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Geologic Mapping of the Vernal NW Quadrangle, Uintah County, UT,
and Stratigraphic Relationships of the Duchesne River Formation
and Bishop Conglomerate

Casey Andrew Webb

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

Geologic Mapping of the Vernal NW Quadrangle, Uintah County, UT, and Stratigraphic Relationships of the Duchesne River Formation and Bishop Conglomerate

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Master of Science

Detailed mapping (1:24,000), measured sections, and clast counts in conglomerates of the Duchesne River Formation and Bishop Conglomerate in the Vernal NW quadrangle in northeastern Utah reveal the middle Cenozoic stratigraphic geometry, the uplift and unroofing history of the eastern Uinta Mountains, and give evidence for the pulsed termination of Laramide uplift. The Uinta Mountains are an EW-trending reverse fault bounded and basement-cored, Laramide uplift. The oldest unit of the Duchesne River Formation, the Eocene Brennan Basin Member, contains 80-90% Paleozoic clasts and <20% Precambrian clasts. Proximal to the Uinta uplift the conglomerates of this member are dominated by Paleozoic Madison Limestone clasts (70-90% of all clasts). Farther out into the basin, Paleozoic clasts still dominate in Brennan Basin Member conglomerates, but chert clasts are more abundant (up to 43%) showing the efficiency of erosion of the carbonate clasts over a short distance (~5 km). Conglomerates in the progressively younger Dry Gulch Creek, Lapoint, and Starr Flat members show a significant upward increase in Precambrian clasts with 34-73% Uinta Mountain Group and 8-63% Madison Limestone.

Duchesne River Formation has a significant increase in coarse-grained deposits from the southern parts of the quadrangle (20-50% coarse) to the northern parts (75% coarse) nearer the Uinta uplift. The lower part of the Duchesne River Formation exhibits a fining upward sequence representing a tectonic lull. Clast count patterns show that pebbly channel deposits in the south maintain similar compositions to their alluvial fan counterparts. To the north, the fine-grained Lapoint and Dry Gulch Creek members of the Duchesne River Formation appear to pinch out completely. This can be explained by erosion of these fine-grained deposits or by lateral facies shifts before deposition of the next unit. Starr Flat Member conglomerates were deposited above Lapoint Member siltstones and represent southward progradation of alluvial fans away from the uplifting mountain front.

Similarities in composition and sedimentary structures have caused confusion surrounding the contact between the Starr Flat Member and the overlying Bishop Conglomerate. Within the Vernal NW quadrangle, we interpret this contact as an angular unconformity (the Gilbert Peak Erosion Surface) developed on the uppermost tilted red siltstone of the Starr Flat Member sometime after 37.9 Ma.

Stratigraphic and structural relationships reveal important details about the development of a Laramide mountain range: 1) sequential unroofing sequences in the Duchesne River Formation, 2) progradation of alluvial fans to form the Starr Flat Member, 3) and the unconformable nature of the Gilbert Peak Erosion Surface lead to the conclusion that there were

at least 3 distinct episodes of uplift during the deposition of these formations. The last uplift episode upwarped the Starr Flat Member constraining the termination of Laramide uplift in the Uinta Mountains to be after deposition of the Starr Flat Member and prior to deposition of the horizontal Bishop Conglomerate starting at about 34 Ma. This, combined with $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 39.4 Ma from the Dry Gulch Creek and Lapoint member, show that slab rollback related volcanism was occurring to the west while the Uinta Mountains were being uplifted on Laramide faults. These new $^{40}\text{Ar}/^{39}\text{Ar}$ ages constrain the timing of deposition and clarify stratigraphic relationships within the Duchesne River Formation; they suggest a significant unconformity of as much as 4 m.y. between the Duchesne River Formation and the overlying Bishop Conglomerate, which is 34-30 Ma in age, and show that Laramide uplift continued after 40 Ma in this region.

Keywords: Uinta Mountains, stratigraphy, geologic map, chronostratigraphy, Laramide, uplift

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Chapter 1: Geologic Mapping of the Vernal NW Quadrangle, Uintah County, UT

1.1 Introduction

Although maps of the Vernal region have been created in the past (Kinney, 1955; Untermann and Untermann, 1964, 1968; Sprinkel, 2007) (Figure 1), the Vernal NW quadrangle has never been mapped at a 1:24,000 scale. The Vernal NW quadrangle, on the southern slope of the Uinta Mountains just south of Little Mountain (Figure 2), contains sedimentary deposits that were emplaced pre-, syn-, and post-uplift of the Uinta Mountains. Swarms of normal faults in the Deep Creek Fault Zone were mapped in areas (Haddox, 2015a, 2015b; Hunt, 2017) north of the Vernal NW quadrangle (Figure 1), yet have never been mapped within the quadrangle until this study. This map (Plate 1) provides detailed surficial geologic unit contacts, faults, folds, bedding inclination, and location of abandoned wells. To accompany this map and better understand the features within, we created detailed map unit descriptions, a stratigraphic column, a cross-section, unit age correlation figures, well data tables (Plate 2), and this manuscript that describes the geology of the Vernal NW quadrangle in greater detail.

The Vernal NW quadrangle contains Jurassic to Oligocene bedrock units, with the majority of the bedrock emplaced in the middle Tertiary as sediments were shed from the Uinta Mountains in its latter stages of uplift (Hintze and Kowallis, 2009). These bedrock units (with exception to the Bishop Conglomerate) strike northwest/southeast and dip as much as 54° to the southwest. The Walker Hollow Syncline crosses the southwestern part of the quadrangle and bedding southwest of this area dips shallowly (1-4°) to the northeast. We also mapped fifteen different Quaternary deposits that make up approximately 1/3 of the surface geology that was mapped.

1.2 Geologic Summary

This study focused particularly on the members of the Eocene Duchesne River Formation (Brennan Basin, Dry Gulch Creek, Lapoint, and Starr Flat members) (Figure 3) and the Oligocene Bishop Conglomerate due to their excellent exposures and unanswered questions about their stratigraphic relationships. Previous research, for example, has questioned whether the Starr Flat Member of the Duchesne River Formation and the Bishop Conglomerate should be separate formations or combined as a single unit (Bryant, 1989; Haddox, 2005; Sprinkel, 2007, 2015). Within the quadrangle these two formations are very similar in composition and sedimentary structure and can be difficult to distinguish. Another important question deals with the relationships between the members of the Duchesne River Formation. Can contacts be mapped that are also chronostratigraphic boundaries or do contacts in this area need to be mapped based upon lithofacies? Do significant unconformities exist between members of the Duchesne River Formation and what do they imply about the uplift of the Uinta Mountains?

Volcanic ash beds within the Lapoint and Dry Gulch members of the Duchesne River Formation have yielded new age data and provide additional chronostratigraphic context for these members to better constrain and supplement ages determined by previous workers (Damon, 1970; Winkler, 1970; McDowell et al., 1973; Hansen et al., 1981; Bryant et al., 1989; Kowallis et al., 2005; Sprinkel, 2015). The complex nature of the Duchesne River Formation and Bishop Conglomerate led to an in-depth study of these formations in Chapter 2 where clast composition, stratigraphic geometry, and age data are used to determine the uplift history and chronostratigraphic relationships of the Duchesne River Formation and Bishop Conglomerate.

Jurassic-Cretaceous units are exposed in the northeast portion of the map. These units dip steeply ($\approx 20\text{-}54^\circ$) to the southwest. Resistant units such as the Cretaceous Frontier and

Mesaverde formations (Figure 3) form prominent east- to southeast-striking ridges. The majority of the northeast area of the map is underlain by the Mancos Shale, which forms highly eroded slopes and gullies.

Late Jurassic subduction of the Farallon Plate along the margin of western North America resulted in crustal thickening throughout what is now Nevada and western Utah (DeCelles, 2004). The load of the increased crustal thickness caused the development of a foreland basin, which, combined with rising sea-level, allowed marine waters to flood much of Utah creating the Sundance Seaway in the Jurassic and eventually led to the Cretaceous Interior Seaway (Figure 4) (Hintze and Kowallis, 2009). These Mesozoic units record the development of the North American Cordillera and the rise and fall of the Cretaceous Interior Seaway (Dickinson, 2004). This includes the seaway highstand that deposited Mancos Shale throughout much of eastern Utah.

As the Farallon Plate transitioned from high-angle to low-angle subduction, uplift extended eastward causing formations previously located in the foreland basin to be uplifted in the Uinta Mountain Range (Hintze and Kowallis, 2009; Blakey and Ranney, 2008). As the Uinta Mountains uplifted, the Uinta Basin formed to the south. These Tertiary deposits record the latter stages of Uinta uplift and were deposited as the mountain front retreated northward.

The Duchesne River Formation members (Brennan Basin Member, Dry Gulch Creek Member, Lapoint Member, and Starr Flat Member) can be mapped at this scale as separate units. This helps us to better understand their stratigraphic relationships and the evolution of the late stage basin fill on the northern fringes of the Uinta Basin. In the northeast part of the quadrangle, the Brennan Basin Member forms a high and prominent ridge where it is in contact with Cretaceous units. The Duchesne River Formation dips steeply ($\sim 15\text{-}20^\circ$) to the southwest near

this ridge and shallows basinward until it reaches the Walker Hollow Syncline axis where it flattens out and begins to dip shallowly ($\sim 1-4^\circ$) to the northeast. With the exception of the massive conglomerate beds found in the Brennan Basin Member and Starr Flat Member, much of the Duchesne River Formation consists of interbedded sandstone, siltstone, and volcanic ash. This lithology is responsible for the badlands topography that is prevalent through much of the quadrangle. The Bishop Conglomerate caps Little Mountain along the northern quadrangle boundary. This unit is essentially horizontal with no distinctive dip. It unconformably overlies the Starr Flat Member of the Duchesne River Formation. This unconformity is the Gilbert Peak erosion surface that has been observed on both the northern and southern flanks of the Uinta Mountains (Hansen, 1986a). In many locations, this unconformity along with the Bishop Conglomerate, which was deposited on the unconformity, forms a relatively flat, broad plain (Bradley 1936, Hansen 1986a). This surface and subsequent deposition of the Bishop Conglomerate may be a result of late Uinta Uplift. In the Vernal NW quadrangle, this surface is not easily identified, although on the southern flank of Little Mountain we have observed a distinct bench above the Starr Flat Member and below the Bishop Conglomerate. We suspect this to be the Gilbert Peak erosion surface.

The quadrangle also contains a variety of Quaternary surficial deposits. The Quaternary piedmont alluvium composed of resistant gravels cap many prominent buttes. Four different levels of piedmont alluvium have been identified indicating distinct periods of stabilization with intervening periods of downcutting and erosion. Quaternary landslide deposits are also found in abundance near outcrops of Bishop Conglomerate. The largest landslide deposit is located in the northeast near the quadrangle boundary where Bishop Conglomerate overlies the Mancos Shale. This single landslide deposit covers approximately 3 square miles. In the broad, flat valleys south

of Little Mountain, other alluvium deposits occur that contain a mixture of fine and coarse grains. The high gradient slopes are mantled in many locations by coarse-grained colluvial deposits. The modern drainages are the locations for the most recent alluvial deposits found in the quadrangle.

1.3 Mapping Methods

Map units were identified using descriptions in previously published maps (Haddox, 2015a, 2015b; Sprinkel, 2007; Haddox et al., 2010) as well as detailed descriptions from Anderson and Picard (1972). In areas where these descriptions didn't correlate with field observations, new unit descriptions and contacts were created relying on lithological differences including clast composition which was calculated from clast count tallies on well-exposed outcrops. For clast counts, an area of about 1 square meter was outlined in a chalk circle (Figure 5). Within that area, each clast over 2 cm in diameter (coarse gravel) was tallied and classified based on source rocks from the Uinta Mountains described in Table 1. Ash fall tuff beds within the Duchesne River Formation were sampled and dated using single crystal $^{40}\text{Ar}/^{39}\text{Ar}$ laser fusion techniques (Jensen, 2017). The locations of accessible geologic contacts were identified in the field and mapped on air photos. Contacts were refined using traces of distinct marker beds and topographic changes in Cardinal Systems VrTwo 3-D mapping software. VrTwo uses high resolution stereo photos that allow the user to clearly view the colors and topography. Map symbols were drawn directly on the 3-D surface. Bedding inclination was measured in the field or as a photogrammetric 3-point solution in VrTwo. Contacts, faults, and field measurements drawn on field maps were transferred to the VrTwo file, which was exported and edited using

ArcGIS software. Additional faults and the cross-section were interpreted using the surface geology and well logs (Plate 2, Table 2).

1.4 Lithology

1.4.1 Bedrock Units

Carmel Formation (Jc)

Exposure of the Jurassic Carmel Formation (Figure 3) is limited to a small area in the northeast corner of the quadrangle in Coal Mine Basin (Plate 1). Its highly erodible nature makes it difficult to distinguish from the surrounding alluvium deposits. The best outcrops are found in stream cuts where the red-brown, green-gray shale, siltstone, and sandstone is exposed forming highly erodible, shaley slopes. The formation is 45-107 meters thick. Due to the abundance of Quaternary deposits surrounding the Carmel Formation, no contacts with overlying and underlying Mesozoic formations were located.

Entrada Formation (Je), Stump Formation (Js), Morrison Formation (Km)

Although the Entrada, Stump, and Morrison formations are not exposed at the surface within the quadrangle, they are certainly present in the subsurface and contribute to a complete stratigraphic sequence. During the time that these formations were deposited the Sundance Seaway (Figure 4) retreated northward leaving a combination of shallow marine, sabkha, and eolian during deposition of the Entrada and Stump formations. As uplift continued to the west in the Nevadan Orogeny (Blakey and Ranney, 2008; Hintze and Kowallis, 2009) and the seaway retreated to the north, a broad terrestrial basin developed throughout much of Utah and Colorado. This Morrison Basin accommodated streams and rivers that flowed north-eastward from the

Nevadan Orogeny. The Morrison Formation contains paleosols and sandstone channels deposited in a broad floodplain.

Cedar Mountain Formation (Kc)

The upper gray member of the Cedar Mountain Formation (Figure 3) is exposed at the base of a ridge southwest of Coal Mine Basin (Plate 1). This unit can be identified by its light gray to grayish purple, slope-forming laminated mudstones with some interbedded sandstones. The formation also contains boulder-sized carbonate concretions that are present on the highly-weathered slopes. The upper contact is identified by appearance of a resistant sandstone above the last appearance of gray-laminated mudstone. The contact with the underlying Morrison Formation is not exposed in the quadrangle.

Dakota Sandstone (Kd)

The Dakota Sandstone (Figures 3 and 4) is a distinct ledge former outcropping on the north slope of the ridge to the southwest of Coal Mine Basin (Plate 1). It is a yellow, coarse-grained, poorly sorted pebble conglomerate and medium to coarse-grained sandstone with some interbedded, organic-rich mudstone. The sandstones and conglomerates are poorly sorted, poorly cemented, and friable with sub-angular to sub-rounded grains. Some parts of the formation are highly oxidized with a purple/reddish color. The coarsest beds are found near the lower contact. Sandstone and conglomeratic beds are typically 3-4 meters thick while interbedded with mudstone beds are a few centimeters thick. The formation has a measured thickness of 80-93 meters. The upper contact is marked by an abrupt change from a ledge-forming sandstone to the slope-forming laminated mudstone of the Mowry Shale.

Mowry Shale (Kmo)

The Mowry Shale (Figure 3) forms a gray slope near the top of the ridge to the southwest of Coal Mine Basin (Plate 1). It is composed of yellow to blue-gray, mostly laminated silica-rich mudstone with some siltstone. We observed that it contains layers of altered volcanic ash that may have visible biotite and feldspar phenocrysts. Gypsum is found throughout the formation especially near the lower contact. Fish scales become increasingly prevalent in the upper part of the formation. The measured thickness is 47 meters. The upper contact is marked by the transition of the slope-forming mudstone to the resistant, cliff-forming Frontier Sandstone.

Frontier Sandstone (Kf)

The Frontier Sandstone (Figure 3) caps the ridge to the southwest of coal miner basin (Plate 1). It is a resistant, cliff forming, white, yellow, or brown, medium to fine-grained, cross-bedded sandstone. It exhibits sub-rounded grains that coarsen upward through the formation. Iron-oxidation is present in many beds. Some disarticulated fossil shells are present. It has a measured thickness of 44 meters. The lower contact is marked by the transition of the slope-forming mudstone to the resistant, cliff-forming Frontier Sandstone. The upper contact to the south is a conformable contact marked by the transition from cliff-forming sandstone to slope forming marine shale.

Mancos Shale (Kms)

The Mancos Shale (Figures 3 and 4) is one of the more widespread units in the quadrangle, covering much of the northeast section. It is easily identified by abundant yellow to gray, slope-forming, marine shale. The unit is homogenous with very little lithological

variability. There are some minor beds of very fine-grained sandstone that are more resistant. It is also the thickest unit in the quadrangle being 1004-1502 meters thick. The upper contact is marked conformably by a transition from slope and valley forming marine shale to a resistant, ridge forming sandstone of the Mesaverde Formation. To the west this contact is abrupt. To the east the contact is gradational, with 1-2 meter beds of Mesaverde formation interbedded with marine shale. To the north, the upper contact is an unconformable contact where the slope forming shale abruptly ends and the conglomeratic Brennan Basin Member of the Duchesne River Formation begins.

Mesaverde Formation (Kmv)

The Mesaverde Formation (Figure 3) is located along a low ridge in the eastern part of the quadrangle (Plate 1). It is a ledge-forming, light-yellow, fine-grained, well-sorted sandstone with some interbedded mudstone. The unit is cross-bedded. In locations observed near Utah State Highway 121 it is saturated with tar. The upper contact is an angular unconformity with the Brennan Basin Member. An abrupt transition from fine-grained sandstone to conglomeratic beds occurs at this contact.

Duchesne River Formation

This is the most laterally extensive formation within the quadrangle covering approximately 2/3 of the area. It is formally subdivided into four members: Brennan Basin Member, Dry Gulch Creek Member, Lapoint Member, and Starr Flat Member. Recently, the formation has been studied by Sato et al. (2015a, 2015b). In this research, the authors identified

the lithofacies and accompanying depositional environments, paleocurrents, and sequence boundaries.

Brennan Basin Member (Tdb)

The Brennan Basin Member (Figure 3) extends southward from the northeast section of the quadrangle. In the northeast, it is primarily composed of a resistant alluvial fan conglomerate. This conglomerate has clasts predominately derived from the Madison Limestone with some Uinta Mountain Group clasts intermixed. There are also gray/white, coarse, lithic rich, cross-bedded sandstones and some reddish siltstones present within the conglomerate facies. The conglomerate transitions basinward into primarily gray to yellow sandstone with some red to brown siltstone. The unit is the thickest member of the Duchesne River Formation being 437-564 meters thick.

The unit generally fines upward, except in the conglomerate facies where it is coarse throughout. In the west, the upper contact is identified by a resistant, white sandstone as the uppermost bed of the Brennan Basin Member (Figure 6). Stratigraphically above this bed is the red siltstone of the Dry Gulch Creek Member. To the northeast, the Dry Gulch Creek Member transitions into a conglomerate that is indistinguishable from, and mapped as, the Brennan Basin Member putting the Brennan Basin Member in contact with the Lapoint Member where the contact is identified by a drastic change from conglomerate to the silt and ash-rich beds of the Lapoint Member. Eventually the Lapoint Member also transitions into a conglomerate that is the same as the Brennan Basin conglomerates and all three of the lower Duchesne River Formation members are then mapped as the Brennan Basin Member with the Starr Flat Member overlying it. Even this division is difficult because this then juxtaposes the Starr Flat Member

conglomerates atop the Brennan Basin Member conglomerates. In these areas, we used differences in clast composition between the two conglomerates to determine the location of the contact. Haddox (2005) noted in his map area to the north of the Vernal NW quadrangle that the steeply dipping Brennan Basin Member was truncated by the Starr Flat Member in an angular unconformity. However, in the Vernal NW quadrangle, the dips of the Brennan Basin Member and Starr Flat Member near this contact are similar, and only the marked change in clast composition (the Brennan Basin Member contains mostly Madison Limestone clasts while the Starr Flat Member typically contains more than 50% Uinta Mountain Group clasts) indicate an unconformable contact.

