SEQUENCE STRATIGRAPHY OF THE UPPER CRETACEOUS SEGO SANDSTONE MEMBER REVEALS SPATIO-TEMPORAL CHANGES IN DEPOSITIONAL PROCESSES, NORTHWEST COLORADO, U.S.A.

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ABSTRACT: The Upper Cretaceous Sego Sandstone Member of the Mesaverde Group has been extensively studied in the Book Cliffs area of Utah and Colorado, and has been the focus of stratigraphic reconstruction aimed at developing an understanding of the evolution of the Western Cretaceous Interior Seaway. The Sego Sandstone Member was deposited in a marginal marine, tide-influenced environment of the Cretaceous Seaway. This study documents the sequence stratigraphy of the Sego Sandstone Member in northwestern Colorado, just north of Rangely, and compares and contrasts it with equivalent strata in the Book Cliffs area of Utah. The Sego Sandstone Member in the study area contains three sequences characterized by progradational and aggradational stacking patterns. The stratigraphically lowest sequence consists of a prograding, tide-influenced delta overlain by marine mudstones, which represents a retrogradation and flooding surface. The second sequence is composed of multiple parasequences and consists of an incised valley filled with stacked tidal bars which then pass into a largely aggradational stacking pattern, composed of barrier-island deposits with back-barrier, flood-tidal-delta deposits, and wave-dominated-shoreface deposits. The third sequence is a broad, tide-dominated distributary-mouth system with a sharp, incisional basal contact. The three sequence boundaries documented in northwestern Colorado are consistent with the three main sequence boundaries identified in the Book Cliffs. However, whereas barrier islands and flood-tidal deltas are characteristic of the Sego Sandstone Member in northwestern Colorado, similar deposits are not as prevalent in the Book Cliffs of Utah, suggesting different depositional processes and paleogeography.

Tidal and fluvio-deltaic processes are the dominant controls on deposition of the Sego Sandstone Member north of Rangely, Colorado. The transition from a tide-dominated fluvio-deltaic system to a mixed wave–tide-influenced coastline indicates a fundamental change in processes and depositional environment in the upper part of Sequence 2. Such change from a prograding fluvio-deltaic system to a more passive tide-modified coastline is not observed in the Book Cliffs, and may be the result either of large scale transgression or of relocation of the river system through large-scale avulsion, which is not observed in the Book Cliffs. Our study shows significant stratigraphic variability between rocks exposed in the Book Cliffs versus time-equivalent rocks exposed in northwestern Colorado in the Upper Cretaceous, which has implications for the regional basin architecture and stratigraphic correlations.

INTRODUCTION

The Sego Sandstone Member of the Mesaverde Group is an Upper Cretaceous, marginal marine to marine sandstone that crops out in central and eastern Utah and western Colorado (Figs. 1, 2, 3). This stratigraphic interval has been documented extensively in the Book Cliffs area in Utah, and its sequence stratigraphy has been interpreted and used as a proxy to trace Cretaceous sea-level variations (Van Wagoner 1991; Willis 2000; Willis and Gabel 2001, 2003; Wood 2004). These sea-level variations have been attributed to eustatic changes and to Sevier tectonic events. We document the Sego Sandstone Member north of Rangely, Colorado, in an area where limited research has been done (Noc 1984; Stancliffe 1984; York et al. 2011) and where the basin architecture seems significantly different from the Book Cliffs in Utah. The aim of this study is to document how depositional environments varied along strike during the Late Cretaceous in the western United States, in order to reconstruct the paleocoastline and to understand its control on stratigraphic expression. In modern systems, along-strike variations in paleogeography and depositional environment over fifty to one hundred kilometers can be drastic. For example, the Fly River delta in Papua New Guinea is a type tide-dominated delta (Dalrymple et al. 2003). Northeast of the Fly River delta and in the Gulf of Papua there are smaller tide-dominated deltas of the Bamu and Turama rivers (Löffler 1974), with an irregular coastline and pervasive tidal inlets. To the west and southwest of the Fly delta, the coastline is a wave-dominated strand plain with only scattered and small tidal inlets. Understanding and recognizing these changes in the geological record is critical for regional stratigraphic correlations and for oil- and gas-play development and exploration strategies. The wealth of information in the Book Cliffs combined with the new data presented in this study provide a unique opportunity to resolve in detail along-strike variability in the Late Cretaceous Seaway stratigraphic record and
investigate how sequence boundaries and depositional environments correlate along strike, providing a predictive scheme.

We document a fourteen-kilometer (along depositional dip) exposure of the Sego Sandstone Member north of Rangely, Colorado, and reconstruct its stratigraphic architecture (Figs. 4, 5). The three dimensionality of the exposures and the facies variability allows a detailed investigation of different depositional environments within the study area. Three sequence boundaries are interpreted, which are consistent, but not demonstrably correlative, with observations in the Book Cliffs area in Utah (Willis 2000). However, the Sego Sandstone Member in the study area records an up-section evolution of depositional environments, which differs from what has been interpreted in the Book Cliffs. The investigated outcrops indicate a prodelta to delta-front environment in the first sequence. This is followed by a period of incision forming an eighteen-meter-deep valley, which is filled with distributary-channel deposits and overlain by stacked tidal bars. Above this, an aggradational succession follows which contains wave-dominated shoreface sandstones, barrier-island sandstones, flood-tidal deltas, and lagoonal mudstone. Following this period of aggradation, an upper incised valley indicates a third sequence boundary, which is filled with sandstones representing a distributary-mouth system. Whereas flood-tidal-delta and barrier-island deposits characterize a significant portion of the study area, similar facies are not as pervasive as in the Book Cliffs (Van Wagoner 1991; Willis 2000; Willis and Gabel 2001, 2003; Wood 2004). These changes in facies along strike indicate variations in depositional environment related to paleogeography and the relative control of wave versus tidal action. An
understanding of these changes is necessary to better understand the controls on such variations and develop better predictive capabilities for oil and gas exploration. Flood-tidal deltas characteristic of the Sego Sandstone Member (York et al. 2011), although relatively small, are potential stratigraphic traps and can be good reservoir plays (Barwis and Hayes 1979; Barwis 1990; Wood 2004).

BACKGROUND

The Sego Sandstone Member was deposited on the western margin of the Cretaceous Western Interior Seaway and is a member of the Mesaverde Group (Warner 1964) (Figs. 1, 2). Whereas the coeval stratigraphy west of Green River, Utah is composed of the Upper Castlegate Sandstone, its basinward correlatives in the study area are the Buck Tongue and the Sego Sandstone Member (Van Wagoner 1991, 1995; Miall 1993; Willis 2000; Miall and Arush 2001) (Fig 1).

