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HIGH-RESOLUTION CORRELATION OF THE UPPER CRETACEOUS STRATIGRAPHY BETWEEN THE BOOK CLIFFS AND THE WESTERN HENRY MOUNTAINS SYNCLINE, UTAH, U.S.A.

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STRATIGRAPHY BETWEEN THE BOOK CLIFFS AND THE WESTERN
HENRY MOUNTAINS SYNCLINE, UTAH, U.S.A.**

By

Drew L. Seymour

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University of Nebraska, 2012

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This study presents high-resolution correlations of the Upper Cretaceous stratigraphy between the Book Cliffs and the western Henry Mountains Syncline in Utah. The objective of this study is to understand changes in patterns of regional sediment dispersal during the Late Cretaceous on the western margin of the Cretaceous Western Interior Seaway. The intensely studied Book Cliffs consist of formations deposited in terrestrial, marginal-marine, and open-marine environments. A composite section was logged at Coal Canyon near Green River, UT. The western Henry Mountains Syncline is located in south-central Utah ~135 km S-SW of Coal Canyon. A composite section was logged at Blind Trail. High-resolution correlation between the Book Cliffs and Henry Mountains is not straightforward because the correlative interval in the Henry Mountains succession is highly condensed (~1015m) relative to the Book Cliffs succession (>1750m). This is in part due to their proximal vs. distal locations from the Sevier thrust front and unequal rates of accommodation creation caused by spatially variable subsidence and uplift patterns. Correlating at high-resolution from Coal Canyon to the Henry Mountains section poses similar challenges as correlating from the eastern Book

Cliffs to the Wasatch Plateau because key stratigraphic surfaces in shallow-marine successions cannot necessarily be carried into coeval coastal plain strata up-depositional dip. Radiogenic isotope ages and biostratigraphic data provide age constraints on correlations between the Coal Canyon and Blind Trail sections. Correlations are based on vertical facies and depositional environmental stacking patterns, and changes in sediment dispersal directions at discrete stratigraphic horizons derived from 745 paleocurrent measurements. Recognition of these patterns suggest that the Muley Canyon Sst., Muley Canyon Coal Zone at the base of the Masuk Fm., and the Masuk Fm. correlate to the Star Point Fm., basal Blackhawk transgressive coal zones, and the Blackhawk Fm., respectively, in the Wasatch Plateau. These interpretations provide the means to then correlate the Henry Mountains and Book Cliffs sections as well as allowing pinning points that constrain correlations both up- and down-stratigraphic section.

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INTRODUCTION

Correlating stratigraphic successions at high-resolution on regional and inter-regional scales allows a broader understanding of the evolution of paleogeography, sediment dispersal, complex basin filling, and the responses of depositional systems to both allogenic and autogenic processes. Recognizing and tracing key stratal relationships at a local scale can facilitate the prediction of optimal sites to explore for accumulations or concentrations of energy resources, such as hydrocarbons and coal, as well as other mineral resources. New regional correlations between the Upper Cretaceous stratigraphy of the southern Uinta and western Henry Mountains basins of Utah provide the potential to understand controls on sediment dispersal, paleogeography, relative sea-level history, and complex basin filling on the western margin of the Cretaceous Western Interior Seaway (KWIS; Fig. 1). Previous regional correlations have been suggested between the Book Cliffs and western Henry Mountains Syncline (Peterson and Ryder, 1975; Eaton, 1990; Corbett et al., 2011) have not been rigorously tested and are constrained by sparse and low-resolution chronometric data such as palynological biozonation. The present study presents a detailed, high-resolution correlation scheme for the condensed Upper Cretaceous section in the western Henry Mountains Syncline and the time-equivalent, relatively expanded Book Cliffs succession, with emphasis on the Campanian interval. Radiogenic isotope ages and molluscan biostratigraphic data from previous researchers provide broad age constraints on correlations. Two detailed composite vertical sections were measured at Blind Trail (Figs. 2, 3) on the western limb of the Henry Mountains Syncline and at Coal Canyon (Figs. 4, 5) in the Book Cliffs immediately northeast of

Fig. 1. - **A)** Aerial image of south-central and east-central Utah showing the location of regional exposures in the Book Cliffs, Wasatch Plateau, and Henry Mountains. Measured sections are shown by red dots at Blind Trail and Coal Canyon. "NE of Watis Road section" taken from Fig. 2. of Hampson et al. (In Press). **B)** Paleogeography of North America during the Campanian showing the location of Utah in relation to the Sevier Orogen and the Western interior Seaway (modified from Roberts and Kirschbaum, 1995; Willis and Gabel, 2003). **C)** Regional cross-section of the Western Cordilleran Foreland Basin in Utah and Colorado illustrating the westward thickening of Cretaceous sediments (highlighted) toward the foredeep. Red vertical line highlights the section of interest in this study (after Armstrong, 1968; Olsen et al., 1995).

Fig. 2. - Map of Henry Mountains Syncline with geology from Hunt et al. (1953). Cretaceous units modified to recent nomenclature include Ktm (Tarantula Mesa Sst.), Kmm (Masuk Fm.), Kmc (Muley Canyon Sst.), Kmbg (Blue Gate Shale Mbr.), Kmf (Ferron Sst.), Kmt (Tununk Shale Mbr.), Kd (Dakota Fm.) Figure modified from Birgenheier et al. (2009).

Fig. 3. - Close up aerial image of Blind Trail in the Henry Mountains showing the path of the Blind Trail measured section. Units dip $\sim 30^\circ$ to the east-northeast and include Ktm (Tarantula Mesa Sst.), Kmm (Masuk Fm.), Kmc (Muley Canyon Sst.), Kmbg (Blue Gate Shale Mbr. of the Mancos Shale), Kmf (Ferron Sst.), Kmt (Tununk Shale Mbr. of the Mancos Shale), Kd (Dakota Fm.). Black dots are locations where GPS readings were taken.

Green River, Utah. Logged sections record thicknesses, lithologies, sedimentary structures, trace fossils, and paleocurrent directions of ~750 m and ~1015 m of almost fully exposed upper Cretaceous successions at Coal Canyon and Blind Trail, respectively (Appendix B). Correlations were based not only on age constraints, but were strengthened by vertical and lateral facies and depositional environmental stacking patterns from measured sections. Correlations were also informed by previously published regional correlations between adjacent regions such as the Wasatch and Kaiparowits Plateaus (Peterson and Ryder, 1975; Eaton, 1990; Jinnah and Roberts, 2011; Hampson et al., 2011, In Press). Most paleogeographic studies of the Campanian in southern- and east-central Utah neglect to incorporate the Henry Mountains succession. The present study places the western Henry Mountains Syncline into a broader inter-regional paleogeographic context.

GEOLOGIC SETTING

Upper Cretaceous sedimentary rocks in the Book Cliffs and the western Henry Mountains Syncline formed on the western margin of the Cretaceous Western Interior Seaway (KWIS; Fig. 1). Sediments were sourced from the Sevier Fold and Thrust Belt to the west and transported generally eastward across the > 1600 km wide, < 4800 km long (north-south elongate) Cordilleran foreland basin (Kauffman, 1977). Various magmatic arc terrains to the southwest may also have been Cretaceous sediment sources at times (Lawton and Bradford, 2011). The Cordilleran foreland basin fill is asymmetric in cross-section and thickens to the west due to tectonic loading of uplifted strata in the

Fig. 4. - Location map of the Book Cliffs/Wasatch Plateau region showing location of Coal Canyon and approximate area of Wasatch Plateau NE of the "Wattis Road" section taken from Hampson et al. (In Press).

Fig. 5. - Close up aerial image of Coal Canyon showing the path of the Coal Canyon measured section. Units include Kbh (Blackhawk Fm. & Mancos Shale), Kc (Lower Castlegate Mbr. of the Castlegate Fm.), and Kmbb-Kt (Buck Tongue Mbr. of the Mancos Shale to Tuscher Fm. interval). The Kmbb-Kt interval includes the Buck Tongue Mbr. of the Mancos Shale, Sego Sst., Neslen Fm., Bluecastle Tongue Mbr. of the Castlegate Fm., Farrer Fm. and incomplete Tuscher Fm. Black dots are locations where GPS readings were taken. See Figure 4 for location.

Sevier Fold and Thrust Belt causing flexural subsidence that allowed a thick succession of Upper Cretaceous sediments to accumulate (Fig. 1). During the latest Cretaceous – Paleogene, the large Cordilleran foreland basin was locally partitioned by basement-involved, thick-skinned (Laramide-style) uplifts leading to the creation of several sub-basins within the larger foreland basin (Dickinson et al., 1988). Basement-cored uplift far inland on the North American continent beginning in the Late Campanian is thought to have been caused by a change in angle, from steep to shallow, of the subducting Farallon plate under the western margin of the North American plate (Dickinson and Snyder, 1978; Saleeby, 2003; DeCelles, 2004).

The Book Cliffs are a series of nearly continuous outcrops along the southern margin of the Uinta Basin extending over 300 km in length from east-central Utah near Helper to western Colorado near Grand Junction (Fig. 4). The cliffs reveal Campanian strata of the Mesaverde Group from broadly west to east in both depositional dip and strike sections in two dimensions, and abundant side canyons within them provide local three dimensional control. The stratigraphy of the Book Cliffs has been intensely studied and consists of eastward thinning siliciclastic wedges of non-marine to marginal-marine deposits that interfinger with fully-marine offshore shale (Young, 1955; Fisher et al., 1960). These deposits have been interpreted to record relative sea-level fluctuations in a predominantly regressive succession during the Late Cretaceous attributed to cyclical variations in, and complex interplay among, local tectonism, sediment supply, and eustatic sea-level position (e.g. Van Wagoner, 1990; Howell and Flint, 2003; Hampson,

Fig. 6. -Time-space correlation of Upper Cretaceous stratigraphic units in Utah. Timescale created using TS-Creator (Ogg and Lugowski, 2007) modified to the timescale of Cobban et al (2006). Diagonal lines represent time gaps bounded by unconformities. Dashed lines represent unconformities with uncertain ages and unknown gaps in time. Red dots represent points of biostratigraphic control from ammonites or inoceramids and yellow dots represent dated bentonites. Other sources: Peterson (1969a, b); Gill and Hail (1975); Peterson and Ryder (1975); Peterson et al. (1980); Fouch et al. (1983); Eaton (1991, 1990); Shanley and McCabe (1995); Hettinger (1995); Van Wagoner (1995); Yoshida (1996); Willis (2000); Willis and Gabel (2003); Lawton et al. (2003); Kirschbaum and Hettinger (2004); Christensen, (2005); Roberts et al. (2005); Edwards et al. (2005); Cobban et al. (2006); Pattison (2007); Jinnah et al. (2009); Hampson (2010), Hampson et al. (2011, In Press); Zhu et al. (In Press).

2010). The Book Cliffs succession is entirely Campanian in age (Fig. 6) and the western portion (west of Green River) contains, from oldest to youngest, the shallow-marine Star Point Formation, the coastal to shallow-marine Blackhawk Formation, the non-marine Castlegate Formation (lower, middle, and Bluecastle Tongue members), and the non-marine Price River Formation. In the eastern Book Cliffs (east of Green River) the Castlegate Formation passes laterally into the non-marine lower Castlegate Member, marine Buck Tongue Member of the Mancos Shale, coastal and near-shore-marine Sego Sandstone – Anchor Mine Tongue Member of the Mancos Shale – Neslen Formation interval, and non-marine Bluecastle Tongue Member of the Castlegate Formation. Overlying the Bluecastle Tongue Member of the Castlegate Formation and Neslen Formation are the non-marine Farrer and Tuscher Formations.

Coal Canyon is located immediately northeast of Green River, Utah (Figs. 4, 5) and south-southeast of the extensively studied Tuscher Canyon section. In the low country south and west of the prominent cliffs, as well as east of the Wasatch Plateau, are moderately continuous exposures of the earlier, Cenomanian – Santonian, stratigraphy consisting of the Dakota Formation, various members of the Mancos Shale, and Ferron Sandstone (Figs. 1, 4). To the west, the Book Cliffs are linked to the NNE trending Wasatch Plateau that similarly exposes time-equivalent Upper Cretaceous rocks to those in the Book Cliffs and other surrounding regions. The stratigraphy in the Wasatch Plateau consists of the Dakota Formation, Mancos Shale, Ferron Sandstone, lower Blue Gate Shale of the Mancos Shale, Emery Sandstone, upper Blue Gate Shale, Star Point Formation, mostly non-marine Blackhawk Formation, Castlegate Formation, and Price

Fig. 7. - Cross-section of nearly all of the Upper Cretaceous succession between Blind Trail, the northern Wasatch Plateau, and Coal Canyon. The Book Cliffs section is expanded relative to the Henry Mountains section. Thicknesses of units in the Wasatch Plateau section are from Dubiel (2000), Edwards et al. (2005), and Hampson et al. (2011, In Press). Projection of the Panther Tongue Member of the Star Point Formation into the Book Cliffs is from Kirschbaum and Hettinger (2004). Location of cross-section is in Figure 1.

River Formation (Fig. 7). The Wasatch Plateau and the eastern Book Cliffs are separated by the San Rafael Swell (Figs. 1, 4), a basement-cored uplift across which the Mesaverde Group is erosionally thinned or missing (Lawton, 1983).

The western Henry Mountains Syncline (Fig. 2) is in south-central Utah, ~ 135 km S-SW of the Book Cliffs at Green River, Utah. The Henry Mountains Syncline (or “Basin” of some authors) is a structural basin formed during the Cretaceous – Paleogene Laramide Orogeny and intruded by large laccoliths of Eocene - Oligocene age (Hunt et al. 1953). The western limb of the syncline spectacularly exposes the Cenomanian – Campanian succession (Fig. 8) consisting, in stratigraphic order, of the non-marine to shallow-marine Dakota Formation, marine Tununk Member of the Mancos Shale, shallow-marine to coastal non-marine Ferron Sandstone, marine Blue Gate Member of the Mancos Shale, shallow-marine to non-marine Muley Canyon Sandstone, coastal and non-marine Masuk Formation, non-marine Tarantula Mesa Sandstone, and non-marine “beds on Tarantula Mesa” (Fig. 7). The Campanian succession includes the uppermost Blue Gate Shale to “beds on Tarantula Mesa” interval (Fig. 6). Early research on these units was recorded by Gilbert (1877), Hunt and Miller (1946), Hunt et al. (1953), Peterson and Ryder (1975), and Eaton (1990). Recent detailed stratigraphic and sedimentologic descriptions of the Upper Cretaceous section at Blind Trail (type reference section of Eaton, 1990) can be found in Birgenheier et al. (2009), Fielding, (2010), Fielding et al. (2010), Antia and Fielding (2011), and Corbett et al. (2011). The Upper Cretaceous section in the Henry Mountains Syncline is somewhat incomplete and

Fig. 8. - Oblique aerial view of the Upper Cretaceous succession at Blind Trail on the western limb of the Henry Mountains Syncline illustrating the spectacular exposure of the section. Beds are dipping $\sim 30^\circ$ to the east. Black line is the vertical transect through the measured section. Image is from Google Earth.

condensed relative to the Book Cliffs. This stratigraphic condensation is in part due to their proximal vs. distal locations from the Sevier thrust front and unequal rates of accommodation caused by spatially variable subsidence and uplift patterns.

AGE CONSTRAINTS

The ages of Upper Cretaceous units in the Book Cliffs and Henry Mountains are variably constrained by ammonite and inoceramid biostratigraphy, following the timescale of Cobban et al. (Fig. 6; 2006), and sparse radiogenic isotope ages (Roberts et al., 2005; Jinnah et al., 2009; Zhu et al., In Press). Locations of bentonite samples, inoceramids, and ammonites used to constrain the stratigraphy of Book Cliffs, western Henry Mountains Syncline, and neighboring regions are illustrated in Figure 9. Palynological analysis has also been used by previous researchers (Peterson and Ryder, 1975; Fouch et al., 1983) to constrain units in these regions, but the taxa present typically have broad ranges and therefore lack the resolution needed for detailed correlations. Using available data from previous researchers provided broad constraints on regional correlations between the two measured sections (Fig. 6).

