Along-strike sequence stratigraphy across the Cretaceous shallow marine to coastal-plain transition, Wasatch Plateau, Utah, U.S.A.

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Current sequence stratigraphic models deal with stratal packages almost exclusively along depositional-dip. A high-resolution outcrop example detailing sequence stratigraphic architecture along depositional-strike is largely lacking. This outcrop study provides a detailed sequence stratigraphic correlation along depositional-strike for a length of ~50 km. Moreover, this study focuses on the facies and stratigraphic relationships particularly at the very transition between coeval marine and nonmarine strata, which is relatively underdocumented. Within the Mesaverde Group of central and eastern Utah, the Upper Cretaceous shallow-marine Star Point Sandstone and parastrach Blackhawk Formation are relatively well studied along depositional-dip, but the nature of their spatio-temporal transition particularly along depositional-strike in the NNE-SSW trending Wasatch Plateau remains poorly documented. Facies-scale to stratigraphic-scale data were gathered from ten outcrop “windows” along the eastern margin of the Wasatch Plateau. The vertical and lateral transition between marine and nonmarine strata varies in complexity within the study area. In the southern part of the study area near the central Wasatch Plateau, the shallow-marine Star Point Sandstone passes stratigraphically upward into the nonmarine Blackhawk Formation in one simple transition without any intercalation of marine and nonmarine strata. In the northern part of the study area, however, where the Star Point Sandstone to Blackhawk Formation transition is complex, aggradationally stacked shallow-marine sandbodies (i.e., parasequences) taper and completely pinch-out within coastal-plain mudstones in a paleo-landward direction over short distances (~1 km), representing potential stratigraphic traps. These marine sandbodies are intercalated with coeval nonmarine strata within the Blackhawk Formation. Fourth-order sequence boundaries and flooding surfaces were correlated along the lower Campanian depositional-strike. The results reveal along-strike undulations in the early Campanian depositional topography, which was characterized by alternating incised valleys, interfusil, topographic highs with mature soil development, and shoreline embayments. In particular, the variable along-strike transition-complexity from shallow-marine to coastal-plain strata is the result of differential tectonic subsidence, where the transition-complexity increases and the stacking pattern is more aggradational towards an early Campanian depocenter in the north of the study area. This study reveals that differential subsidence is the key in controlling along-strike variability of sequence stratigraphy and that correlation of sequence stratigraphic surfaces are far more challenging in nonmarine strata than in adjacent marine strata.

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1. Introduction

Correlation of stratal bounding surfaces rather than stacking patterns is a more reasonable method for unraveling relative sea level history of a basin (e.g., Shanley and McCabe, 1994). However, one of the key challenges in sequence stratigraphy has been the correlation of chronostratigraphic surfaces using discontinuous outcrop across the transition between coeval shallow-marine and nonmarine strata (Shanley et al., 1992; Davies et al., 2006; Corbett et al., 2011), which is a common facies transformation in transgressive or early highstand successions (Sixsmith et al., 2008; Kieft et al., 2011). Common at the transition between shallow-marine and nonmarine strata are facies of marginal-marine origin (e.g., Sixsmith et al., 2008), which may include tidally influenced fluvial sandbodies that can be related to marine flooding events (Shanley et al., 1992). Similarly, coastal-plain coal layers can be time-equivalent to marine flooding surfaces (Davies et al., 2006). Other marginal-marine strata linked to transgressive or early highstand shoreline trajectories commonly have top-truncated barrier islands, spits, and back-barrier lagoons as associated facies (Sixsmith et al., 2008; Kieft et al, 2011).