Dry Gulch Creek Member (Tdg)

The Dry Gulch Creek Member extends from the western boundary of the quadrangle to the east where it eventually merges into the conglomerates of the Brennan Basin Member near Twelvemile Wash. It can be distinguished from the Brennan Basin Member due to an increase in fine-grained rocks and an overall reddish color throughout the member. The member contains approximately 60% fine-grained siltstone and ash and 40% coarse-grained sandstone and minor pebble conglomerates (Figure 7). Sanidine we collected from a volcanic ash bed near the upper contact gave an $^{40}\text{Ar}/^{39}\text{Ar}$ single-crystal laser-probe age of 39.36 ± 0.15 .

We interpreted the upper contact with the Lapoint Member to be defined by the first prominent and laterally extensive ash bed of the Lapoint Member (Figure 8). This contact is easily traced from the western quadrangle boundary until it is covered by piedmont alluvium in the eastern part of the quadrangle. On the opposite side of the piedmont alluvium the prominent

ash of the Lapoint Member is directly in contact with the conglomeratic beds of the Brennan Basin Member. The unit is 0-150 meters thick.

Lapoint Member (Tdl)

This member is distinctive due its slope forming and ash rich nature. It is located in the central part of the map area, along Highway 121 in the west. It thins to the east and eventually pinches out completely near Twelvemile Wash. It is primarily a red-brown, purple-gray, green-gray mudstone and siltstone with relatively low abundance of coarser-grained rocks (10-20%). The exception is two prominent tongues of coarse-grained sandstone/conglomerate of the Starr Flat Member that interfinger with the Lapoint Member and thin basinward. Plagioclase we collected in the lower part of the member gave an $^{40}\text{Ar}/^{39}\text{Ar}$ single-crystal laser-probe age of 39.47 ± 0.16 Ma.

The lower contact is placed below the lowest prominent and laterally continuous ash bed and marks an increase in fine-grained rocks (≈ 80 -90%). The upper contact is interpreted as the first prominent coarse grained bed above the highest ash bed. While this description works, it is complicated by distinct tongues of coarse grained rocks that interfinger with the Lapoint Member (Figure 9). As such we define the contact as the transition from primarily interbedded ash and siltstone to at least 30% coarse grained rocks. In places where these criteria are not easily identified we marked the contact as gradational. The unit is 0-111 meters thick.

Starr Flat Member (Tds)

The Starr Flat Member is also the least laterally extensive of the Duchesne River Formation members within the quadrangle and is only found in close proximity to Little

Mountain. It consists of approximately 30-60% coarse-grained and 40-70% fine-grained rocks. It can be identified as red-brown, red-purple, yellow-gray interbedded siltstone, sandstone, and conglomerate. Coarse-grained deposits are primarily lighter colored conglomerates and form cliffs. The fine-grained rocks consist mostly of red-brown or red-purple silt. Within the quadrangle, the Starr Flat Member coarsens upward with interbedded fine- to coarse-grained sandstone, pebble conglomerates and siltstone at the lower contact and massive beds of cobble to boulder conglomerate with more minor amounts of interbedded siltstone near the upper contact.

The upper contact with the Bishop Conglomerate can be difficult to identify, as both are conglomerates of similar composition. The Bishop Conglomerate, however, is much more massive and has comparatively very little interbedded silt (Figure 10). The basal Bishop Conglomerate has an undulating surface above red silty beds (Figure 11), which shows evidence for an unconformity. Bedding inclination shows that the Starr Flat Member has a dip of 7-21° while the Bishop Conglomerate is virtually horizontal. This contact is identified by the angular unconformity above the uppermost red silty bed. The unit is 102-243 meters thick.

Bishop Conglomerate (Tb)

Capping many of the low peaks on both the north and south flank of the Uinta Mountains is the Bishop Conglomerate. Due to the resistant nature of the formation it creates an erosion resistant surface that holds up broad, relatively-flat surfaces and mesas along the flanks of the range below the main peaks of the Uinta Mountains. This is case in the Vernal NW quadrangle where the distinctive Little Mountain, standing high above surrounding features, is capped by this conglomerate.

Within the Vernal NW quadrangle, the Bishop Conglomerate is composed of light-gray, massive, clast supported cobble and boulder conglomerate with interbedded sandstone and minor amounts of siltstone unstructured. There are also common coarse-grained, lithic rich sandstones beds with sparse and laterally discontinuous fine grained beds observed. Clast sizes can range from pebble (1cm) to boulder (2-3 m) with abundant cobble-sized clasts (5-10 cm). Conglomerate clasts are composed of reddish-purple Uinta Mountain Group quartzite and gray Paleozoic limestone of the Madison Formation. The matrix is poorly sorted, coarse-grained, and lithic-rich. In other localities outside the quadrangle clast compositions show a normal unroofing sequence with younger, Paleozoic limestones at the base of the formation and the older, Precambrian Uinta Mountain Group clasts near the top. This sequence was not observed in the Vernal NW quadrangle.

In locations just north of the Vernal NW quadrangle, the Bishop Conglomerate overlies the silty Mancos Shale. As can be expected from dense resistant rocks in contact with weaker generally slope forming rocks, landslides develop. Multiple generations of landslides have been mapped in the Vernal NW and surrounding quadrangles that are associated with the Bishop Conglomerate and the weak Mesozoic units that underlie it (Bradfield and Kowallis, 2007; Haddox et al., 2010a; Hunt et al., 2017). The most massive landslide deposits are found on the east and west sides of Little Mountain where Bishop Conglomerate overlies Mancos Shale (Figure 12). There are also smaller landslide deposits where the Bishop Conglomerate is in contact with the Starr Flat Member of the Duchesne River Formation. The unit thickness is about 315 meters.

1.4.2 Quaternary Units

Numerous Quaternary aged surficial deposits were mapped within the quadrangle. These were labeled using Utah Geological Survey standards that can be found on other maps. With this labeling system, the first letter is Q denoting Quaternary age. The second letter is an indicator of depositional environment and can be divided into 4 categories that were mapped in the Vernal NW Quadrangle: alluvium, colluvium, mass-movement, and human-influenced. The third letter indicates with greater specificity the depositional environment or morphology. In cases where there are various deposits of very similar depositional environment and characteristics, a number is used to indicate the relative age. One mixed environment deposit was mapped in the quadrangle, mixed alluvium-colluvium. This is denoted using Qac to show that characteristics from both types of deposits are present.

Alluvium (Qa)

Alluvial deposits were the most common and widespread of the Quaternary units. General areas of alluvium (Qa) are described as unconsolidated silt and sand with lesser amounts of gravel. These are deposited in broad valleys, mature drainages, and low gradient slopes that are found in low-lying areas to the south of Little Mountain. The material is derived locally and is characteristic in color and grain-size of nearby bedrock units. There are many ephemeral drainages (Qal) radiating from Little Mountain. Due to the coarse nature of many bedrock units, these Qal units contain mostly pebbles, cobbles, and boulders with lesser amounts of silt and sand. They fine basinward, especially when in contact with other Qa units. Youngest stream alluvium (Qal₁) is deposited in active drainage channels. Older stream alluvium (Qal₂) has been incised 1- 4 meters by active drainages. Alluvial fan deposits (Qaf) can be identified by their

distinct fan shape located at the mouths of incised drainages. They are usually coarse-grained with unconsolidated pebbles to boulders. Smaller fan deposits can be fine-grained when derived from fine-grained units.

The most prominent of the Qa units are deposits of piedmont alluvium (Qap) than can be easily identified by their relatively flat, broad geomorphological character, their coarse-grained nature (cobbles and boulders), and their variable degree of post-depositional incision.

Throughout the southern part of the quadrangle the Qap units cap many prominent ridges and buttes. The deposits form steeper slopes and are less dissected closer to Little Mountain. The gravels exhibit a carbonate rind of varying maturity and in some places the clasts are somewhat consolidated. There are four levels of piedmont alluvium that have been identified (Table 1, Plate 2). Levels that have a greater elevation above local drainages are older and have been more incised. Level 1 piedmont alluvium (Qal₁) consist of sub angular clast supported gravel with some silt and sand 7-10 meters above the modern drainage. Clast count data we collected show that clasts consist of approximately 45% Uinta Mountain Group, 45% Madison Formation or other limestone, and 10% black or gray chert. Level 2 piedmont (Qal₂) is similar to Qal₁ in composition but is 22-37 meters above the modern drainage. Level 3 piedmont alluvium (Qap₃) is the most extensive throughout the quadrangle. It is located 46-100 meters above the modern drainage. The clasts are larger than those found in Qap₁ and Qap₃ with cobble to boulder-sized clasts that also have carbonate rinds. Clasts are approximately 50% Uinta Mountain Group, 50% Madison Formation or other limestone, with trace amounts of Weber Sandstone. Level 4 piedmont alluvium (Qap₄) is only found in northern part of the quadrangle, near Little Mountain. It is elevated 127- 151 meters above the modern drainage. The unit is boulder-rich with clasts up to 1 meter in diameter, largest of all Qap deposits. The clasts have a thick carbonate rind on the

bottom. While other Qap units are less than 5 meters thick, Qap₄ is up to 20 meters thick. Clasts consist of approximately 85% Uinta Mountain Group and 15% Madison Formation or other limestone. On the western flank of tar hill is another Qap unit with variable elevation above the modern drainage. Due to the variable elevation and unique source (not Little Mountain), this unit cannot be subdivided by relative age.

Colluvium

Colluvial deposits (Qc) are composed of unconsolidated silt, sand, and gravel that was derived locally and has been deposited by gravity on many of the high gradient slopes throughout the quadrangle. On slopes below conglomeratic units such as the Brennan Basin Member, Bishop Conglomerate or Qap units, the colluvium is gravel-rich and designated Qcg. On gullied slopes or near major drainages there appears to be a mixture of colluvial and alluvial material that is designated Qac.

Mass-Movement

Landslide deposits (Qms) form hummocky uneven topography commonly found below a landslide escarpment. Deposits are unconsolidated and poorly sorted. Most landslide deposits are located near or in contact with the Bishop Conglomerate and contains poorly sorted sediment with abundant cobbles-boulders. Due to its locations and compositions it is likely that landslide material is derived from the Bishop Conglomerate that caps Little Mountain. A large landslide deposit is located south-east of Little Mountain where Bishop Conglomerate and the Brennan Basin Member of the Duchesne River Formation are in contact with the clay-rich Mancos Shale.

Human-influenced

Although no residential locations are currently found within the quadrangle, there are still areas where surface geology has been altered by human activity for the purposes of resource extraction, road construction, and human waste treatment. Human modified mine deposits (Qhm) include Qap deposits that are mined for their gravel in pits along Utah State Road 121, tar pit mines in the Mesaverde Formation where the fine-grained sandstone is saturated with tar, and land modified near exposures of the Frontier Formation for coal mining. Other human modified deposits (Qh) include areas where land has been modified by oil and gas exploration wells, highway construction, and building of waste treatment ponds in Halfway Hollow.

1.5 Structures

Larger scale maps of the region (Sprinkel, 2007; Untermann and Untermann, 1964, 1968) show that two distinct fault systems (Figure 1), the Uinta Basin Boundary thrust fault and the Deep Creek fault zone, are located in areas near the Vernal NW quadrangle. In Sprinkel's 30' x 60' Vernal quadrangle the Uinta Basin Boundary reverse fault is mapped in the subsurface of the Vernal NW quadrangle while no other faults are mapped. Untermann and Untermann (1964, 1968) also show the Uinta Basin Boundary fault is present in the subsurface and the Deep Creek fault zone is shown extending into the eastern portion of the Vernal NW quadrangle. The Uinta Basin Boundary fault is a concealed, high-angle reverse fault that has up to 2500 meters of offset in Mesozoic formations with decreased offset in Tertiary formations (Stone, 1993). This fault offsets the Uinta Formation in the subsurface, evidenced by well 122Z1 Houston R (Sprinkel, 2007) and possibly extends into the lower Duchesne River Formation.

1.5.1 Folds

Parallel to the Uinta Basin Boundary fault is the Walker Hollow syncline axis. The Walker Hollow syncline is an asymmetrical syncline with the northern limb dipping steeply to the south and the southern limb dipping gently to the north. All bedrock units of the Vernal NW quadrangle are folded in this syncline. In its entirety, this syncline is over 50 km across and covers much of the Uinta Basin. The steeply dipping limb (up to 54°) is most prominent in the north-east section of the quadrangle where strike ridges and dip-slopes are formed along the resistant units of Frontier Sandstone, Mesaverde Formation, and the Brennan Basin Member. We located the syncline axis in the Vernal NW quadrangle within the Brennan Basin, Dry Gulch Creek, and Lapoint Members of the Duchesne River Formation (Plate 1). The Walker Hollow syncline axis trends east-west in the eastern part of the quadrangle then bends to the south as it nears the center (Plate 1). This structure is used to approximate the location of the Uinta Basin Boundary fault in the subsurface (Plate 2). A smaller-scale east-west trending monocline is located near the contact between the Dry Gulch Creek and Lapoint Members near the western margin of the quadrangle south of the Walker Hollow syncline where beds dipping at $1-2^{\circ}$ northward to south of the fold axis suddenly steepen to dip $18-35^{\circ}$ northward.

1.5.2 Faults

We identified five near vertical, small offset faults within the quadrangle. These faults were located at the surface, from well-logs, or inferred from offset beds. All five appear to have normal motion and their subsurface extent is unknown. The first is on the western quadrangle boundary near Utah State Highway 121 in the Dry Gulch Creek Member/ Lapoint Member Boundary (Plate 1). This fault is identified by about 13 meters of offset (down to the south) of

the prominent basal ash bed of the Lapoint Member (Figure 8). It trends east-west. The second fault is located on the northern quadrangle boundary where the Brennan Basin Member is in contact with Starr Flat Member (Figure 12). The two units are side by side, separated by a steep south-east trending ravine indicating that the Starr Flat Member has dropped down to the south-west relative to the Brennan Basin Member. The third fault is just east of fault 2. We did not identify this fault at the surface due to Quaternary cover, but discovered it from well data (Govt Shenandoah 1-x) (Plate 2, Table 2). The fourth fault is also located on the northern quadrangle boundary. This fault was mapped by Haddox et al. (2010a) and likely extends southeastward beneath alluvium deposits (Plate 1 and 2). The fifth fault is located west of the Coal Mine Basin ridge. Here the steeply dipping (20-37° SW) Cretaceous Frontier Formation is offset down to the south indicating another south-east-trending normal fault (Plate 1 and 2). It is likely that these faults are an extension of the Deep Creek fault zone described by Untermann and Untermann (1964, 1968). This northwest/southeast trending fault zone extends 20 km and was mapped in neighboring quadrangles including the Dutch John 30' x 60', Dry Fork 7.5', Steinaker 7.5', Lake Mountain 7.5', and Ice Cave Peak 7.5' quadrangles (Sprinkel, 2006; Haddox et al., 2010a, 2010b; Poduska, 2015; Hunt et al., 2017) (Figure 1). The Deep Creek Fault Zone is a series of many vertical or near vertical normal and oblique-slip faults that create horst-and-grabens or half-graben pairs. These faults exhibit variable offset that ranges from a few meters to 1500 meters (Haddox, 2005).

1.5.3 Cross section

Surface measurements, stratigraphic contacts, faults, and well data (Plate 2, Table 2) were used to constrain the cross section (Plate 2). Cross section (A-A') is from the northeast corner to

the southeast corner of the quadrangle (Plate 1) and goes to -500 meters of depth. Cross section (A-A') shows along dip structure of folded formations. The Uinta Basin Boundary thrust fault is drawn extending into the lower Duchesne River Formation, but not to the surface. This fault location is inferred from wells and seismic data published by Sprinkel (2007) and Stone (1993). Small offset normal faults are shown extending to unknown depths in the subsurface. Mesozoic and Paleozoic formations are dipping 45° SW. The Tertiary Wasatch, Green River, Uinta, and Duchesne River formations are shown onlapping onto an erosionally thinned Mesaverde Formation. These relationships are evidenced by formation tops recorded from dry wells (Plate 2, Table 2). The surface dip of the Brennan Basin Member in contact with Mancos Shale is 30° S-SW, suggesting that uplift along the Basin Boundary fault occurred during or after deposition of the Brennan Basin Member. Two different wells (Maeser Federal 1 and Federal 1-7) (Plate 2, Table 2) show repeated formations, suggesting a reverse fault with up to 1000 meters of offset. These two wells are over 2 km away from the cross section line, therefore their data was not included in this cross section (A-A').

1.6 Economic Resources

Currently the largest ongoing resource operation is the extraction of tar sands from the Mesaverde Formation. This unit only outcrops in the eastern part of the quadrangle, near Highway 121. Tar sand is an exposed petroleum reservoir rock that contains very viscous, crude oil (Blackett, 1996). The tar sands hosted in the Cretaceous Mesaverde Formation (Figure 3) are thought to be derived from oil-rich shales of the Green River Formation. Oil formed, moved, accumulated near the surface, and was then altered by ground water, air, and bacteria (Blackett, 1996). Another modern operation involves mining gravel from the Quaternary piedmont

alluvium deposits (Qap) along Highway 121. Currently there are no active operations involving oil or natural gas at depth. However, many test wells have been drilled in the quadrangle (Plate 2, Table 2), most of which are dry holes. Coal Miner Basin gets its name from coal that was mined from the Frontier Formation. Currently there are no active coal mining operations.

Chapter 2: Stratigraphic Relationships within the Duchesne River Formation and Bishop Conglomerate

2.1 Introduction

The Uinta Mountains, in northeastern Utah and northwestern Colorado, are a basement-cored uplift formed during the Laramide Orogeny that began in the late Cretaceous and continued until the middle Tertiary (Hansen, 1986b; Blakey, 2008; Hintze and Kowallis, 2009; Sprinkel, 2014). Minor contraction from moderate angle reverse faults in the lower crust resulted in flexural basins to the north and south of the mountain range (Figure 1) (DeCelles, 2004). The Vernal NW quadrangle is south of the Uinta Mountains (Figure 2) in the transition between uplifted region and basin. Here deposits which were emplaced in the later stages of uplift, onlap onto folded Cretaceous bedrock. This is an excellent location to explore the geometry of these late-stage basin fill deposits that are proximal to uplifted regions. These deposits are the Eocene Duchesne River Formation with its four members (Brennan Basin Member, Dry Gulch Creek Member, Lapoint Member, and Starr Flat Member) and the Oligocene Bishop Conglomerate.

Traditionally, the Bishop Conglomerate has been mapped separately from the Starr Flat Member (Untermann & Untermann, 1968; Sprinkel, 2007) with the exception of Rowley et al. (1985) who mapped both units as Bishop Conglomerate. Several researchers have also noted the similarities between the two units and have questioned whether there is a sufficient difference in lithology and age to warrant a division (Hansen, 1986; Bryant, 1989; Haddox, 2005; Sprinkel, 2006). To further complicate the issue, the older Brennan Basin Member, particularly proximal to the mountain front, also contains massive conglomerate beds similar to those found in the Starr Flat Member and the Bishop Conglomerate (Figure 3). Therefore, this study tackles three main questions:

1. How can the conglomerates of the Duchesne River Formation and Bishop Conglomerate be identified and distinguished from one another?
2. What do these formations and their associated conglomerates tell us about periods of uplift and quiescence of the Uinta Mountains during the late Eocene and Oligocene?
3. What are the chronostratigraphic relationships within the Duchesne River Formation and Bishop Conglomerate?