Chronostratigraphic analyses of the Sego Sandstone Member in the Book Cliffs area by Gill and Hail (1975) report Baculites perplexus in the Buck Tongue of the Mancos Shale Formation and Baculites scotti in the Anchor Mine Tongue, in Prairie Canyon, located in western Colorado in the Book Cliffs area. The Buck Tongue of the Mancos Shale underlies the Sego Sandstone Member, and the Anchor Mine Tongue divides the lower and upper parts of the Sego Sandstone Member up-section. This places the deposition of the Sego Sandstone in the Book Cliffs area sometime between ~ 77 Ma and 75.5 Ma (Gill and Hail 1975; Obradovich 1993; Izzett et al. 1998; Cobban et al. 2006). Correlations made in the early studies of the Sego Sandstone Member near Rangely, Colorado, are based on lithostratigraphy and facies associations. Early maps of this area and its surrounding geology identify the Castlegate Sandstone, the Buck Tongue, the Sego Sandstone Member, and the overlying Illes and Williams Fork formations (Cullins 1968, 1969, 1971; Barnum and Garrigue 1980). Baculites perplexus has been identified in the Buck Tongue of the Mancos Shale near and west of Rangely, Colorado (Cullins 1971; Molenaar and Wilson 1993), indicating that it is coeval with the Buck Tongue in the Book Cliffs area (Gill and Hail 1975). To date, no ammonite zones have been documented in the Anchor Mine Tongue in this study area. However, a detrital-zircon U-Pb study on the Sego Sandstone Member in the study area reports a maximum depositional age of 76.6 ± 1.5 Ma (York 2010), which is contemporaneous with Baculites scotti (Gill and Hail 1975; Obradovich 1993; Izzett et al. 1998; Cobban et al. 2006). It must be noted that there was only one zircon out of 100 dated zircons that recorded that age, and that this is a maximum depositional age. Based on existing, limited chronostratigraphic data, the Sego Sandstone Member in the study area appears to be coeval with the Sego Sandstone Member in the Book Cliffs area.

Extensive research has been done on the type sections of the Castlegate Sandstone and Sego Sandstone members in the Book Cliffs area in Utah and Colorado, where they have been interpreted as alluvial deposits, stacked incised-valley fills, and tide-dominated deltas (Fouch et al. 1983; Lawton 1986; Van Wagoner 1991; Miall 1993; Olsen et al. 1995; Van Wagoner 1995, 1998; Yoshida et al. 1998; Robinson and Slingerland 1998; Willis 2000; Miall and Arush 2001; Willis and Gabel 2001, 2003; Wood 2004; among others). The focus of Van Wagoner (1991) was to identify sequence boundaries, outline criteria for recognizing them in the rock record, document the geometry of incised valleys, and describe the character of incised-valley fill and transgressive and highstand system tracts. Van Wagoner (1991) identified nine high-frequency sequence boundaries in the Sego Sandstone Member, six in the lower Sego Sandstone, plus one in the Anchor Mine Tongue and two in the upper Sego Sandstone. Van Wagoner (1991) subdivided each of these nine sequences into lowstand, transgressive, and highstand system tracts. Van Wagoner (1991) identified nine high-frequency sequence boundaries in the Sego Sandstone Member, six in the lower Sego Sandstone, plus one in the Anchor Mine Tongue and two in the upper Sego Sandstone. Van Wagoner (1991) subdivided each of these nine sequences into lowstand, transgressive, and highstand system tracts, assigning most of the tidal deposits to the lowstand system tracts, also noting that orientations of incised valleys and tidal bars in the Sego Sandstone Member in the Book Cliffs typically trend to the south, southwest, and southeast. In contrast to the nine sequence boundaries reported by Van Wagoner (1991), Willis (2000) reported four sequence boundaries in the Sego Sandstone Member: one high-order sequence boundary at the base of the Sego Sandstone Member and three more “nested” low-order sequence boundaries higher in the Sego Sandstone Member. Willis and Gabel (2001) instead focus on describing the facies and geometries of what they interpret as three forward-stepping and then backward-stepping tide-dominated deltas. Furthermore, while recognizing that some of the channelized incisions could be incised valleys, they interpret that most are probably deeply cut tidal channels (Willis and
Similarly to Willis (2000), Wood (2004) reports four sequence boundaries. Aschoff and Steel (2011) report up to three sequence boundaries in the Sego Sandstone Member; however, their study focuses on a much larger scale, both spatially and temporally, with respect to others’ work (Van Wagoner 1991; Willis and Gabel 2001, 2003; Wood 2004). Based on existing work, apparent discrepancies exist in the sequence stratigraphic interpretation of the Sego Sandstone Member and in its strongly progradational nature. Some attribute progradational and retrogradational episodes to the relative rise and fall of base level without resolving the cause as eustatic or tectonic in nature (Van Wagoner 1991; Willis and Gabel 2001, 2003; Wood 2004). Based on existing work, apparent discrepancies exist in the sequence stratigraphic interpretation of the Sego Sandstone Member and in its strongly progradational nature. Some attribute progradational and retrogradational episodes to the relative rise and fall of base level without resolving the cause as eustatic or tectonic in nature (Van Wagoner 1991; Willis and Gabel 2001, 2003; Wood 2004). Willis (2000) and Aschoff and Steel (2011) instead attribute the progradational pattern of the Sego Sandstone Member to a tectonic control. Willis (2000) uses the two-phase stratigraphic model of Heller et al. (1988) to explain the high-order sequence boundaries. Heller et al. (1988) proposed that an inactive thrust belt will cause flexural rebound in the orogen, and proximal coarse grained sediment will subsequently be reworked into the distal foreland basin. However, the cause of low-order sequence boundaries is more ambiguous (Willis 2000). A different tectonic driver for the rapid progradation of the Sego Sandstone Member is prescribed by Aschoff and Steel (2011), who propose that the early onset of the Laramide-style deformation and the uplift of the basement-cored San Rafael Swell disrupted the flexural foreland basin, thus reducing accommodation space. As outlined, there is a wide spectrum of interpretations about the controls on the sequence stratigraphy of the Sego Sandstone Member. In contrast, a consensus exists that a large component of the Sego Sandstone Member is tide-influenced to tide-dominated (Van Wagoner 1991; Willis 2000; Willis and Gabel 2001, 2003; Wood 2004; Aschoff and Steel 2011). Regionally the study area and its surroundings are divided into the Uinta Basin and the Piceance Basin (Fig. 3). Whereas the Sego Sandstone...
Member in the Book Cliffs is located in the Uinta Basin (Yoshida et al. 1996; Willis and Gabel 2001, 2003), the Sego Sandstone Member north of Rangely is located along the axis of the Douglas Creek Arch. The Douglas Creek Arch is a southern extension of the Rock Springs uplift and separates the Uinta Basin from the Piceance Basin (Fig. 3). Both the Douglas Creek Arch and the Rock Springs uplift are Laramide structures that simultaneously developed as broad arches during the Late Cretaceous and continued to grow into more discrete uplifts in the Eocene (Bader 2009; Mederos et al. 2005). North and south of Rangely the Mancos Shale, Buck Tongue, and the Castlegate and Sego Sandstone members are exposed on the limbs of the east–west-trending Rangely anticline, which is a surficial expression of the underlying, Douglas Creek Arch (Bader 2009) (Fig. 4).

