ALONG-STRIKE AND DOWN-DIP VARIATIONS IN SHALLOW-MARINE SEQUENCE STRATIGRAPHIC ARCHITECTURE: UPPER CRETACEOUS STAR POINT SANDSTONE, WASATCH PLATEAU, CENTRAL UTAH, U.S.A.

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ABSTRACT: The sequence stratigraphic architectures of shallow-marine deposits in the upper Cretaceous Star Point Sandstone are analyzed over a large (c. 100 km), nearly continuous outcrop section aligned oblique to depositional strike. The unit consists of five parasequences that predominantly comprise wave-dominated shoreface–shelf deposits. Two parasequences contain river-dominated delta-front deposits locally. Within each parasequence, wave-dominated shoreface–shelf deposits record 7–45 km of ESE- to ENE-directed progradation of a linear to moderately lobate shoreline that was supplied with sediment by longshore drift and subjected to strong offshore sediment transport by storms. Wave-dominated shoreface sandstones in each parasequence thin and wedge out over short distances (<500 m) at their updip pinchouts. Lower-shoreface sandstones in each parasequence split down dip into multiple, vertically stacked, upward-coarsening bedsets separated by tongues of offshore mudstones in distal locations associated with rapid deepening of antecedent paleobathymetry. River-dominated delta-front deposits define progradation of strongly lobate shorelines in an overall direction oriented subparallel to the regional shoreline trend and into locations sheltered from wave energy. These progradation directions are consistent with deflection of the deltas by wave-driven longshore currents.

The arrangement of parasequences in the Star Point Sandstone defines an overall concave-landward shoreline trajectory, with decreasing progradation and increasing aggradation through time. Along-strike variations in this trajectory pattern reflect increased tectonic subsidence towards the north combined with highly localized, large-volume, fluvial sediment supply near the northwestern limit of the study area during deposition of an areally extensive (>800 km²) river-dominated delta-front complex (Panther Tongue). This highly focused fluvial sediment flux probably occurred via a structurally controlled sediment entry point between two active thrusts.

INTRODUCTION

Current, widely used sequence stratigraphic models of shallow-marine strata emphasize variability down depositional dip at the expense of changes in facies character and stratigraphic architecture along depositional strike (e.g., Martinsen and Helland-Hansen 1995). Thus, models of along-strike variability of sequence stratigraphic architecture remain largely speculative and are based on relatively few well-documented examples, particularly at outcrop. Here we present and analyze a high-quality outcrop dataset from the Star Point Sandstone of central Utah, U.S.A., which represents a series of predominantly wave-dominated shorelines and associated nearshore to shelfal strata. Exposures of these strata in the eastern Wasatch Plateau provide a large (c. 100 km), nearly continuous section aligned oblique to depositional strike. To date, these strata have been described by few previous workers, who have focused on only specific parts of the outcrop belt (Flores et al. 1984; Dubiel et al. 2000; Holman 2001). Coeval and contiguous strata are exposed in an overall dip orientation in the well-documented Book Cliffs. The aims of this paper are threefold: (1) to present a parasequence-scale sequence stratigraphic framework for the Star Point Sandstone over the whole eastern Wasatch Plateau outcrop belt; (2) to describe the facies character and internal architecture of parasequences within this framework, with particular emphasis on their up-dip and down-dip pinchouts; and (3) to document and interpret along-strike variability in shallow-marine facies character and stratigraphic architecture.

GEOLOGIC SETTING AND PREVIOUS WORK

The Star Point Sandstone was deposited along the western shoreline of the Cretaceous Western Interior Seaway, which extended from north to south across the North American continent (e.g., Kauffman and Caldwell 1993; inset map in Fig. 1). The unit comprises shallow-marine sandstones that overlie and interfinger with the offshore deposits of the Mancos Shale, and it is overlain by the coal-bearing coastal-plain deposits of the
The Star Point Sandstone and the overlying Blackhawk Formation and Castlegate Sandstone crop out along the eastern edge of the Wasatch Plateau in central Utah, where they form a continuous SSW–NNE-oriented cliff face that exposes up to 150 m of shallow-marine strata and 350 m of overlying coastal-plain strata over a distance of c. 100 km (Figs. 1, 2B). This cliff face is oriented subparallel to the regional depositional strike of the wave-dominated deltaic shorelines that constitute the Star Point Sandstone (Flores et al. 1984; Dubiel et al. 2000).

**DATASET AND METHODS**

The Star Point Sandstone and the overlying Blackhawk Formation and Castlegate Sandstone are key components of the Mesaverde Group outcrop belt, which includes the Star Point Sandstone, Blackhawk Formation, and Castlegate Sandstone, in the Wasatch Plateau and contiguous Book Cliffs. The study area is highlighted. The inset map (top right) shows the location of the outcrop-belt map on the western margin of the Late Cretaceous Western Interior Seaway (after Kauffman and Caldwell 1993).
Several WNW–ESE-trending canyons cut through the cliff face, providing some 3D control on stratigraphic architecture. In addition, the Wasatch Plateau exposures are contiguous with the WNW–ESE-oriented Book Cliffs, which expose the same strata in an overall dip orientation (Fig. 1). Thus, the existing stratigraphic framework of the shallow-marine Blackhawk Formation in the Book Cliffs (Balsley 1980; Howell and Flint 2003; Hampson 2010) can be extended into the Star Point Sandstone and Blackhawk Formation of the Wasatch Plateau to provide a regional context.

The continuity and degree of exposure of the Star Point Sandstone outcrops along the eastern edge of the Wasatch Plateau are excellent (e.g., Fig. 2B), although most of the outcrops occur in vertical cliff faces or steep slopes that are inaccessible. Thus, many of the interpretations and correlations presented in this paper are based on low-angle aerial photographs of the cliff faces acquired on overview flights. The photographs provide a continuous view of strata along the main east-facing cliff face, except where canyons dissect this face and small gaps (< 5 km) occur.

Eight measured sections through the Star Point Sandstone were collected from accessible WNW–ESE-trending canyons (Fig. 3). The measured sections record lithology, grain size and sorting, sedimentary structures, paleocurrents, body-fossil and trace-fossil types, and bioturbation intensity in the form of bioturbation index logs (e.g., Gani et al. 2008). Conventional facies analysis has been carried out using these measured sections. Facies identified in the measured sections have distinctive weathering characteristics that allow them to be identified with reasonable confidence in the low-angle aerial photographs (Table 1).

In inaccessible parts of the outcrop belt, in between the measured sections, simple logs over the entire Star Point Sandstone, Blackhawk Formation, and Castlegate Sandstone interval were constructed from the low-angle aerial photographs at locations marked by prominent topographic features, which are readily identified on topographic basemaps (Fig. 3). The thickness of the Star Point–Blackhawk Formation–Castlegate Sandstone interval in each photographic log (typically several hundred meters) was measured using topographic basemaps. The relative thickness of the Star Point Sandstone and its constituent stratigraphic units, compared to the total Star Point–Blackhawk Formation–Castlegate Sandstone interval thickness, was then used to estimate the absolute thickness of each stratigraphic unit. Weathering profiles were used to interpret vertical facies successions in the Star Point Sandstone in each photographic log (e.g., Table 1, Fig. 4). The photographic logs provide a proxy for “ground truth” measured sections in inaccessible parts of the outcrop belt.

199 photographic logs were constructed, with spacings along the cliff face and canyon walls of 0.2–26.9 km, corresponding to straight-line spacings of 0.2–6.0 km (Fig. 3). The distribution of lithologic units was mapped in between the logs using the low-angle aerial photographs. This technique allows mapping of lithologic units along the main cliff face and canyon walls with an estimated accuracy of c. 50 m horizontally and c. 10 m vertically. Although this accuracy is less than that achievable by LIDAR and similar digital data-capture techniques (e.g., Bellian et al. 2005; Pringle et al. 2006), it is nonetheless sufficient to construct a gross stratigraphic framework over such a large study area (c. 100 km × 15 km; Figs. 1, 3) at reasonable time and cost. Our gross stratigraphic framework is based on mapping of stratigraphic units over 10 m thick, although thinner units (c. 1 m) can be consistently distinguished in the photographs.

Although the SSW–NNE-oriented cliff-face outcrops extend over a large area and have a high degree of continuity, they present a large two-dimensional (2D) cross section with 3D control provided by WNW–ESE-trending canyon systems. Consequently, aspects of 3D stratigraphic architecture are poorly constrained if they occur at a scale smaller than the spacing of the cliff face and canyon walls. Some additional 3D control is provided in a few locations by wells drilled behind the outcrop belt for coal mining (e.g., Dubiel et al. 2000) and for hydrocarbon exploration and production.

