Integrating Facies Analysis, Terrestrial Sequence Stratigraphy, and the First Detrital Zircon (U-Pb) Ages of the Twist Gulch Formation, Utah, USA: Constraining Paleogeography and Chronostratigraphy

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Integrating Facies Analysis, Terrestrial Sequence Stratigraphy, and the First Detrital Zircon (U-Pb) Ages of the Twist Gulch Formation, Utah, USA: Constraining Paleogeography and Chronostratigraphy

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A thesis submitted to the faculty of Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

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The Jurassic Twist Gulch Formation of central Utah was deposited in the active Arapien sub-basin of the Western Cordillera foreland trough. We herein demonstrate the utility of integrating facies analysis, terrestrial sequence stratigraphy, and detrital zircon (U-Pb) ages to improve paleogeographic reconstructions as well as identify regional unconformities, locate fluvial depocenters, and infer sediment supply/accommodation space ratios. Strata of the Twist Gulch Formation in Pigeon Creek Canyon (PCC) near Levan, Utah consists primarily of alluvial deposits, while in Salina Canyon (SC) the Twist Gulch Formation is comprised of a mix of alluvial and marginal marine deposits associated with the Jurassic Western Interior Seaway. Within the PCC section, a change from high accommodation system (HAS) mudstones to low accommodation system (LAS) multi-storied channel sandstones and back to HAS deposits exists. This same pattern exists in the SC section but culminates with marine deposits. Terrestrial sequence stratigraphy predicts that the change from HAS to LAS deposits indicate a sequence boundary and thus an unconformity. The J-3 unconformity, a regional unconformity on the Colorado Plateau, separates strata of Callovian age from Oxfordian age in Utah. Using detrital zircons (U-Pb), the first radiometric ages were obtained for the Twist Gulch Formation. The J-3 unconformity is bracketed by detrital zircon (U-Pb) ages and stratigraphic relationships in the study area. These new ages suggest that the Twist Gulch Formation is time-equivalent to the Entrada Sandstone, Curtis, and Summerville formations of the Colorado Plateau. Further, integrating facies analysis, terrestrial sequence stratigraphy, and detrital zircon (U-Pb) ages predicts that the PCC section was an active depocenter during the early Oxfordian in which sedimentation outpaced accommodation space, prograding the Oxfordian shoreline of the Jurassic Western Interior Seaway shoreline eastward. This integration process also predicts that subsurface sandstones positioned above the J-3 unconformity on the west side of the Wasatch Plateau are of a different age, depositional system, and systems tract from subsurface sandstones on the east side of the Wasatch Plateau.
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CHAPTER 1

PALEOGEOGRAPHY OF THE MIDDLE AND LATE JURASSIC FOR CENTRAL UTAH: INTEGRATING FACIES ANALYSIS, TERRESTRIAL SEQUENCE STRATIGRAPHY, AND THE FIRST DETRITAL ZIRCON (U-Pb) AGES OF THE TWIST GULCH FORMATION
The Jurassic Twist Gulch Formation of central Utah was deposited in the active Arapien sub-basin of the Western Cordillera foreland trough. We herein demonstrate the utility of integrating facies analysis, terrestrial sequence stratigraphy, and detrital zircon (U-Pb) ages to improve paleogeographic reconstructions as well as identify regional unconformities, locate fluvial depocenters, and infer sediment supply/accommodation space ratios. Strata of the Twist Gulch Formation in Pigeon Creek Canyon (PCC) near Levan, Utah consists primarily of alluvial deposits, while in Salina Canyon (SC) the Twist Gulch Formation is comprised of a mix of alluvial and marginal marine deposits associated with the Jurassic Western Interior Seaway. Within the PCC section, a change from high accommodation system (HAS) mudstones to low accommodation system (LAS) multi-storied channel sandstones and back to HAS deposits exists. This same pattern exists in the SC section but culminates with marine deposits. Terrestrial sequence stratigraphy predicts that the change from HAS to LAS deposits indicate a sequence boundary and thus an unconformity. The J-3 unconformity, a regional unconformity on the Colorado Plateau, separates strata of Callovian age from Oxfordian age in Utah. Using detrital zircons (U-Pb), the first radiometric ages were obtained for the Twist Gulch Formation. The J-3 unconformity is bracketed by detrital zircon (U-Pb) ages and stratigraphic relationships in the study area. These new ages suggest that the Twist Gulch Formation is time-equivalent to the Entrada Sandstone, Curtis, and Summerville formations of the Colorado Plateau. Further, integrating facies analysis, terrestrial sequence stratigraphy, and detrital zircon (U-Pb) ages
predicts that the PCC section was an active depocenter during the early Oxfordian in which sedimentation outpaced accommodation space, prograding the Oxfordian shoreline of the Jurassic Western Interior Seaway shoreline eastward. This integration process also predicts that subsurface sandstones positioned above the J-3 unconformity on the west side of the Wasatch Plateau are of a different age, depositional system, and systems tract from subsurface sandstones on the east side of the Wasatch Plateau.

**KEY WORDS:** Twist Gulch, paleogeography, detrital zircon, Jurassic, sequence stratigraphy

**INTRODUCTION**

Accurate paloegeographic reconstructions cannot be created without analyzing facies, understanding sequence stratigraphy, and establishing an absolute time framework in which to work. For example, Martinsen et al. (1999) analyzed facies of the Ericson and Almond formations of southwest Wyoming in order to develop a terrestrial sequence stratigraphic model that accounted for changes in relative sea-level within the Cretaceous Interior Seaway. Dickinson et al. (2010) used detrital zircon age dates to establish an absolute timeframe for correlation of lower Middle Jurassic sandstone formations of southern Utah.

Analysis of the Twist Gulch Formation is vital to accurately interpret the paleogeography of the Middle and Late Jurassic for central Utah. The close proximity to an active volcanic arc (Kowallis et al., 2001), deposition during significant sea-level fluctuations, and the mixture of terrestrial and marine strata make the Twist Gulch Formation an ideal formation to analyze in order to test the utility of the multi-disciplinary approach employed in this study. The Twist Gulch Formation crops out along the east and west flanks of the San Pitch Mountains, the mouth of Salina Canyon, and other areas of central Utah, within the Utah Overthrust Belt (Fig. 1). The best exposures of the formation are along the west flank of the San Pitch Mountains, in Pigeon Creek Canyon (PCC), where the section is complete and only partially covered. A near complete
section is exposed in Salina Canyon (SC), but the exposure is vertical due to folding associated with Sevier thrusting (Lawton and Willis, 1987).

