ICNNO-PEDOLOGICAL FACIES OF THE COLTON AND LOWER-MIDDLE GREEN RIVER FORMATIONS: IMPLICATIONS FOR CONTINENTAL PALEOCLIMATE STUDIES

by

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ABSTRACT

Veritcal and lateral changes in ichno-pedological assemblages of the Colton and Lower-Middle Green River Formations in the Uinta Basin, Utah are examined as part of a multidisciplinary study in conjunction with sedimentological and geochemical analysis. The purpose of this study is to examine climatic controls on deposition during the Paleocene-Eocene Thermal Maximum (PETM) and the following hyperthermal events (H1, H2, I1, I2: Cramer et al., 2003; Lourens et al., 2005; Nicolo, 2007) using the sensitivity of organisms, particularly invertebrates, to climatic changes. This study considers soil formation and biogenic behavior to be interlinked (Hasiotis, 2006) and pedogenic features and preserved ichnofossils of the study interval have been given equal consideration in climatic interpretations. Analysis shows a clear correlation between climatic change and seasonality and ichno-pedological assemblages as supported by $\delta_{13}C_{org}$.data. The PETM and post-PETM hyperthermals are recorded as changes in ichno-pedological facies. Aridity, seasonality, and alluvial discharge are all shown to affect soil formation and subsequent preservation.

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CHAPTER 1

INTRODUCTION

Ichno-pedological asssmblages of the Colton and Lower and Middle Green River Fm from outcrops in Nine Mile Canyon have been analyzed in order to gain a better understanding of the climatic and tectonic controls on complex fluvio-lacustrine systems. This project uses a combined ichno-pedological approach to examine the climatic controls on deposition during the Paleocene-Eocene Thermal Maximum (PETM). The results of this study are combined with the results of a larger study group including sedimentological/stratigraphic and geochemical analysis (Birgenheier et al., 2009; Birgenheier and Plink-Björklund, 2009; Plink-Björklund et al., 2010).

1.1 **Introduction to Ichno-pedological facies**

Paleosols have the potential to record tectonic and climatic changes during non-depositional times (Kraus 2002; Müller et al. 2004; Lawton and Buck 2006). Therefore, paleosol analysis acts as an independent assessment of climate, deposition rates, and subsidence rates, all of which are potential controls on deposition. Paleosol analyses have also shown to make it possible to better understand stratigraphic correlations both locally and basin-wide (e.g. Kraus, 1999). Trace fossils are also common within paleosol horizons and can provide additional information on climatic controls on the paleosol's formation (Hasiotis, 1997, 2006).

Soil formation is intimately linked with biological behavior (Hasiotis, 2006), yet few studies have performed integrated ichnopedogenic analysis. This study attempts to bridge this gap by examining both the pedogenic features and preserved ichnofossils of the Colton and Lower-Middle Green River Fm. Using the sensitivity of organisms, particularly invertebrates, to climatic changes, this study aims to correlate changes in paleosol characteristics to show changes in climate during the PETM and the following hyperthermal events (H1, H2, I1, I2: Cramer et al., 2003; Lourens et al., 2005; Nicolo, 2007).

Bioturbation is one of the primary ways parent material is transformed into soil. The amount and type of bioturbation that takes place is dependent upon fluctuations in the water table, oxygen and nitrogen saturation of the sediment, depositional energy, and climate (Hasiotis, 1997). In particular, invertebrate species are very sensitive to changes in soil conditions and their ichnofacies assemblages have shown to have a great potential for the interpretation of soil development (Hasiotis, 2006; Ausich and Bottjer, 1982; Ekdale and Bromley, 1983; Bromley and Ekdale, 1986; Hasiotis and Brown, 1992; Taylor et al., 2003; Genise et al., 2004).

Continental trace fossils are common in terrestrial rocks (Hasiotis, 2006), but have not been utilized in depth by most stratigraphers. These ichnofossils can be of particular use to geologists deciphering paleoclimate change from continental deposits. Many of these studies attempted to apply the concept of ichnofacies and inchnofabrics, developed by marine ichnofossil studies, to paleosols (Taylor and Goldring, 1993; Bottjer and Droser, 1994; Droser and Bottjer, 1986). These studies were only moderately successful. Therefore, it has been suggested that any study dealing with ichnofossils in a terrestrial setting be conducted in conjunction with paleosol analysis (Hasiotis, 1996, 2006; Hasiotis and Brown, 1992; Hasiotis et al., 1993; Hasiotis and Dubiel, 1994).

Trace fossils that form on continents are created by organisms that are reacting to a different suite of environmental factors than organisms in a marine setting. This includes, but is not limited to soil moisture and saturation, temperature, seasonality, and precipitation (Hasiotis 2006). Because of this, the concept of ichnofacies, which is established for marine trace fossils, does not work in contintental environments (Hasiotis, 1997). Due to this principal difference, the continental trace fossil assemblages are significantly less understood. This study considers paleosol morphology and continental ichnology in concert, which ultimately provides more information about climatic and depositional regime changes through the succession.

1.2 **Floodplain Paleosols**

Paleosols that form in floodplain environments can vary on a wide variety of scales from the very localized to basin wide (Kraus and Aslan, 1999). Basin wide variations in paleosols can generally be attributed to either tectonic influence or climatic variability (Kraus and Aslan, 1999). Tectonics may have either a direct or indirect effect on soil formation. Subsidence directly affects the amount of time a soil can develop on exposed sediment. Therefore, in addition to biogenic factors, the influence of deposition on paleosol formation needs to be considered.

When dealing with an aggradational setting, such as a floodplain environment, paleosols may be classified in relation to the balance between pedogenesis and sedimentation rate (Kraus, 1999). The rate and periodicity of erosion may also factor into this classification scheme (Kraus, 1999). This study uses the subdivisions of paleosol stacking patterns used by Kraus (1999). This scheme is used because it takes into account the relationship between rate and frequency of deposition, which can be important when dealing with settings dominated by avulsion deposits (Kraus, 1999; 2002). The sub-divsions used in this scheme are called simple, compound, composite, and cumulative (Kraus, 1999; Kraus, 2002).

Simple paleosols are a single preserved soil horizon, often produced by a long period of quiescence followed by rapid sedimentation (Kraus, 1996). Compound paleosols are weakly developed soil horizions that are separated by slightly weathered sediment often caused by rapid, but unsteady, sedimentation rates (Kraus, 1999). Composite paleosols form where the rate of pedogenesis exceeds the rate of sedimentation, and partially overlapping soil horizons develop (Kraus 1999). Finally, cumulative paleosols may form where there is steady sedimentation that is approximately equal to the rate of pedogenesis (Kraus, 1996, 1999). This has the potential to develop thick continuous soil horizons.

Within floodplain deposits sedimentation rate is caused predominately by overbank and avulsion events (Kraus, 2002; Müller, 2004). Generally avulsion deposits contain poorer sorted material that is deposited rapidly in a single event (Kraus, 1999). These deposits usually contain weakly developed paleosols, with a large amount of unmodified sediment between the preserved horizons (Kraus, 1999).

The slower sedimentation rates and fine-grained nature of overbank deposits is more conducive to the preservation of thicker, well developed paleosols (Kraus, 1999). The periodic nature of sedimentation in these environments is not as extreme as those seen in avulsion deposits and therefore cumulative paleosols commonly develop (Kraus 1996, 1999, 2002) The amount of reworked sediment into the soil horizons also becomes pertinent when examining these types of depositional environments (Müller et al., 2004).

1.3 **Motivation for Study**

This study aims to improve the understanding of the interaction between organisms and soil development in different depositional environments. Such an understanding has the potential to create paradigm shift in our understanding of trace fossil importance in the geologic record and to improve the understanding of how climatic changes affect invertebrate and vertebrate populations. Continental trace fossil assemblages are significantly less understood than their marine counterparts. They have developed to live in a completely different suite of environmental factors, which does not allow for typically marine ichnofossil classifaction schemes to be applied. However, this principal difference allows a novel usage of the continental trace fossils in conjunction with soil formation, combined into ichno-pedological facies associations (Hasiotis, 2006; Smith et al., 2008a). This study provides data towards the development of such an ichno-pedological classification system.

The impact of an ichno-pedological classification system is not simply esoteric. It provides data of value to paleoclimatic studies, such as an improved understanding of changes in the greenhouse-regime climate systems in the continental interiors, regional wet-dry variations, relative CO_2 changes, relative temperature changes, weathering rate changes, and organic matter transfer from continents into deep oceans. Understanding and modeling paleoclimate, specifically the PETM, is supremely relevant to predict future climate change. This study provides an improved understanding of how rivers may respond to a future greenhouse world. This study also demonstrates that ichno-pedological studies can be used to support sedimentological and geochemical analysis, producing a better understanding of the controls on deposition (i.e. climate and tectonics: Dickson, 1974; Burbank and Vergés, 1981; Cramer et al., 2003; Cleveland et al., 2007; and references therein).

CHAPTER 2

GEOLOGIC BACKGROUND OF THE UINTA BASIN

The Uinta Basin and the Colton and Green River Formations have been the subject of a large amount of scientific investigation (Fouch, 1976; Morris et al., 1991; Morris and Richmond, 1992; Remy, 1992; Keighley et al., 2002; Taylor, 2002; Keighley et al., 2003; Morgan et al., 2003; Pusca, 2003; Taylor and Ritts, 2004; Moore Ali-Adeeb, 2005; Kjemperud et al., 2008). This study will build upon the existing body of literature, but uniquely examine paleosols using a multi-disciplinary approach to evaluate climate change during the Paleocene-Eocene Thermal Maximum (PETM) and the following hyperthermals.

2.1 **Stratigraphy of the Uinta Basin**

The Uinta basin is a foreland basin that developed during the Laramide Orogeny (Fig. 2.1.1). The present study focuses on the outcrops of the Colton and Green River Formations located in the Whitmore Park and Nine Mile Canyon sections of the Uinta Basin. Within the study area the Colton Formation lays above the North Horn and Flagstaff Formations (Fig 2.1.3).

The alluvial Colton Formation is dominated by sandstone channel deposits and floodplain paleosols consisting of sandy siltstone to shale. The Colton Formation, along with the overlying Green River Formation, was deposited during the early Eocene (Ypreseian: Fouch et al., 1987; Remy, 1992; Gradstein et al., 2004). The Green River Formation is comprised of two primary facies associations (Zhang et al., 2009). The first is comprised of sandstone, siltstone, shale, dolostone, and limestone lithologies and was deposited in an alluvial and marginal lacustrine enviornment (Fouch, 1975; Surdam and Stanley, 1980; Fouch et al. 1994). The second is composed of lacustrine limestone and shale high in organic content (Fouch, 1975; Surdam and Stanley, 1980; Fouch et al. 1994; Zhang et al., 2009) and was deposited in an open lacustrine environment. This wide variety of lithology within the studied section reflects the complex interaction of alluvial and lacustrine sedimentation (Fouch, 1975; Zhang et al., 2009).

The Uinta Basin is also rich in conventional and unconventional oil and gas fields (Zhang et al., 2009). Organic-rich units of the Green River Formation are a prominent source rock (Schmoker et al., 1996; USGS, 2002; Zhang et al., 2009). Additionally, reservoirs are located in the lacustrine, oolitic limestones and organic rich shales of the Green River Formation (Fouch et al., 1992; Ruble et al., 2001; Longman, 2003; Chidsey et al., 2005; Zhang et al., 2009; Fig. 2.1.2).

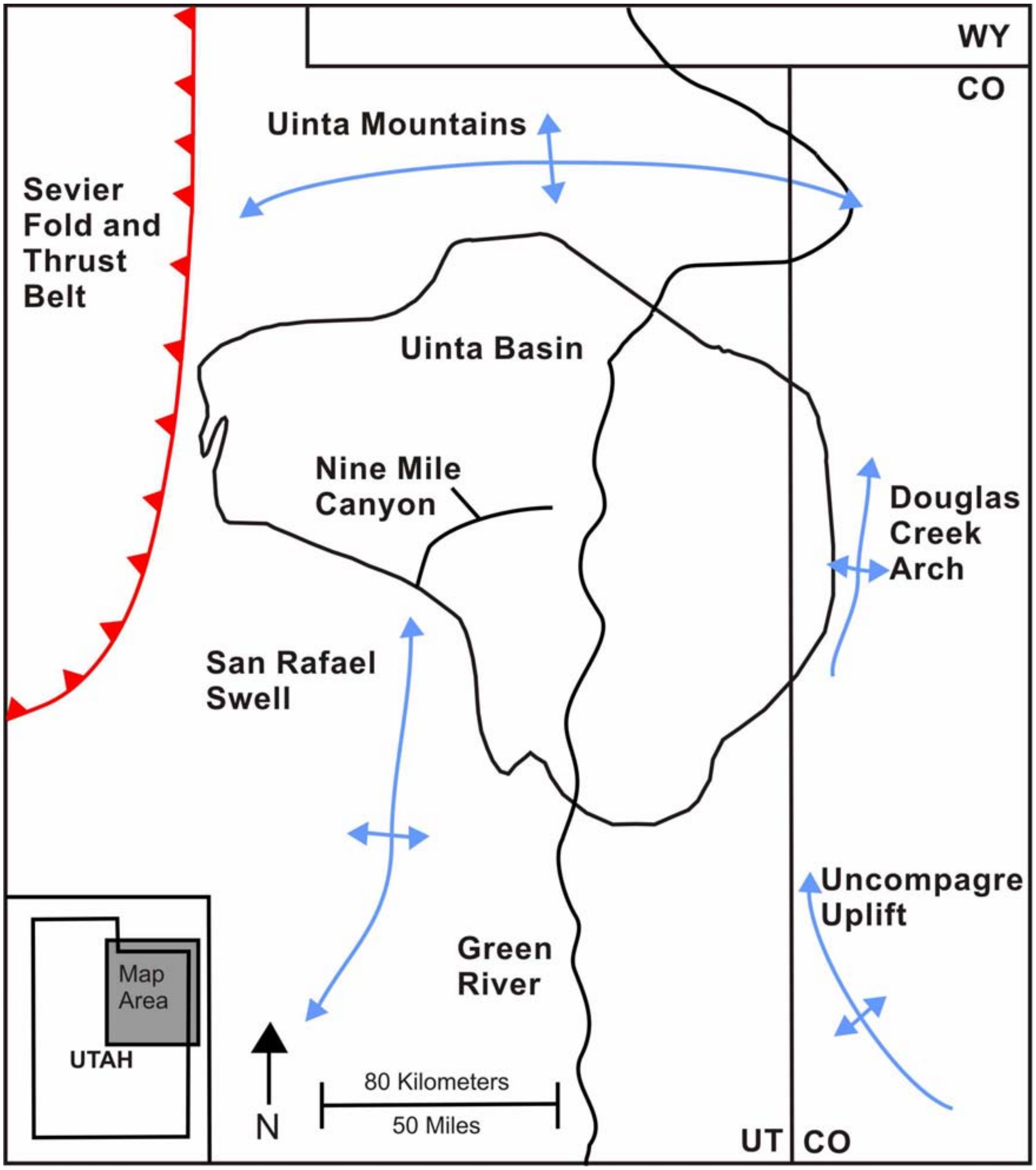


Figure 2.1.1 Generalized present day map of the Uinta Basin with the Nine Mile Canyon study area marked. Map displays major structures surrounding the basin which acted as sediment sources for the outcrops within the study area. Modified from Castle (1990) and Taylor (2002).

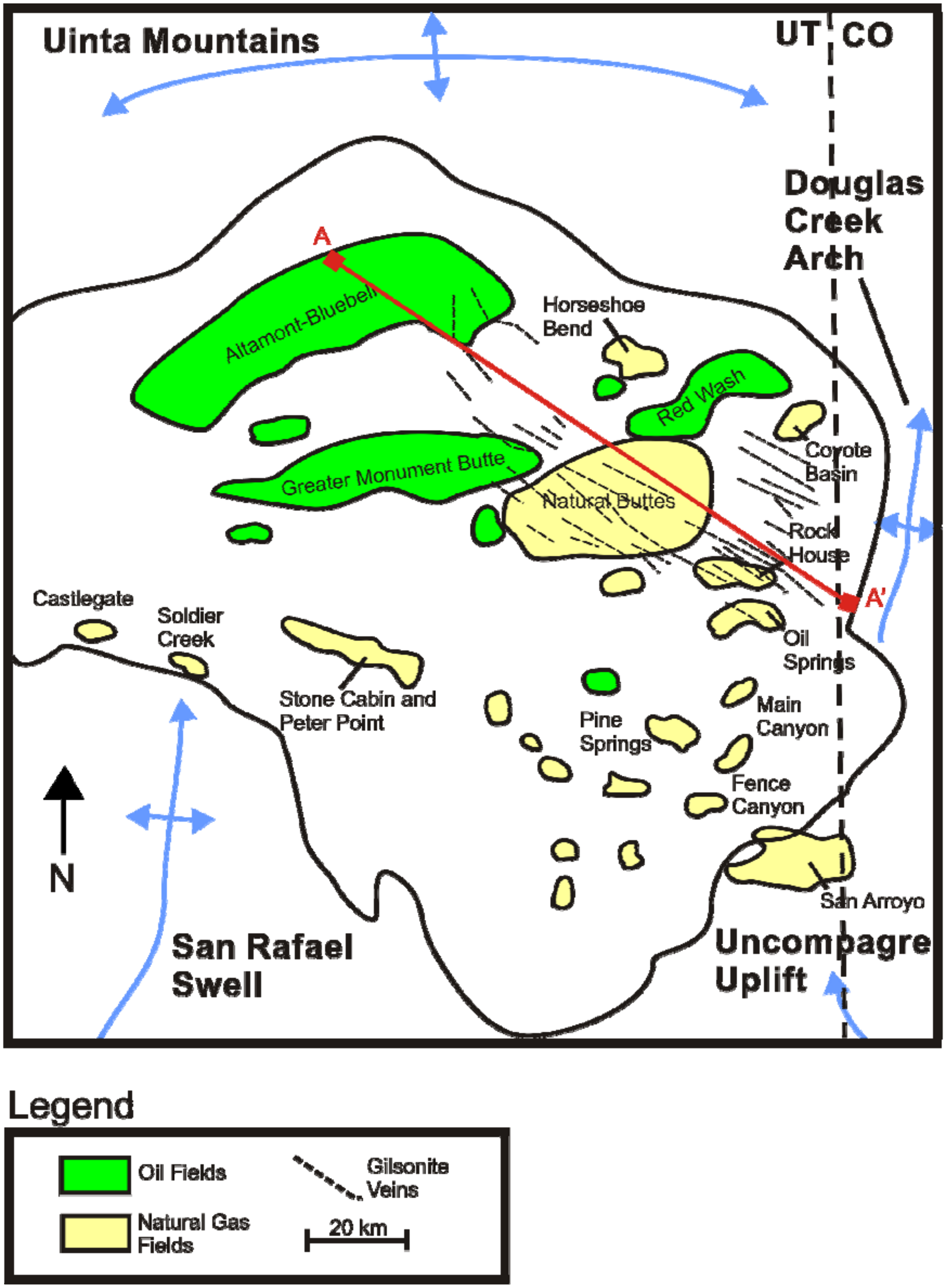


Figure 2.1.2 Generalized Map showing major productive hydrocarbon fields in the Uinta Basin. Major Gilsonite veins are also displayed. Modified from, Fouch et al. (1994), Longman and Morgan (2008), and Zhang et al. (2009).

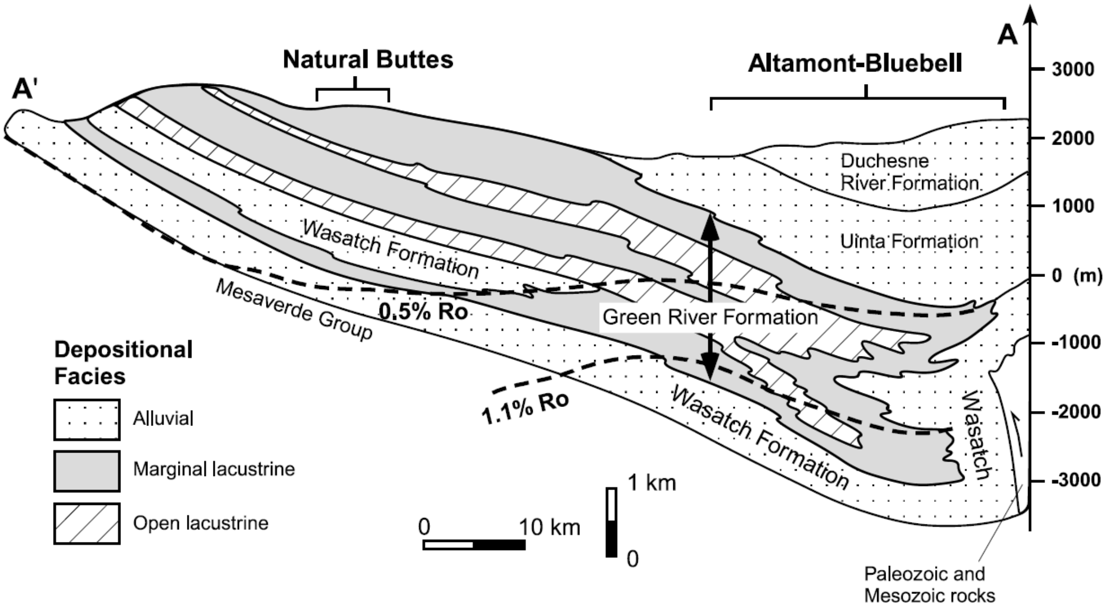


Figure 2.1.3 Generalized northeast-trending cross-section of the Uinta Basin displaying major stratigraphic units and general lithology. From Zhang et al. (2009).

2.2 Tectonic History of the Uinta Basin

The Uinta Basin is an intermontane basin located in the northeast corner of Utah. It began forming during the Late Cretaceous (Maastrichtian) as a result of the Laramide Orogeny, which involved deep basement faulting and overprinted the uplifts created by the earlier Sevier Uplift (DeCelles, 2004; Pietras et al., 2003: fig 2.2.1). The Uinta Basin is a restricted basin that was one of several basins formed from the Sevier foreland basin. Paleotopographic highs include: the Uinta Mountains to the North, the Douglas Creek Arch to the east, the San Rafael swell to the south, the Uncompagre Uplift to the southwest, and the Sevier Fold and Thrust Belt to the west (DeCelles, 2004).