**FACIES ASSOCIATIONS, FACIES SUCCESSIONS, AND STRATIGRAPHIC UNITS**

Eleven facies have been recognized in the Star Point Sandstone and stratigraphically adjacent Mancos Shale and lower Blackhawk Formation...
offshore-shelf deposits (OS facies) (e.g., 37–39 m in Fig. 5B). In paleolandward locations, regressive units are overlain by deposits of the marginal-marine back-barrier facies association (TIC, L facies; Table 1, Fig. 7). Vertical successions of these back-barrier deposits typically comprise lagoonal siltsilstones (L facies) that overlie coal seams across a transgressive surface (sensu Embry 1993, equivalent to the surface of maximum regression sensu Helland-Hansen and Gjelberg 1994) and are eroded locally by tidal-inlet(?) channels (TIC facies) across a tidal ravinement surface (sensu Swift 1968) (e.g., 87–95 m in Fig. 5A). These successions constitute the preserved remnants of barrier-island systems that developed and retreated during transgression. Thus, wave-dominated shoreline-shelf deposits occur within regressive-transgressive tongues that are bounded by flooding surfaces and that correspond broadly to parasequences (sensu Van Wagoner et al. 1990).

Lower-shoreface deposits (dLSF, pLSF facies) in several parasequences “split” in a paleoseaward location into smaller upward-coarsening successions separated by offshore-shelf deposits (OS facies). Hummocky cross-stratified sandstone beds within these smaller successions thickening and amalgamate upwards (Fig. 5B). The boundaries of the successions do not correlate in a paleolandward direction to flooding surfaces (i.e., they are not marked by paleolandward displacement of the upper-shoreface, USF, and foreshore, FS, facies belts), but rather die out within successions of amalgamated hummocky cross-stratified sandstone beds (pLSF facies). Accordingly, these smaller stratigraphic units do not constitute parasequences, although each superficially resembles the distal part of a parasequence in vertical section. The units are instead interpreted as bedsets (sensu Van Wagoner et al. 1990). Robust identification of parasequences requires tracing of facies architecture along depositional dip, such that an abrupt landward facies shift of the upper-shoreface and foreshore facies belts (USF, FS facies), which marks retreat of the shoreline across a flooding surface, is demonstrated at the base and top of each parasequence. Where such facies architectures cannot be demonstrated due to limited updip exposure, upward-coarsening trends in lower-shoreface and offshore-shelf deposits (OS, dLSF, pLSF facies) are ambiguous in origin, and may represent either parasequences or bedsets.

The occurrence of multiple, vertically stacked bedsets in the distal parts of each parasequence has important implications for correlation in lower-shoreface and shelf strata, because a single complete upward-shallowing shoreface succession (dLSF, pLSF, USF, and FS facies) in proximal locations may correlate to multiple upward-coarsening successions of storm-event beds (dLSF and pLSF facies) in distal locations. The former successions constitute parasequences, and their boundaries record significant increases in water depth (c. > 10 m) and paleolandward dislocations of the shoreline (> 1 km) (Hampson et al. 2008). The latter successions constitute bedsets, and their boundaries represent minor (c. 1 m) rises in relative sea level, reductions in sand supply, and/or decreases in the intensity of storm waves (Storms and Hampson 2005; Somme et al. 2008; Hampson et al. 2008). In the Star Point Sandstone, previous workers have interpreted upward-coarsening successions in distal locations as parasequences rather than bedsets (Dubiel et al. 2000; Holman 2001), with the result that the surfaces that bound these units do not correlate to landward displacements of the shoreline (i.e., flooding surfaces sensu Van Wagoner et al. 1990) in proximal locations. In subsurface datasets where data are sparse and different sandstone facies are not easy to distinguish (e.g., in wireline logs), correlations of this type may poorly characterize reservoir architecture (Hampson et al. 2008).

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Fig. 3.—Geologic map of the eastern Wasatch Plateau (Fig. 1), showing the distribution of outcrop and well data used in this study (after Witkind et al. 1987; Weiss et al. 1990; Witkind and Weiss 1991; Dubiel et al. 2000; Doelling 2004). Measured sections and photographic logs shown in Figures 5–8 are located.
**Table 1.** Summary sedimentology of facies associations in the Star Point Sandstone, lower Blackhawk Formation, and Mancos Shale. Intensity of bioturbation is described using the bioturbation index (BI) scheme of Taylor and Goldring (1993). Weathering character is used to interpret facies successions in photographic logs (e.g., Fig. 4).

<table>
<thead>
<tr>
<th>Facies association</th>
<th>Facies</th>
<th>Lithology and sedimentary structures</th>
<th>Ichnology</th>
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<tr>
<td>Offshore shelf</td>
<td>Offshore shelf (OS)</td>
<td>Mudstone and siltstone with rare beds of very fine- to upper-fine-grained sandstone. Parallel lamination, wave and current-ripple cross-lamination.</td>
<td>Moderate to intense bioturbation (BI = 3–5); Cruziana ichnofacies (Planolites, Paleophycus, Schaub cylindrichnus, Chondrites, Terebellina (sensu lato), Helminthopsis).</td>
<td>Predominantly silstone and mudstone deposition from suspended-sediment plumes, waning oscillatory flows during major storm events, and river-derived hyperpycnal flows.</td>
<td>Soft, slope-forming, blue-gray shale.</td>
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<tr>
<td>Wave-dominated shoreline-shelf</td>
<td>Distal lower shoreface (dLSF)</td>
<td>Non-amalgamated beds of upper-fine-grained sandstone with mudstone and siltstone interbeds. Hummocky cross-stratification, minor wavy lamination, and wave-ripple cross-lamination.</td>
<td>Absent to intense bioturbation (BI = 0–6); mixed Skolithos/Cruziana ichnofacies (Ophiomorpha, Cylindrichnus, Planolites, Paleophycus, Arenicolites, Skolithos, Schaub cylindrichnus, Thalassinoides, Asterosoma, Zoophycos, Chondrites, Terebellina (sensu lato), Helminthopsis).</td>
<td>Sandstone deposition from waning oscillatory flows during major storm events. Intervening fairweather mudstones are poorly to well preserved.</td>
<td>Soft, blue-gray shale interbedded with resistant, horizontal ledges of yellow-gray sandstone.</td>
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<tr>
<td>Proximal lower shoreface (pLSF)</td>
<td>Amalgamated beds of upper-fine-grained sandstone. Swaly and hummocky cross-stratification, minor wavy lamination, and wave-ripple cross-lamination.</td>
<td>Absent to intense bioturbation (BI = 0–5); mixed Skolithos/Cruziana ichnofacies (Ophiomorpha, Cylindrichnus, Paleophycus, Thalassinoides, Asterosoma, Planolites).</td>
<td>Sandstone deposition from waning oscillatory flows during major storm events. Intervening fairweather mudstones are not preserved.</td>
<td>Massive, cliff-forming, yellow-gray sandstone.</td>
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<td>Upper shoreface (USF)</td>
<td>Upper-fine- to lower-medium-grained sandstone. Trough and tabular cross-beds, minor planar lamination, and swaly cross-stratification.</td>
<td>Absent to moderate bioturbation (BI = 0–4); Skolithos ichnofacies (Ophiomorpha, Thalassinoides, Skolithos, Cylindrichnus).</td>
<td>Migration of nearshore bars and rip channels due to longshore and offshore-directed currents generated by fairweather-wave approach.</td>
<td>Rugose, cliff-forming, off-white sandstone. Cross-beds visible locally.</td>
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<td>Foreshore (FS)</td>
<td>Upper fine-grained sandstone. Planar-parallel lamination.</td>
<td>Absent to sparse bioturbation (BI = 0–1); Skolithos ichnofacies (Ophiomorpha, Thalassinoides).</td>
<td>Swash lamination due to breaking waves.</td>
<td>Rugose, cliff-forming, off-white sandstone. Parallel bedding visible locally.</td>
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<td>River-dominated delta front</td>
<td>Distal delta front (dDF)</td>
<td>Non-amalgamated beds of fine- to medium-grained sandstone with mudstone and siltstone interbeds. Graded, structureless-to-laminated sandstone beds; rare hummocky cross-stratification, and wave-ripple cross-lamination. Occurs near clinoform toes.</td>
<td>Absent to intense bioturbation (BI = 0–5); mixed Skolithos/Cruziana ichnofacies (Ophiomorpha, Skolithos, Thalassinoides, Arenicolites, Paleophycus, Planolites, Terebellina (sensu lato)).</td>
<td>Sediment-gravity-flow deposits near toe of steeply dipping delta front; rare reworking by waning oscillatory flows during major storm events. Intervening mudstones are poorly to well preserved.</td>
<td>Soft, blue-gray shale interbedded with resistant, inclined ledges of yellow-gray sandstone.</td>
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<tr>
<td>Proximal delta front (pDF)</td>
<td>Amalgamated beds of fine- to medium-grained sandstone. Abundant trough and tabular cross-beds, structureless, and graded, structureless-to-laminated beds; rare hummocky cross-stratification, and wave-ripple cross-lamination. Contains steeply dipping (up to 15°) clinoforms.</td>
<td>Absent to moderate bioturbation (BI = 0–4); Skolithos ichnofacies (Ophiomorpha, Skolithos, Paleophycus, Planolites).</td>
<td>Migration of dunes and sediment gravity flows down steeply dipping delta front; rare reworking by waning oscillatory flows during major storm events. Intervening mudstones are not preserved.</td>
<td>Cliff-forming, yellow-gray sandstone containing inclined partings (bedding surfaces).</td>
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### Table 1. — Continued.