The Twist Gulch Formation is composed primarily of fluvial deposits derived from the “Sevier” highlands to the west (Kocurek and Dott, 1983). It also contains some tidal flat (?), marginal marine, and marine deposits (Lawton and Willis, 1987). It was deposited in the Arapien basin (Fig. 2), a sub-basin at the western margin of the broader foreland basin. This foreland was part of the developing North American Cordillera (Hamilton, 1978; Royse Jr., 1993; Lawton, 1994; Currie, 1998; Hintze and Kowallis, 2009). Twist Gulch Formation strata were tectonically transported a short distance (less than 10 km) eastward on Sevier orogenic thrust sheets during latest Jurassic and Early Cretaceous time and subsequently dissected and exposed by Basin and Range normal faulting (DeCelles and Coogan, 2006; Lawton and Willis, 1987).

Previous to this study, no radiometric ages had been obtained for the Twist Gulch Formation. Several authors, however, had tentatively assigned the Twist Gulch Formation a Callovian to Oxfordian age based on stratigraphic relationships (Imlay, 1980; Sprinkel and Waanders, 1984; Waanders and Sprinkel, 1985; Sprinkel, 1994). Waanders and Currie (2008) used palynomorphs to assign a Callovian to Oxfordian age (undifferentiated) to the Twist Gulch Formation.

Ramajo and Aurell (2008) and Fulthorpe et al., (2008), who studied strata in Europe, stated that there was a major eustatic sea-level fall at the Callovian-Oxfordian boundary, creating an unconformity. On the Colorado Plateau, the J-3 unconformity is a regional unconformity that apparently formed in response to this fall in eustatic sea-level (Pipiringos and O’Sullivan, 1978; Blakey, 1996). The J-3 is thought to lie within the Twist Gulch Formation (Sprinkel, 1994). The time represented by the J-3 unconformity is relatively short, probably less than 2 million years
(Wilcox, 2007). Lawton and Willis (1987) tentatively assigned a location for the J-3 unconformity in the SC section based on a lithostratigraphic correlation. The location of the J-3 unconformity has not been interpreted for the PCC section. Blakey (1996) indicated that the J-3 unconformity is often difficult to recognize throughout the Colorado Plateau because lithology is often similar above and below the unconformity. Keach et al. (2006), however, reported that the J-3 unconformity can be identified in some locations by a slight angular discordance.

A younger time-transgressive unconformity marks the boundary between the Twist Gulch Formation and the Cretaceous Cedar Mountain Formation (Sprinkel, 1994). This unconformity includes the J-5 unconformity of Pipiringos and O’Sullivan (1978), Sprinkel (1994) and Blakey (1996) which formed during very latest Oxfordian time. Thus, the youngest possible age of the uppermost strata of the Twist Gulch Formation is late Oxfordian.

Radiometric ages of the Twist Gulch Formation were obtained in order to (1) locate the J-3 unconformity within the formation, (2) correlate it with hypothesized time-equivalent formations of the San Rafael Swell in east-central Utah, (3) help constrain terrestrial sequence stratigraphic interpretations, and (4) better understand Middle and Late Jurassic paleogeography in central Utah. Ultimately, this multidisciplinary approach to the study of the Twist Gulch Formation leads to a more accurate interpretation of sedimentation patterns, paleo-deposcenters, and general paleogeography of this tectonically active area.

**PREVIOUS STUDIES**

Spieker (1946) named and described a 915 m succession of shale, siltstone, and sandstone as the Twist Gulch Member of the Arapien Shale and assigned it to the Late Jurassic. He described it as “unfossiliferous, composed of red siltstone and shale with many thin layers of greenish-white siltstone and occasional layers of gray sandstone, some of which is coarse”.
Hardy (1952) later raised the stratigraphic rank of the Twist Gulch Member of the Arapien Shale to the Twist Gulch Formation.

*Sequence Stratigraphy*

Havholm and Kocurek (1994) and Carr-Crabaugh and Kocurek (1998) provided a sequence stratigraphic framework for the formations of the San Rafael Group of eastern Utah. Based on other regional stratigraphic studies (Pipiringos and O’Sullivan, 1978), they concluded that the Entrada Sandstone was bounded on top by the J-3 unconformity. Facies analysis and reservoir characterization of the erg-margin of the Entrada Sandstone in east-central Utah has also been established (Marino and Morris, 1996; Morris et al., 2005). A sequence stratigraphic interpretation for this time frame has not been made for central Utah where the partially time-equivalent Twist Gulch Formation is located.

Martinsen et al. (1999) developed a model for sequence stratigraphic interpretation of alluvial deposits. In their model, and based on fluvial architecture, fluvial strata can be divided into alternating low-accommodation system (LAS) and high-accommodation system (HAS) deposits (Fig. 3). Each deposit reflects the ratio of accommodation space to sediment supply. In fluvial systems, accommodation space/sediment supply ratios are controlled by fluvial gradient. Changes in fluvial gradient can occur through tectonic uplift/subsidence or changes in eustatic sea-level. According to their model, the sequence boundary is located at the base of the LAS succession and a fluvial expansion surface exists at its top. A fluvial expansion surface marks an abrupt increase of accommodation space and is the terrestrial equivalent of the transgressive surface utilized in marginal marine sequence stratigraphy. The Martinsen et al. (1999) model is utilized herein for interpreting the sequence stratigraphic framework of the Twist Gulch
Formation in Pigeon Creek Canyon (PCC) and the lower portion of the Salina Canyon (SC) section.

