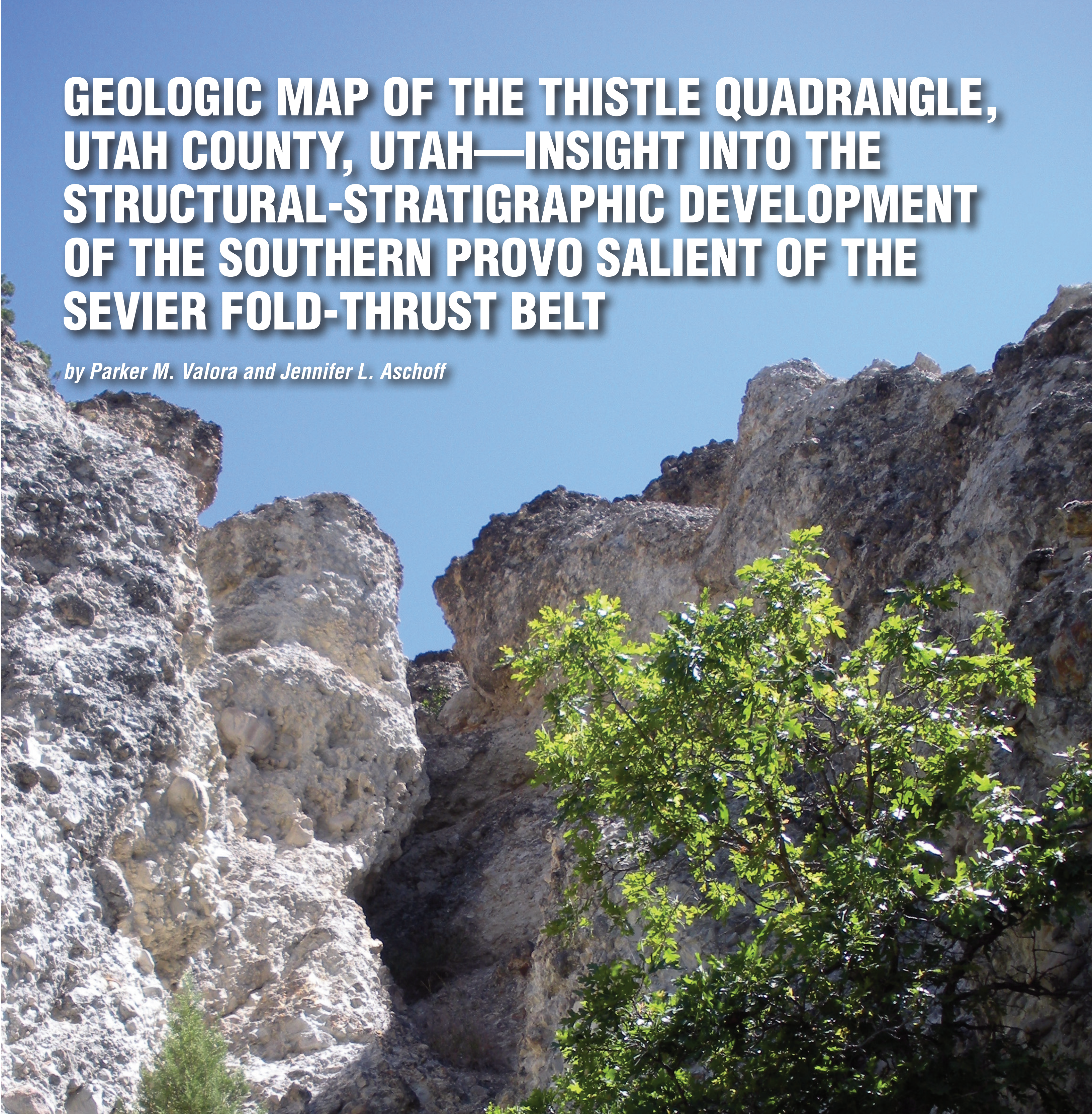
GEOLOGIC MAP OF THE THISTLE QUADRANGLE, UTAH COUNTY, UTAH—INSIGHT INTO THE STRUCTURAL-STRATIGRAPHIC DEVELOPMENT OF THE SOUTHERN PROVO SALIENT OF THE SEVIER FOLD-THRUST BELT

by Parker M. Valora and Jennifer L. Aschoff



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Geologic map of the Thistle Quadrangle, Utah County, Utah—Insight into the Structural-Stratigraphic Development of the Southern Provo Salient of the Sevier Fold-Thrust Belt

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Cover photo: *Morning sunlight on gray cliffs of the conglomerate of Thistle in Dry Creek, southwest corner of the Thistle quadrangle.*

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Geologic map of the Thistle Quadrangle, Utah County, Utah—Insight into the Structural-Stratigraphic Development of the Southern Provo Salient of the Sevier Fold-Thrust Belt

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ABSTRACT

New mapping of the Thistle, Utah, 7.5' quadrangle and integrated analysis of frontal fold-thrust belt structures and associated synorogenic stratigraphy provide new insight into the development of the southern part of the Provo salient of the Sevier fold-thrust belt. Mapping and analysis of growth strata and synorogenic stratigraphy exposed in Dry Hollow, Dry Creek, and Rock Creek support work by Constenius (1998) that showed compressional structural development in the frontal Provo salient occurred from approximately 100 to 40 million years ago, followed by a transition to extension. Furthermore, examination of syntectonic unconformities and synorogenic stratigraphy suggests early development of a series of isolated structures (such as thrust-cored fault propagation folds) as early as the Cenomanian, which evolved in this manner:

1. Deformation in the Thistle area initiated in the northwest (i.e., Dry Hollow area) from the Cenomanian to Campanian (~98 to 77 Ma), before a major phase of uplift and erosion from mid-Campanian to Paleocene (~75 to 50 Ma) affected the entire Thistle area, creating significant relief and new depositional systems;
2. Deformation in the Dry Creek locale began in the Santonian (~85 Ma?), soon after Dry Hollow, and was later affected by the same phase of regional uplift and erosion in the mid-Campanian to the Paleocene;
3. Deformation in the Rock Creek locale began in the early Campanian (~80 Ma) and continued into the Paleocene, including the same major phase of Campanian (~75 Ma) uplift and erosion.

These structures propagated toward the southeast but generally expanded northeastward (laterally) through time, deflecting deltaic deposition and causing localized thinning of deposited strata. The isolated structures were ultimately incorporated into a high-relief culmination with consequent drainages that sourced alluvial fans.

INTRODUCTION

Structural development along segments of the Sevier fold-thrust belt of north-central Utah formed as a complex suite of salients and reentrants that are notable in map view (figure 1). Distinct segments of the thrust belt are marked by pronounced, transverse-oriented features that accommodate along-strike changes in structural style or rates of motion; these features are termed *transverse zones* (TZ) (Evans and Neves, 1992; Apotria, 1995; Mitra, 1997; Paulsen and Marshak, 1998; Paulsen and Marshak, 1999; DeCelles, 2004; Kwon and Mitra, 2006; Valora, 2010). A wide range of structures are present within transverse zones; these occur at multiple scales and can include strike-slip faults, en-echelon tear faults, lateral ramps, and oblique-lateral ramps.

A prime example of the structural complexity of salients and the role of TZs in the development of salients can be found in the Provo salient of north-central Utah. This salient is bounded on the north by a well-exposed lateral ramp TZ (figure 1; also see Paulsen and Marshak, 1999) that transitions southward, along its east flank, into an oblique lateral ramp TZ called the Leamington Zone (Kwon and Mitra, 2006). At large scales, from approximately 100 to 400 square miles (~300–1000 km^2), the Provo salient has been previously analyzed in order to understand how large-scale arcuate segments of fold-thrust belts form (e.g., Mitra, 1997; Kwon and Mitra, 2004a; and Kwon and Mitra, 2004b). However, while aspects of this salient have been studied thoroughly, the southwest segment fits the criteria for an oblique lateral ramp TZ (Valora, 2010) and relatively unanalyzed outcrops of syntectonic strata are present within this zone. For example, the Thistle, Utah, 7.5' quadrangle (within the southern Provo salient, figure 1) contains three locales where crucial exposures of Late Cretaceous to Paleogene growth strata, or progressively deformed synorogenic successions, are present (figure 2). These syntectonic strata have the potential to reveal the temporal/spatial development, as well as the structural-stratigraphic interactions, of growing structures *within* the southern Provo salient TZ.

The growth strata in the Thistle area record the location, geometry, and kinematics of associated structures within

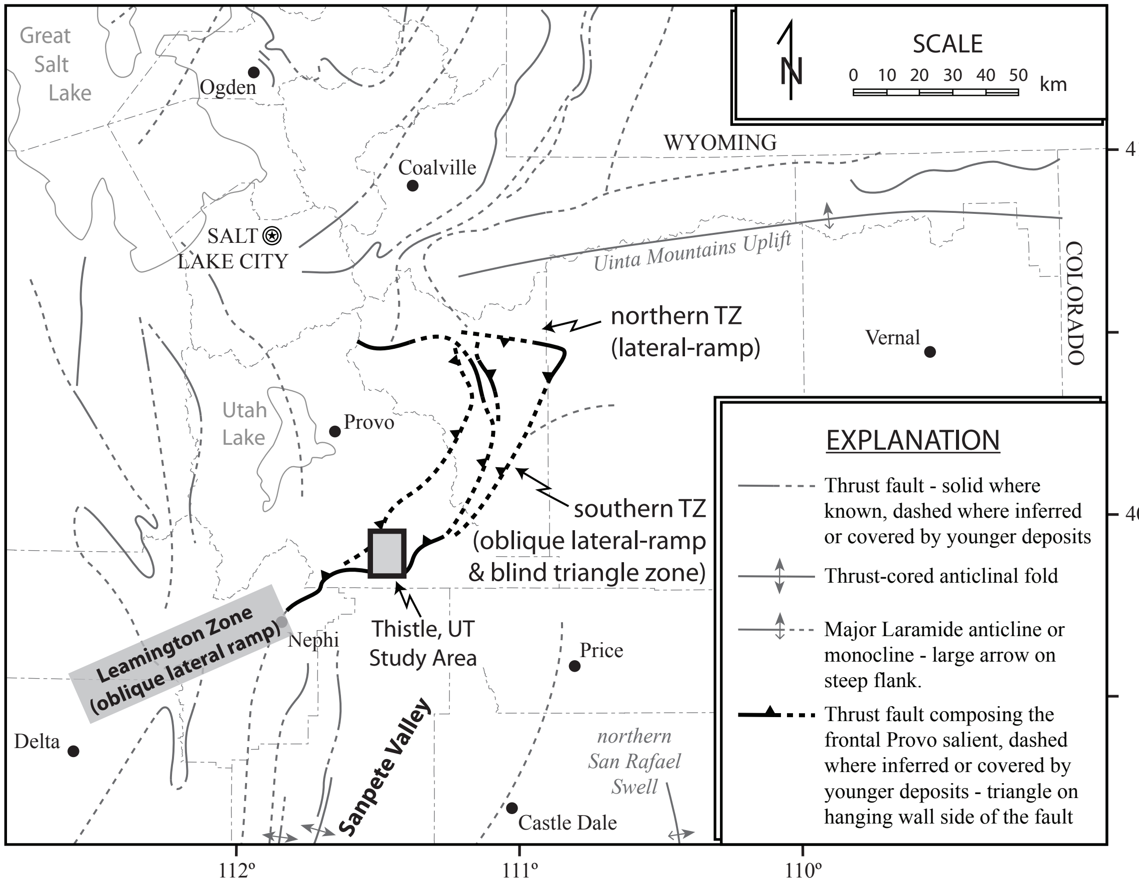


Figure 1. *Regional map of north-central Utah and the Provo salient. Frontal thrusts of the Provo salient are highlighted. The northern transverse zone is parallel, the blind triangle zone is oblique, and the Leamington Zone is oblique to the overall transport direction of the Sevier fold-thrust belt (almost due east). The study area is in the southern portion of the Provo salient, probably within a transitional region between the Provo salient and the Leamington zone. Modified from Willis (2000).*

the southern Provo salient TZ and the depositional systems that were intimately interacting with the growing structures. Growth strata exposures are present in Dry Hollow and along Dry Creek and Rock Creek; these three locales are also conspicuously offset in map view, both axially and transversely, at scales ranging from approximately 1 to 40 square miles (2–100 square km) (figure 2). This map-view pattern suggests a structural fragmentation of the Thistle quadrangle that has not been previously noted.

The vast majority of the Late Cretaceous tectono-stratigraphic information in the Thistle quadrangle is hidden by a thick and extensive cover of Tertiary deposits. These young deposits hide the at-depth structural geometries and syntectonic strata. Thus, in order to more fully understand the three-dimensional interaction between the structures present and the coeval depositional systems they affected, this study documents the exposed growth strata throughout the Thistle quadrangle and provides a three-dimensional context that helps reveal some of the small-scale structural dynamics in the southern Provo salient TZ. This study will provide a detailed stratigraphic and structural analysis in order to (1) understand the three-dimensional spatial kinematics of the structures, (2) interpret their influence on syntectonic deposition, and (3) suggest that the development of smaller scale TZs within the southern Provo salient TZ compensated for, and/or controlled, the spatial distribution of structures present.

GEOLOGIC SETTING

Structural development along segments of the Sevier fold-thrust belt of the Western U.S. formed as a complex suite of salients and reentrants and was marked by pronounced transverse-oriented features called *transverse zones* that accommodated along-strike changes in structural style or rates of motion (Evans and Neves, 1992; Apotria, 1995; Mitra, 1997; Paulsen and Marshak, 1998; Paulsen and Marshak, 1999; DeCelles, 2004; Kwon and Mitra, 2006). The Provo salient is an eastward-convex and strongly north-south asymmetric salient and is a prominent component of the Sevier fold-thrust belt of central Utah (figure 1). The northern boundary of the Provo salient is a lateral ramp/tear fault zone that abuts, and parallels, the east-west axis of the Uinta Uplift, and reaches its easternmost extent near 40° North, 111° West (see figure 1; Paulsen and Marshak, 1999; Conder and others, 2003;

Kwon and Mitra, 2004a; Kwon and Mitra, 2004b). The eastern boundary of the salient continues south-southwest from this point along a series of frontal faults that form a blind triangle zone and transitions into an oblique lateral ramp TZ called the Leamington Zone (figure 1; DeCelles, 2004; Kwon and Mitra, 2004a; Kwon and Mitra, 2006); rocks were apparently transported over the frontal thrust faults in a southeast direction, making the southern Provo salient an oblique lateral ramp zone (Conder and others, 2003; Constenius and others, 2003; Kwon and Mitra, 2004a).

The earliest frontal faults in the salient developed through the Cretaceous while interacting with depositional systems at the forefront (Armstrong, 1968; Constenius et al., 2003; Horton et al., 2004; this study). These structures were subsequently folded or abandoned during the growth of the Provo Culmination and the last phase of thrusting that formed the present frontal triangle zone (Constenius et al., 2003; DeCelles, 2004). The blind triangle zone east of the southern Provo salient comprises a number of small-scale compressional structures (figure 2) with stratigraphic relationships suggesting coeval structural growth and deposition (Armstrong, 1968; Constenius et al., 2003; Horton et al., 2004).

PREVIOUS WORK

Armstrong's (1968) discovery of intraformational unconformities within proximal syntectonic strata in the frontal Sevier fold-thrust belt was astute; however, the significance of such strata was not fully appreciated until Riba (1976) described thrust-related "progressive unconformities" in stratal successions from the Ebro Basin in Spain. The use of growth strata in kinematic analyses of compressional deformation was subsequently developed during the latest 20th and early 21st centuries (e.g., Anadón and others, 1986; Suppe and others, 1992; Burbank and Vergés, 1994; Burbank and others, 1996; Ford and others, 1997; Lawton and others, 1999; Vergés and others, 2002; Aschoff and Schmitt, 2008). While several growth exposures exist in the frontal Sevier fold-thrust belt, a comprehensive three-dimensional tectono-stratigraphic synthesis (i.e., modern growth strata analysis) has not been used

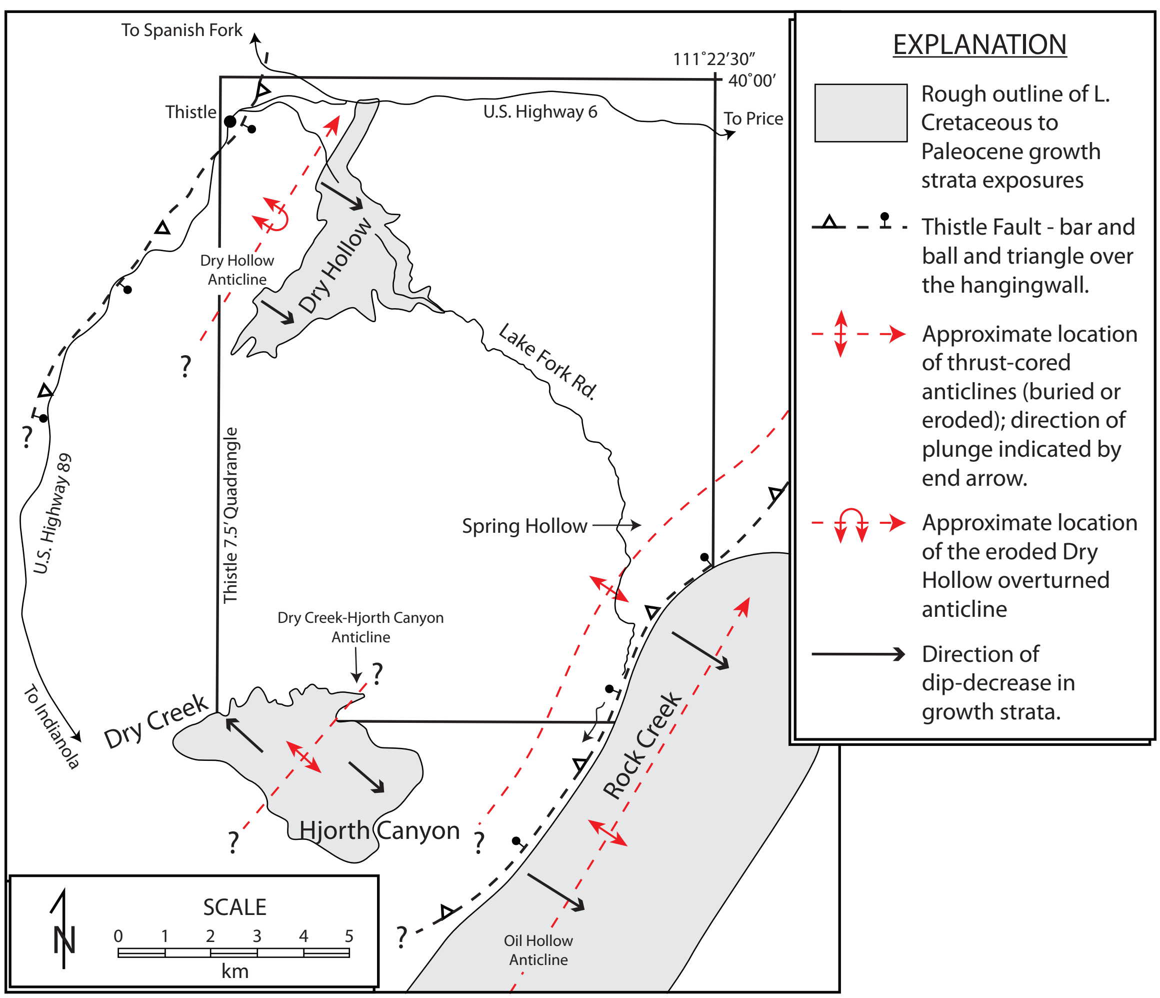


Figure 2. *Local map of the Thistle quadrangle and surrounding area. Anticlines are represented by dashed lines because structures over which strata were deposited are now buried or eroded. Structural growth is preserved in syntectonic strata over all the structures in the area. The strike of the structures is remarkably similar even though they are offset axially and transversely.*

to analyze them; well-exposed growth strata typically have low preservation potential and are relatively rare (e.g., Vergés and others, 2002). Lawton and others (1993), in a study of Late Cretaceous growth strata in the central Sanpete Valley, suggested that strata exposed there inherited lateral variation from the growth of the Gunnison Thrust. Lawton and others (1993), however, did not interpret the three-dimensional development of the structure using the probable presence of along-strike changes in syntectonic unconformities (e.g., Aschoff and Schmitt, 2008; Valora, 2010). Although their study lacks the third dimension, it marks the first detailed analysis of growth strata exposures in Utah's Sevier fold-thrust belt.

