High-frequency tectonic sequences in the Campanian Castlegate Formation during a transition from the Sevier to Laramide orogeny, Utah, U.S.A.

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ABSTRACT

Though stratigraphic correlations are abundant in the Cordilleran basin-fill, they rarely include along-strike transects providing a spatio-temporal sense of deformation, sediment-supply and subsidence. A new, high-resolution, regional strike-correlation of the Castlegate Formation reveals progressive northward-growth of the San Rafael Swell during two embryonic episodes of Laramide-style deformation in central Utah. The intrabasinal deformation-events produced gentle lithospheric-folding punctuated by erosional-truncation of upwarped regions. The earliest episode occurred at 78 Ma in the southern San Rafael Swell likely causing soft-sediment deformation and stratal-tilting. Following this the alluvial-plain was leveled and rapid, extensive-progradation took place.

A second episode, at 75 Ma, where deformation was focused in the northern San Rafael Swell, also caused sediment-liquefaction and erosional beveling. The stratal-tilting and sediment-liquefaction is attributed to seismicity induced by basal-traction between a subducting flat-slab and continental-lithosphere. The south-to north time-transgression of uplift is spatio-temporally consistent with NE-propagation of an oceanic-plateau subducted shallowly beneath the region.

Key Words: Castlegate Sandstone, San Rafael Swell, Wasatch Plateau, Laramide Orogeny, Sevier Orogeny, Cordilleran foreland basin
INTRODUCTION

Clues useful to understanding the timing and style of orogenesis can be found within a foreland basin-fill (Miall and Arush, 2001; Ettenson, 2004; Aschoff and Steel, 2011). Foreland stratigraphic architecture can provide insight about tectonic conditions as it reflects the balance of sediment supply and accommodation change, which can be driven by tectonism (Martinsen and Helland-Hansen, 1995). It is impractical, however, to make regional predictions on the basis of stratal stacking pattern alone (Martinsen and Helland-Hansen, 1995), as crustal upwarping and associated downwarping yield contrasting yet coeval stacking pattern (Krystinik and DeJarnett, 1995). Foreland basins form viscoelastically with often poorly defined shelf breaks in response to superposed isostatic and flexural subsidence patterns (Jordan, 1981; Martinsen and Helland-Hansen, 1995). With increasing subsidence and sediment supply towards the orogenic-load, foreland basins have a characteristic asymmetric cross-sectional profile skewed towards the orogen (Martinsen et al., 1993). Along-strike, foreland basin subsidence and sediment supply can also vary if there is tectonic-diachroneity along the length of an orogeny (Ettenson, 2004), localized intra-foreland uplift (Heller et al., 1993), or multiple sediment sources (Lawton and Bradford, 2011). Bounding surface, not stratal stacking pattern (e.g. systems tract), correlation is useful for resolving tectonic timing and style, which can be constrained temporally using tools such as biostratigraphy (Krystinik and DeJarnett, 1995).

Investigating orogenic style and timing is a possibility for the tectonically-sensitive nonmarine deposits in the North American Cordilleran foreland basin (Fig. 1). Particularly noteworthy are the unconformity-bounded, coarse-grained, anomalously progradational and extensive sheet-like deposits (Figs. 2 and 3) of the Upper Cretaceous (Campanian) Castlegate Sandstone in Utah (Krystinik and DeJarnett, 1995; Aschoff and Steel, 2011). It is well-known
that coarse-grained detritus is delivered to foreland basins in pulses but the timing and mechanism of which are highly contested. Early research (Spieker, 1946) attributed the extensive and rapid Castlegate Sandstone progradation to reflect synchronous loading and erosion in the Sevier fold-and-thrust belt. Subsequent basin-fill architecture models (Heller et al., 1988; Blair and Bilodeau, 1988; Flemings and Jordan, 1990) suggested that coarse-grained sediment-pulses to foreland basins
rather reflect post-tectonic isostatic adjustments such that coarse-grained detritus becomes trapped proximally where subsidence is exceptionally high as thrust sheets are stacking. However, in a 2-D seismic line transecting the Sevier fold-and-thrust belt and proximal Cordilleran foreland basin, Horton et al. (2004) revealed rapid, lengthy Castlegate Sandstone progradation coeval with movement along the Charleston-Nebo thrust and triangle zone (Fig. 2A). Therefore, somehow Cordilleran foreland basin subsidence was reduced enabling Castlegate Sandstone progradation despite active loading in the adjacent Sevier belt.

With the knowledge that thrust-loading increases accommodation and inhibits progradation, there must have been additional but accommodation-reducing forces responsible for the sheet-like distribution and anomalous progradation of the Castlegate Sandstone. Van Wagoner (1995) favored a falling eustatic sea-level hypothesis, which is unlikely because the Late Cretaceous had greenhouse conditions associated with low-amplitude sea-level fluctuations that would have been overprinted by autogenic or tectonic processes (Vakarelov et al., 2006).

Many Cretaceous strata, and Sevier thrust-fault systems in Utah, CN—Charleston-Nebo thrust; CR—Canyon Range thrust; GU—Gunnison thrust; PV—Pavant thrust; PX—Paxton thrust; TZ—triangle zone. The map was modified from DeCelles and Coogan (2006) and Lawton and Bradford (2011). B. Shaded-relief map of the study area showing locations of measured sections and line of correlated sections of Figure 4.
(Lawton, 1986; Van Wagoner, 1995; Miall and Arush, 2001; Aschoff and Steel, 2011) have hinted at the possibility of incipient Laramide deformation driving the accommodation-reduction based on architecture, provenance, and paleocurrent deflection but critical evidence supporting this hypothesis in the form of stratigraphic surfaces with tilting is missing.

The aim of this study is to address two key questions regarding Cordilleran foreland basin stratigraphy: (1) how is deformation style and timing manifested in sequence stratigraphic surfaces and, (2) what caused the transition from Sevier-to Laramide-style deformation? Answering these questions necessitates a high-resolution regional correlation and sequence stratigraphic analysis of the basin-fill, and a spatio-temporal kinematic understanding of the Cordilleran orogenic system. A new, regional (70-km-long), proximal, and basin-parallel (NE-SW oriented) correlation is presented here in the eastern Wasatch Plateau and northwestern Book Cliffs. The correlation is age-constrained with published radiometrically-dated ammonite biostratigraphy.

**Regional Geology**

Upper Cretaceous sedimentary units in the Book Cliffs and Wasatch Plateau were deposited on the western margin of the Cretaceous Western Interior Seaway during Campanian (Fig. 1A) (Spieker, 1949). As evidenced by flora and fauna fossils, central and eastern Utah was humid and sub-tropical during Campanian (Kauffman, 1977). The climate and tectonic conditions yielded an exceptionally-high sediment supply (Aschoff and Steel, 2011). Late Cretaceous experienced a greenhouse climate, and in western North America majority of the region’s annual precipitation likely occurred mid-year from west verging monsoons (Fricke et al., 2010). Sediments were mostly sourced from the Sevier fold-and-thrust belt of the Cordilleran orogenic system and transported in a general eastward (basin-transverse) direction, filling the
north-south elongate retroarc Cordilleran foreland basin (Fig. 1B) (Kauffman, 1977).
Episodically, Jurassic magmatic arc terranes from the Cordilleran retroarc hinterland (Fig. 1B) farther to the west and southwest constituted the sediment supply (Lawton and Bradford, 2011; Hampson, 2014).

**The Cordilleran orogenic system**

An orogenic front-perpendicular transect of the Cordilleran orogenic system (e.g. California to Utah) contains a forearc accretionary complex and basin, magmatic arc, retroarc hinterland, fold-thrust belt, foreland basin, and Laramide foreland belt (Fig. 1B). The orogeny evolved time-transgressively from west to east through protracted Middle Mesozoic to Early Cenozoic paleo-Pacific plate collision with and subduction beneath the North American continent (Yonkee and Weil, 2015).

