. Isopach map of the entire H1 sequence (contour interval = 10 m). Heavy zero-thickness contour approximates the valley edge, except north of about Township 11 where dissection by younger valleys (especially the BAT) is significant. Black dots indicate location of wells used in this study. The indicated position of the valley margin in the southwestern part of the map is loosely constrained by unpublished, in-house data at PanCanadian Petroleum Ltd. **B**. Isopach map of the basal sheet sandbody in the Horsefly 1 sequence (contour interval = 10 m). Heavy line is the zero isopach contour from A. Short solid lines show faults with relative movement indicators (U = upthrown; D = downthrown), as interpreted from cross-sections (e.g. Fig. 12; from Lukie, 1999). Faults are not shown in Townships 7–15 because this part of the map is based on Ardies (1999), who did not map the individual small faults that are present.

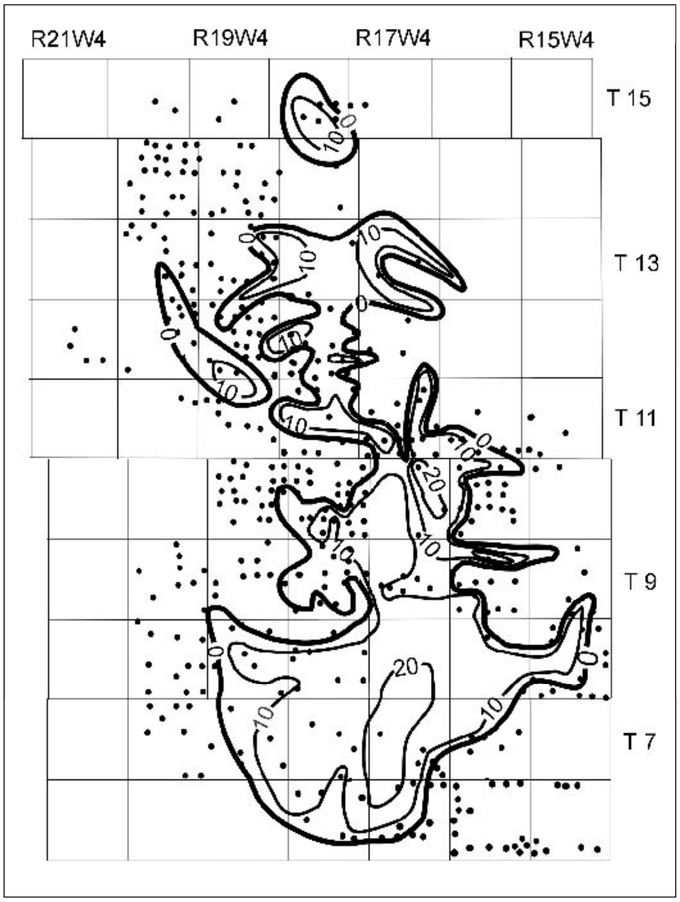

Fig. 11. Isopach map of the entire Horsefly 2 sequence (contour interval = 10 m). Black dots indicate location of wells used to draw the map.

1990). This is shown most strongly by the northward decrease in the grain size of the channel deposits and by the restriction of extrabasinal conglomerates to Montana, and is supported by the observation that the overlying BAT and Ellerslie units become increasingly more marine in that direction (Ardies, 1999; Ardies et al., 2002; Zaitlin et al., 1999, this issue). However, the northward decrease in the width of the valley (Fig. 10) is inconsistent with this interpretation. The probable explanation for this is discussed below.

Controls on Horsefly Sedimentation

In fluvial environments, many factors influence the nature of the facies and their stratigraphic organization (Retallack, 1990; Miall, 1996; Holbrook and Schumm, 1999; Blum and Törnqvist, 2000). Among these are 1) climate and the amount and grain size (suspended load to bedload ratio) of the sediment supplied, which together determine the fluvial equilibrium profile (that in turn determines the type of river system and the nature of the paleosols), and 2) eustatic sea-level change and regional and local tectonic/structural movement, which determine the accommodation history (that then influences the degree of amalgamation of channel deposits and the preservation potential of overbank deposits). Below, we explore the role that these factors may have played in the generation of the two Horsefly sequences, each with its subdivision into a basal sandbody and an upper mudstone-dominated interval, and of the spatial variability in the H1 sequence.