The J-3 unconformity is present between the Entrada Sandstone and Curtis Formation (Gilluly and Reeside, 1928; Sprinkel, 1994; Havholm and Kocurek, 1994; Carr-Crabaugh and Kocurek, 1998; Wilcox, 2007). Wilcox (2007) reported that the J-3 unconformity formed during lowstand erosion near the Callovian-Oxfordian boundary. He studied palynomorphs and ammonites to develop a sequence stratigraphic framework for the Entrada Sandstone, Curtis, and Summerville formations of the San Rafael Swell (Fig. 4). The Entrada Sandstone was interpreted to be a Callovian-aged highstand deposit. The basal portion of the Curtis Formation was interpreted to be a transgressive systems tract deposit of Oxfordian age. The upper part of the Curtis Formation and the Summerville Formation were interpreted to be Oxfordian-aged highstand deposits. Dickinson and Gehrels (2009) used detrital zircons to report maximum depositional age for the Curtis Formation at 165 Ma (early Callovian). They suggest a possible explanation for this relatively old age is that the Curtis Formation is composed primarily of reworked Entrada Sandstone sediments. Furthermore, two of the six grains used to produce this age yielded early Oxfordian ages.

Paleogeography

Kocurek and Dott (1983) reconstructed the paleogeography of the central and southern Rocky Mountains. They noted that the shallow Jurassic Western Interior Seaway transgressed into central Utah from the north and west the Bajocian depositing the Twin Creek Limestone and then the Arapien Shale during the Bathonian. During the Callovian, the Entrada Sandstone was deposited on the margins of the seaway. The seaway regressed during the latest Callovian, retreating north out of present day Utah. The sea then transgressed back into present-day central
Utah from the northeast during early Oxfordian time, reaching its greatest extent of the Jurassic during the middle Oxfordian (Kocurek and Dott, 1983). The Curtis and Summerville formations were deposited during this transgression and subsequent highstand (Wilcox, 2007). Blakey and Ranney (2008) synthesized known paleogeographic studies into a series of physiographic maps.

**Stratigraphic Thickness**

Hintze and Kowallis (2009) reported a thickness of 560 m for the Twist Gulch Formation along the western flank of the San Pitch Mountains. This number results from several different workers analyzing both measured sections and well-logs in the area. Spieker (1946), however, reported a thickness of approximately 915 m for the Twist Gulch near Pigeon Creek Canyon (PCC) while Aubey (1991) showed an approximate thickness of 730 m in a cross-section near PCC. Our own work indicates the Twist Gulch Formation to be approximately 790 m in the PCC section, which Sprinkel (1994) suggests is the thickest Twist Gulch Formation section anywhere. The Salina Canyon (SC) section, which is faulted out at the base, is 500 m thick (Lawton and Willis, 1987). Weiss et al. (2003) suggested that the large discrepancy in thickness could be due to inconsistent mudlog picks in the basal muddy section of the Twist Gulch Formation as it transitions to the Arapien Shale.

Along with thinning basinward to the east, the thickness of the Twist Gulch Formation also varies significantly along the western flank of the San Pitch Mountains (Weiss et al., 2003; Weiss and Sprinkel, 2002). This is probably due to the Twist Gulch Formation being deposited on the undulatory surface of the Arapien Shale which was caused by evaporite diapirism and compressional deformation associated with the Middle Jurassic Elko Orogeny (Thorman and Peterson, 2003) or earliest Sevier orogeny (Royse, 1993). Weiss et al (2003) and Weiss and Sprinkel (2002) noted that a thin pebble conglomerate is present at the lower base of the Twist
Gulch Formation in some areas and they suggested that the lower contact of the Twist Gulch Formation is disconformable with the underlying Arapien Shale in these areas.

**METHODS**

Sections of the Twist Gulch Formation were measured at Pigeon Creek Canyon (PCC) near Levan, Utah and Salina Canyon (SC) (Fig. 1). These sections represent the best and most complete exposures of Twist Gulch Formation strata that could be found. The following data were collected from each section: lithologic variations which were confirmed by thin section analysis, grain size trends, primary and secondary sedimentary structures, and megascopic features. Sedimentary facies were interpreted from these observations. Terrestrial sequence stratigraphic interpretations are based on vertical facies changes (see Fig. 4 and Fig. 5).

Fourteen detrital zircon samples were collected; seven from each section. Mudstone, siltstone, and very fine-grained sandstone beds were sampled because they yield the highest number of euhedral zircons. Samples were collected in one or two 19 l (5-gallon) buckets in order to collect a sufficient amount of rock. To avoid contamination, each piece of rock was collected from at least 0.5 m beneath ground surface. The rock was also split along all fractures and thoroughly scraped clean in order to remove any post-depositional contaminants.

Standard detrital zircon processing procedures were followed, including the use of a rock crusher, Wilfley table, tetrabromoethane (TBE) heavy liquid, and a magnetic separator. When the raw sample had been reduced to the heaviest grains, the sample was placed under a binocular microscope and the most euhedral zircon crystals were picked to be dated. Six samples yielded enough euhedral and sub-euhedral zircons to be dated; three from each section.

U-Pb ages of zircons were obtained by laser-ablation-multi-collector inductively coupled plasma–mass spectrometry at the University of Arizona LaserChron Center. Details of the dating method and data reduction technique have been previously described (Gehrels et al., 2006;
Gehrels et al., 2008; and Johnston et al., 2009). Three of the six samples produced a sufficient cluster \((n = \text{at least } 3)\) of young ages to produce a statistically significant age, two from the PCC section (samples #1 and #2) and one from the SC section (sample #3) (Fig. 5).

**SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHIC INTERPRETATION**

Thorough sedimentologic analysis is necessary in order to develop accurate sequence stratigraphic interpretations and palaeogeographic reconstructions.

*Sedimentology of Pigeon Creek Canyon (PCC)*

The basal 4 m of the Pigeon Creek Canyon (PCC) section (Fig. 5) coarsens upwards into sandy siltstone from the underlying Arapien Shale. Diagnostic sedimentary structures include: normally graded beds, contorted beds, asymmetrical ripple lamination, and herringbone cross-stratification. Overlying the basal 4 m are 250 m of mottled red-gray to red mudstones characterized by pinch and swell features and 3D ripple sets including lunate ripples and sparse flat-top ripples. Over the next 150 m, the section coarsens-up into thin-bedded, red, very fine-grained to fine-grained sandstone with planar lamination, sparse ripple lamination, and interbeds of siltstone and mudstone. Thin sections from fine-grained sandstone within this portion of the section contain sparse crinoid fragments.

