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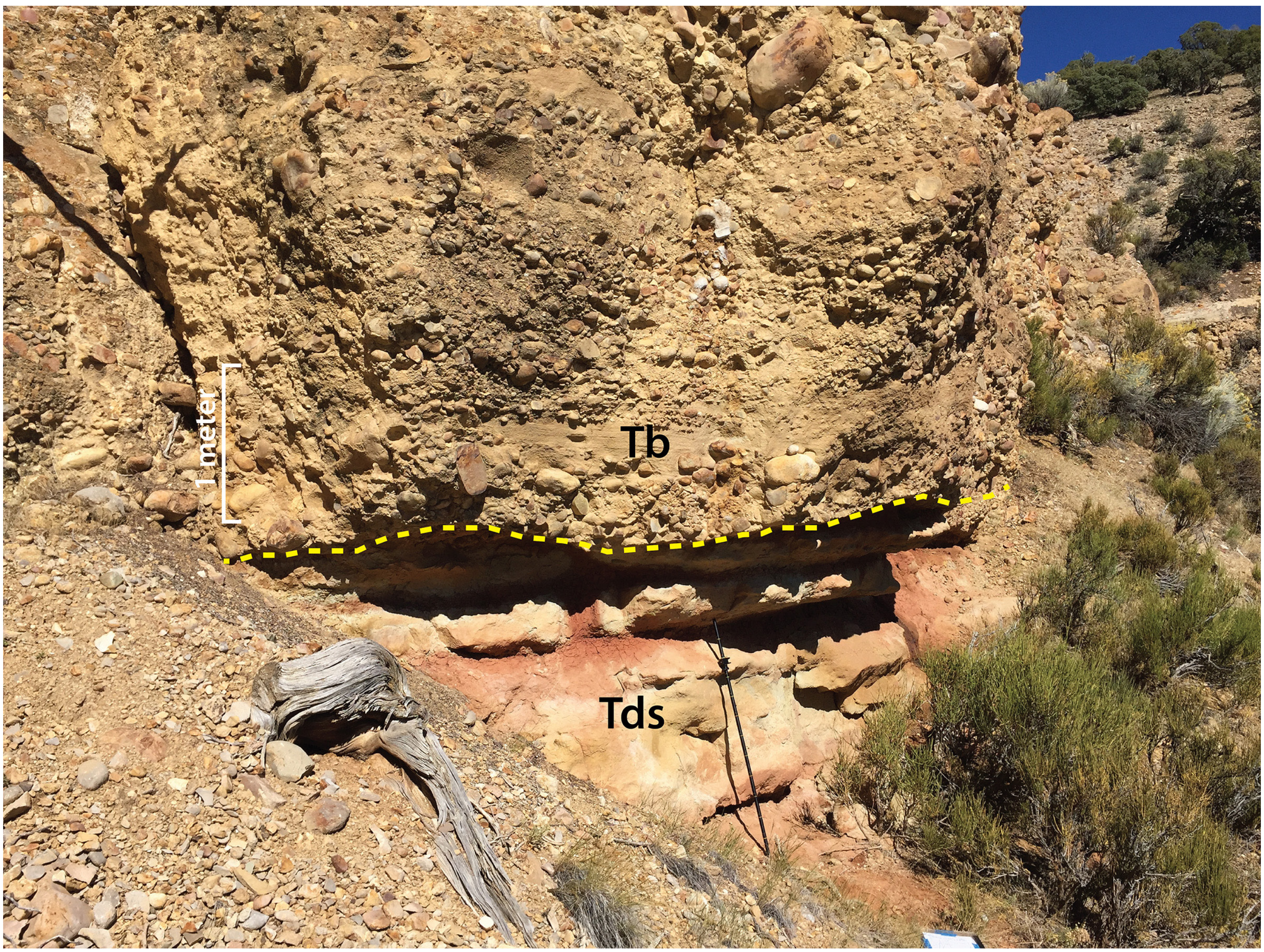

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Cover

The contact between the Starr Flat Member of the Duchesne River Formation (Tds) and the overlying Bishop Conglomerate (Tb). The contact is shown by the yellow dashed line. The contact is easily identified from the abrupt change from reddish-orange to yellow-gray. Photograph was taken to the northeast at 40.4974° N., 109.7311° W.

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Stratigraphic Relationships of the Eocene Duchesne River Formation and Oligocene Bishop Conglomerate, Northeastern Utah—Pulsed Sedimentary Response to Rollback of the Subducted Farallon Slab

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ABSTRACT

The Uinta Mountains are an east-west-trending, reverse fault-bounded, basement-cored Laramide uplift. The Eocene Duchesne River Formation and Oligocene Bishop Conglomerate represent late stage, intermontane basin fill of the Uinta Basin in northeastern Utah. Detailed mapping (1:24,000 scale), clast counts in conglomerate beds, description of lithology and stratigraphic contacts, and radiometric dating of pyroclastic fall beds of the Duchesne River Formation and Bishop Conglomerate in the Vernal NW quadrangle in northeastern Utah reveal stratal geometries of middle Cenozoic depositional units, the uplift and unroofing history of the eastern Uinta Mountains, and give evidence for the pulsed termination of Laramide uplift related to rollback of the Farallon slab and lithospheric delamination. These relationships show the continuation of Laramide uplift in this region until after 37.9 Ma and before 34 Ma, an age younger than the previously reported 45 to 40 Ma.

The Duchesne River Formation consists of four members: the Brennan Basin, Dry Gulch Creek, Lapoint, and the Starr Flat. A normal unroofing signal is found within the formation with a downward increase in Paleozoic clasts and an upward increase in Proterozoic clasts. The oldest member, the Brennan Basin Member contains 80% to 90% Paleozoic clasts and less than 20% Proterozoic clasts. Conglomerate beds in the progressively younger Dry Gulch Creek, Lapoint, and Starr Flat Members of the Duchesne River Formation show significant increases in Proterozoic clasts (34% to 73%) and a decrease in Paleozoic clasts (27% to 66%). The Bishop Conglomerate overlies the Duchesne River Formation, but shows no clear change in clast composition.

In the Duchesne River Formation, the proportion of beds containing fine gravel to boulder-sized clasts decreases significantly with distance from the Uinta uplift, from almost 100% near the source (<0.5 km) to 50% to 20% to the south (10 km). The lower part of the Duchesne River Formation exhibits a fining upward sequence that may represent a lull in tectonic uplift. The fine-grained lithofacies of the Dry Gulch

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Creek and Lapoint Members of the Duchesne River Formation pinch out within about 1 to 2 km from the Uinta uplift. In this proximal region conglomerates equivalent in age to the Lapoint Member cannot be separated from the younger conglomerates of the Starr Flat Member and are mapped together as one unit. Where the fine-grained lithologies appear farther from the uplift, the Starr Flat Member conglomerates deposited above Lapoint Member siltstones represent a southward progradation of alluvial fans away from the uplifting mountain front. The Starr Flat Member is overlain by the Bishop Conglomerate. These units are similar in sedimentary structure and clast composition and are distinguished by an angular unconformity that developed after 37.9 Ma.

Stratigraphic and structural relationships between the Duchesne River Formation and Bishop Conglomerate reveal evidence of at least three episodes of Laramide-age uplift of the Uinta Mountains during the deposition of these formations: (1) deposition of fining upward sequences beginning with a basal coarse-grained unit within the Brennan Basin, Dry Gulch Creek, and Lapoint Members; (2) progradation of alluvial fans to the south form the younger Starr Flat Member resulted from an increase in sediment supply likely associated with renewed uplift; and (3) tilting and truncation of Duchesne River Formation to form the Gilbert Peak erosional surface, and prograding alluvial fans of the Bishop Conglomerate. These episodes of pulsed uplift are possibly the result of dripping lithosphere that occurred during Farallon slab rollback. New $^{40}Ar/^{39}Ar$ ages of 39.4 Ma from ash beds in the Dry Gulch Creek and Lapoint Members emplaced from Farallon rollback volcanism help to constrain the timing of deposition and uplift. These new ages and other existing radiometric and faunal ages suggest a significant unconformity of as much as 4 m.y. between the Duchesne River Formation and the overlying Bishop Conglomerate, which ranges from 34 to 30 Ma in age and show that Laramide uplift continued after 40 Ma in this region.

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 late Paleogene (Hansen, 1986b; Blakey, 2008; Sprinkel, 2014; Hintze and Kowallis, 2021). Minor contraction from moderate angle reverse faults in the lower crust resulted in flexural basins to the north and south of the mountain range (DeCelles, 2004). The Vernal NW quadrangle is near the south flank of the Uinta Mountains (figure 1) in the transition between the uplifted region and basin. Here sediments were deposited onto folded Cretaceous strata in the later stages of uplift. These sedimentary units are the Eocene Duchesne River Formation with its four members (Brennan Basin, Dry Gulch Creek, Lapoint, and Starr Flat from oldest to youngest) and the Oligocene Bishop Conglomerate (figure 2). The Vernal NW quadrangle is an excellent location to explore the geometry of these late-stage basin-fill deposits that are proximal to uplifted regions and to examine the erosional and sedimentary response to tectonic processes.

Historically, the Bishop Conglomerate has been mapped separately from the Starr Flat Member (Untermann and Untermann, 1964; Sprinkel, 2007, 2018) except for Rowley and others (1985) who mapped both units as Bishop Conglomerate, possibly due to the larger map scale. 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, 1986a, p. 18; Bryant, 1989, p. J9). 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 2). Differences in bedding dip between these units have been used to determine contact locations (Sprinkel, 2007, 2018). However, in locations where outcrops are poorly exposed or dips are similar, the conglomeratic units are difficult to distinguish. Finally, the Duchesne River Formation and Bishop Conglomerate formed during an important tectonic reorganization involving rollback of the subducting Farallon plate (e.g., Fan and Carrapa, 2014; Smith and others, 2014).