To answer these questions, we combined traditional geologic mapping with new $^{40}\text{Ar}/^{39}\text{Ar}$ ages and conglomerate clast composition data. Through these methods, we were able to identify stratigraphic changes in the portion of the Duchesne River Formation and Bishop Conglomerate proximal to the Uinta uplift. These changes and other evidences lead us to interpret uplift proximal stratigraphic contacts, locate chronostratigraphic boundaries, and find evidences of uplift events.

2.2 Tectonic Setting

The Uinta Mountains stand as the highest mountain range in Utah with peaks reaching up to 4000 meters in elevation. It can be difficult to imagine that these high mountains used to be the center of a deep basin. Prior to or near the start of the breakup of the supercontinent Rodinia, an episode of intracratonic rifting during the Neoproterozoic formed a basin in the current location of the Uinta Mountains and formed the Laurentian craton (Condie et al. 2001; Dehler et al., 2010). The accumulation of sediments from the Wyoming and midcontinental shields into this basin created the Neoproterozoic Uinta Mountain Group (Figure 13) (Ball et al., 1998; Mueller et al., 2007; Hintze and Kowallis, 2009; Dehler et al., 2010). Rifting produced a passive

margin where an elongate belt of thick sediment accumulated throughout present day Utah and Nevada (Stewart and Poole, 1974; Condie et al., 2001; Dickinson, 2004).

The middle Paleozoic into the Mesozoic was a period of accretion and contraction as subduction occurred along the active margin of Laurentia. This subduction and accretion lead to a long period of orogenic activity that produced the North American Cordillera (Figure 4) (Saleeby, 1983; Lawton, 1994; Dickinson, 2004). Uplift of the Antler highlands to the east contributed to a shallow marine setting that allowed for deposition of formations on a carbonate platform, such as the Mississippian Madison Limestone (Lawton, 1994; Smith et al., 2004; Katz et al. 2007; Hintze and Kowallis, 2009) (Figure 13).

From Middle Jurassic until the Late Cretaceous, northeast Utah was situated in the Sevier Orogenic foreland basin, which was sometimes subaerial and sometimes underwater, dividing Laurentia into two halves, with the Cordillera to the west and continental lowlands to the east (Lawton, 1994; Hintze and Kowallis, 2009). Throughout this time period, oceanic lithosphere subducted at a relatively steep angle producing a typical volcano-plutonic arc extending through Arizona, California, and Nevada (Cross, 1986; Livaccari and Perry, 1993; Lawton, 1994; Kowallis et al., 2001; Christiansen et al., 2015). This subduction caused crustal thickening to the east in the formation of a thin-skinned fold and thrust belt (DeCelles, 2004; DeCelles and Coogan, 2006). Sediment was shed from the uplifted highlands and was deposited in the foreland basin, creating the Jurassic Morrison Formation and Cretaceous Cedar Mountain Formation in a continental basin, and the Mancos Shale and Mesaverde Formation in a marine basin (Hettinger and Kirshbaum, 2002; Hintze and Kowallis, 2009) (Figure 3 and 4).

The end of the Cretaceous was marked by a break in volcanism (Cross and Pilger, 1982; Livaccari and Perry, 1993) caused by a change from steep to shallow subduction angle (Cross,

1986, Livaccari and Perry, 1993). This change, from a subducted aseismic ridge (Cross and Pilger, 1978; Cross, 1986) or oceanic plateau (Dickensen et al., 1988), resulted in an eastward migration of the Cordillera in the Laramide Orogeny at about 69 Ma (Cross, 1986). The Laramide Orogeny, with its characteristic basement-cored uplift, induced the rise of the Uinta Mountains. In the Uinta Mountains shortening occurred on moderate angle thrust faults, including the Uinta Basin Boundary thrust fault located in the subsurface of the Vernal NW quadrangle (Hansen, 1986b; Stone, 1993; Haddox, 2005; Sprinkel, 2007). Another distinguishing characteristic of the Laramide Orogeny is the abundant intermountain basins and lakes that record the rise and erosion of adjacent uplifts (Lawton, 2008; Hintze and Kowallis, 2009). Lake Green River formed at the start of the Eocene 55 Ma in the Uinta basin to the south of the Uinta Mountains (and in adjacent basins to the east and north), and persisted until late Eocene at about 42 Ma (Figure 4) (Hintze and Kowallis, 2009, Kelly et al., 2012). Eventually the lake filled with sediment and drainage was diverted southward (Hansen 1986a). Sedimentation continued after Lake Green River in the Uinta Basin with the Duchesne River Formation (Bryant et al., 1989). Uplift of Laramide Orogeny is said to cease between 40-45 Ma (Coney, 1972; Cross, 1986, Hintze and Kowallis, 2009). The termination of Laramide uplift is poorly constrained due to few features showing clear relationships with Laramide faults (Cross, 1986). This termination was caused by the subducting slab rolling back to an increased angle triggering renewed volcanism, known as the ignimbrite flareup, which swept southward from present day Montana at 54 Ma and ended in the southern Great Basin at about 20 Ma (Lipman et al., 1972; Humphreys, 1995; Best and Christiansen, 2013).

2.3 Previous Work

Anderson and Picard (1972, 1974) provided comprehensive stratigraphic studies of the Duchesne River Formation. They describe the variety of fluvial stratigraphy and give evidence to justify the formation's division into four members: Brennan Basin Member, Dry Gulch Creek Member, Lapoint Member, and Starr Flat Member. Anderson and Picard (1972, 1974) provide key information about each member, including: type section, distribution and thickness, lithology, facies, stratigraphic contacts, and age correlation based on fossil assemblages. They also give interpretations of depositional environment. In their 1974 paper, Anderson and Picard relate the deposition of the Duchesne River Formation to very latest of Laramide uplift terminating near the end of the Eocene

More recently, Sato and Chan (2015a, 2015b) have identified the facies of the Duchesne River Formation and divided these into 6 different facies associations: 1. amalgamated and braided fluvial channels, 2. extensive flood plain and stacked broad fluvial channels, 3. extensive flood plain and isolated small streams, 4. alluvial fan complex, 5. dry and wet flood plains and fluvial channels, and 6. lacustrine deposits. These facies interpretations were made from thirty-five measured sections, including five measured sections in the Vernal NW quadrangle. These facies were mapped to determine the regional facies architecture. Sato and Chan (2015a) note the existence of a fining upward sequence starting at the Brennan Basin Member with grain size decreasing until the Lapoint Member/ Starr Flat Member contact. They interpret the onset of these sequences to be caused by Uinta Mountain uplift which is responsible for the coarse nature of the Brennan Basin Member and the Starr Flat Member.

The Bishop Conglomerate was first described by Powell (1876) and is found on both the north and south flanks of the Uinta Mountains. The Bishop Conglomerate has been described by

Hansen (1986a) as a bajada complex deposited on top of the Gilbert Peak erosional surface, which formed from tectonic quiescence immediately following a period of uplift. This erosional surface is found on both flanks of the Uinta Mountains. He described the lithology as rather loosely cemented bouldery, cobbly conglomerate and coarse, poorly sorted, pebbly, friable sandstone. He interpreted the deposits as originating from debris flows, due to matrix supported clasts. Hansen also includes information about maximum clast size ranges outcrop localities and lateral extent. Hansen explains that deposition of the Bishop Conglomerate occurs on the Gilbert Peak erosion surface as a broad bajada. The opinion is shared between Hansen, Anderson and Picard (1972), Rowley et al. (1985), Bryant (1989), and Haddox (2005), and Sprinkel (2006, 2015) that the Starr Flat Member of the Duchesne River Formation may be the basinward equivalent of the Bishop Conglomerate.

2.4 Methods

Within the Vernal NW quadrangle, the criteria and characteristics developed by Anderson and Picard (1972) were used to identify the members of the Duchesne River Formation. These units were mapped at a 1:24,000 scale using aerial photos. In addition to field mapping, Cardinal Systems VrTwo 3D software was used to map all stratigraphic contacts, faults, and folds onto a 3D surface. This was accomplished using field maps, key marker beds, and topographic expression of the units in VrTwo. All contacts, faults, and folds were then exported to ESRI's ArcMap software where unit polygons, lines, faults, structures, and cross section lines were created. Bedding inclination was measured in the field or using three-point solutions within VrTwo.

In areas where previously described contacts did not correlate with field observation, newly defined contact and unit descriptions were needed. This was accomplished by relying on differences in color, grain size, bedding inclination, or clast composition. One stratigraphic section was measured at the Starr Flat Member/ Bishop Conglomerate contact to identify lithologic changes through the section. In conglomerate-rich areas, clast point counts were taken (Figure 14) to determine the source material (Figure 13) and unroofing signals (Colombo, 1994) of the conglomerate. At exposed conglomeratic outcrops, an area of about 1 square meter was outlined in a chalk circle (Figure 5). Within that area, each clast over 2 cm in diameter (coarse gravel) was tallied and classified based on source rocks from the Uinta Mountains described in Table 1. The 2-cm diameter criterion was used because clasts smaller than this were very difficult to classify. Tallied clasts were then used to determine the percentage of source material found at each outcrop. This percentage represents the number of clasts present and not the overall volume of clast material.

Samples of altered volcanic ash from the Lapoint Member (sample DRF-A) and Dry Gulch Creek Member (sample DRF-H) were collected. Plagioclase (DRF-A) and sanidine (DRF-H) grains were separated from these samples and dated using single crystal $^{40}\text{Ar}/^{39}\text{Ar}$ laser fusion techniques (Jensen, 2017) by Brian Jicha at the University of Wisconsin. These radiometric ages and others (Winkler, 1970; Damon, 1970; McDowell et al., 1974; Bryant et al. 1989; Kowallis et al., 2005; Kelly et al., 2012; Sprinkel, 2015; Sprinkel, unpublished; Kowallis, unpublished) were used to determine the chronostratigraphy of the Duchesne River Formation and Bishop Conglomerate in the Vernal NW quadrangle.

2.5 Results

2.5.1 Lithology

Identifying changes in lithology is an important part of locating stratigraphic contacts and interpreting uplift history. In addition to characterizing distinct facies in the Duchesne River Formation, Sato and Chan (2015a) describe two upward fining sequences within the formation. They explain the first sequence as beginning at the base of the Brennan Basin Member with braided river and some alluvial fan facies, the sequence then fines upward to the Lapoint Member which is dominated by floodplain/ lacustrine facies. The Lapoint/Starr Flat Member contact marks the onset of another cycle with braided river and alluvial fan facies once again. These observations hold true through much of the study area. However, the Starr Flat Member exhibits an overall coarsening upward with the coarsest beds near the Starr Flat Member/ Bishop Conglomerate contact. Within the Vernal NW quadrangle our observations also indicate a distinct lateral shift in facies. The north/northeastern part of the quadrangle contains bedding that dips up to 30° and is closest to the Uinta Mountains. Because these beds are more proximal to the uplift, the average grain size through the Duchesne River Formation Members is greater than in rocks found to the south/southwest (basinward) (Lawton, 1986). Also in the north/northeast the fine-grained facies that compose the Dry Gulch Creek and Lapoint Members appear to pinch out completely where alluvial fan conglomerates become the dominant facies (Figure 15). This lateral change in lithology led to a redefinition of stratigraphic contacts in uplift-proximal parts of the Vernal NW quadrangle (Table 2).

We identified the contacts described by Anderson and Picard (1972) throughout much of the basinward parts quadrangle. In uplift-proximal areas, new contact interpretations were required to subdivide predominantly coarse-grained units (Table 2). Here the predominantly fine-

grained and ash-rich Lapoint Member contains many resistant, coarse-sandstone and pebble conglomerate beds similar to those found in the Starr Flat Member. These coarse beds thin basinward until they terminate (Figures 9 and 15). Since volcanic ash beds were found stratigraphically above many coarse-grained beds, the contact was picked above the highest ash bed that marked an abrupt increase in coarse-grained rocks. In one location both the Dry Gulch Creek Member and the Lapoint Member pinch out completely placing the Brennan Basin Member in contact with the Starr Flat Member. This contact juxtaposes the two conglomeratic units. Here we used a marked change in clast composition (Table 3) to place the contact. We also observed that the Starr Flat Member contains more interbedded fine-grained rocks and has a smaller average clast size at its base than in the underlying Brennan Basin Member.

As mentioned, the Starr Flat Member/ Bishop Conglomerate contact has been questioned by other researchers (Bryant, 1989; Haddox, 2005; Sprinkel, 2007). The difficulty in distinguishing the two units is due to their similarities in conglomerate composition, sedimentary structures, as well as clast size and composition. However, across this contact a distinct color change from reddish brown to gray occurs (Figures 10 and 11). Close inspection reveals that the reddish-brown color is derived from abundant interbedded silt in the Starr Flat Member and the overlying Bishop Conglomerate has less silt. The contact also forms an angular unconformity between the two units. The Starr Flat Member dips 6-21° to the southwest, while the overlying Bishop Conglomerate is flat-lying.

2.5.2 Point Counts

We took the majority of point counts in the cobble/boulder conglomerates of the alluvial fan facies in the Brennan Basin Member, Starr Flat Member, and Bishop Conglomerate. We did

this to identify any unroofing patterns throughout these units (Table 3). The Brennan Basin Member contains 70-90% of Paleozoic clasts, especially Madison Limestone distinguished as a gray, fossil-rich limestone. Upward trends throughout the Brennan Basin Member reveal a slight increase in Precambrian Uinta Mountain Group clasts (Figure 15) made of purple or yellow quartz arenite. As mentioned, the contact between the Brennan Basin Member and Starr Flat Member is marked by a sharp increase in Uinta Mountain Group clasts. There are no notable differences in clast composition through the Starr Flat and Bishop Conglomerate (Figure 16); both are dominated by a relatively even distribution of Uinta Mountain Group and Madison Limestone. We also observed and counted pebble conglomerates from the braided river facies in the basinward Brennan Basin, Dry Gulch Creek, and Lapoint members (Table 3 and Figure 15). The basinward Brennan Basin Member has a similar composition as its uplift-proximal counterpart. The Dry Gulch Creek and Lapoint members exhibit clast composition assemblages similar to the uplift proximal Starr Flat Member, but with more stratigraphically unidentified chert. Madison Limestone contains black chert, which is included in the unidentified chert criteria (Table 1) Overall, chert quantities increase basinward.

2.5.3 Radiometric Ages

DRF-A was collected from a thin tuffaceous sandstone a few meters above the Brennan Basin Member/Lapoint Member contact near Little Mountain. This location is also close to where the Lapoint Member pinches out. DRF-H was collected near Utah State Route 121 a few meters below the prominent volcanic ash bed that marks the Dry Gulch Creek Member/ Lapoint Member contact. Thus, DRF-H is stratigraphically lower and older than DRF-A. Plagioclase from DRF-A returned an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 39.47 ± 0.16 Ma (Table 4). Sanidine from the older

bed (DRF-H) has an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 39.36 ± 0.15 Ma. The radiometric ages are inverted stratigraphically, but are within the stated uncertainties. These two samples were collected 10 km from each other, which makes the actual stratigraphic distance between them difficult to estimate. However, DRF-A is located a few meters above the stratigraphic contact and DRF-H is located a few meters below the stratigraphic contact, making it reasonable that the samples are separated by very little time. These ages are within the range of ages given by previous studies (McDowell et al., 1974; Hansen, 1981; Bryant et al., 1989; Sprinkel, 2015; Sprinkel, unpublished; Kowallis, unpublished). Two ash beds in the Bishop Conglomerate east of the Vernal NW quadrangle were collected and dated by Kowallis et al. (2005). The sample from the lower part of the Bishop Conglomerate on Diamond Mountain Plateau has an age of 34.03 ± 0.04 . The sample from the upper part of the Bishop Conglomerate on Yampa Plateau has an age of 30.54 ± 0.22 (Table 4).

2.6 Discussion

2.6.1 Significance of Clast Counts and Lithology

As described above, the Duchesne River Formation becomes coarser-grained closer to the mountain front. Within the Vernal NW quadrangle this means that all middle Tertiary deposits near Little Mountain contain abundant conglomerate beds as the fine-grained Dry Gulch Creek and Lapoint members pinch out (Figure 12). Although the lithologies are similar, there are still key differences that warrant unit divisions. In the conglomeratic facies of the Brennan Basin Member there is a slight upward increase in Precambrian Uinta Mountain Group clasts (Figure 15). This indicates that unroofing of the Uinta Mountain Group actively occurred during the deposition of this unit, yet Paleozoic rocks were still the primary-source material. An abrupt

increase in Uinta Mountain Group clasts occurs across the Brennan Basin Member/ Starr Flat Member contact. Paleozoic clasts are still present, so this increase cannot be due to a complete stripping of Paleozoic rocks in the source region. It is possible that this variation is due to changes in upstream drainage patterns such as stream capture or a sudden unroofing of the Uinta Mountain Group over a broader area. Another alternative is that the contact is unconformable and is associated with a temporary cessation of deposition. Haddox (2005) mentions the possibility of an intraformational angular unconformity separating the lower and upper Duchesne River Formation. No angular unconformity was observed in the Vernal NW quadrangle, but the possibility of an unconformity does exist. The large increase in Precambrian clasts across the contact suggests a possible tectonic event. An increase in silt and decrease in clast size at the Brennan Basin Member/ Starr Flat Member contact also indicates a decrease in gradient or energy during the deposition of the Starr Flat Member. There is a high percentage of Madison Limestone clasts in both the mountainward and basinward parts of the Brennan Basin Member; this indicates that the Brennan Basin Member (throughout the quadrangle) was deposited at a different time and stage of unroofing than the younger members. The basinward increase in red chert from the Round Valley Limestone and unidentified black chert (likely from the Madison Limestone) reflects the greater durability of the chert: it survives the longer transport while more of the limestone breaks down over the approximately 5 km of fluvial transport.

Clasts counts from the Dry Gulch Creek and Lapoint Members have similar compositions to the Starr Flat Member, but with more unidentified chert. This pattern implies that the Dry Gulch Creek and Lapoint Members are coeval to the lowest part Starr Flat Member and were deposited at the same stage of Uinta unroofing. In the case of the Lapoint Member, we observed an interfingering relationship with the Starr Flat Member, this gives further evidence of the coeval

nature of these two members proximal to the mountain front. The Dry Gulch Creek Member does not interfinger with the Starr Flat Member and is stratigraphically older than the Lapoint Member. Near the conglomeratic facies of the Brennan Basin Member, the contact is covered by Quaternary deposits. It is unclear why the Dry Gulch Creek Member pinches out. However, clast counts, which show a much higher percentage of Uinta Mountain Group, indicate that the Dry Gulch Creek Member was deposited at a later unroofing stage than the Brennan Basin Member. These patterns have not previously been documented. If these patterns hold to a widespread area, then that may indicate an uplift event.

Near the Starr Flat Member/Bishop Conglomerate contact, beds of Starr Flat Member are dipping as much as 21° while the overlying Bishop Conglomerate is horizontal. This angular unconformity suggests that there was significant uplift and erosion associated with displacement along the basin boundary fault after the deposition of the Starr Flat Member but before deposition of the Bishop Conglomerate. However, this uplift episode is not reflected in clast assemblages of these formations. Clast counts from the Starr Flat Member are very similar to those collected from the Bishop Conglomerate (Figure 16). In a locality near Weasel Point in the Lake Mountain quadrangle to the WNW of the Vernal NW quadrangle, we observed that the Bishop Conglomerate has mostly Paleozoic limestone clasts near its basal contact and shows an upward increase in Precambrian clasts. This pattern was not observed in the Vernal NW quadrangle. A plausible explanation for this is the drainage supplying sediment to the Starr Flat Member and Bishop Conglomerate in the Vernal NW quadrangle was more mature than the drainages feeding sediment to the deposits at Weasel Point.

