

Depositional styles in a low accommodation foreland basin setting: an example from the Basal Quartz (Lower Cretaceous), southern Alberta

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ABSTRACT

The Lower Cretaceous Basal Quartz (BQ) of Southern Alberta (Townships 1–40, Ranges 1W5–5W5) can be informally divided into seven mappable units (A Sandstone, composed of the Regional A, Carmangay, Mesa IV, Valley and Terrace; Horsefly, BAT, Ellerslie). The study area is considered to be in an accommodation-limited setting due to the presence of multiple, closely spaced unconformities, and the general absence of marine deposits. Multiple levels of cyclicity exist in the BQ. There are two cycles of increasing-upward mineralogical and textural maturity, the first associated with the A Sandstone and the second associated with the Horsefly–BAT–Ellerslie succession. There are multiple southward marine transgressive events, both on the unit scale and on the cycle scale, indicative of a backstepping stacking geometry.

The high resolution subdivision of the BQ allows for the recognition of changing BQ paleodrainage through time. There is both a progressive spatial and stratigraphic change in incised valley organization, from thin and wide valley forms in the south and at the base of the cycles, to thicker, narrower and more deeply cut systems toward the northwest and top of the cycles. In addition, there is spatial variation in tributary systems for the upper cycle, from no tributaries associated with the thin, wide valley forms associated with the Horsefly, to narrow and thin tributaries in the BAT south of the Vulcan Low, deeply cut complex tributary systems across the Vulcan Low, and linear deep tributaries north of the Vulcan Low for both the BAT and Ellerslie. The style of depositional fill also changes stratigraphically and spatially, from braided to coarse meandering “sheet” deposits south of the Vulcan Low associated with the Carmangay and Horsefly, and low accommodation Valley and Terrace and BAT north of the Vulcan Low; meandering deposits associated with the low accommodation Mesa IV, and higher accommodation Valley and Terrace, Horsefly and BAT; and fluvial-estuarine deposits associated with the Valley and Terrace, BAT and Ellerslie north of the Vulcan Low in higher accommodation setting.

The dominant control on the BQ depositional patterns is the interplay between eustasy and heterogeneous basement subsidence. The tectonic influences on sedimentation are most obvious in the sediments immediately overlying long-duration unconformities. Fluvial erosion on the unconformity surface amplifies the tectonic signal by accentuating the tectonically produced relief in a low accommodation setting. The accommodation-limited conditions occurring during BQ deposition resulted in sequence boundaries amalgamating on the interfluvial, and it is only by detailed correlation and petrographic analysis that BQ units can be differentiated.

RÉSUMÉ

Le Quartz de Base (QB) du Crétacé inférieur du sud de l'Alberta (cantons 1 à 40, rangées 1W5 à 5W5) peut être divisé informellement en sept unités cartographiables (Régional A, Carmangay, Mesa IV, Valley et Terrace, Horsefly, BAT, Ellerslie). La région d'étude est considérée comme étant dans un environnement à accommodement limité dû à la présence de multiples discordances étroitement rapprochées, et par l'absence générale de dépôts marins. De multiples niveaux de cyclicité existent dans le QB. Il y a deux cycles d'augmentation de la maturité minéralogique et texturale vers le haut, le premier est associé au Grès A et le second est associé à la succession Horsefly–BAT–Ellerslie. Il y a de multiples événements transgressifs marins vers le sud à l'échelle des unités et à l'échelle des cycles, indiquant une géométrie en empilement par recul.

La subdivision à haute résolution du QB permet de reconnaître des changements dans le paléo-drainage du QB à travers le temps. Il y a à la fois une progression spatiale et des changements stratigraphiques dans l'organisation des vallées incisées, de formes de vallées minces et larges dans le sud et à la base des cycles, à des systèmes plus épais, plus étroits et incisés plus profondément vers le nord-ouest et au sommet des cycles. De plus, il y a une variation spatiale dans les systèmes tributaires dans le cycle le plus haut, à partir de formes de vallées minces et larges sans association de tributaires dans le Horsefly, jusqu'à des tributaires étroits et minces dans le BAT au sud du Bas de Vulcan, des systèmes complexes de tributaires de l'autre côté du Bas de Vulcan, et des tributaires linéaires et profonds au nord du Bas de Vulcan à la fois pour le BAT et l'Ellerslie. Le style de remplissage de sédiment change aussi stratigraphiquement et spatialement, passant de dépôts en 'nappes' anastomosées et à méandres grossiers au sud du Bas de Vulcan, associé au Carmangay et au Horsefly, et l'accommodement faible du Valley et Terrace et du BAT au nord du Bas de Vulcan; des dépôts de méandres associés à un faible accommodement du Mesa IV, et un accommodement plus élevé pour le Valley et Terrace, le Horsefly et le BAT, et des dépôts fluviaux-estuariens associé au Valley et Terrace, au BAT et à l'Ellerslie au nord du Bas de Vulcan dans des environnements d'accommodement plus élevé.

Le contrôle dominant sur les patrons de sédimentation du QB est un jeu entre l'eustasie et la subsidence hétérogène du socle. Les influences tectoniques sur la sédimentation sont les plus évidentes dans les sédiments qui sont immédiatement au-dessus des discordances de longues durées. L'érosion fluviale sur la surface de la discordance amplifie le signal tectonique en accentuant le relief produit tectoniquement dans un environnement de faible accommodement. Les conditions d'accommodement limité qui se sont présentées durant la sédimentation du QB ont donné lieu à des limites de séquences qui se sont amalgamées sur l'interfluve, et ce n'est donc que par des corrélations de détail et de l'analyse pétrographique que les unités du QB peuvent être différenciées.

Traduit par Lynn Gagnon

INTRODUCTION

The Lower Cretaceous Mannville Group (Fig. 1) is one of the most prolific hydrocarbon-bearing successions in the Western Canada Sedimentary Basin (WCSB; Fig. 2). The Mannville Group is divisible into 1) the Lower Mannville Formation, composed of the Basal Quartz (BQ) and overlying Ostracod Member; and 2) the Upper Mannville Formation, comprising the succession from the Glauconitic Formation to the base Colorado Group. The Lower Mannville Formation is estimated to contain 32% of the conventional oil and 53% of the gas reserves for the Mannville Group (Porter, 1992). Approximately 390 oil pools (each >100,000 bbls) and 961 gas pools (each >2 BCF) have been developed in the Lower Mannville, totalling 1213 MMBLs of oil and 7.1 TCF of gas (ERCB, 1997). A variety of proprietary and government resource base assessments estimate an additional 200–500 MMBLs of oil and 4–5 TCF of gas remain in the Lower Mannville Formation. BQ reservoirs have been shown to exhibit considerable variation in reservoir quality, recovery factor, oil quality, and performance characteristics (e.g. Arnott et al., 2000, this issue). For these reasons, the BQ will undoubtedly continue to be a significant hydrocarbon target in the WCSB. However, in order to better exploit this resource, a more detailed understanding of the complex reservoir and trapping configurations associated with the BQ is required.

Significant debate has ensued over the use of the term Basal Quartz and its stratigraphic equivalents in southern Alberta (e.g. Cutbank, Taber, Sunburst, Success, McCloud; Fig. 1). The BQ is considered a purely descriptive lithological term used for the dominantly quartzose sandstones of the basal Lower Mannville Formation (CSPG Lexicon of Canadian Stratigraphy, 1990, p. 37). The BQ can be considered "*homotaxial*", i.e. com-

posed of rock stratigraphic units found to be in similar position, that are not contiguous, and due to their distribution in discrete (sub-) basins, exhibit their own unique sedimentation patterns and depositional history. For these reasons it has been suggested that the term Basal Quartz be discarded, and that a new stratigraphic framework be developed (CSPG Lexicon of Canadian Stratigraphy, 1990, p. 37).

This paper presents an informal working stratigraphy for the Basal Quartz (Fig. 1). The BQ in southern Alberta is thin (<100 m) and, as will be shown in this paper, is characterized by a complex stratigraphy punctuated by multiple unconformities resulting in a complex stratigraphy. The present stratigraphic nomenclature is not robust enough to define this stratigraphic complexity. The main purpose of this paper, however, is to investigate the influence of accommodation-limited conditions on the stratigraphic development of nonmarine to marginal marine deposits. The specific aims of this paper are 1) to investigate the role of low accommodation in the development and distribution of stratigraphic units deposited across different basement terranes of contrasting rheology; and 2) to postulate the types of controls that influence sedimentation in accommodation-limited foreland basins. This study forms part of a larger scale ongoing investigation on the sequence stratigraphy of nonmarine to marginal marine deposits developed under varying accommodation settings (e.g. Boyd and Diessel, 1994; Zaitlin et al., 1999; Diessel et al., 2000; Boyd et al., 2000a, 2000b).

STUDY AREA, DATA SET AND METHODOLOGY

The study area is located between Townships 1–40, Ranges 1W4–5W5, an area of 51840 sq. miles (83426 km²), or 1440 townships in southern Alberta (Fig. 2). The study correlated

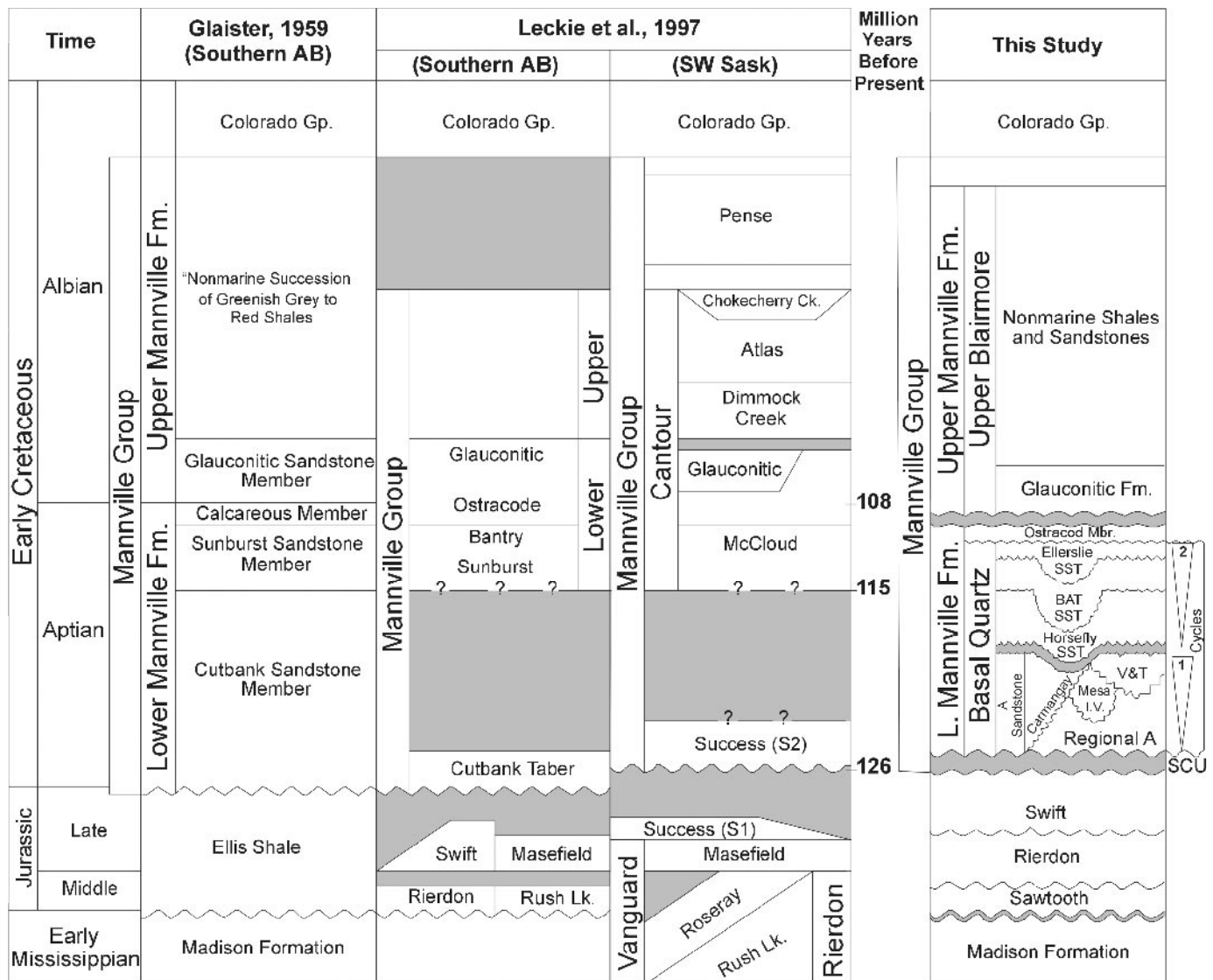


Fig. 1. Early Cretaceous stratigraphic nomenclature in Southern and Central Alberta (AB) and Southwest Saskatchewan (Sask.). A Sandstone (including Regional A, Carmangay, Mesa Incised Valley (I.V.), Valley and Terrace (V&T), Horsely Sandstone (SST), BAT SST (Bantry–Alderson–Taber) and Ellerslie SST are informal stratigraphic units described in this study. Cycles 1 and 2 refer to mineralogical and textural cycles described in text. Geological ages from Gradstein et al. (1994). Gp. = Group; Fm. = Formation; Mbr. = Member; SCU = sub-Cretaceous unconformity.

>9000 wells organized into 88 regional cross-section segments. Regional sections were spaced approximately every two townships north–south, and every five ranges east–west, using the top Mannville Group as the preferred datum. One well per section was chosen along each cross-section where available, prioritized according to core availability/quality, past or present production, drill stem test (DST) information, and/or modern petrophysical log suite. Forty-three additional pool-typing cross-sections were correlated to define play types and characterize reservoir and trapping configuration. An additional 11 detailed pool and 4 semi-regional studies were completed to better define the various play types and within the BQ. The study incorporated >1350 described cores and >750 petrographic thin sections (approximately 260 of which were point counted) in order to calibrate well logs. Deep basement proprietary seismic data and publicly accessible

Lithoprobe data (Ross et al., 1994, 1995, 1997) were incorporated to develop an integrated sedimentological, stratigraphic and tectonic model for the BQ. Two M.Sc. theses (Lukie, 1999; Ardies, 1999) and a series of pool-specific and semi-regional sedimentological and petrographic studies augmented the data set (e.g. Potocki et al., 1998; Arnott et al., 2000, this issue).

REGIONAL SETTING, GEOLOGICAL AGE AND ACCOMMODATION

SETTING

The WCSB comprises a westerly-thickening wedge of mixed clastic and carbonate sediments, onlapping Archean to Helikian-aged cratonic basement of the Canadian Shield (Leckie and Smith, 1992). Monger (1989) recognized two

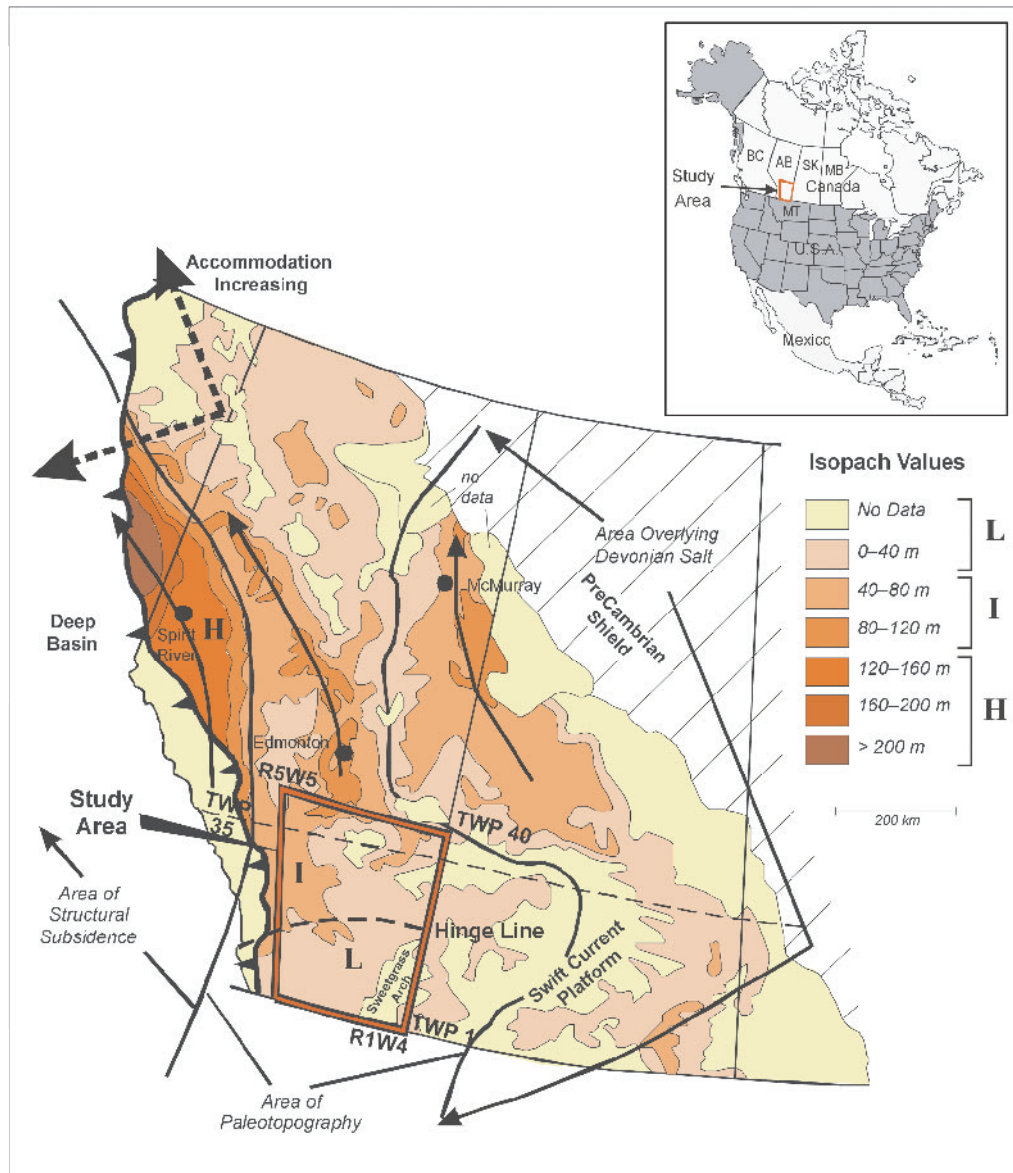


Fig. 2. Isopach map of the Lower Mannville Formation in the WCSB, approximately equivalent to Basal Quartz and Ostracod Member of this study (modified after Cant and Abrahamson, 1996). L = low accommodation area; I = intermediate accommodation area; H = high accommodation area (defined in text). Arrows indicate paleodrainages of the McMurray, Edmonton and Spirit River systems. Heavy dashed arrows indicate NW and W direction of increasing accommodation. Inset map indicates study area in relation to North America (BC = British Columbia; AB = Alberta; SK = Saskatchewan; MB = Manitoba; MT = Montana).

major evolutionary stages within the WCSB. The first stage records Proterozoic through early Jurassic carbonate and minor clastic sedimentation on the western margin of ancestral North America. The second stage records Middle Jurassic through Tertiary sedimentation in an active foreland basin, dominated primarily by westerly-derived clastic sediments, with coals. The transition from a westerly-facing continental margin to the development of a foreland basin was in response to a series of subduction/collision events initiated in Middle Jurassic time (Monger and Price, 1979). The convergent plate boundary and associated subduction/collision events resulted in at least two major episodes of significant thrusting and crustal thickening in

the sedimentary succession, tectonic loading and subsidence of the underlying lithosphere. The result was the development during Early Cretaceous time of an underfilled elongated NNW–SSE trending foreland trough asymmetrical to the west, contemporaneous with episodic incursions of the southern Gulfian and northern Boreal seaways.

Eisbacher et al. (1974) defined two unconformity-bounded tectono-stratigraphic wedges within the foreland basin stage of Monger (1989). These wedges are interpreted to record major exotic terrane accretion events in Middle Jurassic and Cretaceous time (Monger and Price, 1979). Cant and Stockmal (1989) and Stockmal et al. (1992) further subdi-

vided this foreland basin stage into six first-order sedimentary wedges. The uppermost Jurassic to Lower Cretaceous Mannville Group forms the basal part of the second tectono-stratigraphic wedge.

The Mannville was first defined as a Formation by Nauss (1945), and subsequently raised to Group status by Badgley (1952) and Glaister (1959; Fig. 1). Mannville Group sediments were deposited upon an irregular Paleozoic to Early Mesozoic surface with several hundred metres of depositional and erosional relief. The Lower Mannville Formation is developed upon the sub-Cretaceous unconformity (SCU) and below the post-Ostracod unconformity (Fig. 1).

GEOLOGICAL AGE

Significant problems occur when attempting to assign biostratigraphic ages to the Lower Mannville succession in the study area. There is an absence of usable paleontological material due to the predominance of terrestrial deposits, exposure surfaces, and multiple paleosol events. The SCU has variously been dated to have occurred between 1) Berriasian (about 135 Ma) and Tithonian (about 140 Ma) in the southern WCSB foothills (Leckie and Krystinik, 1995; Leckie and Cheel, 1997; Leckie et al., 1996; White and Leckie, 1999), or 2) Kimmeridgian (about 143 Ma) and Hauterivian (about 126 Ma) in south-central Saskatchewan (i.e. the S1 to S2 gap of Leckie et al., 1997; Fig. 1). The amount of time absent across the basal unconformity therefore ranges between 17 Ma and 5 Ma. The age of the Ostracod Member is generally taken to be Aptian (about 108 Ma; Fig. 2). The time available for deposition of the BQ, therefore, ranged between 35 and 17 Ma west to east across the study area.

ACCOMMODATION

Sedimentation is governed by the rate of sediment flux supplied to a depositional system and the rate at which space is made available for potential sediment accumulation (termed accommodation, e.g. Jervy, 1988). Accommodation in Lower Mannville time progressively increased toward the west due to foreland basin subsidence and toward the north due to subsidence toward the Boreal Sea (Fig. 2). A Lower Mannville Formation total isopach map exhibits the major depositional trends across the WCSB (Fig. 2). There is a pronounced isopach thickening toward the northwest in excess of 200 m. Three major north-south paleodrainage systems (Spirit River, Edmonton Channel and McMurray) exist north of Township 35, and are defined on the basis of a >75 m total isopach. South of Township 35, the recognition of individual paleodrainage systems is more difficult using isopach patterns alone.

Based upon regional studies and their Lower Mannville isopach map, Cant and Abrahmsen (1996) proposed a three-fold physiogeographic zonation reflecting the major controlling factors on Lower Mannville Formation deposition (Fig. 2). These zones are oriented north-south, parallel to the long axis of the foreland basin. The eastern zone is underlain by a series of Devonian salt collapse features thought to locally control accommodation and resultant depositional patterns. The middle

zone, is dominated by original erosional paleotopography that was interpreted to control resultant depositional patterns. However, in this zone, Cant and Abrahmsen (1996) did not recognize the importance of changing basement terranes and the resulting control on accommodation that will be developed throughout this paper. Depositional patterns in the western zone are dominated by tectonic subsidence and rapidly increased accommodation in the foredeep adjacent to the fold-thrust belt.

Total isopach thickness for the Lower Mannville Formation ranges between 0 and 100 m (approximately) in the study area (Fig. 2). Using the present day preserved thickness (neglecting erosion and compaction) and the approximate duration of deposition, the net sedimentation rate for the Lower Mannville can be estimated as 6.6 m/Ma. In comparison, the much thicker deposits of the Upper Mannville Formation (about 50–200 m), developed above the Ostracod Member (about 108 Ma) and below the Colorado Group (Middle Albian about 98 Ma), represents approximately ten million years of geological time, with an estimated resultant (net) sedimentation rate of 20 m/Ma. Thus, the study area during the Lower Mannville Formation can be considered as *accommodation-limited* — a situation in which long term subsidence rates are low compared to sediment supply. This will be shown to occur due to the prevalence of low sedimentation rate, closely spaced unconformities, paleosols, and the general absence of marine deposits.

Within the study area, accommodation ranges between the following two end members:

- 1) an area of *extremely low accommodation* along the Saskatchewan-Alberta border and SE corner of Alberta, where isopach values range between 0 and 40 m and net sedimentation rates are less than 2.2 m/Ma. This area was dominated by long periods of erosion and exposure, the development of paleosols, and multicycle incision of valley systems. As will be shown, the area is characterized by thin sheet-like braided to coarse-grained meandering-fluvial deposits that dominate, resulting in a complex stratigraphy; and
- 2) an area of *low-intermediate accommodation* where isopach values range between 40 and 120 m, and net sedimentation rates ranged between 1.3 and 6.6 m/Ma. This area is characterized by mappable valley systems with sheet-like fluvial to coarse-grained meandering deposits, paleosols and thin coals at their base, changing upward into finer-grained meandering-fluvial to fluvial-estuarine systems.

The transition between extremely low and low-intermediate accommodation within the study area corresponds closely to a geophysically defined ENE-trending structural zone, termed the Vulcan Aeromagnetic Low (Fig. 2; Ross et al., 1997) forming a depositional "Hinge Line" as presented in the paleogeographic reconstructions throughout this paper. The tectonic significance and influence of this feature will be fully discussed in a later section.