Therefore, this study addresses four main questions:

1. How can the conglomerates of the Duchesne River Formation and Bishop Conglomerate be

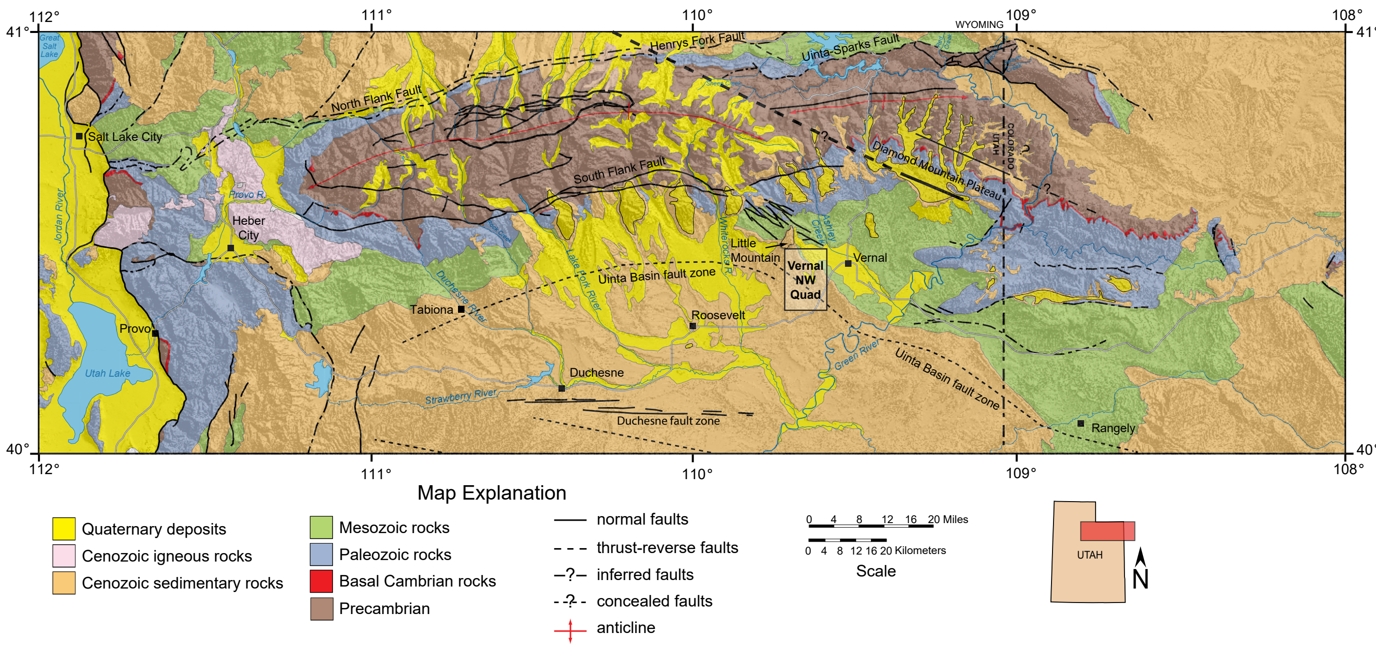

Figure 1. Geologic map modified from Sprinkel (2014) showing the location of the Vernal NW quadrangle relative to geologic formations and structures. The quadrangle is located on the south flank of the Uinta Mountains and contains Quaternary, Cenozoic, and Mesozoic sedimentary rock. Source rocks for Cenozoic formations are derived from Precambrian and Paleozoic formations to the north.

identified and distinguished from one another?

2. What are the chronostratigraphic relationships within the Duchesne River Formation and Bishop Conglomerate?
3. What do these formations, their associated conglomerates, and intervening erosion surfaces tell us about periods of uplift and quiescence of the Uinta Mountains during the late Eocene and early Oligocene?
4. What is the relationship of the stratigraphy to the contemporaneous rollback of the subducting Farallon slab?

To answer these questions, we combined traditional geologic mapping with lithologic observations including compositions of conglomerate clasts and new $^{40}Ar/^{39}Ar$ ages. We identified stratigraphic changes in the parts of the Duchesne River Formation and Bishop Conglomerate proximal to the Uinta uplift. These changes and other evidence lead us to interpret uplift proximal stratigraphic contacts, locate chronostratigraphic boundaries, and find evidence of episodic tectonic uplift, erosion, and deposition.

GEOLOGIC HISTORY

The Uinta Mountains stand as the highest mountain range in Utah with peaks reaching 4000 m in elevation. Near the start of the Neoproterozoic breakup of the supercontinent Rodinia, an episode of intracratonic rifting resulted in basin formation in the current location of the Uinta Mountains and formed the western margin of the Laurentian craton (Condie and others, 2001; Dehler and others, 2010; Yonkee and others, 2014). The accumulation of sediments from the surrounding Wyoming, Mojave, and Yavapai provinces into this rift basin created the Neoproterozoic Uinta Mountain Group (figure 3), which is now extensively exposed throughout the Uinta Mountains (Ball and Farmer, 1998; Mueller and others, 2007; Dehler and others, 2010; Hintze and Kowallis, 2021). Continued rifting along the western margin of Laurentia produced a passive margin where an elongate belt of thick sediment accumulated throughout present day Utah and eastern Nevada (Stewart and Poole, 1974; Condie and others, 2001; Dickinson, 2004). Near the end of the Neoproterozoic, the region under-

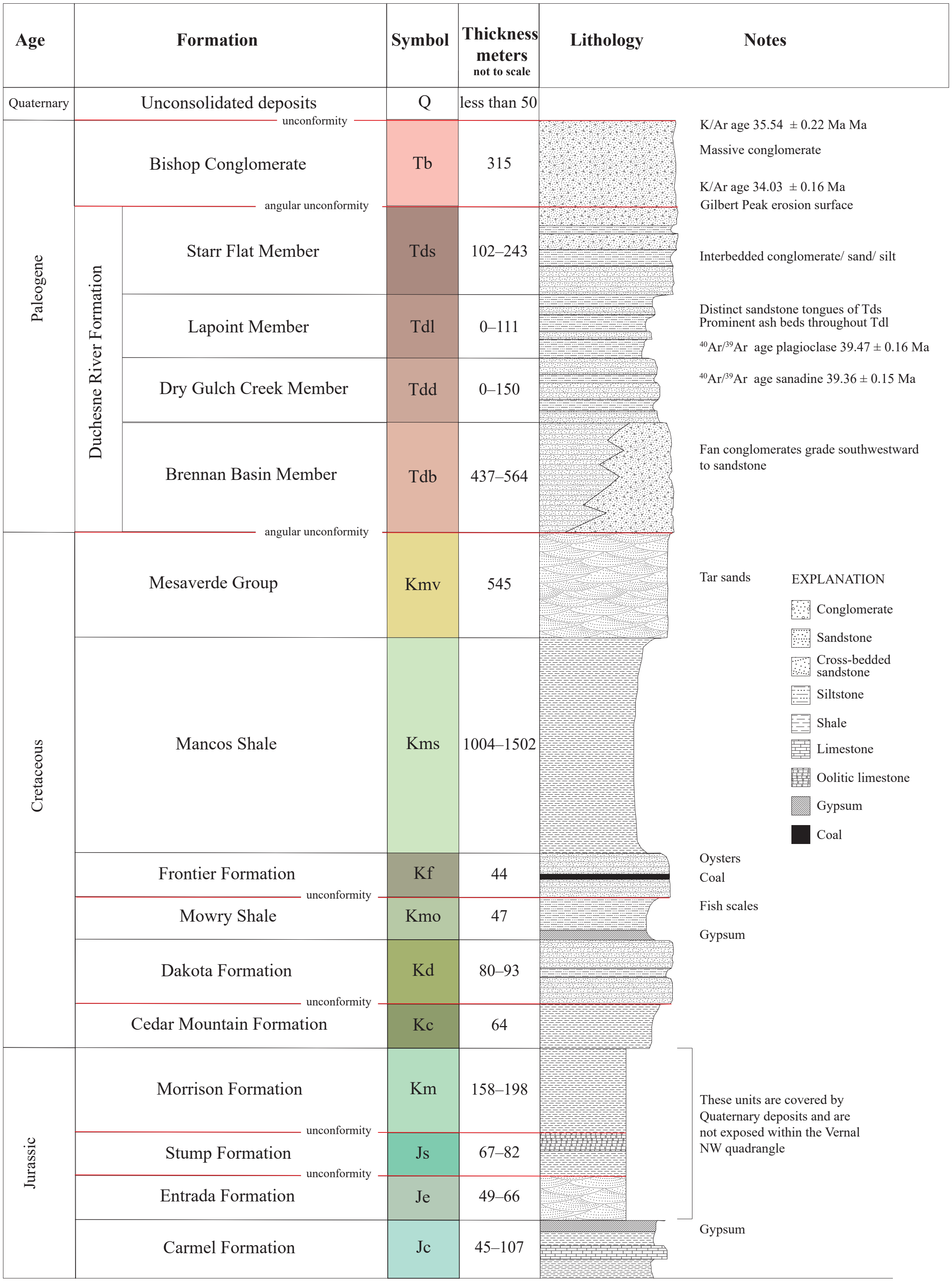

Figure 2. Stratigraphic column of formations exposed within the Vernal NW quadrangle. Thicknesses were measured in the field or calculated from the map using elevation, dip, and surface extent. Sprinkel (in review) and Sprinkel and Kirkland (in preparation) have proposed that the term Dakota Formation be replaced with Muddy Formation in the Uinta Mountains and Uinta Basin.

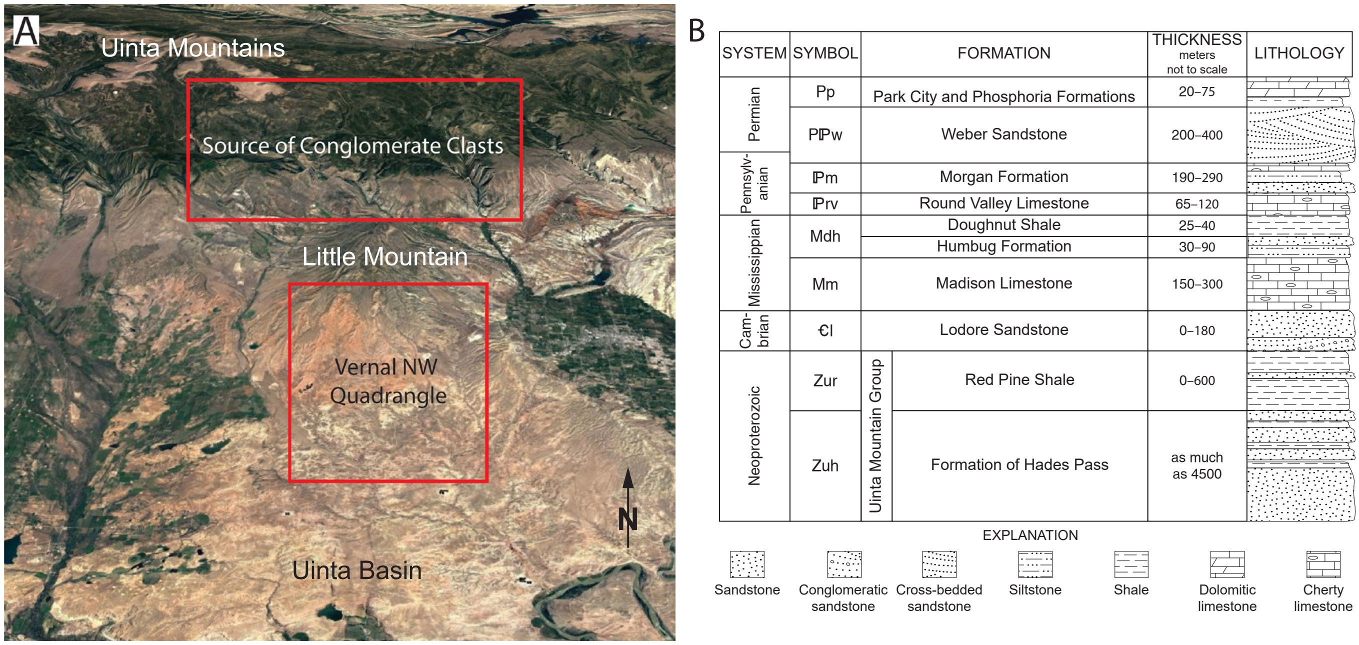

Figure 3. (A) Oblique Google Earth image showing the location of the conglomerates studied within the Vernal NW quadrangle and the likely conglomerate clast source location in the Uinta Mountains. Image is taken from the south to give a sense of relief in the region. (B) Stratigraphic column of Proterozoic and Paleozoic and rocks within the Uinta Mountains (from Sprinkel, 2006), which are the source of clasts in conglomerate beds of the Duchesne River Formation and Bishop Conglomerate.

went basin inversion along reactivated faults to form the Uinta-Cortez arch (Sprinkel, 2014, 2018). During basin inversion the Neoproterozoic strata were tilted and eroded. A Cambrian-age transgression then deposited shallow marine sediments of the Tintic Quartzite (western Uinta Mountains) and Lodore Formation (eastern Uinta Mountains) on the erosional surface.