2.6.2 Timing of Uplift and Deposition

The Duchesne River Formation represents a late-stage basin fill that occurred after the Uinta Basin was mature and had already been filled by thousands of meters of sediment of the Eocene Wasatch, Green River and Uinta formations, which were deposited north and south of the Uinta Mountains in Lake Green River 55 to 42 Ma (Sprinkel, 2007; Hintze and Kowallis, 2009, Kelly et al., 2012) (Figure 4). Ash layers from the Green River Formation exhibit similarities in composition and age to volcanic fields in Montana and Idaho (Smith and Carroll, 2003), indicating that slab roll-back was underway to north while the Uinta Mountains were still rising. After Lake Green River became infilled (Hansen, 1986a), sediment onlapped onto the Uinta mountain front. This onlap is indicated by the Brennan Basin Member being in angular contact (Plate 2) with both the Cretaceous Mesaverde Formation and Mancos Shale. These Cretaceous formations were deposited prior to Uinta uplift in the Cretaceous Interior Seaway. At this contact, the late Cretaceous Mesaverde Formation dips 44-54° SW, while the Eocene Brennan Basin Member dips 24-30° SW. This relationship suggests the late Cretaceous Mesaverde Formation was uplifted and erosionally stripped prior to the deposition of coarse-grained Brennan Basin Member. The coarser nature of Brennan Basin Member, which is younger than the finer-grained Uinta Formation located in the subsurface, gives evidence that it was deposited as a response to uplift as it onlapped onto folded Cretaceous bedrock.

Bryant et al. (1972) obtained low-resolution fission track ages (Figure 17) for the tuffs in the Brennan Basin Member; however, these data fail to constrain the age of this member at a resolution that can be achieved from other methods. The best constraint for age is from land mammal fauna. The first appearance of the Duchesnean land mammal fossils occurs in the lower Brennan Basin Member (Emry, 1981; Rasmussen et al., 1999; Kelly et al., 2012). $^{40}\text{Ar}/^{39}\text{Ar}$ ages

on tephra layers in California and Texas produce an age of ~41.4 Ma for the first appearance of the Duchesnean Fauna which gives a lower constraint on the Duchesne River Formation.

The drastic change in clast composition above the Brennan Basin Member likely indicates a change in drainage patterns or simply unroofing rather than an uplift event, since the general trend into Dry Gulch Creek and Lapoint member deposition is one of continuing upward fining. This upward fining sequence has no upward change in dip and suggests a period of tectonic quiescence. This shows that late-stage uplift in the Uinta Mountains occurred in distinct pulses. It would be interesting to see if other Laramide structures exhibit the same pattern of pulsed uplift to get an overall sense of the tectonic setting that existed as uplift terminated in the Laramide Orogeny. This tectonic lull allowed for sediment to fill the mountain-proximal portion of the basin and for the gradient to decrease over time leading to the fining upward sequence.

The best age constraints for the contact between the Dry Gulch Creek Member and Lapoint Member come from radiometric dates on the altered volcanic ash beds near this contact. Many studies have sampled and dated the prominent ash used as a marker for this contact (McDowell et al., 1974; Bryant et al., 1989; Kelly et al., 2012; Sprinkel, unpublished; Kowallis, unpublished). This ash is the most laterally extensive ash bed from in the Duchesne River Formation and forms a chronostratigraphic marker, however our attempts to sample and date this ash bed failed due to an absence of plagioclase grains. Samples of other thin ash layers (samples DRF-A and DRF-H) a few meters above and below this contact were collected and dated as part of this study. These new ages better constrain the contact to about 39.4 Ma. The compositions and ages of these ash layers are similar to volcanic fields in north-eastern Nevada (Jensen, 2017) suggesting that at 39.4 Ma the ignimbrite flareup had migrated southward to nearly the same latitude where the Uinta Mountains were still actively rising.

The Starr Flat Member represents the next pulse of uplift. This is indicated by the progradation of the member, composed of primarily alluvial fan facies. The angular unconformity observed by Haddox (2005) also provides evidence for this uplift episode. Unfortunately, there are no high-resolution ages from the Starr Flat Member so constraints on the timing of this period of uplift are difficult to determine. Volcanic ash beds are poorly preserved in the high-energy environment. The best constraint comes from Kelly et al. (2012) via Duchesnean land mammal fauna, which gives an upper constraint of the Starr Flat Member of ~37.9 Ma for the last appearance of Duchesnean fauna.

The approximately 4 Ma hiatus (37.92 Ma to 34.03 Ma) between the end of the Duchesnean fauna and a fairly precise age from a tuff low in the Bishop Conglomerate (Kowallis et al., 2005) indicates a significant unconformity between the two formations. This implication is strengthened by the observed angular nature of the unconformity (up to 21° difference) and the presence of the Gilbert Peak Erosional Surface (Hansen, 1986a). Uplift occurred along the Basin Boundary thrust fault, which resulted in warping of the Starr Flat Member and increased the gradient of the Uinta Mountain flanks so that the Gilbert Peak Erosion Surface could form. In the Vernal NW quadrangle, these evidences refute the notion that the Starr Flat Member and the Bishop Conglomerate are coeval and should be grouped as a single unit. Rather, they should continue to be mapped and described as separate units. We found no significant dip or evidence of tectonic deformation in the Bishop Conglomerate. The widespread Gilbert Peak Erosion Surface overlain by Bishop Conglomerate and the deformation of the Starr Flat Member provides evidence that Uinta Mountain uplift continued on the Basin Boundary Fault after 37.9 Ma, which approximates the end of deposition of the Starr Flat Member. Starr Flat Member deformation also shows a clear relationship with late activity on a Laramide fault. These

relationships show the termination of Laramide uplift in this region at an age that is later than the expected 45-40 Ma (Coney, 1972; Cross, 1986, Hintze and Kowallis, 2009). This late uplift age may be related to the unique east-west orientation of the Uinta Mountain Range in the primarily north-south oriented Cordillera. Slab roll back to the north and west created a rotating stress field which allowed for compressional stress to be accommodated in a north-south direction and continue shortening on the north-verging Uinta Basin Boundary fault.

The deposition of the Bishop Conglomerate on the Gilbert Peak Erosion Surface could perhaps provide evidence for a final pulse of uplift that continued in this region until 30 Ma as ages from Kowallis et al. (2005) indicate. However, the Bishop Conglomerate shows no clear relationship with Laramide structures and could have been caused by other factors such as climatic changes, changes in drainage patterns, or base level changes from regional uplift. One possibility is that slab roll back and the reintroduction of hot asthenosphere beneath continental lithosphere caused regional uplift. Another possibility is that isostatic rebound occurred as slab rollback decoupled the shallowly subducting oceanic plate from the overriding continental plate (Cross, 1986).

2.7 Conclusions

Throughout much of the quadrangle, Duchesne River Formation stratigraphic contacts closely match the descriptions given by Anderson and Picard (1972). Exceptions to this include the Lapoint Member/ Starr Flat Member contact and all contacts located near Little Mountain (uplift proximal). We observed an interfingering relationship between the Lapoint and Starr Flat members where the Lapoint Member eventually pinches out completely near Little Mountain. The Dry Gulch Creek Member also pinches out near Little Mountain. All Tertiary formations

near Little Mountain consist of primarily the alluvial fan facies with abundant conglomerates. In this region the Duchesne River Formation can be subdivided into two members. We called the conglomerate in the lower Duchesne River Formation the Brennan Basin Member. This member can be identified by a high percentage of Paleozoic limestone clasts. We called the conglomerate in the upper Duchesne River Formation the Starr Flat Member due to a much higher percentage of Precambrian clasts. The contact separating these Duchesne River Formation conglomerates is likely unconformable. Another unconformable contact exists between the Starr Flat Member and Bishop Conglomerate, although the clast compositions are similar. Clast compositions in uplift proximal outcrops and their downstream counterparts are similar.

The contacts described Anderson and Picard (1972) appear to be conformable and represent chronostratigraphic boundaries. The Duchesne River Formation contacts near Little Mountain do not represent chronostratigraphic boundaries but can still be defined from lithological differences. This pattern may also hold true to other uplift proximal deposits and can be mapped similarly.

We found clear evidence for three major uplift episodes with the possibility of a fourth regional episode in the Duchesne River Formation and Bishop Conglomerate. These are recorded in the Vernal NW quadrangle and correlate with later stages of the Laramide Orogeny. The first is recorded at the contact between Cretaceous units and the Brennan Basin Member and is evidenced by an angular unconformity (54° to 24°) and drastic change in depositional environment. This uplift occurred prior to 41.4 Ma. The second is recorded by the progradation of the alluvial fan facies of the Starr Flat Member and occurred between 39.4 and 37.9 Ma. The third is recorded at the Starr Flat Member/ Bishop Conglomerate contact and occurred between 37.9 and 34 Ma. This is evidenced by another significant angular unconformity ($7-21^{\circ}$ to

horizontal). The presence of the Bishop Conglomerate suggests a possible fourth and final uplift event which places the termination of Uinta Mountain uplift at about 30 Ma. The fourth episode shows no clear relationships with Laramide structures and may be the result of regional uplift.

Evidences of uplift also provide insight into the regional tectonic setting. Ash layer samples from the Dry Gulch Creek and Lapoint members show that Uinta uplift was occurring while slab rollback and the ignimbrite flareup had swept southward into north-eastern Nevada. Displacement on the Uinta Basin Boundary thrust fault warped the Starr Flat Member, giving evidence for Laramide uplift after 37.9 Ma. Thus, new clast count data, radiometric ages, and stratigraphic observations give new insights into the timing of deposition and uplift events of the Laramide Orogeny and provide a model that can be used to map and describe uplift proximal deposits elsewhere.

References Cited

- Andersen, D.W., and Picard, M.D., 1972, Stratigraphy of the Duchesne River Formation (Eocene-Oligocene?), northern Uinta Basin, northeastern Utah: *Bulletin-Utah Geological and Mineral Survey*, v. 97, p.29.
- Andersen, D.W., and Picard, M.D., 1974, Evolution of synorogenic clastic deposits in the intermontane Uinta Basin of Utah, in Dickinson, W.R., ed., *Tectonics and Sedimentation: SEPM Special Publication 22*, p. 167-189.
- Ball, T.T. and Farmer, G.L., 1998, Infilling history of a Neoproterozoic intracratonic basin: Nd isotope provenance studies of the Uinta Mountain Group, Western United States: *Precambrian Research*, v. 87, p. 1-18.
- Best, M.G., Christiansen, E.H., and Gromme, S., 2013, Introduction: The 36–18 Ma southern Great Basin, USA, ignimbrite province and flareup: Swarms of subduction-related supervolcanoes: *Geosphere*, v. 9, no. 2, p. 260–274.
- Blackett, R., 1996, Tar-sand resourced of the Uinta Basin, Utah: Utah Geological Survey, Open-file report 335. 122 p.
- Blakey, R., Ranney, W., 2008, *Ancient Landscapes of the Colorado Plateau: AZ, Grand Canyon Association*, 156 p.
- Bradley, W.H., 1936, Geomorphology of the north flank of the Uinta Mountains: U.S. Geological Survey Professional Paper 185-I, p. 163-204.
- Bradfield, T.D. and Kowallis, B.J., 2007, Pre-historic landslides on the southeast flank of the Uinta Mountains, Utah: characterization and causes, in Turner, A.K and Schuster, R.L., (eds.), *Landslides and Society*: Madison, WI, Omnipress, p. 644-653.
- Bryant, B., Naeser, C.W., Marvin, R.F., and Mehnert, H.H., 1989, Upper Cretaceous and Paleogene sedimentary rocks and isotopic ages of Paleogene Tuffs, Uinta Basin, Utah: U.S. Geological Survey Bulletin 1787, p. J1-J21.
- Christiansen, E.H., Kowallis, B.J., Dorais, M.J., Hart, G.L., Mills, C.N., Pickard, M. and Parks, E., 2015, The record of volcanism in the Brushy Basin Member of the Morrison Formation: Implications for the Late Jurassic of western North America: *Geological Society of America Special Papers*, 513, p. 399-439.
- Colombo, F., 1994, Normal and reverse unroofing sequences in syntectonic conglomerates as evidence of progressive basinward deformation: *Geology*, v. 22, p.235-238.
- Condie, K.C., Lee, D. and Farmer, G.L., 2001, Tectonic setting and provenance of the Neoproterozoic Uinta Mountain and Big Cottonwood groups, northern Utah: constraints from geochemistry, Nd isotopes, and detrital modes: *Sedimentary geology*, v. 141, p. 443-464.

- Cross, T.A., and Pilger, R.H., Jr, 1978, Tectonic controls of Late Cretaceous sedimentation, western interior, USA: *Nature*, v. 270, p. 653-657.
- Cross, T.A., and Pilger, R.H., Jr, 1982, Controls of subduction geometry, location of magmatic arcs, and tectonics of arc and back-arc regions: *Bulletin of the Geological Society of America*, v. 83, p. 545-562
- Cross, T.A., 1986, Tectonic controls of foreland basin subsidence and Laramide style deformation, western United States, *in* Allen, P. A., and Homewood, P., eds., *Foreland basins: International Association of Sedimentologists Special Publication 8*, p. 15-39.
- Coney, P. J., 1972, Cordilleran tectonics and North American plate motion: *American Journal of Science*, v. 272, p. 423-428.
- Damon, P.E., 1970, Correlation and chronology of ore deposits and volcanic rocks: Tucson, University of Arizona, U.S. Atomic Energy Commission Contract AT(11-1)-689, Annual Progress Report COO-689-130, 77 p.
- DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin, western U.S.A.: *American Journal of Science*, v. 304, p. 105-168.
- DeCelles, P.G., Coogan, J.C., 2006, Regional structure and kinematic history of the Sevier fold-and-thrust belt, central Utah: *Geological Society of America Bulletin*, v. 118, p. 841-864.
- Dehler, C.M., Fanning, C.M., Link, P.K., Kingsbury, E.M. and Rybczynski, D., 2010, Maximum depositional age and provenance of the Uinta Mountain Group and Big Cottonwood Formation, northern Utah: *Paleogeography of rifting western Laurentia: Geological Society of America Bulletin*, v. 122, p. 1686-1699.
- Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: *Geological Society of America Bulletin*, v. 100, p. 1023-1039.
- Dickinson, W.R., 2004, Evolution of the North American Cordillera: *Annual Review of Earth and Planetary Sciences*, v. 32, p. 13-45
- Emry, R. J., 1981, Additions to the mammalian fauna of the type Duchesnean, with comments on the status of the Duchesnean "Age": *Journal of Paleontology*, v. 55, p. 563-570.
- Haddox, D.A., 2005, Mapping and kinematic structural analysis of the Deep Creek Fault zone, south flank of the Uinta Mountains, near Vernal, Utah: M.S. Thesis, Brigham Young University, 126 p., 4 plates, scale 1:24,000.
- Haddox, D.A., Kowallis, B.J., and Sprinkel, D.A., 2010a, Geologic map of the Dry Fork quadrangle, Uintah County, Utah: *Utah Geological Survey Miscellaneous Publication 10-4* (1:24,000 scale).

- Haddox, D.A., Kowallis, B.J., and Sprinkel, D.A., 2010b, Geologic map of the Steinaker Reservoir quadrangle, Uintah County, Utah: Utah Geological Survey Miscellaneous Publication 10-3 (1:24,000 scale).
- Hansen, W.R., Carrara, P.E., and Rowley, P.D., 1981, Geologic map of the Crouse Reservoir quadrangle, Uintah and Daggett Counties, Utah: U.S. Geological Survey Quadrangle Map GQ-1554, scale 1:24,000
- Hansen, W. R., 1986a, Neogene tectonics and geomorphology of the eastern Uinta Mountains in Utah, Colorado, and Wyoming: U.S. Geological Survey Professional Paper 1356, 78 p.
- Hansen, W. R., 1986b, History of Faulting in the eastern Uinta Mountains, Colorado and Utah, *in* Stone, D.S., and Johnson, K.S., eds., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 5-17.
- Hintze, L.F., and Kowallis, B. J., 2009, Geologic History of Utah: Brigham Young University Geologic Studies Special Publication 9, 225 p.
- Hettinger, R.D., Kirschbaum, M.A., 2002, Stratigraphy of the upper Cretaceous Mancos Shale (upper part) and Mesaverde Group in the southern part of the Uinta and Piceance basins, Utah and Colorado: U.S. Geological Survey Geologic Investigation Series I-2764, 21 p.
- Humphreys, E.D., 1995, Post-Laramide removal of the Farallon slab, western United States: *Geology*, v. 23, no. 11, p. 987-990.
- Hunt, J.E., Kowallis, B.J., Sprinkel, D.A., May, S.B., and Bradfield, T.D., 2017, Geologic map of the Lake Mountain quadrangle, Uintah County, Utah: Utah Geological Survey Miscellaneous Publication (in press) (1:24,000 scale).
- Jensen, M.S., Webb, C.A., Kowallis, B.J., Christiansen, E.H., and Spinkel, D.A., 2017, $^{40}\text{Ar}/^{39}\text{Ar}$ ages, compositions, and likely source of fallout tuffs from the Duchene River Formation, northeastern Utah: Geological Society of America Abstracts with Programs, v. 49, n. 5.
- Katz, D.A.; Buoniconti, M.R., Montanez, I.P., Swart, P.K., Eberli, G.P., Smith, L.B., 2007, Timing and local perturbations to the carbon pool in the lower Mississippian Madison Limestone, Montana and Wyoming: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 256, p. 231-253.
- Kelly, T.S., Murphy, P.C., Walsh, S.L., 2012, New records of small mammals from the middle Eocene Duchesne River Formation, Utah, and their implications for the Uintan-Duchesnean North American land mammal age transition: *Paludicola*, v. 8, p. 208-251.
- Kinney, D.M., 1955, Geology of the Uinta River-Brush Creek area, Duchesne and Uintah-Counties, Utah: U.S. Geological Survey Bulletin 1007, 185 p.
- Kowallis, B.J., Christiansen, E.H., Deino, A.L., Zhang, C. and Everett, B.H., 2001, The record of Middle Jurassic volcanism in the Carmel and Temple Cap Formations of southwestern Utah: Geological Society of America Bulletin, v. 113, p. 373-387.

- Kowallis, B.J., Christiansen, E.H., Balls, E., Heizler, M.T., and Sprinkel, D.A, 2005, The Bishop Conglomerate ash beds, south flank of the Uinta Mountains, Utah: Are they pyroclastic fall beds from the Oligocene ignimbrites of western Utah and eastern Nevada?: Utah Geological Association Publication 33, p.131-145.
- Lawton, T.F., 1986, Compositional trends within a clastic wedge adjacent to a fold-thrust belt: Indianola Group, central Utah, U.S.A., *in* Allen, P. A., and Homewood, P., eds., Foreland basins: International Association of Sedimentologists Special Publication 8, p. 411– 423.
- Lawton, T.F., 1994, Tectonic setting of Mesozoic sedimentary basins, Rocky Mountain Region, United States, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., eds., Mesozoic Systems of the Rocky Mountain Region, USA, p. 1-26.
- Lawton, T. F., 2008, Laramide sedimentary basins, *in* Sedimentary Basins of the World: The Sedimentary Basins of the United States and Canada, vol. 5, edited by A. D. Miall, p. 429–450.
- Lipman, P.W., Prostka, H.J., Christiansen R.L., 1972, Cenozoic volcanism and plate-tectonic evolution of the Western United States. I. Early and Middle Cenozoic: Philosophical Transactions Royal Society of London, A. 271, p. 217-248.
- Livaccari, R.F., Perry, F.V., 1993, Isotopic evidence for preservation of Cordilleran lithospheric mantle during the Sevier-Laramide orogeny, western United States: *Geology*, v 21, n. 8, p. 719-722.
- McDowell, F.W., Wilson, J.A., and Clark, J., 1973, K-Ar dates for biotite from two paleontologically significant localities--Duchesne River Formation, Utah, and Chadron Formation, South Dakota: *Isochron/West*, v. 7, p. 11-12
- Poduska, G.J., 2015, Geologic mapping of Ice Cave Peak quadrangle, Uintah and Duchesne counties, Utah; with implications from mapping Laramide faults: M.S. thesis, Brigham Young University, Provo, Utah, 91 p. + map (1:24,000 scale).
- Powell, J. W., 1876, Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto: U.S. Geological and Geographical Survey of the Territories (Powell), 218 p.
- Rasmussen, D.T., Hamblin, A.H., and Tabrum, A.R., 1999, The mammals of the Eocene Duchesne River Formation, *in* Gillette, D. D., ed., Vertebrate Paleontology in Utah: Utah Geological Survey Miscellaneous Publication 99-1, p. 421-428.
- Rowley, P. D., Hansen, W. R., Tweto, Ogden, and Carrara, P.E., 1985, Geologic Map of the Vernal 1x2° quadrangle, Colorado, Utah, and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map 1-1526, 1 sheet, scale 1:250,000.
- Saleeby, J.B., 1983, Accretionary tectonics of the North American Cordillera: *Annual Review of Earth and Planetary Science*, v.15, p. 45-73.

