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Late Mesozoic reactivation of Precambrian basement structures and their resulting effects on the sequence stratigraphic architecture of the Viking Formation of east-central Alberta, Canada

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ABSTRACT

The Lower Cretaceous Viking Formation is a siliciclastic unit that occurs in the subsurface of Alberta in the Western Canadian sedimentary basin. This study focuses on a lowstand paleoshoreline trend extending along strike between two hydrocarbon-producing fields, Joarcam and Judy Creek (250 km NW). The Viking Formation in these fields records depositional thicknesses ranging from 20 to 30 m. Between these two fields, however, the formation is anomalously thick (45–60 m), complicating the recognition and correlation of key stratigraphic surfaces. Marine flooding surfaces above and below the Viking Formation are routinely employed as stratigraphic datums in order to remove postdepositional deformation and facilitate the development of a sequence stratigraphic framework. However, as each successive surface is employed as the datum, the other flooding surfaces within the formation become distorted, resulting in unrealistic depositional geometries. These geometries are best explained to be the result of structural readjustments during Viking deposition.

The Precambrian lithosphere of the Canadian Shield forms the Western Canadian sedimentary basin basement, with major structures previously mapped using gravity and magnetic anomaly studies. Locally, the increased accommodation observed within the Viking Formation of central Alberta is attributed to differential reactivation of the Paleoproterozoic Snowbird tectonic zone basement structures, which flank the areas of anomalously thick deposits and trend approximately normal to the regional strike of the Western Canadian sedimentary basin. The Snowbird tectonic zone faults are interpreted to have been reactivated during renewed tectonic loading in the southern Canadian Cordillera during Aptian–Albian time, causing subtle readjustments along basement faults that caused variable syndepositional subsidence. By selecting successive datums, the gross Viking interval can be recognized to have accumulated prior to, during, and following structural reactivation.

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INTRODUCTION

Foreland depositional systems are inherent geologic features that develop within the retroarc region of convergent plate margins where tectonic loading related to orogeny causes flexure of the underlying cratonic lithosphere and epeirogenic subsidence (e.g., Porter et al., 1982; Price, 1994; Catuneanu, 2004). Clearly, the style of flexural response associated with episodes of tectonic loading will be a controlling influence on the overall, first-order basin geometry and depositional characteristics. However, anisotropies within the underlying cratonic basement, such as preexisting faults and shear zones, may become the loci of strain during flexure (e.g., Godin and Harrison, 2014), which can cause these structures to be reactivated, leading to subtle offsets and variations in accommodation space within the basin (e.g., Stein, 1988; Vakarelov et al., 2006; Vakarelov and Bhattacharya, 2009; Lyatsky et al., 2005).

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The reactivation of basement structures and faults has been documented to play a crucial role in the evolution of dynamic sedimentary environments (Holdsworth et al., 1997; Ross and Eaton, 1999; Pană, 2003). The Western Canadian sedimentary basin of Alberta overlies a crystalline basement (i.e., the Canadian Shield) that was assembled in the Paleoproterozoic. This construct has been subdivided into geological domains that represent the mosaic of Archean and Neoproterozoic cratonic fragments and the suture zones that welded them together (Ross et al., 1991; Ross and Eaton, 1999). The crystalline basement is overlain by an eastward-thinning succession of predominantly Paleozoic carbonates that accumulated when the Western Canadian sedimentary basin served as a passive margin. This carbonate interval is unconformably overlain by a predominantly siliciclastic interval that accumulated from the Triassic to late Paleogene as the continental margin evolved into a foreland basin during Jurassic time (Price, 1994). The geometry of deposition of the Phanerozoic section over the crystalline basement was influenced by the reactivation of brittle faults in the subsurface that propagated into the overlying basin (Ross and Eaton, 1999; Lyatsky et al., 2005). These faults may also have controlled the migration of fluids within the subsurface, which may have contributed to

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the accumulation of hydrocarbons and mineral deposits (Ross and Eaton, 1999; Zaitlin et al., 2002; McMechan, 2012). However, the reactivation of such basement structures is commonly overlooked, owing to the fact that such movements along faults and the attendant deformation tend to be subtle. In this study, high-resolution sequence stratigraphic mapping was undertaken at a scale that facilitated detection of such subtle movements during deposition of the Viking Formation.

The Viking Formation is a Lower Cretaceous (late Albian) siliciclastic unit that is widespread in the subsurface of the Western Canadian sedimentary basin (Fig. 1). The interval records a complex depositional history, manifested by the presence of multiple internal discontinuities within the succession and between various hydrocarbon fields (cf. Boreen and Walker, 1991; Pattison, 1991; Leckie and Reinson, 1993; Posamentier and Chamberlain, 1993; Walker and Wiseman, 1995; MacEachern et al., 1999; Roca et al., 2008; Plint et al., 2012). Throughout Alberta, significant quantities of oil and gas have been produced from Viking Formation deposits that are interpreted to record shoreface, deltaic, estuarine valley fill, and transgressive lag settings.

Study Area

The study area (Fig. 1) encompasses deposits that occur along an inferred forced regressive to lowstand paleoshoreline trend developed during early stages of Viking deposition. The Viking Formation is mapped

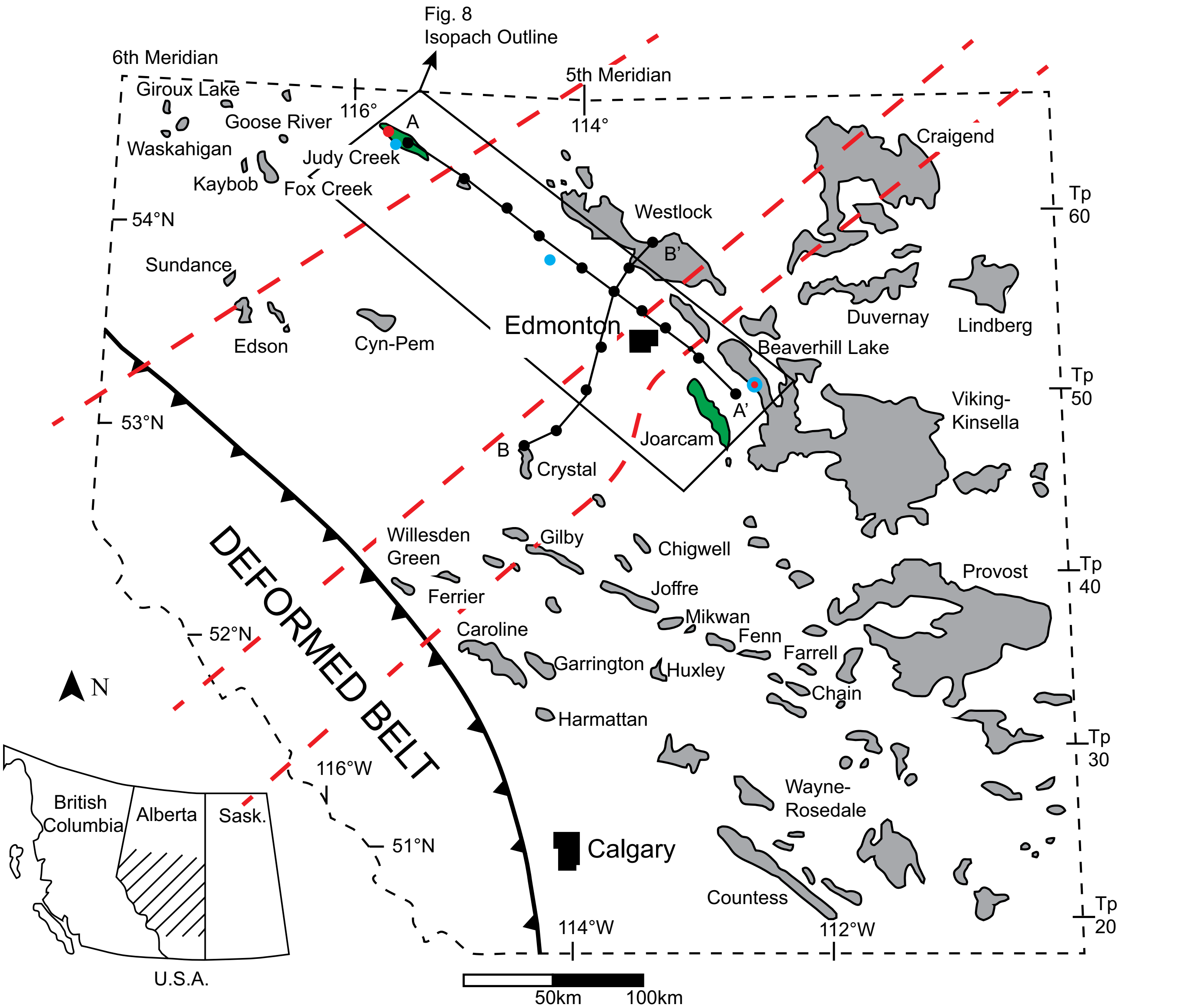

Figure 1. Study area map showing the distribution of fields that produce from the Viking Formation (modified from Pattison, 1991; MacEachern et al., 1998). The Joarcam and Judy Creek Fields are indicated by the green polygons, with the main study outlined by the black box. Solid lines (A-A′ and B-B′) indicate the locations of wells from the cross sections in Figure 2. The cross section A-A′ shows the locations of wells that were selected for the skeletonized cross sections presented in Figure 6. The two red wells indicate the wells used to compare Judy Creek to Joarcam in Figure 3. Locations of the cored intervals from Figure 5 are indicated by the blue dots. The northeast-southwest–striking Snowbird tectonic zone (STZ) has been superimposed onto this map (red dashed lines) from locations presented in previous studies (see Ross et al., 1991; Villeneuve et al., 1993; Pilkington et al., 2000; Lyatsky et al., 2005).

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along depositional strike from the Judy Creek Field (54.45°N, 115.65°W) southeast toward the Joarcam Field (53.40°N, 113.05°W). Hydrocarbon-producing intervals in both fields trend in a general NW-SE orientation.

Currently, there is no published stratigraphic framework along the lowstand paleoshoreline trend between the Judy Creek and Joarcam Fields (Fig. 1). Both Joarcam and Judy Creek are interpreted to have been deposited in a low-accommodation setting in the basin. We hypothesized that the intervening area between the fields would display a similar trend. However, our initial investigations in the intervening area indicated that the Viking Formation there is 1.5 to 2 times thicker than in the Judy Creek and Joarcam Fields. The current study seeks to explain the mechanisms responsible for the increased accommodation and to demonstrate how these deposits can be integrated into the developing sequence stratigraphic framework for the Viking Formation.