The middle Paleozoic into the Mesozoic was a period of accretion and contraction as subduction occurred along the active margin of Laurentia (figure 3). This subduction and accretion lead to a long period of orogenic activity that produced the North American Cordillera (Saleeby, 1983; Lawton, 1994; Dickinson, 2004). Uplift of the Antler highlands to the west 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 and others, 2004; Katz and others, 2007; Hintze and Kowallis, 2021).

During the Middle Jurassic, northeastern Utah was situated along the eastern side of the Sundance sea (figure 4), until the Early Cretaceous when the eastward-advancing Sevier orogeny resulted in the thin-skinned fold and thrust belt of the Sevier highlands in western Utah (DeCelles, 2004; DeCelles and Coogan, 2006). Throughout the Sevier orogeny, oceanic lithosphere subducted at a relatively steep angle producing a typical volcano-plutonic arc extending through present day Arizona, California, Nevada, and Idaho (Cross, 1986; Livaccari and Perry, 1993; Lawton, 1994; Kowallis and others, 2001; Christiansen and others, 2015). The foreland basin in Utah was flooded by the Western Interior seaway in the Late Cretaceous, which ultimately divided Laurentia into two halves, with the Cordillera to the west and continental lowlands to the east (Lawton, 1994; Hintze and Kowallis, 2021). Sediment was shed from the uplifted Sevier highlands and was deposited in the foreland basin, creating the Jurassic Morrison and Cretaceous Cedar Mountain Formations in a continental basin, and the Mancos Shale and Mesaverde Group in a marine basin (Hettinger and Kirshbaum, 2002; Hintze and Kowallis, 2021) (figures 2 and 4).

The end of the Cretaceous was marked by a break in magmatism likely caused by a change from steep

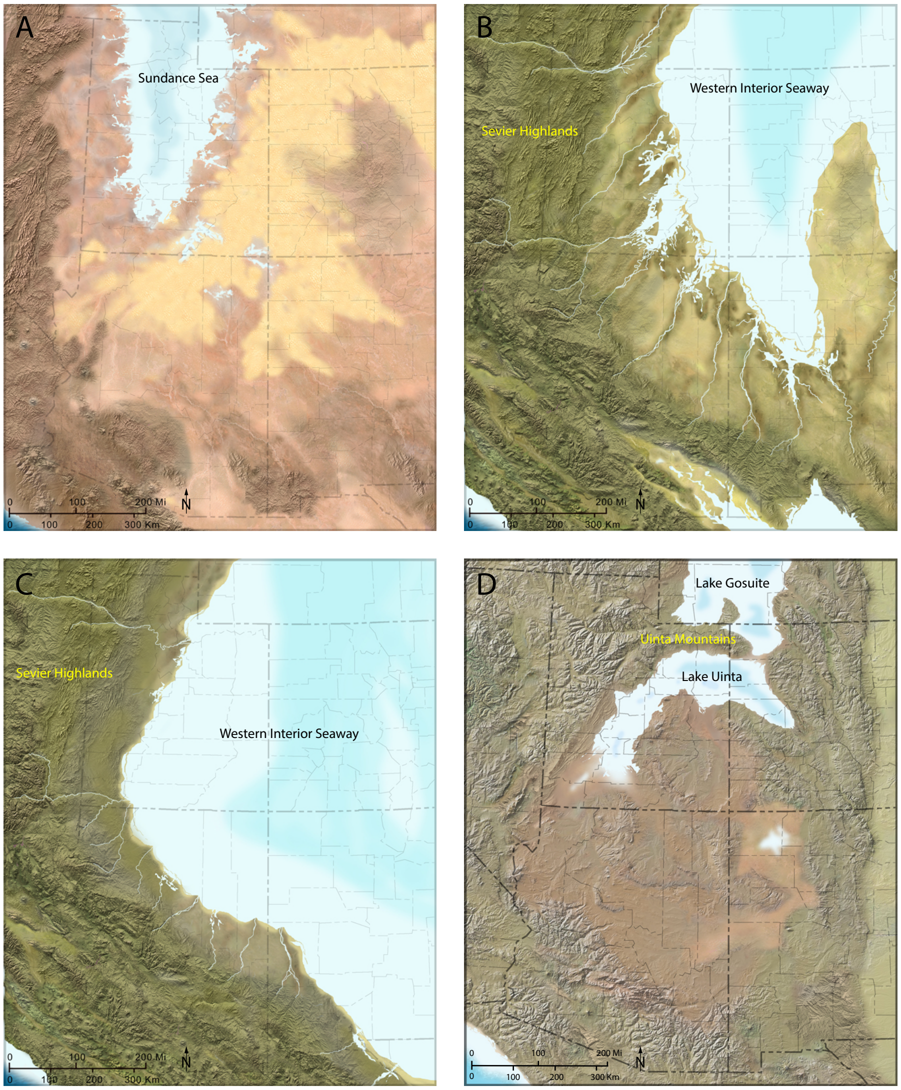

Figure 4. Paleogeography maps of the Colorado Plateau (Blakey and Raney, 2008). (A) Middle Jurassic tectonic subsidence led to the incursion of the shallow Sundance seaway. This seaway and proximal environments lead to the deposition of the Twin Creek Limestone in northern Utah (north of the Uinta Mountains), the Arapien Formation in central Utah, and Carmel Formation in eastern and southern Utah. (B) In the Early to Middle Cretaceous the Sevier highlands rose in Nevada and western Utah, developing an eastward-migrating foreland basin to the east, which was ultimately flooded by the Cretaceous Western Interior seaway. The fluvial, floodplain, deltaic, and nearshore deposits are responsible for the stratigraphy of this time. (C) The Cretaceous Western Interior seaway reached its maximum transgression in the Late Cretaceous, depositing the marine Mancos Shale and deltaic to nearshore marine Mesaverde Group. (D) The Laramide orogeny began in the early Paleocene and created several uplifts in Utah, including the Uinta Mountains. This uplift led to intermountain lakes which eventually became mostly infilled by the late Eocene prior to the deposition of the Duchesne River Formation.

to shallow angle subduction (Cross and Pilger, 1982; Cross, 1986; Livaccari and Perry, 1993). This change, perhaps caused by subduction of an aseismic ridge (Cross and Pilger, 1978; Cross, 1986) or oceanic plateau (Dickinson and others, 1988), resulted in an eastward migration of the Cordilleran deformation front and eventually the Laramide orogeny that started in some regions as early as 100 Ma (Kaempfer and others, 2021). Most Laramide-related tectonism occurred during the Late Cretaceous and early Cenozoic (Cross, 1986; Copeland and other, 2017; Rosenblume and others, 2021). The Laramide orogeny, with its characteristic basement-cored uplifts, induced the rise of the Uinta Mountains. In the Uinta Mountains shortening occurred on moderate angle thrust faults, including the Uinta Basin fault zone located in the subsurface of the Vernal NW quadrangle (figure 1) (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, 2021). Lake Uinta formed at the start of the Eocene (ca. 55 Ma) in the subsiding Uinta and Piceance Basins, south of the Uinta Mountains, and persisted until late Eocene at about 42 Ma (figure 4) (Kelly and others, 2012; Hintze and Kowallis, 2021). The deposits of the Green River and Uinta Formations mark its extent and evolution. Eventually the lake filled, and the Uinta Formation was buried by dominantly fluvial sediment of the Eocene Duchesne River Formation (Anderson and Picard, 1972; Bryant and others, 1989) (figure 2).

The termination of Laramide tectonism is poorly constrained due to few features showing clear relationships with Laramide faults but is estimated to have ceased between 40 and 45 Ma (Coney, 1972; Cross, 1986; Hintze and Kowallis, 2021). This termination was caused by the subducting Farallon slab rolling back to a steeper angle triggering volcanism far from the continental margin, known as the ignimbrite flare-up, which swept southward from present day Montana about 54 Ma and ended in the southern Great Basin about 20 Ma (Lipman and others, 1972; Humphreys, 1995; Best and others, 2013). Slab rollback has also been associated with continued basement-cored uplift, exhumation, and basin subsidence in Wyoming and Utah (Fan and Carrapa, 2014; Smith and others, 2014) and extensional deformation, sedimentation, and extension-related volcanism in Nevada (Canada and others, 2019).

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 three-dimensional (3D) software (https://www.cardinalsystems1.net/vrtwo) 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. Bedding attitudes were measured in the field or as three-point solutions within VrTwo. All contacts, faults, and folds were then exported to ESRI's ArcMap software where unit polygons, faults, structures, and cross section lines were created.

In areas where previously described contacts did not correlate with field observation (color, grain size, bedding inclination, or clast composition), new contacts and unit descriptions were developed. One stratigraphic section was measured at the Starr Flat Member/Bishop Conglomerate contact to identify lithologic changes through the section (figures 5 and 6). In conglomerate-rich areas, counts of clast lithology were taken (figure 6) to determine the source material and unroofing signals of conglomerates in the different units. At conglomeratic outcrops, an area of about 1 m^2 was outlined in a chalk circle (figure 7). 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 cri-