Eustacy

It is tempting to suggest that the stratigraphic organization of the Horsefly is a result of two eustatic lowstands, during which the valleys were eroded, followed by valley filling during the intervening sea-level rises. Eustatic sea-level fluctuations of the appropriate duration are present in the Early Cretaceous (Haq et al., 1988), but a direct link to the Horsefly sequences cannot be proven because of the absence of precise age control and the inability to tie the Horsefly with shoreline deposits further north (because of later erosional truncation). Eustatic sea-level changes may not have had much influence, however, because much of the Western Canada Sedimentary Basin was exposed at this time (Cant, 1989; Cant and Abrahamson, 1996) and the study area probably lay a considerable distance south of the contemporaneous shoreline, as indicated by the absence of tidal structures and brackish-water trace fossils.

Climate and Sediment Supply

Changes in the climate and/or the amount and grain size of the sediment supplied to a fluvial system can cause it to erode or aggrade, producing results that mimic changes in sea level (Miall, 1996; Blum and Törnqvist, 2000). However, evidence indicating that such changes occurred during deposition of the Horsefly is limited. Source-area changes, perhaps associated with unroofing and/or the uplift of new source areas, might have altered the bedload:suspended-load ratio of the material delivered to the area. However, the mineralogy of the sandstones is the same in the two Horsefly sequences (Lukie, 1999; Zaitlin et al., this issue); thus, there do not appear to have been any changes in sediment source. Paleosols are generally similar throughout the upper, mudstone-dominated portion of both Horsefly sequences, and there are no preserved paleosols from the basal sheet-like sandstone interval, so it is not possible to determine if a climate change was linked to changes in the degree of preservation of overbank material.

It is possible, however, that the northward decrease in the abundance of red paleosols in the H1 sequence reflects a northward increase in precipitation, which would have led to a higher water table and a greater tendency to water logging. McCarthy et al. (1997) observed a similar change in paleosol types in the upper Blairmore Group and attributed it to a latitudinal variation in precipitation; however, it might also be related to increased proximity to the sea and/or to differences in the intensity of any rain-shadow caused by the rising Rocky Mountains.

Regional Tectonic Movements

During the Early Cretaceous, the western margin of North America was tectonically active (Monger, 1989). Variations in

