Local tectonic control on parasequence architecture: Second Frontier sandstone, Powder River Basin, Wyoming

Boyan K. Vakarelov and Janok P. Bhattacharya

ABSTRACT

The Cenomanian Second Frontier sandstone, one of the major producing units of the Frontier Formation in the Powder River Basin, Wyoming, is a basin-isolated sand body that pinches out to zero thickness in both seaward and basinward direction. The Second Frontier has previously been viewed as a single, relatively homogeneous, wave-dominated sediment succession. Our high-resolution study, integrating detailed facies relationships in outcrop, core, and well logs, shows that the Second Frontier sandstone comprises an offlapping parasequence set, formed from seven regionally mappable wave-dominated parasequences. The parasequences are bounded by minor flooding surfaces that represent previously unrecognized potential flow barriers or baffles. Parasequence boundaries are oriented obliquely to the well-defined regional north-northwest–south-southeast–elongated trend of the unit, and successive parasequences offlap to the south in an along-strike direction. The seaward pinch-out of the Second Frontier sandstone is depositional in nature, as illustrated by well-preserved healing-phase deposits, whereas the basinward pinch-out is caused by marine truncation over a tectonically uplifted area. Parasequence architecture was strongly affected by syndepositional tectonic movement, which determined both (1) the distribution of the entire parasequence set, forming a depositional remnant, and (2) the position and shape of parasequences internal to the remnant. The Second Frontier is thus interpreted as a depositional remnant of a once more extensive wave-dominated deltaic shoreface complex.

GEOLOGIC NOTE

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AUTHORS

BOYAN K. VAKARELOV ~ Australian School of Petroleum, Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), University of Adelaide, Adelaide, SA 5005, Australia

Boyan K. Vakarelov is a lecturer at the Australian School of Petroleum, University of Adelaide, Australia, in sedimentology and sequence stratigraphy. His research interests are in shallow-marine clastic sedimentology, high-resolution sequence stratigraphy, and CO2 sequestration. He received a B.Sc. (honors) degree from the University of Toronto in 2001 and a Ph.D. from the University of Texas at Dallas in 2006.

JANOK P. BHATTACHARYA ~ Geosciences Department, University of Houston, Houston, Texas 77204

Janok P. Bhattacharya is the Robert E. Sheriff Professor of Sequence Stratigraphy at the University of Houston. His research interests include deltaic sedimentology and sequence stratigraphy, the local control of structure on stratigraphy, and reservoir architecture of clastic depositional systems. He received his B.Sc. degree in 1981 from the Memorial University of Newfoundland, Canada, and completed his Ph.D. in 1989 from McMaster University, Hamilton, Ontario, Canada.

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INTRODUCTION

The formation of parasequences is related to driving mechanisms such as eustatic sea level change, subsidence or uplift, and variation in sediment supply (e.g., Van Wagoner et al., 1990; Schlager, 1993). Detailed mapping of stratigraphic packages, coupled with availability of precise age control, can help differentiate between these factors in ancient systems (e.g., Gale et al., 2002; Vakarelov et al., 2006). Local vertical tectonic movement can, for example, directly affect the amount of shallow marine deposition and transgressive erosion, both of which are essential for prediction of reservoir distribution and compartmentalization.

Martinsen (2003a) introduced the term “depositional remnant” to describe and interpret basinally isolated sand bodies formed by the complex interaction of tectonic deformation, generation of local accommodation, and subsequent marine erosion. We examine the Second Frontier sandstone in the Powder River Basin, Wyoming (Figure 1), to study both the internal architecture and overall distribution of such a depositional remnant in the context of its bounding discontinuities. We show that the Second Frontier sandstone is a top-truncated, wave-dominated, and offlapping parasequence set that was directly affected by syndepositional tectonic control during regional shoreline regression.

A common assumption about ancient wave-dominated systems is that they form relatively simple and homogeneous tanklike reservoirs with little internal heterogeneity (Reynolds, 1999; Clifton, 2006), although recent models for wave-influenced deltas question this assumption (Bhattacharya and Giosan, 2003; Bhattacharya, 2006). Recognizing potential flow barriers or baffles in such systems can therefore have an important impact on successful field development (e.g., Ainsworth et al., 1999; Tye et al., 1999). Unfortunately, few studies exist where distribution of potential flow barriers or baffles in regressive shoreface and wave-dominated deltaic successions has been documented (e.g., Hampson and Storms, 2003; Larue and Lagarré, 2004).

The Second Frontier sandstone is well exposed in outcrops along the flanks of the Powder River Basin, Wyoming, but is also well sampled in the adjacent subsurface, where it is an important producer of hydrocarbons. The combination of outcrop, core, and well-log data allows local to regional correlation and mapping of potential barriers and baffles. This unit may also represent an important analog for similar wave-dominated reservoirs. In this research, we (1) integrate outcrop, core, and closely spaced well-log data to evaluate the three-dimensional (3-D) internal stratigraphic architecture of the Second Frontier sandstone; (2) use this to determine the extent and orientation of potential baffling intervals (flooding surfaces) and the bedsets and parasequences that they define; and (3) relate the distribution and the nature of the parasequences to the factors responsible for their formation, with particular emphasis on tectonic control.

REGIONAL SETTING

The Frontier Formation is a clastic wedge of Cenomanian–Turonian age (Upper Cretaceous) that extended eastward from the Sevier orogenic belt, into a foreland basin, during a relatively prolonged second-order tectono-eustatic highstand of sea level (Greenhouse maxima of Matthews, 1984). The thick succession of nonmarine and shallow-marine facies of the proximal Frontier Formation in western Wyoming and eastern Utah is interpreted to have been deposited in an area of highly asymmetric subsidence, related to foreland thrust loading and associated basin downwarping (Hamlin, 1996). Along the edge of the Powder River Basin several hundred kilometers to the east, the Frontier Formation is interpreted to be dominated by lowstand deltaic sandstones and prodelta mudstones, deposited on the gently sloping floor of the foreland basin, away from areas of rapid asymmetric subsidence (Pang and Nummedal, 1995; DeCelles and Giles, 1996; Bhattacharya and Willis, 2001). This low-accommodation setting resulted in low preservation potential of coastal plain facies and prevalence of top-truncated coarsening-upward shallow-marine successions (Bhattacharya and Willis, 2001), with areas of enhanced erosion interpreted to reflect local tectonic control (Vakarelov et al., 2006).
Figure 1. Map of the study area showing the positions of well logs, cores, and regional outcrop localities. The positions of cross sections used in the study, the Frontier Formation outcrop belt, and the major oil fields in the western part of Powder River Basin, Wyoming are also shown. The shaded area to the east represents the boundary of Powder River Basin.
The Frontier Formation in the southern part of the Powder River Basin has been subdivided into three members: the Belle Fourche Member, the Emigrant Gap Member (locally missing) (Figure 2), and the overlying Wall Creek Member (Merewether et al., 1979). Bhattacharya and Willis (2001) further separated the lower part of the Belle Fourche Member into four distinct allomembers (Harlan, Willow, Frewens, and Posey; the last two are time equivalent), bounded by pebble lag-bearing transgressive surfaces of erosion. The allomembers were interpreted to be of deltaic origin based on mapped elongate to lobate sand-body geometries, upward-coarsening facies successions characterized by stressed river-dominated ichnofauna (MacEachern et al., 2005), basinward-inclined clinoform bedding geometries seen in outcrop, and radiating paleocurrents (Bhattacharya and Willis, 2001). In the study area, the Second Frontier sandstone (an informally defined stratigraphic unit) overlies the Posey allomember and is the youngest regressive unit of the Belle Fourche Member (Merewether et al., 1979). The sandstone corresponds to the Second Wall Creek sand of Towse (1952), unit B of Merewether et al. (1976), and unit III of Merewether et al. (1979). The Second Frontier is locally overlain by sandstones and conglomerates of the Emigrant Gap Member of the Frontier Formation; where the Emigrant Gap is missing, the Second Frontier is overlain by the multiple coarsening-upward successions of the Turonian Wall Creek Member of the Frontier Formation (Howell and Bhattacharya, 2004; Lee et al., 2005).