- Sato, T., and Chan, M.A., 2015a, Fluvial facies architecture and sequence stratigraphy of the Tertiary Duchesne River Formation, Uinta Basin, Utah, U.S.A.: *Journal of Sedimentary Research*, v. 85, p. 1438-1454.
- Sato, T., and Chan, M.A., 2015b, Source-to-sink fluvial systems for sandstone reservoir exploration: example from the basal Brennan Basin Member of Tertiary Duchesne River Formation, Northern Uinta Basin, Utah: *Utah Geological Association Publication* 45.
- Smith, M.E., Singer, B. and Carroll, A., 2003, $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of the Eocene Green River Formation, Wyoming: *Geological Society of America Bulletin*, v. 115, n. 5, p.549-565.
- Smith, L.B., Eberli, G.P., Sonnenfeld, M., 2004, Sequence-stratigraphic and paleogeographic distribution of reservoir-quality dolomite, Madison Formation, Wyoming and Montana, in *Integration of outcrop and modern analogs in reservoir modeling: AAPG Memoir* 80, p. 67-92.
- Sprinkel, D.A., 2007, Interim Geologic Map of the Vernal 30' x 60' Quadrangle, Uintah and Duchesne Counties, Utah, and Moffat and Rio Blanco Counties, Colorado: *Utah Geological Survey Open-File-Report*, scale 1:100,000, 3 sheets.
- Sprinkel, D.A., 2006, Interim Geologic Map of the Dutch John 30' x 60' Quadrangle, Daggett and Uintah Counties Utah, Moffat County, Colorado, and Sweetwater County, Wyoming: *Utah Geological Survey Open-File-Report*, scale 1:100,000, 3 sheets.
- Sprinkel, D.A., 2014, The Uinta Mountains: a tale of two geographies and more: *Utah Geological Survey, Survey Notes*, v. 46, n. 3. p. 1-4.
- Sprinkel, D.A., 2015, Interim Geologic Map of the east part of the Duchesne 30' x 60' quadrangle, Duchesne and Wasatch Counties, Utah (Year 3): *Utah Geological Survey Open-File-Report*, scale 1:100,000, 3 sheets.
- Stewart, J.H., Poole, F.G., 1974, Lower Paleozoic and uppermost Precambrian cordilleran miogeocline, Great Basin, western United States: *Tectonics and Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication* 22, p. 28-57.
- Stone, D.S., 1993, Tectonic evolution of the Uinta Mountains: palinspastic restoration of a structural cross-section along longitude $109^{\circ}15'$, Utah: *Utah Geological Survey Miscellaneous Publication* 93-8, 19 p. 2 plates.
- Winkler, G.R., 1970, Sedimentology and geomorphic significance of the Bishop Conglomerate and Browns Park Formation, eastern Uinta Mountains, Utah, Colorado, and Wyoming: Salt Lake City, University of Utah, M.S. thesis, 115 p.
- Untermann, G.E., and Untermann, B.R., Kinney, D.M., 1964, Geologic Map of Uintah County, Utah: *Utah Geological Survey Map* M-16, scale 1:125,000, 2 plates.
- Untermann, G.E., and Untermann, B.R., 1968, Geology of Uintah County (with map supplement): *Utah Geological and Mineralogical Survey Bulletin* 72, 98 p.

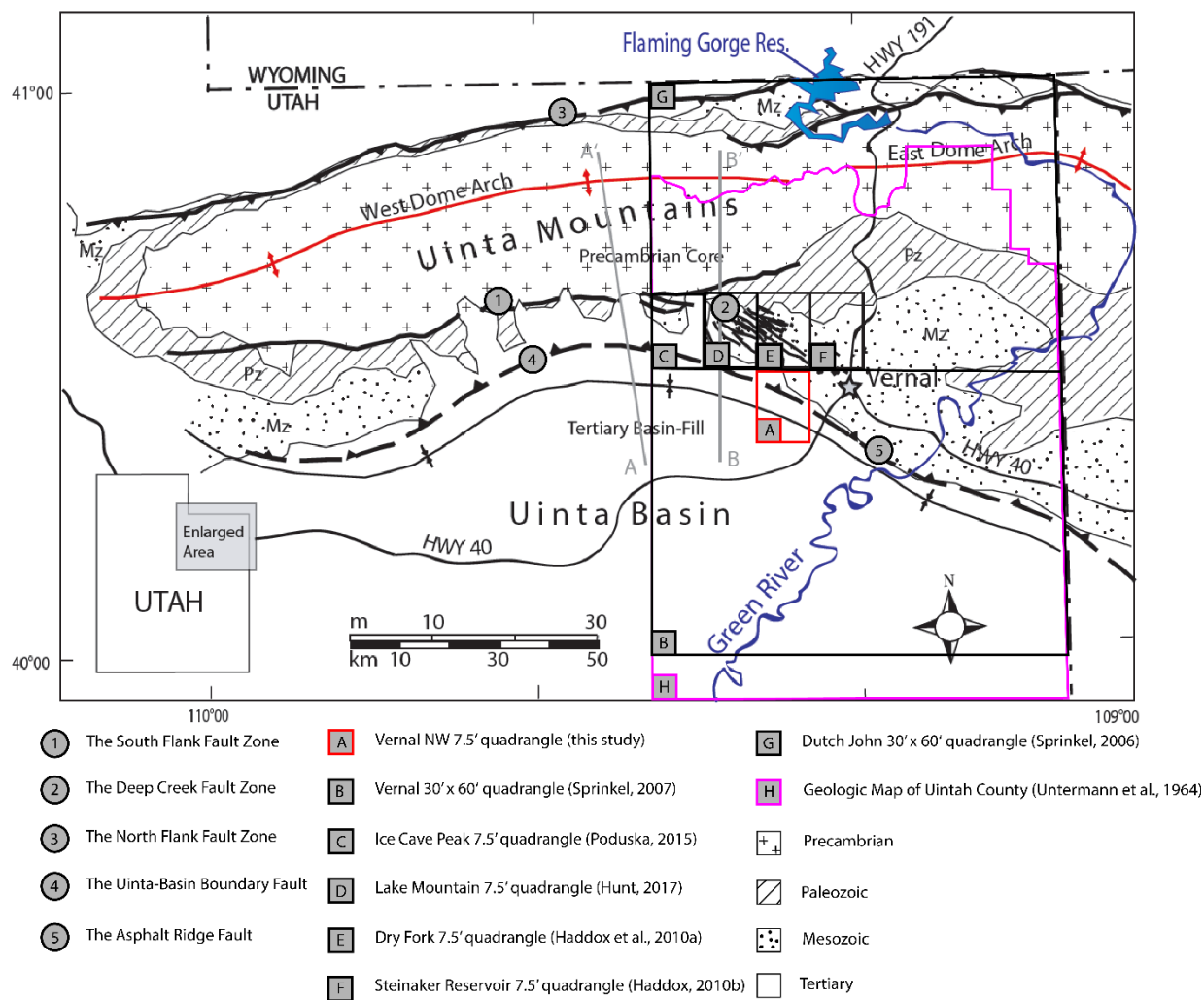


Figure 1. Simplified structural map of the Uinta Mountains showing previously published geologic maps near or overlapping the Vernal NW quadrangle.

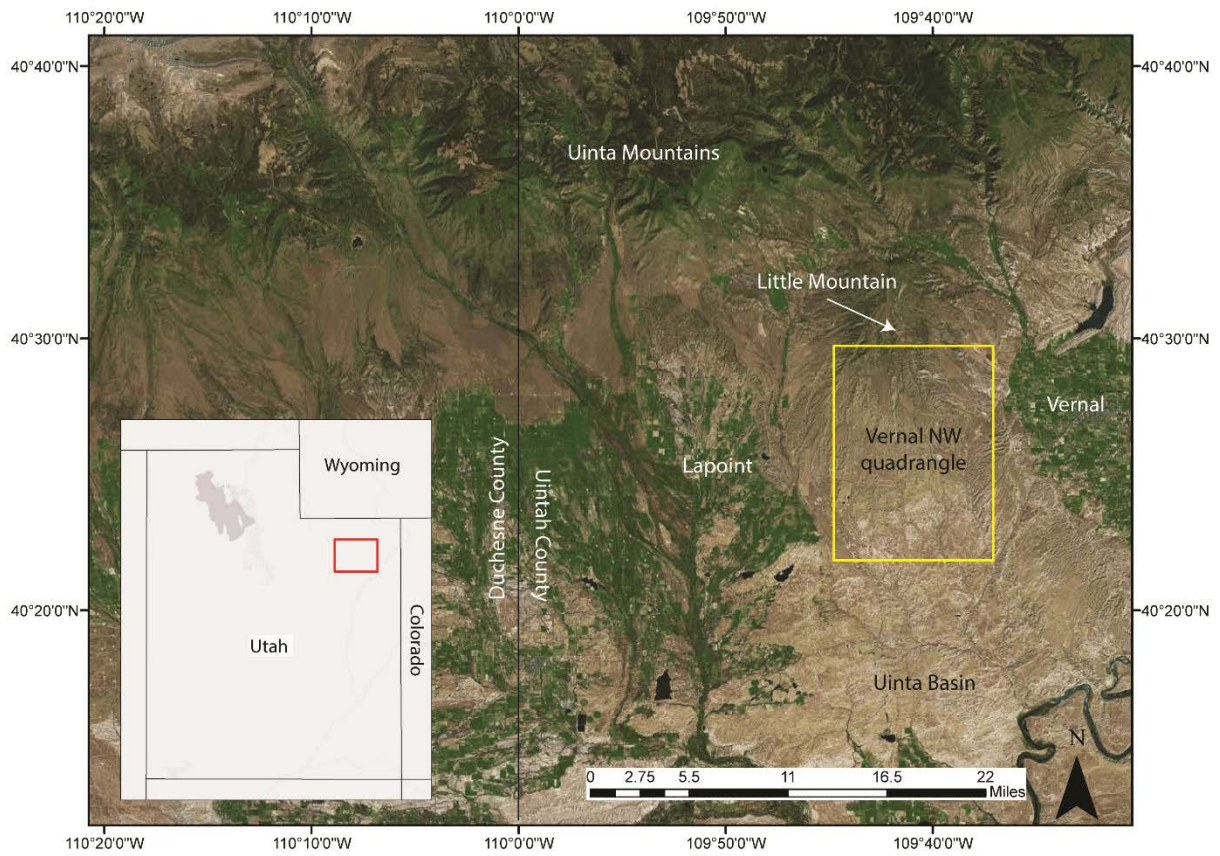


Figure 2. Index map showing the location of the Vernal NW with nearby cities and features.

Age	Formation		Symbol	Thickness m not to scale	Lithology	Notes
Quaternary	Unconsolidated deposits		Q*	less than 50		
Tertiary	Bishop Conglomerate		Tb	315		Massive conglomerate K-Ar age 34.03 ± 0.04 Ma Gilbert Peak Erosion Surface
	Duchesne River Formation	angular unconformity				
		Starr Flat Member	Tds	102 - 243		Interbedded conglomerate/ sand/ silt
		Lapoint Member	Tdl	0 - 111		Distinct sandstone tongues of Tds Prominent ash beds throughout
		Dry Gulch Creek Member	Tdd	0 - 150		$^{40}\text{Ar}/^{39}\text{Ar}$ age plagioclase 39.47 ± 0.16 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age sanidine 39.36 ± 0.15 Ma
Cretaceous	Brennan Basin Member		Tdb	437 - 564		Fan conglomerates grade southwestward to sandstone
	angular unconformity					
	Mesaverde Formation		Kmv	545		Tar sands Kmv grades into Kms
	Mancos Shale		Kms	1004 - 1502		
	Frontier Formation		Kf	44		Oysters Coal
	unconformity					
	Mowry Shale		Kmo	47		Fish scales Gypsum
Jurassic	Dakota Formation		Kd	80 - 93		
	unconformity					
	Cedar Mountain Formation		Kc	64		
	unconformity					
Jurassic	Morrison Formation		Km	158 - 198		These units are covered by Quaternary deposits and are not exposed at the sur- face within the Vernal NW Quadrangle
	unconformity					
	Stump Formation		Js	67 - 82		
	unconformity					
Jurassic	Entrada Formation		Je	49 - 66		
	Carmel Formation		Jc	45 - 107		

Figure 3. Stratigraphic column of formations exposed within the Vernal NW quadrangle. Thicknesses were measured in the field or calculated from the map using elevation, dip, and surface extent.

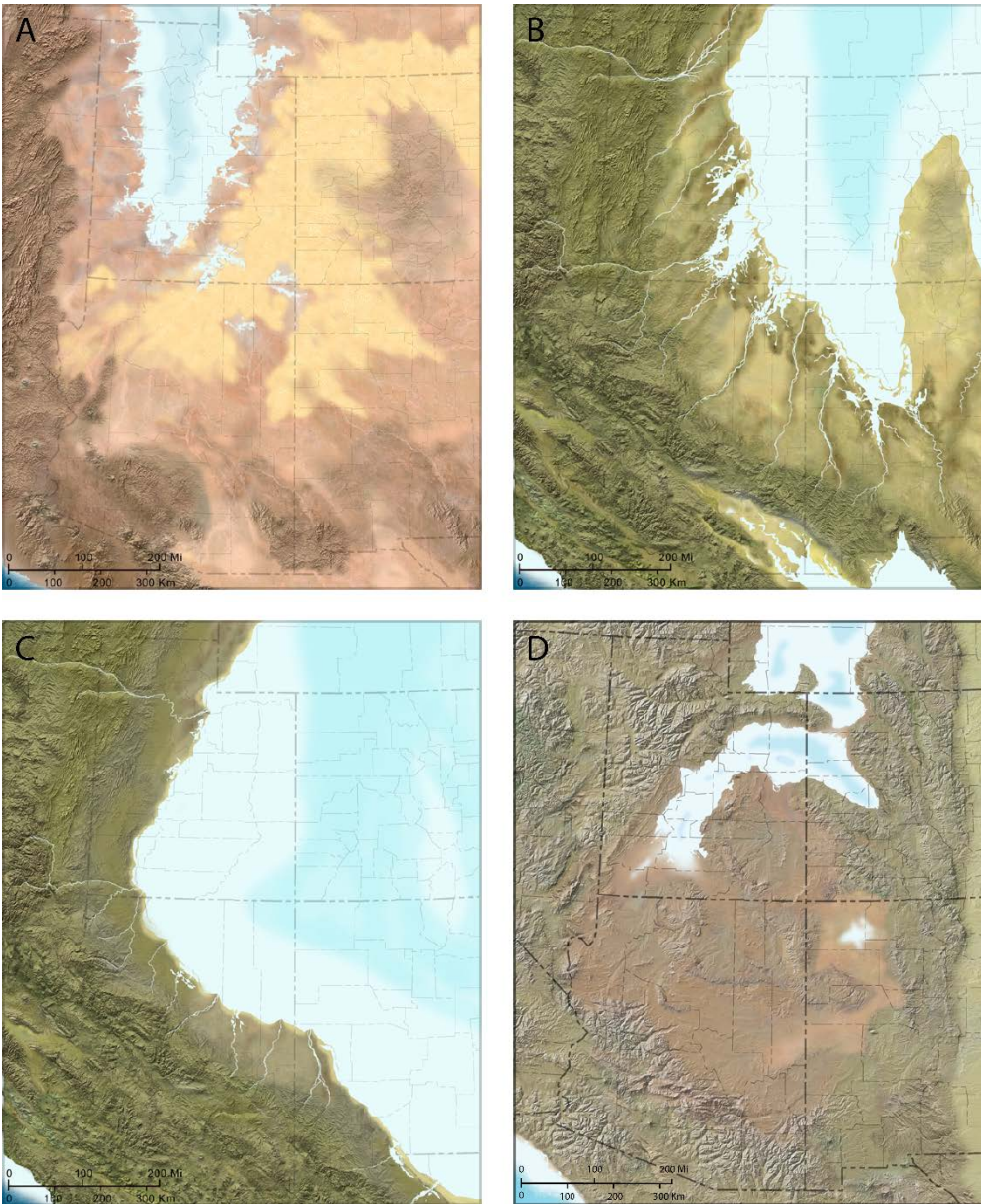


Figure 4. Paleogeography maps of the Colorado Plateau (Blakey and Raney, 2008). A. Middle Jurassic tectonic subsidence led to the incursion of the shallow Sundance Seaway. This seaway and proximal environments lead to the deposition of the Carmel Formation. B. In the early to middle Cretaceous the Sevier Highlands rose in Nevada and western Utah, developing a foreland basin to the east which became the Cretaceous Interior Seaway. The fluvial, floodplain, deltaic, and nearshore deposits are responsible for the stratigraphy of this time. C. The Cretaceous Interior Seaway reached its maximum transgression in the late Cretaceous, depositing the marine Mancos Shale. D. The Laramide Orogeny caused uplift to extend eastward in the Early Paleocene, creating the Uinta Mountains. This uplift lead to intermountain lakes which eventually became mostly infilled by the late Eocene previous to the deposition of the Duchesne River Formation.

