

Extensive thin sequences spanning Cretaceous foredeep suggest high-frequency eustatic control: Late Cenomanian, Western Canada foreland basin

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ABSTRACT

Early-late Cenomanian rocks of the Doe Creek unit are near the base of the Kaskapau Formation and were deposited in a broad, very shallow embayment that occupied the foredeep of the Western Canada foreland basin. The Doe Creek unit consists of 13 upward-shoaling sequences, typically 3–10 m thick. Subsurface correlation shows that sequences can be traced for 100–350 km from the foredeep toward the forebulge. On the proximal and distal margins of the embayment, each sequence is capped by a flooding surface, commonly underlain by a paleosol developed in marine mudstone. In the center of the embayment, most sequences are capped by one or more isolated, sharp-based sandstone bodies interpreted as lowstand delta-front deposits. Flooding surfaces on top of each sequence are continuously traceable in well logs from the foredeep to the vicinity of the forebulge, implying simultaneous transgression across the basin. Every sequence shows an abrupt upward shallowing, usually to emergence, that was caused by accommodation loss, not sediment accumulation. A vertical relative sea-level excursion of ~10 m on a time scale spanning a maximum range of ~9–74 k.y. is estimated for each sequence. Because transgressions and regressions appear to be in phase across the basin, sequences are better explained by eustasy rather than by flexural reciprocal sedimentation: a glacioeustatic mechanism provides the most likely explanation.

Keywords: Cretaceous, Cenomanian, high-frequency sequences, glacioeustasy, Alberta, British Columbia, foreland basin.

INTRODUCTION

Upper Cenomanian strata in northwestern Alberta and British Columbia reveal evidence of high-frequency relative sea-level oscillations manifest as thin (typically 3–10 m) depositional sequences traceable for as much as 350 km across the Western Canada foreland basin (Plint, 2000; Kreitner, 2002; Kreitner and Plint, 2006; Fig. 1A). These rocks provide evidence for meter-scale sea-level oscillations on a scale of <100 k.y. Recent studies of Cenomanian rocks in other parts of the world provide analogs on comparable temporal and spatial scales. For example, biostratigraphic correlation enabled Gale et al. (2002) to infer synchronous relative sea-level oscillations of 2–20 m in Cenomanian strata in India and northwest Europe. Jarvis et al. (2006) showed that Upper Cretaceous $\delta^{13}\text{C}$ curves implied Cenomanian eustatic excursions of as much as ~10 m; their eustatic curve closely resembled the eustatic curves of Gale et al. (2002) and Sahagian et al. (1996). Calculated Upper Cretaceous rates of short-term sea-level change of 10–100 m m.y.⁻¹ were interpreted by Gale et al. (2002), Miller et al. (2003), and Jarvis et al. (2006) as probable evidence of a glacioeustatic control, with higher-frequency cycles spanning a few hundred thousand years. Hemipelagic rocks of Cenomanian age in the Western Interior of North America provide strong evidence for Milankovitch band climatic cycles in the ~20–100 k.y. bands (e.g., Sageman et al., 1997). Elder et al. (1994) suggested that offshore limestone-marl couplets could be correlated with

nearshore transgressive-regressive packages, implying a link between high-frequency climatic and eustatic changes. Laurin and Sageman (2007) documented meter-scale transgressive-regressive packages on ~20–40 and ~65–160 k.y. time scales in uppermost Cenomanian paralic rocks in Utah, and considered glacioeustasy a possible driver.