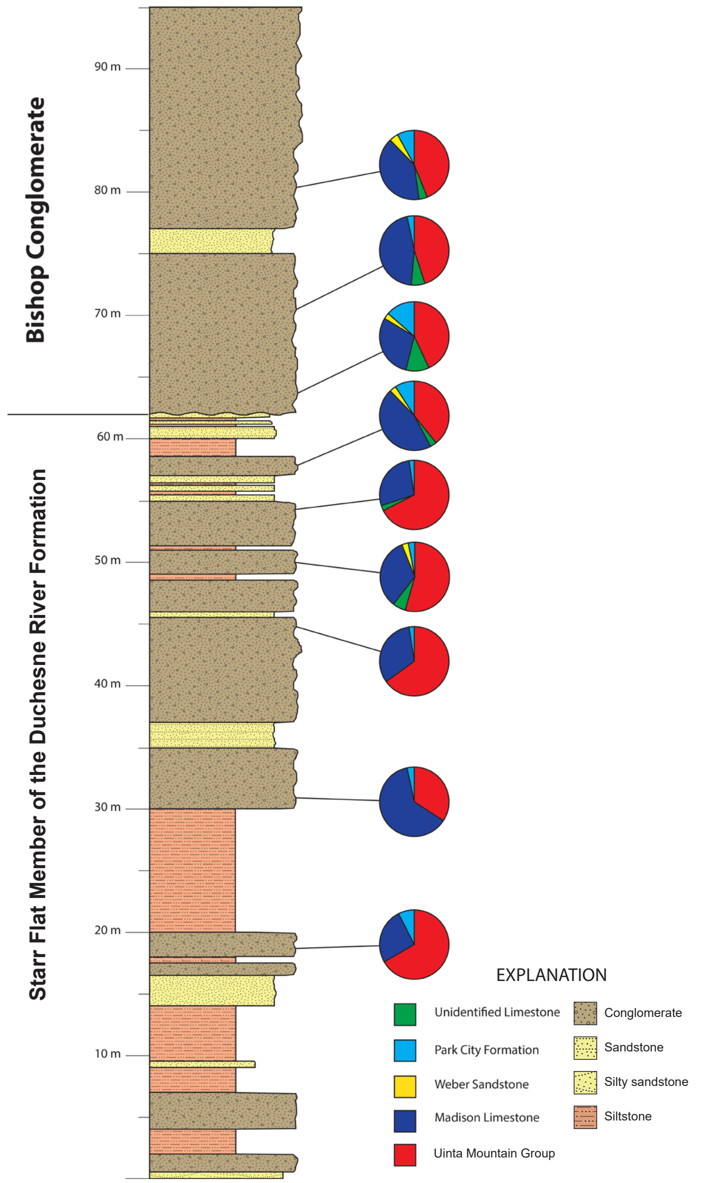

Figure 5. Measured stratigraphic section of upper Starr Flat Member and lower Bishop Conglomerate with clast count data. The contact is the unconformable surface above interbedded conglomerate, sandstone, and reddish-colored siltstone. There are no clear patterns in clast counts to suggest a formation change. The measured section is located in the northwest corner of the Vernal NW quadrangle (40.4924° N., 109.7406° W.).

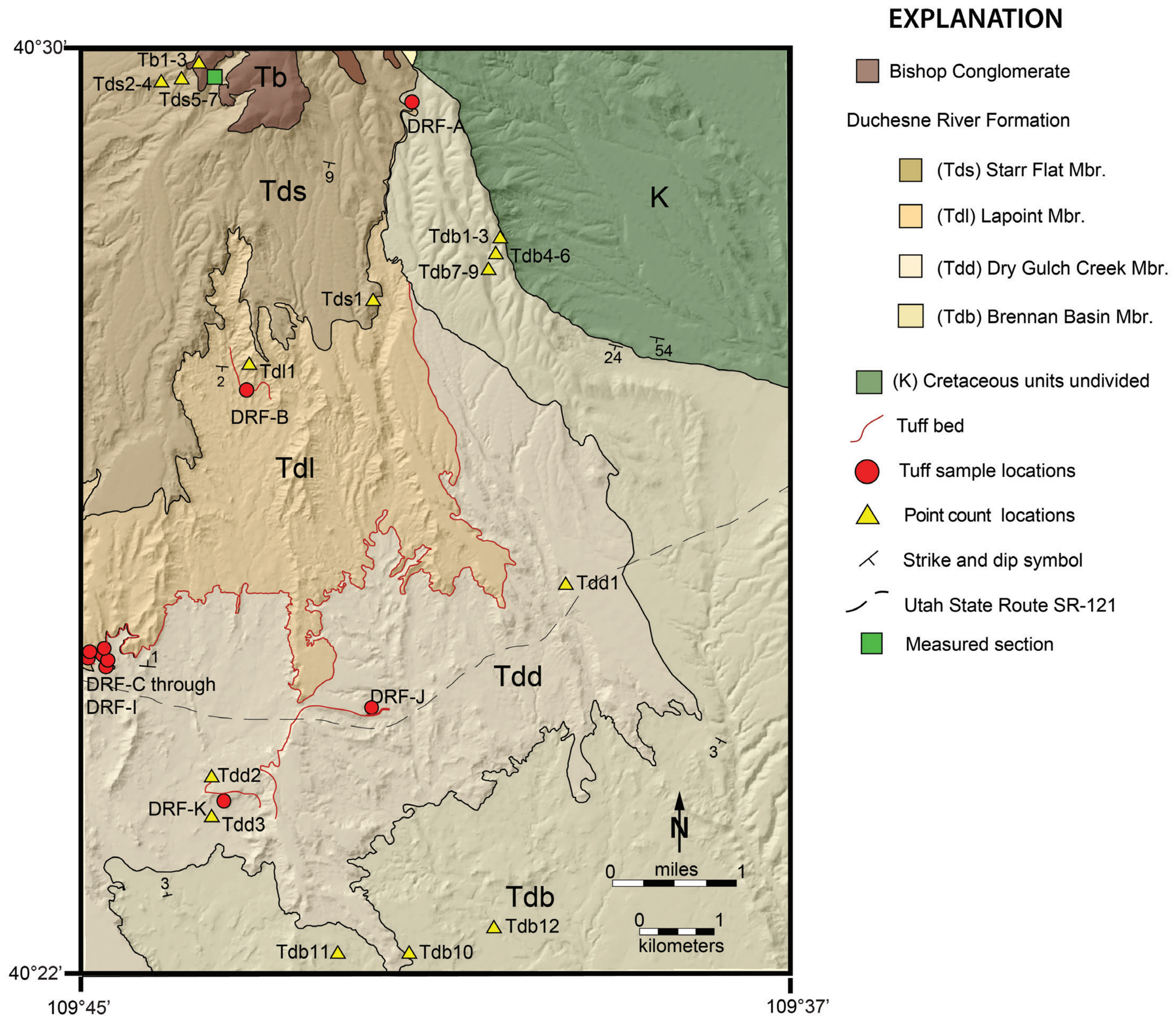

Figure 6. Simplified geologic map of the Vernal NW quadrangle with the locations of clast counts, ash samples, and measured section. The Dry Gulch Creek and Lapoint Members pinch out in the northeastern region of the quadrangle near the Bishop Conglomerate label. Modified from Jensen and others (2020).

terion was used because clasts smaller than this lacked distinctive characteristics and were difficult to classify. The large clast size allowed us to count each clast over 2 cm within the 1-m^2 area, therefore a counting grid as described in Ross and White (2006) was not used. Tallied clasts were then used to estimate the percentage of clasts from different source strata at each outcrop. This percentage was derived from the number of clasts present and not their volumetric proportions.

Samples of bentonitic 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 at the University of Wisconsin WiscAR Lab using a single crystal $^{40}Ar/^{39}Ar$ laser fusion methodology (http://geochronology.geoscience.

Figure 7. Photograph of clast count circle (red dashed outline) within the Brennan Basin Member of the Duchesne River Formation. 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 the scale is 10 cm wide.

wisc.edu/analytical-approaches/). The samples and ages have been previously discussed and published by Jensen (2017) and Jensen and others (2020). These radiometric ages (Damon, 1970; Winkler, 1970; McDowell and others, 1973; Bryant and others, 1989; Kowallis and others, 2005; Sprinkel, 2018; Sprinkel, in review; and B.J. Kowallis, Brigham Young University, verbal communication, 2016) along with faunal ages (Kelly and others, 2012) were used to determine the chronostratigraphy of the Duchesne River Formation and Bishop Conglomerate in the Vernal NW quadrangle.

PREVIOUS STRATIGRAPHIC STUDIES

Anderson and Picard (1972, 1974) describe the variety of fluvial strata in the Duchesne River Formation and divided it into four members: Brennan Basin, Dry Gulch Creek, Lapoint, and Starr Flat, from oldest to youngest. They related the deposition of the Duchesne River Formation to final movement of the Laramide uplift near the end of the Eocene.

Sato and Chan (2015a, 2015b) identified various facies of the Duchesne River Formation and divided these

Table 1. Clast classification in conglomerates.

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

into six different facies associations: (1) amalgamated and braided fluvial channels, (2) extensive floodplain and stacked broad fluvial channels, (3) extensive floodplain and isolated small streams, (4) alluvial-fan complexes, (5) dry and wet floodplains and fluvial channels, and (6) lacustrine deposits. These facies interpretations were made from 35 measured sections, including 5 in the Vernal NW quadrangle. Sato and Chan (2015a) note the existence of a fining upward sequence starting in the Brennan Basin Member with grain size decreasing through the Dry Gulch Creek and Lapoint Members. At the contact with the Starr Flat Member there is a significant increase in grain size. They interpret the onset of sequences to be caused by Uinta Mountain uplift, from which the gravels of the Brennan Basin Member and the Starr Flat Member were sourced.

Overlying the Duchesne River Formation is the Bishop Conglomerate that was first described by Powell (1876) and is found on both the north and south flanks of the Uinta Mountains. The Duchesne River Formation is separated from the Bishop Conglomerate by the Gilbert Peak erosional surface (Hansen, 1986a), which appears to have formed during a period of tectonic quiescence following uplift. This erosional surface is also found on both flanks of the Uinta Mountains. Hansen (1986a) described the Bishop Conglomerate as rather "loosely cemented bouldery, cobbly conglomerate and coarse, poorly sorted, pebbly, friable sandstone." Maximum clast size ranges from 5 cm to 7.6 m and deposits extend 3 to 85 km from their source in the Uinta Mountains. Hansen (1986a) interpreted the Bishop Conglomerate as originating from debris flows, due to matrix-supported clasts, forming a bajada complex abutting the paleo-Uinta Mountain front and built on the Gilbert Peak erosion surface. Hansen (1986a, p. 18), Bryant (1989, p. J9), and Haddox (2005, p. 38–39) suggested that the Starr Flat Member of the Duchesne River Formation may be the basinward equivalent of the Bishop Conglomerate. However, Sprinkel (2018) recognized an angular unconformity between the two units and has suggested that at certain Bishop Conglomerate localities, the unit has been incorrectly mapped as the Starr Flat Member.

RESULTS

Clast Counts in Conglomerates

Clast counting was conducted on cobble/boulder conglomerates within alluvial-fan facies in the Brennan Basin and Starr Flat Members, and Bishop Conglomerate to detect potential changes in sediment provenance associated with Uinta Mountain unroofing (figure 8, table 2). The Brennan Basin Member contains 70% to 90% Paleozoic clasts with a majority (40% to 90%) derived from the Madison Limestone, which is 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 8) made of purplish-gray and yellowish-gray quartz arenite. The basinward part of the Brennan Basin Member has a composition like its uplift-proximal counterpart dominated by Paleozoic clasts.

The typically fine-grained Dry Gulch Creek and Lapoint Members include rare conglomerates in coarse-grained braided river facies. In these locations, they show a sharp increase in Uinta Mountain Group clasts (50% to 59%) when compared to the Brennan Basin Member (0% to 17%). The cobble/boulder conglomerates of the Starr Flat Member also exhibit a large percentage of Uinta Mountain Group clasts (34% to 73%). Overall, the clast counts in the Dry Gulch Creek and Lapoint Members are similar to the Starr Flat Member with the exception of more chert in the Dry Gulch Creek Member. Red chert is characteristic of only the Pennsylvanian Round Valley Limestone whereas the origin of black chert, observed in the Mississippian Madison and Deseret Limestones and Permian Park City Formation, is undetermined at this time. Black chert is listed in table 2 as unidentified chert whereas red chert is grouped with Round Valley Limestone. Overall, chert abundance increases basinward (figure 8), likely due to its durability over long transport distances.