The studied formations were deposited after the main Laramide Orogenic pulse and, therefore, were not affected by tectonic events to the extent of earlier formations (e.g. North Horn Formation). The section lacks any major unconformities or syn-tectonic deposits (i.e. growth strata or conglomerates: e.g. Dickson, 1974; Burbank and Vergés, 1994; Constenius et al., 2003). This implies that there was steady subsidence and

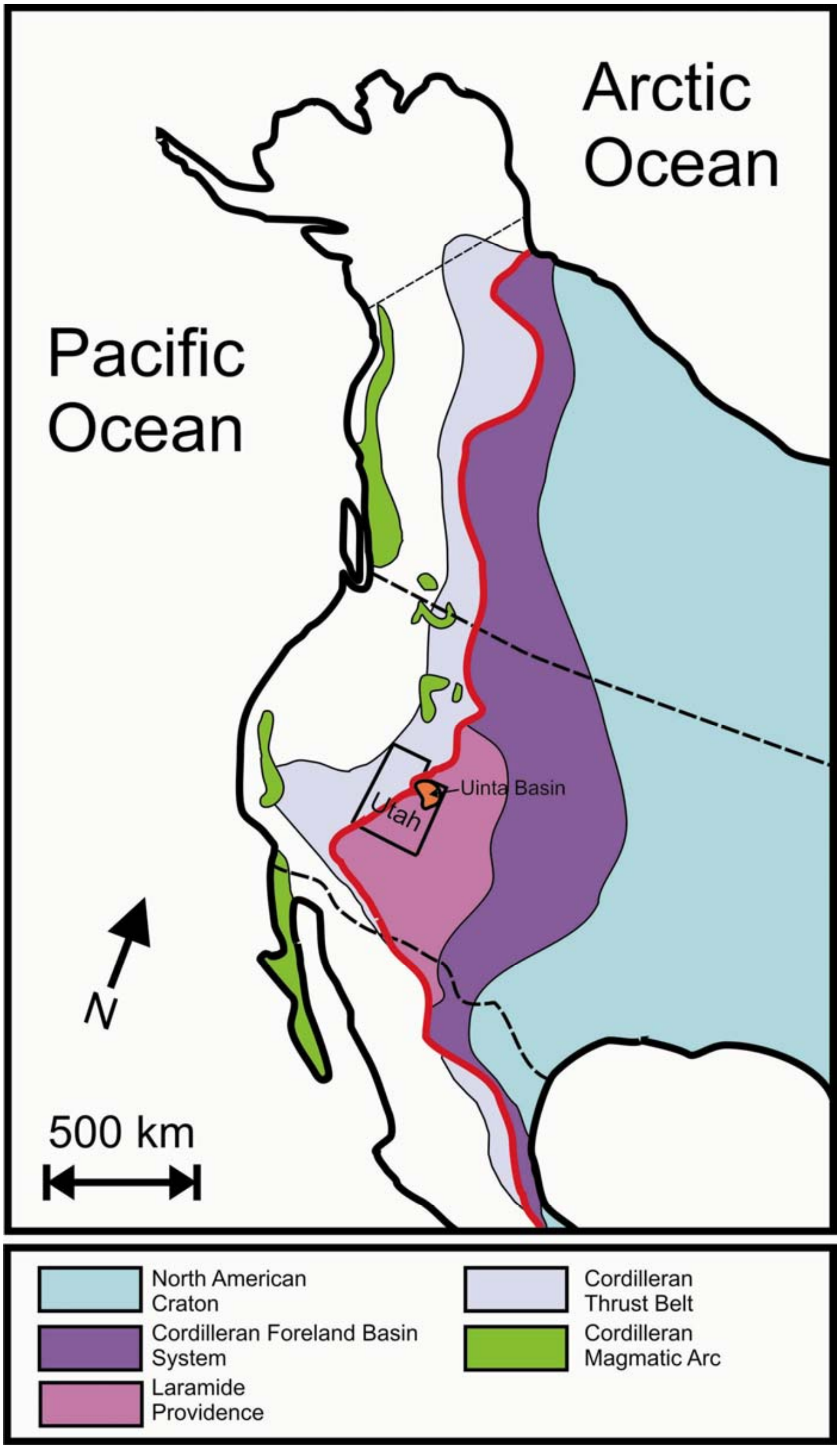


Figure 2.2.1 Generalized map of western North America showing the major regions of the Cordilleran Thrust Belt, and the Laramide Orogenic Providence. The Uinta Basin is highlighted. Modified from Tipper et al. (1981), and Coney and Evenchick (1994), and DeCelles (2004).

sediment influx into the basin during the deposition of the Colton and Lower-Middle Green River deposits.

2.3 **Cretaceous-Eocene Greenhouse Climate**

The Cretaceous through Eocene was greenhouse period in the earth's climate. During this period of time the mean sea surface temperature was significantly warmer than the present, some estimates place this value at up to 6˚C above modern levels (Greenwood and Wing, 1995; Huber et al., 2002). Global sea-level is estimated approximately two hundred meters higher than present level (Greenwood and Wing, 1995; Thomas and Zachos, 2000; Huber et al., 2002; Bowen et al., 2006; Kroon et al., 2007).

During this period, temperature gradients of the sea surface were much lower than the present; creating a paradox of warmer high latitudes and cooler low lattitudes than present (Greenwood and Wing, 1995; Huber et al., 2002). This climate condition has been modeled by several authors and early general circulation models (GCMs) could not replicate conditions found using proxy evidence and inferred lower mean annual temperature but more seasonal variability (e.g. Sloan and Barron, 1990, 1992: Fig 2.3.1). Modern GCMs have been able to more closely duplicate the latitudinal Eocene gradient from paleontological and geochemical proxy records but still have problems matching overall climatic conditions (Hutchison, 1982; Sloan and Barron, 1992; Sloan, 1994; Wing and Greenwood, 1993; Markwick, 1994; Greenwood and Wing, 1995).

Isotope records from marine sediment indicate the Late Paleocene through the Early Eocene was an extremely warm period (Zachos, 2001) within this greenhouse climate regime and was also a period of dramatic abrupt warming events (Miller et al., 1987; Greenwood and Wing, 1995; Tomas and Zachos, 2000). These climatic warming shifts have been termed hyperthermals, and were driven by an increased amount of CO_2 in the atmosphere (Thomas and Zachos, 2000; Bowen et al., 2006; Kroon et al., 2007: Fig. 2.3.3). Negative carbon isotope excursions mark the abrupt release of carbon into the atmosphere. At least five significant carbon isotope excurstions have been identified (Cramer et al., 2003; Nicolo, 2007).

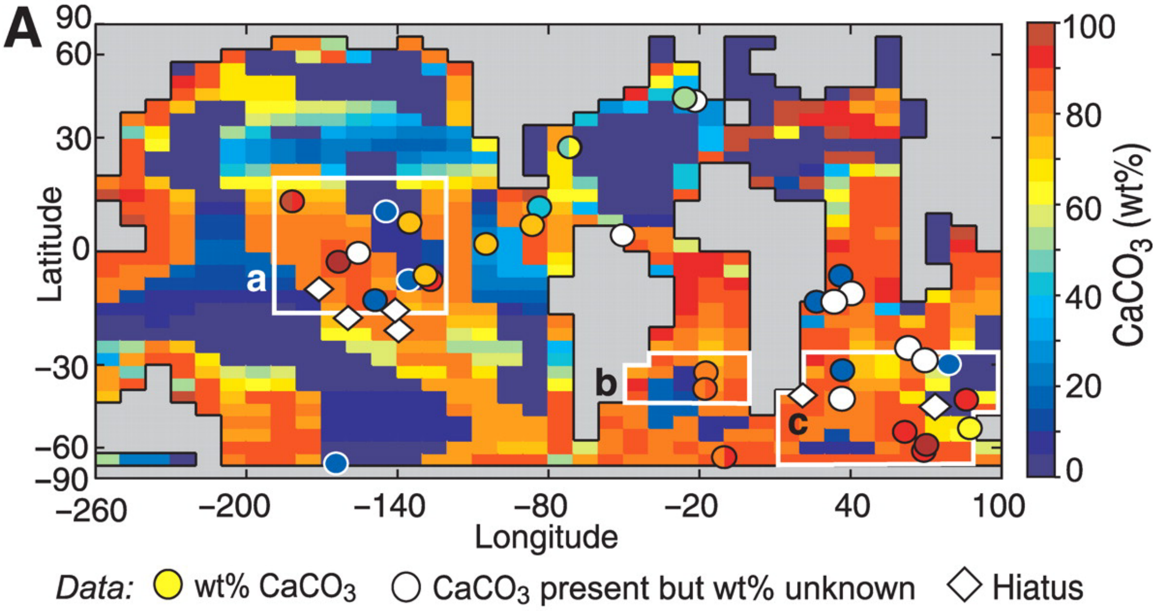


Figure 2.3.1 A pre-Paleocene-Eocene Thermal Maximum (PETM) Global Circulation Model (GCM) displaying wt% $CaCO_3$ from the early Paleocene with superimposed PETM data from marine cores. Accurately creating models that replicate proxy data for the PETM has proven difficult, therefore models like this are often used in the literature. From Van Andel (1975).

The largest of these hyperthermals is the Paleocene-Eocene Thermal Maximum (PETM), which occurred between 55.3 and 55.7 Ma. (Lourens et al., 2005) and marks the boundary between the Paleocene and Eocene. The PETM was followed by several smaller warming periods as evidenced by carbon isotope excursions in marine records (Nicolo. 2007; Cramer et al., 2003). The largest of these post-PETM warm periods has been named H1 and occurred approximately 53.6 Ma. (Cramer et al., 2003; Lourens et al., 2005). H1 was followed by three more distinct climating warmings named H2, I1, and I2 at 53.5, 53.3, and 53.2 Ma respectively (Cramer et al., 2003; Lourens et al., 2005).

The cause of the hyperthermal events has been debated by many authors. The most prevalent theory is that they were caused caused by massive releases of methane clathrates from deep ocean sediments (Thomas et al., 2002; Panchuk et al., 2008). Most records of these events come from carbon isotope values of deep sea benthic formanifera and dissolution of material has significantly condensed the climate record (Cramer et al., 2003; Nicolo, 2007). In contrast, the present study focuses specifically on the Early

Eocene record and attempts to use continental records as a proxy for climatic change. The use of continental sediments for climate analysis has been rather restricted (e.g. Wilf, 2000; Bowen et al., 2004; Wing et al., 2005; Bowen et al., 2006; Kraus and Riggins, 2007; Bowen and Beitler Bowen, 2008; White and Schiebout, 2008). This project is done in conjuction with stratigraphic and geochemical analyses of the study area (Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010).

2.4 **Lake Basins**

Generally, lakes are short-lived features in the geologic record (Hasiotis and Bown, 1992; Hasiotis, 2006), but changes in drainage may be recorded in lacustrine strata of relatively long-lived lakes (Pietras et al., 2003). Historically, lake-level fluctuations have been related exclusively to climatic variations (e.g. Benson, 1981; Pietras et al., 2003). Most studies dealing with lake level changes have focused on glacial lakes and drainage during the Quaternary (e.g. Antevs, 1925, 1928; Ashley, 1973; Fairbanks, 1989; Rea et al., 1994; Breckenridge, 2007). This is in contrast to models that use tectonics as a controlling factor (Carroll and Bohacs, 1999).

Even minor lake level changes can have a drastic effect on lake deposition and paleosol formation (Kraus, 2002; Pietras et al., 2003). This can be seen most distinctly in the carbonate facies of the section, where fluctuations in lake level have produced distinct small-scale facies changes (see Chapter 4). Such lake level changes may be tectonically or climatically driven.

2.5 **Climatic and Tectonic Controls on Paleosol Formation**

Paleosols also have the potential to record tectonic influences (Kraus, 2002; Müller et al., 2004; Lawton and Buck, 2006). Tectonics, along with climate, generally produces large scale changes (Kraus, 2002). This may be accomplished by either direct or indirect means. Directly, tectonism has the potential to alter local topography, affecting what type of soil will form and where (Kraus, 2002; Lawton and Buck, 2006). Subsidence rates have also have direct effect on paleosol formation by influencing the amount of time pedogenic features have to be created, as well as altering preservation potential by

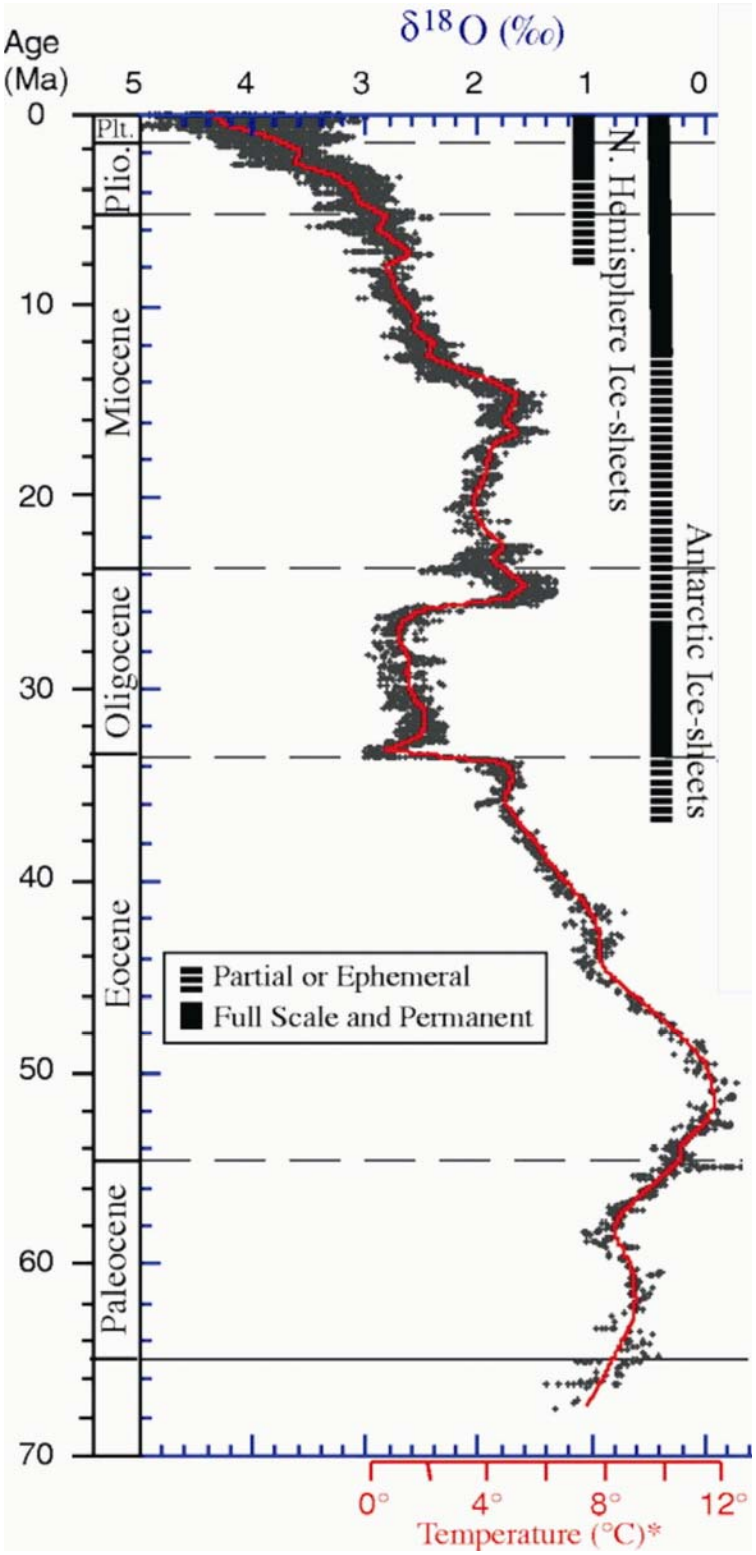


Figure 2.3.3 Global deep-sea oxygen isotope record ($\delta^{18}O$) taken primarily from analysis of benthic *Cibicidoides* and *Nuttallide.* Data values were normalized to *10.64‰* and *10.4‰* respectively. Also included are approximate dates of the onset of glaciation in the northern and southern hemispheres. From Zachos et al. (2001).

influencing burial rates (Kraus, 2002). Indirectly, tectonics can influence sediment supply and the mineralogy of the sediment transported to a local area (Kraus, 2002; Lawton and Buck, 2006).

Floodplain paleosols display a particular suite of features that may aid in the interpretation of tectonic activity in an area (Kraus 2002; Müller et al. 2004). These include the paleosol's stacking patterns, mineralolgy, and degree of pedogenesis.

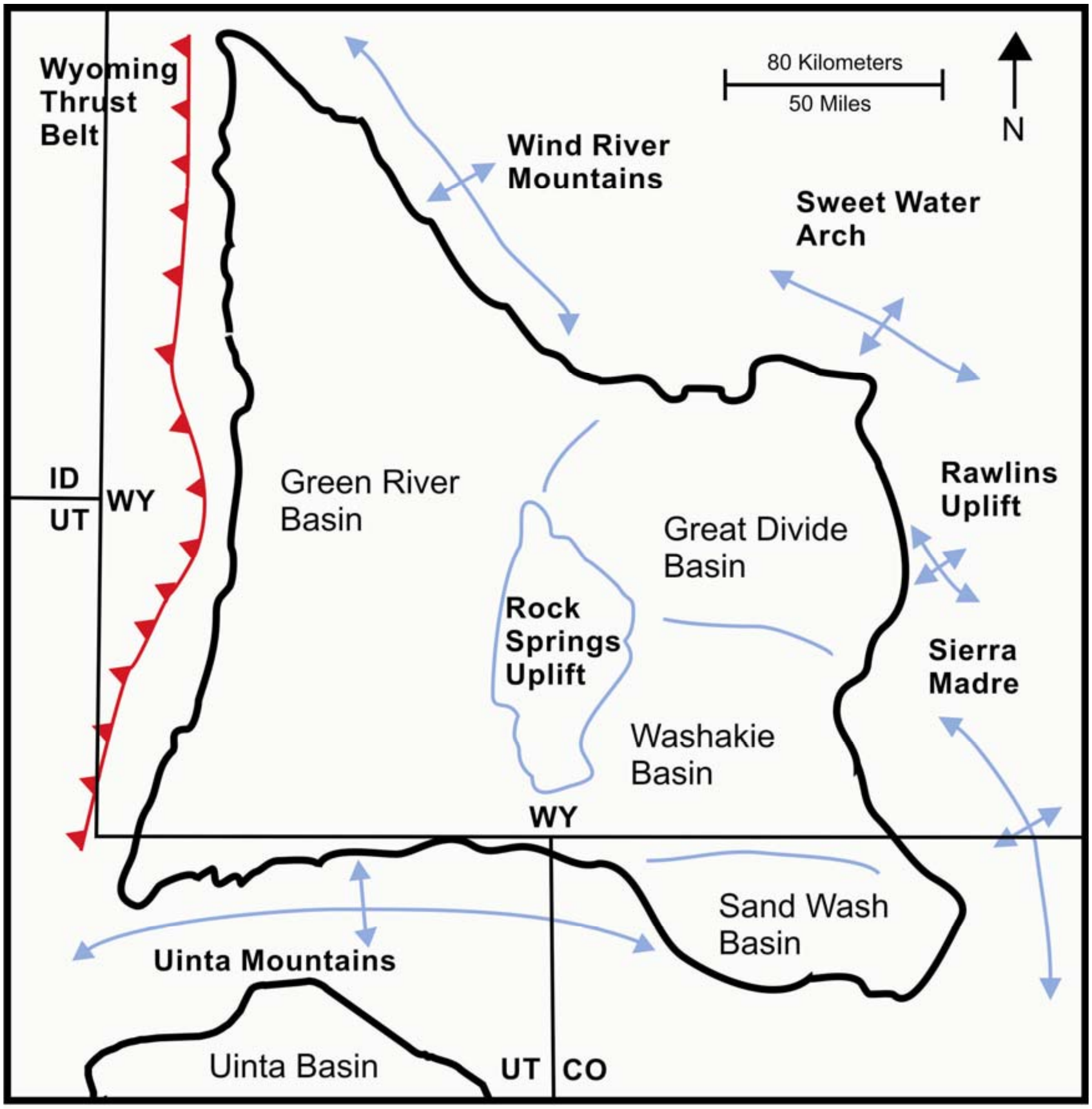


Figure 2.4.1 Generalized present-day map of the Greater Green River Basin with sounding structural highs marked. Geographic relationship to the Uinta Basin is noted. Modified from Murphey (2010) and Pietras et al. (2003).

Tectonic influence on paleosols, when examined in sediments of similar depositional settings and climate, will produce predictable patterns that can be used to reconstruct the tectonic history of an area (Kraus, 1999, 2002).

Kraus (2002) proposed a model to explain the relationship between paleosol development and subsidence. Kraus (2002) compared three different possibilities: 1) avulsion frequency changes at the same rate as subsidence, 2) avulsion rate remains constant as subsidence increases, and 3) avulsion frequency increases more rapidly than subsidence (Kraus, 2002). This study's models show a predictable vertical change in paleosols that may be applied to floodplain analysis (Kraus, 2002; Fig. 2.5.1).

Kraus (2002) shows that in the first case, when avulsion frequency and subsidence increase at the same rate, there is an increase in the amount of paleosols up-section, but they are also increasingly weakly developed as well, but remain relatively thick (Kraus 2002). The second case, with constant avulsion frequency and increasing subsidence, there are an equvilent amount of paleosols in the upper and lower parts of the section, but once again, the upper paleosols are weakly developed (Kraus 2002). The final case, when avulsion frequency increases at a faster rate than subsidence, there are many more

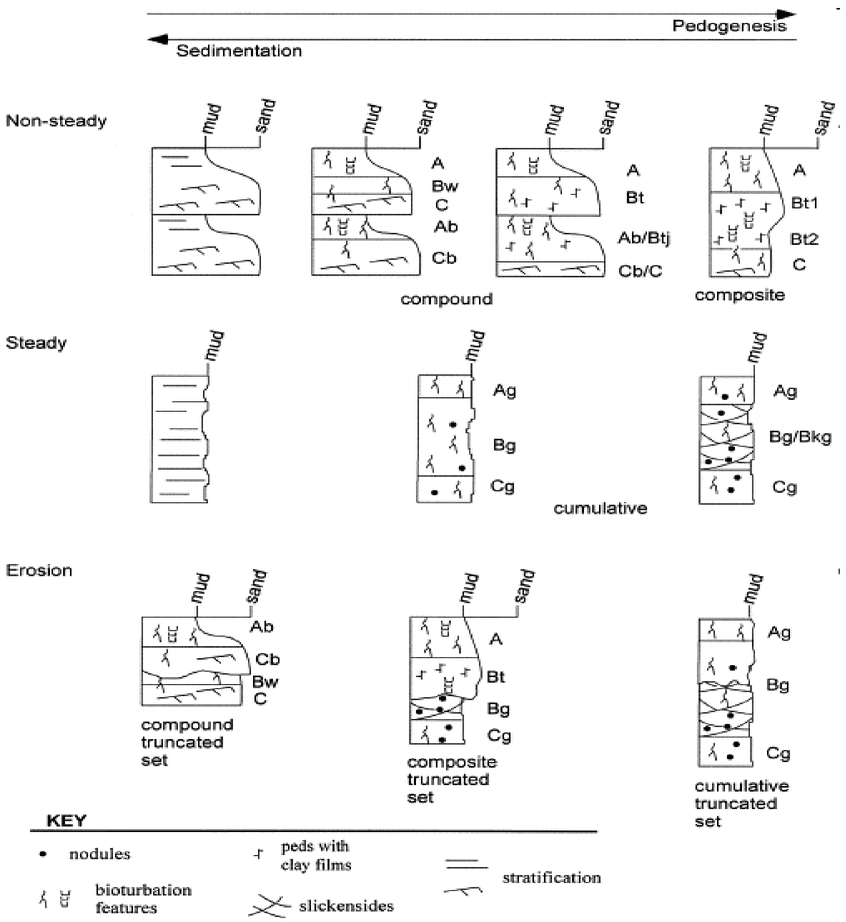


Figure 2.4.2 The relationship between sedimentation and pedogenesis in an aggradational setting. From Kraus (1999).

CHAPTER 3

METHODOLOGY

3.1 **Field Methods**

Ichno-pedological features were examined using a systematic study of vertical stratigraphic sections. This was coupled with examinations of lateral extent and changes in the paleosol horizons. Field descriptions consisted of detailed accounts of structure, color, grain size, carbonate content, trace fossil assemblages, and vertical changes in all of the above features. Colors were described from fresh, dry samples in the field. These features are commonly used in modern pedologic studies, as well as stratigraphic studies (Slate et al., 1996).

Observations were made along a total of thirteen measured sections, measured by members of the Alluvial Depositional Models Consortium (ADMC: see fig 2.1.1; see section 3.2). These sections cover the entire Colton Fm, Lower Green River Fm, and 230m of the Middle Green River Fm (Sunnyside Delta member: total thickness is approximately 350m). The locations these observations were recorded at along the sections were measured with the use of a Jacob staff. Lateral changes were recorded by walking out paleosols between measured sections and noting any changes in features over its extent.

Paleosols were examined in detail via trenching (fig. 3.1.1). Often modern pedogenic modification has taken place on the exposed surface of the paleosols and, therefore trenching allows for fresh examination of the paleosol’s preserved characteristics. Generally, one trench was dug between each major channel body, often crosscutting multiple paleosol horizons. Trenches that cross-cut multiple horizons were used to examine stacking patterns. (fig 3.1.2). Ichnofossils were documented along these sections in both paleosol units and associated channel bodies. The type of ichnofossils, along with their location within the ichno-pedological unit was recorded. Changes in ichnofossil assemblage were of particular interest within the stratigraphic units.

Trench locations were also marked using a Garmin Etrex Venture GPS. Coordinates were recorded in standard latitude and longitude degrees. Photographs of pedogenic features were taken with a Canon EOS Rebel Xsi Camera fitted with a UV filter.