AGE, STRATIGRAPHY, AND PALEOGEOGRAPHY

The study interval is in the lower part of the Kaskapau Formation, which is a westward-thickening, mudstone-dominated wedge as thick as 950 m. Deposition took place during a phase of generally rapid flexural subsidence in the northwestern part of the Western Canada foreland basin (Varban and Plint, 2005; Kreitner and Plint, 2006). The Kaskapau Formation ranges in age from late Cenomanian to late-middle Turonian (Stott, 1967; Caldwell et al., 1978). Flooding surfaces, regionally traceable through ~2000 wireline logs, 32 cores, and 9 outcrop sections, allow the Doe Creek unit to be divided into 10 allomembers (1–8 + 1A and 2A in Fig. 1B; detailed cross sections were given in Kreitner and Plint, 2006). In outcrop (Flatbed Creek), allomember 1 is divisible into three, and allomember 2A is divisible into two smaller allomembers that have not been widely traced in the subsurface. The age of the Doe Creek unit is not precisely known. The X bentonite is present in allomember C of the underlying Dunvegan Formation (Tyagi et al., 2007), and *Dunveganoceras albertense* appears 3 m above the top of the Doe Creek unit (Fig. 1B). The Doe Creek unit appears to be within the *D. problematicum* zone, and possibly all or part of the *D. pondi* zone. If equal time is assigned to the *D. pondi*, *D. problematicum*, *D. albertense*, and *D. conditum* zones, which could span from 0.49 to 1.93 Ma (Fig. 1B), then a mean ammonite zone could span 122.5–482.5 k.y. If the Doe Creek unit encompasses one zone, it might represent 122.5–482.5 k.y., and 245–965 k.y. if it encompasses two zones.

Allomembers can also be interpreted as depositional sequences because they include subaerial unconformities and internal erosion surfaces indicative of relative sea-level fall. The Doe Creek unit was deposited in a broad, shallow, very low gradient embayment that was closed to the northwest (Kreitner and Plint, 2006; Fig. 2). The rising Cordillera provided clastic sediment from the west and northwest. The northeast side of the basin was bounded by a low-lying, intermittently emergent area on the flank of the forebulge. A major river system inherited from the underlying Dunvegan delta complex delivered large volumes of sediment to the northwest margin of the embayment.

FACIES AND DEPOSITIONAL ENVIRONMENTS

Doe Creek rocks can be divided into the following five broad facies, organized in upward-shoaling successions (Figs. 3 and 4).

1. Laminated to weakly bioturbated mudstone, with brackish to marine bivalves (*Corbula*, *Brachydontes*, oysters, inoceramids), *Lingula*, and *Chondrites*, *Gordia*, *Palaeophycus*, and *Planolites*, forms the lower part of most sequences and represents an offshore, storm-influenced setting (Wallace-Dudley and Leckie, 1995; Kreitner, 2002).

2. Centimeter- to decimeter-scale interbeds of mudstone and very fine to fine sandstone with wave ripples, hummocky cross-stratification (HCS), and gutter casts represent a storm-influenced inner shelf. Bioturbation (*Palaeophycus*, *Planolites*, *Rhizocorallium*, *Teichichnus*, *Thalassinoides*) varies from slight to almost total homogenization; the variable

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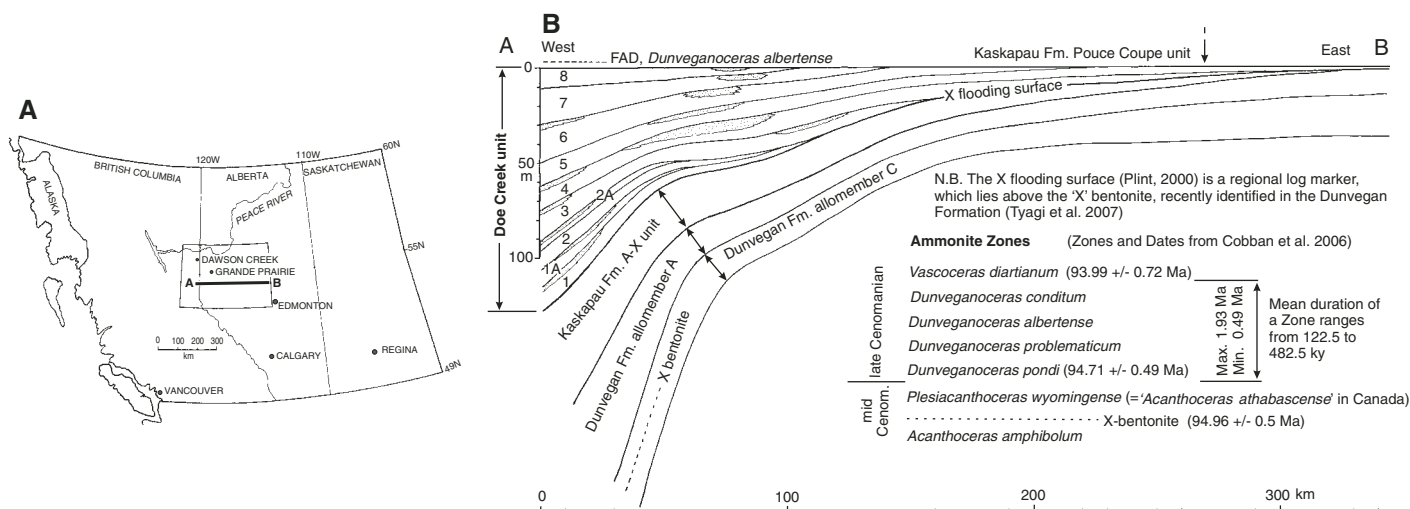