The Starr Flat Member differs slightly from the Bishop Conglomerate in clast composition (figure 5, table 2). The Starr Flat Member typically contains greater than 50% Uinta Mountain Group clasts (averaging 57%), whereas the Bishop Conglomerate consistently contains less than 50% Uinta Mountain Group clasts (averaging 44%). The Permian Park City Formation clasts in the Starr Flat Member range from 2% to 9% (averaging 4.4%), whereas they range from 3% to 14% (averaging 8.3%) in the Bishop Conglomerate. Unidentified limestone clasts account for 0% to 6% of clasts in the Starr Flat Member (averaging 1.7%), whereas making up 4% to 11% (averaging 7.0%) of the Bishop Conglomerate.

Lithology and Contacts

Identifying changes in lithology is an important part of locating stratigraphic contacts and interpreting uplift history. A summary of our stratigraphic contact descriptions can be found in table 3. We identified the contacts described by Anderson and Picard (1972) throughout much of the basinward (southern) part of the quadrangle and recognized the distinct facies with upward fining sequences described by Sato and Chan (2015a). The first sequence begins above the unconformity separating the Uinta Formation from the overlying Brennan Basin Member. The deposits of the Brennan Basin Member consist of braided river and some alluvial fan facies; the sequence fines upward through the Dry Gulch Creek and Lapoint Members, which are dominated by floodplain/lacustrine facies. The contact between the Dry Gulch Creek and Lapoint Members is placed below a very prominent, 39.4-Ma ash layer that can be traced into the mountain front (figure 9). We observed an interfingering relationship between the fine-grained beds of the Lapoint Member and the course-grained al-

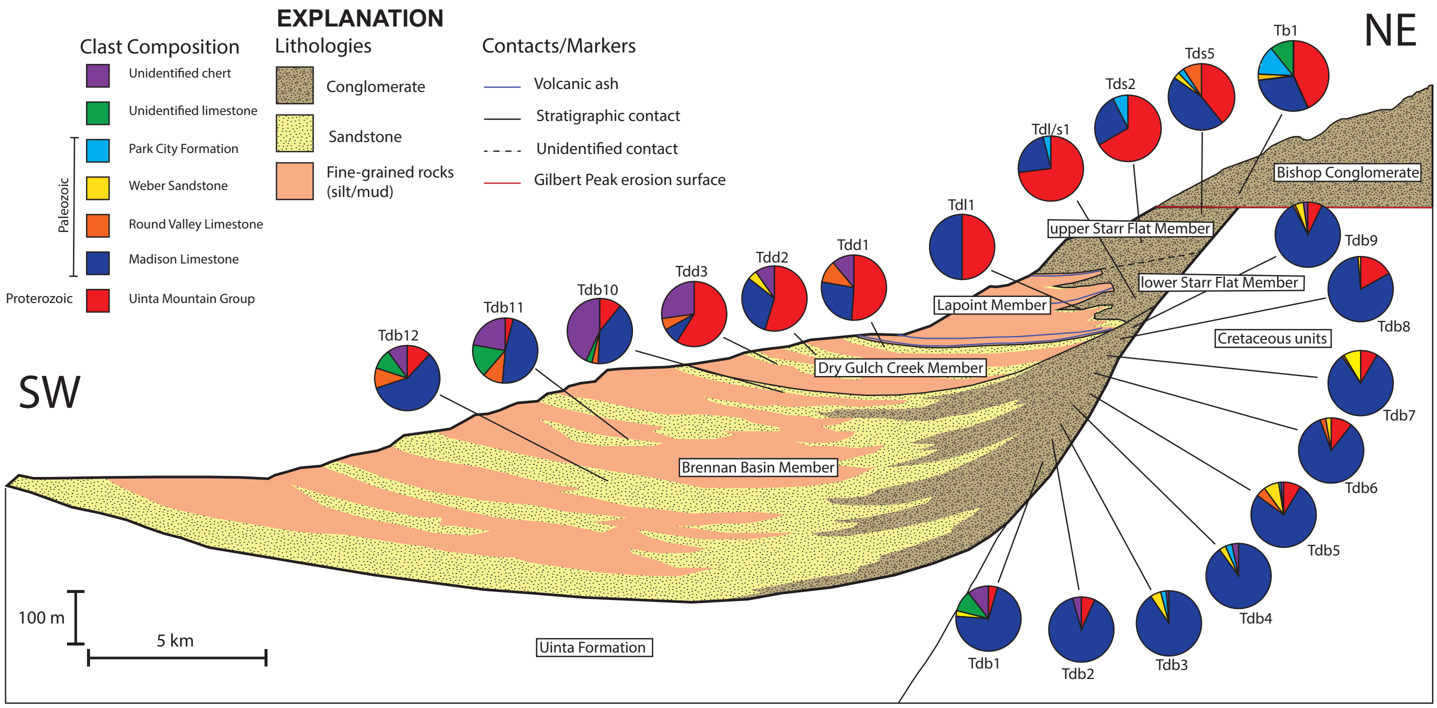

Figure 8. Schematic cross section of the Duchesne River Formation and Bishop Conglomerate in the Vernal NW quadrangle, with conglomerate point count data shown in pie charts. Overall, the formation coarsens to the northeast, where all members are conglomeratic. Clast counts show an upward increase in Uinta Mountain Group and decrease in Madison Limestone. The Duchesne River Formation unconformably overlies Cretaceous units. The Bishop Conglomerate unconformably overlies the Duchesne River Formation and Cretaceous units. Diagram was modified from Anderson and Picard (1974).

luvial fan facies of the lower part of the Starr Flat Member. The upper Starr Flat is represented by progradation of the alluvial fan facies over the top of the youngest beds of the Lapoint Member. The Starr Flat Member exhibits an overall coarsening upward sequence with the coarsest beds near the Starr Flat Member/Bishop Conglomerate contact. Within the Vernal NW quadrangle, we observed increased dips and a distinct shift in facies closer to the uplift. The north-northeastern part of the quadrangle contains bedding of Duchesne River Formation that dips up to 30° to the south, whereas the regional dip is typically less than 10°. Also, the average grain size in each of the Duchesne River Formation members is greater than in rocks of the same age found in more distal settings (table 3). Additionally, in the north-northeast, the predominantly fine-grained and ash-rich Lapoint Member contains many resistant, coarse sandstone and pebble conglomerate beds like those found in the Starr Flat Member. These coarse beds thin and disappear basinward (figure 8). Since volcanic ash beds were found stratigraphically above many of these coarse-grained beds, the Lapoint/Starr Flat contact was picked above the highest ash bed that marked an abrupt increase in coarse-grained rocks (figure 10). In one location, the Dry Gulch Creek Member pinches out completely placing the Brennan Basin Member in contact with the overlying Lapoint/Starr Flat Members. This contact juxtaposes two conglomeratic units. Here a marked increase in Proterozoic Uinta Mountain Group clasts was used to place the basal contact of the Starr Flat Member (figure 8, table 2). Overall, the Starr Flat Member also contains more interbedded fine-grained rocks and has a smaller average clast size at its base than the underlying Brennan Basin Member.

Previous researchers have suggested that the Starr Flat Member is possibly a basinward equivalent of the Bishop Conglomerate (Hansen, 1986a; Bryant, 1989; Haddox, 2005). However, Sprinkel (2018) recognized an angular unconformity between the two units and has suggested that at certain Bishop Conglomerate

Table 2. Point count data showing percentage of each clast type collected at different localities within each member.

Formation/ Member	Locality	No.	Uinta Mountain Group	Madison Limestone	Round Valley Limestone	Weber Sandstone	Park City Formation	Unidentified Limestone	Unidentified Chert
Bishop Cgl.	Tb3	25	0.44	0.4	0	0.04	0.08	0.04	0
Bishop Cgl.	Tb2	31	0.45	0.45	0	0	0.03	0.06	0
Bishop Cgl.	Tb1	37	0.43	0.3	0	0.03	0.14	0.11	0
Starr Flat Mbr.	Tds7	33	0.39	0.45	0	0.03	0.09	0.03	0
Starr Flat Mbr.	Tds6	40	0.68	0.28	0	0	0.03	0.03	0
Starr Flat Mbr.	Tds5	33	0.55	0.33	0	0.03	0.03	0.06	0
Starr Flat Mbr.	Tds4	43	0.65	0.33	0	0	0.02	0	0
Starr Flat Mbr.	Tds3	32	0.34	0.63	0	0	0.03	0	0
Starr Flat Mbr.	Tds2	27	0.67	0.26	0	0	0.07	0	0
Starr Flat Mbr.	Tds1	26	0.73	0.23	0	0	0.04	0	0
Lapoint Mbr.	Tdl1	46	0.5	0	0	0	0	0.5	0
Dry Gulch Creek Mbr,	Tdd2	84	0.55	0.31	0	0.05	0	0	0.1
Dry Gulch Creek Mbr.	Tdd1	45	0.51	0.27	0.11	0	0	0	0.11
Dry Gulch Creek Mbr.	Tdd3	51	0.59	0.08	0	0	0	0.06	0.27
Brennan Basin Mbr.	Tdb12	59	0.12	0.58	0.1	0	0	0.1	0.1
Brennan Basin Mbr.	Tdb11	49	0.04	0.47	0.1	0	0	0.16	0.22
Brennan Basin Mbr.	Tdb10	70	0.11	0.4	0.03	0	0	0.03	0.43
Brennan Basin Mbr.	Tdb9	96	0.07	0.85	0.01	0.04	0.02	0	0
Brennan Basin Mbr.	Tdb8	76	0.17	0.82	0	0.01	0	0	0
Brennan Basin Mbr.	Tdb7	93	0.09	0.82	0.01	0.09	0	0	0
Brennan Basin Mbr.	Tdb6	37	0.11	0.84	0.03	0.03	0	0	0
Brennan Basin Mbr.	Tdb5	80	0.09	0.76	0.05	0.08	0.01	0	0.01
Brennan Basin Mbr.	Tdb4	61	0	0.9	0	0.03	0.03	0	0.03
Brennan Basin Mbr.	Tdb3	75	0	0.91	0	0.05	0.03	0	0.01
Brennan Basin Mbr.	Tdb2	45	0.07	0.89	0	0	0	0	0.04
Brennan Basin Mbr.	Tdb1	67	0.04	0.72	0	0.03	0	0.1	0.1

Table 3. Stratigraphic contact descriptions.

Stratigraphic Contact	Anderson and Picard (1972)	This Study – Basinward	This Study – Uplift Proximal
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.
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 (1972).	Same as Anderson and Picard (1972). 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.
Dry Gulch Creek Member/Lapoint Member	Base of the lowest extensive, continuous, bentonitic bed of the Lapoint Member.	Same as Anderson and Picard (1972).	Not present.
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, whereas the Starr Flat contains a majority Precambrian quartzite clasts. Increase in fine-grained rocks and color change from gray to reddish-brown.
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/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 was not observed.