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The Upper Cretaceous shallow-marine Star Point Sandstone transitions stratigraphically upward to the coastal-plain Blackhawk Formation in eastern and central Utah (Fig. 1), providing an opportunity to investigate facies and stratigraphic complexity across the transition between coeval marine and nonmarine strata. These strata belonging to the Mesaverde Group were deposited along the curvilinear to moderate-ly lobate western margin of the Cretaceous Interior Seaway (Hampson et al., 2011; Fig. 1D). The proximal to distal stratigraphic relationships at the transition between the Star Point Sandstone and Blackhawk Formation is relatively well documented along depositional-dip in the overall E-W trending Book Cliffs (e.g., Kamola and Van Wagoner, 1995; Hampson and Howell, 2005; Davies et al., 2006; Hampson, 2010). However, the spatio-temporal nature of this stratigraphic transition is rarely documented along depositional-strike in the NNE-SSW trending Wasatch Plateau (Hampson et al., 2011; Fig. 1).

In addition to depositional-dip analysis, studies along depositional-strike are essential to capture properly the spatio-temporal stratigraphic framework of a basin (Martinsen and Helland-Hansen, 1995; Martinsen and Helland-Hansen, 1995; Hampson et al., 2011). This is also critical to evaluate the concept of sequence stratigraphy, like the development of surfaces and systems tracts, in basin-parallel dimension. Published sequence stratigraphic models deal with stratal packages almost exclusively along depositional-dip (Payton, 1977; Wilgus et al., 1988; Van Wagoner and Bertram, 1995; Coe, 2003; Catuneanu, 2006). To extend these models along depositional-strike, more studies like this one are needed.

In this study, ten outcrop “windows” exposing the Mesaverde Group were analyzed in a facies architectural context, and correlated to generate an along-strike sequence stratigraphic framework spanning more than 50 km along the northern and eastern margin of the Wasatch Plateau (Fig. 1A). This study has two main objectives: (1) investigate the facies architectures at the transition between the shallow-marine Star Point Sandstone and the coastal-plain Blackhawk Formation, and (2) characterize sequence stratigraphic framework for this transition in a depositional-strike orientation, particularly emphasizing lateral variability of sequence boundaries, flooding surfaces, and coal zones.
2. Regional geology and study area

The western edge of the North American Cordillera extends from Mexico to Alaska and has episodically been an accretionary margin since the late Paleozoic (Windley, 1995) in response to the eastward convergence and subduction of the Farallon Plate. Throughout the Mesozoic, the eastern margin of the resulting retro-arc foreland basin migrated towards the North American craton, from present day Nevada during the Jurassic to the present day western boundary of Utah’s Wasatch Plateau by the late Cretaceous (Windley, 1995). Structurally, Cretaceous strata of central and eastern Utah were influenced by two events linked to the subduction of the Farallon plate, during the late Mesozoic and early Cenozoic (Aschoff and Steel, 2011).

The first event occurred during early Cretaceous and lasted throughout much of the period until the Campanian, as the Farallon plate subducted rapidly and at high angles. The resulting deformation in Utah was controlled by the Sevier Orogeny, which was an event characterized by thin-skinned, fold-and-thrust belt style tectonism (Windley, 1995; Aschoff and Steel, 2011; Hampson et al., 2011). Subduction of the Farallon plate decreased in rate and angle during the Campanian (ca. 77 Ma), triggering a transition from Sevier to Laramide-style deformation (Aschoff and Steel, 2011) and a cratonward shift in uplift structures that became more basement-involved characterized by thick-skinned tectonism. In the study area, strata were tilted orthogonally away from a Laramide uplift structure known as the San Rafael Swell (Lamarre and Burns, 1997; Seymour and Fielding, 2013), but various sedimentary features can be used to determine depositional-strike and dip (Coe, 2003; Hwang and Heller, 2002).

During the late Cretaceous, much of central North America including the Sevier foreland was covered by a north-south trending, epicontinental ocean known as the Western Interior Seaway (Kaufman and Caldwell, 1993) (Fig. 1D). Portions of what was deposited along its western margin in what is now Utah include the lower Campanian succession analyzed in this study. The overall regional depositional-dip is to the east for Campanian strata in Utah (Hampson et al., 2010); thus, the stratigraphic variability along the NNE-SSW trending Wasatch Plateau is sub-parallel to the regional depositional-strike (Flores et al., 1984; Dubiel et al., 2000; Hampson et al., 2011).

