Facies and Sequence Stratigraphy of the Three Forks Formation in Southwestern Montana

A Thesis

Presented in Partial Fulfillment of the Requirements for the

Degree of Master of Science

with a

Major in Geology

in the

College of Graduate Studies

University of Idaho

by

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May 2017

## Authorization to Submit Thesis

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## Abstract

Nine outcrops of the Late Devonian Three Forks Formation were measured and sampled in Southwestern Montana. Six facies associations, comprised of eleven lithofacies, were identified within the Three Forks Formation and reflect six depositional environments that include supratidal, intertidal, shallow subtidal restricted, a transgressive lag, open marine, and lagoonal depositional settings. A sequence stratigraphic framework for the Three Forks Formation was created by correlating depositional environments and key depositional surfaces across the study area. Two stratigraphic sequences were identified. Sequence one is a partial stratigraphic sequence, is composed of a transgressive systems tract, and includes the lower Three Forks Formation lithologies. Sequence two is composed of a transgressive systems tract, an overlying regressive sequence tract, and includes the uppermost Three Forks Formation lithologies. Sequence two pinches out progressively to the east. The Three Forks Formation in southwestern Montana bears striking sedimentological and stratigraphic similarities to the Three Forks Formation in the Williston Basin and can potentially serve as an outcrop analog.

## Acknowledgements

I would first like to thank my advisor, Dr. Peter Isaacson, for his support and encouragement. I would also like to extend gratitude to my committee members Dr. Elizabeth Cassel and Dr. Kenneth Sprenke, who made my defense a truly great experience.

My research would not have possible without guidance and input from Ted Doughty and George Grader at PRISEM Geoscience Consulting. I also would like to sincerely thank John Hohman, John Guthrie, and Aaron Rodriguez for their help and their friendship. I also owe a great deal of thanks to the fine people at the Lewis and Clark Motel in Three Forks, Montana. Additionally, I want to thank Hess Corporation and the Colorado Scientific Society for providing funding for this project.

This thesis is dedicated to my family.

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# Introduction

The Late Devonian Three Forks Formation is a significant hydrocarbon reservoir of the Bakken Petroleum System in the Williston Basin (Bottjer et al., 2011) containing an estimated 3.73 billion barrels of recoverable oil (US Geological Survey report, Fact Sheet - 2013) Due to low porosity and permeability values in Three Forks reservoir lithologies, production from the Three Forks Formation is variable and partly dependent on requisite lithologic development of the reservoir lithofacies (Egenhoff et al., 2011; Sonnenberg et al., 2011). The sequence stratigraphic relationships and lateral lithofacies variability of the Three Forks Formation is poorly understood, despite being critical to effective hydrocarbon production (Gantyno, 2010; Theloy and Sonnenberg, 2013).

The Three Forks Formation in the Williston Basin occurs mostly in the subsurface, making lateral lithofacies relationships difficult to track despite an abundant dataset from wireline logs and core. It has been demonstrated that the lithologic properties, depositional environments, and facies variability in petroleum reservoir lithologies can be more effectively studied in a continuously exposed outcrop of time equivalent strata (Kerans et al., 1994; Grammer et al., 2004; Zecchin and Caffau, 2012). Establishment of a sequence stratigraphic framework for the Three Forks Formation in outcrop will provide much needed insight into the lateral facies variations of the Three Forks Formation reservoir in the subsurface.

The Late Devonian Three Forks Formation in southwestern Montana is time-equivalent and lithologically similar to the to the Three Forks Formation in the Williston Basin (Thrasher, 1987; Sandberg et al., 1988a). The Three Forks Formation in this region is exposed along numerous mountain belts and structural uplifts, making this the ideal location to conduct an outcrop-based study (e.g., Maughan, 1993). Most detailed investigations into Three Forks Formation sequence stratigraphy and lithofacies relationships focused only on lithostratigraphy (Sandberg, 1962, 1965; McMannis, 1955). This study will place the Three Forks Formation in southwestern Montana within an updated sedimentological and sequence stratigraphic framework.

## Regional Geologic Background

The Three Forks Formation and its stratigraphic equivalents were deposited throughout the western United States during the Late Devonian Period and include predominantly carbonate and evaporitic lithologies. In western Montana, Three Forks deposition was influenced by eustatic fluctuations and regional tectonism. In this region, the Three Forks Formation has historically been subdivided into two Members: the restricted Logan Gulch Member and the open marine Trident Member (Sandberg, 1965).

### Regional Tectonics and Paleogeography

By the Devonian Period, Laurentia had rifted away from remnants of Rodinia and had shifted into equatorial latitudes (Kent, 1985; Dickinson, 2004; Miall et al., 2008). From the late Precambrian through Middle Devonian, a passive continental margin had developed along the western extent of Laurentia, which encompasses the present day North American Craton (Dorobek et al., 1991). During the late Middle to Late Devonian, continental subduction to the west of this former passive margin instigated the formation of magmatic arc systems (Poole et al., 1977; Dickinson, 2004) that included coeval foreland deformation and subsidence. Collision of this volcanic arc with the western margin of North America initiated the Antler Orogeny (Speed and Sleep, 1982; Nilson and Stewart, 1980; Dorobek, 1991). Subsidence to the east of the Antler orogenic system, initiated by tectonic loading, led to the formation of the asymmetrical, north-south trending Antler foreland basin along the western North American shelf margin, bounded to the west by the Antler Highlands, and to the east by the North American craton (Isaacson et al., 2008). Flysch deposits of the Middle Devonian Milligan Formation in Idaho record the passive to active transition of the Laurentian Margin and the following subsidence of the Antler foredeep (Sandberg, 1975; Dorobek, Reid, and Elrich, 1991). Late Devonian Antler-related convergence led to the reactivation of Neoproterozoic Belt Basin fault networks, which led to the initiation of numerous structural paleohighs and lows and resulted in rapidly changing paleotopography throughout the region (Peterson 1981, Winston, 1986; Dorobek, 1991; Dorobek, 1995). Paleostructural elements that were active during Devonian-Early Mississippian in southwestern Montana include the Central Montana Trough, the Central Montana Uplift, the

Beartooth Shelf, the Lemhi Arch, The Sweetgrass Arch, and the Muldoon Trough (Peterson, 1981; Peterson and Smith, 1986) (**Figure 1**).

## Development of the Antler Foreland Basin

Deposition of the Three Forks Formation in southwestern Montana was significantly influenced by the concurrent evolution of the Antler Orogeny and the Antler Foreland Basin. The Antler Orogeny was initiated during the late Devonian and persisted through the Mississippian Period (Gutschick et al., 1976; Speed and Sleep, 1982). It developed in response to the eastward convergence of an island arc chain along a portion of the western margin of Laurentia that extended through Nevada, Idaho, and western Montana (Roberts, 1951; Peterson, 1981; Dorobek, 1991). During the Devonian, an acretionary prism had formed along the eastwardly progressing arc system, leading to vertical loading of the underlying lithosphere and instigating flexural subsidence (Speed and Sleep, 1982). This subsidence led to the development of the asymmetrical, NW-SE trending Antler Foreland Basin along the Laurentian margin.

The architecture of the Antler Foreland Basin depositional system gradually evolved throughout Late Devonian-Early Mississippian time as reflected in stratigraphic relationships throughout Idaho and Montana. Stratigraphic and sedimentological evidence from northern and central Idaho indicate a western source terrane and initiation of an adjacent foredeep to the east by at least Early Devonian time (Isaacson, 1983; Dorobek, 1991). Further east, progressive subsidence along the basin margin led to the formation of low-accommodation depocenters that were filled with shallow water and marginal marine deposits. Through the Late Devonian-Early Mississippian time, Antler convergence caused structural instability on eastward margin of the fully formed Antler Foreland Basin, and led to numerous instances of depocenter migration and inversion. These migrations and inversions are evidenced by numerous erosional surfaces and lags within many Devonian and Mississippian deposits throughout the region.

**Late Devonian Depositional System**

The Late Devonian depositional system in western Montana was controlled by the activation of regional tectonic elements throughout the region as well as by eustatic fluctuations. The Taghanic Onlap, a significant transgressive episode that occurred during the late Devonian (Givetian - late Middle Devonian), provided the western ocean a connection to the intracratonic Williston Basin via a narrow channel through western Montana (Sandberg et al., 1982). This transgression, paired with concurrent subsidence of the Central Montana Uplift, led to deposition of the peritidal Jefferson Formation east of the Antler Fordeep on the western shelf platform and within elongate, structurally controlled systems that included estuaries in western Montana (McMannis, 1965; Sandberg et al., 1982; Dorobek and Smith, 1989; Whalen, 1995; Dorobek 1995). Deposition of platform carbonates throughout the western United States prevailed through the remainder of the Middle and most of the Late Devonian (Sandberg et al., 1982). More recent suggestions of sea level drawdown(s) by Gondwana glaciations (Isaacson et al., 1999, 2008, Brezinski et al., 2010) punctuated Montana's Late Devonian marine systems with short-lived eustatic subaerial exposure and unconformities.

A major regressive event during the earliest Late Devonian (Frasnian) halted the advance of platform carbonate development throughout the region and initiated evaporite deposits within sabkha and restricted estuaries. These deposits display both nearshore and offshore facies and include the Logan Gulch Member of the Three Forks Formation in Western Montana, the Potlatch Anhydrite in the Potlatch Basin in Northern Montana, beds of the Bierdneau formation in Idaho and Utah, and the Three Forks Formation in the Williston Basin (Poole et al., 1977).

A rapid transgression during the early Famennian briefly interrupted the period of Late Devonian regression in the Western U.S. and inundated a narrow seaway that extended from southern Alberta through western Montana and southeastern Idaho (Poole et al., 1977; Sandberg et al., 1982; Sandberg et al., 1988a). This transgression only affected the continental shelf margin of Western North America and led to the deposition of the Trident member of the Three Forks Formation in western Montana, The Big Valley Formation and the Costigan Member of the Palliser Formation in Alberta, and the upper Bierdneau Formation in Idaho and Utah (Johnson and Sandberg, 1988). A pulse of epeirogenic uplift and subsequent activation of structural elements throughout western Montana and Wyoming ended this transgressive phase and led to the development of a regional erosional surface (Poole et al., 1977; Sandberg et al., 1988a).

A brief transgressive episode occurred during the latest Famennian. This Upper Famennian Depositional Complex includes the basal black shales of the Sappington Formation, the Leatham Member of the Pilot Shale, the basal Exshaw Formation, and the basal shales of the Bakken Formation (Sandberg et al., 1983; Sandberg et al., 1988a). These units punctuated deposition within a final regressive phase that capped the Devonian Period in the Western U.S. and Canada. During this time, the upper members of the Sappington Formation and the middle member of the Bakken Formation were deposited (Sandberg et al., 1988a).

**Sedimentological and Stratigraphic Background**

Investigations by previous authors (Sloss and Laird, 1947; McMannis, 1955; Sandberg, 1962, 1965) have defined the lithologies, depositional environments, and lithostratigraphic framework of the Three Forks Formation in southwestern Montana. They have provided a solid foundation for this study. The type section of Three Forks Formation is located in Logan, Montana, and was first described by Peale in 1893 as "The Three Forks Shales", a lower and upper shale package, separated by an interval of limestone and bounded by the Devonian Jefferson Formation at the base, and Carboniferous strata at the upper contact. Sloss and Laird (1947) later recognized an upper yellow sandy limestone as the Sappington Member of the Three Forks Formation, and linked a lower interval of evaporite solution breccias to the Three Forks Formation rather than the underlying Jefferson Formation. These breccias were later included into the Three Forks Formation (McMannis, 1955). Sandberg (1962, 1965) was the first to recognize the Logan Gulch Member and the Trident Member of the Three Forks Formation at the Type Section. His lithologic divisions of the Logan Gulch and Trident Members are frequently cited in literature and are used in this study. Due to complications obtaining permission to enter the property upon which the type section of the Three Forks Formation is located, a summation of Sandberg's 1965 description is provided below.

Lower Logan Gulch Member of the Three Forks Formation is 111 feet thick and consists of argillaceous limestone and shale breccias containing interbeds of dolomitic shale and siltstone at the base, and beds of grey limestone and brecciated limestone at the top. The Logan Gulch basal breccias are attributed to dissolution of evaporitic minerals and the collapse of overlying and interbedded strata. Further to the east, the Logan Gulch facies is interpreted to change (Sandberg, 1965), and it displays interbedded dolomitic siltstone and shale with ripple marks, and contains local deposits of collapse breccia in the basal portions. These evaporitic and dolomitic lithologies of the Logan Gulch are interpreted by Sandberg (1965) to be offshore and near shore evaporitic facies that reflect deposition within a restricted basin in southwestern Montana.

The Trident Member at the Logan type section is 73 feet thick. It is composed of a light grey to orange dolostone at the base, 42 feet of light grey fossiliferous shale in the middle, and capped by 9 feet of massively bedded grey fossiliferous limestone. The shale thickens in western outcrops and contains abundant limestone interbeds. The upper limestone is discontinuous. Sandberg (1965) interpreted that the Trident Member was deposited on an open marine shelf that was extended northward from southwestern Montana.

The Sappington Formation was initially included as the third member of the Three Forks Formation by Sandberg (1962, 1965) in his description of the Three Forks Formation type section at Logan Gulch, MT, because it was not considered to be a regionally mappable unit. However, stratigraphic and biostratigraphic investigations show that occurrence of the Sappington Formation is widespread across western Montana (McMannis, 1965), separated from the Three Forks Formation by a regional disconformity (Wheeler, 1963), and contains markedly different faunal assemblages than those of underlying Trident Member (McMannis, 1955, 1962, 1965). For this reason, the Sappington Formation is herein considered stratigraphically independent of the Three Forks Formation.

## Regional Correlations

The nomenclature for equivalent Late Devonian strata in the western United States and Canada is inconsistent between basins, and can be confusing when making stratigraphic and sedimentological correlations. The Three Forks Formation in western Montana is partly equivalent to late Devonian strata in adjacent basins, namely, certain Formations of the Three Forks Group in southern Saskatchewan (Christopher, 1961, 1962) and the Wabamun Group of southern Alberta (Sandberg, 1965; Hartel et al., 2012; Halbertsma, 1994), as well as the Potlatch Anhydrite in northern Montana (Wilson, 1955; McMannis, 1955; Christopher, 1961, 1962; Sandberg 1965, Sandberg et al., 1988a; Grader et al., 2014) (**Figure 1**).

The Three Forks Group was deposited throughout much of southern Saskatchewan and includes the lower Torquay Formation and the Upper Big Valley Formation. The Torquay formation is primarily composed of thickly bedded evaporites (Christopher, 1962) and is correlative to Sandberg's (1965) Logan Gulch member of the Three Forks Formation. The overlying Big Valley Formation is composed of mainly marine deposits (Christopher, 1962) and is correlative in part to the Trident Member of the Three Forks Formation (Sandberg, 1965) as well as the adjacent Big Valley Formation of the Wabamun Group in Alberta.

The Wabamun group was deposited on a shallow shelf margin throughout west-central Alberta during Late Devonian Time (Wonfor and Andrichuck, 1956; Andrichuck, 1960). It consists of the lower Stettler Formation and the upper Big Valley Formation. The Stettler Formation is primarily composed of evaporitic deposits of anhydrite, dolomitic anhydrite, and halite (Wonfor and Andrichuck, 1956). The upper 40' is composed of sachroidal pink to tan dolomite (Wonfor and Andrichuck (1956). It is correlative to the Logan Gulch member of the Three Forks Formation (Sandberg, 1965, Halbertsma, 1994). The Big Valley Formation is composed of Marine shelf deposits and is correlative to the Trident Member of the Three Forks Formation (Sandberg, 1965).

The Potlatch Anhydrite was first described in the subsurface of northwestern Montana and southern Alberta (Wilson, 1955) and contains light colored dolomite and thickly bedded anhydrite (Wilson, 1955; Sandberg and Hammond, 1958). It was deposited in a restricted, evaporitic basin that extends from western Montana to the Alberta Basin to the North (Wilson, 1955; Sandberg and Hammond, 1958; Sandberg, 1962, 1965). Wilson (1955) first recognized that the 200’ to 600’ thick anhydrite beds of the Potlatch Anhydrite could be correlated to the ~100’ thick section of collapse breccia found in sequence 1 of the lower Three Forks Formation at the type section in southwestern Montana. Based on this correlation, the Potlatch Anhydrite was considered to be the Potlatch Member of the Three Forks Formation and included much of the lower Three Forks Formation lithologies (Sandberg and Hammond, 1958). Sandberg (1965) later changed the designation of the Potlatch to only refer to the anhydrite deposition the subsurface of Montana and southern Alberta

Portions of the Three Forks Formation in the Williston Basin are coeval and sedimentologically correlative to the western Montana Three Forks Formation (Sandberg, 1965), however a direct stratigraphic correlation remains unclear. The overlying Devonian-Mississippian Sappington Formation of Western Montana has been biostratigraphically correlated to the Exshaw Formation in the in the Alberta Basin in Alberta, and the Bakken Formation in the Williston Basin in Western North Dakota and Eastern Wyoming (Christopher, 1961; Sandberg, 1988a; Halbertsma, 1994; Grader et al., 2014).

## Methods

Sedimentological analysis of the Three Forks Formation was conducted at 9 outcrops in western and southwestern Montana (**Fig. 2**). Outcrops were measured with a Jacob staff, tape measure, and brunton compass. Standard sedimentological descriptions were used to describe units within field outcrops (Appendix I) . Gamma measurements were taken at 8 locations using a Rs 230 BGO Superspec scentilometer. Gamma counts were converted to API and utilized in Petra, in tandem with outcrop descriptions, to aid in stratigraphic correlations.

Samples were taken at 100 to 20 cm intervals from each location, with more concentrated sampling focused on lithofacies contacts and bounding surfaces. In order to make detailed observations, samples were slabbed using a standard diamond-studded rock saw at the University of Idaho campus. 27 billets were cut and sent to Wagoner Petrographic Inc. to be made into thin sections. Thin sections were analyzed using Petrographic Microscopes located at the University of Idaho, and Morehead State University (KY) campuses.

Lithologies within the Three Forks Formation are predominantly dolomitized. In order to describe dolomitization textures in thin section, the classification scheme of Friedman (1965) and Randazzo and Zachos (1983) as outlined in Flügel (2004) (**Figure. 3**) was employed. The dolomite crystal size scale of Friedman (1965) was used to describe the various dolomite fabrics found within the Three Forks Formation. According to this scale, the term Dolomicrostone refers to dolomite rhombs that are less than 4 µm, dolomicrosparstone refers to dolomite rhombs that are between 4–10 µm, and dolosparstone refers to dolomite rhombs that are greater than 10 µm. The Dunham classification scheme was used to describe additional carbonate lithologies.

# Facies Analysis

11 Lithofacies were identified within the Three Forks Formation. These lithofacies were used to identify 6 facies associations. The facies associations listed from shallowest to deepest depositional setting include a supratidal, intertidal, shallow subtidal, lagoonal, and open marine facies (**Table 1**). A fossiliferous lag was also identified in two locations and included with its own facies association.

## Supratidal Facies Association: FA 1

Facies Association A is identified as supratidal and is comprised of solution breccias and dolomitic mudstones (**Figure 4)**.

### Lithofacies 1

Lithofacies 1 is a dark red to light green, fissile, aphanotopic dolomitic mudstone. Estimated percentage of quartz in this lithofacies is 60%. Quartz grains are mud to silt size, ranging from .003 mm-.05 mm in size. Quartz grain shape is oblate to spherical, and subrounded to angular. Dolomite crystals within this lithofacies display an equigranular, xenotopic crystallization fabric. There is no visible porosity. Lithofacies 1 is significantly oxidized in certain intervals. Thin interbeds of tan dolostone with preserved salt hoppers could be found in the float of this facies. In outcrop, this lithofacies is fissile and susceptible to weathering. It is typically covered but remains distinguishable due to large amounts of dark red clay staining in float.

### Lithofacies 2

Lithofacies 2 is classified as massively bedded, mixed carbonate and dolomitic breccia. This lithofacies displays both clast and matrix-supported fabrics. lithoclasts range in size from 1-50cm, are rounded to angular and are composed of lime mudstones and laminated dolostones. Lithoclasts range from tan, green, red, brown and gray and often contain thin laminations. Occasional desiccation and soft sediment deformation features are noted within lithoclasts. Transitions between matrix and clast supported breccia can be gradual to sharp.

## FA 1 Interpretation

Lithofacies 2 was deposited in an arid supratidal coastal salina. Rare intermittent flooding of this zone from the sea during storms resulted in the accumulation of carbonate mud within supratidal saline mudflats and ephemeral salt pans (Pratt, 2010). The presence of subrounded to subangular grains of fine to very course silt was likely the result of sediment input via eolian processes, however, the transport and deposition of terrigenous sediment as a result of unchannled sheet flow during marine flooding events may be a possibility (Handford, 1982; Pratt, 2010). The green coloring of the dolomitic siltstone is the likely result of reducing environmental conditions caused by periods of increased flooding (Aigner and Bachman, 1988). Conversely, the reddish coloring of the dolomitic siltstone is due to the prolonged periods of subaerial exposure and mudflat-type environmental conditions, leading to oxidization (Wilson, 1975; Aigner and Bachman, 1988).

The presence of salt hoppers within dolostone interbeds in this lithofacies indicates deposition within an arid climate. Cubes of halite containing pyramidal hollows (salt hoppers) are the result of subaerial crystal precipitation from saturated brines and mud (Kendall, 2010). Due to the displasive formation process of salt hoppers within the capillary fringe of the saline mudflat, any previously formed diagnostic sedimentary structures within this lithofacies could have been interrupted or obliterated (Aigner and Bachman, 1988; Kendall, 2010). The precipitation of salt hoppers within this lithofacies indicates periodic subaerial exposure. Salt hoppers are rare in this lithofacies, most likely because of dissolution or eolian transport soon after deposition (Handford, 1982; Kendall 2010).

Lithofacies 2 is interpreted to be an evaporite solution breccia and is indicative of evaporite deposition within a supratidal environment. Gypsum and anhydrite were syndepositionally precipitated in lithofacies 2 in arid supratidal conditions. Dissolution of these evaporitic minerals at depth lead to the collapse of the surrounding host lithologies, creating a dissolution-collapse breccia (Friedman, 1997). The thin laminations, desiccation structures, and soft sediment deformation in lithoclasts found in this lithofacies suggest deposition within an arid supratidal setting. This lithofacies lies in contact with, or contains interbeds of, another supratidal lithofacies (lithofacies 1) further indicating deposition within a supratidal environment.

## Intertidal Facies Association: FA 2

Facies association FA 2 is defined as Intertidal and is composed of three Lithofacies: a silty dolomicrostone, a tan dolomicrosparstone, a light green, and shaley dolomicrostone **(Figure 5).**

## Lithofacies 3

Lithofacies 3 is a yellow to tan fogged mosaic silty dolomicrostone. Dolomite crystals are innequigranular and display a xenotopic crystallization fabric. Lithofacies LG 5 contains 25% estimated quartz. Quartz grains are sub rounded to subangular and are oblate in shape. These quartz grains range in size from .00125mm-0.0075mm and are subrounded. Estimated porosity is less than 5% and is found in fractures. This lithofacies is thinly bedded with beds ranging from 5 to 20 cm. Occasional lenticular bedding is noted throughout this lithofacies. Beds display normal grading, and contain plane parallel laminations. These normal graded packages are typically .01 mm thick. Contacts between these laminations are abrupt **(Figure 6)**.

## Lithofacies 4a

Lithofacies 4a is a light yellow to tan spotted mosaic dolomicrosparstone. Dolomite crystals are inequigranular and display a hypidiotopic crystallization fabric. Estimated porosity is 5% and predominantly occurs within fractures, however, occasional fenestral porosity was observed between planes of lamination. Subangular, spherical quartz grains were recorded with an average size of .0025mm. The estimated quartz percentage seen in thin section is less than 5%. This lithofacies is thinly bedded in outcrop (1-10cm). Sedimentary structures within these beds include plane parallel laminations with fining upward laminae, as well as rare cross laminations.

## Lithofacies 4b

This lithofacies is a light green to grey fissile spotted mosaic dolomicrostone. Dolomite crystals are predominantly equigranular with a xenotopic crystalline fabric. Porosity within this lithofacies is estimated to be less than 5%. Porosity is typically found in fractures with only trace amounts of intercrystalline porosity observed.

## Lithofacies 5

Lithofacies 5 is a light tan sieve mosaic aphanotopic dolostone. Dolomite crystals are nonrhombic, are equigranular, and display a xenotopic crystallization fabric. Porosity in this lithofacies is estimated to be 15%. This lithofacies is medium bedded and contains laterally linked algal laminations, desiccation structures, and ripples on bedding surfaces. This lithofacies is only found interbedded in lithofacies 6 at the section at Dry Hollow.

## FA 2 Interpretation

Lithofacies 3 contains predominantly heterolithic bedding with a low mud-sized sediment content (Diadu, 2013). Heterolithic bedding is common in intertidal environments where ebb and slack tides progressively deposit coarse and fine-grained sediments, respectively (Davis, 2012). Intertidal deposits characteristically coarsen seaward. The presence of coarse silt to fine sand in this lithofacies, in conjunction with a low amount of mud-sized sediment indicate that it was deposited in the lower extent of the middle intertidal zone. Although this lithofacies contains noticeably coarser sediment than the middle intertidal deposits represented in lithofacies 4a and 4b, it does not contain the sedimentary structures associated with the higher energy regime of the lower intertidal zone, and is thus similarly considered indicative of deposition within the middle intertidal zone (Davis, 2012; Dalrymple, 2010; Diadu et. al., 2013).

Lithofacies 4a and 4b were deposited in a middle intertidal setting. These lithofacies gradationally alternate between beds of the courser dolomite fabric of lithofacies 4a, and beds of the mud sized dolomitic fabric of lithofacies 4b. Lithofacies 4a was deposited during periods of ebb tide, and the mud-size sediment of lithofacies 4b settled out during periods of slack tide. These lithofacies display wavy bedding, a spectrum of heterolithic deposition typically representative of tidal influence (Davis, 2012; Diadu, 2013). Monolithic deposition is also noted in lithofacies 4a and is representative of the same kind of tidal influence as heterolithic bedding, only expressed in a single, distinct sediment type (Davis, 2012). Wave ripples such as those found on surfaces of lithofacies 4a are commonly generated within intertidal to tidal flat environments (Allen, 1982, Davis, 2012). The lack of abundant current ripples and terrigenous sediment input indicate that this lithofacies could have been deposited in a back-barrier type setting (Diadu, 2013).

Lithofacies 5 is placed within an upper intertidal-to-tidal flat environment. Desiccation structures indicate periods of subaerial exposure, while wave ripples and wavy bedding indicate periods of current interaction. Lithofacies 5 only occurs interbedded with Lithofacies 6 at the Dry Hollow outcrop. Contacts between Lithofacies 5 and 6 are abrupt and show that periodic variations in mean sea level resulted in sudden transitions between the two different depositional systems.

## Restricted Shallow Subtidal Facies Association: FA 3

Facies association LG - D is interpreted to be a subtidal deposit. It is composed of one Lithofacies: a crystalline lime mudstone with occasional interbeds of pelletal grainstone (**Figure 7**).

## Lithofacies 6

Lithofacies 6 is a light grey to purple crystalline, bioturbated lime mudstone with occasional interbeds of pelletal grainstone. Sedimentary structures in this lithofacies include algal laminations at the Lick Creek and Baker Mountain outcrops. This limestone is ledge forming and outcrops at Lick Creek, Milligan Canyon, Dry Hollow, Mill Creek, and Hardscrabble and ranges in thickness from 2 to 20 ft. Lithofacies 6 is typically highly fractured or brecciated. Where preserved, the contact with both underlying and overlying lithologies is sharp. Lithofacies 6 included interbeds of the intertidal lithofacies 5. At the Three Forks type section, this lithofacies is referred to by Sandberg (1965) as a "brownish-gray limestone and limestone breccia" that caps the Logan Gulch member.

## FA 3 Interpretation

The bioturbated crystalline lime mudstone of this lithofacies is likely the result of shallow water deposition in subtidal settings where circulation was restricted. The general lack of biota in this lithofacies points toward a high salinity, or restricted environmental conditions. Such an environment could possibly occur on the landward lagoon margin (Harris et al., 1985). Interbeds of pelletal grainstone were caused by intermittent increases in current energy, possibly due to local sea level fall (Harris et al., 1985). Brecciation of this lithofacies in places could be the result of dissolution in the phreatic zone during a sea level drawdown (Mylroie and Carew, 1990).

**Transgressive Lag: FA 4**

Facies Association 4 is composed of a lag deposit found in two outcrop sections (**Figure 8**).

**Lithofacies 7**

Lithofacies 7 is a lag deposit that is observed at the Baker Mountain and 63 Ranch sections. The lag contains an abundance of fragmented conodonts, bone material, and plant debris. This lag has a quartz grain matrix and has an estimated porosity of 10%. This lag is typically 5 to 10 centimeters thick and lies in sharp contact with the bounding lithologies.

**FA 4 Interpretation**

Lithofacies 7 is interpreted as being a transgressive lag deposit since the overlying Sappington Formation shales were deposited within a deeper depositional setting than the lithologies below (Cantuneau, 2006).

**Open Marine Facies Association: FA 5**

Facies association FA 5 is classified as open marine, shallow subtidal carbonate shelf facies and is composed of a dark grey marine laminated dolostone lithofacies, and a light grey-green laminated fossiliferous dolostone lithofacies **(Figure 9)**.

**Lithofacies 8**

Lithofacies 8 is a dark grey to dark brown laminated aphanotopic dolostone that lies stratigraphically below, and grades into, Lithofacies 9. No fossils or bioturbation are noted in this lithofacies. Laminations in this lithofacies are planar. Due to the weathered nature of the overlying Lithofacies 9, Lithofacies 8 is typically recessive and covered in outcrop.

**Lithofacies 9**

Lithofacies 9 is a light green to light grey, laminated, fossiliferous, aphanotopic dolostone. Dolomite crystals are equigranular and display a xenotopic crystallization fabric. There is no observable porosity within this lithofacies. Laminations are plane-parallel with occasional ripple laminations present. This lithofacies is highly bioturbated preventing accurate interpretation of most trace fossils, however thalassinoides was noted in core. Brachiopod, gastropod, and echonoderm fossil fragments can be found throughout this lithofacies. Lithofacies 9 is fissile in outcrop and typically weathers in a characteristically “shaley” nature to form slopes.

**Lithofacies 10**

Lithofacies 10 is a light to dark grey to light grey fossiliferous packstone. Estimated porosity is 10%, and is predominantly moldic. The lime matrix is dolomitized and displays a crystalline texture with little to no observable intercrystalline porosity. Fossil fragments in Lithofacies 10 were observed in outcrop and core including brachiopods and trace amounts of gastropods and echinoderms. Whole fossils are rare in this lithofacies. Lithofacies 10 lies in contact with the overlying Sappington Formation. Where exposed, this contact is bleached and unconsolidated.

**Facies Association FA 5 Interpretation**

Lithofacies 8 was deposited on the mid-ramp of a carbonate shelf. Lithofacies 9 shows little to no wave reworking and was deposited below the storm wave base. This lithofacies’ dark grey coloring was caused by deposition in reducing environments. Planar laminations were the result of mud to fine silt-sized sediments settling out of suspension. The transition between Lithofacies 8 and Lithofacies 9 is gradual.

Lithofacies 9 was deposited within a shallow subtidal environment. This lithofacies contains occasional rippled intervals of coarser grained sediment. These occasional intervals of that reflect a higher energy regime indicate that lithofacies 9 was and deposited above the storm weather wave base but below the fair weather wave base. The thin layers of reworked fossiliferous grainstone within this lithofacies imply intermittent periods of higher depositional energy. Burrows identified to be within the cruziana ichnofacies place this lithofacies within the bounds of the lower shoreface and inner shelf (Catuneanu, 2006). The color of Lithofacies 9 changes gradually from dark grey to light grey green, indicating a gradual change from deeper, reducing environments to shallower, more oxygen-rich environments

The abundance of fossil fragments and the lack of any primary sedimentary structures in Lithofacies 10 indicates that deposition occurred within an environment that was subject to frequent reworking. Therefore, Lithofacies 10 is interpreted to have been deposited on the mid ramp above the storm wave base and below the fair weather wave base.

**Lagoonal Facies Association: FA 6**

Facies Association FA 6 is classified as lagoonal and is composed of a light brown dolosparstone (**Figure 10**).

