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# Integrating Ichnology with Sedimentology to Solve Sequence Stratigraphic Problems: Case Study of a Forced Regressive Asymmetric Delta, Viking Formation, Kaybob-Fox Creek, AB

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## Summary

Sequence stratigraphy serves as a methodology employing stacking patterns and key bounding surfaces to erect a framework in which the depositional facies of sedimentary environments can be mapped and interpreted in the context of their paleogeography (Bhattacharya, 2011; Catuneanu *et al*., 2011). Implicit in the framework is that changes in stratal stacking patterns is a response to changes in accommodation and sediment supply, and that the bounding surfaces record depositional breaks or changes in depositional architecture. Sequence stratigraphy is recognized as a "genetic, process-based analytical approach to stratigraphic interpretation that of necessity involves the use of conceptual models" (Catuneanu *et al*., 2011). Ichnology has been shown repeatedly to be crucial in the identification and interpretation of these bounding surfaces and the characterization of their enclosed systems tracts (see MacEachern *et al*., 2012 for a review). Herein, a case study is presented that showcases the integration of ichnological datasets with sedimentology to identify and map the deposits of a falling stage systems tract in the Viking Formation of the Kaybob-Fox Creek fields of Alberta.

## Study Area and Dataset

The Lower Cretaceous (Upper Albian) Viking Formation is a complex, hydrocarbon-bearing siliciclastic succession, distributed widely in the subsurface of Alberta and Saskatchewan, Canada. In the Kaybob-Fox Creek area, the Viking Fm is characterized by a NW-SE trending, sharp-based coarsening-upward succession. The study area extends from Townships 60-64, Ranges 18-21W5; an area of about 1800 km$^2$. Kaybob has 1,306 wells and Kaybob South has 3,837 wells that penetrate the Viking Formation. Fox Creek has 488 wells through the Viking interval. Thirty-three cored intervals were logged in the study area, integrating detailed ichnological and sedimentological datasets in order to identify the stratigraphic discontinuities, characterize the facies successions, and interpret the depositional environments of the various systems tracts. Approximately 620 well log suites were used to correlate the deposits and map the falling stage systems tract.

## Sequence Stratigraphic Framework

This study employs the 4 systems tract framework of Depositional Sequence IV (*e.g.,* Hunt and Tucker, 1992; *cf*. Catuneanu *et al*., 2011). Based on detailed facies analysis, a general sequence stratigraphic framework for the interval can be proposed (Fig. 1). The underlying Joli Fou Fm broadly represents a regionally extensive transgressive systems tract, terminated by a maximum flooding surface. This surface is coincident with a downlap surface marking the onset of normal regression punctuated by marine flooding surfaces, forming a progradational parasequence set of the highstand systems tract, represented by the "Regional Viking". The unit of interest is characterized by a widespread basal discontinuity that records base level fall, the onset of forced regression and deposition of the falling stage systems tract (FSST), marking the initiation of a new depositional sequence. Regionally, this base level fall ultimately shifted the Viking shoreline to a position as far east as Judy Creek, exposing the FSST and developing a widespread subaerial unconformity (SU). Following lowstand conditions at Judy Creek, ensuing base level rise resulted in the progressive shift of the shoreline to the west, leading to a marine flooding surface locally amalgamated with the SU. In the vicinity of the Kaybob-Fox Creek, a wave ravinement surface is coplanar with the SU, and forms the upper bounding surface of the FSST. The upper Viking above this surface forms the transgressive systems tract of the sequence.