North of Rangely, Colorado, the Lower Castlegate Sandstone is overlain by the Buck Tongue, which represents an open marine environment. The Sego Sandstone Member lies erosionally on the Buck Tongue and has been interpreted as barrier-island systems by Stancliffe and Tongue and has been interpreted as barrier-island systems by Stancliffe (1984) in the northwest portion of the study area. A more recent investigation (York et al. 2011) documents flood-tidal-delta deposits northwest of Rangely, whereas just south of Rangely the same member was interpreted as shoreline deposits (Noe 1984). All of these interpretations are quite different from the current interpretation of the Sego Sandstone Member in the Book Cliffs area.

SEDIMENTOLOGICAL AND STRATIGRAPHIC ANALYSIS OF THE SEGO SANDSTONE MEMBER

Thirty-six detailed log sections in the Sego Sandstone Member, measured at the 1:200 and 1:100 scale with a Jacob’s staff, in northwestern Colorado form the basis of the facies analysis described below (Fig. 4). Detailed paleocurrent measurements, conducted by measuring the orientation of the trough axis in trough cross-beds, were taken in three selected facies and are described below. A maximum of approximately seventy meters of detailed Sego Sandstone Member stratigraphy has been measured in the study area. This matches regional thickness documented for the Sego Sandstone Member in the Book Cliffs area (Van Wagoner 1991). In the following section we describe and analyze facies within the three identified sequences and interpret the depositional environment. Regionally mappable surfaces that are incisional and place shallower facies on top of deeper facies, which otherwise would not be found in stratigraphic succession, are identified as sequence boundaries. In this study, we use the following definition for stratigraphic sequence: “a relatively conformable succession of genetically related strata bounded by unconformities” (Mitchum 1977). Mappable surfaces that place significantly deeper facies on top of shallower ones are classified as flooding surfaces (Posamentier and Vail 1987; Van Wagoner et al. 1988; Van Wagoner et al. 1990; Neal and Abreu 2009). In order to provide a full stratigraphic framework we also describe the underlying Buck Tongue. Three sequence boundaries have been interpreted and are numbered as 1, 2, and 3 from bottom to top of the succession. Each facies within a sequence is assigned a letter combination that stands for its distinguishing characteristics and a number that refers to its relative stratigraphic position above the underlying sequence boundary (e.g., lfrb-1, lffc-2, mcrss-3). The Buck Tongue of the Mancos Shale consists mostly of black shales in highly weathered slopes and as a result the facies have been generalized. No number–letter designation has been assigned. All facies are organized and briefly outlined in Table 1.

The Buck Tongue

The Buck Tongue of the Mancos Shale overlies the Castlegate Sandstone within the study area. It is a slope-forming, black, organic-rich shale, approximately 25 m thick, with little to no silt. Bed forms and sedimentary structures are conspicuously absent from the Buck Tongue. The contact with the overlying sandstones is sharp (Fig. 6).

Sego Sandstone Member: Sequence 1 Facies Assemblage A

Lower-fine-grained, rippled, and bioturbated sandstone facies (lfrb-1): Facies lfrb-1 is an upper-fine- to upper-fine-grained (predominantly lower-fine-grained), tan to reddish (oxidized) sandstone (Fig. 5). Sedimentary structures are difficult to identify because of intense bioturbation. Where sedimentary structures are identifiable, they consist of current ripples to wave-modified ripples with occasional small trough cross-beds. Bioturbation is so extensive that specific ichnofossils are not distinguishable. The total thickness of this unit is 2 to 4.5 meters. Its contact with the underlying Buck Tongue is sharp and erosional (Fig. 6) (Table 1).

Lower-fine-grained flaser-bedded to cross-bedded sandstone facies (lffc-1): Laterally, facies lffc-1 transitions into facies lffc-1, which is a lower-fine-grained sandstone with flaser bedding and current ripples near the base that grade into trough cross beds (Fig. 5). The degree of bioturbation is low, but occasionally Ophiomorpha and Schaubcylinдрichnus can be found. Its thickness is 4 to 5 meters, and its contact with the underlying Buck Tongue is sharp and erosional (Table 1). Fifty-four paleocurrent measurements were taken. These paleocurents are polydirectional, trending west–east and southwest–northeast (Fig. 7A).

Planar to rippled sandstone facies (prs-1): Facies prs-1 crops out farther to the east and southeast, down depositional dip from lfrb-1 and lffc-1. It is composed of beds, stacked 0.5 to 1.5 meters thick, consisting of lower-fine- to upper-fine-grained sandstones with intercalated shale and mud layers. The sandstones within these beds grade normally from lower-fine- to upper-fine-grained sand, and from massive to subtly planar-bedding into laminated-bedding, wave-modified current ripples and wavy silty mudstone. This sequence is repeated in beds 0.5 to 1.5 meters thick for a total thickness of 5 to 15 meters. Ophiomorpha are common in this facies assemblage, and often the burrow extends the height of a bed (Figs. 5, 8A, B) (Table 1).

Silty shale facies (ssh-1): Facies ssh-1 overlies lfrb-1, lffc-1, and prs-1 and is a dark gray to variegated gray, silty to sandy shale 8 to 12 meters thick (Fig. 5). Where a clean outcrop can be examined, bioturbation is moderate to high, including Planolites, Thalassinoides, and Schaubcylinдрichnus (Table 1). The contact with facies lfrb-1, lffc-1, and prs-1 is abrupt.

Sego Sandstone Member: Sequence 2 Facies Assemblage B

Carbonaceous shale facies (csh-2): On top of facies ssh-1 is a laterally extensive carbonaceous shale to coaly shale. Where present, its thickness increases and decreases, ranging from 1 to 5 centimeters (Table 1).