The Cordilleran fold-thrust belt (Fig. 1B) formed during the Cretaceous Sevier orogeny. Sevier thin-skinned deformation was caused by eastward high-angle (~30°) subduction of the Farallon plate beneath the western margin of North America’s Cordilleran magmatic arc (DeCelles and Coogan, 2006; Yonkee and Weil, 2015). The fold-thrust belt translated the Paleozoic and Lower to Middle Mesozoic sedimentary cover eastward along basal décollement surfaces (Yonkee and Weil, 2015). Western Sevier thrusts slipped above Neoproterozoic (~720-660 Ma) syn-rift micaceous strata, whereas eastern thrusts translated across middle Cambrian shale and limestone (DeCelles and Coogan, 2006; Yonkee and Weil, 2015). The eastward-migration of the orogenic front stalled with a critical tapering of thrust sheets in central Utah at the Wasatch Hinge (Figs. 1B and 2A) (DeCelles and Coogan, 2006; Yonkee and Weil, 2015). Shortening in triangle zones formed backthrusts, duplexes, and thrust-tip anticlines at the orogenic front (DeCelles et al., 1995). By Late Cretaceous, the Sevier structural front was in
central Utah (Fig. 2A), ~ 700 km from the Farallon trench (DeCelles and Coogan, 2006; Fig. 1B). Middle Jurassic carbonates and evaporites formed detachments in eastern Sevier thrusts (DeCelles and Coogan, 2006; Yonkee and Weil, 2015). In Utah, there were four major detached thrust fault systems (Fig. 2A), the Canyon Range, Pavant, Paxton and Gunnison thrusts, which collectively contributed to ~220 km of crustal shortening (DeCelles and Coogan, 2006).

The early to middle Cretaceous Canyon Range thrust system was the first of the four to develop. Activity of the Canyon Range thrust was ensued by shortening of the Pavant thrust system (DeCelles and Coogan, 2006). These two thrusts accommodated most of the shortening in the Sevier belt as they had the deepest detachment levels (Constenius, 1988). Motion in the Charleston-Nebo thrust and triangle zone, which exposed Pennsylvanian Oquirrh Group quartzite and supplied a large portion of sediments deposited as the Castlegate Sandstone, ceased sometime during Campanian (Constenius, 1998; Horton et al., 2004). Eastward translation of the Charleston-Nebo thrust stalled in a triangle zone at the Sevier front promoting crustal contraction and generation of the Santaquin Culmination consisting of fault-bend-folds and east-dipping backthrusts (Constenius, 1998). The Paxton thrust is the least described of the four major thrust systems because it is not exposed at the surface such that known information regarding the kinematic evolution and unroofing history stems entirely from subsurface data, which are mostly proprietary (DeCelles and Coogan, 2006). The Paxton thrust likely activated during Santonian and began shortening during Campanian (DeCelles and Coogan, 2006). These duplexes were eroded, shedding mostly fine-grained detritus from Jurassic terrane (DeCelles and Coogan, 2006). The Gunnison thrust, the latest of the four, was significantly buried by sediments in the wedge-top depozone and was predominantly a Maastrichtian event (DeCelles and Coogan, 2006). Sediments entered the Cordilleran foreland basin likely within fluvial entry points.
adjacent to growth structures, such as between the Charleston-Nebo and Paxton thrusts (Hampson et al., 2012).

The Cordilleran foreland basin formed coeval to and principally because of loading in the Sevier thrust belt (DeCelles and Coogan, 2006). Foreland basins migrate orogen-perpendicularly and are lithospheric depressions formed cratonward of fold-thrust belts (Jordan, 1981; Ettensohn, 2004). Models attempting to recreate the process of foreland basin formation were unsuccessful until they assumed a lithosphere having viscoelastic instead of elastic rheology (Beaumont, 1981; Jordan, 1981). From proximal to distal, foreland basins have four major components—wedge-top, foredeep, forebulge and backbulge (Jordan, 1981). The migration and loading of a thrust-wedge cause cratonward lithospheric downbending creating a proximal foredeep, and basinward upwarping creating a distal forebulge (Jordan, 1981). Foreland basin-fills in cross-section therefore appear asymmetric, with thicker sedimentary accumulations towards the orogenic load.

The Cordilleran Laramide foreland belt (Fig. 1B) formed during the Late Cretaceous to Eocene Laramide orogeny, which partitioned the foreland basin into smaller sub-basins by localized basement-involved uplifts (Cross, 1986). The uplifts occurred along reverse faults with deeper detachment levels than in the Sevier fold-thrust belt. The Laramide orogeny is hypothesized to record a transition to shallower and more-rapid Farallon plate subduction than during the Sevier Orogeny (Coney and Reynolds, 1977; Cross, 1986; Liu et al., 2010; Painter and Carrapa, 2013; Yonkee and Weil, 2015). The transition at ca. 81 Ma is also coincident with a major shutdown of arc magmatism (DeCelles, 2015; Yonkee and Weil, 2015). The decreased subduction angle has been attributed to increased buoyancy of the subducting slab (Liu et al., 2010; Painter and Carrapa, 2013). This portion of the Farallon plate is often referred to as the
Shatsky Rise (Liu et al., 2010), which was likely an aseismic ridge like the Juan Fernandez Rise of the South American Plate that triggered basement-cored uplifts of the Sierra Pampeanas far inboard of the Andean subduction zone (Jordan and Allmendinger, 1986; Aschoff and Steel, 2011). Laramide deformation occurred with an early and late phase that varied in style (Cross, 1986), as much as ~700 km cratonward of the Franciscan subduction zone. During the early pre-Paleocene phase, deformation was relatively widespread, defined by gentle folding and flexure (Cross, 1986; Marshak et al., 2000). This embryonic phase of deformation began during Campanian, arguably coeval to deposition of the Castlegate Formation (Van Wagoner, 1995; Miall and Arush, 2001; Aschoff and Steel, 2011). During the late phase subsequent to the Early Paleocene and to an apparent ~5 m.y. pause in deformation, structures that developed were more localized and brittle, characterized by large-offset fault-bounded uplifts commonly in extant weakness zones (Cross, 1986).

**Campanian stratigraphy of central and eastern Utah**

Strata have pristine and nearly continuous exposures in the Book Cliffs and eastern Wasatch Plateau but are difficult to access as sandstones form prominent cliffs between steep scree-covered slopes. Spieker (1949) noted, “…the rocks are easy to see but hard to reach”. These rocks are the regressive Mesaverde Group, which, from central to eastern Utah, form a series of basinward-tapering clastic wedges (Fig. 3; Seymour and Fielding, 2013). These strata are renowned for their apparent interfingering relationships and the ease at which they can be correlated down depositional-dip in the Book Cliffs and along depositional-strike in the Wasatch Plateau (Spieker, 1949). At Price Canyon in the northwestern-most Book Cliffs near the town of Helper (Fig. 2B), the Mesaverde Group consists of the intercalated offshore-marine Mancos Shale and shallow-marine Star Point Sandstone which transition upwards to the coastal-plain,
coal-bearing and fluvial Blackhawk Formation, which is capped by the primarily fluvial Castlegate Formation (Fig. 3).

At the type-section in Price Canyon, the middle to upper Campanian Castlegate Formation is divided into three members on the basis of weathering profile (Olsen et al., 1995). The lowest member is the middle Campanian, cliff-forming Lower Castlegate Sandstone, which is characterized by ~60-80 m of amalgamated fine-to-medium grained sandstone, interpreted as braided fluvial deposits (Fig. 3). The overlying unit is ledge-forming, middle to upper Campanian, and known as the Middle Castlegate Sandstone. The ledges form at mudstone-encased fine-grained sandbodies (i.e. lenticular) interpreted as meandering and tidally-influenced fluvial, and bayhead delta deposits (Fig. 3). The upper unit which is cliff-forming, upper

Figure 3. Biostratigraphically-constrained chronologic and spatial stratigraphic diagram showing variation of the Campanian Mesaverde Group from the eastern Wasatch Plateau, to the western and central Book Cliffs. The diagram incorporates data from Miall and Arush (2001), Aschoff and Steel (2011), Seymour and Fielding (2013), and this study. A—Aberdeen Member; AMT—Anchor Mine Tongue; BT—Buck Tongue; D—Desert Member; G—Grassy Member; K—Kenilworth Member; S—Sunnyside Member; SC—Spring Canyon Member.
Campanian and referred to as the Bluecastle Tongue, consists of ~20 m of amalgamated medium-grained sandstone locally with pebble conglomerate interpreted as braided fluvial deposits (Fig. 3).