The Second Frontier sandstone was deposited during the time of the Sevier orogeny and prior to the Laramide orogeny (Brown, 1988; Omar et al., 1994). The unit crops out along the margins of the

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**Figure 2.** Major stratigraphic units in the Belle Fourche Member of the Frontier Formation and correlation to the relative sea level curve from Gale et al. (2002). MS = Mowry Shale. Modified from Vakarelov et al. (2006). The Frewens allomember is time equivalent to the Posey.
Laramide-related Tisdale and Kaycee anticlines, in the northwestern part of the study area (Figure 1).

SECOND FRONTIER SANDSTONE: PREVIOUS INVESTIGATIONS

The Second Frontier sandstone was deposited during the eastward and southward advancement of a shoreline for a period of less than 0.93 ± 0.7 m.y., as determined by 40Ar/39Ar sanidine age dating of bentonites (Obradovich, 1993; Vakarelov et al., 2006). It is the major producing interval in the Salt Creek field and historically is one of the most prolific oil fields in the Western Interior of the United States (Barlow and Haun, 1966). Previous subsurface investigations have shown the unit to be north-south–trending and extending for more than 100 km (62 mi) along strike (Barlow and Haun, 1966). The Second Frontier sandstone has been described to pinch out in both the eastern and western direction in the vicinity of the Salt Creek field (Barlow and Haun, 1966); a more regional investigation by Merewether et al. (1979) showed the unit to be lobate in shape. Based on distribution and facies characteristics, the Second Frontier sandstone in the study area has been described as an offshore bar deposit (Barlow and Haun, 1966) or a tide-dominated shoreface (Merewether et al., 1976). Granules and pebbles found in the interval, locally up to 9 cm (3.5 in.) in diameter (Kaycee area) (Figure 1), were interpreted by Barlow and Haun (1966) to have been transported by marine wave processes.

METHODS

This study covers an area of 3730 km² (1440 mi²) on the western margin of the Powder River Basin, Wyoming (Figure 1). Facies variation within the Second Frontier sandstone was described in 23 outcrop-measured sections and in 17 cores available at the U.S. Geological Survey Core Research Center (Figure 1). The subsurface part of the study also involved the correlation of 493 well logs. Proximity of continuous cliff outcrops to dense subsurface well control allows an effective cross-correlation between the two data sets. Outcrop-measured sections were used to examine facies variability and key stratigraphic relations that could then be extended into the subsurface. Important surfaces used for mapping were (1) a regional transgressive surface of erosion, which could be traced between the outcrop sections and which was found to always cap the Second Frontier sandstone (used as datum in well-log cross sections), and (2) minor flooding surfaces within the Second Frontier, which could also be mapped subregionally and which separate individual coarsening-upward successions (parasequences). These minor flooding surfaces were not typically associated with pebble lags and show little evidence of transgressive wave erosion.

Rocks observed in outcrop could be traced into the subsurface based on the correlation of distinct regional bentonite markers and trends of sand thicknesses; the Second Frontier interval is regionally floored by a mappable bentonite (bentonite 6 in Bhattacharya and Willis, 2001; bentonite 5 in Vakarelov et al., 2006) dated at 95.86 ± 0.45 Ma (Obradovich, 1993) and is overlain by the Soap Creek Bentonite dated at 94.93 ± 0.53 Ma (Obradovich, 1993). Subsurface correlations primarily used spontaneous potential-resistivity well logs because of the limited availability of gamma-ray logs. Uncommonly dense well-log control, with subkilometer well spacing, occurs across large parts of the study area (e.g., Salt Creek field and farther south in the Teapot Dome area, Figure 1), allowing detailed correlation and establishment of 3-D parasequence architecture. As in outcrop, subsurface correlation was based on the identification of a transgressive surface of erosion, which was penetrated in 6 of the 17 cores and was otherwise identified by an abrupt sand-to-mud transition in well logs. Minor flooding surfaces are penetrated by five cores and are represented by commonly highly bioturbated centimeter-to-meter-thick sandy mud to muddy sand intervals, which separate coarsening-upward sand-dominated successions. Minor flooding surfaces in well logs were identified by decreased spontaneous potential values, and peaks in resistivity logs. Such intervals could be traced laterally into adjacent wells and are commonly found to downlap onto well markers within the underlying
mudstones. Areas with subkilometer well spacing were especially useful for identifying trends of key bounding surfaces, which were then extrapolated to areas with sparse well and core control. In addition to the use of cross sections, well-log correlation was also done by a direct well-to-well correlation approach using a 3-D grid incorporating all of the 493 wells in Adobe Illustrator. This approach proved extremely effective for correlation in areas with abundant well logs. The regional data set was used for generation of sand thickness (isolith) maps for all mapped parasequences.

**FACIES VARIATION WITHIN THE SECOND FRONTIER SANDSTONE**

Second Frontier sandstone facies successions are characterized by coarsening-upward trends with strong evidence for wave domination, similar to these observed in shoreface or wave-dominated deltaic successions (e.g., Clifton et al., 1971; Elliott, 1986; Van Wagoner et al., 1990; Reynolds, 1999; Hampson and Storms, 2003; Hampson and Howell, 2005) (Figures 3, 4a). In both outcrop and core, the top of coarsening-upward successions is capped by a regionally significant surface of erosion, identified by the *Glossifungites* ichnofacies; pebble lag; or a pebble-bearing, well-bioturbated muddy sandstone-to-sandy mudstone interval. Such deposits are interpreted as transgressive (MacEachern et al., 1992; Cattaneo and Steel, 2003) and in turn overlain by mud-dominated strata, with varying degrees of marine bioturbation. Five facies, described below, capture most of the variability of Second Frontier parasequences observed in both outcrop and core.

**Facies A(i): Heterolithic Siltstone or Sandstone and Mudstone**

**Description**

Facies A is characterized by laminated mudstone to laminated-to-thin-bedded siltstone or sandstone and mudstone (Figure 4b); sand and silt beds show common cross-lamination formed by unidirectional or combined flow ripples. Bioturbation levels are low with *Planolites* and *Asterosoma* being the most common trace fauna. Facies A(i) has not been observed directly underlying sand-dominated facies successions (Figure 3).

**Interpretation**

The mud-dominated nature of this facies suggests open marine accumulation below storm-wave base (Van Wagoner et al., 1990). A possible prodelta origin is indicated by low levels of bioturbation, related to either high rates of sedimentation or salinity stress (MacEachern et al., 2005).

**Facies A(ii): Bioturbated Mudstone, Siltstone, and Sandy Mudstone (with Silt or Sand Beds)**

**Description**

Facies A(ii) is characterized by alternating silty or sandy mudstone with thin- to medium-thick sandstone beds. The average thickness of sandstone beds increases upward. Sandstone beds appear sharp based and horizontally planar stratified where not obscured by bioturbation. Mud-dominated intervals typically show medium to high levels of bioturbation of the *Cruziana* ichnofacies with *Planolites*, *Thalassinoides*, *Asterosoma*, *Terebellina*, and *Palaeophycus* being the most common ichnogenera. Sand beds typically show a two-tier burrowing relationship with small *Ophiomorpha* and local *Skolithos*, succeeded by a dominant *Cruziana* ichnofacies bioturbation (Figure 4c).