Pinnell (1972) produced a geologic map of the Thistle quadrangle and documented the lithostratigraphic units in detail; however, that study lacked the specific stratigraphic and structural data necessary to fully document the structural-stratigraphic evolution of the Thistle quadrangle (e.g., the presence of unconformities discussed by Aschoff and Schmitt, 2008). Constenius (1998) also documented a number of important relationships in the Thistle area as part of a reassessment of the compressional and extensional structural development of the Provo salient, including the presence of growth strata near Thistle and near Rock Creek in the Indianola quadrangle (Oil Hollow anticline and associated imbricate structures; see figure 2). These relationships helped Constenius (1998) conclude that (1) structural growth in the frontal Provo salient occurred largely between 100 and 40 Ma, (2) the transition between crustal shortening in the Provo salient and post-thrust extension occurred over a relatively short span of 1 to 5 million years, and (3) compressional deformation created preconditioned weaknesses that were reactivated during the post-thrust extension (e.g., the arcuate Thistle fault [see figure 2] was initially the east and west boundaries of a compressional pop-up block that subsequently inverted into the Little Clear Creek extensional half-graben; see structural cross section A–A' on plate 2). Constenius (1998) illustrated the "Thistle growth strata" (strata in Dry Hollow) on a large-scale structural cross section; however, only rough two-dimensional growth geometries were provided. Though the strike-perpendicular cross section from Constenius (1998) shows the Dry Hollow and Rock Creek areas, it does not document the structure along strike, limiting the description and analysis of the temporal/spatial structural-stratigraphic development of Thistle area and the three-dimensionality of the thrust structures present.

Horton and others (2004) and Aschoff (2008) added additional detail locally by noting the presence of several "traditional-type" and "subtle-type" syntectonic unconformities (SUs) (after Aschoff and Schmitt, 2008) in Dry Hollow and provided a regional Cretaceous Foreland Basin context for some of the rocks therein. Identification of traditional-type and subtle-type SUs is important because subtle-type SUs highlight phases of uplift recorded in the growth strata that may otherwise be masked by high sediment supply (after Aschoff and Schmitt, 2008). Aschoff (2008) also documented up-section and along-strike variation in depositional facies and SUs, suggesting three-dimensional kinematic development of the Dry Hollow structure, but did not map these relationships in detail.

Despite significant advances in our understanding of the area, the tectono-stratigraphic development of growth structures in the Thistle area that suggests Late Cretaceous to Paleogene concurrent deformation and deposition has not been fully addressed.

METHODS AND DATA

Mapping the Thistle quadrangle at 1:24,000 scale (plate 1) documents key tectono-stratigraphic relationships used to understand the spatial distribution of the structures within the TZ, their temporal development, and their effect on depositional patterns within the quadrangle. Observations of the Indianola Group, conglomerate of Thistle, and the North Horn Formation (lower and upper members) were compiled for outcrops in Dry Hollow, Dry Creek, and Rock Creek (figure 2). Structural and stratigraphic relationships within these syntectonic formations are key to unraveling the interaction between structures and depositional systems locally. While the aforementioned units are the focal point of this study, descriptions for all the geologic map units within the Thistle quadrangle are presented in plate 2. Syntectonic unconformities related to the growth of structures in the area were interpreted where dip discordance (Δ) is present at laterally continuous horizons in Dry Hollow and where angular unconformities were observed in other areas of the Thistle quadrangle.

While tectono-stratigraphic interactions are present in the Thistle quadrangle at the three locales discussed, spectacular growth-strata exposures in Dry Hollow allow a more detailed four-dimensional kinematic reconstruction. Syntectonic lithofacies and SUs were documented in Dry Hollow using a combination of stratigraphic profiles (Aschoff, 2008; Valora, 2010) and detailed lithofacies analysis (Valora, 2010). These stratigraphic profiles were measured at the 1.5 foot (half-meter) scale and special attention was given to bedding attitudes, discordances along angular syntectonic unconformities, lithofacies descriptions, conglomerate clast composition, and identification of time-equivalent sequence stratigraphic surfaces. A correlation of these stratigraphic profiles is presented in plate 3. Growth strata geometries, the spatial distribution of syntectonic unconformities (numbered sequentially; e.g., SU-1, SU-2, etc.), and important stratigraphic surfaces were subsequently documented with detailed 1:12,000 scale mapping of the Dry Hollow area (plate 3). This combination of data from the correlated stratigraphic profiles (two-dimensional) and the geological mapping (three-dimensional because of excellent exposures) allows a reconstruction of the structural-stratigraphic interactions in Dry Hollow through time (four-dimensional).

Sequence stratigraphy was used to establish rough time-lines within the growth-strata succession where no bio-stratigraphic data were available. Sequence stratigraphic correlation was accomplished using a combination of systematic lithofacies stacking patterns and the regionally extensive surfaces that these patterns highlight. Although sequence stratigraphy works best in marine facies where parasequences and key surfaces are most easily identified, we apply it here using non-marine facies stacking patterns that reflect base-level cycles in a gross sense. Overall, the Indianola Group through conglomerate of Thistle stratigraphic succession is transitional from foredeep fluvial deposits (Sanpete and San Pitch Formations), through a mixture of marine and non-marine foredeep deposits (Funk Valley Formation), culminating in a thick conglomeratic wedge-top interval of braided-fluvial and debris-flow alluvial fan deposits (Valora, 2010). This stratigraphic succession was further divided into parasequence sets that allowed the interpretation of the important chronostratigraphic surfaces. Recognition of these chronostratigraphic surfaces allowed a more exact correlation that gives the three-dimensionally complex growth strata succession a temporal framework.

Facies stacking patterns provide clues about cycles of base-level rise/fall that highlight key surfaces that can be used for correlation. Regional unconformities that mark a period of marked base-level fall are sequence boundaries and tend to be marked by a non-Waltherian shift in facies where more proximal facies overlie the sequence boundary (SB). A non-Waltherian landward shift in the facies stacking, or deepening of facies, marks transgressive surfaces (TS). Surfaces that mark the point of highest accommodation, or highest sea-level are maximum flooding surfaces (MFS); this surface is typically marked by the top of a series of facies that stack in a progressively deepening or retrogradational pattern. The four main stacking patterns that occur in the measured growth strata succession are described below.

1. Shoaling upward packages of marine lithofacies that generally grade from offshore marine mudstones (interbedded with thin very well-sorted and fine-grained sandstones) into thick amalgamated successions of marine sandstone.
2. Fining upward packages of fluvial lithofacies, generally grading from braided-fluvial cobble conglomerates to meandering fluvial deposits.
3. Fining upward packages of marine lithofacies that are generally present as subtle up-section decreases in bed thickness of marine sandstones.
4. Gradational packages from fluvial to alluvial fan lithofacies (prograding alluvial fan) or from alluvial fan to fluvial lithofacies (retrograding alluvial fan).

The sequence boundaries interpreted in Dry Hollow (see plate 3; Valora, 2010) were picked where braided-fluvial conglomerate directly overlies thick successions of amalgamated marine lithofacies from the upper portions of shoaling upward marine packages; other sequence boundaries exist in the Funk Valley Formation where more subtle non-Waltherian shifts are present. Transgressive surfaces (minor flooding surfaces) were picked at sharp boundaries between facies that switch from basinward to landward shifting facies, or at contacts between facies that suggest a strong deepening of depositional environments (e.g., marine mudstones overlying deltaic marine sandstone or non-marine successions). Maximum flooding surfaces were picked at the transition between the relatively deepest fining upward packages of marine lithofacies and shoaling upward packages of marine lithofacies.

Lastly, a structural cross section A–A' (plate 2) was constructed across the Thistle quadrangle using the surface data from geologic mapping and a published seismic line with interpreted horizons (Constenius and others, 2003; Horton and others, 2004). This structural profile, using new data, provides added detail and minor adjustment to previous interpretations.

Previous work (Pinnell, 1972; Horton and others, 2004; Aschoff, 2008; Constenius, 2008) and new data (Valora, 2010) were compiled to interpret the Late Cretaceous to Paleogene tectono-stratigraphic history for the Thistle quadrangle; this study is thus limited to local syntectonic strata that have growth geometries or were deposited during the interval of compressional tectonics (Constenius and others, 2003; Valora, 2010).

COMPRESSIONAL SYNTECTONIC STRATIGRAPHY AND SYNTECTONIC UNCONFORMITIES IN THE THISTLE QUADRANGLE

Synorogenic strata that record the development of the Sevier fold-thrust belt and transition to extensional tectonics include Upper Cretaceous to Tertiary strata. Lithofacies within the synorogenic succession are wide-ranging and complex, including open-marine, wave-dominated deltaic deposits to debris-flow alluvial fan deposits. Intraformational unconformities, including syntectonic unconformities, are present throughout the synorogenic succession, and several locales show a classic fanning-up pattern in bedding dips in addition to intraformational unconformities—classic signatures of growth strata. In order to interpret the structural-stratigraphic interactions within the Thistle quadrangle, lithology, the presence of syntectonic unconformities, general composition, and published ages are described and interpreted herein for each of the compression-related syntectonic units at the three growth strata locales (figure 2).

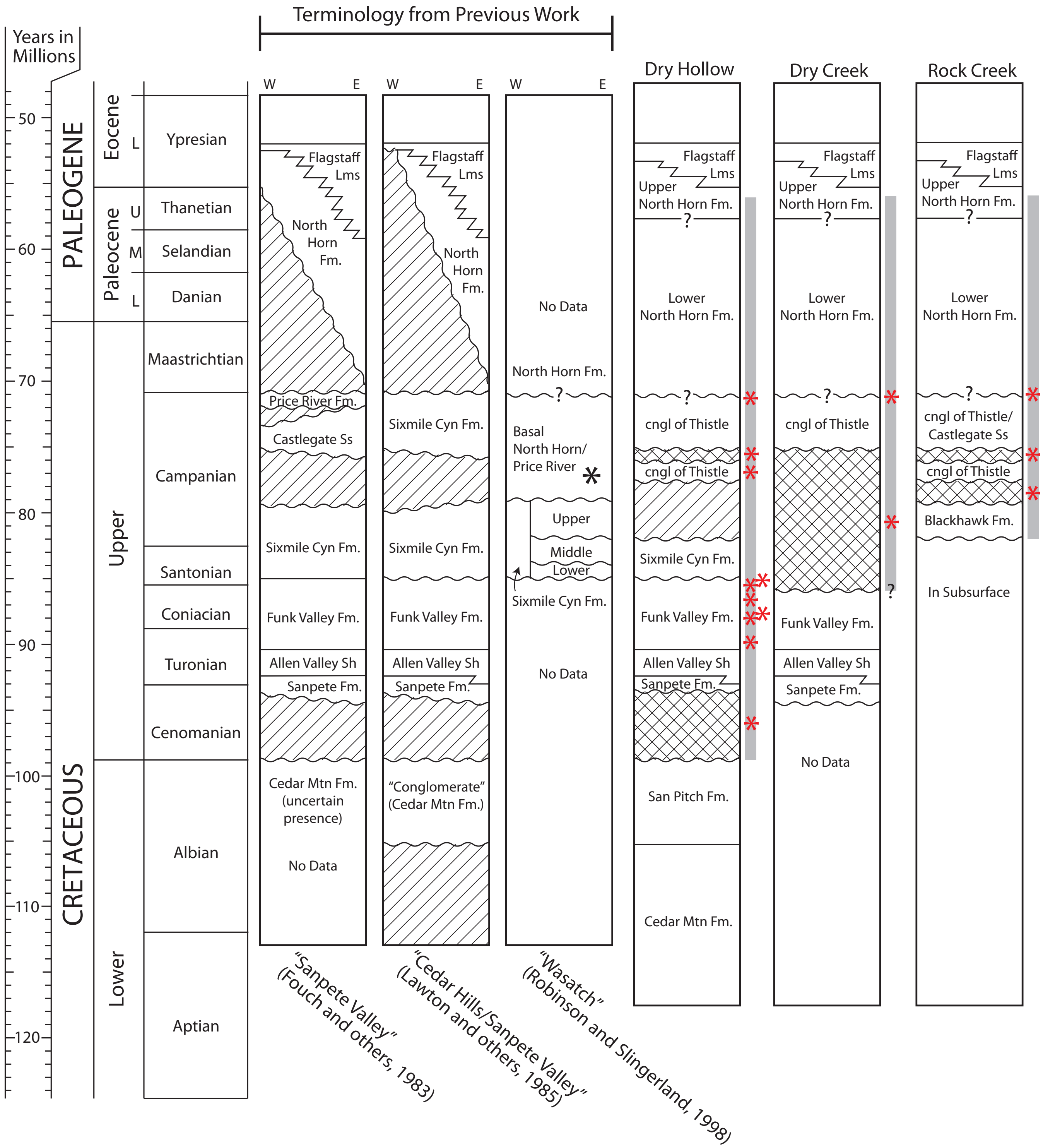


Figure 3. Correlation charts from the Sanpete Valley and Thistle areas showing previous regional interpretations (left three columns) beside tectono-stratigraphic data from this study (right three columns). The black star demarcates the unit previously interpreted as Price River Formation, which Robinson and Slingerland (1998) suggested was time-equivalent with the Castlegate Sandstone. In the correlation charts from the Thistle area, the red stars demarcate positively identified traditional-type syntectonic unconformities or significant dip discordances where the character of discordance was hidden or covered; gray rectangles to the right side of each chart are the interpreted overall duration of structural development at each locale; single-diagonal-line hachures suggest syntectonic disconformities and diamond hachures suggest unconformities from angular syntectonic unconformities; syntectonic hiatuses in the Funk Valley Formation are too short in duration to represent by wavy lines and diamond hachures on this diagram. Though the contact between the conglomerate of Thistle and the North Horn Formation is generally conformable (Robinson and Slingerland, 1998; Horton and others, 2004), at the study locales, dip decreases are measurable through that interval; this suggests the presence of an individual angular unconformity or multiple angular unconformities locally.

Indianola Group (Ki; Early to Late Cretaceous, Albian to Santonian)

The Indianola Group is regionally composed of five formal lithostratigraphic formations: San Pitch Formation (upper Albian), Sanpete Formation (upper Cenomanian), Allen Valley Shale (Turonian), Funk Valley Formation (Santonian to Turonian), and Sixmile Canyon Formation (lower Campanian to Santonian). These formations comprise a thick and heterogeneous package of marine and non-marine rocks deposited from the latest Early Cretaceous to the mid Late Cretaceous (figure 3).

Description

Locally exposed lithofacies are grouped into 4 packages:

1. Mixed sandstone and conglomerate beds—distinctly polymictic conglomerates, but dominated throughout by Pennsylvanian-Permian quartzites (Sprinkel and others, 1999; Horton and others, 2004); grain-sizes range from gravel to boulders; sorting is often moderate, but trough cross-stratification and channels with scoured bases dominate; conglomerates are interbedded and gradational locally with moderately well sorted gravelly sandstone lenses with scoured bases; conglomeratic lithofacies dominate the San Pitch, Sanpete, and Sixmile Canyon Formations (Sprinkel and others, 1999; Valora, 2010; this study); an approximately 197- to 230-foot-thick (~60–70 m) interval of conglomeratic lithofacies is also present *within* the Funk Valley Formation (see plate 3).
2. Mixed sandstone and fine-grained slope formers—trough cross-stratification is abundant in gravelly sandstone and coarse-grained sandstone lenses that compose large horizontal accretionary bedsets; sandstone beds and bedsets are interbedded with thickly bedded, moderate-reddish-brown or variegated slope-forming mudstones/siltstones; these lithofacies dominate the uppermost 98 feet (30 m) of the Sanpete Formation as well as the middle portion of the Funk Valley Formation (see plate 3).
3. Mud-rich slope formers—light-gray, slope-forming, massive, clayey siltstone beds that generally form non-descript slopes; these siltstones typically interbed with thin-bedded, very fine grained, very well sorted and hummocky cross-laminated sandstone that is not amalgamated; this lithofacies dominates the Allen Valley Shale and composes a large portion of the Funk Valley Formation (see plate 3).
4. Fine-grained amalgamated sandstone—very well-sorted, bluish-white to yellowish-gray, very fine to fine-grained, and medium- to thick-bedded sandstone that is hummocky cross-bedded, planar-laminated, or massive; woody material intermittently present; vertical and horizontal burrows (*Thallasinoides* and *Ophiomorpha*) with low diversity are present throughout; beds are medium to thick-bedded and typically vertically amalgamated; bedsets of these amalgamated beds locally vary in thickness from 66 to 263 feet (20–80 m) thick (plate 3).