At approximately 400 m up the section, 60 m of multi-storied channel sandstone beds are exposed in a cliff (Fig. 6a). The multi-storied channel sandstone section is characterized by medium to coarse-grained lithic-rich sandstone, scours with pebble lags, 20 cm-scale trough cross-stratification, and occasional tool marks. Near the top of the multi-storied sandstone beds, beds thicken and scours become deeper and more laterally extensive (Fig. 6b). Pebble lags near the top of the multi-storied sandstone section are weakly imbricated. There is an approximately one meter-thick conglomerate with clasts up to 12 cm in diameter that caps this portion of the
section. A thin section of this conglomerate contains numerous crinoid fragments (~10% total rock), carbonate wackestone rock fragments containing crinoid fragments, altered ooids, echinoids, ostracods, and a trilobite. Above the conglomerate is a sharp transition to fine-grained sandstone containing climbing ripples and asymmetrical ripple lamination which grades into interbeds of coarse siltstone and fine-grained sandstone over the next 200 m of section. Thin sections also contain very sparse crinoid fragments. The uppermost 130 m coarsens to fine-to-medium grained sandstone beds.

**Interpretation.**--- The basal 4 m of the Pigeon Creek Canyon (PCC) section is interpreted to be a small, tidally-influenced deltaic deposit. The deltaic deposits are overlain by 250 m of mudstone deposited on a lower alluvial plain in overbank and interfluve floodplain environments. Asymmetrical ripple lamination indicates deposition under unidirectional flow in the lower flow regime (Southard and Boguchwal, 1990). Sparse flat-topped ripples indicate wave reworking of the lunate ripples. These lower alluvial plain deposits prograded over the basal deltaic deposits. The slight coarsening upward succession within this 250 m interval represents continued progradation and relative sea-level fall. The multi-story channel sandstone section represents a braided, bedload channel complex indicating increasingly higher fluvial gradients and associated fine-grained sediment bypass. The conglomerate bed at the top of the complex represents the culmination of this increasing fluvial gradient. The upper 330 m of the PCC section represents a dramatic decrease in the fluvial gradient and the return of lower alluvial plain deposits. These lower alluvial plain deposits (the uppermost 330 m) are more coarse-grained than the lower alluvial plain deposits at the bottom of the section (bottom 400 m) indicating a higher fluvial gradient. Marine fossil fragments are detrital as evidenced by a trilobite within Jurassic strata and
crinoid fragments within carbonate wackestone fragments. Paleozoic bedrock from the Sevier highlands to the west is the likely provenance for the detrital clastics.

**Sequence Stratigraphy.---** The basal deltaic succession (4 m) and lower alluvial plain deposits (400 m) comprise a high accommodation system (HAS) wherein the ratio of accommodation to sediment supply was relatively high (see Fig. 3; Martinsen et al., 1999). This lower 400 m records a slight decrease in accommodation space through time. The transition from lower alluvial plain beds deposited in HAS conditions to multi-storied channel sandstone beds deposited in a low accommodation system (LAS), indicates a sequence boundary that we interpret as the J-3 unconformity (see Fig. 5). The LAS deposits lie above the sequence boundary. These terrestrial channel complex deposits would be time equivalent to lowstand deposits of a marginal marine sequence. However, no lowstand deposits above the J-3 unconformity are believed to be present east of the Wasatch Plateau, therefore these rocks have no basinal equivalent deposits in eastern Utah (Wilcox, 2007).

The sharp transition from LAS deposits to overlying HAS deposits comprised of fine-grained sandstone defines a fluvial expansion surface (see Fig. 3 and 6a; Martinsen et al., 1999). An expansion surface is the terrestrial equivalent of a marginal marine transgressive surface and results from a relative rise in sea-level (Martinsen et al., 1999).

The upper HAS deposit (upper 330 m) is generally more coarse-grained than the lower HAS deposit (lower 400 m) despite being associated with the highest sea-levels of the Jurassic Western Interior Seaway (Kocurek and Dott, 1983). This indicates an increasingly reduced accommodation space/sediment supply ratio throughout deposition of the Twist Gulch Formation. Because the coarser-grained, upper HAS was deposited at a time when the Jurassic Western Interior Seaway was at its greatest extent, the relatively low accommodation
space/sediment supply ratio is interpreted to result from sediment supply outpacing sea-level rise.

**Sedimentology of Salina Canyon (SC)**

In Salina Canyon (SC) the Twist Gulch Formation is vertical and “capped” by an angular unconformity associated with the Gunnison-Salina thrust (Willis, 1986) (Fig. 5). A portion of unknown thickness has been faulted out of the bottom of the section (Lawton and Willis, 1987).

The bottom 330 m of the exposed portion of the SC section consists of red siltstone with occasional gray sandstone beds. The siltstone beds are generally planar laminated with common green reduction patches and gray sandstone lenses that are cross-stratified. The gray sandstone beds are planar laminated or low-angle trough cross-stratified. Repeating coarsening-up packages are present. Capping each coarsening-up package is a very coarse-grained, poorly sorted sandstone to pebble conglomerate containing cut-and-fill structures. Approximately 330 m up the section, there is a transition from primarily recessive red siltstone to primarily ledge-forming gray sandstone interbedded with red siltstone. Trough cross-stratification and symmetrical ripple lamination are present within these sandstone beds.

A gray pebble conglomerate with crinoid, oyster, brachiopod, and bryozoan fragments (~15 % total rock in thin section) is located approximately 390 m from the base of the section. Green mudstone beds overlie the crinoidal pebble conglomerate. A yellow-white sandstone containing chert pebbles is present above the green mudstone beds. Gray claystone beds are present above the yellow-white sandstone (Fig. 5).