Massive to cross-beded sandstone facies (mcrss-2): An upper-fine-grained, massive to cross-beded, tan to reddish (oxidized), 18-m-thick sandstone constitutes facies mcrss-2. Individual beds are 3 to 10 meters thick. At the base of the cross-beds there is ground organic material, wood, and large (1–10 cm in diameter) mud rip-up clasts. This facies is limited in its extent. Its contact with the underlying prs-1 facies is represented by an erosional unconformity, with an 18-m-deep incision. Multiple stories of this facies are stacked on top of each other to form an 18-meter-thick succession at the deepest part of the incision, which thins laterally to less than 1 meter (Figs. 5, 8C, 9). In the deepest part of the incision, individual stories are 5 to 7 meters thick (Table 1).

Twenty paleocurrent measurements were taken by measuring three-dimensional cross-beds, where available. These paleocurents are dominantly southeast directed (Fig. 7C). Facies mcrss-2 is laterally juxtaposed with facies csh-2.
Table 1.—A brief description of the facies and the interpretation of those facies of the Sego Sandstone Member in the study area.

<table>
<thead>
<tr>
<th>Facies Name</th>
<th>Brief Description (see text for a more detailed description)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assemblage A</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lfrb-1</td>
<td>Lower-fine-grained rippled and bioturbated sandstone—upper-very-fine- to upper-fine-grained (predominantly-lower-fine-grained), tan to oxidized sandstone. The total thickness of this unit is 2 to 4.5 meters with heavy bioturbation, making it difficult to identify sedimentary structures and individual beds. Where sedimentary structures are identifiable, they are constituted by current ripples to wave-modified ripples with occasional, small trough-cross beds.</td>
<td>Prograding delta front</td>
</tr>
<tr>
<td>lffc-1</td>
<td>Lower-fine-grained sandstone with flaser bedding and current ripples near the base that grade into trough cross beds. The degree of bioturbation is low, but there are occasional Ophiomorpha and Schauberichnus. Its thickness is 4 to 5 meters, and its contact with the underlying Buck Tongue is sharp and erosional.</td>
<td>Delta front.</td>
</tr>
<tr>
<td>prs-1</td>
<td>Bouma beds. Stacked 0.5 to 1.5-meter-thick bedsets composed of lower-fine- to upper-very-fine-grained sandstones with intercalated shale and mud layers. The sandstones within these bedsets grade normally from lower-fine- to upper-very-fine-grained sand and also grade from massive to subtly planar bedding into laminated bedding into wave-modified current ripples into wavy silty mudstone.</td>
<td>Shallow-water turbidites (i.e., collapsing margin of prograding delta).</td>
</tr>
<tr>
<td>ssh-1</td>
<td>Dark gray to variegated gray, silty to sandy shale 8 to 12 meters thick.</td>
<td>Inner-shelf mudstones</td>
</tr>
<tr>
<td><strong>Assemblage B</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>csh-2</td>
<td>Laterally extensive carbonaceous shale to coaly shale.</td>
<td>Incised-valley fill</td>
</tr>
<tr>
<td>mcrss-2</td>
<td>Massive to cross-bedded sandstone—upper-fine-grained, massive to cross-bedded, tan to oxidized, sandstone 18 meters thick. Individual bedsets are 3 to 10 meters thick. At the base of the cross beds there is ground organic material, wood, and large mud rip-ups.</td>
<td>Incised valley filled with distributary channel</td>
</tr>
<tr>
<td>lffc-2</td>
<td>Lower-fine-grained sandstone with flaser bed and current ripples near the base and grade into trough cross beds up-section.</td>
<td>Delta front</td>
</tr>
<tr>
<td>lffr-2</td>
<td>Lower-fine-grained, rippled to lenticular to flaser-bedded sandstone with low to moderate degree of bioturbation (Planolites). Synaeresis cracks are present, and the thickness of this facies varies from 1 to 5 meters with broad clinoforms and an elongate and lobate geometry.</td>
<td>Tidal bars</td>
</tr>
<tr>
<td>om-2</td>
<td>Dark brown to black, slope-forming, organic rich mudstone.</td>
<td>Estuarine muds</td>
</tr>
<tr>
<td><strong>Assemblage C</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hcs-2</td>
<td>Slightly coarsening-upward, very-fine- to upper-very-fine-grained, hummocky cross-stratified sandstone.</td>
<td>Barrier islands and flood tidal deltas</td>
</tr>
<tr>
<td>tcs-2</td>
<td>Upper-very-fine- to lower-fine-grained trough cross-stratified sandstones with a low degree of bioturbation consisting of Ophiomorpha and Skolithos.</td>
<td>Lower-shoreface deposits and lower shoreface in barrier-island deposits.</td>
</tr>
<tr>
<td>pcs-2</td>
<td>Upper-very-fine- to lower-fine-grained planar cross-stratified sandstones with a low degree of bioturbation consisting of Ophiomorpha and Skolithos.</td>
<td>Upper-shoreface</td>
</tr>
<tr>
<td>rb-2</td>
<td>Rippled and bioturbated. Thin-beded, upper-very-fine- to lower-fine-grained, rippled to flaser shaly sandstone to sandstone with high degree of bioturbation and occasional root traces compose facies.</td>
<td>Foreshore</td>
</tr>
<tr>
<td>csh-c-2</td>
<td>Less than 5 cm to 10 cm carbonaceous shale to coal. Where it is a coal, this facies is easily visible, whereas when it is composed of carbonaceous shale it is often poorly exposed.</td>
<td>Swamp and coastal-plain deposits</td>
</tr>
<tr>
<td>ssh-oys-2</td>
<td>Silty shale with oysters. 1 to 5 meters of slope-forming, gray, silty, thin-beded shale. Finely ground and reworked organic matter is present throughout this facies, and isolated sandy ledges of oyster hash are found in several places within this facies.</td>
<td>Lagoonal mudstones</td>
</tr>
<tr>
<td>tcs-dmd-2</td>
<td>Trough cross stratification with sporadic double mud drapes. Lower-fine- to upper-fine-grained sandstone 3 to 6 meters thick. The predominant sedimentary structure is trough cross beds, but there are also rippled horizons and occasional mud drapes. Furthermore, double mud drapes are present in this facies.</td>
<td>Flood tidal delta</td>
</tr>
<tr>
<td>ssh-2</td>
<td>Dark gray to variegated gray, silty to sandy shale 5 to 20 meters thick.</td>
<td>Inner-shelf mudstones</td>
</tr>
<tr>
<td><strong>Assemblage D</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mtcs-3</td>
<td>Upper-fine- to lower-medium-grained, trough cross-bedded, to lenticular sandstone. The lower portion contained ground organic woody material, mud rip ups, and occasionally oyster hash and bone fragments. Its thickness varies from 8 to 16 meters, and its base is highly erosional.</td>
<td>Distributary channel</td>
</tr>
</tbody>
</table>

Lower-fine-grained flaser-bedded to trough cross-bedded sandstone facies (lfrb-2): Facies mcrss-2 passes down dip into a lower-fine-grained sandstone with flaser bedding and current ripples near the base, which grade into trough cross beds up-section. The degree of bioturbation is moderate, with Ophiomorpha and Schauberichnus.