**Interpretation**

Mud-dominated parts are interpreted as hemipelagic sediments deposited in an open-marine, ichnologically unstressed, shelf environment. The sharp-based, planar stratified event beds indicate a possible storm- or wave-dominated setting and likely deposition by storm-induced geostrophic currents (Van Wagoner et al., 1990).

**Facies B: Amalgamated Planar and Hummocky Cross-Stratified Sandstone**

**Description**

Facies B comprises amalgamated, planar to hummocky cross-stratified sandstone, with low levels of bioturbation and common *Ophiomorpha* (Figure 4d).
Figure 3. Typical coarsening-upward successions of the Second Frontier sandstone in outcrop with corresponding facies and facies associations. The legend applies to all measured sections and core logs in the article.
Figure 4. Photographs of Second Frontier sandstone facies in core and outcrop. (a) Regional view of Second Frontier coarsening-upward successions. The location is in the area between Tisdale and Kaycee anticlines. (b) Heterolithic and generally poorly bioturbated facies A(i) in outcrop. (c) Facies A(ii) in core, showing a planar stratified sand bed with *Ophiomorpha* in well-bioturbated Cruziana ichnofacies mud-dominated interval. (d) Well-developed hummocky cross-stratification in concretion (facies B). (e) Well-bioturbated *Ophiomorpha* middle-shoreface succession of facies C. (f) Facies D showing thick-bedded, upper shoreface cross-stratification. (g) Facies C overlain by pebble lag (white arrow) and heterolithic muddy sand and sandy mud successions typical of facies E. (h) Petrified wood. (i) Lower part of thick beach conglomerate facies showing a gradational contact between a marine *Ophiomorpha*-burrowed sandstone and an overlying conglomerate.
Unbioturbated mud lenses (10–30 cm [4–12 in.] thick) with local coal fragments are common in the northern part of the study area. Sandstone beds can be traced in outcrop over distances of tens to hundreds of meters but are regionally discontinuous. Rare pockets of granular to pebbly sandstones, locally contained within small scours, are found locally.

**Interpretation**

Facies B is interpreted as a lower shoreface deposit along a wave-storm-dominated strand-plain shoreline or a wave-dominated delta similar to those described by Hampson and Storms (2003). The local coarse granular to pebbly units are interpreted as deposits of storm scours that carried sediments from more proximally gravelly fluvial channels or beaches. Low levels of bioturbation are also interpreted to be caused by frequent sediment reworking by storm waves. Mud lenses (more common in the north) indicate proximity to a river mouth, and deposition from hypopycnal river plumes during flood stages. The unbioturbated and discontinuous nature of the mud beds suggests deposition above storm-wave base, where both storm scour and quicksand burial appear to be important for the preserved nature of these deposits. Where present, such mud beds in an otherwise sand-dominated lower shoreface interval can have an important impact on the vertical permeability of a reservoir.

**Facies C: Planar to Cross-Stratified Ophiomorpha-Burrowed Sandstone**

**Description**

Facies C is characterized by medium-bedded, dominantly horizontal planar and locally dune-scale cross-stratified sandstone (Figure 4e). Levels of bioturbation can vary from moderate to high, with common
monospecific *Ophiomorpha* prevalent. Interspersed granules and pebbles are common. This facies typically overlies facies B with a gradational contact.

**Interpretation**

This facies is interpreted to represent a more proximal, higher energy middle shoreface environment compared to the lower shoreface deposits of facies B (Clifton, 2006).

**Facies D: Cross-Stratified Sandstones**

**Description**

Facies D is characterized by medium to thick-bedded, dune-scale trough cross-stratified sandstone (Figure 4f), with a low to medium intensity of bioturbation dominated by *Ophiomorpha* and rare *Skolithos*. Petrified wood is occasionally observed (Figure 4h). Local pebble-lined scour-and-fill structures are common in outcrop. Facies D is commonly overlain by sand- and pebble-filled sharp-walled *Thalassinoides* burrows of the *Glossifungites* ichnofacies.

**Interpretation**

Facies D is interpreted as an upper shoreface environment dominated by 3-D dune migration affected by fair-weather wave processes (Van Wagoner et al., 1990; Hampson and Storms, 2003; Clifton, 2006).

**Facies E: Pebble-Bearing Muddy-Sand, Sandy-Mud, and Mudstone**

**Description**

Facies E consists of a fining-upward succession of several lithologies: (1) chert and andesite porphyry-bearing pebble to cobble lag (up to 40 cm [16 in.] thick); (2) pebble-bearing, muddy sandstone, of varying grain sizes, with sparse thin-bedded, coarse-sand interbeds; (3) pebble-bearing, sandy mudstone; and (4) a thick mud-dominated interval with varying degrees of bioturbation with common *Helminthopsis* and *Zoophycos* (Figures 4g, 5). Pyrite nodules are common in the lower part of the facies.

**Interpretation**

This facies association is interpreted to represent the remnants (palimpsest sediment) of wave ravine-ment that truncated the top of the Second Frontier sandstone and removed or reworked associated coastal-plain deposits. Evidence for reworked coastal-plain and fluvial sediments is the abundance of pebbles and cobbles, which are assumed to represent completely reworked fluvial and beach deposits. The pebble lag and the *Glossifungites* surface mark the position of a transgressive surface of erosion (MacEachern et al., 1992). An upward increase in mud content is related to water deepening and onset of open-marine shelf deposition (Cattaneo and Steel, 2003).

**Facies F: Beach Conglomerate Facies**

**Description**

Facies F is developed only locally in the northern part of the Kaycee anticline. Facies F comprises an up to 3.5-m-thick (11.4-ft-thick) conglomerate succession dominated by pebble- to cobble-size clasts. Stratification of the units is low angle to horizontal planar. The contact with underlying facies C is gradational to sharp. Where it is gradational (Figure 4i), pebble-lined sand beds transition up into the conglomerate. The texture of the underlying horizontally planar to hummocky cross-stratified sandstone belonging to facies C, the texture of the sand in the pebble-lined beds, and the texture of the sand matrix in the conglomerate appear to be identical. Where sharp-based, the contact between the sand-dominated and the conglomerate intervals appears planar instead of undulatory and shows no evidence of channelization. The only evidence for erosion occurs in well-developed, up to a meter wide, chert pebble-filled, scour-and-fill bodies, which occur both directly underlying the conglomerate or lower down in the underlying sand-dominated interval.

**Interpretation**

The lack of undulating erosional surfaces between the marine sandstone below and the overlying conglomerate, the similarity of the sandy matrix within the conglomerate to the underlying sandstone, and the planar to low-angle cross-stratification within the conglomerate suggest interpretation as a beach conglomerate (Hart and Plint, 1995). The observed
Figure 5. Expression and contact between two parasequences in core B001 (U.S. Geological Survey Core Research Center). Middle: Parasequence E is showing a well-developed coarsening-upward succession and is conformably overlain by a 1-m-thick (3-ft-thick) well-bioturbated sandy mud interval. The upper parasequence is locally sharp based and is capped by a transgressive surface of erosion and facies E. Left and right: Representative core facies shots. See Figure 3 for the legends.
cut-and-fill structures are interpreted to be related to storm current scour instead of fluvial erosion. No diagnostic fluvial features were observed, such as dune or bar-scale cross strata, bar accretion surfaces or channel scours, or associated paleosols or flood-plain deposits (Bridge, 2006).

