Depositional History of the Chadron Formation in North Dakota

by

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Abstract

This report re-evaluates the depositional history, biostratigraphic “age,” and regional correlates of Chadron Formation rocks in North Dakota using a variety of data sources. A series of well-developed paleosols are herein recognized for the first time at the top of the Chalky Buttes Member across much of southwestern North Dakota. Those paleosols are contemporaneous with the Weta Paleosol Series of southern South Dakota developed on top of the Chamberlain Pass Formation, and together these paleosols indicate a period of nondeposition and geomorphic stability throughout the Great Plains region following a first phase of late Eocene deposition. Within the Williston Basin, that first phase of deposition begins with rocks dominated by group A heavy minerals (zircon > staurolite > aluminosilicates, tourmaline) that are overlain by rocks dominated by group B heavy minerals (epidote > garnet > zircon). Deposition of these group A and group B rocks would have occurred sometime in the early Chadronian (Ch1-Ch2: 36.9-35.8 Ma).

The second phase of late Eocene deposition in North Dakota consisted of local downcutting of stream channels that were infilled with rocks dominated by group D heavy minerals (hornblende > diopside > epidote). Two faunas are now known from these group D rocks: the late early Chadronian (Ch2: 36.6-35.8 Ma) Medicine Pole Hills local fauna, and the newly reported middle Chadronian (Ch3: 35.8-34.8 Ma) Stover Site local fauna (Adams County, North Dakota). This second phase of deposition occurred after the onset of paleosol development in North Dakota as indicated by the common presence of ferruginous aggregate grains within the opaque heavy minerals from the Stover Site sample that appear to be derived from erosion of paleosols developed on older Chalky Buttes Member rocks that contained group B heavy minerals. Deposition of group D rocks in North Dakota was contemporaneous with portions of those rocks infilling the base of the Red River Paleovalley in southern South Dakota (Ahearn and Crazy Johnson Members).

Deposition of the South Heart Member began gradually during the development of the paleosols within the Williston Basin, indicating those rocks are younger than the group A and group B rocks of the Chalky Buttes Member. Given the lack of biostratigraphic data from the South Heart Member and absence of those rocks within Bowman and Adams Counties where group D rocks of the Chalky Buttes Member are exposed, insufficient evidence is currently available to determine the relative timing of deposition of group D Chalky Buttes Member rocks and those of the South Heart Member. Overall, this study demonstrates that late Eocene deposition was more complicated than previously reported, though these patterns match those found elsewhere within the Great Plains region.

Acknowledgements

We wish to thank the many private landowners and public land management agencies that provided access to the outcrops examined in this study. Those include Daryl Anderson (Stover Site, Adams County, North Dakota), Harland Johnson (Whetstone Buttes, Adams County, North Dakota), James and Patricia Thomas (White Butte, Hettinger County, North Dakota), the Fitterer family (Fitterer Ranch, Stark County, North Dakota), Ben and Traci Simons (Haystack Butte, North Dakota), Sally Praus and Neil O'Brien (White Butte, Stark County, North Dakota), and the U.S. Forest Service for access to lands in southeastern Montana and northwestern South Dakota. We thank Dr. Allen Kihm for information regarding the Medicine Pole Hills local fauna, for assistance picking and identifying fossils from the Stover Site local fauna, and for overall discussions of late Eocene faunas and deposition within the Great Plains region over the years. The following individuals also assisted in the picking of microvertebrate fossils from the Stover Site local fauna: Jessica Appledorn, Trissa Ford, and Pat Monaco. Undergraduate students at Elmhurst College supervised by Dr. Merrilee Guenther also assisted in the picking and identification of fossils from the Stover Site local fauna. The following Minot State University undergraduate students worked on heavy mineral samples from the Chadron Formation within the Williston Basin that generated some of the new data presented in this study: Mia Bjornson; Allen Christensen; Ryan Curzon; Casey Gleich; Tyias Huck; Nurk Teleu; Matthew Todd; and, Paul Vogelsang. NDGS paleontologist Jeff Person assisted with the collection of field data at many of the sites discussed in this study and with identification of some of the fossils from the Stover Site local fauna. Drs. Bill Korth and Robert Emry provided data regarding the biostratigraphic age of the lower-most beds of the Brule Formation at Fitterer Ranch that assisted with interpretations of the nature of the Chadron-Brule contact. Finally, we thank Betty and James Stover for their discoveries of new Chadron Formation outcrops within Adams County, North Dakota, that provided significant new data that are presented in this study.

Introduction

The Chadron Formation is composed of fluvially deposited rocks that formed during the late Eocene following an extended period of nondeposition and erosion that can be traced across the central and northern Great Plains regions (Terry, 1998). Rocks referred to the Chadron Formation in North Dakota have received little direct study until relatively recently (e.g. Murphy et al., 1993; Hoganson et al., 1998; Webster et al., 2015: though see Leonard, 1922; Stone, 1973), with most older studies briefly addressing these rocks within the broader context of regional geology and/or evaluation of mineral resources (e.g. Douglass, 1909; Denson et al., 1959; Moore et al., 1959; Denson et al., 1965). Within North Dakota, the Chadron Formation is divided into two members, the lower Chalky Buttes Member and the upper South Heart Member, that are easily recognized even in areas of poor or limited outcrop (figure 1). The Chalky Buttes Member is typically composed of channel sandstones that are locally conglomeratic, with finer-grained mudstones and claystones present at the base in some areas (= the informal "Amidon Member" of Stone [1973]). The basal contact is unconformable, and these rocks lay upon rocks of varying age depending on the depth of local downcutting prior to deposition (figure 1). In most areas that contact is a disconformity, though basal channel lags are only locally present. In some places (e.g. Fitterer Ranch in Stark County) the contact is a slight angular unconformity, in that case between the Camels Butte Member of the Golden Valley Formation and the Chalky Buttes Member of the Chadron Formation. The Chalky Buttes Member is considered lithologically equivalent to the "dazzling white" channel sandstones of the Chadron Formation in the Slim Buttes (South Dakota) and other areas of northwestern South Dakota and southeastern Montana, and the Chamberlain Pass Formation of southern South Dakota, Nebraska, and Wyoming (Murphy et al., 1993; Hoganson et al., 1998; Terry, 1998).