Figure 3.1.1 Paleosol horizon showing significant modern pedogenic modification on the surface. Trenching allows for observations on preserved paleosol features, as well as stacking patterns.

Figure 3.1.2 A trenched paleosol. Trenching allows for the examination of paleosol features, such as pedogenic texture and stacking patterns

Photographs have a resolution of 12.40 megapixels and colors were captured through a sRGB primary filter.

3.2 **Analytical Methods**

A variety of previous work was used as a base for this study. Ichnofossils were described using the terminology for continental trace fossils by Hasiotis (2006). Stacking patterns were described using the system of deposition rate versus pedogic modifaction by Kraus (199). Finally, within the associations, soils were interpreted using the U.S. Soil Taxonomic System, developed by the U.S. Department of Agriculture.

Paleosol packages were described in the field using the above mentioned criteria. While performed in conjuction with sedimentary and geochemical studies of the same succession, data on paleosols was taken independent so as to not bias results. The data from the field investigations was then organized into ichno-pedological facies and facies associations. Ichno-pedological facies were based on a combination of observed paleosol characteristics as well as presence and density of ichnofossils. The ichno-pedological facies associations were based on the presence of repeating ichno-pedological facies, stacking patterns, and associated depositional features.

3.3 **Multidisciplinary Study**

This study is part of a multi-proxy study on the controls of alluvial deposition in the Colton and Lower-Middle Green River Formations. The ichno-pedological data presented in this study has been intergrated with sedimentary and geochemical data gathered from other members of the ADMC consortium. Results from this study were intergrated with changes in stratigraphic facies, stacking patterns, and channel types (see Plink-Björklund and Birgenheier, 2009; Bigenheier et al., 2009; Plink-Björklund et al., 2010). Results and paleoclimatic interpretations were compared with geochemical data (see Birgenheier et al., 2009).

Geochemical analysis of the sedimentary bulk bulk organic matter within the mudrocks and siltstones in the Colton and Lower-Middle Green River Fm by Birgenheier et al. (2009) included C_{org}/N_{tot} and $\delta_{13}C_{org}$. Changes in this record were interpreted to record the PETM and several post-PETM hyperthermals (Birgenheier et al., 2009; Plink-Björklund et al., 2010). Generally, negative shifts in $\delta_{13}C_{org}$ are interpreted to be indications of warmer temperatures, and this is true throughout most of the section. However, an anonymously positive trend occurs in unit 4, which is attributed to aridity caused by the PETM (Birgenheier et al., 2009).

CHAPTER 4

ICHNO-PEDOLOGICAL FACIES AND FACIES ASSOCIATIONS

4.1 **Paleosol samples**

Paleosols were analyzed through the study section for pedogenic features as well as ichnofossils. Documented features are pedogenic texture, grain-size, horizonation, color, stacking pattern, and ichnofossil assemblage. The location of these observations are along thirteen measured sections covering approximately 730 m of strata that have been measured by P. Plink-Björklund, L. Birgenheier, and J. Golab (see Plink-Björklund and Birgenheier, 2009; Birgenheier et al., 2009; Plink-Björklund et al., 2010). Within the section, stratigraphic units and key paleosol packages have been walked out laterally to provide an understanding of lateral architecture changes and to confirm the vertical changes as facies, rather than a product of lateral variability.

Within this section the Colton is approximately 345 m thick and the Lower Green River is approx. 150 m thick. The Middle Green River has been measured for approx. 230 m of the Sunnyside Delta Interval, which has a total documented thickness of 350 m total thickness. The location of the paleosol samples in relation to the composite section is illustrated in Figure 4.1.1 and their major features are documented in Table 4.2.1.

4.2 **Ichno-Pedological facies**

This study considers paleosol morphology and continental ichnology in concert, which ultimately provides more information about climatic and depositional regime changes through the succession. Therefore facies interpretations are based on a combination of pedogenic features and ichnofossil assemblages. The study area contains numerous trace fossil located within paleosols, as well as channel bodies (see figures 4.2.1-4.2.15). The type and density of these traces change through the section. The relationship between pedogenic feature and these traces were of particular interest to this study. This section summarizes the ichnopedologic facies that can be found in the study area. These facies were based on pedogenic texture, color, horizonation, grain-size, ichnofossil assemblage, and associated channel morphology. These facies are

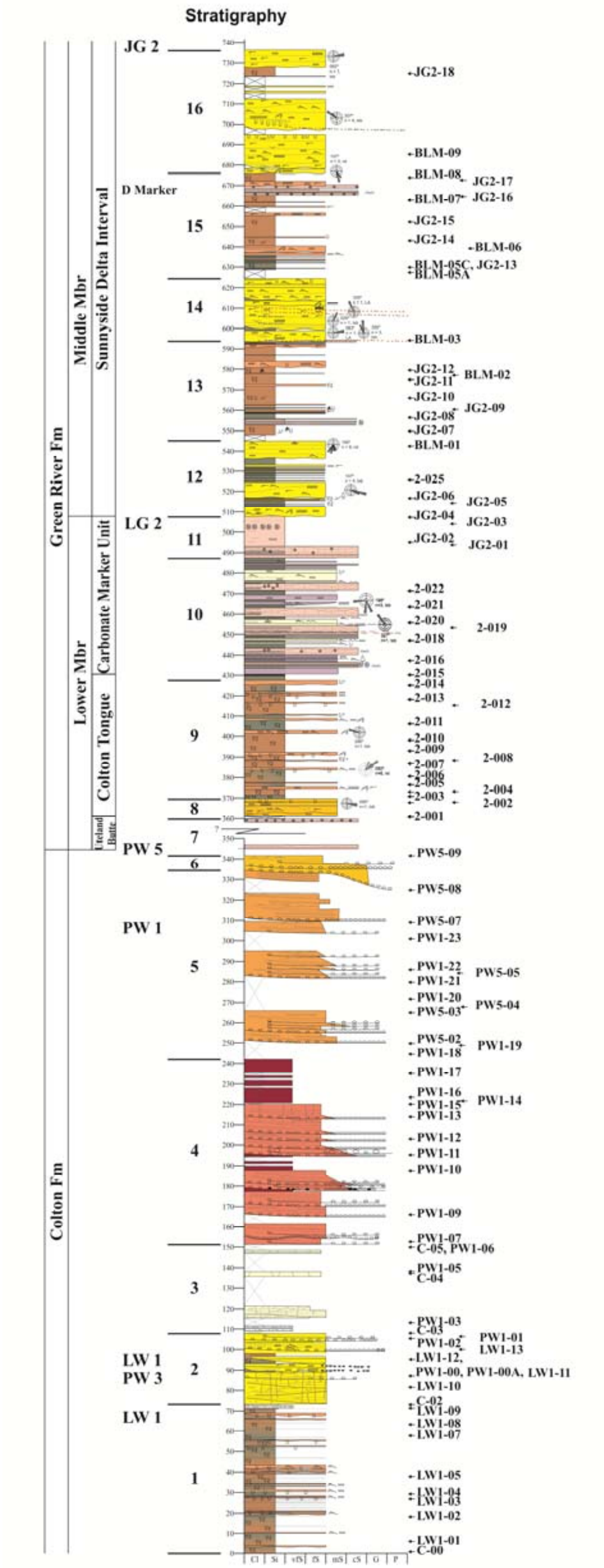


Figure 4.1.1 Stratigraphic column of the Nine Mile Canyon study area. Figure displays stratigraphic unit, informal stratigraphic units, stratigraphy and location of paleosol samples. Composite log created from 13 separate measured sections in the study area.

Table 4.1.1 Table illustrating the major features found throughout the section. Sample numbers correlate to location on composite section Figure 4.3.1.

Sample Number	**Pedogenic Features**	**Color**	**Ichnofossils**
JG2-018	Sandy siltstone. Blocky pedogenic texture	Green, Red, Yellow	Rhizoliths
JG2-017	Sandy siltstone. Blocky pedogenic texture	Green, Red	Rhizoliths
JG2-016	Sandy siltstone. Blocky pedogenic texture	Green	Rhizoliths
JG2-015	Sandy siltstone. Blocky pedogenic texture	Green, Red	Rhizoliths
JG2-014	Sandy siltstone. Blocky pedogenic texture	Green, Red	Rhizoliths
JG2-013	Sandy siltstone. Blocky pedogenic texture	Green, Gray	Rhizoliths
JG2-012	Sandy siltstone. Blocky pedogenic texture	Green, Red	Rhizoliths
JG2-011	Siltstone. Blocky to Platy pedogenic texture	Red	Rhizoliths, Partially Backfilled Burrows
JG2-010	Sandy siltstone. Blocky pedogenic texture	Green, Red	Rhizoliths, Partially Backfilled Burrows
JG2-009	Siltstone. Slightly platy pedogenic texture	Green	Rhizoliths, Partially Backfilled Burrows
JG2-008	Shale. No pedogenic modifacation	Yellow	Rhizoliths, Partially Backfilled Burrows
JG2-007	Sandy siltstone. Blocky pedogenic texture	Green, Red, Orange	Rhizoliths, Partially Backfilled Burrows
JG2-006	Sandstone. Crumb to blocky pedogenic texture	Tan	*Cochlichnus*
JG2-005	Shale. No pedogenic modifacation	Gray	*Cochlichnus*
JG2-004	Shale. No pedogenic modifacation	Gray, Orange	*Cochlichnus*
JG2-003	Shale to siltstone. Possible platy pedogenic texture	Gray	*Cochlichnus*
JG2-002	Shale to siltstone. Possible platy pedogenic texture	Gray	*Cochlichnus*
JG2-001	Shale to siltstone. No pedogenic modifacation	Gray	*Cochlichnus*
JG1-016	Sandstone. Crumb to blocky pedogenic texture		N/A
JG1-015	Sandy siltstone. No pedogenic modifaction	Gray	N/A
JG1-014	Shale to siltstone. No pedogenic modifacation	Gray	N/A
JG1-013	Sandy siltstone. Blocky pedogenic texture	Green, Red	Rhizoliths

Table 4.1.1 Table illustrating the major features found throughout the section. Sample numbers correlate to location on composite section Figure 4.3.1. (cont.)

Sample Number	Pedogenic Features	Color	Ichnofossils
JG1-012	Sandy siltstone. Possible platy pedogenic texture	Green, Gray	Rhizoliths
JG1-011	Shale. No pedogenic modifacation	Gray	N/A
JG1-010	Sandy siltstone. No pedogenic modifaction	Gray, Green	*Cochlichnus*
JG1-009	Sandy siltstone. No pedogenic modifaction	Gray, Green	*Cochlichnus*
JG1-008	Sandy siltstone. No pedogenic modifaction	Gray, Green	*Cochlichnus*
JG1-007	Sandy siltstone. No pedogenic modifaction	Gray	N/A
JG1-006	Shale. No pedogenic modifacation	Gray	Woody Fragments
JG1-005	Sandy siltstone. No pedogenic modifaction	Gray, Green	*Cochlichnus*
JG1-004	Sandy siltstone. No pedogenic modifaction	Gray, Green	*Cochlichnus*
JG1-003	Sandy siltstone. Possible platy pedogenic texture	Gray	N/A
JG1-002	Sandy siltstone. Possible platy pedogenic texture	Gray	*Haplotichnus isp.*
JG1-001	Sandy siltstone. Possible platy pedogenic texture	Gray	*Haplotichnus isp.*
2-025	Sandy siltstone. Blocky pedogenic texture	Green, Gray	Rhizoliths, Gastropods, *Celliforma isp.*
2-024	Siltstone to shale. Possible platy pedogenic texture	Gray	Rhizoliths, Gastropods, *Celliforma isp.*
2-023	Siltstone to shale. Possible platy pedogenic texture	Gray	Rhizoliths, Gastropods, *Celliforma isp.*
2-022	Siltstone. No pedogenic modifacation	Gray, Purple	Rhizoliths, Gastropods, *Celliforma isp.*
2-021	Siltstone to shale. Possible platy pedogenic texture	Gray	Rhizoliths, Gastropods, *Celliforma isp.*
2-020	Siltstone to shale. Possible platy pedogenic texture	Gray	Rhizoliths, Gastropods, *Celliforma isp.*
2-019	Siltstone to shale. Possible platy pedogenic texture	Gray	Rhizoliths, Gastropods, *Celliforma isp.*
2-018	Siltstone to shale. Possible platy pedogenic texture	Gray	Rhizoliths, Gastropods, *Celliforma isp.*
2-017	Sandstone. Blocky to Crumb pedogenic texture	Gray, Tan	N/A
2-016	Sandstone. Blocky to Crumb pedogenic texture	Gray, Tan	N/A

Table 4.1.1 Table illustrating the major features found throughout the section. Sample numbers correlate to location on composite section Figure 4.3.1. (cont.)

Sample Number	**Pedogenic Features**	**Color**	**Ichnofossils**
2-015	Sandy siltstone. Blocky pedogenic texture	Gray, Red	N/A
2-014	Sandy siltstone. Blocky pedogenic texture	Purple, Tan	N/A
2-013	Sandy siltstone. Blocky pedogenic texture	Red	Rhizoliths
2-012	Siltstone. Blocky to Crumb pedogenic texture	Red	Rhizoliths
2-011	Sandy siltstone. Blocky to Crumb pedogenic texture	Gray, Tan	Rhizoliths, *Ancorichnus isp.*, Ant Nests, Adhesive Menescate Burrows
2-010	Siltstone. Blocky pedogenic texture	Red	Rhizoliths, *Ancorichnus isp.*, Ant Nests, Adhesive Menescate Burrows
2-009	Siltstone. Blocky pedogenic texture	Red	Rhizoliths, *Ancorichnus isp.*, Ant Nests, Adhesive Menescate Burrows
2-008	Sandy siltstone. Blocky pedogenic texture	Red, Tan	Rhizoliths
2-007	Sandy siltstone. Blocky pedogenic texture	Red	Rhizoliths
2-006	Sandy siltstone. Blocky pedogenic texture	Red, Green	Rhizoliths
2-005	Sandy siltstone. Blocky pedogenic texture	Red, Green	Rhizoliths
2-004	Sandy siltstone. Blocky to Crumb pedogenic texture	Red	Rhizoliths
2-003	Sandy siltstone. Blocky pedogenic texture	Green, Red	Rhizoliths
2-002	Sandstone. Blocky to Crumb pedogenic texture	Tan	Rhizoliths
2-001	Sandy siltstone. Blocky pedogenic texture	Red, Green	Rhizoliths
PW5-009	Siltstone. Blocky pedogenic texture	Red, Gray, Green	N/A
PW5-008	Clayey siltstone. Blocky pedodenic texture	Red	N/A
PW5-007	Clayey siltstone. Blocky pedodenic texture	Red, Gray	N/A
PW5-006	Clayey siltstone. Blocky pedodenic texture	Red, Green, Tan	N/A
PW5-005	Clayey siltstone. Blocky pedodenic texture	Red, Green, Tan	N/A
PW5-004	Sandy siltstone. Blocky pedogenic texture	Red, Green	N/A

Table 4.1.1 Table illustrating the major features found throughout the section. Sample numbers correlate to location on composite section Figure 4.3.1. (cont.)

Sample Number	**Pedogenic Features**	**Color**	**Ichnofossils**
PW5-003	Siltstone. No pedogenic modifacation	Red	N/A
PW5-002	Siltstone. Blocky to Crumb pedogenic texture	Red, Gray	N/A
PW5-001	Siltstone. Blocky to Crumb pedogenic texture	Gray, Red	N/A
PW1-023	Clayey siltstone. Blocky pedodenic texture	Red, Yellow, Green	N/A
PW1-021	Sandy siltstone. Blocky pedogenic texture	Red	N/A
PW1-020	Sandy siltstone. Blocky pedogenic texture	Red, Gray	N/A
PW1-019	Sandy siltstone. Blocky pedogenic texture	Red, Green	N/A
PW1-018	Sandy siltstone. Blocky pedogenic texture	Red, Green	N/A
PW1-017	Shale. No pedogenic modifacation	Red	Rhizoliths, Ant Nests
PW1-016	Shale. No pedogenic modifacation	Gray	Rhizoliths, Ant Nests
PW1-015	Shale. No pedogenic modifacation	Red, Gray	Rhizoliths, Ant Nests
PW1-014	Shale. No pedogenic modifacation	Red	Rhizoliths, Ant Nests
PW1-013	Sandstone. Blocky to Crumb pedogenic texture	Red	Rhizoliths, Beetle Traces
PW1-012	Clayey siltstone. Blocky pedodenic texture	Gray, Yellow	Rhizoliths, Beetle Traces
PW1-010	Sandy siltstone. Blocky pedogenic texture	Red, Green, Tan	Rhizoliths, Beetle Traces
PW1-009	Sandstone. Crumb to blocky pedogenic texture. Round siliceous concretions	Red, Green, Tan	Rhizoliths,
PW1-008	Sandy siltstone. Blocky pedogenic texture	Red, minor Green	*Maconopsis,* Rhizoliths
PW1-006	Sandy siltstone. No pedogenic modifaction	Gray	Rhizoliths, *Steinichnus,* Adhesive Menescate Burrows
PW1-005	Siltstone. Blocky to Platy pedogenic texture	Gray, Red	Rhizoliths, *Steinichnus,* Adhesive Menescate Burrows
PW1-004	Sandy siltstone. Blocky pedogenic texture	Gray	Rhizoliths, *Steinichnus,* Adhesive Menescate Burrows

Table 4.1.1 Table illustrating the major features found throughout the section. Sample numbers correlate to location on composite section Figure 4.3.1. (cont.)

Sample Number	**Pedogenic Features**	**Color**	**Ichnofossils**
PW1-003	Siltstone. Blocky to Crumb pedogenic texture	Red	Rhizoliths, *Steinichnus,* Adhesive Menescate Burrows Burrows
PW1-001	Sandy siltstone. Blocky pedogenic texture	Red, Gray	Rhizoliths, *Steinichnus,* Adhesive Menescate Burrows
LW1-013	Shale to siltstone. No pedogenic modifacation	Green	Rhizoliths, *Steinichnus,* Adhesive Menescate Burrows
LW1-012	Sandy siltstone. Blocky pedogenic texture	Green, Gray	Rhizoliths, *Steinichnus,* Adhesive Menescate Burrows
LW1-011	Siltstone. Blocky pedogenic texture	Gray	Rhizoliths, *Steinichnus,* Adhesive Menescate Burrows
LW1-010	Sandy siltstone. Blocky pedogenic texture	Red, Green	Rhizoliths, *Steinichnus,* Adhesive Menescate Burrows
LW1-009	Shale. No pedogenic modifacation	Gray, Red	Rhizoliths, *Scoyenia*
LW1-008	Siltstone. Blocky pedogenic texture	Gray, Red	Rhizoliths, *Scoyenia*
LW1-007	Siltstone. Blocky pedogenic texture	Gray	Rhizoliths, *Scoyenia*
LW1-006	Siltstone. Blocky pedogenic texture	Red, Gray	Rhizoliths, *Scoyenia*
LW1-005	Siltstone. Blocky pedogenic texture	Red, Gray	Rhizoliths, *Scoyenia*
LW1-004	Siltstone. Blocky pedogenic texture	Red, Green, Gray	Rhizoliths, *Scoyenia*
LW1-003	Sandy siltstone. Blocky pedogenic texture	Red	Rhizoliths, *Scoyenia*
LW1-002	Siltstone. Blocky pedogenic texture	Gray	Rhizoliths
LW1-001	Clayey siltstone. Blocky pedodenic texture	Red, Gray, Green	Rhizoliths

Figure 4.1.2 *Scoyenia* traces from Colton Fm. These are characteristic burrows made by beetles that display peristaltic narrowing and widening along the burrow and are primarily oriented horizontally. Occurs in a variety of sediment types and is generally associated with high soil moisture, such as seasonality associated with monsoonal climatic systems (Hasiotis, 2006).

Figure 4.1.3 *Steinichnus isp*. Traces from the Colton Fm. These fossils are characterized by predominately horizontal burrows that may branch created by beetles or mole crickets (Hasiotis and Bown, 1992; Hasiotis, 2006). Striations may be seen on the walls of the burrows in finer sediment (Hasiotis, 2006). Generally these are found in association with wet climates or in proximity to permanent lakes or rivers (Hasiotis, 2006).

Figure 4.1.4 Adhesive Menescate Burrows found in the Lower Green River Fm (Colton Tongue). These are characteristic burrows with backfill menisci (Bown and Kraus, 1983; Hasiotis, 2006). These traces are created by locomotion and feeding of invertebrate larvae (Willis and Roth, 1962; Hasiotis, 2006). These traces indicate higher soil moistures near the surface, within A and B soil horizons (Hasiotis, 2006).

Figure 4.1.5 Maconopsis burrow in a Colton Fm sandstone body. These can exhibit multiple different configurations, but generally end with a bulbous termination as shown (Hasiotis, 2006). These are created by multiples species of spiders such as Tarantulas and Wolf Spiders (Hasiotis, 2006). These are generally associated with relatively dry soil conditions, but can be found in multiple environmental conditions (Hasiotis, 2006).

Figure 4.1.6 Vertical beetle traces found in a red sandstone body in the upper Colton Fm. This example is interpreted to be the vertical shaft of to a beetle nest. Beetle traces are often associated with semi-arid, alluvial settings (Hasiotis, 2006). They are most often found in A and B oil horizons (Hasiotis et al., 1993; Hasiotis, 2006). The red oxidation of this sandstone is consistent with the upper levels of a soil horizon.

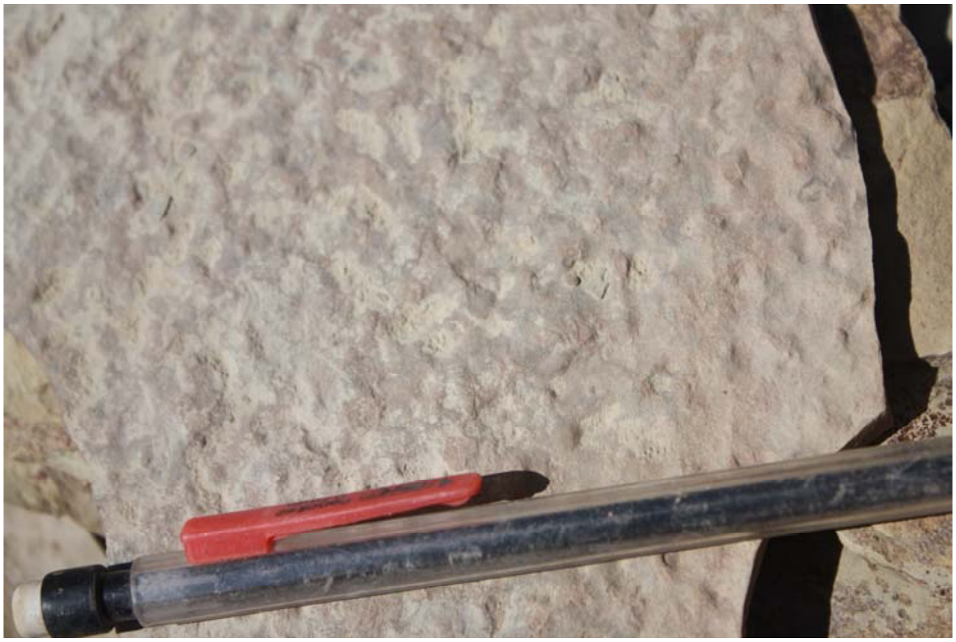


Figure 4.1.7 Invertebrate Tracks found in the Lower Green River Fm (Colton Tongue). These are small scratches on sandstone and siltstone bodies from locomotion of invertebrate insects.

Figure 4.1.8 Unit displaying Rhizoliths from the Colton Fm. These have many varying morphologies but are usually vertical and commonly taper downward (Hasiotis, 2006). Can be used as an indicator for water table levels, as they only form in vadose soil zones (Hasiotis, 2006). Deep roots will indicate well-drained, low water table conditions and shallow roots will generally indicate water-logged soils (Hasiotis, 2006).

Figure 4.1.9 Ant Nest in a red sandstone body of the Colton Fm. These are characterized by a distribution of chambers and inter-connected tubes (Hasiotis, 2006). The depth of the nest is an indicator of soil moisture conditions, deeper nests will indicate well-drained, dry soil conditions.