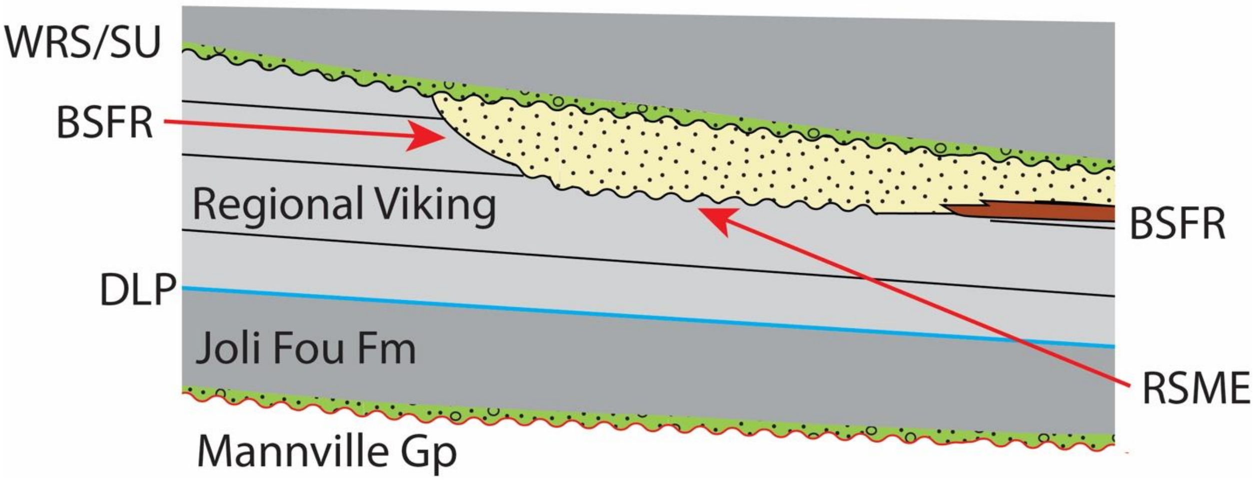


Figure 1: Sequence stratigraphic model for Joli Fou - Viking formations in the Kaybob-Fox Creek area, Alberta. The Joli Fou Fm constitutes a transgressive systems tract and is separated from the Viking Fm in the area by a downlap surface (DLP) marking the transition to the highstand systems tract. Firmground omission suites of the *Glossifungites* Ichnofacies are associated with the regressive surface of marine erosion (RSME) and amalgamated wave ravinement surface and subaerial unconformity (WRS/SU), bounding the falling stage systems tract. The basal surface of forced regression (BSFR) is depositional and challenging to identify except through the use of subtle facies juxtaposition, highlighted through the integration of ichnology and sedimentology.

The key basal surface of the FSST is represented by the regressive surface of marine erosion (RSME) and it depositional counterpart, the basal surface of forced regression. Where facies of the FSST represent deposition above fairweather wave base and are cut into compacted mudstones of the underlying highstand systems tract, firmground omission suites consisting of *Thalassinoides* and *Skolithos* of the *Glossifungites* Ichnofacies demarcate the RSME. Facies juxtaposition is also apparent by the abrupt placement of proximal facies onto distal facies. Landward of this, a subtle sand-on-sand expression of the basal surface of forced regression (BSFR) is encountered, where the highstand deposits lying above fairweather wave base are overlain falling stage deposits that likewise accumulated above fairweather wave base. This subtle contact is not readily apparent ichnologically but does show a pronounced increase in sand calibre associated with erosion and sediment bypass during the onset of base level fall. Distally, offshore mudstones of the older highstand systems tract are overlain by prodeltaic mudstones of the forced regressive shoreline, marking the distal expression of the BSFR (Fig. 1). In these occurrences, ichnology is instrumental in identifying the boundary, using the juxtaposition of trace fossil suites and marked changes in bioturbation index.

The falling stage systems tract is bounded at its upper surface by a transgressively modified subaerial unconformity (WRS/SU). This surface preserves no evidence of exposure owing to significant wave ravinement. A transgressive lag, largely consisting of gravel cannibalized from the lowstand deposits and reworked landward during ensuing base level rise highlights the discontinuity. In some locations, this discontinuity is also demarcated by omission suites of the *Glossifungites* ichnofacies, manifest by firmground *Skolithos* and *Diplocraterion*. The upper Viking deposits are characterized by retrogradationally stacked parasequences of the transgressive systems tract.

## Facies Analysis of the Falling Stage Systems Tract

The main reservoir interval of the Viking Fm in the area resides within the deposits of the falling stage systems tract. Facies analysis of the FSST shows marked variability along paleodepositional strike. In the Kaybob area to the north and northwest, successions display pervasively to sporadically distributed bioturbation in oscillation rippled to HCS- and micro-HCS-bearing coarsening-upward successions. Trace fossil suites are diverse, with BI values ranging from 0-5 at the bed scale, depending on the abundance of storm beds. Ichnogenera are robust and show little evidence of environmental stress with the exception of episodic emplacement of high-energy tempestites. Rare, carbonaceous mudstone layers showing BI 0-1 drape some storm beds and burrowed zones. These successions are consistent with progradation of a moderately storm-dominated lower to middle shoreface with only minor fluvial influence from rivers residing along depositional strike (*e.g*., MacEachern and Bann, 2008).

By contrast, in the Fox Creek Field lying to the south and southeast, facies successions are markedly heterolithic, with discrete and recurring carbonaceous mudstone interbeds showing BI 0-1 typically draping storm beds and burrowed units in both distal and proximal facies. HCS, micro-HCS, and oscillation ripple-bearing sandstones are common, with minor combined flow and current ripples. Syneresis cracks are locally present. Trace fossil suites are somewhat less diverse and less abundant. Facies typically show BI 0-3 with a higher proportion of diminutive forms as well as facies-crossing elements. Nevertheless, fully marine ichnogenera are sporadically distributed, including *Phycosiphon*, *Chondrites*, *Asterosoma*, *Rhizocorallium*, and *Zoophycos*. These facies show a strong wave influence on deposition, but with persistent evidence of fluvial and possibly tidal conditions, reflected by abundant mud drapes attributed to fluid mud and/or flocculation of mud from buoyant (hypopycnal) plumes. These successions are interpreted to be characteristic of a mixed river- and wave/storm-influenced delta complex (*e.g*., MacEachern *et al*., 2005).