<table>
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<tr>
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<td>Marginal-marine back-barrier</td>
<td>Tidal-inlet channels (TIC)</td>
<td>Heterolithic channel fills comprising fine- to coarse-grained sandstone with carbonaceous mudstone and siltstone interbeds. Trough and tabular cross-beds, planar lamination, and current-ripple cross-lamination. Lateral-accretion surfaces with siltstone drapes. Discontinuous shell-hash and oyster-shell lags.</td>
<td>AbSENT to moderate bioturbation (BI = 0–4); low-diversity trace fossil assemblage (Ophiomorpha, Thalassinoides, Paleophycus, Planolites).</td>
<td>Intermittent migration of sandy dunes and ripples, alternating with deposition of mud and silt from suspension, within meandering channels. Large variations in flow velocity across entire height of point bars. Influxes of brackish-to-marine water.</td>
<td>Laterally discontinuous bodies of gray-brown shale with resistant, inclined ledges of yellow-gray or off-white sandstone.</td>
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<tr>
<td>Lagoonal (L)</td>
<td>Carbonaceous mudstone and siltstone with rare beds of very fine- to upper-fine-grained sandstone. Parallel lamination and wave-ripple cross-lamination. Monospecific fauna of oysters.</td>
<td>Absent to moderate bioturbation (BI = 0–4); low-diversity trace fossil assemblage (Thalassinoides, Planolites).</td>
<td>Deposition from suspension, with episodic wave reworking. Brackish salinity.</td>
<td>Soft, gray-brown shale locally containing resistant ledges of yellow-gray sandstone.</td>
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<tr>
<td>Coastal plain</td>
<td>Fluvial sandbodies (F)</td>
<td>Channelized sandbodies comprising very fine- to coarse-grained sandstone. Trough and tabular cross-beds, planar-parallel lamination, and soft-sediment folding (water escape). Architectural elements in sandbodies include lateral accretion, downstream accretion, simple “cut and fill”, and fine-grained channel plugs. Some sandbodies are arranged in multistory and multilateral complexes.</td>
<td>Bioturbation absent (BI = 0); some channels have root-penetrated tops.</td>
<td>Migration of sandy dunes and barforms within and adjacent to channels. Barforms accrete downstream and laterally, but are not present in all sandbodies. Channel abandonment results in reduced flow velocity and deposition of mud and silt from suspension. Sandbody stacking reflects variety of controls.</td>
<td>Laterally discontinuous, rugose, cliff-forming, yellow-gray or off-white sandstone.</td>
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<tr>
<td>Aggradational floodplain (AF)</td>
<td>Root-penetrated carbonaceous mudstones and siltstones containing thin sheets and small channels of current-ripped and trough cross-bedded, very fine- to medium-grained sandstone. Paleosols and coals occur at specific, mappable horizons.</td>
<td>Absent to sparse bioturbation (BI = 0–2); low-diversity trace fossil assemblage in a few intervals only (Planolites, Terebellides, Paleophycus, Diplocraterion*).</td>
<td>Sandstone deposition from waning unidirectional currents during major river floods. Intervening mudstones and siltstones record deposition from suspension during smaller, more frequent floods. Paleosols and coals record reduced clastic sedimentation.</td>
<td>Soft, gray-brown shale locally containing with resistant ledges of yellow-gray sandstone. Coals are commonly black, but recent burning of exposed coals produces red staining.</td>
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#### River-Dominated Delta-Front Facies Association

Two facies are interpreted to represent river-dominated delta-front deposits (dDF, pDF; Table 1). Successions of the river-dominated delta-front facies association have been described from the Panther Tongue (Howard 1966; Newman and Chan 1991; Posamentier and Morris 2000; Hwang and Heller 2002; MacEachern et al. 2005; Olariu et al. 2005; Howell et al. 2008; Enge et al. 2010; Olariu et al. 2010) and also from some parts of the shallow-marine Blackhawk Formation in the Book Cliffs (e.g., Kamola and Van Wagoner 1995; Hampson and Storms 2003; Hampson and Howell 2005; Charvin et al. 2010). Facies are arranged in upward-coarsening successions up to 20 meters thick that gradationally overlie offshore-shelf deposits (OS facies) and exhibit a consistent trend from distal delta-front deposits (dDF facies) grading upwards into proximal delta-front deposits (pDF facies) (Figs. 5C, 8). The successions record thicker and more abundant sediment-gravity-flow sandstone beds towards the top of the delta front. Trace-fossil assemblages constitute a mixture of impoverished Cruziana and Skolithos ichnofacies (Pemberton et al. 1992), consistent with ecological stresses due to mixing of fresh and marine waters, episodic sedimentation, and a high proportion of suspended sediment in the water column (MacEachern and Bann 2008). River-dominated delta-front successions contain prominent clinoforms with a concave-up shape and steep dips (up to 15°) (Fig. 8C). Channelized scours that truncate and interfinger with the upper parts of the clinoforms...
are interpreted as terminal distributary channels (Olariu et al. 2005; Olariu and Bhattacharya 2006). Mapping of lateral facies trends define local shoreline paleogeographic and proximal-to-distal trends. Offshore-shelf deposits (OS facies) are poorly developed or missing in paleo-landward areas but become thicker and more fully developed in a paleoseaward direction. To compensate this trend, proximal delta-front deposits (pDF facies) thin and pinch out in a paleoseaward direction.

Stratigraphic units that contain the complete association of river-dominated delta-front facies (dDF, pDF), upward-coarsening vertical facies successions, and proximal-to-distal facies trends described above record regression. Such regressive successions are abruptly overlain by offshore-shelf deposits (OS facies), laterally extensive hummocky cross-stratified sandstones, and interbedded siltstones (dLSF facies), or estuarine mudstones within flooded distributary channels (Hwang and Heller 2002). These vertical facies relationships record an increase in water depth, either directly across a flooding surface (in the first case) or via a transgressive, upward-deepening succession that is capped by a flooding surface (in the second and third cases). Transgressive successions in the uppermost part of the Panther Tongue commonly contain lag deposits above a basal transgressive erosion surface (e.g., wave ravinement surface at 29 m in Fig. 5C) (Hwang and Heller 2002). River-dominated delta-front deposits therefore occur within regressive-transgressive tongues that are bounded by flooding surfaces, and that correspond to parasequences (sensu Van Wagoner et al. 1990). On this basis, the Panther Tongue is considered as a single parasequence, although it contains multiple delta lobes arranged in an offlapping pattern that indicates forced regression (Hwang and Heller 2002). In addition, at least two wave-dominated shoreline-shelf parasequences in the shallow-marine Blackhawk Formation of the Book Cliffs contain river-dominated delta-front deposits that define single or multiple lobes near their down-dip pinchouts (Kamola and Van Wagoner 1995; Hampson and Storms 2003; Hampson and Howell 2005; Charvin et al.)