Along-strike, to the southwest, at Joe’s Valley the Castlegate Formation lacks the alternated cliff and slope weathering profile of the type-section, and is entirely cliff-forming. The Joe’s Valley section is also coarser grained and thinner (Fig. 3). Paleo-landward, to the west from the type-section, sandstones interfinger with conglomerates, where boulder-sized clasts locally exist in a thick coeval-succession of piedmont-type deposits at the Cedar Hills and Gunnison Plateau (Spieker, 1949). Paleo-seaward, to the east of the type-section near the Green River in the Book Cliffs, the Lower Castlegate Sandstone is finer-grained, reduced to ~20 m, and is capped by the paleolandward-tapering, offshore-marine Buck Tongue Member of the Mancos Shale (Fig. 3; Aschoff and Steel, 2011). The estuarine to shallow-marine Sego Sandstone truncates the Buck Tongue and is conformable to the overlying coal-bearing Neslen Formation (Fig. 3; Miall and Arush, 2001). The Neslen Formation intercalates basinward with the marine Anchor Mine Tongue (Fig. 3) and is likely age-equivalent to the up-dip Middle Castlegate Sandstone (Yoshida et al., 1996; Miall and Arush, 2001; Aschoff and Steel, 2011). The Bluecastle Tongue also caps the succession in these more basinward locations (Fig. 3) but is finer-grained (Aschoff and Steel, 2011).

The Mesaverde Group is progressively, east to west tilted (Spieker, 1949) because of deformation in the Sevier thrust belt (Horton et al., 2004). In the Wasatch Plateau, the Star Point Sandstone, and Blackhawk and Castlegate Formations in combination form two and arguably three 3rd-order, ~3-5 m.y. sequences (Miall and Arush, 2001; Seymour and Fielding, 2013). The lowest Mesaverde Group sequence extends from the forced-regressive Panther Tongue (of the
Star Point Sandstone) up to the base of the Lower Castlegate Sandstone (Seymour and Fielding, 2013). The overlying Mesaverde Group strata may actually represent two distinct 3rd-order sequences (Miall and Arush, 2001), but were originally defined (by Olsen et al., 1995) as a single sequence from the base of the Lower Castlegate Sandstone to the base of the Bluecastle Tongue. Farther basinward in the Book Cliffs, these 3rd-order sequences split into numerous (10-15) higher frequency sequences (Seymour and Fielding, 2013).

In the Wasatch Plateau, most of the Star Point Sandstone and all of the Blackhawk Formation has been interpreted to represent the highstand systems tract (HST) of the lowest 3rd-order Mesaverde Group sequence (Seymour and Fielding, 2013). Within this HST, nested higher-frequency sequences likely occur (Gani et al., 2015). Widespread sheet-like foreland basin deposits like the Lower Castlegate Sandstone have basal, sequence-bounding unconformities (Schwans, 1995). This basal Castlegate unconformity marks the base of the second 3rd-order sequence. This surface is angular close to the Sevier thrust belt, and forms a “smooth” denudational erosion surface near the Price Canyon type-section and narrow paleo-valleys further basinward near the Green River (Spieker, 1949). Farther down-dip, east of the Green River, the surface is likely a correlative conformity (Spieker, 1949; and Bhattacharya and Holbrook, 2011).

The base of the Sego Sandstone is likely correlative up-dip to surface “D” defined by Miall and Arush (2001) at the Castlegate type-section. They postulate that their “D” surface is a ‘cryptic’ sequence boundary forming the base of the potential third, uppermost (3rd-order) Mesaverde Group sequence, with the uppermost sequence boundary as the base of the Bluecastle Tongue. Miall and Arush (2001) identify surface “D” as a cryptic sequence boundary based on sandstone petrography, diagenesis and paleocurrent data because regional erosion surfaces are
commonly obfuscated by the immensity of localized channel erosions. Below surface “D”, Miall and Arush (2001) identified evidence for early diagenesis and a relative abundance of lithic and feldspar grains. They found sandstones above surface “D” to contain higher modal-percentages of quartz and porosities (i.e. less cement), indicating minimal early diagenesis (i.e. prolonged subaerial exposure) and possibly source area (thrust) rejuvenation of the quartzitic Oquirrh Group source.

**Methods**

In order to address the questions of the representation of transitioning deformation style in stratigraphic surfaces, we developed a dataset that includes: (1) a 70-km-long transect (Fig. 2B) that correlates the Castlegate Formation along-strike from Joe’s Valley in the central Wasatch Plateau to the Price Canyon area in the northwestern-most Book Cliffs, tied to (2) a rendering of Aschoff and Steel’s (2011) approximately 400-km-long along-dip transect correlating the Castlegate Formation from source-to-sink, perpendicular to the Wasatch Plateau and through the Book Cliffs, (3) sediment-dispersal patterns obtained from 257 paleocurrent measurements of dune trough cross-stratifications, (4) a QFL (quartz, feldspar, and lithics) diagram for samples collected in the central Wasatch Plateau and its comparison to type-area samples collected by Miall and Arush (2001), (5) thin-section photomicrographs, (6) and high-resolution outcrop photo-mosaics. The new data were obtained from 14 Castlegate Formation measured sections (Fig. 2B). Sections were analyzed for grain-sizes, sedimentary structures, ichnology, facies, channel and facies architecture, and the nature of bounding discontinuities. Seven of the 14 sections had covered portions or were incomplete (eroded at the top). Some sections have vertical-cliff faces that were measured on rope. Others were traversed via physical climbing without rope through scree-covered slopes. With the exception of the type-area and
Joe’s Valley, each section measured contains ‘frontier’ data on the Castlegate Formation as accessing outcrops required daring and strenuous efforts. 138 hand samples were collected, and 18 were examined by petrographic microscope. Thin-sections were analyzed for QFL ratios, nature of grain contacts, and types and percentages of cement.

The correlation of measured sections forms a two-dimensional cross-section parallel to depositional-strike (the Wasatch Plateau) that has been tied to Aschoff and Steel’s (2011) depositional-dip correlation. The tying of strike and dip transects provides a regional three-dimensional perspective of the studied successions. Detailed interpretations (e.g. surface-tracing) of high-resolution photomosaics, hand sample (including thin-section) analysis and comparison, and field mapping aided key surface correlation between sections. Uncertainty is common to nonmarine bounding-surface correlation. To counter this uncertainty, marine flooding surfaces or condensed sections of the Western Interior Seaway in which high-resolution ammonite biozones were established (Cobban et al., 2006), have been correlated up-dip to the type-section by Aschoff and Steel (2011) and to the Wasatch Plateau herein. Notably, the ammonite zones have ~200 k.y. of time-constraint (Cobban et al., 2006). Marine flooding surfaces in predominantly nonmarine successions are manifested by tidally-influenced facies. Sequence boundaries were correlated based on mineralogy, diagenesis, paleocurrent patterns, and prominent erosional surfaces, as demonstrated by Miall and Arush (2001). This method assumes that sandstones above similarly-aged (more or less) erosion surfaces will have similar mineralogical compositions and sediment dispersal patterns, and that strata below a sequence boundary can show evidence for early diagenesis.
RESULTS

Facies

At the type-locality, McLaurin and Steel (2007) characterized three Castlegate Formation depositional environments. In order of decreasing prevalence, they identify thalweg-fill, barform, and floodplain deposits. Thalweg-fill facies occupied the basal portion of a channelized succession, and were thus least susceptible to post-depositional erosion (McLaurin and Steel, 2007). Most barforms were classified as downstream accreting with rare lateral and upstream accretion. Floodplain deposits, which are least preserved are present up-section.

Of the nine facies established in this study, six are deemed in some cases, sequence stratigraphically significant. They are bioturbated sandstone (1), intraformational lag (2), extraformational lag (3), sandstone with soft-sediment deformation (4), sandstone with rhythmic mudstone (5), and mudstone with lenticular sandstone (6). The bioturbated sandstone facies represents floodplain deposits subject to considerable primary diagenesis as evidenced by ichnology and concretion. The prevalence of *Teredolites longissimus* and *clavatus* ichnofossils in this facies indicate brackish-water deposition, particularly during marine transgression (Shanley and McCabe, 1992). Also present are siderite nodules, indicative of burial and humid, oxygen-reducing environment. The intraformational and extraformational lag facies coincide with thalweg-fills but in some cases major erosional surfaces. These thalweg-fill, matrix-supported conglomerate facies suggest deposition from dense-inertia flows or “traction carpets” likely triggered during high-energy, flood-stages. Linking a depositional environment to the sandstone with soft-sediment deformation facies is difficult as preexistent sedimentary structures were destroyed. Beds or sandbodies with pervasive (km’s continuity) convolutions can indicate seismicity (Kundu et al., 2011; Balsamo et al., 2013). Both the sandstone with rhythmic
mudstone and mudstone with subordinate sandstone facies record tidal influence indicated by sedimentary structures and ichnology.