Figure 1. A: Location of study area. Line A–B is cross section shown in B. B: Scale cross section showing allomembers (defined by flooding surfaces) in Doe Creek unit, underlying A–X unit, and allomembers C–A of Dunvegan Formation. The X bentonite and first appearance datum (FAD) of *Dunveganoceras albertense* zone provide the only chronostratigraphic and biostratigraphic control; other ammonite zones have not been identified in the study area. Datum = top of Doe Creek unit.

intensity probably reflects local rates of sedimentation, and possibly other stresses such as reduced salinity.

3. Clean sandstone is fine grained, dominated by parallel lamination, swaley cross-stratification (SCS), HCS, and occasionally cross-bedding and wave ripples. Ichnofossils include *Ophiomorpha*, *Rhizocorallium*, *Skolithos*, and *Thalassinoides*. The base of every sandstone unit is sharp, commonly with gutter casts. On the southwest basin margin, sandstone is 1–3 m thick and capped by roots and dinosaur tracks. In the basin center, sandstone is present in sequences 3–8, and forms lenticular units 2–9 m thick, as wide as 40 km, and 180 km long (Kreitner, 2002; Figs. 2–4). This facies is interpreted to represent a wave-influenced delta-front environment.

4. Rubbly mudstone units, 10 cm to 2 m thick, have a distinctive blocky fabric and pale yellow-gray color, and contain carbonaceous roots from 1 to 2 mm to as much as 30 mm wide, and rare tree stumps. In some cases, the rooted mudstone is overlain by 2–15 cm of coal. This facies is developed at the top of packages of marine mudstone (facies 1) or heterolithic facies 2, and is interpreted as a paleosol. The coal probably accumulated at the beginning of the next sea-level rise.

5. At Highland Park, a unique, 20-m-thick, fine- to medium-grained sandstone forms a lenticular body <1 km wide. The lower part of the sandbody contains well-developed tidal bundles and sigmoidal cross-stratification, whereas the upper part contains decimeter-scale trough cross-bedding. This facies is interpreted as a tidally influenced paleovalley fill.

VERTICAL AND LATERAL FACIES SUCCESSIONS

The key feature of all Doe Creek sequences is the abrupt vertical juxtaposition of shallower- to deeper-water facies. For example in the southwest, in sequences 1iii, 2Aii, and 4 at Flatbed Creek (Fig. 3), a thin delta-front sandstone (facies 3) sharply overlies laminated offshore mudstone (facies 1). More remarkable is the presence of isolated gutter casts filled with HCS sandstone, abruptly capping laminated marine mudstone, in turn capped by a muddy paleosol and coal (e.g., sequences 1ii, 1A, 2, and 3 in Flatbed Creek; Fig. 3). Lateral tracing of sequences along Flatbed Creek shows that over 1–2 km, some gutter cast packages amalgamate into shoreface sandstone of facies 3. This implies that local availability of sand, presumably related to river-mouth proximity, controlled the type of sandstone package. Total sand starvation or bypass is represented by sequences 1i and 5, in which marine mud (facies 1) is directly capped by rooted paleosol (facies 4). At Pratts Landing in the northeast, sequences

1–3, consisting of apparently marine silty clay, grade up into a paleosol with roots; the tops of sequences 4–7, which are sandier, do not preserve evidence of emergence beneath their bounding flooding surfaces. In basin-center areas, sequences 3–8 contain one or more, isolated, sharp-based delta-front sandstone bodies (facies 3) up to 9 m thick that erosively overlie bioturbated shelf mudstone and sandstone (facies 2; Figs. 3 and 4). Overall, the sandstones in sequences 3–8 are arranged in a backstepping pattern, progressively offset to the northwest (Fig. 2).