The lower contact of this facies is abrupt with the underlying facies ssh-1 and in places lies unconformably on top of facies prs-1 (Table 1).

Lower-fine-grained rippled to flaser-bedded sandstone facies (lffc-2): Facies lffr-2 is a lower-fine-grained, rippled to lenticular-bedded to flaser-bedded sandstone with a low to moderate degree of bioturbation (Planolites). Synaeresis cracks are present, and the thickness of this facies varies from 1 to 5 meters with broad clinoforms, approximately 3 meters high, and an elongate and lenticular geometry (Table 1).

Organic mudstone facies (om-2): Dark brown to black, slope-forming, organic-rich mudstone are exposed at various stratigraphic levels in Sequence 2. They are found interbedded with and overlying facies lffr-2 (Table 1).

**Facies Assemblage C**

Hummocky cross-stratified sandstone facies (hcs-2): Facies hcs-2 is a slightly coarsening-upward, very-fine- to upper-very-fine-grained, hummocky cross-stratified sandstone (Fig. 8E). This facies has a low degree of...
contact is sharp, placing upper-fine-grained sand on black marine shale. The double mud drapes are present in this facies. Bioturbation is minimal, and tcs-dmd-2 is a white, lower-fine- to upper-fine-grained sandstone 3 to 10 cm thick (Table 1). This facies overlies facies tcs-2, pcs-2, and lfrf-2 (Fig. 5). and isolated sandy ledges of oyster hash are found in several places within Finely ground and reworked organic matter is present throughout this facies, consists of a 1 to 5 meters of slope-forming, gray, silty, thin-bedded shale. The thickness of this interval varies from 1 to 4.5 meters (Table 1).

Trough cross-bedded sandstone facies (tcs-2): Conformably above facies hcs-2 are upper-very-fine- to lower-fine-grained trough cross-stratified sandstones with a low degree of bioturbation consisting of Ophiomorpha and Skolithos (Table 1). Planar cross-stratified sandstone facies (pcs-2): Low-angle and laminated, lower-fine-grained sandstone is found on top of facies tcs-2. In places, this facies has a rooted top and, where overlain by a coal, a poorly developed paleosol. The thickness of this facies is less than 1 meter (Table 1).

Rippled and bioturbated sandstone facies (rb-2): Thin-bedded, upper-fine- to lower-fine-grained, rippled to flaser-bedded shaly sandstone to sandstone with high degree of bioturbation and occasional root traces constitutes facies rb-2. The total thickness of this facies is 3 to 4 meters and is found, regionally, in the updip direction of facies lfrf-2 and pcs-2 facies (Fig. 5) (Table 1).

Carbonaceous shale to coal facies (csh-c-2): Overlying facies tcs-2 and pcs-2 is often facies rb-2, which is composed of a less than 5 cm to 10 cm carbonaceous shale to coal (Table 1). Where it is composed of coal, this facies is easily visible, whereas where it is composed of carbonaceous shale it is often poorly exposed (Fig. 8G).

Silty shale with sporadic oyster-hash facies (ssh-oys-2): Facies ssh-oys-2 consists of a 1 to 5 meters of slope-forming, gray, silty, thin-bedded shale. Finely ground and reworked organic matter is present throughout this facies, and isolated sandy ledges of oyster hash are found in several places within this facies (Table 1). This facies overlies facies tcs-2, pcs-2, and lfrf-2 (Fig. 5).

Trough cross-beds with double mud drapes facies (tcs-dmd-2): Facies tcs-dmd-2 is a white, lower-fine- to upper-fine-grained sandstone 3 to 6 meters thick. The predominant sedimentary structure is trough cross-beds and occasional rippled horizons and mud drapes. Furthermore, double mud drapes are present in this facies. Bioturbation is minimal, and where present consists of Ophiomorpha. Reactivation surfaces and sigmoidal bedding are also present (Table 1).

Facies tcs-dmd-2 is relatively laterally constrained, approximately 1.2 km along dip, and is lenticular in geometry (Fig. 7H).

Silty shale facies (ssh-2): Facies ssh-2 overlies lfrf-2, mcrrs-2, and hcs-2 and is dark gray to variagated gray, silty to sandy shale 5 to 20 meters thick (Fig. 5). Where a clean outcrop can be examined, bioturbation intensity is moderate to high, including Planolites, Thalassinoides, and Schaubertrichnus. The contact with facies lfrf-2, mcrrs-2, and hcs-2 is abrupt (Table 1).

Sego Sandstone Member: Sequence 3 Facies Assemblage D

Medium-grained, trough cross-bedded facies (mtcs-3): Facies mtcs-3 is an upper fine- to lower-medium-grained, trough cross-bedded, to lenticular sandstone. The lower portion contains ground carbonaceous material, mud rip-up clasts, and occasionally oyster hash and bone fragments. Its thickness varies from 8 to 16 meters, and its base is highly erosional (Figs. 8I, J, 10) (Table 1). In places it overlies facies om-2, whereas in other locations it is unconformable on top of csh-c-2. In two documented locations this facies has eroded through multiple stratigraphic horizons of more basinward facies and rests on top of facies rb-2 (Figs. 5, 8I, J).

Interpretations of the Sego Sandstone Member Facies Interpretations

Interpretation of the Buck Tongue.—The lack of bed forms and sedimentary structures indicates pervasive bioturbation (i.e., a high bioturbation index), which is generally associated with low sedimentation rates and stable physicochemical parameters commonly found in open marine, mid-shelfal to outer-shelfal environments (MacEachern et al. 2010). This interpretation is also supported by ammonite fossils found near the study area and in other areas where the Buck Tongue crops out (Cullins 1971; Gill and Hail 1975; Molenaar and Wilson 1993).

Interpretation of Sequence 1: Delta Front.—As a whole, Sequence 1 is interpreted as a delta-front assemblage, characterized by facies lfrf-1, lffc-1, prs-1, that was later flooded, placing inner-shelfal to mid-shelfal muds on top, characterized by facies ssh-1.

Given the high degree of bioturbation, and its lateral proximity to lffc-1, a rippled, flaser-bedded and cross-bedded sandstone, facies lfrf-1 is interpreted as the low-energy margins of the delta front of an advancing lobe (Hori et al. 2001). Lffc-1 was deposited in moderate- to high-energy regimes subject to currents from multiple directions represented by the trough cross-beds and polydirectional paleocurrents (Fig. 7A). Its sharp basal contact supports the interpretation that this facies represents part of the uppermost part of a delta front that was deposited subaqueously, above fair-weather wave base, and exposed to longshore currents and tides.