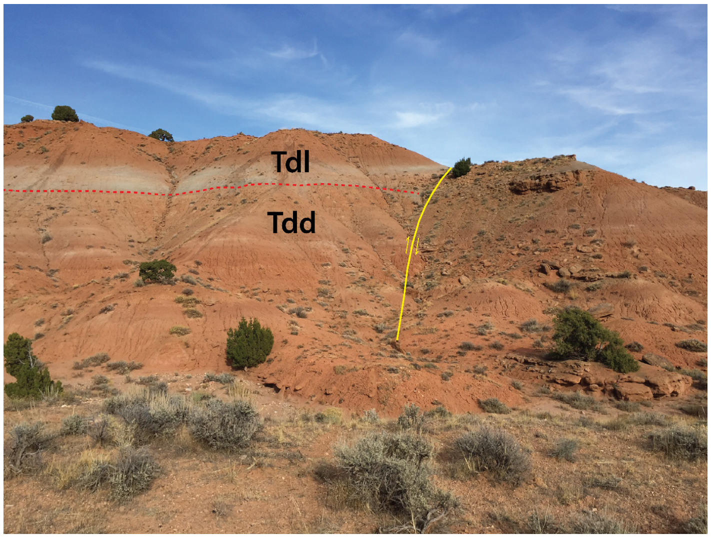

Figure 9. Lapoint (Tdl)/Dry Gulch Creek (Tdd) contact. The base of the lowest prominent volcanic ash bed is used for the contact. Offset of the volcanic ash bed shows down drop on the small fault to the south. Photograph location is just west of Halfway Hollow near Highway 121. View is to the west.

localities, the unit has been incorrectly mapped as Starr Flat Member. Our observations support those of Sprinkel (2018) as we were able to note key differences between the Starr Flat Member and the overlying Bishop Conglomerate. Mapping of this contact is primarily based on a distinct color change from reddish-brown (below) to gray (above) (figures 11 and 12). The reddish-brown color is derived from abundant interbedded silt in the Starr Flat Member, and less silt in the overlying Bishop Conglomerate resulting in an overall grayish color within the Vernal NW Quadrangle. This contact also marks an angular unconformity, which was described by Sprinkel (2018). The Starr Flat Member dips 6 to 21° to the southwest, whereas the overlying Bishop Conglomerate is close to horizontal, dipping less than 5°.

Radiometric Ages

Laterally extensive, exposed ash beds were targeted and sampled to identify chronostratigraphic markers in the Duchesne River Formation (figure 6; DRF-A through DRF-K). Due to sample quality, only samples DRF-A and DRF-H were selected for $^{40}Ar/^{39}Ar$ laser fusion methods at the University of Wisconsin-Madison WiscAR Geochronology lab. DRF-A returned an age of 39.47 ± 0.16 Ma (table 4). DRF-A was collected from a thin tuffaceous sandstone a few meters above the Brennan Basin/Lapoint contact near Little Mountain where the Dry Gulch Creek Member has pinched out. DRF-H returned an age of 39.36 ± 0.15 Ma. DRF-H was collected near Utah State Route 121 a few meters below the prominent volcanic ash bed that marks the Dry Gulch Creek/Lapoint contact. Thus, DRF-H is stratigraphically lower and older than DRF-A. The radiometric ages are inverted stratigraphically, but they are not statistically different, overlapping within the stated uncertainties. These two samples were collected 10 km from each other, which makes the relative stratigraphic position difficult to estimate. However, DRF-A is located a few meters above the stratigraphic contact between the two members and DRF-H is located a few meters below that contact, making it reasonable that the samples are separated by very little time. These ages are within the range of ages published in previous studies (McDowell and others, 1973; Hansen and others, 1981; Bryant and others, 1989; Sprinkel, 2018; Sprinkel, unpublished data; Kowallis, unpublished data). Two ash beds in the Bishop Conglomerate east of the Vernal NW quadrangle were collected and dated by Kowallis and others (2005). The sample from the lower part of the Bishop Conglomerate on Diamond Mountain Plateau has an age of 34.03 ± 0.04 Ma. The sample from the upper part of the Bishop Conglomerate on Yampa Plateau has an age of 30.54 ± 0.22 Ma (table 4).

DISCUSSION

Significance of Clast Counts and Lithology

The Duchesne River Formation becomes increasingly rich in gravel to boulder-sized clasts closer to the mountain front. Within the Vernal NW quadrangle, all Paleogene deposits near Little Mountain contain abundant conglomerate beds as the fine-grained facies of the Dry Gulch Creek and Lapoint Members pinch out south of this point (figure 6). Although the lithologies are similar, key differences in the conglomeratic facies of each unit warrant unit divisions. In the con-

Figure 10. Lapoint (Tdl)/Starr Flat (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. Photograph taken to the northwest from 40.4617° N., 109.6943° W.

glomeratic facies of the Brennan Basin Member there is an observable up-section increase in the proportion of Precambrian Uinta Mountain Group clasts (figure 8). 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 clast abundance occurs across the Brennan Basin/Starr Flat contact in the northeast part of the quadrangle, from 0% to 12% in the Brennan Basin Member to 34% to 73% in the Starr Flat Member. 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 rapid unroofing of the Uinta Mountain Group over a broader area. An alternative explanation is that the contact is unconformable and associated with a temporary

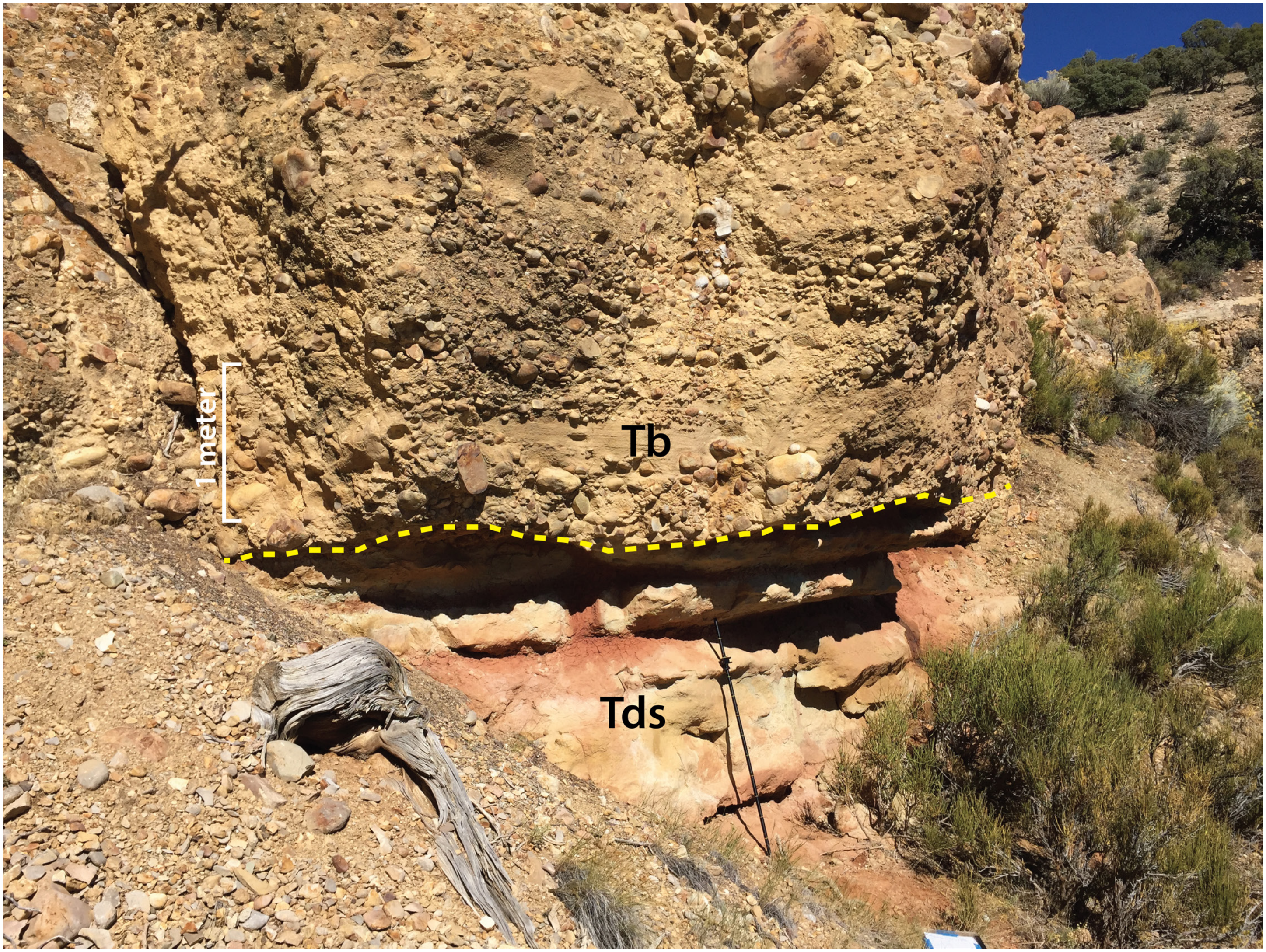

Figure 11. Close-up photograph of the Starr Flat (Tds)/Bishop Conglomerate (Tb) contact. The contact is identified by the undulating, unconformable surface above interbedded conglomerate, sandstone, and reddish-colored siltstone. Photograph was taken to the north from 40.4974° N., 109.7311° W.

cessation of deposition followed by renewed uplift and unroofing. Haddox (2005) mentions the possibility of an intraformational angular unconformity separating the lower and upper Duchesne River Formation nearby in the north adjacent Dry Fork quadrangle. Although no angular unconformity was observed in the Vernal NW quadrangle, the possibility of an unconformity cannot be eliminated.

The observed increase in Neoproterozoic clasts across the contact, the increase in silt, and the decrease in cobble to boulder clast size at the Brennan Basin/Starr Flat contact indicate a change not only in the source of the clasts, but a decrease in gradient or energy during the deposition of the Starr Flat Member. A much greater abundance of Madison Limestone clasts in both the proximal and distal parts of the Brennan Basin Member than in younger strata indicates that it was deposited throughout the quadrangle at a different time and earlier 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 survived the approximate 5 km of fluvial transport while the limestone breaks down over this distance.

Figure 12. Starr Flat (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. Photograph was taken to the northeast from 40.4974° N., 109.7311° W.