Sequence Stratigraphy

Sequence stratigraphy describes the relationship and distribution of stratal stacking patterns of sedimentary bodies that are genetically related and conformable at any temporal or spatial range (Catuneanu et al., 2011). One of the sequence stratigraphic frameworks currently accepted by the International Stratigraphic Commission is the four systems tract model, which includes the lowstand systems tract, the transgressive systems tract, the highstand systems tract, and the falling stage systems tract (i.e., forced regression; sensu Catuneanu et al., 2011). Stratal stacking patterns in this model are related to changes in accommodation space and sediment supply, which are controlled by changes in base level.

A sequence stratigraphic framework has been proposed for the Judy Creek Field (MacEachern et al., 2012), and we extended correlations southeast from this model to test the validity of the key stratigraphic surfaces along strike (Fig. 2). The reservoir deposits at Judy Creek have been interpreted to represent the lowstand position of a major relative sea-level fall during early deposition of the Viking Formation. There, remnants of a falling-stage systems tract shoreface pass seaward across a correlative conformity into the progradational and aggradational shoreface deposits of the lowstand systems tract, extending to its maximum regressive limit for that sequence. Similarly, the Joarcam Field has been previously interpreted to represent deposition of a lowstand systems tract (Power, 1988; Posamentier and Chamberlain, 1993). When comparing the deposits between Judy Creek and Joarcam, the relative depositional thicknesses remain constant, and stratigraphic surfaces can be correlated broadly along depositional strike from one field to the other (Fig. 3). Therefore, the intervening area between Judy Creek and Joarcam was hypothesized to follow a similar trend, with the key surfaces correlative along strike.

Structural History

The Western Canadian sedimentary basin underwent multiple phases of tectonic evolution before becoming a foreland basin sedimentary depocenter. Three main tectonic phases are proposed for the basin: (1) Precambrian to Paleozoic rifted and passive margin related to continental extension (Bond and Kominz, 1984); (2) Devonian to Early Jurassic conversion to a convergent margin, resulting in long-lived continental arc magmatism accompanied by a series of collisional events involving the accretion of allochthonous terranes and the development of back-arc basins; and (3) Jurassic to Paleogene foreland basin development and infill during terrane collision with the North American margin (Price, 1994).

The development of the foreland basin is attributed to Mesozoic to early Cenozoic crustal thickening in the Cordilleran orogen along the western margin of North America, which caused an isostatic flexural response in the rigid lithosphere supporting the orogen (Fig. 4; Price, 1973; 1994; Beaumont, 1981). The lithospheric flexure also resulted in reactivation of some preexisting basement structures, which have been constrained using depositional patterns in Phanerozoic strata. For instance, it has been suggested that reactivation served as a control on some Devonian reef orientations and development, the orientation of strandplain shoreline deposits, and the accumulation of hydrocarbons and mineral deposits (Ardies et al., 2002; Zaitlin et al., 2002; Fielding, 2011; McMechan, 2012). However, few studies have addressed how the reactivation of Precambrian basement structures affected accommodation space during the deposition of the Phanerozoic succession. Understanding movements along Precambrian basement structures during Viking deposition will provide a unique way to reconcile ambiguous stratigraphic relationships and constrain the timing of fault reactivation.

Basement Structures—Snowbird Tectonic Zone

Precambrian basement structures and domains beneath the Western Canadian sedimentary basin in Alberta have been identified and mapped using gravity and magnetic anomaly data (e.g., Ross et al., 1991; Pilkington et al., 2000; Lyatsky et al., 2005), supplemented by U-Pb analyses from drill-core samples (Ross et al., 1991). Subtle, high-angle, block-bounding brittle basement structures were also identified by Lyatsky et al. (2005) by integrating multiple geophysical data sets compiled and leveled by the Geological Survey of Canada (GSC).

The Snowbird tectonic zone has been the subject of numerous studies in the Northwest Territories and northern Saskatchewan, where it is exposed at the surface. The Snowbird tectonic zone has been mapped into the subsurface of Saskatchewan and Alberta, where it trends southwestward beneath the Phanerozoic rocks of the interior platform and Western Canadian sedimentary basin. The Snowbird tectonic zone is a sinuous, generally steeply dipping zone of intensely sheared rocks, which has been variably interpreted as the remnants of a collision, a rift zone, or an intracontinental shear zone (cf. Gibb and Walcott, 1971; Lewry and Sibbald, 1980; Hoffman, 1988; Hanmer et al., 1995; Ross et al., 2000; Mahan and Williams, 2005; Berman et al., 2007). Although its origin remains controversial, the steeply dipping structure is readily identified through gravity and magnetic surveys (Ross et al., 1991; Pilkington et al., 2000; Lyatsky et al., 2005). In central Alberta, the Snowbird tectonic zone is a geophysical anomaly reflecting a structural fault zone between two Archean crustal fragments (Hoffman, 1989; Ross et al., 1991).

METHODOLOGY

Wells that contain cores of the Viking interval were logged in order to identify the key stratigraphic surfaces. High-resolution descriptions of cores provide a detailed account of the sedimentology, ichnology, and position of key stratigraphic surfaces (Fig. 5). Along the Judy Creek–Joarcam lowstand shoreline trend, roughly 250 cores intersect the Viking Formation. Of these, 60 cores at Joarcam, 70 cores along the Judy Creek–Joarcam trend, and 42 cores at Judy Creek were incorporated in this study.

Significant stratigraphic surfaces identified in cores were keyed to their corresponding geophysical well-log responses (Fig. 5). Along the Judy Creek to Joarcam trend, ~400 wells with 900 well-log suites were incorporated into the stratigraphic framework. As these key stratigraphic surfaces were identified, cross sections were created to test their validity along depositional strike. Stratigraphic datums were selected in order to remove the effects of postdepositional tectonism and deformation. Datums were assessed to fit as closely as possible to the following set of criteria: (1) originally deposited as close to horizontal as possible; (2) associated with limited paleotopographic relief; and (3) easily identifiable and present in all sections.

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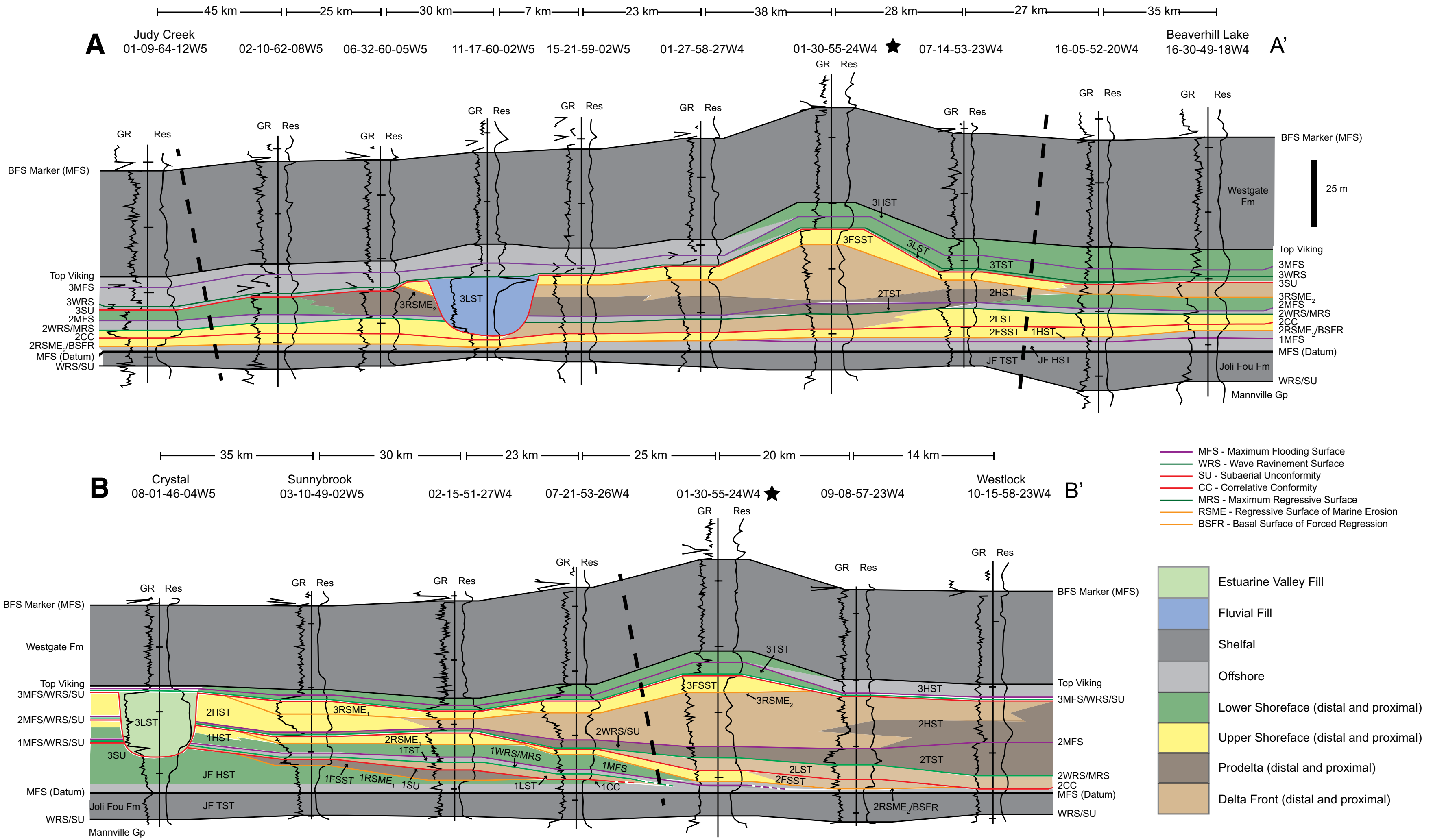

Figure 2. Proposed sequence stratigraphic framework for the deposits that intersect the overthickened sections. (A) A-A′ extends from the producing oil field at Judy Creek southeast toward the Joarcam Field. (B) B-B′ extends from the producing oil field at Crystal Field (incised valleys) and intersects the A-A′ cross section in well 01–30–55–24W4 (highlighted by the star). This cross section crosses over the Snowbird tectonic zone between the 07–21 well and the 01–30 well. BFS Marker—Base of Fish Scales Marker datum; MFS—maximum flooding surface; LST/TST/HST/FSST—lowstand, transgressive, highstand, and falling-stage systems tracts; GR—gamma-ray log; Res—resistivity log.