Less commonly, successions show prodeltaic to distal delta-front successions sharply overlain by stacked trough and planar tabular cross-stratified sandstone bedsets with intercalated current rippled layers. Mudstone interbeds are common, locally sideritized and eroded to form rip-up clasts. Facies show BI 0-2, with diminutive and widely distributed burrows that include *Palaeophycus*, *Planolites*, *Bergaueria*, and *Cylindrichnus*. These successions are interpreted to record brackish-water distributary channels. Cross-sections show these channel deposits to occur at various stratigraphic levels within the FSST, consistent with autogenic channel avulsion during delta progradation.

Mapping of a single systems tract permits a more accurate paleogeography for the study interval. The spatial distribution of the facies suggests that the FSST reflects a mixed river- and wave-influenced asymmetric delta (*e.g.,* Bhattacharya and Giosan, 2003) trending roughly NW-SE. Updrift positions (northwest) show little fluvial influence and fairly persistent fully marine conditions. Downdrift areas (southeast) received the bulk of river discharge, leading to a markedly heterolithic succession and based on ichnology, a more highly stressed setting. Trunk distributary channels occur within the FSST at various levels, but define a zone that broadly separates areas dominated by shoreface-style deposition from those characterized by greater deltaic influence. Towards the west and northwest, the RSME steps up stratigraphically and the WRS/SU amalgamates with it to produce an erosional zero-edge to the FSST (Fig. 1).

## Novel Contribution – Integrating Ichnology

The recognition of a forced regressive origin of the deposit as well as the facies interpretations of delta asymmetry could only be achieved through the full integration of ichnology with the sedimentology. While geophysical well logs were invaluable in correlating and mapping the falling stage systems tract, core descriptions were essential to establish the sequence stratigraphic model and achieve the depositional interpretation of the succession.

The high-resolution paleogeography established for the FSST also helps to explain the spatial changes in reservoir quality of the Viking Fm in the area. Reservoir quality generally declines towards the SW, showing that the increase in fluvial influence on deposition is detrimental to the petrophysical properties of the reservoir interval. Updrift wells, while showing only half the $K_{max}$ values present in downdrift sandstones, and constituting thinner overall successions, have far more producing wells and have supplied more hydrocarbons from the relatively homogeneous reservoirs. Kaybob and Kaybob South have a total of 1,880 wells providing commingled production. The Kaybob field has cumulative oil production of $2.39 \times 10^7$ $m^3$, with the vast majority ($2.37 \times 10^7$ $m^3$) derived from the Viking Fm alone (AER pers. comm., May 2018). Cumulative gas production is $3.49 \times 10^7$ $e^3m^3$, with $2.05 \times 10^7$ $e^3m^3$ coming from the Viking. Kaybob South has cumulative oil production of $2.18 \times 10^7$ $m^3$, again with the bulk ($2.13 \times 10^7$ $m^3$) coming from the Viking Fm. Cumulative gas production at Kaybob South is $2.49 \times 10^8$ $e^3m^3$, approximately two thirds ($1.69 \times 10^8$ $e^3m^3$) delivered from the Viking.

Downdrift wells of the Fox Creek field, by contrast, produce from a poorer and more strongly partitioned reservoir. Only 133 wells provide commingled production in the area. Cumulative oil production is only $1.35 \times 10^6$ $m^3$, though virtually all of it ($1.33 \times 10^6$ $m^3$) is supplied by the Viking Fm (AER pers. comm., May, 2018). Cumulative gas production is $1.20 \times 10^7$ $e^3m^3$, with only $2.62 \times 10^6$ $e^3m^3$ delivered from the Viking Fm. Reduced reservoir properties are attributed to the abundant fluvially supplied mudstone drapes interstratified with sandstones of the prodelta and delta front. Only distributary channel deposits show significantly thick sandstones uninterrupted by mudstone interbeds, and these appear to be the main reservoir facies in the area.

Additionally, continued base level fall during forced regression exposed these forced regressive deposits subaerially as the shoreline was allogenically shifted to the east, leading to top truncation and locally, cementation of the upper part of the FSST. Correspondingly, reservoir quality also decreases markedly towards the west (the erosional landward edge) where the succession thins and proximal facies are cemented.

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