The Star Point Sandstone consists of five tongues (e.g., parasequences) (Dubiel et al., 2000; Hampson et al., 2011) that intercalate eastward with offshore deposits of the Mancos Shale (Clark, 1928; Spieler, 1931) or pass westward into nonmarine deposits of the Blackhawk Formation (Fig. 1C). Three of the five parasequences are entirely wave-dominated shoreface sandstones, whereas the other two locally contain river-dominated deltaic deposits (Hampson et al., 2011). One of the two river-delta parasequences known as the Panther Tongue occurs within the northern part of the study area. These river deltas were the sediment source for overlying wave-dominated shoreface parasequences, as they often were top-truncated and had their sediments redistributed by wind-wave processes. In order of decreasing age, the Spring Canyon, Aberdeen, Kenilworth, Sunnyside, Grassy, and Desert Members constitute the Blackhawk Formation, which records a mixture of marine and nonmarine depositional environments.

3. Methodology and data set

The Mesaverde Group crops out continuously along the eastern margin of the Wasatch Plateau for more than 100 km (Hampson et al., 2011). Along a 50 km depositional-strike from where the Wasatch Plateau joins the Book Cliffs near Gentle Wash to Trail Mountain Mine near the central Wasatch Plateau, ten canyons dissecting the Wasatch Plateau served as ideal study locations to capture the facies architecture and sequence stratigraphic relationships between the Star Point Sandstone and Blackhawk Formation (Fig. 1A). Along each of the ten canyons, outcrop “windows” encompassing the upper Star Point Sandstone and lower Blackhawk Formation were measured and described in log (around 15) and panel (around 12) formats. These lithologies detail bed thicknesses, sedimentary structures, grain size variations, ichnology, bioturbation, and paleocurrents. Bioturbation was quantified using Taylor and Goldring’s (1993) bioturbation index (BI) scale, such that the degree of bioturbation was recorded numerically alongside each litholog, which is a technique of ‘BI log’ as shown by Gani et al. (2008). All lithologies were hung from the top of the Star Point Sandstone in a correlation panel, using the Axel-Anderson Coal Zone as a stratigraphic datum.

In addition, photos were taken at each “window” and combined to mosaics to illustrate sequence stratigraphic relationships at sub-kilometer scales along depositional-dip. These photomosaics were also analyzed in a facies architectural context to complement the stratigraphic framework. Using the Coal Zones of the Blackhawk Formation (Hampson et al., 2011, 2012) as marker beds, correlation of these ten outcrop “windows” produce a regional sequence stratigraphic framework along depositional-strike for 50 km.

4. Results

4.1. Facies associations and depositional environments

Eight facies associations, each representing a particular subenvironment of deposition, were recognized in this study. They include offshore marine, lower shoreface, upper shoreface, fluviol channel, tidal channel, swamp, coastal/flood plain, and bay facies associations (Table 1, Fig. 2). In combination, these associations are interpreted to represent three major depositional settings: shallow-marine, marginal-marine, and nonmarine (Fig. 3). Facies associated with marginal-marine strata are of particular interest in this study, as they occur at the transition between coeval shallow-marine and nonmarine strata.

4.1.1. Offshore marine facies association (Fig. 2A)

Light-grey mudstones prevalent in the oldest portions of the studied successions interbed with very fine to fine-grained hummocky cross-stratified (HCS) sandstones. HCS sandstone beds range in thickness from 10 cm to 50 cm and coarsen upward overall. Thin bedded (few cm thick) and lenticular silstones to very fine-grained sandstones displaying parallel lamination to wave-ripple structures are also present. This facies association displays Cruziana ichnofacies with BI ranging from 3 to 5. The lowermost beds in this association have ichnogenera that include Siphonichnus, Terebellina, and Helminthopsis, whereas the ichnogenera in the upper unit include Terebellina, Helminthopsis, Palaeophycus tubularis, Ophiomorpha, and Cyrtocorte.