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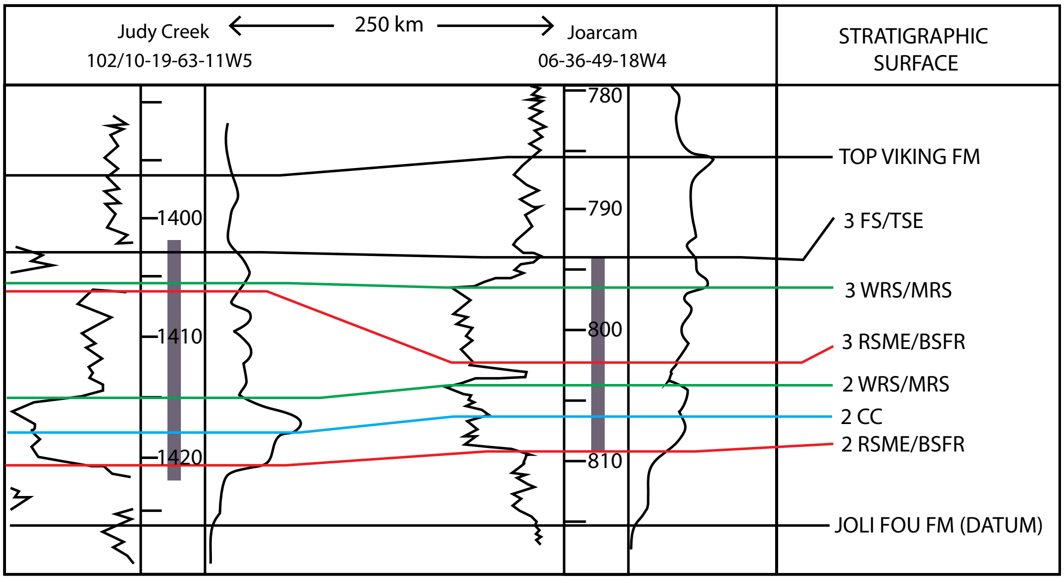

Figure 3. Comparison between stratigraphic surfaces of Judy Creek (102/10–19–63–11W5) and Joarcam (06–36–49–18W4). The gray bars represent the cored interval in each well. At Judy Creek, the second sequence of deposition is preserved as a falling-stage systems tract/lowstand systems tract deposit. Higher up in the interval, the third sequence is expressed as a complex, amalgamated surface. At Joarcam, the second sequence of Viking deposition is preserved as a falling-stage systems tract/lowstand systems tract deposit. The third sequence of deposition is preserved as a falling-stage systems tract/lowstand systems tract delta that can be correlated limited distances along strike. FS/TSE—flooding surface/transgressive surface of erosion; WRS/SU—wave ravinement surface/subaerial unconformity; WRS/MRS—wave ravinement surface/maximum regressive surface; RSME/BSFR—regressive surface of marine erosion/basal surface of forced regression; CC—correlative conformity.

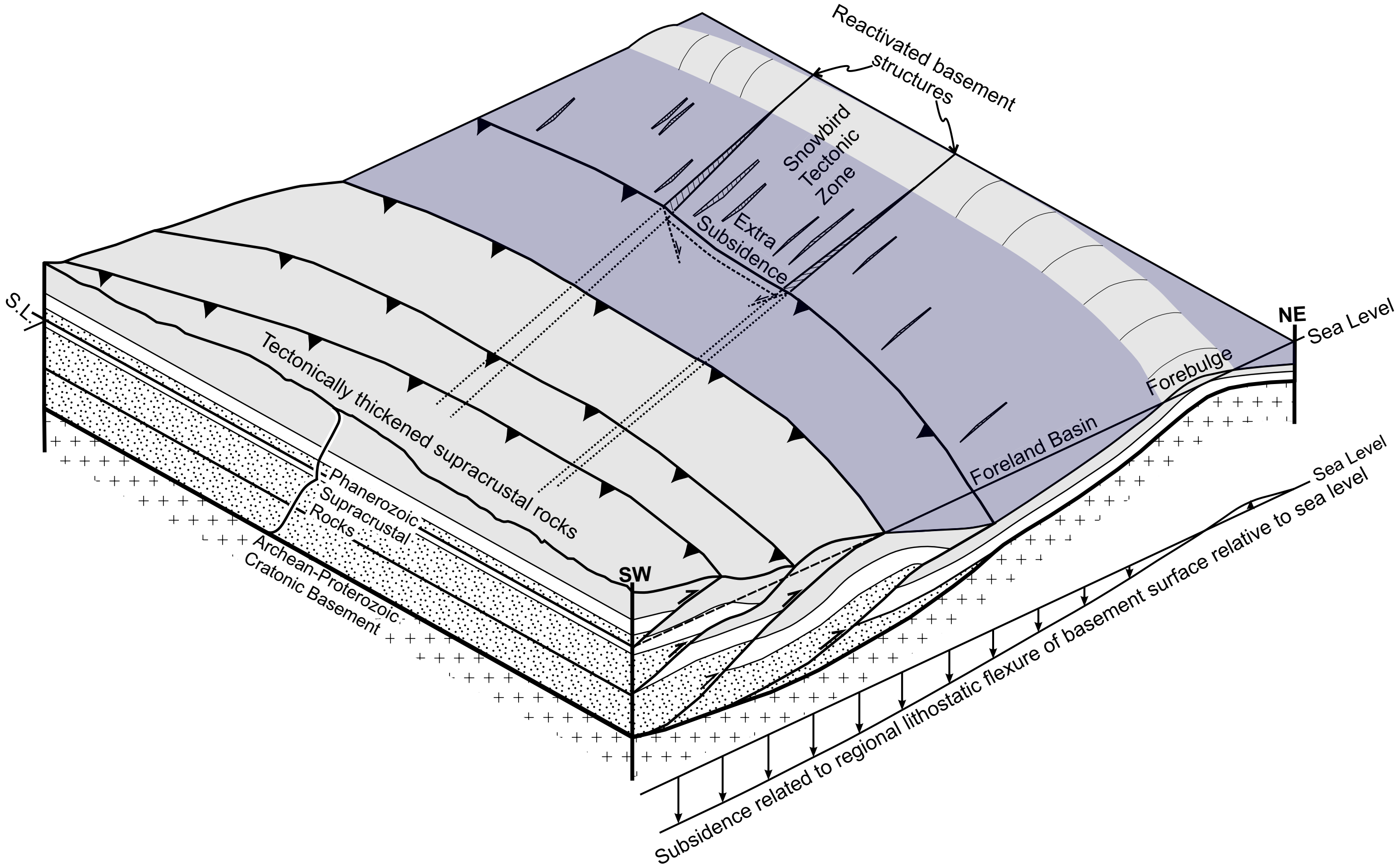

Figure 4. Schematic block diagram showing conceptual model for the formation of the foreland basin by regional lithostatic flexure of the cratonic lithosphere induced by loading of the tectonically thickened supracrustal rocks of the fold-and-thrust belt (modified after Price, 1994, 1973). Also shown is the additional subsidence in the area affected by basement structures that were reactivated as a result of the lithostatic flexure. The forebulge experiences a low rate of subsidence and/or subtle uplift, leading to increased rates of erosion in subaerially exposed sections (Crampton and Allen, 1995; DeCelles and Giles, 1996). The forebulge (and hinge line separating it from the foredeep) represents an area that shifts or migrates over time in response to shortening of the foreland basin with continued subduction (DeCelles and Giles, 1996).

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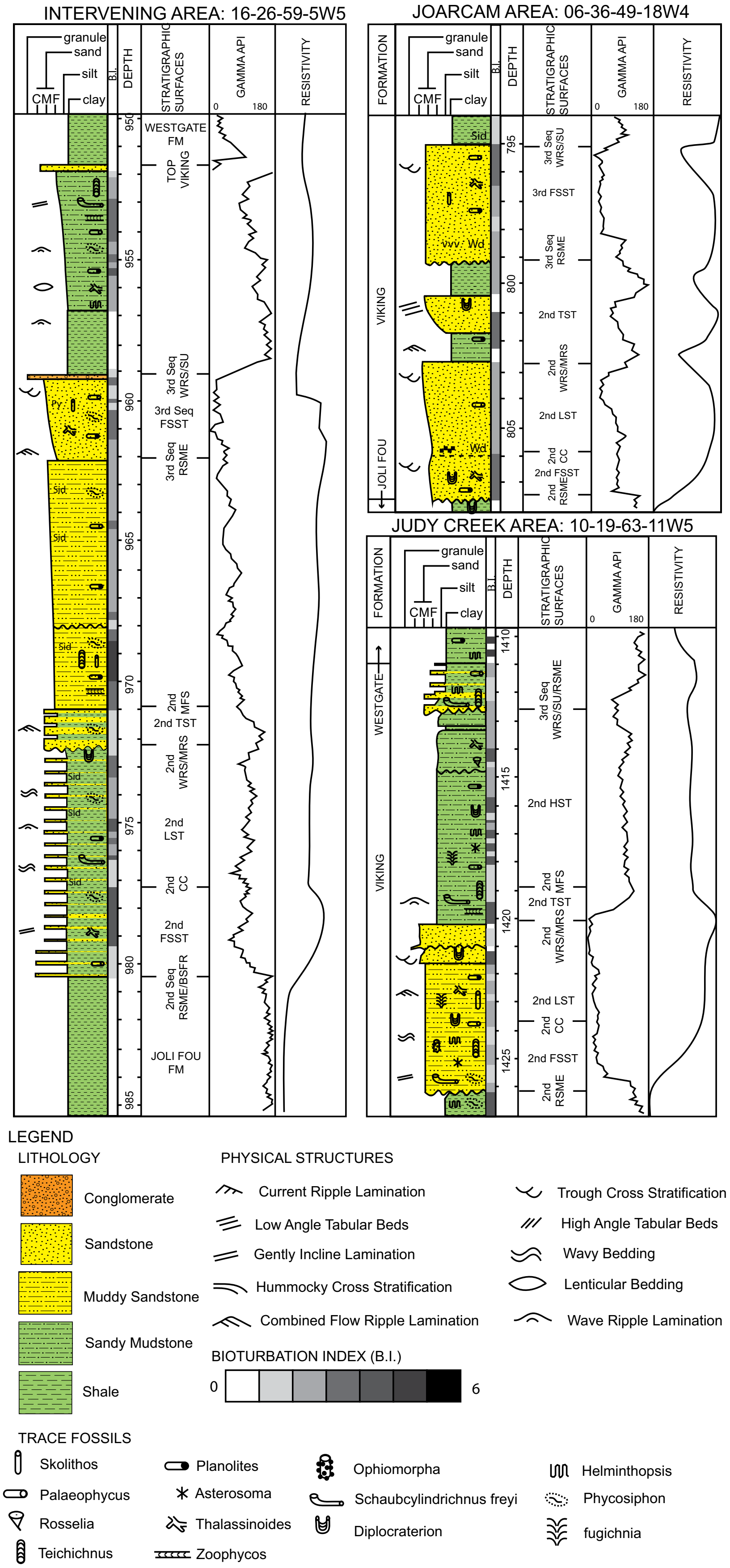

Figure 5. Representative core and well logs for intervening area, showing representative well for the overthickened section, Joarcam, and Judy Creek. CMF—coarse, medium, fine. See Figures 2 and 3 for surface acronyms and abbreviations. Measured depth for the cored intervals is recorded in meters.