**FIG. 4.—** A) Uninterpreted and B) interpreted cliff-face photograph illustrating interpretation of facies successions and stratigraphic units in a representative photographic log. Three parasequences (Ksp 040, Ksp 030, and Ksp010) comprise wave-dominated shoreline-shelf deposits, whereas a fourth (Ksp 020) locally consists of river-dominated delta-front deposits that contain relatively steeply dipping (up to 3°) clinoforms. One of the shoreline-shelf parasequences (Ksp 030) is subdivided locally into two beds. The photograph is located in Figure 9.
FIG. 5.—Measured sections illustrating facies successions, bioturbation intensity (BI), grain size, sedimentary structures, and sequence stratigraphic interpretations in the Star Point Sandstone: A) complete upward-shallowing, wave-dominated shoreface–shelf succession (parasequence Ksp 050) overlain by coal seam, lagoonal siltstones, and tidal-inlet channel interpreted as preserved remnants of a transgressive barrier-island system (from Coal Mine Creek measured section, Figs. 3, 9, 10). B) two upward-coarsening successions of variably amalgamated storm-event beds; regional mapping shows that these two successions occur in the middle and upper parts of the same parasequence (Ksp 050), and they therefore constitute bedsets (Link Canyon measured section, Figs. 3, 9, 10). C) upward-shallowing, river-dominated delta-front succession (parasequence Ksp 040; Panther Tongue) that is truncated by a transgressive erosion (ravinement) surface lined by a coarse-grained lag (Wattis Road measured section, Figs. 3, 9, 10).
Thus, parasequences may contain the deposits of multiple river-dominated delta lobes, and also wave-dominated shoreline–shelf deposits (e.g., in an asymmetrical wave-dominated delta system; Charvin et al. 2010). The deposits of individual delta lobes are more akin in scale to bedsets (cf. Enge et al. 2010) in wave-dominated shoreline–shelf parasequences, although their formative mechanisms may have been different (Charvin et al. 2010).

**Coastal-Plain Facies Association**

Two facies are interpreted to represent coastal-plain deposits (F, AF; Table 1). Laterally discontinuous sandstones with a variety of internal architectures are interpreted to be fluvial sandbodies that resulted from deposition of bars adjacent to migrating channels (F facies). Fluvial sandbodies that erode directly into wave-dominated shoreline–shelf deposits and river-dominated delta-front deposits may be deltaic distributary channels, based on their context. Other fluvial sandbodies are enclosed in root-penetrated mudstones and siltstones that contain coals and thin sheet sandstones, interpreted as floodplain deposits (AF facies), and are less likely to be distributary in origin. Fine-grained channel plugs cannot be confidently identified throughout the outcrop belt, and are thus grouped with fine-grained floodplain deposits (AF facies).

Sequence stratigraphic interpretation of the coastal-plain deposits is the subject of ongoing work. Most of the fluvial sandbodies (F facies) in the lower part of the Blackhawk Formation have a single-story or multilateral geometry, although a few have a multistory, multilateral geometry and appear to be contained within deep erosional surfaces; the latter are candidates for incised-valley fills (sensu Van Wagoner et al. 1990).

**STRATIGRAPHIC FRAMEWORK**

The various facies and stratigraphic units described above were interpreted in each of the measured sections and photographic logs (e.g., Fig. 4), and then traced out along the cliff faces and canyon walls. Figure 9 presents the resulting stratigraphy along the cliff line and canyon faces, over a distance of approximately 340 km (corresponding to a straight-line distance of approximately 100 km). Figure 10 shows the same stratigraphy interpreted along a nearly straight line behind the cliff line between five of the measured sections, while Figure 11 presents maps views of facies-belt extent at maximum regression within each parasequence.

Five parasequences are interpreted (Ksp 050, Ksp 040, Ksp 030, Ksp 020, and Ksp 010; Table 2), whose upper and lower boundaries constitute flooding surfaces marked by significant landward displacements of the shoreline and associated increases in water depth. The distal parts of two more upward-coarsening units are exposed in the southern part of the study area, but they are not exposed in proximal locations; these units would constitute parasequences if their boundaries are associated with significant landward displacements of the shoreline in proximal locations (Ksp 070? and Ksp 060?, as labeled in Figs. 9, 10), or bedsets within parasequence Ksp 050 if not. Most of the parasequences split in a paleoseaward direction into multiple bedsets in their distal parts, but they thin and pinch out abruptly in a paleolandward direction. Each parasequence is described briefly below, in ascending stratigraphic order, and then generic aspects of their up-dip and down-dip pinchouts are documented.

**Parasequence Ksp 050**

Parasequence Ksp 050 crops out in the southern part of the study area (Figs. 9, 10, 11A), where it records progradation of a wave-dominated shoreline. Within each parasequence, the up-dip and down-dip pinchouts of foreshore and upper-shoreface deposits (USF and FS facies) are used as respective proxies for the initial and final positions of the shoreline during progradation (cf. Kamola and Huntoon 1995; Hampson and Howell 2005; Hampson 2010). The up-dip pinchout of these deposits in parasequence Ksp 050 is not exposed in the study area, whereas their down-dip pinchout intersects the cliff-face exposures in one location (Fig. 11A). Upper-shoreface and foreshore deposits therefore form a belt at least 15 km wide, implying that the shoreline prograded a similar distance during deposition of the parasequence (Fig. 11A, Table 2). Paleocurrents in upper-shoreface deposits are oriented towards the south-southeast (Fig. 11A), indicating transport of significant sediment volumes by longshore drift driven by oblique wave approach from the north or northeast. The distance between the down-dip pinchouts of upper-shoreface and distal lower-shoreface sandstones (USF and dLSF facies) in each parasequence defines the width of a storm-rewarmed, nearshore sandstone belt during maximum regression of the shoreline (cf. Hampson 2010). The width of this belt in parasequence Ksp 050 is approximately 15 km (Fig. 11A, Table 2). Lower-shoreface deposits (pLSF and dLSF facies) in the lower and paleoseaward part of the parasequence split into several upward-coarsening bedsets (possibly including Ksp 070? and Ksp 060?), which are arranged in a paleoseaward-stepping pattern in the up-dip part of the parasequence but are vertically stacked near its down-dip pinchout (Figs. 9, 10, Table 2). Lower-shoreface sandstones (pLSF and dLSF facies) at a similar stratigraphic level are mapped in the northwestern part of the study area, as part of the Trail Canyon Sandstone Member of the Mancos Shale (Hansen 1996). Correlation of these sandstones with parasequence Ksp 050 implies that the subregional shoreline exhibited a broad curvature from a NNW–SSE orientation in the south to a NNE–SSW orientation in the north (Fig. 11A).

Parasequence Ksp 050 is mapped to have a flat top defined by a single, nearly horizontal surface (e.g., Sanchez et al. 1983a; Flores et al. 1984; Dubiel et al. 2000) and corresponds to parasequences 0, –1, –2, and –3 of Dubiel et al. (2000), which were mapped using a combination of outcrop and subsurface well-log data. These latter units are correlated as a series of paleoseaward-stepping cliniforms (sensu Rich 1951) whose boundaries are not associated with major landward shifts of the shoreline in proximal locations, but with subtle wireline-log trends that correlate to intercalations of shale in distal locations (plate 1 in Dubiel et al. 2000); we interpret these units as bedsets rather than parasequences.

**Parasequence Ksp 040**

Parasequence Ksp 040 crops out over most of the study area (Figs. 9, 10, 11B) but has distinctly different facies character and stratigraphic
Teredolites indicates marine influence above coal seam

lateral accretion surfaces

channel base
architecture in the northern and southern parts of the study area. In the southern part of the study area, the parasequence records regression of a NNW–SSE-trending wave-dominated shoreline (Fig. 11B). The width of the upper-shoreface and foreshore facies belt implies that the shoreline prograded a distance of approximately 16 km during deposition of the parasequence (Fig. 11B, Table 2). Paleocurrents in upper-shoreface deposits are again oriented towards the south and south-southeast (Fig. 11B), implying sediment transport by wave-driven longshore drift. The storm-reworked, nearshore sandstone belt in these deposits is approximately 20 km wide (Fig. 11B, Table 2). Lower-shoreface deposits (pLSF and dLSF facies) in the paleoeseaward part of the parasequence split into three upward-coarsening bedsets that are vertically stacked (Figs. 9, 10, Table 2).