Figure 4.1.10 *Ancorichnus isp.* from the Lower Green River Formation (Colton Tongue). Traces display chevon-shaped back-fill menisci (Frey et al., 1984) that weather in bos relief, in contrast to adhesive menescate burrows (Bown and Kraus, 1983). They are little understood and do not indicate a great deal about environmental conditions other than relatively moist conditions.

Figure 4.1.11 *Haplotichnus isp.*from the Middle Green River Fm (Sunnyside Delta Member). These are surface traces with irregular directionality created by small insect larvae in supra-littoral fresh water conditions (Hasiotis, 2006). These indicate permanent bodies of freshwater are present, as well as high water tables.

Figure 4.1.12 *Celliforma isp.* from the Lower Green River Formation (Carbonate Marker Unit). These are created by bees as reproductive centers underground (Hasiotis, 2006). This example was found in isolation. These are found in association with supra-littorial to distal alluvial floodplain settings and are also generally in immature soils.

Figure 4.1.13 *Cochlichnus isp.* from the Middle Green River Formation (Sunnyside Delta Member). These sinuous trails are created by nematodes and are generally associated with supra-littoral to littoral lacustrine conditions. These indicate movement within a wet environment (Hasiotis, 2006).

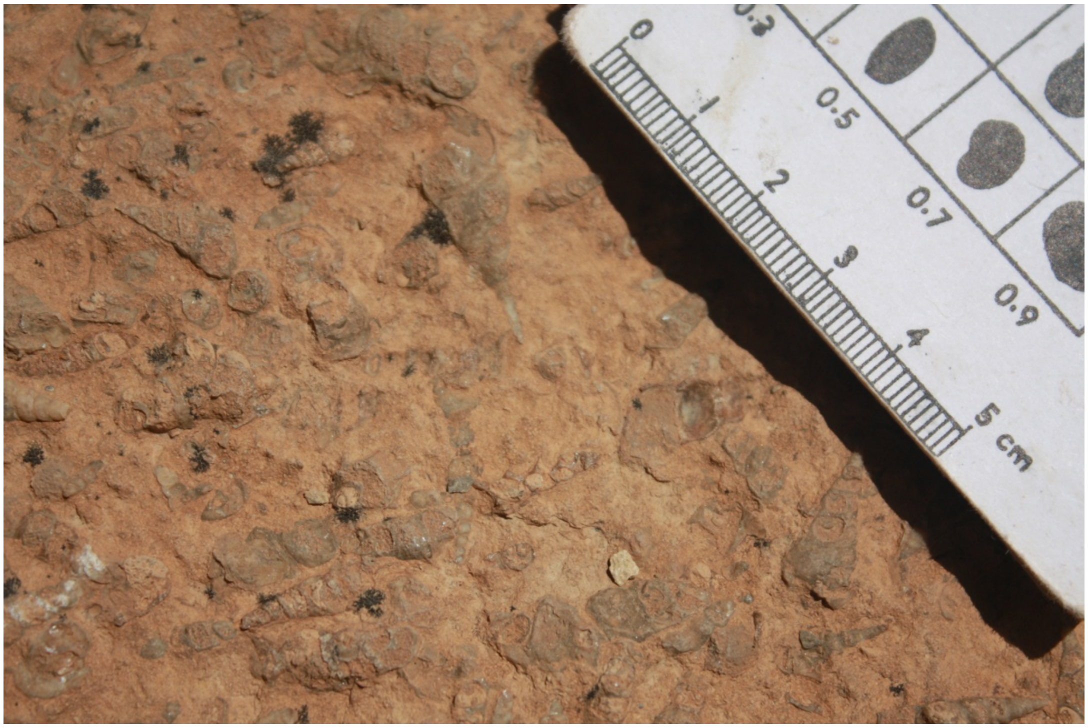


Figure 4.1.14 Gastropods found in association with the lacustrine facies of the Lower Green River Fm (Carbonate Marker Unit).

Figure 4.1.15 Woody Fragments found in association with organic rich lacustrine shales in the Lower Green River Fm.

described in this section and summarized in table 4.2.2.

4.2.1 **Facies A**

Facies A (Fig 4.2.1.1) consists of clayey siltstone with a prismatic pedogenic structure (fig 4.2.1.2). When dry this facies produces deep mud-cracks resulting pedogenic sliden-sides. Ichnofossils include rhizoliths within the paleosol horizons and *Scoyenia* traces located within associated channel bodies (Fig 4.2.1.3). It is gray colored with significant red mottling. This facies has a compound stacking pattern and coarsens upwards through the soil horizons, with the very top of the section containing a large amount of sand, creating a clay loam.

The palesosols from this unit are interpreted to be vertisols; soils with characteristic vertical cracks due to the presence of significant amounts of swelling clays (Soil Survey Staff, 1999). This creates a distinctive vertical trend within the paleosols termed prismatic pedogenic texture. These soils are wet during development. They are sticky when wet and very hard and dense when dry (Soil Survey Staff, 1999). They are most commonly found in seasonal climates, but can be found in temperature regimes that range from cryic to tropical (Soil Survey Staff, 1999). The shrinking and swelling of the smectite clay they contain, however, do not account completely for the vertical trend in the soil (Soil Survey Staff, 1999). Additionally, these soils were subject to both confining pressure and biogenic interaction. Thick soil horizons (approximately 5m) are evidence of the confining pressure on the soil. Abundant crayfish burrows (*Camborygma)* in the associated sandstone bodies are evidence for the biogenic intervention.

Camborygma traces are commonly associated with prismatic pedogenic textures in a variety of climatic regimes (Hasiotis, 2006; Smith et al., 2008b). The vertical nature of the traces in the associated channels indicates a well-drained system with a low water table (Hasiotis, 2006; Smith et al., 2008b). *Scoyenia* traces indicate high soil moisture and can be associated with a wet, poorly drained system. This dichotomy is evidence of a monsoonal climatic pattern, with a long dry season with deep water tables and a short wet season.

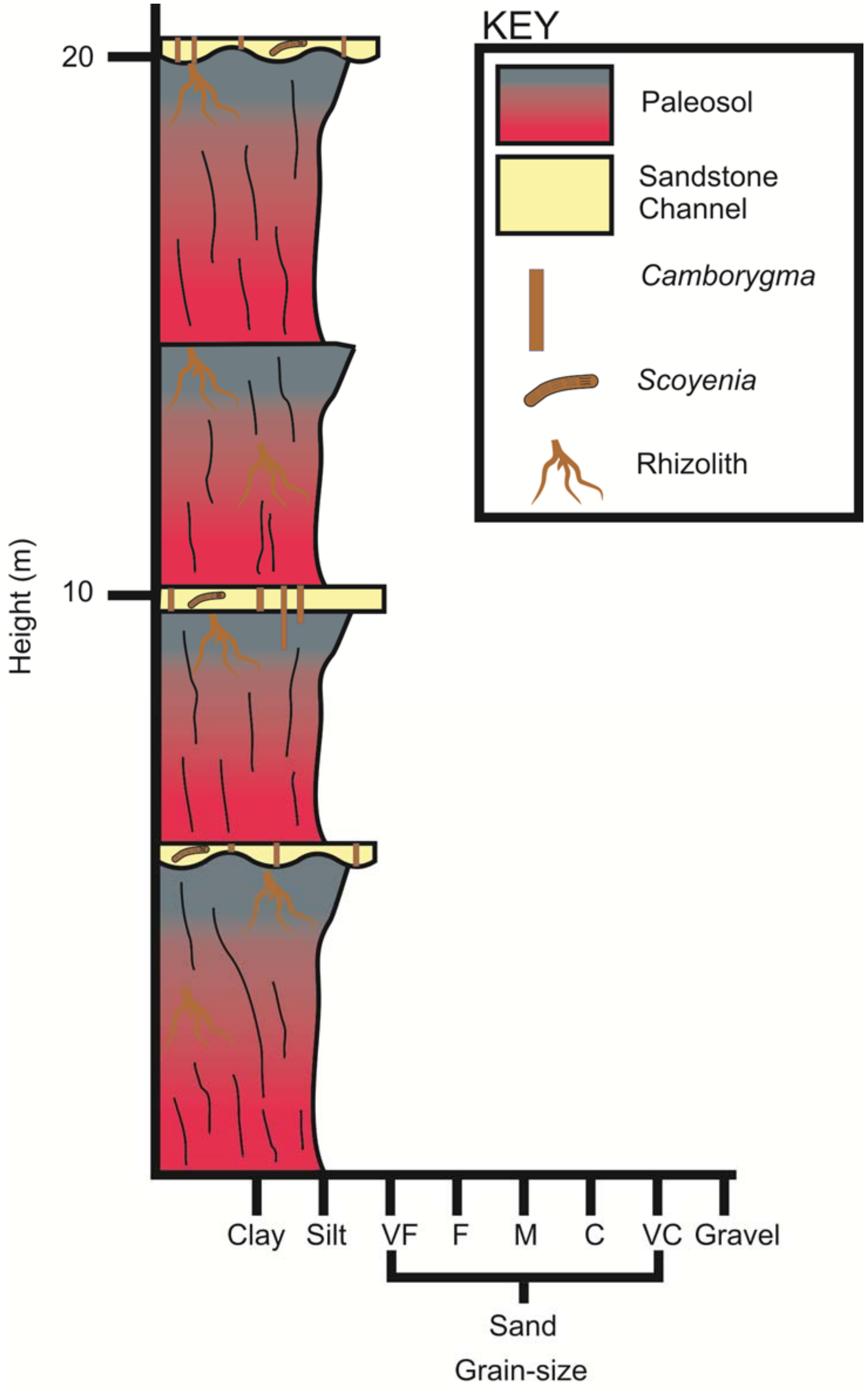


Figure 4.2.1.1 Generalized stratigraphic column of Facies A. This is interpreted to be a vertisol and is associated with Rhizoliths, *Scoyenia, and Camborygma.*

Figure 4.2.1.2 Facies A trench in the lower Colton Fm. Facies A is characterized by mudcracks on the surface due to the shrinking and swelling of smectite clays.

Figure 4.2.1.3 *Scoyenia* traces are common in channel sandstones associated with Facies A. These beetle traces indicate a high level of moisture and were created during wet seasons or within permanent water bodies.

4.2.2 **Facies B**

Facies B is siltstone to sandy-siltstone with a blocky pedogenic texture (Fig 4.2.2.1). The color of this facies is red to gray. The ichnofossil assemblage is similar to Facies A with rhizoliths and *Scoyenia* in associated channel bodies. It also exhibits a compound stacking pattern and coarsens upwards through the soil horizons, to sand at the top (Fig. 4.2.2.2).

Unlike Facies A, this facies does not contain the vertical mud-cracks and prismatic texture, but instead displays a blocky pedogenic texture. This results from less smectite clay due to slightly less biogenic modification. Together these indicate higher deposition rates. These soils are interpreted as ultisols; soils characterized by a high degree of leaching and little to no carbonate content (Soil Survey Staff, 1999). Utisols may form in a variety of climatic conditions, but always form in areas that have a dry season, in which the carbonate material is drained from the soil. Red coloration is also common in modern examples of Ultisols (Soil Survey Staff, 1999).Similarly to Facies A, the presence of *Scoyenia* and *Camborygma* are indicators of high soil moisture,. This means these traces must have formed during the wet season of the climatic regime.

Figure 4.2.2.1 Trench in Facies B from the lower Colton Formation, Unit 1.

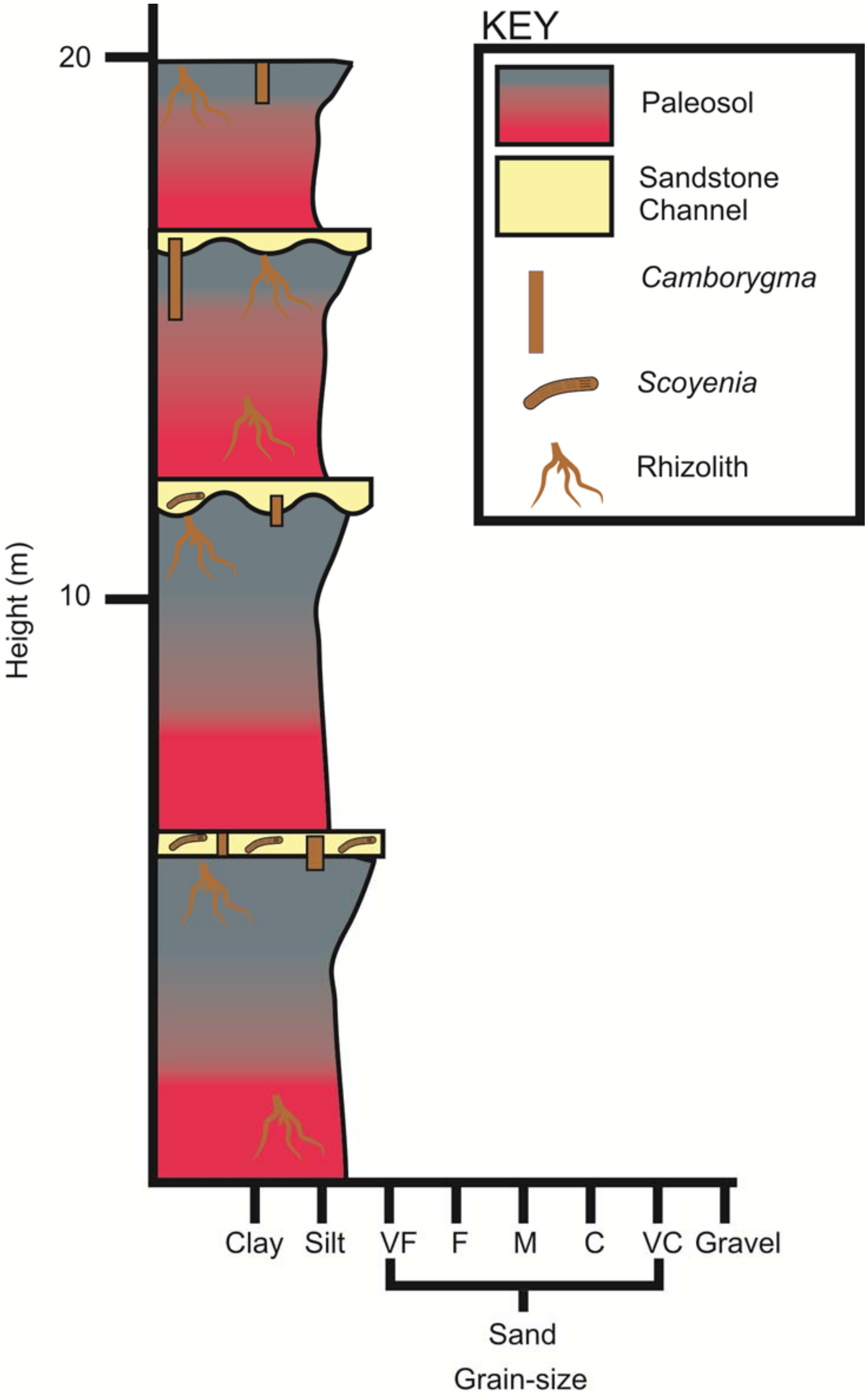


Figure 4.2.2.2 Generalized stratigraphic column of Facies B. This is interpreted to be a ultisol and is associated with Rhizoliths, *Scoyenia, and Camborygma.*

4.2.3 **Facies C**

Facies C consists of a sandy-siltstone with a blocky pedogenic texture (Fig. 4.2.3.1). This facies is colored green and red and often highly mottled. The soil horizons show a compound stacking pattern topped by a channel body (Fig. 4.2.3.2). Fining upward is accompanied by a change from green to red in color. Ichnofossils in this facies include rhizoliths, Adhesive Menescate Burrows, Ant Nests, *Steinichnus*, *Ancorichnus isp.*(Fig. 4.2.3.3).

Facies C is interpreted to be an Ultisol. The red color of these soils is attributed to hematite and goethite (Bigham et al., 1978; Schwertmann and Taylor, 1989; Smith et al., 2008a). The green color of the mottles and horizons of this section are attributed to water logged conditions below the water-table and in proximity to a channel body causing an oxygen depleted, reducing environment. Green colored sections show less pedogenic modification and have been interpreted to be C horizons, or weathered parent material.

Well-developed ultisols take a significant amount of time to develop; on the order of thousands of years (Soil Survey Staff, 1999). Facies C is therefore interpreted to be a under-developed Ultisol, lacking the depth and modification seen in many modern examples (Fig 4.2.3.4). This is caused by the periodic avulsion events and high deposition rates associated with channel deposits (see Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund, 2010)

The ichnopedological assemblage of this facies is complex. The presence of ant nests with a vertical trend indicates relatively low water tables and dry conditons (Hasiotis, 2006). *Steinichnus* traces are, however, associated with wet conditions and often found in humid climates or in association with permanent bodies of water. This divergence can be attributed to episodic deposition as well as a monsoonal climate, in which permanent channels could avulse and cover what originally was a dry floodplain. This facies shows a trend toward much more extreme seasonality than Facies A or B.

Figure 4.2.3.1 Photograph of Facies C from the lower Colton Fm. displaying green coloration and blocky pedogenic texture.

Figure 4.2.3.2 Trench in Facies C from the Lower Green River Fm. (Colton Tongue) displaying a compound stacking pattern caused by avulsion events onto floodplains.

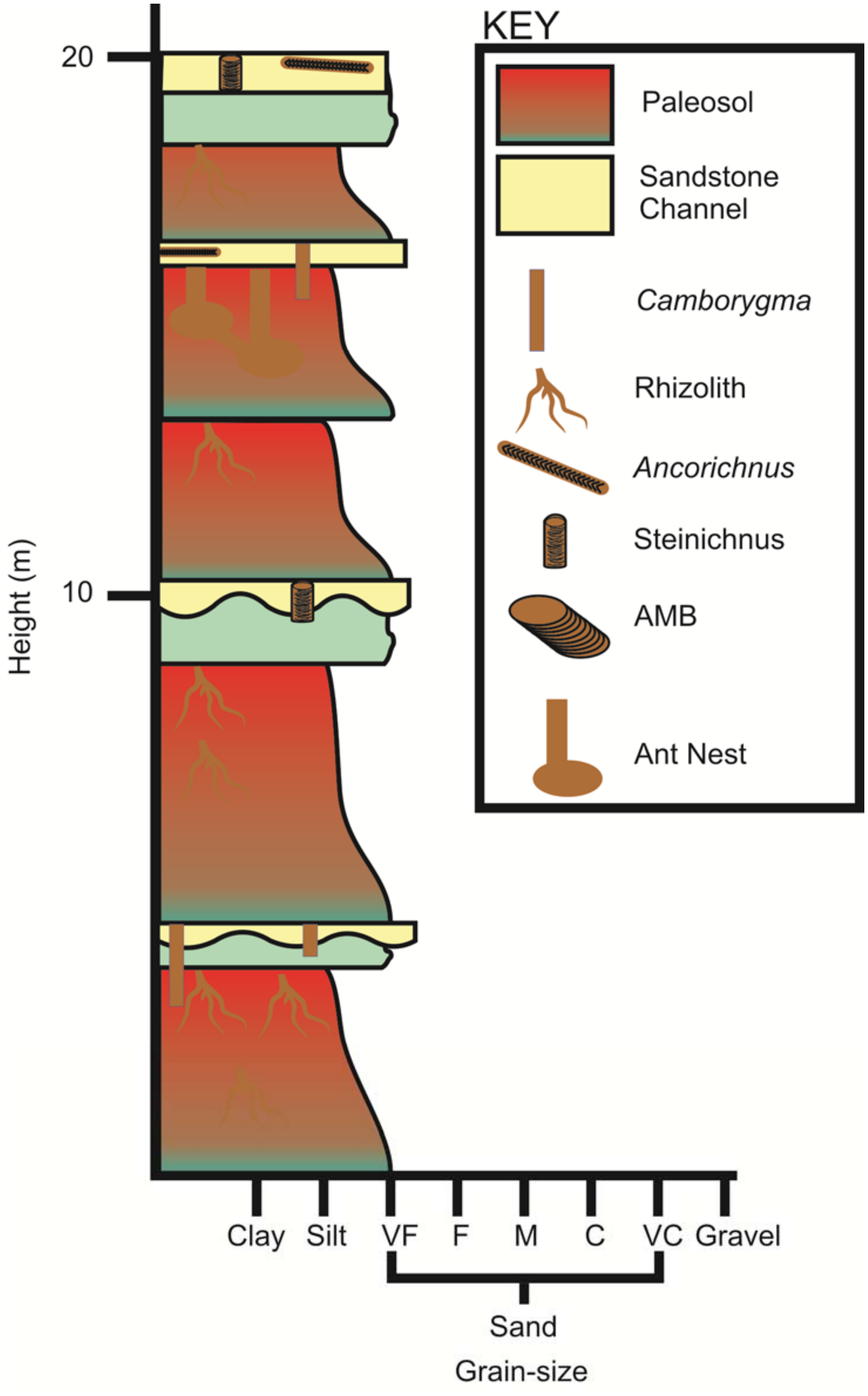


Figure 4.2.3.3 Generalized stratigraphic column of Facies C. This is interpreted to be a poorly developed ultisol and contains rhizoliths, Adhesive Menescate Burrows, Ant Nests, *Steinichnus*, *Ancorichnus isp.*

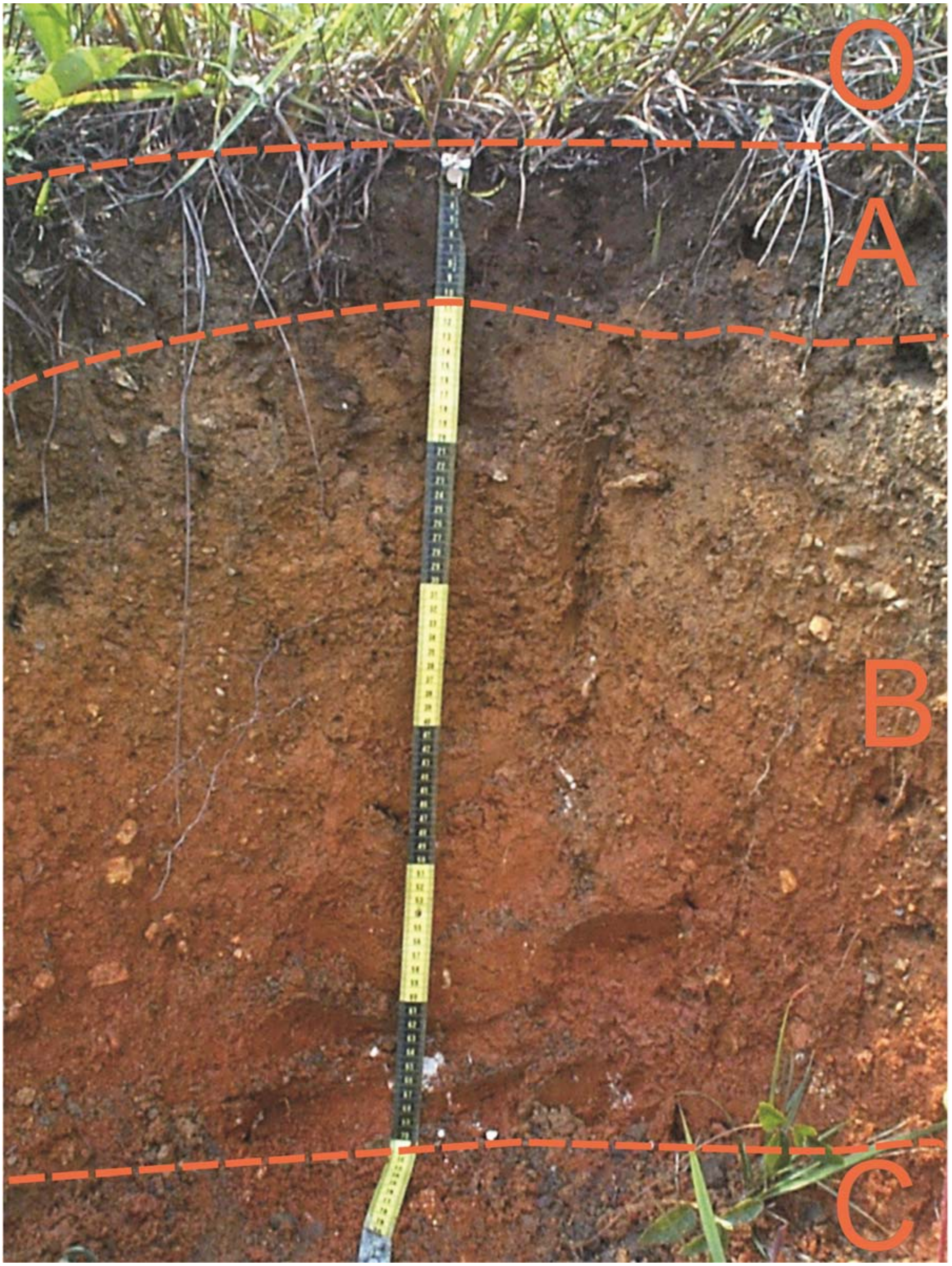


Figure4.2.3.4 Modern example of an Ultisol from Tennessee with soil horizons marked. Note the dark A horizon near the surface which does not get preserved often in the geologic record. Paleosols from Facies C have no A horizon, attributed to erosion from avulsion events. Modified from UT Pedology (2004).