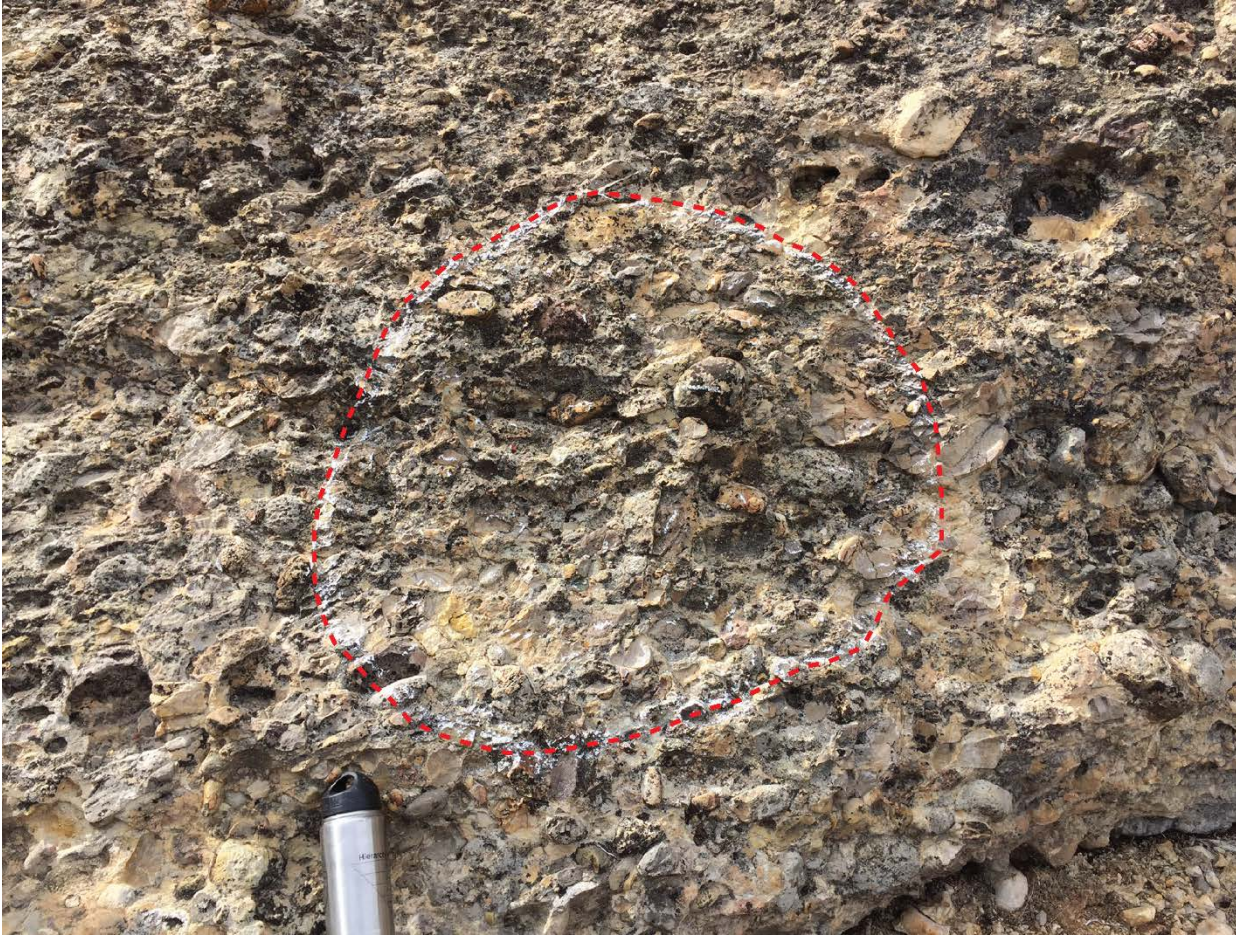


Figure 5. Photo of clast count circle within the Brennan Basin Member. All clasts larger than 2 cm in diameter within the circle were counted and classified based on table 1. Clasts smaller than 2 cm were not counted because the source material was much more difficult to determine. Water bottle used for scale is 10 cm wide.

Table 1. Clast Classification in Conglomerates

Name	Criteria
Uinta Mountain Group	purple or yellow quartzite arenite
Madison Limestone	gray, fossil-rich limestone
Round Valley Limestone	contains red chert
Weber Sandstone	well sorted, cross-bedded, medium to fine grained sandstone
Park City Formation	light colored, dolomitic, contains glauconite
Unidentified limestone	limestone, doesn't fit any other criteria
Unidentified chert	non-red chert

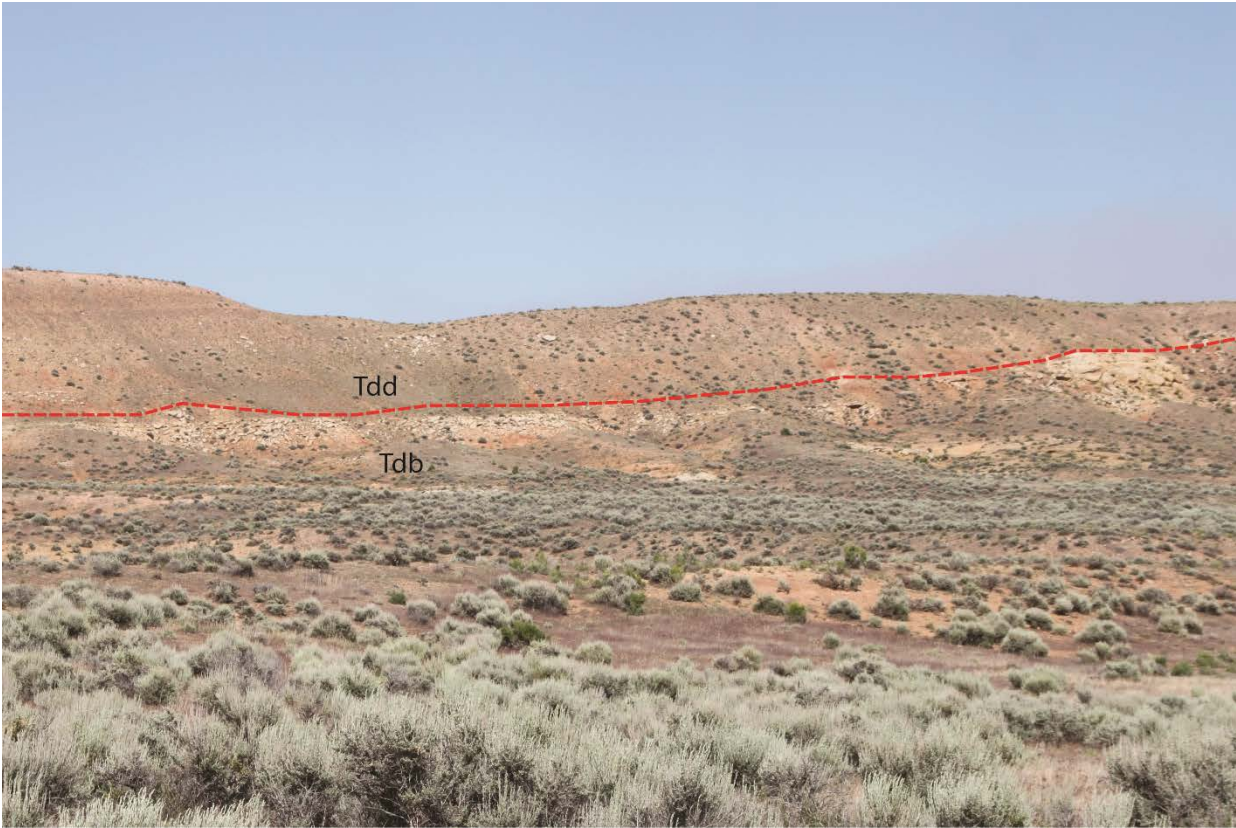


Figure 6. Brennan Basin Member (Tdb)/ Dry Gulch Creek Member (Tdd) contact in the southern part of the quadrangle. The contact is identified by the uppermost resistant sandstone of the Brennan Basin Member.



Figure 7. Exposure of the Dry Gulch Creek Member of the Duchesne River Formation showing the interbedded sandstone and siltstone with gray ash beds marked with a yellow dashed line.

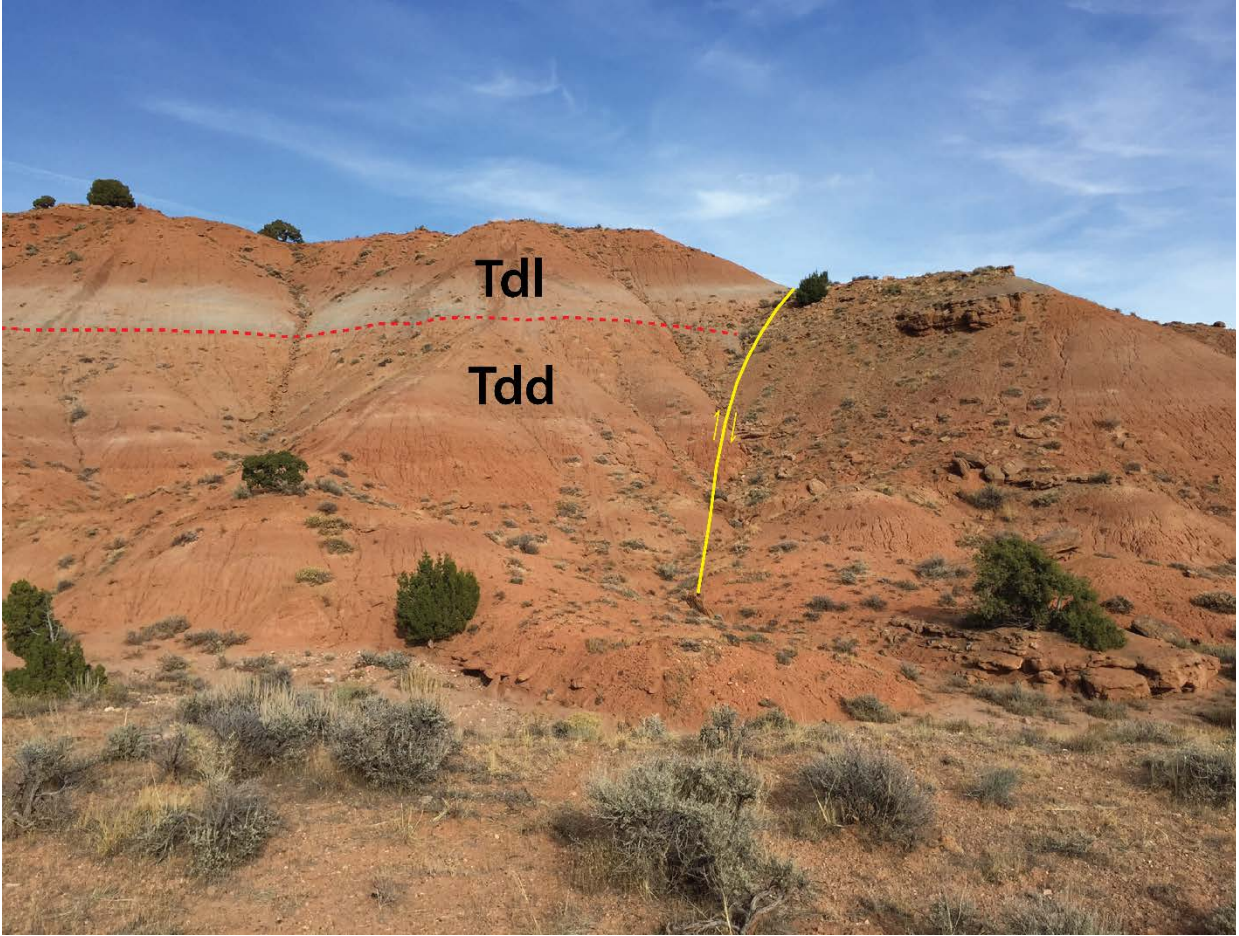


Figure 8. Lapoint Member (Tdl)/ Dry Gulch Creek Member (Tdd) contact. The base of the lowest prominent volcanic ash bed is used for the contact. Offset of the volcanic ash bed shows down drop on the small fault to the south. Photo location is just west of Halfway Hollow near Highway 121.



Figure 9. Lapoint Member (Tdl)/ Starr Flat Member (Tds) contact on the southern slope of Little Mountain. The upper Lapoint Member contact is marked by the highest laterally extensive ash fall tuff bed. The dashed yellow line shows the location of the contact where the ash bed terminates against a resistant conglomeratic bed that is characteristic of the Starr Flat Member. The contact continues below this coarse bed where it is in contact with a lower ash bed. This interfingering relationship is typical of the contact near the upwarped part of the Duchesne River Formation.



Figure 10. Starr Flat Member (Tds)/ Bishop Conglomerate (Tb) contact is shown by the red dashed line. The contact is easily identified from the abrupt change from reddish orange to yellow gray.

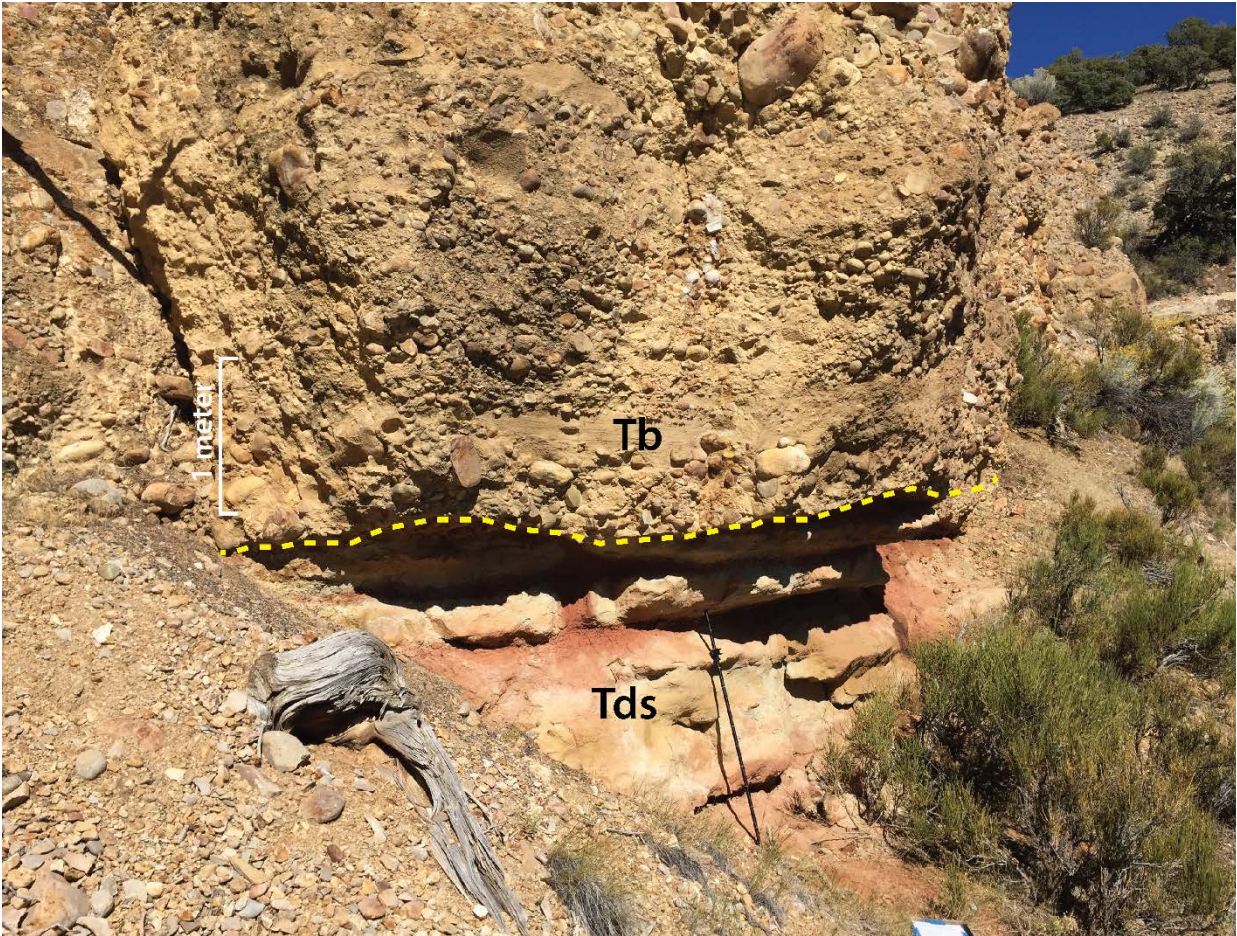


Figure 11. Close-up photo of the Starr Flat Member (Tds)/Bishop Conglomerate (Tb) contact. The contact is identified by the undulating, unconformable surface above interbedded conglomerate, sandstone, and red siltstone.

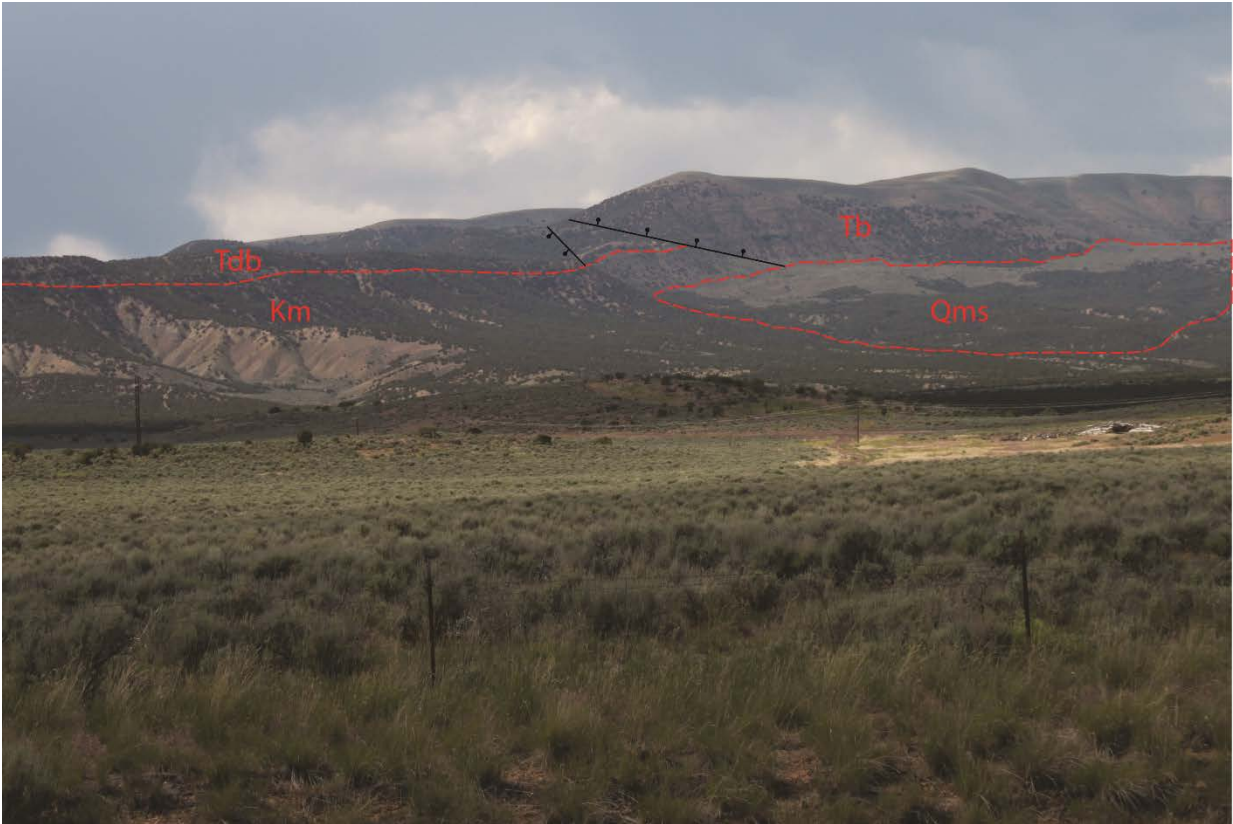


Figure 12. Photograph showing the location of faults and stratigraphic contacts on the eastern slope of Little Mountain. Qms- Landslide deposit, Tb- Bishop Conglomerate, Tdb- Brennan Basin Member, Km- Mancos Shale.