SECOND FRONTIER PARASEQUENCES

Parasequences in Core and Outcrop

The coarsening-upward successions of the Second Frontier sandstone appear to resemble classical shoreface parasequences, similar to those defined by Van Wagoner et al. (1990). The uppermost parasequences are topped by a transgressive surface of erosion, overlain by facies E. Parasequences within the Second Frontier, in contrast, are conformably capped by a thin mud-dominated interval of facies A that lacks evidence of basal scour, lag, or other evidence of transgressive erosion (Figure 5). The transgressive surface of erosion always caps the top parasequence in the Second Frontier parasequence set. The mud-dominated succession overlying the transgressive surface is regionally mappable and is interpreted to be related to the permanent retreat of the shoreline west of the study area. The mud-dominated intervals separating individual parasequences can be attributed to local autocyclic processes associated with short-term punctuation of shoreline progradation and alongshore migration or related to subtle changes in relative sea level of possible eustatic origin that resulted in short pulses of transgression in an overall regressive system. Such mud-dominated intervals can be thought of as minor flooding surfaces, similar to those described by Bhattacharya (1993). The correlation of the wells in subsurface and walking out of key bounding surfaces in outcrop show that the Second Frontier can be subdivided into seven individually mappable parasequences that are bounded by minor marine flooding surfaces. These parasequences show that the Second Frontier sandstone forms a highly progradational to offlapping parasequence set. The offlapping nature of the parasequences means that, in any one well log or outcrop section, only one or two parasequences are sampled.

The facies expression and lateral change in parasequences are well illustrated in outcrop and core cross sections. A thick parasequence in one area (e.g., Figure 6) can thin laterally and become conformable with overlying strata. Where this happens, a second parasequence typically lies on top, with the transition between the two parasequences characterized by an increase in proportion of mud and an increase in bioturbation, with a corresponding lack of evidence for transgressive erosion (such as the truncation of log markers and the presence of a pebble lag that marks the regional transgressive flooding surface that caps the parasequence set). The organization of successive parasequences shows a classic compensation pattern, which in part explains the offlapping nature.

Recognition of Parasequences in Well Logs

Two criteria are important for the correlation of parasequences in the subsurface: (1) facies observations in outcrop and core suggest that the Second Frontier sandstone is not characterized by significant facies variation between parasequences and (2) the tendency of parasequences to coarsen upward, to be bounded by a transgressive surface of erosion or minor flooding surfaces, and the outcrop observations that individual parasequence can extend laterally for several to several tens of kilometers suggest that parasequences should be correlatable between closely spaced well logs. Well logs are especially useful for the correlation of the mud-dominated intervals, which bound the Second Frontier sandstone, and were used to help elucidate its internal 3-D architecture.

Examples of well-log correlation in dip and strike cross sections are illustrated in Figures 7 and 8. The sand-dominated parts of the Second Frontier interval are identified by inflections of spontaneous potential and resistivity curves, which correspond to coarsening-upward trends. The key correlatable features in well-log cross sections in the study area are best observed in Figures 7c, d, and 8. The Second Frontier downlaps onto a regionally mappable
surface (green line), characterized by high-resistivity values and is interpreted to be a maximum flooding surface (Van Wagoner et al., 1990; Posamentier and Allen, 1999). The top of the Second Frontier sandstone is defined by an abrupt transition from sand- to mud-dominated facies, as suggested by a sharp

![Figure 6. Parasequence transition and offlap as observed in outcrop. A thick parasequence to the north (left), overlain by a pebble lag and a transgressive facies association becomes conformable to the south (right), and is, in turn, overlain by a new parasequence. The contact between the parasequences is a mud-dominated interval with varying degrees of bioturbation that lacks evidence of significant basal scour or a pebble lag at its base. The pebble lag instead overlies the top parasequence, which compensationally thickens to the south. See Figure 1 for the locations. Clinoforms are schematic. See Figure 3 for the legends.](image-url)
Figure 7. Representative spontaneous potential-resistivity well-log cross sections with dip orientation, perpendicular to regional Second Frontier trend. The cross sections transect all parasequences (color coded) except for parasequence A, which is limited to the area north of AA’. Cross sections AA’ and BB’ are located in the northern part of the study area, where the Second Frontier interval is thicker and more prone to parasequence stacking. Datum is top of the Second Frontier sandstone (transgressive surface of erosion). Cross sections CC’ and DD’ are from the central and southern part of the study area, respectively, where accommodation was lower and resulted in a well-developed parasequence offlap. The entire Second Frontier interval overlays the Thatcher bentonite. Mapped parasequences downlap a regional maximum flooding surface. The thinning of sands to the west (left) in cross sections is attributed to a tectonically driven erosion (see text). Cross section DD’ shows an additional erosional surface that has been mapped in the overlying Second Frontier sandstone mud-dominated succession. Datum is top of the Second Frontier sandstone (transgressive surface of erosion).
Figure 7. Continued.
Figure 8. Parasequences in an along-strike orientation. Top: Well-log cross section WW’ of the central and southern parts of the study area, which shows a well-developed offlapping parasequence trend to the south. This suggests that parasequence offlap also occurs in strike direction relative to the elongated trend of the Second Frontier sandstone. Datum is top of the Second Frontier sandstone (transgressive surface of erosion). Bottom: Parasequence offlap as observed in core. Note that parasequences E and F are separated by a finer grained interval, which is thick enough to act as a potential baffle or barrier to flow. Core demarcation is in feet.
drop in spontaneous potential values, which is interpreted to correspond to the position of a transgressive surface of erosion. The sand-dominated parts can be subdivided into several parasequences mapped on the basis of minor peaks in spontaneous potential and resistivity curves. The minor peaks are caused by an increase in mud content and are interpreted as minor flooding surfaces; the facies expression of these can be seen in corresponding core cross sections (Figure 8). The minor flooding surfaces can be traced into the underlying mud-dominated intervals by traceable peaks in resistivity, which ultimately downlap onto the maximum flooding surface forming an offlapping, clinoform pattern. Such clinoforms are observed in both dip (Figure 7) and strike directions (Figure 8).

Although the Second Frontier sandstone thins and pinches out both to the east and to the west, the nature of the pinch-outs is fundamentally different, suggesting different causal mechanisms. The most distal parasequences in the dip cross sections to the east thin in a gradual and conformable manner (e.g., Figure 7c). Internally, the parasequences show an overall increase in mudstone as they thin, suggesting a depositional pinch-out. These sand-bearing clinoforms are overlain by fine-grained sediment (as indicated by low spontaneous potential (SP) values on well logs), which compensationally thicken seaward. Similar successions seaward from distal shorefaces and deltas have been referred to as healing-phase deposits and have been interpreted to be transgressive in origin (Posamentier and Allen, 1993). The thinning of the Second Frontier sandstone to the west, however, is clearly erosional in character (see Figure 7c, d). This is shown by convergence and discordance between underlying and overlying Second Frontier well-log markers. Underlying well-log markers are truncated by the erosional surface (stippled lines in Figure 7c, d). Correlation shows that the erosional surface is a continuation of the transgressive surface of erosion mapped on top of the Second Frontier sandstone farther to the east. Erosional truncation of bentonite markers in the mud-dominated interval, directly overlying the Second Frontier sandstone, is also indicated by detailed well-log correlation (Figure 7d).