4.2.4 **Facies D**

Facies D is a sandy siltstone with a blocky to granular pedogenic texture (Figure 4.2.4.1). In places this section contains round siliceous concretions on the order of 1cm in diameter (Figure 4.2.4.2). Soils show a compound stacking pattern but no distinct soil horizons (Figure 4.2.4.3). These paleosols are predominately tan in color but show some green and red mottles. They are found in association with Rhizoliths, Beetle Traces, and *Maconopsis* traces.

The lack of any distinct soil horizons leads to the interpretation that these are entisols. This type of soil frequently develops in environments where deposition is periodic, and at regular intervals. These are commonly associated with slopes and floodplain environments. This facies is associated with the highest rate depositional channels in the system and consequently the pinnacle of the PETM (see Chapter 5; see Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010).

The presence of Maconopsis and vertically oriented beetle traces indicate relatively dry soil conditions. This is to be expected from a immature soil. It is possible that the upper layers of these soils could be classified as aridisols because of sediment turnover by spiders and beetles, but any primary evidence of this has since been eroded .

Figure 4.2.4.1 Facies D from the middle Colton in outcrop displaying a granular pedogenic texture and tan to brown color. This facies is often truncated by channel bodies.

Figure 4.2.4.2 Siliceous concretions in Facies D.

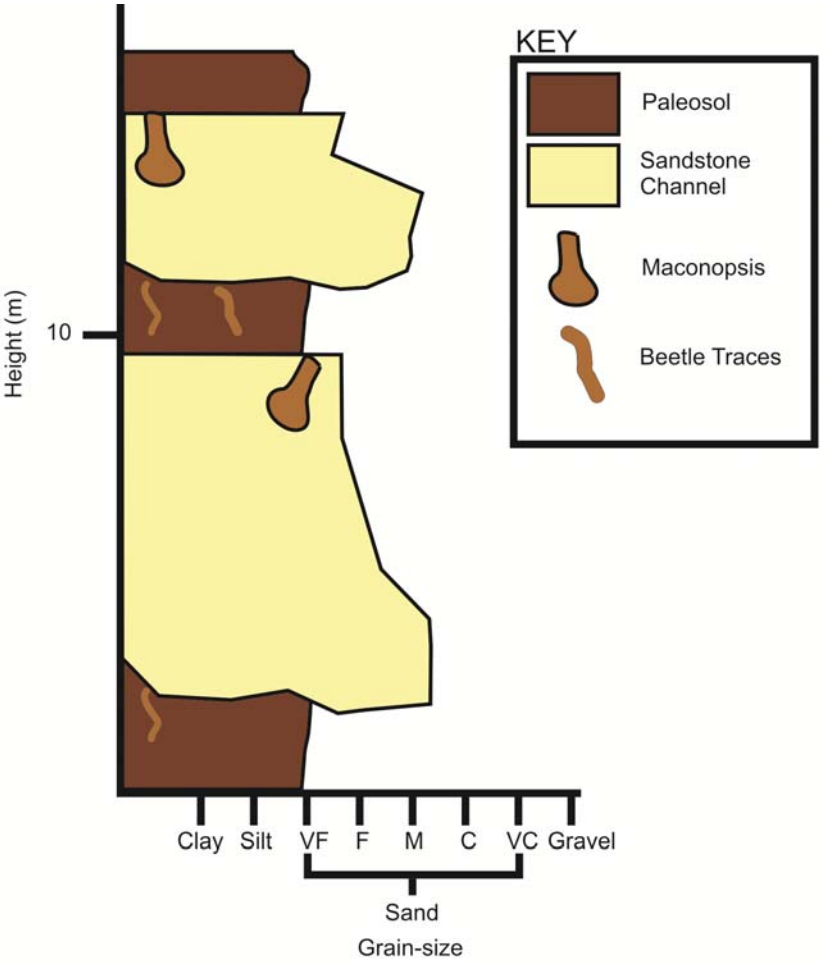


Figure 4.2.4.3 Generalized stratigraphic column of Facies D. This is interpreted to be an entisol and is associated with beetle and *Maconopsis* traces.

4.2.5 **Facies E**

Facies E consists of red to gray shale and siltstone that shows very little, pedogenic modification (Fig. 4.2.5.1). In some isolated areas a platy pedogenic texture can be observed. The channels associated with this facies are bioturbated at the upper boundaries of accretion sets by *Camborygma* and Rhizoliths from the top down (Fig. 4.2.5.2). This facies is laterally associated with Facies D (Fig. 4.2.5.3).

The lack of pedogenic modification of these siltstones indicates high rates of deposition and little biogenic activity. Facies E is interpreted to be an inceptisol. Such soils only have very weak horizonation and are typically buried immature (Soil Survey Staff, 1999). Inceptisols require a higher residence time to develop as compared to entisols, explaining the thin nature and weak horizons. Inceptisols generally indicate extreme conditions, either extreme moisture or aridity. The lack of bioturbation leads to the conclusion that these were deposited in extremely arid conditions. *Camborygma* and Rhizoliths in associated sandstone bodies indicate that water tables were relatively low.

Unlike Facies D, inceptisols do not indicate regular periodic deposition, rather they indicate irregular deposition with long, variable residence time at the surface. This can be explained in a distal floodplain situation in which deposition was infrequent. This is in contrast to Facies D, where deposition was more regular, such as in a proximal floodplain or point bar (see Fig. 4.2.5.3).

Most invertebrate species avoid areas of extreme aridity and attempt to locate areas where a balance between moisture and oxygen levels can be achieved (Hasiotis and Bown, 1992; Hasiotis et al., 1993; Hasiotis, 2006). Biogenic activity was occurring near bodies of water, but not significantly out onto the floodplain during times this facies was being deposited, indicating a very arid environment.

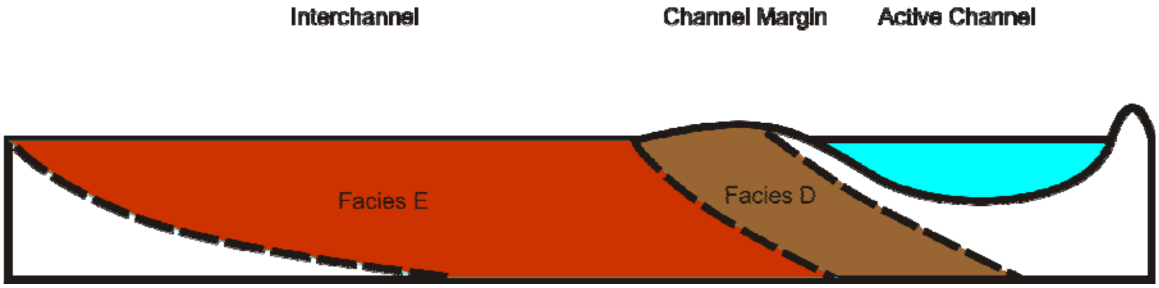


Figure 4.2.5.3 Lateral association of Facies D and E.

Figure 4.2.5.1 Photograph of Facies E, note the red color and platy pedogenic texture.

Figure 4.2.5.2 Photograph of *Camborygma* traces in a sandstone body associated with Facies E. The long vertical nature of these burrows indicates a deep water table.

4.2.6 **Facies F**

Facies F is a sandy-siltstone to siltstone that displays either a platy pedogenic texture or no pedogenic modification (Fig. 4.2.6.1). This facies is found in association with carbonate beds of the Carbonate Marker Unit of the Green River Fm. These paleosols are simple isolated soil horizons (see Fig. 4.2.7.2). It is gray to tan in color and found in association with woody fragments, gastropod fossils, *Haplotichnus* and *Celliforma isp*.

This facies is interpreted to be an inceptisol, but unlike Facies E, are associated with water-logged conditions. Inceptisols are usually associated with humid to sub-humid climates, but have more recently been described in almost every climatic regime (Soil Survey Staff, 1999). The association with lacustrine limestones, woody fragments, and gastropods indicate littoral lacustrine deposition. Whereas, *Celliforma isp.* and *Haplotichnus* are indicative of supra-littoral conditions and are commonly found in immature soils (Hasiotis, 2006). Therefore, this facies records fluctuating littoral lacustrine to supra-littoral lacustrine conditions

Figure 4.2.6.1 Photograph of Facies F from the Lower Green River Fm. (Carbonate Marker Bed). Displays platy pedogenic texture and dark gray color, indicating high organic contnent.

4.2.7 **Facies G**

Facies G consists of siltstone with a platy to prismatic pedogenic texture and a purple-gray color and yellow mottling (Fig.4.2.7.1). This facies is found in association with carbonate beds of the Carbonate Marker Unit of the Green River Fm and are also simple isolated horizons (Fig. 4.2.7.2). This facies also displays pedogenic slickensides. As with Facies F, they are associated with ichnofossils that indicate wet, supra-littoral conditions: *Haplotichnus* and *Celliforma isp*. (Hasiotis, 2006). These are also associated with rhizoliths and pedogenic slickensides.

Purple coloration is attributed to poor-drainage and highly reducing conditions (Hasiotis, 2006; Smith et al., 2008a). This is consistent with a supra-littoral conditions (see Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010). Pedogenic slickensides and prismatic texture lead to the interpretation that these are vertisols (Soil Survey Staff, 1999), however, some isolated purple horizons may be classified as poorly developed inceptisols (Soil Survey Staff, 1999; Smith et al., 2008a).

Figure 4.2.7.1 Photograph of Facies G displaying prismatic texture. Note numerous vertical cracks from tectonic stresses that have been subsequently filled.

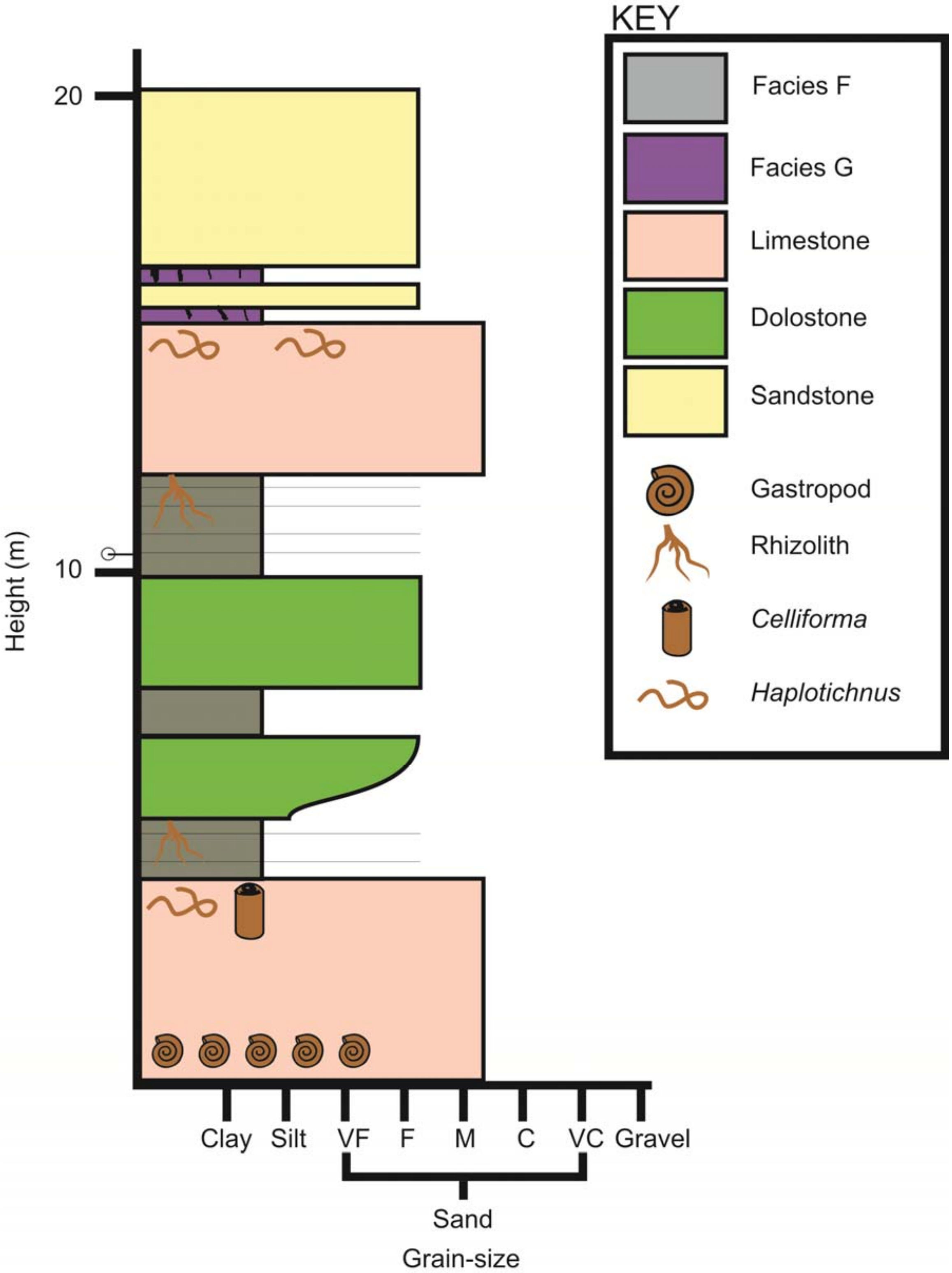


Figure 4.2.7.2 Generalized stratigraphic column showing Facies F and G. Note the association with lacustrine limestone and dolomite and sandstone mouthbars. Associated ichnofossils are *Celliforma*, *Haplotichnus,* and rhizoliths.

4.2.8 **Facies H**

Facies H is a sandy siltstone with a platy pedogenic texture (fig. 4.2.8.1). It is gray and green in color and displays a compound stacking pattern (fig 4.2.8.2). It is associated with *Cochlichnus, Haplotichnus isp.,* and woody fragments. This facies is interpreted to be an entisol, similar to Facies D, but differentiated because of its association with lacustrine limestones and supra-littoral ichnofossils as well as its gray color from abundant organic material.

Cochlichnus and *Haplotichnus isp.* indicate high moisture levels with the water table at or above the ground surface (Hasiotis, 2006). The thick, underdeveloped nature of these paleosols is attributed to constant periodic deposition in proximity to mouthbars (Soil Survey Staff, 1999; Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010).

Figure 4.2.8.1 Photograph of Facies F showing platy pedogenic texture and ichnofossils. This facies shows very little to no horzionation.

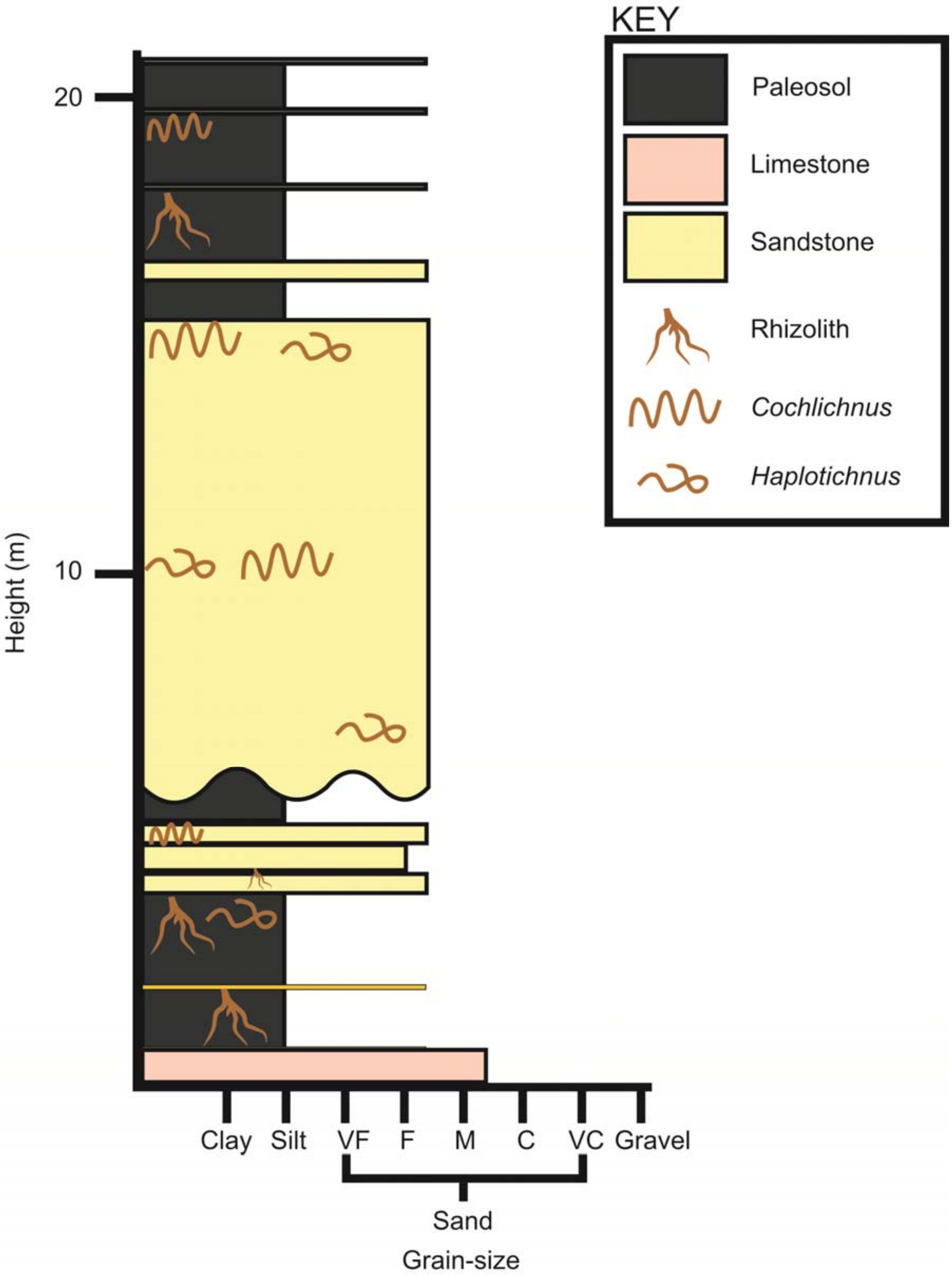


Figure 4.2.8.2 Generalized stratigraphic column showing Facies H and associated sandstones and limestones. Associated trace fossils are *Haplotichnus, Cochlichnus,* and Rhizoliths.

Table 4.2.2 Summary table of ichno-pedological facies from the Colton and Lower-Middle Green River Fm.

Name	**Pedogenic Texture**	**Color**	**Ichnofossils**	**Soil Type**	**Climatic Interpretation**
A	Prismatic	Red and Gray	Rhizoliths, *Scoyenia, Camborygma*	Vertisol	Seasonal
B	Blocky	Red and Gray	Rhizoliths, *Scoyenia, Camborygma*	Ultisol	Seasonal
C	Blocky	Red and Green	Rhizoliths, AMB, Ant Nests, *Steinichnus, Ancorichnus isp., Camborygma*	Ultisol	Monsoonal
D	Blocky to Granular	Tan, with red and yellow mottles	Rhizoliths, Vertical Beetle Burrows, *Maconopsis, Camborygma*	Entisol	Arid
E	Platy	Red	Rhizoliths, *Camborygma*	Inceptisol	Arid
F	Platy	Gray	Gastropods, Rhizoliths, *Celliforma, Haplotichnus isp.*	Inceptisol	Monsoonal
G	Platy to Prismatic	Purple with yellow and gray mottles	Gastropods, Rhizoliths, *Celliforma, Haplotichnus isp.*	Vertisol	Seasonal

Table 4.2.2 (cont.) 2 Summary table of ichno-pedological facies from the Colton and Lower-Middle Green River Fm.

Name	Pedogenic Texture	Color	Ichnofossils	Soil Type	Climatic Interpretation
H	Platy	Gray	Rhizoliths, *Haplotichnus isp.*, *Cochlichnus*	Entisol	Seasonal

4.3 **Ichno-pedological facies associations**

The ichnopedogenic facies described above can be grouped into six facies associations and are illustrated in table 4.3.1. These associations are based on recurring facies over significant vertical distances and stacking patterns. These associations represent periods of relatively similar climate and depostional regime.

Table 4.3.1 Ichno-pedological facies associations.

Name	Description	Facies
Compound, monsoonal vertisols (I)	Display a compound stacking pattern and red to gray in color. Prismatic to blocky pedogenic texture Very clay rich and display mud-cracks when dry	A
Compund, monsoonal ultisols (II)	Display a compound stacking pattern and are red to green in color. Blocky pedogenic texture Green colored portions are significantly coarser than red	B,C
Compound, high-deposition entisols (III)	Display a compound stacking pattern and are gray to tan in color. Lack distinct mottles or soil horizons.	D,H
Simple, high-depostion inceptisols (IV)	Single paleosol horizons that show little to mild pedogenic modification. Original depositional features can often be seen. Red in color and associated with high alluvial deposition rates	E
Simple, lacustrine inceptisols and vertisols (V)	Single paleosol horizons that show little pedogenic modification. Gray in color and associated with lacustrine sedimentation.	F
Compound, lacustrine entisols (VI)	Display a compound stacking pattern and moderate pedogenic modification. No distinct horizons and gray to tan in color.	H

CHAPTER 5

ICHNO-PEDOLOGICAL CHANGES

5.1 **Vertical Changes in Paleosol Characteristics**

Vertical changes in paleosols were recorded along multiple measured sections though the interval in question. Vertical changes throughout the section reflect overall changes in deposition and pedogenic modification through time on both regional and local scales. Changes are referenced to the informal stratigraphic units for the Nine Mile Canyon area as described by Birgenheier et al. (2009), Plink-Björklund and Birgenheier (2009)Plink-Björklund et al. (2010) and (see Fig 4.1.1) Noted changes are pedogenic structure, color, trace fossil assemblage and clay content. Changes were analyzed in both small-scale depositional features, as well as in overall architecture. These changes are summarized in Table 5.1.1.

5.1.1 **Vertical Changes in the Colton Formation**

The Colton Fm. displays two ichno-pedological facies associations: compound monsoonal vertisols and compound monsoonal ultisols. The Colton Formation has been divided into six informal stratigraphic units (see Plink-Björklund and Birgenheier, 2009; Birgenheier et al., 2009; Plink Björklund et al., 2010).

Unit 1 contains Ichno-pedological Facies A: compound, monsoonal vertisols. Vertisols are characterized by clay-rich horizons that are dry for some time of the year (Soil Survey Staff, 1999). The combined ichnopedologic data suggest a wet monsoon climate and high soil moisture. Additionally, sedimentary data suggests very low water discharge coupled with high-deposition rate sedimentary events. Together this indicates a very seasonal output for the system. (Birgenheier et al., 2009; Birgenheier and Plink-Björklund, 2009; Plink-Björklund et al., 2010). The channels associated with this unit are small, laterally and vertically isolated sandstone bodies that contain abundant vertical crayfish burrows (Birgenheier et al., 2009; Birgenheier and Plink-Björklund, 2009; Plink-Björklund et al., 2010).