**Lithofacies 11**

Lithofacies 11 is a light brown dolosparstone with occasional floating rhombs. Dolomite crystals are inequigranular and display a hypidiotopic crystallization fabric. Estimated porosity in this Lithofacies is less than 5% and is intercrystalline in type. This lithofacies is mediumly bedded at the Hardscrabble and Dry Hollow sections with beds ranging from 10-40 cm. This lithofacies contains planar laminations and isolated microbial laminations. This lithofacies is moderately bioturbated at the Milligan Canyon Section. Root casts are found in this lithofacies at the type section in Logan, MT (Doughty and Grader, personal communication). This lithofacies is recorded at the Hardscrabble section, the Milligan Canyon section, the Mill Creek Section, and the Dry Hollow section. It ranges in thickness from 5 to 15 feet.

**FA 6 interpretation**

Lithofacies 11 shows evidence of deposition within a subtidal lagoonal environment. Predominantly fine grained sediments and planar laminations in Lithofacies 11 are indicative of deposition under low energy conditions, typical of lagoonal systems (Boggs, 2006). Algal laminations within this lithofacies point toward deposition along the lagoonal margin (Davis and Fitzgerald, 2004). Although moderately bioturbated, this lithofacies contains no evidence of faunal abundance. This could be related to hypersaline conditions that are usually characteristic of arid lagoonal systems.

## Sequence Stratigraphy

Sequence stratigraphy is used to study how changes in base level affect sedimentation within a depositional system by defining key surfaces and depositional sequences that reflect changes in the direction of the shifting shoreline (Boggs, 2006; Cantuneau, 2006, 2009). For the Purpose of this study, the Transgressive-Regressive sequence stratigraphic model of Embry and Johannessen (1992) was applied. In this model, sequences are composed of a transgressive systems tract and an overlying regressive systems tract that are bounded by subaerial unconformities. The transgressive and regressive systems tracts are separated by a maximum flooding surface that marks the point of both maximum transgression and the onset of renewed regression.

A sequence stratigraphic framework for the Three Forks Formation in western Montana was created using observations and data collected from 9 outcrops. Trends in lithofacies stacking were used to define transgressive and regressive sequence tracts. An upward-deepening trend in lithofacies corresponds to a transgressive systems tract, while an upward-shallowing trend corresponds to a regressive systems tract. Key stratigraphic surfaces were identified and classified using the criteria outlined by Cantuneau, (2006). This criteria includes the following: *"(1) the nature of the contact (conformable or unconformable); (2) the nature of depositional systems that are in contact across that surface; (3) types of stratal terminations associated with that surface; and (4) depositional trends that are recorded below and above that stratigraphic contact"*. Sequence Stratigraphic surfaces were traced across the study area. Systems tracts and surfaces were used to construct stratigraphic correlations of sequences across the study area.

### Sequence Stratigraphic Framework

In southwestern Montana, the Three Forks Formation contains two stratigraphic sequences. The lower sequence (sequence 1) is a partial sequence and is composed of a transgressive systems tract (TST 1). The upper stratigraphic sequence (sequence 2) consists of a transgressive systems tract (TST 2) and an overlying regressive systems tract (RST 1). TST 2 and RST 1 are separated by a maximum flooding surface. Three subaerial unconformities were observed within the Three Fork Formation and are recognized as sequence boundaries (**Figure 14)**.

**Sequence 1**

Sequence 1 of the Three Forks Formation is a partial sequence and is composed of TST 1. It is bounded by two subaerial unconformities: one that separates it from the underlying Birdbear Member of the Jefferson Formation, and one that separates it from the overlying sequence 2 of the Three Forks Formation. The component lithologies of TST 1 include the supratidal deposits of Lithofacies 1 and 2, the intertidal deposits of Lithofacies 3, 4a, 4b and 5, and the restricted, subtidal Lithofacies 6. This sequence encompasses the lithologies of Sandberg's Logan Gulch Member of the Three Forks Formation (1962, 1965).

The subaerial unconformity (**Figure 11)** that separates sequence 1 from the underlying Birdbear Member of the Jefferson Formation is considered a sequence boundary in this study (Sequence Boundary 1). This contact is recognized as a regionally extensive erosional surface associated with a significant regressive episode (Sandberg, 1988a.). The surface is exposed at the Milligan Canyon, Lick Creek, Hardscrabble, Mystic Lake, and 63 Ranch sections (Appendix I), where it is observed to be sharp. At the hardscrabble section, the contact surface of the upper Birdbear Member is highly oxidized, indicating some degree of subaerial exposure.

Sequence 1 is capped by a second subaerial unconformity that is evident in western and centrally located sections of the study area, including the Milligan Canyon, Dry Hollow, Hardscrabble, and Mill Creek sections. At these sections, the upper surface of the Lithofacies 6 limestone is brecciated, creating a sharp, irregular contact with the overlying lithologies. At the Mill Creek section, overlying lithologies of sequence 2 are found infilling the brecciated depressions in Lithofacies 6. This could be indicative of karsting caused by meteoric weathering during a period of subaerial exposure (Flugel, 2004). This subaerial unconformity is interpreted as sequence boundary 2.

The TST that comprises sequence 1 is interpreted based on a deepening upward trend in lithofacies and indicates a landward shoreline shift. TST 1 is generally composed of a deepening upward succession of lithologies belonging to supratidal FA 1, intertidal FA 2, and the restricted subtidal FA 3. At the Lick Creek, Mill Creek, and Baker Mountain sections, thick deposits of the supratidal FA 1 interfinger with the intertidal lithologies of FA 2. Boulder-sized lithoclasts of FA 2 lithologies are often observed in the anhydrite collapse breccia of Lithofacies 2 at all sections where the supratidal breccia is present (Appendix A), This suggests that the interfingering of facies association 2 and 1 occurs even in outcrops where a complete expression of FA 2 is not observed. Thick deposits of FA 2 directly overly FA 1 lithologies at the Lick Creek, Mill Creek, and Baker Mountain sections. Deeper water limestone of Lithofacies 6 overly FA 1 and FA 2 lithologies at Milligan Canyon, Dry Hollow, Lick Creek, Hardscrabble, Mystic Lake, and Mill Creek. Lithofacies 6 is the uppermost lithofacies of TST 1 and is overlain by sequence boundary 2.

A surface is observed between the Lithofacies 6 limestone and the lower interbedded lithologies of FA 1 and FA 2 at Milligan Canyon, Hardscrabble, Lick Creek, Mystic Lake, Mill Creek, and Baker Mountain. At the Lick Creek section, the Lithofacies 6 limestone is observed to cut into the lower intertidal deposits of Lithofacies 3, forming a scoured contact (**Figure 13**). The change in facies across this contact at the locations listed above, along with the scoured surface observed at Lick Creek implies that a rapid rise in base level occurred. This surface is classified as a transgressive ravinement surface (Cantuneau, 2006) that occurs within TST 1.

Sequence 1 includes one systems tract bounded by two sequence boundaries. The sequence only reflects a single, transgressive shift in base level and is therefore considered to represent a partial sequence. Intervals of this partial sequence can be observed in all outcrops of this study.

**Sequence 2**

Sequence 2 of the Three Forks Formation is bounded by sequence boundary 2 at the base (**Figure 12)**, and by sequence boundary 3 at the top. It includes a lower transgressive systems tract (TST 2) and an overlying regressive systems tract (RST 1). The systems tracts are separated by a maximum flooding surface. Sequence 2 includes Lithofacies 8, 9, and 10 of the open marine FA 5, and Lithofacies 11 of the lagoonal FA 6. Sequence 2 encompasses the entirety of Sandberg's (1962, 1965) Trident Member of the Three Forks Formation.

The lithologies of sequence 2 are underlain by a subaerial unconformity identified as the previously discussed sequence boundary 2. Sequence 2 is capped by an unconformable surface that separates the Three Forks Formation from the overlying Sappington Formation (**Figure 9**). McMannis (1962) first recognized this surface as an erosional unconformity. Gutschick (1964) also observed this surface at outcrops within central and western Montana, and described a weathered "soil zone" between the uppermost Three Forks Formation and the lower Sappington shale at the Logan type section. Similar to this description, a bleached, highly weathered interval occurs between sequence 2 and the Sappington Formation at the Milligan Canyon outcrop and is interpreted as a paleosol.

Like TST 1, the interpretation of the transgressive systems tract of sequence 2 is based on a deepening upward trend in lithologies. This TST includes the lagoonal deposits of Lithofacies 11 and the open marine shales of Lithofacies 8. At the Milligan Canyon section, the lagoonal dolostone of Lithofacies 11 continuously grade into the open marine shales of Lithofacies 8 over a 3 ft. interval. At this point, the shales of Lithofacies 8 start to grade into the shallower deposits of Lithofacies 9. It is inferred that a maximum flooding surface lies somewhere in the Lithofacies 8 shales and marks the gradual end of the transgressive phase of TST 2. The Lithofacies 8 shales have been eroded out of section at all other locations. Correlative to the maximum flooding surface, a sharp contact exists between Lithofacies 11 and Lithofacies 9 at the Dry Hollow and Hardscrabble sections, and between Lithofacies 11 and Lithofacies 10 at the Mystic Lake and Mill Creek sections.

The overlying regressive systems tract of sequence 2 is recognized based on an overall shallowing-upward trend in lithologies. It includes the open marine deposits of Lithofacies 8, 9 and 10. At the distal outcrops of Milligan Canyon, Dry Hollow, and Hardscrabble, thick deposits of Lithofacies 9 lie below the shallower limestone of Lithofacies 10. At the more eastern outcrops of Mystic Lake and Mill Creek, Lithofacies 9 and 10 do not occur. Here, RST 1 is composed wholly of thick expressions of the Lithofacies 10 limestone, which is deposited directly above the lower TST 2.

Sequence 2 of the Three Forks Formation reflects a complete cycle of base level change. It occurs in outcrop in the westward sections in the study area, including Milligan Canyon, Dry Hollow, Hardscrabble, Mystic Lake, and Mill Creek. Sequence 2 is completely eroded out in the eastern outcrops of 63 Ranch, Baker Mountain, and Meyer

Creek. At these locations, a composite surface is exposed that includes SB 2, the maximum flooding surface of sequence 2, SB 3, and the transgressive ravinement surface of sequence 1. This surface separates the lower deposits of sequence 1 of the Three Forks Formation from the overlying Sappington Formation and Cottonwood Canyon Member of the Lodgepole Formation. The Lithofacies 7 lag is present At 63 Ranch and Baker Mountain and contains bone and conodont fragments.

**Basin Development**

Sequence one of the Three Forks Formation was deposited during a transgressive episode after a significant, regionally expansive regression formed Sequence Boundary 1. As sea level began to rise, arid conditions prevailed across the basin and led to the development of a supratidal sabkha on the margins of the basin, and an intertidal depositional system in more distal locations. The eastward termination of supratidal deposits, paired with the eastward thickening of intertidal lithologies indicates that deeper-water conditions were located in the eastern portion of the study area during this time. A rapid rise in sea level inundated the basin and led to widespread restricted, open marine conditions. This base level rise formed a transgressive ravinement surface on top of older supratidal and intertidal deposits. At this point, a regression led to the subaerial exposure of Sequence 1 and formed an erosional surface (SB 2) on top of TST 1. It is unclear how much time is represented by this sequence boundary.

TST 2 of Sequence 2 of the Three Forks Formation records a period of renewed transgression on top of SB 2. Shallow, lagoonal environments were flooded and eventually covered by open marine deposits. The thickening of open marine deposits to the west indicates an eastward shoreline shift during this transgression.

A gradual drop in sea level led to the shallowing-upward deposits of RST 1 throughout western portion of the basin. These deposits overlay the maximum flooding surface that caps the lower TST 2. An erosional surface separates RST 1 from younger Devonian strata and records a significant, basin-wide depositional hiatus. During this time, Sequence 2 of the Three Forks Formation was eroded out of section where it was exposed on the basin margins of Beartooth shelf.

## Comparisons to the Williston Basin Three Forks Formation

Three Forks Formation facies relationships between the shelf platform of western Montana and the Williston Basin are complex and poorly understood. This complexity is due in part to differences in the basin architecture across these two regions. Late Devonian Three Forks Formation deposits in both western Montana and the Williston Basin reflect differing effects from the development of the Antler Orogeny and the evolution of the Antler Foreland Basin.

### The Late Devonian Williston Basin Depositional System

The Williston Basin first developed as a depocenter during the Cambrian period (Kent and Christopher, 1994) and did not become the Williston Basin as it is reffered to today until later Laramide deformation (Kent and Christopher, 1994; Root, 2001; Dykes, 2015). It is thus interpreted to have been part of the distal foreland of the Antler Foreland Basin during Middle to Late Devonian Time (Root, 2001). Initial subsidence within the Williston Basin is attributed to thickened underlying crust caused by continent-continent convergence during the Pre-Cambrian Trans-Hudson Orogen (Green et al., 1985; Kent and Christopher, 1994). During the Devonian Period, The emplacement of allochthonous terranes during the Devonian-Missippian Antler Orogeny also greatly affected subsidence in the basin (Dorobek, 1991, Root, 2001). Deposition of the Three Forks and Bakken Formations occurred during this time.

The Williston Basin Three Forks Formation is primarily composed of mudflat, intertidal, arid supratidal facies (Berwick and Hendrix, 2011; Bottjer et al., 2011). Here, facies are found deposited in a genetically continuous manner both vertically and laterally throughout the region and record a basin wide transgression (Bottjer et al., 2011; Dykes, 2014). The Three Forks Formation is bounded by two regional unconformities. The lower unconformity separates the Three Forks Formation from the underlying Birdbear Formation (Jefferson Fm. equivalent). The upper unconformity separates the Three Forks Formation from the overlying Bakken Formation (Sappington Fm. equivalent).

Toward the basin center, the Pronghorn Member of the Bakken Formation, a transgressive sandstone-to-limestone unit, sits unconformably above the Three Forks Formation and pinches out toward the basin margins (Berwick and Hendrix, 2011; Johnson, 2013). This interval has been correlated northward and is thought to be equivalent to the Big Valley Formation of southern Saskatchewan (Christopher, 1961; Sandberg, 1965; Sandberg, 1988a.).

The Williston Basin Three Forks Formation is equivalent to Sandberg's Logan Gulch Member of the Three Forks Formation (Sandberg, 1965) and can be correlated to Sequence 1 of this study. It has been recognized, however, that the thick expressions of anhydrite within the Williston Basin Three Forks Formation are not preserved in the southwestern Montana Three Forks Formation, and are instead replaced by the anhydrite collapse breccias of FA 1 of this study (Sandberg and Hammond, 1958; Sandberg, 1965; Halbertsma, 1994). Additionally, the transgressive open marine deposits Sandberg's Trident Member (Sequence 2 of this study) are expressed differently in the Williston Basin and are most likely equivalent to the transgressive Pronghorn Member of the Bakken Formation (Johnson, 2013; Schietinger, 2014).

**Effects of Basin Dynamics on Three Forks Formation Deposition**

Difference in facies relationships and depositional characteristics of the Three Forks Formation between southwestern Montana the Williston Basin can most likely be attributed to variations in basin dynamics and basin development over time. In southwestern Montana, deposition of the Three Forks Formation occurred within low accommodation depocenters within the Antler Foreland Basin that were subject to inversion and migration throughout the Late Devonian (Peterson, 1981; Dorobek, 1991). Depocenter inversion can be observed between Sequences 1 and 2 of the Three Forks Formation of this study: In sequence 1, a depocenter lies to the east while in sequence 2 the depocenter lies westward. The transition from the restricted lithologies of sequence 1 to the open marine lithologies of Sequence 2 suggest that a structural shift occurred across SB 2 that opened up the basin to the west and allowed for increased marine influence.

The occurrence of migrating depocenters and subaerial unconformities within the Three Forks Formation and overlying Sappington Formation in southwestern Montana can be taken as indicators of Antler-related convergent pulses. Because the Three Forks and Sappington Formations were deposited on the shelf margin of Antler Foreland Basin, it can be interpreted that the development of structural instability could be related to the passage of a flexural forebulge onto the craton (eg. Price and Hatcher, 1983). The migration of a flexural forebulge is expressed by regional uplift followed by subsidence (Allen and Allen, 2013). Forebulge migration, paired with related activation of fault networks throughout the area (Dorobek, 1991) would explain the complex occurrence of basinal shifts and subaerial exposure of strata in southwestern Montana throughout the Late Devonian and into the Mississippian. Additionally, low accommodation along the shelf platform where the Three Forks Formation was deposited would have caused even slight changes in relative sea level to form a complex succession of disconformable surfaces (Isaacson, 1983). Pulses of eustatic fluctuations during this time could have also exacerbated the effects of relative sea level change in the region.

As part of the distal Antler Foreland Basin During the Middle to Late Devonian, the Williston Basin also experienced Antler related subsidence. However, the position of the Williston Basin in relation to the convergent front had a different effect on Three Forks Deposition. The Williston Basin Three Forks Formation was deposited concurrently with Sequence 1 of this study, and includes restricted supratidal to intertidal lithologies. Because of the orientation of the basin on the distal backbulge basin of the Antler Foreland System, the Three Forks Formation here would not have been subject to the significant uplift and exposure seen further east. This could explain the heightened preservation of thick beds of anhydrite in the Williston Basin Three Forks Formation. The unconformity that separates the Three Forks Formation from the overlying Bakken Formation has been attributed to relative sea level change related to a pulse of Antler Convergence, as it does not conform to the global sea level curve (Dykes, 2014).

The following transgressive episode representative of sequence 2 of this study is observed in the Williston Basin within The Pronghorn Member of the Bakken Formation. The Pronghorn Member does not contain the thick deposits of marine shales that occur in sequence 2 and contains more terrigenous sand (Johnson, 2013). This highlights the difference in marine influence between the western Montana shelf platform and distal backbulge basin (Williston Basin) during this time: Sequence 2 was subject to more open marine conditions and displays a westward deepening of marine lithologies toward the Antler Fordeep, whereas the shallower lithologies of the Pronghorn Member thicken east of the forebulge toward the Williston Basin depocenter and record shallower depositional conditions.

**Lithologic Comparisons to the Williston Basin Three Forks Formation**

In the Williston Basin, the Three Forks Formation is one of the targeted reservoir units in the Bakken Petroleum System (BPS) (Bottjer et al., 2011). The Three Forks Formation of the BPS is limited to subsurface expression, and therefore can only be studied by means of core and log analysis. Due to later, post-Paleozoic tectonic instability to the west, the equivalent Three Forks Formation in western Montana is exposed along numerous thrust sheets, providing ample opportunity for outcrop analysis. The establishment of an outcrop analog to the Three Forks Formation reservoir of the BPS allows for possible interpretations regarding lateral variations in reservoir facies, and could positively affect production from this interval.

Past investigations of the BPS Three Forks reservoir have attributed the highest production values to the uppermost facies of the Three Forks Formation that are in closest proximity to the Lower Bakken Shale source rock (Bottjer et al., 2011, Sonnenburg et al., 2011). The reservoir lithologies are typically interbedded dolomitic mudstones and silty dolostones (Bottjer et al., 2011) and are interpreted to be intertidal in origin (Berwick and Hendricks, 2011).

The Three Forks Formation in southwestern Montana is coeval in part to the Williston Basin Three Forks Formation (Sandberg et al., 1988a.). Certain Intervals of Sequence 1 of this study display much of the same heterolithic, intertidal facies as the upper Three Forks reservoir. These intertidal facies are best exposed to the east on the margins of the Beartooth Shelf. Further evaluation of outcrops of the Three Forks Formation in these areas could potentially yield further positive comparisons between the lithologies in outcrop and the producing lithologies in the subsurface.

## Summary

- The Three Forks Formation in Western Montana is divided into 11 lithofacies: dolomitic mudstones (Lithofacies 1), dissolution breccia (Lithofacies 2), silty rippled dolomicrosparstone (Lithofacies 3), rippled dolomicrosparstone (Lithofacies 4a), laminated dolomicrostone (lithofacies 4b), rippled dolostone (Lithofacies 5), crystalline mudstone with occasional grainstone interbeds (Lithofacies 6), a fossil lag (Lithofacies 7), laminated dolostone (Lithofacies 8), laminated, fossiliferous dolostone (Lithofacies 9), fossiliferous packstone/grainstone (Lithofacies 10), and stromatolitic dolostone (Lithofacies 11).
- Five facies associations are identified within the Three Forks Formation and are composed of genetically associated lithofacies. The facies associations include a supratidal facies association (Lithofacies 1 and 2), an intertidal facies association (Lithofacies 3, 4a, 4b, and 5), a restricted shallow subtidal facies association (Lithofacies 6), a fossil lag (Lithofacies 7), and open marine facies association (Lithofacies 8, 9, 10), and a lagoonal facies association (Lithofacies 11).
- Two depositional sequences are recognized within the Three Forks Formation in western Montana. Sequence One is a partial sequence, consisting of one transgressive systems tract. The younger Sequence 2 is a complete depositional sequence consisting of a lower transgressive systems tract and an upper regressive systems tract.
- The Three Forks Formation in western Montana is partially equivalent to certain lithologies of the Three Forks Formation reservoir of the Bakken Petroleum System. The intertidal Facies Association of Sequence 1 is sedimentologically similar to the Three Forks Reservoir lithologies and could potentially serve as an outcrop analog.

## Future Work

- More precise dating of the Three Forks Formation is required in order to determine the effects of eustatic vs. local sea level fluctuations, as well as to enhance regional correlations. Of the Sequences identified in this study, only Sequence 2 has been bracketed by conodont zonation (Sandberg 1988a). Sequence 1 and the Three Forks Formation within the Williston Basin have yet to be biostratigraphically constrained.
- Provenance of detrital grains within three forks lithologies should be determined in order to confirm and constrain the presence and relative location of key foreland basin components through time.

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# Tables

**Table 1.1**: Three Forks Formation Lithofacies and Facies Associations

| Facies Association | Depositional Setting | Lithofacies # | Lithology | Sedimentary Structures | Past Investigations: Sandberg, 1965 | Past Investigations: McMannis, 1955 | |
|---|---|---|---|---|---|---|---|
| FA 1 | Supratidal | 1 | Aphantopic dolomitic mudstone | planar laminations, salt hoppers | Logan Gulch Member | Logan Gulch Potlatch Member | |
| | | 2 | Dissolution breccias | n/a | | | |
| FA 2 | Intertidal | 3 | Yellow to tan fogged mosaic dolomicrostone | planar laminations; ripples | | | |
| | | 4a | Light yellow to tan dolomicrosparstone | ripples, planar lamination | | | |
| | | 4b | Light green to grey fissile dolomicrostone | planar laminations | | | |
| | | 5 | Light tan aphanotopic dolostone | algal laminations, ripples | | | |
| FA 3 | Saline Shallow Subtidal | 6 | Grey to dark purple crystalline carbonate mudstone w/ occ. grainstone interbeds | Karsting | | | |
| FA 4 | Lag | 7 | Fragmented fossilized bone and plant material | n/a | | | |
| FA 5 | Open Marine/Ramp | 8 | Dark brown laminated aphanotopic dolostone | planar laminations | Trident Member | Green Shale Member | |
| | | 9 | Light grey, laminated, fossiliferous, aphanotopic dolostone | Thalasoniodes, flame structures, fossil lags | | | |
| | | 10 | Light to dark grey to light grey fossiliferous packstone | Bedded fossil fragments | | Carbonate Member | "Limey Facies" |
| FA 6 | Lagoonal | 11 | Light brown, fogged mosaic dolosparstone with occasional floating rhombs | Algal laminations | | | "Dolomite Faceis" |

# Figures

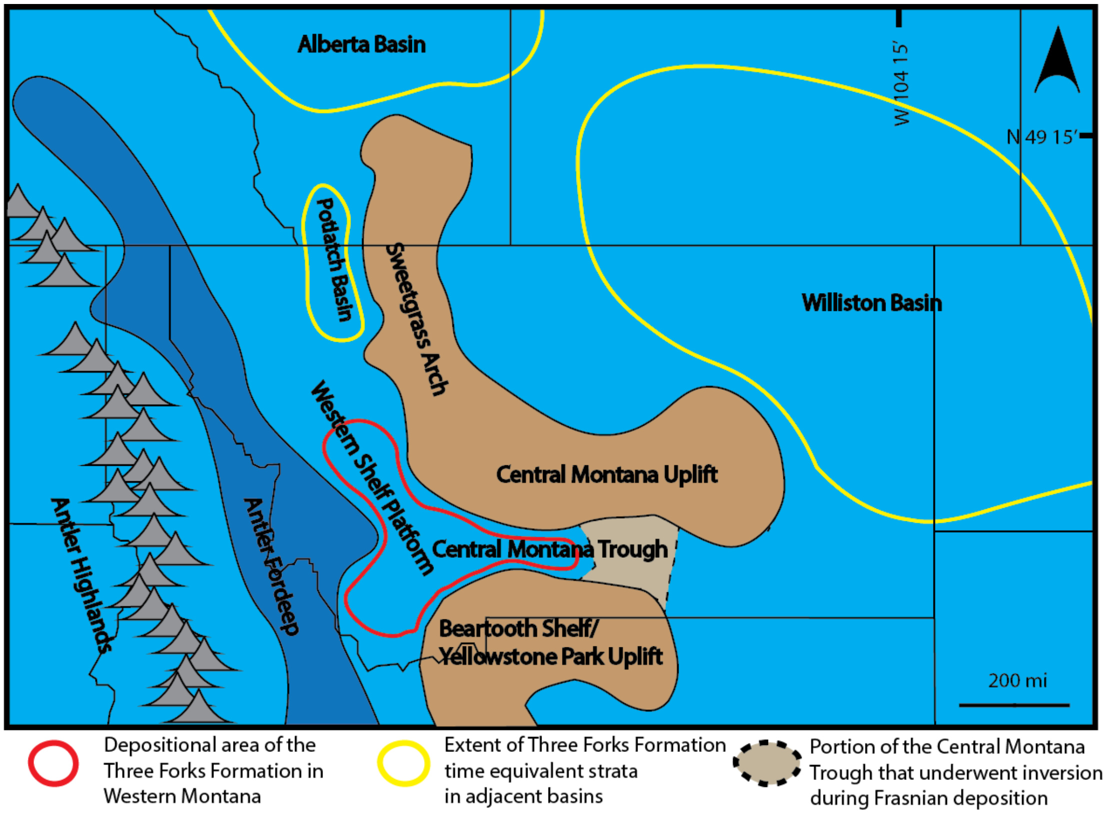



**Figure 1**: Western Montana paleogeography during the Late Devonian (After Peterson (1981) and Dorobek (1991)).

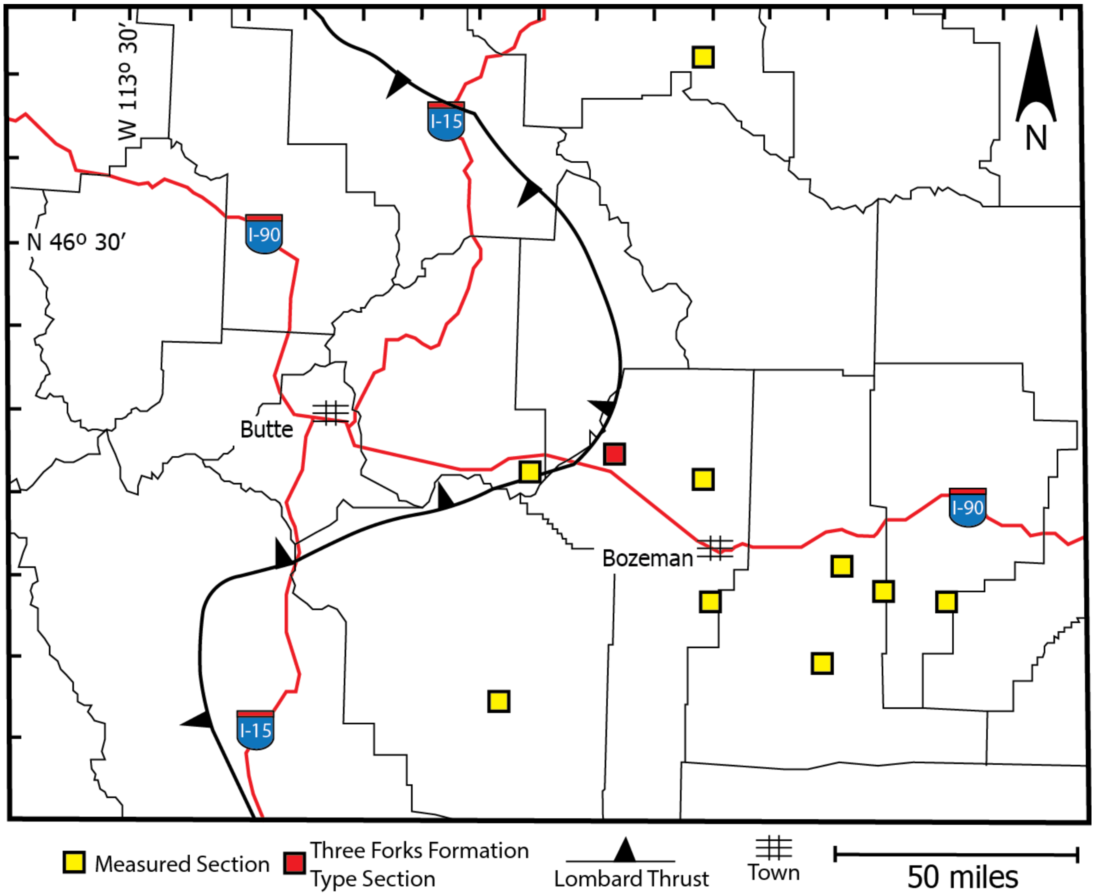



**Figure 2:** Map of outcrops and study area.

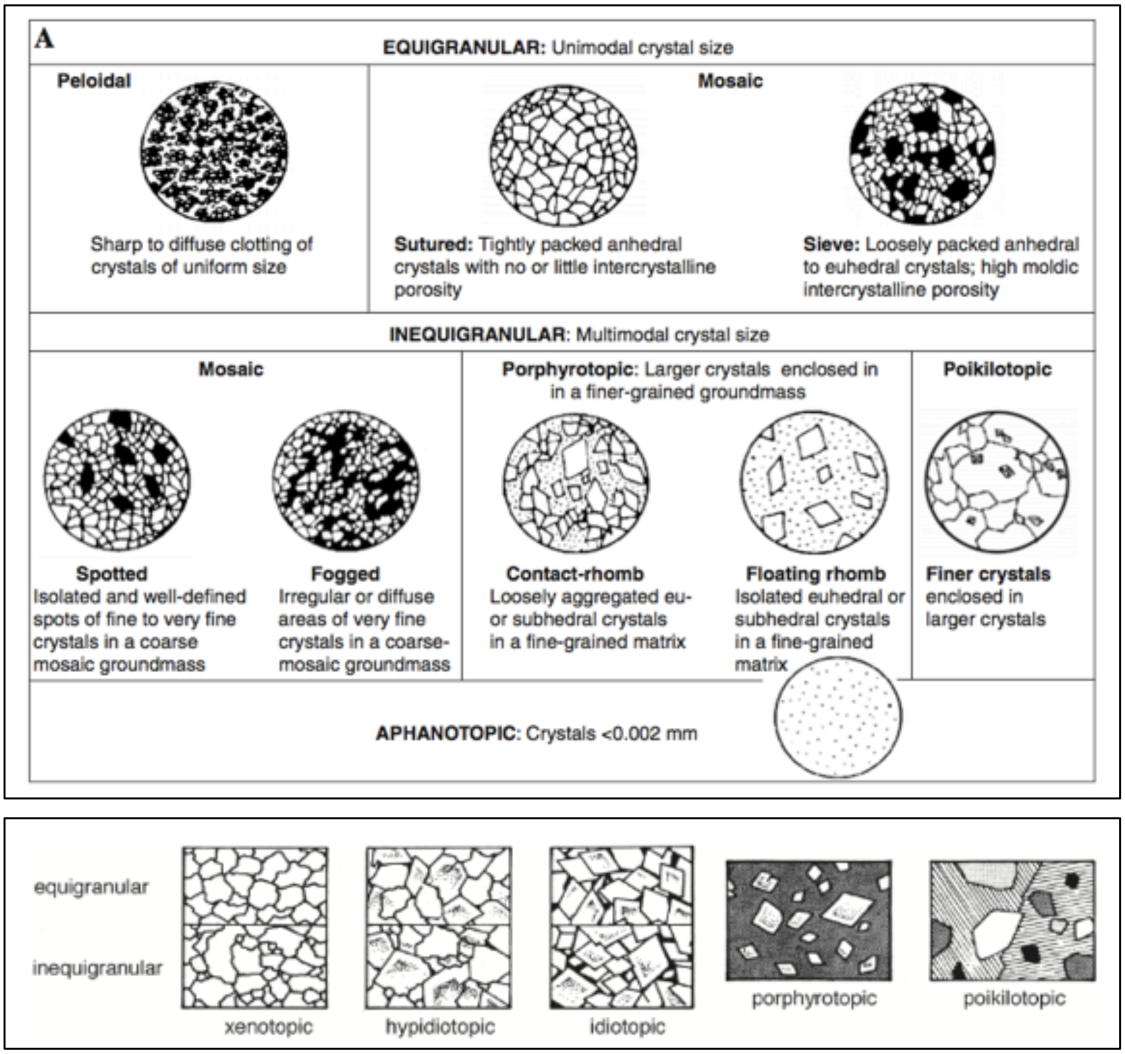



**Figure 3**: Classification scheme used for describing dolomite textures and fabrics in thin section: A.) Terminology of basic crystallization textures (Randazzo and Zachos, 1983; From Flügel, 2004.) B.) Descriptors for crystallization fabrics of recrystallized carbonate rocks. Crystallization fabric refers to the size and spatial relationship of crystals in a sample. Equigranular fabrics are crystallization fabrics that are composed of crystals that are approximately the same size. Innequigranular fabrics are composed of crystals of differing sizes. Xenotopic refers to a sample with predominantly anhedral crystals, hypidiotopic refers to a sample with predominantly subhedral crystals, and idiotopic refers to a sample with predominantly euhedral crystals. Innequigranular fabrics are further subdivided into porphyrotopic fabrics, wherein larger crystals are enclosed in a fine grain matrix, and Poikilotopic, in which crystals of a larger size enclose crystals of a