**Strike-variability of stratigraphy**

The datum for this new, ~70-km-long stratigraphic correlation along depositional-strike (Fig. 4) is a maximum flooding surface (TS4) correlative to the *Didymoceras nebrascense* ammonite biozone from the Anchor Mine Tongue condensed section. This surface was traced up-dip through the Book Cliffs to the type-section (Price Canyon) by Aschoff and Steel (2011) and herein was correlated in the Wasatch Plateau (Fig. 4). Surface TS4 at the type-section is capped by the mudstone with lenticular sandstone facies, and by a sandstone with rhythmic mudstone facies near Joe’s Valley. Transgressive surfaces in the proximal setting are linked to the fine-grained heterolithic deposits (associated with tidal-influence), which have southwestward-tapering thicknesses (Fig. 4). In fluvial-dominated successions, transgressive and flooding surfaces are commonly underlain by ellipsoidal diagenetic concretions or thin calcareous-cemented horizons (Taylor et al., 2000; Al-Ramadan et al., 2013).

The correlation reveals significant spatio-temporal facies and architectural variability induced by protracted tectonism within the Cordilleran foreland. There is an abrupt southward increase in sandbody amalgamation and grain sizes along-strike from the type-section onto an interpreted structural paleo-high that began forming during early Castlegate Sandstone deposition in the Wasatch Plateau (Fig. 4). Mudstone-rich intervals at the type-locality are the age-equivalents of sandstone-dominated intervals along-strike (Fig. 4). As the Castlegate Formation becomes increasingly amalgamated, it also thins (Fig. 4). The Lower Castlegate Sandstone between the basal sequence boundary (CGSB) and Miall and Arush’s (2001) surface “D”, which is ~20 m-thick at the type section, is as thin as 5 m on the paleo-high (Fig. 4).
Figure 4. An approximately 70-km-long, along-strike stratigraphic transect of middle Campanian in the eastern Wasatch Plateau and northwestern Book Cliffs of Utah. Note distinct southwestward thinning, coarsening and amalgamation of strata towards an uplifted structure. Refer to Fig. 2B for location abbreviations and location of cross-section. CGSB—Castlegate sequence boundary; “D”—Miall and Arush’s (2001) surface D (up-dip equivalent to base of Sego Sandstone); “E”—Miall and Arush’s surface E; TS—transgressive surface; AU—angular unconformity; MCGU—Middle Castlegate unconformity.
Extraformational lag deposits approximately age-equivalent to strata resting on Miall’s surface “E” are prevalent on this paleo-high, and taper northeastward along-strike into a topographic paleo-depression flanking the paleo-high (Fig. 4). The Lower Castlegate Sandstone is progressively northeast-tilted away from the paleo-high that formed its margin between Wattis Road and Price Canyon, beneath a subtle, low-angle angular unconformity (surface AU1) (Fig. 4). The structural-tilt abruptly steepens southwestward between Wilberg Mine and Joe’s Valley, as the Middle Castlegate Sandstone’s ledge-forming weathering profile disappears (Fig. 4). Near Joe’s Valley, the lowest three Castlegate Formation transgressive surfaces (TS1, TS2, and TS3) are truncated by surface AU1 (Fig. 4).

In the northwestern Book Cliffs, strata are northeast-tilted below angular unconformity 2 (AU2), away from the younger of the two identified structural paleo-highs (Fig. 4). Surface AU2, which forms the base of the Bluecastle Tongue, truncates strata resting on a Middle Castlegate Sandstone unconformity (MCGU) (Fig. 4). In places such as at the type-section, strata between surfaces AU2 and MCGU are completely absent (Fig. 4). Below surfaces AU1 and AU2, strata commonly display Liesegang banding and laterally-extensive soft sediment deformation (Fig. 4).

**Paleocurrent analysis**

Measurements \((n = 111)\) of fluvial paleocurrent direction gathered from dune trough cross-stratifications were analyzed temporally between significant bounding surfaces and spatially between the northwestern Book Cliffs and the Wasatch Plateau (Fig. 5).

In the northwestern Book Cliffs, Castlegate Formation fluvial paleocurrent directions gradually shift anticlockwise from SE \((131^\circ)\) near the base to NE \((53^\circ)\) in the Bluecastle Tongue, maintaining an overall basinward-dispersal pattern (Fig. 5). In the Wasatch Plateau, there are two
distinct temporal perturbations in Castlegate Formation fluvial paleocurrent direction (Fig. 5). Below the lowermost perturbation, within the basal 5-20 m of the Lower Castlegate Sandstone, fluvial transport is basinward (SE) as is age-equivalent northwestern Book Cliff strata. The perturbations are abrupt, 136-171° shifts in fluvial transport direction (Fig. 5). The older of the two is defined across surface “E” above the basal 5-20 m of the Lower Castlegate Sandstone,

Figure 5. Rose diagram analysis of paleocurrent measurements. Notice how drainage patterns were basinward prior to 78 Ma. Around 78 Ma, fluvial systems developed an axial trend and seemingly converged in the northern Wasatch Plateau. Subsequent to 78 Ma, drainage direction gradually shifted clockwise in the Wasatch Plateau and anticlockwise in the northwestern Book Cliffs. Ensuing the development of surface AU2, drainages became axial again but fluvial systems between the Wasatch Plateau and northwestern Book Cliffs were divergent to each other.
where an anticlockwise (SE to NW), 136° shift from basinward to basin-axial fluvial transport direction is observed (Fig. 5). Between surface “E” and the base of the Bluecastle Tongue, fluvial paleocurrent direction in the Wasatch Plateau gradually rotates clockwise (from NW to NE) and basinward by ~40° (Fig. 5). Across the Bluecastle sequence boundary, the younger of the two perturbations is expressed as an abrupt, 171° clockwise (NE to SW) change in fluvial transport direction to a basin-axial pattern (Fig. 5).

**Sandstone petrography**

Thin sections ($n = 18$) are from samples gathered at the Wattis Road, Trail Canyon Road, Joe’s Valley, Price Canyon, and Straight Canyon measured section localities (Fig. 2B and 6). QFL estimates from these samples were compared with those gathered from the type-area (Fig. 6) by Miall and Arush (2001). Photomicrographs ($n = 4$) of samples at Joe’s Valley and the type-area were compared (Fig. 7).

Figure 6. Quartz-feldspar-lithics (QFL) diagram of middle to late Campanian Sandstones of this study in the Wasatch Plateau, and compiled by Miall and Arush (2001) in the northwestern Book Cliffs (B). The provenance divisions in the ternary diagrams are taken from Lawton et al. (2014).
Sandstone mineralogy and provenance

Based on analysis of sandstone mineralogy, Miall and Arush (2001) hypothesized that the Castlegate Formation contains three, ‘shingled’ tectonic sequences with the bases of the Lower Castlegate Sandstone, Sego Sandstone, and Bluecastle Tongue forming the boundaries. They discovered a mineralogical similarity between the Joe’s Valley section and the Bluecastle Tongue at Price Canyon. They therefore suggest that the amalgamated sandstones resting on the Blackhawk Formation at Joe’s Valley are younger than and not age-equivalent to those at the type-section. Compare Fig. 7A to Fig. 7C to more thoroughly understand their reasoning.

Figure 7. Thin section photomicrographs of comparing samples from Joe’s Valley and the type-area, at the base of the Castlegate Formation (B and D) and the base of the Bluecastle Tongue (A and C). Notice the coarser grains and relative abundance of lithics and feldspars in the Joe’s Valley samples.
The proximal 2-D seismic dip-transect of Horton et al. (2004) reveals that the Castlegate Sandstone at the type-section was unroofed from Pennsylvanian Oquirrh Group quartzite in the Santaquin culmination. Miall and Arush’s (2001) type-area samples are also quartz-rich sandstones (Fig. 6), suggesting this quartzitic orogenic-source. Samples presented here from the Wasatch Plateau still contain mostly quartz but cluster separately from the type-section sample suite, and contain higher percentages of carbonate, lithic, and feldspars grains (Fig. 6). Quartz grains in the Wasatch Plateau are typically coarser and more rounded than those at the type-section (Fig. 7). The main source areas in the Wasatch Plateau are likely the Canyon Range and Pavant thrust systems. The prevalence of carbonate grains strongly suggests that the Wasatch Plateau between 75-80 Ma was fed sediments from the Canyon Range and Pavant thrust systems, which were the only of the Sevier thrusts in Utah to expose limestones (DeCelles and Coogan, 2006). Some of the feldspars appear to be of Cordilleran hinterland, arc-terrane origin, as evidenced by QFL-plotting (Fig. 6) and mineralogical properties. For example, some feldspar gravels at the Wattis Road location display exsolutional lamellae and still have well-defined cleavages. The presence of mineral-cleavage in fluvially-transported grains strongly might suggest they are not orogenically-recycled.