North and west of the study area, isopach values for the Lower Mannville Formation exceed 200 m, with depositional rates of 5 to 11.1 m/Ma (Fig. 2). In these areas, the BQ is characterized by *intermediate-high accommodation*, and are characterized by “ribbon” meandering-fluvial to fluvial-estuarine sandstones, thick coals, and overbank deposits interbedded with coastal and marine deposits. Sequence-bounding surfaces are effectively separated and easier to map.

During BQ time, the study area was significantly landward of a marine basin to the northwest. Therefore, the majority of sediments in the Early Cretaceous in the southeast of the WCSB accumulated in nonmarine to estuarine depositional environments (Jackson, 1984; Leckie and Smith, 1992). The rate of thrusting and tectonic subsidence and uplift also varied with time, resulting in both changing accommodation and sediment supply. The interplay between tectonically and eustatically driven base level changes, access to multiple source areas and basin configuration, and an extensive time period for deposition resulted in an extremely complex stratigraphic framework for the BQ.

In a sequence stratigraphic context, accommodation-limited areas promote the preservation of lowstand systems tract deposits (Fig. 3). Lowstand deposits are preferentially deposited in stratigraphically low positions such as the base of

incised valleys. Transgressive systems tracts will also have potential for preservation, especially if deposited within back-filling valleys. Thin highstand systems tracts, however, will be more subject to removal by subsequent cycles of erosion. The basic sequence stratigraphic correlation surface in terrestrial settings will be the sequence boundary, often located at the base of incised valleys and correlated laterally onto interfluvial at the position of well developed soil profiles. In active tectonic areas, such as the WCSB in the Early Cretaceous, variations in basin geometry and source area promoted variations in sediment composition and paleocurrent direction between individual unconformity-bounded sequences, permitting their recognition and correlation. However, because of the accommodation-limited conditions during BQ deposition, sequence boundaries tended to amalgamate on the interfluvial, and it is only by detailed correlation and petrographic analysis that units can be differentiated.

STRATIGRAPHY AND DISTRIBUTION PATTERNS

The BQ is divisible into a series of depositional units based on detailed correlations, depositional style and petrographic composition (Figs. 1, 4, 5). The petrography is essential, as subtle but systematic variations in rock type exist which can

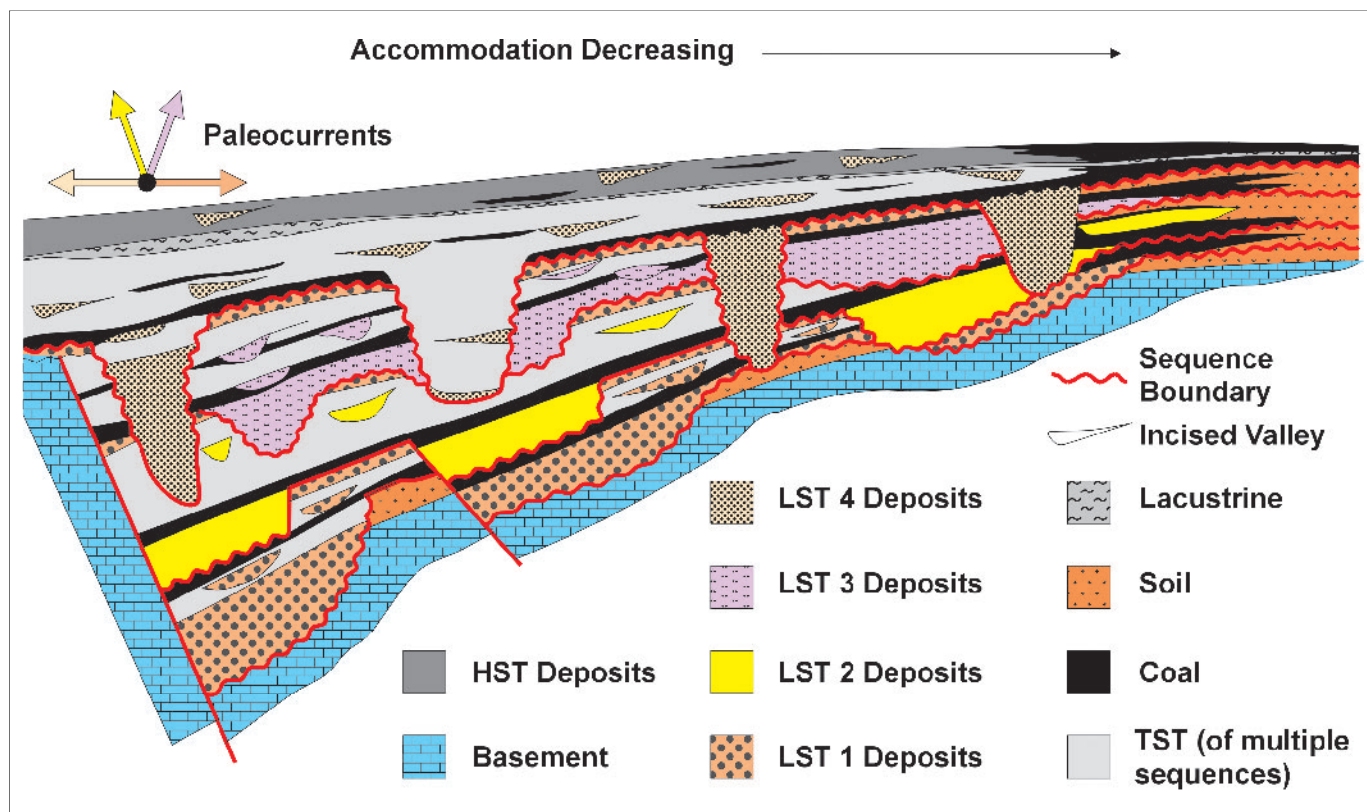


Fig. 3. Typical stratigraphy developed in a low accommodation terrestrial setting (modified after Boyd et al., 2000a). Accommodation decreases from left to right. The deposits of four lowstand systems tracts (LST) sequences are shown, dominated by closely spaced unconformities and incised valley fills in areas of low accommodation. The influence of structure and paleotopography determines the location and thickness of sedimentation. Soils are well developed in the lowest accommodation settings. Individual sequences can be differentiated on their texture and composition (different fill patterns – as is demonstrated in this paper) and their paleocurrents (overlying arrows show a wide range of vector resultants).

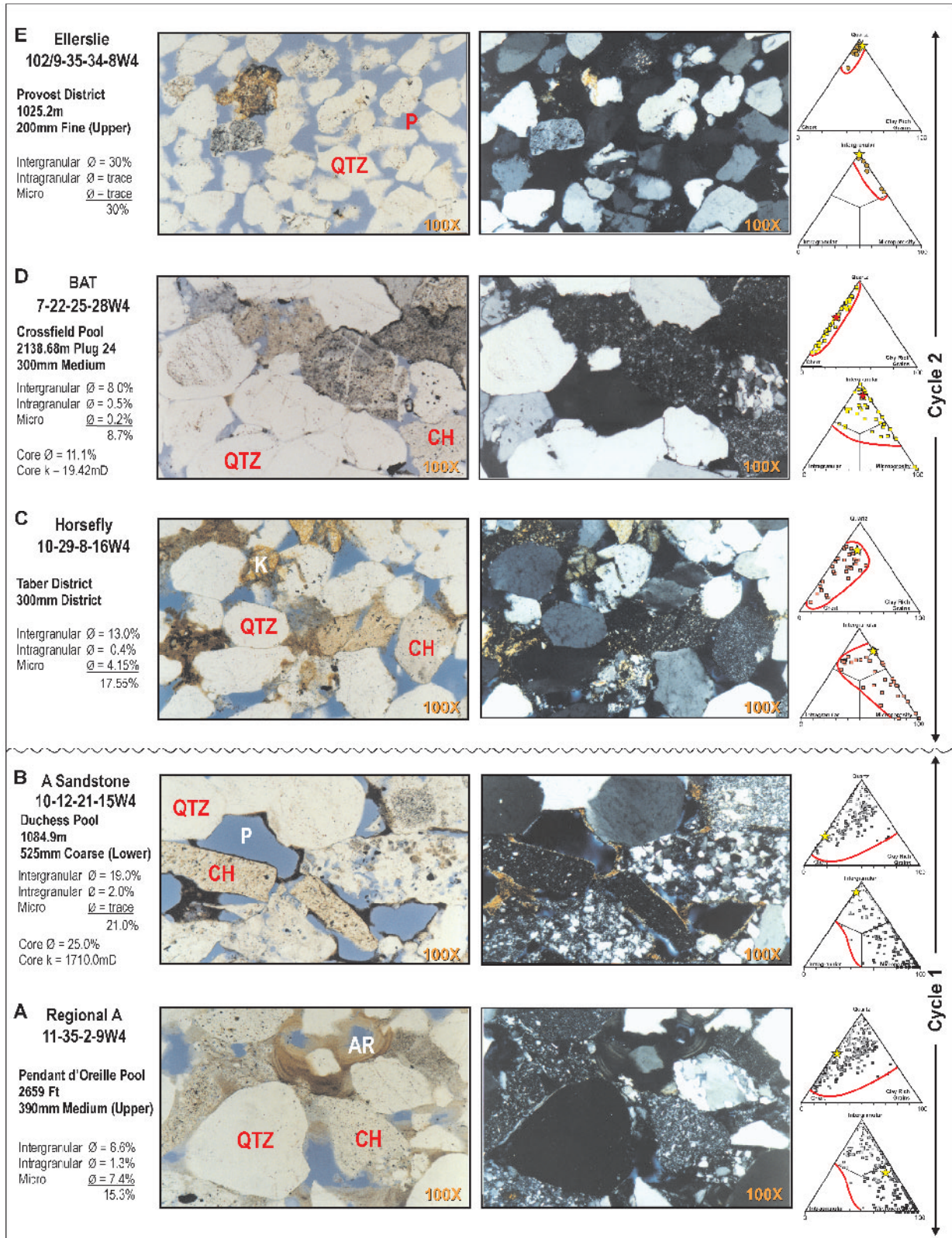


Fig. 4. Representative thin-sections of the major Basal Quartz units with associated point count data. Two sets of ternary diagrams are used to illustrate variations in textural and mineralogical maturity. The upper ternary diagram of each pair exhibits quartz, chert and clay-rich grains at the apices, and is effective in partitioning the petrographic data into distinctive populations of mineralogical maturity. The lower ternary diagram of each pair exhibits intergranular, intragranular and microporosity pore types at the apices and is used to illustrate porosity fabric and reservoir quality. The representative thin-sections are organized into two cycles (see Fig. 5). Star and triangles represents sample locations of point counted data in ternary diagrams. Left photomicrograph in each pair taken in plane light, right of each pair in cross-polars. Magnification 100x. QTZ = quartz; CH = chert; AR = argillans; P = porosity; K = potassium feldspar.

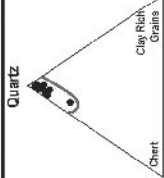
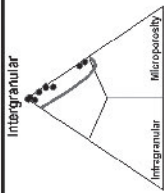

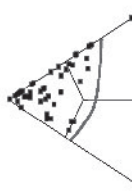
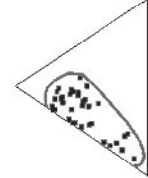
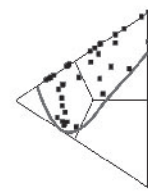



Stratigraphic Nomenclature	Rock Type		Overall Mineralogic & Textural Maturity	Diagnostic Framework Grains and Key Alteration Features																
	Framework Grains	Porosity Type		provenance								early diagenetic								
Ellerslie																				
BAT Bantry-Alderson- Taber																				
Horsefly																				
A Sandstone																				

Fig. 5. Summary lithostratigraphic comparison of the Basal Quartz as proposed in this study. A Sandstones are not subdivided. A ternary diagram with quartz, chert, and clay-rich grains at the apices is effective in partitioning the petrographic data into distinctive populations. A second set of ternary diagrams, with intergranular, intragranular, and microporosity pore types at the apices is used to illustrate porosity fabric and reservoir quality. Key diagnostic grains and alteration features are used to exhibit the two cycles of mineralogical, textural, and reservoir quality cyclicity.

be used to unravel the relative timing of the depositional units and cyclicity in the BQ (Figs. 4, 5). In order to accomplish this, a systematic petrographic sampling program was undertaken to understand the stratigraphic relationships and basic litho-reservoir quality trends for the BQ. Thin-sections were quantified through modal point count analysis (Fig. 4). In addition, textural characteristics (e.g. grain size, sorting, packing heterogeneity), weathering features (e.g. orange chert, tripolitic chert, sphaerosiderite, clay argillans), presence or absence of potassium feldspars, schistose rock fragments, glauconite, phosphate, carbonaceous material and light vs. dark chert, and other key diagnostic alteration features, were noted (Fig. 5).

Ternary diagrams with quartz, chert and clay-rich grains at the apices are an effective means of partitioning the petrographic data of the quartz-rich BQ sandstones into distinctive populations (Figs. 4, 5). A second set of ternary diagrams, with intergranular, intragranular, and microporosity pore types at the apices, were used to illustrate porosity fabric and reservoir quality (Figs. 4, 5). Generally, sandstones dominated by intergranular porosity have the best effective porosities and highest reservoir deliverability. Sandstones dominated by microporosity have the poorest effective porosity and permeability.

Three key observations stem from the petrographic analysis (Figs. 4, 5): 1) BQ rock types can be recognized by subtle but systematic differences in the proportions of major framework components; 2) two levels of cyclicity exist in the BQ that reflect increasing-upward mineralogical and textural maturity; and 3) two levels of cyclicity in reservoir quality are also developed that mimic the textural and mineralogical cycles. The following sections describe the stratigraphic relationships and distribution of the various BQ units organized on the basis of integrated lithologic-stratigraphic analysis.

A-SANDSTONE

The A Sandstone ranges in thickness from 0 to 30 m (Fig. 6), and is the oldest stratigraphic unit of the BQ (Figs. 1, 7). The A Sandstone is divisible into four units, organized from oldest to youngest as:

- 1) the Regional A unit, present as remnants and beneath the other A units throughout the study area (not mapped in Fig. 6);
- 2) the Carmangay, present on the Del Bonita Highland in the SW portion of the study area;
- 3) the Mesa Incised Valley (Mesa IV), present associated with areas of Jurassic isopach thicks (e.g. Skiff-Conrad, Medicine Hat and Hackett highs); and
- 4) the Valley & Terrace (V&T), distributed dominantly north of the hinge line parallel to the "Zone of Flexure".

Regional A

The Regional A ranges in thickness from 0 to 20 m, and extends eastward across Alberta into Saskatchewan, where

it may be time-equivalent to the S2 in Saskatchewan (Christopher, 1980, 1985; Leckie et al., 1997; Fig. 1). The Regional A is dominantly present as the basal A Sandstone deposit.

Primary sedimentary features in the Regional A are at times difficult to identify due to the variable degree of pedogenic alteration, but, where discernible, commonly consist of blocky to poorly developed fining-upward cycles of erosionally based crossbedded to rippled sandstones and siltstones, commonly capped by massive to waxy paleosols. The well developed paleosols are found associated with the top of the Regional A. The paleosols consist of tan, buff to light-grey pedogenic mudstones and shales exhibiting an oxidized and bleached weathered appearance. Paleosols may exhibit fracturing, slickenside development, and are rubbly in appearance. Spherulitic siderite and pyrite commonly replace carbonaceous roots (Fig. 4A). The Regional A is interpreted as an erosional remnant of a regionally extensive sheet deposit across the study area.

The Regional A sandstones are composed of highly weathered, very fine- to coarse-grained, poorly to moderately sorted, highly rounded to angular, matrix-rich sandstone with a chalky to kaolinitic appearance. Framework grains are composed of quartz, chert, and abundant clay-rich rock fragments (Fig. 4A). The porosity fabric is dominated by clay-associated microporosity. Reservoir quality is poor and these deposits are invariably non-reservoir. Notable secondary porosity exists in rare places where leaching has occurred, but these zones are commonly of limited extent and volume.

The common occurrence of orange-rusted chert grains, tripolitic chert grains, sphaerosiderite cement, microfractures, infiltrated clays, and root structures suggest extensive weathering (Fig. 4A). Due to advanced weathering, it is difficult to accurately discern the origin of the matrix in most sandstone samples. Petrographic examination indicates that much of the chalky matrix is either a pseudomatrix created by the squeezing of ductile clay-rich grains between more rigid grains, or is clay which infiltrated the sand at some point following deposition. In some of the finer-grained sandstones, the matrix appears to be true detrital clay. In many instances, however, the origin of clay-rich material in these rocks is uncertain owing to advanced weathering, compaction, and leaching. As such, modal point count determination of the clay-rich grain content is difficult, owing to uncertainty regarding its origin.

In the extreme northern limit of the study area (Hackett High; Fig. 6), the Regional A is characterized by at least two (?) coarsening-upward sequences. Each sequence is composed of sparsely bioturbated marine mudstones and interbedded mudstones and wavy-bedded sandstones grading upward into (?) hummocky-bedded sandstones. This succession is tentatively interpreted as marine shoreface deposits. The presence of nonmarine deposits to the south and possible marine shoreface deposits to the north are the evidence used to indicate that Regional A paleodrainage flowed from south to north, despite the fact that no distinct valley or channel systems are recognizable at the scale of this study.

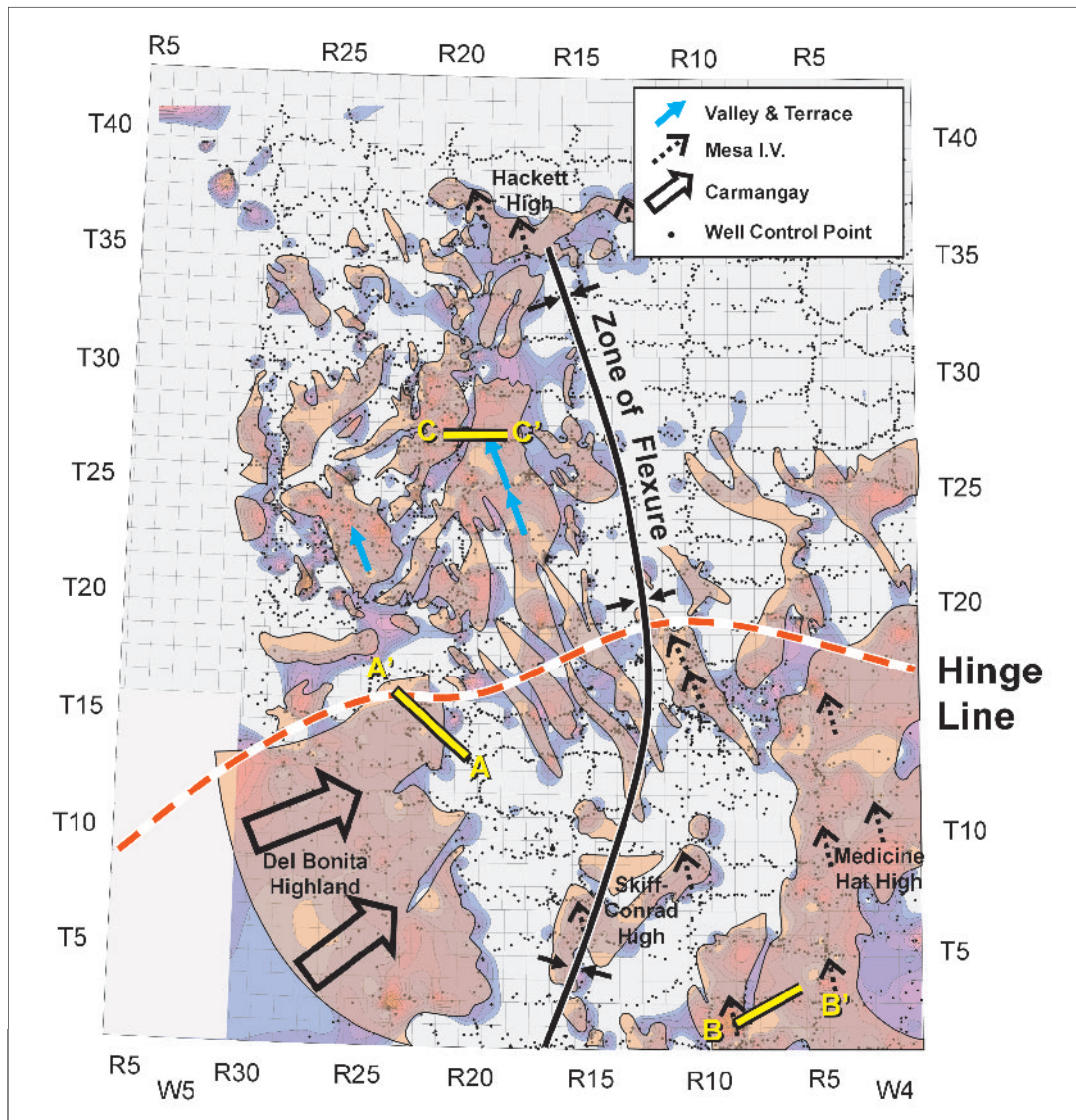


Fig. 6. Composite isopach and paleogeographic map of the A Sandstone and the distribution of the Carmangay, Mesa Incised Valley (IV) and Valley & Terrace. Contour interval = 5 m, values range from 0 m to 30 m. Arrows represent inferred paleodrainage direction for each of the A Sandstone units. Where no contours are present, no A deposits are present, either due to nondeposition or subsequent erosion. Location of cross-sections A–A' (Fig. 9), B–B' (Fig. 12) and C–C' (Fig. 14) are shown.

Paleosols

Paleosols are associated with pedogenic alteration and form due to the downward percolation of fine-grained material associated with infiltration of rain water. These clays block pore throats (Fig. 4A) and are important barriers to flow. Porosity and permeability values from core for the Regional A are in the order of 5–10% porosity and less than 0.01 mD. The Regional A exhibits no effective reservoir quality and no known production.

The Carmangay, Mesa IV, and Valley and Terrace (all discussed below) do not exhibit the same degree of pedogenic alteration suggestive of shorter durations of weathering as in the Regional A (Figs. 4B, 5). These units are grouped, and are characterized as variably weathered, fine- to medium-grained,

moderately well sorted sandstones to conglomerates, commonly with a marginal chalky appearance. Framework grains are composed of quartz and chert with significant amounts of ductile clay-rich grains. The porosity fabric is dominated by microporosity associated with clay-rich grains and infiltrated clays. Commonly there is sufficient intergranular and intra-granular porosity that these less weathered sandstones are capable of economic oil and gas production (Potocki et al., 1998).

Textural analysis of these three units reveals that the framework composition is in part related to grain size. Quartz percentage increases in the finer-grained fraction, whereas chert increases in the coarser-grained fraction. The textural control on framework composition and fining-upward trends in these units result in a cleaning-upward gamma-ray log profile. This is the inverse of the dirtier-upward response com-

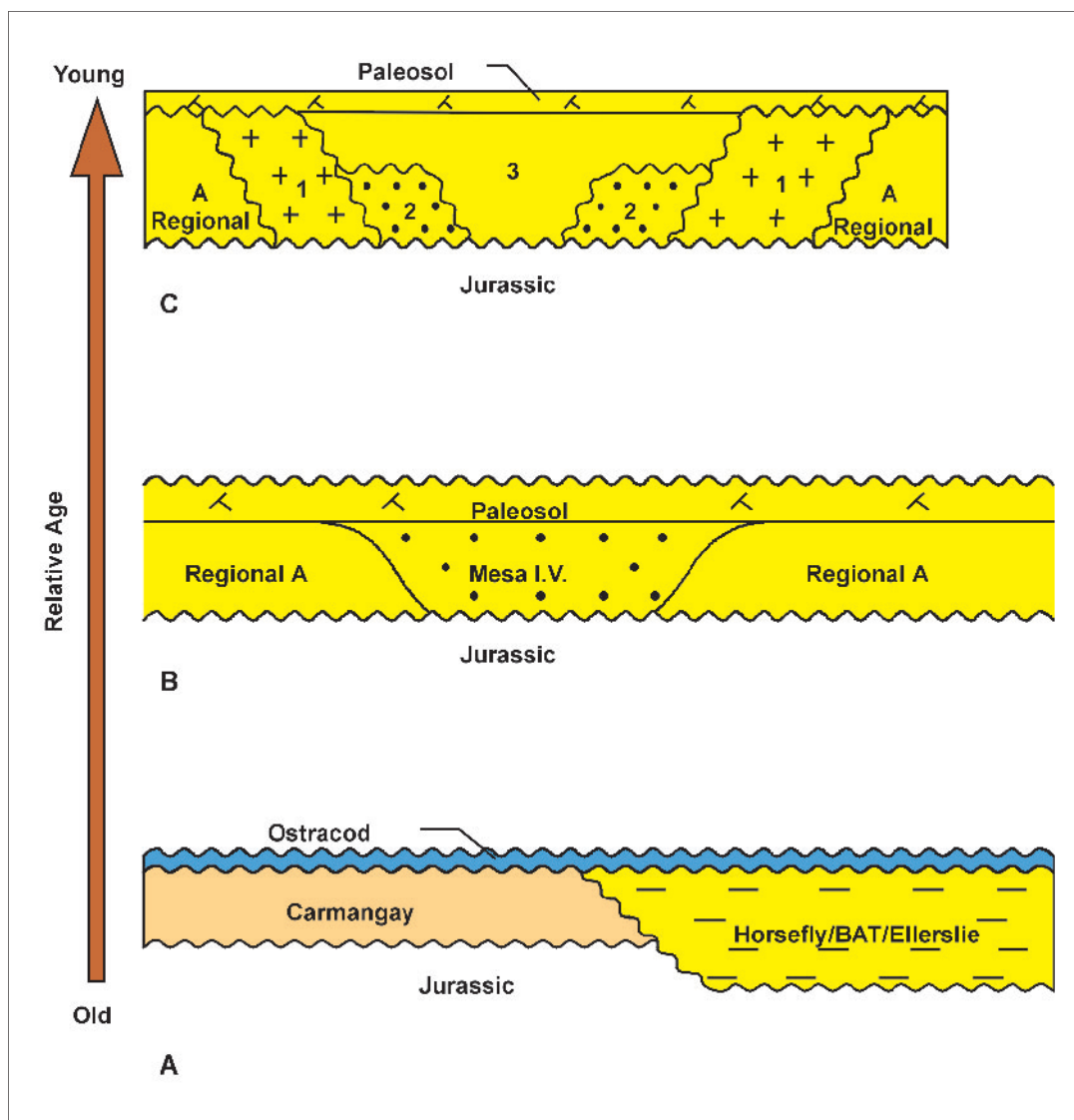


Fig. 7. A Sandstone geometries for the: **A)** Carmangay, a sheet-like sandbody overlain by the Ostracod and truncated to the east by Horsefly, BAT or Ellerslie; **B)** Mesa Incised Valley (IV) exhibiting thin sinuous channel deposits overlain by paleosols eroding into older Regional A deposits, and **C)** Valley and Terrace deposits exhibiting multiple stages of cut and fill (e.g. 1–3). The Regional A is a sheet-like body that has undergone a high degree of pedogenic alteration, thought to be older than the Carmangay, and is not presented in this figure.

monly accepted as representative of meandering channel deposits. The cleaning-upward gamma-ray log profile reflects the relative upward decrease in clay-bearing chert, and concomitant increase in quartz, within these channels (Potocki et al., 1998).