Stratigraphic-Structure Relationships in Dry Hollow

The basal conglomeratic unit of the Indianola Group (San Pitch Formation) between stratigraphic profiles 1 and 2 dips 54° west overturned (plate 1 and plate 3); near Lake Fork Road this same stratigraphic interval is vertical to sub-vertical (plate 1 and plate 3; and at the base of stratigraphic profile 4 the dip is 79° southeast. From the lowermost Indianola Group, the bedding attitudes decrease across distinct angular hiatuses. Overall, the Indianola Group succession tends to thicken from the south-southwest to the north-northeast in Dry Hollow and contains seven syntectonic unconformities (SUs) that have a few degrees to more than 30° of angular discordance (see plate 3). With the exception of SU-1 (Δ32° and ~1 km in lateral extent), at the base of the measured Indianola Group succession, the SUs within the Indianola Group have an average of about 8° discordance. Successive SUs tend to lengthen along-strike to the north-northeast from approximately 0.9 mile to more than 2 miles (1.5–3 km) (see plate 3). The stratigraphic positions of SUs in Dry Hollow also tend to correspond to significant thickness decreases in the mixed sandstone and fine-grained slope-forming lithofacies that are interpreted as meandering fluvial (see plate 3 and Valora, 2010), or tend to be present in the stratigraphic position and along-strike vicinity of amalgamated packages of fine-grained sandstone interpreted as marine wave-dominated deltas (Valora, 2010; see also plate 3).

Stratigraphic-Structure Relationships in Dry Creek

A ridge of largely conglomeratic lithofacies (see the southwest corner of plate 1, SE ¼ section 8 and SW ¼ section 9, T11 S., R. 4 E.) from the lower Indianola Group grades upward into lithofacies of amalgamated fine-grained sandstone (figure 4A). Where the fine-grained sandstone assemblage is exposed on the north side of Dry Creek it is angularly unconformably (~Δ15°) overlain by disorganized conglomerate of the conglomerate of Thistle. The Indianola Group in Dry Creek consistently dips to the northwest at approximately 40° (figure 4A). Just south of Dry Creek, outside the study area in Hjorth Canyon, a correlative stratigraphic succession dips to the SE (Horton and others, 2004).

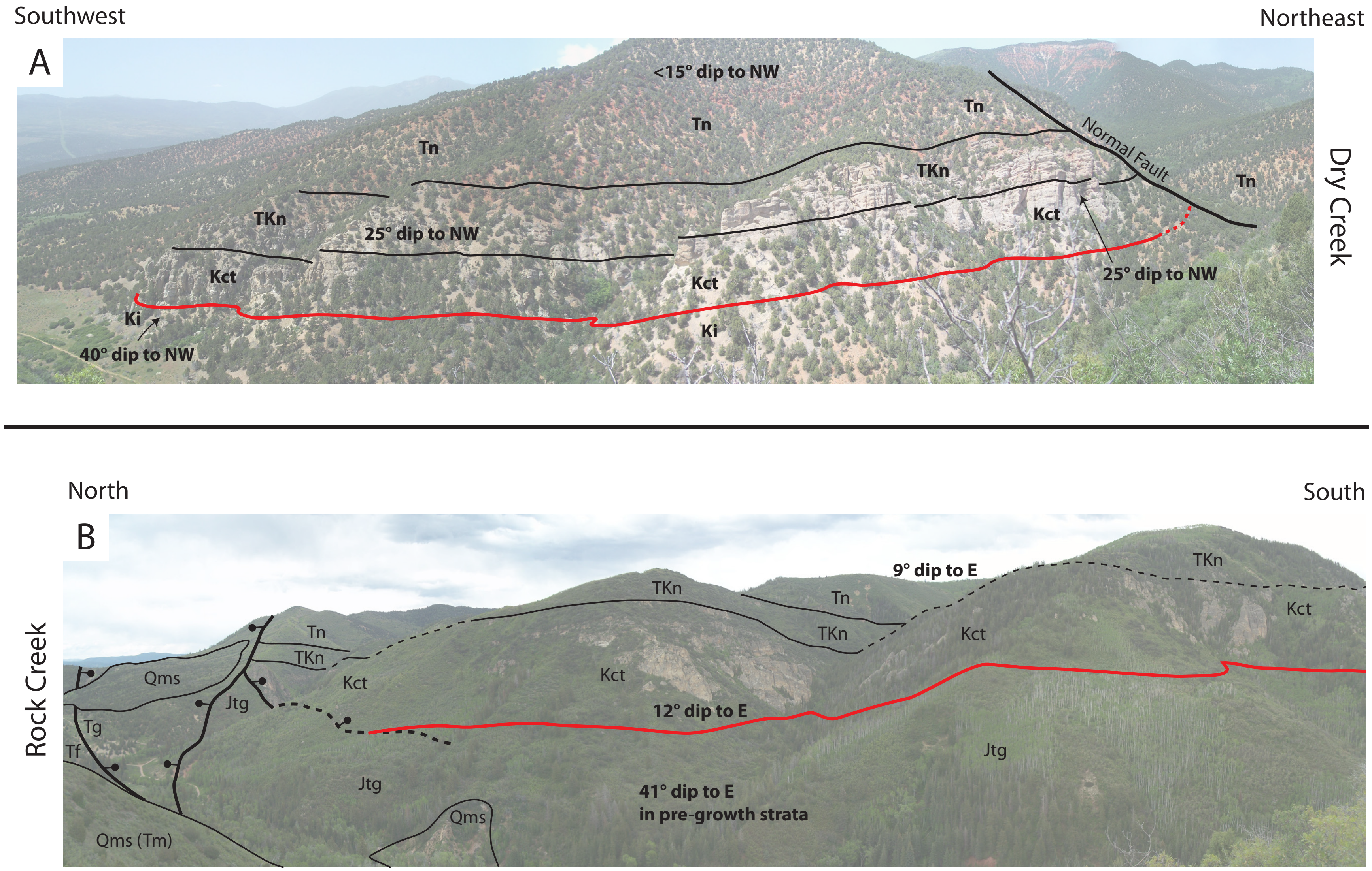


Figure 4. *Photos of Dry Creek and Rock Creek. (A) Sequential decreasing dips in Late Cretaceous growth strata on the north side of Dry Creek. The only defined angular syntectonic unconformity in this succession is marked by the red line and is between the sandstone lithofacies assemblage of upper Indianola Group and the conglomerate of Thistle. (B) Tectono-stratigraphic relationships in Rock Creek are complicated by abundant normal faulting; however, the conglomerate of Thistle lies directly on top of Jurassic Twist Gulch Formation and the stratal succession subtly flattens upward from there; the angular syntectonic unconformity marked by the red line in this photomosaic occurs* within *the conglomerate of Thistle to the south in the Indianola quadrangle (Kurt Constenius, verbal communication, 2009).*

Stratigraphic-Structure Relationships in Rock Creek

The Indianola Group is not exposed along Rock Creek; however, subsurface interpretation by Constenius and others (2003) suggests the entire Indianola succession is cut by the frontal Charleston-Nebo thrust and is subhorizontal in the footwall.

Interpretation of the Indianola Group in the Three Areas

In Dry Hollow, non-marine fluvial conglomerates and sandstones interstratified with marine deltaic sandstones and marine offshore siltstones represent deposits in the fringes of the Cretaceous Foreland Basin foredeep of central Utah and also represent depositional sequences related to relative sea-level fluctuations (see plate 3). Because only localized exposures were analyzed in this study, it is unclear what role tectonics, eustacy, and sediment supply played in the sequence stacking patterns. Still, they provide a chronostratigraphic framework that aids in the reconstruction of the Dry Hollow structure's growth (Valora, 2010). Plate 3 shows a correlation of these stratigraphic surfaces, picks for the lithostratigraphic formations of the Indianola Group (e.g., Lawton, 1985), and interpreted depositional sequences. The stratigraphic surfaces have also been mapped at 1:12,000 scale (plate 3).

Growth of the Dry Hollow structure had a significant localized initial uplift (suggested by the $\Delta 32°$ at SU-1). Our observation that SUs tend to lengthen laterally along strike suggests structural growth settled into a relatively consistent expansion from the south-southwest to the north-northeast (plate 3), and that this structural expansion occurred at distinct intervals (represented by SUs) during deposition of the San Pitch/Sanpete Formations through the Funk Valley Formation. The angular discordance along these SUs and their lateral extent suggest deformation expanded both laterally and basinward in three-dimensions from 1 square mile to approximately 6 square miles (~3–15 km^2) (see SU-2 through SU-7 shown on plate 2 and plate 3). Significant along-strike thickness and depositional variation associated with the SUs (plate 3) further suggests that the small-scale structural growth of Dry Hollow affected the local stratigraphic accommodation and controlled depositional processes in three dimensions (Valora, 2010).

The structure near Dry Creek–Hjorth Canyon is likely an anticline because of the opposing dips in correlative rocks from Dry Creek (northwest dips) to Hjorth Canyon (southeast dips). The lack of progressive dip decrease within the exposures of Indianola Group in Dry Creek suggests that growth of the structure began after the preserved portions of the upper Indianola Group were deposited. This suggests that growth initiated, at the earliest, during the late Coniacian because of the locally present and truncated lithofacies of fine-grained sandstone from the Funk Valley Formation. Truncation of sub-horizontal Indianola Group in the subsurface beneath Rock Creek (Constenius and others, 2003) also suggests the frontal triangle zone developed post-deposition of the Indianola Group.

Blackhawk Formation (Kbh; Upper Cretaceous, Campanian)

The Blackhawk Formation is not well represented in surface exposures within the Thistle quadrangle, but plays a role in the tectono-stratigraphic history of the study area, so descriptions and interpretations from previous workers constitute our discussion of this formation.

Description

Very pale orange and coarse- to medium-grained sandstone interbedded with dusky-yellowish-brown slope-forming siltstone (Pinnell, 1972); exposures are limited to a very small area in the southeast corner of the Thistle quadrangle and are more prominent in the northeast portion of the Indianola quadrangle near Lake Fork Road; approximately 820 feet (250 m) thick at the surface (Pinnell, 1972), increasing to almost 3300 feet (1 km) thick in the subsurface to the south (Horton and others, 2004).

Interpretation of the Blackhawk Formation in the Three Areas

The Blackhawk Formation has been interpreted by previous workers (e.g., Horton and others, 2004) as a fluvial, deltaic, and shallow marine sandstone and siltstone deposited from early to middle Campanian (Robinson and Slingerland, 1998). Robinson and Slingerland (1998) also correlated the Blackhawk Formation with the upper Sixmile Canyon Formation of the Indianola Group. However, Blackhawk Formation facies or conglomerates equivalent to the Blackhawk Formation (i.e., upper Sixmile Canyon Formation) are likely not present in Late Cretaceous outcrops along the west side of the Thistle quadrangle. The minimal thickness of conglomerates in the uppermost Indianola Group near Thistle compared to the type section of Sixmile Canyon Formation to the south (Lawton, 1985) suggests frontal uplift of the Provo salient caused nondeposition or erosion of these early Campanian rocks. Subsurface interpretation by Constenius and others (2003) suggests structural growth of the frontal triangle zone beneath Rock Creek (e.g., the thrust-cored Oil Hollow anticline) began during deposition of the Blackhawk Formation, sometime during the early Campanian.

Conglomerate of Thistle (Informal Unit, Kct; Upper Cretaceous, Maastrichtian[?] to late Campanian)

The term "conglomerate of Thistle" is used to incorporate new dating by Robinson and Slingerland (1998) that provided a middle to late(?) Campanian age for the regionally extensive quartzite-dominated conglomeratic unit between the Indianola

Group and North Horn Formation. Formerly, this unit had been incorrectly considered time-equivalent to the Price River Formation, which is early Maastrichtian to latest Campanian (Robinson and Slingerland, 1998). "Conglomerate of Thistle" provides an informal name for a unit that is temporally separate from the Price River Formation. The conglomerate of Thistle is exclusively conglomeratic throughout the Thistle quadrangle, but locally the average cobble/pebble size tends to decrease and sorting becomes better to the east.

Description

White to very light gray, thick- to very thick bedded, cobble to boulder conglomerate with well-rounded clasts; basal matrix is bluish-gray sandstone with light-blue-green siltstone clasts; poorly sorted throughout; composition is almost exclusively Pennsylvanian-Permian quartzite and Paleozoic chert (Horton and others, 2004); subordinate reddish-orange iron-oxide staining is common. Locally, the conglomerate of Thistle has a completely disorganized and structureless fabric for up to approximately 410 feet (125 m) of section and contains distinctive light-blue-green siltstone rip-up clasts (see Aschoff, 2008). Wherever disorganized conglomerates crop out, clast composition grades upward from purely quartzite to bimodal white sandstone and quartzite (Horton and others, 2004). Locally, the distinctive disorganization and structureless fabric begins to grade into slightly more organized conglomerates in the upper portions of the conglomerate of Thistle after a thick succession of purely disorganized conglomerate (plate 3). The conglomerate of Thistle has been interpreted as conformably overlain by lower North Horn Formation and correlative with the Castlegate Sandstone (Robinson and Slingerland, 1998; Horton and others, 2004). While the stratigraphic transition between the conglomerate of Thistle and the lower North Horn Formation is locally gradational, the dip sequentially decreases up section through both units at Dry Hollow, Dry Creek, and Rock Creek. Because of difficult access and poor exposures, it is unclear whether these dip decreases are progressive (Riba, 1976) or accommodated by several subtle- and traditional-type SUs (Aschoff and Schmitt, 2008). Angular unconformities at the boundary between the conglomerate of Thistle and North Horn Formation are likely localized surfaces from structural growth (also temporally variable based on location) that become conformable eastward (basinward) of structures in the Thistle area. The conglomerate of Thistle's upper contact is selected regionally by a sudden substantial inclusion of lithic clasts (lower North Horn Formation composition) or locally by the first stratigraphic appearance of the lower North Horn Formation mudstone-rich and green-mottled red-beds.

Stratigraphic-Structure Relationships in Dry Hollow

The basal conglomerate of Thistle is composed of conglomerates with trough cross-stratified lenses and scoured bases that are interbedded with heavily disorganized, structureless, poorly sorted, and crudely bedded boulder conglomerates (figure 5A). Basal organized conglomerates decrease in volume upward until exclusively disorganized conglomerates appear above an extensive syntectonic angular unconformity that has laterally variable discordance between approximately 14° and 32° (see SU-9, plate 3).

Stratigraphic-Structure Relationships in Dry Creek

The conglomerate of Thistle overlies marine deltaic lithofacies of the Indianola Group above a syntectonic angular unconformity that has approximately 15° discordance (figure 4A). The lower conglomerate is disorganized and structureless, and contains distinctive light-blue-green siltstone rip-up clasts; up section, however, the disorganized conglomerates begin to interbed with better organized and trough cross-stratified lenses of conglomerate of similar composition, transitional to the overlying and more polymictic lower North Horn Formation (figure 4A).

Stratigraphic-Structure Relationships in Rock Creek

Exposed conglomerate of Thistle in Rock Creek differs from Dry Hollow and Dry Creek by its organized fabric, trough cross-stratification, and better sorting throughout; lens-shaped beds also form obvious channels with scoured bases. The conglomerate of Thistle in Rock Creek also angularly unconformably overlies the Blackhawk Formation within the Indianola quadrangle (directly south of the Thistle quadrangle; see plate 1). Up-section angular discordance is also present *within* the conglomerate of Thistle; this discordance is approximately 30° to the south in the Indianola quadrangle (Kurt Constenius, written communication, 2009) and laterally increases to approximately 42° to the north-northeast. The lower portions of the conglomerate of Thistle sequentially thin to the north-northeast below this discordance until they disappear and the conglomerate of Thistle above the discordance lies directly on deformed Jurassic Twist Gulch Formation (figure 4b) in the Thistle quadrangle (Horton and others, 2004; Kurt Constenius, written communication, 2009; this study). It is unclear whether this large discordance occurs on a single surface or multiple surfaces in the Indianola quadrangle. Cross-section A–A' (plate 2) illustrates the relatively large-scale removal of Indianola Group and lowermost conglomerate of Thistle beneath SU-9 in the south-eastern half of the Thistle quadrangle (over the hanging wall of the eastern verging portion of the Thistle thrust). A portion of the upper conglomerate of Thistle is interpreted to be present above the SU-9 unconformity that apparently removed significant portions of the older strata.