The common absence of shoreface sandstone in basin-marginal sequences, the development of paleosols directly on marine mudstone, and the erosive superposition of shoreface sandstone on muddy shelf facies all suggest that shoreline regression, and surfaces of subaerial exposure, were the result of relative sea-level fall, rather than passive aggradation of sediment to sea level. The basinally isolated sandstones are interpreted as detached, lowstand delta-front deposits, the erosive basal surface of each sandstone being interpreted as a marine expression of the sequence boundary. In each sequence, this surface can be traced to a transgressively modified subaerial unconformity on the southwest and northeast basin margins (Fig. 3).

DISCUSSION

Sea-Level Changes: Mechanism, Frequency, and Amplitude

The absence of a regressive accretionary delta-front sandstone from most basin-margin sequences provides strong evidence for repeated sea-level-fall events that lead to emergence, regardless of sediment supply. The flooding surfaces bounding Doe Creek sequences can be traced continuously across the foredeep to a lap out against the southwest flank of the forebulge, suggesting that relative sea level rose simultaneously in both proximal and distal areas. There is no evidence that subaerial unconformities pass distally or proximally across the basin into maximum flooding surfaces, which is the pattern predicted by the reciprocal model of sequence generation involving episodic thrust activity (Catuneanu, et al., 1997). For similar reasons, the sequences are unlikely to be explicable as a result of flexure due to basinwide changes in in-plane stress (Cloetingh, 1988).

The wedge shape of the Doe Creek unit (Fig. 1B) indicates deposition during a period of asymmetrical flexural subsidence. Sequences could be attributed to alternating periods of subsidence and uplift, perhaps related to alternating thrust loading and erosional isostatic uplift. Although load-induced subsidence can easily explain transgressions, it is difficult to

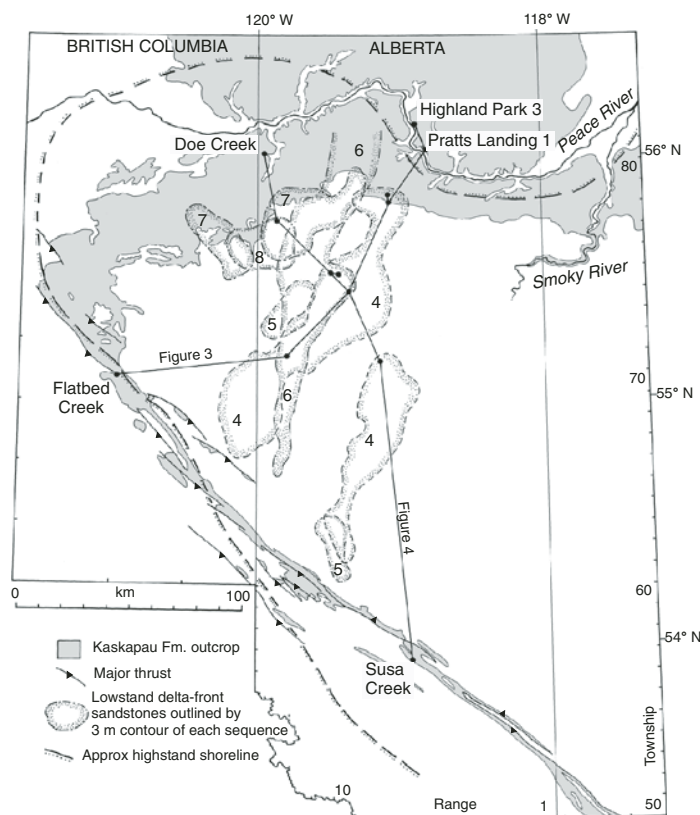


Figure 2. Map of western part of study area showing outcrop of Kaskapau Formation and location of outcrop and core sections illustrated in Figures 3 and 4. Map also shows generalized highstand shoreline position, defining a broad shallow embayment. Lowstand sandstone bodies in sequences 4–8 are confined to center of embayment, and each is outlined by 3 m isopach. Sandstone in sequence 3 is very localized and is not shown.