In some cases, framework grains in Valley and Terrace deposits are composed of quartz and chert and lack significant clay-rich (i.e. ductile) grains (0–4%, average 2%). Framework grains in Valley and Terrace sandstones are commonly better sorted and more rounded than Regional A sandstones. In contrast to the underlying Regional A, the porosity fabric of these Valley and Terrace units is dominated by intergranular porosity. Porosities and permeabilities are locally >30% and >1 Darcy. These reservoirs are capable of excellent oil and gas production (Potocki et al., 1998).

Carmangay

The Carmangay (Figs. 1, 7A) forms a thin sheet-like sandbody, up to 20 m thick, developed on a Jurassic isopach thick (i.e. Del Bonita Highland) in the southwest corner of the study area (Fig. 6). The Carmangay consists of multiple cycles of erosionally based, fining-upward cycles, 1–5 m thick, of medium- to coarse-grained, pebbly, crossbedded quartz and rusty-chert sandstones, fining-upward into fine- to medium-grained crossbedded to rippled, well sorted sandstones (Fig. 8). Where preserved, the tops of the cycles are occasionally capped by thin variegated to green waxy paleosols. The Carmangay is the coarsest-grained A Sandstone unit, and due to regional grain-size variations, appears to have been sourced from the southwest (Fig. 6).

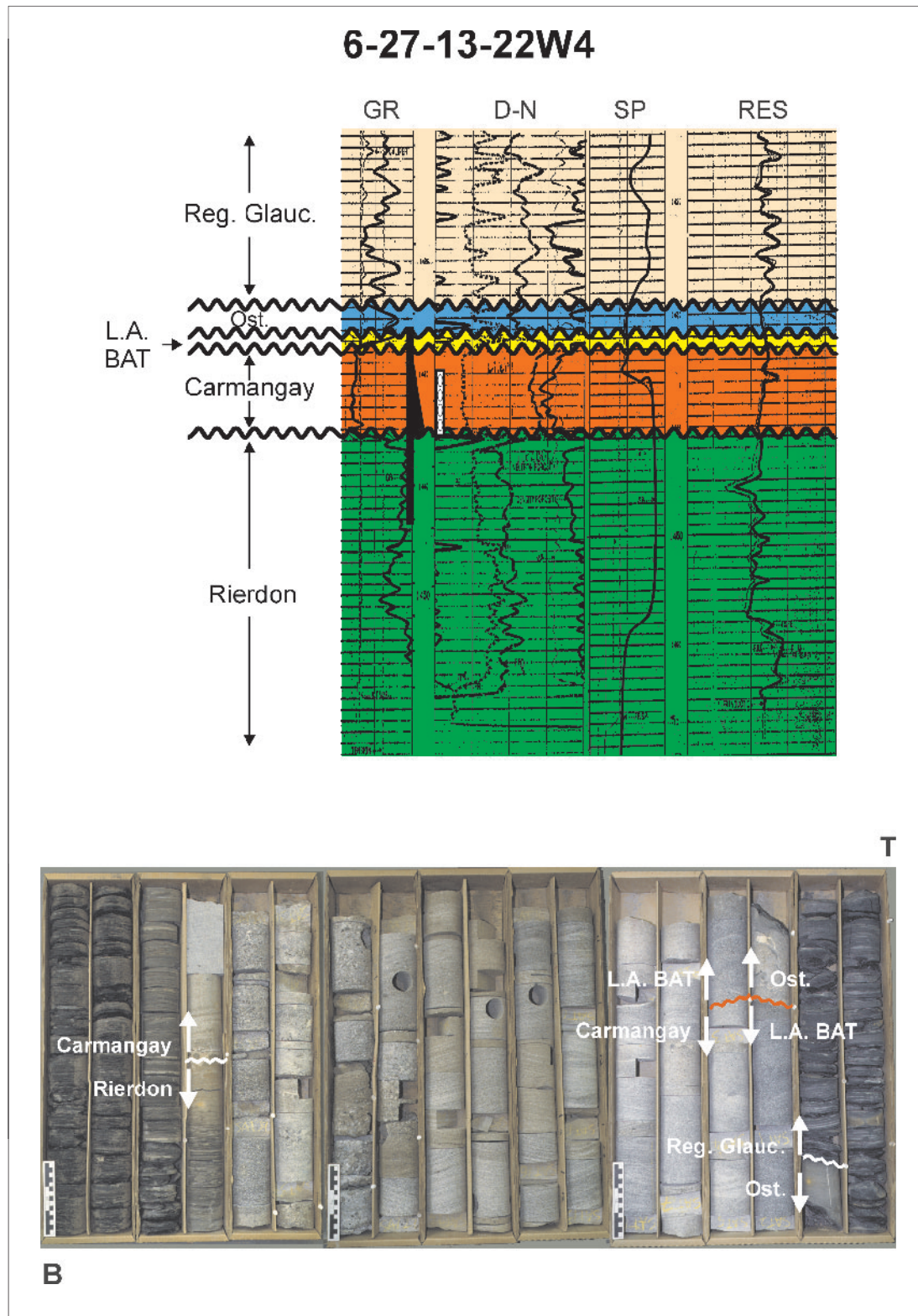


Fig. 8. Northstar (Sceptre) Carmangay 6-27-13-22W4 (1426–1444 m). Type core example for the Carmangay. Jurassic Rierdon Formation marine mudstones and interbedded siltstones unconformably overlain by conglomeratic to pebbly sandstones of the Carmangay. The Carmangay is interpreted as a multicyclic braided to coarse-grained meandering sheet sandstone unit. The Carmangay in turn is overlain by low accommodation (L.A.) BAT, Ostracod (Ost.) and Regional Glauconitic (Reg. Glauc.) deposits. B = bottom of core; T = top of core. Petrophysical logs include Gamma Ray (GR), Density-Neutron (D-N), Spontaneous Potential (SP) and Resistivity (RES) logs. Note the blocky 15–30 Gamma API and >15% porosity of the D-N logs. The black bar representing cored interval, the triangular bar represents the position of a drill stem test, and the open circles represent the perforated interval. Stratigraphic position of core is displayed in Figure 9.

The Carmangay unconformably overlies a thick Jurassic succession, subcrops to the east with the Ellerslie and the BAT, and is overlain by the Ostrocod (Fig. 9). Low accommodation, high sediment supply and a paucity of fines during A-Carmangay time resulted in braided-fluvial to coarse-grained meandering-fluvial deposits migrating across the depositional surface. The apparent lateral migration of the channels effectively removed most fine-grained overbank deposits and left multiple basal scour surfaces (Fig. 8).

Reservoir parameters range from 7–20% porosity and <0.01 mD to 4 Darcy permeability (e.g. Fig. 10A), together exhibiting excellent reservoir quality. Partial pedogenic clay plugging is locally present, degrading the porosity and permeability of these reservoirs. The key risk is the presence of trap. The Carmangay is characterized by oil and gas production at Long Coulee (16-21W4) and Carmangay (13-22W4). Steep compressional faults have cut through the Carmangay, and are an important component in the trapping of hydrocarbons in these pools.

Mesa Incised Valley

The Mesa IV is present predominantly in the southeast and south-central portions of the study area (Mannyberries–Medicine Hat and Skiff-Conrad–Bow Island highlands) and northern outliers (Hackett High; Fig. 6). The Mesa IV consist of multiple cycles of erosionally based fining-upward medium- to coarse-grained pebbly crossbedded quartz and “rusty” chert sandstones fining upward into fine- to medium-grained cross-bedded to rippled, well sorted sandstones (Fig. 11). These sandstones may be capped by thin, variegated to green waxy paleosols (Fig. 11). Partial pedogenic clay plugging is pervasive and typically degrades porosity and permeability of the Mesa IV reservoirs (Fig. 5).

The Mesa IV form narrow, sinuous, ribbon-like channel deposits, less than 15 m thick and 1.6 km wide (Figs. 7B, 12). Individual channels are difficult to map in the absence of core. The Mesa IV is interpreted as coarse-grained meandering-fluvial deposits. Detailed pool mapping indicates that the channel

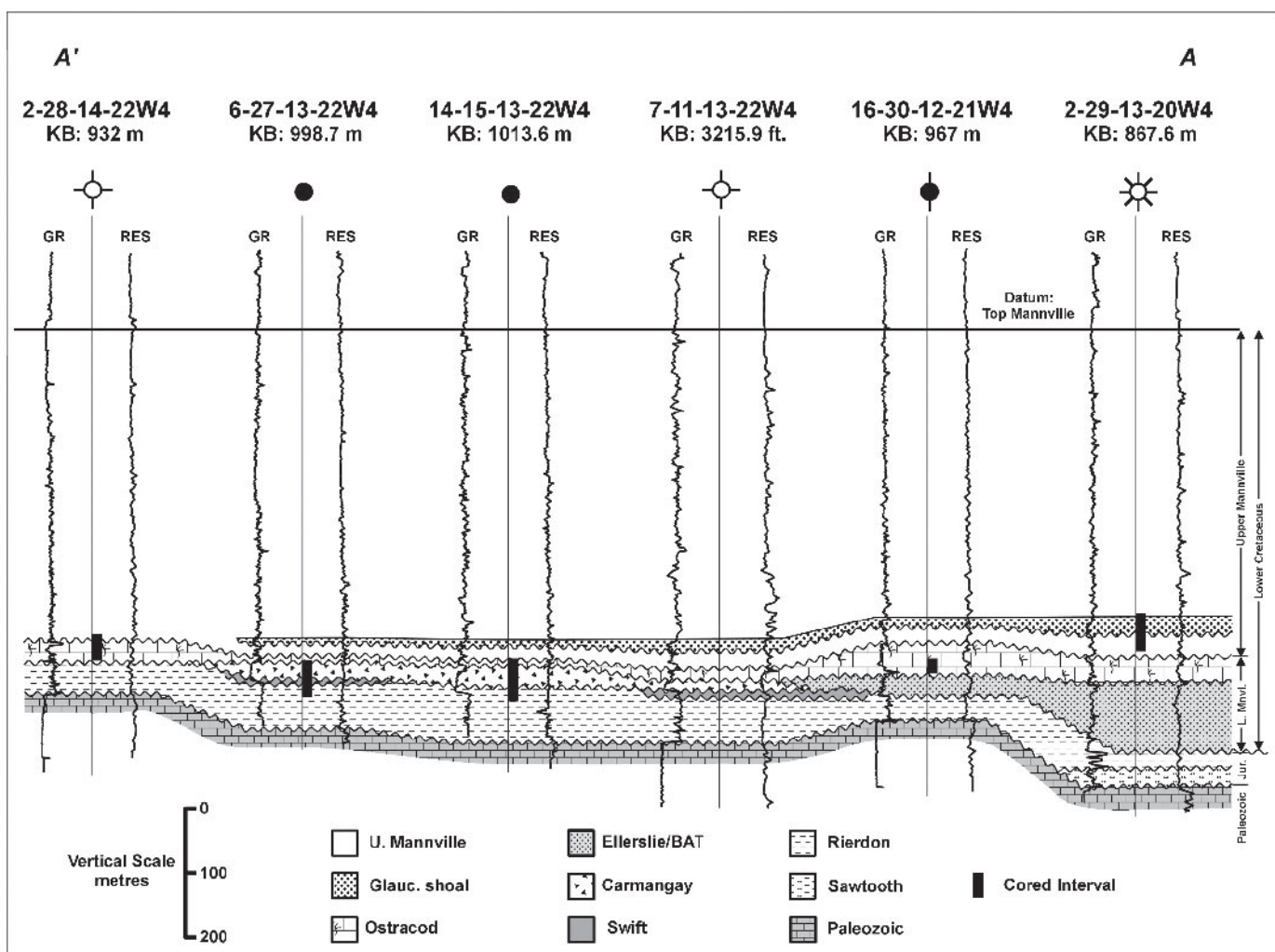


Fig. 9. Stratigraphic cross-section A–A' displaying subcropping geometry of Carmangay (triangles) with the Ellerslie and the BAT, overlain by the Ostrocod. The Carmangay unconformably overlies a thick Jurassic succession (Rierdon and Swift). Black bars represents core control. GR = gamma ray curve; RES = resistivity curve. Location of cross-section is shown in Figure 6.

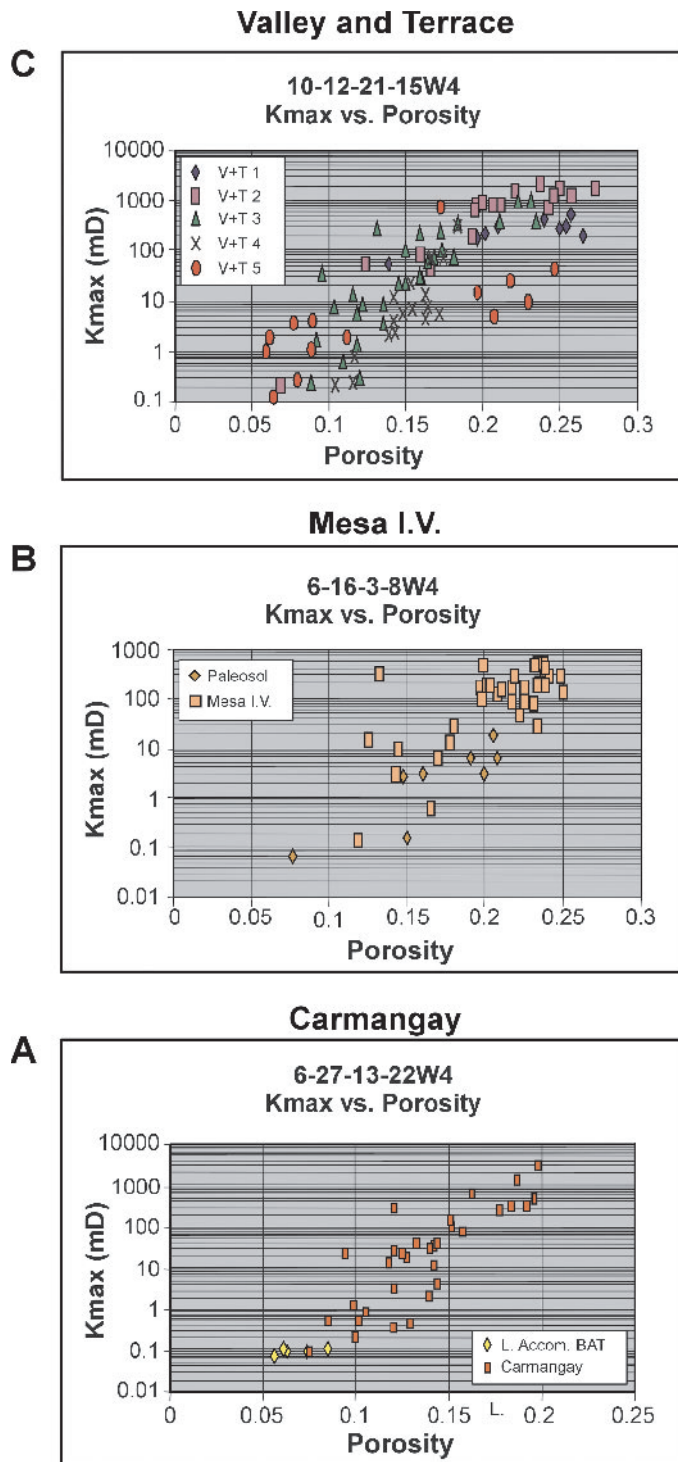


Fig. 10. Core Porosity (%) versus Permeability (Kmax; mD = millidarcies) to air for **A)** Carmangay at Northstar (Sceptre) Carmangay 6-27-13-22W4 (1426–1444 m) – Carmangay and Low Accommodation BAT (see Fig. 8); **B)** Mesa Incised Valley at Home CMG Pendor 6-16-3-8W4 (2784.1–2846.1 ft.) – Mesa IV overlain by paleosol (see Fig. 11); **C)** Valley and Terrace at PCP Countess 10-12-21-15W4 (1080–1112.4 m). Five Valley and Terrace cut-and-fill events (V+T 1–5) are recognized (see Fig. 13).

forms have paleodrainage south to north, consistent with the regional depositional gradient associated with the Regional A. The Mesa IV sandstones comprises fair to excellent gas reservoirs (e.g. Pendant D'Oreille, Black Butte, Bow Island, Pakowki and Hackett) and marginal oil production (e.g. Medicine Hat, Manyberries) with reservoir parameters from 12–25% porosity, and <0.1 mD to 0.8 Darcy permeability (Fig. 10B).

Valley and Terrace

The Valley and Terrace (Fig. 7C) is predominantly present north of the hinge line in the central and northern portions of the study area (Fig. 6). The Valley and Terrace can reach as thick as 40 m, and again is difficult to map if core and production data are not available. Individual terraces can be mapped on a pool or semi-local scale, but the complexity of the Valley and Terrace geometry precludes mapping beyond the trend level on the regional scale (e.g. Potocki et al., 1998). Syndepositional faulting is an important control on the distribution of the terracing (e.g. Hamilton et al., 2001).

The Valley and Terrace consists of braided and coarse-grained meandering-fluvial deposits, grading upward into fluvial and interbedded floodplain/paleosols, fluvial-estuarine channel, and central basin deposits (Figs. 13, 14). The Valley and Terrace sub-unit represents stepped, repeated periods of base-level fall and subsequent backfilling, resulting in a complex compound incised valley system (Fig. 7C) similar in style to the Quaternary Colorado River System (Blum, 1990, 1994; Blum and Valashko, 1994; Blum et al., 1994). Southward-directed transgression of the northern Boreal Seaway during Valley and Terrace time resulted in an overall backfilling of individual paleovalleys, and the backstepping of estuarine deposits over fluvial deposits.

Examples of oil and gas pools which produce from sandstones of the A-Valley and Terrace sub-unit pools include: Duchess Lower Mannville X Pool, Duchess "A" Pool, Gladys, Blackie and Dalemead, Kininvie, Alderson, Lower Mannville D4D pool, Rosemary, Lower Mannville Z pool, Scandia, and Wayne-Rosedale. Reservoir parameters range from 5–28% porosity and 0.06 mD to 1.2 Darcy permeability (Fig. 10C).

HORSEFLY

The Horsefly unit is confined to two major compound incised valley systems termed the Whitlash Valley and Taber-Cutbank Valley (Fig. 15). The Horsefly is present south of the hinge line and separated by an interfluvial area (termed the zone of flexure in Fig. 15). Isolated erosional remnants (e.g. Princess pool) occur north of the hinge line, along trend with the valley forms. Both the Taber-Cutbank Valley (Lukie, 1999; Lukie et al., 1999; Lukie et al., this issue; Arnott et al., 1999, 2000, this issue) and the Whitlash Valley (Hayes, 1986; Hayes et al., 1994) extend southward into northern Montana (e.g. Dolson and Piombino, 1994, where the Horsefly is termed the Cutbank Sandstone). The total Horsefly succession is up to 25 m thick, and the valley form is in the order of 50 km wide (Figs. 15, 16). The Horsefly unit is present at the base of the valley form (e.g. Fig. 16).

The Horsefly consists of repeated fining-upward successions of braided-fluvial to coarse-grained meander sandstones fining upward into a paleosol (Fig. 17). The basal strata consist of poorly sorted matrix-supported conglomerate with a medium- to coarse-grained sandstone matrix. Clasts are subrounded and several decimetres in diameter and are composed of sandstone

and silty mudstone. The basal unit is overlain by medium-scale cross-stratified upper medium- to coarse-grained sandstone, gradationally overlain by massive- to small-scale cross-stratified fine-grained sandstone, that, in turn, are overlain by siltstone and silty mudstone. Sideritized tabular mudstone clasts are common and concentrated along horizons subparallel to the

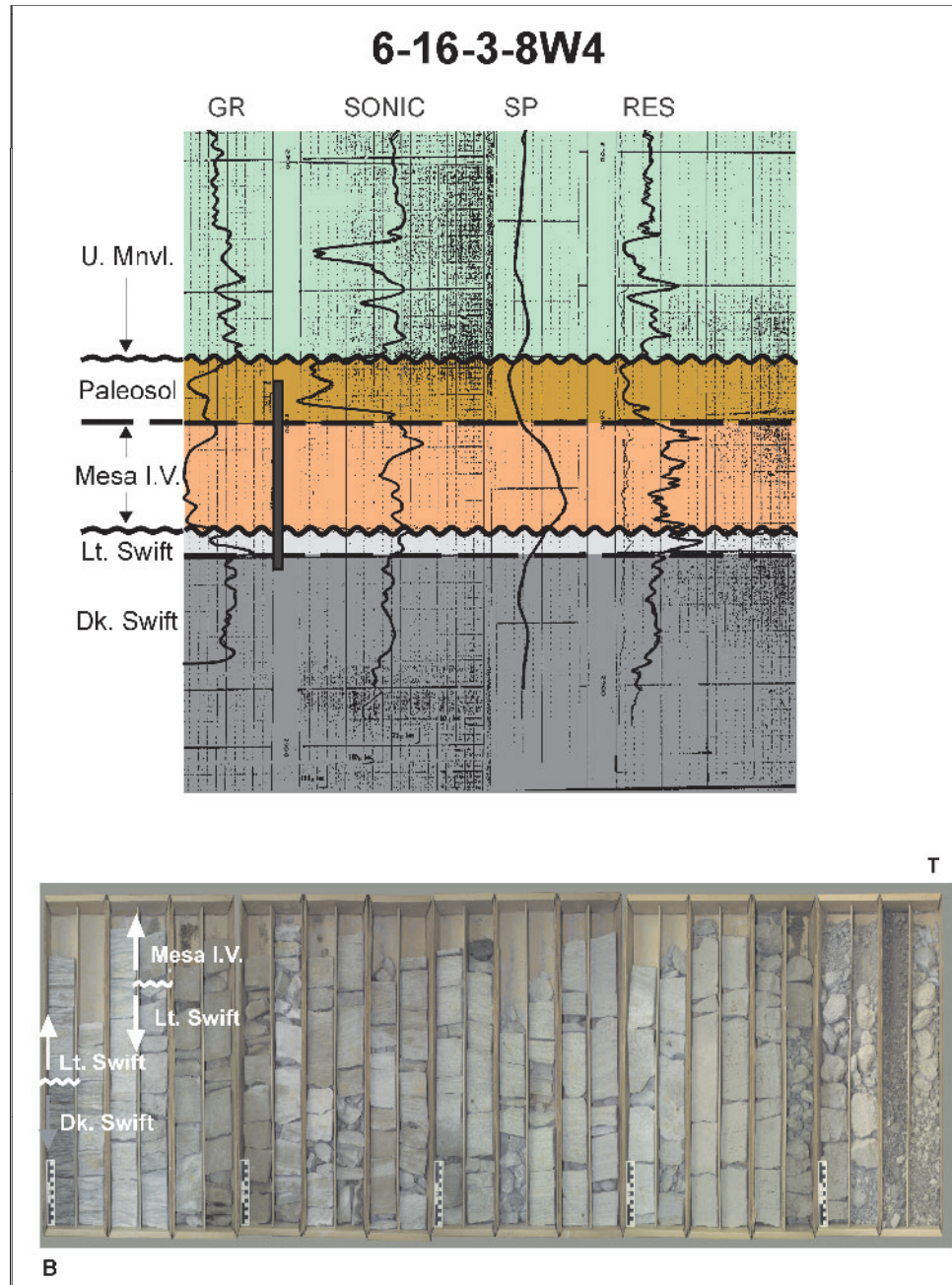


Fig. 11. Home CMG Pendor 6-16-3-8W4 (2784.1–2846.1 ft.). Type example of the Mesa Incised Valley. Core exhibits Mesa Incised Valley deposits unconformably overlying Jurassic Swift and below a well developed amalgamated paleosol. Mesa Incised valley deposits are medium-grained cross-bedded sandstones fining upward into ripple cross-stratified to cross-laminated sandstones and siltstones overlain by well developed paleosol (rubbly in core photo). B = bottom of core; T = top of core. Petrophysical logs include Gamma Ray (GR), Sonic, Spontaneous Potential (SP) and Resistivity (RES) logs. Note low API of Gamma Ray log, serrated nature of the Sonic and Resistivity logs and the inverse SP response (due to invert mud system). Black bar represents cored interval. Stratigraphic position of core is displayed in Figure 12.