Within facies prs-1, the normal grading from massive to laminated to rippled sandstone to mudstone is consistent with units A, B, C, and E of the Bouma sequence (Bouma 1962). Unit D of the Bouma sequence is missing; however, horizon D is seldom preserved in the rock record in general (Hsu¨ 1989). This facies is interpreted as shallow-water turbidites produced on the unstable front of an advancing delta or by hyperpycnal flow during flooding events in the fluvial system landward (Bates 1953; Fisher et al. 1969; Enge et al. 2010a, 2010b).

Ssh-1 is interpreted as the result of waning energy conditions leading to deposition of the lower-energy silty shale on top of lower fine sandstones. The relatively low-energy depositional environment and relatively high bioturbation suggest that these strata were deposited as inner-shelf mudstones (Hobday and Morton 1984). This facies represents a deeper-water depositional environment than facies lfrf-1, lffc-1, and prs-1, and therefore the lower contact with the underlying strata is interpreted as a flooding surface.

Interpretation of Sequence 2: Distributary Channel, Stacked Tidal Bars, Flood-Tidal Deltas, and Barrier Islands.—Csh-2 is a carbonaceous shale and in some places a coaly shale, and it overlies ssh-1, a shale that is interpreted as an open marine, mid- to inner-shelfal shale. The amount of...
carbonaceous material in csh-2 indicates a much more proximal environment of deposition. Where csh-2 is a coaly shale, it was deposited in a subaerial to nearly subaerial environment. The surface between ssh-1 and csh-2 is interpreted as a sequence boundary (Sequence Boundary 2). The interpretation of a sequence boundary is supported by the fact that this surface is laterally extensive and that downdip ssh-1 (a marine shale deposit) is juxtaposed against incision-filling sandstone that is described in the following section. These incisions are cut into facies prs-1, which represents a low-energy, inner-shelf, silty mudstone.

Facies mcrss-2, a massive to cross-bedded sandstone with rip-up clasts and large organic debris, occupies the incision of Sequence Boundary 2 and is interpreted as an incised-valley fill (Fig. 11). Twenty paleocurrents measurements in the upper portion of mcrss-2 have an overall southeast direction (Fig. 7C), which is perpendicular to the southwest–northeast orientation proposed for the shoreline (Stancliffe 1984).

Depositionally updip of the incised-valley fill, facies lfrf-2 overlies csh-2 and comprises bar forms, which are often stacked on top of one another (Figs. 5, 8D). Laterally, these bar forms pinch out into highly organic-rich mudstone and generally overlie the csh-2 facies. Based on the flaser and sigmoidal cross beds, synaeresis cracks, bar-form geometry, and lateral relationships we interpret this facies to represent stacked tidal bars, deposited in an estuarine environment (Plummer and Gostin 1981; Thomas et al. 1987).

Facies om-2 is interpreted to have been deposited in the central basin area of an estuarine system as described by Dalrymple et al. (1992). This is where the estuary was deepest and was starved of both marine and riverine sand.

Facies hcs-2 crops out at multiple stratigraphic levels and is interpreted as distal lower shoreface to lower shoreface (Dumas et al. 2005; Dumas and Arnott 2006) (Figs. 5, 8E). In the updip (northeasterly) area the hcs-2 often is part of a coarsening-upward shoreface succession with trough cross-beds (facies tcs-2) with a transition into low-angle cross-stratification that is interpreted as high flow regime and that represents upper-shoreface deposits (facies pcs-2) (Reinson 1984). In places the top of pcs-2 is rooted. Where this is the case it is interpreted as foreshore and berm deposits (Figs. 5, 8F, G). Overlying the upward-coarsening shoreface...
Fig. 8.—Photographs of A, B) facies prs-1, C) mcrss-2, D) lfrf-2, E) hcs-2, F) rooted tcs-2, G) csh-c-2, H) tcs-dmd-2, and I, J) mits-3.
succession are often the csh-c-2 facies, a coal, and ssh-oys-2 facies, a silty shale with sporadic oyster beds. Facies csh-c-2 is interpreted to have been deposited in a swamp to coastal-plain environment, as expected in case of a complete, upward-coarsening and prograding shoreface succession. Because of the interpreted low energy, occurrence of oyster shell hash, thin beds, and the presence of organic material of facies ssh-oys-2, this facies is interpreted as a lagoonal, back-barrier mudstone. Barrier shoreface sandstones are found down dip of this facies, supporting this interpretation. Facies tcs-dmd-2 has been the focus of recent detailed research indicating flood-tidal-delta affinity. Paleocurrents indicate a bidirectional pattern with a significant landward component (York et al. 2011). Given the tidal indicators, such as bidirectional cross-beds, sigmoidal bedding, and double mud drapes, we interpret this facies to represent a flood tidal delta, in agreement with York et al. (2011). Furthermore, the following stratigraphic relationship further supports this interpretation: facies tcs-dmd-2 pinches out landward into facies csh-c-2, which represents a lagoonal, back-barrier mudstone; facies tcs-dmd-2 is juxtaposed seaward with facies hcs-2 and tcs-2, which are lower- and upper-shoreface sandstones interpreted to represent a preserved barrier island.

The thin-bedded, upper-very-fine- to lower-fine-grained, rippled to flaser-bedded shaly sandstone to sandstone with a high degree of bioturbation and occasional root traces that characterizes facies rb-2 are interpreted as tidal-flat deposits (Kumar and Sanders 1974). Interfingering sandstones and shales in Sequence 2, ssh-2, is the result of waning energy conditions leading to deposition of the lower-energy silty shale on top of lower-fine-grained sandstones. Because of the relatively low energy and relatively high degree of bioturbation we interpret this facies as inner-shelf mudstones (Hobday and Morton 1984). Also, because this facies represents a deeper-water depositional environment than facies mcrss-2 and lffc-2, the lower contact with the underlying strata is interpreted as a flooding surface.

**Interpretation of Sequence 3: Distributary Channel.**—The upper-fine- to lower-medium-grained, trough cross-bedded to lenticular sandstone, mtcs-3 is interpreted as distributary-channel and mouth system deposits, filling an incised valley. The lower portion contains ground organic woody material, mud rip-up clasts, and occasionally oyster hash and bone fragments. Its thickness varies from 8 to 16 meters, and its base is highly erosional (Fig. 10). Its basal contact is erosional in the northwest portion of the study area and sharp in the southeast portion of the study area. This basal surface is interpreted as a sequence boundary.