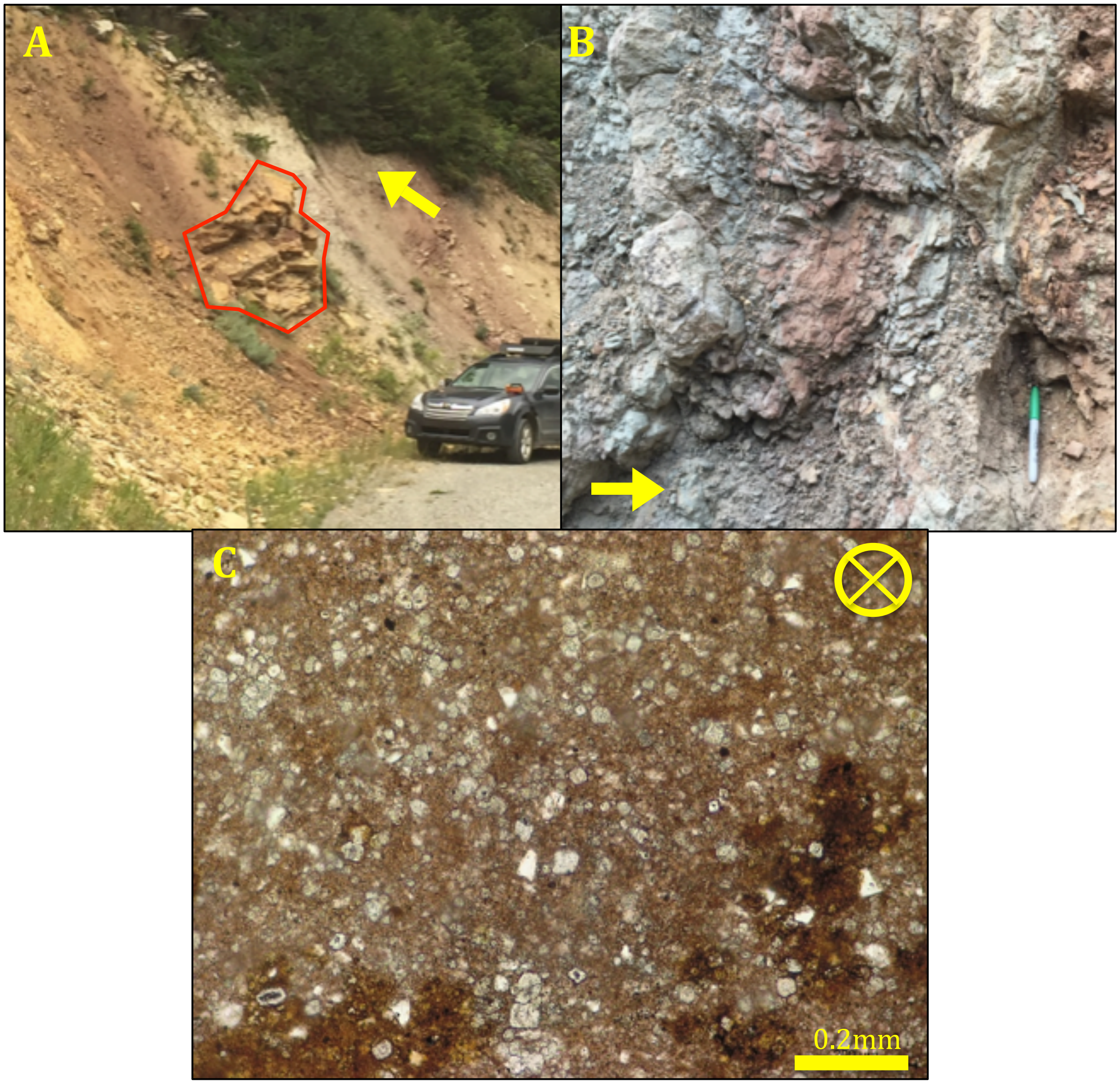



**Figure 4:** Facies Association 5. Arrows indicated stratigraphic up.: A.) Lithofacies 1 and 2 interbedded in outcrop at the Lick Creek section. A large clast of the overlying Lithofacies 3 is incorporated into the breccia of lithofacies 2 and is outlined in red. B.) Lithofacies 2 at the Mystic Lake Section. C.) Thin section of the dolomitic mudstone Lithofacies 1. Quartz grains appear subangular.

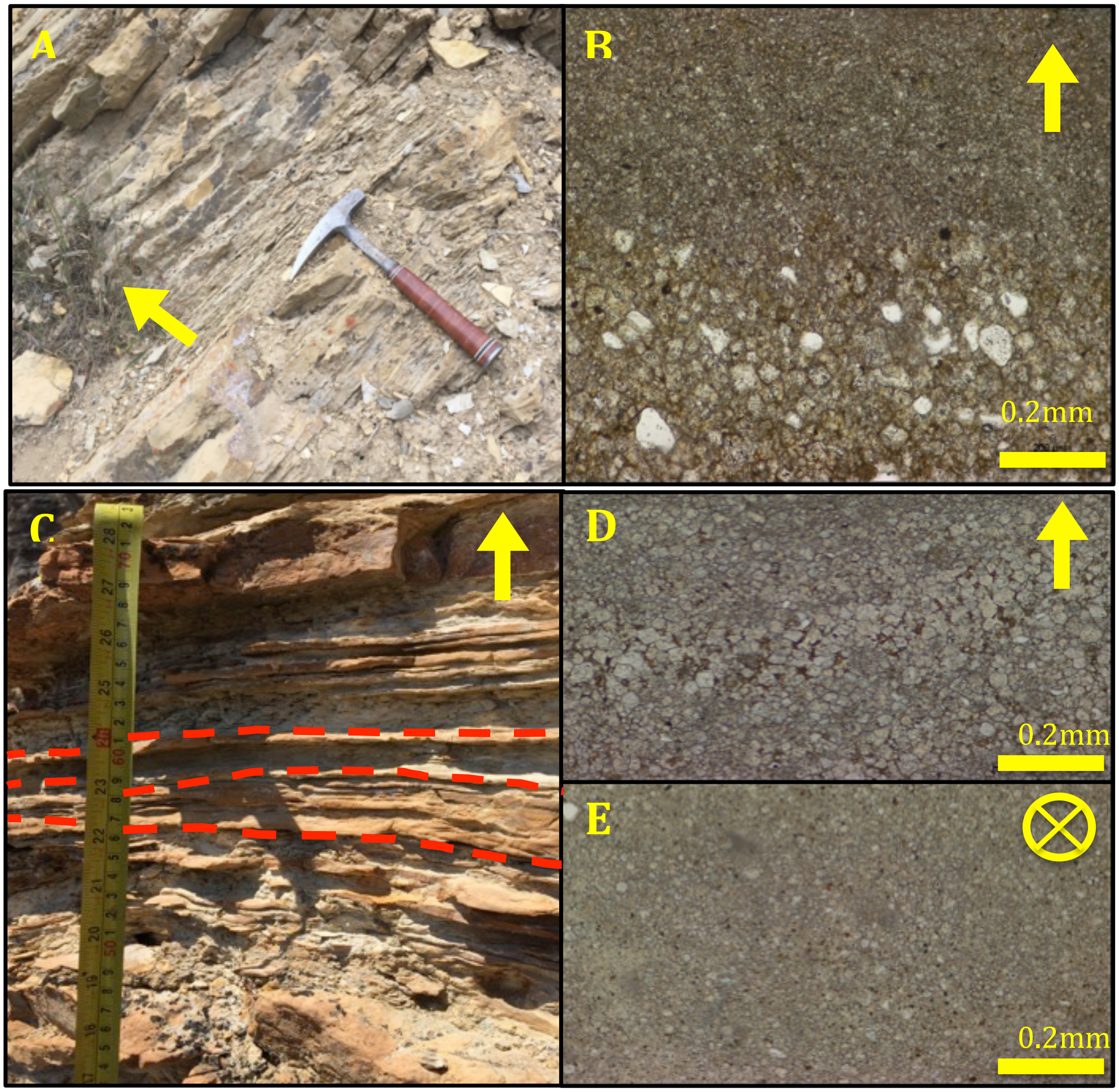
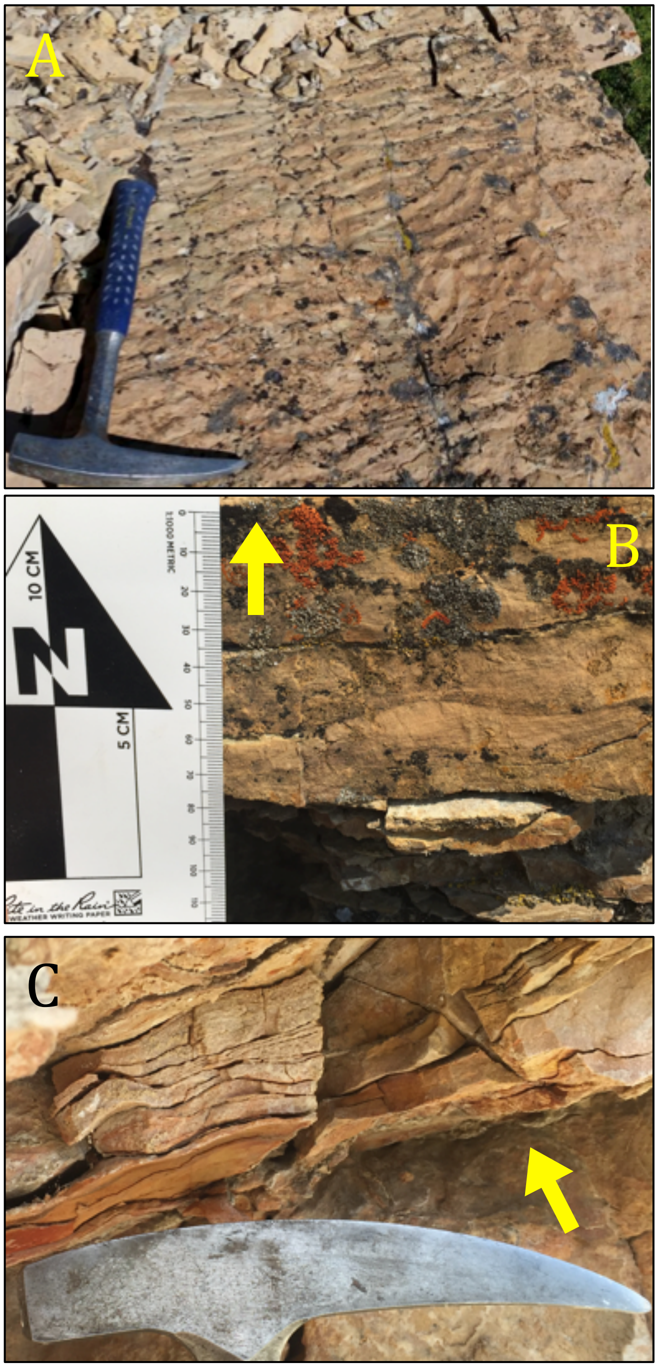



**Figure 5:** Facies Association 2. Arrows indicated stratigraphic up: A.) Lithofacies 3 in outcrop at the Lick Creek section. B.) Lithofacies 3 thin section from the Lick Creek section. Quartz grains appear subrounded to rounded. C.) Lithofacies 4a and 4b interbedded at the East Baker Mountain outcrop. D.) Thin section of




A.) Oscillation ripples on exposed surface of lithofacies 4a at the Baker Mountain section

B.) Current ripple in lithofacies 4a at the Baker Mountain section

C.) Wave laminations in lithofacies 5 at the Dry Hollow section near Ennis, MT.

**Figure 6:** Facies Association 2 Sedimentary Structures.

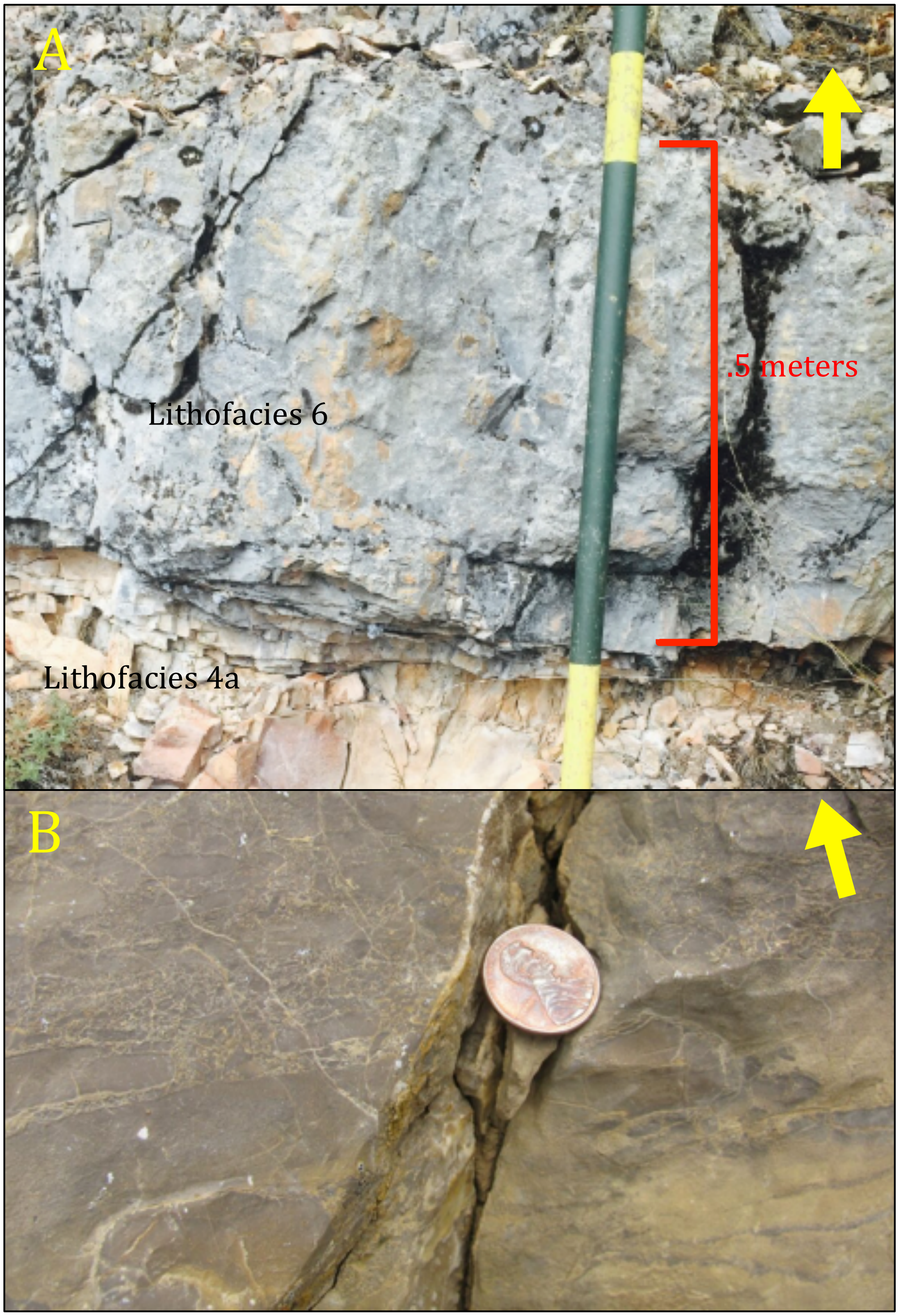



**Figure 7:** Restricted shallow subtidal Facies Association 6. Arrow indicate stratigraphic up: A.) Lithofacies 6 limestone overlying lithofacies 4a at the Mill Creek section. B) Fractures in Lithofacies 6 at the Hardscrabble Section.

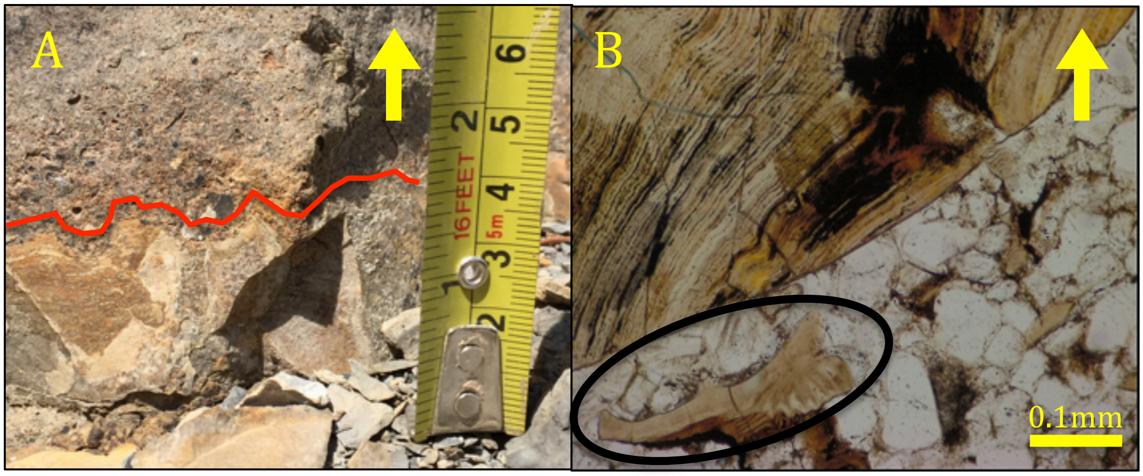



**Figure 8:** Facies Association 9, Lithofacies 7 lag. Yellow arrows indicate stratigraphic up: A.) Lithofacies 7 lag sitting on a sharp contact overlying lithofacies 4a at the Baker Mountain section. B.) Thin section of Lithofacies 7 lag at the Baker Mountain Section showing a large shell fragment to the upper left, and a conodont circled in the bottom left corner.

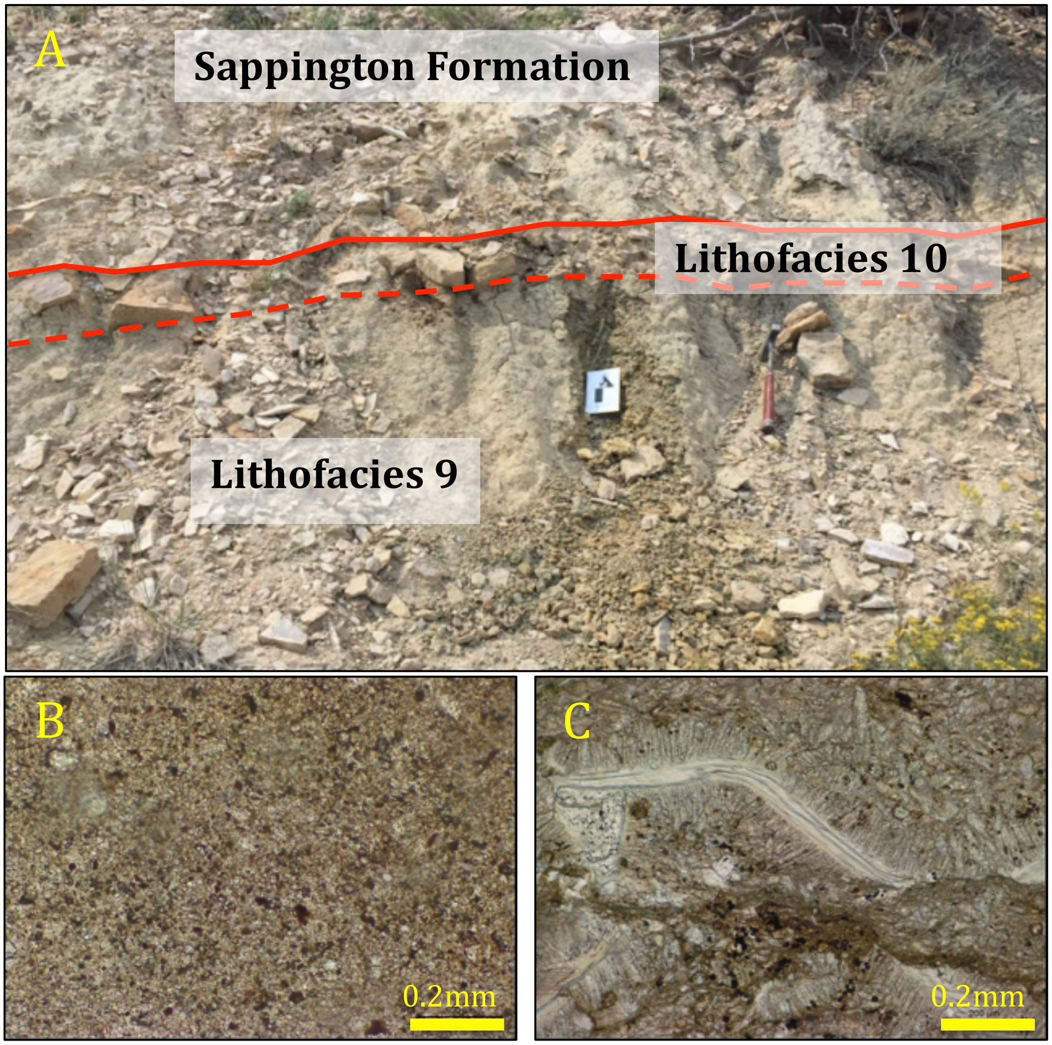



**Figure 9**: Open marine, Facies Association 5: A.) Dolomitic shales of Lithofacies 9 overlain by a thin packstone of Lithofacies 10 at the Dry Hollow section near Ennis, MT. The dashed line represents a within trend facies contact. The bold red line represents Sequence Boundary 3 with the overlying Sappington Formation. Sections of FA 5 are typically highly weathered. B.) Thin section taken of Lithofacies 9 from the Milligan Canyon section showing aphanotopic dolostone with minor Fe staining. C.) Thin section of Lithofacies 10 taken from Milligan Canyon section showing a fragmented shell.

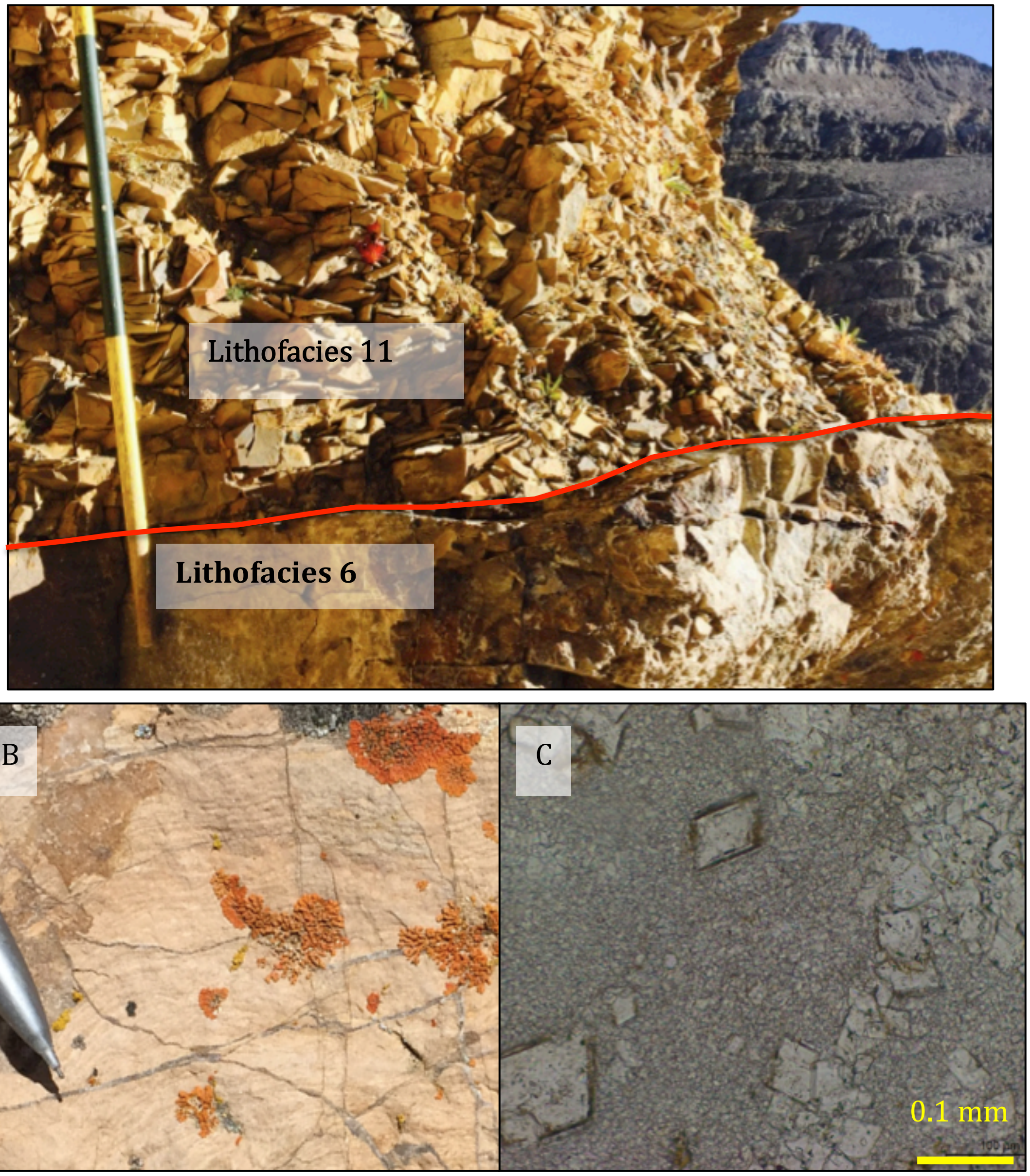



**Figure 10:** Lagoonal Facies Association 6; Lithofacies 11 A.) Medium bedded lithofacies 11 overlying Lithofacies 6 at the Hardscrabble Section, one coloured devision on the staff is equall to 0.5 meters. B.) Faint algal laminations in lithofacies 11 at the Milligan Canyon Section. C.) Thin section from Lithofacies 11 at Hardscrabble: Fogged mosaic dolosparstone with occasional floating rhombs.

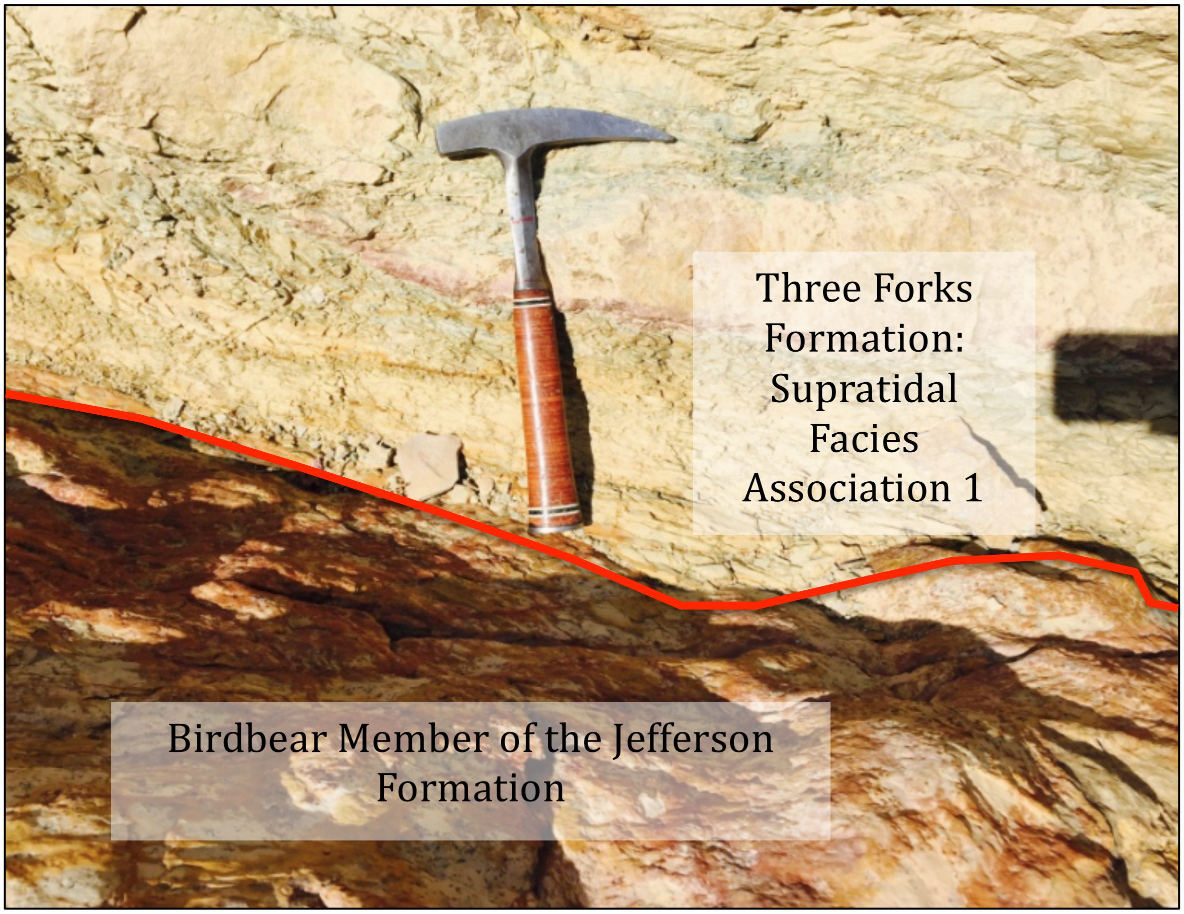



**Figure 11**: Sequence Boundary One as seen at the Hardscrabble Section. Sequence Boundary One separates the Birdbear Member of the Jefferson Formation from the overlying Three Forks Formation.

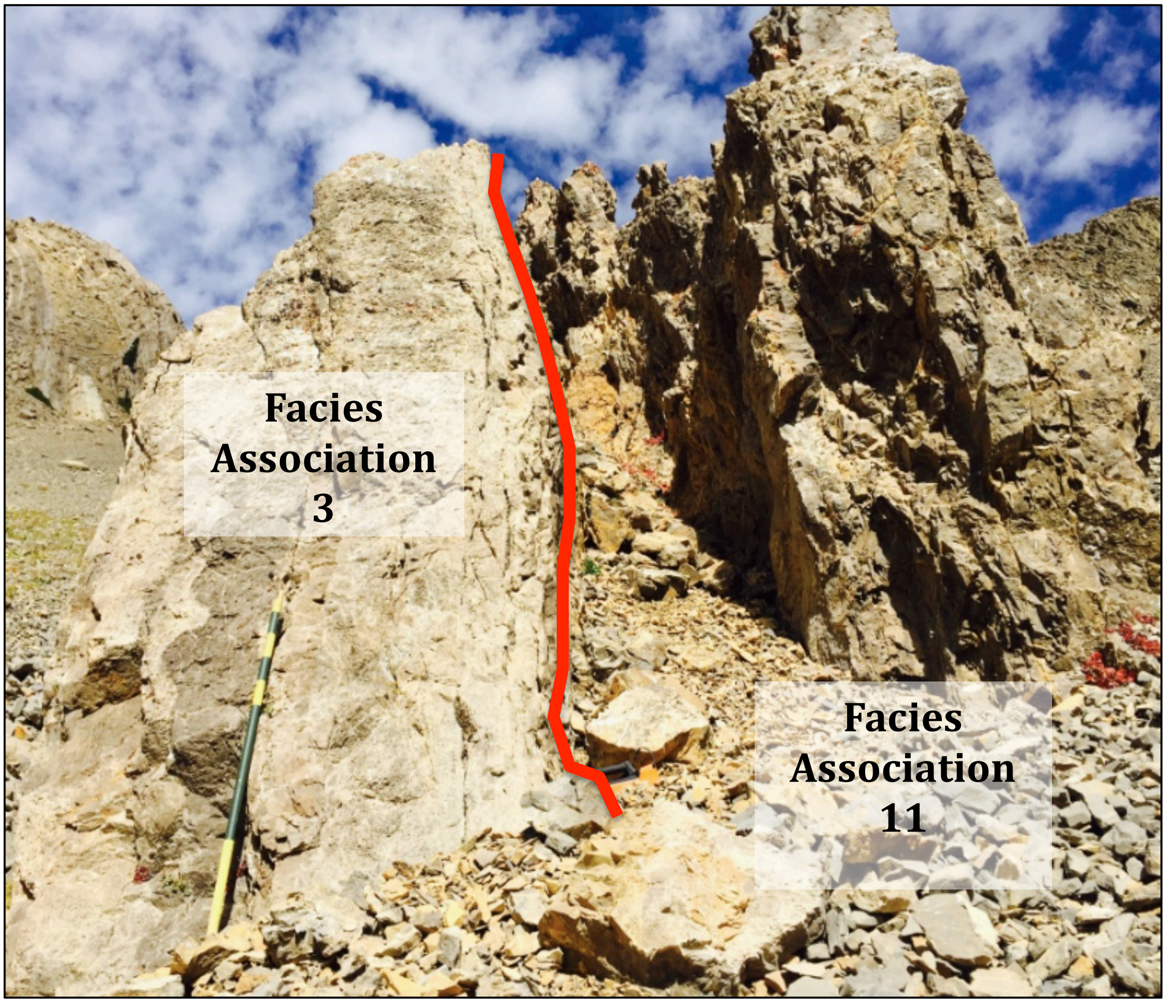



**Figure 12**: Sequence Boundary 2 as seen at the Hardscrabble section. The Jacob Staff in the lower left corner is 1.5 meters long. This sequence boundary is evidenced by karsting within Lithofacies 6 of Facies Association 3.