Book Cliffs

Age assignment of units in the Book Cliffs is based primarily on the molluscan biostratigraphy of Gill and Hail (1975), who recorded the stratigraphic level and location of ammonites and inoceramids in the far eastern portion of the Book Cliffs

Fig. 9. - Location map of bentonites samples, inoceramids, and ammonites used to constrain the stratigraphy of the Book Cliffs, Wasatch Plateau, western Henry Mountains Syncline, and neighboring regions. Data derived from references in Figure 6. Cross-sections in Figures 7 and 10 (A-A'), and 17 (B-B') also shown.

in eastern Utah and western Colorado. Dating of units further along the middle and western portions of the Book Cliffs by subsequent researchers is based on physical correlations using key sequence stratigraphic surfaces of units containing these index fossils to their up-depositional dip time-equivalent facies (e.g., Van Wagoner, 1995; Kirschbaum and Hettinger, 2004). These correlations are accepted in order to constrain the Campanian stratigraphy at Coal Canyon in this study. A summary of the ages of the units is given below in ascending stratigraphic order and illustrated in Figure 6.

Fouch et al. (1983) claim that the Panther Tongue Member of the Star Point Formation at Price, Utah correlates to marine mudrocks of the Mancos Shale six miles north of Green River, Utah which contain *Scaphites hippocrepis I*. The correlations were made using bore-hole log data and by physical correlation. These correlations suggest that the Star Point Formation is earliest Campanian in age (83.5 – 81.86 Ma; Fig. 6). The lower members of the Blackhawk Formation that are not exposed in the Book Cliffs at Coal Canyon (Spring Canyon, Aberdeen, and lower Kenilworth Members) are not well dated because of a lack of biostratigraphic data. Pattison (2007) reported occurrences of *Scaphites hippocrepis III* in distal, coarse-grained sandstones and oolitic ironstone bodies further east that physically correlate to near the top of the Aberdeen Member near Green River, Utah. This correlation suggests that the lower two members of the Blackhawk Formation are Lower Campanian in age (around 81.86 Ma; Fig. 6). Gill and Hail (1975) reported several ammonite species in the Mancos Shale immediately below the shallow-marine lower Castlegate Sandstone from Sulphur Canyon to Prairie Canyon in the eastern Book Cliffs (Fig. 9). In stratigraphic order, they reported *Baculites* sp. (weak flank ribs),

Baculites obtusus, *Baculites maclearni*, and *Baculites asperiformis* with the lowermost specimen found ~110 m below the lower Castlegate Sandstone at Sulphur Canyon (Fig. 9). According to Van Wagoner (1995), this interval correlates to the Desert Member of the Blackhawk Formation further up-depositional dip to the west. Recent wireline log correlations by Hampson (2010) indicate that this ammonite bearing interval falls within the Desert Member and also within the shallow-marine Castlegate parasequences C1-C3. Therefore, the contact between the Blackhawk and Castlegate Formations is no younger than mid Middle Campanian (somewhere in the range 80.56 – 75.84 Ma, but likely around 79-77 Ma based on correlations to well constrained units in other regions discussed later; Fig. 6). The lower Castlegate member of the Castlegate Formation is bracketed by the appearance of *Baculites asperiformis* below and *Baculites perplexus* above in the marine Buck Tongue Member of the Mancos shale in the Sulphur – Prairie Canyon (Fig. 9) area (Gill and Hail, 1975), suggesting that the lower Castlegate Member is mid Middle Campanian in age (somewhere in the range 80.56 -75.84, but likely around 78-76 Ma; Fig. 6). Many authors have correlated the basal contact of the lower Castlegate member at Sulphur Canyon (Fig. 9) up-depositional dip into the Green River area and further west, indicating a similar age at Coal Canyon (Fouch et al., 1983; Van Wagoner, 1995; Yoshida et al., 1996; Willis, 2000; Willis and Gabel, 2003; Pattison, 2010; Hampson, 2010; Hampson et al. (2011, In Press; and others). At these same localities and further east at Adobe Creek (Fig. 9), the Buck Tongue Member of the Mancos Shale contains *Baculites perplexus* and *Baculites gregoryensis* suggesting it is mid – upper Middle Campanian in age (somewhere between 80.56 – 75.84 Ma, but likely around 77-

76 Ma; Fig. 6). The Sego Sandstone contains a lower sandstone unit and an upper sandstone unit separated by the Anchor Mine Tongue of the Mancos Shale. The Lower Sego Sandstone is constrained by the appearance of *Baculites perplexus* and *Baculites gregoryensis* below and *Baculites scotti* above in the Anchor Mine Tongue at various sections from Sulphur Canyon to the Corcoran Mine (Fig. 9; Gill and Hail, 1975). The Upper Sego Sandstone also contains *Baculites scotti* suggesting that the entire Sego Sandstone is mid – upper Middle Campanian in age (somewhere in the range 80.58 – 75.56 Ma, but likely around 76 – 75 Ma; Fig. 6). According to Kirschbaum and Hettinger (2004), the Neslen Formation correlates down-depositional dip eastward to an interval containing the Corcoran, Cozzette, and Rollins Sandstone Members of the Mount Garfield Formation. Gill and Hail (1975) report *Didymoceras nebrascense* from a marine tongue of the Mancos Shale between the Corcoran and Cozzette Members at Watson Creek (Fig. 9) and *Didymoceras stevensoni* in the Cozzette Member at Dirty George Creek (Fig. 9). These ammonite occurrences and correlations suggest that the Neslen Formation at Coal Canyon, by correlation, is lower Upper Campanian in age (~75.56 – 75.08 Ma; Fig. 6). The Bluecastle Tongue Member of the Castlegate Formation is hard to identify at Coal Canyon and is thought to pinch out near Floy Canyon (Kirschbaum and Hettinger, 2004). It is difficult to correlate the Bluecastle Tongue Member further east, but it is likely time-equivalent to the Cozzette or Rollins Members of the Mount Garfield Formation. Fouch et al. (1983) claim that the top of the Castlegate Formation (i.e. top of Bluecastle Tongue Member) in Price Canyon correlates to the Cozzette Member, but based on the correlations of Kirschbaum and Hettinger (2004) it is unclear what time-

equivalent level the Bluecastle Tongue Member correlates to exactly. Cobban (1973) reported *Exiteloceras jenneyi* from just east of Grand Junction, CO in a tongue of Mancos Shale just below the Rollins Member and therefore deduced that the Rollins Member likely lies in the *Didymoceras cheyennense* ammonite zone. These ammonite occurrences suggest that the upper part of the Neslen and Bluecastle Tongue Member at Coal Canyon may be as young as lower – mid Upper Campanian in age (75.08 – 74.67 Ma). The Farrer and Tuscher Formations are Upper Campanian in age based on palynology from Fouch et al. (1983) and their stratigraphic position above previously discussed units.

Western Henry Mountains Syncline

The Upper Cretaceous succession in the western Henry Mountains Syncline is well constrained by molluscan biostratigraphy and radiogenic isotope ages (Peterson and Ryder, 1975; Peterson et al., 1980; Eaton, 1990, 1991; and Zhu et al., In Press); however, the Campanian section is not confidently dated due to the absence of bentonite ages, sparse biostratigraphic data, and a lack of robustness and resolution inherent in palynological analyses. Recent work by Roberts et al. (2005) and Jinnah et al. (2009) has allowed for improved age determination of the Campanian section based on regional correlations to the nearby Kaiparowits Plateau where radiogenic isotope ages from bentonite beds have been calculated (Fig. 9). Outlined below is a summary of how the ages of the Upper Cretaceous units in the western limb of the Henry Mountains Syncline section have been determined.

Peterson and Ryder (1975) record the stratigraphic position and location of ammonite and inoceramid index fossils in the Henry Mountains region, with many specimens coming from Blind Trail (Fig. 9). The Dakota Formation is considered no younger than Late Cenomanian based on molluscan fossils found within the upper part of the formation. The Tununk Shale of the Mancos Shale contains *Mytiloides mytiloides* in the lower-middle part, *Collignonicerias woollgari* in the upper-middle part, and *Prionocyclus hyatti* and *Prionocyclus macombi* near the top at Blind Trail and Tank Wash. These ammonite occurrences suggest the Tununk Shale is Lower – mid Middle Turonian (within the range 93.5 – 90.21 Ma; Fig. 6). Recent work on the Ferron Notom Delta complex in and around Caineville in the northern Henry Mountains region by Zhu et al. (In Press) suggests that the upper contact of the Tununk Shale with the overlying Ferron Sandstone is no younger than 91.25 ± 0.77 Ma calculated using $^{40}\text{Ar}/^{39}\text{Ar}$ isotope ages from a 25-35 cm thick bentonite in the uppermost Tununk Shale (Fig. 6). In their study they report five bentonites ages (UH-BHA-B1 – UH-BHA-B5) within, immediately below, and immediately above the Ferron Sandstone (Fig. 6). The youngest bentonite (UH-BHA-B4) within the Ferron Sandstone is from near the top of the formation above a coal seam, and yields an age of 90.64 ± 0.25 Ma (Fig. 6). The uppermost bentonite was found immediately above the Ferron Sandstone within the lowermost Blue Gate Shale of the Mancos Shale and yielded an age of 87.27 ± 0.54 Ma (Fig. 6). These new data suggest that the Ferron Sandstone is entirely mid Middle Turonian in age in this region ($\sim 91.25 - 90.64$ Ma; Fig. 6) and confirm that there is a hiatus between the Ferron Sandstone and the Blue Gate Shale recording a $\sim 3-3.5$ Ma hiatus (Fig. 6). The Blue Gate

Shale contains *Clioscaphtes veriformis* at ~700 ft. (213 m) above the base and *Desmoscaphtes bassleri* at ~545 ft. (166 m) below the top of the member at Swap Canyon and Blind Trail, respectively (Fig. 9; Peterson and Ryder, 1975). Peterson et al. (1980) also report *Clioscaphtes choteauensis* from 500 and 563 ft. (152 and 172 m) above the base of the member. Eaton (1990) reports ammonites belonging to the *Scaphites leei* and *Scaphites hippocrepis* groups at University of Colorado Museum locality 84155 just northeast of Steele Butte. All these data suggest that the Blue Gate Shale spanned from Upper Coniacian to lowermost Campanian (~87.27 to slightly younger than 83.5 Ma; Fig. 6).

The Muley Canyon Sandstone, Masuk Formation, and Tarantula Mesa Sandstone lack robust age-diagnostic data. The Masuk Formation contains Campanian palynomorphs reported by previous researchers (Peterson and Ryder, 1975; Peterson et al., 1980; Eaton, 1990; 1991) but as mentioned earlier, these taxa are inherently broad-ranging and do not allow the resolution desired for high-resolution regional stratigraphic analysis. Recent work by Roberts et al. (2005) and Jinnah et al. (2009) in the Kaiparowits Plateau have allowed for improved age constraints on the Muley Canyon Sandstone – Tarantula Mesa Sandstone interval from bentonites found within the correlative Wahweap and Kaiparowits Formations (Figs. 6, 9). Jinnah et al. (2009) report the age of a bentonite (CF05-B) 40 m above the base of the Wahweap Formation in the lower part of the middle member to be 80.1 ± 0.3 Ma (Fig. 6). Based on the correlations made by Peterson and Ryder (1975), Peterson et al. (1980), Eaton (1990), and Jinnah and Roberts (2011), the lower, middle, upper, and capping sandstone members of the Wahweap

Formation correlate to the lower, middle, and upper members of the Masuk Formation and the Tarantula Mesa Sandstone, respectively (Fig. 6). These correlation suggest that the lower part of the middle member of the Masuk Formation must also be about 80.1 Ma in age (Fig. 6). This claim in turn suggests that the Muley Canyon Sandstone and lower member of the Masuk Formation are lowermost Campanian to lower Middle Campanian in age (83.5 – 80.1 Ma; Fig. 6). Roberts et al. (2005) report several bentonites ages from the Kaiparowits Formation with the oldest bentonite (KDR-5) yielding an age of 75.96 ± 0.14 Ma (Fig. 6). This bentonite lies ~80 m from the base of the formation. Based on the regional correlations between the Wahweap and Masuk Formation/Tarantula Mesa Sandstone, these data suggest that the interval from the lower part of the middle member of the Masuk Formation to the “beds on Tarantula Mesa” is lower – upper Middle Campanian in age (~80.1 – 75.96 Ma; Fig. 6).

Based on these data alone, the stratigraphic successions of the two regions of interest can be correlated with each other, although with some ambiguity, particularly in the Campanian section (Figs. 6, 7). The uppermost Blue Gate Shale and Muley Canyon Sandstone in the western Henry Mountains Syncline are roughly time-equivalent to the Mancos Shale, Star Point Formation, and lower Blackhawk Formation in the Book Cliffs (Fig. 7). The Masuk Formation and Tarantula Mesa Sandstone are broadly equivalent to the middle and upper Blackhawk Formation and the lower Castlegate Member of the Castlegate Formation (Fig. 7). The “beds on Tarantula Mesa” are therefore equivalent to the middle Castlegate Formation and Buck Tongue Member of the Mancos Shale in the western and eastern Book Cliffs, respectively. These correlations are robustly supported

by stratigraphic analysis of each section, by recognizing depositional environmental and facies stacking patterns, as well as understanding the stratigraphy of the nearby Wasatch Plateau.

FACIES, STRATIGRAPHY, AND CORRELATIONS

As mentioned previously, the Book Cliffs succession has been intensely studied, and the facies and stratigraphy have been documented in great detail (e.g. Young, 1955; Lawton, 1983; Fouch et al., 1983). With the introduction of modern sequence stratigraphy, the quality and lateral continuity of exposure in the Book Cliffs has allowed great insights into the understanding of allogenic and autogenic controls on stratigraphy (Van Wagoner, 1995; Olsen et al., 1995, Yoshida et al., 1996, Willis, 2000; McLaurin and Steel, 2000, 2007; Miall and Arush, 2001; Howell and Flint, 2003; Willis and Gabel, 2003; Kirschbaum and Hettinger, 2004; Adams and Bhattacharya, 2005, Pattison, 2005, 2005, 2007, 2010; Davies et al., 2006; Hampson, 2010, Charvin et al., 2010, Aschoff, 2010, Aschoff and Steel, 2011, Hampson et al. 2011). A majority of the research performed in the Book Cliffs has focused on the down-depositional dip (west to east) coastal plain to marginal-marine sequence stratigraphy. A particular challenge that has been the focus of more recent studies is correlating well-understood key stratigraphic surfaces up-depositional dip from marine into non-marine successions in the western Book Cliffs and the Wasatch Plateau (Hampson et al., In Press). This challenge is mirrored when trying to correlate the Campanian section in the Book Cliffs to the time-equivalent succession in the western Henry Mountains Syncline. As will be shown in the

following sections, the stratigraphy of the western Henry Mountains Syncline was deposited in a more proximal, obliquely up-depositional dip position from the Sevier thrust front relative to the section at Coal Canyon. In addition to the inherent complications of correlating marginal-marine strata up-depositional dip into non-marine strata, attempting to correlate these depositional environments from near Green River to the Henry Mountains Syncline is further limited by a lack of continuous outcrop between sections (in contrast to continuous outcrops up-depositional dip along the entire Book Cliffs into the NE Wasatch Plateau) due to the intervening San Rafael Swell uplift and Henry Mountains intrusions. Because the section at Blind Trail is obliquely up-depositional dip from the section at Coal Canyon, it is logical to correlate to a section in either the western Book Cliffs or the Wasatch Plateau. Therefore, in order to link the Campanian depositional systems in the western Henry Mountains Syncline to those of the Book Cliffs at Coal Canyon, an along-depositional strike (or slightly oblique) section must be used from the Wasatch Plateau. Recent work by Hampson et al. (2011, In Press) provides the link in their analyses of the Star Point and Blackhawk Formations in the Wasatch Plateau. I chose a section in the northeastern-most portion of the Wasatch Plateau just northeast of the ‘Wattis Road’ section of Hampson et al. (2011, In Press). The justification for the choice of this particular section is given below.

Facies

Conventional facies analyses have been performed on all three sections used in this study by previous authors, and so detailed facies descriptions will not be given here.

The facies classification used herein was derived from previous work and my own analysis of the two measured sections (Appendix B). Facies from the Book Cliffs section at Coal Canyon are derived solely from the measured section (Appendix B). Readers are referred to Edwards et al., (2005) and Hampson et al. (2011, In Press) for detailed facies descriptions of the Wasatch Plateau section, and Birgenheier et al. (2009), Fielding (2010), Fielding et al. (2010), Antia and Fielding (2011), and Corbett et al. (2011), for detailed descriptions of the western Henry Mountains section. Emphasizing only the Campanian interval, 22 facies were recognized and organized into 7 facies associations. A summary of these facies and associations is given in Table 1 (Appendix A).