**Sequence Stratigraphic Surfaces**

The following summary is a more detailed explanation of why the surfaces that are documented in this study are interpreted as sequence boundaries and flooding surfaces, using the definitions set forth in the literature (Mitchum 1977; Posamentier and Vail 1988; Van Wagoner et al. 1988; Van Wagoner et al. 1990; Neal and Abreu 2009). Flooding surfaces have been identified in each of these sequences, and they are identified with two numbers; the first represents which sequence the surface is found in, and the second is the number of the flooding surface in that sequence.
For example, the first flooding surface to appear above Sequence Boundary 1 is identified as flooding surface 1-1, whereas the second flooding surface to appear above Sequence Boundary 2 is identified as flooding surface 2-2. Minor flooding surfaces in largely aggradational strata were not numbered; we consider a minor flooding surface to be where less than two facies are missing across the flooding surface, for example, marginal marine shale deposited on top of hummocky cross-stratified sandstone.

![Incised-valley fill overlying Sequence Boundary 2. Photo taken just east of section 28 (Figs. 4, 5).](image1)

![Detailed view of section 15 (Nate Springs Draw) (Figs. 4, 5) with a corresponding photo. All three sequence boundaries are visible.](image2)
Sequence Boundary 1.—Sequence Boundary 1 marks the base of the Sego Sandstone and the top of the Buck Tongue. The base of the Sego Sandstone Member consists of facies lfrb-1, lffc-1, and prs-1, which have been interpreted as a delta-front assemblage and include the low-energy margins of the delta front, the advancing body of the delta front, and associated shallow-water turbidites.

In the case of facies lffc-1 and prs-1 the contact with the underlying Buck Tongue is sharp, with the upper-fine-grained sandstone overlying the black shale with very little silt (Fig. 6). The surface is regionally mappable, and the combination of the grain-size change and the sharp contact represents a significant basinward shift in facies. These characteristics qualify it as a sequence boundary.

Flooding Surface 1-1.—Flooding surface 1-1 is recognized by facies ssh-1, a mid-shelfal shale abruptly overlying the delta-front assemblage below. FS 1-1 is exposed in the northwest portion of the study area, but it has been eroded in the southeast portion of the study area by incision at Sequence Boundary 2 (Figs. 5, 12).

Sequence Boundary 2.—Sequence Boundary 2 is a highly erosional surface that can be mapped throughout the study area; however, the highest amount of relief within the incision and the most discordant facies juxtaposition is located in the central and northwest portions of the study area (Fig. 5). At its deepest incision, there are eighteen meters of relief, as seen in measured section 28 (Figs. 9, 11). This incised valley is filled with facies mcrss-2 and lffc-2, which have been interpreted as a distributary-mouth facies assemblage, as well as facies lfrf-2 and rb-2, which have been interpreted as stacked tidal bars and tidal flats (Fig. 5). These tide-influenced distributary-mouth deposits overlie the ssh-1 facies in the central to northwest portions of the study area and the delta-front assemblage to the southeast (Fig. 5). Where incisional relief is high, these incised-valley-fill deposits juxtapose and onlap the ssh-1 facies, which is constituted by a mid-shelfal shale. In places, the ssh-1 facies is overlain by the csh-2 facies, a carbonaceous shale that is coaly in places.

The incisional nature of the surface with tide-influenced distributary deposits onlapping mid-shelfal shales represents a significant basinward shift in facies and is identified as a sequence boundary.

Flooding Surface 2-1.—On top of the incised-valley fill there is a consistent deepening of facies. Toward the southeast of the study area this is marked by ssh-2 facies, a marine shale, overlying mcrss-2 and lffc-2 facies, which have been interpreted as a distributary-mouth facies assemblage (Figs. 5, 12, 13, 14). In the northwest portion of the area this surface is represented by ssh-2 and hcs-2 facies, a marine shale and lower-shoreface deposits, overlying lfrf-2 facies, which are stacked tidal bars. In parts of the study area, this surface is also marked by an increased concentration of Ophiomorpha ichnofossils. After the transgression, the system passed from a tide-dominated system into a wave-dominated system with a small amount of tide influence, as indicated by the barrier-island and shoreface assemblages with lagoonal and flood-tidal-delta deposits landward of them. It also passed into a largely aggradational system.
Flooding Surface 2-2.—SSh-2, a marine shale, overlies those more proximal flood-tidal-delta and lagoonal deposits found in the northwest portion of the study area (Fig. 5). This transgression marks the base of the Anchor Mine Tongue of the Mancos Shale.

Sequence Boundary 3.—Sequence Boundary 3 is a regionally mappable incisional surface. Incisional relief is highest, seventeen meters, in the very northwest of the study area, as documented in measured section 1 (Fig. 5). There, facies mtcs-3, a medium-grained distributary sandstone,
overlies lagoonal shales, facies om-2. Farther down depositional dip, distributary-channel deposits overlie marine shale and lower-shoreface sandstones, facies ssh-2 and hcs-2. In some areas the hcs-2 facies is truncated by the incisional contact. This can be seen between measured sections 3 and 4, 15 and 17, and 26 and 27 (Figs. 5, 10, 12, 13, 14).

The highly incisional nature of this surface, its regional extent, and the basinward shift in facies across it are all consistent with a sequence-boundary interpretation.

Flooding Surface 3-1.—Flooding surface 3-1 represents the top of the Sego Sandstone Member in the study area. The strata above this surface includes the Neslen Formation in the Book Cliffs area (Van Wagoner 1991; Willis 2000; Wood 2004; Aschoff and Steel 2011) and the Illes and Williams Fork formations in the study area (Cullins 1968; Barnum and Garrigues 1980). Where this surface overlies facies mtcs-3, a distributary-channel deposit, an oyster shell hash is commonly present, which is interpreted as a transgressive lag deposit.