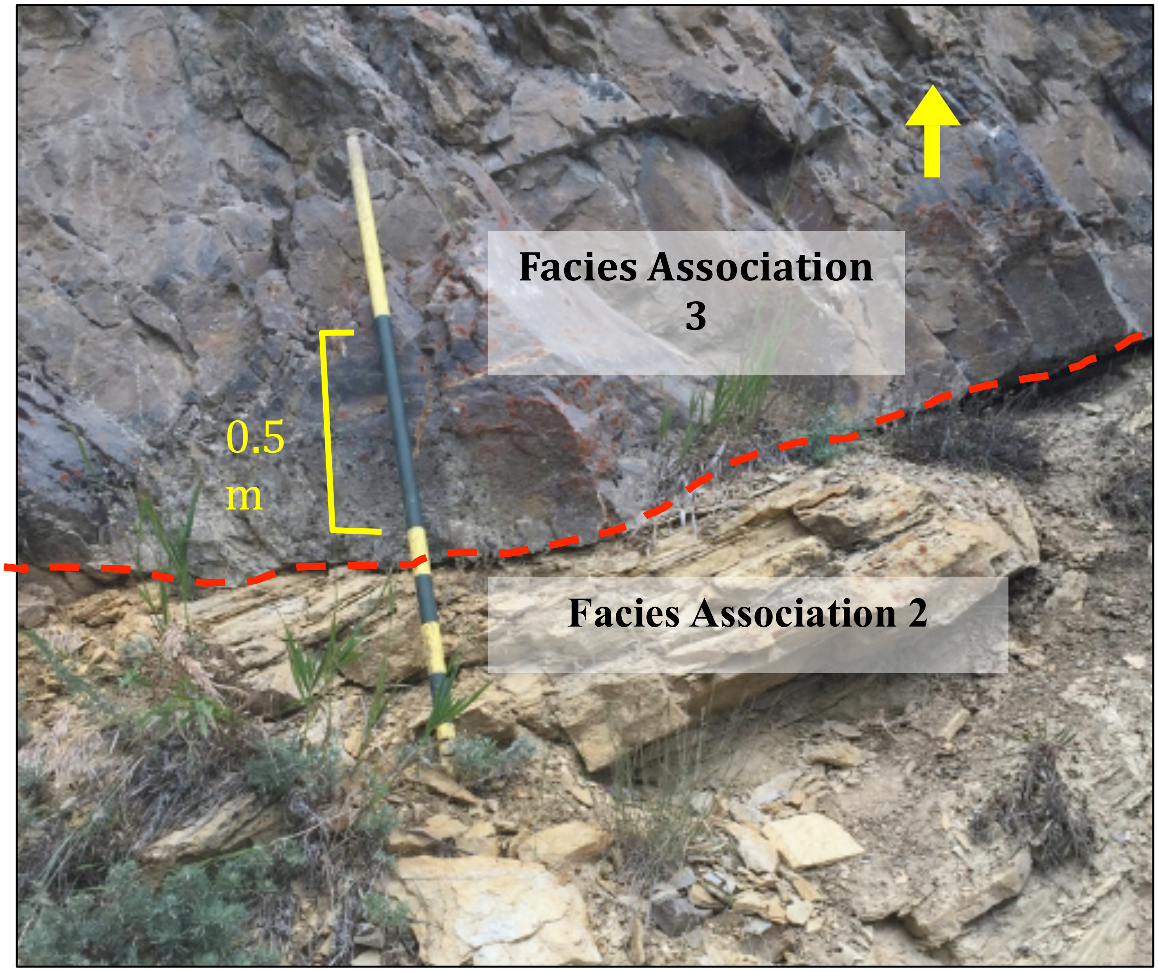



**Figure 13**: Scoured surface between Facies Association 2 and 3 at the Lick Creek section indicative of abrupt deepening. The yellow arrow indicates the stratigraphic up direction. This is interpreted to be a flooding surface within Sequence 1

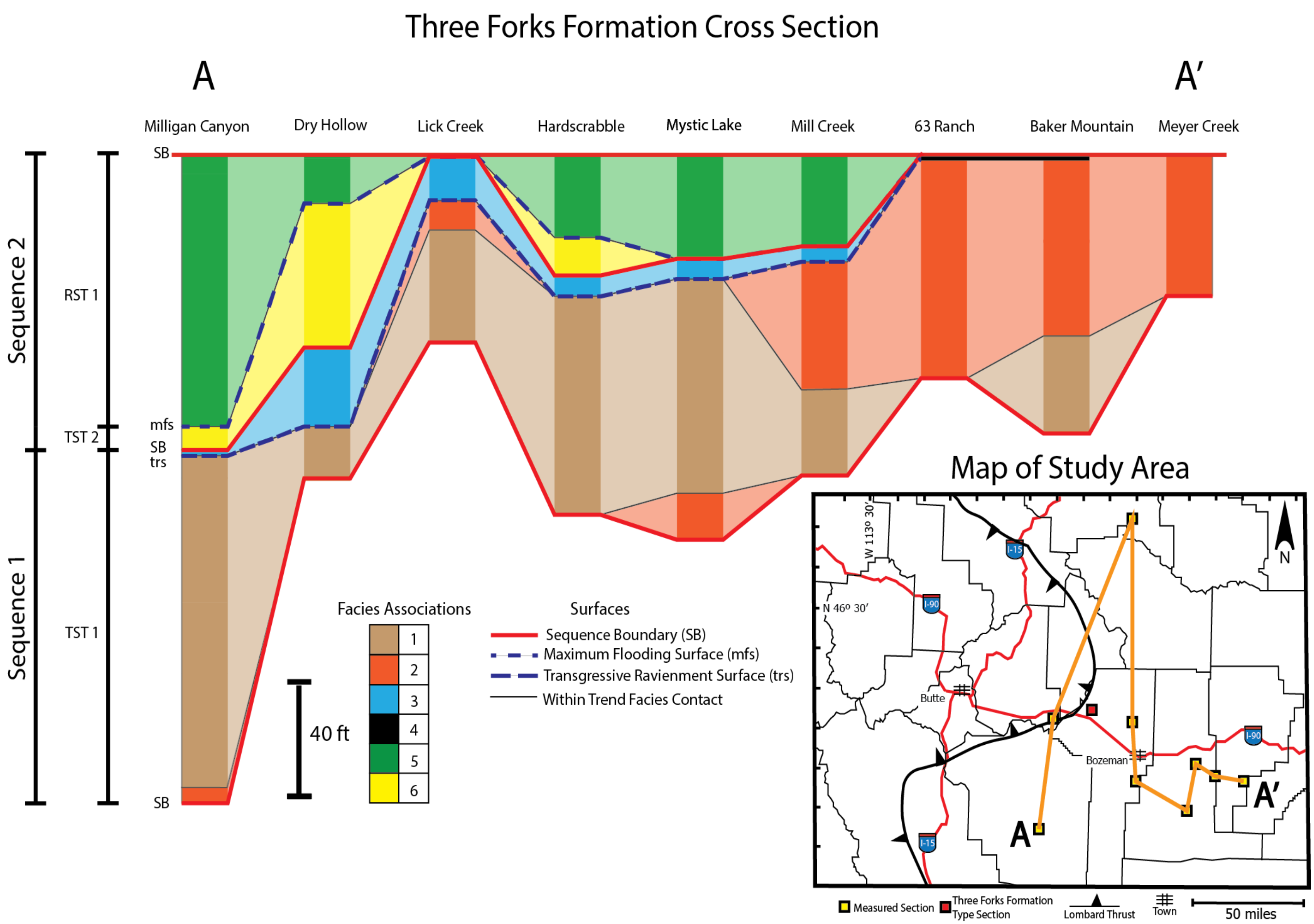
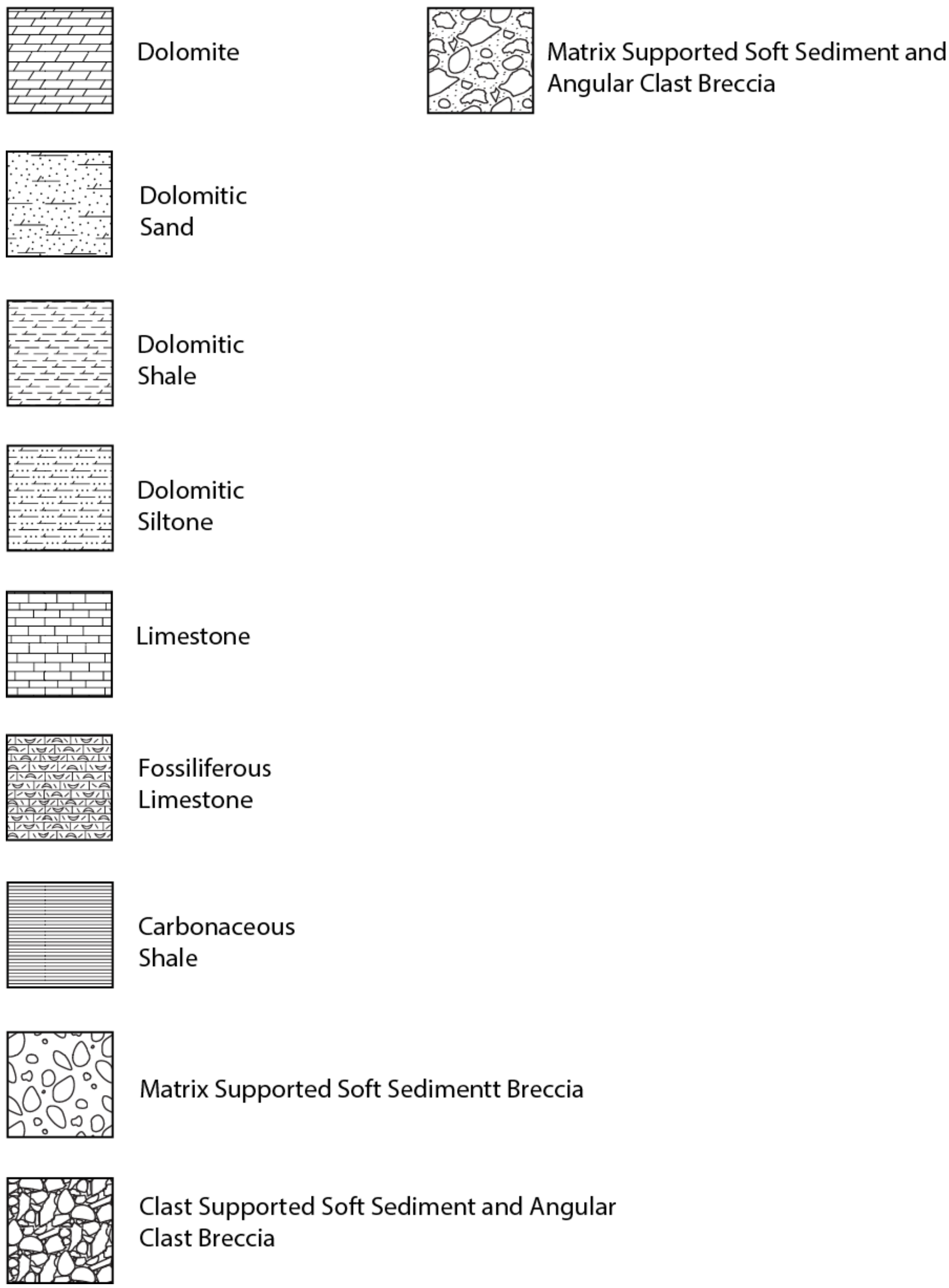


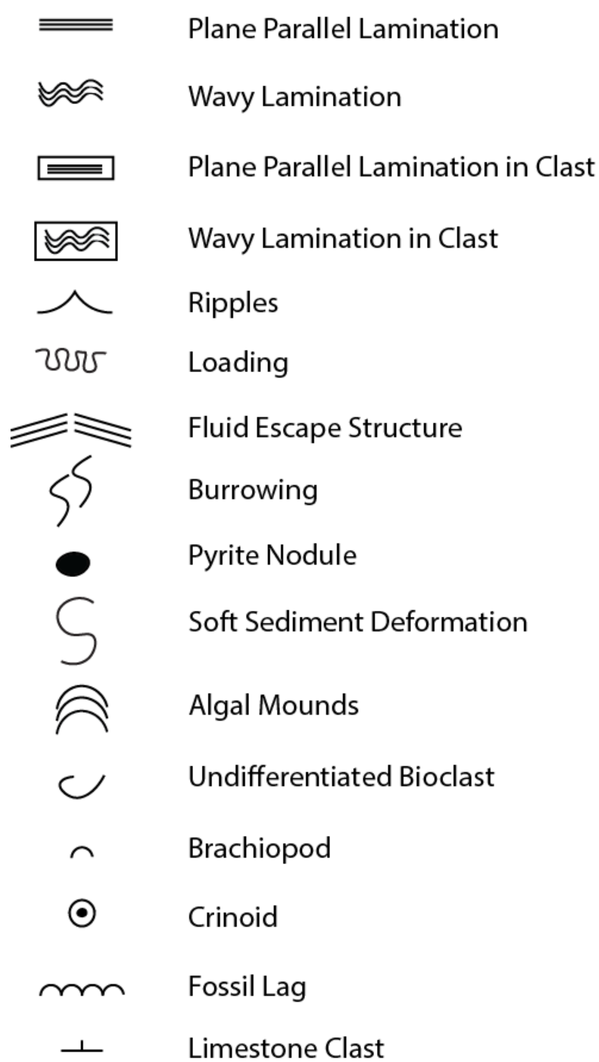

**Figure 14**: Stratigraphic Cross Section of the three Forks Formation

# Appendix I

## Lithology Legend



Symbol Legend



**Milligan Canyon**

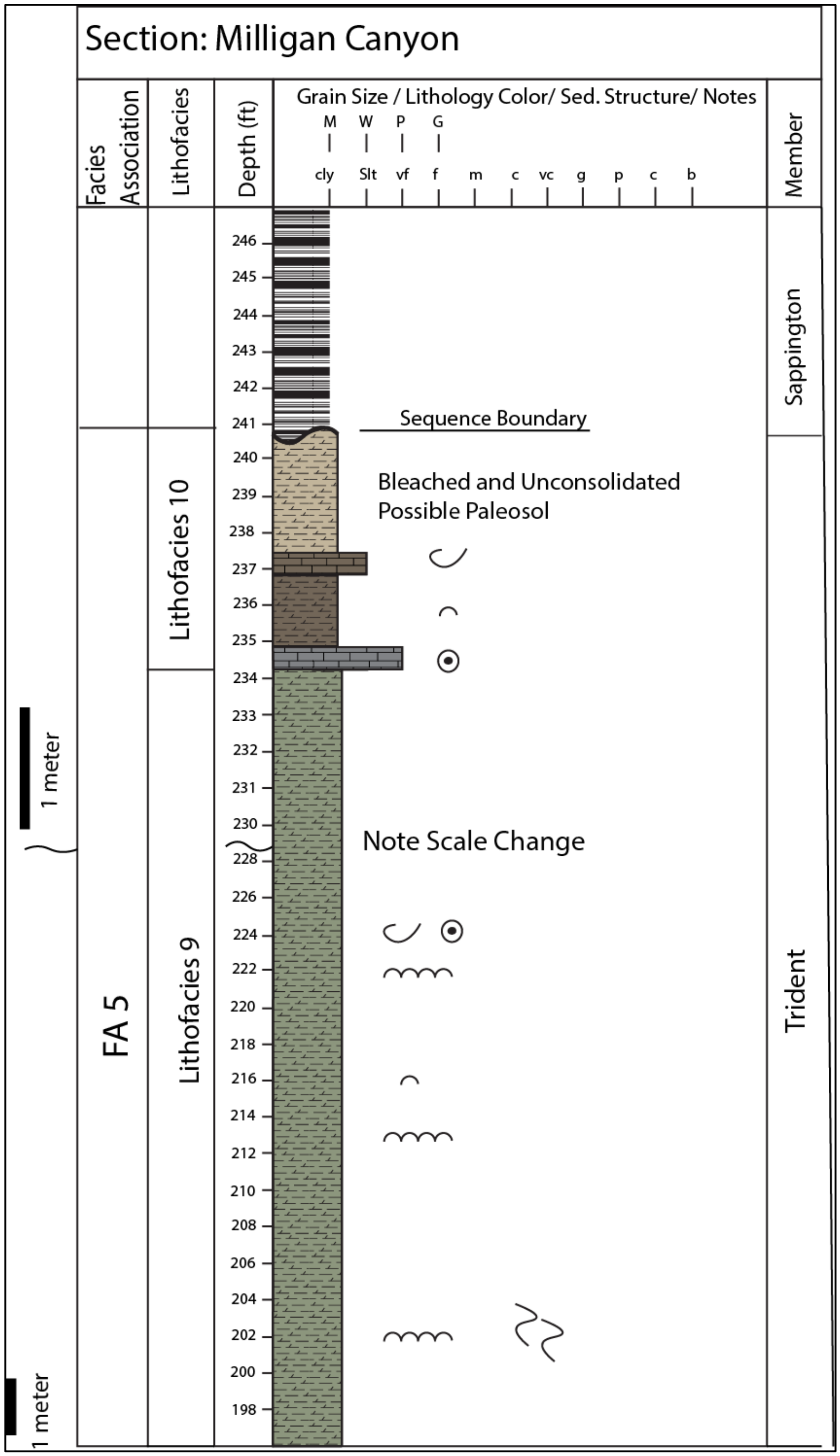
The Three Forks Formation at Milligan Canyon is 235.90 feet thick. It is bounded at the base by Birdbear Member of the Jefferson Formation and is overlain by the lower shales of the Sappington Formation. This outcrop represents a full expression of the Three Forks Formation.

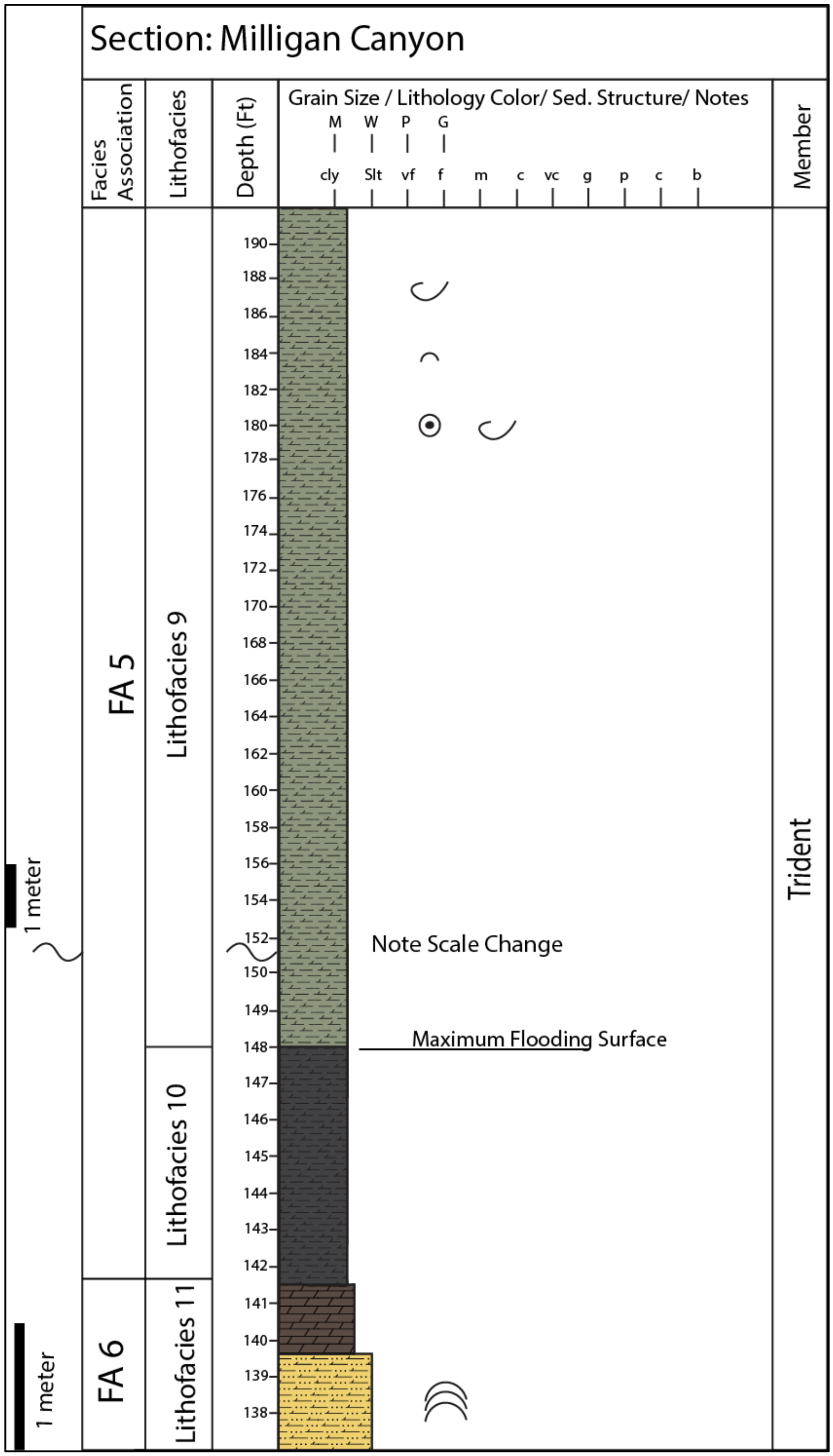
**Lithofacies Thicknesses:** Thicknesses in feet are listed in stratigraphic order from the top to bottom of the section.

| | |
|---|---|
| Lithofacies 10 | 6.4’ |
| Lithofacies 9 | 92.6’ |
| Lithofacies 11 | 6.8’ |
| Lithofacies 6 | 2.5’ |
| Lithofacies 1 | 10.3’ |
| Lithofacies 1 (covered) | 44.9’ |
| Lithofacies 1 | 25.5’ |
| Lithofacies 1 (covered) | 44.2’ |
| Lithofacies 4a/4b | 2.7’ |
| **Total Thickness** | **235.9’** |

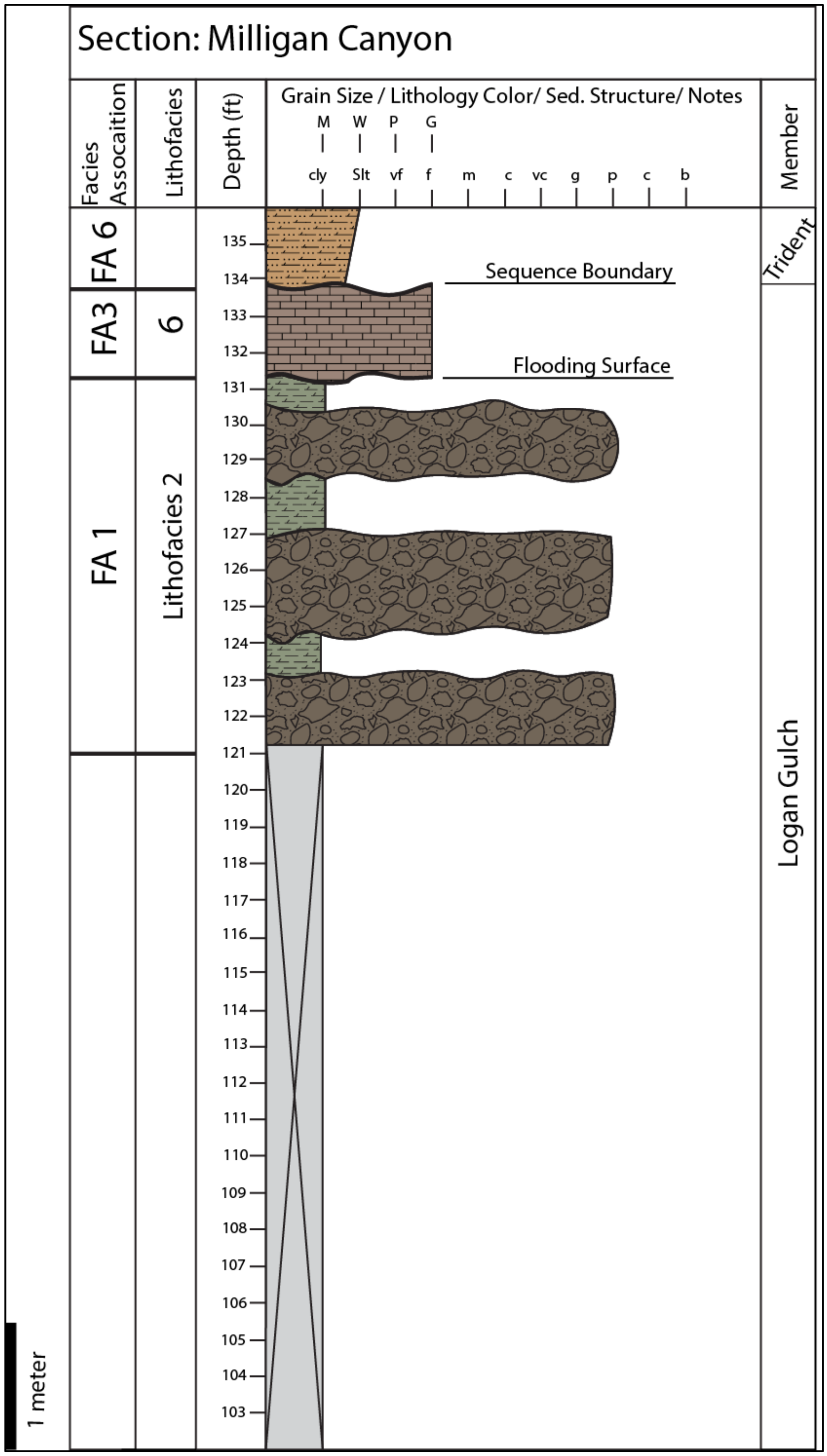
**Lithofacies Contact Observations:** 4 major contacts were observed at this location: the lower contact separating the Birdbear Member of the Jefferson Formation from lithofacies 4a/4b of the Three Forks Formation; The contact separating lithofacies 1 and lithofacies 6; The contact separating lithofacies 6 from the overlying lithofacies 11; and the upper contact separating lithofacies 10 from the Sappington Formation. At the lower contact, an abrupt change in lithology occurs from the sucrosic, coarser grained dolomite of the Birdbear Member of the Jefferson Formation to the fine-grained intertidal dolomites of interbedded lithofacies 4a/4b of the Three Forks Formation. This contact represents a major sequence boundary (Sandberg, 1988a) and is sequence boundary 1 in this study. It displays no erosional lag or signs of scouring. The contact between lithofacies 1 and lithofacies 6 is irregular, displaying as much as .5’ of relief. The overlying crystalline limestone of lithofacies 6 infills where the underlying lithofacies 1 has collapsed. The contact between lithofacies 6 and the lagoonal lithofacies 11 is subtle and abrupt. There is a sharp contact between these two lithologies. The upper contact separates lithofacies 10 from the overlying Sappington Formation. The change in lithologies from fossiliferous limestone to anoxic black shale is abrupt. There is a .5' bleached interval between the Three Forks Formation and the Sappington Formation. This contact also represents a major sequence boundary (SB 3) (Sandberg, 1988a.).

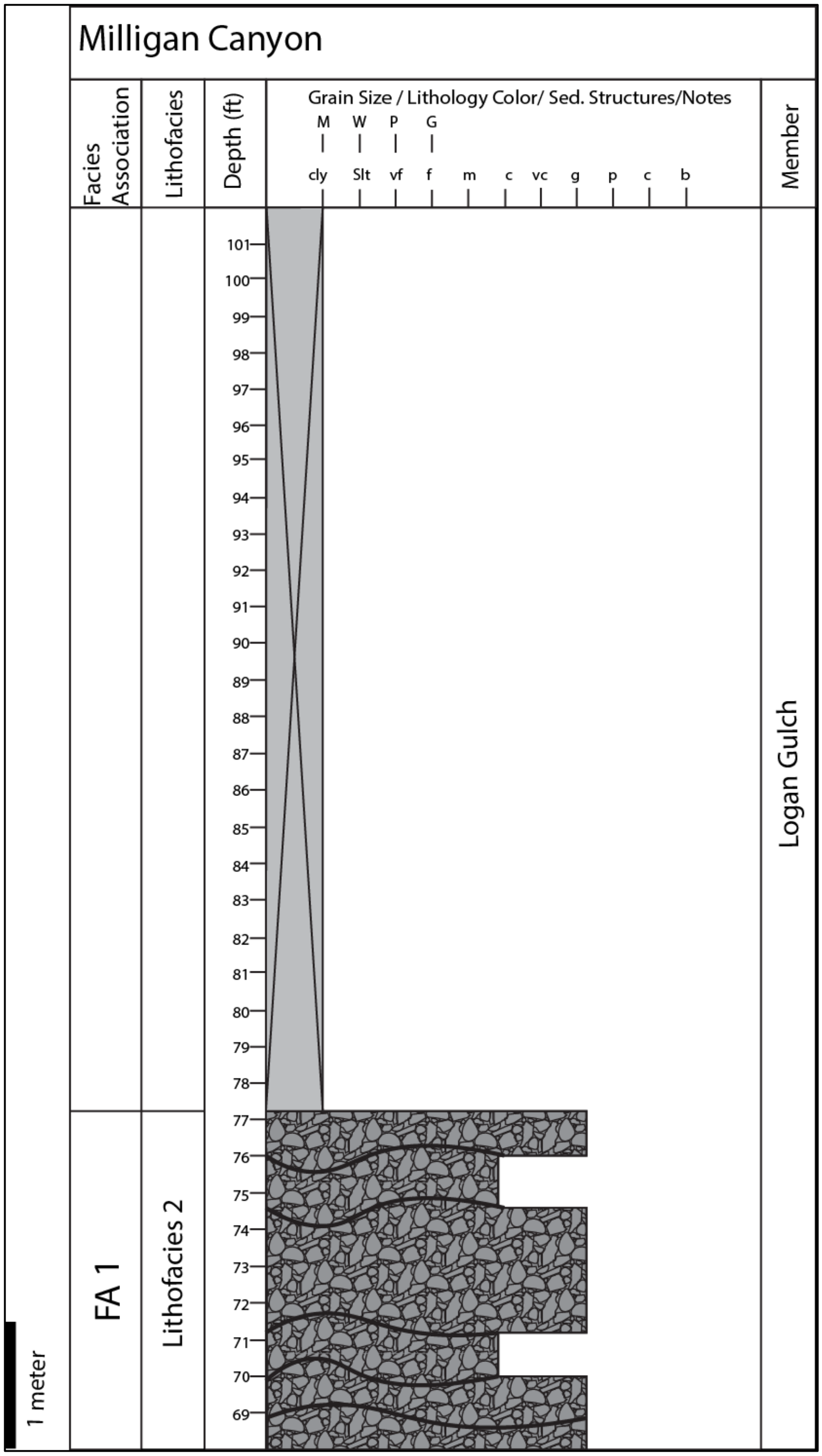
**Supplemental Notes:** Of the outcrops described for this study, The Milligan Canyon outcrop is the closest measured section to the Three Forks type locality of Sandberg (1965) in Logan, Montana. It exhibits similarities to Sandberg's type section description; however, one major difference in facies stacking is noted: In Sandberg's type section, the interbedded green shales and tan dolomites, interpreted as FA 2 in this study, sit above collapse breccia. This relationship is reversed at this section. This is the best section to observe the gradual changes within the shales and limestones of FA 8, as they are thicker and better exposed here than at any other described location.