Interpretation of the Conglomerate of Thistle in the Three Areas

Aschoff (2008) noted that the locally disorganized fabric, grain size, and very poor sorting of some conglomerates from

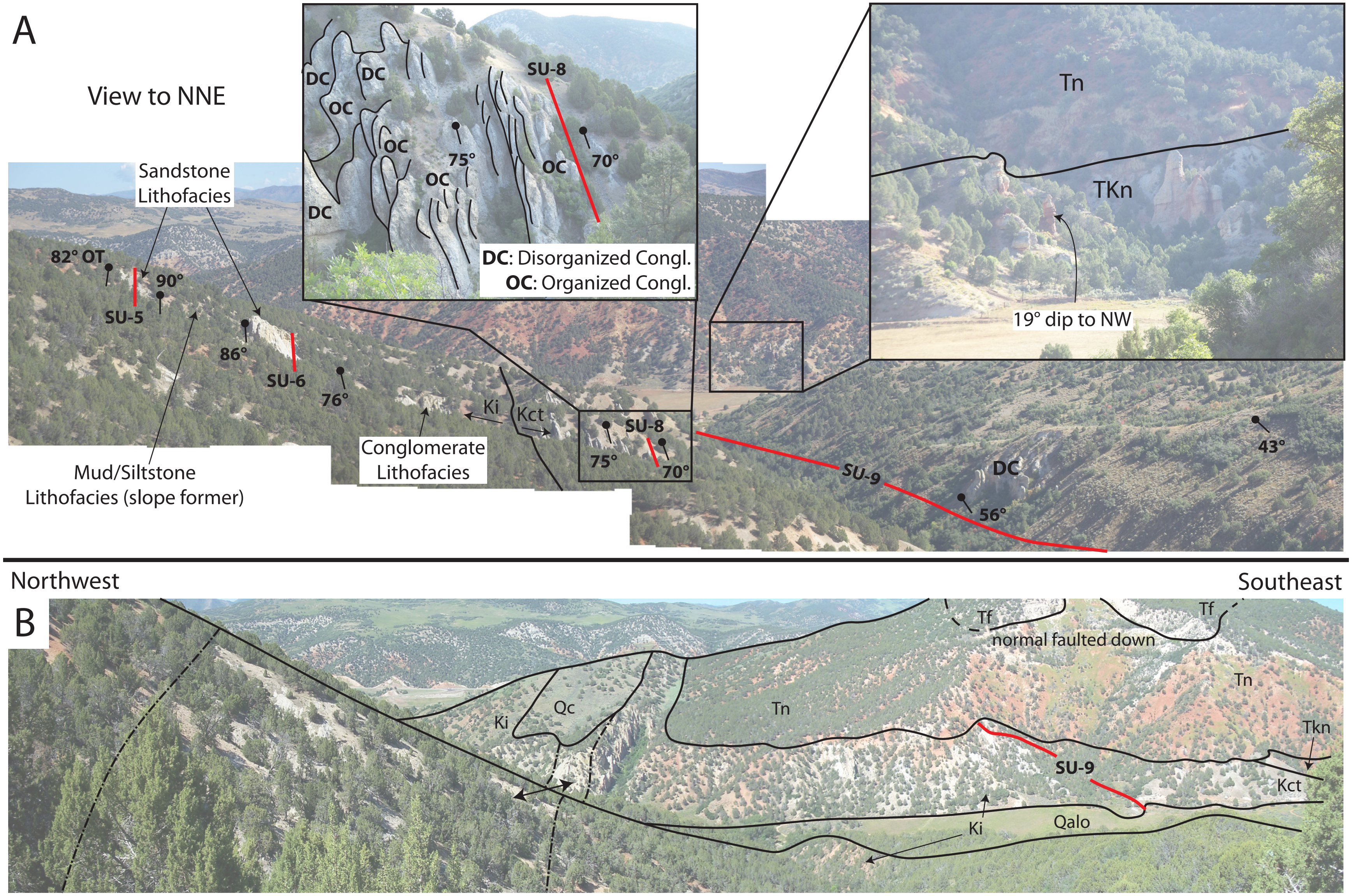


Figure 5. *Photos of Dry Hollow. (A) Panorama of the Indianola Group (same trend as stratigraphic profile 3, see plates 1 and 3) through upper North Horn Formation; note the sequential decrease in dips that occurs across SU-5, SU-6, SU-8, and SU-9; inset photos show (left) the interbedded disorganized/organized conglomerates in basal conglomerate of Thistle and (right) the northwest-dipping contact between the lower and upper North Horn Formation. (B) Photo of the growth strata succession along Lake Fork Road; this view is blocked in photo A by the slope composed of sub-vertical Indianola Group; photo B shows the presence of SU-9 along-strike and the onlapping of upper North Horn Formation against sub-vertical to steeply dipping Indianola Group; dash-dotted lines are a thick interval of amalgamated sandstone lithofacies to show the correlation between exposures along Lake Fork Road and the foreground.*

the conglomerate of Thistle are consistent with debris-flow alluvial-fan deposits. Alluvial fans are localized depositional environments, at most a little more than 6 miles (10 km) in extent, and require significant proximal relief in order to develop (Blair and McPherson, 1994). Organized conglomerates with trough cross-stratification, better sorting, and channels with scoured bases are interpreted as largely braided-fluvial. In Dry Hollow, the mixed disorganized and organized conglomerates below SU-9 are likely middle Campanian in age because compositions are equivalent to the conglomerate of Thistle (see discussion of "Castlegate-Price River" compositions by Horton and others, 2004). The up-section transition throughout the conglomerate of Thistle in Dry Hollow likely represents a progradation and subsequent retrogradation of an alluvial fan system that interacted at its fringes with a braided-fluvial depositional system. Dry Creek exposures of conglomerate of Thistle record the greatest local extent of alluvial fans after a regional thrusting period (SU-9 in Dry Hollow and the large SU at the base of the conglomerate of Thistle in Dry Creek) and the subsequent retrogradation of those alluvial fans. The exposures of conglomerate of Thistle in Rock Creek were likely deposited in braided-fluvial systems; the lack of debris-flow deposits in Rock Creek is reasonable considering the localized nature of debris-flow alluvial fans (Blair and McPherson, 1994). The debris-flow and alluvial-fan facies from Dry Hollow likely transition in the subsurface to braided-fluvial systems between the west and east sides of the Thistle quadrangle. Progressive dip decreases within the conglomerate of Thistle in Dry Hollow (two or three syntectonic unconformities with Δ 5° to 8° near the top of stratigraphic profile 3; see plate 2 and plate 3) and similar dip decreases in Dry Creek suggest concurrent structural growth during coeval deposition of upper(?) to middle Campanian sediment along the west side of the Thistle quadrangle.

North Horn Formation, Lower Member (TKn)

The lower North Horn Formation is conglomeratic and transitional from the conglomerate of Thistle, but up section it contains heavily oxidized and muddy intervals that increase in abundance as it transitions into the upper North Horn Formation.

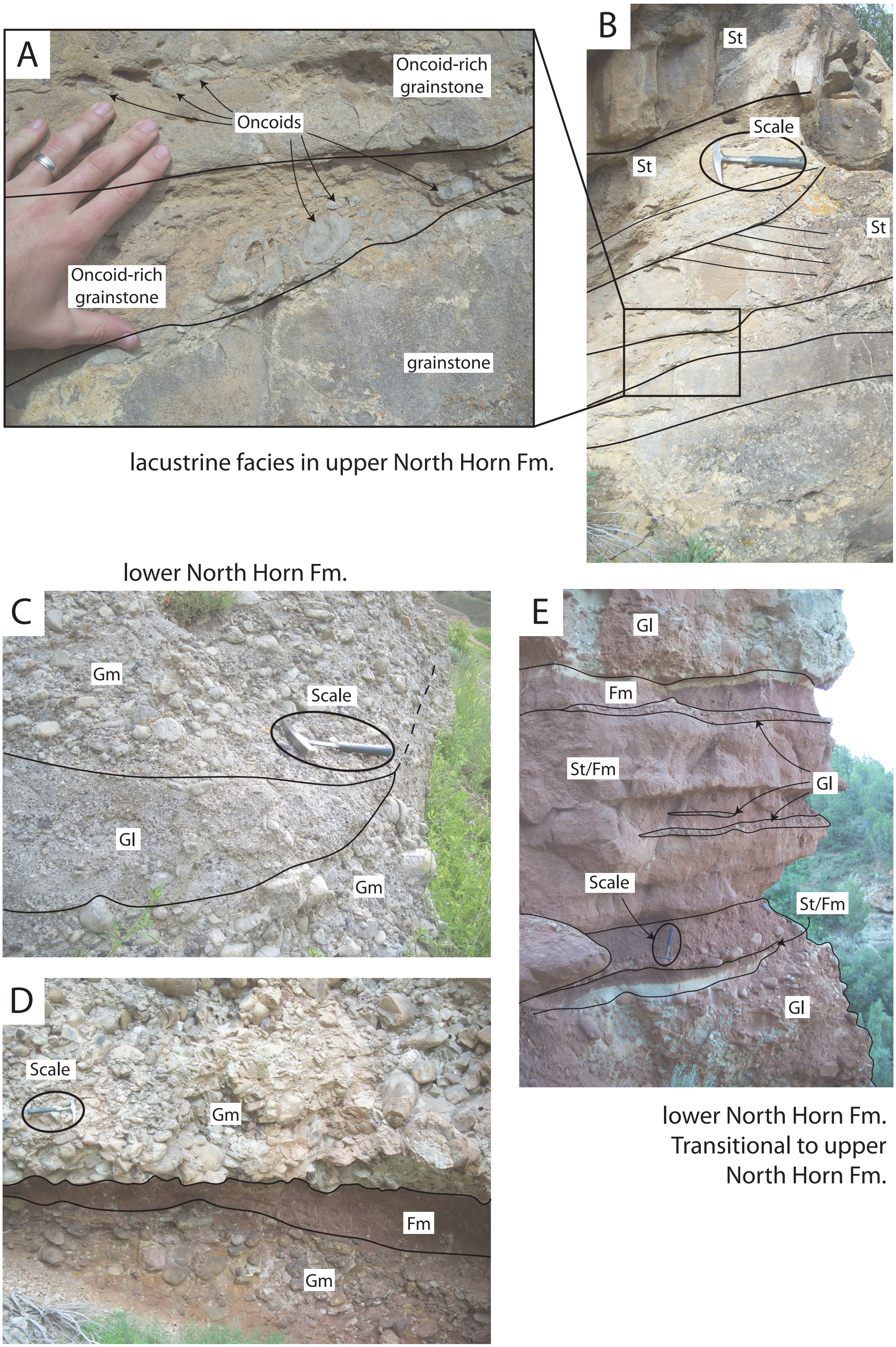
Description

Grayish-pink to very dark red, medium- to very thick bedded, trough cross-stratified, cobble to boulder conglomerate (see figure 6) interbedded with thin- to thick-bedded, very dark red mudstone that is mottled a very pale green color (see figure 6D and 6E). Conglomerate beds are commonly stained very dark red from the muddy intervals (see lower conglomerate bed in figure 6D). The lower North Horn Formation regionally conformably overlies the conglomerate of Thistle, but is locally angularly unconformable at distinct SU surfaces or where measureable dip decrease is present across the basal contact. The basal lower North Horn Formation is dominated by Paleozoic quartzite clasts in well-organized and trough cross- and low-angle stratified conglomerate beds (figure 6C), but variable clast composition differentiates it from conglomerate of Thistle ("Castlegate-Price River" of Horton and others, 2004). Clast composition varies up section to include larger proportions of argillite(?), black chert, limestone, minor sandstone, and friable semi-variegated shaly sandstone. This unit is also differentiated from conglomerate of Thistle by the first stratigraphic appearance of the very dark red mudstone (figure 6D and 6E) or the first presence of exclusively organized, trough cross-stratified, and channelized conglomerates. The abundance and thickness of mudstone beds gradually increase up section (figure 6E). The upper contact of this unit is selected on the last laterally continuous and thick conglomeratic beds. Thicknesses of the entire unit range from 0 up to approximately 500 feet (0–150 m) of incomplete section (Constenius, 2008); the thickness increases to the southeast in the subsurface to as much as 1640 feet (500 m) thick (Horton and others, 2004; Constenius, 2008). The lower North Horn succession is most easily observed in the northeast portion of the Thistle quadrangle in Red Narrows along U.S. Highway 6, where Late Cretaceous to Paleogene structural growth was either more subdued or nonexistent.

Stratigraphic-Structure Relationships in Dry Hollow

Upward trends in the lower North Horn Formation are difficult to observe near Dry Hollow because of poor exposures. There is, however, a relative shortage of lower North Horn conglomerate facies along the east side of Dry Hollow (strati-

Figure 6. (opposite page) *Photos of key North Horn lithostratigraphic units in the Thistle quadrangle. (A) Lacustrine limestone facies within the upper North Horn Formation that resemble the Flagstaff Limestone; this outcrop contains oncoids that range in diameter from a few mm to a few cm and are commonly brecciated; this photo was taken on the northern side of the mouth of Oil Hollow. (B) A small-scale view of the same facies in A; notice the abundant trough cross-stratification (St) and scour surfaces; grainstones, trough cross-stratification, and broken oncoids are abundant in cliff-forming Flagstaff-like facies of the upper North Horn Formation; located on the northern side of the mouth of Oil Hollow. (C) Organized boulder and cobble conglomerates of the basal lower North Horn Formation; alternating lenses of massive (Gm) and low-angle cross-stratification (Gl); clasts are largely quartzites; rock hammer for scale; located north of Highway 6 at approximately 111° 24.79' West longitude. (D) Interbedded boulder conglomerates and massive mottled mudstone (Fm) from the middle portions of the lower North Horn Formation; the mudstone facies are not very laterally continuous; rock hammer for scale; located north of Highway 6 at approximately 111° 24.79' West longitude. (E) Interbedded low-angle cross-stratified cobble conglomerates (Gl), massive sandy mudstone intervals (St/Fm), and massive mudstone facies (Fm) of the lower North Horn Formation transitional to the upper North Horn Fm; notice the abundance of mudstone and sandy mudstone compared to D; rock hammer for scale; this photo was taken near Lake Fork Road and Dry Hollow; see upper right inset photo in figure 6A where a strike and dip is provided.*


A
Oncoid-rich grainstone
Oncoids
Oncoid-rich grainstone
grainstone
B
St
Scale
St
St
lacustrine facies in upper North Horn Fm.
lower North Horn Fm.
C
Gm
Scale
Gl
Gm
D
Scale
Gm
Fm
Gm
E
Gl
Fm
St/Fm
Gl
Scale
St/Fm
Gl
lower North Horn Fm. Transitional to upper North Horn Fm.

graphically between the conglomerate of Thistle and upper North Horn Formation) while more than 330 feet (100 m) of thickly-bedded conglomeratic lower North Horn Formation is present 0.5 mile (0.75 km) to the southeast. This suggests the lower North Horn Formation thickens from the vicinity of Dry Hollow toward the southeast.

Stratigraphic-Structure Relationships in Dry Creek

A well-exposed but relatively thin (~65 to 160 feet [20–50 m]) succession of lower North Horn Formation is present in Dry Creek (figure 4A). Figure 4A illustrates that there is little or no dip decrease between the conglomerate of Thistle and the lower North Horn Formation; however, dip data are not abundant, so it remains unclear whether any dip decrease occurs *within* the lower North Horn Formation at this locale. There is a subtle thickening of the lower North Horn Formation from east to west in photo A in figure 4, and the same apparent thickening is present in the geologic map in the southwest corner of the Thistle quadrangle (plate 1). This could be related to variable uplift rates of the structure that created localized accommodation; however, it might simply be apparent because of bedding attitudes and different topographic styles from east to west (figure 4A).

Stratigraphic-Structure Relationships in Rock Creek

A thick succession of lower North Horn Formation is present in the southeast corner of the Thistle quadrangle and northeast Indianola quadrangle, but is not well-exposed because of heavy vegetative cover and local normal faulting (figure 4B). Within the Indianola quadrangle, the dip decreases up section from approximately 40° southeast in the uppermost conglomerate of Thistle, to approximately 16° southeast in the upper portions of the lower North Horn Formation (~24° dip decrease). Along-strike to the north-northeast (at the boundary of the Thistle and Indianola quadrangles) this up-section dip change shrinks to approximately 11° (Kurt Constenius, 2009, written communication). This trend of diminishing dip decrease continues to the north-northeast where it becomes even more subtle in the Thistle quadrangle (figure 4B).

Interpretation of the Lower North Horn Formation in the Three Areas

Previous studies have largely interpreted the lower North Horn Formation to be a succession of alluvial-fan deposits (e.g., DeCelles and others, 1995), but cobble to boulder conglomerates from northern Utah and western Wyoming that are coeval with and have very similar depositional styles to the North Horn Formation were recently re-interpreted as fluvial megafan deposits resembling those present in the modern Himalayan foreland (DeCelles and Cavazza, 1999; Leier and others, 2005). Limited age control of the undivided North Horn Formation places the base somewhere near the boundary of the Campanian and Maastrichtian, and the upper boundary somewhere in the early Eocene (Lawton and others, 1993; Robinson and Slingerland, 1998). The age of the transition from lower to upper North Horn Formation remains unclear, but is generally accepted to be late Paleocene (e.g., Constenius and others, 2003; Constenius, 2008). Thinning trends from mapping and the cross section A–A' (plates 1 and 2), and the accepted ages, suggest compressional growth of the Dry Hollow and Rock Creek structures continued locally during deposition of large-scale fluvial megafan systems during the late Campanian[?] or Maastrichtian into the Paleocene. It is uncertain whether growth occurred during this interval in the Dry Creek locale.

North Horn Formation, Upper Member (Tn)

The upper North Horn Formation is another remarkably heterogeneous group of rocks largely deposited in non-marine fluvial and lacustrine settings; only minor conglomerate facies are present. Facies in the upper North Horn Formation along the east side of the Thistle quadrangle are poorly stratified and largely resemble the conformably overlying Flagstaff Limestone (figure 6A and 6B). Subtle changes in dip and mapping relationships suggest angular unconformities are present in the upper North Horn Formation along the east side of the Thistle quadrangle. However, Constenius and others (2003; their figure 19) interpreted the Flagstaff Limestone as having growth geometries associated with extensional faults, suggesting it was deposited during post-thrust extension. Thus, rocks in the Flagstaff Limestone are not included in this analysis of local compressional tectonics.

Description

The lower portion of the upper North Horn is moderate-reddish-brown, thick- to very thick-bedded mudstone, marlstone, and siltstone interbedded with medium- to thick-bedded, trough cross-stratified sandstone and conglomerate. The upper portion is laterally variable and is either:

1. A moderate-reddish-orange, slope-forming siltstone interbedded with medium-bedded conglomerates composed of distinctive dark-grayish-blue Paleozoic clasts.
2. A moderate-red, moderate-orangish-pink, or grayish-orange-pink, crudely stratified, crudely thick-bedded, and well-cemented marlstone.
3. A laterally discontinuous oncoidal limestone (cliff-forming facies similar to the Flagstaff Limestone) that is present as a crudely bedded and often trough cross-stratified limy sandstone or trough cross-stratified grainstone (see figure 6A and 6B).