The light-grey mudstones are interpreted to represent offshore marine facies associated with the Mancos Shale. The Cruziana ichnofacies indicates relatively low-energy conditions and flow regimes coincident with offshore environments below fair-weather wave base (Dott and Bourgeois, 1982). The uniform-and-high trend in BI log is also indicative of offshore marine environment (Gani et al., 2008). The sharp-based HCS sandstones are interpreted to be of storm origin (Myrow and Southard, 1991).

4.1.2. Lower shoreface facies association (Fig. 2B)

Up to 1 m thick very fine-grained sandstone beds were identified transitioning in a vertical succession from hummocky to swaley and then planar stratifications. Wave ripples were found at some bed tops, and bioturbated wavy-bedded mudstones were observed locally. The BI of this facies association ranges from 3 to 4 and is characterized by a mixed Cruziana and Skolithos ichnofacies. The ichnogenera include Puleophycus heberti, Skolithos, Ophiomorpha, Palaeophycus tubularis, Chondrites, Terebellina, Asterosoma, and Thalassinoidea.

Based on sedimentary structures and trace fossil assemblage, this facies association pertains to lower shoreface deposits (Hampson et al., 2011). The upward transition from hummocky to swaley and
then planar-laminated sandstones records a reduction in antecedent bathymetry and increase in the flow regime, as storm- and fair-weather waves had an increasingly powerful impact on the sea floor (Wright et al., 1979).

4.1.3. Upper shoreface facies association (Fig. 2C)
Well sorted, fine- to lower coarse-grained sandstone beds ranging in thickness from 5 cm to 3 m were identified, with trough and planar cross-stratifications. Paleocurrent directions of cross-stratifications are predominantly NE in the northern part of the study area and NW in the southern part. Trace fossil assemblages identified in these strata include Skolithos and Ophiomorpha and BI ranges from 0 to 2.

This facies association was deposited entirely above normal wave base as evidenced by sedimentary structures and trace fossils (e.g., MacEachern et al., 2005). Paleocurrent directions measured from dune-scale cross-stratifications are consistent with the regional wave climate (during the early Campanian in the study area), which acted to disperse sediments via longshore transport along the western shorelines of the Interior Seaway (Hampson, 2010; Hampson et al., 2011).

4.1.4. Tidal channel facies association (Fig. 2D)
Inclined and laterally accreted, thin to medium beds of very fine-grained sandstones were cyclically draped by mudstones. These beds are confined within asymmetrical convex-upward “lenses” with an erosional base. As the sandstones terminate down dip, current ripples are especially prevalent. Paleocurrent directions of these ripples are consistently perpendicular to the direction of lateral accretion. The BI ranges from 0 to 2, and the ichnogenera identified includes Skolithos, Terebellidites, Planolites, and Thalassinoides.

The beds identified in this facies association are characterized by inclined heterolithic strata (IHS; sensu Thomas et al., 1987). Based on the presence of cyclical mud drapes and marine trace fossils, this association is considered to have been tidally influenced (Shanley et al., 1992). The sandstones were deposited as lateral accretions in the form of a point bar and draped by mudstones during periods of tidal slackwater (Thomas et al., 1987). The sudden record of tidal facies within a stratal succession could be indicative of marine transgression (Shanley et al., 1992).

4.1.5. Bay facies association (Fig. 2E)
Very fine-grained symmetrically wave-rippled sandstones, with bed thicknesses ranging from a few to 30 cm, are commonly in erosional contact with underlying bioturbated mudstones. A mixed Cruziana and Skolithos ichnocoenoses with a BI ranging from 0 to 4 was observed. The ichnogenera include Terebellina, Palaeophycus heberti, and Thalassinoides.

Because of the absence of HCS and Helminthopsis (cf., offshore marine facies association), this facies association is interpreted as a bay-fill. Bays (or lagoons) are fetch-limited basins in shallow water that form upon a breach in the foreshore and development of a tidal inlet (Hampson, 2000). Tidal inlet and hence bay formation commonly occurs during transgression, which is also coincident with the development of other marginal-marine facies (Sixsmith et al., 2008).