In the northern part of the study area, parasequence Ksp 040 constitutes the Panther Tongue, which records forced regression of a strongly lobate, river-dominated deltaic shoreline that had an overall NE–SW orientation (Posamentier and Morris 2000; Hwang and Heller 2002; Howell et al. 2008; Enge et al. 2010; Olaru et al. 2010) (Fig. 11B). The up-dip and down-dip pinchouts of proximal delta-front deposits (pDF facies) are used as respective proxies for the initial and final positions of the deltaic shoreline during progradation. The up-dip pinchout of these deposits is not exposed in the study area, and their down-dip pinchouts and local progradation directions, as recorded by the orientation of delta-front clinoforms, are highly variable along the outcrop belt; a minimum of 7–14 km of progradation is interpreted locally in directions ranging from southeastward to west-northwestward (Fig. 11B, Table 2), but these progradation distances may be significant underestimates. The distance between the down-dip pinchouts of proximal and distal delta-front deposits (dDF and pDF facies) is taken to define the local width of a narrow (2–5 km), storm-reworked, nearshore sandstone belt during maximum regression of the deltaic shoreline (Fig. 11B, Table 2). The Panther Tongue contains multiple, laterally stacked delta lobes, which may correspond to bedsets (Enge et al. 2010). However, their detailed geometry and plan-view stacking arrangement is beyond the scope of this study.

Mapping of the wave-dominated shoreline and river-dominated deltaic shoreline deposits within the same parasequence indicates that the subregional shoreline exhibited a broad curvature from a NNW–SSE orientation in the north to a NE–SW orientation in the north (Fig. 11B). The river-dominated deltaic shoreline deposits lack overlying coastal-plain deposits and successive lobes exhibit an offlapping pattern, indicating a forced-regressive architecture developed during relative sea-level fall (Posamentier and Morris 2000). The wave-dominated shoreline deposits lack clear evidence for deposition under such conditions, for example the local development of foreshortened, “sharp-based” shoreface facies successions (sensu Plint 1988) and correlative incised valleys, although the large shoreline progradation distance (c. 16 km) is consistent with forced regression (Posamentier et al. 1992; Plint and Nummedal 2000; Posamentier and Morris 2000). Either these wave-dominated shoreline deposits contain only a subtle expression of forced regression that requires more detailed reconstruction of intra-parasequence stratigraphic architecture to be elucidated (e.g., Hampson 2000), or they record deposition under conditions of rising relative sea level prior to the relative sea-level fall that forced progradation of the Panther Tongue delta complex.

In the southern part of the study area, parasequence Ksp 040 corresponds to parasequences 1, 2, and 3 of Dubiel et al. (2000), which we interpret as bedsets for the same reasons as given in the discussion of parasequence Ksp 050. The up-dip pinchout of parasequence Ksp 040 into the Blackhawk Formation corresponds to Star Point Sandstone tongue 2 of Sanchez et al. (1983a) in the southern part of the study area. Tongue 1 of Sanchez et al. (1983a) is a landward-tapering sandbody that is truncated at its paleoeseaward limit by the upper-shoreface deposits of parasequence Ksp 040; we infer that tongue 1 was deposited in a back-barrier setting (e.g., flood-tidal delta, washover fan).

In the northern part of the study area, the Panther Tongue is interpreted as a single parasequence (cf. regressive–transgressive tongue) that records deposition during falling and lowered relative sea level, and during subsequent transgression (Posamentier and Morris 2000; Hwang and Heller 2002). Transgressive deposits include estuarine, lower-shoreface, and lag deposits (Hwang and Heller 2002). We include these transgressive deposits within parasequence Ksp 040 because they lie beneath an extensive flooding surface, although they have been previously allocated at some locations to a different, additional parasequence (Holman 2001).

**Parasequence Ksp 030**

Parasequence Ksp 030 records progradation of a curved, NNW–SSE to NE–SW-trending wave-dominated shoreline across the study area (Figs. 9, 10, 11C). The width of the upper-shoreface and foreshore facies belt implies that the shoreline prograded a distance of 7–9 km in the southern part of the study area, although the progradation distance is poorly constrained in the north (Fig. 11C, Table 2). Paleocurrents in upper-shoreface deposits are oriented towards both the south-southeast and north-northwest (Fig. 11C), which can be attributed to longshore drift on either side of a poorly preserved (deltaic?) headland, to seasonal reversal of longshore currents, or to shoreline-parallel transport by tides. The storm-reworked, nearshore sandstone belt in parasequence Ksp 030 is approximately 12 km wide (Fig. 11C, Table 2). Lower-shoreface deposits (pLSF and dLSF facies) in the paleoeseaward part of the parasequence split into two or more upward-coarsening bedsets that are vertically stacked (Fig. 9, Table 2).

Parasequence Ksp 030 is mapped in the southern part of the study area to have a flat top defined by a single, nearly horizontal surface (e.g., Sanchez et al. 1983b; Flores et al. 1984; Dubiel et al. 2000) and corresponds to parasequences 4 of Dubiel et al. (2000). The up-dip pinchout of parasequence Ksp 030 into the Blackhawk Formation corresponds to Star Point Sandstone tongue 4 of Sanchez et al. (1983b) (equivalent to unnamed sandstone tongue of Hayes and Sanchez 1979; Sanchez and Hayes 1979) in the southern part of the study area. Tongue 3 of Sanchez et al. (1983b) is a channelized sandbody that cuts into, and is amalgamated with, underlying shoreface deposits in parasequence Ksp 040.

In the northern part of the study area, parasequence Ksp 030 constitutes the Storrs Tongue, and only its distal components are
exposed. Here Holman (2001) identified four tongues of lower-shoreface deposits (pLSF and dLSF facies) in this interval, which she interpreted as parasequences; we interpret these tongues as bedsets for the same reasons as given in the discussion of parasequence Ksp 050.

Parasequence Ksp 020

Parasequence Ksp 020 records progradation of a NW–SE-trending wave-dominated shoreline of complex geometry across the southern and
Fig. 9.—Panel showing stratigraphy and facies architecture in the Star Point Sandstone mapped along the main cliff line and canyon faces along the eastern edge of the Wasatch Plateau (Figs. 1, 3). Five parasequences are interpreted with confidence (Ksp 050, Ksp 040, Ksp 030, Ksp 020, Ksp 010), and the distal parts of two more potential parasequences (Ksp 070?, Ksp 060?) are exposed in the southern part of the panel. Most of the parasequences split into multiple bedsets in their distal parts. Some parasequences appear to exhibit several updip and/or down-dip pinchouts within the panel, due to the irregular re-entrant geometry of the cliff line with respect to regional depositional strike and dip orientations. The top of the uppermost parasequence in different parts of the panel is used as a local datum. Measured sections in Figure 5 and interpreted cliff-face photographs in Figures 4 and 12 are located.
FIG. 10.—Simplified correlation panel showing stratigraphic framework of the Star Point Sandstone and overlying Blackhawk Formation and Castlegate Sandstone in the eastern Wasatch Plateau. The top of the uppermost Star Point Sandstone parasequence in different parts of the panel is used as a local datum. Coal-zone stratigraphy in the Blackhawk Formation is taken from Sanchez and Brown (1983, 1986, 1987), Flores et al. (1984), Sanchez et al. (1983a, 1983b), Brown et al. (1987), Sanchez and Ellis (1990), Dubiel et al. (2000), Gloyn et al. (2003), and Quick et al. (2005). Stratigraphy in the Price Canyon area of the northern Book Cliffs is taken from Van Wagoner et al. (1990), Kamola and Van Wagoner (1995), and Hampson et al. (2005). Keys to facies and stratigraphic surfaces are the same as for Figure 9.
central parts of the study area (Figs. 9, 10, 11D). In the southern part of the study area, the parasequence contains a nearly linear belt of upper-shoreface and foreshore deposits that record approximately 13 km of shoreline progradation and contain a range of paleocurrent orientations (Fig. 11D, Table 2). However, in the central part of the study area, the parasequence contains a N–S-elongate lobe of river-dominated delta-front deposits containing clinoforms that indicate approximately 8 km of deltaic shoreline progradation towards the south (Figs. 4, 11D). These delta-front deposits onlap onto and are traced towards the south into distal lower-shoreface deposits (dLSF facies), whereas their northern limit is marked by a curved belt of lower-shoreface deposits (pLSF and dLSF facies) that trend NW–SE (Fig. 11D). We interpret this paleogeography to represent an asymmetrical wave-dominated delta (sensu Bhattacharya and Giosan 2003), in which the updrift, northern delta flank is represented by wave-dominated strandplain and spit system and the downdrift, southern delta flank comprised a sheltered embayment that was partly infilled by a river-dominated bayhead delta. This interpretation implies that upper-shoreface and foreshore deposits should occur to the north of, and be contiguous with, the proximal delta-front deposits (pDF facies); the apparent absence of these upper-shoreface and foreshore deposits is attributed to their inferred position to the west of the outcrop belt, although they may also have been truncated by transgressive erosion at the top of the parasequence. Similar river-dominated delta-front deposits are documented in the down-dip parts of wave-dominated shoreface–shelf parasequences in the shallow-marine Blackhawk Formation of the Book Cliffs (Kamola and Van Wagoner 1995; Hampson and Storms 2003; Charvin et al. 2010), where asymmetrical delta interpretations have been proposed (Hampson and Howell 2005; Charvin et al. 2010). This interpretation is also implicit in Flores et al.’s (1984) paleogeographic reconstructions of wave-dominated deltas containing barrier-island and spit systems in the Star Point Sandstone. The storm-reworked, nearshore sandstone belt in parasequence Ksp 020 is approximately 10 km wide according to our interpretation of an asymmetrical wave-dominated deltaic shoreline (Fig. 11D, Table 2).