Unit 2 contains Facies B and C; red and green sandy siltstone with a blocky pedogenic texture (Fig. 5.1.1.4). These paleosols are interpreted to be compound

Table 5.1.1 Summary of changes in informal through the Colton and Lower-Middle Green River Formations. Based on informal stratigraphic units by Birgenheier et al. (2009), Plink-Björklund and Birgenheier (2009), and Plink-Björklund et al. (2010).

Unit	Ichno-pedological Assemblage	Interpretation
16	Facies D: High-deposition entisols	Deltaic deposition with high-deposition rates and seasonal water output
15	Facies D: High-deposition entisols	Deltaic deposition with high-deposition rates and seasonal water output
14	Facies D: High-deposition entisols	Deltaic deposition with high-deposition rates and seasonal water output
13	Facies D: High-deposition entisols	Deltaic deposition with high-deposition rates and seasonal water output
12	Facies H: compound lacustrine entisols	High water table deltaic deposition
11	N/A	Littoral lacustrine deposition
10	Facies F and G: simple lacustrine inceptisols and vertisolsn	Lacustine deposition with fluctuating lake level. Inter-bedded littoral lacustrine carbonates and supra-littoral delta influenced sandstones and carbonates
9	Facies B and C: compound monsoonal ultisols	Moderate water discharge and seasonal water output. Relatively high water table. Rising water table
8	Facies B and C: compound monsoonal ultisols	Moderate water discharge and seasonal water output. Relatively high water table
7	Facies F: simple lacustrine inceptisols	Littoral lacustrine depositional systems
6	Facies B and C: compound monsoonal ultisols (Lack of *Camborygma* traces)	Moderate water discharge and seasonal water output. Rising water table.
5	Facies B and C: compound monsoonal ultisols	Moderate water discharge and seasonal water output. Rising water table
4	Facies D and E: High-deposition entisols and inceptisols	Extreme aridity and extremely monsoonal climate regime

Table 5.1.1 Summary of changes in informal through the Colton and Lower-Middle Green River Formations. Based on informal stratigraphic units by Birgenheier et al. (2009), Plink-Björklund and Birgenheier (2009), and Plink-Björklund et al. (2010). (cont.)

Unit	**Ichno-pedological Assemblage**	**Interpretation**
3	Facies B: Compound monsoonal ultisols	Distributary channels with low water discharge
2	Facies B and C: Compound monsoonal ultisols	Moderate water discharge and seasonal water output
1	Facies A: Compound monsoonal vertisol	Low water discharge and seasonal water output.

monsoonal ultisols, Ultisols form in many climatic regimes, but must have some length of dry season, in which the carbonate material is drained from the soil. They require relatively long residence times to form (Soil Survey Staff, 1999; Kraus, 2002). Red coloration is also common in modern examples of Ultisols (Soil Survey Staff, 1999).The presence of adhesive meniscate burrows and *Steinichnus,* lead to the interpretation of a wet environment with a high water table. Unit 2 is associated with erosionally based, vertically isolated channels that are significantly larger than those found in Unit 1 (Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010). The larger size and erosional bases of these channels, as well as upper high-deposition rate plane-parallel laminations, together with bioturbation on individual accretion set surfaces, indicate a higher seasonal outflow than seen in Unit 1 (Plink-Björklund and Birgenheier, 2009; Birgenheier et al., 2009; Plink-Björklund et al., 2010).

Unit 3 contains Facies B, similar to Unit 2, but contains no green mottling (fig. 5.1.1.6). The combined ichnopedologic data suggest a seasonal climate. Additionally, sedimentological data suggests a relatively low water discharge (Plink-Björklund et al, 2010). There are two distinct channel facies associated with this unit. The first are sharp based tabular sandstones with climbing ripples and plane-parallel laminations. These are interpreted to be mouth bars due to their tabular structure and high deposition rate features (Björklund and Birgenheier, 2009; Birgenheier et al., 2010; Björklund et al., 2010). This facies grades laterally into lenticular sandstones with erosional bases with plane-parallel laminae and or cross stratification (Plink-Björklund et al., 2010; Birgenheier et al., 2009). Their association with the mouth bar bodies couples with their lower deposition rate features suggests that these are distributary channels.

Unit 4 contains two distinct ichno-pedological facies: Facies D and E, which are laterally associated (see Fig. 4.2.5.3). The combined ichno-pedological data suggests that this unit was represents a very monsoonal climate regime, with extremely arid dry season and short wet season. Additionally, sedimentological data suggests that Unit 4 is associated with the highest deposition rates in the system. This is futher evidenced by the associated lenticular channel bodies that are almagamated both vertically and laterally (Plink-Björklund and Birgenheier, 2009; Birgenheier et al., 2009; Plink-Björklund et al., 2010). The trace fossil assemblage, which are consistent with a relatively wet depositional environment, indicaties most soil development occurred during major flooding events over a relatively short period of time during the year (Hasiotis, 1997).

Units 5 and 6 contain Facies B and C red to gray siltstone with a blocky pedogenic texture and red and green sandy siltstone with a blocky pedogenic texture, respectively. The combined ichno-pedological data suggests these units are associated with a seasonal climate, similar to units 2 and 3. The only difference is large vertical traces, such as Rhizoliths and *Camborygma,* are absent in these units. A lack of large vertical crayfish burrows possibly indicating a slight reduction of the residence time of the soil, as well as a lowered water table (Hasiotis, 1997; Hasiotis 2006; Smith et al., 2008a). Additionally, sedimentological evidence suggests less seasonal variation than unit 4. The channel bodies within Unit 5 are large bodies with complex accretion patterns and indicating than found in lower units. There is only one channel body in Unit 6 that is comparable in thickness to those found in Unit 5. However, its isolated nature and high-depostion rate sedimentary structures indicate an increased monsoonal intensity compared to Unit 5. (Plink-Björklund and Birgenheier, 2009; Birgenheier et al., 2009; Plink-Björklund et al., 2010).

Figure 5.1.1.1 Photograph of trench taken in unit 1 (Colton Formation) displaying a blocky pedogenic texture.

Figure 5.1.1.2 Photograph of a trench taken in unit 1 (Colton Formation) displaying blocky pedogenic texture, with rhizoliths highlighted.

Figure 5.1.1.3 Top of a sandstone channel in unit 1 (Colton Formation) with *Scoyenia* traces.

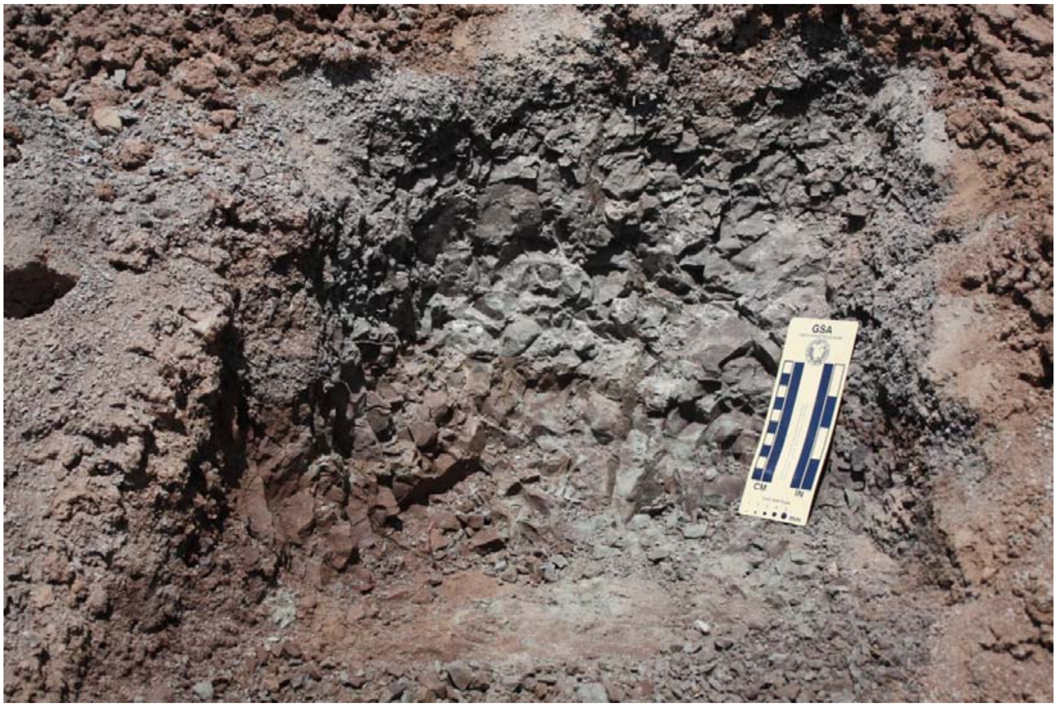


Figure 5.1.1.4 Photograph of a trench taken in unit 2 (Colton Formation). Note the additional green color compared to Unit 1.

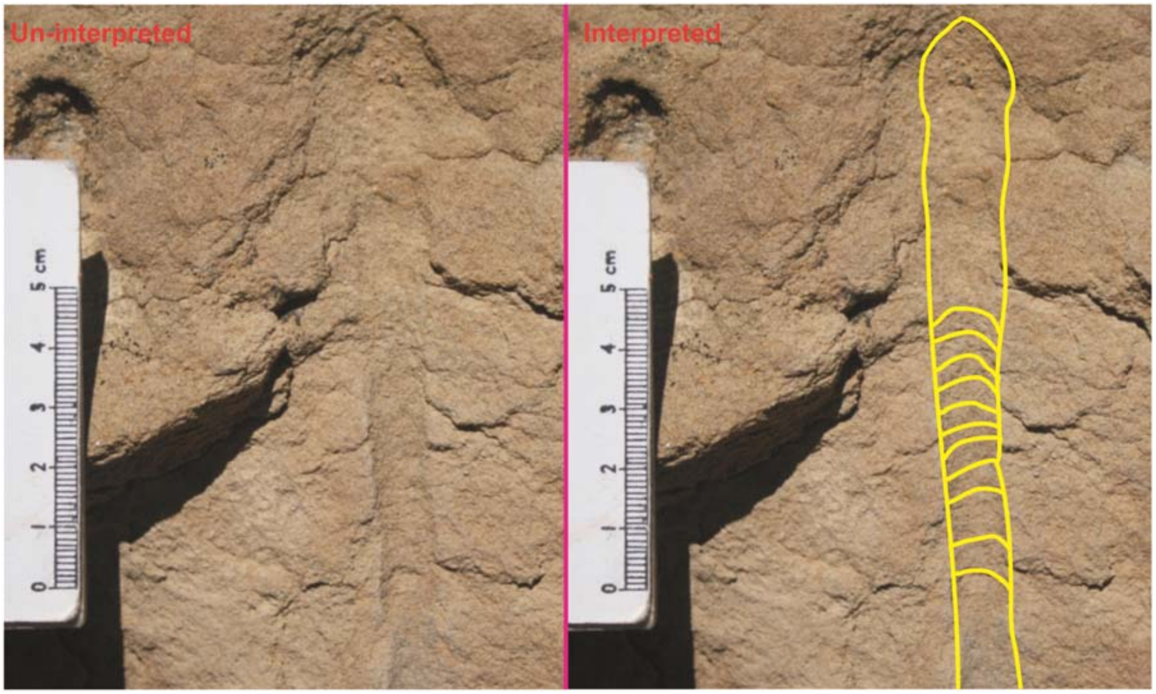


Figure 5.1.1.5 Photograph of an Adhesive Menescate Burrow taken from a sandstone channel in Unit 2. Outline of the burrow and Menescae are highlighted on the right.

Figure 5.1.1.6 Photograph of a trench taken in unit 3 (Colton Formation).

Figure 5.1.1.7 Photograph of a sandstone body from unit 4 displaying a crumb pedogenic texture.

Figure 5.1.1.8. Red siltstone from unit 4. This displays little to no pedogenic modification.

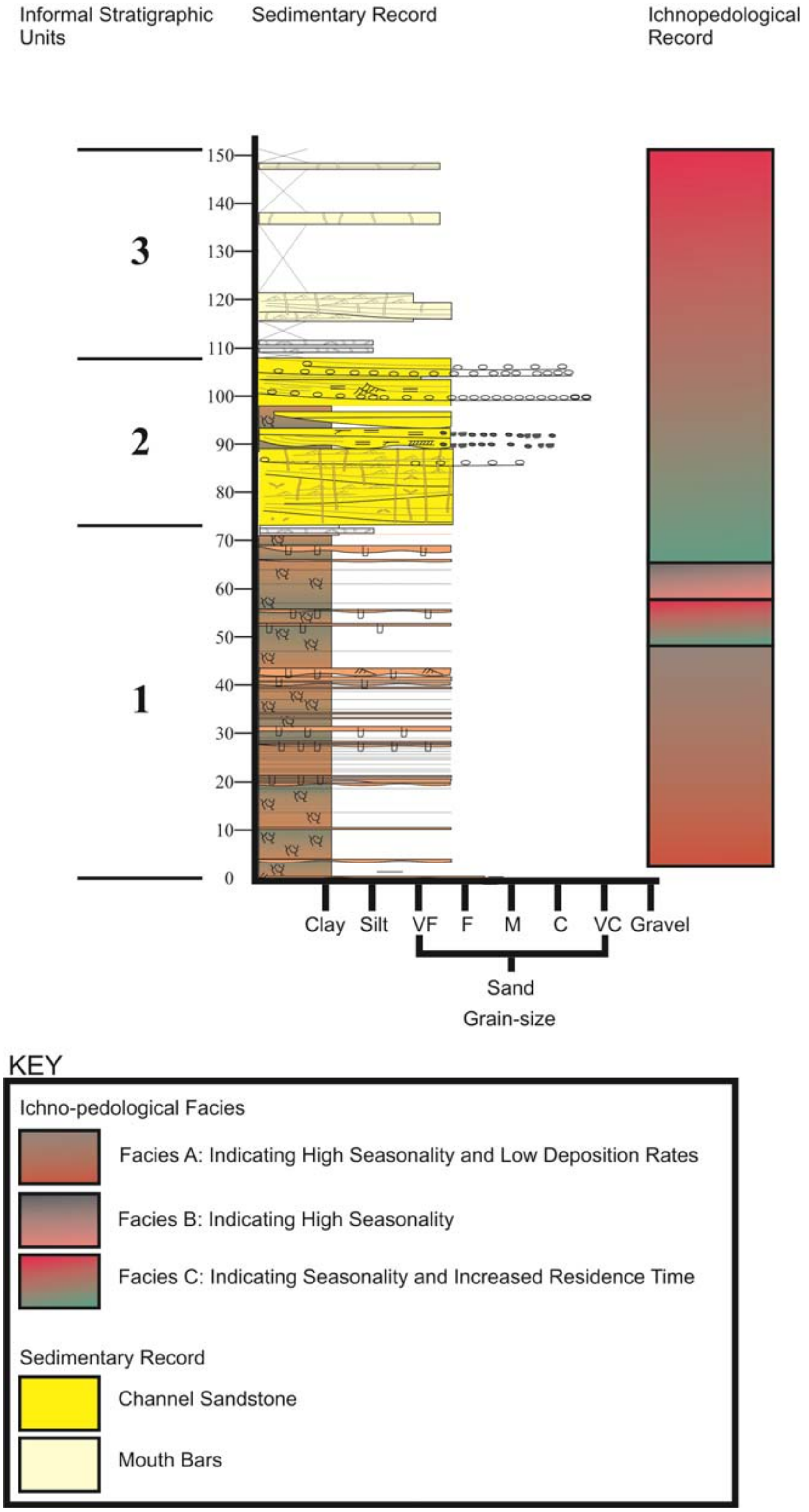


Figure 5.1.1.9 Stratigraphic section showing informal stratigraphic Units 1 through 3 (The Lower Colton Formation). Bar on right indicates inferred depositional environment from ichno-pedological analysis.

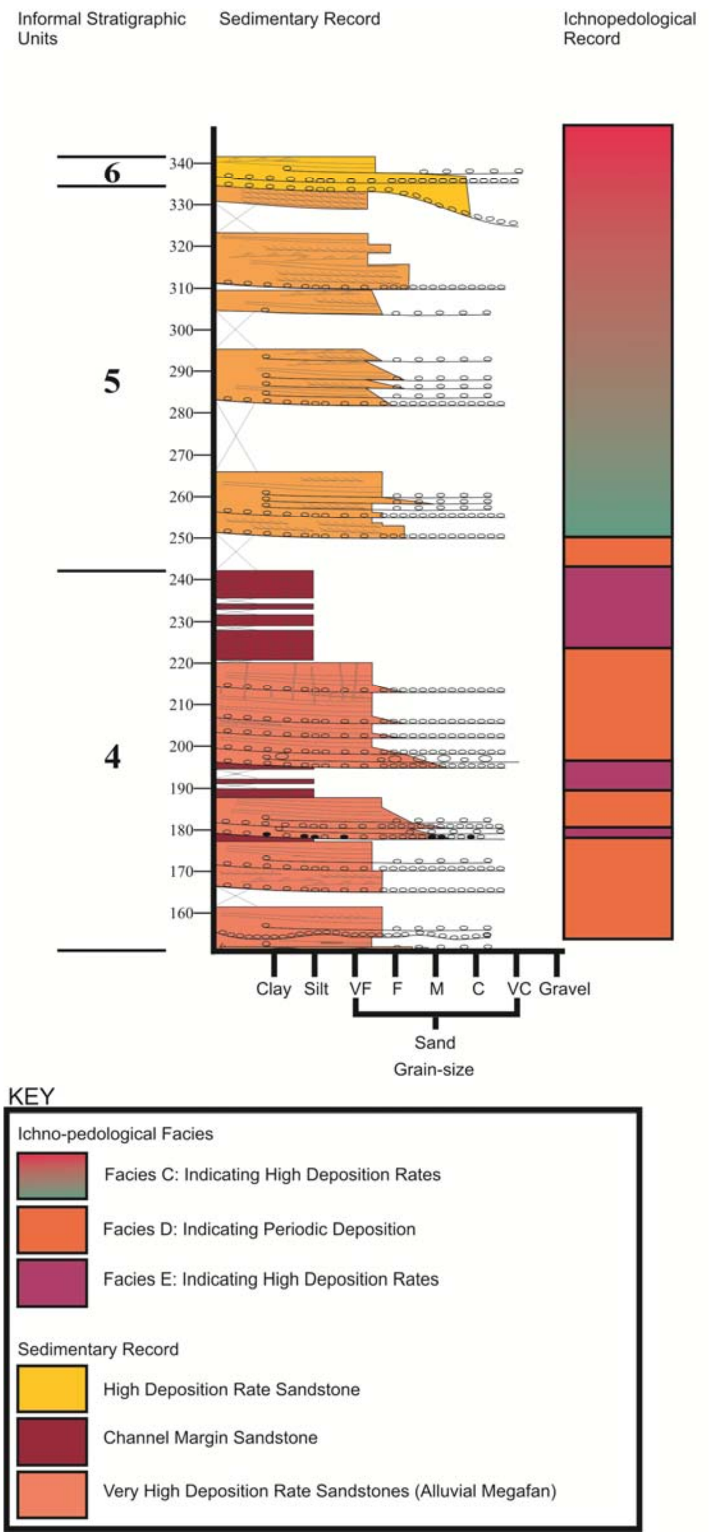


Figure 5.1.1.10 Stratigraphic section showing informal stratigraphic Units 4 through 6 (The Colton Formation). Bar on right indicates inferred depositional environment from ichno-pedological analysis.

5.1.2 Vertical Changes in the Green River Formation

The overlying Green River Formation is characterized by the complex interaction of alluvial and lacustrine sedimentation. Overall the paleosols in this formation can be broadly grouped into those formed in alluvial settings, such as floodplains and on barforms and into those formed in lacustrine supralittoral and littoral settings. The paleosols here can also be further divided using the same stratigraphic system used for the Colton Formation, in which the Green River Formation consists of Units 7 – 16 (Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010).

Unit 7 is characterized by the onset of lacustrine sedimentation. It consists of Gray siltstone to shale, as well as gray limestone. The fine-grained intervals of this unit are not well exposed in the study area and difficult to examine in great detail. It is, however, used extensively as a sub-surface correlation unit, the Uteland Butte Limestone (Morgan et al., 2003; Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010). From what can be observed, the paleosols associated with this Unit are most likely simple, lacustrine inceptisols (Facies F; see Unit 10).

Units 8 and 9 contain Facies B and C: generally red, green, and tan sandy siltstone with a blocky pedogenic texture (Fig. 5.1.2.1). The combined ichnopedological data suggests that the dominant climatic regime was highly seasonal and was similar to the interpreted climate patterns from units 2 and 3. However, a horizontal trend to burrows and shallow nature of the identified ant nest indicate a relatively high water table. Additional sedimentological data indicates a less monsoonal climate than seen in the lower sections of the Colton. Channel bodies associated with the “Colton Tongue” are generally vertically isolated and have erosional bases (Birgenheier et al., 2009). These bodies generally have plane parallel laminations and are similar to the channel in Unit 6.

Units 10 and 11 contain Facies F and G; displaying a return in lacustrine sedimentation. This section contains carbonate lake beds and delta-influenced shallow lake beds, as well as mouthbar deposits, and distributary channels (Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010). The combined ichnopedological data suggests that this unit was a supralittoral lacustrine depostional environment. Associated limestone deposits also contain woody fragments and gastropods. Areas of no pedogenic modification within the shale horizons are interpreted to have been deposited in a littloral setting. These shales often contain only minor numbers of trace fossils. Littoral sections of unit 12 are characterized by gastropod fossils and preserved woody fragments in shale horizons.

Units 12 through 16 are classified as part of the "Sunnyside Delta Member" and exhibit a transition to an alluvial depositional environment. Unit 12 contains Facies D and H. The most abundant trace fossil in this section is *Cochlichnus* (fig. 5.1.2.9). The combined ichnopedological data suggests that these are associated with a supra-littoral lacustrine setting. Units 13 - 16 contain Facies. The combined ichnopedological data indicate a seasonal climatic regime with a high water table Trace fossils consist of Rhizoliths, partially backfilled beetle burrows, and *Ancorichnus isp.* Units 13 – 16, display much less pedogenic modification than those found in the Colton Fm. and often have a platy texture.

Figure 5.1.2.1 Outcrop view of Unit 8. Note the vertical change from red to green coloration. This trend is coupled with an increase in grain size.

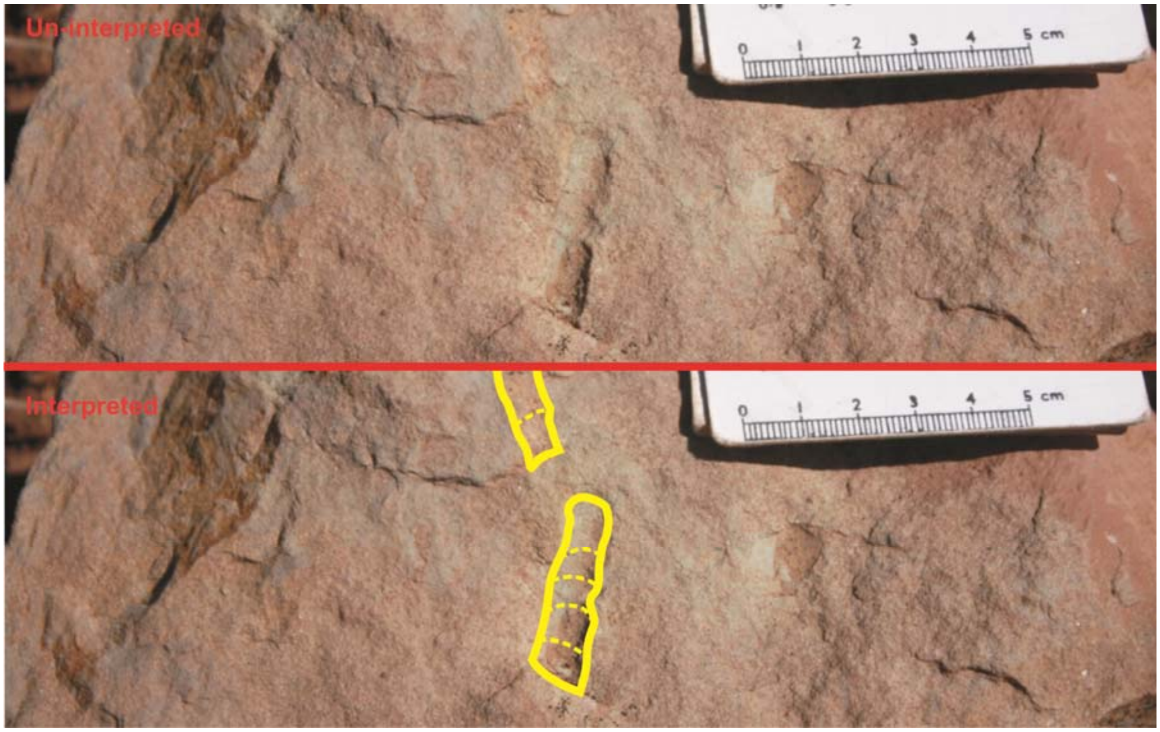


Figure 5.1.2.2. Adhesive Meniscate Burrows are common in the “Colton Tongue”

Figure 5.1.2.3. An ant nest in outcrop from the “Colton Tongue.” These traces consist of multiple tunnels and chambers.