**Interpretation.**---The bottom 390 m of the Salina Canyon (SC) section are interpreted as alluvial deposits. Although Lawton and Willis (1987) suggested that this interval contains some tidal flat deposits, we found no definitive sedimentary structures indicating tidal influence (e.g.,
herringbone cross-stratification, draped laminae, tidal bundles, etc.). The ledge-forming gray sandstone beds that lie above the 330 m recessive red siltstone interval comprise an approximately 60 m thick section that we also interpret as alluvial deposits. The upper 110 m of the SC section are comprised of marine strata. The crinoidal pebble conglomerate, green mudstone, and the overlying yellow-white sandstone as represents shallow marine facies. We recognize that the fossil fragments found in the gray pebble conglomerate are detrital and suggest the concentration of those detrital fossil fragments are a result of nearshore marine, high energy processes. Jurasssic-aged marine palynomorphs collected from the green mudstone that lies between the gray pebble conglomerate and yellow-white sandstone confirm this interpretation (Waanders and Currie, 2008). The gray claystone above these shallow marine deposits are interpreted to be relatively deepwater facies.

**Sequence Stratigraphy.**---We interpret the bottom 330 m of the Salina Canyon (SC) section as high accommodation system (HAS) deposits that are time-equivalent to the Pigeon Creek Canyon (PCC) section’s lower HAS. The coarsening-up packages within this interval may be the terrestrial equivalents to the parasequences of marginal marine sequence stratigraphic terminology. The pebble conglomerate at the top of each package represents the most progradational extent of the coarsening-up packages. The transition from primarily recessive red siltstone to ledge-forming gray sandstone marks the J-3 unconformity and a transition from HAS to low accommodation system (LAS) deposits (Fig. 5 and Fig. 6a). These 60 m thick LAS deposits are correlative to the LAS interval of the PCC section.

The crinoidal pebble conglomerate located above the alluvial portion of the section is the base of the marine transgressive systems tract as also suggested by Lawton and Willis.
The green mudstone, yellow-white sandstone, and overlying gray claystone beds are transgressive to highstand deposits. They are equivalent to the upper HAS of the PCC section.

**U-Pb GEOCHRONOLOGY**

U-Pb geochronology of detrital zircons has proved to be a valuable tool for determining the maximum depositional age of clastic strata (Gehrels et al., 2006). Sampling euhedral zircons allows for the best estimate of depositional age. Samples containing subeuhedral zircons are likely to yield ages much older than the actual depositional age because they have been eroded and reworked. U-Pb ages, therefore, do not eliminate the possibility that the rocks are younger than the reported age.

Fourteen samples were collected for detrital zircon analysis, seven from each section (see Fig. 5). Six of the fourteen samples, three from each section, yielded enough euhedral and sub-euhedral zircons to be dated. Only three of the six dated samples produced a sufficient cluster (n = at least 3) of young ages to be statistically significant (Fig. 7). The ages represent the mean of the youngest cluster of ages at a standard error of 2-sigma. Age plots were generated using Isoplot 3.00 software (Ludwig, 2003). Full analytical data are included in the accompanying data archive.

Sample #1 was taken from the Pigeon Creek Canyon (PCC) section about 15 m above the base of the low accommodation system (LAS) (Fig. 5). The sample contained several sub-euhedral zircons but no euhedral zircons. Therefore, the calculated age is most likely older than the actual depositional age. The sample yielded an age of 167.4 ± 3.4 Ma (Bathonian). Sample #2 was collected approximately 10 m above the expansion surface of the PCC section and contained sub-euhedral and euhedral zircons. The sample yielded an age of 154.9 ± 6.4 Ma (Oxfordian to Kimmeridgian). Sample #3 was collected near the middle of the Salina Canyon (SC) section, near the location that we interpreted as the sequence boundary (i.e., J-3
unconformity). The sample contained sub-euhedral and euhedral zircons and yielded an age of 159.5 ± 5.1 Ma (Callovian to Oxfordian).

DISCUSSION

Zircon U-Pb Ages and the J-3 Unconformity

Detrital zircon sample #1 (167.4 ± 3.4 Ma) must be older than the actual depositional age because palynomorphs from the very top of the Arapien Shale are Callovian in age (Sprinkel and Waanders, 1984; Waanders and Sprinkel, 1985). Based on this stratigraphic relationship, the base of the Twist Gulch Formation, which is conformable with the underlying Arapien Shale in this location, is lower Callovian in age (Fig. 4 and Fig. 5). Sample #2 yielded an age of (154.9 ± 6.4 Ma). The error margin constrains the sample to an age of Oxfordian to Kimmeridian. The unconformity that lies above the Twist Gulch Formation was initiated no later than 156 Ma (Sprinkel, 1994; Kowallis et al., 1998; Wilcox, 2007; Hintze and Kowallis, 2009). This constrains sample #2 and the upper high accommodation system (HAS) in Pigeon Creek Canyon (PCC) to the Oxfordian (Fig. 4 and Fig. 5). Thus, the J-3 unconformity, which was formed at approximately 161 Ma to 162 Ma (Sprinkel, 1994; Wilcox, 2007; Hintze and Kowallis, 2009), is present within the Twist Gulch Formation. Sample #3 yielded an age of 159.5 ± 5.1 Ma. This age places the sample near the J-3 unconformity. Together, the vertical lithofacies change from recessive red siltstone to dominantly ledge-forming gray sandstone and the U-Pb age date strongly support the interpretation of the J-3 unconformity being located at this point in the section (Fig. 4 and Fig. 5).

In summary, integration of U-Pb zircon ages, known stratigraphic relationships, and sedimentologic facies analysis have allowed us to constrain the age of the Twist Gulch Formation and the position of the J-3 unconformity.
**Terrestrial Sequence Stratigraphy**

The interpreted transition from high accommodation system (HAS) to low accommodation system (LAS) back to HAS deposits in the Pigeon Creek Canyon (PCC) section records (1) highstand conditions present during the early Callovian, (2) a major eustatic fall in sea-level near the Callovian-Oxfordian boundary, and (3) a major transgression during early Oxfordian time which raised the Jurassic Western Interior Seaway to its greatest extent (Fig. 4 and 5). Thus, the lower HAS at PCC is Callovian in age and equivalent to the Entrada Sandstone in eastern Utah (Wilcox, 2007). The LAS of PCC has no equivalent rocks to the east. A paleogeographic map drafted by Wilcox (2007) shows that the Jurassic Interior Seaway retreated out of Utah and into southwest Wyoming at the time of the formation of the J-3 unconformity. This suggests that any Oxfordian lowstand deposits associated with the Jurassic Interior Seaway are likely located in southwest Wyoming. The upper HAS in the PCC is time equivalent to the Curtis and Summerville formations in eastern Utah. Together, these relationships suggest that more time is captured in the J-3 unconformity in eastern Utah than was captured in central Utah.