**Sandstone diagenesis**

Sandstone samples contain variable modal-percentages and types of cement. The cements are mostly interparticle with calcareous, ferrous and siliceous compositions. Samples contain as much as ~28% cement. Macroscopically, carbonate-cementation was documented occurring in localized, as much as 4-m thick concretionary-bodies or in thinner more laterally-extensive horizons. Both features likely reflect early meteoric diagenesis (Taylor et al., 2000). The localized concretionary diagenetic features are truncated by sequence boundaries and thus likely
indicate diagenesis during subaerial exposure (Taylor et al., 2000). The thin laterally-extensive horizons exist below surfaces that correlate to marine flooding events farther in the basin, likely suggesting diagenesis when there was a high water-table, and low-sediment supply (Taylor et al., 2000).
DISCUSSION

Manifestation of deformation-style in stratigraphic surfaces

In the Cordilleran foreland basin, several studies (Cross, 1986; Pang and Nummedal, 1995; Aschoff and Steel, 2011; Liu et al., 2011) linked subsidence and uplift patterns to spatio-temporal variability of: (1) supralithospheric flexural loading by thrust sheets, (2) sublithospheric dynamic loading by a shallowly-subducted Farallon plate, and/or (3) differential sediment loading. Using the technique of along-strike stratigraphic correlation, two distinct intra-foreland basin uplifts were documented here. The earliest of the two events is
apparent towards the southwest in the Wasatch Plateau as the Lower Castlegate Sandstone abruptly thinned, coarsened, and northeast-tilted onto a structural paleo-high at Joe’s Valley (Figs. 4 and 8). The later of the two deformation phases also caused strata to develop a northeast tectonic-tilt but below the Bluecastle Tongue (Figs. 4, 9 and 10) onto a paleo-high in the northwestern Book Cliffs. Each phase was ensued by erosional beveling and development of a low-angle angular unconformity, beneath which as much as 30-m of strata were removed.

In the Alberta foreland basin, flexure-induced erosional beveling has been interpreted to reflect the location and transgressive truncation of the forebulge (Plint et al., 1993). Van Wagoner (1995) hypothesized that the forebulge coeval to the Castlegate Sandstone is overlain by oolitic ironstones near the Utah-Colorado border. The erosional beveling documented in this
study is ~60 km from the Sevier thrust front, whereas the interpreted forebulge locations of Van Wagoner (1995) and Plint et al. (1993) are several hundred kilometers basinward from the source area and in a marine-setting. As evidenced by down depositional-dip middle Campanian facies changes, the observed beveling in this study is not related to truncation of the forebulge.

Another hypothesis to be considered is that the structural-tilts beneath surfaces AU1 and AU2 (Figs. 4, 8, 9 and 10) developed during and in response to Sevier deformation, implying a ‘growth strata’ origin. Bounded by progressive unconformities, growth strata develop
synchronously to growth folding, whereby erosion records thrusting and sedimentation reflects tectonic quiescence (Vergés et al., 2002). Growth strata typically develop only within a few kilometers of the deformation front (Aschoff, 2008). They inherit wedge shapes that progressively taper and tilt towards the thrust front (Aschoff, 2008). However, wedge-tapering and structural-tilts documented here progress in a basin-parallel direction. Another hypothesis that could explain intra-foreland uplift is post-thrusting crustal rebound (Heller et al., 1988; Flemings and Jordan, 1990; Ettensohn, 2004). This is unlikely however as Horton et al. (2004) showed that the deposition of the Castlegate Sandstone was coeval to Sevier thrusting.

The structural-tilts beneath surfaces AU1 and AU2 (Figs. 7 and 8) most likely formed during incipient episodes of Laramide deformation linked to sub-lithospheric loading by a shallowly-subducted flat slab (e.g. an aseismic ridge) in the Farallon plate (Yonkee and Weil, 2015). Deep-seated subsurface faults (e.g. blind thrusts) were probably (re)activated by stress transfer between the flat slab and the North American lithosphere. Aschoff and Steel (2011) calculated that the Middle Castlegate Sandstone and down-dip lithostratigraphic equivalents (Neslen Formation and Sego Sandstone) prograded at an anomalous rate and extent. They contributed this unusual long-transit, rapid progradation, hence reduced subsidence, to embryonic development of the Laramide San Rafael Swell basement-cored uplift. The evidence presented here suggests that incipient growth of the San Rafael Swell was episodic (not a gradual transition from Sevier to Laramide-style deformation as they describe), and that the initial phase occurred even earlier, during deposition of the Lower Castlegate Sandstone spanning the biozones *Baculites asperiformis* and *Baculites perplexus* (late), between ca. 79 and 77 Ma. The anomalous Middle Castlegate Sandstone progradation commenced with the development of
surface AU1, and was subsequent, not coeval, to a preliminary growth-episode of the San Rafael Swell.

**Manifestation of deformation-style in drainage patterns and provenance**

Basin-margin structures strongly dictate the volume and transport-destination of a sediment supply (Heller et al, 1993; Ettensohn, 2004). In addition to surfaces AU1 and AU2, evidence for middle to late Campanian growth of the San Rafael Swell is recorded in paleo-drainage patterns (Fig. 5). In the lowermost Castlegate Sandstone (between CGSB and AU1), fluvial channel networks were likely distributive with a fairly direct cratonward path. Up-section (between surfaces “D” and AU2), paleocurrents have orogen-parallel orientations, where fluvial systems flowed southward in the northwestern Book Cliffs and northward in the Wasatch Plateau. Thus, they seemingly converged into an area in the northernmost Wasatch Plateau. Farther up-section (between surfaces “D” and AU2), drainage patterns are characterized even more by channel confluence rather than bifurcation (Fig. 5) because accommodation space was increasingly confined between the fold-thrust belt and growing San Rafael Swell. Just below the Bluecastle Tongue (between MCGU and surface AU2), drainage patterns were again distributive and basinward, reflecting erosional-flattening of positive surface-topography generated by the early San Rafael Swell folding-episode. Within the Bluecastle Tongue (above surface AU2), transport directions are parallel (NE) or oblique (SW) to the fold-thrust belt and divergent around the San Rafael Swell, which underwent rejuvenated uplift around 75 Ma.

Evidence for middle to late Campanian Laramide-modification of the Cordilleran foreland also comes from spatio-temporally variable sedimentary provenance (Figs. 6 and 7). The Lower Castlegate Sandstone (from CGSB to surface TS1) in the northwestern Book Cliffs appears enriched with eroded Late Paleozoic quartzite (Oquirrh Group) from the Charleston-
Nebo thrust and triangle zone (Miall and Arush, 2001). Mineralogy and associated thrust-orthogonal (south-southeast) paleocurrent directions in the northwestern Book Cliffs confirm the source of these middle Campanian sandstones. The Castlegate Formation’s muddy middle member (between surfaces TS1 to MCGU), stems from a Jurassic clay-rich lithology unroofed from the Paxton thrust sheet, ~100 km south of the northwestern Book Cliffs. Grain mineralogy, textures and sizes coupled to coeval along-strike Wasatch Plateau paleocurrent-directions helped pinpoint this Paxton thrust source, located in south-central Utah. Though the mudstones in the muddy, middle member of the Castlegate Formation likely originated from the Paxton thrust, it is conceivable that the sandstones maintained an Oquirrh Group derivation in the northwestern Book Cliffs.