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Datum Selection

Marine flooding surfaces are commonly selected in cross sections as stratigraphic datums because they are deposited relatively parallel to paleo–sea-level, and they approximate the paleo-seafloor prior to or immediately following deposition; they can therefore be used to identify and remove the effects of postdepositional deformation. The locations of wells selected for a skeletonized along-strike cross section are shown in Figure 1. Selection of varying datums (Fig. 6) demonstrates the patterns of overthickening in the Viking Formation. Cross sections were created along depositional strike from Judy Creek southeast toward Joarcam. In this study, the following surfaces were tested as datums: (1) the Joli Fou Formation downlap surface (JF in Fig. 6A); (2) a transgressive surface (3S in Fig. 6B) that is coplanar between the third and fourth sequences of deposition; (3) the top of the Viking Formation (VIK in Fig. 6C); (4) the marine flooding surface in the Westgate Formation (WG in Fig. 6D); and (5) the Base of Fish Scales Marker (BFS in Fig. 6E). Some datums are associated with erosion and may exhibit a limited amount of topographic relief, but in areas of low accommodation, there are limited options available for selecting a regionally extensive stratigraphic datum. Thus, multiple datums were employed in order to accurately construct a stratigraphic framework. Several bentonite beds are found in the Viking Formation, but without further studies to document the areal extent of the ash plumes, or geochemical and geochronological analyses to discriminate between them, they cannot be used as reliable datums. Since the cross sections are arranged along depositional strike, depositional dips of the datum surfaces are deemed to be minor.

RESULTS

Cross Sections and Datum Selection

Joli Fou

The top of the Joli Fou Formation represents a maximum marine flooding surface at the top of a transgressive systems tract, across which progradational regression of the highstand systems tract resumed. This downlap surface is relatively easily identifiable in well logs and expressed as an increase in the interstitial silt and sand contents in the mudstones of the normal regressive cycles. When the Joli Fou Formation is employed as a datum at a local scale, the geometries of the systems tracts can be resolved at both Joarcam and Judy Creek (Fig. 3). However, when the wells in the intervening area are added to the cross section, surfaces in sequences 2–4 become distorted, and sections become overthickened from 54.05°N, 114.80°W southeast toward 53.5°N, 113.30°W. (Figs. 2 and 6A). Toward the center of the cross section, a depositional "mound" is created, with all surfaces above the Joli Fou Formation rising up toward the apex in well 01–30–55–24W4. In this area, depositional thicknesses (base to top of Viking Formation) gradually increase from 25 m to ~40–60 m.

Third Sequence Flooding Surface and Transgressive Surface of Erosion

The top of the third sequence is reflected by a widespread erosional stratigraphic contact formed during transgression. There is limited topographic relief associated with this surface along depositional strike, making it a reasonable selection as a datum. However, when this surface is selected as a datum, the top of the Joli Fou Formation and the top of the second sequence of the Viking Formation drop down to form a trough-like depression in the center of the cross section (Fig. 6B). The maximum flooding surface marking the top of the Joli Fou Formation from 16–05–52–20W4 to the 01–30–55–24W4 well shows a 25–30 m downward shift in the area across a distance of 15 km, a geometry difficult to reconcile as primary, given that the cross section is approximately strike oriented.

Top of the Viking Formation

The top of the Viking Formation marks the transition to the next major marine transgression in the basin, manifested by the introduction of the Westgate Formation shales. When this surface is selected as a datum, it displays a similar influence on the underlying stratigraphy as the 3S surface datum (Fig. 6C). Surfaces below the datum drop downward to form a trough-like shape, while flooding surfaces above appear to undulate along depositional strike.

Westgate Formation Flooding Surface

The flooding surface in the Westgate Formation is a well-log pick based on an increase in resistivity and a decrease in gamma-ray API (American Petroleum Institute) units. Small coarsening-upward cycles can be identified in the Westgate Formation above this flooding surface. When this surface is selected as a datum, the center of the cross section defines a wedge-shaped body (Fig. 6D); the top of the Viking Formation and third sequence form a small mound, while the top of the second sequence and the Joli Fou Formation are still observed as a minor depression in the study area. The 01–30–55–24W4 well shows a downward shift in the Joli Fou Formation by 10–15 m and an upward shift of the top of the Viking Formation by ~5–10 m. This geometry is challenging to reconcile in a sequence stratigraphic framework, as both surfaces were probably close to horizontal when originally formed.

Base of Fish Scales Marker

The Base of Fish Scales Marker records a significant hiatus that can be identified throughout the subsurface of Alberta, Saskatchewan, and Manitoba and extending into Oklahoma and Montana. Throughout the basin, the surface appears to display a paleotopographic dip to the SW (Caldwell et al., 1978). In Alberta, strata above and below the Base of Fish Scales Marker appear to be conformable, based on foraminiferal studies, suggesting that this surface could represent a condensed section (Stelck and Armstrong, 1981). Although there is paleotopographic dip associated with the Base of Fish Scales Marker across the study area, the magnitude appears to be minor, and the effect on stratigraphic architecture should be minimal. When this surface is selected as a datum, the systems tracts geometries are similar to those observed when selecting the Westgate Formation flooding surface as a datum (Fig. 6E). The Joli Fou Formation displays a downward shift of between 5 and 10 m, while the top of the Viking Formation is shifted upward by 10–15 m.

When comparing the cross sections that are created in the study area, a trend can be observed between Judy Creek and Joarcam Fields. If wells from these producing fields were isolated and the intervening area removed, the depositional geometries at both fields would be well preserved regardless of the datum selected. All stratigraphic horizons broadly correlate to one another, and the systems tract geometries appear to be realistic. Systems tracts geometries only become distorted when the intervening area is incorporated into the cross section, indicating that syn- to postdepositional deformation has occurred in that location.

Comparison of the Intervening Area to Magnetic and Gravity Anomaly Surveys

We used the magnetic and gravity anomaly maps of Lyatsky et al. (2005) to assess the influence that Precambrian basement structures may have had on Western Canadian sedimentary basin architecture and, more specifically, to locate the positions of potential brittle basement faults in

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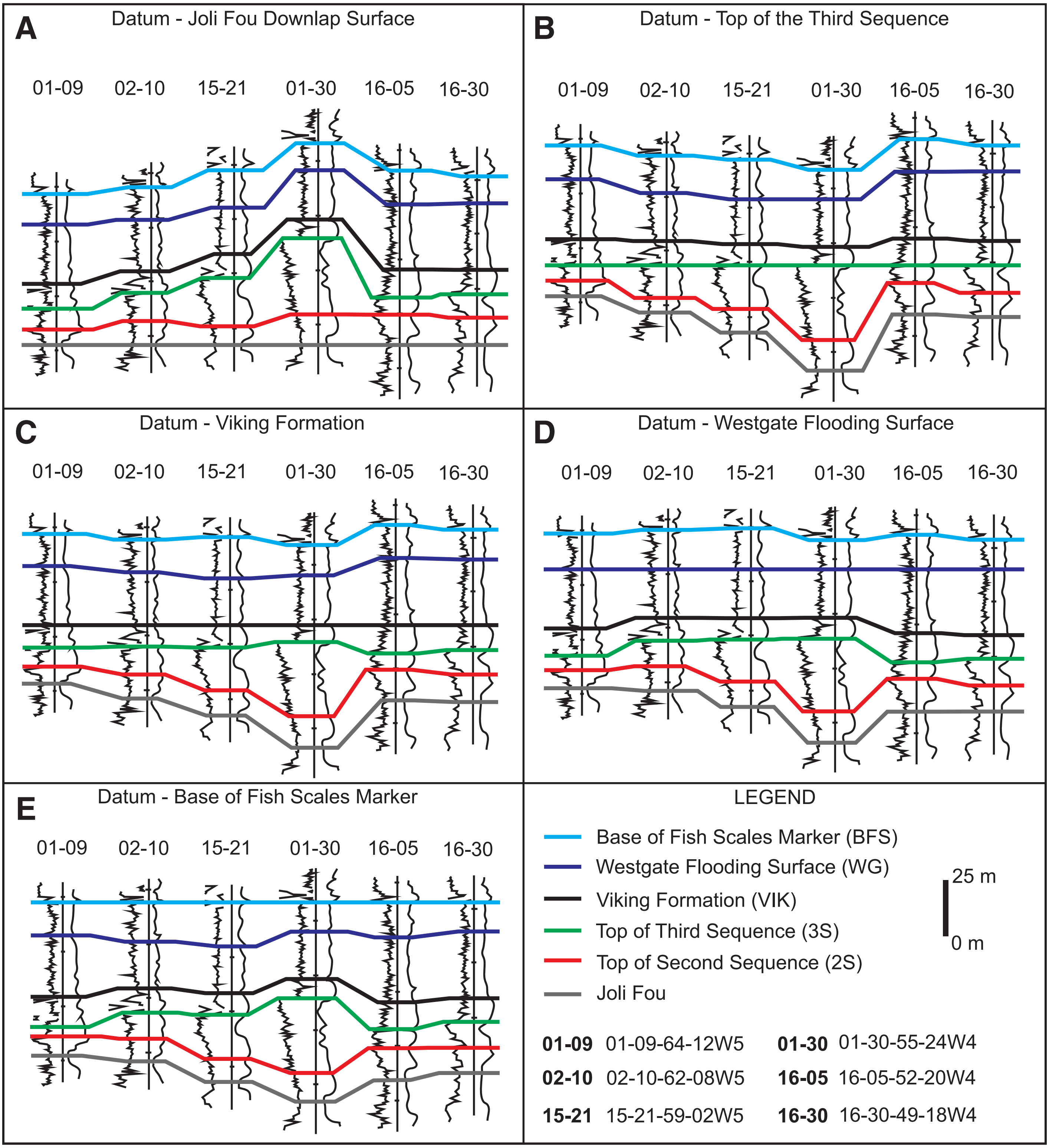

Figure 6. Cross section using the Joli Fou Formation downlap surface as the datum. This cross section is skeletonized from the A-A′ section of Figure 2. The transgressive surfaces in the Viking Formation are highlighted to demonstrate the variations that occur along strike. Wells are distributed at approximately the same distance. (A) Joli Fou Formation datum. (B) Third sequence (3S) datum. (C) Top of the Viking Formation datum. (D) Westgate flooding surface datum. (E) Base of Fish Scales Marker datum.