Beds of upper North Horn Formation thin over up-turned Late Cretaceous exposures: the thickness is nearly 1500 feet (460 m) in the central and southwest portions of the Thistle quadrangle, but thins to approximately 320 feet (~100 m) on the western ridge of Dry Hollow above outcrops of up-turned Indianola Group. A distinctive angular unconformity is present in the uppermost part of the upper North Horn Formation in the vicinity of Spring Hollow (see figure 2 for location). Laterally discontinuous upper North Horn oncoidal limestone cliffs and marlstones are truncated by younger upper North Horn discontinuous oncoidal limestone beds (see plate 1).

Interpretation of the Upper North Horn Formation in the Three Areas

The upper North Horn Formation is gradational from fluvial megafans of the lower North Horn Formation and was likely deposited in braided-fluvial, meandering-fluvial, and lacustrine depositional systems during the latest phases of compressional tectonics that quickly transitioned into post-thrust extension (Constenius and others, 2003; Constenius, 2008). The thickness trends related to Late Cretaceous outcrops suggest that structural uplift had created enough paleotopography during the late Paleocene that the upper North Horn Formation was forced to onlap hogbacks composed of Jurassic to Late Cretaceous rocks in Dry Hollow and Dry Creek (figure 5; see also Valora, 2010).

Angular unconformities and lateral variation in the uppermost upper North Horn Formation along the east side of the Thistle quadrangle are likely related to compression on the frontal-most Charleston-Nebo thrust as suggested by thinning trends from mapping and as interpreted in cross-section A–A' (plate 2). Constenius and others (2003) also placed the boundaries of the development of the Santaquin culmination structural phase (~80–40 Ma) near the timing of upper North Horn Formation deposition (late Paleocene and early Eocene) and suggested the transition from compression to post-thrust extension was relatively rapid (within ~5 million years). The syntectonic unconformities in the upper North Horn Formation may thus record the transition from late thrusting to post-thrust extension, but this interaction needs further study.

SUMMARY OF KEY STRATIGRAPHIC-STRUCTURAL RELATIONSHIPS IN THE THISTLE QUADRANGLE

The stratigraphic-structural relationships presented here (Dry Hollow, Dry Creek, and Rock Creek) are grouped by location. Temporal tectono-stratigraphic relations for these locations are summarized in figure 3. Previously published correlation charts are compiled in figure 3 to show the progression of nomenclature and stratigraphic understanding regionally (e.g., Fouch and others, 1983; Lawton, 1985; and Robinson and Slingerland, 1998).

Dry Hollow

Figure 5A illustrates the overall tapered and upward-fanning geometry, up-section flattening of dips and the presence of SUs in stratigraphic profile 3 from Dry Hollow. In figure 5A, the contacts between the conglomerate of Thistle, lower North Horn Formation, and upper North Horn Formation are in heavily vegetated slopes on the southeast side of the panorama. Upslope from this point the rocks gently plunge north-northeast and rotate counterclockwise (relative to the photo) so that the contact between the upper and lower members of the North Horn Formation is exposed at a lower elevation on the northeast side of the small valley along Lake Fork Road. The upper portions of the upper North Horn Formation are exposed as red-orange slopes north-northeast of Dry Hollow (figure 5A). Figure 5B illustrates the onlapping upper North Horn Formation over Late Cretaceous outcrops north-northeast of Dry Hollow.

Traditional-type SUs (Aschoff and Schmitt, 2008) are most easily recognizable in Dry Hollow. Parameters for recognizing subtle-type SUs in the field were developed by Aschoff and Schmitt (2008) as part of their study. However, exposures from Dry Hollow are intermittent enough that positively identifying subtle-type SUs from covered intervals that potentially contain traditional-type SUs is very difficult; nevertheless, sequential flattening intervals seen in outcrop, whether separated by poor exposure or not, unequivocally represent structural growth.

Nine traditional-type SUs were positively identified in Dry Hollow. These SUs have varying along-strike lengths and have varying dip discordance along their individual extents. The following SUs, their discordance (Δ), and along-strike extent are illustrated on plate 2 and plate 3.

SU-1 — present at the base of stratigraphic profile 1, has Δ32° that dies out along strike to the NNE in a little over 0.6 mile (~1 km); mapping relationships suggest that this SU cuts down section slightly so that onlapping(?) lithofacies from lower in the stratigraphic section are present where this SU appears to die out. Recent construction of multiple structural profiles in Dry Hollow (see Valora, 2010, chapter 4) as well as along-strike dip changes near the base of stratigraphic profile 4, suggest that SU-1 emerges again between stratigraphic profiles 2 and 4 below Tertiary cover. The tips of this portion of SU-1 are interpreted to cut down-section in order to resemble the mapping pattern observed for SU-1 near stratigraphic profile 1.

SU-2 — present in stratigraphic profile 1 at about 460 feet (140 m), has Δ5° ± 2, and was interpreted to extend along-strike approximately 1.25 miles (2 km) from profile 1, a little past profile 2.

SU-3 — present at approximately 345 feet (105 m) in stratigraphic profile 2 and has Δ7° ± 2. Because of slope-forming intervals and the fining upward fluvial package in the middle Funk Valley Formation, it is difficult to pin-point while walking over it. It is, however, easily observed looking along strike to the north-northeast from a ridge about 0.2 mile (0.3 km) to the SSW. It is unclear how far SU-3 extends to the south-southwest because of the extensive covered interval in stratigraphic profile 1. SU-3 is interpreted to die out between profile 3 and 4 because there is no measurable angular discordance along profile 4 in the same stratigraphic interval.

SU-4 — not present as angular discordance in any stratigraphic profiles, but was interpreted based on (a) a significant angular discordance observed between stratigraphic profiles 2 and 3 within the fining upward fluvial succession, (b) the along-strike thickness decrease of this stratigraphic package between stratigraphic profiles 2 and 4, and (c) the presence of abundant large-scale soft sediment deformation (a potential indication of tectonic activity; see Aschoff and Schmitt, 2008) in stratigraphic profiles 2 and 4 at a correlative stratigraphic height. Similar to SU-3, SU-4 is interpreted to die out between profiles 3 and 4.

SU-5 — present in stratigraphic profile 2 at approximately 640 feet (195 m) and just below stratigraphic profile 3 on the 1:12,000 scale map (see plate 3). SU-5 occurs in an interval of fine-grained amalgamated deltaic sandstone within the Indianola Group. The discordance of SU-5 at stratigraphic profile 1 is interpreted based on dip changes between 490 and 1575 feet (150–480 m). If any discordance is present along profile 1 at SU-3, then $\Delta 6°$ for SU-5 would be a maximum. The lateral extent of SU-5, as interpreted, is approximately 1.9 miles (3 km).

SU-6 — present as $\Delta 10° \pm 2$ in an interval of fine-grained amalgamated sandstone from the middle Funk Valley Formation. Along profile 3 and along-strike dip discordance variability revealed in the detailed mapping suggest this SU emerges rather quickly from the south-southwest, reaches its largest angular discordance along profile 3, and then dies out again to the north-northeast; all within approximately 0.9 mile (~1.5 km) along strike between profiles 2 and 4.

SU-7 — present as $\Delta 8° \pm 2$ at about 1640 feet (500 m) in stratigraphic profile 1 below the contact between the Funk Valley Formation and the Sixmile Canyon Formation. At this same interval in stratigraphic profile 2 there is no discordance, suggesting that uplift died out laterally in a maximum of approximately 1 mile (~1.6 km).

SU-8 — is represented by $\Delta 5°$ in stratigraphic profile 3 at approximately 970 feet (295 m) in mixed braided-fluvial and debris-flow conglomerates of the conglomerate of Thistle. Because of the relatively small angular discordance, its lateral extent is slightly enigmatic, but likely does not extend far beyond where it is illustrated to be truncated by SU-9 on plate 3.

SU-9 — extends at least 5 km along-strike throughout Dry Hollow until it is covered in the north-northeast by upper North Horn Formation and disappears beneath Quaternary deposits. Angular discordance is variable along its extent: 31° in profile 2, 14° ± 2 in profile 3, and 30° ± 2 in profile 4. It is unclear how far SU-9 extends to the south-southwest because of heavy vegetation and colluvial cover east-southeast of stratigraphic profile 1.

Above SU-9 — dip changes in the upper portions of stratigraphic profile 3 suggest there are likely 2 to 3 SU's, each with approximately $\Delta 5°$ to $\Delta 8°$, in the covered intervals and hard-to-access debris-flow conglomerates of the conglomerate of Thistle.

The presence of definable traditional-type SUs, as just described, from the lowermost Indianola Group (Albian) through the conglomerate of Thistle (middle to late Campanian) and the presence of up-section, dip-decreasing geometries in the lower member of the North Horn Formation (Maastrichtian through Paleocene) suggest that structural growth began in Dry Hollow sometime after the Albian and continued intermittently until the late Paleocene (see figure 3). The along-strike variability of SUs (e.g., extent and location) and their overall lengthening to the north-northeast suggest that the Dry Hollow structure underwent phases of strike-parallel expansion and vertical growth, first from the south-southwest to the north-northeast (SU-1 through SU-8) during deposition of the non-marine San Pitch and/or Sanpete Formations, through the mixed marine and non-marine Funk Valley Formation. Braided-fluvial conglomerates of the Sixmile Canyon Formation were deposited during the Santonian below a relatively long-lived local hiatus (~6 million years) that was not found to be associated with angular discordance (see figure 3). After this early Campanian hiatus, the conglomerate of Thistle was deposited in a mixture of braided-fluvial and debris-flow conglomerates prior to a significant uplift phase during the late Campanian (SU-9) that extended throughout Dry Hollow and likely farther, into Dry Creek and Rock Creek.

Dry Creek

Figure 4A illustrates the sequential dip decreases present at the Dry Creek locale (view is from the southeast to the northwest). The photo was taken from a ridge composed of the conglomeratic Indianola Group and dips are consistently approximately 40° to the northwest. The first dip decrease occurs at the SU with approximately 15° dip discordance between the Indianola Group and conglomerate of Thistle. The Indianola Group below the unconformity is largely fine-grained amalgamated sandstone that is lithologically identical to deltaic marine facies in the upper Funk Valley Formation in Dry Hollow. The conglomerate of Thistle is completely disorganized above the 15° discordant SU and is interpreted as debris-flow alluvial-fan facies deposited during the Campanian (after Aschoff, 2008). The conglomerate of Thistle then transitions gradationally into fluvial megafan deposits of the lower North Horn Formation, which in turn transition gradationally into fluvial and lacustrine deposits of the upper North Horn Formation.

The lack of dip change in the Dry Creek exposures of the Indianola Group imply that the growth of this structure occurred after deposition of the upper Funk Valley Formation—around the Coniacian/Santonian transition at the earliest (see figure 3). The lack of overturned or steeply dipping beds in Dry Creek, up-section decreasing northwest dips in Dry Creek, and much steeper south-southeast dips in Hjorth Canyon (Horton and others, 2004) suggest that sedimentation in Dry Creek occurred over the backlimb of a southeast-vergent thrust that likely cored the Dry Creek–Hjorth Canyon anticline. Gentle dip decreases from the conglomerate of Thistle to the upper North Horn Formation suggest that growth continued through the Paleocene, but was not as prominent as the structural growth near Dry Hollow.

Structural complexities seen in aerial photography suggest the Dry Creek–Hjorth Canyon structure is more complex than a 'simple' anticline and requires further study to understand its kinematic development. According to observations from this study, no Blackhawk Formation exists below the large syntectonic unconformity in Dry Creek. However, Horton and others (2004) provide a stratigraphic profile from Hjorth Canyon that reveals a SU between Blackhawk Formation and conglomerate of Thistle. Thus the relationships between the Indianola Group and the Blackhawk Formation, as well as the structural growth preserved in Hjorth Canyon, remain unclear.

Rock Creek

Near Rock Creek, the Indianola Group in the subsurface (as seen in seismic profiles from Constenius and others, 2003) is truncated by the frontal Charleston-Nebo thrust (part of the southern Provo salient frontal triangle zone) and contains no growth geometries. Exposed growth strata in the SE corner of the Thistle quadrangle show very minor dip decreases between the conglomerate of Thistle and upper North Horn Formation. Figure 4B is a photo of the northernmost exposures of the Rock Creek structure and shows the conglomerate of Thistle angularly unconformably overlying pre-growth Jurassic Twist Gulch Formation. Unpublished data (Kurt Constenius, written communication, 2009) suggest that the conglomerate of Thistle is present to the south stratigraphically *below* the SU in figure 4B where sequential dip decreases occur in outcrop between the Blackhawk Formation and upper North Horn Formation. The Blackhawk Formation (early Campanian) and the lower portions of the conglomerate of Thistle thin significantly from south-southwest to north-northeast and are likely truncated by undefined and defined SUs (e.g., the SU in figure 4B and others observed by Kurt Constenius, written communication, 2009). Depositionally, the presence of purely braided-fluvial conglomerates in the Rock Creek locale differs from debris-flow conglomerates in the Dry Hollow and Dry Creek locales; this is consistent with a localized (~6.5 mile radius) depositional model for debris-flow alluvial fans (Blair and McPherson, 1994; and Aschoff and Schmitt, 2008). Perhaps the abundant normal faults in the area mask the growth geometries in the southeast Thistle quadrangle (figure 4B). Alternatively, discordance along SUs in the North Horn Formation succession may decrease laterally until they are minimal or not present in the Thistle quadrangle.

These relationships suggest three-dimensional growth of the Rock Creek structure began sometime during the early Campanian, was punctuated by a number of uplift phases during the latest Cretaceous (based on the presence of multiple dip discordances greater than ~20°), and continued more gradually into the late Paleocene.

DISCUSSION

A Four-Dimensional Perspective

Stratigraphic analysis and mapping at multiple scales is compiled in figure 3. The interpreted timelines provided in figure 3 illustrate the remarkable difference between the preserved stratigraphic record and the timing of structural development between the Dry Hollow, Dry Creek, and Rock Creek locales. Geologic data suggest the temporal and spatial structural-stratigraphic development of the structures within the Thistle quadrangle occurred in the following manner:

1. Deformation near the paleo Dry Hollow locale began during the Cenomanian (after ~98 Ma), coeval with deposition of non-marine and marine deposits in the proximal Cretaceous Foreland Basin foredeep (Indianola Group). Growth continued into the earliest Campanian and deformation expanded in three-dimensions to the north-northeast, as recorded by traditional-type SUs.
2. The Dry Creek locale was uplifted after the beginning of the Santonian (sometime after ~ 85 Ma), but it is unclear exactly when because a large portion of syntectonic strata (the Santonian to late Campanian stratigraphic interval) was removed by an angular SU (see figure 4). Irrespective of when structural uplift began, sediments deposited during the Santonian are missing, but are likely present in the subsurface at Rock Creek because structural growth at that locale had apparently not initiated.
3. During the early Campanian (~ 80 Ma) the structure near Rock Creek (Oil Hollow anticline) began to be uplifted, coeval with deposition of non-marine and marine facies of the Blackhawk Formation that likely represent the last foredeep deposits in the area; a long hiatus (not associated with an angular SU; see figure 3) began in the Dry Hollow locale at this time. Perhaps early relief

on the Rock Creek structure (i.e., expressed as a paleo-exposure of the pre-growth Twist Gulch Formation, figure 4B) acted as a barrier for marine incursion during Blackhawk time. Additionally, uplift along the western edge of the paleo Thistle quadrangle may have diminished accommodation locally and allowed Blackhawk fluvial systems to largely bypass the area.

4. The first instance of the conglomerate of Thistle is present *below* the large SUs in Dry Hollow and Rock Creek; this lower unit is not present in the Dry Creek area, either because of erosion or non-deposition. Interpretations of the conglomerate of Thistle suggest an interfingering of braided-fluvial and alluvial-fan depositional systems in Dry Hollow at approximately 77 million years ago and purely braided-fluvial depositional systems in the Rock Creek locale. This suggests significant relief began appearing approximately 6.5 miles (~11 km) west of Dry Hollow (Blair and McPherson, 1994; Aschoff and Schmitt, 2008) with associated alluvial fans and an interfingering/fringing braided-fluvial system, likely representing a classic wedge-top zone.
5. Above the basal conglomerate of Thistle (see figure 3), SU-9 in Dry Hollow and SUs present in Dry Creek and Rock Creek (figure 4) are present *within* the stratal succession (middle Campanian age) and have the largest angular discordance at each locale. These relatively large SUs likely represent a significant compressional phase in the area at approximately 75 Ma. This interpretation is substantiated by the presence of purely debris-flow alluvial-fan conglomerates at a correlative stratigraphic height in Dry Hollow and Dry Creek, suggesting significant relief likely appeared less than approximately 6.5 miles (~11 km) to the west (Blair and McPherson, 1994; Aschoff and Schmitt, 2008) and allowed debris-flow alluvial-fan systems to prograde over the area.
6. Subsequent to the large middle Campanian uplift phase, structures in Dry Hollow, Dry Creek, and Rock Creek continued growing, likely sporadically, during the latest Cretaceous and into the Paleocene. During this approximately 15 million-year interval, sediment was deposited coeval with the structural growth in a mixture of braided-fluvial, meandering-fluvial, and lacustrine depositional systems.