**DISCUSSION AND CONCLUSION**

The Sego Sandstone Member within the study area shows significant lateral and vertical changes. The lowermost portion is characterized by Sequence Boundary 1, which represents a relative drop in sea level and the progradation of a delta system. Based on northwest to southeast gutter-cast orientation, the general shoreline geometry was southwest to northwest (Stancliffe 1984; Leckie and Krystinik 1989). Fifty-four paleocurrent measurements (Fig. 7A) indicate a southwest to northeast shore-parallel component suggesting a significant amount of wave reworking. The facies recognized in the study area change down dip from rippled and bioturbated sandstone, representing the margins of the delta, to trough cross-bedded sandstone, representing the subaqueous delta front. Farther down dip, these facies pass into event beds produced by turbidity currents, which we interpret as the front and margins of this prograding deltaic system (Fig. 7A). The upper contact of these deposits represents an overall deepening and a flooding surface. In this now lower-energy environment silty to sandy, inner shelf mudstones were deposited (Fig. 7B). This series of facies units constitute Sequence 1. Sequence 2 is marked by an incisional event at its base that placed distributary-channel sandstone and carbonaceous to coaly mudstone on top of inner-shelf mudstone. Paleocurrents from the incised-valley fill show predominately southeast, basinward currents, suggesting that these facies were deposited more up dip within the system and were more strongly affected by river processes (Fig. 7C). Another transgression is represented by a retrogradational succession of stacked tidal bars on top of incised valley fill and coaly mudstone. Lower-shoreface sandstone overlies the stacked tidal bars (Fig. 7D). Above this succession, the system was largely aggradational and is represented by the stacking of multiple shoreface sandstone, barrier-island, lagoonal, and flood-tidal-delta deposits, which were later flooded and capped with another shoreface deposit (Fig. 7E–J). This succession of retrogradational to aggradational deposits constitutes Sequence 2.

Another incisional surface marks the base of Sequence 3. This incision cuts into the lower-shoreface deposits below and in places removes the underlying lagoonal, barrier-island, and flood-tidal-delta deposits. Sequence Boundary 3 is overlain by a distributary-channel system. The paleocurrents within the distributary channel are bidirectional in nature, indicating a strong tidal component. This distributary system lies at the top of the Sego Sandstone Member in this area (Fig. 7K–L).

Similarly to the equivalent Sego Sandstone Member deposits in the Book Cliffs, the Sego Sandstone Member in the study area is characterized by three sequence boundaries (Fig. 15) and is heavily influenced by tidal processes as indicated by the pervasiveness of lenticular and flaser bedding, double mud drapes, reactivation surfaces, bidirectional paleocurrents, synaeresis cracks, and low-diversity, stressed...
ichnofossil assemblages (Nio and Yang 1991; MacEachern et al. 2007). However, in the Book Cliffs area no clear transition from a tide-dominated, fluvio-deltaic system to an aggradational shoreface, barrier-island, and flood-tidal-delta system has been documented. Paleogeographic maps were compiled based on our new and existing data for three phases during the deposition of the Sego Sandstone Member for the area between Rangely, Colorado and the Book Cliffs in Utah (Fig. 16). The paleogeographic reconstruction for the Book Cliffs area was compiled from a cross section produced by Wood (2004). The matching number of sequence boundaries, roughly coeval timing of deposition and similar thickness of the Sego Sandstone Member in the study area and the Book Cliffs suggest that this is a plausible interpretation. However, direct ties have still not been made to the Sego Sandstone Member in the Book Cliffs area, and until done so with finer-scale biostratigraphic data, it is not certain that each of these sequence boundaries are laterally continuous between the two geographical areas. The timing of phases I, II, and III are shown in Figure 5 and are located at the base of Sequence 1, the top of Sequence 2, and the base of Sequence 3. Phase I was during a time when tide-dominated deltas were present in both geographic regions. However, during phase II the Rangely, Colorado, area was characterized by barrier islands and flood-tidal deltas, whereas the Book Cliffs area was characterized by tidal creeks and possibly smaller deltas (Wood 2004). Phase III represents yet another time of strong progradation of tidal deltas, placing the Rangely, Colorado, area in a distributary-channel system, with the delta front and delta toe farther basinward to the southeast (Fig. 16).

In order to explain the transition during phase II, the distributary channel-system must have been either flooded due to transgression or laterally displaced through avulsion. Large-scale avulsions have been documented in the modern and have been shown to completely change the axes of the fluvial valley (Blum and Price 1998; Blum and Törnqvist 2000). We propose that this type of avulsion was responsible for relocating the distributary river valley within the Sego Sandstone Member and allowed long-shore transport and tidal processes to dominate. There are two possibilities for why this large avulsion event is not seen in the Book Cliffs area: 1) the rivers in that area did not experience this large avulsion, perhaps because of a different coastal paleogeography; 2) if the rivers did undergo this large avulsion, the evidence was not preserved; the subsequent incisional event when the distributary reoccupied the area could have removed any evidence of avulsion (i.e., a transition to non-fluvio-deltaic environments). This latter scenario would require a higher magnitude of erosion in the Book Cliffs, which given the proximity of the two areas is difficult to explain. However, the fluvio-deltaic system in the Book Cliffs area may have been slightly larger, or the accommodation space in the Book Cliffs area might have been slightly lower. Either of these controls would have produced larger incisions. Evidence for early Laramide deformation in central Utah (~ 77 Ma) is reported by Ashoff and Steel (2011). Their isopach maps show a distinct thinning across the San Rafael Swell at ~ 77 Ma (Ashoff and Steel 2011). This early deformation could be the explanation of reduced accommodation rates in the Book Cliffs area, whereas the Sego Sandstone Member north of Rangely, Colorado, was less proximal to this early deformation and thus had slightly higher accommodation rates.

The Sego Sandstone Member exposed on the northern and southern limbs of the Rangely anticline represents tide-dominated deposits and consists of three sequences. Sequence Boundary 1 places the Sego Sandstone Member on top of the Buck Tongue and is overlain by a prograding delta lobe. Sequence Boundary 2 is marked by thick (18 m) incised-valley-fill deposits composed of distributary channels, stacked tidal bars, and tidal flats. Overlying these fill deposits, the depositional environment changes from a fluvio-deltaic system to a barrier-island and flood-tidal-delta system. We propose that this change was driven by a large avulsion that displaced the distributary system. Subsequently the distributary system reoccupied the area and produced Sequence Boundary 3.

The documented stratigraphic variations, which we interpret as being the result of spatio-temporal changes in the paleogeography, also have important implications for reservoir quality and hydrocarbon exploration. The evolution of the Sego Sandstone Member from deltaic to tide-dominated deltaic system to a barrier-island and flood-tidal-delta system and back into a distributary system provides much stratigraphic heterogeneity within only sixty to seventy meters of stratigraphy and fourteen kilometers laterally. In Sequence 1, the delta-lobe complexes could be highly connective in nature. In Sequence 2, the flood-tidal-delta deposits have already been identified as a hydrocarbon reservoir resource (York et al. 2011); however, because of their relatively small volume and lateral discontinuity, these types of reservoirs would require a different development strategy. Sequence 3 should be similar to Sequence 1 in terms of lateral connectivity.

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REFERENCES

Fig. 5.—Stratigraphic cross section of the Sego Sandstone with the associated facies labels. Outcrop photos with their corresponding stratigraphic columns are seen for Amphitheater (Fig. 13), Nate Springs Draw (Fig. 12), and White River North (Fig. 14).