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the basin with respect to Viking Formation isopachs. The Judy Creek and Joarcam Field locations were superimposed on the gravity and magnetic maps and appear to flank either side of a basement anomaly known as the Snowbird tectonic zone (Figs. 1 and 7). The Joarcam Field is located southeast of the Snowbird tectonic zone, whereas Judy Creek resides northwest of the Snowbird tectonic zone. The region between the basement lineaments of the Snowbird tectonic zone corresponds to the zone of increased accommodation recorded in overthickened sections wherein the Viking Formation is ~1.5–2 times thicker than it is at Joarcam and Judy Creek.

The Snowbird tectonic zone has been primarily mapped using gravity and magnetic anomaly studies, and so the exact locations of the fault boundaries can differ depending on the quality of data and interpretation. In order to map the exact locations of domain boundaries, quality seismic data must be integrated with the magnetic and gravity studies. Seismic data were not available for this study, so the boundaries selected for the Snowbird tectonic zone followed those of Lyatsky et al. (2005), where magnetic and gravity anomaly maps were used to generate the fault trends of the Snowbird tectonic zone.

A preliminary assessment to determine whether the Snowbird tectonic zone recorded overthickening throughout central Alberta was undertaken by selecting wells up and down depositional dip from the skeletonized cross sections in Figure 6. Isopach maps of the total Viking thickness (Joli Fou downlap surface to the top of the Viking Formation) were created (Fig. 8), with the Snowbird tectonic zone fault trends superimposed to determine whether overthickening is widespread throughout central Alberta. As the formation passes into the Snowbird tectonic zone, depositional thicknesses clearly record an increase by as much 25 m.

DISCUSSION

Accommodation Space

The results of this study demonstrate that patterns of increased accommodation along depositional strike for the lowstand paleoshoreline trend between Judy Creek and Joarcam are coincident with the trend of the Snowbird tectonic zone basement anomaly (Figs. 1, 7, and 8). Various mechanisms for increasing accommodation in depositional setting may typically include processes such as relative sea-level rise or valley incision. However, based on the patterns of differential subsidence observed in the strike-oriented cross sections (Fig. 6), it is most reasonable to infer that the overthickened section correlates to differential movement along strike-perpendicular basement faults that were reactivated while the Viking Formation was being deposited. Aside from the correspondence of the overthickened zone of the Viking Formation with the Snowbird tectonic zone basement anomaly noted above, further support for this hypothesis is based on the following arguments:

(1) The anomalously thick zone overlying the Snowbird tectonic zone cannot be explained by simply raising base level as a result of relative sea-level rise, given the sequence stratigraphic framework being developed. Base-level changes as a result of relative sea-level changes during Viking deposition are well constrained at both Judy Creek and Joarcam; both fields record deposition in a low-accommodation setting. The area along strike must, therefore, record a different mechanism for increased accommodation.

(2) The increased accommodation space cannot be explained by valley incision or spatial variations in the depths of incision of the various erosional discontinuities in the succession. The overthickened zone occurs gradually across a 200 km zone between Judy Creek and Joarcam. Valley widths in other Viking occurrences span only ~2 townships (12 miles; 19 km) and show rather abrupt changes in accommodation as well as facies across short (1–2 km) distances (e.g., Reinson, 1985; Pattison and Walker, 1994, 1998). Further, the depositional thicknesses of the sequence 2 forced regressive to lowstand paleoshoreline are relatively consistent along strike (Figs. 2 and 3). In cored intervals, there is no obvious evidence of significant incision into the underlying strata, suggesting that this unit was uniform and persistent along strike prior to the deposition of sequence 3.

Correspondingly, we contend that differential movement occurring along basement faults that transected the depositional strike of the Viking Formation is the most likely mechanism for the localized and stratigraphically variable (in a superpositional sense) increase in accommodation space in the study area.

Aptian to Albian Tectonism

Following the initial development of the foreland basin in the Jurassic, various allochthonous terranes continued to accrete to the western edge of the North American plate. During the Aptian, the terminal accretion of the Wrangellia terrane to the southwestern margin of the North American margin created renewed widespread compression, tectonic thickening, and loading in the southern Canadian Cordillera (Monger et al., 1994; Gibson et al., 2008; Nelson et al., 2013). The renewed loading and northeastward propagation of the Cordilleran deformation front accompanied a general eastward migration of the foreland basin depocenter axis (Price, 1994). During this time, the ongoing subsidence within the basin related to lithospheric flexure in front of the evolving deformation front was heterogeneous (Zaitlin et al., 2002). For instance, crustal anisotropies in the form of inherited basement structures that obliquely transect the strike of the basin may have been variably reactivated as brittle faults (see Lyatsky et al., 2005), leading to lesser or greater degrees of isostatic readjustments along these structures. In turn, this would have created along-strike variations in the accommodation space for strata deposited within the basin (see Fig. 4).

The deformation of the Snowbird tectonic zone has been ongoing since the Precambrian. Brittle reactivation and differential movement along and within the margins of the Snowbird tectonic zone in the Albian may account for the increased accommodation observed in the study area. The movements were likely subtle, and accommodation space appears to have increased gradually toward the center of the Snowbird tectonic zone anomaly. Furthermore, the along-strike, trough-like depression that we have established for the Viking Formation likely reflects differential movements on a series of brittle faults paralleling the Snowbird tectonic zone that propagated up into the overlying Phanerozoic rocks (>2 km thickness), rather than all movement taken up on only a few discrete faults flanking either side the Snowbird tectonic zone.

In the Western Canadian sedimentary basin, NW-SE–oriented extensional faults related to foreland flexure are common and have been documented in multiple studies (Murray et al., 1994; Donaldson et al., 1998; Lemieux, 1999; Warren, 2000; Zaitlin et al., 2002; Ardies et al., 2002; Mei et al., 2015). In the current study area, there were no orogen-parallel basement faults identified, making it challenging to assess their possible influence on Viking depositional geometries in the study area. In the Viking Formation, the NE-SW isopach variations are more notable than the NW-SE gradient, which may be the result of the subtle structural influence by NW-SE–oriented foreland flexural extensional faults, similar to those identified in other Cretaceous intervals in Alberta (Fig. 8; e.g., Murray et al., 1994; Donaldson et al., 1998; Lemieux, 1999; Warren, 2000; Zaitlin et al., 2002; Ardies et al., 2002; Mei et al., 2015). However, if unidentified orogen-parallel basement extensional faults were present (outside the scope of the current study), we would expect there should be

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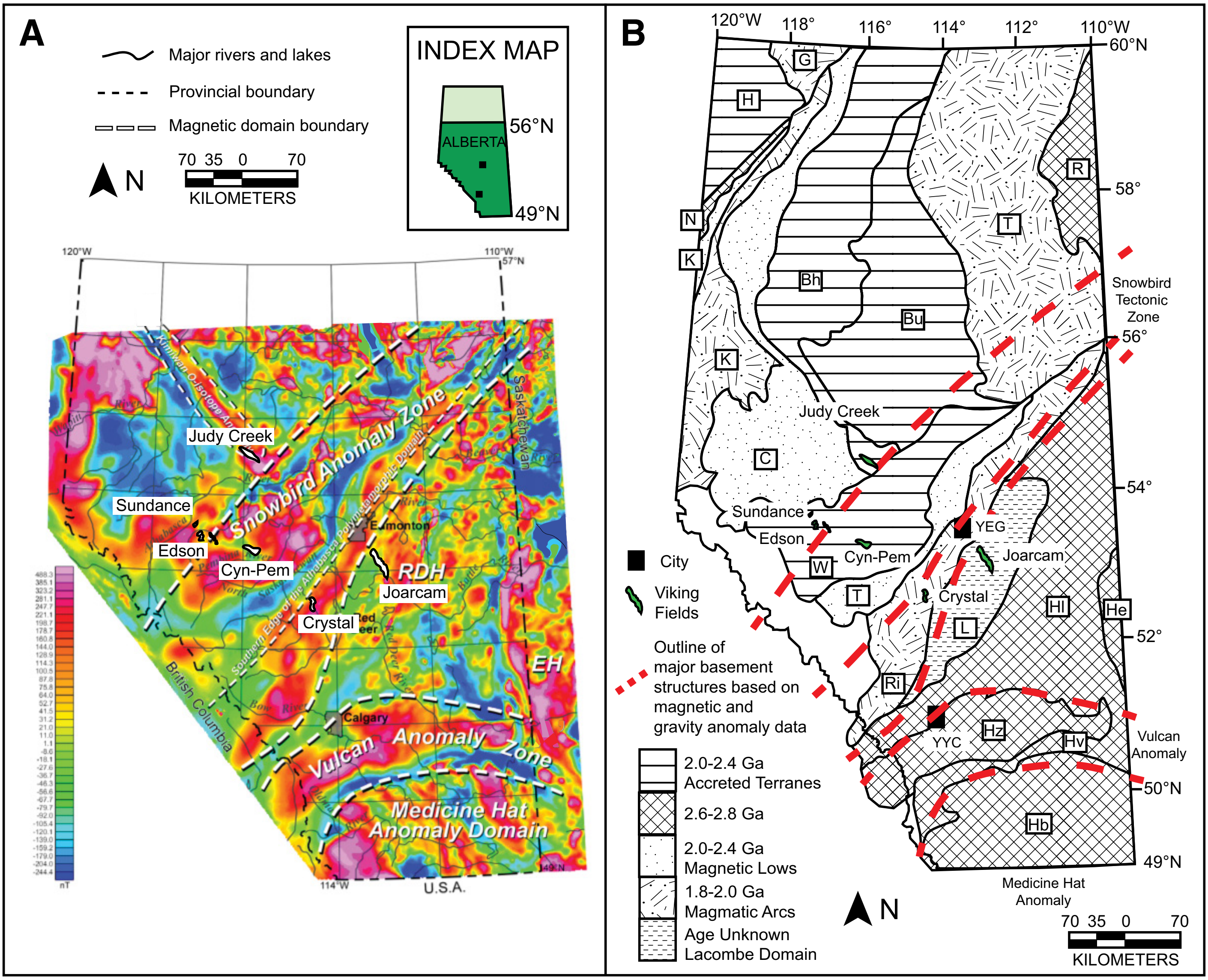

Figure 7. (A) Basement anomaly map created using magnetic and gravity data obtained from various surveys over Alberta. Superimposed on this map are the Judy Creek and Joarcam Fields. Joarcam Field lies southeast of the Snowbird tectonic zone, whereas Judy Creek Field occurs to the northwest of this zone. RDH—Red Deer Magentic High, EH—Eyehill Magnetic High. (B) Map of the Precambrian domains with the Snowbird tectonic zone superimposed onto the map (modified from Ross et al., 1991; Pattison, 1991; Villeneuve et al., 1993; MacEachern et al., 1998; Pilkington et al., 2000; Lyatsky et al., 2005). The magnetic domains highlighted on the figure include: L—Lacombe, Ri—Rimbey, K—Ksituan, F—Fort Simpson, T—Talston, G—Great Bear, Fn—Fort Nelson, T—Thorsby, C—Chinchaga, K—Kiskatinaw, Na—Nahanni, H—Hottah, Bh—Buffalo High, Bu—Buffalo Utikuma, W—Wabamun, N—Nova, H—Hearne, R—Rae, Hv—Vulcan, Hb—Medicine Hat, Hz—Matzhiwin, He—Eyehill, Hl—Loverna.