Stratigraphy and Correlations

The Campanian stratigraphy of the three sections from Blind Trail, ‘Wattis Road’, and Coal Canyon has been correlated and separated into four intervals (Intervals 1 – 4) shown in Figure 10. The emphasis here is on correlation of the Campanian interval because such correlations have not yet been made in detail. The correlations are not straightforward because the western Henry Mountains Syncline section is slightly condensed relative to the section at Coal Canyon, and contains more abrupt vertical changes in depositional environments. Correlations made in the lower part of the Upper Cretaceous (Dakota to Blue Gate Shale/Mancos Shale interval) are straightforward and less complex (Fig. 7), but are important for understanding foreland basin evolution during the Late Cretaceous.

Fig. 10. - Cross-section of the Lower - Middle Campanian successions at Blind Trail, northern Wasatch Plateau, and Coal Canyon. Wasatch Plateau section and right half of the diagram modified from Hampson et al. (2011, In Press). The left half represents a broadly along- depositional strike section between Blind Trail and immediately NE of the 'Wattis Road' section. The right half represents a depositional dip section between the northern Wasatch Plateau and the Book Cliffs to Coal Canyon. Relative amounts of local progradation and retrogradation shown in curves alongside the sections. Vertical lines represent times of aggradation. Progradational, retrogradational, and aggradational patterns within in the intervals correlate well between the northern Wasatch Plateau and western Henry Mountains regions, but no to the section at Coal Canyon in the Book Cliffs. Locations of sections are shown in Figures 1 and 9.

Dakota – Blue Gate Shale/Mancos Shale Interval. --- Thicknesses of these units at Blind Trail have been measured by previous researchers (Birgenheier et al. 2009; Fielding, 2010; Fielding et al., 2010; Antia and Fielding, 2011). Thicknesses of the Dakota through Blue Gate/Mancos Shale interval in the Wasatch Plateau and near Coal Canyon where these units are in the subsurface or crop out in the lowland country were compiled from Dubiel (2000) and Edwards et al. (2005). The correlations are simple: the Dakota Formation, Tununk Shale/Mancos Shale, and Ferron Sandstone correlate to the same units in the Wasatch Plateau and in the low country below the Book Cliffs (Fig. 7). There is a disconformity between the Ferron Sandstone and the Blue Gate Shale in the Henry Mountains region spanning 3-3.5 Ma during which there was erosion or non-deposition of most of the lower Blue Gate Shale (Fig. 6). This disconformity has yet to be documented in the Wasatch Plateau and Book Cliffs regions where the lower Blue Gate Shale is preserved. The Blue Gate Shale at Blind Trail correlates to an interval containing part of the lower Blue Gate Shale, the Emery Sandstone, and part of the upper Blue Gate Shale in the Wasatch Plateau and western Book Cliffs (Fig. 6) and to the Mancos Shale further east near Coal Canyon where the Emery Sandstone is absent because it has pinched out down-depositional dip at a position located further west (Fig. 10; Dubiel, 2000). According to Dubiel (2000), the Emery Sandstone pinches out down-depositional dip just past Price River Canyon in the western Book Cliffs; a location far enough east for the Emery Sandstone to reach the western Henry Mountains Syncline if it pinches out in a similar position in the southern part of the Wasatch Plateau. The Emery Sandstone is divided into a northern part that contains paleocurrent data indicating mainly eastward

sediment dispersal and a southern part that contains paleocurrent data suggesting initially east-southeastward dispersal that was subsequently deflected northeastward (Edwards et al., 2005). From these data it seems the Emery Sandstone appears to be missing from the succession at Blind Trail either: 1) because sediment was not dispersed in that direction from the Wasatch Plateau or 2) because the Blind Trail area was just beyond the reach of Emery Sandstone deposition down-depositional dip. Speculative distal equivalents of the Emery Sandstone are the thin sandstone benches evident in large cliffs near the Caineville Gap (Fig. 11) along the Fremont River and elsewhere in the northern Henry Mountains (Fig. 2), but further research is needed in order to confirm this hypothesis.

Interval 1: Lowermost Campanian. --- Interval 1 is the lowermost Campanian interval beginning in the uppermost Santonian/lowermost Campanian. In the western Henry Mountains succession, the record of Interval 1 begins in the upper 75 m of the Blue Gate Shale, below the Muley Canyon Sandstone (Figs. 6, 10). In the Wasatch Plateau and western Book Cliffs, Interval 1 begins in the Mancos Shale slightly below the Panther Tongue Member of the Star Point Formation. Interval 1 at Blind Trail consists of alternating offshore deposits and shallow-marine deposits of the uppermost Blue Gate Shale and lower Muley Canyon Sandstone (Fig. 10). In the northern Wasatch Plateau, Interval 1 similarly consists of alternating offshore and shallow-marine deposits of the Mancos Shale and Panther/Storrs/Ksp010 Tongues (Hampson et al., 2011, In Press). At Coal Canyon, Interval 1 is in the subsurface and consists of undifferentiated Mancos Shale.

Fig. 11. - Photograph of the Blue Gate Shale near the Caineville Gap (location in Fig. 2). Thin sandstone benches (arrows) in prodeltaic shales may be distal equivalents to the Emery Sandstone of the southern and northern Wasatch Plateau.

The Muley Canyon Sandstone has been informally subdivided into five units (A – E), and a detailed sequence stratigraphic assessment of the entire formation is summarized in Figure 12 after Birgenheier et al. (2009). Interval 1 of this study consists of the upper part of the Blue Gate Shale and Units A and B of the lower Muley Canyon Sandstone which, together are interpreted to comprise a low-frequency falling stage sequence set (FSSS) containing two complete high-frequency sequences underlain by a partial sequence.

At Blind Trail, the Blue Gate Shale consists of a broadly coarsening upward package of interbedded siltstone and sandstone containing a single, 1-2 meter thick convolute- and chaotically-bedded debris flow breccia (Fig. 13). Cross-bedding and ripple cross-lamination preserve variable paleocurrent directions indicating generally east-southeastward sediment dispersal. A large-scale clinoform set also records a maximum dip direction to the SE (142°; Birgenheier et al., 2009). The lithology and sedimentary structures suggest this succession was deposited in a prograding prodeltaic (proD; Table 1) to middle delta front (mDF; Table 1) environment. The middle delta front facies is sharply overlain by fine- to medium-grained sandstone containing unidirectional low angle dipping surfaces of Unit A (Fig. 12) of the basal Muley Canyon Sandstone. This unit is interpreted as a deltaic mouthbar (Dmb; Table 1) and falling stage systems tract (FSST) of the first high-frequency sequence in the Muley Canyon Sandstone. A sequence boundary at its base records a basinward shift in facies and a foreshortened stratigraphy (Birgenheier et al., 2009).

MULEY CANYON SANDSTONE

Fig. 12. - Illustration of measured section, facies character and architecture, and sequence stratigraphic interpretations from the Muley Canyon Sandstone at Blind Trail (modified from Birgenheier et al., 2009).

Fig. 13. - Photographs of a spectacular sub-marine debris flow breccia in the upper part of the Blue Gate Shale in the middle delta front facies at Blind Trail. Person for scale is 1.7 m tall.

Overlying the mouthbar unit is an interval of offshore transition (OT; Table 1) deposits of interbedded siltstone and sandstone coarsening upward into very fine-grained sandstone (Fig 12). The base of this unit is a maximum flooding surface (MFS) and marks the base of Unit B of the Muley Canyon Sandstone. These offshore transition deposits are interpreted as a progradational highstand systems tract (HST) of the first Muley Canyon high-frequency sequence. The offshore transition deposits are overlain by fine-grained middle – upper shoreface sandstone interpreted as the FSST of the second Muley Canyon high-frequency sequence (Fig. 12). The base is erosional and the vertical change from offshore transition to middle – upper shoreface deposits represents a foreshortened stratigraphy and a basinward shift in facies. This suggests the base is a sequence boundary. Subsequent to shoreface deposition was a rise and then fall in paleobathymetry leading to the deposition of a second set of offshore transition and shoreface deposits (the rest of Unit B and Interval 1; Figs. 10, 12). The second set of offshore transition facies consists of very fine-grained sandstone and is bounded below by a MFS. This unit conformably coarsens upward into fine-grained shoreface sandstone interpreted as a progradational HST of the second Muley Canyon high-frequency sequence (Fig. 12).

As mentioned earlier Interval 1 consists of two complete sequences underlain by a partial sequence. The vertical facies and depositional environmental shifts in Interval 1 thus record three falls and two rises in formative water depth. According to Birgenheier et al. (2009) there are minor lateral and shoreward – basinward facies and thickness variations within these units and their defining internal and bounding surface

characteristics and stacking order are remarkably consistent over a $\sim 100 \text{ km}^2$ (40 mi^2) area suggesting an allogenic control on deposition.

In the northern Wasatch Plateau, Interval 1 exhibits a similar succession NE of the ‘Wattis Road’ section of Hampson et al. (2011, In Press). The base is in offshore shale of the Mancos Shale and coarsens upward into the falling stage deposits of offlapping distal – proximal delta front lobes, containing sediment gravity-flow horizons, of the Panther Tongue Member of the Star Point Formation (Olariu et al., 2010; Enge et al., 2010; Hampson, 2011). Similar to the deltaic deposits in the uppermost Blue Gate Shale and basal Unit A of the Muley Canyon Sandstone at the Blind Trail section, the Panther Tongue Member in the northern Wasatch Plateau preserves paleocurrent trends suggesting a range from southwestward to southeastward progradation (Posamentier and Morris, 2000; Olariu et al., 2010; Enge et al., 2010; Hampson et al., 2011). Moreover, in both regions the deltaic deposits are overlain by two coarsening-upward packages of offshore shales and shoreface deposits, with the first package being more distal than the deltaic deposits below (Storrs Tongue Member of the Star Point Formation in Wasatch Plateau section and first offshore transition – shoreface package above delta mouthbar in the Muley Canyon Sandstone at Blind Trail; Fig. 10). These facies and depositional environmental shifts, and overall progradational-retrogradational-progradational stacking patterns, are the basis of the correlations made in Interval 1 (Fig. 10). The similarities also justify the choice of the location NE of the ‘Wattis Road’ section of Hampson et al. (2011, In Press) in the northern Wasatch Plateau to be the link point between the western Henry Mountains Syncline and Book Cliffs at Coal Canyon.

One difference in Interval 1 between the northern Wasatch Plateau and Blind Trail sections is that the Wasatch Plateau section is documented as being a relatively conformable succession of shallow marine parasequences whereas the section at Blind Trail records high-frequency sequences with minor gaps in the rock record as previously described. This suggests that there was along-depositional strike variability in accommodation between these regions with a higher rate of accommodation in the northern Wasatch Plateau relative to the western Henry Mountains region allowing for a more conformable succession to accumulate there. Along-depositional strike variability in accommodation during the deposition of Interval 1 has been documented between the northern and southern Wasatch Plateau by Hampson et al. (2011). They report the northern Wasatch Plateau as having had a higher tectonic subsidence rate (i.e. higher rate of accommodation) relative to the southern Wasatch Plateau. This interpretation is evidenced by a progradational-retrogradational-progradational stacking pattern (Fig. 10) in the northern part as opposed to an entirely progradational stacking pattern of time-equivalent non-deltaic Star Point parasequences in the southern part (See Fig. 9 of Hampson et al., 2011). These interpretations suggest that during deposition of Interval 1, the western Henry Mountains region may also have had a lower rate of accommodation relative to the northern Wasatch Plateau leading to deposition of the less conformable succession at Blind Trail. The progradational-retrogradational-progradational stacking pattern (Fig. 10) of Interval 1 at Blind Trail suggests that it too was a region with a higher rate of accommodation relative to the southern Wasatch Plateau, however.

Hampson et al. (2011) also question how the Panther Tongue Member of the Star Point Formation could be strongly progradational (deposited during a short-term relative sea level fall) during a time with an increasing rate of subsidence (Fig. 10). They suggest that because the Panther Tongue Member prograded so much further into the basin relative to the overlying Storrs Tongue Member and the underlying Star Point Formation parasequence (Ksp050; Fig. 10), the rate of local sediment supply must have increased. They attribute this increase in sediment influx to active thrusting that provided additional sediment from the Wasatch and Santaquin culminations via a sediment entry point between the Paxton and Charleston – Nebo thrust systems (See Fig. 14 of Hampson et al., 2011). The correlative deltaic units at Blind Trail also have a strongly progradational character despite possibly being deposited during a time where the subsidence rate was increasing (evidenced by a similar progradational-retrogradational-progradational stacking pattern as the northern Wasatch Plateau; Fig. 10). This similarity suggests that the progradation of deltaic units at Blind Trail may also have been the result of increased sediment supply, or that sediment supply remained constant and the rate of subsidence was, in fact, not increasing during this time. Based on the correlation between deltaic units of the uppermost Blue Gate Shale/basal Unit A of the Muley Canyon Sandstone to the Panther Tongue Member in the northern Wasatch Plateau and not to the time-equivalent non-deltaic Star Point parasequences in the southern plateau, the latter hypothesis of an increased rate of sediment supply during an increased rate of subsidence seems more probable.

Interval 2: Lower Campanian. --- Interval 2 spans most of the Lower Campanian and the record begins within the Muley Canyon Sandstone in the western Henry Mountains Syncline (Fig. 10). In the northern Wasatch Plateau and western Book Cliffs, Interval 2 begins at the base of the Blackhawk Formation. At Blind Trail, Interval 2 consists of alternating coastal, fluvial, and shallow-marine deposits of the upper part of the Muley Canyon Sandstone and also the lowermost part of the Masuk Formation known as the Muley Canyon Coal Zone (Tabet, 2000; Birgenheier et al., 2009). In the northern Wasatch Plateau, Interval 2 similarly consists of alternating coastal, non-marine, and shallow-marine deposits of the up-depositional dip coastal/non-marine equivalent of the shallow-marine Spring Canyon Member and lower Aberdeen Member of the Blackhawk Formation (Fig. 10; Hampson et al., 2011, In Press). Interval 2 is the key interval in establishing regional correlations because the facies and depositional environmental shifts recorded upward through this interval in the Henry Mountains and northern Wasatch Plateau regions are the anchor points from which the rest of the successions (both above and below Interval 2) at Blind Trail, the northern Wasatch Plateau, and Coal Canyon are correlated. Correlations made in Interval 2 provided the primary basis for the choice of the NE of ‘Wattis Road’ section as the linking section between the Blind Trail and Coal Canyon successions rather than a section further east along the Book Cliffs or further south along the middle to southern Wasatch Plateau.

Fig. 14. - A) Muley Canyon Coal Zone near Sweetwater Creek in the western Henry Mountains. Coal beds present both below and above coarsening-upward bayhead delta sandstone unit. B) Heterolithic siltstone, carbonaceous shale, and sandstone in the top part of the Muley Canyon Coal Zone below the first major fluvial sandstone in the Masuk Formation at Blind Trail. Red lines trace the erosional base (high-frequency sequence boundary) of the major fluvial sandstone. Blue is the maximum flooding surface of the 4th Muley Canyon/Masuk high-frequency sequence.

Interval 2 at Blind Trail and the surrounding Henry Mountains region consists of Units C, D, and E of the Muley Canyon Sandstone (Fig. 12) and the overlying coal-rich zone in the basal Masuk Formation (Fig. 14). Together, these units comprise two complete high-frequency sequences that together make up a low-frequency transgressive sequence set (TSS) and maximum flooding zone (MFZ; Birgenheier et al., 2009). Unit C (Fig. 12) erosionally overlies shoreface sandstone of Unit B (upper part of Interval 1) and consists of heterolithic and thickly interbedded fine-grained sandstone and siltstone packages deposited in tidally influenced coastal-fluvial channels (Ctch, Chtch; Table 1). Tidal and coastal influence is indicated by carbonaceous partings, mud drapes, bimodal paleocurrent trends, and inclined heterolithic stratification (IHS) in places. Paleocurrent data indicate a W – E and NNW – SSE bimodality suggesting a broadly NNE – S-SW paleoshoreline orientation (Appendix B). The base of Unit C is interpreted as both a high- and low-frequency sequence boundary (Fig. 12) based on a basinward facies shift from shoreface to coastal-fluvial deposits recorded at the erosional contact representing a foreshortened stratigraphy. Unit C (Fig. 12) is interpreted as the lowstand to transgressive systems tracts (LST/TST) of the third Muley Canyon high-frequency sequence with a MFS at the top (Birgenheier et al., 2009).