**DEFINITION OF PARASEQUENCES**

Although the Second Frontier sandstone has frequently been mapped as a single north-northwest–south-southeast–trending sand body (e.g., Barlow and Haun, 1966) (see Figure 9, total isolith map), we show that internally the unit contains at least seven parasequences bounded by regionally mappable minor flooding surfaces. From oldest to youngest, the parasequences are named A, B, C, D, E, F, and G. Parasequences A, B, C, and D are constrained to the northwestern part of the study area, whereas younger parasequences (E, F, and G) progressively migrated as they offlapped to the south, a trend clearly visible in Figure 8.

**Parasequence A**

Evidence for a sand-dominated interval in the very northern part of the study area (parasequence A) is seen only in well logs north of cross section AA’ (Figure 7a), where a 4.7-m-thick (15.4-thick) sand-dominated interval has been mapped. The most distal expression of the unit can be seen below the flooding surface, underlying parasequence B (Figure 3). An isolith map of the unit (Figure 10) shows it to be lobate in shape and increasing in thickness to the west, away from the study area.

**Parasequences B and C**

Parasequence B forms the major sandstone unit of the Second Frontier that crops out throughout the Kaycee anticline, and most of the northern part of the Tisdale anticline (Figure 1). Parasequence B is characterized by facies A(ii), B, C, and D, suggesting deposition in a wave-dominated setting. Net southward sediment transport (Figure 10) is suggested by 21 paleocurrent measurements from 3-D dunes measured in outcrop (facies D). Where not abruptly truncated (see Vakarelov et al., 2006), parasequence B thins toward the south, in the outcrop belt, and is overlain by parasequence D. The correlation of parasequence B in the subsurface is based on thickness trends and the position of
an underlying bentonite. Parasequence B attains a maximum thickness of more than 40 m (131 ft) in outcrop (Figure 10). Although the true extent of the parasequence to the southwest cannot be determined because of postdepositional erosion, a depo-

center, consistent with outcrop observations, occurs in the northwestern part of the study area. The isolith map shows two local thick areas, suggesting two depositional lobes (Figure 10). The second lobe can be attributed either to the presence of an additional

Figure 9. Combined isolith thickness of the Second Frontier sandstone showing the well-defined north-northwest–south-southeast–elongated trend of the unit. Contour lines are in meters.
parasequence farther to the south or to a local topographic high in the middle part of the unit. No cores have been examined in parasequence B, so facies characteristics in the southeastern part of the unit are unknown, although the well logs show similar coarsening-upward facies trends. An additional parasequence of local significance (parasequence C) is mapped in the most northern part of the study area (see Figure 7a). Parasequence C reaches a maximum thickness of about 8 m (26 ft). This unit was identified solely on well-log data, and no additional facies information is available, although the coarsening-upward well-log pattern suggests a similar deltaic or shoreface environment.

Parasequence D

Parasequence D crops out in the middle part of the Tisdale anticline, where it overlies parasequence B. Two sections have been measured in this area (Figure 1).

In the southern section, parasequence D is 8 m (26 ft) thick and sharp based (Figure 6).

At this locality, parasequence D is made up of facies C and D and is overlain by a pebble lag marked by a well-developed Thalassinoides-burrowed passively infilled Glossifungites surface. The well-log expression of parasequence D is shown in Figure 7a–c. An isolith map of the unit (Figure 10) is strongly elongated, with a maximum thickness of about 18 m (59 ft).

Parasequence E

Mapping of parasequence E is based entirely on subsurface data. In core, the facies succession appears similar to that in parasequence B. Where thick, parasequence E is characterized by an upward-coarsening succession of facies A(ii), B, C, and D. The parasequence thins and grades laterally to the south and east into a mudstone-dominated interval (Figure 8). As the parasequence thins, its upper part facies suggest lower energy and it is overlain by fine-grained facies lacking evidence for erosion. The offlapping nature of parasequence E is well illustrated in Figures 7b, c, and 8. Parasequence E has a north-northwest–south-southeast–elongated lobate geometry with a depocenter directly south of the depocenter of parasequence D (Figure 10).

Parasequence F

Mapping of Parasequence F is based entirely on subsurface data.

In core, the unit appears similar to the previously described parasequences, showing a transition of facies A(ii), B, C, and D. Where overlying a sand-dominated part of another parasequence, parasequence F can be locally sharp-based, with a basal pebble lag. This pebble lag appears local in extent and does not extend to adjacent cores. The well-log signature of parasequence F can be observed in Figures 7c, d, and 8. In an isolith map (Figure 10), the parasequence appears elongated in a north–south direction, with a depocenter directly south of parasequence E.

Parasequence G

Parasequence G is the youngest parasequence in the Second Frontier sandstone in the study area. This parasequence has not been observed in outcrop and has been penetrated by only one of the examined cores. Only the top part of the parasequence is sampled, showing a cross-stratified sandstone succession with Ophiomorpha typical of facies D. The parasequence is the most distal of the mapped units in both eastward (dip) and southward (strike) directions (Figures 7c, d; 8). An isolith map of the unit (Figure 10) shows an elongated two-arm geometry, suggesting that the parasequence might be made up of two units.

INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

A previous interpretation of the Second Frontier sandstone favored an offshore bar model (Barlow and Haun, 1966). This interpretation was based on the lack of evidence for nonmarine facies, the planview geometry of the unit, and the basin-isolated nature of the unit with an apparent detachment of
Figure 10. Isolith maps for parasequences A to G. The area referred to as “tectonically forced truncation” is the mapped extent of erosion in the west-central part of the study area. Contour intervals are in meters. The underlying pale-color areas show distribution in plan view of underlying parasequences.
Figure 10. Continued.
the sandstone from contemporaneous shorelines to the west.

A large number of mud-encased sandstones in the Cretaceous Western Interior, previously thought of as offshore bars, are better interpreted to be of marine shoreface or deltaic origin (e.g., Plint, 1988; Posamentier et al., 1992; Bhattacharya and Willis, 2001). Shorelines are known to migrate across significant distances, and in low accommodation settings, wave ravinement can remove all traces of coastal-plain deposition. A shallow-marine interpretation readily fits the various observations presented here in the Second Frontier sandstone (see also Merewether et al., 1976).

The coarsening-upward character of parasequences and pervasive shallow-marine Ophiomorpha burrowing suggest the progradation of a shallow-marine shoreface, with locally preserved conglomeratic beach deposits. The well-defined pebble lag topping the succession, the occurrence of petrified wood, and abundant unbioturbated mud lenses in sand-dominated intervals in the north all likely suggest proximity to a fluvial sediment source.

An interpretation based solely on plan-view geometry as well as the internal facies evidence for wave domination of the entire Second Frontier sandstone might be suggestive of a linear, wave-dominated shoreface deposit. Internal flooding surfaces would therefore be expected to be subparallel to this trend and to bound strongly elongated parasequences (Reynolds, 1999; Clifton, 2006). Such interpretation does not explain the lobate geometries of several mapped isoliths and the tendency of parasequences to offlap in a southerly (along strike) direction oblique to the regional trend of the Second Frontier sandstone.

Modern analogs such as the wave-dominated Grijalva-Usumacinta delta or strand-plain system in the southern Gulf of Mexico (Psuty, 1967) show similar geometries to the ones observed in the Second Frontier sandstone. Wave-dominated delta lobes and strand plains in this system also occur on a similar spatial scale to the mapped parasequences in this study (Figure 11). Progradation and partial erosion of the delta lobes are accompanied by longshore migration of sediments to the east and building of beach-ridge complexes in a laterally extensive strand plain. The presence of beach ridges in both the delta lobe and the strand-plain parts of the systems clearly indicates wave domination along the entire shorelines, although in terms of plan-view geometries, the various components of the system appear markedly different (Figure 11).