4.1.6. Swamp facies association (Fig. 2F)
Carbonaceous mudstones and four low-ash coal seams were identified. The coal seams ranging in thickness from 20 cm to 1.5 m are commonly fractured and contain leaf impressions and root traces. Intra-coal bedding planes were identified as oxidized or containing very thin layers of siliciclastic materials. Vertebrate burrows and the Terebellidites ichnofacies within the coals are sparse. Overall, BI was not estimated to exceed 1.

Coals and carbonaceous mudstones of the Mesaverde Group are associated within the Blackhawk Formation. These coals were transformed from peats that accumulated likely on raised mires, which formed shoreline-parallel belts as much as tens of km wide behind the western shoreline of the Interior Seaway (McCabe and Shanley, 1992). The low-ash content in coals suggests that peats accumulated above the high-water levels generated during low-recurrence interval floods or spring tides, as these processes would augment in delivering siliciclastics to the mires. The coal flora within the study area indicates that the Campanian climate was rainy and temperate to subtropical (Parker, 1976) at approximately 42° N paleo-latitude (Fig. 1D) (Cole et al., 2005). The low BI index likely reflects low-oxygen condition of the swampy environment.

4.1.7. Coastal-plain/flood plain facies association (Fig. 2G-H)
Rooted, commonly carbonaceous mudstones and siltstones were found with subordinate sheet-like, fine-grained sandstones. These
deposits were identified intercalating locally with calcareous paleosols, which are weathered light red in color. The maximum thickness of the paleosol is 12 m, identified in the outcrop “window” along Trail Canyon Road (Fig. 4). Paleosols are zoned, fractured conchoidally, and have an off-white fresh-piece coloration. Pedogenic features include concretions, root tubes, clay cutans, and calcite precipitates.

The interbedded carbonaceous mudstones and siltstones in combination with very fine-grained sandstones are interpreted as fluvial over-bank, and crevasse-splay deposits. Calcic paleosols are interpreted to develop in evaporitic environments with dry seasonal climates, commonly during sea level fall and lowstands (Tandon and Gibling, 1997).

4.1.8. Fluvial channel facies association (Fig. 2H)

Cliff-forming and laterally discontinuous sandbodies with erosional bases and sharp upper contacts, grade from very fine- to medium-grained sandstones, and are commonly intercalated or encased with weakly bioturbated mudstones. Mud clasts are preferentially scattered along and overlying the basal erosion surfaces. The sandbodies, showing
Fig. 3. (A) Trail Mountain Mine litholog illustrates a smooth and gradual upward transition from marine to nonmarine strata in the northern part of the study area. (B) Wattis Road litholog reveals a rather complex upward transition from marine to nonmarine strata. (C) Legend for lithologs, facies architectures, and regional correlation panel (Figs. 3–6, 8).
their story characteristics are a function of accommodation (Adams and Bhattacharya, 2005; Hampson et al., 2012). Where these sandbodies are more amalgamated, they are coincident with low-accommodation, strongly progradational settings.

4.2. Overall depositional pattern

Along the Wasatch Plateau, the Star Point Sandstone is capped by the laterally extensive Axel-Anderson Coal Zone (Fig. 8), which forms the base of the Blackhawk Formation (Hampson et al., 2012). The lowermost sandbody of this study is marine and known as the Spring Canyon Member, which is the uppermost member of the Star Point Sandstone along the Wasatch Plateau (Clark, 1928) but is referred to as the lowermost member of the Blackhawk Formation in the Book Cliffs (Hampson et al., 2012).

The lower Blackhawk Formation constitutes an overall coastal-fluvial environment (Spieker, 1931; Hampson et al., 2012), containing coastal to bay-fill heterolithics, tidal point-bar IHS (inclined heterolithic strata), coals, and multi-story to multi-lateral fluvial sandbodies (Fig. 3). The Spring Canyon Member is overlain by the Aberdeen Member (of the Blackhawk Formation), which comprises both marine and nonmarine strata (Fig. 8). Encased within the Blackhawk Formation coastal-plain mudstones are fluvial channel sandbodies (Fig. 5).