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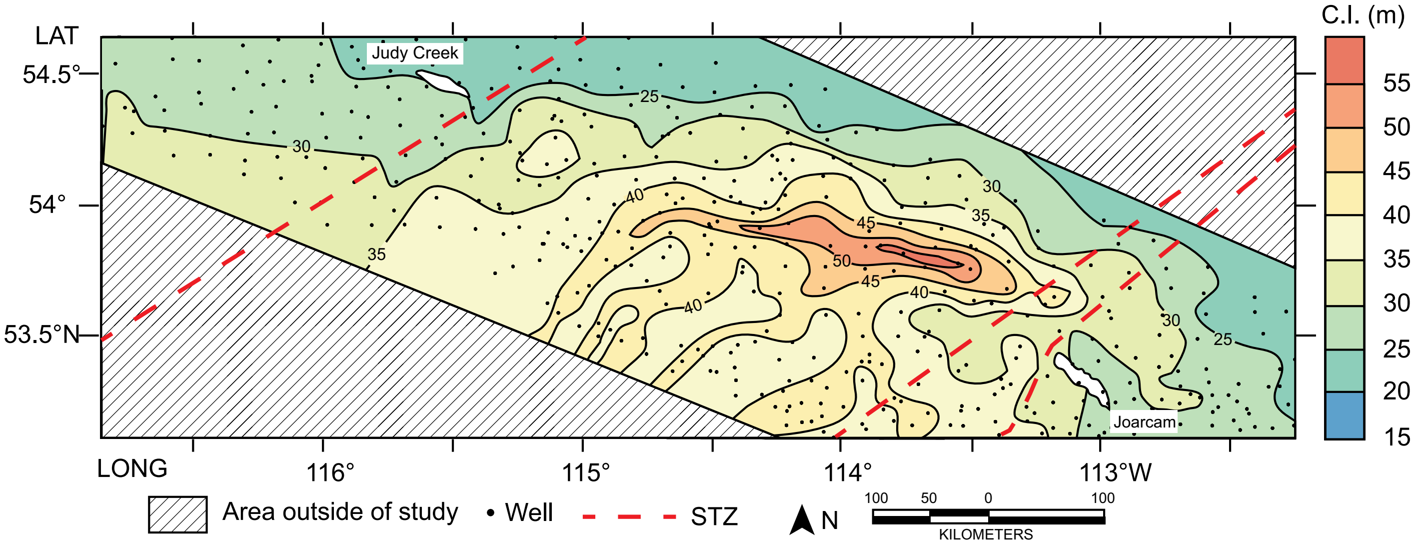

Figure 8. Total thickness isopach for the Viking Formation from the Joli Fou downlap surface to the top of the Viking Formation. The extent of the study area is highlighted by the black box in Figure 1. The flanking margins of the Snowbird tectonic zone (STZ) record average thicknesses of 20–35 m, whereas the Snowbird tectonic zone (outlined by red dashes) records average thicknesses of 35–60 m. Contour interval (C.I.) = 10 m.

abrupt thickness changes in the depositional dip orientation of the Viking stratigraphy. Although this was not documented in this study, this does not preclude the possibility of these faults existing outside of the current study area, and therefore they should be kept in mind when undertaking similar sequence stratigraphic analyses elsewhere.

Systems Tracts and Facies Responses

The interplay and rates of differential subsidence and sedimentation would have had a significant control on the depositional geometries of the different systems tracts. Stratigraphic frameworks applied to broader hierarchal scales may overlook the subtle overthickening that occurred due to basement structures being reactivated. Therefore, higher-resolution models that incorporate mapping of the subtle facies changes (i.e., sedimentology, ichnology, palynology) that occur during fluctuations in base level must be integrated in order to recognize their influence. Importantly, mapping of the facies distributions within discrete systems tracts of each sequence allowed us to recognize those sequences that were overthickened due to differential subsidence along depositional strike (Fig. 2).

Postburial compaction needs to be accounted for in areas where formations record mud-dominated deposits. In these scenarios, the deposits must be decompacted in order to accurately assess the magnitude of movement along faults (for a summary and formulas, see Chapman, 1983). In the current study area, the deposits in the intervening area are sand-dominated deltaic successions, so the effects of compaction are assumed to be minimal. Future studies focusing on areas downdip of this study would need to employ such decompaction formulae, owing to the predominance of mud-dominated strata.

In the Viking interval, accommodation space was created during the highstand systems tract. The resulting deposits are expressed as overthickened parasequences, reflecting sedimentation rates in excess of accommodation. The dominant facies expression in the Snowbird tectonic zone is an overthickened prodelta and delta-front facies. The prodeltaic deposits are overthickened relative to the basinal facies of the flanking margins at Judy Creek and Joarcam (Fig. 2). The overthickening of the basinal prodelta facies suggests that water depths were progressively increasing due to accommodation space being created during progradation (i.e., syndepositional subsidence). In a high-resolution facies model, these deposits display stressed trace fossil suites, reflecting the higher sedimentation rates that impede substrate colonization. The result is a reduction in trace fossil diversity and bioturbation intensity in these deposits.

Patterns of Differential Subsidence

By selecting successive datums from oldest to youngest, periods of tectonic quiescence and tectonic subsidence can be identified in the Viking stratigraphic interval. The wells used in the construction of the skeletonized cross section (Fig. 1) were selected in order to have one well to the NW (01–09–64–12W5) and two wells to the SE (16–05–52–20W4 and 16–30–49–18W4) of the Snowbird tectonic zone. The remaining three wells (02–10–62–08W5, 15–21–59–02W5, and 01–30–55–24W4) occur within the anomaly zone and reflect significant overthickening of strata. By reproducing the cross sections using the different datums, the changes in accommodation space during Viking time can be elucidated (Fig. 6). The wells that occur outside of the Snowbird tectonic zone anomaly were used as baselines to compare the other wells against when selecting different datums across the study area. Regardless of which datum was employed, the stratigraphic architecture of the wells outside of the Snowbird tectonic zone showed minimal change in their depositional geometries, confirming their suitability as key surfaces. They can, therefore, be used to estimate the timing and magnitude of reactivation of basement structures within the Snowbird tectonic zone anomaly.

The transition from the transgression of the Joli Fou Formation to the highstand systems tract of the regional Viking Formation is marked by a maximum flooding surface. The maximum flooding surface was likely as close to parallel to paleo–sea-level as any other produced in the basin. Given that the cross sections are strike oriented, this surface serves as an excellent datum. When the Joli Fou Formation is selected as the datum, the geometries of the falling stage and lowstand systems tracts in sequence 2 remain consistent along the cross section (Fig. 6A). This indicates that from the end of the Joli Fou transgression to the end of the deposition of the lowstand systems tract of sequence 2, there was tectonic quiescence.

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By contrast, when the top of the third sequence (wave ravinement surface/subaerial unconformity) is employed as a datum, the intervening area shows additional subsidence of ~25 m relative to the margins flanking the Snowbird tectonic zone at Judy Creek and Joarcam. This indicates that some 25 m of additional accommodation space was created in the area during the deposition of the highstand systems tract of sequence 2 and the falling-stage systems tract of sequence 3. This package is a sand-dominated unit in the study area, with minor mudstone interbeds observed. It is likely that the extra accommodation space observed in this section reflects overall net displacement along the brittle faults within the Snowbird tectonic zone anomaly. Correlation of systems tracts following the deposition of the lowstand deposits of sequence 2, therefore, must address these changes in accommodation and their corresponding impacts on proximal-distal trends, depositional environments, and magnitudes of base-level change associated with relative sea level.

The top of the Viking datum (Fig. 6C), a flooding surface/transgressive surface of erosion, shows that there was little or no movement following the deposition of sequence 3, and that tectonic quiescence ensued. By contrast, when the Westgate Formation flooding surface and the Base of Fish Scales Marker (MFS) are selected as datums (Figs. 6D–6E), a wedge-like geometry of the systems tracts is observed in the Snowbird tectonic zone. It appears that some point after Viking deposition, there was minor uplift within the Snowbird tectonic zone anomaly, possibly related to an episode of subtle transpression as has been documented in the Fort St. John graben system to the north (Eaton et al., 1999).

Other Evidence in Support of Precambrian Basement Reactivation and Changing Subsidence Patterns

Syndepositional subsidence leading to patterns of overthickening have been documented in other studies of Phanerozoic and Paleozoic strata in the basin. Most studies have focused on the structural aspects of basement reactivation, with few papers documenting the effect(s) on the resulting stratigraphic frameworks.

A study by Plint et al. (2012) explored the relationship of tectonism to deposition patterns in the Colorado allogroup. They suggested that there is little evidence for preexisting topographic depressions in the basin floor that would allow for thicker packages of sediment to accumulate. Rather, thicker sections likely correspond to actively subsiding areas that were rapidly filled as accommodation space was created. In the Colorado allogroup, a distinct switch between depocenters was documented between northern Alberta and British Columbia. The abrupt switch was attributed to the collision and accretion of allochthonous terranes with the western North American plate margin. The study suggested that thrust sheet loading and structural weaknesses of the Precambrian basement created subsidence changes at a local scale.

The Red Deer zone and Vulcan Low basement structures in southern Alberta have been periodically reactivated, leading to changes in facies distribution and thickness, mineralization, and hydrothermal flow patterns in carbonate-dominated successions (McMechan, 2012). In these examples, the localization of certain facies over basement structures led to changes in mineralization patterns at the margins of the overthickened sections. Most examples documented in the study by McMechan (2012) directly overlie Precambrian basement, with movement along faults expressed from the Cambrian to Permian.

Examination of the Muddy Sandstone Formation in the Denver Basin (age equivalent to the Viking Formation) documented that tectonic readjustments of basement structure were a dominant control on the locations of paleovalleys and shallow-water facies (Weimer, 1990). Channels and paleovalleys accumulated in topographic lows that were formed due to differential subsidence of basement structures. Areas that experienced isostatic uplift formed topographically high areas that were prone to erosion and the generation of unconformities.

Reactivation of Basement Structures Beneath Evolving Foreland Basins—Global Context

Reactivation of basement structures has been documented in a variety of tectonic settings globally, including beneath developing orogens, continental margins, foreland basins, and rift basins (Stein, 1988; Ross et al., 1991; Lyatsky et al., 2005; Zhao and Cawood, 2012; Zaitlin et al., 2002; Zhao and Cawood, 2012; Godin and Harris, 2014; Skalbeck et al., 2014; Kayode et al., 2017; Araujo et al., 2018).