reconcile repeated relative sea-level-fall events with erosional unloading of the accretionary wedge and isostatic uplift, despite denudation rates potentially on the order of 1–10 m/10 k.y. (e.g., Saunders and Young, 1983), because the eroded sediment would continue to load and depress the proximal foredeep. Alternatively, sequences might have developed in response to a slow eustatic fall through Doe Creek time, superimposed on episodic thrust loading, which caused the subsidence rate to alternately outpace eustatic fall, causing transgression, or to be overtaken by eustatic fall, causing emergence. However, it is difficult to reconcile this mechanism with the overall stratal geometry of the Doe Creek unit (Fig. 1B), which shows progressive onlap toward the forebulge from sequence 1 to sequence 5, followed by progressive offlap through sequence 8 (Kreitner and Plint, 2006; Fig. 1B).

Given the well-established evidence for Milankovitch-band climatic cycles in the late Cenomanian (Sageman et al., 1997), the Doe Creek sequences seem to be most parsimoniously explained as a result of a high-frequency glacioeustatic signal. As others have pointed out (e.g., Gale et al., 2002; Miller et al., 2003), glacioeustasy offers the only plausible mechanism to explain high-frequency sea-level changes with amplitudes of 2–20 m. If the Doe Creek unit is assigned to one (ca. 122–482 ka) or two ammonite zones (ca. 245–965 ka), simple averaging suggests that each of the 13 Doe Creek sequences might span ~9.3–37 k.y. to 18.8–74.2 k.y., respectively. Within each sequence, transgressive and highstand systems tracts are typified by widespread deposition of mud and very thin, localized nearshore sandstones. Falling-stage shoreface sandstones are very thin and sharp based, whereas lowstand delta-front sandstones are thicker and volumetrically dominant.

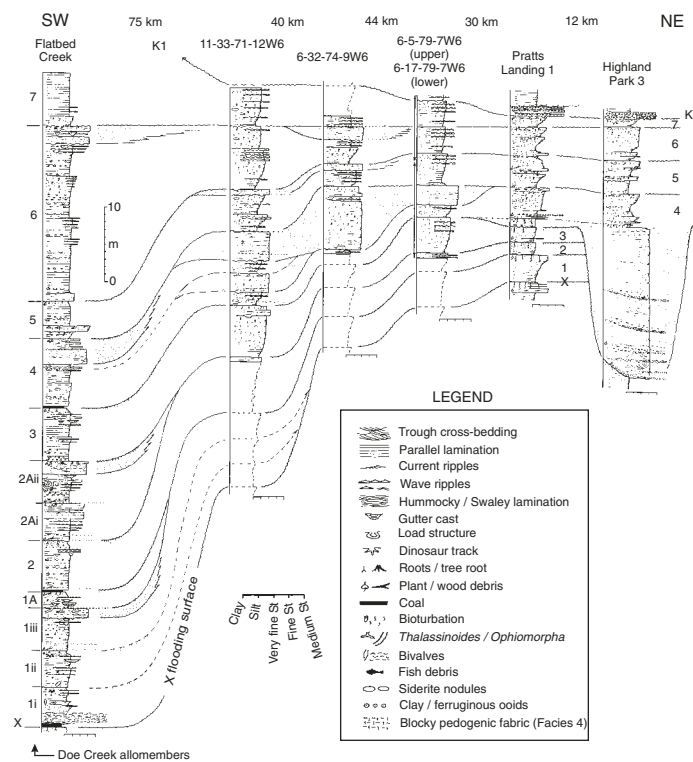


Figure 3. Cross section oriented SW-NE, transverse to axis of the basin (Fig. 2). Combined unconformity and/or flooding surfaces bounding sequences 1–6 in Flatbed Creek are correlated (on the basis of hundreds of well logs; details in Kreitner and Plint, 2006) to outcrop on distal side of the basin where paleosols also bound sequences 1–3. Sharp-based, clean sandstone bodies in sequences 4, 5, and 6 are interpreted as delta-front deposits emplaced in basin center at lowstand. Dashed lines in cored wells are simplified representation of resistivity log.