Based on the general south-southwest/north-northeast structural strike, each of the structures in the Thistle area at Dry Hollow, Dry Creek, and Rock Creek is located consecutively basinward of the previous and, respectively, uplifted prior to the next (see figure 3): this suggests in-sequence thrusting. Additionally, the three growth strata locales in the Thistle quadrangle are axially offset 2.5 to 5 miles (4–8 km) relative to one another. In map view this occurs on a scale from less than 1 mile to approximately 40 square miles (1–100 square km). Though three-dimensional structural information associated with these three locales is largely eroded or buried, their spatial distribution and the stratigraphic data available record variable spatial and temporal histories depending on location within a relatively small area. The along-strike variability in stratigraphic thickness and SUs also suggest the Rock Creek and Dry Hollow structures grew in three-dimensions; with the current data it is unclear whether the Dry Creek structure grew in the same manner. In order for these structures to grow in three-dimensions at different times (as suggested by the stratigraphic record) and to become offset from one another, the differential structural deformation would have required different thrust styles and/or rates at each location at different times. This is most easily explained by transverse zones (presently of unknown structural style because of burial) that compensated for the differential development at lateral tips of the individual structures.

Extended Application to the Sevier Fold-Thrust Belt

This analysis highlights several key areas for future work in the frontal Sevier fold-thrust belt. The interpretation of structural development presented here was constrained using stratigraphic ages provided by previous work but deviates slightly from previous regional interpretations (see figure 3; Fouch and others, 1983; Lawton, 1985; Robinson and Slingerland, 1998). Though many of these regional studies incorporate data from the Thistle area, they did not document the small-scale structural kinematics. For example, the presence and/or depositional style of the Funk Valley Formation was affected by accommodation patterns and erosion above local structural growth (plate 3; figures 3, 4, and 5), but this remains hidden in basin-wide correlations that interpret the Funk Valley Formation as a largely continuous interval with, perhaps, only an unconformity at the top (Fouch and others, 1983; Lawton, 1985; Robinson and Slingerland, 1998). Correlations from this study relative to previous workers provided in figure 3 reveal other major differences, including:

1. A potential significant decrease in preserved Sixmile Canyon Formation locally;
2. Blackhawk Formation is present only locally and this presence is likely related to localized tectonics;
3. Deposition of the conglomerate of Thistle (including equivalent rocks with previously different names) may have occurred over a longer period of time than previously thought, and it was deposited locally in debris-flow alluvial fans, implying significant proximal topographic relief;

4. This study provides a significant increase in the number of known local unconformities during the Late Cretaceous.

The discrepancy between this analysis and regional analyses is also significant because the tectono-stratigraphic development of other similar structures (or suites of structures) in the Sevier fold-thrust belt could differ significantly from previous regional analyses. While regional analysis is invaluable, the small-scale spatial and temporal interactions in the Sevier fold-thrust belt are likely being averaged out at larger-scales. Future tectono-stratigraphic analyses in the frontal Sevier fold-thrust belt cannot disregard the three-dimensional complexity inherent in these smaller structures, and should apply analytical methods or concepts that take this three-dimensionality into account. This study serves as a reminder that making basin-wide interpretations should be avoided (especially respecting tectonics, sediment supply, and eustatic sea level fluctuations) when based solely on an individual outcrop or even based on multiple outcrops in relatively close proximity.

CONCLUSION

Geologic mapping, growth strata analysis, and the recognition of traditional-type syntectonic unconformities (SUs) in growth strata exposures highlight the location and growth of three separate structures in the Thistle quadrangle (within part of the southern Provo salient). The data from this study contribute three new details regarding the structural development of the Thistle area:

1. Deformation in the Thistle area initiated in the northwest (i.e., Dry Hollow area) from the Cenomanian to Campanian (~98 to 77 Ma), before a major phase of uplift and erosion from mid Campanian to Paleocene (~75–50 Ma) affected the entire Thistle area and created significant relief.
2. Deformation in the Dry Creek locale began soon after uplift in Dry Hollow during the Santonian (~85 Ma?) and was later affected by the same phase of regional uplift and erosion in the mid Campanian to the Paleocene;
3. Deformation in the Rock Creek locale began in the early Campanian, (~80 Ma) and continued into the Paleocene, including the same major phase of Campanian (~75 Ma) uplift and erosion.

Examination of syntectonic unconformities, the spatial distribution of local structures, and synorogenic stratigraphy further suggest that this early development of isolated structures created spatially complex relief throughout the Thistle area which deflected early deltaic deposition and caused local thinning near early structures. Later, these isolated structures became much higher-relief at the toes of the Santaquin culmination with consequent drainages that sourced alluvial fans. Insight from this study's detailed analyses (multiple methods at multiple scales), as well as multidisciplinary approach (structural *and* stratigraphic), reveals a previously unrecognized and dynamic interaction between growing structures and evolving depositional systems at the forefront of the Provo salient during the Late Cretaceous to Tertiary. In the Thistle area (and potentially in other areas of the Sevier fold-thrust belt) these dynamics created remarkably different stratigraphic records, even in relatively small geographic areas.

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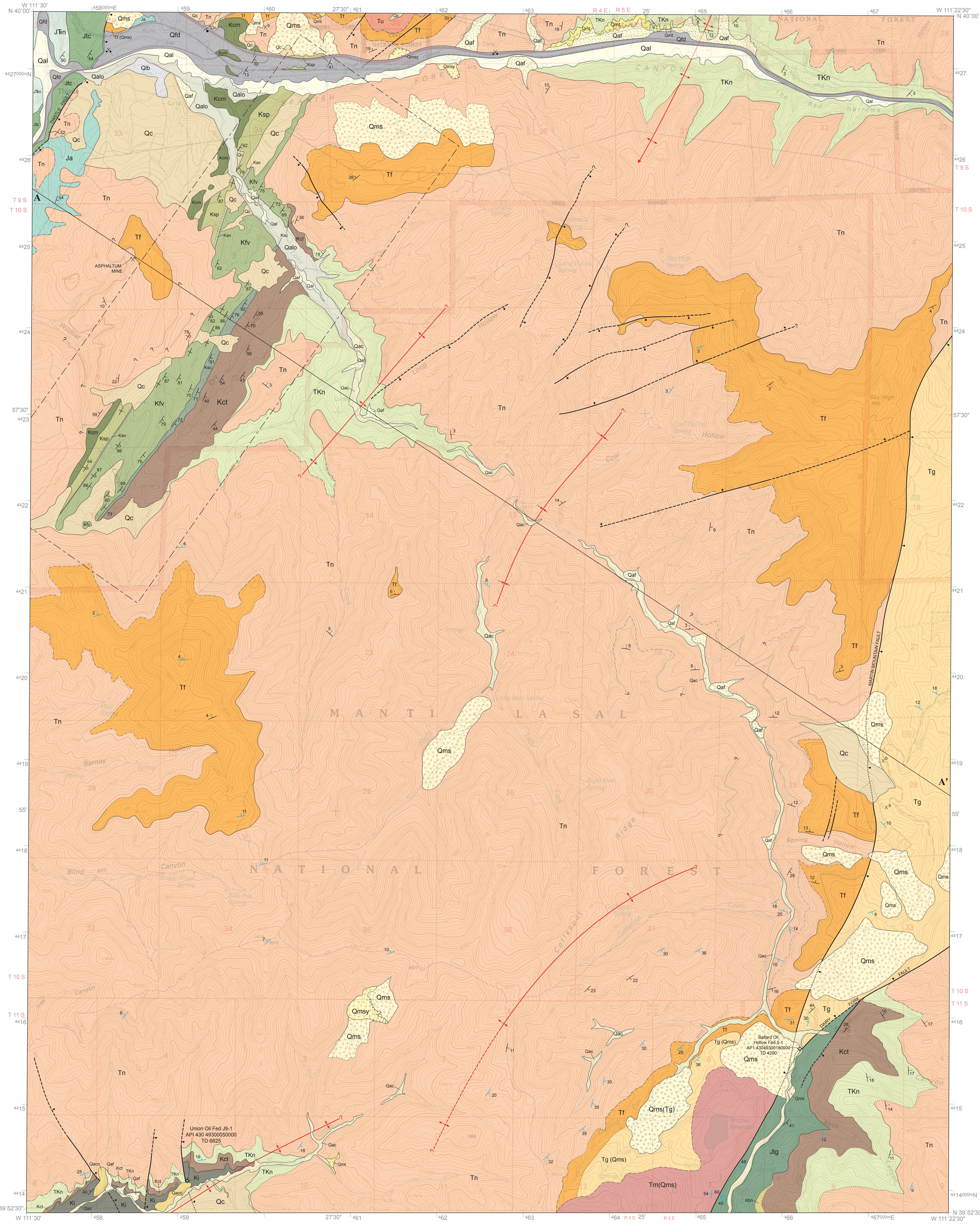

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SCALE 1 : 24,000

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CONTOUR INTERVAL 40 FEET

Base map from U.S. Geological Survey
Thistle, 7.5' quadrangle, 1967

Field work: by authors in 2009
Grant C. Willis, UGS Project Manager

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Extent of geologic inset map of Dry Hollow

GEOLOGIC MAP OF THE THISTLE QUADRANGLE, UTAH COUNTY, UTAH

by

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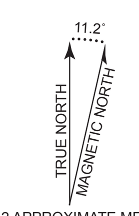
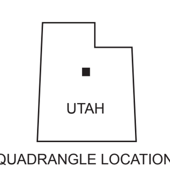
2012



2012 APPROXIMATE MEAN DECLINATION AT CENTER OF SHEET



QUADRANGLE LOCATION

1	2	3	1. Spanish Fork Peak 2. Billies Mountain 3. Ray's Valley 4. Birdseye 5. Mill Fork 6. Spencer Canyon 7. Indianola 8. C Canyon
4		5	
6	7	8	

ADJOINING 7.5' QUADRANGLE NAMES

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DESCRIPTION OF MAP UNITS

QUATERNARY

Artificial Deposits

Qfd **Human-made debris**, human-reworked bedrock, and fill from highway and railroad construction; variable thickness up to 30 to 40 feet (9–12 m).

Colluvial Deposits

Qc **Colluvial deposits (Holocene to Pleistocene)** – Poorly consolidated, poorly to moderately sorted, angular, clay- to boulder-sized, locally derived sediment; deposited by rock-fall, slopewash, and soil creep on shallow to moderately steep slopes; mapped deposits are limited to those of significant thickness because a large portion of bedrock is covered with a thin veneer of colluvium (largely in the upper North Horn Formation); maximum thickness about 30 feet (9 m).

Alluvial Deposits

Qal **Stream and floodplain alluvial deposits (Holocene)** – Unconsolidated deposits of sand, silt, clay, gravel, and cobbles in channels and floodplains; composition commonly depends on proximal source area; estimated to be 0 to 20 feet (0–6 m) thick.

Qalo **Older stream and floodplain alluvial deposits (Holocene)** – Unconsolidated deposits of sand, silt, clay, gravel, and cobbles that forms a terrace (with moderate soil development) that has been incised by a younger active fluvial channel; estimated up to 30 feet (9 m) thick.

Qaf **Alluvial-fan deposits (Holocene and upper Pleistocene)** – Unconsolidated, poorly sorted, clay- to boulder-size sediment deposited by debris flows; grain size and color depend on locally derived sediment; debris-flow activity was observed on many fans during heavy rain; less than 30 feet (9 m) thick.

Mixed-environment Deposits

Qac **Alluvial and colluvial deposits (Holocene to Pleistocene)** – Poorly to moderately sorted, poorly stratified, clay- to boulder-sized, locally derived sediment deposited in small drainages and as natural levees of larger streams (both perennial and ephemeral) by fluvial, debris-flow, slopewash, and creep processes; locally includes small active alluvial fans from small side canyons and colluvium from adjacent slopes; generally less than 30 feet (9 m) thick.

Qaco **Older alluvial and colluvial deposits (upper Pleistocene)** – Poorly to moderately sorted, poorly stratified, clay- to boulder-sized, locally derived sediment forming terraces above younger Qac and Qaf deposits in Dry Creek; likely deposited by fluvial, debris-flow, slopewash, and creep processes; approximately 20 to 50 feet (6–15 m) thick.

Lacustrine Deposits

Qlb **Lacustrine terrace gravels related to Lake Bonneville (Upper Pleistocene)** – Poorly consolidated and poorly- to moderately-sorted, clay- to cobble-sized, well-stratified, moderate-orange-pink to dark-reddish-brown sediment forming a wave-built terrace at approximately 5200 feet (1585 m) elevation; likely a remnant of the Spanish Fork delta that was constructed during Lake Bonneville's highest level; thickness estimated at 0 to 20 feet (0–6 m) thick.

Mass-movement Deposits

Qmt **Talus deposits (Holocene)** – Very poorly sorted, clay- to boulder-sized, angular rocks and blocks deposited beneath cliffs and ledges; commonly associated with Flagstaff Limestone (Tf) and North Horn Formation (Tn and TKn); typically finer grained where associated with upper North Horn Formation (Tn), allowing moderately stabilized slopes; 0 to 30 feet (0–9 m) thick.

Qmsy **Young slumps and landslides (Holocene)** – Poorly sorted, angular, clay- to boulder-sized material; characterized by hummocky topography and relative lack of vegetation; scarps are well-exposed; commonly occur on dip-slopes of fine-grained units in the upper North Horn Formation (Tn); thickness unknown and likely variable.

Qms **Slumps and landslides (Holocene to Pleistocene[?])** – Poorly sorted, angular, clay- to boulder-sized material; characterized by hummocky and well-vegetated topography; scarps are poorly exposed; only large well-defined landslides are mapped–additional unmapped landslides are likely present; commonly occur on dip-slopes of fine-grained units in the Green River Formation (Tg) and upper North Horn Formation (Tn); thickness unknown and likely variable.

TERTIARY

Tm **Moroni Formation (lower Miocene to upper Eocene)** – Exposures mainly consist of surface float clasts and boulders that are commonly: (1) medium-light-gray to medium-dark-gray andesite with a slightly vuggy aphanitic matrix containing subhedral to euhedral phenocrysts of amphibole, or (2) a distinctive trachyte that is either dark-purple or very dusky purple with visible plagioclase and amphibole phenocrysts; weathers to light-blue-green. More extensive deposits are present outside the Thistle quadrangle and are interpreted as synextensionally deposited in local half-grabens as a mixture of stream reworked and deposited volcanic debris, lahar flows, and tuffaceous deposits (Constenius and Dawson, 2008); early Miocene to late Eocene age based on biostratigraphic work by Constenius and Dawson (2008) as well as radiometric ages provided by Ziga (2006) ranging from 34.4 Ma to 22.9 Ma; thickness unknown in the Thistle quadrangle.

Tu **Uinta Formation, main body (middle Eocene)** – Light gray, tan, and red-brown, thin- to thick-bedded, lenticular-bedded, pebbly sandstone, mudstone, sandy conglomerate, and marlstone; unit is at least 2000 feet (600 m) thick to north (Constenius and others, 2011), but only lower few tens of feet preserved within quadrangle. Constenius and others (2011) reported that in the Billies Mountain area immediately north of the Thistle quadrangle, the Green River Formation is completely cut out by erosion along the basal Uinta Formation unconformity and that this strata overlies the unconformity and is younger than the Colton Formation as it was mapped by Young (1976).

Tg **Green River Formation, undivided (middle to lower Eocene)** – Light-blue-green and grayish-blue-green, thick-bedded mudstone with light-gray fissile shale that typically forms colluvial slopes with only minor outcrops; possible paleosol horizons appear as variegated light-blue-green, very dark red, and various brown colors; the greenish mudstone is interbedded with medium-bedded (0.5 to 3 feet [0.15–0.9 m] thick), fissile very fine grained sandstone, massive fine- to medium-grained sandstone (also medium-bedded), or fossiliferous coquina composed of framework-supported lacustrine gastropods in a limy mud matrix; exposures are largely present along the eastern edge of the Thistle quadrangle in the hanging-wall block of the Martin Mountain normal fault; minimal bedrock outcrops and faulting make thicknesses difficult to determine; Pinnell (1972) estimated it to be 1800 feet (550 m) at its thickest in the southeast part of the Thistle quadrangle.

Tf **Flagstaff Limestone (lower Eocene)** – Very light gray to medium-gray, thick- to very thick bedded intervals of microcrystalline limestone, oncoidal limestone, oolitic limestone, massive or low-angle, trough cross-stratified, limy, fine-grained sandstone, and grayish-orange-pink marlstone; facies vary vertically and laterally; the basal portion of this formation is nearly identical to facies that exist in the upper North Horn Formation (TKn); the lower contact was picked at the base of a laterally extensive, cliff-forming, oncoidal limestone where present; incomplete sections, poor exposures, and laterally changing facies make the thicknesses difficult to define in the southern half of the Thistle quadrangle; along the northern edge of the quadrangle the observable thickness ranges from 300 feet (90 m) in the west to approximately 600 feet (180 m) in the east (Pinnell, 1972).

Tn **North Horn Formation, upper member (lower Eocene and upper Paleocene)** – Lower portion is moderate-reddish-brown, thick- to very thick bedded mudstone, marlstone, and siltstone interbedded with medium- to thick-bedded sandstone and conglomerate; oncoidal limestone similar to the Flagstaff Limestone (Tf) is also present; the upper portion is laterally variable and is either: (1) moderate-reddish-orange, slope-forming siltstone interbedded with medium-bedded conglomerates composed of distinctive dark-grayish-blue Paleozoic clasts, (2) moderate-red, moderate-orange-pink, or grayish-orange-pink, crudely stratified, crudely thick-bedded, and well-cemented marlstone, or (3) a laterally discontinuous oncoidal limestone cliff-former similar to the Flagstaff Limestone; generally conformable with overlying Flagstaff Limestone (Tf). A distinctive angular unconformity is present in the uppermost exposures of upper North Horn Formation (Tn) just south of Spring Hollow and is likely related to the latest local phase of thrusting as well as early post-thrust extension (Constenius and others, 2003; Valora, 2010); thickness patterns are generally related to deposition over Indianola Group (Ki) and conglomerate of Thistle (Kct) paleotopography; thickness is nearly 1500 feet (460 m) in the central and southwest portions of the Thistle quadrangle, but thins to approximately 320 feet (97 m) on the western ridge of Dry Hollow above outcrops of Indianola Group (Ki).