The South Heart Member is typically composed of mudstones and claystones dominated by smectite clays and locally containing lenses of freshwater limestones or marlstones up to a few feet in thickness (Murphy et al., 1993). Surficial exposures tend to weather into rounded hills of low relief, displaying a characteristic 'popcorn' surface texture. Weathered surfaces also tend to drape down over underlying rocks of the Chalky Buttes Member, obscuring their presence and the exact position of that basal contact. The contact between the Chalky Buttes and South Heart Members is reported as conformable (e.g. Stone, 1973; Larsen, 1983; Murphy et al., 1993; Hoganson et al., 1998). In nearly all locations the South Heart Member sits atop at least a thin bed of the Chalky Buttes Member, with the most notable exception being at Sentinel Butte (Golden Valley County) where the South Heart Member sits directly on the Golden Valley Formation (Murphy et al., 1993: fig. 59). These rocks are considered lithologically equivalent to the "typical Chadron" portion of the Chadron Formation in the Slim Buttes (South Dakota) and other areas of northwestern South Dakota and southeastern Montana, and the Peanut Peak Member of the Chadron Formation in southern South Dakota, Nebraska, and Wyoming (Murphy et al., 1993; Hoganson et al., 1998; Terry, 1998). The South Heart Member is overlain by the Oligocene Brule Formation, and that contact within North Dakota is also traditionally considered to be conformable (e.g. Stone, 1973; Larsen, 1983; Murphy et al., 1993; Hoganson et al., 1998).

Many questions remain regarding these rocks within North Dakota resulting from the fact that they are typically unfossiliferous, tend to crop out over very small areas of aerial extent, display variable lithologies in different geographic areas, and typically lack distinct marker beds