We suggest a depositional model for the Second Frontier sandstone, which explains the offlapping parasequences as representing individual delta lobes or strand plains similar to those observed in modern wave-dominated systems. The westward pinch-out, however, is clearly interpreted to be related to syn- or postdepositional tectonic control as will be discussed in the following sections. Such erosion ultimately resulted in the formation of a depositional remnant as defined by Martinsen (2003a).

**Paleogeographic Reconstruction**

Our paleogeographic reconstruction of the Second Frontier is based on the following observations and suggested interpretations. (1) Observations from cores and outcrops from five parasequences suggest similarities in facies characteristics among the various parasequences, which everywhere suggest conditions of wave domination. Parasequences are therefore interpreted as wave-dominated delta and shoreface (strand plain) deposits. (2) The Second Frontier sandstone is everywhere top-truncated by a transgressive surface of erosion, and no preservation of nonmarine strata anywhere in the study area is observed. (3) Abundant unbioturbated mud beds associated with hummocky cross-stratified intervals in the northern part of the study area that have not been observed in the south exist. This likely indicates proximity to a fluvial point source in the north capable of delivering large quantities of mud to the inner shelf. (4) Paleocurrent indicators in outcrop suggest a net southward sediment transport, which we interpret as indicating dominant longshore sediment transport. (5) Barlow and Haun (1966) reported a gradual decrease of pebble sizes south of the Kaycee area and an abrupt decrease to the north of this point, suggesting that gravel-bearing rivers lay to the northwest instead of the west. (6) The Second Frontier sandstone is also thickest in the northwestern part of the study area.
Figure 11. Grijalva-Usumacinta wave-dominated delta or strand-plain system showing appreciable complexity of internally mappable units that occur on similar spatial scale to parasequences mapped in the Second Frontier sandstone. Such complexity is not unusual in modern systems and may be present in many wave-dominated reservoirs. Colored lines represent different delta lobes and stand plains (reprinted with permission from Google).
(Figure 7a, b). (7) Parasequences dominantly offlap to the southeast, suggesting that the main progradation direction was to the southeast. (8) Consecutive parasequence depocenters tend to migrate to the southeast with time. (9) Mapped isolith geometries are elongate to lobate in shape, suggesting a broadly deltaic character. (10) Evidently, although regional isolith maps of the entire Second Frontier sandstone show the unit to trend roughly north–south (Figure 9), internal parasequence orientations (and associated flooding surfaces) are oblique to this trend. (11) Evidence of truncation of marine markers in well logs and observations in outcrop suggest that syntectonic deformation was an important factor in much of the western part of the study area.

The position of the early parasequences suggests that deposition was limited in the northwestern part of the study area (Figure 12). Although transgressive erosion has removed all evidence of trunk-stream positions, indirect evidence such as pebble-size distribution, maximum thickness of the Second Frontier sandstone in the northwest, and abundance of unbioturbated mud lenses in sand-dominated intervals suggests proximity to a river mouth in the northwest. Such reasoning as well as the shapes of the early parasequence (A–D) points to deposition in a wave-dominated deltaic instead of purely strand-plain environment. If uplift of the paleohigh to the west was already initiated at this time, it might have localized the position of feeding streams. Although the sand part of parasequences B, C, and D did not extend to the southern part of the study area, contemporaneous prodelta mud (mudstone belt) was deposited farther to the south (see Figure 8) and was likely affected by alongshore current transport. Similar deposits are commonly observed in Holocene systems but are thus far poorly recorded in the ancient record (see Diaz et al. 1996; Cattaneo et al. 2003, for modern examples).

A paleogeographic reconstruction of the study area at the time of deposition of parasequence D is shown in Figure 12a, at which time it is shown that sediment depocenters gradually migrated to the south. The lobate-to-elongate geometries of parasequences E, F, and G, suggest a strong net southerly component of sedimentation, affected by an emerging paleohigh to the west (Figure 12b–d), and this is also seen for parasequences F and G. This explains the observation, across much of the central and southern part of the study area (including the Salt Creek field), that successive parasequences offlap in an along-shelf (southward) direction at high angle to the regional trend of the Second Frontier sandstone. A paleohigh area would have prevented significant local riverine sediment input from the west, ensuring the dominance of alongshore sediment transport. Southward sediment migration explains the compensational depositional trends of successive isoliths. The paleogeographic reconstruction shows the position of the paleohigh area and the net southward shoreline progradation during deposition of parasequences E and F (Figure 12b, c). Although it cannot be separated using available data, the two-arm geometry of the isolith of Parasequence G (Figure 10) likely indicates that the unit is composed of two parasequences. The western arm (G1 in Figure 12d) was deposited as a continuation of the southern trend of progradation, whereas the eastern arm (G2) represents the offshore progradation of the entire system, caused either by infilling of accommodation to the south, further uplift of the topographically high area, or forced regression.

**EVIDENCE FOR TECTONIC INFLUENCE IN THE SECOND FRONTIER SANDSTONE**

Effects of local tectonic control in Cenomanian strata of the Frontier Formation, including the Second Frontier sandstone, were documented by Bhatacharya and Willis (2001) and Vakarelov et al. (2006). A regional investigation of missing ammonite biozones by Merewether and Cobban (1986) revealed that the Emigrant Gap unconformity, overlying the Second Frontier interval, is also tectonic in origin. The tectonic control discussed here occurs on a local scale and does not exclude the importance of other processes that affected the system regionally. The lowstand shorelines that reach the study area from the west likely responded to larger scale eustatic or regional tectonic forcing, which we have not attempted to resolve.
Evidence for local erosion can be directly documented along an approximately 1-km-long (0.6-mile-long) continuous outcrop, where about 10 m (33 ft) of section is missing (Figure 13) (Vakarelov et al., 2006). Truncation occurs underneath a pebble lag bed that can be walked along the entire outcrop and that overlies upper shoreface facies D to the north and lower shoreface facies B to the south.
Figure 13. Example of tectonically enhanced truncation in outcrop. Top: About 10 m (33 ft) of section is missing in the southern part of this continuous outcrop, resulting in truncation of stratigraphic markers underneath a pebble lag-bearing erosional surface. Truncation is interpreted to be caused by the wave erosion of an uplifted area. See the text for further explanation. Bottom right: An aerial photograph showing positions of measured sections and orientation of outcrop. Bottom left: Photo of the portion of the outcrop. Modified from Vakarelov et al. (2006). oph = *Ophiomorpha*; pa = *Palaeophycus*; St = silt; vF = very fine sand; F = fine sand; M = medium sand; C = coarse sand; VC = very coarse sand.
Beds in underlying successions are truncated by the erosional surface and locally show well-developed Glossifungites surfaces. The erosional surface appears to be sharp, non-undulating, and horizontal and is overlain by transgressive-to-marine deposits of facies E. Facies E strata show no noticeable variation across the outcrop and appear similar to the fining-upward successions overlying the Second Frontier sandstone regionally. The net result of the erosion is abrupt thinning of the Second Frontier sandstone over a relatively short distance.

A similar style of thinning is regionally mappable in the well logs. Cross sections CC’ and DD’ (Figure 7) show that accommodation decreases to the west; this trend is indicated by the decreasing distance between the maximum flooding surface underlying Second Frontier strata and the overlying bentonites. As in outcrop, the sand part of the Second Frontier thins and eventually pinches out, with stratigraphic markers in underlying mud-dominated successions truncated by an erosion surface. The erosional surface appears continuous with the transgressive surface of erosion farther to the east. Bentonite markers above are subparallel to and do not onlap the erosional surface, suggesting that the posterosion topography did not have significant relief.