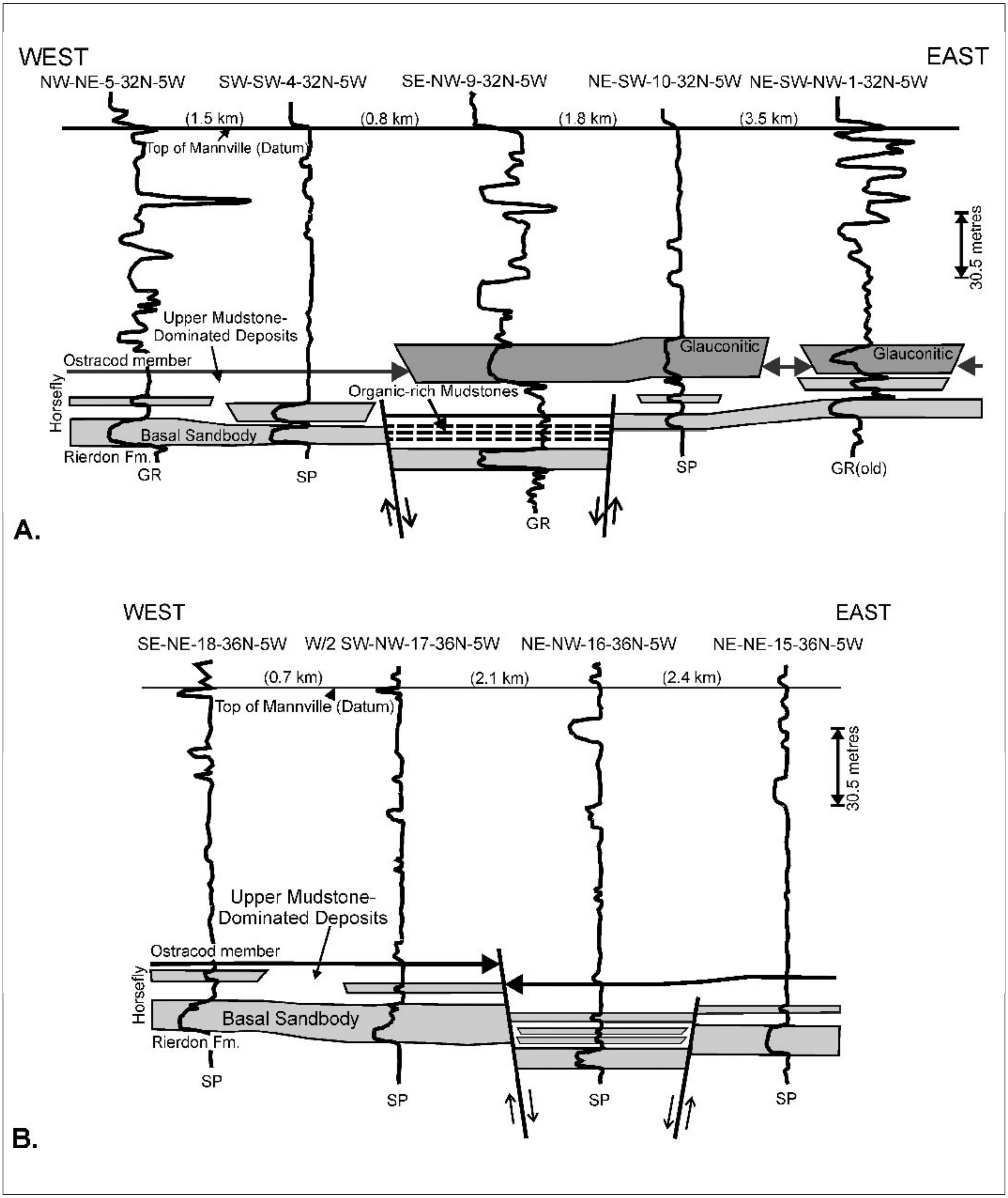

Fig. 12. A. East–west cross-section in Township 32N, Montana, hung on the top of the Upper Mannville, showing localized down-drop of the basal sheet sandbody, Horsefly 1 sequence. Note the restriction of organic-rich mudstone (as identified using Neutron-Density and Caliper logs) to the down-faulted area. **B**. East–west cross-section in Township 36N, Montana, hung on the top of the Upper Mannville, showing a down-faulted area that is overlain by a greater number of thin, channel sandstones than adjacent areas. See text for discussion. The log types shown are indicated at the base of each section. Numbers in brackets between logs are the distances between wells.

the rate of shortening associated with the docking of exotic terranes caused the western edge of the craton to alternately subside and rebound (Cant and Stockmal, 1989). The Sweetgrass Arch that forms the eastern flank of the Horsefly valley experienced intermittent movement throughout the Mesozoic (Lorenz, 1982; Ardies et al., 2002), possibly related to episodic loading by thrusts. In addition, there is abundant evidence of syndepositional block faulting during Horsefly time (see below). Therefore, we suggest that alternating episodes of regional uplift and subsidence may be largely responsible for the accommodation changes reflected in the two Horsefly sequences. The orientation of the Taber-Cutbank valley subparallel to the thrust front is strongly suggestive that the tectonic grain controlled the fluvial drainage.

Local Block Faulting

As shown in Figures 10B and 12, the Horsefly unit is cut by numerous small faults that were presumably caused by the ongoing flexure of the basin and/or any in-plane lithospheric stresses associated with orogenesis. These faults are inferred to have been active during Horsefly time, because of their spatial association with abrupt changes in valley dimensions and/or facies. Two zones of particularly significant faulting appear to trend across the valley, one near the U.S.–Canada border in Township 1 and another in Township 7, both of which show relative upward movement of their northern side. These fault zones coincide with, and are thought to be responsible for, the abrupt changes in the width of the valley and in the thickness of the entire H1 sequence (Fig. 10A) and the basal sandbody (Fig. 10B) at these locations. Apparently the uplifted, northern side caused slightly greater confinement of the river, relative to the adjacent downdropped areas, thereby creating an alternate pinching and swelling of the valley (cf., Schumm et al., 2000, Fig. 1.9).

Large and small areas of relatively greater subsidence were the sites of thicker valley-fill sedimentation. The large area of subsidence in northern Montana had a particularly important affect on the facies: it appears to have trapped all of the northward-moving, extrabasinal gravel, thereby accounting for its absence in Canada; and it allowed the presence of a relatively high water table, that in turn favoured the development of grey-green gleysols, in contrast to the red vertisols that formed in adjacent uplifted areas. At least some of the anomalous, organic-rich mudstones accumulated in localized areas of greatest subsidence (Fig. 12B). Conversely, it is possible that the "paleosol islands" (Fig. 7) represent small, subtly uplifted areas that diverted the rivers into adjacent areas of slightly greater subsidence (Fig. 12B).