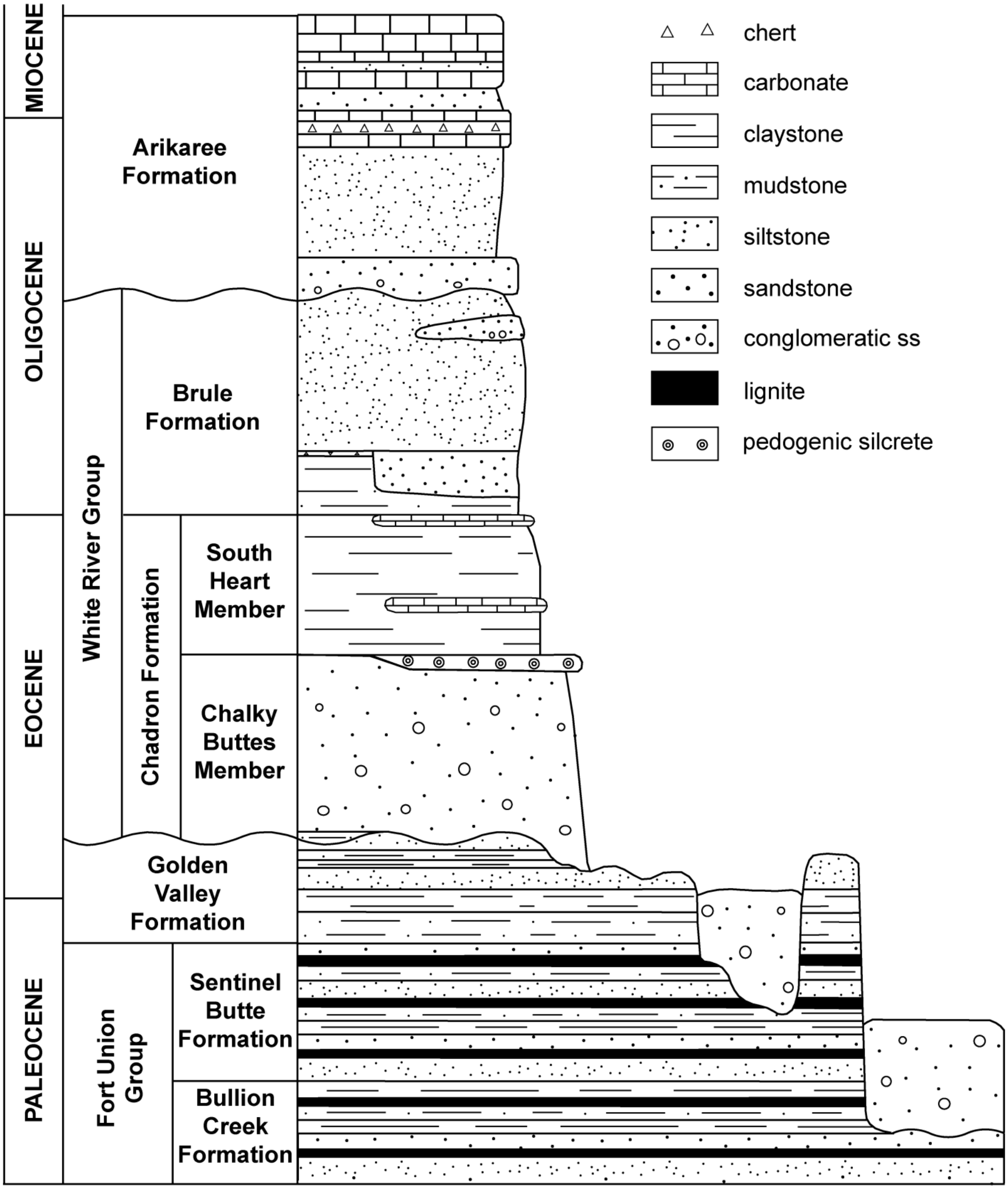

Figure 1. Updated North Dakota stratigraphic column of upper Paleocene through Miocene sediments. Modified from Webster et al. (2015:fig. 2). Isolated pockets of conglomeratic sandstone on the lower right-hand side of column represents localized channel downcuts infilled with Chalky Buttes Member conglomeratic sandstones in southern North Dakota. **Abbreviations**: **ss**, sandstone.

that can be used to correlate between widely separated outcrops. Those facts make these rocks difficult to study and place within broader regional contexts. For example, it remains uncertain whether the entirety of the Chalky Buttes Member represents a single period of deposition across southwestern North Dakota, or if there were diachronous episodes of localized downcutting and infilling of paleotopographic lows as occurred in other areas of the Great Plains region during this time. Additionally, the timing of late Eocene deposition in North Dakota relative to depositional events across Great Plains remains uncertain.

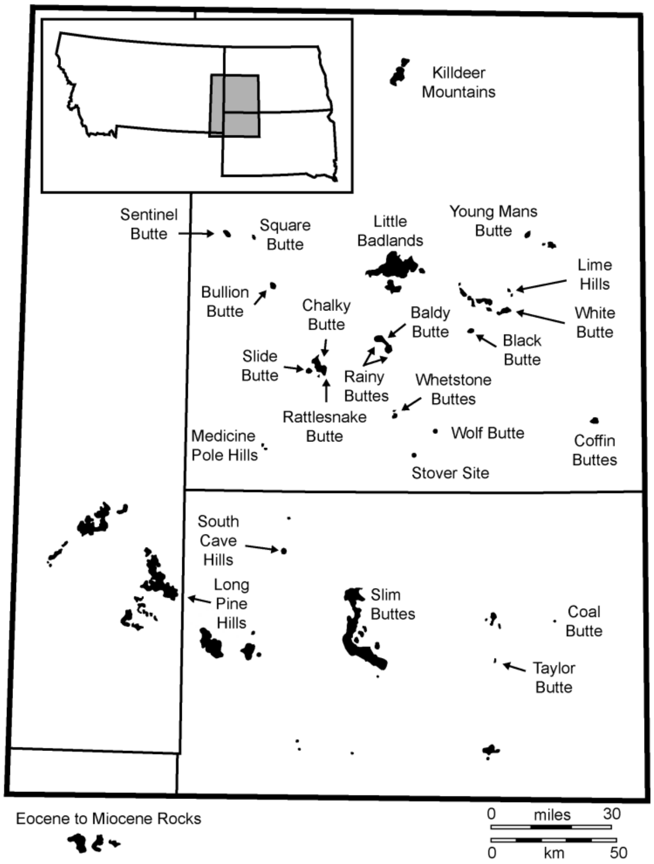

Figure 2. Map showing geographic locations within the Williston Basin region in Montana, North Dakota, and South Dakota that are discussed in this study.

In this report we present new data gathered from the study of paleosols (fossil soils), fossils, and heavy minerals from the Chadron Formation in North Dakota and lithologic equivalents within the Williston Basin areas of Montana and South Dakota (figure 2) that are relevant to addressing these questions and improves our overall knowledge of these rocks. While this study is not intended to be a comprehensive review of all aspects of the Chadron Formation in North Dakota, the data presented herein provide a more nuanced understanding of late Eocene deposition in this region of the Great Plains and informs potential research directions for future studies, both on the Chadron Formation and other geologic formations within North Dakota.

Institutional Abbreviations: F:AM, Frick Collection, American Museum of Natural History, New York, New York; MSU, Minot State University, Minot, North Dakota; NDGS, North Dakota State Fossil Collection, North Dakota Geological Survey, Bismarck, North Dakota; PTRM, Pioneer Trails Regional Museum, Bowman, North Dakota; USNM, United States National Museum, Washington, D.C.

Late Eocene Paleosols of North Dakota

Over half a century ago it was recognized that a distinct set of beds, originally termed the "silicified sandy bentonite" beds (Denson et al., 1965) and later the "silicified smectites" (sensu Murphy et al., 1993), are present at the contact between the Chalky Buttes and South Heart Members in the Chadron Formation of North Dakota. Those beds are traditionally placed within the South Heart Member (e.g. Stone, 1973; Murphy et al., 1993), though some have argued that they more properly belong in the Chalky Buttes Member (Larsen, 1983). While these beds are present across much of southwestern North Dakota where rocks of the Chadron Formation crop out (Denson et al., 1965; Stone, 1973; Murphy et al., 1993), they have received little detailed study of their composition and origin. Examination of these rocks at White and Haystack Buttes in the Little Badlands area of Stark County reveals that those beds are paleosols, or "fossil soils." Paleosols containing silicified horizons, or silcretes, are also present within the Chamberlain Pass Formation elsewhere in the Great Plains region, which is considered a lithostratigraphic equivalent of the Chalky Buttes Member (Murphy et al., 1993; Terry and Evans, 1994; Hoganson et al., 1998). Additional examination of the contact between the Chalky Buttes and South Heart Members within Stark County revealed that paleosols are present at that contact even in areas where prominent silcretes are absent, though the pedogenic features in these paleosols may vary substantially between locations.