Proportions of clasts from the Uinta Mountain Group are similar in the Dry Gulch Creek (55% to 59%), Lapoint (50%), and Starr Flat (34% to 73%) Members. The main difference between these members is that no black chert was observed in the Starr Flat and Lapoint Members whereas 10% to 27% black chert was found in the Dry Gulch Creek Member. This pattern shows that the relatively fine-grained Dry Gulch Creek and Lapoint Members were deposited at the same stage of Uinta unroofing (figure 8) as the Starr Flat Member. In the case of the Lapoint Member, we observed an interfingering relationship with the lower part of the Starr Flat Member, which gives further evidence of the coeval nature of these two members proximal to the mountain front. The coarse-grained, gravel-rich beds identified as the Starr Flat Member can be traced basinward where they pinch out completely amongst the fine-grained, mud- and silt-rich beds of the Lapoint Member. The upper Starr Flat Member is represented by progradation of the alluvial fan facies over the fine-grained Lapoint Member. The Dry Gulch Creek Member does not interfinger with the Starr Flat Member and is stratigraphically older than the Lapoint Member as the contact can be traced by a prominent ash bed at the base of the Lapoint (red dashed line; figures 9 and 10). Near the conglomeratic facies of the Brennan Basin Member, the contact with the overlying unit is covered by Quaternary deposits, obscuring the Dry Gulch Creek Member. Closer to the mountain front, the Brennan Basin Member is in direct contact with the Starr Flat Member as indicated by the increase in Neoproterozoic clasts. 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

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

Study Source	Age (Ma)	Formation	Method	Quadrangle
This Study (DRF-A)	39.47 ± 0.16	Lapoint Member	40Ar/39Ar, plagioclase	Vernal NW
This Study (DRF-K)	39.36 ± 0.15	Dry Gulch Creek Member	40Ar/39Ar, sanidine	Vernal NW
Hansen and others (1981)	29.58 ± 0.86	Bishop Conglomerate	K-Ar, hornblende	Blair Basin
Hansen and others (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 and others (2005)	30.54 ± 0.22	Bishop Conglomerate	40Ar/39Ar, sanidine	Jensen Ridge
Kowallis and others (2005)	34.03 ± 0.04	Bishop Conglomerate	40Ar/39Ar, sanidine	Stuntz Reservoir
McDowell and others (1973)	39.3 ± 0.8	Lapoint Member	K-Ar, biotite	Lapoint
Sprinkel (unpublished)	39.24 ± 1.79	Lapoint Member	U-Pb, zircon	Vernal NW
Kowallis (unpublished)	41.52 ± 0.13	Lapoint Member	40Ar/39Ar, biotite	Lapoint
Kowallis (unpublished)	41.53 ± 0.61	Lapoint Member	40Ar/39Ar, biotite	Lapoint
Kowallis (unpublished)	41.10 ± 0.32	Brennan Basin	40Ar/39Ar, biotite	Lake Mountain
Sprinkel (2018)	40.66 ± 1.9	Brennan Basin	U-Pb, zircon	Hancock Cove
Kelly and others (2012)	40.26 ± .08	Lapoint Member	40Ar/39Ar, biotite	Vernal NW or Lapoint
Kelly and others (2012)	37.92 ±?	Starr Flat Member	Duchesnean Fauna	?
Bryant and others (1989)	30.4 ± 3.0	Duchesne River Formation (undivided)	Fission-track, zircon	Strawberry Reservoir NW
Bryant and others (1989)	30.6 ± 1.5	Duchesne River Formation (undivided)	Fission-track, zircon	Blacktail Mountain
Bryant and others (1989)	33.6 ± 3.1	Duchesne River Formation (undivided)	Fission-track, zircon	Dry Mountain
Bryant and others (1989)	37.2 ± 1.7	Duchesne River Formation (undivided)	Fission-track, zircon	Farm Creek Peak
Bryant and others (1989)	38.2 ± 1.8	Duchesne River Formation (undivided)	Fission-track, zircon	Farm Creek Peak
Bryant and others (1989)	30.0 ± 1.5	Starr Flat Member	Fission-track, zircon	Kidney Lake
Bryant and others (1989)	34.0 ± 1.7	Starr Flat Member	Fission-track, zircon	Kidney Lake
Bryant and others (1989)	30.5 ± 1.4	Starr Flat Member	Fission-track, zircon	Ice Cave Peak
Bryant and others (1989)	30.9 ± 3.1	Starr Flat Member	Fission-track, zircon	Pole Creek Cave
Bryant and others (1989)	32.2 ± 2.8	Starr Flat Member	Fission-track, zircon	Neola
Bryant and others (1989)	36.7 ± 3.9	Starr Flat Member	Fission-track, zircon	Neola
Bryant and others (1989)	28.7 ± 2.0	Lapoint Member	Fission-track, zircon	Neola NW
Bryant and others (1989)	33.7 ± 5.6	Lapoint Member	Fission-track, zircon	Neola NW
Bryant and others (1989)	32.9 ± 4.5	Lapoint Member	Fission-track, zircon	Neola NW
Bryant and others (1989)	35.2 ± 1.6	Lapoint Member	Fission-track, zircon	Lapoint
Bryant and others (1989)	36.9 ± 1.8	Lapoint Member	Fission-track, zircon	Vernal NW
Bryant and others (1989)	33.0 ± 3.4	Dry Gulch Creek Member	Fission-track, zircon	Bluebell
Bryant and others (1989)	34.5 ± 4.4	Dry Gulch Creek Member	Fission-track, zircon	Bluebell

not previously been documented and likely indicate uplift and exhumation of older units within the Uinta Mountains. The widespread nature of this pattern is unknown and a shift in provenance for the Dry Gulch Creek Member is possible.

Near the Starr Flat/Bishop Conglomerate contact, beds in the Starr Flat Member dip southwest as much as 21°, whereas beds in the overlying Bishop Conglomerate dip less than 5°. This angular unconformity suggests that there was significant uplift and erosion associated with displacement along the Uinta Basin fault zone 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 proportions in the Starr Flat Member are very similar to those of the Bishop Conglomerate (figure 5). In a locality we observed near Weasel Point in the Lake Mountain quadrangle to the west-northwest of the Vernal NW quadrangle, the Bishop Conglomerate has mostly Paleozoic limestone clasts near its basal contact and shows an upward increase in Proterozoic clasts suggesting unroofing during deposition of the Bishop. 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 and had incised more deeply than the drainages feeding sediment to the deposits at Weasel Point. It is also important to note that the Bishop Conglomerate in the Vernal NW quadrangle is much more conglomeratic than outcrops of the same formation in other areas, possibly also due to a more mature trunk stream sourcing the sediment in the quadrangle.

Timing of Uplift and Deposition

The Duchesne River Formation represents a late-stage basin fill that formed 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 Gosiute (north) and Lake Uinta (south) between 55 to 42 Ma (Sprinkel, 2007; Kelly and others, 2012; Hintze and Kowallis, 2021) (figure 4). Volcanic ash layers in the Green River Formation in Wyoming exhibit similarities in composition and age to volcanic rocks in Montana and Idaho (Smith and others, 2003; Chandler, 2006). The eruptive source of the ash beds in the Green River Formation in Utah has not been documented, but they are likely from the same sources identified in Wyoming. The abundance of ash indicates that Farallon slab rollback was underway to the north while the Uinta Mountains were still rising (Christiansen and Lipman, 1972; Fan and Carrapa, 2014; Best and others, 2016). Late-stage basin fill of the Uinta Basin is marked by the onset of deposition of the Duchesne River Formation onto deformed strata along the Uinta Mountain front (Sato and Chan, 2015a, 2015b). This onlap is expressed in the Vernal NW quadrangle by the deposition of Brennan Basin Member on an angular unconformity cutting both the Cretaceous Mesaverde Group and Mancos Shale. These Cretaceous formations were deposited prior to Uinta Mountain uplift near the western shoreline of the Cretaceous Interior seaway (Hettinger and Kirschbaum, 2002). In the northwest part of the Vernal NW quadrangle, the Upper Cretaceous Mesaverde Group dips 44 to 54° southwest, whereas the Eocene Brennan Basin Member dips 24 to 30° southwest. This relationship indicates the Mesaverde Group was uplifted and tilted prior to the deposition of the Brennan Basin Member.

A two-stage uplift history for the Uinta Mountains has been proposed by Untermann and Untermann (1969). Bradley (1995) attributed the first phase, from Cretaceous to early Paleogene, to displacement on the North Flank and Uinta thrusts. Whereas the second phase, from early to middle Eocene, resulted primarily from displacement on the Uinta Basin fault zone (formerly called the Uinta Basin-Mountain boundary fault zone). Fan and Carrapa (2014) suggested that the first phase occurred during flat-slab subduction and initiated Laramide uplift. The second phase occurred during slab rollback with uplift and associated basin subsidence occurring at an accelerated rate during the Eocene (Fan and Carrapa, 2014; Smith and others, 2014). Based on its age, deposition of the Duchesne River Formation would have occurred during the second slab rollback phase, while uplift and tilting of Cretaceous units occurred during the first phase. Within the Duchesne River Formation and overlying Bishop Conglomerate, we find evidence that, during this second phase, uplift was not constant but consisted of at least three periods of activity followed by quiescence. Additional evidence of intermittent uplift and quiescence can be found in progressive unconformities between Late Cretaceous and Paleocene units and Early Eocene to Oligocene units near the town of Tabiona, Duchesne County, Utah (Sprinkel, 2018). If these features are related to slab rollback, Uinta Mountain uplift must have been discontinuous and punctuated. Smith and others (2017) have attributed Farallon slab removal to pulsed uplift in Nevada. They propose that isostatic rebound in the Eocene was caused by dense eclogite dripping off the base of the previously thickened lithosphere. Garzione and others (2008) described similar, punctuated uplift in the subduction-related Altiplano, in west-central South America, with a stage of rapid uplift of about 1.5 to 2.5 km related to dripping and delamination of eclogitic lower crust (and the underlying mantle lithosphere) that was preceded by a stage of crustal thickening. The thickness of the crust below the Uinta Mountains might then be evidence for this process. Thick crust would be expected from the contractional history, but if the crust is anonymously thin, it could provide independent evidence for lithospheric delamination as the mechanism for periodic uplift in this region. However, the crustal thickness of the Uinta Mountains is not well constrained and seismic data-based crustal thickness range from less than 30 km thick (Gilbert and Sheehan, 2004), like that in the Basin and Range Province to the west, to about 48 km thick (Gilbert, 2012). It would be insightful to see if other late-stage Laramide structures have thin or thick crust and 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.

The Duchesne River Formation and Bishop Conglomerate document the final episodes of uplift in the Uinta Mountains. The first period of uplift recorded in these units is evidenced by the coarser nature of Brennan Basin Member of the Duchesne River Formation compared to the finer-grained underlying Uinta Formation. This pulse of coarse material suggests that it was deposited as a response to erosion following uplift. Bryant and others (1989) obtained low-resolution fission track ages (table 4) for the tuffs in the Brennan Basin Member but these data fail to constrain the age of the lower contact of this member at a resolution that can be achieved from other methods. The best constraint for age here is from the Duchesnean land mammal fossils that occur in the lower Brennan Basin Member (Emry, 1981; Rasmussen and others, 1999; Kelly and others, 2012). Global Polarity Time Scale correlations for Duchesnean fauna in California places the Uintan-Duchesnean faunal boundary at an age of about 41.4 Ma, which constrains the age of the lower part of the Duchesne River Formation (Kelly and others, 2012). This faunal age correlates well with an 40.66 ± 1.88 Ma age from an altered tuff from the middle of the Brennan Basin Member (Utah Geological Survey and Apatite to Zircon Inc., 2014; Sprinkel, 2018).

The change observed in clast composition above the Brennan Basin Member likely indicates shifting drainage patterns or unroofing by incision rather than renewed uplift, since the general trend into deposition of the Dry Gulch Creek and Lapoint Members is one of continuing upward fining. This upward fining sequence shows no change in dip up section and suggests a period of tectonic quiescence. This tectonic lull allowed sediment to fill the restricted basin and the gradient to decrease over time leading to the fining upward sequence.