Quartz grains have a different origin, and feldspar and calcite grains are more abundant in the Wasatch Plateau compared to coeval deposits in the northwestern Book Cliffs. Related-paleocurrents are directed away from the Canyon Range, Pavant and Paxton thrust systems (Fig. 2) in south-central Utah. The coarse-grained material was derived mostly from the oldest and westernmost mechanically-rigid Canyon Range and Pavant thrusts (DeCelles and Coogan, 2006). Though the Canyon Range and Pavant thrusts had early Cretaceous and middle Cretaceous emplacements, respectively, they must have constituted the Campanian coarse-grained sediment supply as the Paxton and Gunnison thrusts exposed mainly fine-grained rocks and their frontal structures became buried by wedge-top Indianola conglomerate and sandstone (DeCelles et al., 1995; DeCelles and Coogan, 2006). Provenance data from Indianola wedge-top sediments indicate that most quartz-grains were derived from Neoproterozoic quartzite, which was only exposed at the Canyon Range thrust hanging wall (DeCelles and Coogan, 2006). Majority of calcite (or dolomite) grains were shed from the Canyon Range or Pavant thrusts as they exposed
thick Cambro-Ordovician successions of passive-margin carbonate rocks (DeCelles and Coogan, 2006).

Though clays shed from the Paxton thrust prior to its late Campanian burial likely passed through fluvial systems in the Wasatch Plateau, they were not significantly preserved there because of the presence of a paleo-high generated by preliminary uplift of the San Rafael Swell. Upon this early growth of San Rafael Swell, fluvial systems in the Wasatch Plateau were drained towards the northwestern Book Cliffs rather than in an immediate basinward direction. Of the sediments passing through middle to late Campanian axial, northeast-flowing fluvial systems in the Wasatch Plateau, conceivably only the fine-grained fraction reached downstream areas in the northwestern Book Cliffs.

Arkosic gravels were observed on surface “E” in the Wasatch Plateau, displaying exsolutional-lamellae and well-intact cleavage planes, which conceivably been destroyed during fold-thrust related metamorphism. They most likely originated west of the Sevier thrust belt in Jurassic back-arc plutons of eastern Nevada and western Utah (Fig. 1B). Their presence within the basin-fill is indicative of catchment-enlargement (Hampson et al., 2014), which was likely facilitated by a reduction of subsidence.

**Origin of orogeny**

With the waning of Sevier deformation and onset of Laramide deformation, around 81 Ma, the process of foreland accommodation creation or destruction shifted from flexural by supralithospheric loading to dynamical by sublithospheric loading (Figs 11 and 12; Painter and Carrapa, 2013). This cratonward and detachment-level shift in deformation was accompanied by a major shutdown of arc magmatism (Yonkee and Weil, 2015; DeCelles, 2015) and a reduction
of Farallon plate subduction angle (Figs. 11 and 12; Coney and Reynolds, 1977; Cross, 1986; Liu et al., 2010; Painter and Carrapa, 2013; Yonkee and Weil, 2015). Steep subduction promotes near-trench arc-magmatism, slab-dehydration, and the basalt-eclogite transition as the subducting oceanic crust is relatively dense. Reduction of oceanic plate density occurs at lesser distances.
inboard of the plate-boundary (Liu et al., 2010). With the reduction of subduction angle hence plate density, the basalt-eclogite transition is reached farther inboard of the subduction zone, allowing for surface topography to adjust dynamically well-within cratonal regions (Fig. 11; Liu et al., 2010; Painter and Carrapa, 2013; Yonkee and Weil, 2015).

The interacting effects between an oceanic flat slab and overriding continent on dynamic topography are heavily debated (Yonkee and Weil, 2015). It is broadly assumed that sublithospheric loading by a flat slab generates dynamic subsidence and widespread marine incursion (Cross and Pilger, 1978; Liu et al., 2011; Painter and Carrapa, 2013). Two hypotheses have emerged (Painter and Carrapa, 2013) for the creation of dynamic subsidence. The earlier one favors near-horizontal subduction whereby coupling of oceanic and continental plates
generate subsidence by replacement of the asthenosphere with colder, denser oceanic lithosphere (Cross and Pilger, 1978). The newer model favors shallow (less horizontal) subduction such that dynamic subsidence results from viscous flow within the asthenosphere above the plunging oceanic plate (Liu et al., 2010; Painter and Carrapa, 2013). Dávila and Lithgow-Bertelloni (2015) argue however that positive dynamic topography (uplift) develops above anomalously buoyant flat slabs (Fig. 11), and that negative dynamic topography (subsidence) develops at the slab’s leading-edge.

It is useful to draw clues from a modern analog where the effects of subduction zone plate-interactions on dynamic topography can be modeled inversely. The most widely accepted modern analog to Laramide-style deformation are the uplifts and piggyback basins inboard of the Andean subduction zone such as the Sierra Pampeanas in Argentina and Fitzcarrald Arch in Brazil (Dávila and Lithgow-Bertelloni, 2015). These uplifts partitioned cratonic regions along localized basement-bounded reverse faults beginning around 6 Ma. As evidenced by geophysical data, these South American intra-cratic uplifts are directly linked to flat-slab subduction of aseismic ridges embedded within the Nazca plate (Gutscher et al., 1999). Dávila and Lithgow-Bertelloni (2015) found that even though the subducted intra-plate ridges are relatively cold, they represent anomalously buoyant segments of lithosphere because of prior and substantial partial-melting, which made them less dense and drier than typical mid-ocean ridge basalt (MORB). The low water content and cold temperature of the flat slabs inhibit the basalt to eclogite transition, thus making them buoyant (Dávila and Lithgow-Bertelloni, 2015). The effects of flat-slab subduction on dynamic topography as explained by Dávila and Lithgow-Bertelloni (2015) can be applied to uplift of the San Rafael Swell. Dynamic uplift above a flat-slab segment could correspond to basal traction between the flat-slab and overriding continental plate or flat-slab
dehydration (Yonkee and Weil, 2015), rather than to crustal rebound upon foundering of the
sublithospheric load (Liu et al., 2010). Regardless, preexisting weakness zones are likely
required to generate the Laramide, multi-km reverse-fault offsets in mechanically-rigid
continental crust (Marshak et al., 2000).

Evidence in the form of angular unconformities and drainage deflection have been
presented herein for middle to late Campanian Laramide-style deformation in Utah. The angular
unconformities are consistently underlain by laterally-extensive (multi-km) horizons of
sandstone with soft sediment deformation. The lateral continuity of this facies is suggested to
record seismicity (Kundu et al., 2011), which may provide a record of the stress transfer
mechanism from the subducted flat slab to overlying lithosphere during the early Laramide
orogeny. If the angular unconformities are linked to Laramide-style deformation, the seismicity-
origin that generated the sandstone with soft-sediment deformation is probably sublithospheric.
Sublithospheric seismicity is mostly known to occur within the Wadati-Benioff zone, either via
internal slab deformation (e.g. the compositional transformation from basalt to eclogite) or by
basal traction at the top of the subducting slab (Coney and Reynolds, 1977). Flat subduction in
the study region implies that the basalt to eclogite transition had yet to be reached (Dávila and
Lithgow-Bertelloni, 2015). Therefore, these middle to late Campanian probable seismic events
were focused likely at the top of the aseismic ridge, induced by basal traction with the overriding
plate.

The NE-SW axial trend of the San Rafael Swell parallels the compressive-stress that
would have been applied by the subducting aseismic ridge, assumed to be a conjugate of the
Shatsky-Hess Rise (Liu et al., 2010) (Figs. 11 and 12). Therefore, the San Rafael Swell should
display some tensional or trans-tensional geometry. Like many Laramide structures in the
Colorado plateau, the San Rafael Swell is a fault-propagation fold (Marshak et al., 2000) that likely formed by inversion of a Proterozoic extensional fault. Incipient slip of the fault underlying the swell was likely oblique given the NE-propagation of the subducted Shatsky plateau. However, detailed mapping of the structure would be required to validate this claim. Paradoxically, formation of the San Rafael Swell required significant compressive forces oriented orthogonally to the NE-propagation direction of the Shatsky plateau. We therefore predict that the stress transfer mechanism to generate Laramide uplifts likely evolved. Embryonic stages (e.g. incipient growth of the San Rafael Swell) were likely induced by sublithospheric basal traction between the North American plate and NE-propagating Shatsky plateau often involving transpressional deformation. The later, better-known Laramide phase of deformation that brought about uplift of the Colorado Plateau and reactivation of Ancestral Rocky Mountain faults resulted from the Cenozoic foundering of the Shatsky-Hess Rise conjugate (Liu et al., 2010).
CONCLUSIONS

Two incipient growth-episodes of the San Rafael Swell recorded in middle to late Campanian stratigraphy played a significant role in reshaping the Cordilleran foreland in Utah. Documented low-angle (<10°) angular unconformities are the removal-sites of thick (as much as 30-m) sediment-accumulations, which were redistributed in long, rapid, basinward-transits. The earliest episode, around 78 Ma that records growth in the southern San Rafael Swell caused uplift in the Joe’s Valley area of the Wasatch Plateau. The later phase began around 75 Ma, prior to deposition of the Bluecastle Tongue in the northern San Rafael Swell, causing uplift in the northwestern Book Cliffs.