Subsequent to tidal-fluvial deposition was a rise and fall in formative water depth leading to deposition of shoreface (SF; Table 1) medium-grained, hummocky cross-stratified sandstone of Unit D. Unit D is interpreted as a HST of the third Muley Canyon high-frequency sequence and is erosionally overlain by trough cross-bedded and plane-parallel to low-angle-laminated fine- to medium-grained sandstone deposited in estuary

channel (ECh; Table 1) and estuary mouth (Em; Table 1) environments of Unit E (Fig. 12). Evidence for estuarine deposition is recorded by bimodal (herringbone) paleocurrent distributions with an E-NE – W-SW bimodality suggesting tidal activity, rhythmically interlaminated sandstone and carbonaceous siltstone, and overall transgressive stacking pattern with outer estuary mouth deposits overlying inner estuary channel facies. The base of Unit E is an erosional sequence boundary (Fig. 12), recording a basinward shift in facies from shoreface below to estuarine channels above, representing a foreshortened stratigraphy. Unit E (Fig. 12) is the uppermost unit in the Muley Canyon Sandstone and is interpreted as the LST/TST of the fourth Muley Canyon/Masuk high-frequency sequence with a locally bioturbated transgressive surface at or near the top of the unit throughout the western Henry Mountain region (Birgenheier et al., 2009).

Overlying Unit E is interbedded siltstone and sandstone, coarsening-upward sandstone, carbonaceous shale, and coal of the Muley Canyon Coal Zone in the basal Masuk Formation. The top of this zone is the top of Interval 2 in the western Henry Mountains region. Units within the Muley Canyon Coal Zone were deposited in coastal mires and swamps (CcsM; Table 1), coastal overbank (Cob; Table 1), coastal tidal-fluvial channels (Chtch, Ctch; Table 1), and inner – central estuarine and lagoonal environments (Eb; Table 1). Readers are referred to Birgenheier et al. (2009) and Corbett et al. (2011) for a detailed sedimentologic, stratigraphic, and ichnologic description of the Muley Canyon Coal Zone. They interpret the Muley Canyon Coal Zone as a low-frequency maximum flooding zone (MFZ) separating a low-frequency transgressive sequence set (TSS) below (rest of Interval 2) from a low-frequency highstand sequence set (HSS)

above (rest of the Masuk Formation; Fig. 19). The coarsening-upward sandstone unit previously mentioned within the Muley Canyon Coal Zone is interpreted as the deposits of a bayhead delta (Eb; Table 1), which overlies marine interlaminated sandstone and siltstone containing the most marine influence in the Masuk Formation. Evidenced for the most marine influence consists of a trace fossil assemblage with an extremely high diversity and density relative to the rest of the Masuk Formation (Corbett et al., 2011). The base of this coarsening-upward unit is also interpreted as the MFS (Fig. 14) of the fourth high-frequency sequence in the Muley Canyon/Masuk succession. Coal located below this coarsening-upward unit is considered the uppermost part of the fourth Muley Canyon/Masuk high-frequency transgressive systems tract (TST) and coal above this unit is considered part of the fourth high-frequency highstand systems tract (HST; Fig. 14). The rest of the fourth high-frequency HST varies locally and consists of heterolithic, interbedded siltstone, sandstone, and carbonaceous shale below the first major, laterally continuous channel unit within the Masuk Formation (Fig. 14). The coarsening-upward unit is not present at Blind Trail, thus the MFS is correlated to a horizon within the coal interval.

Like Interval 1, Interval 2 in the western Henry Mountain succession records several relative rises and falls in formative water depth leading to abrupt shifts (both landward and seaward) in facies and interpreted depositional environments upward through the stratigraphy. In general, the stacking pattern in Interval 2 in the western Henry Mountains Syncline records two cycles of non-marine/coastal to shallow-marine progradation-retrogradation followed lastly by coastal/non-marine aggradation-

progradation (Fig. 10). From base to top, the tidal-fluvial channels of Unit C record coastal/non-marine progradation-retrogradation (Fig. 10). Shoreface sandstone of Unit D records shallow-marine progradation followed by continued progradation of estuarine channels in the lower part of Unit E (Fig. 10). Estuary mouth deposits of the upper part of Unit E and coastal plain mire and swamp deposits of the lower part of the Muley Canyon Coal Zone record retrogradation and aggradation (Fig. 10). Finally, the coarsening-upward bayhead delta deposit and overlying coal beds record progradation/aggradation (Fig. 10).

Interval 2 in the northern Wasatch Plateau just NE of the ‘Wattis Road’ section of Hampson et al. (2011, In Press) similarly contains non-marine/coastal to shallow-marine units that record relative sea-level cyclicity. The base is the lower contact of the Blackhawk Formation (Fig. 10) in alluvial-to-coastal plain deposits that conformably overlie the Star Point parasequence Ksp010 (Hampson et al., 2011, In Press). Facies in these non-marine/coastal deposits have been reported by Hampson et al. (In Press) but have been incorporated into the facies and facies associations herein (Table 1) and include multi-storey amalgamated and heterolithic channels (Fmach, Fhch; Table 1), small single-storey splay channels (Aspl; Table 1), paleosols and overbank deposits (Apo, Cob; Table 1), and coastal plain mire and swamp coals (Ccsn; Table 1). These deposits are the up-depositional dip equivalents to the shallow-marine Spring Canyon Member of the Blackhawk Formation (Fig. 10). Four prominent parasequences (SC4-SC7) within the Spring Canyon Member have been mapped by Hampson et al. (In Press) recording overall progradation-aggradation-retrogradation (Fig. 10). Each parasequence

records an orbitally forced high-order relative sea-level cycle (Howell and Flint, 2003) and contains laterally persistent coal zones up-depositional dip from the westward shoreface pinchouts associated with maximum transgression (Hampson et al., In Press). Overlying the non-marine/coastal equivalents to the Spring Canyon Member NE of the 'Wattis Road' section are shoreface sandstones of the lowermost A0 and A1 parasequences of the Aberdeen Member of the Blackhawk Formation (Fig. 10). The basal part of the Aberdeen Member is strongly progradational, as indicated by a major basinward shoreline shift of more than 50 km within parasequences A0 and A1 (Hampson et al., In Press). Subsequent to shoreface deposition was a short-term relative rise and fall in formative water depth leading to the return of alluvial-to-coastal plain deposition in the northern Wasatch Plateau region (Fig. 10). Directly overlying the A0-A1 parasequences are laterally continuous coal horizons known as the Wattis-Castlegate A-Aberdeen Coal Zone and Bob Wright-McKinnon-Castlegate B Coal Zone (Hampson et al., In Press). Similar to those in the Spring Canyon Member, these coal zones are also associated with maximum transgression and aggradation (Fig. 10).

Similar to Interval 1, Interval 2 in the northern Wasatch Plateau and western Book Cliffs is relatively conformable compared to the western Henry Mountains interval. Interval 2 at Blind Trail records abrupt vertical changes in depositional environment associated with regional sequence boundaries formed by non-marine and coastal fluvial incision, creating a foreshortened stratigraphy (bases of Units C & E; Figs. 10, 12). Although similar basinward and landward vertical shifts in depositional environment are preserved in the northern Wasatch Plateau, there are no associated sequence boundaries

at the bases of non-marine and coastal plain intervals there recording nearly continuous deposition throughout the Early Campanian (Fig. 10).

Just as in Interval 1, the conformable vs. non-conformable successions can be explained by an along-depositional strike variation in accommodation between these two regions. As with Interval 1, Interval 2 in the northern Wasatch Plateau and western Book Cliffs records a higher rate of accommodation relative to the western Henry Mountains Syncline during the Early Campanian. This is indicated by the amount of aggradation recorded, relative to Interval 2 at Blind Trail, within the shallow-marine parasequence stacking patterns further east in the Spring Canyon and lower Aberdeen Members, and abundant coal horizons up-depositional dip from those parasequences. In contrast, at Blind Trail relatively little aggradation is recorded in Interval 2 until the uppermost coal zone. Overall, the environmental shifts from non-marine/coastal to shallow-marine and back to non-marine/coastal are evident in Interval 2 at both the Blind Trail and NE of ‘Wattis Road’ sections.

The stacking pattern at Blind Trail records progradation-retrogradation within tidal-fluvial channels of Unit C that correlate to the non-marine/coastal deposits up-depositional dip from the progradational-aggradational-retrogradational Spring Canyon parasequences (Fig. 10). This non-marine interval further south (oblique along-depositional strike and in a more proximal up-depositional dip position) along the Wasatch Plateau contains large, laterally discontinuous incised valley sandbodies (Hampson et al., In Press) suggesting a regional relative sea-level fall during the early part of Interval 2. Shoreface deposits of Unit D and estuarine channel and mouth deposits

of Unit E at Blind Trail record progradation-retrogradation and correlate to progradational shoreface sandstones of the lower Aberdeen A0 and A1 parasequences and the overlying aggradational non-marine/coastal deposits (Fig. 10). Finally aggradational-progradational coastal plain coal in the MFZ and coarsening-upward estuarine bayhead delta deposits at Blind Trail correlate to one of the lower coal horizons above the lower Aberdeen A0 and A1 parasequences associated with maximum transgression and aggradation (Fig. 10).

The facies and depositional environmental stacking patterns found in Interval 2 in the northern Wasatch Plateau are not found anywhere else in the Wasatch Plateau further south from NE of the ‘Wattis Road’ section. Further east along the western Book Cliffs, the only potential candidate section with similar depositional environmental shifts from non-marine/coastal plain to shoreface and back to non-marine/coastal plain at a stratigraphic level similar to Interval 2 in the western Henry Mountains is just east of the westward termination of the lowermost Kenilworth parasequence K1 (Fig. 10). This section is ruled out as a correlative to Interval 2 at Blind Trail because it violates biostratigraphic and other geochronologic constraints shown in Figure 6. In addition, vertical facies and depositional environmental stacking patterns in Interval 1 below would no longer correlate. It is possible that Interval 2 at Blind Trail correlates to a section slightly south of the ‘Wattis Road’ section of Hampson et al., (2011, In Press; see their Fig. 2) where the depositional environmental shifts from non-marine/coastal to shoreface and back to non-marine/coastal of Interval 2 are replaced entirely by non-marine/coastal deposits and where the underlying Interval 1 correlations are still upheld;

however, this would suggest that the shoreline did not transgress as far west in the middle to northern Wasatch Plateau as in the western Henry Mountains region. I suggest that the northern Wasatch Plateau region just NE of the 'Wattis Road' section is the more appropriate along-depositional strike linking region in order to correlate from the western Henry Mountains Syncline to the Book Cliffs at Coal Canyon. Any section further south along the Wasatch Plateau would be located obliquely up-depositional dip from the western Henry Mountains region and landward of marine incursion and shoreface deposition during the late part of Interval 2. Any section further east along the Book Cliffs would be located obliquely down-depositional dip from the western Henry Mountains region.

Interval 3: lower – mid Middle Campanian --- Interval 3 spans the lower to middle part of the Middle Campanian. In the Henry Mountains region, the record of Interval 3 begins at the base of the first major fluvial sandstone in the lower member of the Masuk Formation and ends at the erosional contact between the Masuk Formation and Tarantula Mesa Sandstone (Fig. 10). In the northern Wasatch Plateau Interval 3 begins at the top of the Bob Wright-McKinnon-Castlegate B Coal Zone just above the A0 and A1 Aberdeen shallow-marine parasequences and ends at the erosional contact between the Blackhawk and Castlegate Formations (Fig. 10). Interval 3 at Blind Trail consists of a series of non-marine-to-coastal/estuarine fluvial and floodplain deposits with varying degrees of tidal influence. In the northern Wasatch Plateau, Interval 3 consists of aggradational floodplain and fluvial deposits (Hampson et al., In Press). Interval 3 is the

first interval to correlate to more than exclusively undifferentiated Mancos Shale in the Coal Canyon section (Figs. 7, 10). Interval 3 at Coal Canyon consists of an overall regressive succession of offshore, shallow-marine, and coastal deposits of the Aberdeen, Kenilworth, Sunnyside, Grassy, and Desert Members of the Blackhawk Formation.

In the western Henry Mountains Syncline the base of Interval 3 is the base of the first laterally continuous major fluvial sandstone in the lower member of the Masuk Formation above the Muley Canyon Coal Zone (Fig. 14). The Masuk Formation is separated into three members; lower, middle, and upper. The lower member is sandstone, heterolithic sandstone and siltstone, and chaotically mixed sandstone and siltstone-dominated (Fig. 15) and consists of laterally continuous horizons of non-marine and coastal amalgamated tidal-fluvial and fluvial channels (Fmach, Fhch, Chtch, Ctch; Table 1). Corbett et al. (2011) calculated channel and channel belt dimensions from average trough cross-bed set thicknesses and other criteria, and reported that channels in the lower member averaged 5.4 m in depth and channel belt widths averaged 1,238 – 1,925 m. They compare these estimates with average measured channel and channel belt dimensions of 5.8 m for individual channel depth and 2,502 – 4,390 m in channel belt width. They also report an average sediment dispersal direction towards the east for the lower member. In the present study, a new detailed measured section was compiled through the Masuk Formation at Blind Trail, and additional paleocurrent data from the measured section suggest a significant W-NW component in addition to the eastward mode (Appendix B). Along with other facies indicators such as inclined heterolithic interbedding of sandstone and siltstone, syneresis cracks, paired mud drapes, and

Fig. 15. - Internal character of channel units within the lower and middle Masuk Formation displaying sandstone, heterolithic, and chaotically mixed sandstone and siltstone-dominated channel fills. The internal architecture of channel units consist dominantly of lateral accretion sets that preserve small-scale sedimentary structures oriented roughly perpendicular to the large-scale dipping surfaces. Picture from Blind Trail.

carbonaceous laminae on trough cross-bed foresets, the bimodal paleocurrent distribution suggests the channels were deposited with varying degrees of tidal influence. Large-scale (macroform) dipping surfaces (Inclined Heterolithic Stratification; IHS) are the dominant internal architectural feature in these channels, and IHS sets are oriented roughly perpendicular to small-scale paleoflow structures suggesting the HIS sets formed by lateral accretion (Fig. 15). This relationship between small-scale sedimentary structures and large-scale architecture is consistent throughout the Masuk Formation (although less prevalent in the upper member) and is interpreted to record the preservation of migrating bar forms within high-sinuosity meandering channel belt systems (Corbett et al., 2011).

The middle member of the Masuk Formation contains a higher proportion of mudstone-dominated facies relative to the lower and upper members (Fig. 16). This member is dominated by floodplain and overbank deposits, and heterolithic to chaotically mixed channels (Aspl, Apo, Fhch, Chtch; Table 1) with a few horizons of laterally continuous single- to multi-storey, sandstone-dominated channels (Ctch; Table 1). On average, channel belt dimensions within the middle member increase in depth and width relative to the lower member despite decreasing in proportion. Average estimated and measured channel depths are 6.6 m and 10.3 m respectively, and average estimated and measured channel belt widths are 1,810 – 2,571 m and ~4,200 m respectively (Corbett et al., 2011). Paleocurrent trends in the middle member recorded by Corbett et al. (2011) suggest a NE paleoflow direction, although my additional data from Blind Trail record a

Fig. 16. - Mudstone-rich middle member and sandstone-dominated upper member of the Masuk Formation and overlying Tarantula Mesa Sandstone at Blind Trail (location in Figs. 1, 2, 3).

bimodal distribution involving NNW and SE paleoflow directions, suggesting tidal influence similar to channels in the lower member (Appendix B).

The upper member of the Masuk Formation (Fig. 16) is sandstone-dominated and consists of single- to multi-storey, multi-lateral, amalgamated tidal fluvial and fluvial channels (Famch, Ctch; Table 1) and a minor proportion of heterolithic channels (Chtch, Fhch; Table 1). On average, channel and channel belt dimensions within the upper member increase in depth and width relative to the lower and middle members and increase markedly in sandstone proportion. Average estimated and measured channel depths are 7.2 m and 15.8 m respectively, and average estimated and measured channel belt widths are 2,089 – 2,867 m and ~12,400 m respectively (Corbett et al., 2011). Paleocurrent trends are dominantly northward with a slight south-southeastward bimodality suggesting tidal influence (Appendix B).