In the Salina Canyon (SC) section, the transition from primarily recessive red siltstone to ledge-forming gray sandstone marks the sequence boundary (J-3 unconformity) and a transition from HAS to LAS deposits (Fig. 5). These LAS deposits are interpreted to be correlative to the LAS interval of the PCC section. The crinoidal pebble conglomerate is the first marine deposit, the base of the transgressive systems tract, and the first deposits of Oxfordian age. All rocks above the crinoidal pebble conglomerate are transgressive to highstand deposits equivalent to the Curtis and Summerville formations located in east-central Utah (Fig. 4 and 5).
Sequence Stratigraphic vs. Lithostratigraphic Correlations

The interpreted cross-section shown in Figure 8 illustrates the importance of using a sequence stratigraphic approach rather than a lithostratigraphic approach when correlating well-logs. In the Pigeon Creek Canyon (PCC) section, and in all four well-logs, a large sandstone package is located directly above the J-3 unconformity. Without the U-Pb geochronology and sequence stratigraphic approach used herein, the geoscientist would likely correlate these sandstones. However, the sandstones on the western side of the Wasatch Plateau (Twist Gulch Formation) relative to the sandstones on the eastern side of the Wasatch Plateau (Curtis Formation) are: 1) of a different age, 2) deposited by different depositional systems, 3) deposited in different systems tracts, and 4) cannot be assumed to be in fluid communication with one another. This approach would be very important for hydrologic or petroleum exploration applications within the central-Utah Overthrust Belt, as well as analogous settings elsewhere.

Paleogeographic Implications

The Twist Gulch Formation is thicker in the Pigeon Creek Canyon (PCC) section than any other outcrop or well-log in the state (Sprinkel, 1994). The Twist Gulch Formation thins significantly under the Wasatch Plateau (Fig. 8) and generally thins to the north and south as well (Sprinkel, 1994; Hintze and Kowallis, 2006). This observation, along with the anomalous presence of (LAS) (lowstand equivalent) deposits above the J-3 unconformity indicates that this area was an active depocenter during early Oxfordian time and probably throughout the Oxfordian. This depocenter was associated with the subsiding Arapien basin. We speculate that the LAS of the PCC section may have been deposited in the up-dip terrestrial equivalent of an incised valley. We were not able to locate multi-storied channel sandstone beds with equivalent
thickness in other canyons along the west flank of the San Pitch Mountains or in Salina Canyon (SC).

The upper high accommodation system (HAS) deposit (Oxfordian) in the PCC section is generally more coarse-grained than the lower HAS deposit (Callovian) despite being associated with the highest sea-levels of the Jurassic Western Interior Seaway. This is due to an increasingly reduced accommodation space/sediment supply ratio at the location of the alluvial plain through Callovian and Oxfordian time. The Oxfordian HAS was deposited at a time when the Jurassic Western Interior Seaway was at its greatest extent. Yet compared to the Callovian HAS it represents a relatively low accommodation space/sediment supply ratio. This apparent paradox can be explained by sediment supply outpacing sea-level rise.

In summary, we believe that the anomalously thick stratigraphic section at PCC resulted from a combination of rapid sub-basin subsidence (Arapien basin) and high sediment supply from the encroaching hinterlands of the developing Sevier Orogeny of the North American Cordilleran. Thus, this study sheds new light on the Middle and Late Jurassic paleogeography and sedimentation patterns of central Utah. Our data shows that the western shoreline of the Jurassic Western Interior Seaway was located significantly further to the east than previously interpreted, especially in the PCC area (Fig. 2). Further, relatively high hinterlands, with the ability to supply abundant sediment, were proximal to this rapidly subsiding sub-basin. Pebble and cobble conglomerates within the LAS succession in PCC indicate a very proximal sediment source.

CONCLUSIONS

The combined use of facies analysis, terrestrial sequence stratigraphy, and detrital zircon (U-Pb) ages improves prediction of unconformities, depocenters, sedimentation patterns, and
paleogeography. We have demonstrated that this integrated approach is useful when studying Mesozoic rocks of the Colorado Plateau and suggest it can be applied in other siliciclastic basins.

1. The first radiometric ages for the Twist Gulch Formation of the central-Utah Overthrust Belt are herein reported. These detrital zircon (U-Pb) ages and known stratigraphic relationships confirm and constrain the location of the J-3 unconformity within the Twist Gulch Formation in the Pigeon Creek Canyon (PCC) and Salina Canyon (SC) sections. The Twist Gulch Formation is time-equivalent to the Entrada Sandstone, Curtis, and Summerville formations of east-central Utah.

2. Terrestrial sequence stratigraphy constrained by U-Pb ages and known stratigraphic relationships predicts that subsurface sandstones of the western Wasatch Plateau have different ages, different depositional systems, different systems tracts, and cannot be assumed to be in fluid communication with subsurface sandstones of the eastern Wasatch Plateau.

3. The anomalous thickness of Twist Gulch Formation strata at PCC indicates that this area was a major fluvial depocenter during early Oxfordian time. This is supported by the presence of lowstand equivalent deposits (LAS), which are not present in other areas of the basin. As sediment supply outpaced subsidence of the Arapien Basin during a major sea-level rise, the western shoreline prograded eastward, precluding the ongoing marine transgression and dramatically affecting the paleogeography of the Jurassic Western Interior Seaway.