The best age constraints for the contact between the Dry Gulch Creek and Lapoint Members come from radiometric dates on altered volcanic ash beds directly above and below this contact. This contact is identified by a prominent and laterally extensive ash bed, which has been sampled and dated by other researchers (McDowell and others, 1974; Bryant and others, 1989; Kelly and others, 2012; Sprinkel, unpublished data; Kowallis, unpublished data). This ash bed is the most laterally extensive ash bed found 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 usable feldspar grains. We were able to sample and date other ash beds located just above and below the marker bed used for the lower Lapoint Member contact. The ages of our samples DRF-A (39.47 ±

0.16 Ma) above and DRF-H (39.36 ± 0.15 Ma) below constrain the contact to about 39.4 Ma (figure 13). The compositions and ages of these ash layers are similar to volcanic fields in northeastern Nevada (Jensen, 2017; Jensen and others, 2020) confirming that by 39.4 Ma the ignimbrite flare-up had migrated southward to nearly the same latitude where the Uinta Mountains were still actively rising (compare with Christiansen and Lipman, 1972; Best and others, 2016). Like the late tectonic activity in the Uinta Mountains, the flare-up is related to the rollback of the subducting Farallon slab.

The upper Starr Flat Member represents the next pulse of uplift. This is indicated by its progradation over underlying members with deposits of primarily alluvial-fan facies (figure 8). Haddox (2005) observed an angular unconformity between the Starr Flat Member and the underlying members in the Dry Fork quadrangle but this relationship was not observed in the Vernal NW quadrangle. Unfortunately, volcanic ash beds are poorly preserved in the high-energy environment and 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. The best age constraint for the Starr Flat Member comes from Kelly and others (2012) via Duchesnean land mammal fauna, which gives an upper constraint of the Starr Flat Member of about 37.9 Ma for the last appearance of Duchesnean fauna.

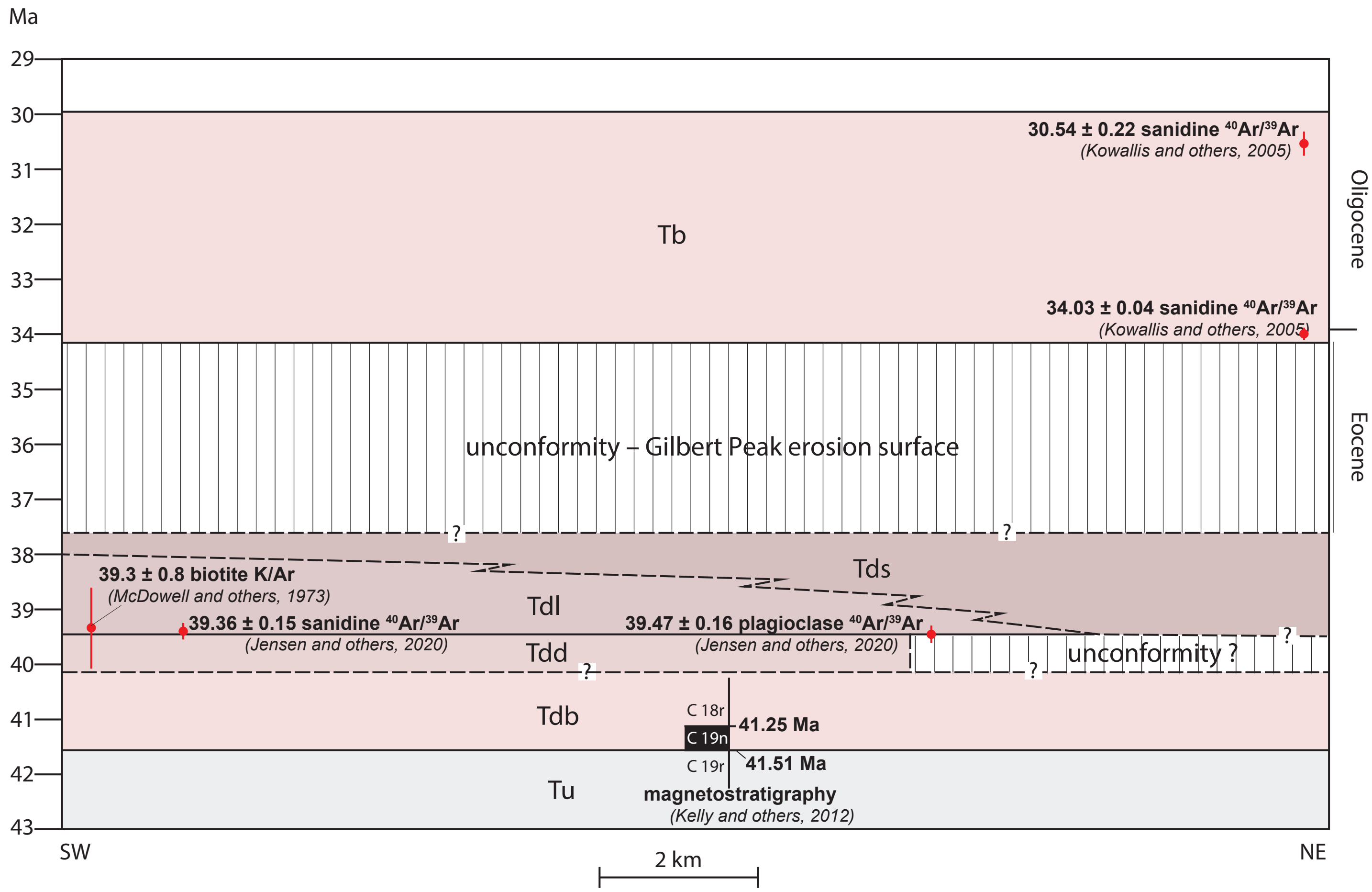

Figure 13. Chronostratigraphic diagram for the Duchesne River Formation and Bishop Conglomerate in the Vernal NW quadrangle. Ages from previous studies and from our own samples collected within the quadrangle are shown. Dashed lines are inferred due to weak constraints on contact age. Solid lines indicate a strong age approximation. Tu – Uinta Formation, Tdb – Brennan Basin Member, Tdd – Dry Gulch Creek Member, Tdl – Lapoint Member, Tds – Starr Flat Member, Tb – Bishop Conglomerate.

The approximately 4 m.y. hiatus (37.9 to 34.0 Ma) between the end of the Duchesnean fauna and an age from a tuff near the base of the Bishop Conglomerate (Kowallis and others, 2005) indicates a significant unconformity between the two formations (figure 13). This implication is strengthened by the angular nature of the unconformity (up to 21° difference in dip) and the presence of the Gilbert Peak erosional surface (Hansen, 1986a). Uplift must have occurred along the Uinta Basin fault zone, which resulted in warping of the Starr Flat Member and increasing the gradient of the Uinta Mountain flanks so that the Gilbert Peak erosion surface could form and truncate the already deformed Duchesne River Formation.

In the Vernal NW quadrangle, all the evidence refutes 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 evidence of tectonic deformation in the Bishop Conglomerate that would suggest otherwise. 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 along the Uinta Basin fault zone after 37.9 Ma, which approximates the end of deposition of the Starr Flat Member. These relationships show the continuation of Laramide uplift in this region until an age younger than the previously reported 45 to 40 Ma (Coney, 1972; Cross, 1986, Hintze and Kowallis, 2021).

The formation of the Gilbert Peak erosion surface and subsequent deposition of the Bishop Conglomerate represents a final pulse of Paleogene uplift that continued in this region until as late as 30 Ma. Uplift is documented by the widespread erosion forming the Gilbert Peak surface followed by renewed unroofing of the Uinta Mountains producing the alluvial fan deposits of the Bishop Conglomerate. Subsequent downcutting by the Colorado River drainage and post-10 Ma uplift (Aslan and others, 2010, 2017; Karlstrom and others, 2012) has dissected the Bishop Conglomerate deposits and lowered the local base level so that these deposits are now found only as remnants of the former bajada that likely surrounded the Uinta Mountains 30 Ma.

CONCLUSIONS

Throughout much of the Vernal NW quadrangle on the southern flank of the Uinta Mountains, stratigraphic contacts in the Duchesne River Formation closely match the descriptions given by Anderson and Picard (1972). Exceptions to this include the Lapoint/Starr Flat contact and all contacts proximal to the mountains. We observed an interfingering relationship between the Lapoint and Starr Flat Members where the fine-grained Lapoint eventually pinches out completely near Little Mountain. The Dry Gulch Creek Member also pinches out near Little Mountain. All Paleogene formations near Little Mountain consist primarily of alluvial-fan facies with abundant conglomerates. In this northern part of the quadrangle two different conglomeratic units of the Duchesne River Formation (Brennan Basin and Starr Flat Members) are in contact with each other. The Brennan Basin Member can be identified by a high percentage of Paleozoic limestone clasts (72% to 91%) whereas the Starr Flat Member contains a much higher percentage of Neoproterozoic clasts (34% to 73%). The contact separating these two conglomeratic units is possibly unconformable. The contact between the Starr Flat Member and Bishop Conglomerate is also an angular unconformity despite the similar clast compositions between the two formations. Clast compositions in uplift-proximal outcrops and their downstream counterparts are also similar.

The member contacts in the Duchesne River Formation as described by Anderson and Picard (1972) appear to be conformable and represent chronostratigraphic boundaries in the deposits that are distal from the mountain front. However, the Duchesne River Formation member contacts near Little Mountain may not represent chronostratigraphic boundaries but can still be distinguished from lithological differences and clast composition. This pattern may also hold true to other uplift proximal deposits and can be mapped similarly.

We found clear evidence for three distinct uplift events not previously documented in the Duchesne River Formation and Bishop Conglomerate, each occurring during a period of slab rollback as described by Fan and Carrapa (2014) and resulting in the final stages of uplift in the Uinta Mountains. Ash layers found in the

Dry Gulch Creek Member and abundant in the Lapoint Member add additional evidence that uplift of Uinta Mountains during the Eocene occurred as the Farallon slab rolled back and the ignimbrite flare-up swept southward into northeastern Nevada.

The first of these uplift events is recorded at the contact between Cretaceous units and the Brennan Basin Member and is evidenced by an angular unconformity (54 to 24^0) and deposition atop the unconformity of coarse conglomerates that fine upward. The age of the Brennan Basin Member is estimated to be around 40.7 Ma (Sprinkel, 2018). The second episode of uplift is recorded by the progradation of the alluvial fan facies of the Starr Flat Member across the finer-grained deposits of the Lapoint Member and the angular discordance between the Lapoint and Starr Flat Members seen in the north adjacent to the Dry Fork quadrangle (Haddox, 2005). This period of uplift occurred between 39.4 and 37.9 Ma. A third episode is recorded at the Starr Flat/Bishop contact and occurred between 37.9 and 34 Ma. This is evidenced by another significant angular unconformity (7 to 21^0 to less than 5^0) followed by deposition of the coarse alluvial fan deposits of the Bishop Conglomerate. Distinct pulses of uplift may be related to delamination and dripping of lithospheric mantle. Neogene uplift, not associated with the Duchesne River/Bishop Conglomerate deposits later affected the region.

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