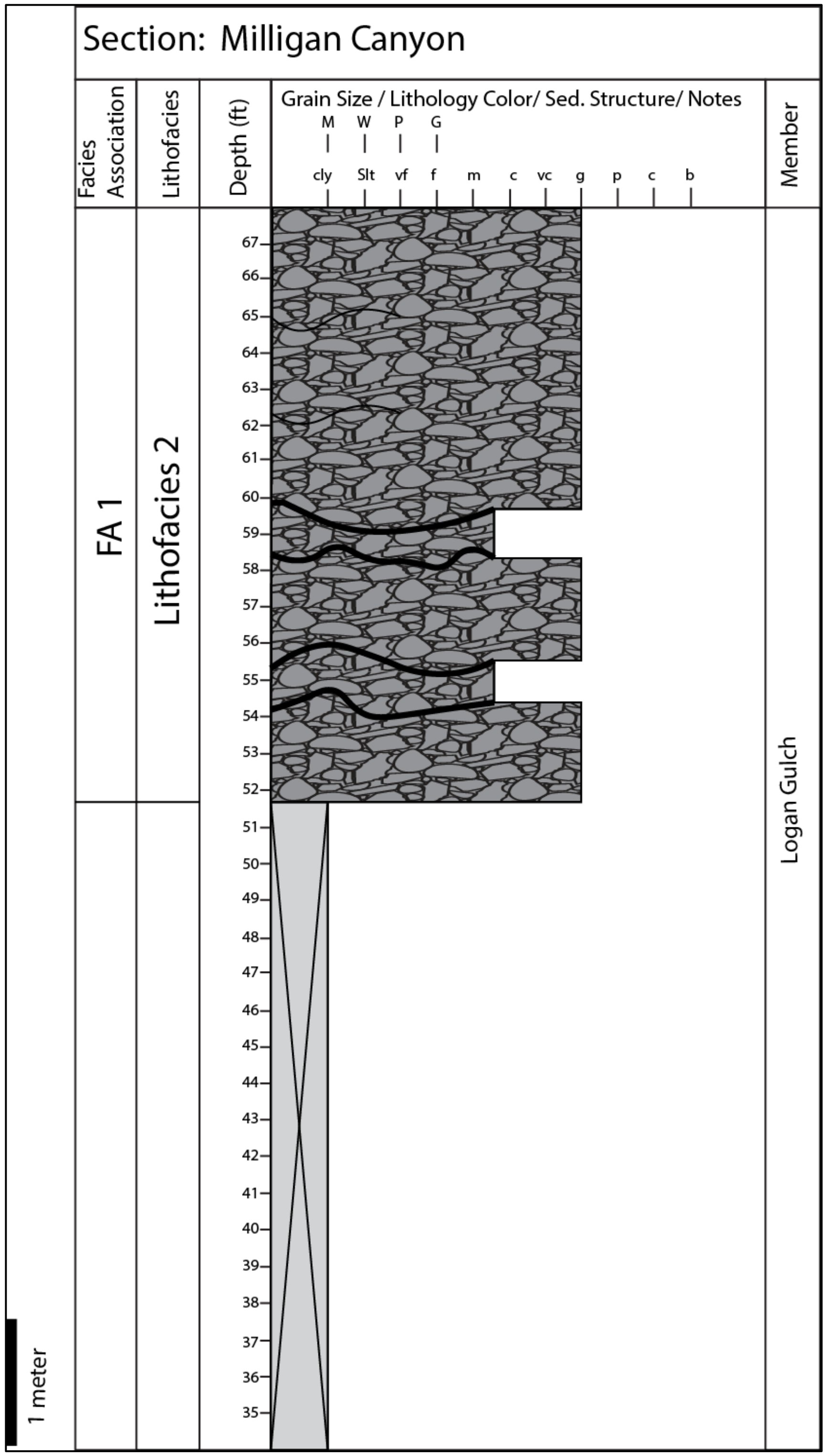

Section: Milligan Canyon
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
246 245 244 243 242 241 240 239 238 237 236 235 234 233 232 231 230 228 226 224 222 220 218 216 214 212 210 208 206 204 202 200 198
Sequence Boundary
Bleached and Unconsolidated
Possible Paleosol
Note Scale Change
Lithofacies 10
Lithofacies 9
FA 5
Sappington
Trident
1 meter
1 meter

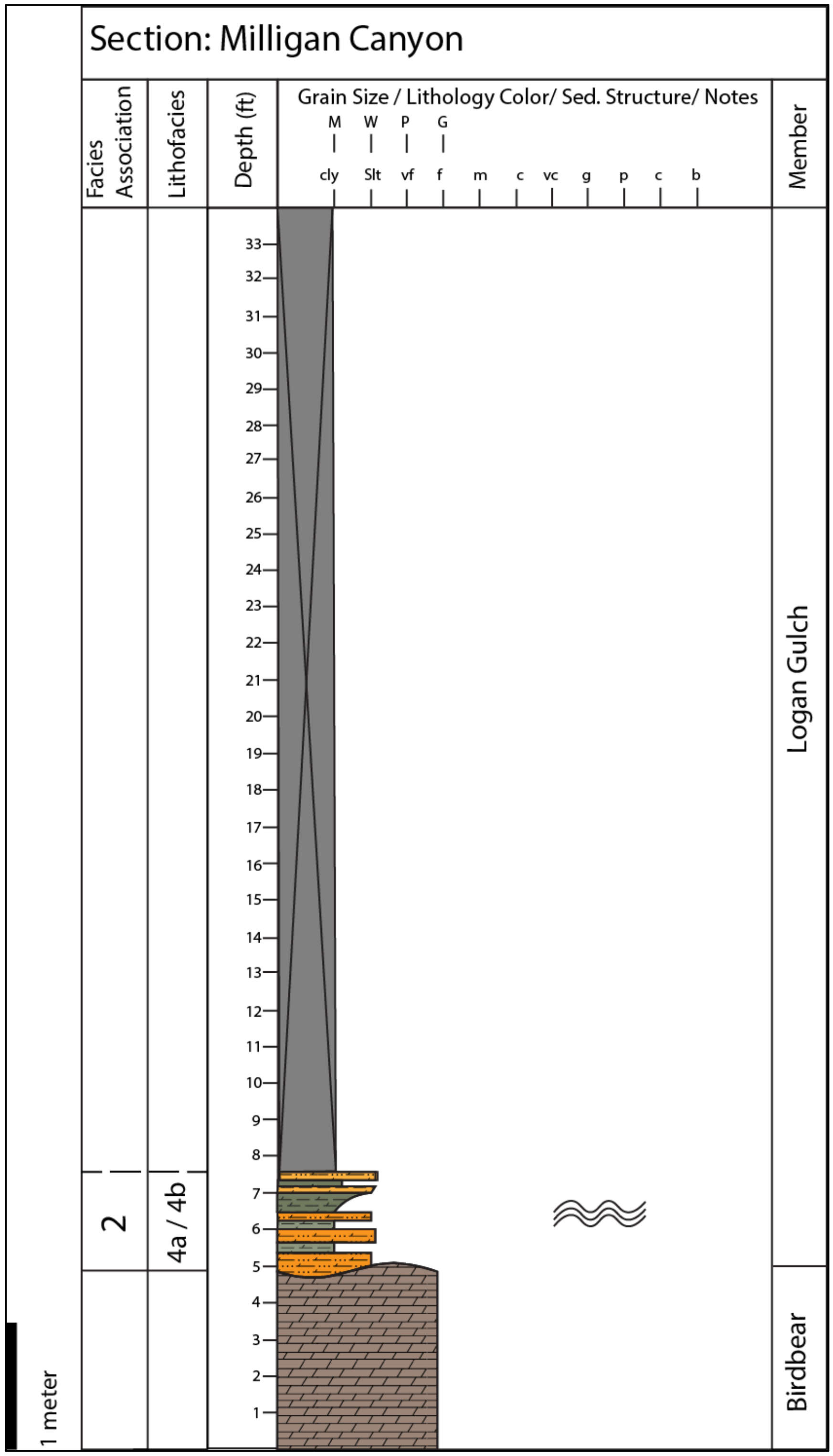


Section: Milligan Canyon
Facies Association
Lithofacies
Depth (Ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 5
FA 6
Lithofacies 9
Lithofacies 10
Lithofacies 11
190 188 186 184 182 180 178 176 174 172 170 168 166 164 162 160 158 156 154 152 150 149 148 147 146 145 144 143 142 141 140 139 138
Note Scale Change
Maximum Flooding Surface
Trident
1 meter
1 meter


Section: Milligan Canyon
Facies Assocaition
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 6
FA3
6
FA 1
Lithofacies 2
Sequence Boundary
Flooding Surface
Trident
Logan Gulch
1 meter
135
134
133
132
131
130
129
128
127
126
125
124
123
122
121
120
119
118
117
116
115
114
113
112
111
110
109
108
107
106
105
104
103


Milligan Canyon
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structures/Notes
M W P G
cly Slt vf f m c vc g p c b
Member
101 100 99 98 97 96 95 94 93 92 91 90 89 88 87 86 85 84 83 82 81 80 79 78 77 76 75 74 73 72 71 70 69
FA 1
Lithofacies 2
Logan Gulch
1 meter


Section: Milligan Canyon
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 1
Lithofacies 2
67 66 65 64 63 62 61 60 59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42 41 40 39 38 37 36 35
Logan Gulch
1 meter



Section: Milligan Canyon
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
2
4a / 4b
Logan Gulch
Birdbear
1 meter

## Dry Hollow

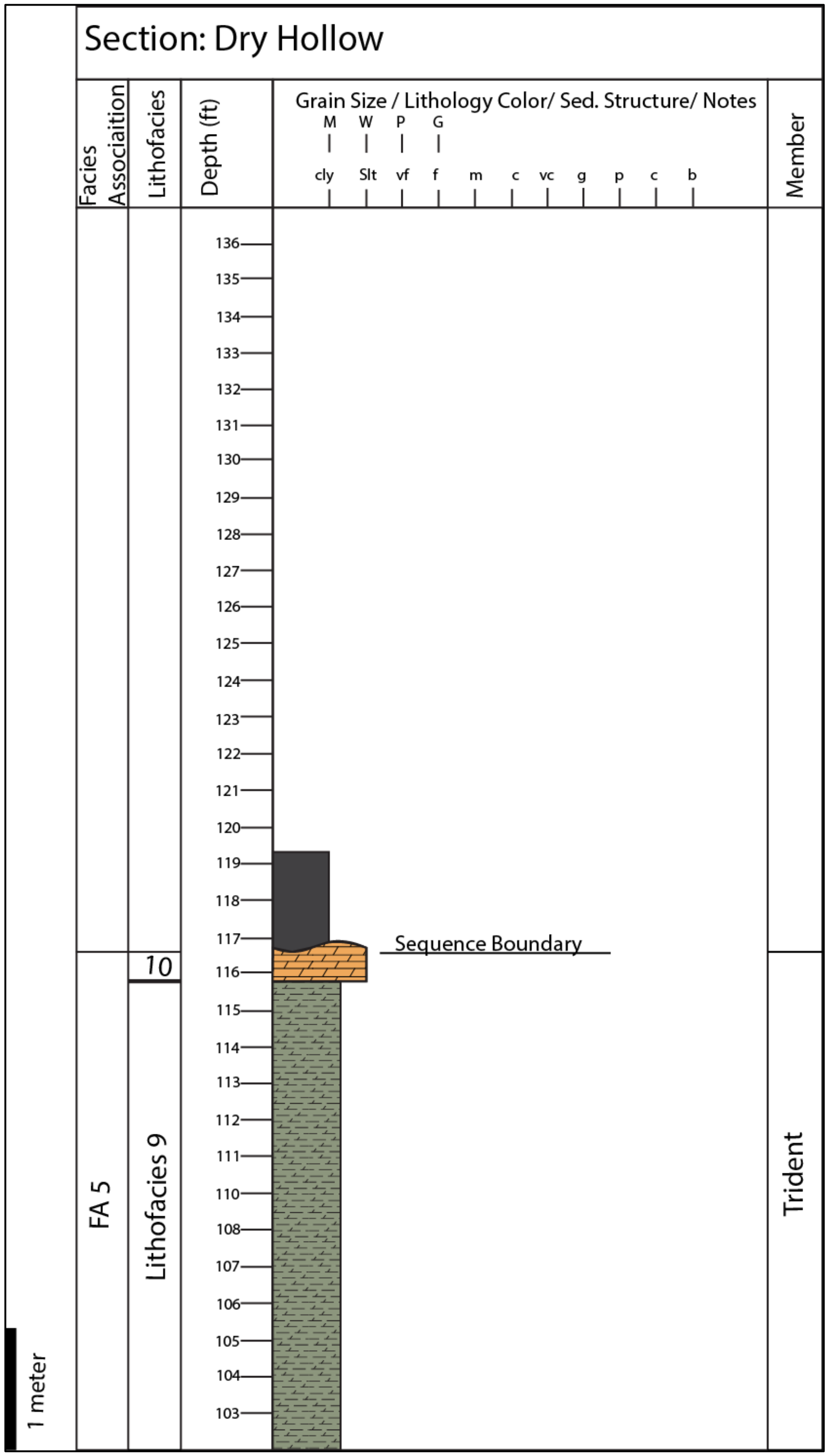
The Three Forks Formation at Dry Hollow is 116.6 feet thick. Its base is covered, but it is overlain by the Sappington Formation. This outcrop includes a partial expression of the Three Forks Formation.

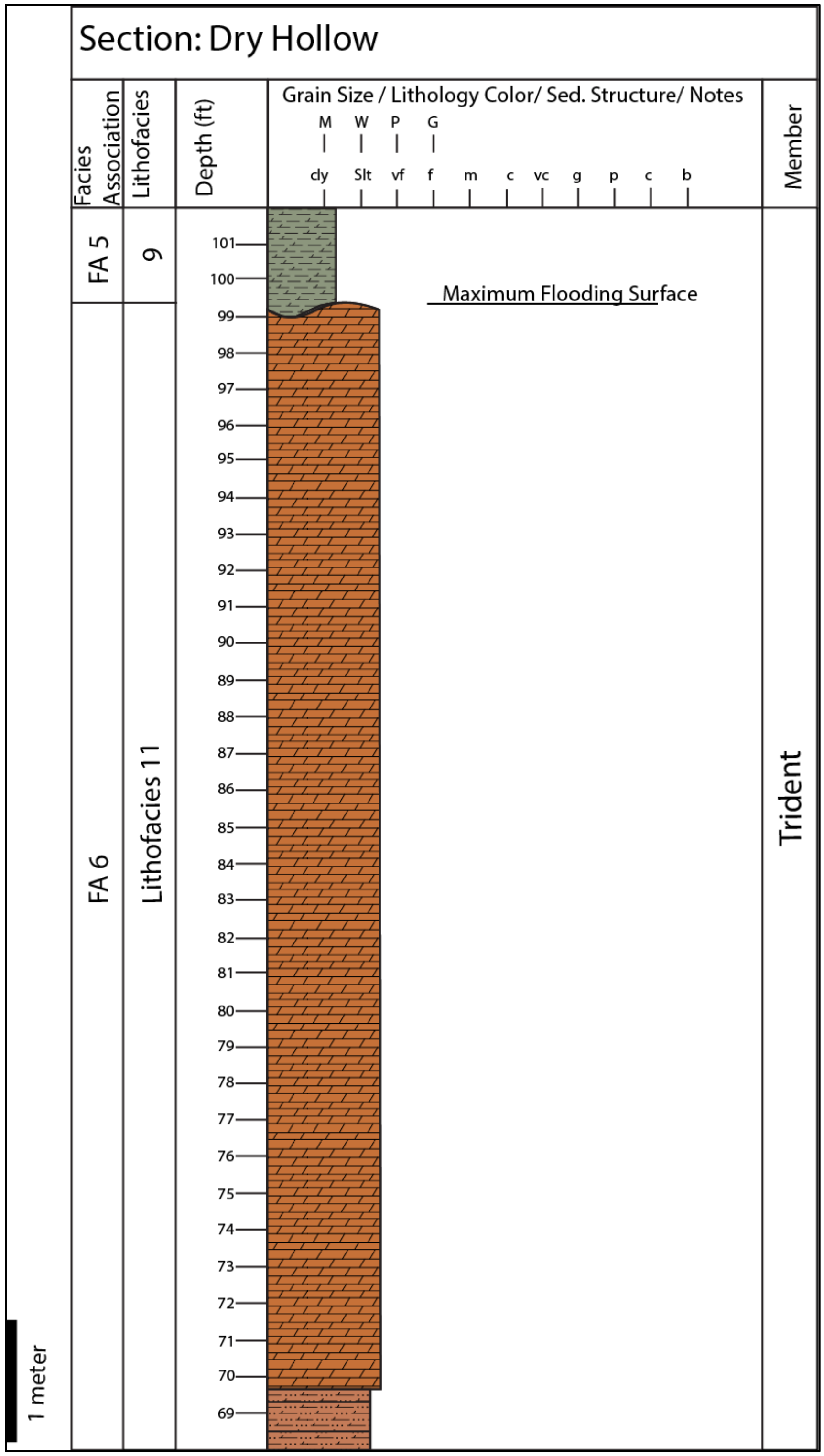
**Lithofacies Thicknesses:** Thicknesses in feet are listed in stratigraphic order from the top to bottom of the section.

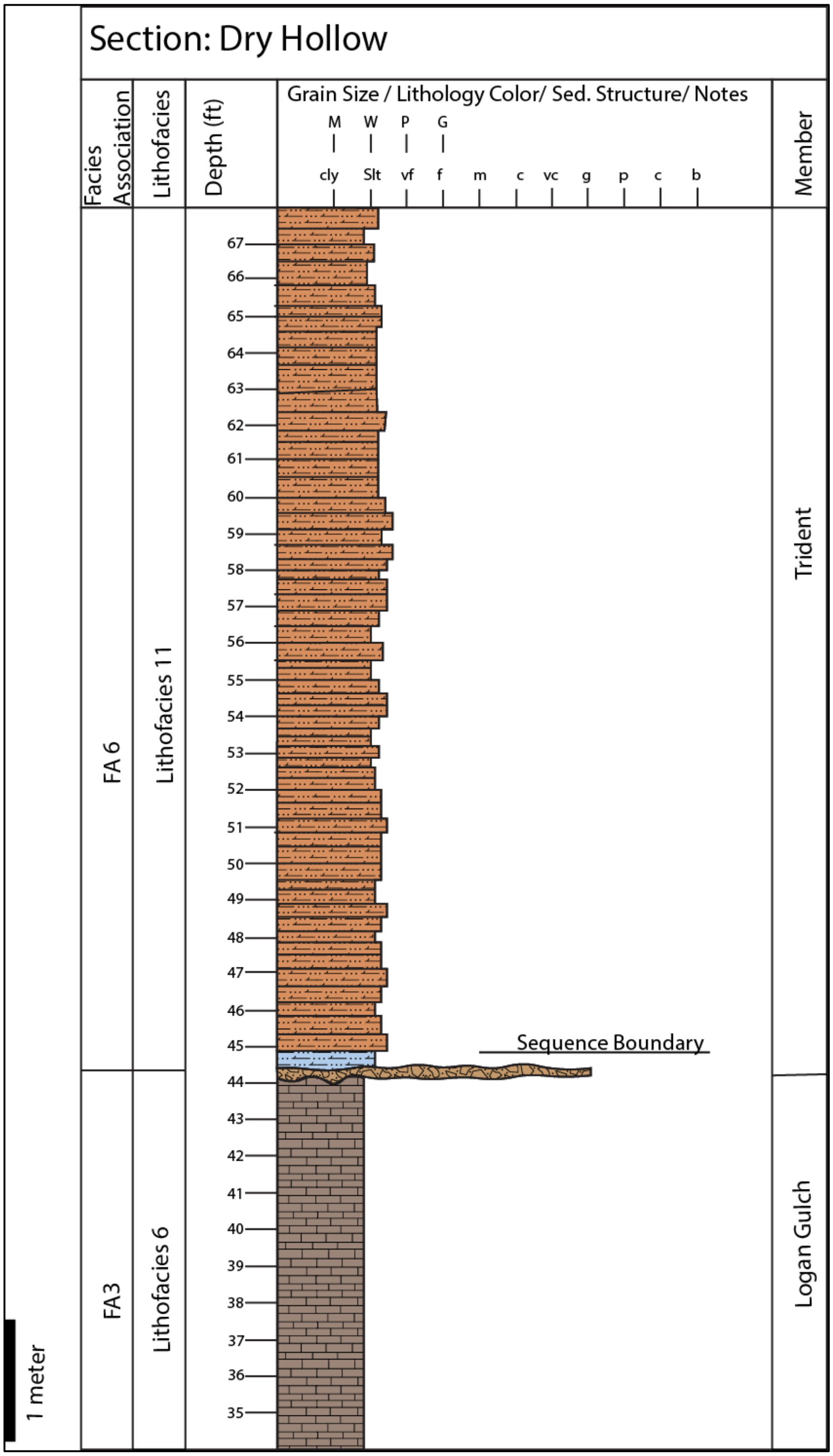
| | |
|---|---|
| Lithofacies 10 | 0.9’ |
| Lithofacies 9 | 16.7’ |
| Lithofacies 11 | 55.0’ |
| Lithofacies 6 | 11.7’ |
| Lithofacies 5 | 16.1’ |
| Lithofacies 6 | 16.2’ |
| Lithofacies 1 (covered) | ------ |
| **Total Thickness** | **116.6’** |

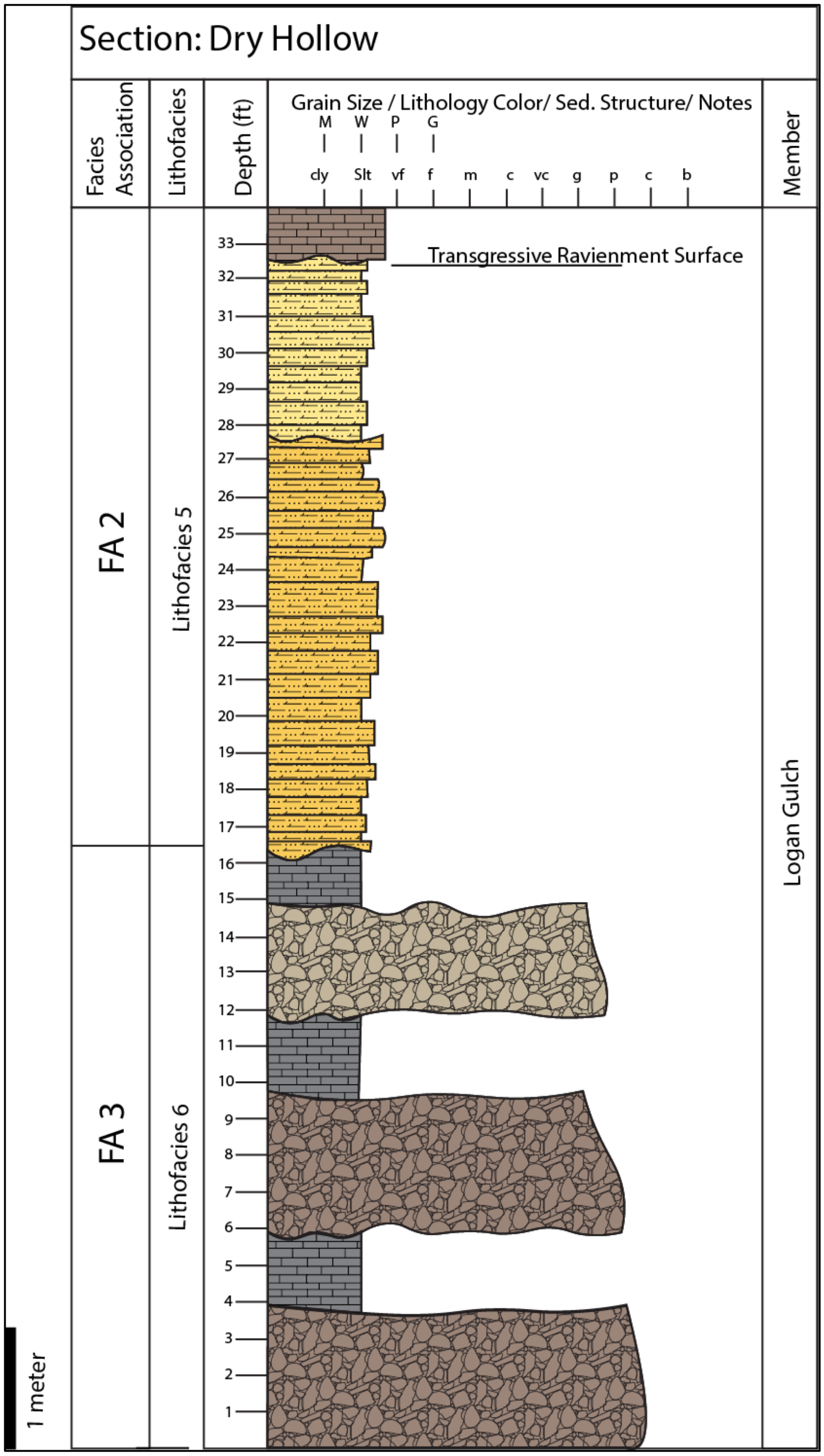
**Lithofacies Contact Observations:** The contacts between the lower beds of lithofacies 4 and 6 are gradational. Occasionally, these contacts are brecciated due to the fractured nature of the underlying crystalline limestones of lithofacies 4. The contact that separates lithofacies 11 from the underlying lithofacies 4 is sharp. Across this contact, there is a 2 inch interval that is bleached light blue and is unconsolidated. The contact that lies above lithofacies 11, separating it from lithofacies 9, is sharp. There is no gradation across this contact. The contact between Lithofacies 9 and 10 is gradational over an interval of 2 inches. The upper contact between Lithofacies 10 and the Sappington Formation is sharp and is known to be a regional sequence boundary (Sandberg, 1988a.)

**Supplemental Notes:** At this location, the lower Three Forks lithologies are not exposed. However, it is assumed that the covered interval includes the lithologies of FA 1 due to red mud staining on the adjacent slopes underlying the exposed section. A reference to the lower lithologies of this outcrop is briefly mentioned in Hadley (1980). Access to this section is extremely easy, as it is exposed in outcrop along the side of Call Road (NF-292) on the west side of the Madison River near of Ennis, MT. This is the only location where lithofacies 6 and lithofacies 4 are found to be interbedded.  Normally, Lithofacies 6 overlies FA 2 lithofacies.


Section: Dry Hollow
Facies Associaition
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
136
135
134
133
132
131
130
129
128
127
126
125
124
123
122
121
120
119
118
117
116
115
114
113
112
111
110
108
107
106
105
104
103
Sequence Boundary
10
FA 5
Lithofacies 9
Trident
1 meter


Section: Dry Hollow
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 5
9
FA 6
Lithofacies 11
Maximum Flooding Surface
Trident
1 meter
101
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
71
70
69


Section: Dry Hollow
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 6
Lithofacies 11
Trident
67
66
65
64
63
62
61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
45
Sequence Boundary
44
43
42
41
40
39
38
37
36
35
FA3
Lithofacies 6
Logan Gulch
1 meter



Section: Dry Hollow
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
Transgressive Ravienment Surface
FA 2
FA 3
Lithofacies 5
Lithofacies 6
Logan Gulch
1 meter
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

**Lick Creek**

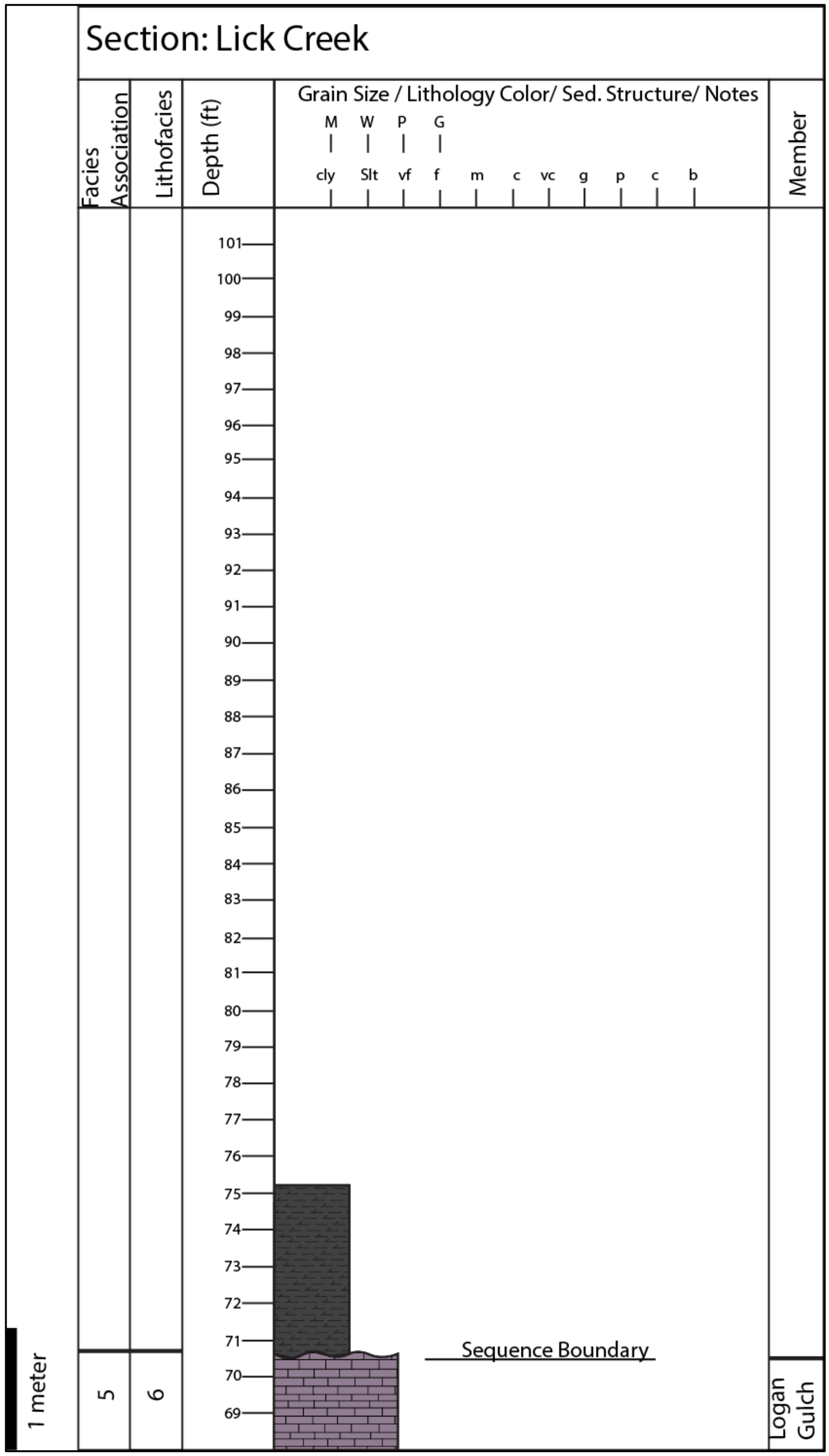
The Three Forks Formation at Lick Creek is 58.1 feet thick. It is bounded at the base by Birdbear Member of the Jefferson Formation and is overlain by the Sappington Formation. This section includes a full expression of the Three Forks Formation.