The detailed work required to complete proper descriptions, identifications, and potential formal designation of new pedotypes based on these deposits was beyond the scope of this investigation. Specifically, geochemical and microscopic examination of these rocks needs to be conducted before these paleosols can be fully understood (e.g. Retallack, 1983, 2004; Retallack et al., 1999). However, the recognition of paleosols within a stratigraphic column can provide important information regarding the paleoenvironment during the time of formation, along with providing evidence of periods of time during which sedimentation was either greatly reduced or temporarily ceased. The contact between the Chalky Buttes and South Heart Members is traditionally considered to be conformable across North Dakota (Stone, 1973; Larsen, 1983; Murphy et al., 1993; Hoganson et al., 1998), but the presence of well-developed paleosols on the upper surface of the Chalky Buttes Member would conflict with that interpretation. For those reasons preliminary descriptions and discussions of paleosols at the contact between those two members in North Dakota are provided herein to aid in furthering our understanding of the deposition of the Chadron Formation.

In this study the descriptions of pedogenic features follows the terminology and definitions detailed by Retallack (1988, 1997, 2001). Identifications of soil horizons follows the guidelines proposed for modern soils by the Soil Survey Staff (1999), though differences specific to identifying those horizons in paleosols as proposed by Retallack (1988, 1997, 2001) were also utilized. A second system for describing and naming paleosols developed by Mack et al. (1993) was also utilized because that system was developed specifically for paleosols, avoiding some of the problems encountered with the classification system for modern soils that sometimes requires information that cannot be gleamed from paleosols (e.g. number of days per year the soil is wet). The term 'sesquioxide' is used to refer to the weathering products of iron- and aluminum-rich silicates that form via oxidation (e.g., goethite, hematite) and is a standard term used in describing paleosols (e.g., Retallack, 1998, 2001). Field measurements were recorded using a Jacob's staff and abney level. Rock coloration was evaluated using the standard Munsell rock color chart. Location data was recorded with a Trimble Geo 5T handheld GPS unit in the Universal Transverse Mercator coordinate system recorded using the World Geodetic Survey 1984 (WGS84) datum.

Paleosols at White and Haystack Buttes (Stark County)

At White Butte (T139N, R97W, Sections 31 and 32) and Haystack Butte (T139N, R97W, Section 29) in Stark County a thick series of resistant beds is present at the contact between the

Chalky Buttes and South Heart Members of the Chadron Formation. While noted by other researchers working in this area (e.g. Stone, 1973; Larsen, 1983; Murphy et al., 1993), their identity as a stacked set of successive paleosols was not reported. Portions of up to four paleosols are present in this area, though the complete series is not preserved at all sites, and there is variability in the characteristics of these paleosols across the region. Therefore, two measured sections of these paleosols are provided that display some of the observed variability. To simplify discussion, these paleosols are hereafter informally referred to as the White Butte paleosols and the name White Butte in this section refers to the above mentioned geographic feature in Stark County, North Dakota.

Description of Section 1

The first section (figures 3 and 4) was recorded along the northeast margin of an east-west trending gully on the northern edge of White Butte in section 32 (T139N, R97W: 13T, 656369mE, 5186763mN).

+125 in (318 cm); cover; claystone; yellowish gray (5Y7/2); weathering pale yellowish brown (10YR6/2) into rounded slopes that tend to drape over underlying units; generally massive beds of smectite clays; noncalcareous; diffuse wavy contact to

0 in (0 cm); A (paleosol 3); claystone; light olive gray (5Y5/2); weathering yellowish gray (5Y7/2); ortho-isotubules ranging from less than one up to 1/4 inch in diameter that are difficult to identify (same color as peds and argillans) without excavating fresh rock; very coarse to medium granular beds with very thin (1/16 inch or less) argillans of yellowish gray (5Y7/2); weakly indurated by silica cement (Retallack, 2001:table 12.1); occasional pebbles composed of highly resistant minerals (e.g. petrified wood, chert) between 3/8 and 3/4 inch in diameter on average; discontinuous thin layer of white (N9) siliceous mineral deposited along the contact between this horizon and the underlying horizon; noncalcareous; abrupt wavy contact to