TERTIARY-CRETACEOUS

TKn **North Horn Formation, lower member (upper Paleocene to Upper Cretaceous—upper Campanian[?] or Maastrichtian)** – Grayish-pink to very dark red, medium- to very thick bedded, cobble to boulder conglomerate; conglomerates are interbedded with thin- to thick-bedded, very dark red mudstone that is mottled a very pale green; conglomerate beds are commonly stained very dark red from the muddy intervals; conformably overlies the conglomerate of Thistle (Kct); in Dry Hollow and Dry Creek, disorganized conglomerate lithologies of the conglomerate of Thistle grade into, and are interbedded with, more well organized cobble and pebble conglomerates of the North Horn formation; basal part is dominated by Paleozoic quartzite clasts deposited in exclusively braided-fluvial streams, but presence of compositionally variable clasts differentiates it from the conglomerate of Thistle (Horton and others, 2004); furthermore, clast composition varies upward to include larger portions of slates, black chert, limestone, minor sandstone, and friable semi-variegated shaly sandstone; also differentiated from conglomerate of Thistle by the first appearance of very dark red mudstone or the presence of exclusively braided-fluvial deposits (see conglomerate of Thistle description); mudstone bed thicknesses gradually increase up section; the upper contact is selected on the last continuous and thick conglomeratic bed; exposed thicknesses range from 0 feet up to approximately 500 feet (150 m) of incomplete section; for age assignment see work by Lawton and others (1993), Constenius (1998), Robinson and Slingerland (1998), and Constenius (2008); thickness increases to the southeast in the subsurface to as much as 1640 feet (500 m) thick (Constenius, 1998; Horton and others, 2004; and Constenius, 2008).

CRETACEOUS

Kct **Conglomerate of Thistle (Upper Cretaceous, upper[?] to middle Campanian)** – White to very light gray, thick- to very thick bedded, cobble to boulder conglomerate with well-rounded clasts; at the base of the unit the matrix is a bluish-gray sandstone with light-blue-green silty clasts and is composed of trough cross-stratified, erosionally based, lenticular bedded conglomerates (braided-fluvial) that are interbedded with heavily disorganized, poorly sorted, and crudely-bedded conglomerates (debris-flow); the fluvially deposited conglomerates disappear upward until exclusively debris-flow deposited conglomerates are present; poorly sorted throughout; dominated by quartzite clasts with moderate-reddish-orange iron-oxide staining.

The informal name "conglomerate of Thistle" is used in an effort to incorporate previous work by Robinson and Slingerland (1998), Constenius and others (2003), and Horton and others (2004) that provides a middle to late(?) Campanian age for the regionally extensive and quartzite-dominated conglomerate unit between the Indianola Group (Ki) and North Horn Formation (Tn and TKn); this unit had previously, and incorrectly, been interpreted as time-equivalent with the Price River Formation (latest Campanian to early Maastrichtian).

Regionally, the conglomerate of Thistle (Kct) is present above an extensive unconformity (Lawton and others, 1993); an unconformity was observed in Dry Creek (southwest Thistle quadrangle) with ~15° to 20° discordance, where this unit lies directly above Indianola Group (Ki); near Rock Creek (northeast Indianola quadrangle) a similar unconformity has approximately 30° angular discordance across it, marking the boundary between the conglomerate of Thistle and the underlying Blackhawk Formation (Horton and others, 2004; Kurt Constenius, written communication, 2009); in the southeast corner of the Thistle quadrangle the conglomerate of Thistle (Kct) unconformably overlies Jurassic Twist Gulch Formation (Jtg); a large unconformity is also present in Dry Hollow, but appears within the lithologically and compositionally defined conglomerate of Thistle (Kct) and has a laterally variable angular discordance between ~14° to >30°.

In Dry Creek and Dry Hollow the conglomerate of Thistle (Kct) is completely disorganized, is structureless, contains light-blue-green rip-up clasts, and lacks any semblance of fluvial processes for up to 410 feet (125 m) of section above the previously described syntectonic unconformity; also above this unconformity in Dry Hollow and Dry Creek, the clast composition grades to bimodal white sandstone and quartzite; distinctive disorganization also begins to grade into slightly more organized, subtly fluvially influenced deposits; near Rock Creek, exposed conglomerate of Thistle differs from Dry Hollow and Dry Creek by being trough cross-stratified, more organized, and less poorly sorted throughout; this may suggest fluvial deposition as opposed to disorganized debris-flow alluvial fan deposits. The conglomerate of Thistle (Kct) is conformably overlain by lower North Horn Formation (TKn) and is locally correlative with the Castlegate Sandstone (Robinson and Slingerland, 1998; in Dry Hollow and Dry Creek, disorganized conglomerate lithologies of the conglomerate of Thistle grade into, and are interbedded with, more well organized cobble and pebble conglomerates of the North Horn Formation; Horton and others, 2004; and Aschoff, 2008); the upper contact is selected regionally by a sudden substantial inclusion of lithic clasts or locally by the first appearance of red-beds from the lower North Horn Formation (TKn); thickness ranges from 0 to nearly 1115 feet (0–340 m).

Kbh **Blackhawk Formation (Upper Cretaceous, lower Campanian)** – Very pale orange, coarse- to medium-grained sandstone interbedded with dusky-yellowish-brown, slope-forming siltstone (Pinnell, 1972); exposures are more abundant to the south and east, and have been interpreted as fluvial, deltaic, and shallow marine (Horton and others, 2004); exposures are limited to a small area in the southeast corner of the Thistle quadrangle and are more prominent in the northeast portion of the Indianola quadrangle along the east side of Lake Fork Road; approximately 820 feet (250 m) thick (Pinnell, 1972); increases to almost 3200 feet (1000 m) of thickness to the south and into the subsurface (Horton and others, 2004).

Ksc **Sixmile Canyon Formation, Lower(?) (Upper Cretaceous, Santonian)** – This unit is exposed as steep conglomerate slopes on the low northwest flank of Dry Hollow; it is covered by Quaternary and Tertiary sediment and rock to the south-southwest, is angularly unconformably overlain by the upper portions of the conglomerate of Thistle (Kct) in the vicinity of stratigraphic profile 4 (northwest end of Dry Hollow), and disconformable with overlying conglomerate of Thistle through the majority of Dry Hollow; smaller clasts and sand grain-sizes include well-cemented sandstone, black chert, and a distinct inclusion of labile and sub-angular white sandstone grains ranging from coarse sand to gravel in size. At Dry Hollow this formation can be grouped into three distinct and consecutive intervals: (1) at its base (near stratigraphic profiles 2 and 3) this formation is very well-sorted, fine-grained sandstone (reworked uppermost Funk Valley Formation?) that is generally structureless with subordinate pebbles and/or cobbles suspended in the sand; locally grades upward into better organized, fining-upward, and thin (<4 inches [10 cm]) beds of pebble and cobble conglomerate dominated by fine-grained sandstone; (2) a laterally continuous and relatively thin (approximately 30 feet [10 m] thick) assemblage of thick-bedded, sharp-based, moderate-reddish-orange, poorly stratified (low-angle?), moderately well sorted, and highly polymictic conglomerate; clasts include gray-blue micritic limestone, chert in various colors, various well-cemented well-sorted sandstones (e.g., thinly laminated or massive), and tan or purple mudstone; can locally be matrix- or clast-supported but is moderately well sorted throughout; matrix is very well sorted, medium-grained lithic arenite sandstone; clasts are subangular to rounded and discoid clasts are often imbricated; bedding geometry is distinctly tabular with minimal scouring at bases; uncommon 1.5-foot-thick (0.5 m) trough cross-stratified and well-sorted tabular beds of sandstone (resembling the conglomerate matrix) are also present intermittently and interbed with the polymictic conglomerate; and (3) thick-bedded, clast-supported, low-angle cross-stratified, minorly fining-upward, and crudely lenticular cobble conglomerate containing moderately imbricated clasts; the matrix is very coarse grained sand and gravel with very fine grained sand filling the interstices; low-angle inclined bedsets of conglomerate are often amalgamated with lens-shaped beds dominated by the conglomerate matrix; conglomerate clasts are always rounded to well-rounded and are often greater than 6 inches (15 cm) in diameter; clasts throughout this interval are largely grey to pink crystalline quartzites, but do contain low amounts of a distinctive grayish-red-purple rudite quartzite. The thickness ranges from approximately 30 to 310 feet (10–95 m).

Kfv **Funk Valley Formation (Upper Cretaceous, Coniacian)** – Funk Valley Formation is a remarkably heterolithic group of strata that crops out within and around Dry Hollow and also in Dry Creek (southwest corner of the Thistle quadrangle).

The base of the Funk Valley Formation conformably overlies Allen Valley Shale and is present in Wildcat Canyon (southwest end of Dry Hollow) and at the mouth of Dry Hollow on both sides of Lake Fork Road; the middle and upper portions are present throughout Dry Hollow and on the northern flank of Dry Creek. The base of the Funk Valley Formation in Dry Hollow is 180 to 260 feet (55–80 m) of amalgamated, well-sorted, bluish-white to yellowish-gray colored, very fine to fine-grained, and medium- to thick-bedded sandstones that are hummock cross-bedded, planar laminated, or massive; symmetric ripple laminations are present as remnant ripples in subordinate massive beds; vertical and horizontal burrows are abundant, are subordinately lined, and have low diversity throughout; burrows are interpreted as *Thallasinoides* and *Ophiomorpha*, which typically occur in marine shoreface depositional environments; minor beds are present at different intervals with whole and broken Inoceramid clams (William Cobban, oral communication, 2009) in both matrix and framework support; woody material is present intermittently. The base of the Funk Valley Formation is typically exposed as vertically amalgamated intervals of evenly stacked beds up to 3 feet (1 m) thick that alternate between bluish-white and yellowish-gray in color.

Sharply overlying the basal amalgamated sandstone are tabular, trough, and low-angle (planar?) cross-stratified, coarse-grained, gravelly sandstone beds locally containing pebble and cobble stringers (see the base of stratigraphic profile 3, sequence boundary); thin interbeds of ripple cross-laminated, very fine grained sandstone are locally present; outsized cobbles and pebble stringers locally found throughout lens-shaped, low-angle cross-stratified, and sharp-based beds or at the bases of horizontally accreting sub-sigmoidal beds. Pebbles and cobbles increasingly dominate up section and begin to form thick-bedded, clast-supported, low-angle cross-stratified, minorly fining-upward, and crudely lenticular-bedded cobble conglomerate containing moderately imbricated clasts; the matrix is a very coarse grained sand and gravel with very fine grained sand filling the interstices; low-angle inclined bedsets of conglomerate are often amalgamated with lens-shaped beds dominated by the matrix; clasts are always rounded to well rounded; pebble clasts include chert and distinct, labile, and sub-angular white sandstone grains; cobbles are often grey to pink quartzite, but distinctive grayish-red-purple rudite quartzite is locally present in abundance. Where not covered by Quaternary and Tertiary overburden on the northwest ridge of Dry Hollow, this conglomeratic interval is easily recognizable as vertical outcrops of conglomeratic fins from south-southwest Dry Hollow, along-strike nearly to U.S. Highway 6.

Gradationally overlying the conglomeratic interval is medium- to thick-bedded, yellow-white colored, trough cross-stratified, low-angle cross-stratified, ripple-laminated, and fine- to coarse-grained lithic-rich sandstone with abundant ripple laminae interbedded with strongly oxidized light-red or subtly variegated slope-formers; trough and low-angle cross-stratification typically occurs in coarse-grained sandstones; ripple laminae tend to occur in finer-grained sandstones and some ripple laminae locally have thin mud drapes, but this is uncommon; soft sediment deformation is abundantly present locally; bed morphology is difficult to interpret because of associated interbedded slope formers and lateral discontinuity, however, beds are often lens shaped when trough cross-stratified. The aforementioned succession is interrupted only twice by anomalous lithofacies: in the middle portion of this unit in stratigraphic profile 2, three feet (1 m) of massive, bioturbated, and medium-grained sandstone is present (transgressive surface?); likewise, along both stratigraphic profile 2 and 4 also in the middle of this unit (110 m in stratigraphic profile 2 and 350 m in profile 4) a single anomalous pebbly cobble conglomerate bed is present (sequence boundary?). In Dry Hollow this interval thins along-strike from approximately 490 feet (150 m) in stratigraphic profile 4 to approximately 195 feet (60 m) stratigraphically below profile 3; it thickens from this point to approximately 260 feet (80 m) in profile 2 and continues to the south-southwest where it is covered by Quaternary colluvium before reaching profile 1.

Above the succession of interbedded sandstone and oxidized slope-formers are poorly exposed slopes containing individual thin- to medium-bedded (not vertically amalgamated) sandstones interbedded with gray slope-forming mudstone/siltstone; this interval strongly resembles the Allen Valley Shale and is conformably overlain by another thick interval of bluish-white and yellowish-gray amalgamated sandstone that is lithologically indistinguishable from the basal Funk Valley Formation; conformably overlying these sandstones is another succession of gray slopes containing individual thin- to medium-bedded sandstone beds that is subsequently conformably overlain by more amalgamated sandstone of the uppermost Funk Valley Formation. This uppermost sandstone interval differs from the previous two, however, by being very well sorted, very fine to fine-grained, and medium- to thick-bedded sandstone that is rarely hummocky/swaley laminated and nearly always massive; beds are locally up to 13 feet (4 m) thick, are typically hummocky cross-bedded within the basal 4 to 8 inches (10–20 cm), but are otherwise massive or syndepositionally slumped. This interval contains remarkably abundant and distinctive dark- to pale-yellowish-orange deformation bands; clams are absent and marine burrows are less common than in the previous marine sandstone of the Funk Valley Formation.

Kav **Allen Valley Shale (Upper Cretaceous, Turonian)** – Massive bedded, white-gray to gray, clayey siltstone interbedded with very well sorted, bluish-white to yellowish-gray, very fine to fine-grained, and thin- to medium-bedded sandstone that is hummock cross-bedded, planar laminated, or massive; sandstone beds are not vertically amalgamated. Allen Valley Shale is similar/identical in lithology to stratigraphic intervals in the Funk Valley Formation and can be distinguished only by stratigraphic position; directly overlies trough cross-stratified, medium- to coarse-grained sandstones of the uppermost Sanpete Formation; the upper contact is conformable (and likely diachronous) with overlying amalgamated sandstones of the Funk Valley Formation. In Dry Hollow the thickness ranges from 98 to more than 345 feet (30–105 m).

Ksp **Sanpete Formation (Upper Cretaceous, Turonian to Cenomanian) and San Pitch Formation (Lower Cretaceous, Albian), undivided** – The San Pitch and Sanpete Formations are overturned to steeply dipping in both Wildcat Canyon and at the mouth of Dry Hollow. The San Pitch Formation is composed of gray or moderate reddish-brown, polymictic, pebble to cobble conglomerates (dominated by quartzite and carbonate clasts) forming lenticular beds containing subtle, large-scale, trough cross-stratification; interbedded with calcareous and noncalcareous mudstone as well as buff, well-sorted, fine- to coarse-grained, feldspathic litharenite sandstone with well-developed trough cross-stratification; and locally with a relatively thin and heterolithic version of equivalent and thicker rocks that are described in more detail by Sprinkel and others (1999).

The San Pitch grades, fining upward slightly, into similar low-angle cross-stratified, polymictic, clast-supported, light-red pebble to cobble conglomerate of the Sanpete Formation (disconformable?); contains rounded to well-rounded clasts in a gravelly sandstone matrix; clasts include distinctive cherts in various colors; gray-blue limestone, well-cemented sandstone, and quartzite are also common; cobbles are generally less than 6 inches (15 cm) in diameter; bedding architecture is moderately lens-shaped with sharp bases; sorting is moderate to moderately well in coarser beds so that trough cross-stratification is subtle; lenses are from approximately 3 to 9 feet (1–3 m) across and the bases of sharp-based beds truncate cross-stratification in beds below or lateral to them. Conglomerates of the Sanpete Formation are laterally and vertically gradational with yellow-white to white-gray, fine- to coarse-grained, fining-upward, and poorly sorted feldspathic litharenite sandstone; geometries in sandstone beds are strongly lens-shaped with locally sharp bases from 3 to 6 feet (1–2 m) in width; stratification ranges between trough-cross, low-angle cross, and planar laminated; planar lamination is subtle and typically associates with low-angle cross-stratification in medium- to coarse-grained sandstone or with thin asymmetric ripple cross-beds in fine-grained sandstones. Conglomerate and sandstone beds as previously described subsequently grade upward into similarly composed sandstone interbedded with strongly oxidized slope-formers. The entire Sanpete Formation succession is overlain by very fine grained sandstones and mudstones of the Allen Valley Shale. The thickness of the Sanpete and San Pitch Formations is unknown.

Ki **Indianola Group, undivided (San Pitch Formation, Sanpete Formation, Allen Valley Shale, Funk Valley Formation, Sixmile Canyon Formation [lower?]) (Upper to Lower Cretaceous, Santonian to Albian)** – Locally exposed and heterolithic facies composing formations from the Indianola Group. In the northwest corner of the Thistle quadrangle the Indianola Group, at its northernmost extent, is largely marine sandstones and mudstones resembling facies of the Funk Valley Formation, but is mapped undivided because of relatively poor exposures. In the southwest corner of the Thistle quadrangle the Indianola Group forms a conglomeratic ridge flanking the southern side of Dry Creek, and bluish-white to yellowish-gray amalgamated, massive, marine sandstone forms the base of the northern face of Dry Creek; these marine sandstones are angularly unconformably overlain sharply by the conglomerate of Thistle (Kct). The gross thickness of the Indianola Group locally ranges from 1800 to greater than 2300 feet (550–>700 m).

Kcm **Cedar Mountain Formation (Lower Cretaceous)** – Variegated siltstone, sandstone, limestone, and conglomerate underlain by moderate-orange-pink, medium-light-gray, and light-brown conglomerate and sandstone (Pinnell, 1972; Sprinkel and others, 1999); conglomerate beds are interbedded with coarse, poorly consolidated sandstone and medium-bedded siltstone; exposures are minimal, patchy, and difficult to interpret because of debris cover and overlying moderate-reddish-brown upper North Horn Formation (Tn) that mixes with the variegated Cedar Mountain Formation (Kcm) in colluvium and slopewash; thickness unknown locally; previous descriptions (e.g., Pinnell, 1972) included polymictic conglomerates of San Pitch Formation (see Sprinkel and others, 1999).