On the scale of the entire Horsefly valley, the preferential north-side-up movement seen on many of the faults (Fig. 10B) may have caused the relative uplift of the northern part of the study area, which may, in turn, be responsible for the northward (downstream) narrowing of the valley. In this context, the apparent absence of paleosol islands from the narrower part of the valley north of Township 7 may result from the fact that a greater proportion of the valley floor was occupied by channels, making it less likely for overbank deposits to escape erosion.

Summary and Conclusions

The Horsefly unit is a mineralogically distinct, unconformity-bounded component of the Basal Quartz (Early Cretaceous) in the Western Canada Sedimentary Basin, and is one of the earliest units to be deposited following a long period of exposure. It occupies a north–south trending valley that lies immediately west of the Sweetgrass Arch and extends for a distance of at least 215 km, from south of Township 31N in Montana to Township 15 in Alberta where it has been truncated by later erosion. This valley, which is also known as the Taber-Cutbank Valley, is broad (28–52 km wide) and flat-floored, with a maximum incision of about 50 m. The rivers flowed to the north, as indicated by the northward decrease in grain size of the channel deposits. Tributary valleys are small and few in number; they were either not well developed and/or are not preserved.

The valley-fill deposits are entirely fluvial in origin and can be grouped into four facies associations: FA 1 – sandstones and conglomerates (fluvial-channel deposits), FA 2 – medium-bedded sandstones in mudstone (crevasse splays), FA 3 – heterolithic deposits (levee, distal crevasse splay, and abandoned-channel deposits), and FA 4 – mudstone-dominated deposits (distal overbank paleosols). They are organized into two, large-scale, upward-fining successions that average about 25–30 m thick (maximum 60 m). Both lie on a regionally mappable erosion surface and are interpreted as sequences, the upper of which (H2) is only present north of Township 6. Each begins with a sheet-like sandbody that extends across the entire width of the valley. It was deposited by either braided or coarse-grained meandering rivers and consists of amalgamated channel deposits (FA 1); contemporaneous overbank muds existed, but have been cannibalized by channel erosion. This sandbody is overlain by a mudstone-dominated deposit consisting of terrestrial overbank sediments (FAs 2–4) that contain isolated, ribbon-shaped channel sandstones (FA 1). These successions are interpreted to reflect a progressive increase in accommodation space that lead to successively less amalgamation of the channel deposits.

It is not possible to determine definitively the cause of the regional changes in accommodation. However, eustatic sea-level changes may have had little influence because the study area lies far inland of the contemporaneous shoreline. Changes in the gradient of the fluvial equilibrium profile (as a result of climatic or source-area control on water discharge and/or sediment supply) also appear to have been minor, because the indicators of climate (paleosol type) and source area (sandstone petrology) do not vary markedly throughout the Horsefly. We suggest that the main control on accommodation was tectonic movement, associated with the ongoing development of the Cordilleran fold and thrust belt.

The older, H1 sequence, which comprises the entire thickness of the Horsefly unit throughout most of its extent, is cut by many syndepositional block faults with offsets of 5–30 m. The most prominent fault zones cross the valley in Townships 1 and 7, southern Alberta. Both of them show preferential uplift of their northern side, with accompanying narrowing of the valley. Large and small areas of net subsidence contain thicker deposits and preferentially trapped the extrabasinal gravel fraction, thereby accentuating the northward fining trend. They also tended to have wetter conditions, leading to the development of gleysols and even organic-rich mudstones (as opposed to vertisols in areas with less subsidence that were drier). Because channels tended to flow in the areas with greater subsidence, these locations can contain a greater number of channel sandstones, while adjacent areas have few or none. Regionally, the northern part of the valley appears to have experienced relative uplift, causing the valley to become narrower in a downstream direction.

These observations indicate that contemporaneous faulting can have a significant influence on the characteristics of a valley-fill succession, including the production of facies juxtapositions with hydrocarbon-trapping potential. Such influence is likely to be pronounced when the rate of sedimentation is low (i.e. in accommodation-limited settings), because tectonically generated relief is not as quickly masked by sediment deposition. This would not be the case in areas with high rates of creation of accommodation and sediment deposition; under such conditions, the influence of contemporaneous faulting might not be as obvious. On the other hand, basin flexure would be more intense during times of greater subsidence (and accommodation production); therefore, basement faults might be more active. Additional studies are needed to determine at what time(s) in the history of the Western Canada Sedimentary Basin syndepositional faulting is most important.

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