Fluvial systems developed longer, winding transits as the San Rafael Swell grew as an intra-foreland basin-boundary. One of the effects was that clay-rich sediments were deposited northeast of their Jurassic Paxton thrust source area by basin-axial trending rivers. The incipience of Laramide deformation and waning of Sevier deformation also allowed for sediments shed from back-arc plutons to appear within the sediment supply, as catchments enlarged due to thrust-inactivity-and-burial and as thrust-induced subsidence was reduced.

The NE-propagation of deformation in the San Rafael Swell can be attributed to NE-propagation of an underlying, subducted oceanic plateau conjugate of the Shatsky-Hess Rise. The documented angular unconformities are consistently underlain by laterally-extensive (multi-km) and horizon-like sandstone with soft-sediment deformation, interpreted to record Wadati-Benioff Zone seismicity. Early (ca. 80-75 Ma) Laramide deformation associated with flat-slab plateau subduction likely caused uplift prior to Cenozoic slab steepening as Laramide-deformation became isostatic in nature.
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APPENDIX

Regional Geology (Extended)

*Pre-Cordillera sedimentary cover and tectonics*

The oldest sedimentary rocks of western North America record localized intracratonic deposition on the Mesoproterozoic to Early Neoproterozoic supercontinent Rodinia. These strata are highly localized but thick (~5 km) basin-accumulations, one of which is an aulacogen-fill now inverted in the E-W trending Uinta-Cottonwood Arch of northeast Utah (Bradley and Bruhn, 1988). With the ensuing breakup of Rodinia, volcanic and siliciclastic rocks accumulated in the Neoproterozoic to Early Cambrian rift basin bounding western Laurentia (Yonkee and Weil, 2015). The Wasatch hinge line centered in the Sevier belt, represents the eastern limit of Proterozoic rifting (DeCelles, 2004). Pre-Cordillera sedimentary cover west of the Wasatch hinge-line is on average 12-km-thick whereas in regions east, cover is on average ~1.5-km-thick (DeCelles, 2004). Proterozoic extensional faults likely played a significant role during Phanerozoic, thick-skinned (Ancestral Rockies and Laramide) orogenies as they acted as preexisting weakness planes necessary for uplift (Marshak et al., 2000). The thick-skinned orogenies were likely confined to the east of the Wasatch hinge-line because of the relatively thin pre-Cordillera sedimentary cover (DeCelles, 2015). Western Laurentia from the Middle Cambrian to Middle Devonian records post-rifting, passive-margin, and predominately carbonate deposition during the Sauk and Tippecanoe transgressions (Yonkee and Weil, 2015).

The western (present-day coordinates) Laurentian passive-margin trend that was subsequently modified by Late Jurassic sinistral offset (induced by oblique Farallon Plate convergence) strongly dictated the future curvature of the Sevier fold-and-thrust belt (Yonkee
and Weil, 2015). The western Laurentian margin became convergent during the Late Devonian-Mississippian Antler Orogeny. The long-standing yet enigmatic hypothesis is that the Antler Orogeny involved a continent-arc collision wherein an oceanic basin was closed and the Lower Paleozoic deep-marine sediments deposited within were emplaced onto Laurentia (Speed and Sleep, 1982). The allochthonous blocks were translated to present day Nevada, ~140 km from the subsiding western-edge of the continent and contemporaneously eroded into the load-induced foreland basin continentward of the orogeny (Speed and Sleep, 1982). During Late Mississippian-Pennsylvanian, Laurentia collided with Gondwana, the Ancestral Rocky Mountains uplifted, and ~6 km of extensional growth-faulted strata were deposited in the N-S Oquirrh Basin of northern Utah (Erskine, 1997). The Oquirrh Basin was later inverted along the Charleston-Nebo thrust during the Sevier orogeny (Erskine, 1997) and reworked into the Cordilleran foreland basin-fill (Horton et al., 2004). Additional terranes were welded to the Antler terranes during the Early Mesozoic Sonoman orogeny. From west to east in the Lower Mesozoic, marine strata transition to continental deposits. Middle Jurassic marine carbonates and evaporites were deposited on the subsiding Utah-Idaho trough of the Sonoman retroarc foreland, and subsequently formed detachments in the eastern Sevier belt (DeCelles and Coogan, 2006; Yonkee and Weil, 2015).

**The Cordilleran orogenic system (Extended)**

The westernmost and oldest portion of the Cordilleran is the forearc region. The forearc developed with the accretion of Middle Jurassic (~165 Ma) volcanic arcs and interarc sediments to form California’s Sierra Foothills and Coast Range (DeCelles, 2004; Yonkee and Weil, 2015). Though speculative, their accretion onto the North American continent was manifested by foundering of the “Mezcalera plate” between two Late Triassic to Early Jurassic volcanic arcs
during the Nevadan Orogeny (DeCelles, 2004; Yonkee and Weil, 2015). Coeval subduction (Franciscan) generated metamorphism of the accreted terranes, intraplate shortening and extensional arc-plutonism. These early Cordilleran plutons were partially eroded and deposited in the Franciscan subduction trench and then underplated, offscraped, and accreted as the Franciscan complex in California’s Coast Range by Early Cretaceous (Yonkee and Weil, 2015). The Nevadan Orogeny culminated with the accretion of an ophiolite terrane in California’s Coast Range. Upon accretion of the arcs, interarc-basin and trailing-ophiolite (complete foundering of the “Mezcalera plate”), the Farallon plate began subducting beneath the western North American margin. The Early Cretaceous involved the initial major flare-up of the Cordilleran magmatic arc (e.g. Sierra Nevada’s calc-alkaline plutons) (DeCelles and Coogan, 2006). The second and final major Cordilleran arc flare-up occurred during the Late Cretaceous, at ca. 90 Ma (DeCelles, 2004; DeCelles, 2015; Yonkee and Weil, 2015). The forearc basin consists mostly of clastic sediments shed westward from the magmatic arc deposited as the ~2 to 10 km-thick Great Valley Group, draping the forearc accretionary complex (Yonkee and Weil, 2015).

The retroarc hinterland which was dramatically subject to extension during the Oligocene-Miocene Basin and Range event, encompasses the area between the magmatic arc and fold-thrust belt (Fig. 1B), and mostly developed during Late Jurassic (Nevadan) crustal thickening, metamorphism, and igneous intrusion events (Yonkee and Weil, 2015). From Nevada to western Utah, the hinterland’s major components (Fig. 1B) include the Luning-Fencemaker fold-thrust belt, the central Nevada fold-thrust belt, mid-crustal metamorphic rocks, and gently deformed Paleozoic strata (DeCelles and Coogan, 2006; Yonkee and Weil, 2015). The Luning-Fencemaker fold-thrust belt (Fig. 1B) which is the oldest of the retroarc elements
formed with incipient Franciscan subduction, coeval to the obduction of the Coast Range ophiolite (Yonkee and Weil, 2105).

**Campanian stratigraphy of central and eastern Utah (extended)**

The Lower Campanian Star Point Sandstone contains several shallow-marine parasequences that pass basinward into the Mancos Shale (Fig. 3). The Panther Tongue of the lower Star Point Sandstone has been interpreted as a detached fluvial delta from which some of the shallow-marine parasequences received sediments (Posamentier and Allen, 1993). The upper parts of the Star Point Sandstone such as the Spring Canyon Member pass landward into the Blackhawk Formation (Fig. 3). The lower to middle Blackhawk Formation is mostly mudstone but contains isolated fluvial sandbodies and numerous coal seams that decrease in prevalence upwards (Fig. 3). The proportion of channelized sandbodies increases upwards, from ca. 10% to ca. 30% (Hampson et al., 2012). The Blackhawk Formation transitions basinward from coastal-plain and fluvial strata to shoreface sandbodies, which pass further basinward into the Mancos Shale (Fig. 3). The Blackhawk Formation has a rising, concave-down shoreline trajectory (Hampson, 2010). The total Blackhawk Formation thickness (~250 m in the Wasatch Plateau) tapers down-dip and pinches-out within the Mancos Shale in the Book Cliffs near the Green River area (Fig. 3). Stratigraphic architecture changes abruptly across the unconformable contact between the Blackhawk and Castlegate Formations.