In the southern part of the study area, parasequence Ksp 020 corresponds to parasequences 5 and 6 of Dubiel et al. (2000), which we interpret as bedsets for the same reasons as given in the discussion of parasequence Ksp 050. The up-dip pinchout of parasequence Ksp 020 into the Blackhawk Formation is not identified in coal-resource maps, although only sparse data are available near the pinchout to construct such maps (Sanchez and Brown 1983).

In the central part of the study area, Holman (2001) identified two tongues of lower-shoreface deposits (pLSF and dLSF facies) in parasequence Ksp 020. We interpret these tongues as bedsets, although each has been previously interpreted as a parasequence based on their upward-coarsening trends in grain size (Holman 2001). In the northern part of the study area, parasequence Ksp 020 is represented by an interval of Mancos Shale that separates the Star Point Sandstone below from the Spring Canyon Member of the Blackhawk Formation above (Fig. 10).

**Parasequence Ksp 010**

Parasequence Ksp 010 records progradation of a linear to weakly lobate, NW–SE-trending wave-dominated shoreline across the central and northern parts of the study area (Figs. 9, 10, 11E). The width of the upper-shoreface and foreshore facies belt implies that the shoreline prograded a distance of approximately 45 km (Fig. 11E, Table 2). Paleocurrents in upper-shoreface deposits are oriented towards the south-southeast (Fig. 11E), implying sediment transport by wave-driven long-shore drift. The storm-reworked, nearshore sandstone belt in parasequence Ksp 010 is at least 15 km wide but extends beyond the eastern limit of the study area (Fig. 11E, Table 2). Lower-shoreface deposits (pLSF and dLSF facies) in the paleoseaward part of the parasequence split into three upward-coarsening bedsets that are vertically stacked (Figs. 9, 10, Table 2).

In the central part of the study area, parasequence Ksp 010 corresponds to parasequences 7 and 8 of Dubiel et al. (2000), which we interpret as bedsets for the same reasons as given in the discussion of parasequence Ksp 050. Holman (2001) also interpreted a single parasequence here, which was allocated to the Spring Canyon Member of the Blackhawk Formation. The up-dip pinchout of parasequence Ksp 010 into the Blackhawk Formation corresponds to Star Point Sandstone tongue 5 of Sanchez and Brown (1987). Tongue 6 of Brown et al. (1987) is a poorly exposed, laterally discontinuous sandbody that is locally amalgamated with underlying shoreface deposits in parasequence Ksp 010.

Parasequence Ksp 010 constitutes the lower part of the Spring Canyon Member of the Blackhawk Formation in the northwestern Book Cliffs (labeled Price Canyon in Fig. 10). We tentatively interpret parasequence Ksp 010 to correspond to four tongues of lower-shoreface deposits (pLSF and dLSF facies) mapped by Van Wagoner et al. (1990; their fig. 12) in the lower 35 m of the Spring Canyon Member. Van Wagoner et al. (1990) interpreted each of these tongues as a distinct parasequence (their fig. 12), but we instead interpret them as bedsets because their boundaries are not marked by landward shifts of the shoreline in proximal locations to the west of the area mapped by Van Wagoner et al. (1990).

**Shallow-Marine Strata above Parasequence Ksp 010**

Four parasequences have previously been documented directly above parasequence Ksp 010 in the upper part of the Spring Canyon Member of the Blackhawk Formation in the northwestern Book Cliffs (labeled Price Canyon in Fig. 10) (Sowbelly, Hardscrabble, Heiner, and Helper parasequences of Kamola and Van Wagoner 1995, corresponding to parasequences SC4-7 of Hampson and Howell 2005). The oldest of these parasequences is comparable in shoreline type, thickness (17 m), progradation distance (13–21 km), and width of storm-reworked nearshore sandstone belt (12 km) to those described above in the Star Point Sandstone (Kamola and Huntoon 1995; Hampson and Howell 2005; Hampson 2010). However, the three younger parasequences have significantly smaller progradation distances (1–4 km) despite being similar in facies character and interpreted shoreline type (Kamola and Huntoon 1995; Hampson and Howell 2005; Hampson 2010).

**Up-Dip Pinchouts of Parasequences**

The up-dip pinchouts of four parasequences (Ksp 040, Ksp 030, Ksp 020, and Ksp 010) are well exposed in the southern and central parts of the study area (Figs. 9, 10, 11). All four pinchouts occur over short distances (< 500 m; e.g., Fig. 12A–D) in a depositional-dip orientation, while each case is mapped between multiple (3–5) cliff faces to be linear or slightly sinuous in plan view over distances of 3–7 km (Fig. 11B–E). Similarly abrupt up-dip pinchouts of wave-dominated shoreface sandstone tongues are documented in the Book Cliffs (e.g., Basiley 1980; Van Wagoner et al. 1990; Anderson 1991; Kamola and Van Wagoner 1995). Two types of up-dip pinchout are observed. The first type consists of a landward-tapering sandstone wedge of pLSF, USF, and FS facies with a gently dipping (< 1°), concave-upward lower surface (Fig. 12A, B). Facies boundaries are parallel to the top of the wedge and onlap its lower surface. This facies architecture suggests that the lower surface of the wedge had a paleoseaward-dipping geometry, and the surface is thus interpreted as a wave ravinement surface (sensu Swift 1968) whose geometry mimics the profile of the retreating shoreface that cut it. Shoreline–shelf sandstones in the wedge itself are interpreted to have been deposited during subsequent shoreface regression. The second type of up-dip pinchout consists of a landward-tapering sandstone wedge of pLSF, USF, and FS facies with an upper boundary that descends in a...
TABLE 2.—Parameters defining gross facies architecture in the five mapped parasequences of the Star Point Sandstone.

<table>
<thead>
<tr>
<th>Parasequence</th>
<th>Parasequence stacking pattern (shoreline trajectory relative to underlying parasequence)</th>
<th>Shoreline type and morphology</th>
<th>Distance of shoreline progradation</th>
<th>Width of storm-reworked, nearshore sandstone belt</th>
<th>Organization of lower shoreface and inner shelf sandstones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ksp 010</td>
<td>Strongly progradational (ascending regressive trajectory of c. 0.02°, based on compacted thicknesses).</td>
<td>Linear to weakly lobate wave-dominated shoreline trending NW–SE.</td>
<td>4.5 km</td>
<td>&gt; 12 km</td>
<td>3 vertically stacked bedsets in expanded section beyond pinchout of pLSF sandstones in underlying parasequence Ksp 020 (Fig. 10). Interpreted to contain 4 additional paleoseaward-stepping to vertically stacked bedsets near down-dip pinchout (figure 12 of Van Wagoner et al. 1990).</td>
</tr>
<tr>
<td>Ksp 020</td>
<td>Moderately progradational (ascending regressive trajectory of 0.03–0.06°, based on compacted thicknesses) in southern part of study area.</td>
<td>Weakly to moderately lobate wave-dominated shoreline trending NW–SE, with local lobate river-dominated deltaic shoreline.</td>
<td>1.3 km</td>
<td>1.0 km</td>
<td>2 paleoseaward-stepping bedsets near down-dip pinchout; upper bedset comprises local river-dominated delta lobe (paleoseaward of cross section in Fig. 10).</td>
</tr>
<tr>
<td>Ksp 030</td>
<td>Strongly retrogradational, but poorly constrained by dataset, in northern part of study area.</td>
<td>Weakly to moderately lobate wave-dominated shoreline trending NNW–SSE (southern part of study area) to NE–SW (northern part of study area).</td>
<td>7–9 km</td>
<td>1.2 km</td>
<td>2–4 vertically stacked bedsets in expanded section beyond pinchout of pLSF sandstones in underlying parasequence Ksp 040 (paleoseaward of cross section in Fig. 10).</td>
</tr>
<tr>
<td>Ksp 040</td>
<td>Strongly progradational (forced regressive trajectory of c. –0.2° within the parasequence), but poorly constrained by dataset, in northern part of study area.</td>
<td>Strongly lobate river-dominated deltaic shoreline trending NE–SW in northern part of study area.</td>
<td>&gt; 7–14 km</td>
<td>2–5 km</td>
<td>Multiple laterally stacked delta lobes (bedsets?), which are not fully resolved in dataset.</td>
</tr>
<tr>
<td>Ksp 050</td>
<td>Not constrained by dataset.</td>
<td>Linear to weakly lobate wave-dominated shoreline trending NNW–SSE in southern part of study area.</td>
<td>1.6 km</td>
<td>20 km</td>
<td>3 vertically stacked bedsets in expanded section beyond pinchout of pLSF sandstones in underlying parasequence Ksp 050 (Fig. 10).</td>
</tr>
</tbody>
</table>