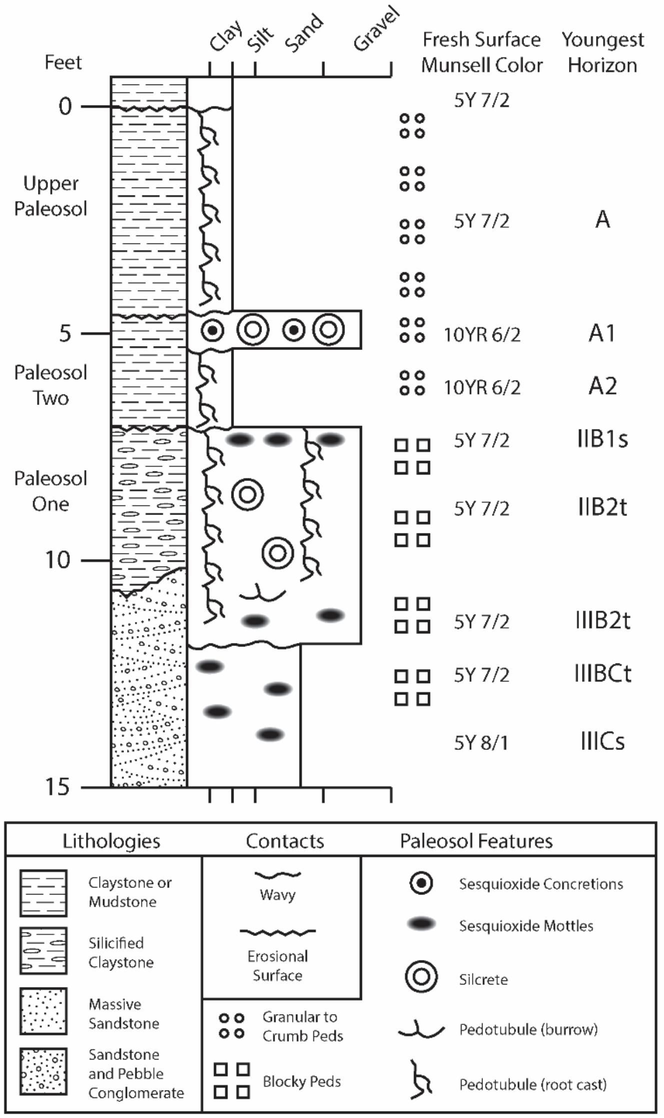

Figure 3. Diagram of White Butte paleosol at section one at White Butte (Stark County). Key to lithologic and pedogenic symbols provided at bottom.

-54 in (138 cm); A1 (paleosol 2): claystone and claystone breccia; pale yellowish brown (10YR6/2); weathering yellowish gray (5Y8/1); crumb (medium to very fine) and granular (very coarse to medium) peds surrounded by thin argillans; occasional rounded pebbles of petrified wood, siliceous rocks (e.g. chert), and siliceous relict soil clasts up to 3/4 inch in diameter; rounded sesquioxide concretions up to 5/16 inch in diameter sparsely distributed throughout horizon, either embedded within silicified peds (figure 5G) or eroded out as isolated pieces; apparently siliceous (nonreactive to dilute acid) para-isotubules (root casts) of white (N9) that are less than 1/16 inch thick (figure 5G: black arrows); strongly indurated with silica cement; noncalcareous; gradual wavy contact to

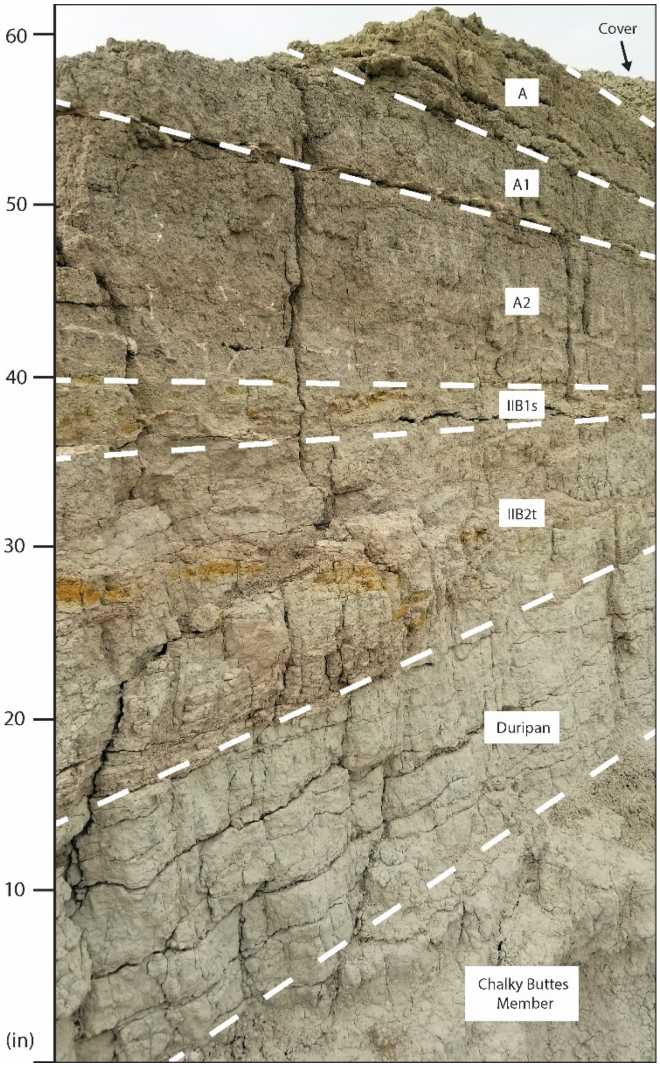

Figure 4. Photograph of a sheer vertical outcrop of the White Butte paleosol near section one. This section closely matches the horizons described at section one, but the duripan is still intact and the IIIBCt horizon is absent. These paleosols are also thinner at this site than at section one. Photograph is taken at an angle, so the right margin of the image is farther away than the left margin.

-62 in (159 cm); A2 (paleosol 2): claystone; pale yellowish brown (10YR6/2); weathering yellowish gray (5Y7/2); abundant para-isotubules infilled with a white (N9), apparently siliceous (nonreactive to dilute acid) mineral that range from less than 1/16 inch to 1/4 inch in diameter (figure 5F); very coarse to medium granular peds typically surrounded by argillans of similar minerology and color; discontinuous silans of white (N9) siliceous minerals (similar to that forming the para-isotubules) locally surround peds (figure 6B); weakly indurated by silica cement; noncalcareous; clear wavy contact to

-84 in (215 cm); IIB1s (paleosol 2) and A (paleosol 1): silicified claystone; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); many diffuse, prominent, coarse mottles of pale yellowish orange (10YR8/6) and dark yellowish orange (10YR6/6); in some areas thin silans of a white (N9), siliceous mineral surround very thick to medium platy peds, while in other areas the very coarse to medium angular blocky peds surrounded by argillans typical of the underlying layer extend into this horizon (figure 7D); noncalcareous; gradual wavy contact to