In the lower Blackhawk Formation of the Wasatch Plateau, multi-story fluvial sandbodies confined within sequence-bounding incised valleys transition laterally to well-developed interfluvial calcareous paleosols (Gani et al., 2015). Gani et al. (2015) also identified coal seams to correlate with marine flooding surfaces in these 4th order sequences. This presence of coeval marine and nonmarine strata along basin-strike serves as one line of evidence for a marine-
embayment that encompassed the northern Wasatch Plateau and northwestern Book Cliffs. Known as the Utah Bight (Hampson, 2010), this marine embayment was a long-lived (>5 m.y.) depocenter and may have influenced Castlegate Formation sequence architecture as discussed later herein.
RESULTS (EXTENDED)

Facies

1. Organic-rich mudstone

Dark gray mudstone containing a greenish-gray weathering-tint has massive or nodular bedding. These deposits are moderately pedogenic (e.g. gleysol) with root tubes that harbor diagenetic concretions. Woody debris and charcoal also occur.

This facies is interpreted to have accumulated in a vegetated floodplain. The dark color of this facies is related to the organic content.

2. Bioturbated sandstone

Fine to medium grained sandstone displays bioturbation. Bedding is thin to massive. Some thinly bedded sandstone contains siderite nodules. Coal chips occur locally. Ichnofossils include Teredolites longissimus, Teredolites clavatus and Fugichnia. The bioturbation index (BI) of this facies does not exceed 2.

This facies is interpreted as coastal plain deposits. The presence of wood-boring Teredolites trace fossils indicates brackish-water setting (Shanley and McCabe, 1992). Siderite nodules are diagenetic and formed during burial in a reducing environment such as a sediment-starved swamp or floodplain (Taylor et al., 2000).

3. Intraformational lag

Conglomerate with fine to medium grained sandy matrix. The deposits are poorly sorted and infill scour pits or blanket erosion. Fills comprise pebble and cobble-sized clay rip-up clasts and plant materials such as large tree stumps, small twigs and leaves. Some plant materials display Teredolites longissimus and Teredolites clavatus ichnofossils.
This facies represents sand-dominated fluvial deposition. Intraformational lags are interpreted as channel-thalweg deposits (McLaurin and Steel, 2007). They represent high-energy, probable debris flows (Sohn et al., 1999).

4. **Extraformational lag**

Quartz, chert, or arkosic pebble-cobble conglomerate with a medium to coarse-grained sandy matrix. Most commonly, the facies contains sub-rounded gravels. Sub-angular gravels are typically arkosic or cherty and less common. Grains are poorly sorted and randomly-oriented.

This facies is interpreted as alluvial fan and gravel-dominated fluvial deposits. The lack of plant material and mud rip-up clasts, and presence of rounded pebbles suggest that these deposits are extraformational, potentially transported by antecedent rivers that dissected the Sevier thrust belt. The round pebbles and cobbles indicate a long fluvial transit. The matrix-support of this facies suggests deposition from dense inertia flows or “traction carpets” (Sohn et al., 1999). Poor sorting and absence of grading supports that this facies records river flood-stage deposition (Sohn et al., 1999).

5. **Sandstone with soft-sediment deformation**

Sandstone with convolute laminae, slump folds, recumbent folds, flame structures, or dish-and-pillar structures.

Soft-sediment deformation doesn’t necessarily indicate an environment of deposition as it is the product of sudden incompetency or instability (i.e. loss of strength) in semi-liquefied sediments (Kundu et al., 2011). These instabilities are commonly local in origin, controlled by slope-failure, rapid sedimentation or differential loading. Seismicity can also produce soft-sediment deformation (Kundu et al., 2011; Balsamo et al., 2013). Seismic events are evident if
the sedimentary structures are spatially extensive, forming a horizon bounded by undeformed strata (Kundu et al., 2011). McLaurin and Steel (2007) argue though that at the type-locality, soft-sediment deformations in sandstone lack continuity, and thus represent bank slumping into adjacent channels. Further south, we found however rather continuous (multi-km) soft-sediment deformation horizons in the Wasatch Plateau, likely suggesting their seismic origin. Some occurrences of soft-sediment deformation appear more localized as McLaurin and Steel (2007) suggested.

6. **Ripple cross-laminated sandstone**

Fine to medium-grained sandstone displays asymmetric ripple cross-lamination. Rare climbing ripples occur.

Ripple cross-laminated sandstone reflects either bar-top, levee, or floodplain deposition (Reference). Vertical grain size trends within rippled intervals assist in specifying whether these are bar or over bank deposits.

7. **Dune cross-stratified sandstone**

Fine to medium-grained sandstone displays dune-scale trough cross-stratification. Cross-set thicknesses vary between 5 and 50 cm.

This facies is interpreted to record deposition in either the middle-portion of channels bars or in overbank splays (Reference). Dune set-thickness is proportional to formative water depth whereby the smaller the set-thickness, hence dune, the shallower the water (LeClair and Bridge, 2001).

8. **Parallel-laminated sandstone**
Fine to medium grained sandstone displays planar cross-lamination. The planar cross-laminations are typically inclined-gently relative to horizontal.

This facies is interpreted to reflect deposition on the lower to middle portions of braided-channel bars, adjacent to the channel thalweg (Reference).

9. **Sandstone with rhythmic mudstone**

Sandstone with subordinate rhythmic mudstone occurs as thin to thick beds. Sedimentary structures include herringbone cross-stratification, flaser bedding, sigmoidal bedding, inclined heterolithic strata, and dune or ripple cross-stratification with single or double mud drapes. Cross-stratifications commonly have bi-directional paleocurrents. Ichnofossils include *Fugichnia* and *Ophiomorpha*.

This facies is interpreted to reflect tidally-influenced fluvial and estuarine deposits (Yoshida et al., 2006). The heterolithic yet sandstone-dominated nature of this facies is due to higher depositional energy with a relative abundance of coarse-grained compared to fine-grained detritus.

10. **Mudstone with lenticular sandstone**

This facies consists of mudstone with lensoidal fine-grained sandstone. These deposits show coarsening-upward trend. Sedimentary structures include wavy-lenticular bedding. Locally, there is comminute-distribution of organic detritus. Ichnofossils include *Fugichnia* and *Ophiomorpha*.

This facies is interpreted as part of bay-head or tidal-deltaic deposits. Despite having a coarsening-upward grain size trend, a fluvial overbank splay interpretation for these deposits is
discarded because of the trace fossil assemblage, wavy bedding, and absence of pedogenic modifications.
DISCUSSION (EXTENDED)

Manifestation of deformation-style in stratigraphic surfaces (Extended)

Surface-loading by retroarc fold-thrust belts cause lithospheric depression in the direction of thrust-advancement, strongly dictating sediment-accumulation across broad areas (Ettensohn, 2004). Therefore, if fold-thrust belt loads decrease along-strike, the cratonward accommodation does too. Observable stratigraphic and facies architecture in the underlying Blackhawk Formation and Star Point Sandstone form complex relationships along the margin of a long-lived depocenter, where there was a large marine embayment known as the Utah Bight (Hampson, 2010; Gani et al., 2015) that spanned a region cratonward of the Charleston-Nebo thrust system. The inter-depocenter regions therefore were hypothetically cratonward from inactive thrust sheets. Although accommodation was relatively higher within the depocenter, it was still relatively low when compared to the middle and upper Campanian. Accommodation was reduced but active thrusting should promote the opposite, trapping of coarse-grained sediments within the wedge-top depocenter, and fine-grained organic rich deposition across wide areas further basinward. It is possible that variable loading within the fold-thrust belt caused the lithosphere to rise or subside and had some contribution to the observed erosional beveling, but given the long-transit progradation of coarse-grained material, there was likely an additional force acting to reduce accommodation.

In Wyoming, Cenomanian Second Frontier marine strata record a similar tectonic influence characterized by episodic, localized uplift ensued by development of angular unconformities (Vakarelov et al., 2006). The localized uplift was attributed to nascent growth of the Laramide Tisdale Anticline (Vakarelov and Bhattacharya, 2009). These Second Frontier angular truncation surfaces commonly contain *Glossifungites* and overlie a pebble lag facies.
Surfaces AU1 and AU2 which formed in terrestrial setting, contain *Teredolites* rather than *Glossifungites* but the bioturbation associated with angular unconformities from both the Second Frontier and Castlegate Formation is strongly indicative of subaerial exposure.
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