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Figure 1. Location of the study area in central Utah. The Twist Gulch Formation crops out in various places along the east and west flanks of the San Pitch Mountains, in Salina Canyon, and other areas of the Utah Overthrust Belt in central Utah. Pigeon Creek Canyon (PCC) displays the most complete and continuous exposures. A partial section is also located in Salina Canyon (SC). The San Rafael Swell (SRS) is located immediately east of the study area.
Figure 2. Early Oxfordian paleogeography of Utah. The Twist Gulch Formation was deposited in the Arapien basin (dotted line) of the Jurassic Western Interior Seaway (gray with shoreline dashed). The Arapien basin was a subbasin within the broader foreland basin in the developing North American Cordillera. A) An early Oxfordian paleogeographic reconstruction by Blakey and Ranney (2008). Modified from Blakey and Ranney (2008) and Hintze and Kowallis (2009). B) A revised paleogeographic map of the early Oxfordian based on new data gathered in this study. Note the revised position of the western shoreline and the proximal highlands.
According to the terrestrial sequence stratigraphic model proposed by Martinsen et al. (1999), fluvial deposits in southwest Wyoming can be divided into alternating low-accommodation systems (LAS) and high-accommodation systems (HAS). Sequence boundaries are located at the base of the LAS successions and expansion surfaces at their top. Vertical facies changes within the PCC section of the Twist Gulch Formation can be explained by Martinsen’s (1999) model. Note that the lower HAS is finer grained than the upper HAS, indicating a decreasing accommodation space/sediment supply ratio through time.
Figure 4. Stratigraphic correlation of Twist Gulch Formation and time-equivalent formations of the San Rafael Swell. San Rafael Swell stratigraphy is from Wilcox (2007). Time scale is from Gradstein et al. (2004). Note that the J-3 unconformity captures more time in the San Rafael Swell than it does in the study area.
Figure 5. Stratigraphic columns for PCC and SC with sequence stratigraphic interpretation. Detrital zircon samples and associated ages are shown in red. The detrital zircon ages support the sequence stratigraphic interpretation (see text for discussion).
Figure 6. Photographs of study area. A) Northward view of the PCC outcrop illustrating the lower HAS succession (Callovian), J-3 unconformity, LAS succession (Oxfordian), expansion surface, and upper HAS succession (Oxfordian). B) Northwest view of the top of the multi-storied sandstones in the PCC section. The beds thicken and scours become deeper and more laterally extensive.

Figure 7. Age plots for detrital zircon samples. Three of the six dated samples produced a sufficient cluster (n = at least 3) of young ages to be statistically significant. The ages reported in this paper are based on $^{206}\text{Pb}/^{238}\text{U}$ and represent the mean of the youngest cluster of ages (Best age) at standard error of 2-sigma. The three samples, along with stratigraphic relationships, bracket the J-3 unconformity in the PCC section (Samples #1 and #2) and help locate the J-3 unconformity in the SC section (Sample #3). Full analytical data are included in the accompanying data archive.
Figure 8. Gamma Ray well-log correlation across Wasatch Plateau. An interpreted well-log correlation (hung on the J-3 unconformity) across the Wasatch Plateau links the Twist Guleh Formation at PCC to time-equivalent formations of the San Rafael Swell. The cross-section illustrates the importance of using a sequence stratigraphic rather than a lithostratigraphic approach when correlating well-logs (see text for discussion).
APPENDIX 1 – DETRITAL ZIRCON RAW DATA

Six detrital zircon samples were dated at the University of Arizona, three samples from the Pigeon Creek Canyon (PCC) section and three from the Salina Canyon (SC) section. Three of the six samples produced a sufficient cluster (n = at least 3) of young ages to be statistically significant. These 3 samples are listed as “Sample #1”, “Sample #2” and “Sample #3” in the following raw data spreadsheets and cumulative age probability plots. These samples correspond to Samples #1, #2, and #3 in Chapter 1 of this thesis.

U-Pb geochronologic analysis of detrital zircon –Text adapted from University of Arizona LaserChron Center

U-Pb geochronology of zircons was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center. The analyses involve ablation of zircon with a New Wave/Lambda Physik DUV193 Excimer laser (operating at a wavelength of 193 nm). The ablated material is carried in helium into the plasma source of a GVI Isoprobe, which is equipped with a flight tube of sufficient width that U, Th, and Pb isotopes are measured simultaneously. All measurements are made in static mode, using 10e11 ohm Faraday detectors for 238U, 232Th, 208Pb, and 206Pb, a 10e12 ohm faraday collector for 207Pb, and an ion-counting channel for 204Pb. Ion yields are ~1.0 mv per ppm. Each analysis consists of one 12-second integration on peaks with the laser off (for backgrounds), 12 one-second integrations with the laser firing, and a 30 second delay to purge the previous sample and prepare for the next analysis. The ablation pit is ~12 microns in depth.

For each analysis, the errors in determining 206Pb/238U and 206Pb/204Pb result in a measurement error of ~1-2% (at 2-sigma level) in the 206Pb/238U age.

Common Pb correction is accomplished by using the measured 204Pb and assuming an initial Pb composition from Stacey and Kramers (1975) (with uncertainties of 1.0 for 206Pb/204Pb and 0.3 for 207Pb/204Pb). Our measurement of 204Pb is unaffected by the presence of 204Hg because backgrounds are measured on peaks (thereby subtracting any background 204Hg and 204Pb), and because very little Hg is present in the argon gas.

Inter-element fractionation of Pb/U is generally ~20%, whereas apparent fractionation of Pb isotopes is generally ~2%. In-run analysis of fragments of a large zircon crystal (generally every fifth measurement) with known age of 564 ± 4 Ma (2-sigma error) is used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally 1-2% (2-sigma) for both 206Pb/207Pb and 206Pb/238U ages.

Interpreted ages are based on 206Pb/238U for <1000 Ma grains and on 206Pb/207Pb for >1000 Ma grains. This division at 1000 Ma results from the increasing uncertainty of 206Pb/238U ages.
and the decreasing uncertainty of $^{206}\text{Pb}/^{207}\text{Pb}$ ages as a function of age. Analyses that are $>30\%$ discordant (by comparison of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages) or $>5\%$ reverse discordant are not considered further.


All uncertainties are reported at the 1-sigma level, and include only measurement errors. Systematic errors would increase age uncertainties by 1-2%.

U concentration and U/Th are calibrated relative to our Sri Lanka standard zircon, and are accurate to ~20%.