In foreland basins, the evidence for reactivation of preexisting basement structures can be quite subtle, and they have generally been identified by combining careful stratigraphic studies with geophysical data (e.g., Ross et al., 1991; Lyatsky et al., 2005). In areas where the sediment is adjacent to the basement, fault and distinct facies offsets due to basement reactivation should be more readily discernible. Examples include the Vulcan Low and Red Deer zone documented by McMechan (2012), and the study by Araujo et al. (2018) of the Rio de Peixe Basin in Brazil, where basement fault reactivation is suggested to have caused a sag that resulted in a thickening of clastic sediments overlying the basement.

However, in areas where the sediment is separated by a significant distance from the basement, the identification of the influence imposed by reactivated basement structures will be more nuanced, such as the patterns of along-strike overthickening in the Viking Formation documented in this study. In these cases, the utilization of high-resolution sequence stratigraphy provides a powerful tool for delineating fault trend boundaries, timing of fault reactivation, and patterns and amounts of differential subsidence. Furthermore, if the overlying sedimentary basins are of interest to hydrocarbon and/or mineral exploration, then the results of this study could have significant implications where correlating regional facies relationships and reconciling depositional anomalies in the along-strike and downdip directions are critical.

CONCLUSION

This study documented subtle movements that occurred along reactivated Precambrian basement faults during the late Albian (Early Cretaceous) in east-central Alberta, Canada. Mapping of the Viking Formation along a lowstand trend showed an overthickened section directly overlying the Snowbird tectonic zone. In that area, no single datum can effectively resolve the depositional geometries of the Viking Formation, pointing to syndepositional basement readjustment. Multiple datums were employed in order to properly assess these tectonic effects.

Movement along the basement structures occurred prior to and/or during the deposition of the third sequence of the Viking Formation. The falling stage and lowstand deposits of the second sequence show no significant changes in thickness along depositional strike and so are interpreted to have accumulated during a time of tectonic quiescence. Following the deposition of the falling stage and lowstand shorefaces, differential subsidence of the Snowbird tectonic zone occurred, increasing the accommodation space in areas lying between Judy Creek and Joarcam. During the deposition of the Westgate Formation and Base of Fish Scales Marker, the basement structures in the Snowbird tectonic zone were reactivated, as the margins that flank the anomaly indicate differential subsidence relative to the Snowbird tectonic zone.

Careful mapping and identification of systems tracts were essential in order to accurately assess the magnitude and timing of reactivation of

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basement faults and their heterogeneous effects on creating accommodation space within the basin. Changes in facies distribution (i.e., rapid landward shifts in facies), sedimentology, and depositional thicknesses must be identified in order to package sediments into their genetically related systems tracts. By doing so, and selecting successive datums, the timing of fault movement and the amount of accommodation space created can be estimated. Conversely, the recognition and careful assessment of reactivated basement structures likewise help to explain the shifts of paleoshorelines along depositional strike as a function of the interplay between regional base-level variations and more localized changes in accommodation space owing to differential subsidence. In fact, in this study, the systems tract characteristics, their thicknesses, and their distributions could not be reliably correlated without recognizing the role of tectonically induced overthickening.

Major phases of Cordilleran orogenesis related to convergence along the western margin of the North American craton occurred throughout the Mesozoic and into Paleogene time. It is likely that accumulation patterns in other shallow-water foreland basin deposits were affected by basement reactivation as well. By carefully mapping units within the basin and knowing the locations of underlying basement structures, it may be possible to identify similar patterns of pre-, syn-, and postdepositional movements on reactivated basement faults. In turn, this will help to reconcile observed along-strike anomalies when correlating strata in the Western Canadian sedimentary basin and other similar basins flanking orogenic belts.

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REFERENCES CITED

Araujo, R.E.B., Bezerra, F.H.R., Nogueira, F.C.C., Balsamo, F., Carvalho, B.R.B.M., Souza, J.C.D., Sanglard, J.C.D., de Castro, D.L., and Melo, A.C.C., 2018, Basement control on fault formation and deformation band damage zone evolution in the Rio de Peixe Basin, Brazil: Tectonophysics, v. 745, p. 117–131, https://doi.org/10.1016/j.tecto.2018.08.011.

Ardies, G.W., Dalrymple, R.W., and Zaitlin, B.A., 2002, Controls on the geometry of incised valleys in the Basal Quartz Unit (Lower Cretaceous), Western Canada sedimentary basin: Journal of Sedimentary Research, v. 72, no. 5, p. 602–618, https://doi.org/10.1306/032101720602.

Beaumont, C., 1981, Foreland basins: Geophysical Journal of the Royal Astronomical Society, v. 65, no. 2, p. 291–329, https://doi.org/10.1111/j.1365-246X.1981.tb02715.x.

Berman, R.G., Davis, W.J., and Pehrsson, S., 2007, Collisional Snowbird tectonic zone resurrected; growth of Laurentia during the 1.9 Ga accretionary phase of the Hudsonian orogeny: Geology, v. 35, no. 10, p. 911–914, https://doi.org/10.1130/G23771A.1.

Bond, G.C., and Kominz, M.A., 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for subsidence mechanism, age of breakup and crustal thinning: Geological Society of America Bulletin, v. 95, no. 2, p. 155–173, https://doi.org/10.1130/0016-7606(1984)95<155:COTSCF>2.0.CO;2.

Boreen, T., and Walker, R.G., 1991, Definition of allomembers and their facies assemblages in the Viking Formation, Willesden Green area, Alberta: Bulletin of Canadian Petroleum Geology, v. 39, no. 2, p. 123–144.

Caldwell, W.G.E., North, B.R., Stelck, C.R., and Wall, J.H., 1978, A foraminiferal zonal scheme for the Cretaceous System in the Interior Plains of Canada, *in* Stelck, C.R., and Chatterton, B.D.E., eds., Western and Arctic Canadian Biostratigraphy: Geological Association of Canada Special Paper 18, p. 495–575.

Catuneanu, O., 2004, Retroarc foreland systems—Evolution through time: Journal of African Earth Sciences, v. 38, no. 3, p. 225–242, https://doi.org/10.1016/j.jafrearsci.2004.01.004.

Catuneanu, O., Galloway, G.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H.W., Strasser, A., and Tucker, M.E., 2011, Sequence stratigraphy: Methodology and nomenclature: Newsletters on Stratigraphy, v. 44, no. 3, p. 173–245, https://doi.org/10.1127/0078-0421/2011/0011.

Chapman, R.E., 1983, Compaction of sediment and sedimentary rocks, and its consequences, *in* Chapman, R.E., ed., Petroleum Geology: Amsterdam, Netherlands, Elsevier, Developments in Petroleum Science Volume 16, p. 41–65, https://doi.org/10.1016/S0376-7361(08)70087-6.

Crampton, S.L., and Allen, P.A., 1995, Recognition of forebulge unconformities associated with early stage foreland basin development: Example from the North Alpine foreland basin: American Association of Petroleum Geologists Bulletin, v. 79, p. 1495–1514.

DeCelles, P.G., and Giles, K.A., 1996, Foreland basin systems: Basin Research, v. 8, p. 105–123.

Donaldson, W.S., Plint, A.G., and Longstaffe, F.J., 1998, Basement tectonic control on distribution of the shallow marine Bad Heart Formation, Peace River Arch area, northwest Alberta: Bulletin of Canadian Petroleum Geology, v. 46, no. 4, p. 576–598.

Eaton, D.W., Ross, G.M., and Hope, J., 1999, The rise and fall of a cratonic arch: A regional seismic perspective on the Peace River Arch, Alberta: Bulletin of Canadian Petroleum Geology, v. 47, no. 4, p. 346–361.

Fielding, C.R., 2011, Foreland basin structural growth recorded in the Turonian Ferron Sandstone of the Western Interior Seaway Basin, USA: Geology, v. 39, no. 12, p. 1107–1110, https://doi.org/10.1130/G32411.1.

Gibb, R.A., and Walcott, R.I., 1971, A Precambrian suture in the Canadian Shield: Earth and Planetary Science Letters, v. 10, no. 4, p. 417–422, https://doi.org/10.1016/0012-821X(71)90090-2.

Gibson, G.M., Rubenach, M.J., Neumann, N.L., Southgate, P.N., and Hutton, L.J., 2008, Syn- and post-extensional tectonic activity in the Palaeoproterozoic sequences of Broken Hill and Mount Isa and its bearing on reconstructions of Rodinia: Precambrian Research, v. 166, no. 166, p. 350–369.

Godin, L., and Harris, L.B., 2014, Tracking basement cross-strike discontinuities in the Indian crust beneath the Himalayan orogen using gravity data – relationship to upper crustal fault: Geophysical Journal International, v. 198, no. 1, p. 198–215.

Hanmer, S., Williams, M., and Kopf, C., 1995, Striding-Athabasca mylonite zone; implications for the Archean and early Proterozoic tectonics of the western Canadian Shield: Canadian Journal of Earth Sciences, v. 32, no. 2, p. 178–196, https://doi.org/10.1139/e95-015.

Hoffman, P.F., 1988, United Plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia: Annual Review of Earth and Planetary Sciences, v. 16, p. 543–603, https://doi.org/10.1146/annurev.ea.16.050188.002551.

Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A.W., and Palmer, A.R., eds., The Geology of North America—An Overview: Boulder, Colorado, Geological Society of America, v. A, p. 447–512, https://doi.org/10.1130/DNAG-GNA-A.447.

Holdsworth, R.E., Butler, C.A., and Roberts, A.M., 1997, The recognition of reactivation during continental deformation: Journal of the Geological Society [London], v. 154, no. 1, p. 73–78, https://doi.org/10.1144/gsjgs.154.1.0073.

Kayode, J.S., Nawawi, M.N.M., Abdullah, K.B., and Khalil, A.E., 2017, Integrating aeromagnetic and Landsat™ 8 data into subsurface structural mapping of Precambrian basement complex: Journal of African Earth Sciences, v. 125, p. 202–213, https://doi.org/10.1016/j.jafrearsci.2016.11.010.

Leckie, D., and Reinson, G.E., 1993, Effects of middle to late Albian sea-level fluctuations in the Cretaceous Interior Seaway, Western Canada, *in* Caldwell, W.G.E., and Kauffman, E.G., eds., Evolution of the Western Interior Basin: Geologic Association of Canada Special Paper 39, p. 151–175.

Lemieux, S., 1999, Seismic reflection expression and tectonic significance of late Cretaceous extensional faulting of the Western Canada sedimentary basin in Southern Alberta: Bulletin of Canadian Petroleum Geology, v. 47, no. 4, p. 375–390.