The Masuk Formation (i.e. Interval 3) above the basal Muley Canyon Coal Zone (low-frequency MFZ) is interpreted as a low-frequency highstand sequence set (HSS) erosionally overlain by a low-frequency sequence boundary at the base of the Tarantula Mesa Sandstone (Birgenheier et al., 2009; Corbett et al., 2011). In general, sandstone proportion decreases from the lower to the middle member and then increases in the upper member. This suggests that there was some fluctuation in accommodation or sediment supply within the HSS, resulting in variations in the amount of fine-grained floodplain and overbank facies being preserved rather than erosionally removed due to lateral migration and repeated incision common in amalgamated channel deposits. Overall the upward low-frequency variations in the preservation of overbank floodplain

mudrocks and channel fill bodies with IHS versus amalgamated sandstone-dominated channels in the Masuk Formation are consistent with early, middle, and late highstand conditions in non-marine sequence stratigraphic models (Shanley and McCabe, 1991, 1994; Catuneanu et al, 2009). In the early to middle highstand, accommodation is high leading to increased preservation of overbank facies and in the late highstand accommodation is reduced and channel bodies begin to amalgamate and erosionally remove floodplain deposits.

A similar upward trend in sand:mud ratio has been reported by Jinnah and Roberts (2011) in up-depositional dip time-equivalent rocks of the lower, middle, and upper members of the Wahweap Formation in the Kaiparowits Plateau, southwest of the Henry Mountains (Figs. 6, 9, 17). They suggest that the low-frequency fluctuations in the sand:mud ratio upward through the lower, middle, and upper members were allogenically forced by low-frequency variations in eustatic sea-level. This interpretation is based on the nature of the underlying upper Drip Tank sequence boundary (Fig. 6, 17) in the upper part of the Drip Tank Member of the Straight Cliffs Formation (Christensen, 2005), across which there is no change in paleoflow direction or sandstone composition from the units below. The interpretation is also based on the abruptness of the up-section decrease and eventual increase in the sand:mud ratio in the middle and upper members, respectively (Fig. 17). Lastly, it is based on assumed correlations to global sea level curves (Haq et al., 1987) and to an ~80 Ma sequence boundary that has been recognized across the Western Interior Basin by Van Wagoner et al. (1990) and Rogers (1998) that was followed by the subsequent Claggett transgression (Rogers et al., 1993). On the basis

Fig. 17. - Correlations and sequence stratigraphy between the Lower to Middle Campanian successions in the Kaiparowits Plateau and the western Henry Mountains Syncline. The lower, middle, and upper members of the Wahweap and Masuk Formation are correlative, suggesting the Drip Tank sequence boundary in the upper part of the Drip Tank Member (as defined by Christensen, 2005) is correlative to one of the upper two sequence boundaries in the Muley Canyon Sandstone. Observed low-frequency maximum flooding zones (MF) do not correlate between the two sections. A maximum flooding surface may be present in the middle member of the Masuk but has not yet to be recognized. Thicknesses and lithology of the Kaiparowits Plateau section are after the Alvey Wash section of Christensen (2005) and section 7 (Caine Bench) of Jinnah and Roberts (2011). See Figure 9 for location.

of correlations between the lower, middle, and upper members of the Wahweap and Masuk Formations, the upper part of the underlying Drip Tank Formation likely correlates to the upper part of the Muley Canyon Sandstone in the Henry Mountains region (Fig. 17). The correlations made in Interval 2 between the upper part of the Muley Canyon Sandstone and the basal Blackhawk Formation in the Wasatch Plateau and eastern Book Cliffs suggest that the upper Drip Tank sequence boundary is slightly older than (in between 81.86 and 80.58 Ma) the recognized ~ 80 Ma sequence boundary in the northern part of the Western Interior Basin (Fig. 6). This claim suggests that the Drip Tank sequence boundary and overlying fluctuations in the sand:mud ratio within the Wahweap Formation may not have been controlled by eustasy alone, indicated by weak association with an ~80 Ma sequence boundary and the subsequent Claggett transgression, but rather might also be partially controlled by more local allogenic forcing such as sediment supply or tectonism. The lack of coincidence between events as constrained herein suggests there is no correlation to an 80 Ma regional event (Fig. 6). Because the Masuk Formation correlates to the Wahweap Formation and has similar facies and stratigraphic organization (i.e. similar upward sand to mud trends; Fig. 17), I suggest that the low-frequency fluctuations within the Masuk Formation were also controlled by a combination of eustasy, local sediment supply, and tectonism. However, because the Masuk Formation contains more abundant tidal and near-shore influence relative to the Wahweap Formation, the low-frequency trends are likely driven by downstream forcing rather than upstream forcing, suggesting eustatic fluctuations were

Fig. 18. - Sequence stratigraphy of the Masuk Formation displaying nested high-frequency sequences within a low-frequency highstand sequence set. Facies numbers and locations refer to those in Birgenheier et al. (2009) and Corbett et al. (2011) from which this diagram is taken.

the dominant allogenic control. Birgenheier et al. (2009) and Corbett et al. (2011) suggest an allogenic control on deposition of the entire Masuk Formation, based on the lateral extent of channel belt horizons measured in outcrop exceeding predicted channel belt widths derived from channel depth estimates; however, they do not however discuss the possible types of allogenic forcing.

Within the low-frequency HSS of the Masuk Formation there is a higher-frequency level of stratigraphic organization in the form of widespread fluvial incision and migration within distinct channel belts (Fig. 18; Birgenheier et al., 2009). The bases of these channel belts are erosional and are typically overlain by transgressive amalgamated tidally-influenced heterolithic channel fills and sheet-like fluvial sandstones. These channel deposits are sharply overlain by floodplain mudrocks with more isolated channel bodies. This stacking pattern is interpreted to record the transgressive and highstand systems tracts (TST/HST) of nested high-frequency sequences (Fig. 19; Corbett, 2009; Birgenheier et al., 2009; Corbett et al., 2011). Lowstand deposits are typically erosionally removed by subsequent fluvial amalgamation, but where present consist of sheet-like fluvial sandstones. The high-frequency sequences in the lower member contain fewer highstand isolated channels relative to the middle member due to amalgamation with subsequent overlying sequence boundaries (Fig. 19). Similar to the low-frequency trends, the abundant tidal and near-shore influence in the Masuk Formation suggests that they were either located closer to the shoreline or that the high-frequency sequences were driven by downstream forcing

Fig. 19. - Schematic diagram showing high-frequency fluvial sequences within the context of the longer-term, lower-frequency sequence set. A) Low-frequency sequence set model for the upper strata of the Henry Mountains Syncline succession. The boundary between the transgressive sequence set (TSS) and highstand sequence set (HSS) is within the coal zone where the maximum flooding zone (MFZ) is identified. Fluvial stacking patterns within the HSS show an increase in floodplain mudrocks and greater preservation of isolated channels up-section. The HSS is truncated by thick fluvial deposits of the lowstand sequence set (LSS) overlying an upper sequence boundary (SB). B) Model for high-frequency fluvial sequences. Transgressive amalgamated tidally-influenced heterolithic channel fills and sheet-like fluvial sandstones overlie an erosional SB. Sharp contact with floodplain mudrocks marks the boundary with highstand deposits, which contain more isolated channel bodies. In the upper portions of the highstand, channels occasionally amalgamate with deposits from overlying sequences (from Corbett, 2009; Birgenheier et al., 2009).

rather than upstream forcing, suggesting eustatic fluctuations were the dominant allogenic control.

Interval 3 within the northern Wasatch Plateau and western Book Cliffs begins at or near the top of the Bob Wright-McKinnon-Castlegate B Coal Zone in the lower non-marine Blackhawk Formation and ends at the erosional contact between the Blackhawk and Castlegate Formations (Fig. 10). Further east along the Book Cliffs, deposits of Interval 3 change from undifferentiated non-marine units to regressive highstand shallow-marine units within the Aberdeen, Kenilworth, Sunnyside, Grassy, and Desert Members of the Blackhawk Formation. Similar to the Masuk Formation in the western Henry Mountains Syncline, the Blackhawk Formation in the Book Cliffs has been interpreted as a low-order highstand systems tract (HST) or low-frequency highstand sequence set (HSS; e.g. Howell and Flint, 2003). For a more detailed description of the non-marine Blackhawk Formation in the Wasatch Plateau and western Book Cliffs readers are referred to Hampson et al. (2005, In Press). They report that the non-marine Blackhawk Formation in the northern Wasatch plateau was deposited in alluvial-to-coastal plain environments and consists of aggradational floodplain deposits and fluvial sandbodies (facies associations F, A, and C of this study, Table 1). In contrast to the Masuk Formation, the non-marine Blackhawk Formation in the northern Wasatch Plateau seems to display relatively little stratigraphic organization in the spatial distribution of channelized sandbodies (Hampson et al., In Press). One possibility as to why little to no organization is observed is the nature of their data (widely spaced, >20 km apart, measured sections and low-resolution photographic logs of distant cliff faces, variably

covered by talus). The data may have limited interpretations of facies and stratigraphic organization. Alternatively, there may indeed be little stratigraphic organization in these rocks. The only low-frequency similarity between the Masuk and Blackhawk Formations is that channel body dimensions increase upward through the succession; however, there is local variability in this trend within the Blackhawk Formation where the opposite trend is observed (Hampson et al., In Press). In the upper part of the non-marine Blackhawk Formation, the upward increase in sandbody dimensions is interpreted to have been caused by decreasing tectonic subsidence through time (Hampson et al., In Press).

Interval 3 NE of the 'Wattis Road' section contains mostly the upper, coal-poor part of the Blackhawk Formation where channelized sandbody complexes make up ~30% of the total rock volume (Hampson et al., In Press). In the middle to upper Blackhawk Formation, laterally offset and vertically stacked channelized sandbodies that are not confined by a "master" composite erosion surface make up <10% of the total volume of fluvial units. These sandbodies do not occur at distinct stratigraphic intervals or in distinct paleogeographic regions, rather they are randomly distributed (Hampson et al., In Press). The rest of the fluvial sandbodies consist of isolated channelized units with a variety of multi-lateral and/or multi-storey internal architectures. According to Hampson et al. (In Press) the laterally offset and vertically stacked clusters formed due to large-scale avulsion processes. The lack of apparent stratigraphic organization within the upper non-marine Blackhawk Formation suggests that high-frequency variations in allogenic controls did not dominate the stratigraphic architecture in the upstream region as they evidently did in the down-depositional dip coastal plain and shallow-marine Blackhawk

Fig. 20. - Outcrop photo annotated with stratigraphy of the exposed Blackhawk and lower Castlegate Formations at the northern entrance to Coal Canyon.

Formation in the Book Cliffs, but rather autogenic avulsion processes were the dominant controls (Hampson et al., In Press).

In the Book Cliffs at Coal Canyon, Interval 3 begins within marine shale of the Aberdeen Member in the subsurface, and ends at the erosional contact between the shallow-marine to coastal/non-marine Desert Member of the Blackhawk Formation and the non-marine lower Castlegate Member of the Castlegate Formation (Fig. 20). My stratigraphic log begins at the base of the outcrop in the canyon floor within the Kenilworth Member (Fig. 10). At Coal Canyon, the members of the Blackhawk Formation consist of shallow marine offshore shale (OS; Table 1), interbedded sandstone and siltstone deposited in offshore transition (OT; Table 1) and lower shoreface (LSF) environments, amalgamated upper shoreface (USF; Table 1) sandstones, and coastal to non-marine fluvial, tidal-fluvial, overbank, and swamp deposits (facies associations F, A, and C; Table 1). These deposits have been extensively studied and interpreted to record the regressive stacking (Fig. 10) of progradational shallow- to near-shore marine parasequences and high-frequency sequences within a low-frequency highstand succession (Van Wagoner, 1995; Howell and Flint, 2003; Pattison, 2005, 2005, 2007, 2010; Davies et al., 2006; Hampson, 2010; Charvin et al., 2010; Hampson et al., 2001, 2005, 2011, In Press). A summary of the plausible allogenic controls on the stratigraphy of the Book Cliffs can be found in Howell and Flint (2003). They suggest that a combination of high-frequency orbitally forced sea-level fluctuations and thrust belt-controlled lower-frequency cycles of subsidence were the controlling mechanisms for the stratigraphic development of the Blackhawk Formation. High-frequency member-scale

cycles may broadly coincide with the high-frequency sequences within the Masuk Formation; however, correlating specific sequences would be nearly impossible or extremely difficult because of the lack of age control and continuous outcrop between the western Henry Mountains Syncline and the Book Cliffs.

Interval 4: upper Middle Campanian --- Interval 4 spans the upper Middle Campanian and its record comprises the Tarantula Mesa Sandstone in the Western Henry Mountains Syncline. In the Wasatch Plateau and Book Cliffs regions, Interval 4 is represented by the lower member of the Castlegate Formation (Fig. 10). In all of these regions, Interval 4 consists of strongly amalgamated sandstone-dominated fluvial channel deposits formed in braided or low-sinuosity river systems (Lawton, 1983, Fouch et al., 1983; Van Wagoner, 1995; Olsen et al. 1995; Yoshida et al., 1996; Howell and Flint, 2003; Adams and Bhattacharya, 2005; McLaurin and Steel, 2007; Pattison, 2010; Peterson and Ryder, 1975; Fielding et al., 2010). The bases of these formations are erosional and estimated channel depths decrease across the contact with underlying units suggesting accommodation was lower during the deposition of these units (McLaurin and Steel, 2000; Adams and Bhattacharya, 2005; Birgenheier et al., 2009; Corbett et al., 2011). Previous researchers have attributed amalgamation and sheet-like geometry of fluvial bodies to increased lateral migration of rivers within a channel belt system resulting from decreasing accommodation (cf. Shanley and McCabe, 1991, 1994; Olsen et al., 1995; Catuneanu et al., 2009; Birgenheier et al., 2009). This interpretation is consistent in a sequence stratigraphic context with the Tarantula Mesa Sandstone and

lower Castlegate member of the Castlegate Formation because these formations are interpreted as low-frequency lowstand sequence sets (LSS) formed in response to a relative fall in sea-level (i.e. decreased accommodation) resulting in widespread regional incision that created a low-frequency sequence boundary at their bases. The reduced accommodation during the deposition of the lower Castlegate Member and Tarantula Mesa Sandstone was the result of tectonic driving mechanisms indicated by changes in paleocurrent directions, provenance, fluvial styles, and basinward shifts in facies from coastal non-marine to completely non-marine (Peterson and Ryder, 1975; Yoshida et al., 1996; Howell and Flint, 2003; Adams and Bhattacharya, 2005). A similar interpretation was reported by Jinnah and Roberts (2011) for the time-equivalent Capping Sandstone Member of the Wahweap Formation in the Kaiparowits Plateau. They claim, however, that because of differences in tectonic activity in the Sevier thrust belt between the Book Cliffs and Kaiparowits regions, the sequence boundaries at the bases of the lower Castlegate Member and Capping Sandstone Member do not correlate. Based on correlations made herein, I suggest they do indeed correlate and were controlled by a time-equivalent inter-regional tectonic pulse in the Sevier Orogen to the west.

DISCUSSION

The inter-regional correlations proposed in this study between the Blind Trail, northern Wasatch Plateau, and Coal Canyon sections provide the opportunity to place the Campanian stratigraphy of the western Henry Mountains Syncline into a broader paleogeographic context with the well-studied and documented paleogeography of the

Book Cliffs and Wasatch Plateau (Fig. 21). Understanding the detailed sedimentology and stratigraphy of the Lower – Middle Campanian Intervals 1 – 4 at all the locations brings to light the relative paleogeographic (proximal vs. distal and along-depositional strike vs. down-depositional dip) positions of the three regions during each interval and how they evolved during this time. In general, the northern Wasatch Plateau section and the western Henry Mountains sections were oriented along depositional-strike. The Coal Canyon section was located somewhat down-depositional dip from the northern Wasatch Plateau and obliquely down-depositional dip from the western Henry Mountains region. Paleoshoreline orientations between the regions where there are no data are projected from regions of good quality exposure, and are more speculative.