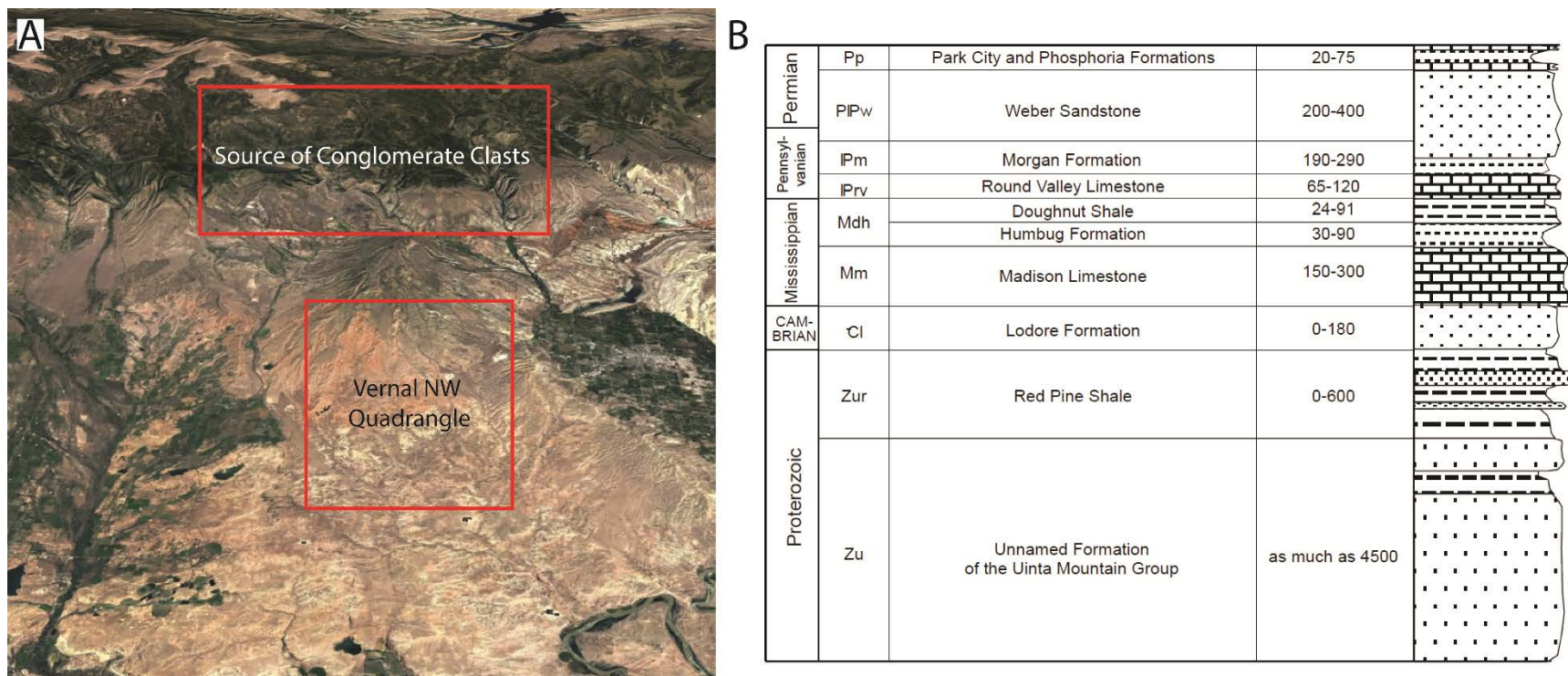


Figure 13. A) Google Earth image showing the location of the conglomerates studied within the Vernal NW quadrangle and the likely conglomerate clast source location in the Uinta Mountains. Image is taken from the south to give a sense of relief in the region. B) Stratigraphic column of Paleozoic and Proterozoic rocks within the Uinta Mountains. Clasts located within the Vernal NW quadrangle include: Weber Sandstone, Morgan Formation, Round Valley Limestone, Madison Limestone, and Uinta Mountain Group. Stratigraphic column was taken from Sprinkel (2006)

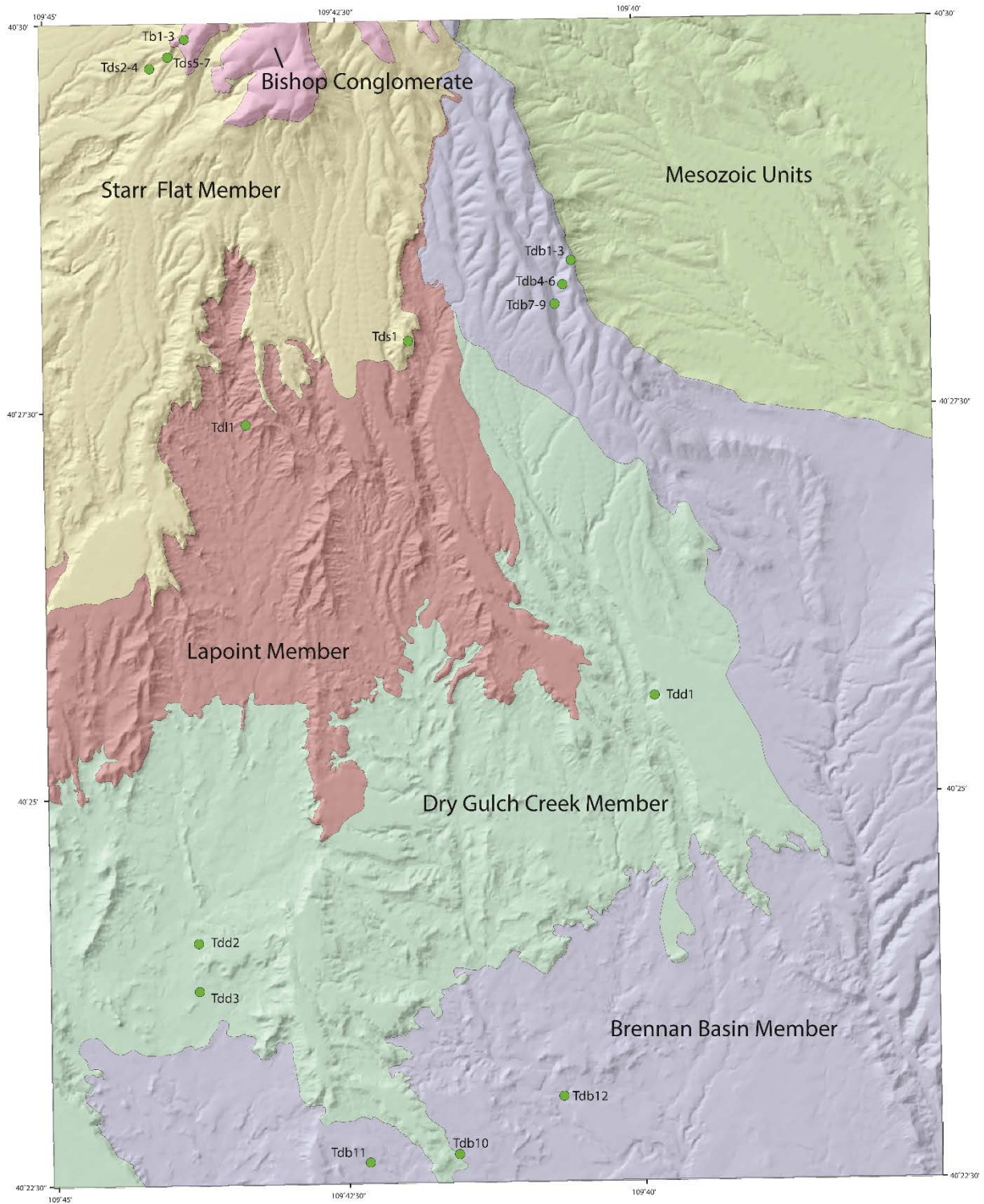


Figure 14. Simplified geologic map of the Vernal NW quadrangle with the locations of clast counts are shown in green. The Dry Gulch Creek and Lapoint members pinch out in the north-eastern region of the quadrangle.

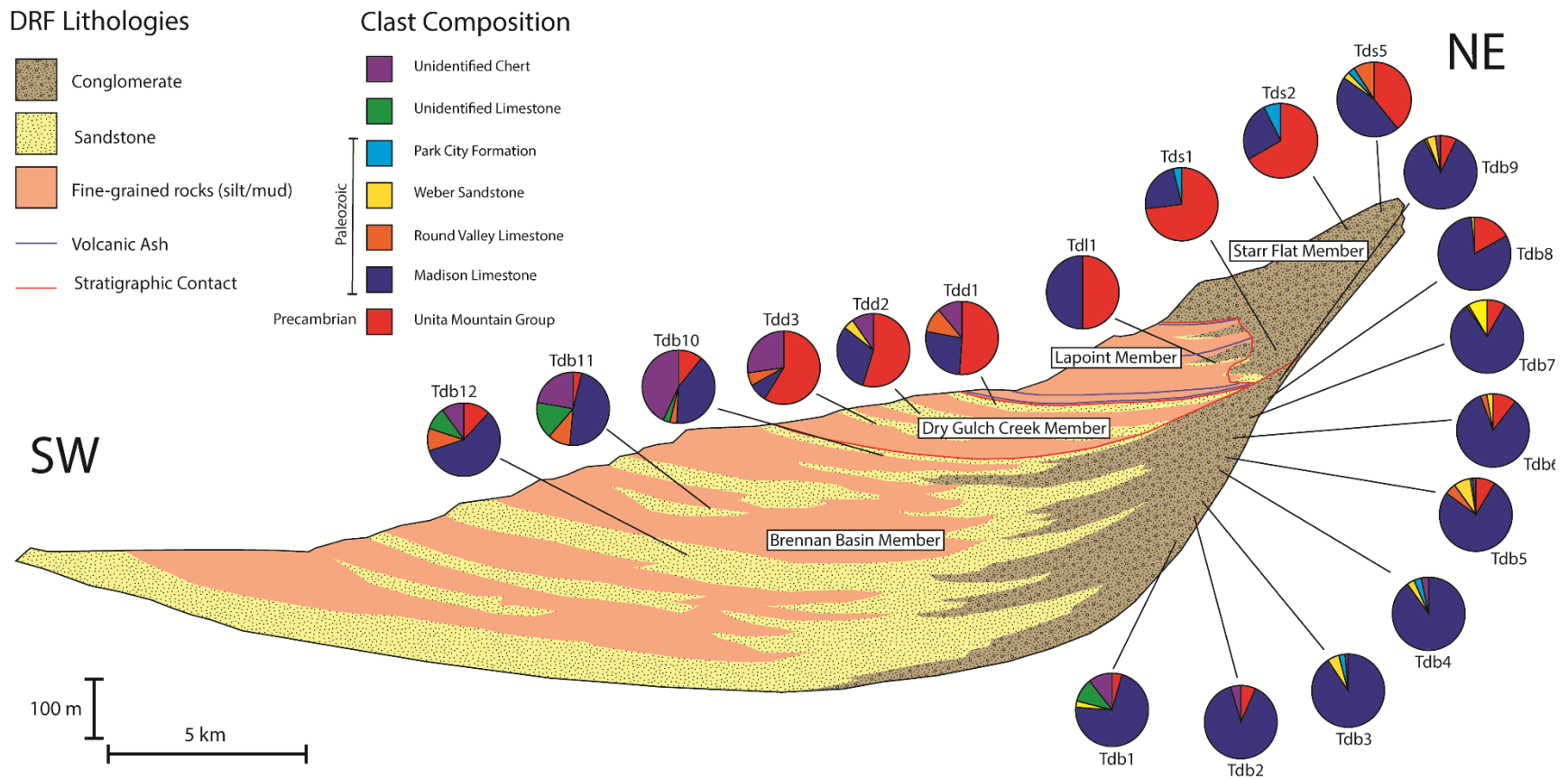


Figure 15. Schematic cross section of the Duchesne River Formation in the Vernal NW quadrangle, with conglomerate point count data shown in pie charts. Overall the formation coarsens to the northeast, where all members are conglomeratic. Clast counts show an upward increase in Uinta Mountain Group and decrease in Madison Limestone. Diagram was modified from Anderson and Picard (1974).

Table 2. Stratigraphic Contact Descriptions

Stratigraphic Contact	Anderson and Picard (1972)	This Study- Basinward	This Study- Uplift Proximal
Brennan Basin Member/ Dry Gulch Creek Member	Top of the highest resistant sandstone of the Brennan Basin Member. Increase in fine-grained rocks and reddish brown color.	Top of the highest light-colored resistant sandstone. Change from light to darker colored rock. Increase in fine-grained rocks.	This contact is covered by surficial deposits and wasn't observed.
Brennan Basin Member/ Lapoint Member	Not observed.	Not present.	The Dry Gulch Creek Member pinches out placing the Lapoint Member in contact with the Brennan Basin Member. The contact is the base of the lowest extensive, continuous, bentonitic bed of the Lapoint Member above the gray, conglomeratic beds of the Brennan Basin Member.
Brennan Basin Member/ Starr Flat Member	Not observed.	Not present.	The Lapoint Member pinches out placing the Starr Flat Member in contact with the Brennan Basin Member. The contact is an upward change in clast composition. The Brennan Basin Member contains primarily Paleozoic limestone clasts, while the Starr Flat contains majority Precambrian quartzite clasts. Increase in fine-grained rocks and color change from gray to reddish brown.
Dry Gulch Creek Member/ Lapoint Member	Base of the lowest extensive, continuous, bentonitic bed of the Lapoint Member.	Same as Anderson and Picard.	Not present
Lapoint Member/ Starr Flat Member	Base of the lowest reddish brown sandstone or conglomerate overlying the highest bentonitic claystone of the Lapoint Member.	Same as Anderson and Picard.	Same as Anderson and Picard. Due to the interfingering nature of the Lapoint and Starr Flat Members, marker beds are not laterally continuous. The contact is also marked by an abrupt upward increase in coarse-grained rocks.
Starr Flat Member/ Bishop Conglomerate	Erosional unconformity that can be identified by an abrupt upward decrease of consolidation. The Starr Flat Member is darker than overlying beds.	No contact present	Angular unconformity marked by a color change from reddish brown to gray. Decrease in fine-grained rocks.

Table 3. Point count data showing percentage of each clast type collected at different localities within each member.

Formation	Locality	Number	Uinta Mountain Group	Madison Limestone	Round Valley Limestone	Weber Sandstone	Park City Formation	Unidentified Limestone	Unidentified Chert
Bishop Conglomerate	Tb3	25	0.44	0.40	0.00	0.04	0.08	0.04	0.00
Bishop Conglomerate	Tb2	31	0.45	0.45	0.00	0.00	0.03	0.06	0.00
Bishop Conglomerate	Tb1	37	0.43	0.30	0.00	0.03	0.14	0.11	0.00
Starr Flat Member	Tds7	33	0.39	0.45	0.00	0.03	0.09	0.03	0.00
Starr Flat Member	Tds6	40	0.68	0.28	0.00	0.00	0.03	0.03	0.00
Starr Flat Member	Tds5	33	0.55	0.33	0.00	0.03	0.03	0.06	0.00
Starr Flat Member	Tds4	43	0.65	0.33	0.00	0.00	0.02	0.00	0.00
Starr Flat Member	Tds3	32	0.34	0.63	0.00	0.00	0.03	0.00	0.00
Starr Flat Member	Tds2	27	0.67	0.26	0.00	0.00	0.07	0.00	0.00
Lapoint Member	Tds1	26	0.73	0.23	0.00	0.00	0.04	0.00	0.00
Dry Gulch Creek Member	Tdl1	46	0.50	0.00	0.00	0.00	0.00	0.50	0.00
Dry Gulch Creek Member	Tdd2	84	0.55	0.31	0.00	0.05	0.00	0.00	0.10
Dry Gulch Creek Member	Tdd1	45	0.51	0.27	0.11	0.00	0.00	0.00	0.11
Dry Gulch Creek Member	Tdd3	51	0.59	0.08	0.00	0.00	0.00	0.06	0.27
Brennan Basin Member	Tdb12	59	0.12	0.58	0.10	0.00	0.00	0.10	0.10
Brennan Basin Member	Tdb11	49	0.04	0.47	0.10	0.00	0.00	0.16	0.22
Brennan Basin Member	Tdb10	70	0.11	0.40	0.03	0.00	0.00	0.03	0.43
Brennan Basin Member	Tdb9	96	0.07	0.85	0.01	0.04	0.02	0.00	0.00
Brennan Basin Member	Tdb8	76	0.17	0.82	0.00	0.01	0.00	0.00	0.00
Brennan Basin Member	Tdb7	93	0.09	0.82	0.01	0.09	0.00	0.00	0.00
Brennan Basin Member	Tdb6	37	0.11	0.84	0.03	0.03	0.00	0.00	0.00
Brennan Basin Member	Tdb5	80	0.09	0.76	0.05	0.08	0.01	0.00	0.01
Brennan Basin Member	Tdb4	61	0.00	0.90	0.00	0.03	0.03	0.00	0.03
Brennan Basin Member	Tdb3	75	0.00	0.91	0.00	0.05	0.03	0.00	0.01
Brennan Basin Member	Tdb2	45	0.07	0.89	0.00	0.00	0.00	0.00	0.04
Brennan Basin Member	Tdb1	67	0.04	0.72	0.00	0.03	0.00	0.10	0.10

Table 4. Age data compilation for Duchesne River Formation and Bishop Conglomerate.

Study Source	Age (Ma)	Formation	Method	Quadrangle
This Study	39.47 ± 0.16	Lapoint Member	40Ar/39Ar, plagioclase	Vernal NW
This Study	39.36 ± 0.15	Dry Gulch Creek Member	40Ar/39Ar, sanidine	Vernal NW
Hansen et al. (1981)	29.58 ± 0.86	Bishop Conglomerate	K-Ar, hornblende	Blair Basin
Hansen et al. (1981)	29.50 ± 1.08	Bishop Conglomerate	K-Ar, biotite	Blair Basin
Winkler (1970), Damon (1970)	26.2 ± 0.7	Bishop Conglomerate	K-Ar, biotite	Blair Basin
Winkler (1970), Damon (1970)	41.3 ± 1.1	Bishop Conglomerate	K-Ar, biotite	Stuntz Reservoir
Kowallis et al. (2005)	30.54 ± 0.22	Bishop Conglomerate	⁴⁰ Ar/ ³⁹ Ar, sanidine	Jensen Ridge
Kowallis et al. (2005)	34.03 ± 0.04	Bishop Conglomerate	⁴⁰ Ar/ ³⁹ Ar, sanidine	Stuntz Reservoir
McDowell et al. (1974)	40.3 ± ?	Lapoint Member	K-Ar, biotite	?
Sprinkel (unpublished)	39.24 ± 1.79	Lapoint Member	U-Pb, zircon	Vernal NW
Kowallis (unpublished)	41.52 ± 0.13	Lapoint Member	⁴⁰ Ar/ ³⁹ Ar, biotite	Lapoint
Kowallis (unpublished)	41.53 ± 0.61	Lapoint Member	⁴⁰ Ar/ ³⁹ Ar, biotite	Lapoint
Kowallis (unpublished)	41.10 ± 0.32	Brennan Basin	⁴⁰ Ar/ ³⁹ Ar, biotite	Lake Mountain
Sprinkel (2015)	40.66 ± 1.9	Brennan Basin	U-Pb, zircon	Hancock Cove
Kelly et al. (2012)	41.4 ± ?	Brennan Basin	Duchesnean Fauna	Vernal NW, Vernal SW
Kelly et al. (2012)	40.26 ± .08	Lapoint Member	⁴⁰ Ar/ ³⁹ Ar, biotite	Vernal NW or Lapoint
Kelly et al. (2012)	37.92 ± ?	Starr Flat Member	Duchesnean Fauna	?
Bryant et. Al (1989)	30.4 ± 3.0	Duchesne River Formation (undivided)	Fission-track, zircon	Strawberry Reservoir NW
Bryant et. Al (1989)	30.6 ± 1.5	Duchesne River Formation (undivided)	Fission-track, zircon	Blacktail Mountain
Bryant et. Al (1989)	33.6 ± 3.1	Duchesne River Formation (undivided)	Fission-track, zircon	Dry Mountain
Bryant et. Al (1989)	37.2 ± 1.7	Duchesne River Formation (undivided)	Fission-track, zircon	Farm Creek Peak
Bryant et. Al (1989)	38.2 ± 1.8	Duchesne River Formation (undivided)	Fission-track, zircon	Farm Creek Peak
Bryant et. Al (1989)	30.0 ± 1.5	Starr Flat Member	Fission-track, zircon	Kidney Lake
Bryant et. Al (1989)	34.0 ± 1.7	Starr Flat Member	Fission-track, zircon	Kidney Lake
Bryant et. Al (1989)	30.5 ± 1.4	Starr Flat Member	Fission-track, zircon	Ice Cave Peak
Bryant et. Al (1989)	30.9 ± 3.1	Starr Flat Member	Fission-track, zircon	Pole Creek Cave
Bryant et. Al (1989)	32.2 ± 2.8	Starr Flat Member	Fission-track, zircon	Neola

Table 4 cont. Age data compilation for Duchesne River Formation and Bishop Conglomerate.