Lewry, J.F., and Sibbald, T.I.I., 1980, Thermotectonic evolution of the Churchill Province in northern Saskatchewan: Tectonophysics, v. 68, p. 45–82, https://doi.org/10.1016/0040-1951(80)90008-6.

Lyatsky, H.V., Pană, D.I., and Grobe, M., 2005, Basement Structure in Central and Southern Alberta: Insights from Gravity and Magnetic Maps: Alberta Geological Survey Special Report 72, 83 p.

MacEachern, J.A., Zaitlin, B.A., and Pemberton, S.G., 1998, High-resolution sequence stratigraphy of early transgressive deposits, Viking Formation, Joffre Field, Alberta, Canada: American Association of Petroleum Geologists Bulletin, v. 82, no. 5A, p. 729–756.

MacEachern, J.A., Zaitlin, B.A., and Pemberton, S.G., 1999, A sharp-based sandstone of the Viking Formation, Joffre Field, Alberta, Canada: Criteria for recognition of transgressively incised shoreface complexes: Journal of Sedimentary Research, v. 69, no. 4, p. 876–892, https://doi.org/10.2110/jsr.69.876.

MacEachern, J.A., Dashtgard, S.E., Knaust, D., Catuneanu, O., Bann, K.L., and Pemberton, S.G., 2012, Sequence stratigraphy, *in* Knaust, D., and Bromley, R., eds., Trace Fossils as Indicators of Sedimentary Environments: Amsterdam, Netherlands, Elsevier, Developments in Sedimentology 64, p. 157–194, https://doi.org/10.1016/B978-0-444-53813-0.00006-X.

Mahan, K.H., and Williams, M.L., 2005, Reconstruction of a large deep-crustal terrane: Implications for the Snowbird tectonic zone and early growth of Laurentia: Geology, v. 33, no. 5, p. 385–388, https://doi.org/10.1130/G21273.1.

McMechan, M.E., 2012, Deep transverse basement structural control of mineral systems in the southeastern Canadian Cordillera: Canadian Journal of Earth Sciences, v. 49, p. 693–708, https://doi.org/10.1139/e2012-013.

Mei, S., Pana, D., and Schultz, R., 2015, Mapping formation-top offsets in Southwest Alberta, Canada: Methodology and Results, GeoConvention 2015, Calgary, Alberta, Abstract.

Monger, J.W.H., van der Heyden, P., Journeay, J.M., Evenchick, C.A., and Mahoney, J.B., 1994, Jurassic–Cretaceous basins along the Canadian Coast belt; their bearing on pre–Mid-Cretaceous sinistral displacements: Geology, v. 22, no. 2, p. 175–178, https://doi.org/10.1130/0091-7613(1994)022<0175:JCBATC>2.3.CO;2.

Murray, C., Ehrlich, R., Mason, E., and Clark, R., 1994, Evaluation of the diagenetic and structural influences on hydrocarbon entrapment in the Cardium Formation, Deep Basin, western Alberta: Bulletin of Canadian Petroleum Geology, v. 42, no. 4, p. 529–544.

Pană, D.I., 2003, Precambrian Basement of the Western Canadian Sedimentary Basin in Northern Alberta: Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2002–02, 39 p.

Pattison, S.A.J., 1991, Sedimentology and Allostratigraphy of Regional, Valley-Fill, Shoreface and Transgressive Deposits of the Viking Formation (Lower Cretaceous), Central Alberta [Ph.D. thesis]: Hamilton, Ontario, Canada, McMaster University, 380 p.

Pattison, S.A.J., and Walker, R.G., 1994, Incision and filling of a lowstand valley: Late Albian Viking Formation at Crystal, Alberta, Canada: Journal of Sedimentary Research, v. 64, p. 365–379.

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Pattison, S.A.J., and Walker, R.G., 1998, Multiple transgressive filling of an incised valley and shoreface complex, Viking Formation, Sundance-Edson area, Alberta: Bulletin of Canadian Petroleum Geology, v. 46, no. 1, p. 89–105.

Pilkington, M., Miles, W.F., Ross, G.M., and Roest, W.R., 2000, Potential-field signatures of buried Precambrian basement in the Western Canada sedimentary basin: The Lithoprobe-Alberta basement transect: Canadian Journal of Earth Sciences, v. 37, p. 1453–1471, https://doi.org/10.1139/e00-020.

Plint, A.G., Tyagi, A., McCausland, P.J.A., Krawetz, J.R., Zhang, H., Roca, X., Varban, B.L., Hu, Y.G., Kreitner, M.A., and Hay, M.J., 2012, Dynamic relationship between subsidence, sedimentation, and unconformities in mid-Cretaceous, shallow-marine strata of the Western Canada foreland basin: Links to Cordilleran tectonics, *in* Busby, C., and Azor, A., eds., Tectonics of Sedimentary Basins: Recent Advances (1st ed.): UK, Wiley-Blackwell, p. 480–507.

Porter, J.W., Price, R.A., and McCrossan, R.G., 1982, The Western Canada sedimentary basin: Philosophical Transactions of the Royal Society of London, v. 305, p. 169–192, https://doi.org/10.1098/rsta.1982.0032.

Posamentier, H.W., and Chamberlain, C.J., 1993, Sequence-stratigraphic analysis of Viking Formation lowstand beach deposits at Joarcam Field, Alberta, Canada, *in* Posamentier, H.W., Summerhayes, C.P., Haq, B.U., and Allens, G.P., eds., Stratigraphy and Facies Associations in a Sequence Stratigraphic Framework: International Association of Sedimentologists Special Publication 18, p. 469–485.

Power, B.A., 1988, Coarsening-upwards shoreface and shelf sequences: Examples from the Lower Cretaceous Viking Formation at Joarcam, Alberta, Canada, *in* James, D.P., and Leckie, D.A., eds., Sequences, Stratigraphy, Sedimentology: Surface and Subsurface: Canadian Society of Petroleum Geologists Memoir 15, p. 185–194.

Price, R.A., 1973, Large-scale gravitational flow of supracrustal rocks, southern Canadian Rockies, *in* De Jong, K.A., and Scholten, R., eds., Gravity and Tectonics: New York, Wiley and Sons, p. 491–502.

Price, R.A., 1994, Cordilleran tectonics and the evolution of the Western Canada sedimentary basin, *in* Mossop, G.D., and Shetsen, I., eds., The Geological Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists, p. 13–24, https://ags.aer.ca/publications/chapter-2-cordilleran-tectonics.htm.

Reinson, G.E., 1985, Facies Analysis and Reservoir Geometry of the Crystal Viking Field, Tp. 45 and 46, Rg. 3 and 4W5, Central Alberta: Geological Survey of Canada Open-File Report 1193, 168 p.

Roca, X., Rylaarsdam, J.R., Zhang, H., Varban, B.L., Sisulak, C.F., Bastedo, K., and Plint, A.G., 2008, An allostratigraphic correlation of Lower Colorado Group (Albian) and equivalent strata in Alberta and British Columbia, and Cenomanian rocks of the Upper Colorado Group in southern Alberta: Bulletin of Canadian Petroleum Geology, v. 56, no. 4, p. 259–299, https://doi.org/10.2113/gscpgbull.56.4.259.

Ross, G.M., and Eaton, D.W., 1999, Basement reactivation in the Alberta Basin: Observational constraints and mechanical rationale: Bulletin of Canadian Petroleum Geology, v. 47, no. 4, p. 391–411.

Ross, G.M., Parrish, R.R., Villeneuve, M.E., and Bowring, S.A., 1991, Geophysics and geochronology of the crystalline basement of the Alberta Basin, western Canada: Canadian Journal of Earth Sciences, v. 28, p. 512–522, https://doi.org/10.1139/e91-045.

Ross, G.M., Eaton, D.W., Boerner, D.E., and Miles, W., 2000, Tectonic entrapment and its role in the evolution of continental lithosphere: An example from the Precambrian of western Canada: Tectonics, v. 19, p. 116–134, https://doi.org/10.1029/1999TC900047.

Skalbeck, J.D., Koski, A.J., and Peterson, M.T., 2014, Estimation of Precambrian basement topography in central and southeastern Wisconsin from 3D modeling of gravity and aeromagnetic data: Journal of Applied Geophysics, v. 106, p. 187–195, https://doi.org/10.1016/j.jappgeo.2014.04.019.

Stein, A.M., 1988, Basement controls upon basin development in the Caledonian foreland, NW Scotland: Basin Research, v. 1, p. 107–119, https://doi.org/10.1111/j.1365-2117.1988.tb00008.x.

Stelck, C.R., and Armstrong, J., 1981, *Neogastroplites* from southern Alberta: Bulletin of Canadian Petroleum Geology, v. 29, p. 399–407.

Vakarelov, B.K., and Bhattacharya, J.P., 2009, Local tectonic control on parasequence architecture: Second Frontier sandstone, Powder Basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 93, p. 295–327, https://doi.org/10.1306/10150807015.

Vakarelov, B.K., Bhattacharya, J.P., and Nebrigic, D.D., 2006, Importance of high-frequency tectonic sequences during greenhouse times of Earth history: Geology, v. 34, p. 797–800, https://doi.org/10.1130/G22348.1.

Villeneuve, M.E., Ross, G.M., Theriault, R.J., Miles, W., Parrish, R.R., and Broome, J., 1993, Tectonic Subdivision and U-Pb Geochronology of the Crystalline Basement of the Alberta Basin, Western Canada: Geological Survey of Canada Bulletin, v. 447, 86 p., https://doi.org/10.4095/77642.

Walker, R.G., and Wiseman, T.R., 1995, Lowstand shorefaces, transgressive incised shorefaces, and forced regressions: Examples from the Viking Formation, Joarcam field, Alberta: Journal of Sedimentary Research, v. 65, p. 132–141.

Warren, M.J., 2000, Extensional faulting, paleodrainage patterns and impact on reservoir quality and distribution during foreland basin subsidence: A case study from the Lower Mannville of south-central Alberta: GeoCanada 2000 Convention, Abstracts, v. 25.

Weimer, R.J., 1990, Sequence stratigraphy and paleotectonics, Denver Basin area of Lower Cretaceous foreland basin, U.S.A., *in*, Ginsburg, R.N., and Beaudoin, B., eds., Cretaceous Resources, Events and Rhythms: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 23–32.

Zaitlin, B.A., Warren, M.J., Potocki, D., Rosenthal, L., and Boyd, R., 2002, Depositional styles in a low accommodation foreland basin setting: An example from the Basal Quartz (Lower Cretaceous), southern Alberta: Canadian Society of Petroleum Geologists Bulletin, v. 50, no. 1, p. 31–72.

Zhao, G., and Cawood, P.A., 2012, Precambrian geology of China: Precambrian Research, v. 222–223, p. 13–54, https://doi.org/10.1016/j.precamres.2012.09.017.

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