Figure 5.1.2.4. *Ancorichnus isp.* in the "Colton Tongue."

Figure 5.1.2.5a Close-up view of a paleosol from unit 10. Note the platy pedogenic texture, indicating some sedimentary structures are still present.

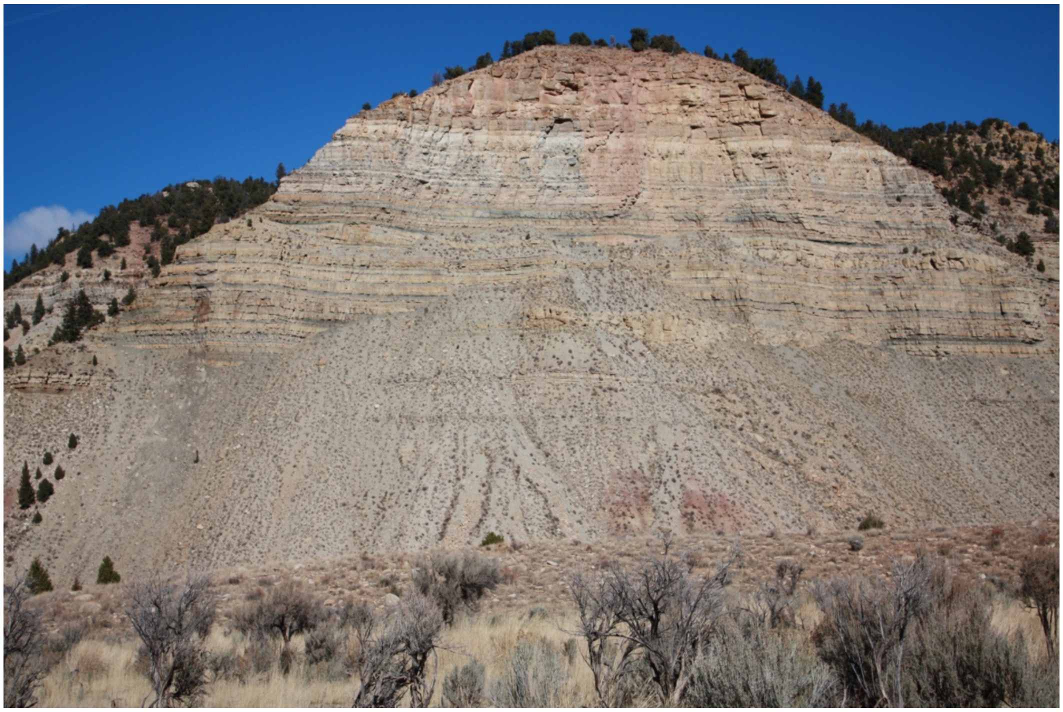


Figure 5.1.2.5b Outcrop view of units 10 and 11. The limestone and dolostone bodies in this unit create large vertical outcrops.

Figure 5.1.2.6 *Haplotichnus is.* in a limestone body from unit 10.

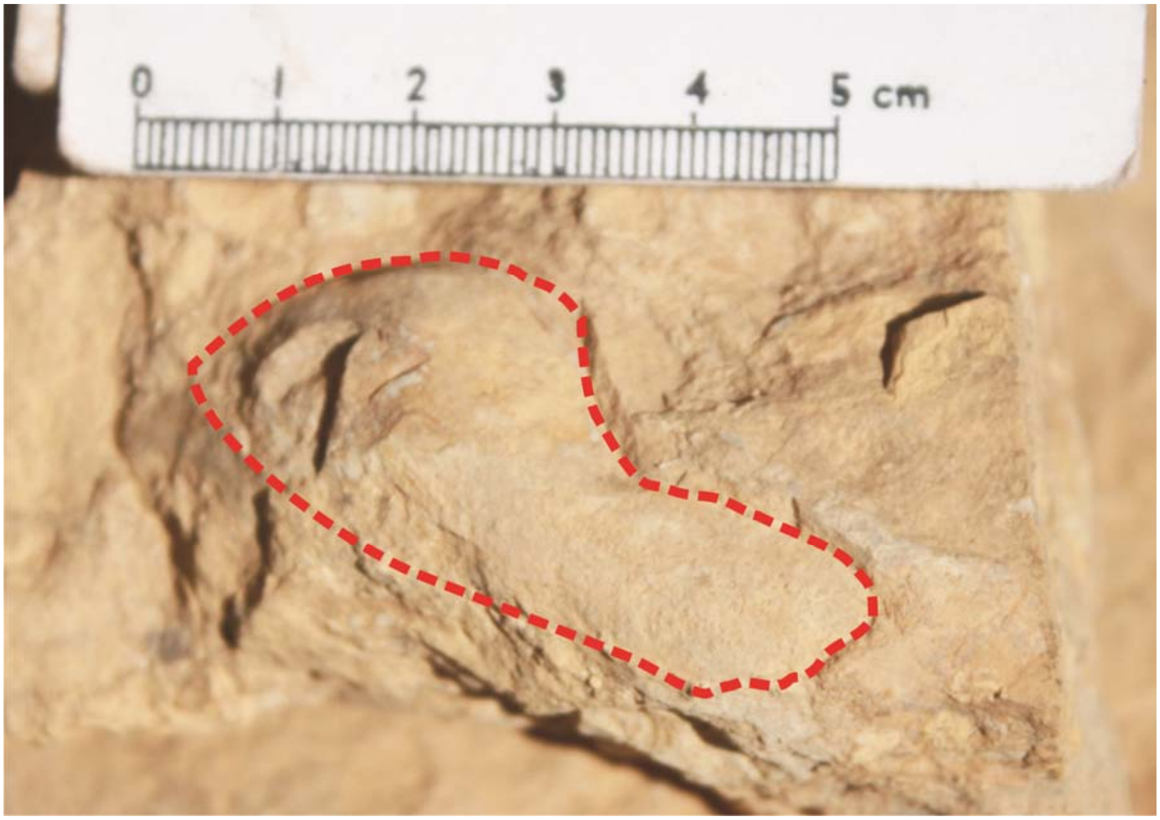


Figure 5.1.2.7 *Celliforma* in a limestone bed from unit 10.

Figure 5.1.2.8 Siltstone from unit 12 displaying a lack of pedogenic modification.

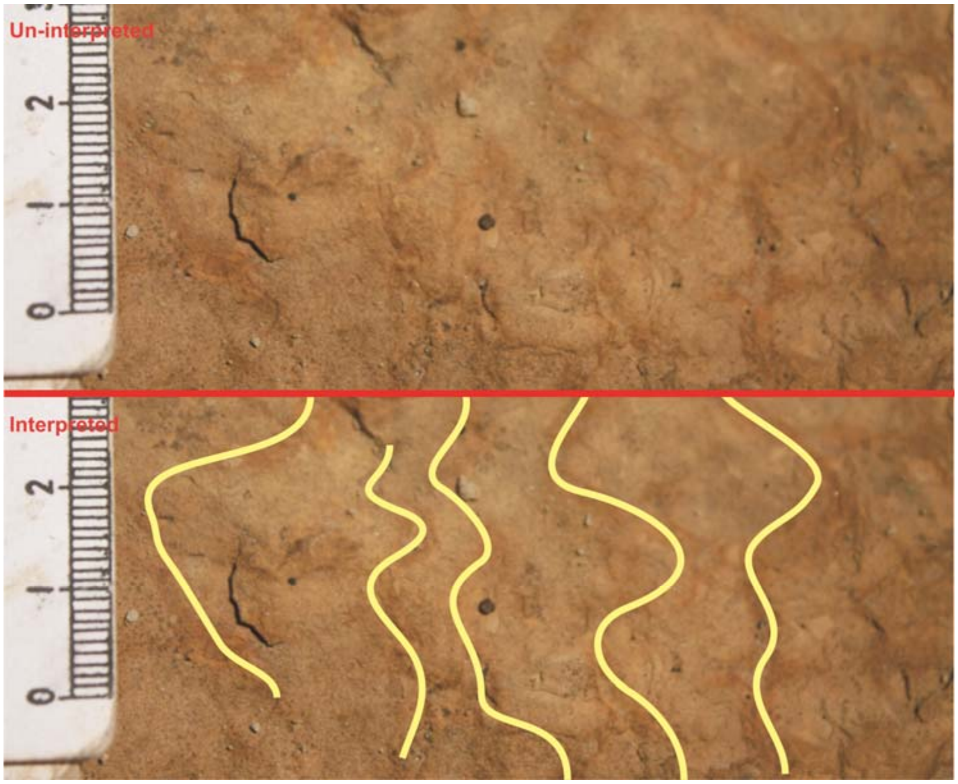


Figure 5.1.2.9 *Cochlichnus* trails in Unit 12.

Figure 5.1.2.10 Paleosol from unit 14. The Sunnyside Delta is characterized by these gray to red blocky paleosols. They are more weakly developed than those associated with alluvial deposition lower in the section.

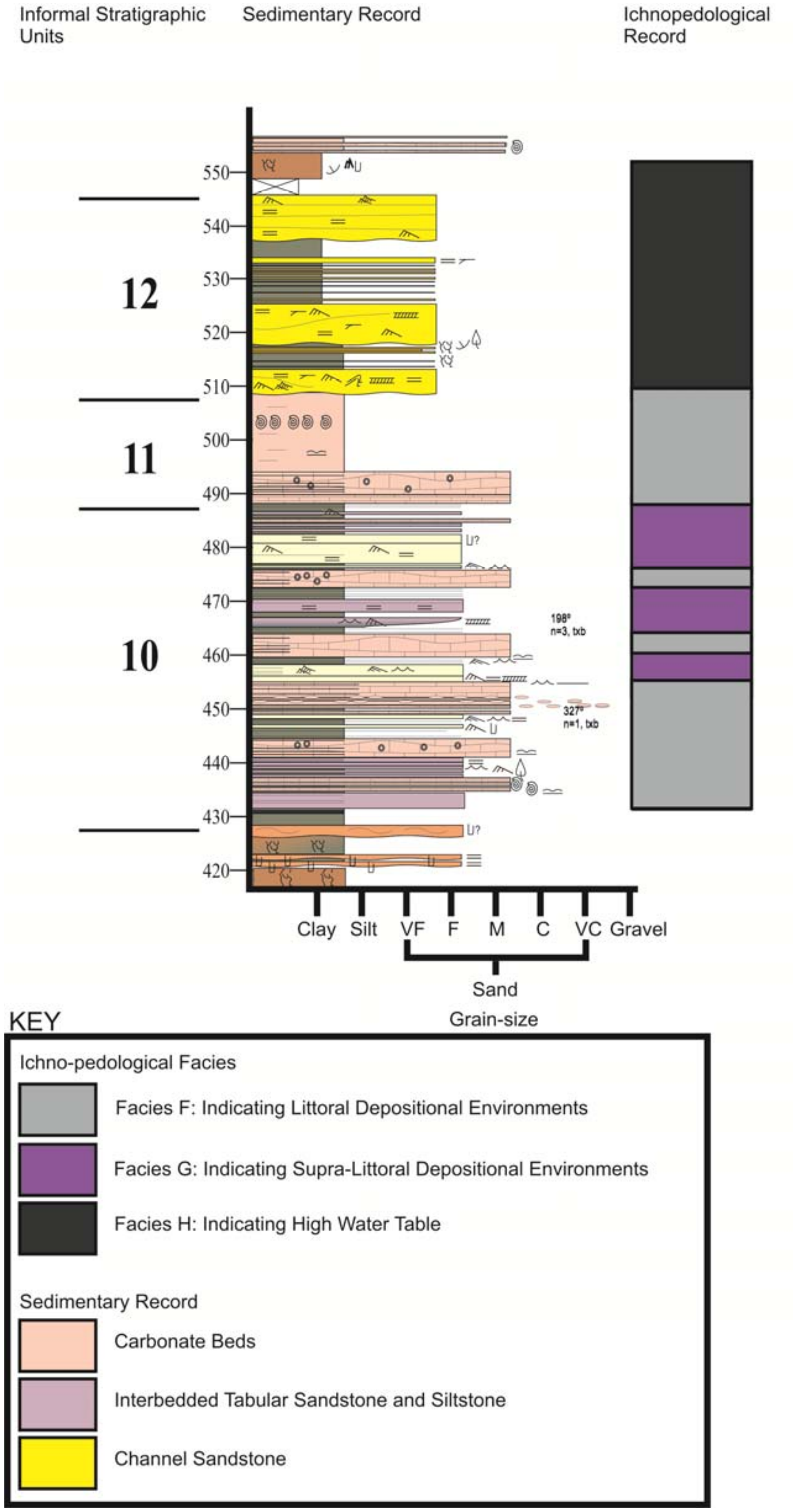


Figure 5.1.2.11 Stratigraphic section showing informal stratigraphic Units 10 through 12. Bar on right indicates inferred depositional environment from ichno-pedological analysis.

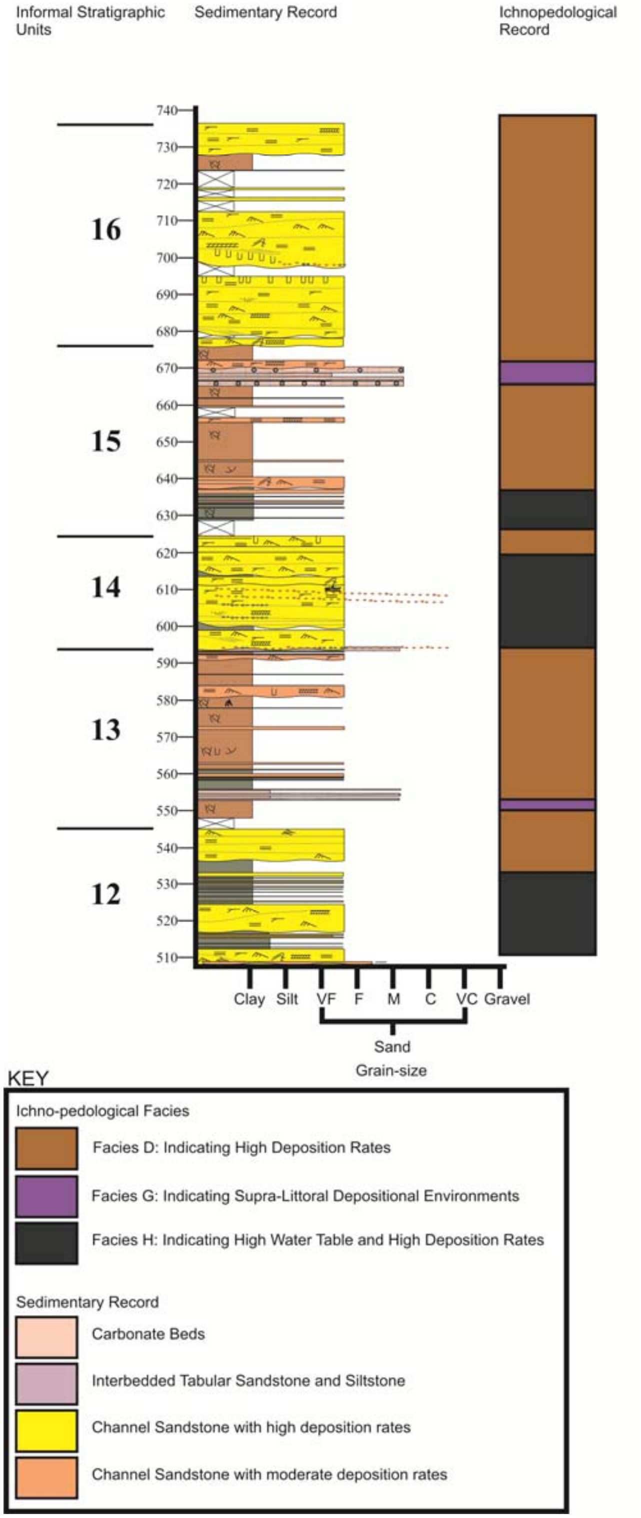


Figure 5.1.2.12 Stratigraphic section showing informal stratigraphic Units 12 through 16 (The Sunnyside Delta). Bar on right indicates inferred depositional environment from ichno-pedological analysis.

5.2 **Lateral changes in Paleosol Characteristics**

Lateral changes in the paleosols have the potential to record environmental changes in deposition. Most paleosols can be traced for long distances laterally with very little change in composition or trace fossil assemblage. Generally, in areas where paleosols are downcut into by channel deposits, there are some changes in paleosol characteristics.

5.2.1 **Lateral Changes in the Colton Formation**

Units 1 through 3 can be traced laterally without interruption for distances in the scale of hundreds of meters if not crosscut by channel deposits. Where such down cutting occurs, paleosols bordering the channels will be less well developed, green in color, and exhibit a larger grain-size than elsewhere in the section. This trend of increased grain-size and green color can also be seen at the base of all the channel cuts in the section.

Unit 4 displays the most laterally variable paleosol in the Colton Formation. Here areas of little to no pedogenic modification transition laterally into moderately developed paleosols with blocky peds. Units 5 and 6 display similar laterally variability as described for Units 1 through 3.

5.2.2 **Lateral Changes in the Green River Formation**

The Green River Formation displays a complexity in the laterally variability of the paleosols that is not seen in the Colton Formation. This is due to the interaction of alluvial and lacustrine deposition present in the area. Areas of fluvial deposition may crosscut lacustrine sedimentation areas (Fig. 5.2.2.1).

Unit 10, in particular, shows lateral variation clearly. Facies F and G merge laterally with distance. Generally Facies G is associated with mouth bar deposits; whereas, Facies F is associated with littoral lacustrine deposits (Fig. 5.2.2.2) There is a general grade from littoral to supra-littoral conditions: poorly developed Facies F, well developed Facies F, poorly developed Facies G, well developed Facies G. This reflects a change from water-logged conditions to partially drained conditions in supra-littoral conditions and on the surface of mouth bars.

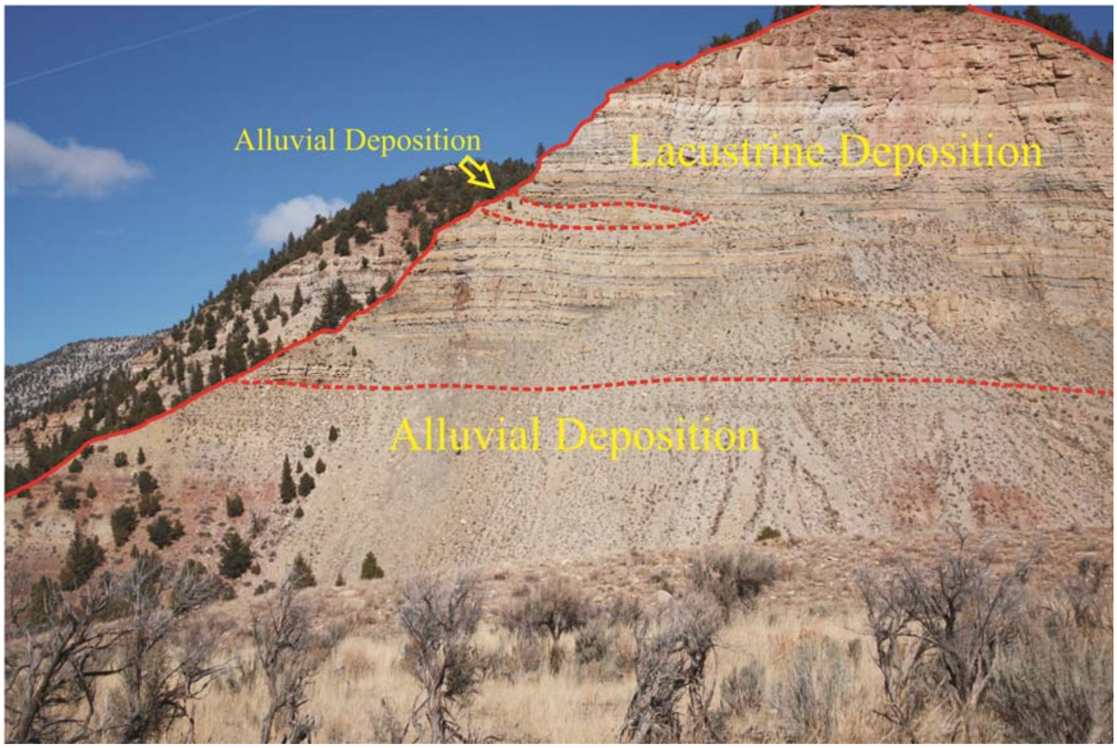


Figure 5.2.2.1 Section LG-2, Lower Green River Formation, displaying the interaction between alluvial and lacustrine sedimentation.

5.3 **Paleosol Architecture**

All of the paleosols in the study area are notably lacking any carbonate nodules. This is in contrast to other alluvial paleosol sections, such as the Bighorn Basin, Wyoming (Kraus, 1996, 1999, 2002). The lack of carbonate nodules suggests that is area was well drained.

Paleosols found in alluvial portions of the section predominantly display a compound stacking pattern. This indicates that sedimentation occurred relatively quickly, most likely due to rapid avulsion and flooding events. Due to the increased amount of sediment, residence time for the paleosols was isolated to time periods between avulsions (Kraus 2002). The strength and periodicity of these avulsions changes through time, and can be seen in vertical changes in both sandstone channel bodies and facies, as documented from the stratigraphic record. For instance, the Colton Formation displays an overall increase upsection of avulsion frequency and discharge. The section changes from isolated channel bodies to amalgamated channels upsection (unit 4). This co-varies with a change in paleosols from well developed cumulative paleosols at the base to well developed compound paleosols, and finally to area where floodplains show little to no pedogenic modifaction (unit 4).

The Green River Fm. also displays changes in paleosol development through the section. The paleosols of the “Colton Tongue” are much better developed than those of the “Sunnyside Delta Member” This is attributed to lower residence time of the soils, caused by increased sedimentation rates. Avulsion rates in the “Sunnyside Delta Member” are interpreted to have been more frequent than lower in the Colton Fm.

CHAPTER 6

ICHNO-PEDOLOGICAL ASSEMBLAGES AS A PALEOCLIMATE PROXY

6.1 Correlations between Ichno-pedological Facies and Geochemical Data

Ichno-pedogical facies show a change from compound, monsoonal vertisols in Unit 1 to compound, monsoonal ultisols in Units 2 and 3. The onset of the PETM marked a change in climatic conditions from relatively stable to extremely seasonal. The change from vertisols to ultisols indicates a rise in the water table for part of the year. It also indicates less clay material being deposited in the floodplains, which is to be expected if fluvial discharge was extremely seasonal and, therefore higher energy. It can be inferred that the preserved floodplain paleosols were created during the wet season of the monsoons, and that any soil horizons, such as aridisols, were overprinted. The change into arid climatic conditions is also marked by decreasing density of crayfish burrows (*Camborygma*) in the associated channel bodies.

This is confirmed by geochemical analysis (see Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010: Fig 6.1.1). The base of the Colton formation shows an abrupt 3.5‰ negative shift in $\delta^{13}C_{org}$ and a further, more gradual 2‰ negative shift into the Lower Colton. Birgenheier et al. (2009) interpreted this to be the onset of the PETM, as it is within PETM values recorded by previous authors (Norris and Rohl, 1999; Kroon et al., 2007; White and Schiebout, 2008). This 2‰ shift happens in three stages. Units 1 through 3 display a pulsed decrease in $\delta^{13}C_{org}$, each Unit is characterized by a sharp drop in $\delta^{13}C_{org}$ values followed by a slight positive excursion (Birgenheier et al., 2009).