JURASSIC

Jtg **Twist Gulch Formation (Upper to Middle Jurassic)** – Thin- to medium-bedded reddish-brown sandstone interbedded with laminated to thin-bedded, moderate-red, siltstone and shale mottled a light-blue-green (Pinnell, 1972); outcrops are commonly light-red colored and heavily vegetated slopes along Lake Fork Road in the southeast corner of the Thistle quadrangle; exposures are much more extensive south of the quadrangle; time-equivalent with the Entrada/Curtis/Summerville Formations (Pinnell, 1972); thickness unknown in the Thistle quadrangle because of poor outcrops and extensive compressional and extensional structural deformation.

Ja **Arapien Formation (Middle Jurassic)** – Basal part is heavily ripple-laminated, red and gray-green, muddy sandstone bed 3 to 6 feet (1–2 m) thick overlain by approximately 30 feet (10 m) of thick-bedded limestone that is light brown gray, finely crystalline to aphanitic, sandy, shaly to thin bedded and less resistant than the underlying Watton Canyon Member of the Twin Creek Limestone; limestones grade upward into buff-gray, greenish-gray, very thin to thick-bedded siltstones interbedded with thin- to medium-bedded, very fined grained sandstones that are heavily ripple laminated; lateral equivalent of the Leeds Creek and Giraffe Creek members of the Twin Creek Limestone (Jtc) (Pinnell, 1972; Hintze and Kowallis, 2009); approximately 680 feet (210 m) thick in the northwest corner of the Thistle quadrangle and upwards of 1000 feet (300 m) thick (Pinnell, 1972) in the west-central and west-southern portions of the quadrangle.

Jtc **Twin Creek Limestone (Middle Jurassic)** – Predominantly light- to dark-gray dense and oolitic limestone separated by predominantly reddish to light-green-gray mudstone, siltstone, sandstone, and brown-gray limestone (Doug Sprinkel, written communication, 2010); also see Pinnell (1972) for further description; total thickness is approximately 860 feet (260 m) thick.

JTRn **Nugget Sandstone (Lower Jurassic to Upper Triassic)** – Moderate-reddish-orange to moderate-orange-pink, thick- to very thick bedded, very well sorted, well-rounded, medium-grained sandstone; commonly contains frosted grains; abundant large-scale (>3 to 16 feet [1–5 m] thick) trough cross-stratification; although a complete section is not exposed in the Thistle quadrangle, it is approximately 1450 feet (440 m) thick locally (Pinnell, 1972; Constenius, 1998; Constenius, 2008; and Doug Sprinkel, written communication, 2010).

MAP SYMBOLS

Contact - dashed where approximately located, dotted where inferred

Contact - local Tf base that is laterally gradational with uppermost Tn facies

Normal fault - dashed where approximately located, dotted where covered, bar and ball on downthrown side (hanging wall)

Tf/Tn marker beds - picked at the base of Tf cliff-former greater than 6-9 feet (2-3 m) thick, dash-dotted where Tf facies laterally grade into uppermost Tn facies; locally blue, green, and red lines are stratigraphically lower to higher and do not necessarily correlate across the quadrangle

Asymmetric syncline - shorter arrow on steeper limb

Symmetric anticline - equilateral triangle indicates plunge

Asymmetric anticline - shorter arrow on steeper limb

Landslide/Slump scarp - hachures on down-dropped side

30 Strike and dip of inclined bedding - blue symbols indicate attitudes from Pinnell (1972) and Kurt Constenius unpublished mapping

54 Strike and dip of overturned bedding

Strike of vertical bedding

17 Estimated strike and dip

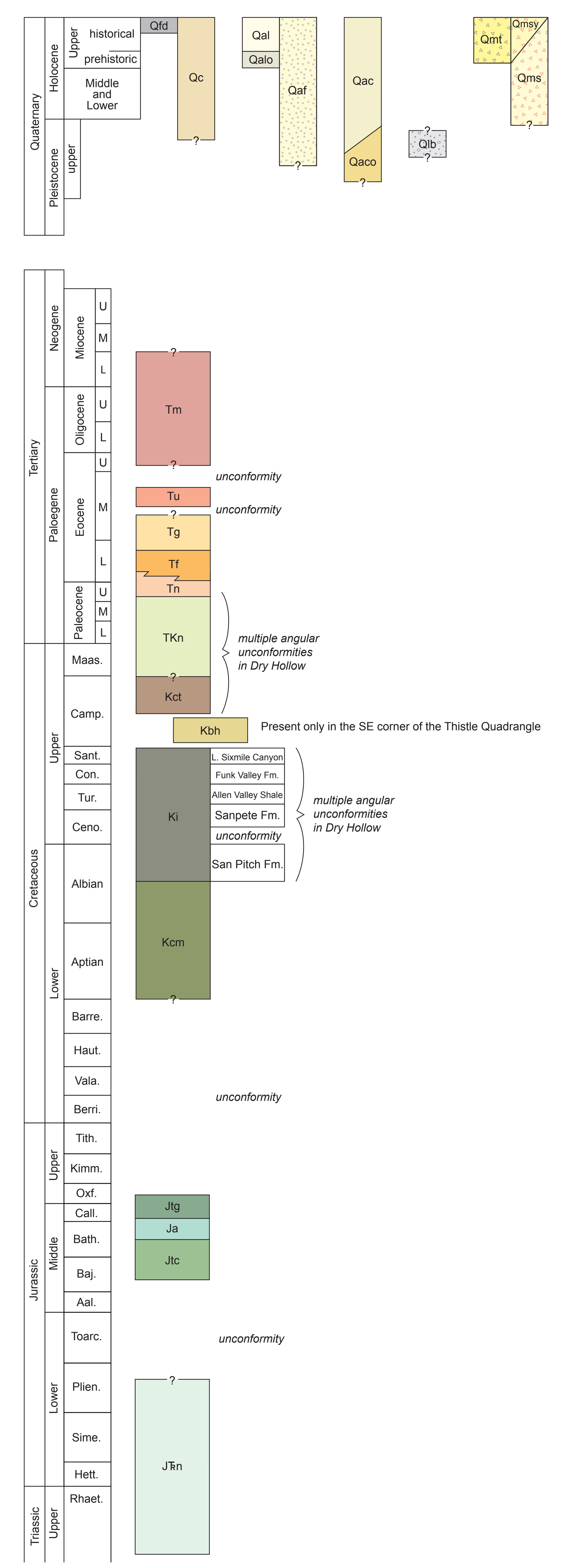
2 Dip, shown on cross section

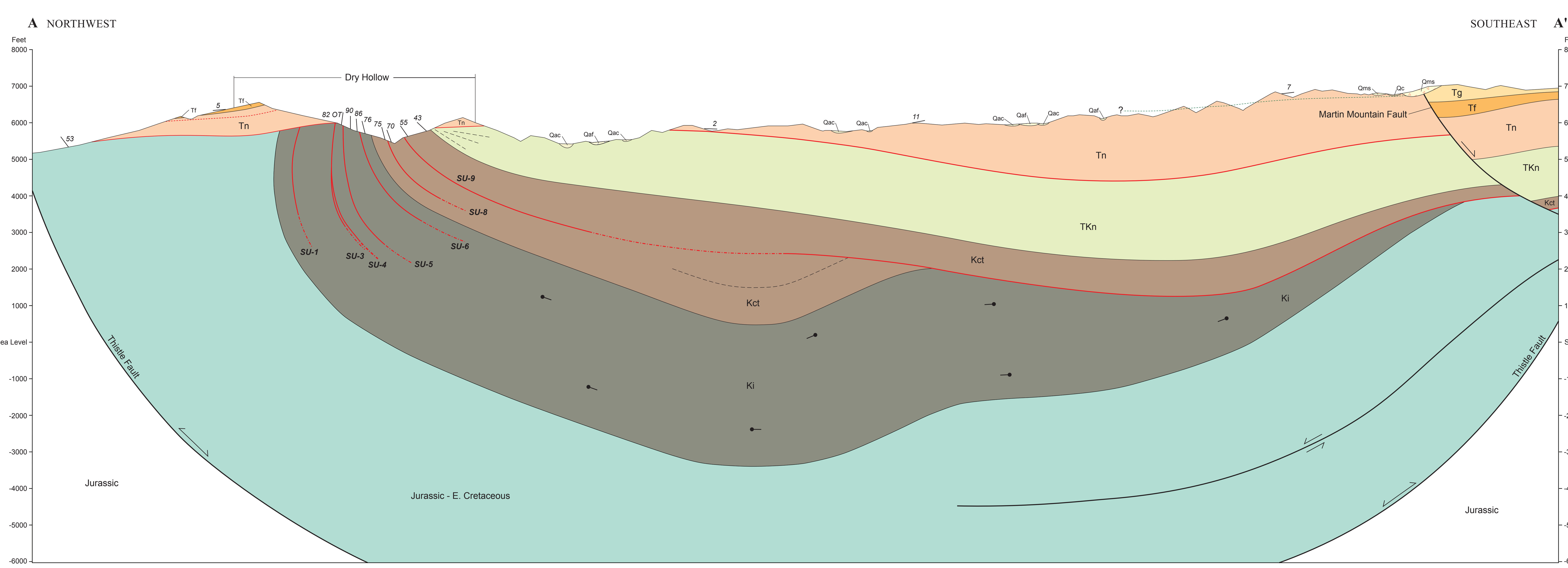
Mine - asphalt

b Prospect - bitumin

Exploration drill hole - plugged and abandoned

CORRELATION OF MAP UNITS





Regional structural cross section built from surface data, growth strata analysis in Dry Hollow, and a 2D seismic line published in Constenius and others (2003) and Horton and others (2004). Unit thicknesses change dramatically because of synorogenic deposition (Ki through TKn, and perhaps the lowermost portions of Tn), synorogenic erosion (syntectonic unconformities), and post-thrust extension (Tn through Tg). Expanding syntectonic unconformities and overturned Indianola Group beds above Jurassic beds that dip 53° east suggest that an east-verging fault-propagation fold deformed much of the Indianola Group interval. The structure was further rotated clockwise, relative to this northward view, by backthrusting during the development of the Santaquin Culmination (Constenius and others, 2003; Valora, 2010).

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MAP SYMBOLS FOR DRY HOLLLOW ENLARGED MAP

- Contact - long-dash where approximately located, short-dash where inferred
- Contact - local Tf base that is laterally gradational with uppermost Tn facies
- Normal fault - dashed where inferred, bar and ball on downthrown side (hanging wall)
- Syntectonic Unconformity - dashed where approximately located, dotted where inferred, dash-dotted where laterally discontinuous.
- Marine Maximum Flooding Surface - dashed where approximately located, dotted where inferred
- Sequence Boundary - dashed where approximately located, dotted where inferred
- Transgressive Surface - dashed where approximately located, dotted where inferred
- 2 Location and number of stratigraphic profiles
- 54 Strike and dip of inclined bedding
- 54 Strike and dip of overturned bedding
- Strike of vertical bedding

11.2°
TRUE NORTH
MAGNETIC NORTH
2012 APPROXIMATE MEAN DECLINATION

Detailed map of Late Cretaceous to Paleogene growth strata in Dry Hollow showing traditional-type syntectonic unconformities (after Aschoff and Schmitt, 2008) and key stratigraphic surfaces within the Indianola Group; also shown are the locations of stratigraphic profiles. The figure to the right provides a correlation of these profiles. Notice that the Indianola Group thins to the south-southwest and syntectonic unconformities (SU) tend to expand laterally up section. SU-9, within or at the base of the conglomerate of Thistle, is locally the most laterally continuous. A similar laterally continuous angular unconformity can be observed in the southwest corner of the Thistle quadrangle, as well as in the northeast corner of the Indianola quadrangle (Kurt Constenius, written communication, 2009).

SCALE 1:12,000

1/2 0 1/2 1 MILE
1000 0 1000 2000 3000 4000 5000 FEET
.5 0 .5 1 KILOMETER

CORRELATION EXPLANATION

Stratigraphic Profiles

- 1 Section Number
- Claystone/Siltstone
- Organized Conglomerate
- Disorganized Conglomerate
- Sandstone
- Covered

Depositional Environments

- Debris-Flow Alluvial Fan
- Mixed Debris-Flow and Braided Fluvial
- Braided Fluvial
- Meandering-Fluvial
- Wave-Dominated Marine Delta
- Marine offshore

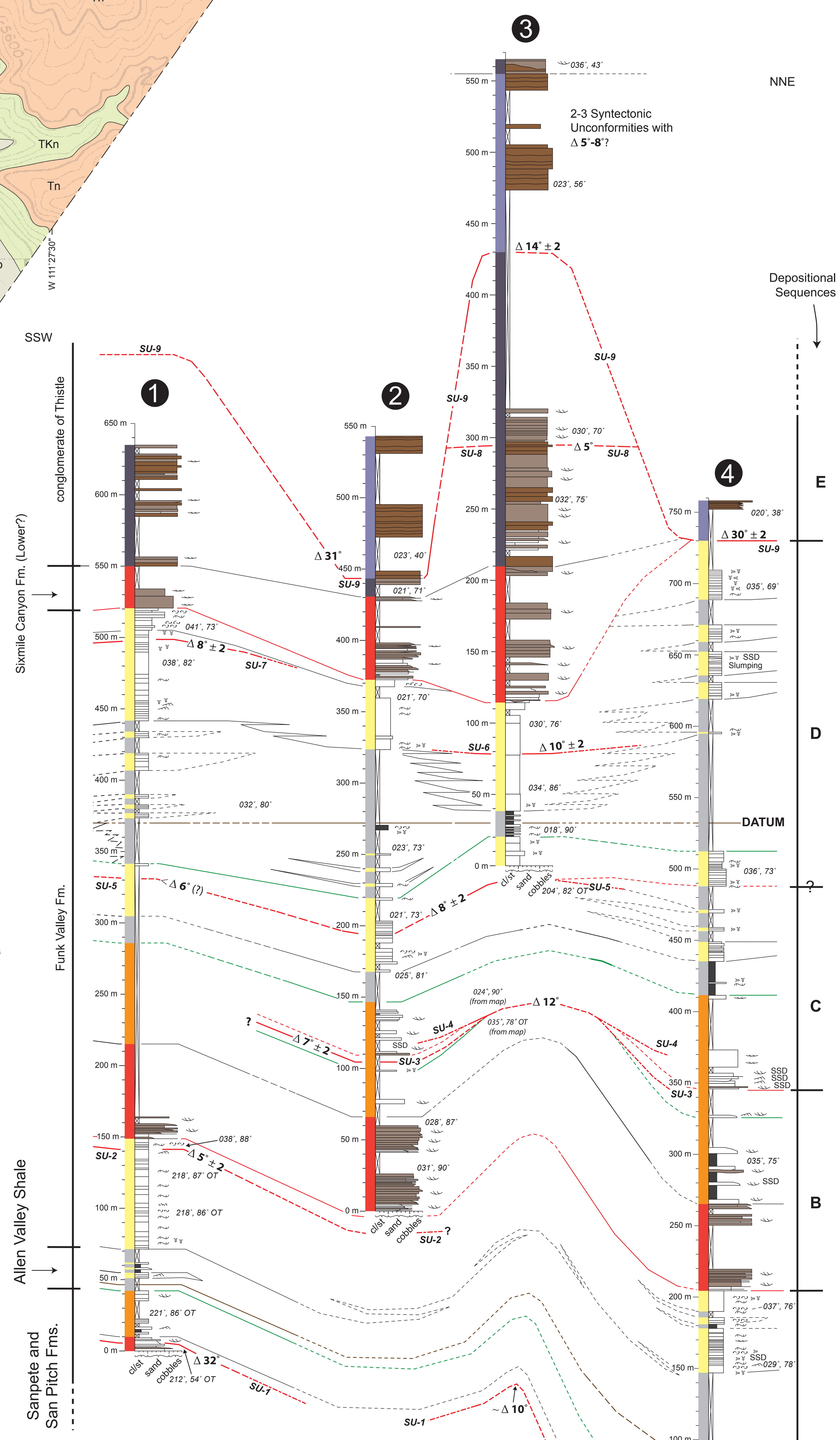
Contacts (all long-dashed where approximate and short-dashed where inferred)

- Depositional Environment Contacts
- Syntectonic Unconformity (dot-dash where discontinuous)
- Sequence Boundary
- Maximum Flooding Surface
- Transgressive Surface
- Δ 10° Localized Angular Dip-discordance of Syntectonic Unconformity
- 020°, 50° Strike and Dip of Bedding along Measured Sections
- SU-5 Syntectonic Unconformity
- cl/st sand cobbles Grain Size in Stratigraphic Profiles

Generalized Sed. Structures

- Trough Cross-Stratified
- Low-Angle TCS
- Hummock Stratified
- Ripples
- Burrows (Horiz. & Vert.)
- Bivalves/Clams
- SSD Soft Sediment Deformation

50 m
1 km
SCALE
10x vertical exaggeration



Sequence-stratigraphic correlation of stratigraphic profiles measured through the growth-strata section in Dry Hollow showing the relative timing, lateral continuity and amount of discordance of syntectonic unconformities. Note that the oldest syntectonic unconformities are relatively isolated and laterally discontinuous, but these become more laterally extensive and migrate to the north-northeast through time. In general, the syntectonic unconformities have a greater angular discordance in the youngest part of the synorgenic succession, and locally coincide with regional unconformities (i.e., sequence boundaries). Additionally, syntectonic unconformities locally correlate with the amalgamated intervals of wave-dominated marine delta lithofacies directly along strike from the syntectonic unconformities. Covered units below profile 3 were constructed by keeping thicknesses constant for stratigraphic packages of constant thickness in the other profiles and by thinning stratigraphic packages that have strong syn-growth characteristics (e.g., the interpreted meandering-fluvial interval that contains SU-3 and SU-4).

GEOLOGIC MAP OF GROWTH STRATA IN DRY HOLLOW, THISTLE QUADRANGLE, UTAH COUNTY, UTAH

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CORRELATED STRATIGRAPHIC PROFILES THROUGH GROWTH STRATA IN DRY HOLLOW