4.3. Transitional complexity

The shallow-marine Star Point Sandstone transitions stratigraphically upwards to the nonmarine Blackhawk Formation in the southern part of the study area (Figs. 3A, 5). It is a transition characterized by a monotonous normal regression such that facies belts prograded paleo-seaward (eastward) with negligible intervening events involving a retrogradation, which commonly leads to vertical repetition of marine and nonmarine strata (Figs. 3A, 5). In other words, marine strata are never repeated in vertical succession if overlain by nonmarine strata. In the northern part of the study area, however, marine and nonmarine strata intertongue in a complex fashion (Figs. 3B, 6).

The southern part of the study area contains more complex fluvial architecture characterized by multi-story channels and channel-belt complexes (Figs. 3A, 5) in comparison to the northern part (Figs. 3B, 6), which has multi-lateral and single-story sandbody architectures encased within the Blackhawk Formation mudstones (Fig. 6). Fluvial sandbodies are more amalgamated in the southern portions of the study area (Fig. 5) because they were likely part of a more long-lived channel system in a relatively low-accommodation setting, whereas in the northern portions, accommodation was created more readily due to tectonic subsidence (Hampson et al., 2011, 2012), which exacerbated the likelihood of multi-story channelization. Notably, abrupt and up-dip pinch-outs of the two uppermost marine sandbodies of the Blackhawk Formation within coastal-plain mudstones are distinctly developed in the Wattis Road section (Fig. 6).

4.4. Sequence stratigraphic framework

Particular attention was paid to distinguish incised valley fills from regular channel deposits because incisions (e.g., sequence boundaries) develop upon drops in relative sea level (Posamentier and Vail., 1988). In outcrop, incised valleys were identified based on a number of criteria including 1) fluvial channel cutting into marine sandbody (Fig. 7), 2) multi-story and multi-lateral complex fills of channels (Fig. 5), and 3) mature paleosoils in the interfluve (Fig. 4).

Incised valleys are particularly common at the three high-frequency (4th order; cf., Seymour and Fielding, 2013) sequence boundaries that have been correlated within the lower Blackhawk Formation (Fig. 8). The lower two incised valleys were originally identified by Hampson et al. (2011).
Fig. 5. Trail Mountain Mine outcrop photomosaic (upper) and its corresponding facies and stratigraphic architecture (below). This location shows a simple upward transition from marine to nonmarine strata. However, fluvial channel architecture is more complex in this southern outcrop compared to northern outcrops (Fig. 5). For legend, see Fig. 3C.

Fig. 6. Photomosaic (upper) and corresponding facies and sequence stratigraphic framework (lower) of the Wattis Road section, showing a complex lateral and upward transition from marine to nonmarine strata. Note the abrupt up-dip pinch-outs of the two uppermost marine sandbodies into coastal-plain mudstones. For legend, see Fig. 3C.
5. Discussion

5.1. Paleogeography

In the study area, a local marine embayment was likely to exist near the Wattis Road section (Hampson et al., 2011). This is supported by our observation of a complex inter-tonguing of marine and nonmarine strata in the lower Blackhawk Formation at the Wattis section (Figs. 7, 8). Early Campanian shoreline morphologies of the Western Interior Seaway in Utah were previously characterized by alternating headlands and bays within a larger regional embayment referred to as the 'Utah Bight' (Hampson, 2010). These headlands probably formed broad basinward protrusions in the shoreline that were morphologically cuspate or wave-deltaic, and comprised of progradationally stacked curvilinear beach ridges (Hampson, 2010). Locations of embayments like the one in Wattis area within the "Utah Bight" were coincident with depocenters and localized entry points for sediments shed from the Sevier fold-and-thrust belt (Hampson et al., 2011, 2012). As a depocenter, this Wattis embayment was subject to higher rates of tectonic subsidence than surrounding headlands (Hampson et al., 2011, 2012), and in the event of a decrease or cutoff of sediment supply, this area was the first to undergo facies retrogradation.