The Ichno-pedological Facies of Unit 4 include high-deposition entisols and high-deposition inceptisols, two types of soil that are relatively immature and display no distinct soil horizons. The ichno-fossil assemblage also shifts from being dominated by *Steinichnus, Scoyenia,* and adhesive menescate burrows to traces that indicate lower water-table levels such as *Maconopsis* and vertically trending Rhizoliths. This dichotomy of trace fossils indicates an extreme seasonal shift in the climate regime, such as in a monsoonal climate. This Unit is also shows a trend of decreasing *Camborygma* traces. This Unit is associated with the highest depositional rates in the system and is interpreted

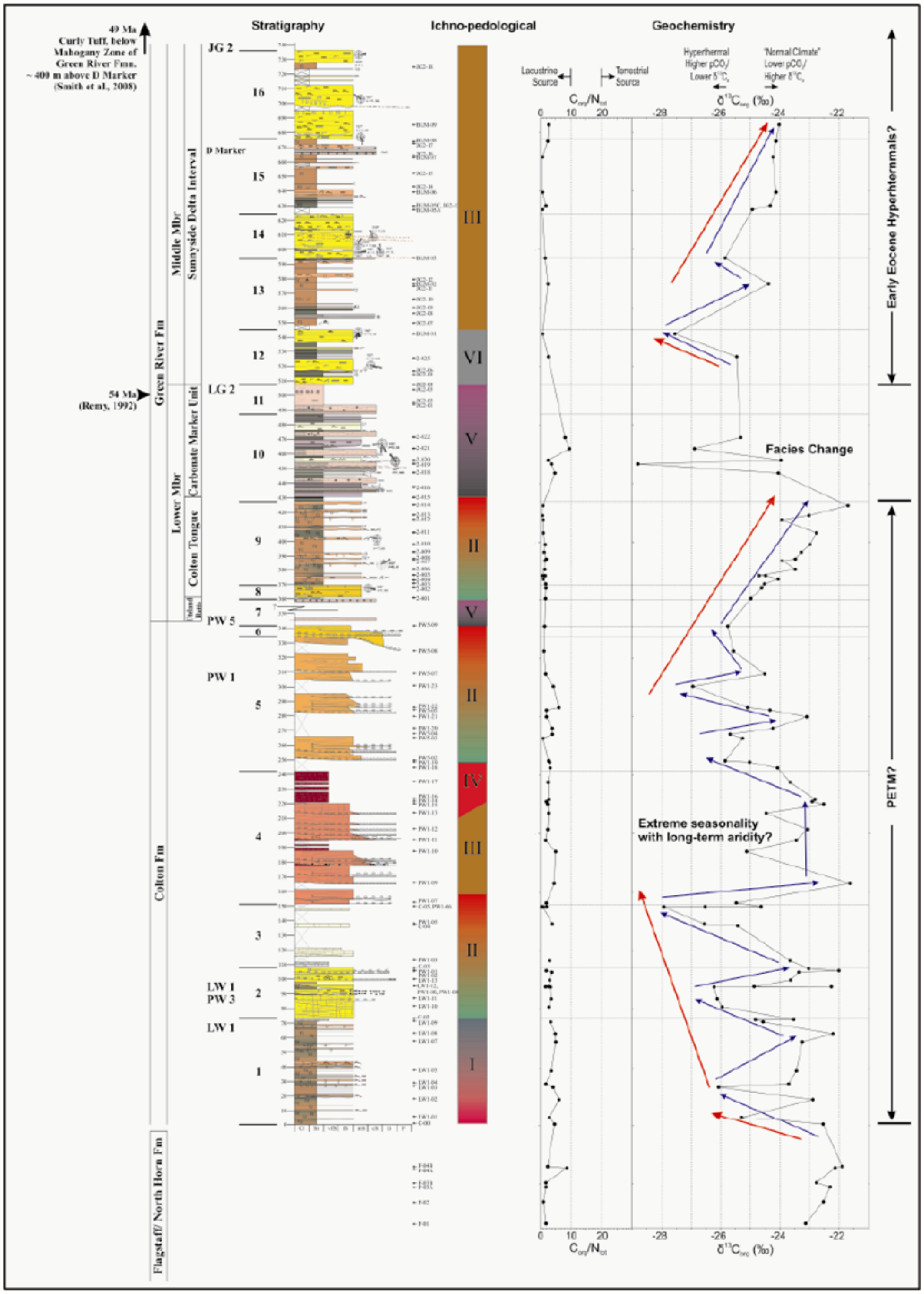
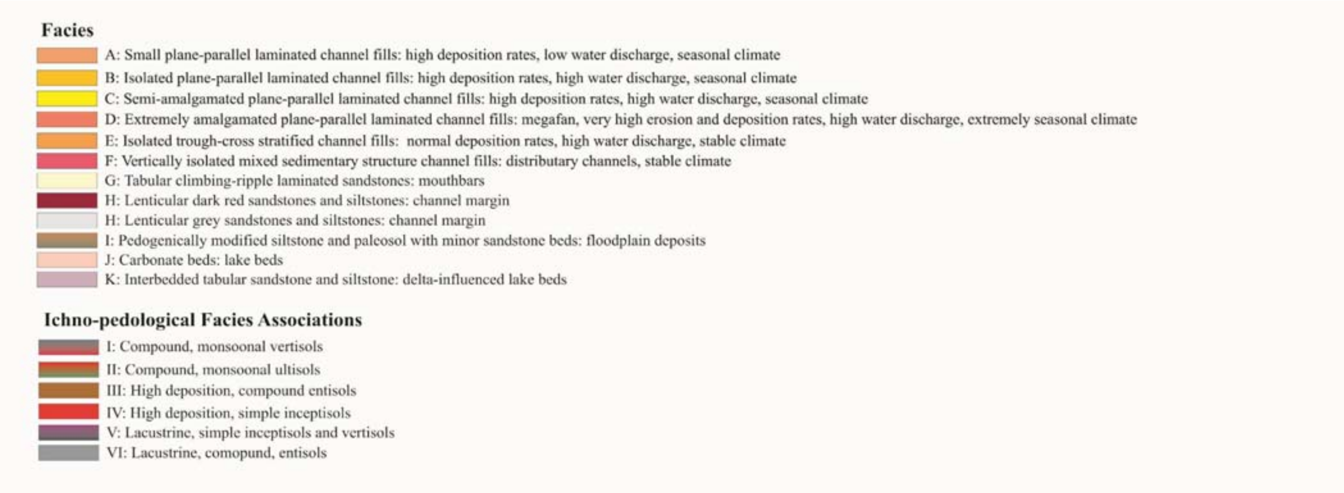


Figure 6.1.1a Stratigraphic column for the Colton and Lower-Middle Green River Fm. in the Uinta Basin, Utah. Diagram shows (from left to right) formation names, industrial formation names, informal stratigraphic units, sedimentary structures and architecture, sample numbers, ichno-pedological facies associations and stable carbon isotope analysis. Modified from Birgenheier et al. (2009), Plink-Björklund and Birgenheier (2009), and Plink-Björklund et al., (2010).



Facies

A: Small plane-parallel laminated channel fills: high deposition rates, low water discharge, seasonal climate
B: Isolated plane-parallel laminated channel fills: high deposition rates, high water discharge, seasonal climate
C: Semi-amalgamated plane-parallel laminated channel fills: high deposition rates, high water discharge, seasonal climate
D: Extremely amalgamated plane-parallel laminated channel fills: megafan, very high erosion and deposition rates, high water discharge, extremely seasonal climate
E: Isolated trough-cross stratified channel fills: normal deposition rates, high water discharge, stable climate
F: Vertically isolated mixed sedimentary structure channel fills: distributary channels, stable climate
G: Tabular climbing-ripple laminated sandstones: mouthbars
H: Lenticular dark red sandstones and siltstones: channel margin
H: Lenticular grey sandstones and siltstones: channel margin
I: Pedogenically modified siltstone and paleosol with minor sandstone beds: floodplain deposits
J: Carbonate beds: lake beds
K: Interbedded tabular sandstone and siltstone: delta-influenced lake beds

Ichno-pedological Facies Associations

I: Compound, monsoonal vertisols
II: Compound, monsoonal ultisols
III: High deposition, compound entisols
IV: High deposition, simple inceptisols
V: Lacustrine, simple inceptisols and vertisols
VI: Lacustrine, comopund, entisols

Figure 6.1.1b Key for interpretation of stratigraphic and ichno-pedological facies in Fig. 6.1.1a

to have been deposited by a fluvial megafan (Plink-Björklund and Birgenheier, 2009; Birgenheier et al., 2009; Plink-Björklund et al., 2010). Ichno-pedological analysis of this unit indicates the extremely high deposition rates of this system did not allow for a long residence time of sediment on the surface, preventing well-developed soils from forming. Unit 4 is characterized by a series of relatively high $\delta_{13}C_{org}$ values (Birgenheier et al., 2009; Plink-Björklund et al., 2010), which are interpreted to be the result of an arid, extremely seasonal climate and marks the pinnacle of the PETM (Meyers, 1997; Gröcke, 2002; Birgenheier et al., 2009).

Units 5 and 6 have paleosols similar to those found in Units 2 and 3, compound monsoonal ultisols. This indicates a return to conditions similar to before the PETM: a return of similar monsoonal climates and floodplain deposition. This is interpreted to be a climatic recovery from the PETM (Birgenheier et al., 2009; Plink-Björklund et al., 2010). These units, however; lack any *Camborygma* traces, indicating a severe drop in crayfish population following the pinnacle of the PETM.

This is in agreement with geochemical data, which shows a return to relatively negative values, beginning with an abrupt 3.5‰ drop in $\delta_{13}C_{org}$, and followed by two more negative pulses (Birgenheier et al., 2009). Carbon isotope values in this unit begin similar to those as seen in Units 2 and 3 and then begin a gradual positive excursion half way through Unit 5 and into Unit 6 (Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010).

The trend of gradually increasing $\delta_{13}C_{org}$ continues through units 7, 8, and 9. (Birgenheier, 2009). Overall, this is consistent with the ichno-pedological facies. Unit 7, as previously noted, does not outcrop well in the study area but is characterized by lacustrine sedimentation, indicating a possible rise in water table levels and a stabilization of the climate. Units 8 and 9 are dominated by compound, monsoonal oxisols, similar to Units 2 and 3. These sections also show an increase in water table levels during wet seasons as evidenced by horizontally trending Rhizoliths and shallow ant nests (see Chapter 5).

Unit 10, the carbonate maker unit, has highly variable $\delta_{13}C_{org}$ values (Birgenheier et al., 2009); this is attributed to the onset of lacustrine sedimentation. Paleosols here are simple, lacustrine inceptisols and were water-logged for most of the year. Many of these paleosols are dark black to gray in color, indicating that they are rich in organic matter. This inclusion of organic carbon is interpreted to be the cause of the carbon isotope variability (Birgenheier et al., 2009). This unit represents a period between the PETM and the posyt-PETM hyperthermals, during which time the climatic conditions were relatively stable (Birgenheier et al., 2009). Unit 11, the carbonate marker bed, has not yeilded carbon isotope values, but is interpreted to also be part of this period of relative climatic stability (Birgenheier et al., 2009).

The Sunnyside Delta member displays a return to high-deposition entisols and inceptisols similar to those found in Unit 4. Unit 12 contains various high water-table ichnofossils such as *Cochlichnus* and *Haplotichnus*, but these no longer appear in Unit 13. Units 13 through 16 are dominated by Rhizoliths, partially backfilled beetle burrows, and *Ancorichnus isp.,* indicating a drop in the water-table and a return back to extremely seasonal conditions.

Unit 12, the base of the Sunnyside Delta Member, contains an abrupt 2‰ decrease in $\delta_{13}C_{org}$ values near the top of the unit, followed by a slow recovery. This is interpreted to be a post-PETM hyperthermal event (Birgenheier et al., 2009). There is a second, 1.5‰ negative excursion of $\delta_{13}C_{org}$ values near the top of Unit 13, which is interpreted to be another post-PETM hyperthermal event (Birgenheier et al., 2009). Currently it is not possible to definitively name these hyperthermal events without further study (Birgenheier et al., 2009).

6.2 **Benefits of Using Ichnopedological Facies**

A complete understanding of the interaction of organisms and soil development in different depositional environments may prove useful to the study of geosciences as a whole, particularly paleoclimatic studies. Paleosols are formed during periods of non-deposition, exposing them to weathering processes from exposure to the atmosphere (Kraus, 1999; Smith et al., 2008a). Additionally, invertebrate species are particularly sensitive to changes in climate and have shown to have a great potential for the interpretation of soil development (Hasiotis, 2006; Ausich and Bottjer, 1982; Ekdale and Bromley, 1983; Bromley and Ekdale, 1986; Hasiotis and Brown, 1992; Taylor et al., 2003; Genise et al., 2004; Smith et al., 2008a). The use of ichno-pedological facies allows for an accurate assessment of paleo-hydrolic regimes and landscape changes (Jenny, 1941; Thorp, 1949; Hole, 1981; Retallack, 2001; Smith et al., 2008a).

Pedogenic features alone can be affected by tectonic activity (Kraus, 2002; Müller et al., 2004; Lawton and Buck, 2006). Directly, tectonism has the potential to alter local topography, affecting drainage patterns (Kraus, 2002; Lawton and Buck, 2006). Indirectly, tectonics can influence sediment supply, discharge and the mineralogy of the sediment transported to a local area (Kraus, 2002; Lawton and Buck, 2006). This affects residence time of the soil, as seen clearly in Unit 4. The intergration of ichnofossils into paleosol analysis allows features caused my tectonics and features caused by climate to be separated.

Previous studies on paleosols and ichno-pedogolical assemblages have focused exclusively on paleosols with little intergration of sedimentological and geochemical analysis (e.g. Hasiotis et al., 1993; Hasiotis and Dubiel, 1994; Kraus and Aslan, 1993; Kraus, 1996, 1999, 2002; Smith et al., 2008a, 2008b). This study takes a novel multidisciplinary approach to the study continental paleoclimate by combining these three disciplines.

The ichnopedological facies from the Colton and Lower-Middle Green River Fm. indicate well drained conditions over all, indicating little change in drainage patterns.

This indicates very little tectonic activity in the study area. The facies also show a change to drier moisture regimes during the pinnacle of the PETM and a subsequent recovery. This is consistent with sedimentological analysis (Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010). Ichno-pedological analysis has been shown in other studies to support sedimentological analysis (Kraus, 1999; Smith et al., 2008a), but also has the potential to provide new insight into climate change that would otherwise be missed.

6.3 **Implications of *Camborygma* trace distribution**

Crayfish impact soil development by redistributing mineral and organic matter along their burrows (Thorp, 1949; Hole, 1981; Hobbs and Whiteman, 1991; Smith et al., 2008a, 2008b). This increases the rate of pedogensis by aerating the soil, improving drainage, and allowing smaller organisms to burrow deeper into the sediment; crayfish burrows are also help create prismatic pedogenic textures (Richardson, 1983; Stone, 1993; Hobbs and Whiteman, 1991; Smith et al., 2008). Crayfish burrows increase the amount of oxidation of hematite and goethite (Bingham et al., 1978; Schwertmann and Taylor, 1989; Schwertmann, 1993; PiPujol and Buurmann, 1997). The vertical extent of crayfish burrows in an indicator of water table levels and proximity to permanent water bodies (Hobbs 1942, 1981; Jenny, 1941; Thorp, 1949; Hole, 1981; Retallack, 2001; Smith et al., 2008b).

This study shows that biogenic activity particularly that of crayfish communities was diminished by the extremely arid conditions brought on by the PETM and did not fully recover. The base of the section, Unit 1, displays widespread paleosols with a prismatic texture and a high density of crayfish burrows within the associated channel sandstones. There are no interpreted floodplain paleosols above Unit 1 that display a prismatic texture (see Chapter 5). This indicates increasing aridity and lower water tables which may have disallowed crayfish to live on the distal floodplain (Taylor, 1983; Smith et al., 2008b) and relegated them to proximal floodplain and within channels (Acosta and Perry, 2001; Smith et al., 2008b).

This is followed by a general trend upsection through the Colton Fm. of decreasing *Camborygma* traces in channel sandstone bodies, indicating increasing aridity and improved drainage (Hobbs 1942, 1981; Jenny, 1941; Thorp, 1949; Hole, 1981; Retallack, 2001; Smith et al., 2008b). There are very few *Camborygma* traces associated with Unit 4, the interpreted climax of the PETM (see Chapter 4: Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010).

Paleosols and channel bodies above the interpreted PETM interval show a return in similar alluvial deposition as before (Birgenheier et al., 2009; Plink-Björklund and Birgenheier, 2009; Plink-Björklund et al., 2010), but ichno-pedological analysis shows that biological communities did not recover as quickly through a decrease in the maturity of the soils upsection (see Chapter 5). Studies in the Willford Fm. in the Greater Green River Basin, Wyoming have shown that crayfish populations there were also dimished by the PETM (Smith et al., 2008b). This was also attributed to extremely arid conditions and improved soil drainage (Kraus, 1999; Smith et al., 2008b).

The PETM has been attributed to changes in biogenic activity in marine studies as well as continental. A large scale extinction of benthic formanifera, has been attributed to the extreme climatic changes brought forth by the PETM through carbon isotope records (Cramer et al., 2003; Nicolo, 2007). Therefore, it is not out of the realm of possibilities that the species of crayfish present before the PETM at the Nine Mile Canyon study area were unable to adapt to the changing climatic conditions in the area and were therefore displaced.

6.4 **Correlations with Modern Pedological Studies**

This study used the U.S. Department of Agriculture's Soil Taxonomy System for the classification of soil types (see Chapter 4). This choice was made to help bridge the gap between pedologists and geologists by incorporating pedologic terminology within a geologic study. This taxonomy system was chosen the other two main soil taxonomic systems (The Food and Agriculture Organization of the United Nations Soil Taxonomy Sytem and the Duchaufor, 1982 sytem) because it is the most familiar system in the United States and its classifications are familiar to both pedologists and many geologists. A system for the classifaction of paleosols by Mack et al. (1993) was also rejected because it was considered too broad-based for this study

There are, however, several difficulties when applying modern classes to paleosols. The largest of which is the lack of preservation of certain characteristics used in modern studies such as cation exchange, oxygen and nitrogen concentration, and pH (Kraus, 1999; Soil Survey Staff, 1999). In addition, the upper horizons of soil structures are not easily preserved in the geologic record (Kraus, 1999). Often paleosols are only remnants of the B horizon and lower of the soils that were forming on the paleo-landscape (Kraus, 1999; Smith et al., 2008a). Due to these difficulties it should be noted that the soil classes presented in this study should be considered interpretations of the most likely soils that were forming at the time of deposition rather than a direct interpretation..

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 **Conclusions**

Soil formation and bioturbation are intimately linked to one another and therefore both need to be carefully considered when attempting to interpret paleoclimatic changes through paleosols. Continental invertebrates are extremely sensitive to changes in soil moisture, CO_2 levels, oxygen levels, and pH (Hasiotis, 2007; Smith et al., 2008a); therefore, assemblages of ichnofossils in association with pedogenic features will indicate a restricted set of environmental conditions (Hasiotis, 2006; Ausich and Bottjer 1982; Ekdale and Bromley, 1983; Bromley and Ekdale, 1986; Hasiotis and Brown, 1992; Taylor et al., 2003; Genise et al., 2004) and when coupled with pedogenic analysis can be used as an independent measure of climate change . This study was performed in conjuction with geochemical and sedimentological studies. This integrated approach has provided a new understanding of the relationship between climate change and changes in alluvial deposition (Plink-Björklund, 2010) and shows promise for future continental paleoclimate studies

The paleosols of the Colton and Lower-Middle Green River Fm were deposited during the PETM and sub-sequent post-PETM hyperthermals, Geochemical and sedimentary records from the PETM indicate that these were periods of extreme changes in paleoclimate and paleohydrology, (Zachos, 2000; Bowen et al., 2006; Kroon et al., 2007), characterized by short-lived climatic warming events, wide-spread arid conditions which lead to drastic changes in the faunal record, including mass-extinction events (Thomas and Zachos, 2000; Bowen et al., 2006; Kroon et al., 2007; Smith et al., 2008a). Such climatic changes have the potential to be recorded in paleosols by in the form of pedogenic features and ichnofossil assemblages.

Soil morphology was described using the Soil Taxonomy system developed by the U.S. Department of Agriculture. There is no universal way of classifying paleosols, therefore, this scheme was used because of its widespread use and familiarity of the terminology with most geologists and soil scientists. Applying this scheme to the paleosols in the studied section, however, proved difficult because most of the criteria for classifying modern soil profiles are not preserved after burial, such as cation exchange capacity and amount of living organic material present (Kraus, 1999). The limitations of using soil classification for paleosols can be overcome by the integration of ichnofossil analysis with the paleosol morphology (Hasiotis, 2007; Ausich and Bottjer 1982; Ekdale and Bromley, 1983; Bromley and Ekdale, 1986; Hasiotis and Brown, 1992; Genise et al., 2004; Hasiotis, 2006; Taylor et al., 2003; Smith 2008a,b).

Eight ichno-pedological facies have been recognized in the Colton and Lower-Middle Green River Fm in Nine Mile Canyon, Utah. These can be grouped into six facies associations. Vertical stratigraphic changes in these facies associations reflect changes in soil drainage, annual temperature, and faunal populations during the PETM and possibily two sub-sequent hyperthermal events. These associations primarily reflect changes in climatic conditions, but also record some tectonic variations from within the section.

The predominance of paleosols with a compound stacking pattern within the floodplain paleosols of the section indicated that deposition was rapid, but episodic (Kraus, 1999). There is a lack of carbonate nodules throughout the section, but $CaCO_3$ is associated with rhizoliths, indicating that these soils were moderately to well drained, but could become waterlogged during avulsion events (PiPujol and Buurman, 1997; Kraus, 1999; Smith, 2008a). Most floodplain paleosols are interpreted to have developed during monsoonal flooding seasons because of the present clay content and pedogenic slickensides created by periodic wetting and drying of the soils (Yalon and Kalmar, 1978). This is in contrast to the ichno-pedological facies associated with the pinnacle of the PETM display little horizonation and a decreased abundance of ichnofossils, attributed to the extremely arid conditions present at the time (Meyers, 1997; Gröcke, 2002; Birgenheier et al., 2009).

Paleosols associated with lacustrine sedimentation are generally simple and dark black to gray in color, indicating that they are rich in organic matter. These are interspersed with purple blocky paleosols are interpreted to have been formed under water-logged conditions resulting in high amounts of oxidation (Smith et al., 2008a; 2008b) These are associated with supralittoral, waterlogged conditions. These variations occur in rapid succession, which is interpreted to be too quick for climatic changes

(Pietras et al., 2003). Instead these changes are attributed to high-frequency lake-level changes.

7.2 **Implications for Future Studies**

This study builds upon an existing body of studies involving paleosols (Kraus and Aslan, 1993; Kraus, 1996, 1999, 2002; Müller 2004; Lawton and Buck 2006; Kraus and Riggins, 2007; and references therein) and continental trace fossils (Fursich and Mayr, 1981; Bromley and Asgaard, 1991; Retallack and Feakes, 1987; Hasiotis, 1992, 1997, 2006; Hasistis and Bown, 1992; Hasiotis et al., 1993; and references therein), but the use of intergrated ichno-pedological analysis is a new field of study and has had little practical application to date (Hasiotis, 2007; Smith et al., 2008a). This study aims to add a working example of such an analysis to this small body of work. The use of ichno-pedological analysis has the potential to refine the understanding of soil formation and biological behavior in continental settings. It also poses to refine the knowledge of paleoclimate studies by introducing a paradigm shift from completely marine dominated studies to the use of both continental and marine records simultaneously.

A complete understanding of the interaction of organisms and soil development in different depositional environments may prove useful to the study of geosciences as a whole. This includes studies involving paleoclimate. The direct impacts include an improved understanding of river behavior during warmer, greenhouse-climate regimes.

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