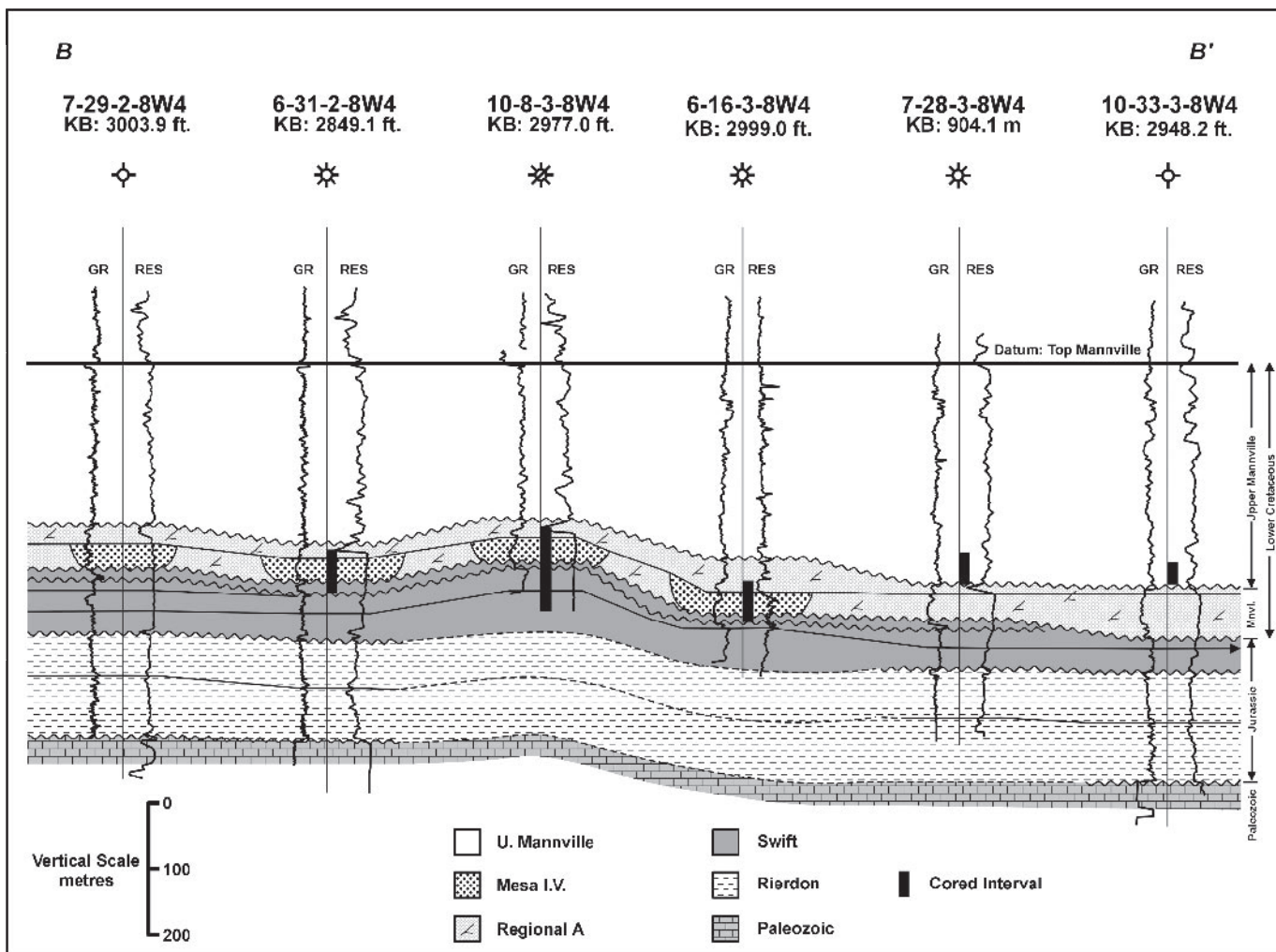


Fig. 12. Stratigraphic cross-section B–B' displaying Mesa Incised Valley geometry at Pendant D'Oreille (see Fig. 6 for location of cross-section). The Regional A and Mesa Incised Valley unconformably overlies a thick Jurassic succession up to the Swift. The incised valley deposits erode into the Regional A deposits and are in turn overlain by paleosols. Black bars represents core control. GR = gamma ray curve, RES = resistivity curve.

base of individual beds. Isolated remnants of interfluvial flood-plain mudstones (Fig. 18), up to 30 m thick, are locally present, and are composed of variegated red, green, and grey siltstones, mudstones and paleosols (Lukie, 1999; Lukie et al., this issue; Arnott et al., 2000, this issue).

The Horsefly sandstones contain significant amounts of ductile clay-rich sedimentary grains, low-grade schistose metamorphic grains, and small amounts of potassium feldspar (Figs. 4C, 5). Porosity in these sandstones is a function of clay-rich grain content and varies from intergranular dominated (sandstone poor in clayey grains) to microporosity dominated (sandstone rich in clayey grains). Compaction of Horsefly sandstones rich in clayey grains has resulted in the production of pseudomatrix and attendant reduction in reservoir quality. In general, despite the occurrence of clay-rich grains, reservoir quality is sufficient in most Horsefly sandstones to sustain economic production (Arnott et al., 1999, 2000, this issue).

Horsefly sandstones are compositionally similar to portions of the A Sandstone, as both contain similar volumes of clay-rich

sedimentary rock fragments. Differentiation of the Horsefly is facilitated primarily by the occurrence of potassium feldspar, which is absent in underlying A sandstones, and in the overlying BAT unit (Figs. 4, 5). Hence, all thin-sections in this study were stained for potassium feldspar using sodium cobaltinitrite. In some petrographic samples, potassium feldspar has been diagenetically leached and removed from the Horsefly. In such cases, additional criteria can be used to help distinguish Horsefly sandstones (Fig. 5). Specifically, chert grains frequently contain pyritic inclusions and are darker in colour relative to cherts in the A Sandstone. In addition, the Horsefly sandstones rarely exhibit the white chalky-weathering features which are widespread in the underlying A sandstones. Additionally, the Horsefly unit can display well developed variegated paleosols in the finer overbank material indicative of a different style of pedogenic weathering. The Horsefly also is defined by an absence of carbonaceous material in comparison to the overlying BAT sandstones.

Production from the Horsefly is associated with low accommodation incised valley fills, with the Cutbank field in

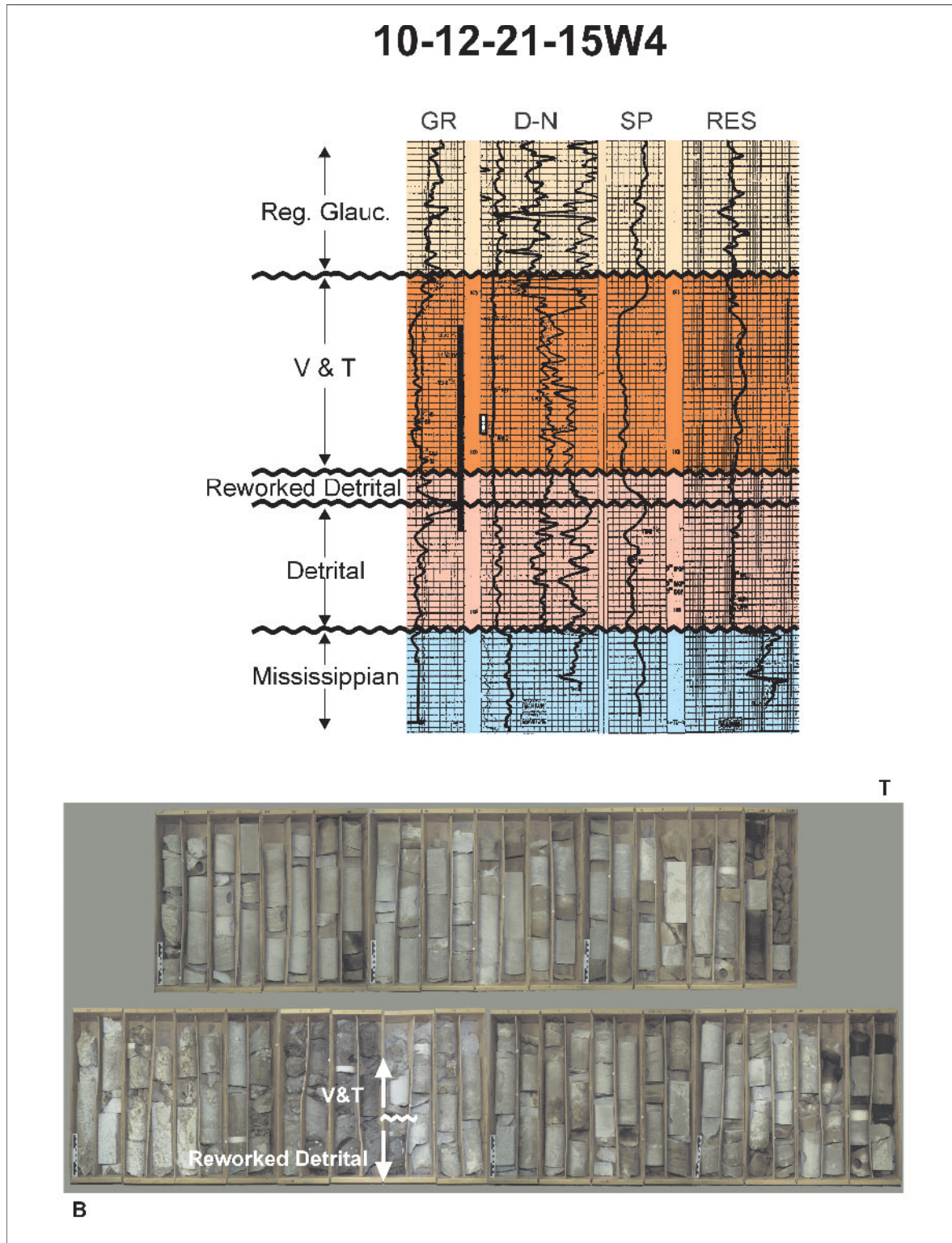


Fig. 13. PCP Countess 10-12-21-15W4 (1080–1112.4 m). Type example of the Valley and Terrace. Core exhibits detrital and reworked detrital deposits overlain by multiple cut-and-fill Valley and Terrace deposits. B = bottom of core; T = top of core. Petrophysical logs include Gamma Ray (GR), Density-Neutron (D-N), Spontaneous Potential (SP) and Resistivity (RES) logs. Note the low API on the Gamma Ray, the serrated nature of the Gamma Ray and the change in log separation upwards through the Density-Neutron logs. Changes in log character represent changes in the Valley and Terrace cut-and-fill events. The black bar represents the cored interval. Stratigraphic position of core is displayed in Figure 14.

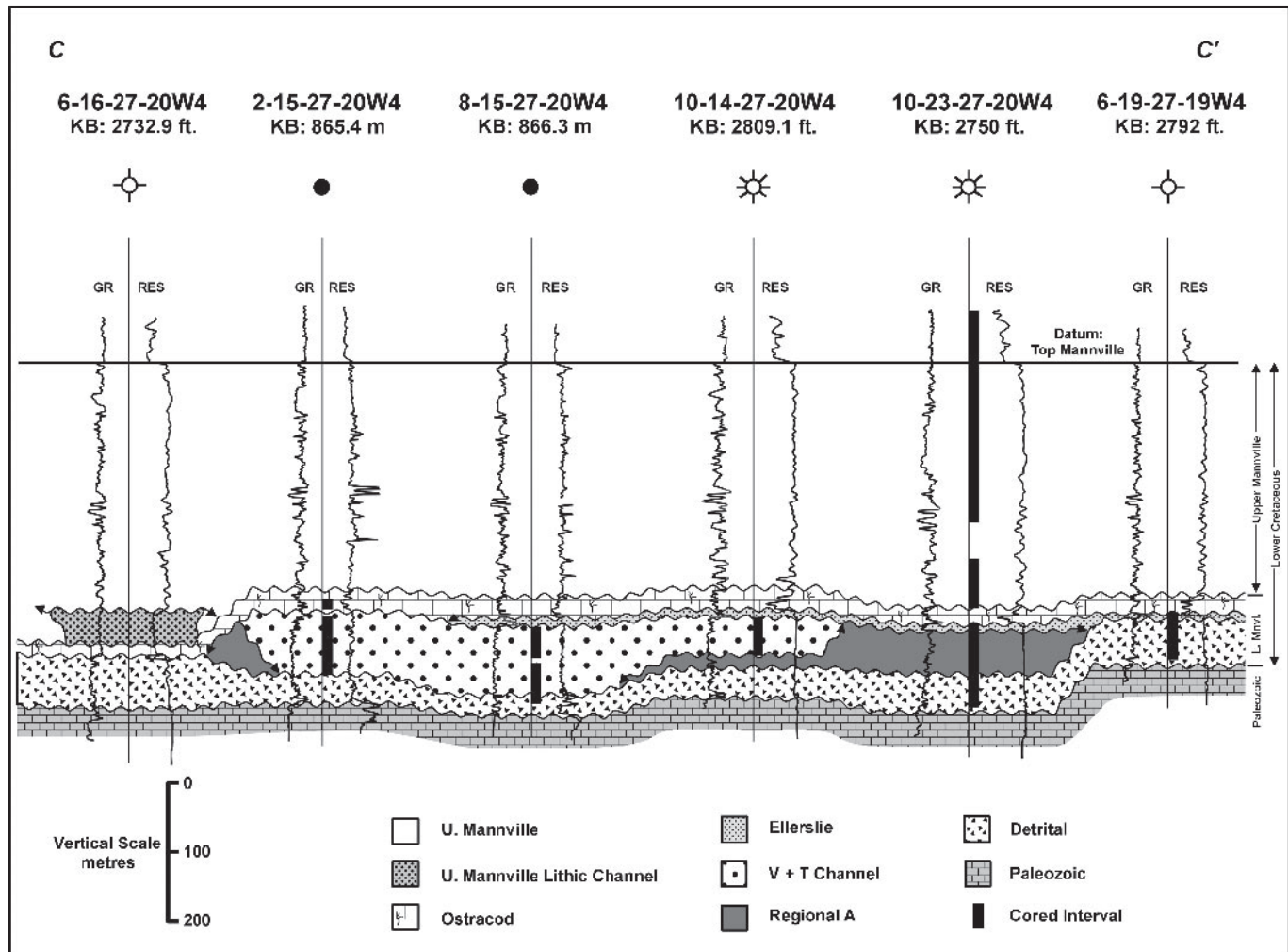


Fig. 14. Stratigraphic cross-section C–C' displaying the Valley and Terrace geometry at Wayne Rosedale (see Fig. 6 for location of cross-section). The Paleozoic carbonates are overlain by the Detrital, which is, in turn, erosionally cut into by the Valley and Terrace deposits. The Ellerslie overlies the Valley and Terrace in this location, and is, in turn, overlain by the Ostracod. Black bars represent core control. GR = gamma ray curve; RES = resistivity curve.

Montana (Lukie, 1999), and the Ferguson, Horsefly Lake and Taber-Retlaw areas in the Taber-Cutbank Valley; and Knappen, Forty Mile Coulee, and Kininvie West associated with the Whitlash Valley. The Princess field area is an example of an erosional remnant north of the hinge line. Reservoir parameters of the Horsefly unit range from 3–24% porosity and <0.01 mD to >1.2 Darcy permeability (Fig. 19).

BAT (BANTRY–ALDERSON–TABER)

The BAT (Fig. 1) can be divided spatially, based on depositional style, into two sub-units (Figs. 20 and 21). The first is a low accommodation BAT in areas where the total BAT unit isopach is less than 30 m (Fig. 21). South of Twp. 20 along the Taber–Cutbank–Carseland–Crossfield–Penhold valley system, and south of Twp. 30 along the Bantry valley system, the width is in the order of 1–5 km. The second is a high accommodation BAT (Figs. 20, 21) along the Carseland–Crossfield–Penhold

trend (Fig. 22), and the Provost trend (where the term Dina is used), where total isopach values can reach up to 100 m and the valley width is in the order of 6 to 10 km.

The BAT consists of light-grey to brown, fine- to coarse-grained, moderate to moderately well sorted, quartz and dark chert-bearing sandstones (Figs. 4D, 5, 23, 24). The sandstones may contain abundant carbonaceous debris, especially north of Twp. 5, insignificant amounts of ductile clay rich sedimentary rock fragments, and essentially no feldspar, except locally where cannibalized from below (in comparison to the Horsefly which contains K-feldspar). The absence of potassium feldspar and clay-rich sedimentary rock fragments help to differentiate the BAT from the underlying Horsefly unit. Owing to the paucity of clay-rich grains and absence of infiltrated clay material, the BAT unit sandstones are typically “clean” and the porosity is dominated by intergranular porosity.

In low accommodation areas, the BAT consists of stacked, erosionally based fining-upward “sheet-like” sandstones (Fig. 23;

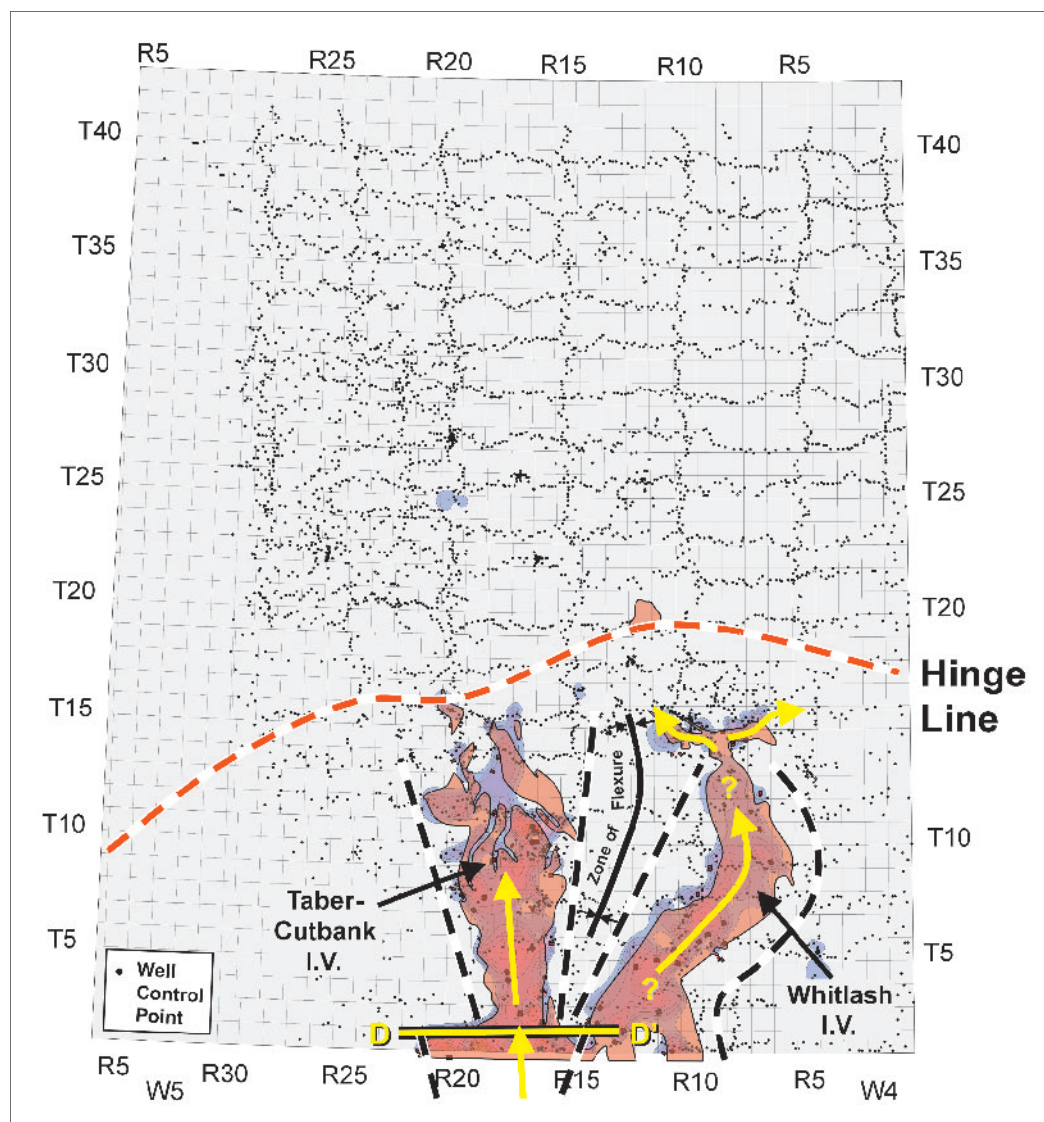


Fig. 15. Composite isopach and paleogeographic map of the Horsefly. Arrows represent inferred paleodrainage direction. Where no contours are present, no Horsefly was deposited or preserved. Location of cross-section D–D' is shown.

Ardies, 1999, Ardies et al., in press; Arnott et al., 2000, this issue). Each succession grades upward from coarse to medium sandstone, commonly with dispersed chert pebbles and tabular shale clasts, to lower medium/upper fine sandstone. Sandstone is pervasively stratified by medium scale planar-tabular and trough cross-stratification. Reservoir type is interpreted to be sand-dominated braided to coarse-grained meandering deposits. Very rarely does the low accommodation BAT display any form of marine bioturbation.

In high accommodation areas, the BAT consists of thick (up to 10 m) fining-upward successions (Fig. 24). Each succession comprises stacked several-metre-thick units, separated by 5 to 10 m of brackish-restricted marine shales with minor thin paleosols and pedogenically rooted horizons. The basal (<0.5 m) strata consist of poorly sorted matrix-supported conglomerate and medium- to coarse-grained sandstone matrix. Clasts are sub-

rounded and several decimetres in diameter, and are composed of sandstone and silty mudstone. The basal unit is overlain by a few metres of medium-scale cross-stratified upper medium- to coarse-grained sandstone, gradationally overlain by a few metres of massive to ripple cross-stratified fine-grained sandstone.

In the high accommodation BAT, bioturbated sandstone and mudstone strata up to several metres thick are developed toward the top in stacked fining-upward successions. Mudstone laminae and interbeds are common, and drape sandstone surfaces. Burrows are also present, and carbonaceous debris can be scattered throughout. Flaser and lenticular bedding is common, and associated soft-sediment deformation and roots may be developed. Taken together, these features are indicative of probable estuarine origin.