Study Source	Age (Ma)	Formation	Method	Quadrangle
Bryant et. Al (1989)	36.7 $\pm$ 3.9	Starr Flat Member	Fission-track, zircon	Neola
Bryant et. Al (1989)	28.7 $\pm$ 2.0	Lapoint Member	Fission-track, zircon	Neola NW
Bryant et. Al (1989)	33.7 $\pm$ 5.6	Lapoint Member	Fission-track, zircon	Neola NW
Bryant et. Al (1989)	32.9 $\pm$ 4.5	Lapoint Member	Fission-track, zircon	Neola NW
Bryant et. Al (1989)	35.2 $\pm$ 1.6	Lapoint Member	Fission-track, zircon	Lapoint
Bryant et. Al (1989)	36.9 $\pm$ 1.8	Lapoint Member	Fission-track, zircon	Vernal NW
Bryant et. Al (1989)	33.0 $\pm$ 3.4	Dry Gulch Creek Member	Fission-track, zircon	Bluebell
Bryant et. Al (1989)	34.5 $\pm$ 4.4	Dry Gulch Creek Member	Fission-track, zircon	Bluebell

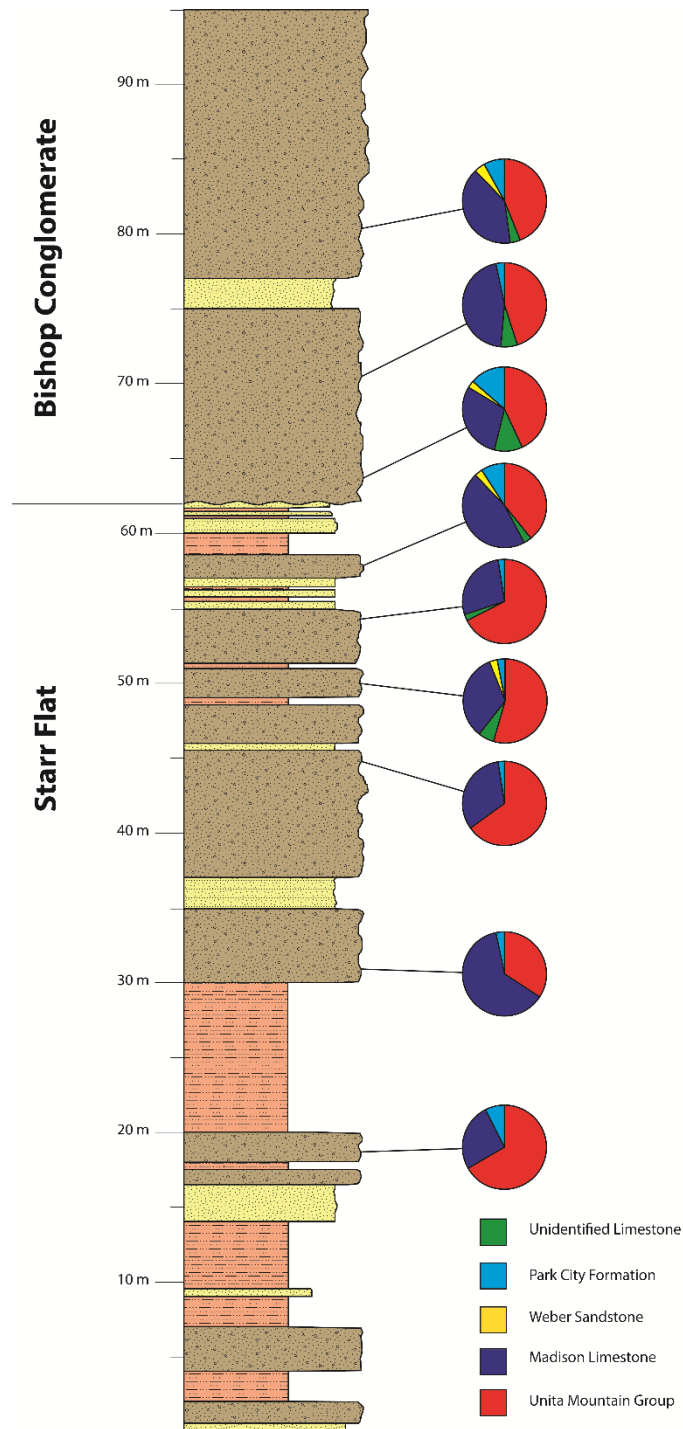


Figure 16. Measured stratigraphic section of upper Starr Flat Member and lower Bishop Conglomerate with clast count data. The contact is the unconformable surface above interbedded conglomerate, sandstone, and red siltstone. There are no clear patterns in clast counts to suggest a formation change. The measured section is located in the northwest corner of the Vernal NW quadrangle.

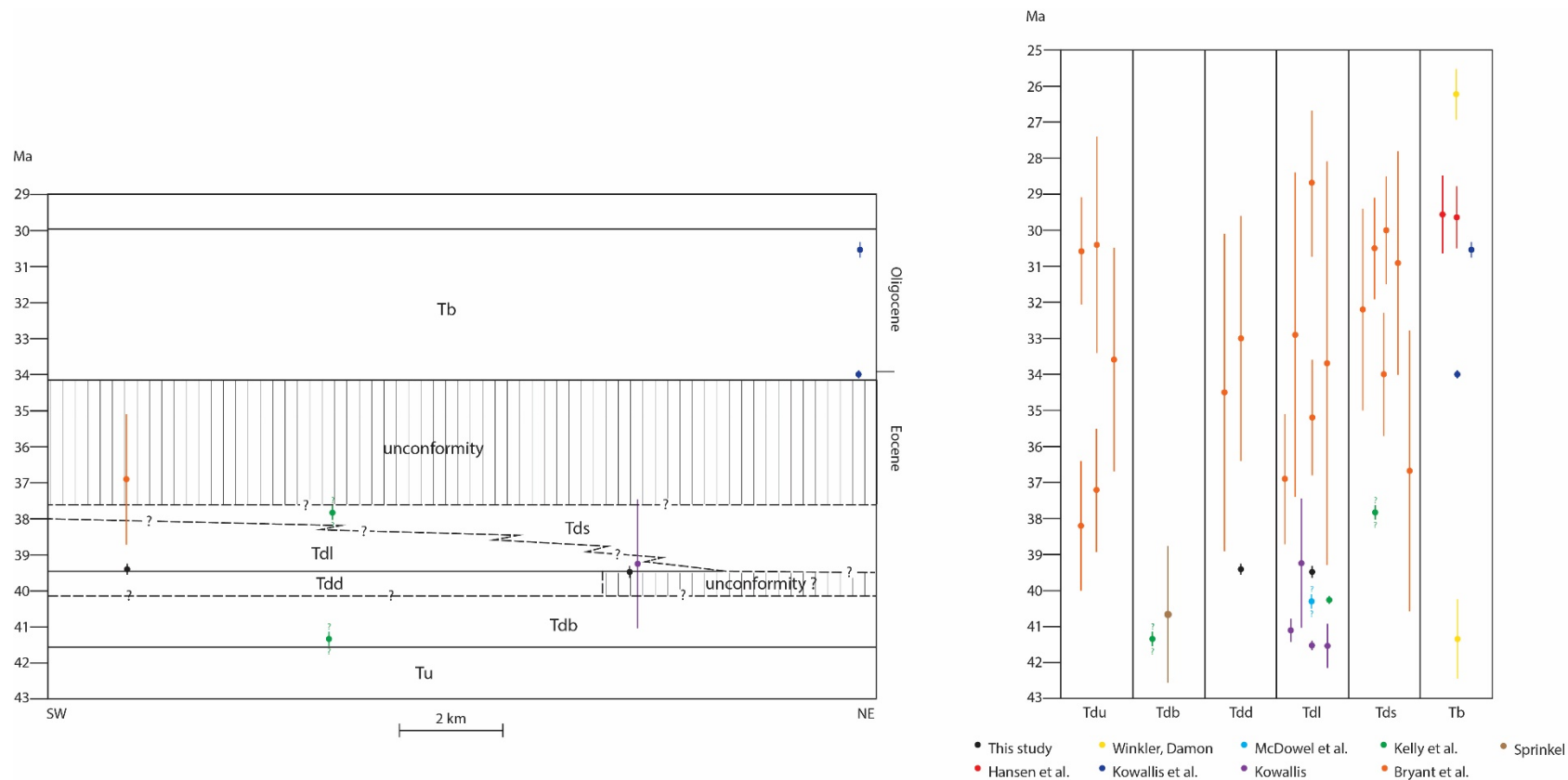
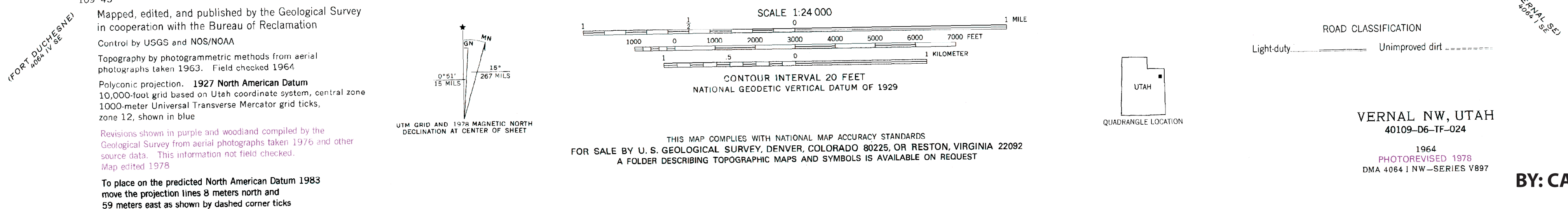


Figure 17. Chronostratigraphic diagram for the Duchesne River Formation and Bishop Conglomerate in the Vernal NW quadrangle. Ages from previous studies and from our own samples collected within the quadrangle are shown. Dashed lines are inferred due to weak constraints on contact age. Solid lines indicate a strong age approximation. Tu- Unita Formation, Tdu- Duchesne River Formation undivided, Tdb- Brennan Basin Member, Tdd- Dry Gulch Creek Member, Tdl- Lapoint Member, Tds- Starr Flat Member, Tb- Bishop Conglomerate.

VERNAL NW QUADRANGLE
UTAH-UINTAH CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)



Qhm	Human Modified Mine Deposits- Areas where land has been significantly altered by humans; remnants from past oil and gas exploration wells; land that has been modified to build highway 121; waste treatment ponds; variable thickness.	Tb
Qh	Other Human Modified Deposits- Areas where land has been significantly altered by humans; remnants from past oil and gas exploration wells; land that has been modified to build highway 121; waste treatment ponds; variable thickness.	Tds
Qa	Alluvium- Unconsolidated silt and sand with lesser amounts of gravel deposited in broad valleys, mature drainages, and low gradient slopes; material is derived locally; less than 10 meters thick.	
Qal ₁	Youngest Stream Alluvium- Unconsolidated pebbles, cobbles, and boulders with lesser amounts of silt and sand; less than 8 meters thick.	
Qal ₂	Older Stream Alluvium- Unconsolidated pebbles, cobbles, and boulders with lesser amounts of silt and sand; deposited in drainage channels that have been incised; less than 10 meters thick.	Tdl
Qap	Piedmont Alluvium- Unconsolidated to poorly consolidated pebble and cobble clast-supported gravel; unlike other Qap deposits that radiate from Little Mountain, this deposit originates from far hill; variable elevation above modern drainages; less than 10 meters thick.	
Qap ₁	Level 1 Piedmont Alluvium- Unconsolidated to poorly consolidated pebble and cobble clast-supported gravel found 7 to 10 meters above modern drainages; sub angular; mature carbonate rind on clasts; less than 5 meters thick.	Tdd
Qap ₂	Level 2 Piedmont Alluvium- Unconsolidated to poorly consolidated pebble- and cobble- clast supported gravel found 22 to 37 meters above modern drainages; sub angular; mature carbonate rind on clasts; less than 5 meters thick.	
Qap ₃	Level 3 Piedmont Alluvium- Unconsolidated to poorly consolidated pebble-, cobble-, and boulder- clast-supported gravel found 46 to 100 meters above modern drainages; sub rounded; carbonate rind on clasts; less than 10 meters thick.	Tdb
Qap ₄	Level 4 Piedmont Alluvium- Unconsolidated to poorly consolidated pebble, cobble, and boulder clast supported gravel found 127 to 151 meters above modern drainages; sub rounded; mature carbonate rind only on the bottom of clasts; less than 20 meters thick.	
Qaf	Alluvial fan Deposits- Unconsolidated silt, sand, pebbles, cobbles, and boulders; poorly sorted; typically fan-shaped deposits located at the mouths of incised drainages; may grade into other Q deposits such as Qa; less than 30 meters thick.	Kmv
Qac	Mixed Alluvium and Colluvium- Unconsolidated mud, silt, sand, and gravel derived locally; deposited on gullied slopes near major drainages; deposited through a combination of alluvial and colluvial processes; less than 10 m thick.	Kms
Qc	Colluvium- Unconsolidated sand and gravel derived locally from bedrock and Quaternary map units; deposited on high-gradient slopes; less than 10 meters thick.	Kf
Qcg	Colluvial Gravel- Unconsolidated gravel derived locally from Brennan Basin Member of Duchesne River Formation and Bishop Conglomerate; deposited on high-gradient slopes; less than 10 meters thick.	Kmr

Elevation Above Maximum Incision (meters)	Qap ₁	Qap ₂	Qap ₃	Qap ₄
Minimum	7	22	46	127
Maximum	12	37	100	151
Average	10	30	67	137
Average Above Younger Unit		20	37	70

Tb Bishop Conglomerate- Light-gray, massive, clast-supported cobble and boulder conglomerate with interbedded sandstone and minor amounts of siltstone; clasts are composed of reddish-purple Uinta Mountain Group quartz arenite and gray Paleozoic limestone of the Madison Formation; unconformably overlies Duchesne River Formation on the southern slope of Little Mountain; the majority of landslide deposits are derived from this unit; about 315 meters thick.

Tds Starr Flat Member of Duchesne River Formation- Red-brown, red-purple, yellow-gray interbedded siltstone, sandstone, and conglomerate; coarsens upward with interbedded fine- to coarse- grained sandstone, pebble conglomerates and siltstone at the lower contact and massive beds of cobble to boulder conglomerate with more minor amounts of interbedded siltstone near the upper contact; the lower contact with the Lapoint Member is gradational with coarse-grained beds extending basinward and interfingering with fine-grained beds; the upper contact with the Bishop Conglomerate is identified by the angular unconformity above the uppermost red silty bed; contains ~ 40-60% fine-grained rocks and 40-60% coarse-grained rocks; 102-243 meters thick.

Tdl Lapoint Member of Duchesne River Formation- Red-brown, purple-gray, yellow-gray, green-gray mudstone and siltstone with minor amounts of sandstone; contains abundant volcanic ash fall tuff beds; $^{40}\text{Ar}/^{39}\text{Ar}$ age from the primary fine-grained unit transitions into the coarser-grained Starr Flat Formation; in one location the unit appears to pinch out completely as the Duchesne River Formation transitions to uplift proximal coarse-grained deposits; lower contact is placed below the lowest prominent and laterally continuous ash bed and marks an increase in fine-grained rocks (c. 80-90%); 0-111 meters thick.

Tb	Oligocene
unconformity	
Tdb	
Tdd	
Tdl	
Tds	Eocene
Tu	
unconformity	
Tg	
Tw	
unconformity	
Kmv	
Kms	Upper Cretaceous
Kf	
unconformity	
Kmr	
Kd	Lower Cretaceous
unconformity	
KJcm	
Jm	Upper Jurassic
unconformity	
Jst	
Je	Middle Jurassic
Jc	
unconformity	
Jrn	Lower Jurassic
rc	Upper Triassic
unconformity	
rm	Lower Triassic
unconformity	
Pp	Middle Permian
unconformity	
PpW	Upper Pennsylvanian
Pm	Middle Pennsylvanian
Prv	Lower Pennsylvanian
Md	
unconformity	Upper Mississippian
Mh	
Mm	Lower Pennsylvanian
unconformity	
Zu	Upper Proterozoic

[illegible]

System	Series	Stage	Age (years)	Human disturbances	Alluvial deposits	Colluvial deposits	Mass-movement deposits	Mixed deposits		
Quaternary	Holocene	historical		Qh	Qhm					
		pre-historical								
	Pleistocene		11,700		Qa	Qa ₁ Qa ₂	Qap ₁	Qc	Qcg	Qac
		upper			Qap	Qap ₂	Qaf	Qms		
			126,000			Qap ₃				
		middle								
			781,000			Qap ₄				
		lower								

Age	Formation	Symbol	Thickness m not to scale	Lithology	Notes
Quaternary	Unconsolidated deposits	Q*	less than 50		
Tertiary	Bishop Conglomerate	Tb	315		Massive conglomerate K-Ar age 34.03 ± 0.04 Ma Gilbert Peak Erosion Surface
	angular unconformity				
	Starr Flat Member	Tds	102 - 243		Interbedded conglomerate/ sand/ silt
	Lapoint Member	Tdl	0 - 111		Distinct sandstone tongues of Tds Prominent ash beds throughout
	Dry Gulch Creek Member	Tdd	0 - 150		⁴⁰ Ar/ ³⁹ Ar age plagioclase 39.47 ± 0.16 Ma ⁴⁰ Ar/ ³⁹ Ar age sandine 39.36 ± 0.15 Ma
	Brennan Basin Member	Tdb	437 - 564		Fan conglomerates grade southward to sandstone
	angular unconformity				
Cretaceous	Mesaverde Formation	Kmv	545		Tar sands Kmv grades into Kms
	Mancos Shale	Kms	1004 - 1502		
	Frontier Formation	Kf	44		Oysters Coal
	unconformity				
	Mowry Shale	Kmo	47		Fish scales Gypsum
	Dakota Formation	Kd	80 - 93		
	unconformity				
Jurassic	Cedar Mountain Formation	Kc	64		
	Morrison Formation	Km	158 - 198		These units are covered by Quaternary deposits and are not exposed at the sur- face within the Vernal NW Quadrangle
	unconformity				
	Stump Formation	Js	67 - 82		
	Entrada Formation	Jc	49 - 66		
	Carmel Formation	Jc	45 - 107		

API	Name	Top (meters)	Thickness (meters)	Thickness (feet)	Status	Longitude	Latitude
43 047 343338-00-00	Formo Oil Corporation Twelve Wells 1-15-20 NELLINEA Section 15, T. 5 S., R. 20 E. LINCOLN County, UT	1067	1007	3321.0	Location Abandoned	-100.55438	40.2871
		1372	853				
		2225					
		2225					
43 047 30822-00-00	Tapscott Oil & Gas Corp Tapscott Section 1, T. 1 S., R. 20 E. LINCOLN County, UT	78	78	256.0	Plugged and Abandoned	-100.61984	40.4931
		345	37				
		662	24				
		627	25				
		662	24				
		796					
		796					

- ③ Volcanic ash fall tuff sample locations. Samples A and I yielded $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 39.47 ± 0.16 Ma and 39.36 ± 0.15 Ma respectively.
- ◇ Dry Hole
- ✂ Gas Well
- ∅ Test Well
- ∅ Unknown Well
- Contact, approximately located
- Contact, gradational, approximately located
- Contact, well located
- ▲ Fault, normal, approximately located
- ▲..... Fault, normal, concealed
- ▲———— Fault, normal, well located
- Cross section, A-A'
- ⊕ Fold, monocline, well located
- ⊕ Fold, syncline, upright, approximately located
- ⊕ Bedding, horizontal, map digitized
- ⊕ Bedding, inclined, field measured
- ⊕ Bedding, inclined, photogrammetric (3-point)