Doe Creek sequences show progressive onlap toward the forebulge, culminating in sequence 5, followed by offlap through sequence 8, with further offlap in the overlying Pouce Coupe unit (Kreitner and Plint, 2006; Fig. 1B). Sequences 1–2A contain no detached lowstand sandstones; sequences 3, 7, and 8 have minor detached lowstand sandstones; and sequences 4–6 contain volumetrically large lowstand sandstones. Thus the period of maximum onlap (sequences 4–6) coincides with emplacement of the largest lowstand sandstone bodies. If a constant rate of sand supply is assumed, then the volume of each lowstand sandbody might be directly proportional to the duration of the lowstand, suggesting that lowstands in sequences 4, 5, and 6 were of the longest duration, with lowstand duration diminishing both down section and upsection. This suggests a lower-frequency modulation of the dominant high-frequency signal. This observation is comparable to the nested cycles documented by Laurin and Sageman (2007) that are suggestive of multifrequency orbital forcing of ice volumes. Alternatively, the volume of sand delivered to the basin may have fluctuated in response to cyclical changes in precipitation, perhaps related to the interaction of the precession and eccentricity cycles, as predicted by numerical models (Floegel et al., 2005), in which case sandstone volume may have no relation to lowstand duration.

It is not possible to determine with any precision the amplitude of the high-frequency sea-level oscillation. Facies successions at Flatbed Creek indicate abrupt transitions from offshore mudstone, deposited in 5–10 m of water, to a very thin sharp-based shoreface sandbody deposited in 1–2 m of water, or directly from offshore mudstone to a paleosol without an intervening sandy shoreface. Both successions imply relative sea-level fall of at least several meters. The valley fill at Highland Park apparently

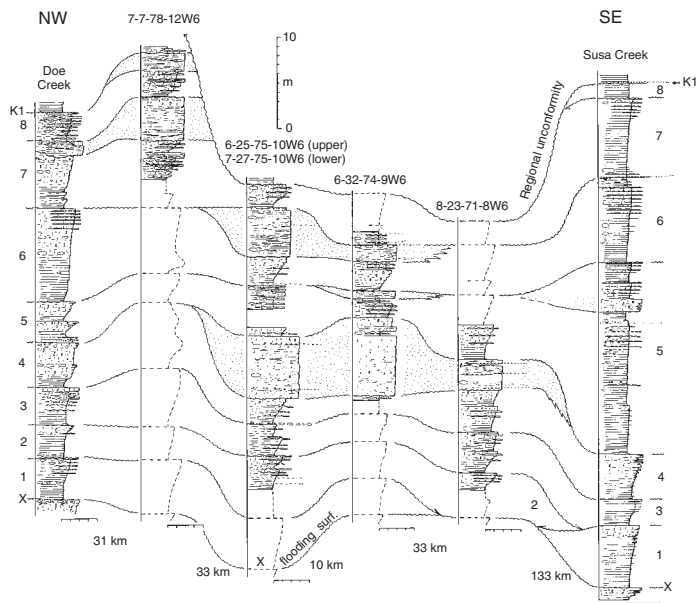


Figure 4. Cross section oriented NW-SE along axis of the basin (see Fig. 2). At Doe Creek, intensely bioturbated siltstones and sandy siltstones represent offshore transgressive and highstand deposits, whereas sharp-based, lenticular clean sandstones in sequences 4–8 are interpreted as lowstand shoreface deposits. Susa Creek represents very distal location, dominated by laminated silty mudstone. See Figure 3 for legend; dashed lines in cored wells are simplified representation of resistivity log.

indicates 20 m of incision, although it is not known whether the unit represents erosion related to one or multiple sequences, or whether erosion can be attributed to eustatic fall, or to some combination of eustasy, fluvial discharge, and sediment-load changes, and isostasy. Although the horizontal displacement of successive shorelines from highstand to lowstand locations can be mapped with some confidence, lack of knowledge of the bathymetric gradient makes it impossible to calculate the vertical change in sea level. Intuition suggests that it was probably <10; this value is similar to that estimated by Laurin and Sageman (2007) for slightly younger rocks in Utah. We suggest that the tectonic mechanisms advocated by Catuneanu et al. (1997) and Vakarelov et al. (2006) as the cause of high-frequency sequences in greenhouse periods should not be considered the only viable genetic processes.

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