BAT sandstones are prolific hydrocarbon reservoirs. The high accommodation BAT produces gas at Crossfield and oil

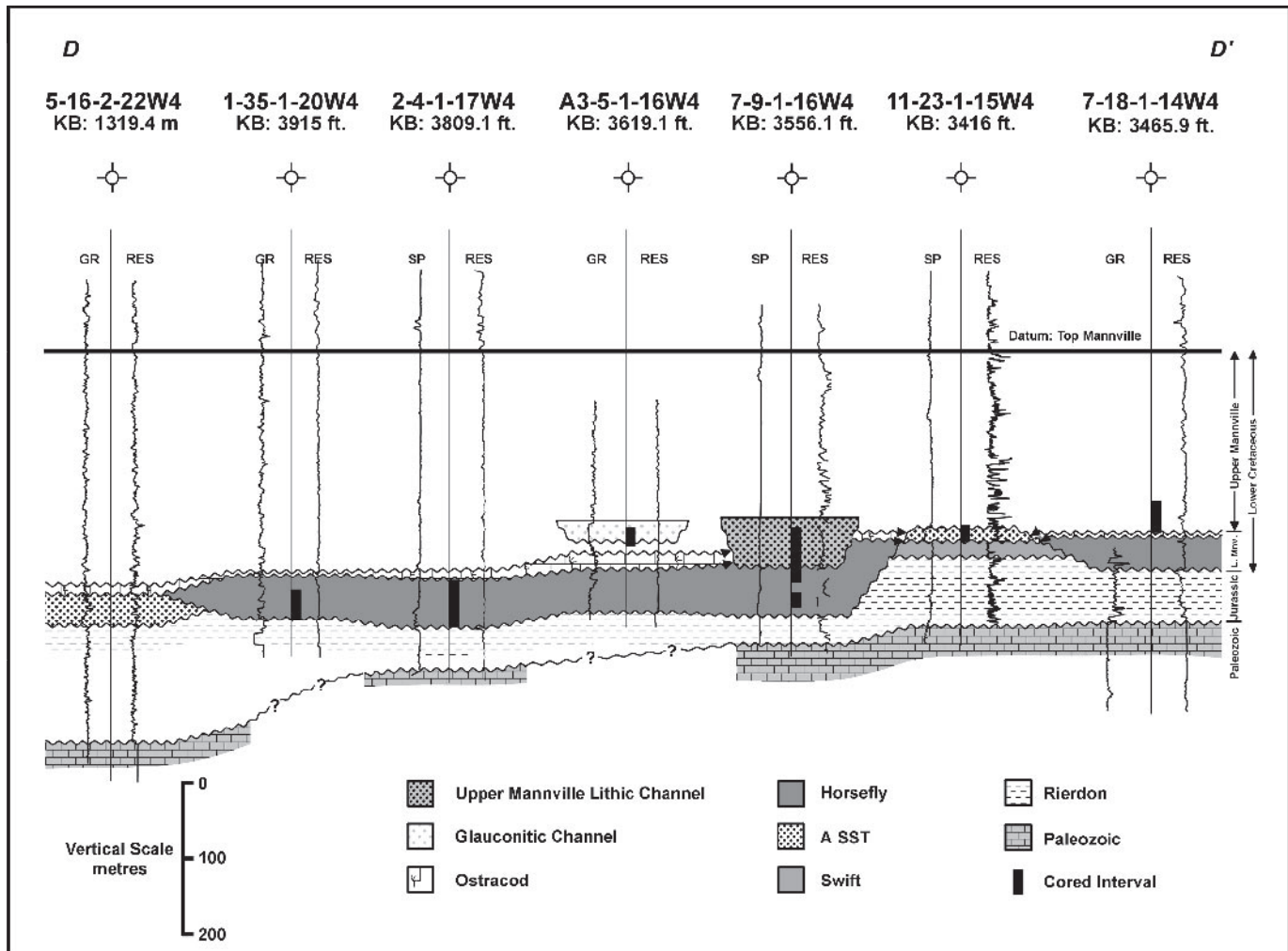


Fig. 16. Stratigraphic cross-section D–D' displaying low accommodation Horsefly valley-fill geometry near Moulton-Red Coulee (see Fig. 15 for location of cross-section). Black bars represent core control. GR = gamma ray curve; RES = resistivity curve.

at Carseland and throughout the Provost district, where it is called the Dina. Low accommodation BAT unit production comes from Bantry and Turin. The BAT displays excellent reservoir quality and is a prime exploration target. Reservoir parameters vary between the low accommodation (Fig. 25A, B) and the high accommodation BAT (Fig. 25C, D). In low accommodation BAT reservoirs in the south and east portions of the study area, reservoir parameters range from 3–28% porosity and <0.01 mD to 5 Darcy permeability. High accommodation BAT reservoirs can range from 7–20% porosity and <0.07 mD to 1 Darcy permeability. The principle control on reservoir quality within the BAT is burial depth, with poorer reservoir quality associated with the northern extension of the western valley trend (depths about >2000 m in Crossfield) in comparison to low accommodation eastern trend BAT (e.g. Bantry district) reservoirs at depths of about 800 to 1200 m.

ELLERSLIE

The Ellerslie is stratigraphically the youngest of the BQ units (Figs. 1, 4, 5). The Ellerslie is characterized by high

accommodation in the northern limit of the study area, where isopach values can exceed 75 m (Fig. 26). Isopach values vary markedly in thickness, however, and where the Ellerslie onlaps the A-unit highlands, or in the upper reaches of an Ellerslie valley system, the unit pinches out entirely. The Ellerslie is characterized as an interbedded fine-grained quartz-rich sandstone and bioturbated mudstone with minor muddy sandstone (Fig. 27).

The sandstones commonly consist of fine-grained, well to very well sorted quartz-dominated sandstones containing very minor amounts of potassium feldspar, and little to no dark coloured chert (Figs. 4E, 5). Intergranular pores dominate the porosity and reservoir quality is good to excellent. Although the Ellerslie is mineralogically and texturally more mature than the underlying BAT unit sandstones, permeability values in the Ellerslie unit sandstones are commonly lower, as they are limited by the significantly finer grain sizes of the Ellerslie (Fig. 28). The Ellerslie is divisible into

- 1) A succession of brackish-restricted marine mudstones with thin shoreface sandstone successions located

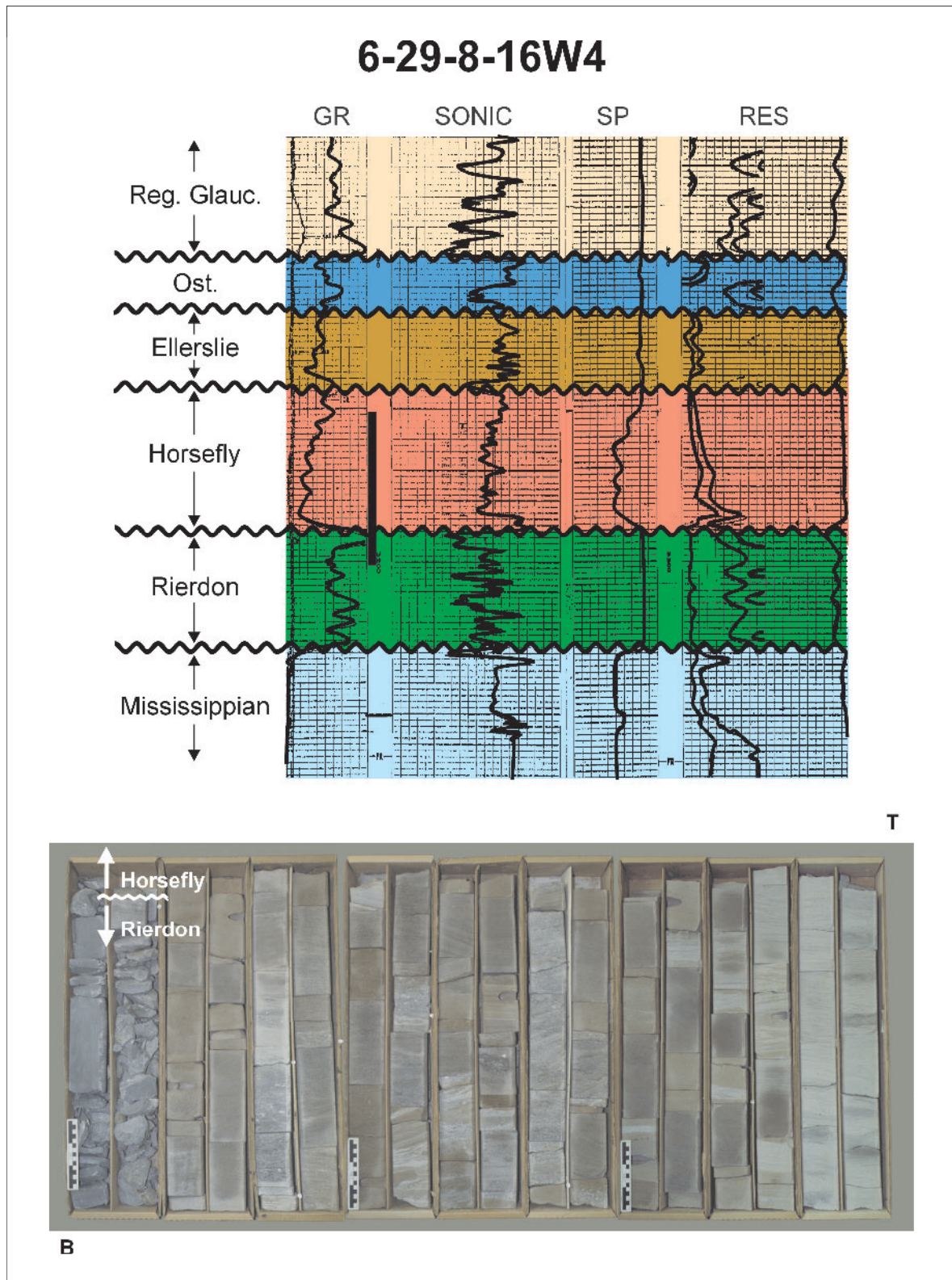


Fig. 17. Renaissance Horsefly 6-29-8-16W4 (3149.9–3192.9 ft.). Type example of the Horsefly. Core exhibits marine mudstones of the Rierdon erosionally overlain by braided-fluvial to coarse-grained meander sandstones overlying of the Horsefly, fining upwards into a paleosol. B = bottom of core; T = top of core. Petrophysical logs include Gamma Ray (GR), Sonic, Spontaneous Potential (SP) and Resistivity (RES) logs. Note serrated and fining-upward log motifs associated with the Gamma, Sonic and SP curves. Black bar represents cored interval; Reg. Glauc. = Regional Glauconitic; Ost. = Ostracod.

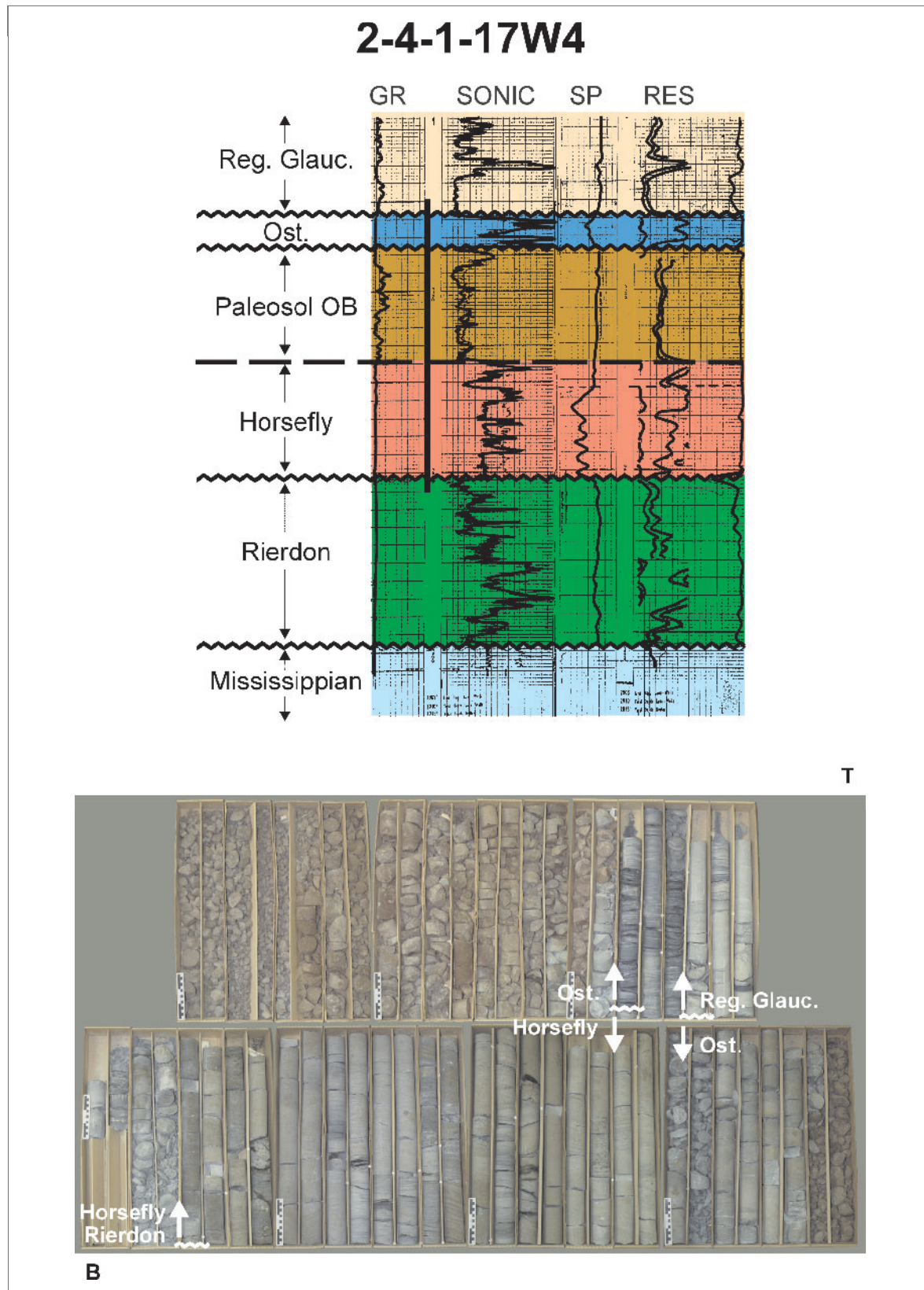


Fig. 18. Decalta et al. Milk River 2-4-1-17W4 (2600–2811 ft.). Type example Horsefly braided-fluvial to coarse-grained meander sandstones, overlain by a thick variegated paleosol complex, in turn overlain by a thin Ostracod and Regional Glauconitic. B = bottom of core; T = top of core. Petrophysical logs include Gamma Ray (GR), Sonic, Spontaneous Potential (SP) and Resistivity (RES) logs. Note serrated and fining-upward log motifs associated with the Gamma, Sonic and SP curves in turn overlain by high SP low Resistivity mudstone signature of the overbank deposits. Black bar represents cored interval. Reg. Glauconitic = Regional Glauconitic; Ost. = Ostracod; OB = overbank deposit. Stratigraphic position of core is displayed in Figure 16.

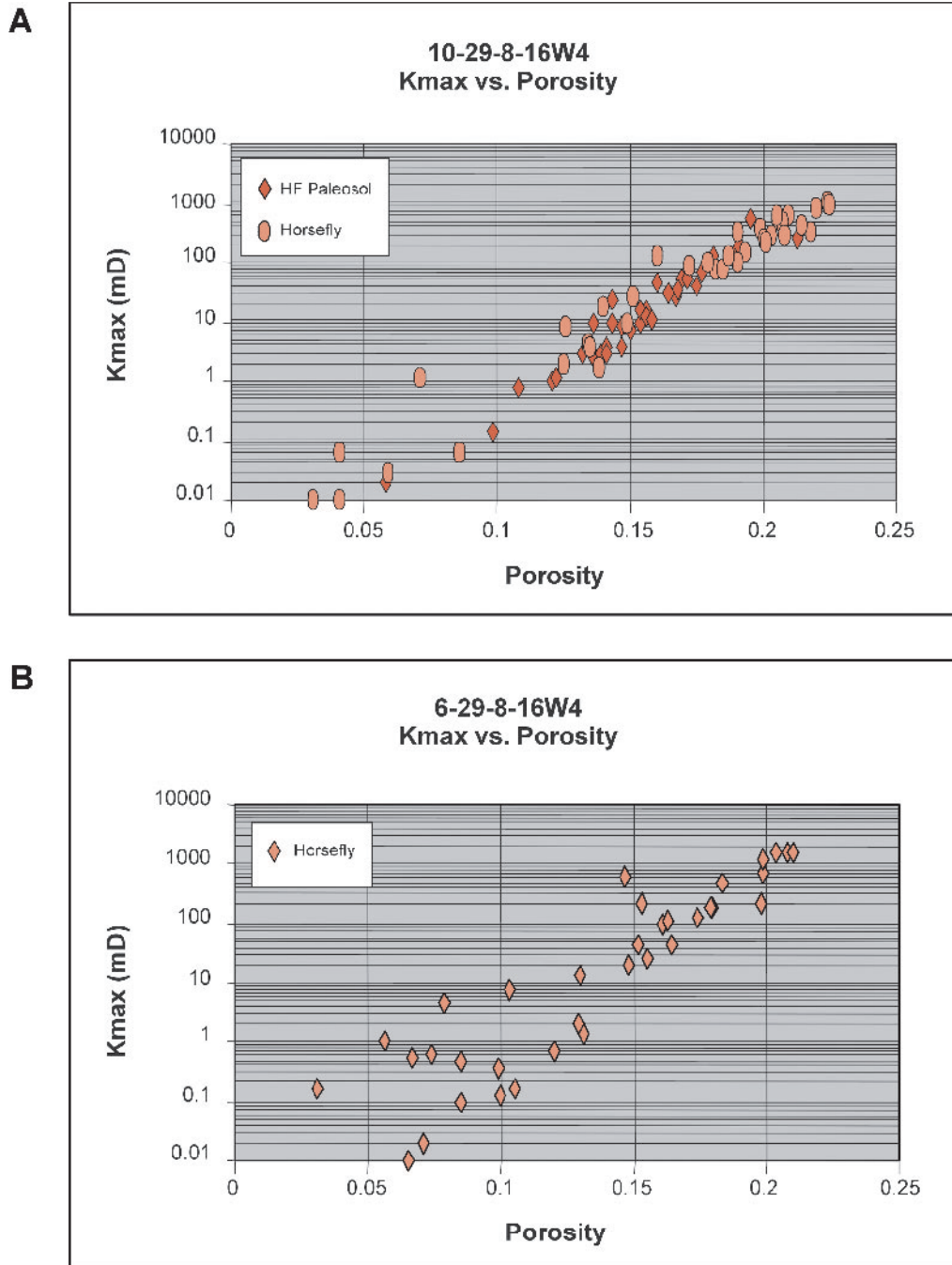


Fig. 19. Core Porosity (%) versus Permeability (Kmax; mD = millidarcies) to air for **A)** Renaissance Horsefly 10-29-8-16W4 (3159-3201.1 ft.). **B)** Renaissance Horsefly 6-29-8-16W4 (3149.9–3192.9 ft.) (see Fig. 17).

directly below the Ostracod unconformity in the north-west quadrant of the study area (Fig. 26). The Ellerslie sub-unit shorefaces typically trend east–west or north–east–southwest. These shorefaces shoal upward from bioturbated mudstones (offshore deposits), to interbedded bioturbated mudstones and wave-rippled sandstones (offshore transition beds) to wave-rippled and hummocky (HCS) fine-grained sandstones (lower shoreface) to amalgamated HCS and crossbedded sand-

stones (middle or upper shoreface deposits), defining parasequences. The parasequences may be capped by either rooted coaly mudstones, siltstones, and sandstones, or, alternatively, by shoaling-upward cycles capped by paleosols or limestone. At Carseland, shorefaces subcrop under the Ostracod Member and wells have been recompleted in the middle and upper shoreface sandstones in the Ellerslie with excellent oil and gas rates. Reservoir quality is excellent in the

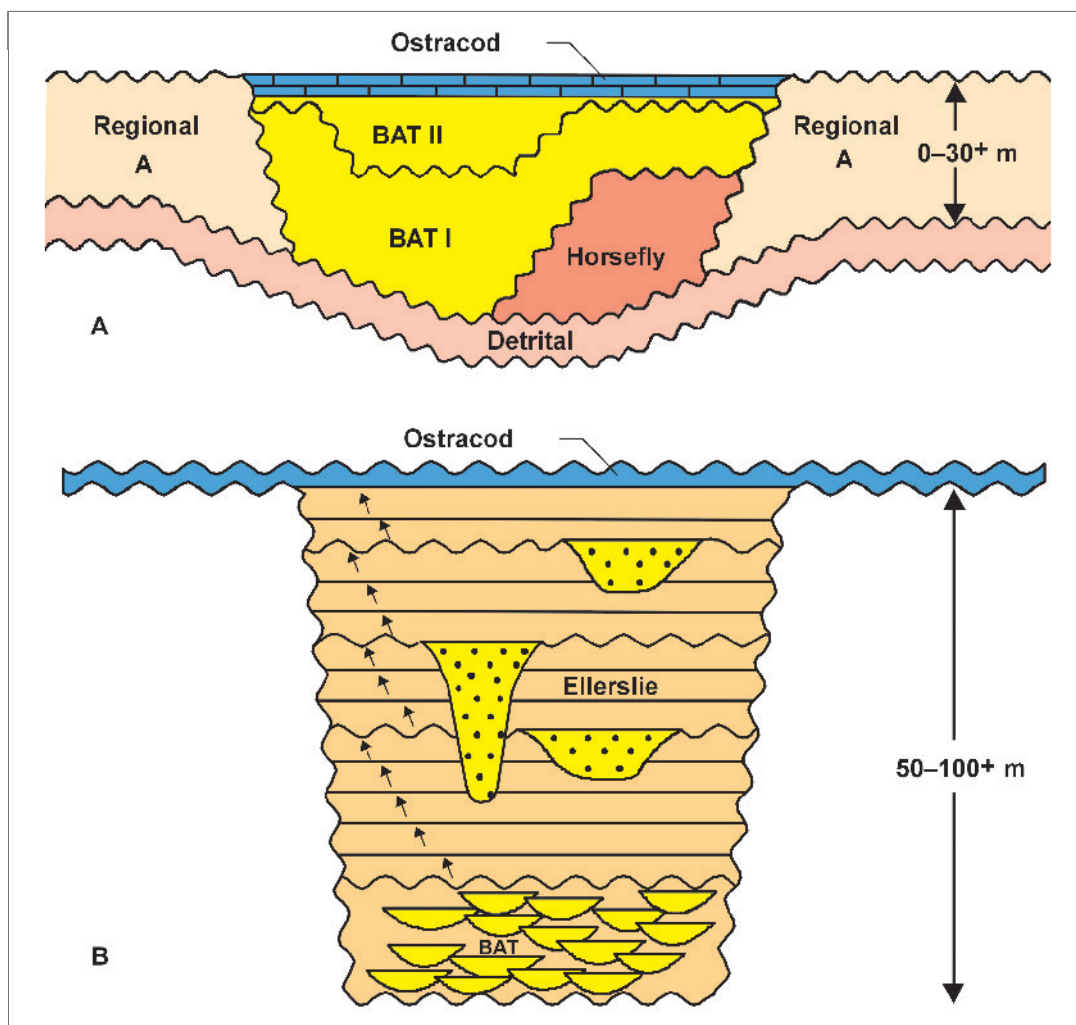


Fig. 20. Schematic geometries for (A) low accommodation Horsefly and BAT units and (B) high accommodation BAT and Ellerslie units. Note change in vertical scale between low accommodation (<30 m) and high accommodation (50–100+ m) geometries. Under low accommodation setting, units amalgamate, and it is easier to separate key bounding surfaces under high accommodation conditions. (see Fig. 3 for additional details).

100% fine-grained quartz sandstones. There is minor subsidiary chert in the middle to upper shoreface facies. Bioturbation degrades reservoir quality in the lower shoreface and offshore facies (Fig. 24). Reservoir parameters of the Ellerslie shoreface deposits range from 3–10% porosity and 0.01 mD to 0.3 Darcys; and

- 2) Fluvial to fluvial-estuarine incised valley deposits (Figs. 24, 27). There are at least five mappable erosional surfaces from which Ellerslie unit incised valley systems were developed. Ellerslie valley-fill deposits consist of very fine-grained, well sorted bioturbated quartz arenites. The valley fill is composed of massive to bioturbated sandstones which may contain fining-upward crossbedded to tidally bedded sandstones. Double mud drapes and a brackish trace fossil assemblage are common. The incised valley fill represents an estuarine to central basin deposit (cf. Zaitlin

et al., 1994). Ellerslie valley-fill deposits range from 8–18% porosity and <0.10 mD to 100 mD permeability (Fig. 28).

Valley systems are separated by thick successions of shoaling-upward cycles capped by paleosols, shallow water limestones, or erosional (sequence-bounding) surfaces. It can be difficult at times to clearly separate the Ellerslie unit shoaling-upward cycles from Ostracod Member parasequences. The break is marked by a 3–5 ohm-meter decrease in the resistivity. In addition, a marked increase in the interval transit time facilitates the differentiation between Ellerslie and the Ostracod.