-86 in (220 cm); IIB2t (paleosol 2) and A (paleosol 1): silicified claystone; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); very coarse to coarse peds surrounded by argillans that range in thickness from 1/8 inch to up to 1 1/2 inches (figure 7B); common, thin silans and a few slickensides present within cutans; surfaces between peds are parallel in some areas and mimic wedge or lentil peds, but this feature may be a result of fracturing of the previously silicified claystone of the parent rock (see below); occasional para-isotubules present that remain within the cutans and do not penetrate the peds; few very diffuse, distinct, coarse mottles present (figure 6C), often concentrated in discontinuous horizontal bands; parent rock (composed of an older paleosol) contains vertically oriented para-isotubules (likely root casts) and ortho-isotubules (likely burrows) within the peds that are often cut by the cutans (figures 5A and 5B); noncalcareous; abrupt wavy contact to

-127 in (323 cm); IIIB2t (paleosol 2) and IIA (paleosol 1): silicified sandstone and pebble conglomerate; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); vertically oriented para-isotubules (likely root casts) and ortho-granotubules (apparent burrows) averaging 3/4 inch in diameter (figure 5B); very coarse to coarse angular blocky peds that are most often wider than tall (but not enough to be considered platy) surrounded by thin argillans (1/8 inch wide) of pale yellowish brown (10YR6/2); a few, very diffuse, distinct, coarse mottles of sesquioxides; noncalcareous; diffuse wavy contact to

-140 in (357 cm); IIIBCt (paleosol 2) and IICs (paleosol 1): sandstone and pebble conglomerate; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); very coarse angular blocky peds that are well-developed in some portions, while adjacent areas consist of slightly modified parent rock that lacks peds (figure 7A); cementation (unknown cement, possibly silica) of parent rock sandstone typically concentrated along outer margins of peds; differential weathering of the central, uncemented portions of peds, creating a ‘honeycomb’ pattern on weathered surfaces (figures 7A and 7C); a few, very diffuse, prominent, coarse mottles of sesquioxides; in some places sesquioxide concentrations are high enough that they are encrusted along the margins of peds; noncalcareous; diffuse irregular contact to

-156 in (398 cm); IIICs (paleosol 1 and possibly 2): sandstone and pebble conglomerate; yellowish gray (5Y8/1); weathering very light gray (N8); friable; concentration of sesquioxides into a discontinuous horizon that consists of many diffuse, prominent, coarse mottles; noncalcareous; gradual wavy contact to

-163 in (415 cm); IIIR: sandstone and pebble conglomerate; yellowish gray (5Y8/1); weathering to very light gray (N8); friable; noncalcareous.

Description of Section 2

This section (figures 8 and 9) is located approximately 175 feet northeast of section 1 on the west face of an outcrop that extends north off of the main portion of White Butte (T139N, R97W, Section 32: 13T, 656411mE, 5186796mN). At this location the overall set of paleosols is thicker (20 feet 5 inches [6.24 m] versus 13 feet 7 inches [4.15 m]) and paleosol four is present.

+106 in (271 cm); cover; claystone; yellowish gray (5Y7/2); weathering pale yellowish brown (10YR6/2) into rounded slopes that tend to drape over underlying units; generally massive beds of smectite clays; noncalcareous; diffuse wavy contact to