5.2. Along strike variability of sequence stratigraphy

Sequence stratigraphically, the Book Cliffs has been studied extensively parallel to depositional-dip (e.g., Taylor and Lovell, 1995; Van Wagoner and Bertram, 1995; Yoshida et. al, 1998; Hampson and Howell, 2005; Hampson, 2010). Along-strike sequence stratigraphy of these strata is rarely documented along the Wasatch Plateau (e.g., Hampson et al., 2011). Even outside the Book Cliffs, outcrop studies of sequence stratigraphy are comparatively very rare along depositional-strike, leading to a clear paucity of along-strike sequence stratigraphic models in textbooks (e.g., Coe, 2003; Catuneanu, 2006). To fill this knowledge gap, this study emphasizes high-resolution sequence stratigraphic framework of the same Book Cliffs’ strata along depositional-strike in the Wasatch Plateau of central Utah (Fig. 8).

The measured sections of this study are comprised entirely within a highstand systems tract of a 3rd-order (few Myr cycles) sequence, which, according to Seymour and Fielding (2013), has lower and upper erosional boundaries at the base of a transgressive lag deposit overlying the Panther Tongue (the lowermost member of the Star Point Sandstone) and at the base of Castlegate Sandstone, respectively. Nested within this highstand systems tract are higher frequency 4th-order (<1 Myr cycles) sequences (Seymour and Fielding, 2013) that may reflect smaller-scale climate variability (e.g., Milankovitch cycles) during the early Campanian when sea level was likely periodically fluctuated by approximately 10 m (Hampson et al., 2012).

The coals, which likely developed in up to 20 km-wide raised-mires that paralleled the western shoreline of the Interior Seaway (McCabe and Shanley, 1992) are particularly useful as marker beds in sequence stratigraphic correlation along depositional-strike (Fig. 8). The onset of peat accumulation related to the development of regionally extensive coal in the study area have been linked to 4th-order marine flooding events (Ryer, 1983; Davies et al., 2006). Despite this, few studies have attempted to correlate coeval surfaces from coal to marine strata. From a unique depositional-strike perspective along the Wasatch Plateau, the Blind Canyon coal seam is suggested to laterally transition into a marine flooding surface, between the Hiawatha and Wattis Road sections (Fig. 8). The basal portions of wetting-upward trends within these coals have been shown in previous studies (Davies et al., 2006) as temporally equivalent to marine flooding surfaces. Petrographic analysis can reveal a stratification plane within coal where a marine flooding surface is coeval, as the presence of pyrite is a strong indicator of saltwater incursion (Davies et al., 2006).
Although no sequence boundaries were identified within the Spring Canyon Member in the depositional-dip-oriented Book Cliffs (Hampson, 2010; Hampson et al., 2012), this study provides a detailed correlation of the two sequence boundaries within the Spring Canyon Member in the strike-oriented Wasatch Plateau. Notably along basin-strike, these sequence boundaries likely laterally transition to correlative conformities within marine strata in the northern part of the study area (between Hiawatha and Gentile Wash in Fig. 8), where an embayment was interpreted to exist because of the higher tectonic subsidence in the area (Hampson et al., 2011). This high accommodation is also reflected in the aggradational stacking of parasequences in the Spring Canyon Member near the Price Canyon along the Book Cliffs (Hampson and Howell, 2005). The sequence boundary interpreted at the top of the Aberdeen Member in the Wattis Road section (Fig. 8) is correlatable with the Aberdeen Sequence Boundary documented at the top of the Aberdeen Member in the Book Cliffs. In this case, the flooding surface (FS100 in Hampson et al., 2012) demarcating the top of the Aberdeen Member in the Book Cliffs correlates with the Bob Wright-McKinnon-Castlegate B Coal Zone in the Wasatch Plateau (Fig. 8).