The Ellerslie valleys are narrow (<3 km) and deeply incised (up to 30 m). Estuarine “shoal” or wing facies may be developed above a transgressive surface of erosion which widens the valley during transgression. In some cases, the deposits extend out of the valleys and onto the interflues,

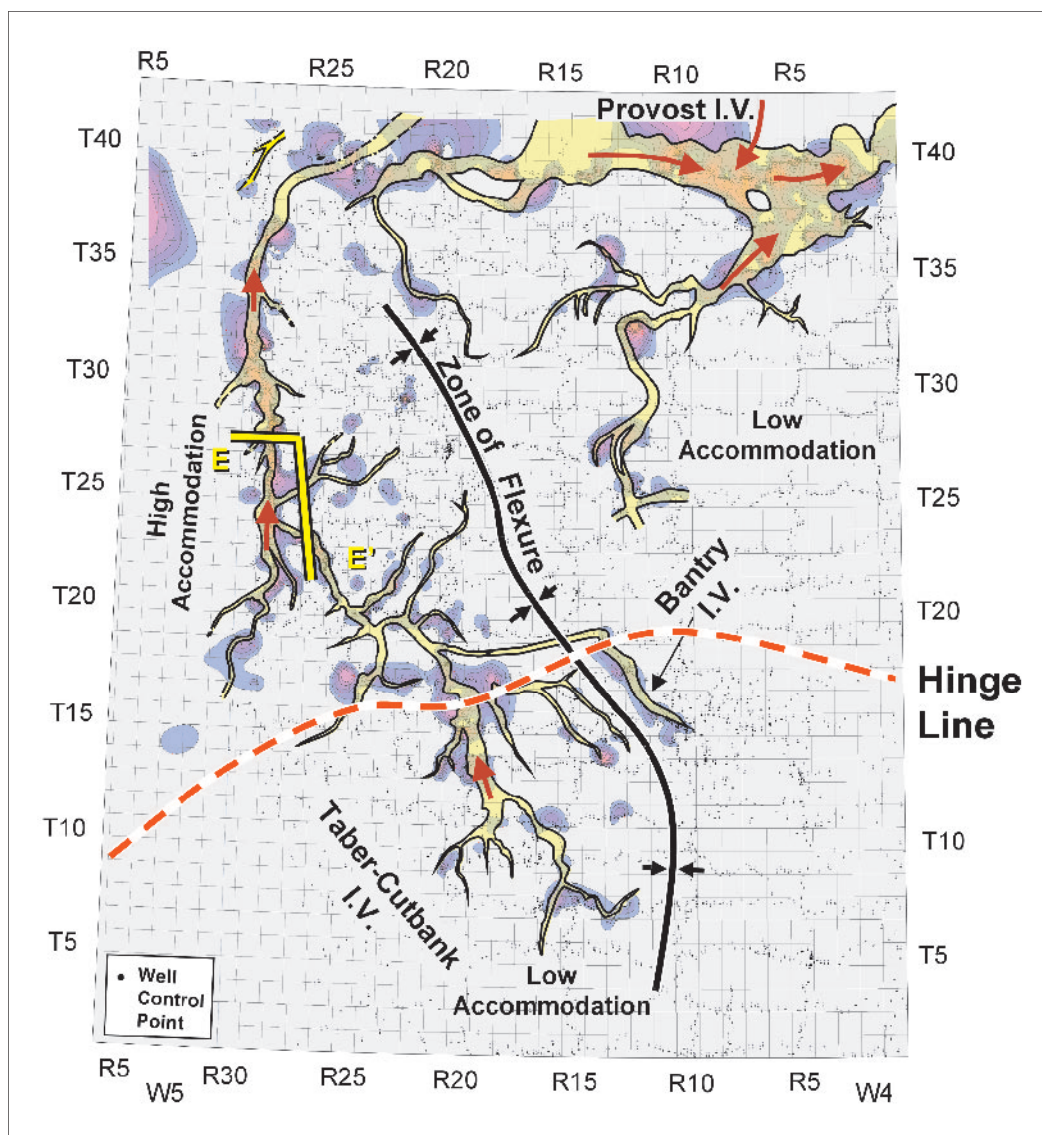


Fig. 21. Composite isopach and paleogeographic map of the BAT. Arrows represent inferred paleodrainage direction. Where no contours are present, no BAT was deposited or preserved. Location of cross-section E–E' is shown.

where they have been interpreted as estuarine muddy central basin or lagoonal fill behind a transgressive barrier complex (Ardies, 1999). In areas (e.g. along the axis of the Crossfield and Penhold Channels) thick channel-fill breccias occur in the base of these valley systems. Some valley deposits are finer grained, argillaceous, bioturbated, and completely lack reservoir quality due to quartz overgrowths or disruption of the primary sedimentary fabric.

Low to intermediate accommodation dominates the Ellerslie (i.e. Dina) in the Provost district. A major intersection of the Provost and Cessford-Stanmore systems occur near Twp. 35 Rge. 8. Here the valley is up to 39 km wide and 30 to 50 m thick. The Provost and Cessford-Stanmore systems both narrow headward so that systems are much narrower (less than 6 km wide, more commonly 1–2 km wide) and average 15 to 30 m thick. Local extensional faulting significantly influenced

Ellerslie accommodation in the Cessford-Stanmore valley system near Twp. 29 Rge. 12 (Warren, 2000).

DISCUSSION OF THE DISTRIBUTION AND CYCLICITY OF THE BQ UNITS

As discussed previously, the BQ is divisible into a series of depositional units based on detailed correlation, depositional style and petrographic analysis. The A Sandstone and the Horsefly–BAT–Ellerslie exhibit a number of well defined stratigraphic and spatial variations.

The A Sandstone exhibits

- 1) a well developed increase in mineralogical and textural maturity (Figs. 4, 5) indicative of either a changing source area with time, or a response to changing climatic conditions.

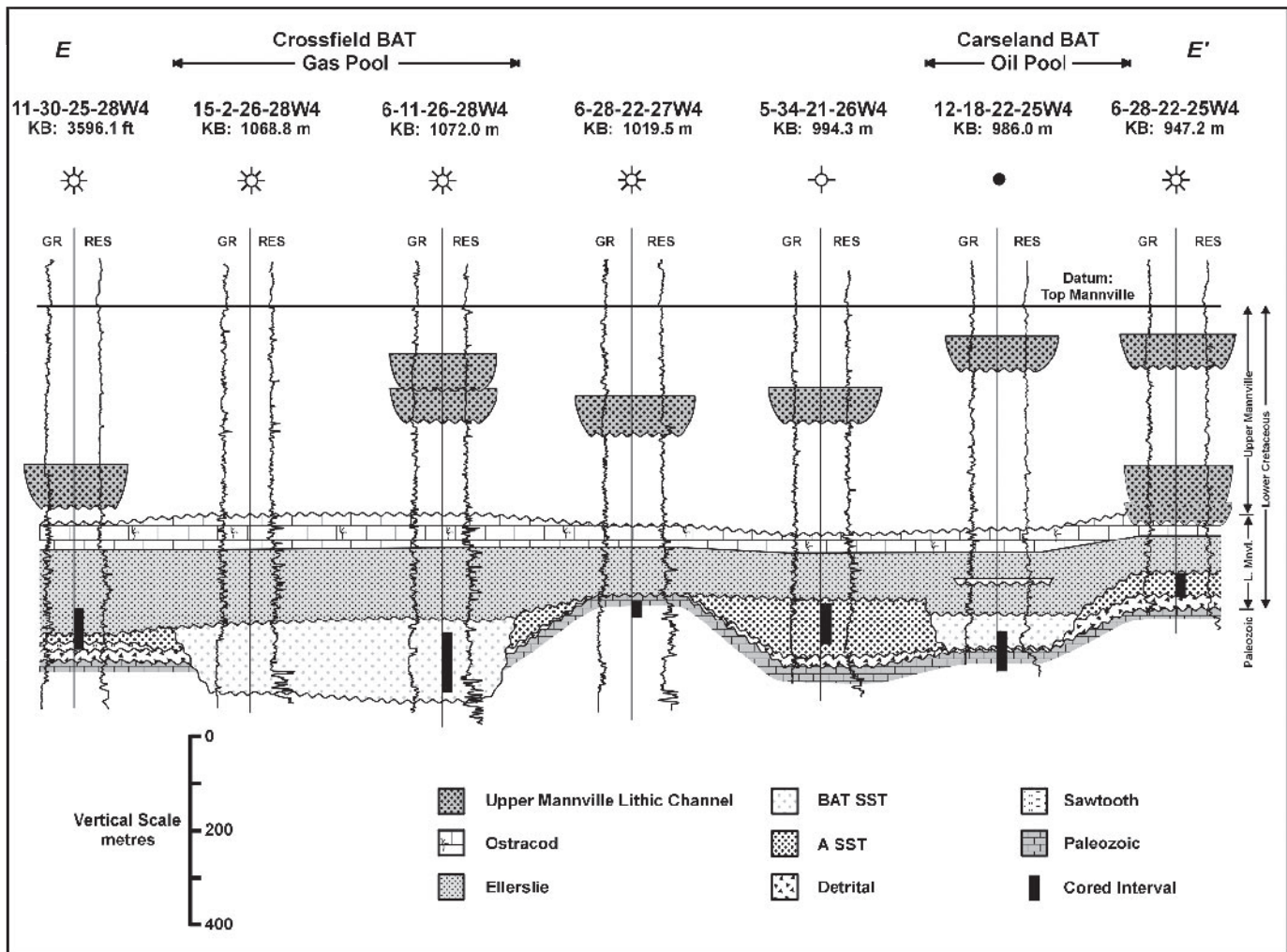


Fig. 22. Stratigraphic cross-section E-E' displaying low accommodation BAT valley-fill geometry near Crossfield-Carseland (see Fig. 21 for location of cross-section). Black bars represent core control. GR = gamma ray curve; RES = resistivity curve.

- 2) a progressive change in A Sandstone channel geometry and style (Figs. 6, 7). The Regional A is spatially extensive; the Carmangay is composed of SW-NE amalgamated sheet-like braidplain deposits (Fig. 7A); the Mesa IV is composed of isolated sinuous and ribbon-like channel deposits (Fig. 7B); and the Valley and Terrace is composed of a complex cut-and-fill geometry (Fig. 7C). Channel geometry therefore changes stratigraphically from thin and sheet-like to thicker, narrower and more sinuous channel geometries; and from simple to more complex from south to north across the hinge line.
- 3) a progressive southward increase in marine influence with time. The Carmangay and Mesa IV are totally fluvial in character. Marine deposits associated with the Regional A are confined to the northern limits of the study area. The Valley and Terrace has been interpreted to have estuarine deposits as far south as Township 10, indicative of a southward incursion of marine/estuarine influence. Therefore, there is a larger-scale transgressive or backstepping stacking geometry to the A

Sandstone stratigraphically, and a southward limit of the transgressive estuarine deposits coincident with the position of the hinge line (Fig. 6).

- 4) the Carmangay to Mesa IV/Valley and Terrace is characterized by a perpendicular SW-NE to SE-NW shift in paleodrainage direction (Fig. 6).
- 5) the different units of the A Sandstone are distributed preferentially through the study area (Fig 6). The Carmangay and Mesa IV are associated with areas of preserved Jurassic thicks south of the hinge line or isolated outliers (e.g. Hackett High), whereas, the Valley and Terrace deposits are present predominately north of the hinge line (Fig. 6). The importance of the hinge line will be more fully discussed later.

The Horsefly, BAT and Ellerslie also exhibit a number of well defined stratigraphic and spatial variations, as follows:

- 6) There is a well developed increase in mineralogical and textural maturity from the Horsefly-BAT-Ellerslie, indicative of a changing source area with time (Figs. 4, 5). This is similar to the A Sandstone.

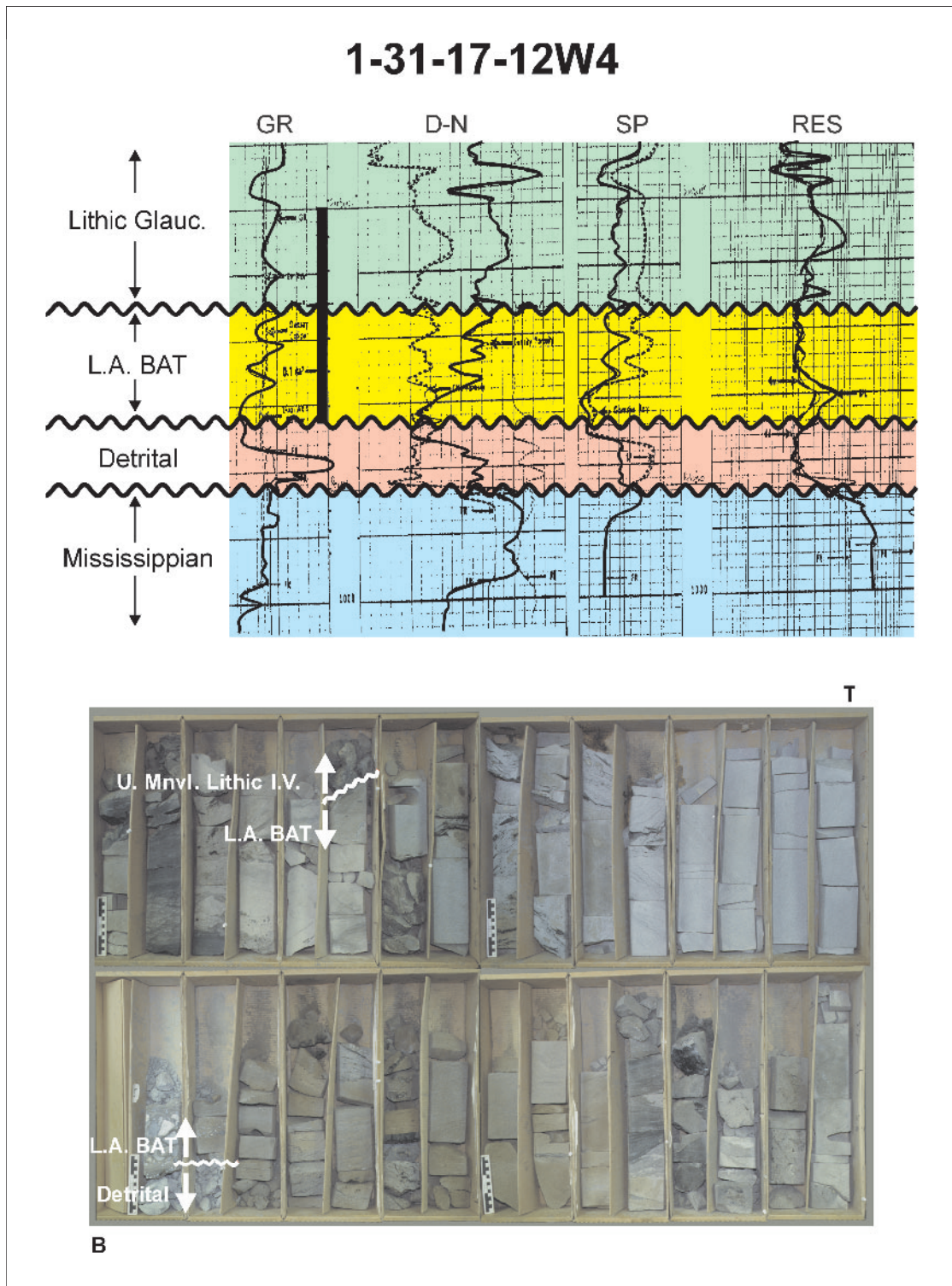


Fig. 23. Chevron Bantry 1-31-17-12W4 (976–1001 m). Type example of low accommodation BAT braided to coarse-grained meandering-fluvial deposits. Core displays change from Detrital to channel geometry overlain by Mannville Lithic channel. B = bottom of core; T = top of core. Petrophysical logs include Gamma Ray (GR), Density-Neutron (D-N), Spontaneous Potential (SP) and Resistivity (RES) logs. Note serrated and fining-upward log motifs associated with the Gamma, Sonic and SP curves. Black bar representing cored interval.

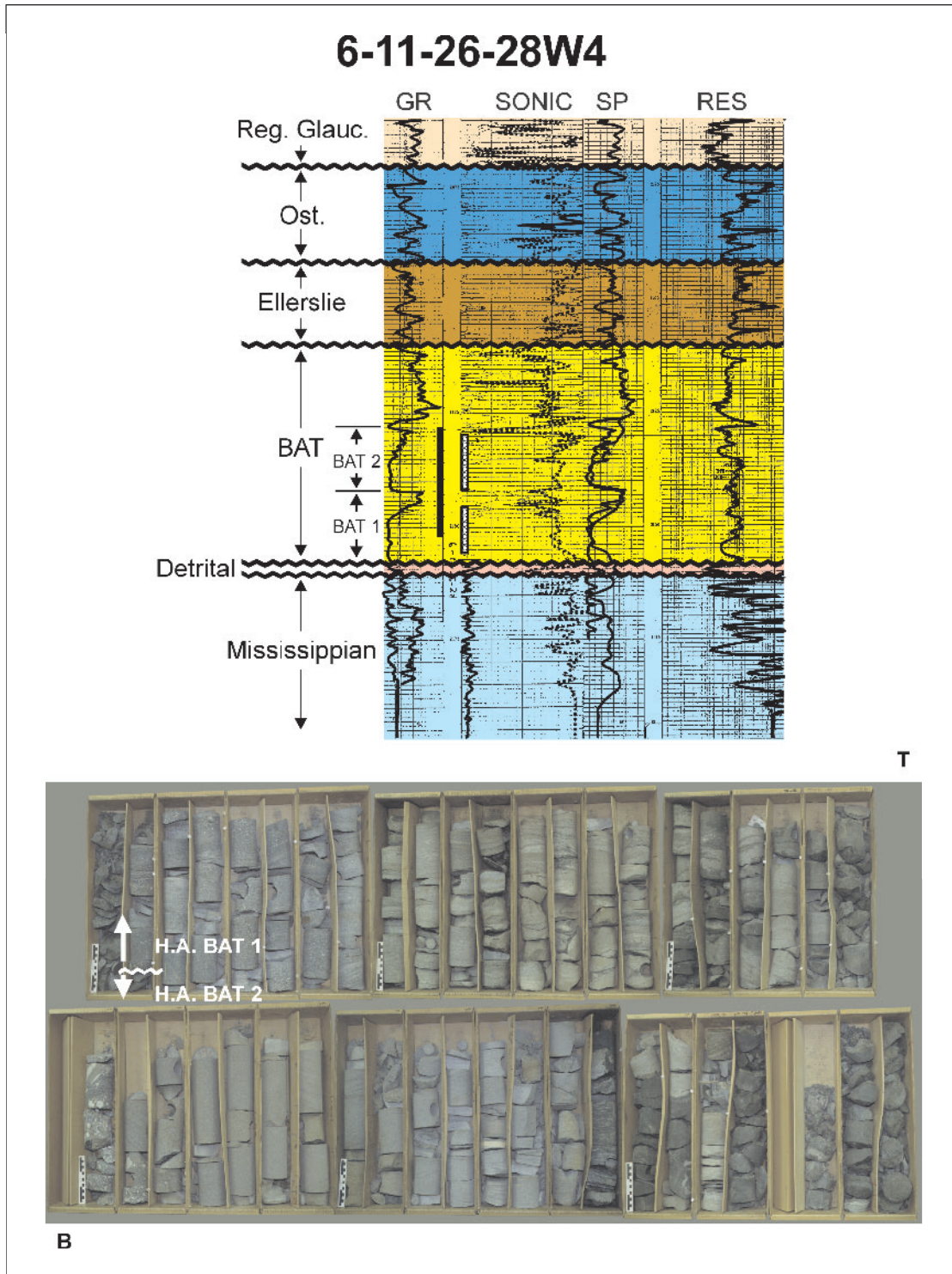
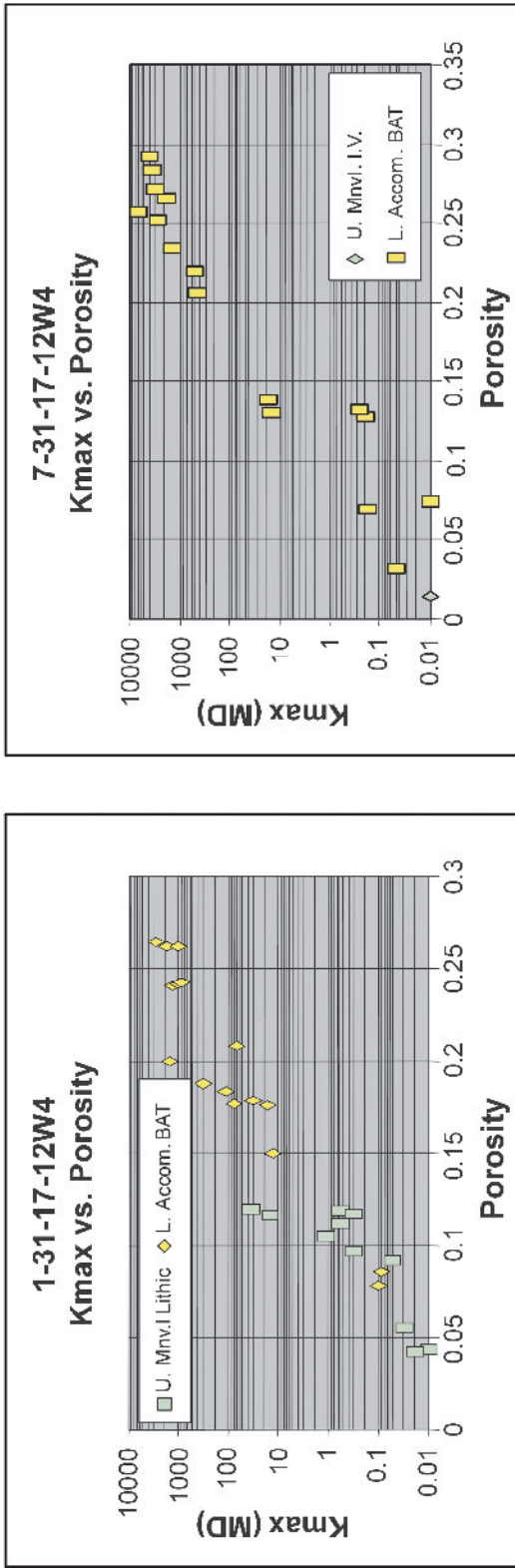


Fig. 24. CDNOXY et al. Crossfield 6-11-26-28W4 (2128–2153 m). Type well of the high accommodation BAT. Core displays two well developed fining-upward fluvially-dominated point-bar sequences. B = bottom of core; T = top of core. Petrophysical logs include Gamma Ray (GR), Sonic, Spontaneous Potential (SP) and Resistivity (RES) logs. Note serrated and fining-upward log motifs associated with the Gamma, Sonic and SP curves. Stratigraphic position of core is displayed in Figure 22.

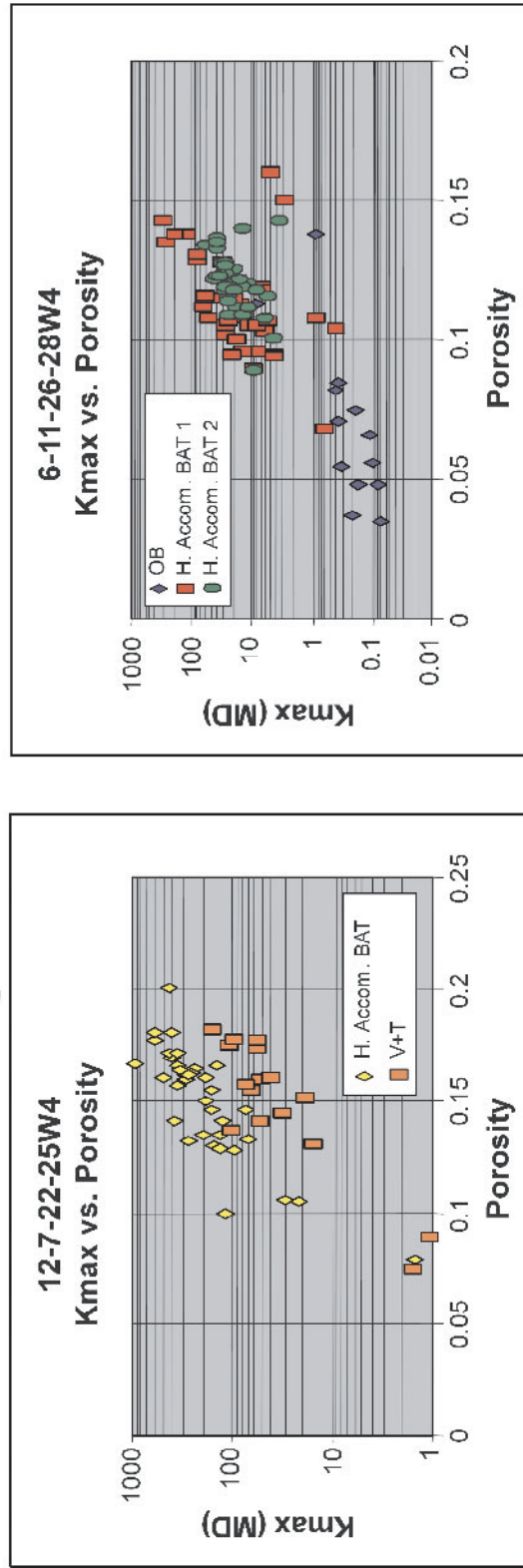
Low Accommodation BAT



A

B

High Accommodation BAT



C

D

Fig. 25. Core Porosity (%) versus Permeability (Kmax; mD = millidarcies) to air for low accommodation [(A) Chevron Bantry 1-31-17-12W4 (970–987 m; Fig. 23); (B) Chevron Bantry 7-31-17-12W4 (976–1001 m)] and high accommodation [(C) PCP Strathmore 12-7-22-25W4 (1801–1819 m); (D) CDNOXY et al. Crossfield 6-11-26-28W4 (2128–2153 m; Fig. 24)].