An additional erosional surface is present in the mud-dominated, bentonite-bearing interval, directly overlying Second Frontier strata. The erosional surface is identified by truncation of bentonites (see cross section DD’, Figure 7) and appears to coincide in position with the underlying mapped truncation of the Second Frontier sandstone.

**Interpretation of Erosional Mechanism**

Two main erosional mechanisms can result in removal of shoreface successions in a low accommodation, shallow-marine setting. The erosional mechanisms are (1) valley incision during relative sea level fall (e.g., Posamentier and Allen, 1993) and (2) wave erosion after transgression (e.g., Cattaneo et al., 2003) with enhanced peneplanation of an uplifted area (e.g., Barnes, 1995).

The following observations argue against an incised valley interpretation for the truncation observed associated with the Second Frontier sandstone: (1) the interpreted trend of erosion is subparallel to the trend of regional Second Frontier sandstone; valley incision would be expected to be normal to this trend; (2) the erosional surface is sharp, non-undulating, and is overlain by transgressive marine facies instead of fluvial deposits; (3) the pebble lag overlies a marine Glossifungites surface, requiring marine instead of fluvial erosion (MacEachern et al., 1992); although the pebbles may have been fluvial in origin, they have clearly been reworked by wave (and possibly tidal) processes; (4) evidence of onlap in the overlying mud-dominated strata is lacking; onlap is a defining characteristic of incised valley fills.

A mechanism involving local tectonic uplift and subsequent truncation by wave erosion is well supported by observations. The planar nature of the erosional surface is typical for transgressive surfaces of erosion (Nummedal and Swift, 1987), as is the presence of a pebble lag, an overlying marine fining-upward facies succession (Cattaneo and Steel, 2003), and a Glossifungites surface (MacEachern et al., 1992). As discussed by Vakarelov et al. (2006), the regional erosional trend also resembles the orientation of present-day Laramide structures (e.g., Tisdale anticline), suggesting underlying tectonic control. A second pulse of uplift is suggested by the described truncation in the overlying mud-dominated successions, which also could not have been generated by river erosion.

A study shows how Quaternary wave erosion over a topographic high resulted in geometries similar to the ones mapped in this study. Barnes (1995) showed a high-resolution seismic example from the Quaternary Canterbury shelf of New Zealand, where an uplifting anticline has been peneplaned during several glacioeustatic transgressions. Each time the transgression passed over the uplifted area, topography was leveled and underlying strata were truncated. Because of the nature of transgressive surfaces of erosion, the erosional contact was sharp and lacked significant relief (Figure 14).

**Timing of Uplift**

Tectonic movement can result in changes in topography and bathymetry that can directly affect
deposition in a prograding shoreline. Topographic lows may act as sites for accumulation of sediment, whereas topographical highs will tend to form headlands and wave-cut platforms, which will be characterized by nondeposition and sediment bypass.

Tectonic movement that postdates regression and predates transgression can also greatly affect preserved sediment distribution. A topographically high area can be preferentially removed by wave ravinement, which can result in removal of large sections of previously accumulated sediment.

In low accommodation settings, where all coastal-plain deposits are prone to removal after transgression, both scenarios can result in similar plan-view geometries and in similar apparent thinning of sand-dominated successions. Facies distribution will nonetheless be expected to be different. Headlands and wave-cut platforms will locally limit accommodation and will tend to be associated with the highest energy facies in a system. Lower energy facies will be deposited away from these geomorphologic features where water depth increases. Upon transgression, the top of the wave-cut platform will likely become continuous with the transgressive surface of erosion over the adjacent shoreface, which can result in an effective pinch-out of coarse-grained strata. The area of thinning will correspond to increase in facies energy.

If the timing of uplift postdates the progradation of shorelines in an area, there would be no depositional relationship between accumulated sediment and the area of uplift. Subsequent transgressive wave ravinement would still be capable of removing all coarse-grained strata over an uplifted area, but in this case, the area of thinning will correspond to apparent decrease in facies energy below the erosional surface. The apparent decrease in facies energy will be related to differential erosion into sediments originally deposited into a more distal or deeper water setting relative to the shoreline that has been uplifted. Both uplift scenarios can result in the formation of pebble lags over the paleo-high area, can be overlain by similar transgressive facies, and in the absence of facies data, may be difficult to differentiate.

Based on the above considerations, we interpret the outcrop truncation shown in Figure 13 to be postdepositional based on the evident preservation of deposits showing a progressively lower facies energy underneath the transgressive surface with increased amounts of erosion. This is in contrast to the study of Bhattacharya and Willis (2001) who demonstrated syndepositional tectonics in the underlying Frewens allomember.

Although facies observations in the southwestern part of the study area are not available, where the Second Frontier sandstone thins to the west, the architecture of parasequences F and G1 (Figures 7c, d; 10) suggests that a topographic high already lay to the west. In these parasequences, the thinning of sand bodies is more gradual, and a definite tendency for southward along-strike progradation exists (likely constrained by the trend of the uplifting area). Nonetheless, a topographic high, uplifting

Figure 14. A Quaternary example of wave peneplanation over an uplifting area from the Canterbury shelf of New Zealand. Continuous uplift of an area results in tilt and angular truncation during several transgression episodes. Modified from Barnes (1995). x = position of measured section.
much of the western part of the study area, ultimately determined the plan-view geometry of the Second Frontier sandstone. This uplift appears to have dominated the stratigraphic architecture and development of reservoirs within the unit.

**IMPLICATIONS FOR PETROLEUM EXPLORATION AND PRODUCTION**

The parasequence architecture outlined in this study illustrates the complexity that can be associated with many wave-dominated reservoirs, although they have historically been considered to be relatively homogenous (e.g., Clifton, 2006). The Second Frontier sandstone is shown to have high degree of internal heterogeneity, similar to Holocene wave-dominated systems such as the Grijalva-Usumacinta, Mexico (Psuty, 1967), and the Caravelas strand plain, Brazil (Andrade et al., 2003). This heterogeneity may have potentially important implications for petroleum exploration and field development, especially in secondary and tertiary recovery. The Second Frontier is currently the focus of a major CO₂-enhanced oil recovery project, and the internal complexity documented here needs to be considered to understand and predict the ultimate reservoir behavior. Instead of representing a single, homogenous reservoir compartment, we suggest that the Second Frontier comprises a set of seven minor-flooding surface-bounded parasequences, which have orientations highly oblique to the regional trend of the Second Frontier sandstone. Such minor flooding surfaces are mud rich and can potentially act as baffles and even barriers to flow during reservoir production and CO₂ injection. The impact of similar features for field development using a modeling approach was examined by Larue and Lagarre (2004), who showed that flow simulations omitting such level of heterogeneity were incorrect in predicting water breakthroughs and distribution of bypassed oil.

Such heterogeneity is especially important when taken in accord with the demonstrated tectonic influence over the deposition of the Second Frontier sandstone. On a regional scale, the Second Frontier sandstone is a depositional remnant (Martinsen, 2003a) with its distribution limited to the west by tectonic uplift. Also, parasequence set complexity is internal to the remnant and its architecture was directly affected by the tectonically driven changes in topography and bathymetry. The high degree of along-strike migration of successive parasequences to the south and the oblique nature of their boundaries are attributed to this tectonic forcing. The Second Frontier sandstones can therefore act as an important analog to other fields where producing intervals are interpreted to have been affected by syndepositional tectonic control. Although the effect of local tectonic control of large-scale reservoir architecture is well-established (Slack, 1981; Martinsen, 2003a, b), we suggest that such effects can also operate at smaller scales, affecting the parasequence distribution within parasequence sets.