Pineleaf direction and truncates facies boundaries that are parallel to the base of the wedge at successively deeper positions (Fig. 12C, D). These pinchouts are interpreted to record erosional truncation at the margins of sandstone- and mudstone-filled channels, which may have formed as the result of regressive erosion by distributary channels, forced-regressive erosion at the base of incised valleys, and/or transgressive erosion by tidal-inlet channels. Deep (up to 18 m) erosion by mudstone-filled channels occurs locally at the top of each parasequence in locations other than their up-dip pinchouts (e.g., Fig. 12E, F), suggesting that incision and subsequent abandonment of deep channels was not confined to the stratigraphic level at the top of any particular parasequence. Both types of pinchout geometry are locally modified by postdepositional compaction.

**Down-Dip Pinchouts of Parasequences**

Each parasequence is interpreted to contain multiple bedsets (sensu Van Wagoner et al. 1990) (Table 2, Figs. 9, 10), each containing upward increases in grain size and bed amalgamation. Bedsets are particularly evident in the down-dip parts of wave-dominated shoreline-shelf parasequences, where they are stacked vertically and separated by tongues of offshore shale (Figs. 9, 10). These shale tongues occur where...
Figs. 12.—A, C, E) Uninterpreted and B, D, F) interpreted cliff-face photographs illustrating the up-dip pinchout geometries of parasequences that comprise wave-dominated shoreline-shelf deposits: A, B) landward-tapering sandstone wedge with a concave-upward lower surface, Ksp 030 in cliff face south of Muddy Creek (Figs. 9, 11C); C, D) landward-tapering sandstone wedge with an erosional, concave-upward upper surface, Ksp 010 in cliff face northeast of Ferron Creek (Figs. 9, 11E), and E, F) deep erosion by fine-grained channel fill into the top of Ksp 040 in cliff face northeast of Convulsion Canyon (Fig. 9).
a parasequence expands in thickness paleoseaward of the pinchout of upper-shoreface and proximal lower-shoreface deposits (USF and pLSF facies) in the underlying parasequence (Figs. 9, 10), suggesting that they reflect deposition in the deep water that characterized these locations. Similar architectures have been documented in more detail in parasequences in the Blackhawk Formation exposed in the Book Cliffs (Pattison 1995; Hampson 2000; Hampson and Storms 2003; Somme et al. 2008). In the Star Point Sandstone parasequences, sandstone beds in distal lower-shoreface deposits (dLSF facies) occur up to c. 100 m below foreshore deposits (FS facies), suggesting that they were deposited in water of similar or greater depths (Figs. 9, 10). Thus, storms were capable of transporting and reworking sand in such water depths.

**CONTROLS ON GROSS STRATIGRAPHIC ARCHITECTURE**

Parasequence stacking patterns in the southern Wasatch Plateau are progradational (Figs. 9, 10) (Dubiel et al. 2000), while those in the northern Wasatch Plateau are more variable and, from base to top, consist of strongly progradational (Panther Tongue), retrogradational (Storrs Tongue), and progradational (Spring Canyon Member) patterns (Figs. 9, 10) (Howell and Flint 2003). In the northwestern Book Cliffs, the internal architecture of the Panther Tongue implies deposition during falling and lowered relative sea level (Posamentier and Morris 2000; Hwang and Heller 2002), and the base of the unit is interpreted to represent a major sequence boundary (Krystinik and DeJarnett 1995; Howell and Flint 2003). The top of the Storrs Tongue is interpreted as a maximum flooding surface (Krystinik and DeJarnett 1995; Howell and Flint 2003). The two contrasting parasequence stacking patterns in the southern and northern Wasatch Plateau are in part coeval (Table 2, Figs. 9, 10, 11), indicating that some of the controls on gross stratigraphic architecture varied along regional depositional strike.

The differences in parasequence stacking pattern between the southern and northern Wasatch Plateau are quantified below using the shoreline trajectory concept (Helland-Hansen and Martinsen 1996; Helland-Hansen and Hampson 2009). Shoreline trajectory is a descriptive tool that considers the combined effect of sediment supply and relative sea level in creating shallow-marine stratigraphic architecture. The likely controls on along-strike variations in stratigraphic architecture are then interpreted in the descriptive context of the reconstructed shoreline trajectories.

**Parasequence Stacking and Associated Shoreline Trajectories**

Figure 13 shows reconstructed shoreline trajectories for the southern and northern Wasatch Plateau. Each parasequence is represented by a regressive–transgressive “sawtooth.” Longer-term patterns in shoreline trajectory, corresponding to parasequence stacking patterns, are recorded by trends in the position of successive “sawteeth” (e.g., Table 2).

The up-dip and down-dip pinchouts of foreshore and upper-shoreface deposits (USF and FS facies) or proximal delta-front deposits (pDF facies) have been used as respective proxies for the initial and final positions of the shoreline during regression, as in the facies-belt maps shown in Figure 11 (cf. Kamola and Huntoon 1995; Hampson and Howell 2005; Hampson 2010). The down-dip pinchout of foreshore deposits may underestimate the shoreline position at maximum regression (by up to c. 3 km), because transgressive erosion and reworking is likely to have removed foreshore deposits from the down-dip part of each tongue; upper-shoreface and proximal delta-front deposits are less likely to have been removed by transgressive erosion, but they extend a small distance (< 1 km) paleoseaward of the shoreline position at maximum regression. Several of the interpreted positions of wave-dominated shorelines were projected for large distances into the line of section used.
to calculate trajectories in the southern Wasatch Plateau (from c. 10 km for parasequence Ksp 040 to c. 80 km for parasequence Ksp 010; inset map in Fig. 13), on the assumption that these shorelines are linear or weakly lobate (Fig. 11). River-dominated deltaic shorelines in the Panther Tongue are strongly lobate (Fig. 11B), and the associated shoreline trajectory in the northern Wasatch Plateau was measured at a location where the outcrop belt constrains the down-dip pinchout of proximal delta-front deposits perpendicular to the subregional shoreline orientation (line of section shown in inset map in Fig. 13). Shoreline trajectories in the Spring Canyon Member of the Blackhawk Formation (parasequences SC4-SC7 in Fig. 13) are taken from the northwestern Book Cliffs (Hampson 2010; line of section shown in inset map in Fig. 13). Along-strike variations in trajectory are constrained by the outcrop belt in parasequences Ksp 020 and Ksp 040, and are shown as bold horizontal bars in Figure 13.

The vertical component of shoreline trajectory in each parasequence is calculated relative to the flooding-surface datum at the base of the parasequence (cf. Hampson 2010). The horizontal component of transgressive shoreline trajectory associated with each parasequence-bounding flooding surface is determined from the paleolandward bold horizontal bars in Figure 13. River-dominated deltaic shorelines in the Panther Tongue were measured at a location where the outcrop belt constrains the down-dip pinchout of proximal delta-front deposits perpendicular to the subregional shoreline orientation (line of section shown in inset map in Fig. 13). Along-strike variations in trajectory are constrained by the outcrop belt in parasequences Ksp 020 and Ksp 040, and are shown as bold horizontal bars in Figure 13.