For ~50 km along depositional-strike, the identified sequence boundaries, particularly the lower two (Fig. 8), mimic the distinct form of coastline-parallel paleo-topographic profiles, showing alternating incised valley floors and interfluve highs. However, along-strike variation of subsidence linked to tectonics and/or differential compaction of coal-precursor-peat resulted in localized incision of fluvial valleys, the bases of which are challenging to correlate laterally without the presence of mature paleosols. Remarkably in contrast, marine flooding surfaces and their correlative coal zones are relatively easy to correlate across the study area (Fig. 8). This highlights the fact that flooding surfaces are far less controversial than subaerial unconformities while used in sequence stratigraphic correlation (Bhattacharya, 2011).

5.3. Landward (up-dip) pinch-out of the marine sandbody

Facies architecture of marine sandbodies (i.e., parasequences) as they terminate basinward (down-dip) is well-documented, especially in the Book Cliffs (Pattison, 1995; Hampson, 2000; Samme et al., 2008), where they are known to split basinward into vertically stacked bedsets before tapering out into the Mancos Shale over a long (tens of km) distance (e.g., Hampson et al., 2011). However, documentations of landward (up-dip) pinch-outs of parasequences are rare. For example, Hampson et al. (2011) identified that Star Point Sandstone parasequences pinch-out in the up-dip direction over short distances along the Wasatch Plateau. Here, we present a detailed documentation (Fig. 6) of this type of up-dip pinch-outs of marine sandbodies of the Aberdeen Member (Blackhawk Formation) at the Wattis Road section. As those up-dip pinch-outs occur abruptly (~500 m distance) and within coastal-plain mudstones, they represent a unique type of potential stratigraphic traps in the coastal-plain reservoirs of hydrocarbon or groundwater.
6. Conclusions

1. Eight distinct facies associations were identified at the stratigraphic transition between the Cretaceous shallow-marine Star Point Sandstone and coastal-plain Blackhawk Formation in the Wasatch Plateau, Utah. These are offshore marine, lower shoreface, upper shoreface, tidal channel, bay, swamp, coastal-plain, and fluvial facies associations.

2. During sea level fall, localized incisions developed across the coastal plain. Erosion surfaces marking the bases of incised valleys correlate laterally with interfluve paleosols. Along depositional-strike for a length of 50 km, these sequence boundaries take the distinct form of a coastline-parallel paleo-topographic profile that shows alternating fluvial valleys, interfluval highs, and marine embayments where the sequence boundary becomes a cumulative conformity.

3. At Rilda and Trail Canyon Road sections, calcareous mature paleosols with sequence stratigraphic significance were identified. These paleosols may hold clues regarding the regional paleoclimate. A detailed petrographic and geochemical analysis of the paleosols can be pursued in future to shed light on the Campanian paleoclimatic of the region.

4. Sequence stratigraphic framework of the study area supports that high-frequency (<1 Myr cycles) sea level fluctuations occurred in the Western Interior Seaway during Late Cretaceous. Outcrop studies of sequence stratigraphy are mostly along depositional-dip. Hence, this study of sequence boundary, flooding surface, and coal zone correlations at the transition between the upper Star Point Sandstone and lower Blackhawk Formation presents a rare outcrop example of sequence stratigraphic framework along depositional-strike. This study also supports that flooding surfaces are far less controversial than subaerial unconformities while used in sequence stratigraphic correlation.

5. Differential tectonic subsidence was the fundamental process in the study area controlling the variability of facies and stratigraphy in coeval marine and nonmarine strata along depositional-strike. Where subsidence was high (i.e., depocenter in north), the vertical and lateral transition between marine and nonmarine strata is complex. Coeval strata to the south away from the depocenter were subject to lower subsidence rate, prompting the marine Star Point Sandstone to pass stratigraphically upward to nonmarine Blackhawk Formation in one simple transition.

6. A unique type of potential stratigraphic trap is emphasized in this outcrop-analy study, where shallow marine sandbodies abruptly (<500 m) terminate landward (up-dip) within coastal-plain mudstones.

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