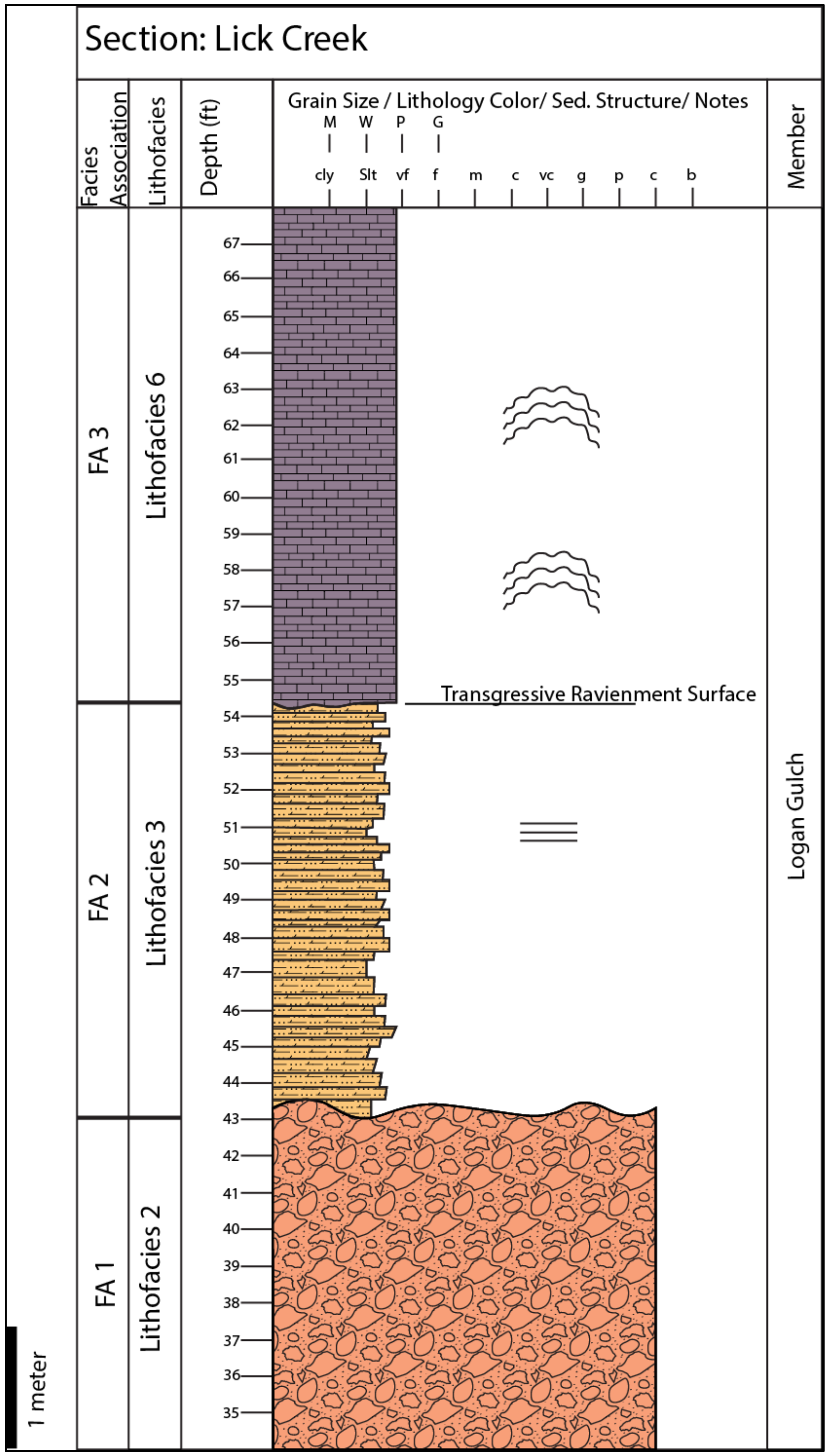
**Lithofacies Thicknesses:** Thicknesses in feet are listed in stratigraphic order from the top to bottom of the section.

| | |
|---|---|
| Lithofacies 6 | 16.4’ |
| Lithofacies 3 | 10.9’ |
| Lithofacies 2 | 16.4’ |
| Lithofacies 1 | 14.4’ |
| **Total Thickness** | **58.1’** |

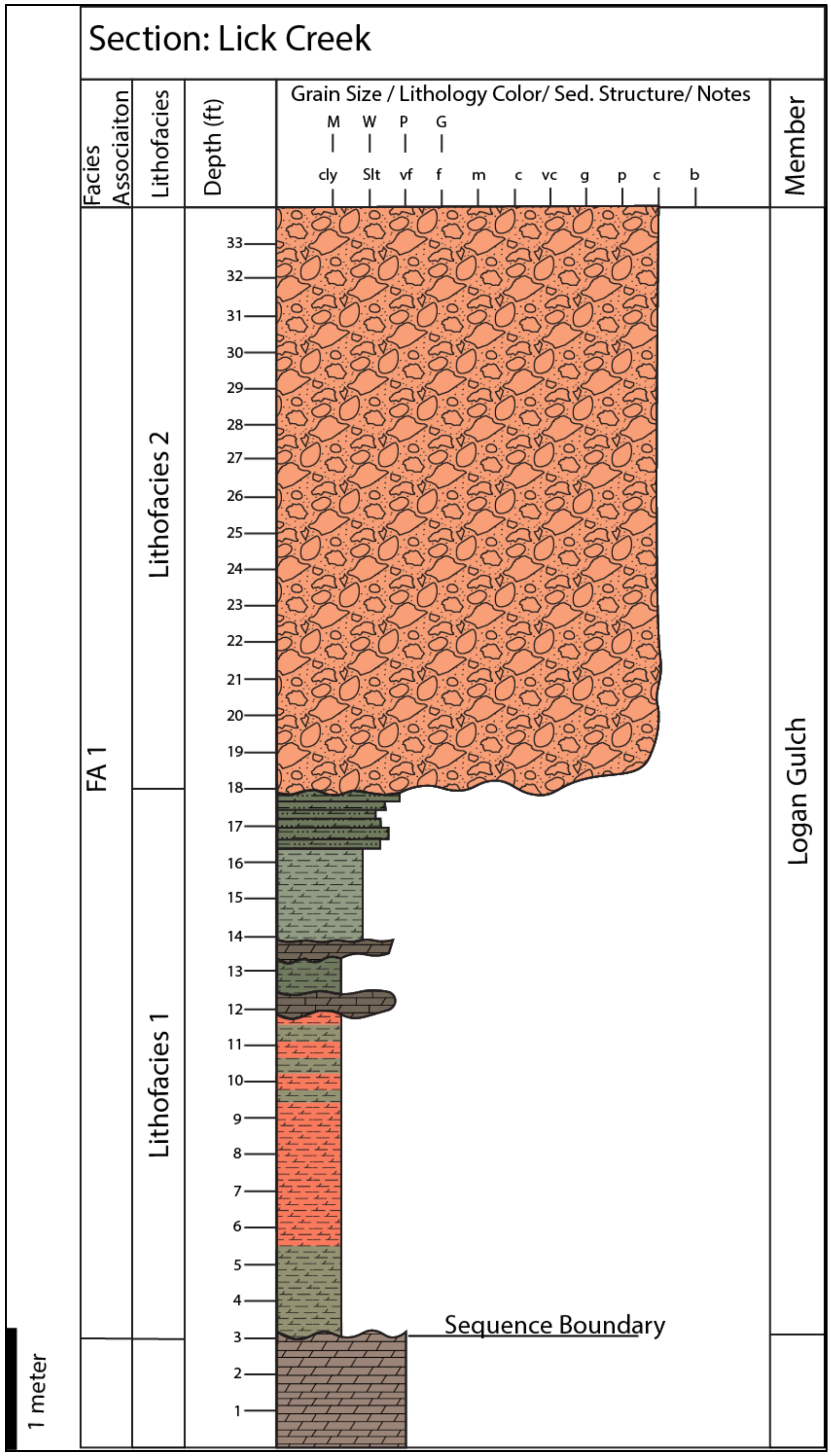
**Facies Contact Observation:** The contact that separates the Three Forks Formation from the underlying Birdbear Member of the Jefferson Formation is well exposed in this location. The transition across this contact from the sucrosic dolomite of the Birdbear Formation to the silty shales of lithofacies 1 of the Three Forks Formation is abrupt. This contact is a regionally recognized unconformity and is referred to as Sequence Boundary 1. Above, the contact between lithofacies 1 and the collapse breccia of lithofacies 2 is indistinguishable, as lithofacies 1 is often included in clasts of lithofacies 2. The contact between lithofacies 2 and lithofacies 3 can be described similarly. Here, large boulder-size clasts of lithofacies 3 are incorporated into the underlying breccia. The contact between lithofacies 3 and 6 is distinct and abrupt. The contact forms a scoured surface and cuts into lithofacies 3. The surface has approximately 2.5’ of relief and is considered to be a transgressive ravientment surface. The upper contact that separates lithofacies 6 from the overlying Sappington Formation is sharp, however, it is poorly exposed at this location. This surface separates Sequence 1 of the Three Forks Formation from the Sappington Formation. Sequence 2 of the Three Forks Formation has been eroded away completely. Because of this, the upper erosional surface is a composite surface that includes Sequence Boundary 2, the Maximum flooding surface of Sequence 2, and Sequence Boundary 3.

**Supplemental Notes:** The Lick Creek section is easily accessible. The section occurs within a road cut directly adjacent to a forest service road in Sluice Boxes State Park in Belt, Montana. Due to excellent exposure within this road cut the Lick Creek section is perhaps the best section to view the lithologies of supratidal FA 1. At other sections, these lithologies are usually completely or partially covered due to the recessive nature of the breccia and shales. Additionally, Lick Creek is the only section to display the scour contact between lithofacies 3 of FA 2 and lithofacies 3 of FA 3.


Section: Lick Creek
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
101
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
71
70
69
Sequence Boundary
1 meter
5
6
Logan Gulch



Section: Lick Creek
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 3
Lithofacies 6
FA 2
Lithofacies 3
FA 1
Lithofacies 2
67
66
65
64
63
62
61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
Transgressive Ravienment Surface
Logan Gulch
1 meter


Section: Lick Creek
Facies Associaiton
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 1
Lithofacies 2
Lithofacies 1
33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
Sequence Boundary
Logan Gulch
1 meter

## Hardscrabble

The Three Forks Formation at Hardscrabble is 147.3 feet thick. It is bounded at the base by Birdbear Member of the Jefferson Formation and is overlain by the Sappington Formation.

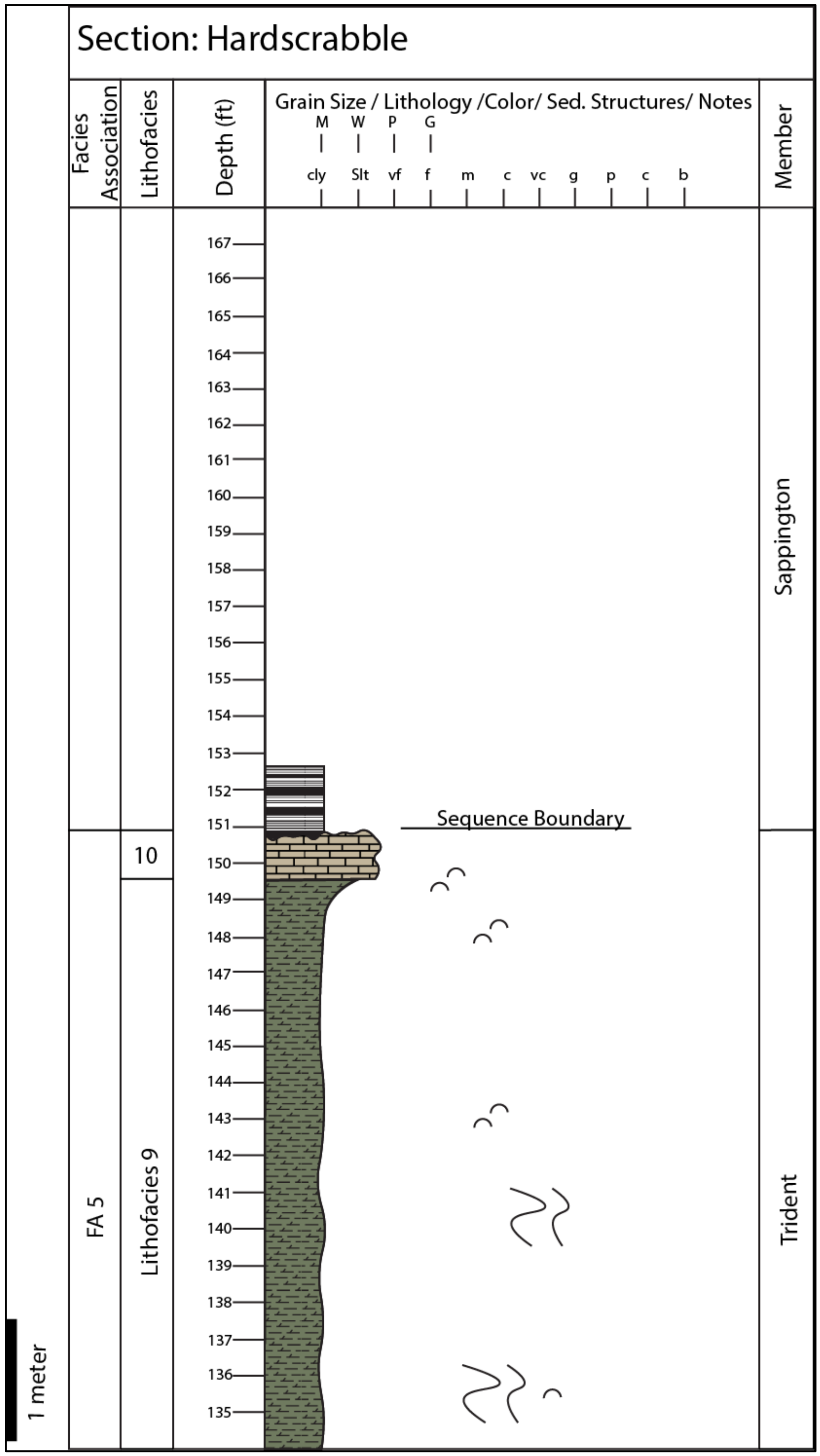
**Lithofacies Thicknesses:** Thicknesses in feet are listed in stratigraphic order from the top to bottom of the section.

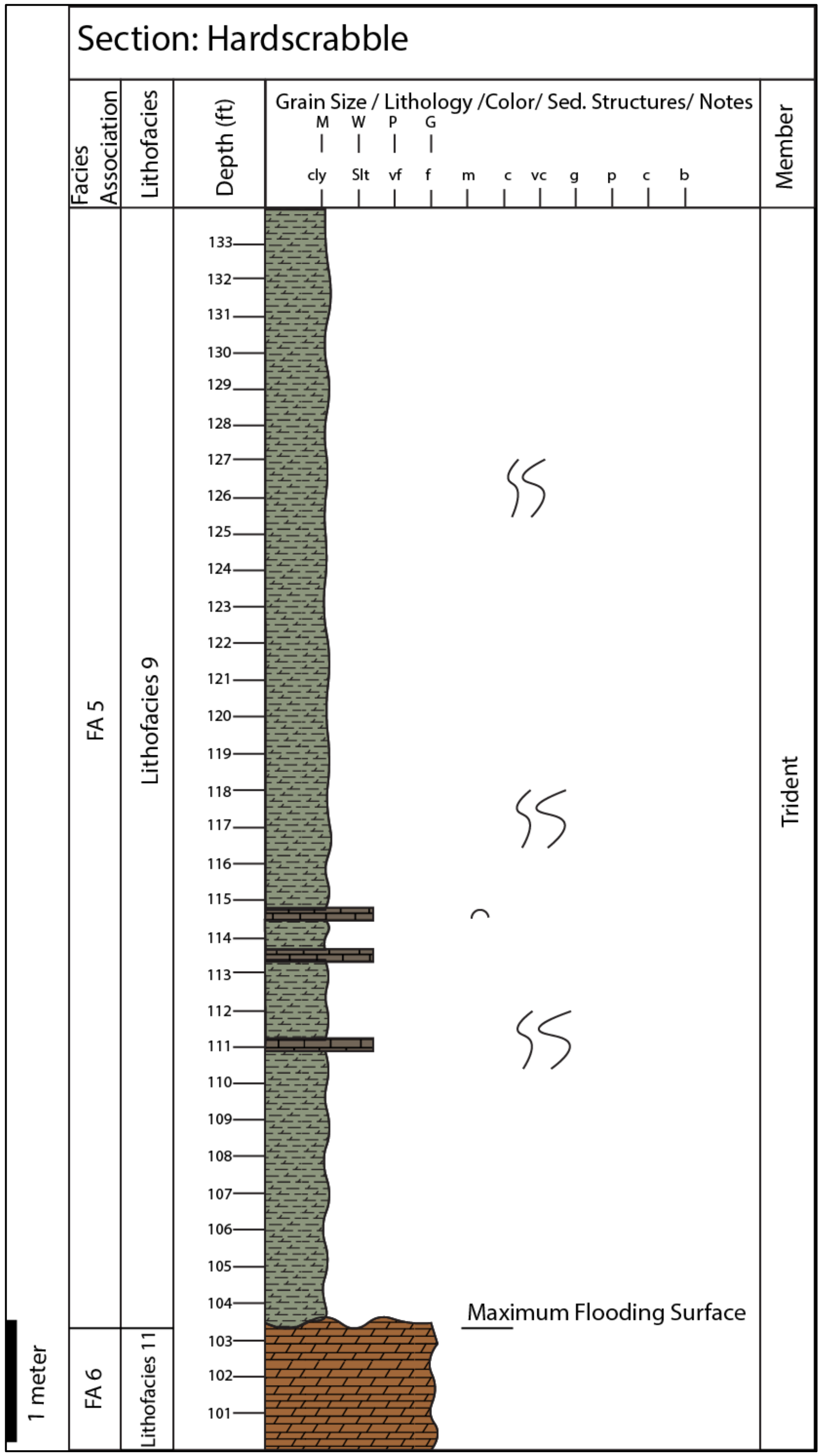
| | |
|---|---|
| Lithofacies 10 | 1.1’ |
| Lithofacies 9 | 46.0’ |
| Lithofacies 11 | 15.4’ |
| Lithofacies 6 | 7.8’ |
| Lithofacies 2 | 3.9’ |
| Lithofacies 2 (covered) | 70.1’ |
| Lithofacies 1 | 3.0’ |
| **Total Thickness** | **147.3** |

**Facies Contact Observations:** The contact between lithofacies 1 and the underlying Birdbear Member of the Jefferson Formation is abrupt. The uppermost surface of the Birdbear Member of the Jefferson Formation is slightly discolored and weathered. This surface is Sequence Boundary 1. The contact between the shales of lithofacies 1 and the overlying breccia is not observed due to the precarious nature of the outcrop. The contact that separates lithofacies 2 with the overlying limestones of lithofacies 6 is irregular and has up to 4 feet of relief where measured. The lithofacies 6 limestone is heavily fractured and infills into the underlying breccia of lithofacies 2. Although no scouring is present, correlations to other outcrops suggest that this contact represents the transgressive ravienment surface of Sequence 1. The lagoonal deposits of lithofacies 11 are separated from the underlying limestone by a sharp contact. The change is facies across this contact suggest a depositional hiatus occurred, making this surface Sequence Boundary 2. The lower 4.5 feet of lithofacies 11 is composed of a finer dolomitic crystal fabric and is more recessive than the upper 10.9 feet. The contact between Lithofacies 11 and 9 is gradational with the transition from dolostone to dolomitic shale occurring over approximately 1 foot. It is interpreted that the maximum flooding surface of Sequence 2 occurs across this interval..

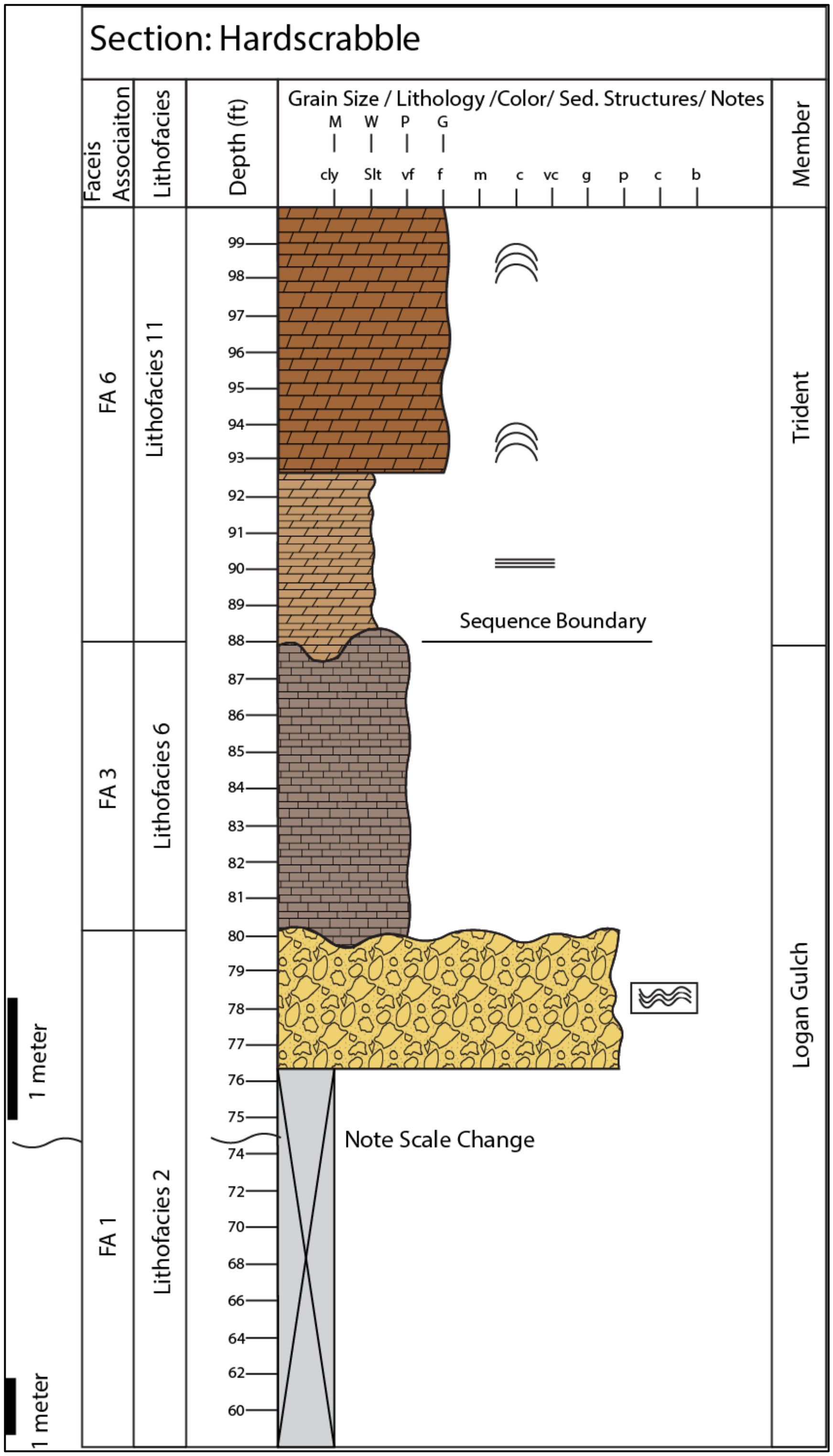
The contact between lithofacies 9 and 10 is gradational and spans approximately 6 inches. The contact the separates the Three Forks Formation from the Lower Sappington shales is bleached and irregular. It is approximately 6 inches thick. This contact is known to be a regional subaerial unconformity and represents Sequence Boundary 3.

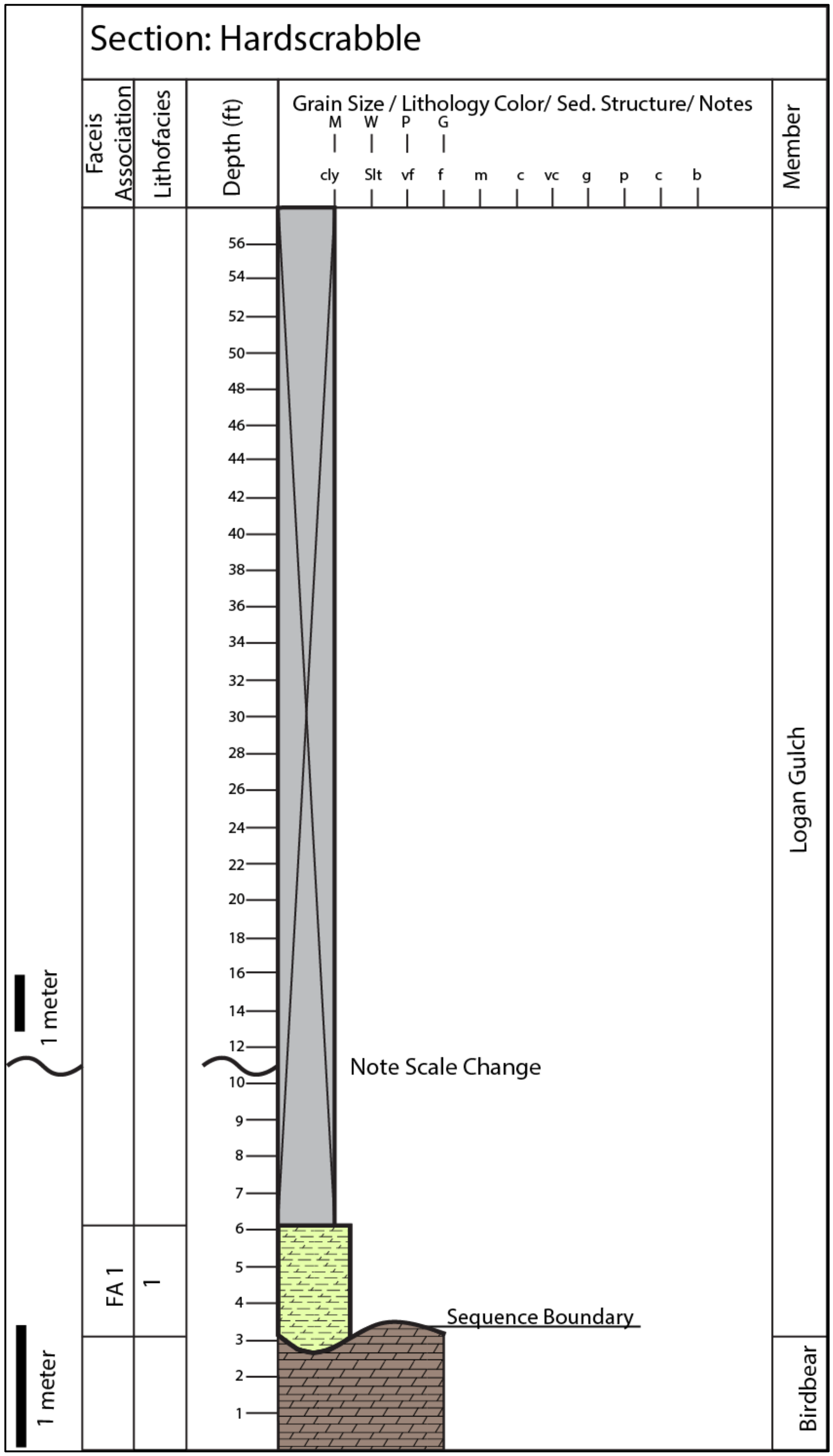
**Supplemental Notes:** The Hardscrabble section is an ideal location to view the algal laminations in lithofacies 9. Although it is difficult to access, the best way to view the Three Forks Formation here is to follow the rib of lithofacies 6 instead of taking the trail that traditionally leads to the top of Hardscrabble Peak.


Section: Hardscrabble
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
167
166
165
164
163
162
161
160
159
158
157
156
155
154
153
152
151
150
149
148
147
146
145
144
143
142
141
140
139
138
137
136
135
Sequence Boundary
Sappington
Trident
FA 5
10
Lithofacies 9
1 meter



Section: Hardscrabble
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
133
132
131
130
129
128
127
126
125
124
123
122
121
120
119
118
117
116
115
114
113
112
111
110
109
108
107
106
105
104
103
102
101
FA 5
Lithofacies 9
Trident
Maximum Flooding Surface
FA 6
Lithofacies 11
1 meter


Section: Hardscrabble
Faceis Associaiton
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 6
Lithofacies 11
Trident
Sequence Boundary
FA 3
Lithofacies 6
Logan Gulch
FA 1
Lithofacies 2
Note Scale Change
1 meter
1 meter


Section: Hardscrabble
Faceis Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
9
8
7
6
5
4
3
2
1
Note Scale Change
Sequence Boundary
FA 1
1
1 meter
1 meter
Logan Gulch
Birdbear

**Mystic Lake**

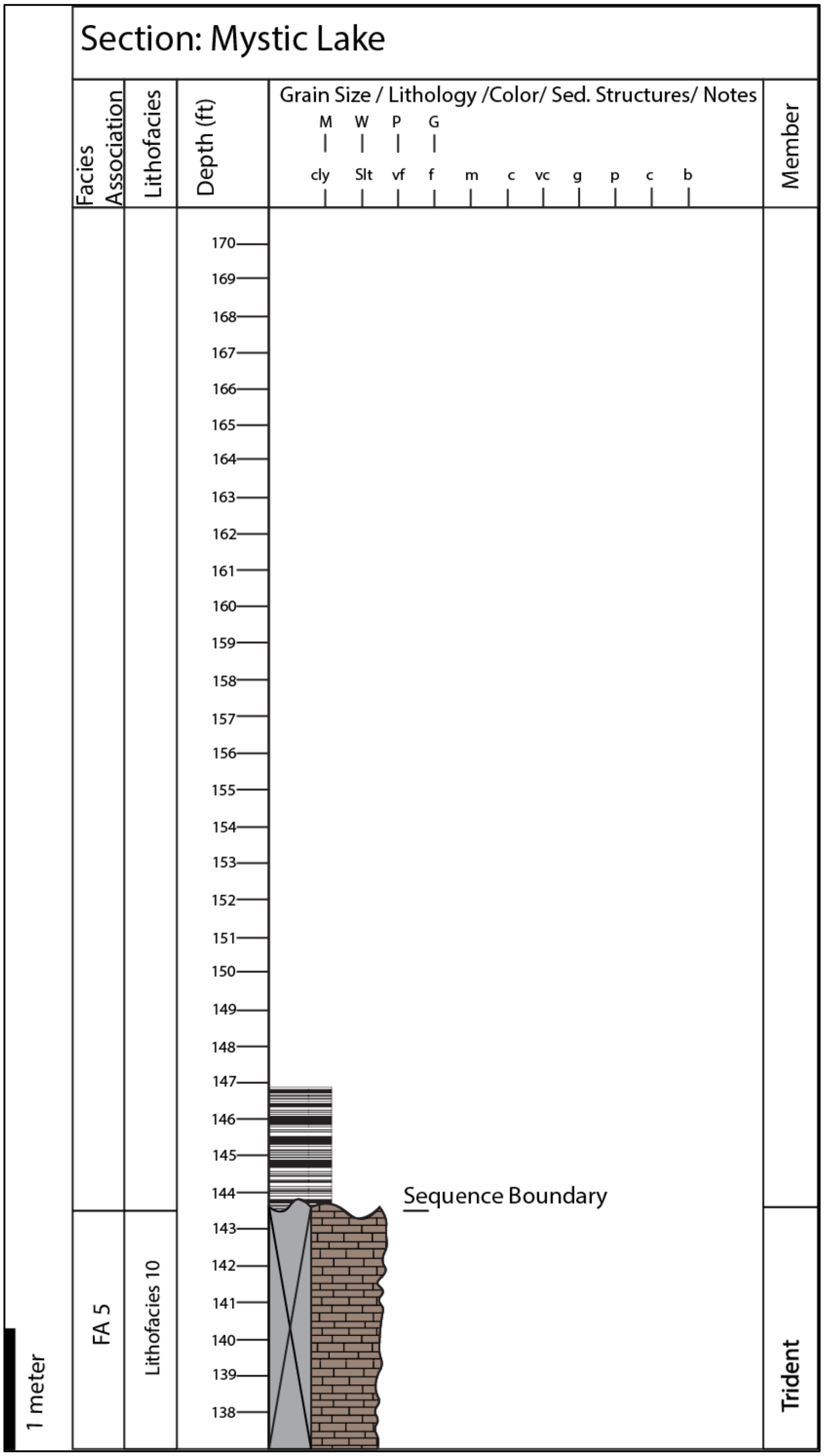
The Three Forks Formation at Mystic Lake is 140.4 feet thick. It is bounded at the base by Birdbear Member of the Jefferson Formation and is overlain by the Sappington Formation.