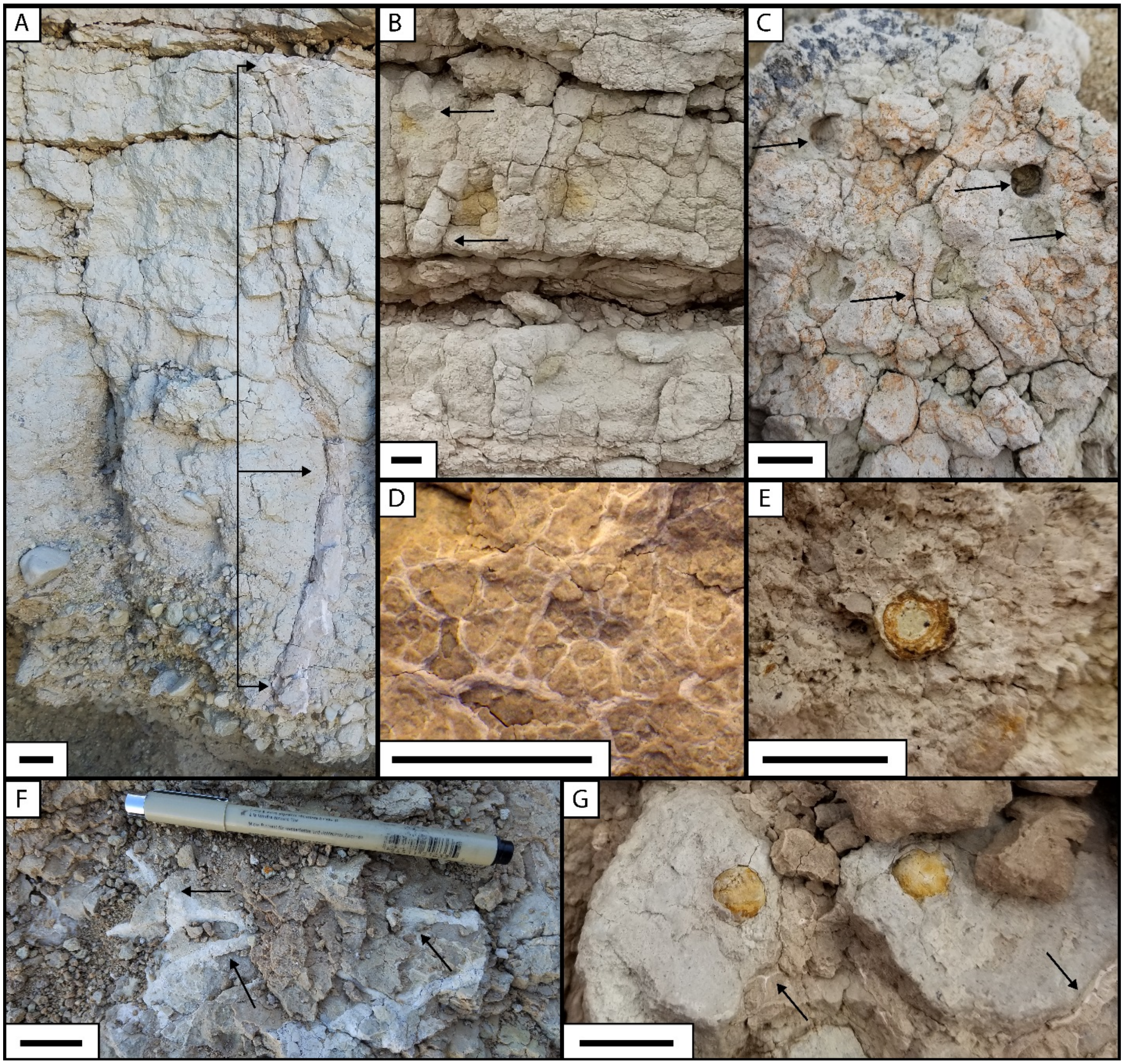

Figure 5. Pedogenic features in the White Butte paleosols. **A**. large, vertically-oriented pedotubule (black arrows: silicified root trace) in the base of the lower-most silcrete that is truncated at the top by one of the cutans formed in the Bt horizon of paleosol two (note conglomeratic sandstone forming bottom portion of silcrete). **B**. pedotubules (black arrows: likely burrows) within the silicified sandstone at the base of the lower-most silcrete. **C**. looking down on the upper surface of the A1 horizon of paleosol three showing the densely packed pedotubules (black arrows: likely burrows) present in much of that horizon. **D**. fine, 'hair-like' pedotubules (silicified root traces) developed in the A2 horizon of paleosol two. **E**. sesquioxide concretion within the base of the A1 horizon of paleosol four. **F**. larger, horizontally-oriented pedotutules (silicified root traces) in the A2 horizon of paleosol two. **G**. sesquioxide concretions within the silcrete peds of the A1 horizon of paleosol two, and well developed argillans from the overprinted Bt horizon from paleosol three containing fine pedotubules (black arrows: silicified root traces) that do not penetrate the peds. Scale bars equal 1/2 inch.