Paleogeography

Interval 1 --- Paleoflow directions from the Blue Gate Shale of the Mancos Shale in the western Henry Mountains during Interval 1 record dominantly east-southeastward sediment dispersal trends based on ripple cross-lamination, trough cross-bedding, and a clinoform set with a maximum dip direction toward the SE. This evidence suggests a NNE – SSW trending paleoshoreline orientation (Fig. 21 A). Based on paleogeographic maps from Hampson et al. (2011, In Press) shoreline orientations in the southern Wasatch Plateau during Interval 1 were oriented NW – SE indicated by northeastward progradation of shallow-marine Star Point parasequences. Along the middle to northern Wasatch Plateau, the paleoshoreline became concave eastward with the northern part oriented roughly NNE – SSW indicated by deltaic progradation of the Panther Tongue

Fig. 21. - Maps illustrating the evolution of paleogeography in east- and south-central Utah during the Early - Middle Campanian. Arrows illustrate progradation and sediment dispersal directions. **A)** Early Interval 1 - Panther Tongue/Blue Gate Shale. **B)** Late Interval 1 - Ksp010/top shelf package in Unit B of the Mule Canyon Sandstone. **C)** Early Interval 2 - Spring Canyon 5 - 6 parasequences/Unit C of Mule Canyon Sandstone. **D)** Late Interval 2 - Aberdeen A0 - A1 parasequences/Unit D of the Mule Canyon Sandstone. **E)** Middle Interval 3 - Kenilworth 4 parasequence/Middle Masuk Formation. **F)** Interval 4 - L. Castlegate/ Tarantula Mesa Sandstone. Data from Wasatch Plateau and Book Cliffs modified after Howell and Flint (2003), Hampson (2010), and Hampson et al., (2011, In Press).

Member of the Star Point Formation toward the SSE. This paleoshoreline trend changes to NW – SE as successive parasequences in the Star Point Formation record northeastward progradation in Interval 1. These data suggest that the Wasatch Plateau and the western Henry Mountains shorelines were broadly along-depositional strike though roughly perpendicular to one another during most of Interval 1 with the northern part of the Wasatch Plateau nearly parallel to the western Henry Mountains during the early part of the interval (Fig. 21 A). During the early part of Interval 1 there were two concave westward trends (northernmost Wasatch Plateau and Henry Mountains) separated by one concave eastward trend (southern Wasatch Plateau) between the shorelines of the western Henry Mountains and Wasatch Plateau regions (Fig. 21 A). During the latter part of Interval 1 only one broader concave westward trend was present between the regions with the Wasatch Plateau shoreline prograding toward the NE and the Henry Mountains shoreline prograding toward the SE (Fig. 21 B). Coal Canyon was located in a distal open-marine, down-depositional dip position from the Wasatch Plateau during Interval 1 (Fig. 21 A, B).

Interval 2 --- As described in previous sections Interval 2 is characterized by abrupt depositional environmental shifts from non-marine/coastal to shallow-marine to non-marine/coastal in both the Henry Mountains and northern Wasatch Plateau regions. Although these environmental changes record landward and seaward shoreline shifts they do not record much change in shoreline orientations throughout the interval. In the western Henry Mountains region, paleocurrent data from the Muley Canyon Sandstone preserve W – E and NNW – SSE bimodal trends from trough cross-bedding and ripple

cross-lamination in tidally influenced fluvial and estuarine channels suggesting a broadly N – S and NNE – S-SW paleoshoreline orientation further east. In the northern Wasatch Plateau region NE of the ‘Wattis Road’ section, non-marine deposits in the lower and upper part of Interval 2 were located just up-depositional dip from coeval Spring Canyon and lower Aberdeen shorelines (Fig. 21 C). During deposition of the middle part of Interval 2 (A0 and A1 Aberdeen parasequences), the shoreline retreated into the area just NE of the ‘Wattis Road’ section. According to Hampson et al. (In Press) these shorelines were oriented NNE – S-SW and prograded and retrograded in E-SE and W-NW directions, respectively (Fig. 21 D). The exposures in the middle and southern Wasatch Plateau record non-marine strata and coeval shorelines are eroded to the east of the outcrops. Based on the data from the northern Wasatch Plateau and western Henry Mountains Syncline, the two regions had similarly-oriented paleoshorelines to each other. Because the Blind Trail and northern Wasatch Plateau sections are practically due N-S of each other, these data suggest that there had to be some variation in the shoreline orientation between the two sections. At some point the shoreline must have been oriented NW – SE, creating a concave westward trend (Fig. 21 C, D). Whether only one broad concave trend or several lower amplitude concave westward-to-eastward-to-westward trends existed between these regions will remain unknown due to a lack of exposure over the San Rafael Swell. Similarly to Interval 1, the western Henry Mountains Syncline was oriented along-depositional strike to the northern Wasatch Plateau and obliquely up-depositional dip from subsurface distal shale deposits at Coal Canyon. The

southern Wasatch Plateau was oriented obliquely along-depositional strike and up-depositional dip in a more proximal position from the Blind Trail location.

Interval 3 --- Interval 3 is characterized by frequent paleogeographic reorganizations in the Book Cliffs region (Howell and Flint, 2003; Hampson, 2010; Hampson et al., In Press) and relatively little change in paleogeography in the Wasatch Plateau and western Henry Mountains regions. At Blind Trail, paleocurrent data from tidal fluvial channels of the Masuk Formation record a slight change from W – E and NNW – SSE trends in the lower and middle member to N – S and NNW – SSE in the upper member (Appendix B). These up-depositional dip near-shore tidal fluvial channels were likely oriented perpendicular to the shoreline east of the western Henry Mountains Syncline. Unfortunately the time-equivalent shoreline has been eroded further east. During Interval 3, the northern Wasatch Plateau was located in an along-depositional strike, but more proximal, position relative to the western Henry Mountains Syncline (Fig. 21 E). The stratigraphy at both locations records terrestrial paleoenvironments; however, the Masuk Formation at Blind Trail is interpreted to have been in a more distal near-shore location relative to the middle – upper Blackhawk Formation in the northern Wasatch Plateau because of the amount of coastal and tidal influence preserved throughout the formation. It is more likely that the Masuk Formation correlates to positions further east along the western Book Cliffs during Interval 3 (Fig. 21 E). The lack of coastal and tidal influence documented by Hampson et al. (In Press) within the middle to upper part of the Blackhawk Formation in the northern Wasatch Plateau may

be an artifact of the low-resolution data collection methods and outcrop accessibility discussed previously.

Similarly to Intervals 1 and 2, the Book Cliffs region was oriented down-depositional dip and obliquely down-depositional dip from the Wasatch Plateau and western Henry Mountains regions, respectively (Fig. 21 E). During Interval 3, the Book Cliffs region was subject to numerous paleoshoreline shifts. Paleogeographic summaries of the evolution of shoreline migration during this time can be found in Howell and Flint (2003) and Hampson (2010). Coal Canyon was located in a distal offshore position during the early part of Interval 3. The up-depositional dip shorelines of the upper Aberdeen and Kenilworth Members of the Blackhawk Formation were oriented NNE – S-SW and NNW – SSE, respectively. As the Sunnyside Member was being deposited, Coal Canyon was in an offshore to lower shoreface position and the shoreline orientation was N – S. This orientation is corroborated by predominantly eastward paleoflow directions recorded in ripple cross-lamination structures from the measured section (Appendix B). As the shoreline prograded during deposition of the Grassy Member, Coal Canyon was located generally in a proximal shoreface position and the shoreline changed to a slightly NNE – S-SW orientation. Finally, during deposition of the Desert Member at Coal Canyon was located in a shoreface to coastal/non-marine position with a broadly NW – SE paleoshoreline orientation. Paleocurrent data from trough cross-bedding in tidal fluvial channels within the Desert Member (Appendix B) show an upward change from eastward in the lower part to a bimodal north-northeast – south-southwestward in the upper part. These data also suggest a roughly NW- SE oriented paleoshoreline.

Interval 4 --- Interval 4 at all locations is characterized by significant basinward shifts in depositional environments (Fig. 21 F). In the western Henry Mountains Syncline near-shore tidally-influenced channels in the upper Masuk Formation are erosionally overlain by fully non-marine braided channel deposits of the Tarantula Mesa Sandstone. In the northern Wasatch Plateau and Book Cliffs regions a similar shift in paleoenvironment is recorded in the transition from non-marine/coastal deposits of the upper Blackhawk Formation to braided fully non-marine channel deposits of the lower Castlegate member of the Castlegate Formation. Paleocurrent trends within the lower Castlegate member along the Book Cliffs record dominantly SE and E directed sediment dispersal (Fig. 21 F; Hampson, 2010). At Coal Canyon, paleocurrent data from trough cross-bedding in braided channels preserve a SE directed paleoflow direction (Appendix B). These data suggest progradation toward the E-SE and a paleoshoreline orientated NE – SW in the east during this time (Fig. 21 F). In the western Henry Mountains, paleocurrent data in the Tarantula Mesa Sandstone similarly record an eastward paleoflow direction (Fig. 21 F). In contrast to the lower Castlegate member of the Castlegate Formation in the Book Cliffs, there is limited exposure of the Tarantula Mesa Sandstone in the western Henry Mountains Syncline and a coeval shoreline down-depositional dip is not preserved. The paleogeography of near-shore environments during Interval 4 in the south-central Utah region is thus open to interpretation based on the position of the up-depositional dip non-marine Tarantula Mesa Sandstone. All three sections used in this study were in a broadly N – S oriented, fully non-marine paleogeographic belt during Interval 4 (Fig. 21 F).

CONCLUSIONS

This study presents a high-resolution correlation scheme for the Upper Cretaceous stratigraphy between the western Henry Mountains Syncline, the northern Wasatch Plateau, and the Book Cliffs near Green River, Utah with emphasis on the Lower – Middle Campanian interval. Focus has been placed on the Lower to Middle Campanian interval because the Henry Mountains succession is slightly condensed and unconformable compared to the northern Wasatch Plateau and Book Cliffs successions. This is in part due to their proximal vs. distal locations from the Sevier thrust front and unequal rates of accommodation caused by spatially variable subsidence and uplift patterns during this time. A majority of the research performed in east- and south-central Utah has neglected the importance of the Henry Mountains succession. This study places the Campanian Henry Mountains stratigraphy in a broader inter-regional context. The Lower – Middle Campanian successions have been separated into four Intervals (1 – 4) and their characteristics, depositional controls, and paleogeography are summarized below.

Interval 1: Lowermost Campanian

1. Interval 1 in the western Henry Mountains comprises a low-frequency falling stage sequence set (FSSS) containing two complete high-frequency sequences underlain by a partial sequence. The vertical facies and depositional environmental shifts in Interval 1 thus record three falls and two rises in

formative water depth. Interval 1 in the northern Wasatch Plateau similarly consists of falling stage deposits.

2. The stacking patterns in Interval 1 in the northern Wasatch Plateau and the western Henry Mountains record two cycles of progradation-retrogradation followed by progradation. This differs with an entirely progradational stacking pattern in time-equivalent Star Point parasequences in the southern Wasatch Plateau due to an along-depositional strike variability in accommodation. The northern Wasatch Plateau had the highest rate of accommodation relative to the other regions, resulting from increased tectonic subsidence, allowing for the deposition of a relatively conformable succession. The western Henry Mountains region had a slightly lower accommodation rate relative to the northern Wasatch Plateau, indicated by an unconformable succession, but a higher rate of accommodation relative to the southern Wasatch Plateau (indicated by similar cycles of progradation-retrogradation-progradation as the northern Wasatch Plateau versus an entirely progradational stacking pattern in the southern Wasatch Plateau).

3. The western Henry Mountains and the Wasatch Plateau were along depositional strike to one another during Interval 1. In the western Henry Mountains the shoreline was oriented NNE – S-SW. In the early part of Interval 1 the northern Wasatch Plateau shoreline was also oriented NNE – S-

SW, but changed to a NW – SE orientation in the later part. The southern Wasatch Plateau was oriented NW – SE throughout Interval 1. During the early part of Interval 1 there were two concave westward trends (northernmost Wasatch Plateau and Henry Mountains) separated by one concave eastward trend (southern Wasatch Plateau) between the shorelines of the western Henry Mountains and Wasatch Plateau regions. During the latter part of Interval 1 only one broader concave westward trend was present between the regions with the Wasatch Plateau shoreline prograding toward the NE and the Henry Mountains shoreline prograding toward the SE. Coal Canyon was located in a distal open-marine down-depositional dip position from the Wasatch Plateau during Interval 1.

Interval 2: Lower Campanian

1. Correlations made in Interval 2 provided the primary basis for the choice of the NE of ‘Wattis Road’ section as the link point between the Blind Trail and Coal Canyon successions. Interval 2 at Blind Trail and the surrounding Henry Mountains region comprises two complete high-frequency sequences that together make up a low-frequency transgressive sequence set (TSS) and maximum flooding zone (MFZ). The Muley Canyon Coal Zone is interpreted as a low-frequency MFZ separating a low-frequency TSS below (rest of Interval 2) from a low-frequency highstand sequence set (HSS) above (rest of the Masuk Formation).

2. In general, the stacking pattern in Interval 2 in the western Henry Mountains Syncline records two cycles of non-marine/coastal to shallow-marine progradation-retrogradation followed lastly by coastal/non-marine aggradation-progradation. Interval 2 in the northern Wasatch Plateau NE of the 'Wattis Road' section similarly contains non-marine/coastal to shallow-marine units that record relative sea-level cyclicity.

3. Similar to Interval 1, Interval 2 in the northern Wasatch Plateau and western Book Cliffs is relatively conformable compared to the western Henry Mountains interval. The conformable vs. non-conformable successions can be explained by an along-depositional strike variation in accommodation between these two regions. As with Interval 1, Interval 2 in the northern Wasatch Plateau and western Book Cliffs records a higher rate of accommodation relative to the western Henry Mountains Syncline during the Early Campanian. This is indicated by the amount of aggradation recorded, relative to Interval 2 at Blind Trail, within the shallow-marine parasequence stacking patterns further east in the Spring Canyon and lower Aberdeen Members and abundant coal horizons up-depositional dip from those parasequences. Overall, the environmental shifts from non-marine/coastal to shallow-marine and back to non-marine/coastal are evident in Interval 2 at both the Blind Trail and NE of 'Wattis Road' sections.

4. The facies and depositional environmental stacking patterns found in Interval 2 in the northern Wasatch Plateau are not found anywhere else in the Wasatch Plateau further south from just NE of the 'Wattis Road' section. Any section further south along the Wasatch Plateau was located obliquely up-depositional dip from the western Henry Mountains region and landward of marine incursion and shoreface deposition during the late part of Interval 2. Any section further east along the Book Cliffs was located obliquely down-depositional dip from the western Henry Mountains region.
5. Based on the data from the northern Wasatch Plateau and western Henry Mountains Syncline the two regions had similarly oriented paleoshorelines oriented NNE – S-SW. At some point the shoreline had to have been oriented NW – SE creating a concave westward trend between the two regions. Whether only one broad concave trend or several lower amplitude concave westward-to-eastward-to-westward trends existed between these regions will remain unknown due to no exposure over the San Rafael Swell. Similar to Interval 1, the western Henry Mountains Syncline was oriented along-depositional strike to the northern Wasatch Plateau and obliquely up-depositional dip from subsurface distal shale deposits at Coal Canyon. The southern Wasatch Plateau was oriented obliquely along-depositional strike and up-depositional dip in a more proximal position from the Blind Trail location.

Interval 3: lower – mid Middle Campanian

1. The Masuk Formation (i.e., Interval 3) above the basal Muley Canyon Coal Zone (low-frequency MFZ) is interpreted as a low-frequency highstand sequence set (HSS) erosionaly overlain by a low-frequency sequence boundary at the base of the Tarantula Mesa Sandstone. In general, sandstone proportion decreases from the lower to the middle member and then increases in the upper member. This suggests that there was some fluctuation in accommodation within the HSS resulting in variations in the amount of fine-grained floodplain and overbank facies being preserved rather than erosionaly removed due to lateral migration and repeated incision common in amalgamated channel deposits. Overall the upward low-frequency variations in the preservation of overbank floodplain mudrocks versus amalgamated sandstone-dominated channels in the Masuk Formation are consistent with early, middle, and late highstand conditions in non-marine sequence stratigraphic models.
2. The low-frequency fluctuations within the Masuk Formation are likely controlled by some combination of eustasy, local sediment supply, and tectonism. Within the low-frequency HSS of the Masuk Formation there is a higher-frequency level of stratigraphic organization in the form of widespread fluvial incision and migration within distinct channel belts. Similar to the low-frequency trends, the abundant tidal and near shore influence in the Masuk Formation suggests the high-frequency sequences are likely driven by

downstream forcing rather than upstream forcing suggesting eustatic fluctuations were the dominant allogenic control.