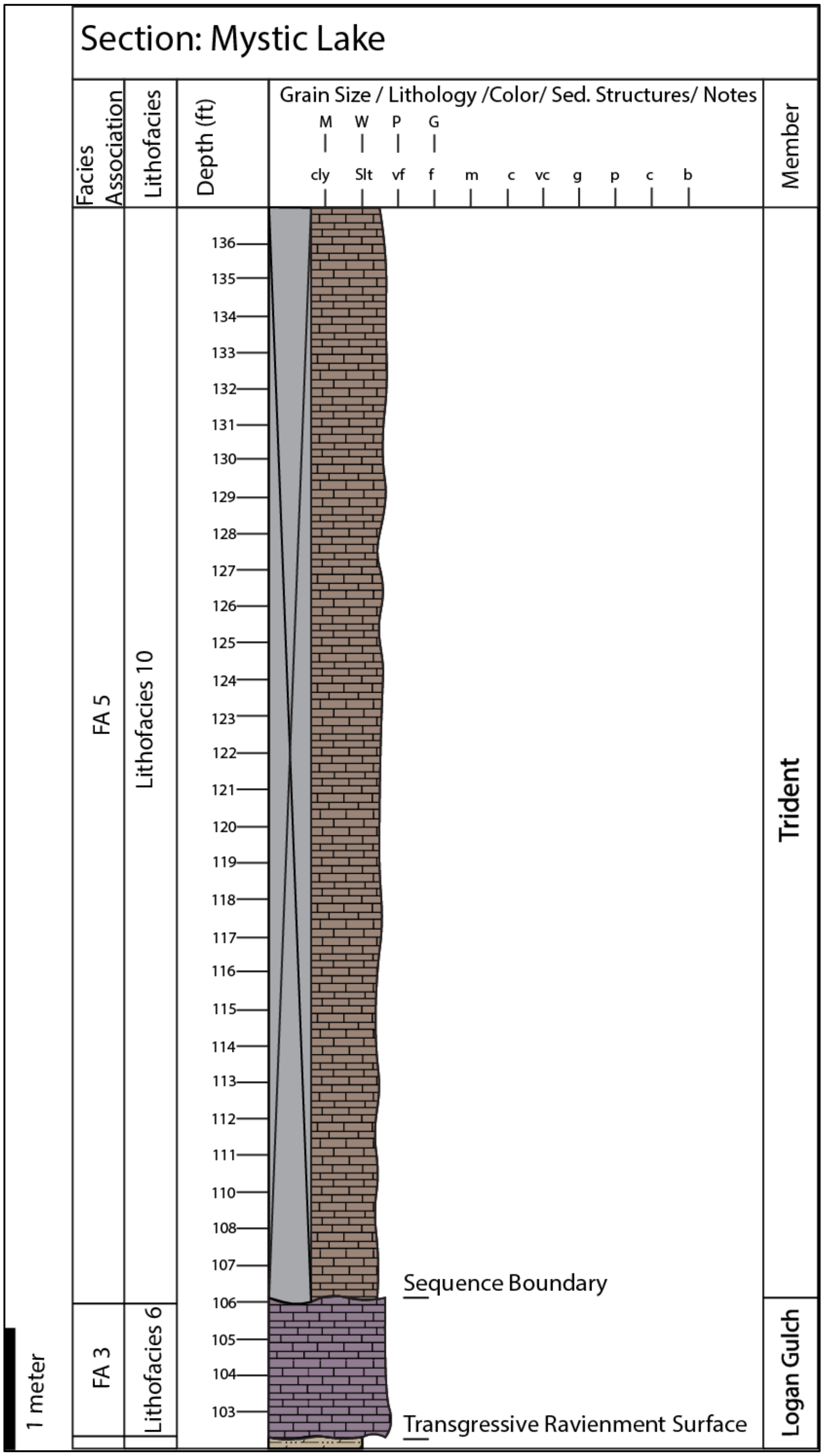
**Lithofacies Thicknesses:** Thicknesses in feet are listed in stratigraphic order from the top to bottom of the section.

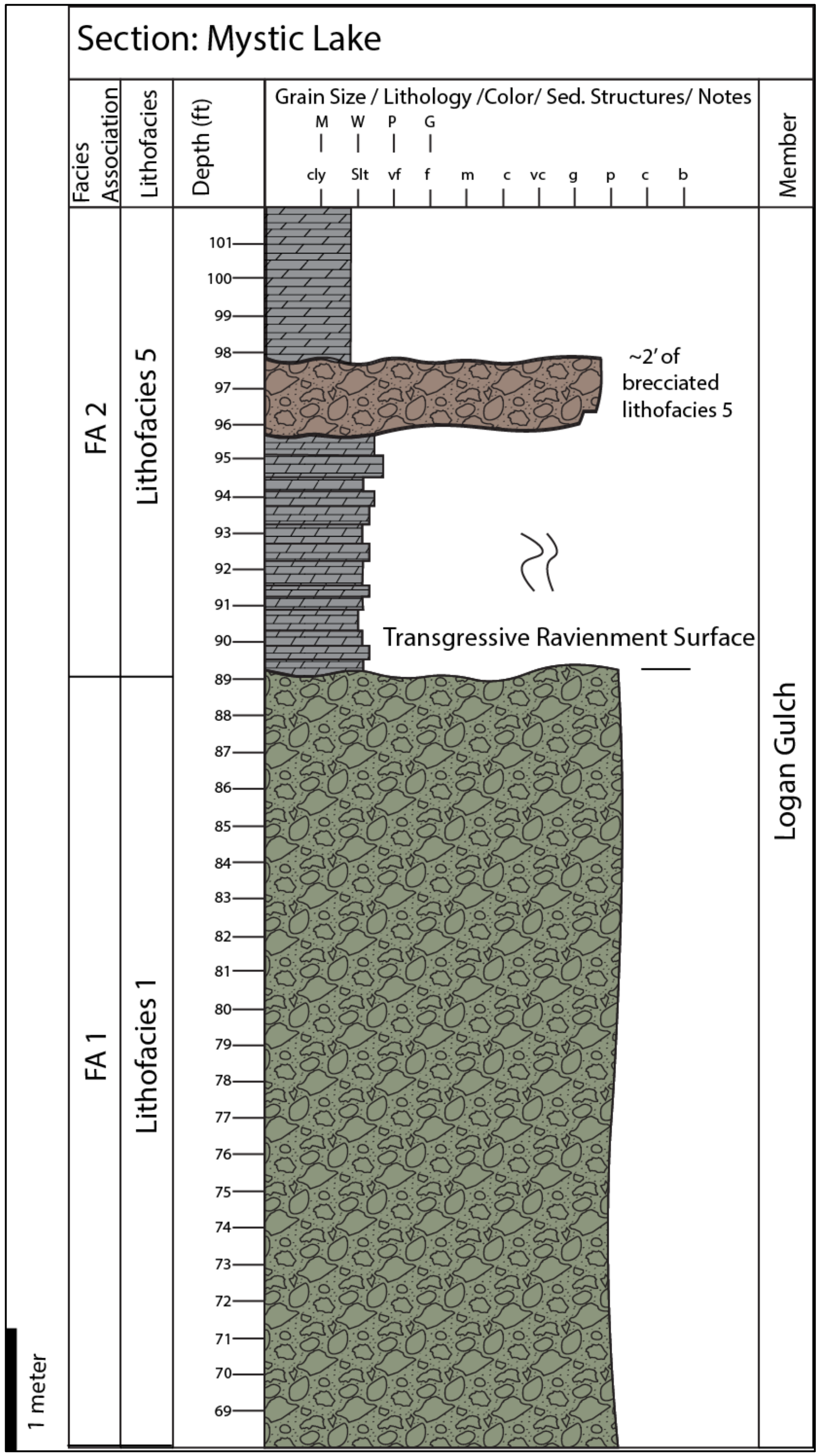
| | |
|---|---|
| Lithofacies 10 | 37.5’ |
| Lithofacies 6 | 3.8’ |
| Lithofacies 5 | 13.1’ |
| Lithofacies 2 | 42.4 |
| Lithofacies 1 | 27.4 |
| Lithofacies 4a/4b | 16.2 |
| **Total Thickness** | **140.4** |

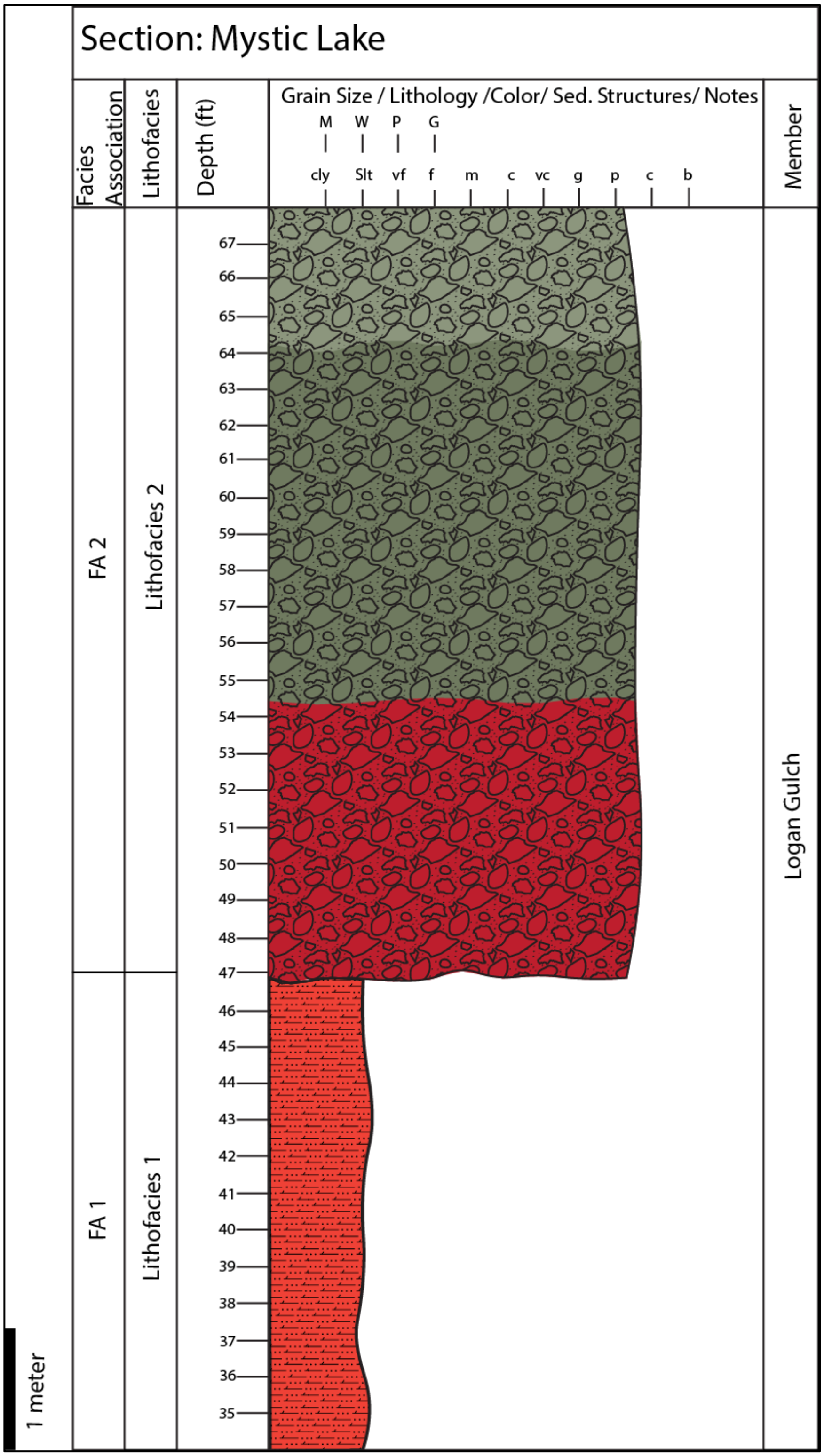
**Surfaces and Facies Contact Observations:** The lower Three Forks in this location is bounded at the base by sequence boundary 1, which separates the lower Three Forks lithofacies 4a and 4b from the underlying Birdbear Member of the Jefferson Formation. Above, the transition from lithofacies 4a/4b to the overlying lithofacies 1 is gradual and occurs over ~5 inches. The transition between lithofacies 1 and 2 is difficult to decipher, as the breccias of lithofacies 2 obscure any definitive contact. The contact between lithofacies 2 and 5 is sharp. The lower contact of lithofacies 5 is irregular with ~2ft of relief. This surface is considered to be the transgressive ravinement surface. Above, a transitional contact separates lithofacies 5 from the overlying limestone on lithofacies 6. Lithofacies 6 is separated from lithofacies 10 by a sharp contact that is interpreted to be a subaerial unconformity. This unconformity is referred to as sequence boundary 2. Lithofacies 10 is separated from the overlying Sappington Formation by an unconsolidated, bleached transitional surface that is ~1 inch thick. This contact is considered to be a subaerial unconformity and is referred to as sequence boundary 3.

**Supplemental Notes:** The Mystic Lake outcrop is located just outside of Bozeman off of Forest Service Road 979. The fastest way to reach the outcrop is to follow this road for approximately 6 miles before dropping off into the adjacent ravine. The outcrop is on the opposite bank of the South Fork of Bozeman Creek. The Three Forks Formation at this outcrop is difficult to reach, however, it is only one of two locations where lithofacies 5 and 6 are interbedded. McMannis(1962) made reference to this section.

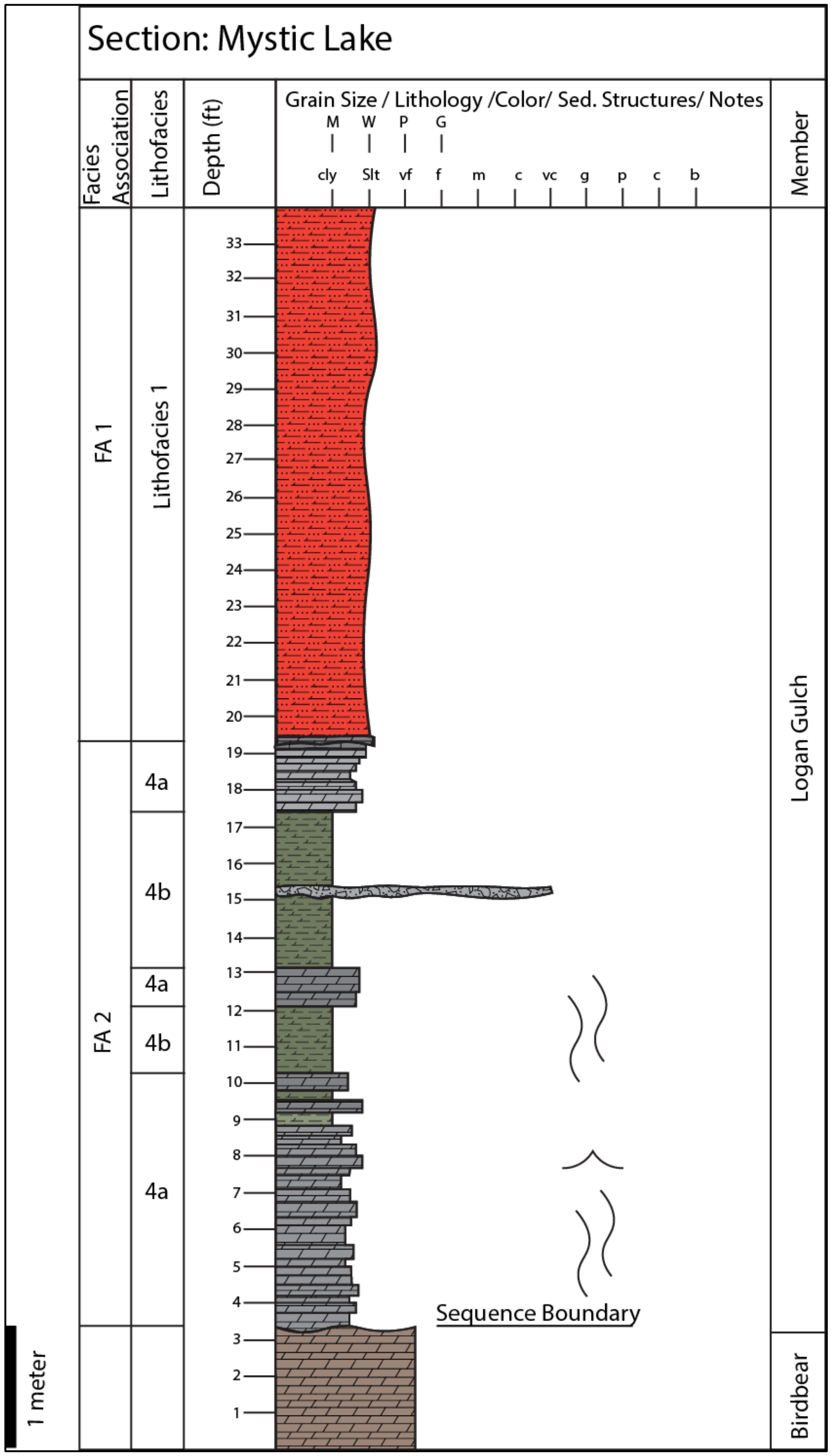



Section: Mystic Lake
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 5
Lithofacies 10
Trident
Sequence Boundary
FA 3
Lithofacies 6
Logan Gulch
Transgressive Ravienment Surface
1 meter
136
135
134
133
132
131
130
129
128
127
126
125
124
123
122
121
120
119
118
117
116
115
114
113
112
111
110
108
107
106
105
104
103


Section: Mystic Lake
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 2
Lithofacies 5
FA 1
Lithofacies 1
101
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
71
70
69
~2' of brecciated lithofacies 5
Transgressive Ravienment Surface
Logan Gulch
1 meter



Section: Mystic Lake
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 2
FA 1
Lithofacies 2
Lithofacies 1
67 66 65 64 63 62 61 60 59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42 41 40 39 38 37 36 35
Logan Gulch
1 meter


Section: Mystic Lake
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 1
Lithofacies 1
FA 2
4a
4b
4a
4b
4a
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Sequence Boundary
Logan Gulch
Birdbear
1 meter

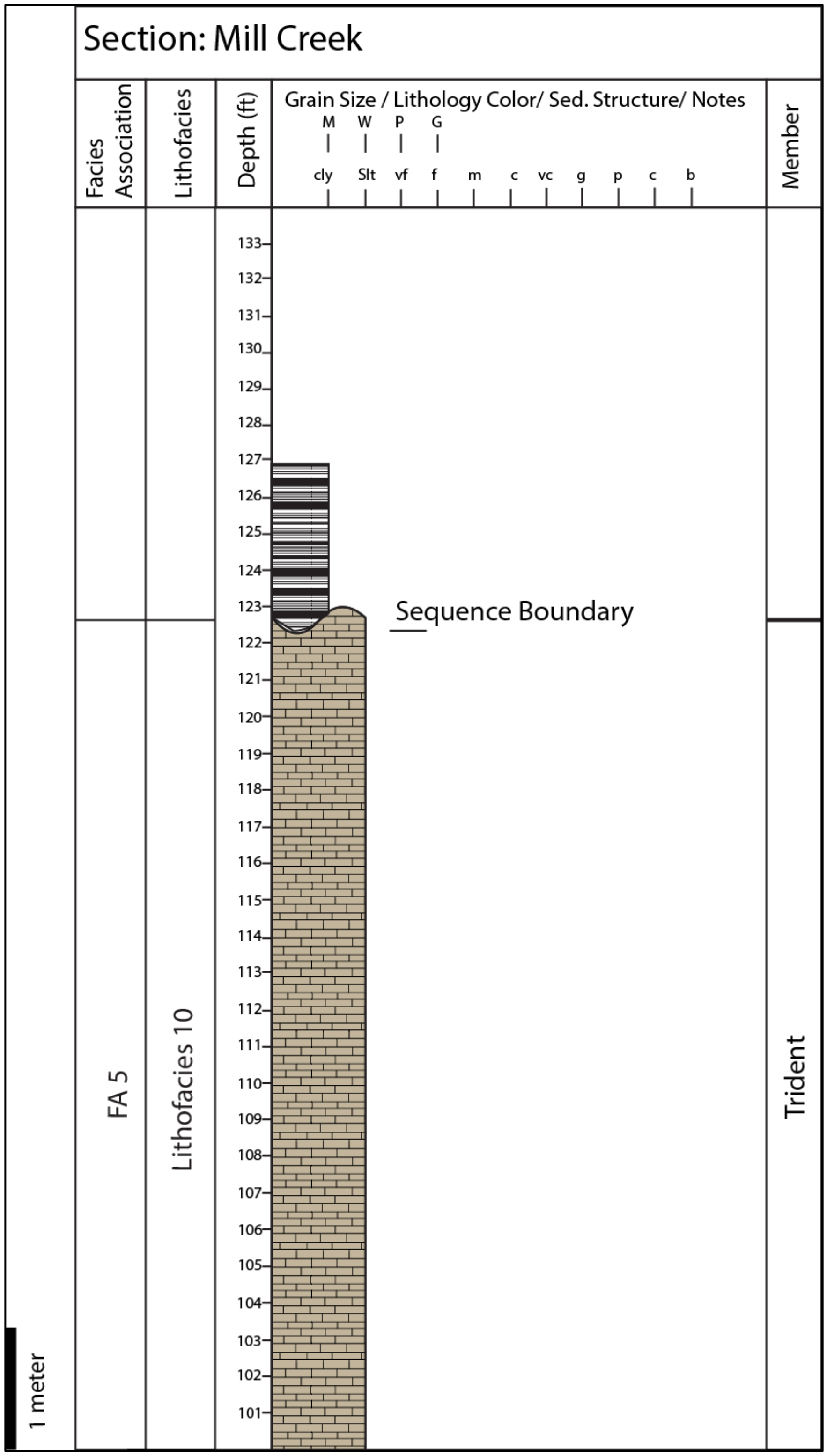
## Mill Creek

The Three Forks Formation at Mill Creek is 123.5 feet thick. It is bounded at the base by Birdbear Member of the Jefferson Formation and is overlain by the Sappington Formation.

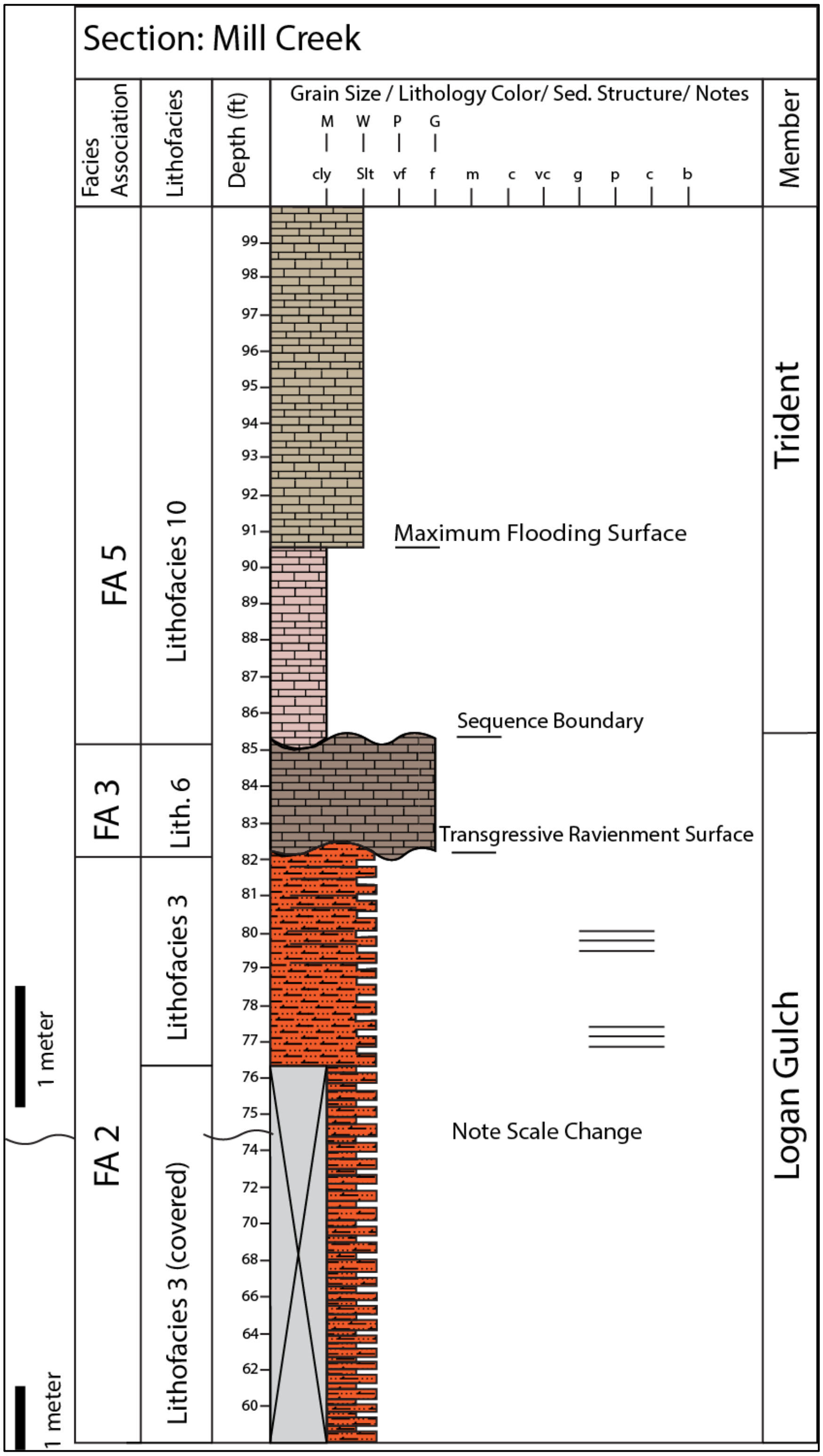
| | |
|---|---|
| Sappington | .4.3’ |
| Lithofacies 10 | 37.1’ |
| Lithofacies 6 | 3.2’ |
| Lithofacies 3 | 5.8’ |
| Lithofacies 3 (Covered | 37.8’ |
| Lithofacies 1 (Covered) | 35.3’ |
| **Total Thickness** | **123.5’** |

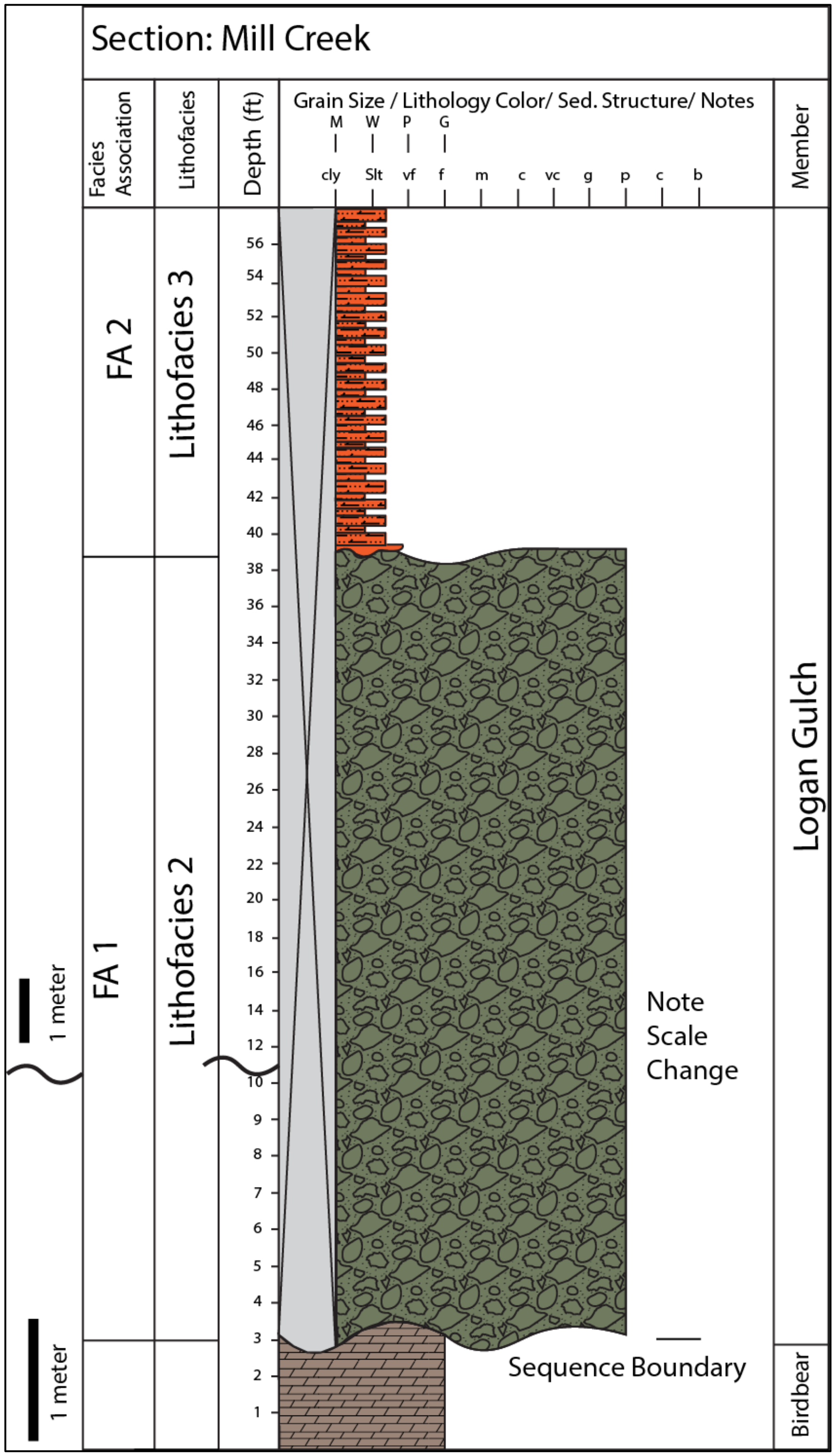
**Surfaces and Facies Contact Observations:** The contact that separates Lithofacies 1 from the underlying Birdbear Member of the Jefferson Formation is covered by substantial scree . However, this surface is considered to be the subaerial unconformity of Sequence Boundary 1 based on correlations to adjacent outcrops in the study area, as well as from reports from previous investigations that list this surface as a regional unconformity. The covered interval of Lithofacies 1 is inferred from red siltstone and salt cast-bearing dolostone in float. Lithofacies 3 emerges above the covered interval. The contact between Lithofacies 3 and lithofacies 6 is sharp and somewhat scoured. Lithofacies 6 has approximately .5’ of relief into lithofacies 3. This contact is referred to as a transgressive ravienment surface of Sequence 1. Above, a subtle but sharp contact separates the Lithofacies 3 limestones from the overlying limestones of Lithofacies 10. Here, clasts of lithofacies 10 can be found in brecciated depressions of lithofacies 6. Because this surface separates the TST of Sequence 1 and intervals of the TST of Sequence 2, it is considered a composite surface that includes both Sequence Boundary 2 and the overlying Maximum Flooding Surface of Sequence 2. Above Lithofacies 10, a ~1 inch bleached interval separates the Three Forks Formation from the overlying Sappington Formation. This surface is considered to be a subaerial unconformity and is a regionally recognized erosional surface (Sandberg, 1988a.). This surface is referred to as Sequence Boundary 3 and caps Sequence 2 of the Three Forks Formation.