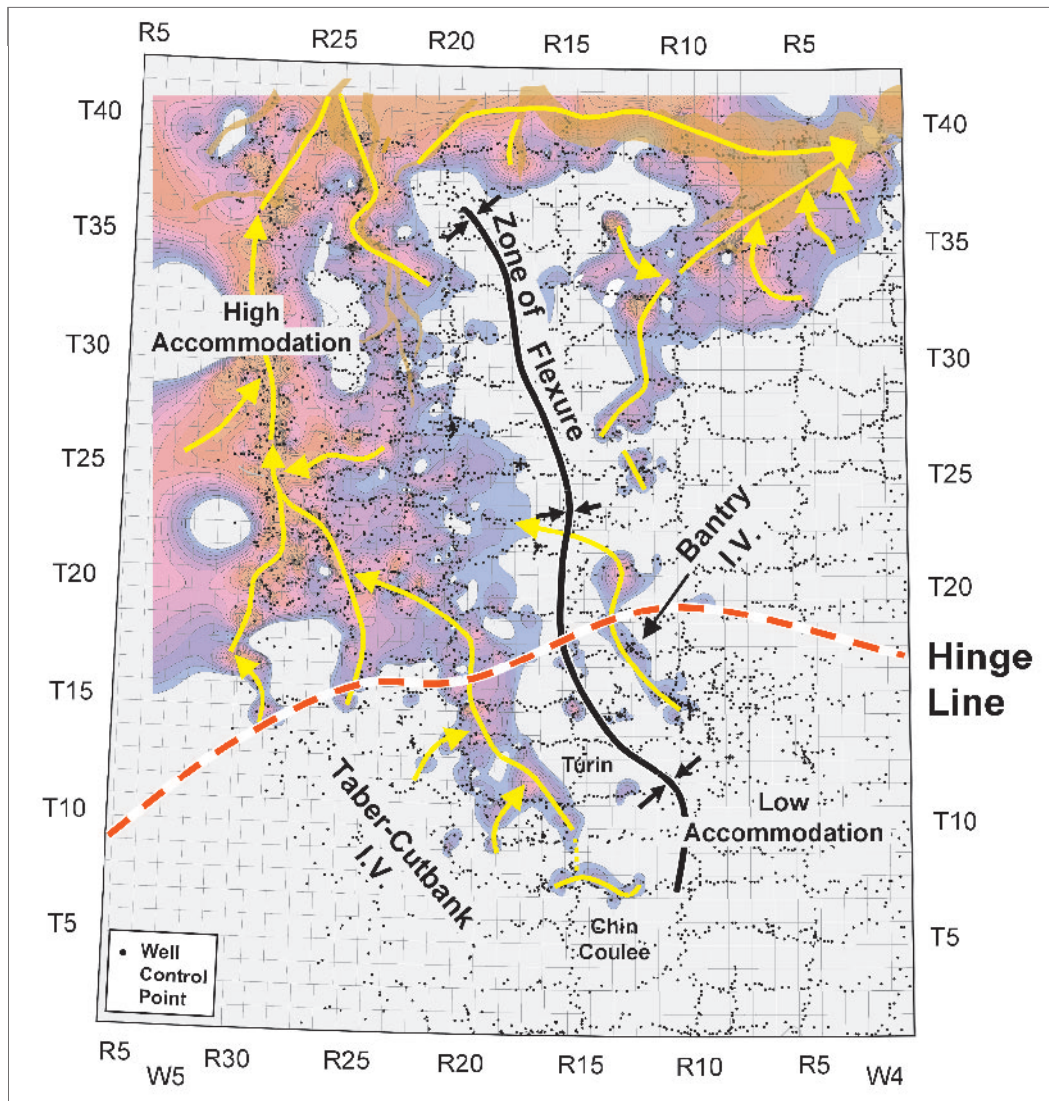


Fig. 26. Composite isopach and paleogeography map of the Ellerslie. Arrows represent inferred paleodrainage direction. Where no contours are present, no Ellerslie was deposited or preserved.

- 7) Under low accommodation conditions, the Horsefly south of the Vulcan Low, and BAT both south of the Vulcan Low and east of the hinge line, are characterized by amalgamated braided to coarse-grained channel-fill deposits. The Horsefly is locally characterized by high accommodation meandering deposits coincident with the downthrown side of syndepositional faults south of the Vulcan Low (Lukie, 1999; Lukie et al., 1999, Lukie et al., this issue; T. Hobbs, unpublished data), as is the BAT north of the Vulcan Low and west of the hinge line (Fig. 21). The Ellerslie is always characterized by high accommodation fluvial-estuarine to brackish-marine deposits (Fig. 26).
- 8) Channel form geometry changes from thin and wide for the Horsefly, to progressively narrower and thicker channel forms from south to north for the BAT, and narrow and deep for the Ellerslie.
- 9) There is an absence of recognizable tributary systems in the Horsefly. The BAT is characterized by a complex tributary zonation. Along the Taber-Cutbank to Crossfield system, BAT tributaries change from a dendritic tributary pattern south of the Vulcan Low (Fig. 21), to a rectilinear NW-SW pattern across a 10 mile zone associated with the Vulcan Low, to a NE-SW oriented dendritic tributary pattern north of the Vulcan Low. Ellerslie tributaries appear to form simple Y-junctions.
- 10) There is a progressive southward migration in marine influence from the Horsefly (fluvial) to the BAT (fluvial to fluvial estuarine) to the Ellerslie (fluvial estuarine to brackish bay/marine). The maximum marine incursion occurs during the Ostrocod Member (Cant and Abrahmsen, 1996).

Figures 6, 15, 21 and 26 display the isopach values and distribution of the A Sandstone, Horsefly, BAT and Ellerslie. The

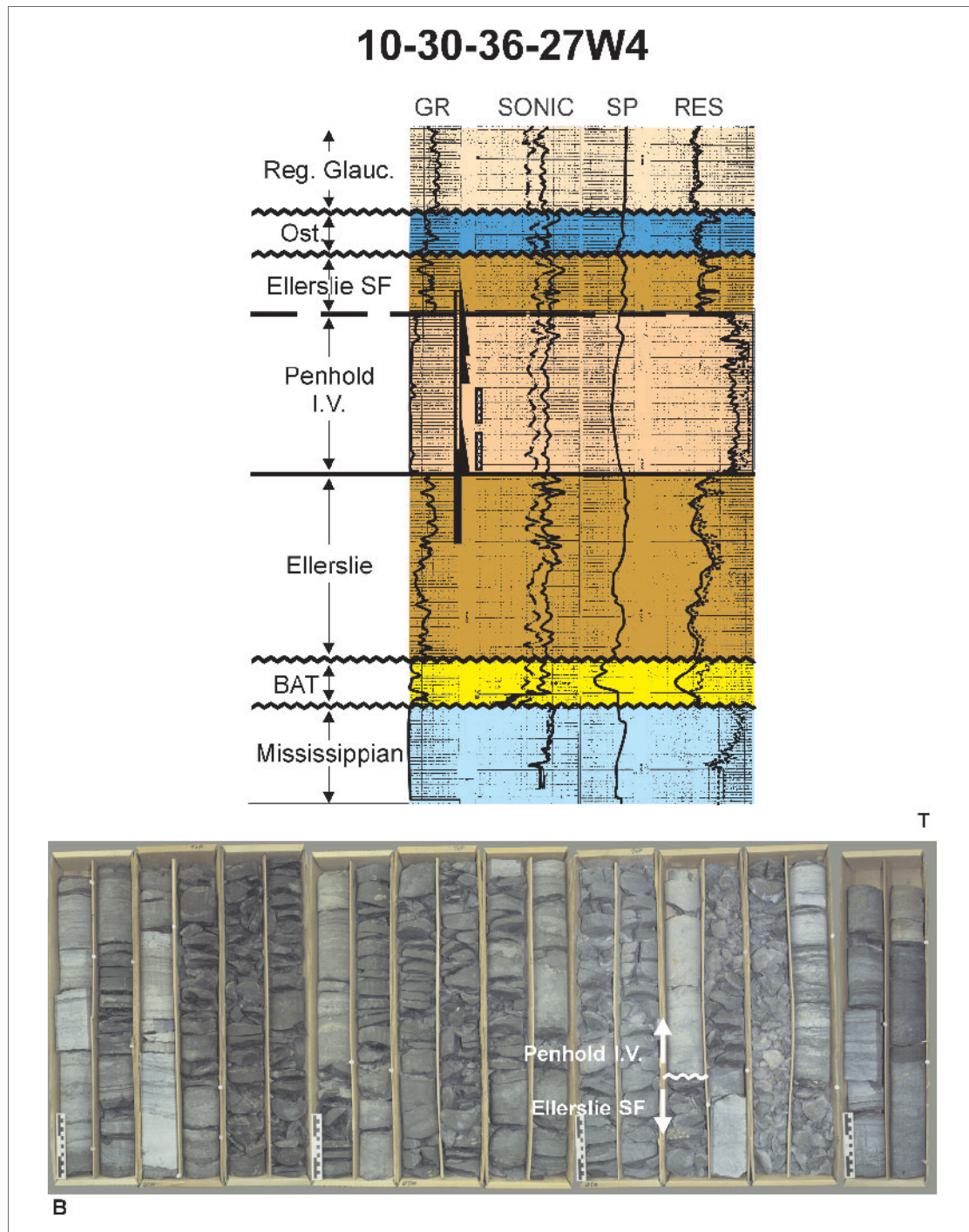


Fig. 27. Altex Lario Penhold 10-30-36-27W4 (6306–6354 ft.). Type well of Ellerslie (Penhold) Incised Valley fill cutting into Ellerslie shoaling-upward parasequences, eroded into by Ellerslie estuarine Penhold incised valley. B = bottom of core; T = top of core. Petrophysical logs include Gamma Ray (GR), Sonic, Spontaneous Potential (SP) and Resistivity (RES) logs. Note serrated and fining-upward nature of log motif associated with Ellerslie parasequences, blocky signature and low Gamma API associated with incised valley fill. Black bar represents cored interval.

zone of flexure is interpreted to represent the approximate position of the main drainage divide or interfluvium, based on the equal distance between mapped paleodrainage networks. In all cases, there is an offset in the zone of flexure north and south of the hinge line, directed toward the west. Second, the relative position of the zone of flexure migrates from west to east from the

A Sandstone, to Horsefly, to BAT, by approximately 60 km. However, the position of the zone of flexure for the BAT, Ellerslie and Ostrocod Member are approximately coincident, indicative of no further eastward migration after BAT deposition. During this period there is a significant southward transgression from Horsefly, through BAT, Ellerslie and Ostrocod

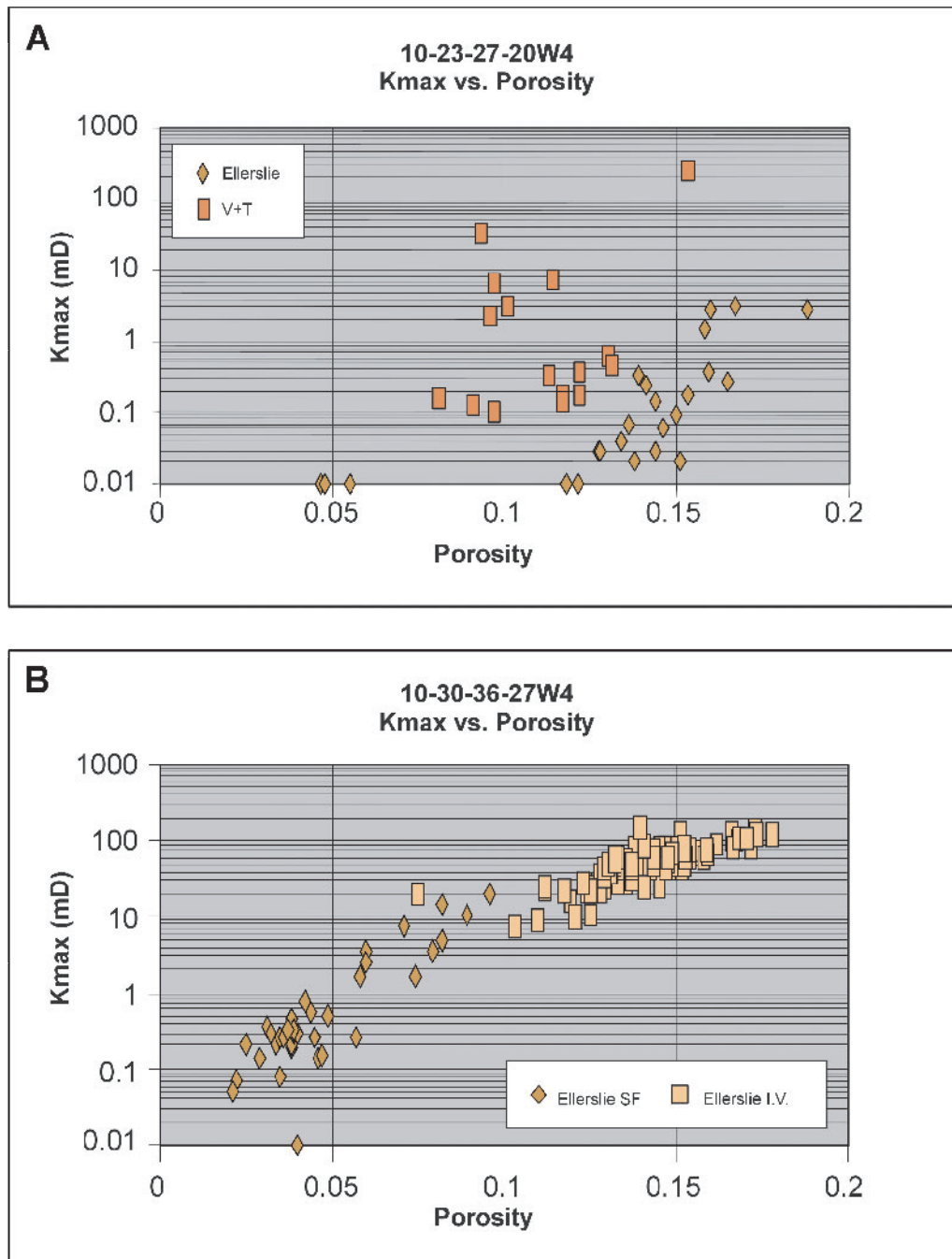


Fig. 28. Core Porosity (%) versus Permeability (Kmax; mD = millidarcies) to air for representative Ellerslie deposits. **A)** Ellerslie parasequences overlying valley and terrace (V&T) deposits at Mobil et al Wayne 10-23-27-20W4 (4424.9-4525.9 ft.). **B)** Ellerslie shoreface parasequences (SF) overlain by incised valley (IV) deposits at Altex Lario Penhold 10-30-36-27W4 (6306-6354 ft.; see Fig. 27).

Member, that manifests itself as a progressive widening of the depositional fairways.

The intersection of the zone of flexure with the hinge line divides the area into four quadrants, characterized by changes in depositional style and accommodation setting. The SE quadrant has been an area of low accommodation throughout BQ time, and is dominated by Regional A and Mesa IV deposits (Fig. 29). The Horsefly, present in the Whitlash Valley, is the approximate limit of the western margin of this quadrant (Fig. 15). The SW

quadrant was also an area of low accommodation, but with periods of rapid subsidence, as noted from the absence of significant pedogenic alteration of the Carmangay. Changes in the Horsefly valley depositional fill from low accommodation braided deposits to higher accommodation meandering are associated with syndepositional faulting; deposits indicate periods of short-lived higher accommodation conditions existed in this area. The NE quadrant was also an area of low accommodation. Thin, low accommodation BAT, Ostracod nondeposition, and prevalence

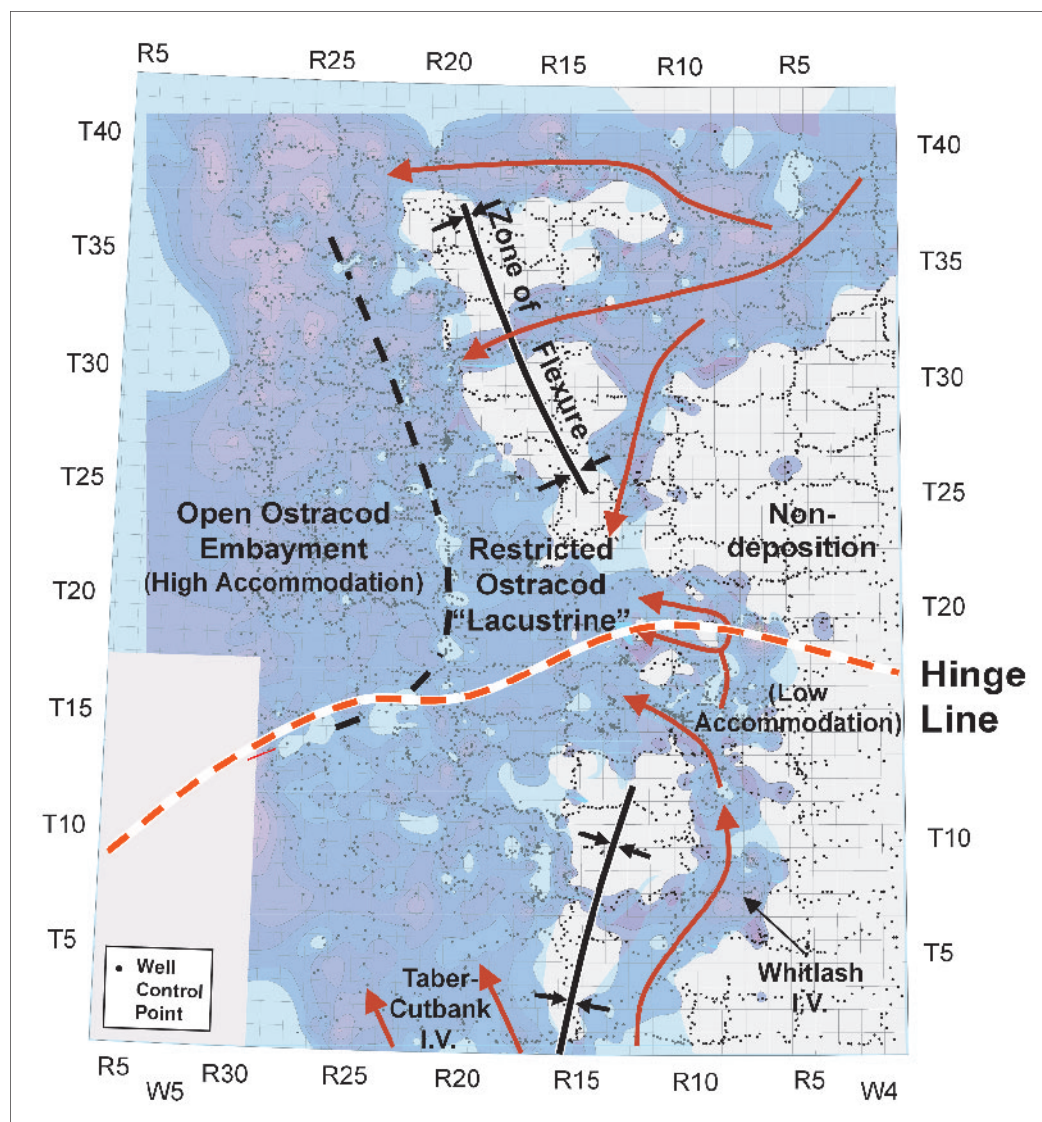


Fig. 29. Composite isopach and paleogeographic map of the Ostracod Member. Dots with no values are either representative of amalgamated paleosols over paleotopographic highs, or are areas truncated by Glauconic- or Upper Mannville-aged incised valleys. Arrows represent inferred paleodrainage direction.

of Regional A are indicative of low accommodation conditions for most of BQ time. Accommodation increased toward the northern limit of the NE quadrant with the deposition of the thick BQ sandstones associated with the Provost system. The quadrant with the highest accommodation conditions was toward the NW, north of the Vulcan Low and west of the zone of flexure. Deposition of the high accommodation BAT, Ellerslie and thick Ostracod, and the absence of extensive pedogenically altered deposits can be taken as evidence of rapid development of accommodation in this quadrant during BQ time.

TECTONIC MODEL CONTROLLING ACCOMMODATION IN THE BQ

The high resolution subdivision of the BQ presented in this paper allows for an examination of changing BQ depositional

patterns through time (Figs. 1, 5). Regional correlations summarized in Figures 30 and 31 show the abrupt change in complexity and stratigraphic distribution between low and higher accommodation quadrants north and south of the Vulcan Low and east and west of the zone of flexure (to be discussed below).

The primary process that influenced foreland basin accommodation was tectonic loading of the lithosphere during compression and crustal thickening. The observed stratigraphic relationships can be explained as a function of the interplay between eustasy and heterogeneous basement subsidence during the development of the Cretaceous foreland basin (Figs. 32, 33). More specifically, the BQ mapping highlights east-west and north-south changes in accommodation, related primarily to regional and local variations in mechanical response of the underlying basement during tectonic loading of the lithosphere

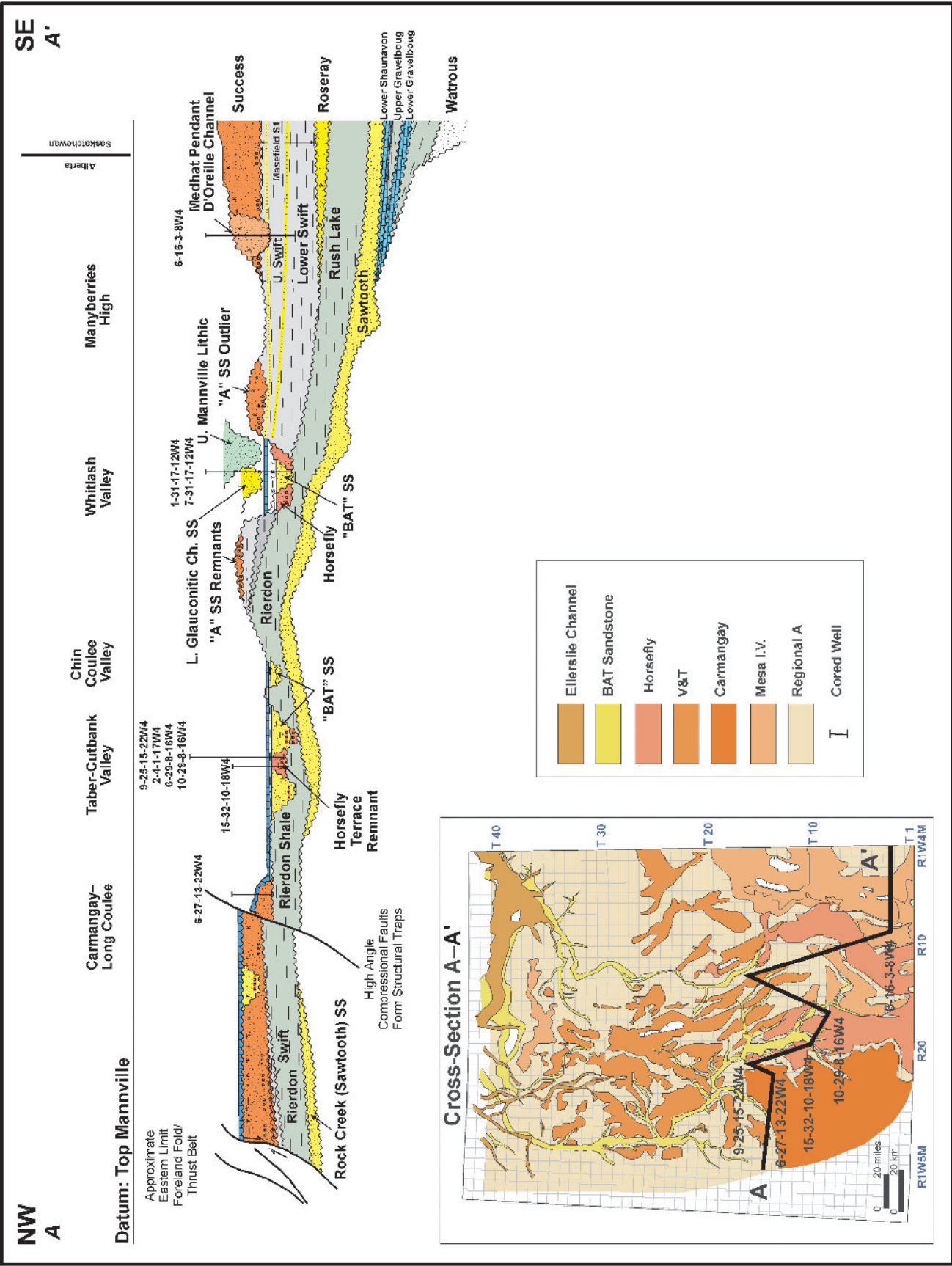


Fig. 30. Northwest-southeast schematic cross-section of Lower Mannville across southern Alberta. Cross-section A-A' exhibiting the distribution of Jurassic and BQ units in a low accommodation setting. Vertical bars and well locations refer to type wells. (see inset for location of cross-section).