3. Similar to the Masuk Formation in the western Henry Mountains Syncline, the Blackhawk Formation in the Book Cliffs has been interpreted as a low-order highstand systems tract (HST) or low-frequency highstand sequence set (HSS). In contrast to the Masuk Formation, the non-marine Blackhawk Formation in the northern Wasatch Plateau has relatively little stratigraphic organization in the spatial distribution of channelized sandbodies. One possibility as to why little to no organization is observed is possibly due to the nature of data collection (widely spaced, >20 km apart, measured sections and low-resolution photographic logs of distant cliff faces, variably covered by talus). This may have allowed for misinterpretations of facies and stratigraphic organization.
4. The only low-frequency similarity between the Masuk and Blackhawk Formations is that channel body dimensions increase upward through the succession; however, there is local variability in this trend within the Blackhawk Formation where the opposite trend is observed. In the upper part of the non-marine Blackhawk Formation the upward increase in sandbody dimensions is interpreted to have been caused by decreasing tectonic subsidence through time. The little apparent stratigraphic organization within the upper non-marine Blackhawk Formation suggests that high-frequency

variations in allogenic controls did not dominate the stratigraphic architecture in the upstream region like they evidently did in the down-depositional dip coastal plain and shallow-marine Blackhawk Formation in the Book Cliffs, but rather autogenic avulsion processes were the dominant controls.

5. In the Book Cliffs at Coal Canyon, Interval 3 has been interpreted to record the regressive stacking of progradational shallow- to near-shore marine parasequences and high-frequency sequences within a low-frequency highstand succession. A combination of high-frequency orbitally forced sea-level fluctuations and thrust belt-controlled lower-frequency cycles of subsidence were the controlling mechanisms for the stratigraphic development of the Blackhawk Formation.
6. High-frequency member-scale cycles may broadly coincide with the high-frequency sequences within the Masuk Formation; however correlating specific sequences would be nearly impossible or extremely difficult because of the lack of age control and continuous outcrop between the western Henry Mountains Syncline and the Book Cliffs.
7. Interval 3 is characterized by frequent paleogeographic reorganizations in the Book Cliffs region and relatively little change in paleogeography in the Wasatch Plateau and western Henry Mountains regions. At Blind Trail paleocurrent data within tidal fluvial channels of the Masuk Formation record a slight change from W – E and NNW – SSE trends in the lower and middle

member to N – S and NNW – SSE in the upper member. These up-depositional dip near-shore tidal fluvial channels likely were oriented perpendicular to the shoreline east of the western Henry Mountains Syncline.

8. During Interval 3 the northern Wasatch Plateau was located in an along-depositional strike, but more proximal, position relative to the western Henry Mountains Syncline. The stratigraphy at both locations record terrestrial paleoenvironments however the Masuk Formation at Blind Trail is interpreted to have been in a more distal near-shore location relative to the middle – upper Blackhawk in the northern Wasatch Plateau. It is more likely that the Masuk Formation correlates to positions further east along the western Book Cliffs during Interval 3. The lack of coastal and tidal influence documented within the middle to upper part of the Blackhawk Formation in the northern Wasatch Plateau may be an artifact of the low resolution facies collection methods and outcrop accessibility discussed above.
9. Similar to Intervals 1 and 2, the Book Cliffs region was oriented down-depositional dip and obliquely down-depositional dip from the Wasatch Plateau and western Henry Mountains regions, respectively. During Interval 3 the Book Cliffs region was subject to numerous paleoshoreline shifts. The overall shoreline orientation was broadly N – S with variations at parasequence scale to slightly NE – SW and NW-SE at certain intervals.

Interval 4: upper Middle Campanian

1. Amalgamation and sheet-like geometry of fluvial bodies at all three locations in interval 4 is attributed to increased lateral migration of rivers within a channel belt system resulting from decreasing accommodation. This interpretation is consistent in a sequence stratigraphic context with the Tarantula Mesa Sandstone and Castlegate Formations.
2. These formations are interpreted as low-frequency LSS formed due to a relative fall in sea-level resulting in widespread regional incision creating a low-frequency sequence boundary at their bases. The reduced accommodation during the deposition of the lower Castlegate member of the Castlegate Formation and Tarantula Mesa Sandstone was the result of tectonic driving mechanisms.
3. Paleocurrent trends within the lower member of the Castlegate Formation along the Book Cliffs record dominantly SE and E directed sediment dispersal. At Coal Canyon braided channels preserve a SE directed paleoflow direction. These data suggest progradation toward the E-SE and a paleoshoreline orientated NE – SW further east during this time. In the western Henry Mountains paleocurrent data in the Tarantula Mesa Sandstone similarly record an eastward paleoflow direction.
4. All three section used in this study were in a broadly N – S oriented fully non-marine paleogeographic belt during Interval 4.

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APPENDIX A: TABLES

Table 1. - *Lithologic facies and facies associations for the Campanian successions at Blind Trail, the northern Wasatch Plateau, and Coal Canyon.*

Facies Associations	Facies/Depositional Environment	Lithology and Sedimentary Structures	Ichnology
Fluvial (F)	Multi-storey Almalgamated Channels (Fmach)	Fine- to medium-grained multi-storey trough cross-bedded sandstone, erosionally based with up to 5 m of incision. Individual storeys are <5-10 m thick and can be separated by up to 3.5 m siltstone and carbonaceous shale partings with root traces and plant debris. Internal structure can be sheetlike or consist of large-scale dipping surfaces (lateral or downstream accretion) and planar, massive, and flaggy bedding. Beds contain siltstone partings and clasts, ripple cross-lamination, flat lamination, undulatory bedding, and soft sediment deformation, with or without downward protruding (animal prints?). Basal surfaces contain abundant plant and wood fragments and imprints, and siltstone clasts. Macerated plant debris and broad leaf and conifer imprints are found locally on bedding planes. Some root penetration on bed tops.	Basal surfaces contain rare bioturbation (small <i>Diplocraterion</i> , and <i>Teredolites</i> in bored logs). Locally the tops of units contains abundant large <i>Diplocraterion</i> traces where overlain by a flooding surface.
	Heterolithic Channels (Fhch)	Sandstone-dominated thickly interbedded sandy siltstone and fine- to medium-grained sandstone containing flat lamination, ripple cross-lamination, and low angle dipping surfaces (lateral or downstream accretion).	Basal sandstone surfaces contain rare bioturbation.
	Small Single Storey Splay Channels (Aspl)	Thin (<1 m) sheets and small (<3 m) thick, <20 m wide) lenses of current-rippled and trough cross-bedded very fine- to medium-grained sandstone. Commonly associated and interspersed with Coastal Plain Overbank Deposits (Cob).	Absent to sparse bioturbation (BI = 0); low-diversity trace fossil assemblage in a few intervals only (<i>Planolites</i> , <i>Teredolites</i> , <i>Palaeophycus</i> , <i>Diplocraterion</i> ?).
Aggradational Floodplain (A)	Paleosols and Overbank Deposits (Apo)	Root-penetrated paleosols with carbonaceous mudstone, siltstone, and minor sandstone. There are portions that are wavy bedded with thin ripple cross-laminated sandstones. Also has intervals that contain slickensides, rhizoliths, and plant and coaly debris up to log size. Commonly associated and interspersed with Coastal Plain Overbank Deposits (Cob).	Little to no bioturbation evident.

Coastal Plain/Coal (C)	Coal Swamps and Mires (C _{cm})	Coal and carbonaceous shale with rare, thin beds of fine-grained sandstone. Thin sulfur residue common on exposed surfaces and cleats. Coals can be laterally continuous or discontinuous.	Locally penetrated by burrows filled with sandstone from overlying beds.
	Coastal Plain Overbank Deposits (C _{ob})	Siltstone, carbonaceous shale or sandstone-dominated interbedded siltstone, vfg sandstone, and carbonaceous shale. Sandstone beds are very thin (<10 cm) and lack internal structure although occasional bimodal trough cross-bedding, ripple cross-lamination, and combined-flow ripple cross-lamination can be seen in siltstone and carbonaceous shale-dominated intervals. In sandstone-dominated intervals sandstone beds can be up to 1 m thick and contain ripple cross-lamination, combined-flow ripple cross-lamination and rare wave ripples. Macerated plant material and root traces are abundant with rare <i>in situ</i> tree trunks and coaly rip-up clasts and laminae. Carbonaceous shale intervals are fissile, contain root penetrated horizons and lack bioturbation. Bivalve/Gastropod? shell fragments are present in some sandstone interbeds.	Bioturbation is sparse, but locally abundant with low diversity, and generally on the bases of sandstone beds (<i>Planolites</i>). <i>Diplocraterion</i> , <i>Teichichnus</i> , and <i>Thalassinoides</i> also sparse.
	Heterolithic Tidally Influenced Fluvial Channels (C _{htch})	Fine-grained, single- and multi-storey, sandstone-dominated heterolithic, erosionally based channel fills containing bimodal trough cross-bedding, carbonaceous partings, paired mud drapes, ripple cross-lamination, combined-flow ripple cross-lamination, and flat lamination. Large-scale dipping surfaces (lateral accretion) dominate the architecture at certain intervals and inclined heterolithic strata are present in places. Siltstone, heterolithic, and coaly rip-up clasts, carbonaceous foreset laminae, plant debris, root traces, and petrified wood are common. Sparse frond leaf imprints, load casts, and downward protruding soft sediment deformation (animal prints?). Shell fragments are common causing some beds to be calcareous. A shell lag with bone fragments is present at the top of one of these sandstone bodies.	Bioturbation is variable from absent to common with <i>Cylindrichnus</i> , small <i>Diplocraterion</i> , <i>Phycodes</i> , <i>Planolites</i> , <i>Gyrochorte</i> , <i>Teredolites</i> , and small vertical burrows. Bioturbation is common on the sandstone bases of channels.

Estuarine (E)	Tidally Influenced Fluvial Channels (Ctch)	Amalgamated large-scale trough cross-bedded (50 cm to several meter sets), fine- to medium-grained erosionally-based sandstone; overall sheet architecture with internal channel forms evident. Siltstone clasts common on bases and within sand bodies. Basal surfaces can contain plant and wood fragments and imprints. Sandstone beds can be thickly bedded (4-6.5m) and contain ripple cross-lamination, mud drapes on foresets and trough cross-bed boundaries, coaly laminae, flat and low angle lamination, and soft sediment deformation.	Little to no bioturbation evident.
	Bayhead Delta/Central Basin/Tidal Lagoon (Eb)	Thinly interlaminated mudrock and sandstone. Pinstripe to wavy bedded with common ripple cross-lamination and paired mud drapes. Usually sheet-like; in some instances appears to form erosionally-based lense-shaped bodies.	Trace fossil assemblage composed primarily of <i>Teichichnus</i> , <i>Thalassinoides</i> and <i>Planolites</i> .
	Estuarine Channels (ECh)	Smaller-scale (10 cm to 1 m) trough cross-bedded fine- to medium-grained sandstone; herringbone cross-stratification and bimodal paleocurrent trends present; internal channel forms evident with multi-storey architecture; siltstone and heterolithic partings evident locally; rhythmically interlaminated sandstone and carbonaceous siltstone present locally.	Bioturbation absent except in some localities that display burrows subtending from the top of the channel complex.
	Heterolithic Wave Influenced Estuarine Channels. (Ehet)	Heterolithic thinly planar interbedded siltstone, fine-grained sandstone, and carbonaceous shale. Contains sandstone, siltstone, and carbonaceous shale-dominated intervals. Interbeds alternate typically at a <20 cm scale, but can range up to 40 cm with one sandstone channel unit up to 1.8 m thick. Units show variable flaser to pinstripe, undulatory to planar bedding containing ripple cross-lamination, flat and low angle lamination, small-scale hummocky cross-stratification, combined-flow ripple cross-lamination, small-scale trough cross-bedding, sole structures, possible load structures?, syneresis cracks, and macerated plant debris. Some intervals are calcareous. Alternating sandstone, siltstone, and carbonaceous shale-dominated units occur at a <3-4 m scale. Long (~50-100 m scale) and short (<5 m) channel forms are the dominant arrangement of architectural stacking with erosionally-based incision into underlying packages. Channel margins display large-scale dipping surfaces.	Bioturbation is common throughout but generally found on the bases of sandstone beds with <i>Planolites</i> , <i>Thalassinoides</i> , <i>Diplocraterion</i> , <i>Taenidium</i> , <i>Lockeia</i> , <i>Gyrochorte</i> , <i>Shaubcylindrichnus</i> , and resting in traces. <i>Planolites</i> and <i>Phycodes</i> in siltstone interbeds. Bivalve shell lags also occur at certain horizons.

Outer Estuary/Barrier Shoreface (Eo/b)	Thin and undulatory bedded to massive fine-grained sandstone containing hummocky cross-stratification, flat and low angle lamination, minor small-scale trough cross-bedding, combined-flow ripple cross-lamination. Internal bedding is often unrecognizable.	Heavily bioturbated with <i>Planolites</i> , <i>Thalassinoides</i> , <i>Ophiomorpha</i> , <i>Cylindrichnus</i> , large and small <i>Diplocraterion</i> , <i>Lockeia</i> , and <i>Taenidium</i> , <i>Gyrochorte</i> , and <i>Phycodes</i> . Upper contacts can contain bivalve shell lag concentrations and bivalve shells sporadically present throughout unit.
Estuarine Mouth (Em)	Plane-parallel laminated to low angle laminated fine- to medium-grained sandstone; locally heterolithic and carbonaceous.	Bioturbation commonly present at the top of units (sub-tending burrows common).
Upper Shoreface (USF)	Amalgamated, tabular, thickly bedded and inter-bedded very fine- to medium-grained sandstone and minor siltstone with sandstone beds up to 4 m thick containing large-scale hummocky cross-stratification, flat and low angle lamination, and wave ripples. Inter-bedded siltstones contain small plant fragments.	Deep vertical to sub-vertical burrows at the top of sandstone beds; bioturbation index ranging from 0 to 2, with <i>Ophiomorpha</i> , small <i>Diplocraterion</i> , <i>Gyrochorte</i> , <i>Taenidium</i> , <i>Planolites</i> , <i>Cylindrichnus</i> , and fugichnia.