The overall, long-term shoreline trajectory of the Star Point Sandstone is ascending regressive, with a mean trajectory across the stacked parasequences of 0.09° (Fig. 13). In more detail, the long-term shoreline trajectory in the lower Star Point Sandstone (parasequences Ksp 050 to Ksp 030) is ascending regressive in the southern Wasatch Plateau but regressive (parasequences Ksp 050 to Ksp 040) and then transgressive (parasequences Ksp 040 to Ksp 030) in the northern Wasatch Plateau (Table 2). In the middle to upper Star Point Sandstone and overlying Spring Canyon Member (parasequences Ksp 030 to SC7), the trajectory is also ascending regressive, but with an increasingly steep angle that records decreasing progradation and increasing aggradation (Fig. 13; Table 2). The vertical component of shoreline trajectory for the interval comprising parasequences Ksp 040 to Ksp 010 is larger in the northern Wasatch Plateau than in the southern Wasatch Plateau (Fig. 13), reflecting the greater thickness of this interval in the north (Fig. 10). This lateral variation in trajectory is explored further below.

The overall concave-landward shoreline trajectory of the middle to upper Star Point Sandstone and overlying Spring Canyon Member (parasequences Ksp 030 to SC7) records a gradual, long-term decrease in sediment supply to the shoreline relative to the long-term rate of relative sea-level rise. Although this may reflect an increasing rate of relative sea-level rise or decreasing sediment flux due to allogenic controls (e.g., Kamola and Huntoon 1995), it is most simply explained by autogenic rotation arising from differential tectonic subsidence (Hampson et al. 2009). Decomposition of the study interval, which has been buried up to c. 2.5 km (Nuccio and Roberts 2003), would increase each vertical increment of shoreline trajectory.

Along-Strike Variations in Parasequence Stacking and Shoreline Trajectory

The differences in long-term shoreline trajectory in the lower Star Point Sandstone (parasequences Ksp 050 to Ksp 030) between the southern and northern Wasatch Plateau (Fig. 13; Table 2) can be accounted for by spatial variations in tectonic subsidence and sediment supply along regional depositional strike (SSW–NNE). The larger vertical component of shoreline trajectory in the northern Wasatch Plateau indicates that tectonic subsidence was greater here than in the southern Wasatch Plateau. This higher tectonic subsidence rate is consistent with retrogradational stacking of the Storrs Tongue (parasequence Ksp 040) in the northern Wasatch Plateau, but it does not account for the strongly progradational stacking of the Panther Tongue (parasequence Ksp 050) in the northern Wasatch Plateau.

High, localized sediment supply must be invoked to explain the latter relationship, which is consistent with the river-dominated deltaic character of the Panther Tongue (Fig. 11B). The forced regressive character of the Panther Tongue also accounts for its large progradational extent (50 km, Posamentier and Morris 2000) and requires a short-term relative sea-level fall of c. 20 m. There is no evidence for a comparable relative sea-level fall in the wave-dominated shoreline deposits of parasequence Ksp 040 in the southern Wasatch Plateau (e.g., an attenuated, “sharp-based” shoreface succession sensu Plint 1988), although such evidence may well be below the resolution of our stratigraphic analysis to date.

High, localized sediment supply to the Panther Tongue may reflect the presence of a long-lived, structurally controlled sediment entry point near the northwestern limit of the study area (Edwards et al. 2005). This sediment entry point may coincide with a structural recess between the Paxton thrust and Charleston–Nebo thrust system (Fig. 14), both of which were active during the Campanian (Horton et al. 2004; DeCelles and Coogan 2006). During Panther Tongue deposition, sediment flux through this entry point was elevated relative to periods represented by underlying and overlying parasequences (Edwards et al. 2005). Higher tectonic subsidence in the northern Wasatch Plateau likely reflects greater flexural subsidence here, due to loading by stacked thrust sheets in the nearby Sautaquin and Wasatch culminations (Fig. 14) (Johnson 2003; Horton et al. 2004). The relative sea-level fall recorded by the internal stratigraphic architecture of the Panther Tongue, and the relative sea-level rises recorded by parasequence-bounding flooding surfaces suggest the operation of a low-amplitude (< 30 m), high-frequency (< 400 kyr) allocyclic control on relative sea level, most likely glacio-eustasy under greenhouse conditions (cf. Miller et al. 2003).

Two further aspects of the Panther Tongue delta system (Fig. 11B) are noteworthy. Firstly, the delta system prograded southward, subparallel to regional depositional strike. Similar river-dominated delta-front deposits in other parasequences in the Star Point Sandstone and the Blackhawk Formation have an orientation subparallel to the regional shoreline trend (Fig. 11D. Kamola and Van Wagoner 1995; Hampson and Storms 2003; Charvin et al. 2010), which is attributed to southward deflection of the delta by wave-driven longshore currents (cf. Bhattacharya and Giosan 2003). Secondly, the Panther Tongue delta system is much larger (> 800 km² in area) than other river-dominated delta-front deposits in the Star Point Sandstone and Blackhawk Formation (e.g., river-
dominated delta-front deposits in parasequence Ksp 020 are c. 30 km² in area; Fig. 11D). The Panther Tongue may therefore represent the downdrift flank of an asymmetric wave-dominated delta, as proposed for much smaller deposits of similar facies character in the Blackhawk Formation (Hampson and Howell 2005; Charvin et al. 2010), although neither wave-dominated spit deposits nor a wave ravinement surface have been documented from the eastern margin of the Panther Tongue delta system as implied by this interpretation. Alternatively, the Panther Tongue delta system may have built out into a sheltered embayment bounded on its eastern margin by seafloor topography above an actively growing structure (e.g., San Rafael Swell thrust; Fig. 14). This interpretation is difficult to reconcile with the occurrence of wave-dominated shorelines, implying an open, non-sheltered setting, in underlying and overlying parasequences. Further work is required to satisfactorily address these aspects of the Panther Tongue delta system, including characterization of its lateral pinchouts, and of regional thickness trends in the unit that contains it (parasequence Ksp 040).

CONCLUSIONS

The upper Santonian to lower Campanian Star Point Sandstone is exposed in a large (c. 100 km), nearly continuous section aligned oblique to depositional strike along the eastern edge of the Wasatch Plateau in central Utah. The unit is diachronous, and becomes younger from south to north. The upper part of the Star Point Sandstone in the northern Wasatch Plateau is coeval and contiguous with the lower part of the
Spring Canyon Member of the Blackhawk Formation in the depositional-dip-oriented Book Cliffs. Outcrop mapping of the Star Point Sandstone using low-angle aerial photographs and measured sections reveals that the unit comprises five parasequences (labeled Ksp 050, Ksp 040, Ksp 030, Ksp 020, and Ksp 010, from oldest to youngest). Each parasequence records 7 to 45 km of ESE- to ENE-directed progradation of a predominantly linear to moderately lobate, wave-dominated shoreline. Parasequence-bounding flooding surfaces record 3 to 19 km of shoreline retreat. Upper-shoreface deposits contain SSE-directed, shoreline-parallel paleocurrents that record sediment transport by wave-driven longshore currents. Lower-shoreface deposits extend paleoeward of these upper-shoreface deposits to form broad (5–20 km) belts of hummocky cross-stratified sandstones that record strong offshore sediment transport by storms. Wave-dominated shoreline parasequences pinch out up dip over short distances (<500 m) as landward-tapering sandstone wedges. Lower-shoreface deposits in each parasequence split down dip into multiple, vertically stacked, upward-coarsening beds separated by tongues of offshore shelf in distal locations associated with rapid deepening of antecedent paleobathymetry. Strongly lobate river-dominated delta-front deposits occur locally within two parasequences. In the younger example (parasequence Ksp 020), such deposits define a minor (c. 30 km² in area) progradation into a spit-bounded embayment that is aligned subparallel to the regional shoreline trend; these deposits are interpreted to represent an asymmetric wave-dominated delta. In the older example (parasequence Ksp 040; Panther Tongue), river-dominated delta-front deposits are much more areally extensive (>800 km²) although they also exhibit a progradation direction subparallel to the regional shoreline trend into a location sheltered from wave energy. The arrangement of parasequences in the Star Point Sandstone defines an overall concave-landward shoreline trajectory with decreasing progradation and increasing aggradation through time. Along-strike variations in this trajectory pattern reflect a combination of two controls. First, tectonic subsidence was greater towards the north. Second, a highly localized, large-volume, fluvial sediment supply was routed via a structurally controlled sediment entry point near the northwestern limit of the study area during deposition of the older, widespread river-dominated delta-front complex (parasequence Ksp 040; Panther Tongue).

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