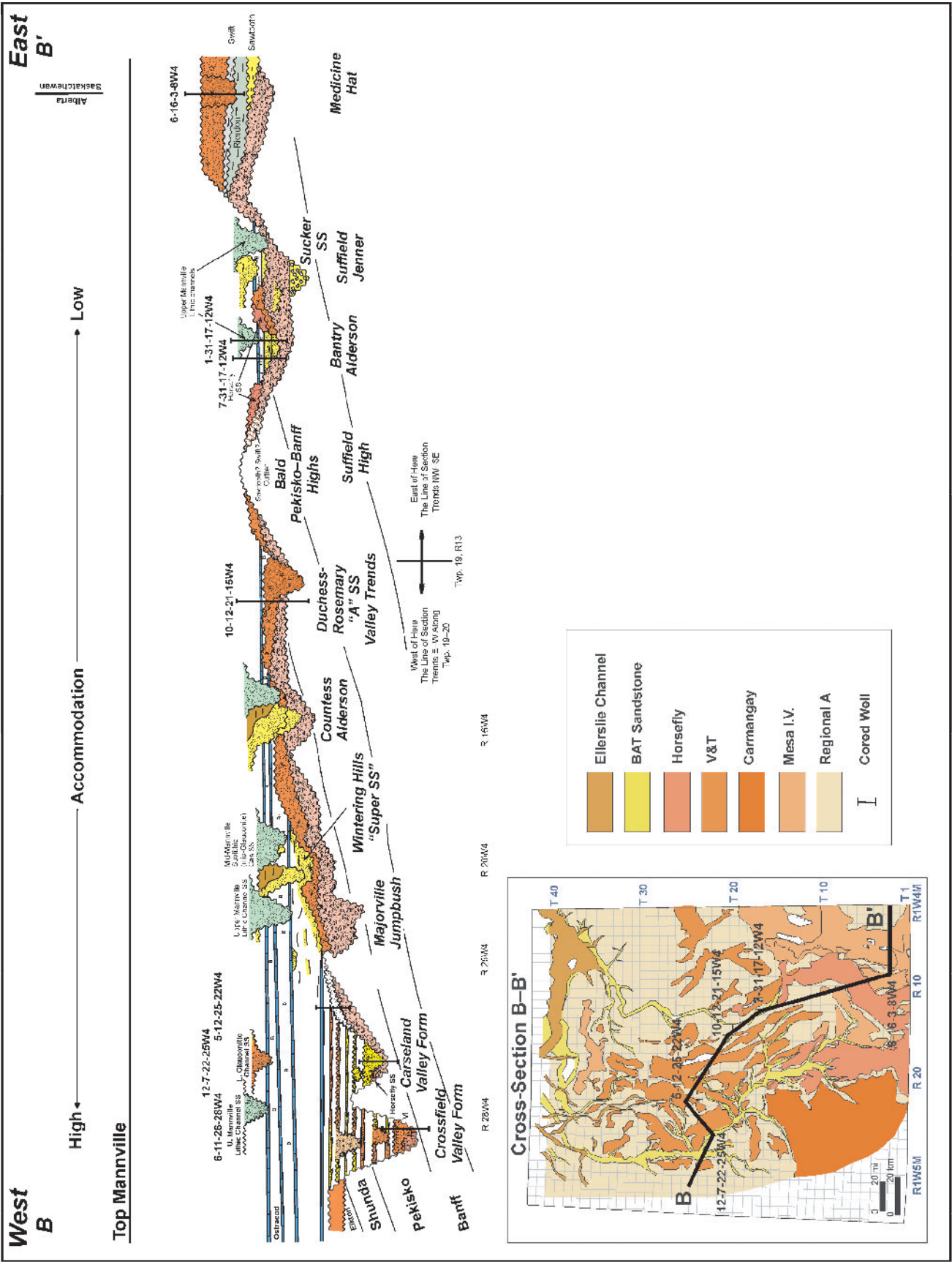


Fig. 31. West-east schematic cross-section of Lower Mannville across south-central Alberta. Cross-section B-B' exhibiting the distribution of Jurassic and BQ units in a low accommodation setting to the east, with increasing accommodation to the west. Vertical bars and well locations refer to type wells. (see inset for location of cross-section).

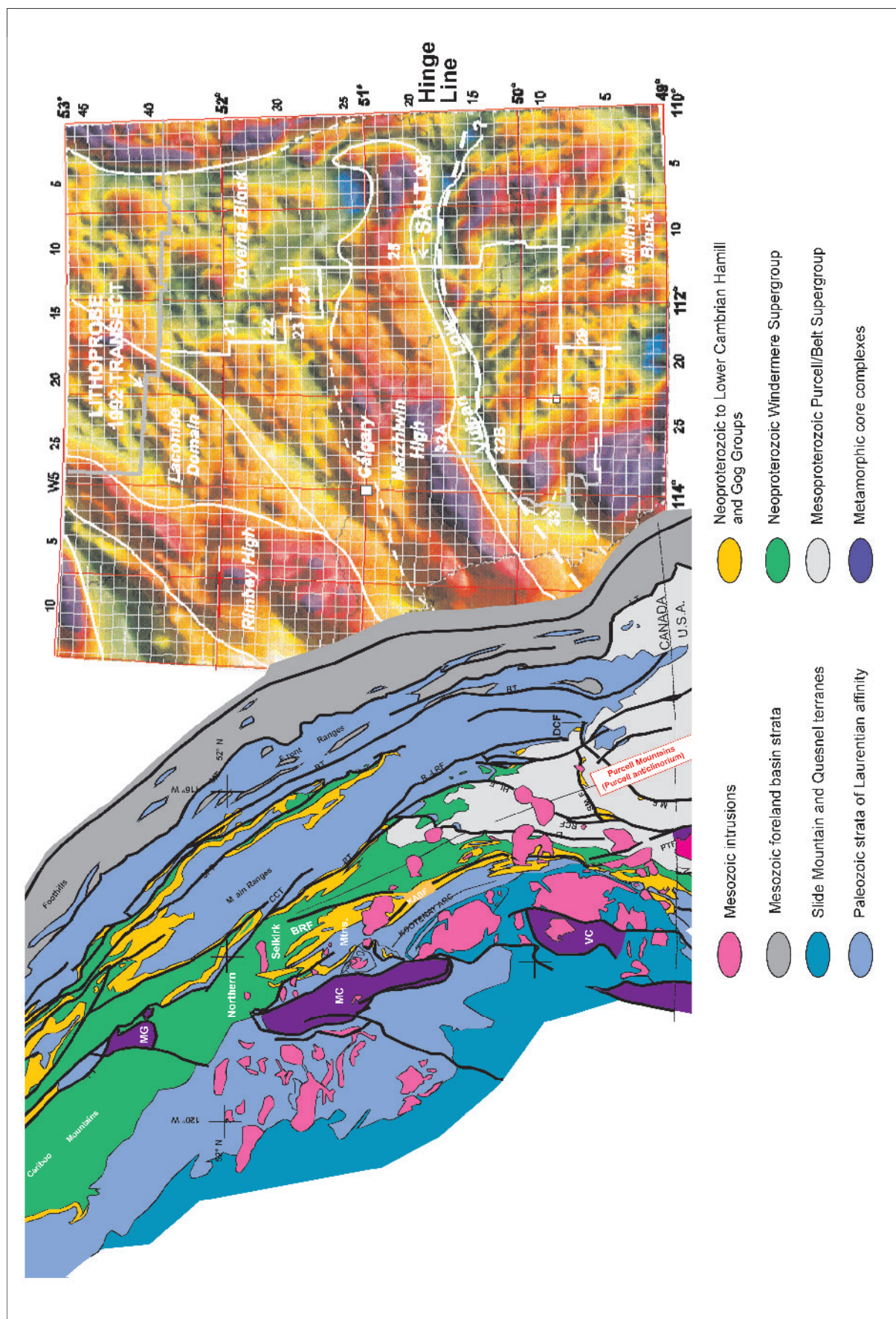


Fig. 32. Simplified geological map of the southeastern Canadian Cordillera, showing regional distribution of exposures of the Windermere Supergroup, and major structures and physiographic provinces (after Wheeler and McFeeley, 1991), adjacent to aeromagnetic map with interpreted basement terranes (Ross et al., 1997). Map depicts the variation in structural "grain" north and south of the Vulcan Low Hinge Line as discussed in text. MT = McConnell thrust; BT = Bourgeau thrust; SIT = Snake Indian thrust; SPT = Simpson Pass thrust; CCT = Chatter Creek thrust; PT = Purcell thrust; R-LRF = Redwater-Lussier River fault; DCF = Dibble Creek fault; MF = Movie fault; SMF = St. Mary fault; HLF = Hall Lake fault; RCF = Redding Creek fault; MFT = Mount Forster thrust; SRMTF = Southern Rocky Mountain Trench fault; PTF = Purcell Trench fault; BRF = Beaver River fault; KABF = Kootenay Arc boundary fault; PRC = Priest River Complex; MC = Monashee Complex; MG = Malton Gneiss; DR = Dogtooth Range.

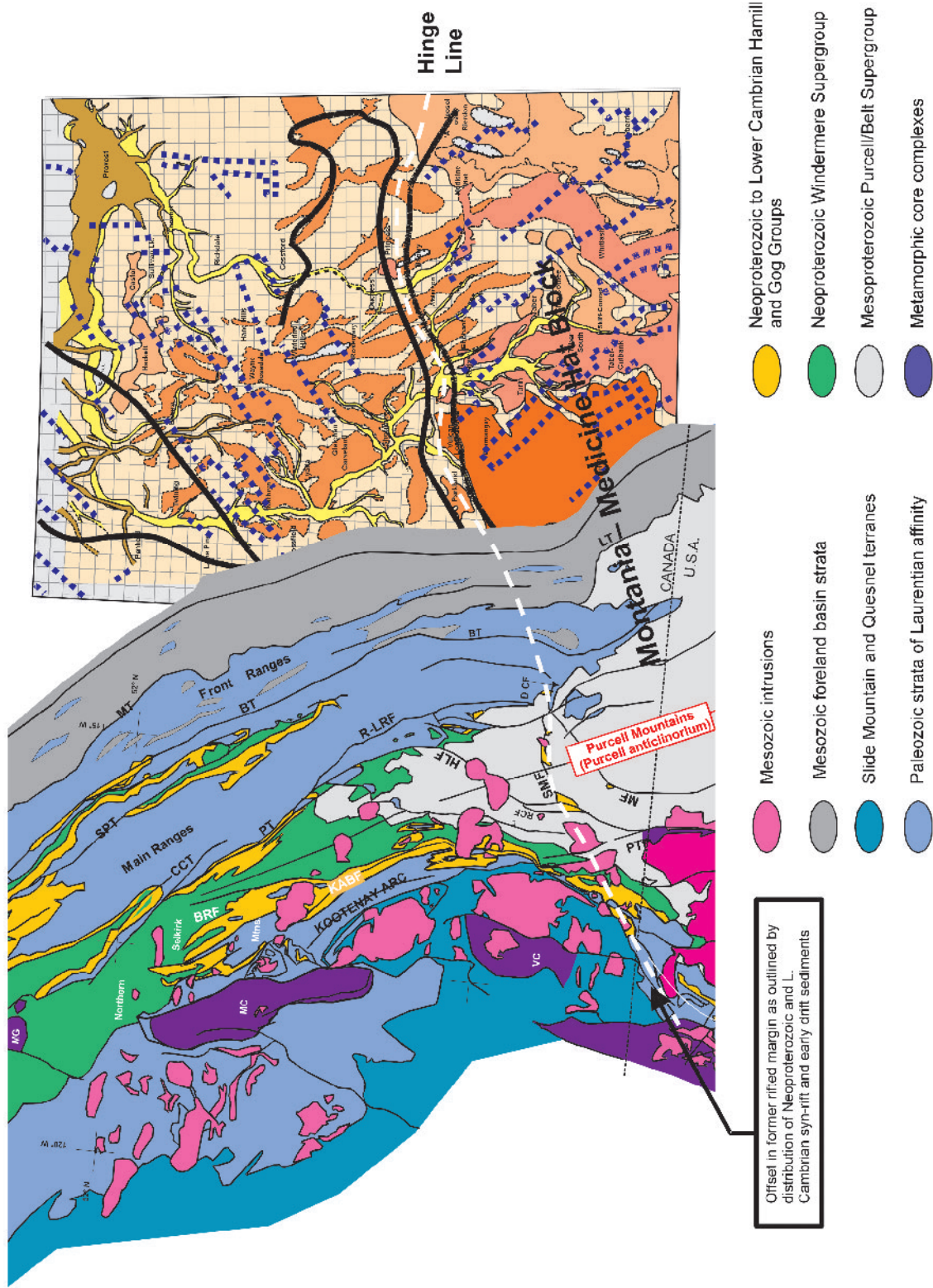


Fig. 33. Composite basement elements map (Ross et al., 1997) superimposed on the composite paleogeographic distribution map of BQ units (this paper), adjacent to the simplified geological map of the southeastern Canadian Cordillera, showing regional distribution of exposures of the Windermere Supergroup, and major structures and physiographic provinces (after Wheeler and McFeeley, 1991 – abbreviations listed in caption on Fig. 32). Note 1) the northern limit of the A-Carmangay, A-Mesa, and Horsefly units in the Taber-Cutbank and Whittash valleys south of the Vulcan Low and 2) the distribution of the A-Valley and Terrace north of the Vulcan Low.

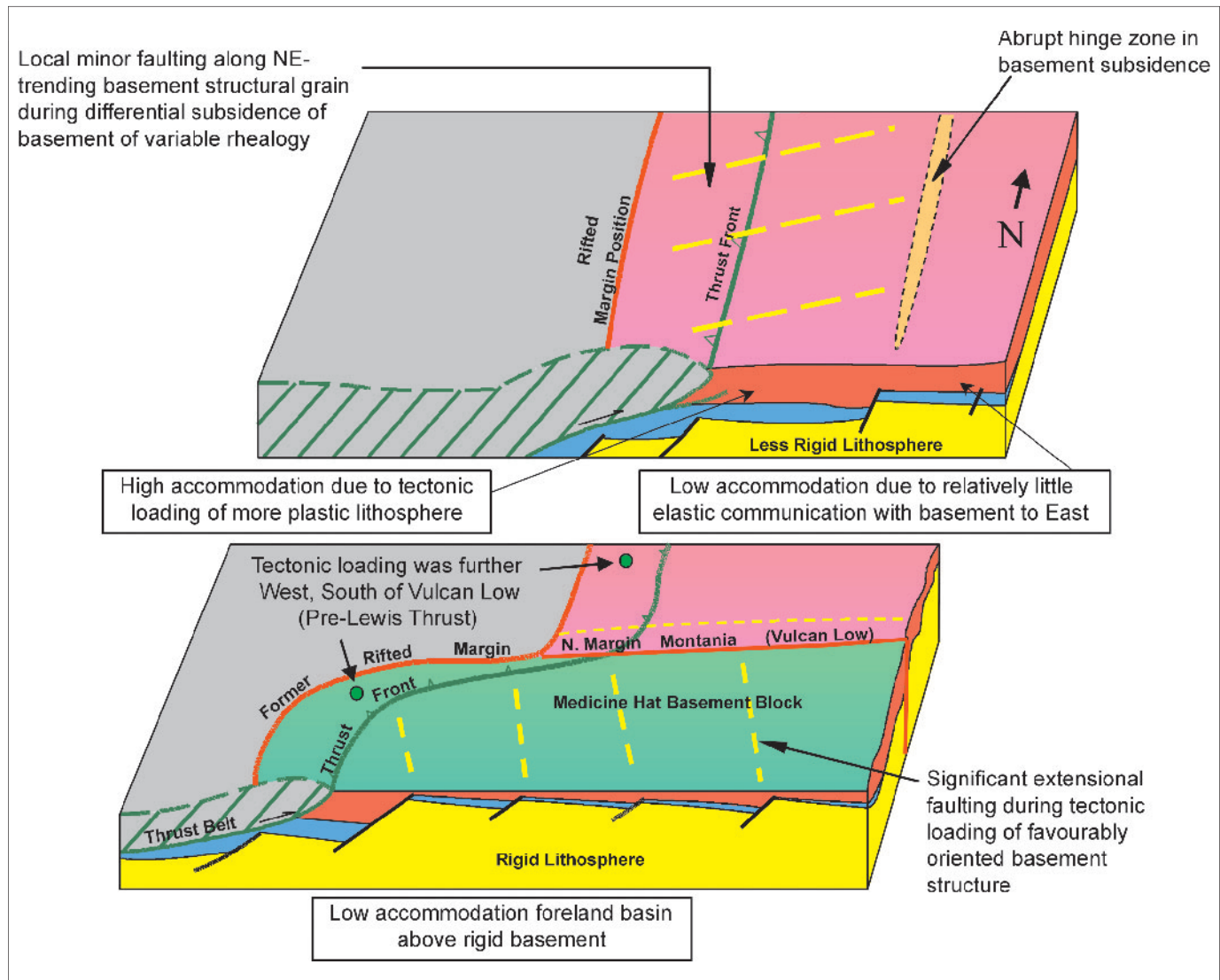


Fig. 34. Conceptual tectonic model for the southern WCSB, illustrating influence of Precambrian basement geology on foreland basin subsidence and structure in Cretaceous time.

(Fig. 34). The accommodation-limited setting helps to highlight relatively small-scale (often sub-seismic scale) faulting (e.g. Ardies, 1999; Lukie, 1999) and subtle variations in basement tectonic response that are otherwise difficult to document.

Several inter-related factors determined the amount of subsidence and local faulting in BQ time. Variations in lithospheric response were controlled both by variations in mechanical properties of underlying Precambrian basement and by along-strike variations in the geometry of the Neoproterozoic-Cambrian rifted margin, that was subsequently inverted during Jurassic-Cretaceous thrusting. On a local scale, pre-existing crustal weaknesses, reactivated as fracture systems or extensional faults during lithospheric flexure, served to localize and direct BQ drainage trends, particularly if favourably oriented with respect to the thrust front.

The basement geology of the WCSB has been investigated and discussed extensively (e.g. Ross et al., 1991, 1994, 1995). Precambrian basement beneath the southern WCSB comprises

several distinct Archean and early Paleo-Proterozoic terranes that were tectonically assembled during Paleo-Proterozoic collision and growth of the Canadian Shield (Ross et al., 1995). The aeromagnetic anomaly map of southern Alberta (Fig. 32) highlights basement trends beneath the present study area that are the product of tectonic assembly of terranes of different compositions and different structural "grain." The Medicine Hat block in the south is separated from several basement domains to the north, grouped together in this discussion as the Loverna Block, by the Vulcan Aeromagnetic Low (Fig. 32, 33). Ross et al. (1995) have interpreted the Vulcan Aeromagnetic Low as the locus of a major suture between the Archean Medicine Hat block and the Loverna Block. They have discussed evidence for differences in the mechanical properties and strength of lithosphere that underlies these different basement domains: specifically, a contrast between greater flexural rigidity of the Medicine Hat block versus less rigid lithosphere underlying domains north of the Vulcan Aeromagnetic Low. Aeromagnetic

data also highlight conspicuous differences in the orientation of the basement structural grain in these different blocks, i.e. strong NW–SE grain in the Medicine Hat block, in contrast to a NE–SW grain in the Loverna Block (Figs. 32, 33).

The Vulcan Aeromagnetic Low and Paleo-Proterozoic tectonic suture are on trend with a major, long-lived ENE-trending zone of extensional faulting in the thrust belt to the west (Fig. 33). This significant structural discontinuity separates a high-standing crustal block to the south (termed “Montania” by Deiss, 1940, 1941) from a much more deeply subsided block to the north, and was intermittently active from Neoproterozoic through mid-Paleozoic time (e.g. Price, 1981). The structural zone coincides with a 200 km westward deflection in the former rifted continental margin (Price, 1981) and may represent a major transform fault on the margin (Warren, 1997). The distribution of BQ lithostratigraphic units suggests that this crustal-scale discontinuity was again reactivated as a hinge line (Figs. 33, 34) during Early Cretaceous time.

The strong correlation between the distribution and style of the various BQ cycles and units and underlying basement structure allows us to present a conceptual model summarizing the tectonic controls on foreland basin subsidence (Fig. 34). Three inter-related factors resulted in lower accommodation during BQ time to the south of the Vulcan Low. Southernmost Alberta is underlain by more rigid lithosphere associated with an Archean basement domain. The high flexural rigidity of lithosphere is compounded by the transition to continental crust that was highly attenuated during Neoproterozoic or Early Cambrian continental rifting located at least 200 km farther to the west than it is north of the Montania–Medicine Hat block (e.g. Price, 1981). Finally, pre-108 Ma (pre-Ostracod Member) compressional inversion of the Proterozoic and Paleozoic marginal basin followed the locus of the hinge zone in the former rifted margin, resulting in tectonic loading and a related initial foredeep axis that was also farther west to the south of the Vulcan Low.

The older units (up to and including the Horsefly unit) are better preserved in the south where the accommodation was the least. The Medicine Hat block would appear to have been relatively high and the area to the north relatively low. The reversal of maximum preservation between Horsefly and BAT times suggests that the area of maximum flexural loading changed: in the south first, and later in the north. A possible reason for this is that the continental margin on the south side of the Vulcan Low (Montania) protruded further to the west, and may have been impacted earlier than the part of the continental margin further north. This first contact in the south is consistent with the change from an eastward-directed paleoslope in the earlier A Sandstone, to a NNW-directed system in the later units, implying that the onset of flexural loading occurred during latest A-unit time.

Lower overall accommodation over the Montania–Medicine Hat crustal block during BQ time is recorded by a markedly thinner BQ succession (Fig. 31). Specifically, lower accommodation is recorded by widespread exposure and

pedogenic alteration of existing Regional A and Mesa IV, and by limited southward incision or preservation of Valley and Terrace, BAT, and Ellerslie. Slightly greater lithospheric flexure and subsidence closer to the thrust front is recorded by preservation of the Carmangay and the subsequent protection from pedogenic alteration, resulting in overall better reservoir quality compared with other A-units. The extensionally-faulted and relatively high-standing northern edge of Montania–Medicine Hat block acted as a hinge line across which northwest-trending structurally-controlled Valley and Terrace and BAT unit valley systems cut downward and drained northwestward into higher accommodation areas.

To the north of the Montania–Medicine Hat block, the WCSB was underlain by less elastic lithosphere comprising a combination of Paleo-Proterozoic and Archean basement terranes. Relatively lower flexural rigidity resulted in greater overall accommodation to the northwest and in a more abrupt gradient in accommodation from east to west, recorded by the contrast in thicknesses of major north-draining BAT incised valley systems from east to west (Fig. 32).

SUMMARY AND CONCLUSIONS

The Lower Cretaceous Basal Quartz (BQ) of Southern Alberta can be informally divided into seven mappable lithostratigraphic units based on detailed correlations, depositional styles, and lithostratigraphic analyses. The study area is considered to be accommodation-limited — where long term subsidence rates are low compared to sediment supply. This high-resolution subdivision of the BQ presented allows for an examination of changing BQ paleodrainage through time.

The zone of flexure represents the approximate position of the main drainage divide. In all cases, there is an offset in the zone of flexure north and south of the Vulcan Low toward the west. The zone of flexure migrates from west to east from the A Sandstone through BAT time, by approximately 60 km. During BAT, through the Ostrocod, the zone of flexure is coincident, indicative of no further eastward migration. However, there is a significant southward transgression from Horsefly through Ostrocod that manifests itself as a progressive widening of the depositional fairways.

The intersection of the zone of flexure with the hinge line divides the area into four quadrants, characterized by changes in depositional style and accommodation setting. The SE quadrant has been an area of low accommodation, dominated by Regional A and Mesa IV deposits (Fig. 29). The SW quadrant was also an area of low accommodation, however the absence of significant pedogenic alteration of the Carmangay indicates relatively rapid subsidence. Changes in the Horsefly depositional fill from low accommodation braided deposits to higher accommodation meandering are associated with local syn-depositional faulting. The NE quadrant was also an area of low accommodation with thin low accommodation BAT, Ostracod nondeposition, and prevalence of Regional A. Accommodation increased toward the northern limit of the NE quadrant with the deposition of the thick BQ sandstones associated with the

Provost system. The quadrant with the highest accommodation conditions was toward the NW. Deposition of the high accommodation BAT, Ellerslie, and thick Ostracod, and the absence of extensive pedogenically altered deposits are evidence of rapid development of accommodation.

Multiple levels of cyclicity exist in the BQ, from cycles that reflect increasing-upward mineralogical and textural maturity to progressive changes in channel geometry organization associated with changes in accommodation.

The data can be integrated with existing geological and geophysical data from the WCSB and the Cordilleran thrust belt, to explain the observed stratigraphic relationships as a function of the interplay between eustasy, heterogeneous basement subsidence and the position relative to the thrust front. From this interplay four quadrants can be attributed to the combination of along-strike change in deep basin structure and differential foreland basin loading across basement terranes. Tectonic influences on sedimentation are most obvious in the sediments immediately overlying long-duration unconformities. Fluvial erosion on the unconformity surface amplifies the tectonic signal by accentuating the tectonically produced relief in a low accommodation setting. The accommodation-limited conditions occurring during BQ deposition resulted in sequence boundaries amalgamating on the interfluvial, and it is only by detailed correlation and petrographic analysis that BQ units can be differentiated.

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