Shoreface (SF)	Lower Shoreface (LSF)	<p>Thinly interbedded mudstone and very fine- to fine-grained sandstone (2.5-5.0% sst) packages with sandstone coarsening and thickening upward in <5-10 m packages. Sandstone beds thicken upward to <5-2 m thick and are commonly 5-25 cm thick. Sandstone beds contain wave ripples, combined-flow ripple cross-lamination, small-scale and minor large-scale hummocky cross-stratification, ripple cross-lamination, flat and low angle lamination, soft sediment deformation, calcareous beds with small bivalve shells, and rare syneresis cracks. Macerated plant debris is common to abundant in mudstones.</p>	<p>These packages have a BI = 0-3 and sandstone beds sparsely contain large bivalve molds (<15 cm diameter). The bases typically consist of mudstone with sparse to no bioturbation. In mudstone dominated intervals the trace fossils consist of <i>Planolites</i>, <i>Shaubcylindrichnus</i>, <i>Zoophycos</i>, <i>Chondrites</i>, and rare <i>Gyrolithes</i>. Sandstone beds typically contain <i>Planolites</i>, <i>Locketia</i>, <i>Ophiomorpha</i>, <i>Diplocraterion</i>, <i>Thalassinoides</i>, <i>Taenidium</i>, <i>Monocraterion</i>, <i>Cylindrichnus</i>, <i>Shaubcylindrichnus</i>, crawling and resting traces, and sinuous surface trails.</p>
	Delta Mouth Bar (Dmb)	<p>Fine- to medium-grained sandstone containing unidirectional low angle dipping surfaces; erosionally-based.</p>	<p>Tops of beds bioturbated with <i>Ophiomorpha</i>, <i>Conichnus</i>, <i>Thalassinoides</i>, <i>Diplocraterion habichi</i>, <i>D. parallelum</i>; BI ranging from 0 at base of bed up to 2 at top of bed.</p>
	Proximal Delta Front (pDF)	<p>Amalgamated beds of fine- to medium-grained sandstone. Abundant trough and tabular cross-beds, structureless, and graded, structureless-to laminated beds; rare hummocky cross-stratification, and wave-ripple cross-lamination. Contains steeply dipping (up to 15°) clinoforms.</p>	<p>Absent to moderate bioturbation (BI = 0-4); (<i>Ophiomorpha</i>, <i>Skolithos</i>, <i>Palaeophycus</i>, <i>Planolites</i>).</p>

Deltaic (D)	Middle Delta Front (mDF)	Mostly interbedded siltstone-dominated very fine- to fine-grained sandstone and siltstone with minor shale; ripple cross-lamination, combined-flow ripple cross-lamination, pinstripe lamination, wave ripples, load structures, and syneresis cracks. Also contains 1-2 m thick debris flow unit with up to boulder size material and pervasive soft sediment deformation.	No bioturbation observed.
	Distal Delta Front (dDF)	Non-amalgamated beds of fine- to medium-grained sandstone with mudstone and siltstone interbeds. Graded, structureless to laminated sandstone beds; rare hummocky cross-stratification, and wave-ripple cross-lamination. Occurs near clinoform toes.	Absent to intense bioturbation (BI = 0-5); (<i>Ophiomorpha</i> , <i>Skolithos</i> , <i>Thalassinoides</i> , <i>Arenicolites</i> , <i>Palaeophycus</i> , <i>Schaubcylindrichnus</i>).
	Prodelta (proD)	Finely laminated shale, siltstone and very fine- to fine-grained sandstone. Sandstone beds contain combined-flow ripple cross-lamination, ripple cross-lamination, flat lamination, and pinstripe lamination.	Very little to no bioturbation.
	Offshore Transition (OT)	Interbedded sandstone and siltstone; plane-parallel lamination, hummocky cross-stratification; current, wave, or wave-modified current ripples present; base and top of sandstone beds display long wavelegh undulating bedding surfaces; sandstone beds amalgamated in places.	BI = 2-3 in well-exposed intervals.
	Offshore/Shelf (OS)	Fissile light to dark grey shale with occasional isolated calcareous fine-grained sandstone <.5 m thick.	Minor bioturbation BI = 0-1 with <i>Phycosiphon</i> , <i>Cylindrichnus</i> , <i>Taenidium</i> , and <i>Planolites</i> .
Offshore Marine (O)			

APPENDIX B: LOGGED SECTIONS

Masuk Formation: Lower Member - Blind Trail

Masuk Formation: Middle Member - Blind Trail

Masuk Formation: Upper Member & Tarantula Mesa Sandstone (incomplete) - Blind Trail

Blackhawk Formation: Kenilworth Member - Coal Canyon

Blackhawk Formation: Sunnyside Member - Coal Canyon

Blackhawk Formation: Grassy Member - Coal Canyon

Blackhawk Formation: Desert Member &
Castlegate Formation: Lower Member - Coal Canyon

Buck Tonge Member of the Mancos Shale
& Sego Sandstone - Coal Canyon

Neslen Formation & Bluecastle Tongue Member of the Castlegate Formation - Coal Canyon

Depositional Environment

Farrer Formation (lower part) - Coal Canyon

Farrer Formation (lower part)

Thickness (m)

Depositional Environment

Variably Dominated Fluvial Channels & Aggradation Flooplain Deposits (Fmach, Fhch, Aspl, Apo)

Farrer Formation (middle part) - Coal Canyon

Tuscher Formation (incomplete) - Coal Canyon

Tuscher Formation (incomplete)

Thickness (m)

Depositional Environment

Variably Dominated Fluvial Channels & Aggradation Flooplain Deposits (Fmach, Fhch, Aspl, Apo)

APPENDIX C: PALEOCURRENT DATA

Data Type		Thickness (cm)		Paleocurrent Direction (Azimuth)	
LSDS: Large-scale dipping surfaces	TXB: Trough cross-bedding	RXL: Ripple cross-lamination	CFRXL: Combined-flow ripple cross-lamination	GC: Gutter casts	
WESTERN HENRY MOUNTAINS SYNCLINE					
MASUK FORMATION					
Lower Member					
LSDS				22	
TXB		50		90	
TXB		30		124	
TXB		40		3	
TXB		30		3	
TXB		30		10	
TXB		30		11	
TXB		20		26	
TXB		25		227	
TXB		30		232	
TXB		10		242	
TXB		30		282	
TXB		40		286	
TXB		20		289	
TXB		30		306	
TXB		60		340	
TXB		30		354	
TXB		15		359	
RXL				82	
RXL				272	
RXL				274	
LSDS		250		302	

TXB	10	265
TXB	30	274
TXB	20	274
TXB	20	288
TXB	10	305
LSDS	200	152
RXL		315
RXL		326
TXB	10	66
TXB	30	62
TXB	20	70
TXB	10	142
TXB	30	159
TXB	40	175
TXB	80	309
TXB	70	310
TXB	30	312
Middle Member		
LSDS	600	72
LSDS		52
LSDS	1000	273
RXL		7
RXL		8
RXL		17
RXL		306
RXL		312
RXL		322
TXB	60	2
TXB	60	9
TXB	50	18
TXB	30	25
TXB	100	40
TXB	60	57
TXB	60	64
TXB	60	64
TXB	50	255
TXB	30	283
TXB	40	333
TXB	20	3
TXB	30	24
TXB	30	25

TXB	20	41
TXB	30	45
TXB	30	87
TXB	30	332
RXL		88
RXL		118
RXL		128
RXL		139
RXL		142
RXL		152
TXB	40	144
TXB	40	262
TXB	30	285
TXB	50	290
TXB	50	328
TXB	50	342
TXB	40	312
TXB	20	85
TXB	10	92
TXB	10	106
TXB	10	120
TXB	15	121
TXB	30	123
TXB	30	125
TXB	30	136
TXB	40	141
TXB	10	150
RXL		310
RXL		318
RXL		326
RXL		332
RXL		336
RXL		342
RXL		342
RXL		343
RXL		344
RXL		359
Upper Member		
TXB	30	2
TXB	50	2
TXB	40	7

TXB	20	8
TXB	70	11
TXB	40	14
TXB	50	14
TXB	60	18
TXB	60	18
TXB	30	24
TXB	40	34
TXB	40	64
TXB	80	68
TXB	20	102
TXB	50	344
TXB	80	352
TXB	80	359
TXB	20	360
TXB	50	360
TXB	40	8
TXB	20	13
TXB	60	143
TXB	80	149
TXB	30	172
TXB	30	172
TXB	30	187
TXB	15	347
TXB	10	348
TXB	20	352
BOOK CLIFFS		
BLACKHAWK FORMATION		
Kenilworth Member		
CFRXL		12
CFRXL		17
CFRXL		54
CFRXL		57
CFRXL		88
CFRXL		96
CFRXL		97
CFRXL		99

RXL		90
RXL		102
RXL		112
RXL		112
RXL		87
RXL		103
RXL		104
RXL		106
RXL		110
Sunnyside Member		
RXL		72
RXL		73
RXL		78
RXL		102
RXL		114
RXL		114
RXL		122
RXL		125
RXL		132
RXL		137
RXL		144
RXL		72
RXL		96
RXL		97
RXL		97
Desert Member		
TXB	30	54
TXB	30	55
TXB	50	58
TXB	50	93
TXB	20	105
TXB	30	108
TXB	40	108
TXB	30	118
TXB	30	12
TXB	40	28
TXB	30	88
TXB	40	107
TXB	50	132

TXB	50	135
TXB	40	186
TXB	70	342
TXB	10	352
TXB	10	3
TXB	15	25
TXB	10	27
TXB	15	28
TXB	15	28
TXB	8	30
TXB	10	35
TXB	15	38
TXB	25	54
TXB	50	148
TXB	40	174
TXB	20	172
TXB	20	182
TXB	60	182
TXB	40	185
TXB	25	187
TXB	15	198
TXB	20	198
TXB	120	343
LOWER CASTLEGATE FORMATION		
TXB	20	132
TXB	40	133
TXB	60	142
TXB	35	142
TXB	15	144
TXB	50	145
TXB	20	146
TXB	30	147
TXB	20	148
TXB	20	149
TXB	40	150
TXB	30	156
TXB	20	172
BUCK TONGUE		
CFRXL		128

CFRXL		138
CFRXL		149
CFRXL		166
CFRXL		304
SEGO SANDSTONE		
TXB	20	215
TXB	50	230
TXB	70	234
TXB	60	235
TXB	20	238
TXB	50	327
TXB	20	290
TXB	20	327
TXB	30	337
TXB	50	338
TXB	30	31
TXB	30	32
TXB	30	46
TXB	50	55
TXB	30	57
TXB	50	57
TXB	15	58
TXB	30	60
TXB	15	61
TXB	60	62
TXB	30	62
TXB	20	62
TXB	30	74
TXB	50	75
TXB	10	80
TXB	25	82
TXB	40	90
NESLEN FORMATION		
LSDS		182
CFRXL		53
CFRXL		56
CFRXL		61
CFRXL		62
CFRXL		62

CFRXL		69
CFRXL		160
CFRXL		105
CFRXL		230
CFRXL		244
CFRXL		249
CFRXL		69
LSDS		300
LSDS		335
RXL		57
RXL		69
RXL		232
RXL		240
TXB	15	93
TXB	10	100
TXB	20	212
TXB	15	217
TXB	20	252
TXB	10	259
TXB	30	262
TXB	30	273
TXB	25	292
TXB	20	301
TXB	20	68
RXL		62
RXL		74
RXL		215
RXL		222
RXL		232
RXL		233
RXL		240
RXL		249
TXB	20	224
TXB	20	17
TXB	10	182
LSDS		137
RXL		222
RXL		244
TXB	40	119
TXB	30	147
TXB	60	154
TXB	150	160
TXB	150	160

TXB	50	172
TXB	30	172
TXB	60	172
TXB	100	173
TXB	150	173
BLUECASTLE TONGUE MEMBER OF THE CASTLEGATE FM.		
TXB	15	117
TXB	10	124
TXB	20	360
LSDS	150	59
TXB	30	43
TXB	50	43
TXB	150	62
TXB	70	62
TXB	40	64
TXB	30	96
TXB	30	108
TXB	70	111
TXB	100	117
TXB	30	127
TXB	40	127
TXB	30	127
TXB	30	133
TXB	15	133
TXB	30	139
TXB	15	142
TXB	30	142
RXL		103
RXL		105
RXL		106
TXB	40	7
TXB	60	50
TXB	10	92
TXB	20	95
TXB	20	101
TXB	30	121
TXB	30	123
TXB	20	125
TXB	50	127
TXB	35	132
TXB	30	144

FARRER FORMATION		
TXB	70	58
TXB	20	66
TXB	10	77
TXB	30	79
TXB	10	97
TXB	30	135
TXB	30	152
TXB	50	157
TXB	20	162
TXB	35	172
TXB	10	180
TXB	20	232
GC		177
GC		360
TXB	20	4
TXB	20	8
TXB	10	11
TXB	10	17
TXB	20	20
TXB	30	28
TXB	30	39
TXB	30	42
TXB	35	44
TXB	30	50
TXB	15	322
TXB	50	323
TXB	100	332
TXB	40	341
TXB	50	358
TXB	25	8
TXB	15	18
TXB	10	22
TXB	15	25
TXB	15	26
TXB	70	42
TXB	10	42
TXB	20	52
TXB	20	65
TXB	25	67
TXB	30	69

TXB	30	78
TXB	30	78
TXB	10	80
TXB	20	81
TXB	20	82
TXB	10	87
TXB	20	117
TXB	15	122
TXB	50	133
TXB	20	143
TXB	10	302
TXB	30	330
TXB	15	10
TXB	20	14
TXB	20	20
TXB	40	21
TXB	30	25
TXB	40	27
TXB	30	32
TXB	30	35
TXB	20	38
TXB	20	39
TXB	30	40
TXB	20	50
TXB	30	53
TXB	30	66
TXB	30	357
TXB	20	2
TXB	40	26
TXB	45	38
TXB	40	268
TXB	40	302
TXB	15	304
TXB	30	306
TXB	15	306
TXB	10	332
TXB	40	14
TXB	45	33
TXB	30	242
TXB	30	245
TXB	30	302
TXB	30	336
TXB	60	350

TXB	25	210
TXB	15	232
TXB	50	262
TXB	40	274
TXB	20	286
TXB	20	294
TXB	50	302
TXB	10	340
RXL		291
RXL		303
RXL		305
RXL		310
RXL		320
RXL		320
RXL		322
RXL		328
RXL		330
RXL		331
RXL		347
RXL		292
RXL		298
RXL		106
RXL		110
RXL		112
RXL		113
RXL		116
RXL		117
RXL		119
RXL		121
RXL		130
TXB	20	85
TXB	15	99
TXB	15	101
TXB	20	101
TXB	30	102
TXB	10	106
TXB	40	112
TXB	70	112
TXB	30	113
TXB	50	125
TXB	40	127
TXB	50	127
TXB	60	130

TXB	40	132
TXB	10	134
TXB	40	157
TXB	70	312
TXB	70	317
TXB	20	342
TXB	20	342
RXL		72
RXL		74
RXL		82
RXL		83
RXL		86
RXL		91
RXL		93
RXL		97
RXL		101
RXL		103
RXL		103
RXL		115
TXB	20	42
TXB	20	71
TXB	10	60
TXB	50	68
TXB	20	6
TXB	60	172
TXB	60	175
TXB	40	294
TXB	30	304
TXB	15	348
TXB	15	352
TXB	30	354
TXB	35	358
TXB	20	195
TXB	50	104
TXB	60	115
TXB	30	132
TXB	20	8
TXB	30	13
TXB	30	14
TXB	10	32
TXB	25	36
TXB	10	39
TXB	10	352

TXB	15	28
TXB	15	46
TXB	15	58
TXB	10	83
TXB	10	292
TXB	50	302
TXB	30	314
TXB	80	317
TXB	20	320
TXB	10	322
TXB	20	328
TXB	20	345
TXB	10	346
TXB	10	56
TXB	30	70
TXB	30	32
TXB	80	17
TXB	30	26
TXB	40	32
TXB	30	42
TXB	50	42
TXB	10	52
TXB	30	53
TXB	80	54
TXB	80	60
TXB	30	62
TXB	50	63
TXB	80	68
TXB	80	70
TXB	70	72
TXB	70	72
TXB	80	76
TXB	60	96
TXB	40	42
TXB	80	70
TXB	100	76
TXB	30	86
TXB	30	92
TXB	30	96
TXB	30	100
TXB	30	102
TXB	40	106
TXB	40	106

TXB	30	124
TXB	20	132
TXB	50	170
TXB	50	172
TXB	150	60
TXB	80	67
TXB	40	73
TXB	80	80
TXB	40	80
TXB	20	81
TXB	90	82
TXB	15	82
TXB	15	86
TXB	30	95
TXB	10	98
TXB	70	101
TXB	10	102
TXB	15	102
TXB	20	106
TXB	20	107
TXB	10	113
TXB	200	117
TXB	80	122
TXB	80	132
RXL		236
RXL		247
TXB	20	276
TXB	30	290
RXL		17
RXL		23
RXL		80
TXB	40	5
TXB	10	14
TXB	10	27
TXB	10	50
TXB	10	60
TXB	20	82
TXB	30	83
TXB	60	90
TXB	20	103
TUSCHER FORMATION		

RXL		16
RXL		17
RXL		18
RXL		32
RXL		34
RXL		36
RXL		41
RXL		43
RXL		50
RXL		62
RXL		68
RXL		70
RXL		72
TXB	50	12
TXB	100	20
TXB	40	27
TXB	20	27
TXB	30	38
TXB	30	42
TXB	40	43
TXB	30	50
TXB	60	52
TXB	30	56
TXB	30	42
TXB	20	63
TXB	20	23
TXB	150	27
TXB	200	38
TXB	60	38
TXB	200	39
TXB	70	42
TXB	100	43
TXB	60	44
TXB	150	54
TXB	60	72
TXB	50	241
TXB	100	244
TXB	100	244
TXB	100	252
TXB	50	252
TXB	50	270
TXB	15	272
TXB	15	278

TXB	100	282
TXB	50	342
TXB	30	17
TXB	60	27
TXB	40	30
TXB	60	32
TXB	30	40
TXB	20	41
TXB	60	46
TXB	30	53
TXB	30	57
TXB	30	60
TXB	20	67
TXB	20	72
TXB	30	119
TXB	20	144
TXB	50	152
TXB	40	168
TXB	40	304