**Supplemental Notes:** The Mill Creek section is located just south of Livingston, MT in the Absaroka Range. It can be reached via a trail that begins at the end of E Fork Mill Creek Rd. This location contains expressions of Lithofacies 3 and Lithofacies 6 that exhibit a notable amount of oxidation compared to other outcrops. McMannis (1962) refers to the entire outcrop as the "Dolomite Facies" of the Three Forks Formation



Section: Mill Creek
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
133
132
131
130
129
128
127
126
125
124
123
122
121
120
119
118
117
116
115
114
113
112
111
110
109
108
107
106
105
104
103
102
101
Sequence Boundary
FA 5
Lithofacies 10
Trident
1 meter


Section: Mill Creek
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 5
Lithofacies 10
Trident
Maximum Flooding Surface
Sequence Boundary
FA 3
Lith. 6
Transgressive Ravienment Surface
FA 2
Lithofacies 3
Lithofacies 3 (covered)
Note Scale Change
Logan Gulch
1 meter
1 meter
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
72
70
68
66
64
62
60


Section: Mill Creek
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 2
Lithofacies 3
FA 1
Lithofacies 2
Logan Gulch
Birdbear
1 meter
1 meter
Note Scale Change
Sequence Boundary
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
9
8
7
6
5
4
3
2
1

## 63 Ranch

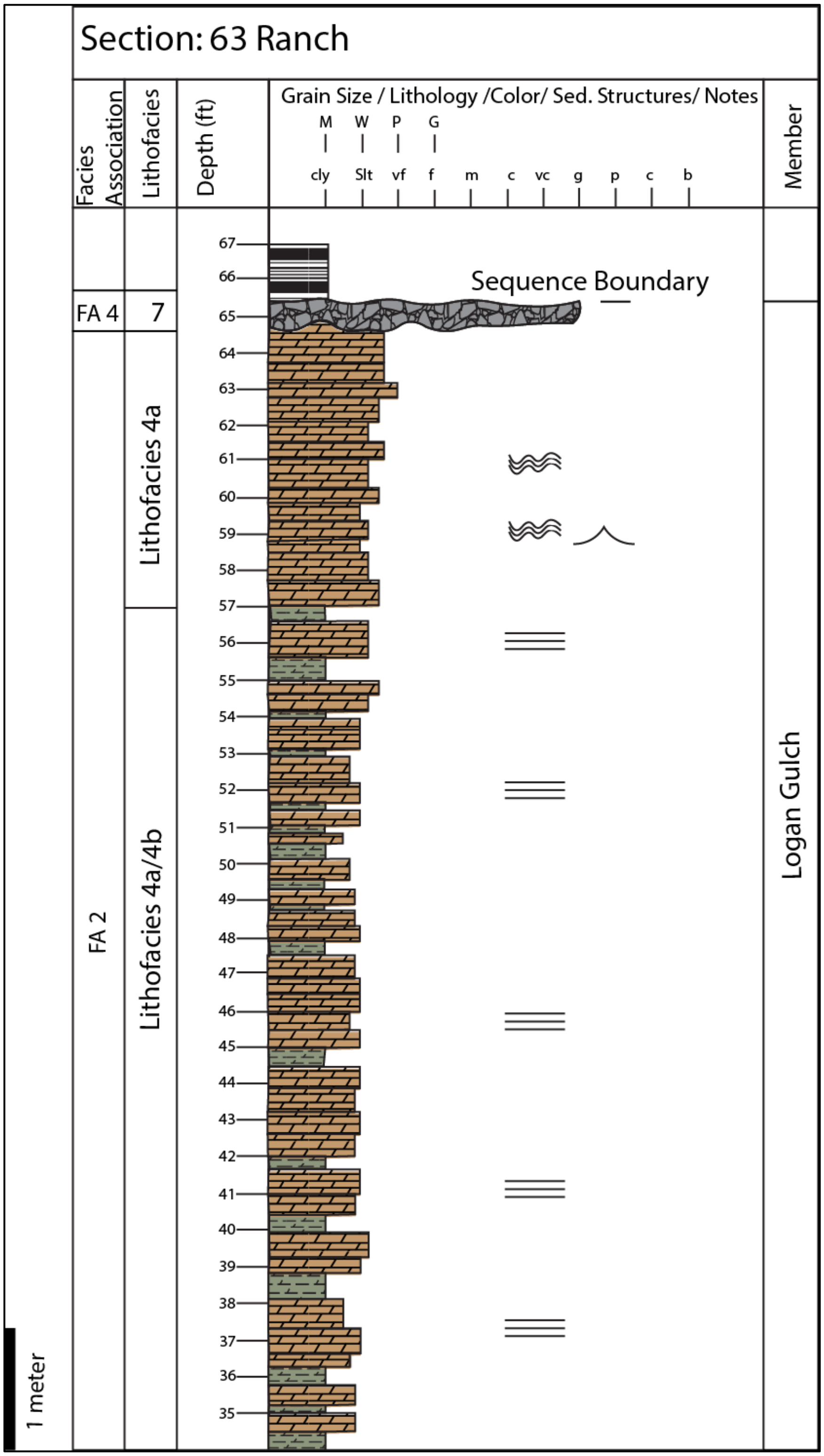
The Three Forks Formation at Mill Creek is 61.8 feet thick. It is bounded at the base by Birdbear Member of the Jefferson Formation and is overlain by the Sappington Formation.

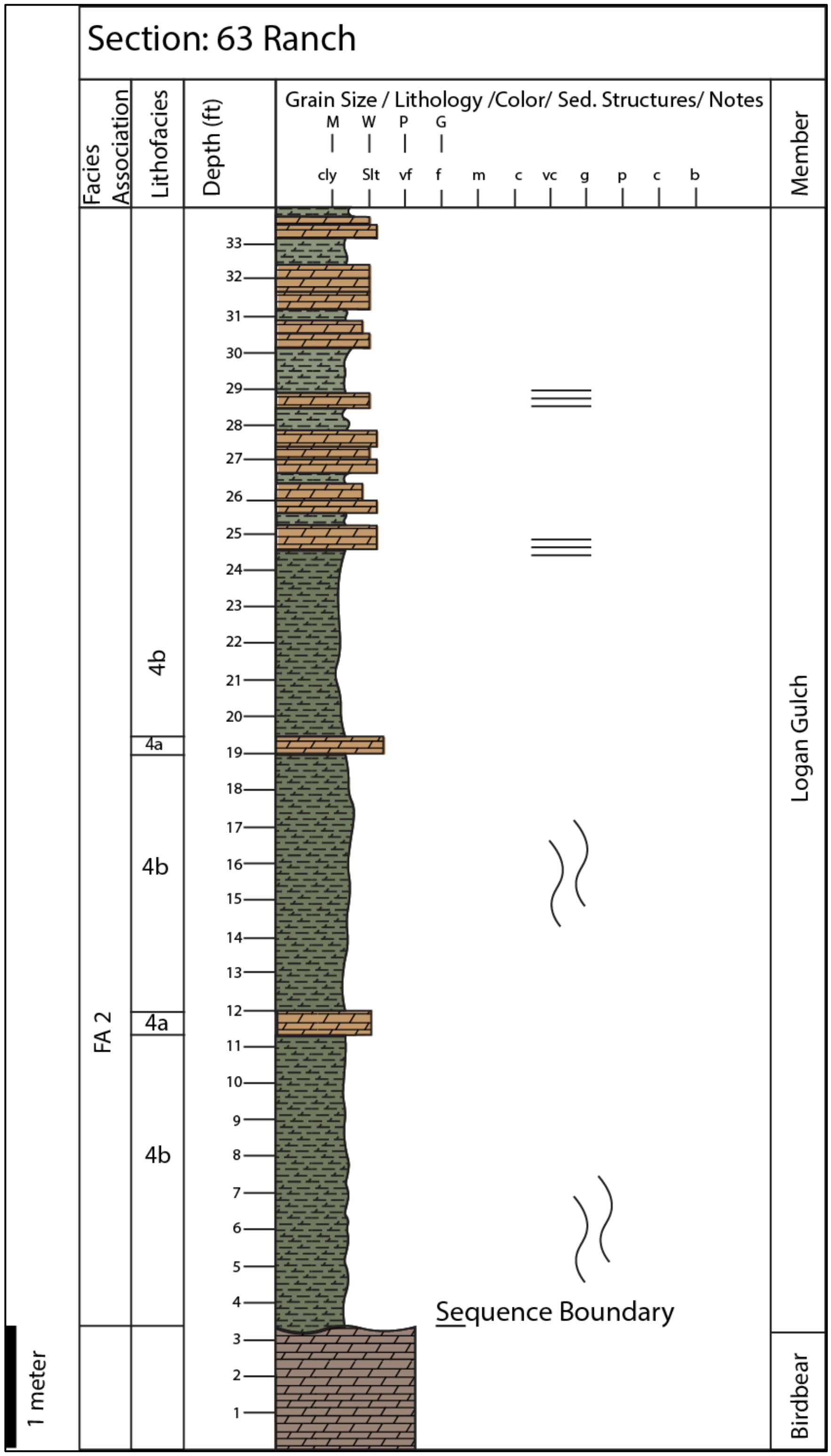
**Lithofacies Thicknesses:** Thicknesses in feet are listed in stratigraphic order from the top to bottom of the section.

| | |
|---|---|
| Lithofacies 7 | 0.5' |
| Lithofacies 4a/4b (Interbedded) | 61.3' |
| **Total Thickness** | **61.8'** |

**Surfaces and Facies Contact Observations:** Lithofacies 4a/4b are separated from the underlying Birdbear member of the Jefferson Formation by a sharp contact that is a subaerial unconformity. This unconformity is sequence boundary one. Lithofacies 7 is separated from the underlying lithofacies 4 by a very abrupt, irregular surface. Lithofacies 7 is separated from the Sappington Formation by a sharp contact. The Lithofacies 7 lag indicates a unconformable surface between the Three Forks Formation and the overlying Sappington Formation, however it should be noted that that this is a composite surface that includes the transgressive ravienment surface of sequence 1, sequence boundary 2, the maximum flooding surface of sequence 2, and sequence boundary 3.

**Supplemental Notes:** 63 Ranch is located east of Livingston in the Absaroka Range just south of Mission Creek. The outcrop lies beyond a recently downed stand of trees and is thus difficult to access. This section is unique in that it includes only two lithofacies of the Three Forks Formation between sequence boundary one below and a composite surface that includes both sequence boundary 2 and 3 above. This location is one of two sections in which the lithofacies 7 lag can be found at the composite surface at the top of the outcrop. The only other section where lithofacies 7 is recognized is the East Baker Mountain Section.


Section: 63 Ranch
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
Sequence Boundary
FA 4
7
FA 2
Lithofacies 4a
Lithofacies 4a/4b
Logan Gulch
1 meter
67
66
65
64
63
62
61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35


Section: 63 Ranch
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
4b
4a
4b
4a
4b
FA 2
Sequence Boundary
Logan Gulch
Birdbear
1 meter

## Baker Mountain

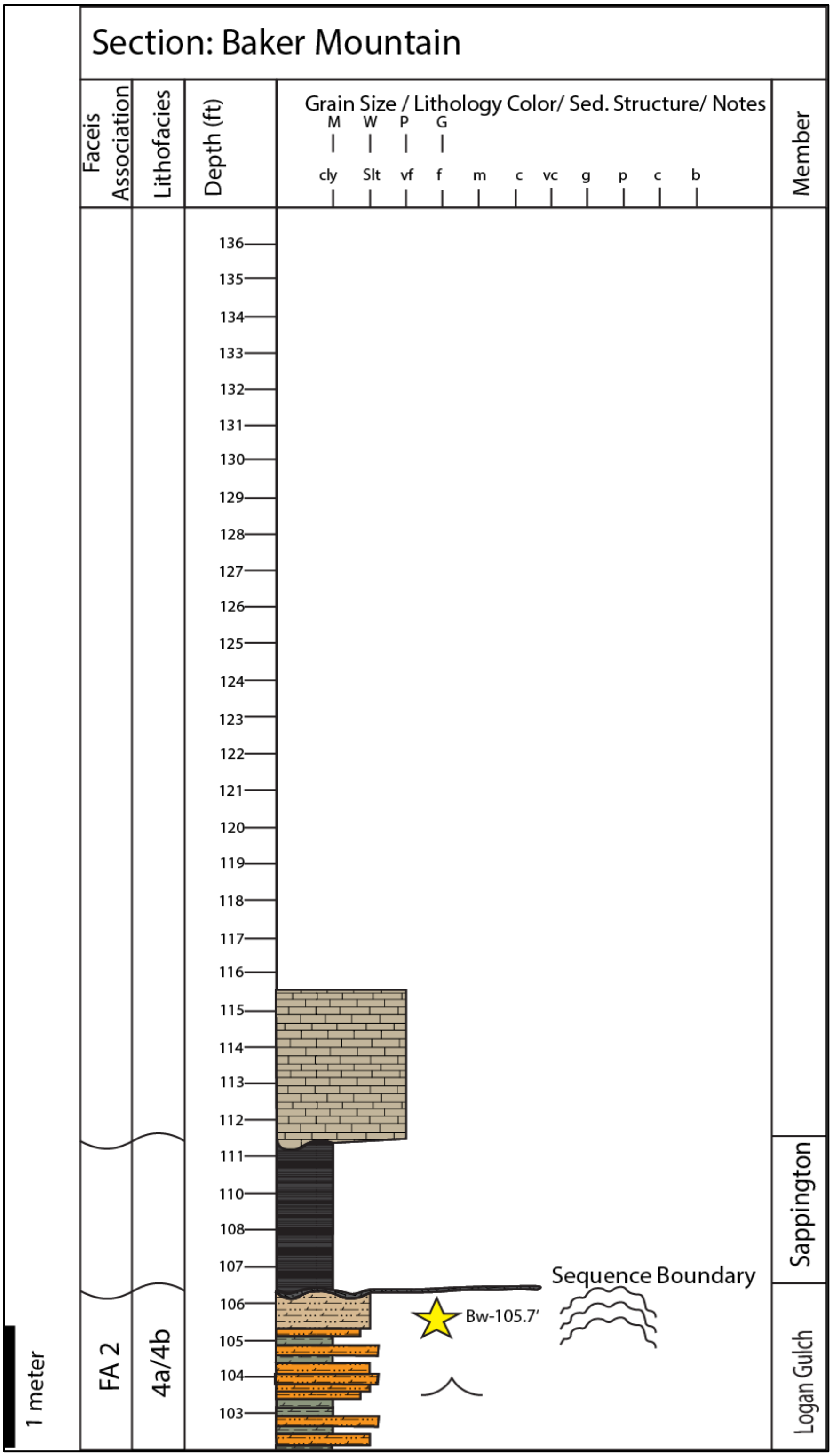
The Three Forks Formation at Baker Mountain is 123.5' feet thick. It is bounded at the base by Birdbear Member of the Jefferson Formation and is overlain by the Sappington Formation.

**Lithofacies Thicknesses:** Thicknesses in feet are listed in stratigraphic order from the top to bottom of the section.

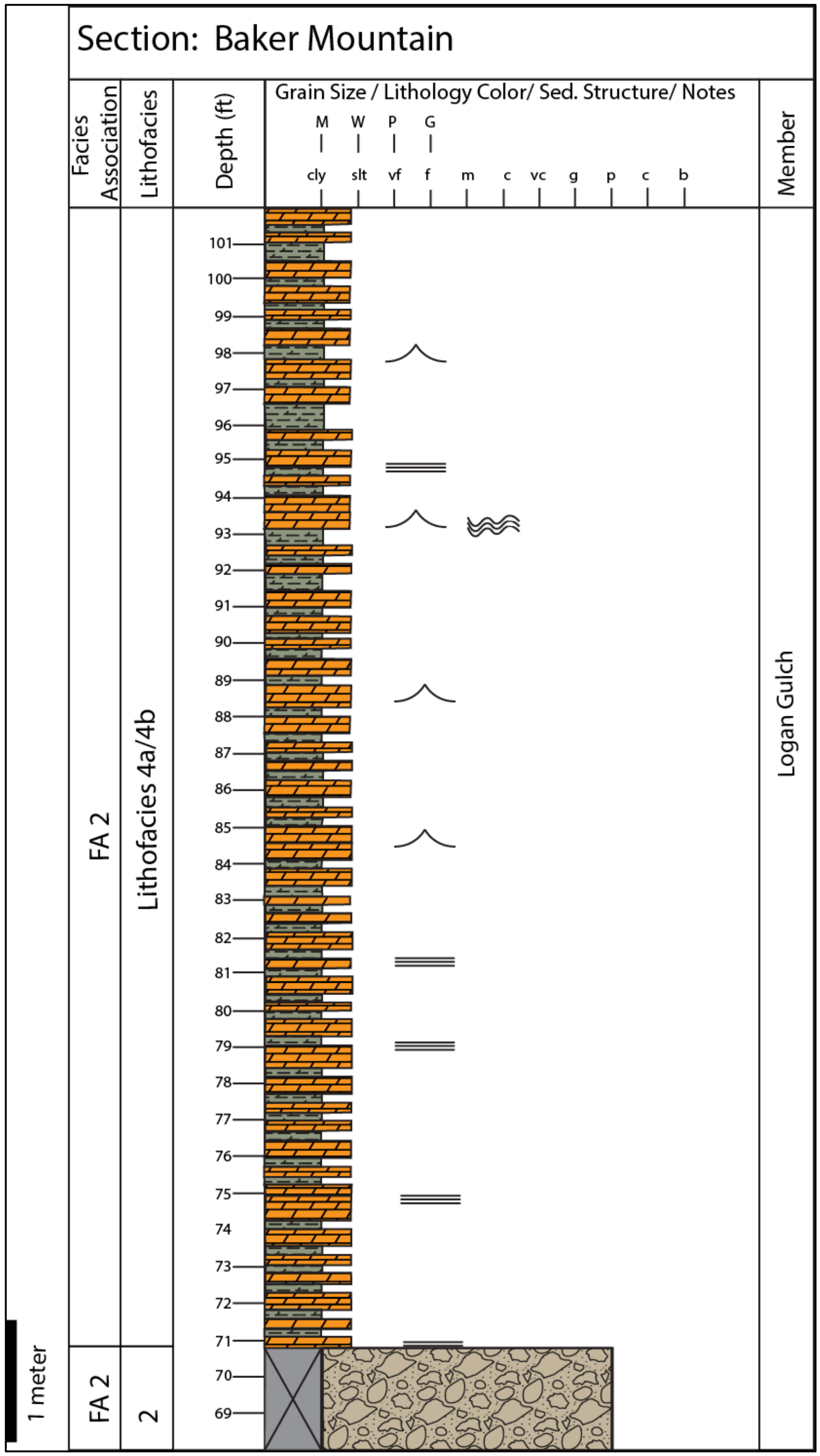
| | |
|---|---|
| Sappington | 5.1 |
| Lithofacies 7 | 0.2' |
| Lithofacies 4a/4b (Covered | 35.3' |
| Lithofacies 1 (Covered) | 67.6' |
| **Total Thickness** | **123.5'** |

**Surfaces and Facies Contact Observations:** The contact between Lithofacies 1 and the underlying Birdbear Member of the Jefferson Formation is not observed at this location as it is covered by a substantial amount of scree. It could not be safely trenched due to its occurrence on a precarious ledge. Based on correlations to other outcrops in the study area, this surface is considered a subaerial unconformity and is referred to Sequence Boundary 1. Lithofacies 1 is covered at this location. It is because salt cast-bearing dolostone is found in float. The contact that separates the interbedded Lithofacies 4a/4b from the overlying lithofacies 7 lag is irregular and eroded. This surface and the overlying lag are evidence of an erosional surface. This surface is considered to be a composite surface because it separates the TST of sequence 1 from the overlying shales of the Sappington Formation, completely displacing Sequence 2. The surface includes the transgressive ravienment surface of Sequence 1, Sequence Boundary 2, the maximum flooding surface of Sequence 2, And Sequence Boundary 3.

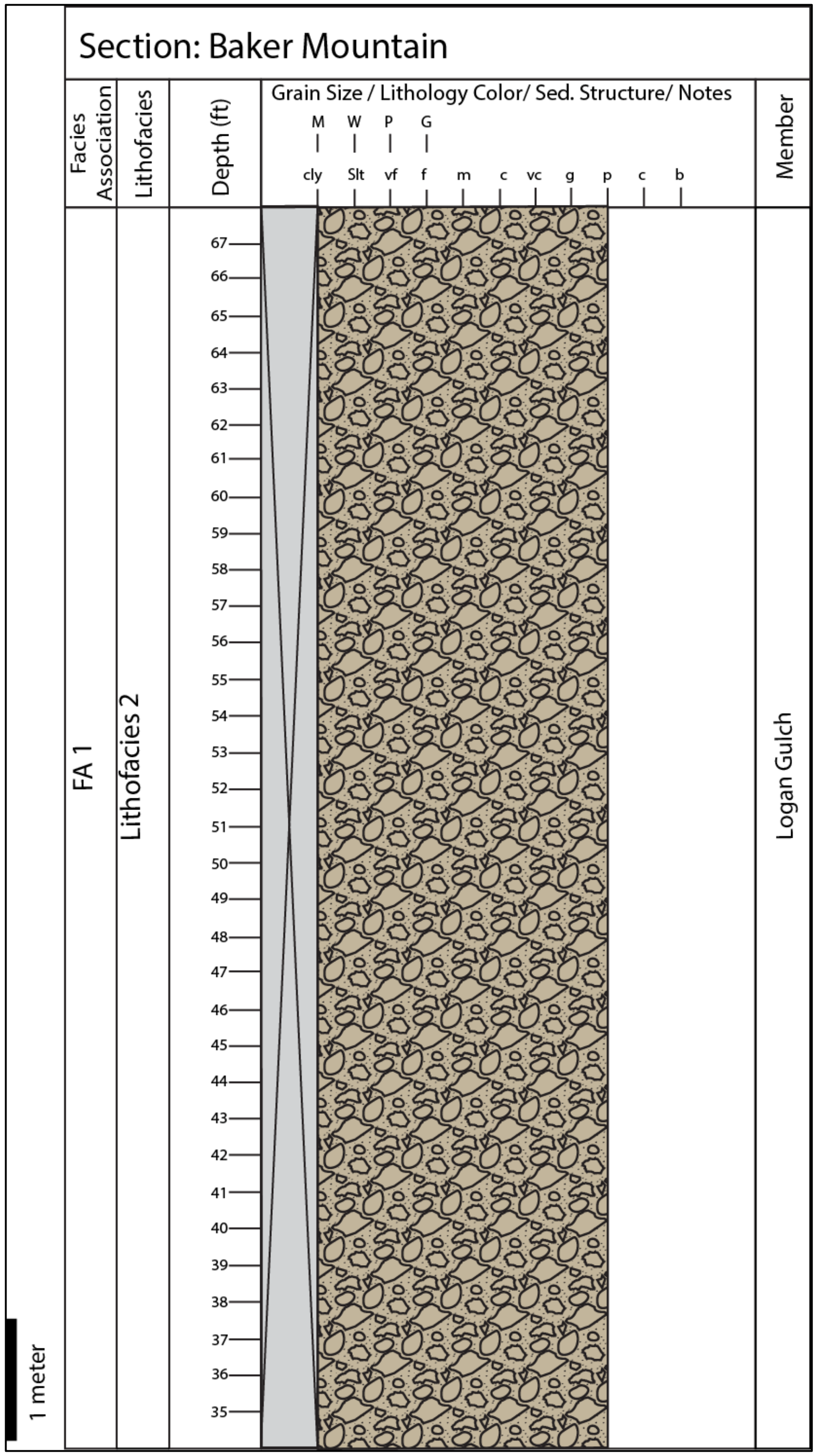
**Supplemental Notes:** The East Baker Mountain section is located on western side of the Boulder River in the Absaroka Range. It can be reached via Main Boulder Road. East Baker Mountain has the best exposure of the interbedded Lithofacies' 4a and 4b and the lithofacies 7 lag. It should be noted that an outcrop of Lithofacies 4a and 4b was found in the adjacent valley to the west of this location. However, the outcrop was folded and prevented accurate measurement.

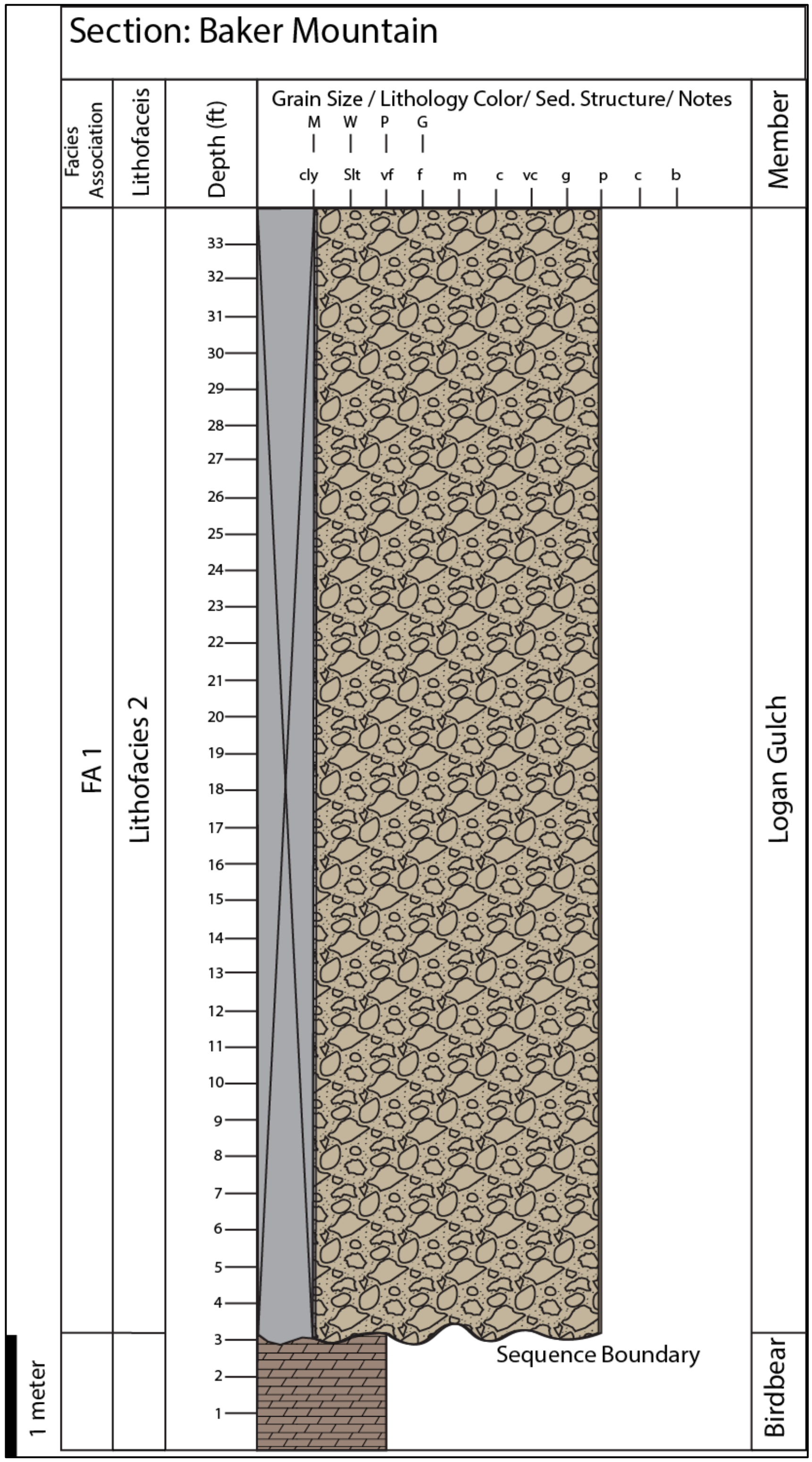


Section: Baker Mountain
Faceis Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
136
135
134
133
132
131
130
129
128
127
126
125
124
123
122
121
120
119
118
117
116
115
114
113
112
111
110
108
107
106
105
104
103
Sequence Boundary
Bw-105.7'
Sappington
Logan Gulch
FA 2
4a/4b
1 meter



Section: Baker Mountain
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly slt vf f m c vc g p c b
Member
101
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
71
70
69
FA 2
Lithofacies 4a/4b
Logan Gulch
FA 2
2
1 meter


Section: Baker Mountain
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
FA 1
Lithofacies 2
67 66 65 64 63 62 61 60 59 58 57 56 55 54 53 52 51 50 49 48 47 46 45 44 43 42 41 40 39 38 37 36 35
Logan Gulch
1 meter


Section: Baker Mountain
Facies Association
Lithofaceis
Depth (ft)
Grain Size / Lithology Color/ Sed. Structure/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
FA 1
Lithofacies 2
Logan Gulch
Sequence Boundary
Birdbear
1 meter

## Meyer Creek

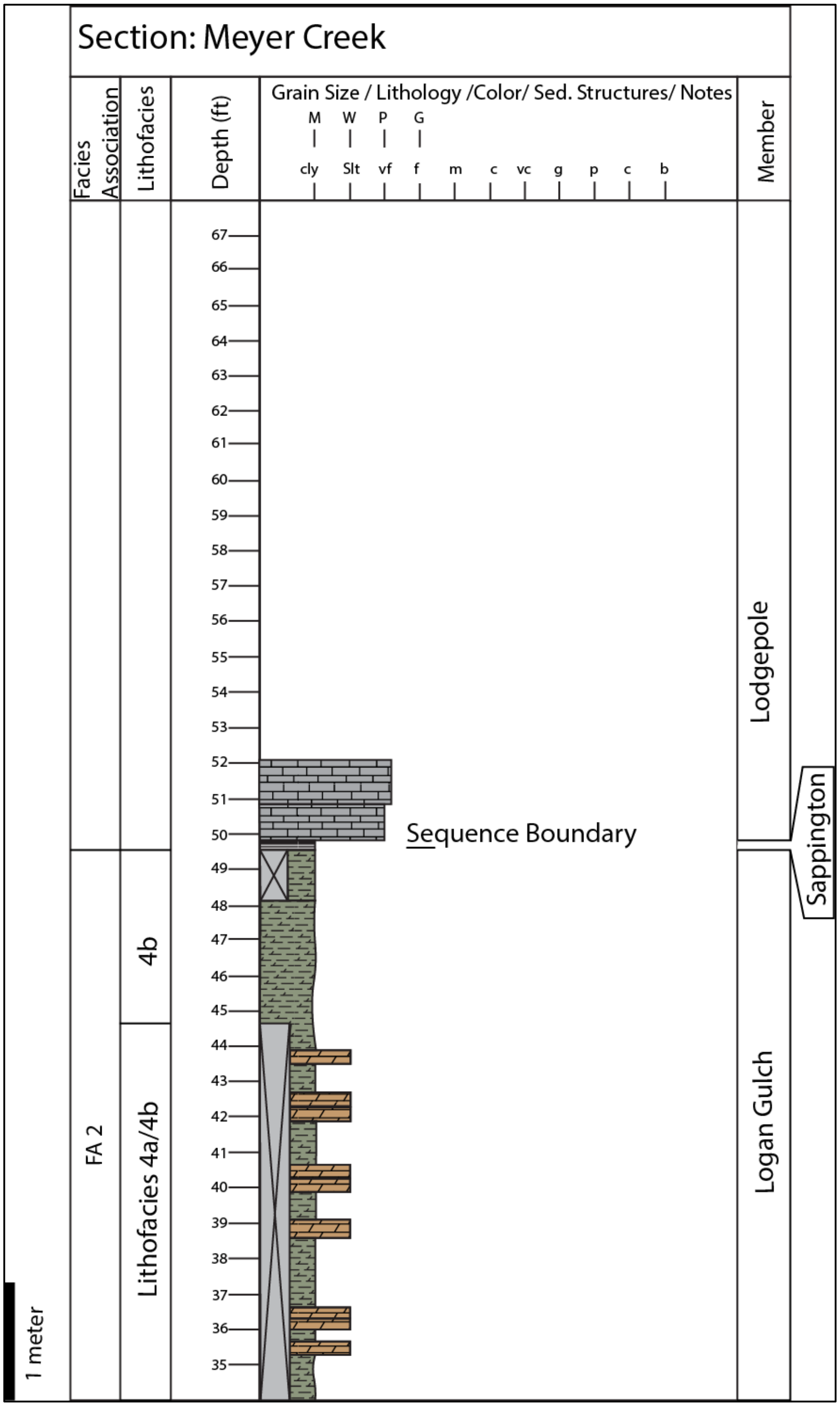
The Three Forks Formation at Meyer Creek is 46.5 feet thick. It is bounded at the base by Birdbear Member of the Jefferson Formation and is overlain by the Sappington Formation.

**Lithofacies Thicknesses:** Thicknesses in feet are listed in stratigraphic order from the top to bottom of the section.

| | |
|---|---|
| Sappington | .07' |
| Lithofacies 4b (Covered) | 1.5' |
| Lithofacies 4b | 3.4' |
| Lithofacies 4a/4b (Covered) | 18.2' |
| Lithofacies 4a | 2.6' |
| Lithofacies 4a/4b (Covered) | 20.7' |
| **Total Thickness** | **46.5'** |

**Surfaces and Facies Contact Observations:** Lithofacies 4a/4b are separated from the underlying Birdbear Member of the Jefferson Formation by a sharp contact. This contact is interpreted to be a subaerial unconformity and is referred to as Sequence Boundary 1. Above, Lithofacies 4a subtly coarsens upward into Lithofacies 4b. The contact between interbeds of lithofacies 4a and overlying, finer grained beds of lithofacies 4b are sharp. There is a ~ 1 inch discolored interval in lithofacies 4b preceding the contact with the overlying Sapping Formation. The change in facies across this contact from intertidal to marine indicates a lapse in time across this surface. It is interpreted that this surface is a subaerial unconformity. Because Sequence 2 of the Three Forks Formation is missing from this section, the subaerial unconformity is interpreted to represent a composite surface. This surface includes the a transgressive ravienment surface found in the westward outcrops in sequence 1; Sequence Boundary 2 that normally separates Sequence 1 and Sequence 2; the maximum flooding surface that separates the TST from the RST in Sequence 2; and Sequence Boundary 3 that separates the Three Forks Formation from the overlying younger strata.

**Supplemental Notes:** This outcrop is located in the Beartooth Range on a ridge approximately 4 miles east of the Meyers Creek Ranger Station. This outcrop is difficult to access and is situated above a substantial scree slope.  Like the East Baker Mountain section, and the 63 Ranch Section, the Meyer Creek Section only includes portions of Sequence 1 in outcrop.


Section: Meyer Creek
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
67
66
65
64
63
62
61
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
Sequence Boundary
Lodgepole
Sappington
Logan Gulch
FA 2
4b
Lithofacies 4a/4b
1 meter


Section: Meyer Creek
Facies Association
Lithofacies
Depth (ft)
Grain Size / Lithology /Color/ Sed. Structures/ Notes
M W P G
cly Slt vf f m c vc g p c b
Member
Lithofacies 4a/4b
4a
Lithofacies 4a/4b
FA 2
33 32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
Sequence Boundary
Logan Gulch
Birdbear
1 meter