Common Pb correction is from 204Pb, with composition interpreted from Stacey and Kramers (1975) and uncertainties of 1.0 for $^{206}\text{Pb}/^{204}\text{Pb}$, 0.3 for $^{207}\text{Pb}/^{204}\text{Pb}$, and 2.0 for $^{208}\text{Pb}/^{204}\text{Pb}$.

U/Pb and $^{206}\text{Pb}/^{207}\text{Pb}$ fractionation is calibrated relative to fragments of a large Sri Lanka zircon of 564 ± 4 Ma (2-sigma).

U decay constants and composition as follows: $^{238}\text{U} = 9.8485 \times 10^{-10}$, $^{235}\text{U} = 1.55125 \times 10^{-10}$, $^{238}\text{U}/^{235}\text{U} = 137.88$
APPENDIX 2 – STRATIGRAPHIC COLUMNS FROM OF PIGEON CREEK CANYON

The basal 4 meters of the Pigeon Creek Canyon (PCC) section are interpreted as a small tidally-influenced deltaic succession that coarsens up from the underlying Arapien Shale (see figure 6a). Appendix 2 contains a more detailed measured section of this deltaic succession. A more detailed measured section of the low accommodation system (LAS) portion of the PCC section is also included.
Unit 1: Very fine-grained sandstone; planar laminated; 5-6 cm partings; friable; ledge-former.

Unit 2: Siltstone; planar laminated; recessive; slope-former.

Unit 3: Same as Unit 1

Unit 4: Same as Unit 2

Unit 5: Five pulses fining-up from very fine-grained to fine-grained sandstone; bottom pulse has unidirectional ripples; ledge-former.

Unit 6: Fine-grained sandstone; highly contorted beds.

Unit 7: Fines up from fine-grained to very fine-grained sandstone.

Unit 8: Fine-grained sandstone; alternating beds containing 1 to 2 cm high poly-directional ripples and planar lamination; ledge former.

Unit 9: Siltstone; planar lamination

Unit 10: Fine-grained sandstone; herringbone cross-stratification.

Unit 11: Fine to medium-grained sandstone; contains discontinuous scours; scours contain mud drapes.

- Scour with mud drape
- Herringbone cross-stratification
- Poly-directional ripple stratification
- Contorted beds
- Unidirectional ripple stratification
LAS of Pigeon Creek Canyon
APPENDIX 3 – STRATIGRAPHIC COLUMN OF SALINA CANYON

The Salina Canyon section was originally measured by students in the BYU 2008 Field Camp. Each portion of the section has been checked and edited for accuracy. In some instances, significant changes were made. The measured section is displayed here in a reduced scale from the original. A portion of unknown thickness has been faulted out at the base of this section.
APPENDIX 4 – THIN-SECTION ANALYSIS

To more accurately interpret the lithology and depositional environment of the Twist Gulch in Pigeon Creek Canyon (PCC) and Salina Canyon (SC), five thin-sections were analyzed from each section. Data obtained from this analysis are included in the main body of this paper. Marine fossils located within the PCC section are detrital in origin and were eroded from Paleozoic strata of the nearby Sevier Thrust Belt.

Photomicrograph Descriptions

PCC1: Basal deltaic succession of Pigeon Creek Canyon (PCC). Sample contains siltstone to very fine-grained sandstone.

PCC2: Near the top of the lower high accommodation system (HAS) succession in PCC. Sample contains fine-grained sand clasts and very sparse (less than 1%) crinoid fragments.

PCC3: LAS of PCC. Sample contains coarse-grained sand clasts, numerous lithics, carbonate grains, sparse crinoids and radial ooids. A crinoid fragment is shown.

PCC4-1: Conglomerate at the top of LAS of PCC. Sample contains approximately 10% crinoids fragments, bivalve fragments, ostracod fragments, brachiopod fragments, and a trilobite fragment. Crinoid fragments within a wackestone rock fragment are shown.

PCC4-2: Conglomerate at the top of LAS of PCC. Crinoid fragments are present in the wackestone rock fragment.

PCC4-3: Conglomerate at the top of LAS of PCC. Ostracod fragments are shown.

PCC4-4: Conglomerate at the top of LAS of PCC. Trilobite fragment is shown.

PCC4-5: Conglomerate at the top of LAS of PCC. Echinoid fragment is shown.

PCC5: A few feet above the LAS section at PCC. Sample contains fine-grained sand clasts and very sparse (less than 1%) crinoid fragments.

SC1: Sandstones at the lowest exposed portion of the Salina Canyon (SC) section. Sample contains fine-grained sand clasts and no carbonate grains.

SC2: Sandstones about 40 m from the base of the exposed portion of the SC section. Sample contains fine-grained sand clasts and no carbonate grains.
SC3: Ledge forming sandstones directly above the interpreted J3 unconformity in the SC section. Sample contains fine-grained sand clasts and no carbonate grains.

SC4-1: Crinoid hash gray pebble conglomerate in the SC section. Sample contains abundant crinoid fragments, altered radial ooids, bryzoan fragments, bivalve fragments, and brachiopod fragments. Bivalve fragment is shown.

SC4-2: Crinoid hash gray pebble conglomerate in the SC section. Crinoid fragment is shown.

SC4-3: Crinoid hash gray pebble conglomerate in the SC section. Radial ooid is shown.

SC4-4: Crinoid hash gray pebble conglomerate in the SC section. Two crinoids columns cemented together are shown.

SC4-5: Crinoid hash gray pebble conglomerate in the SC section. Brachiopod fragment is shown.

SC4-6: Crinoid hash gray pebble conglomerate in the SC section. Bryzoan fragment is shown.

SC-5: Yellow-white shallow marine sandstone from the SC section. Sample contains fine and medium-grained sand clasts, abundant pore space and areas of heavy cementation.
APPENDIX 5 - POROSITY

Core plugs were collected from multiple sites in Pigeon Creek Canyon (PCC) and Salina Canyon (SC). The core plugs were measured for porosity using the Ultra-Pore™ 300. Core plugs from rock that was not cemented well enough to allow for a measurement to be taken are recorded with “0” values. An Excel spreadsheet with porosity data is included as well as stratigraphic columns to indicate where the sample was collected. Reservoir characterization was originally planned for this thesis but the emphasis of the study was later changed. The porosity data is still reported in order to not lose any data that was collected.