A database compiled by Reynolds (1999) shows that progradational shallow-marine regressive systems in tectonically inactive areas are typically built by parasequences that extend for between 2 and 40 km (1.2 and 25 mi) in dip direction (mean of 17.3 km [10.7 mi]). In the strike direction, such systems may extend up to hundreds of kilometers (Reynolds, 1999). Such high degree of along-strike elongation is not present in Second Frontier parasequences, which have width-to-length ratios of about 0.5 (e.g., parasequence E 25 km/50 km [15 mi/31 mi], parasequence F 16 km/40 km [10 mi/25 mi], parasequence G 30 km/>70 km [19 mi/43 mi]). This smaller degree of elongation, coupled with the along-strike parasequence migration, can be related to the effects of local tectonic control, which affected both accommodation distribution and position of sediment point sources in the system.

**IMPLICATIONS FOR SEQUENCE STRATIGRAPHY**

The application of sequence-stratigraphic nomenclature in low accommodation settings where coastal-plain deposits are prone to erosion is difficult (see Bhattacharya and Willis, 2001). In such settings, wave or tide ravinement commonly removes all evidence of subaerial erosion, making the very definition of sequence boundaries (c.f. Van Wagoner,
highly problematic. Further subdivision into systems tracts is also fraught with difficulty. To address these problems, Bhattacharya and Willis (2001) used an allostratigraphic approach in the lower part of the Belle Fourche Member, where pebble-bearing transgressive surfaces of erosion were shown to be the most useful bounding discontinuities for mapping purposes.

The regionally correlative surface in this study comprises a pebble-bearing transgressive surface of erosion that regionally caps the Second Frontier sandstone. In addition, recognition of several minor flooding surfaces allowed us to separate the Second Frontier into seven smaller scale, but nevertheless mappable individual parasequences. Mapping also shows that the most southerly parasequence contains two lobes and might actually comprise distinct parasequences or bedsets, although the extent of the surfaces and data did not allow us to correlate or map them separately. Although neither of these surfaces satisfy the criteria for defining sequence boundaries as surfaces that show evidence for subaerial erosion or exposure (sensu Van Wagoner, 1995), they are clearly the most important surfaces useful for correlation and mapping in this study.

Although seven parasequences and one parasequence set were defined in this study, determining what systems tract the Second Frontier belongs to remains a challenge. The sandstone clearly represents the most distal shoreline deposits of a regressive pulse that was either deposited during a time of forced regression and/or subsequent normal regression in a low accommodation setting. The lack of coastal-plain deposits, extensive top-truncation, strong offlap geometry, and basin distal position all support an interpretation of forced regression (Posamentier et al., 1992). Unfortunately, no agreement as to which systems tract forced regressive deposits should be assigned to exists. They have been variably assigned to the late highstand systems tract (Van Wagoner et al., 1990) or early lowstand systems tract (Posamentier and Allen 1999), whereas other workers have suggested a separate falling stage or forced regressive wedge systems tract (Hunt and Tucker, 1995; Plint and Nummedal, 2000). Embry (1995) placed all regressive facies into a regressive systems tract.

The definition of a sequence boundary in itself for such a deposit may be highly ambiguous. According to one school of sequence stratigraphers (see Posamentier and Allen, 1999), the sequence boundary should underlie a forced regressive lowstand deposit. However, in our study, no surface below the deposits could be confidently picked as a sequence boundary or its correlative conformity. We could postulate that, in this position in the basin, the lowstand deposits should theoretically overlie a cryptic correlative conformity. In practice, this surface is exceedingly difficult to identify, let alone correlate and map, in the well-log, outcrop, and core data that we have access to. As a consequence, we have not attempted to match any such conformable surfaces below the Second Frontier with more obvious fluvial unconformities that might exist in the equivalent nonmarine Frontier Formation deposits farther west. This task is considered to be both beyond the scope of this study and potentially unresolvable because the Laramide-age Bighorn Mountains separate the once-contiguous deposits of the Cretaceous seaway. An alternate placement of a sequence boundary favored by other workers (e.g., Van Wagoner et al., 1990; Hunt and Tucker, 1992) is on top of forced regressive deposits. The definition of such a sequence boundary is also problematic in the study area because all evidence for subaerial erosion has been removed by transgressive ravinement.

Although we have used many elements of sequence stratigraphy in our stratigraphic approach, such as correlation of flooding surfaces and mapping of parasequences and parasequence sets, and interpreted the tectonostratigraphic history of the units, this study illustrates that the simple application of parasequence stacking pattern concepts and the use of the three-fold systems tract terminology may not be warranted in such tectonically dominated low accommodation settings, which nevertheless form an important class of petroleum system.

The syntectonic influence introduces additional complications. Local factors, such as uplift and subsidence and direction of longshore currents, determined the stratigraphic architecture of the Second Frontier sandstone. Both the limit of the Second Frontier sandstone to the west and the parasequence
distribution were affected by tectonic control. Although other factors such as sediment supply, eustasy, or basinal warping were responsible for delivering sediment to the study area, they did not significantly impact the resultant stratigraphy and are therefore difficult to discern. The most significant unconformity that affected the Second Frontier interval and limited the extent of the unit to the west is of local tectonic origin and is thus of only subregional importance (Vakarelov et al., 2006). Depositional remnants can be associated with various erosional surfaces, and regional cross-basin correlation of such units can be complex (Martinsen, 2003a). The internal 3-D geometries, however, are readily resolvable and determine both the level of heterogeneity of the interval and paleogeographic reconstruction. Because depositional remnants can be related to early activity along later major anticlinal features, such units can be part of combined traps.

Such is the case of the Salt Creek field in the study area.

CONCLUSIONS

A high-resolution study of the Second Frontier sandstone, Powder River Basin, Wyoming (based on outcrop, core, and well-log data), has deciphered the 3-D internal parasequence architecture of the unit.

The Second Frontier sandstone, previously considered to be a single sand body, is shown to be made up of seven regionally mappable parasequences, bounded by minor flooding surfaces, and topped by a transgressive surface of erosion. Successive parasequences are dominated by offlapping relationships and migrate in an along-strike southward direction with time.

The Second Frontier parasequence set in this area pinches out to the east and to the west, resulting in a north-northwest–south-southeast–trending plan-view geometry. We show that the extent of the unit to the east is depositional in nature, related to limits of shoreline progradation. The extent of the unit to the west is limited by tectonically forced truncation. The truncation was caused by transgressive wave erosion of a topographically high area.

The distribution of these parasequences is best explained by a depositional model involving a northwestern point sediment source north of a rising topographic high and deposition by along-strike sediment migration in a wave-dominated setting. This explains both the complex parasequence architecture with net southward parasequence migration, and facies evidence for frequent wave agitation.

The Second Frontier sandstone is a depositional remnant with internal complexity related to tectonic control and autocyclic variability. Mud-dominated successions that separate successive parasequences occur at high angles to the regional sandstone trend and can potentially act as flow barriers and baffles that may be important for oil field development.

As in other mapped intervals in the Frontier Formation in the Powder River Basin, application of traditional sequence-stratigraphic nomenclature is difficult. This has to do with erosion of nonmarine strata leading to ambiguities of defining sequence boundaries and complexities introduced by syntectonic deformation.

The results of this study can be applied to similar sand bodies abundant in the U.S. Western Interior, which may also show complex parasequence architecture in response to tectonic forcing.

REFERENCES CITED


Bhattacharya, J. P., 1993, The expression and interpretation