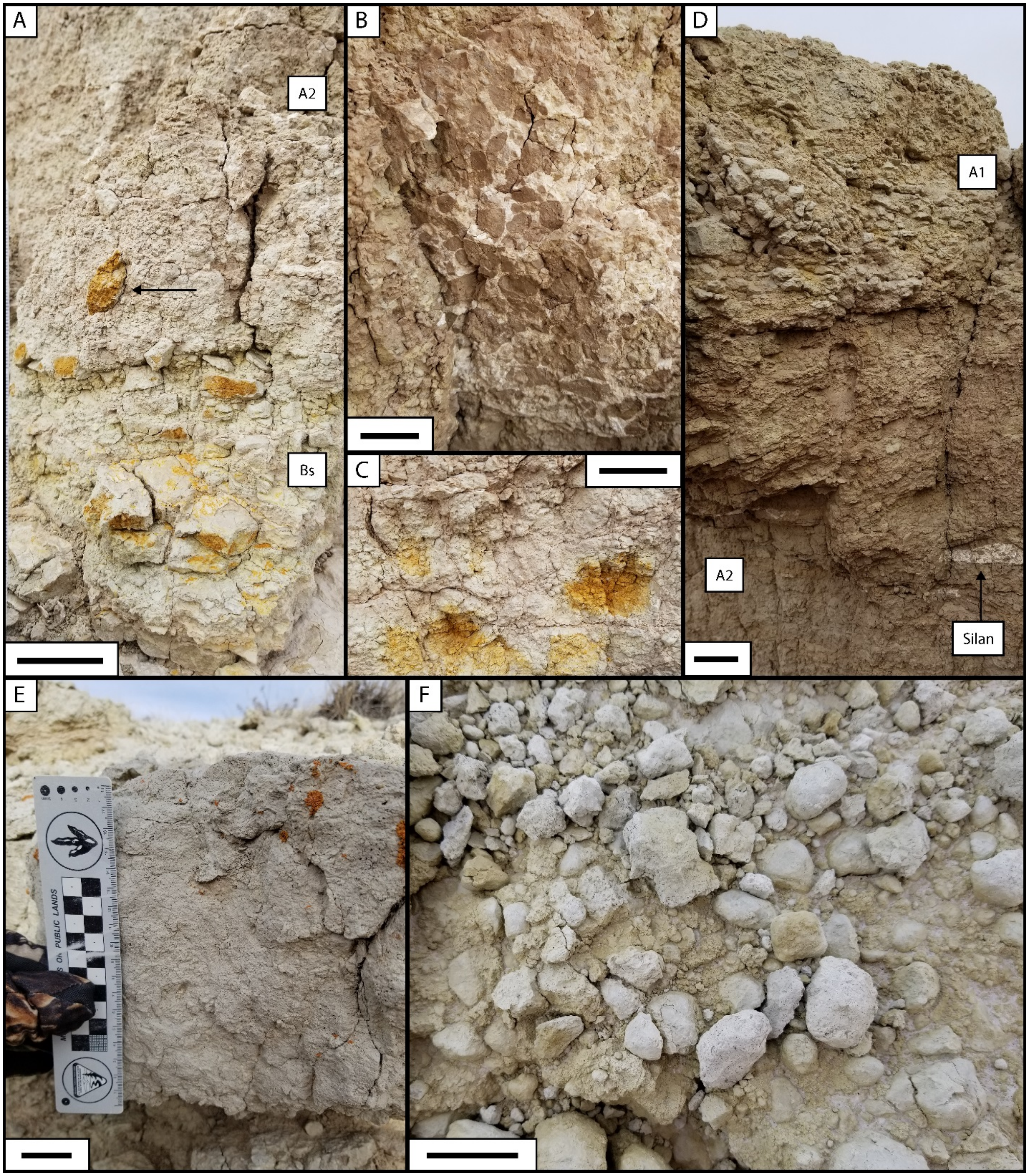

Figure 6. A horizons within the White Butte paleosols. **A**. rip-up clast (black arrow) from the upper surface of the lower-most silcrete incorporated into the A2 horizon of paleosol two. **B**. granular peds (brown) surrounded by silans (white) within the A2 horizon of paleosol two. **C**. coarse sesquioxide mottles the A horizon of paleosol one. **D**. A1 and A2 horizons of paleosol two showing the highly fractured nature of the A1 horizon (silcrete) resulting from the development of a Bt horizon in the overlying paleosol three. **E**. A1 horizon of paleosol three displaying the massive, blocky texture. **F**. coarse, granular peds of silcrete in the upper-most portion of the A1 horizon of paleosol four. Scale bars equal 1 inch.

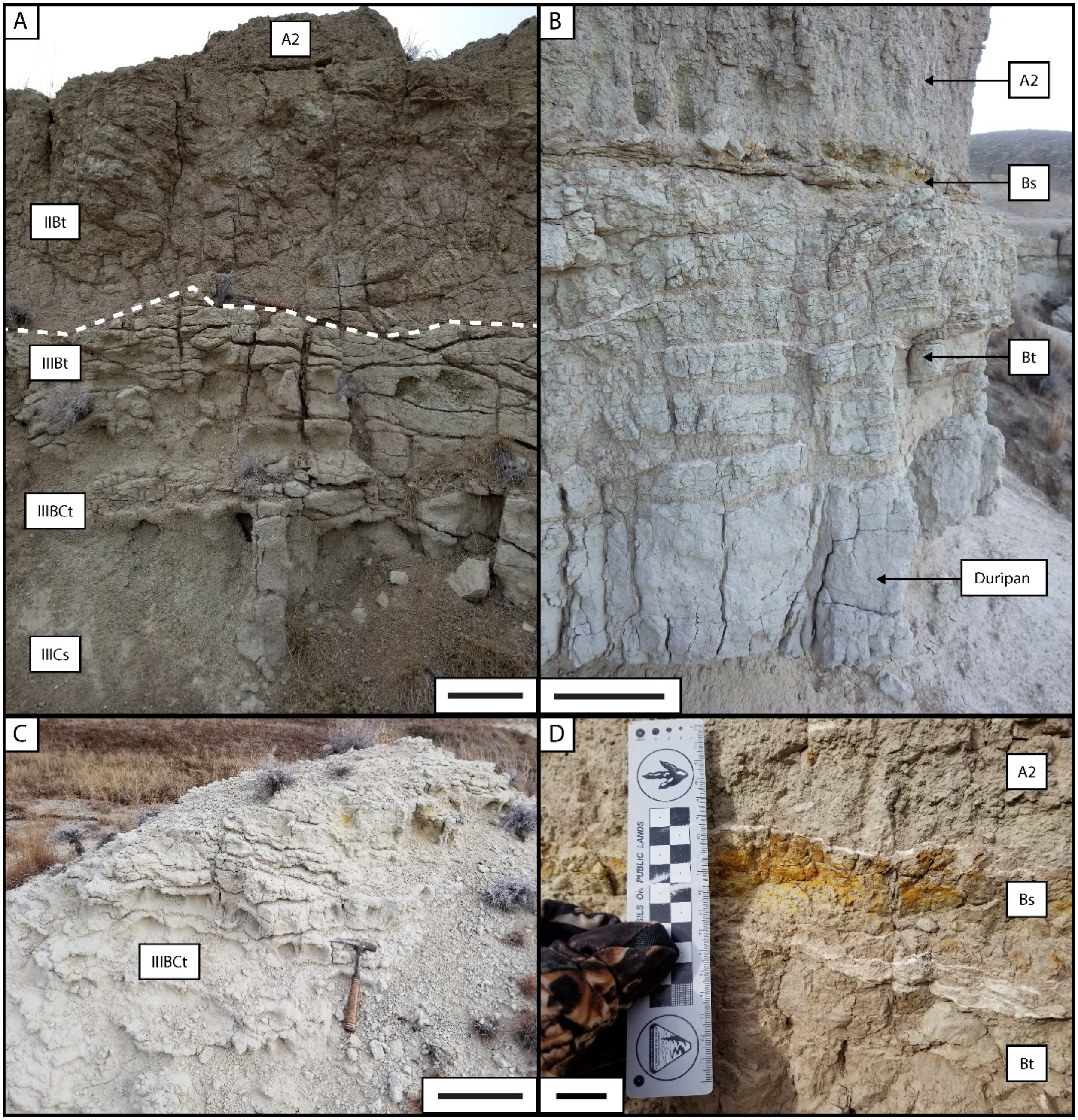

Figure 7. B horizons within the White Butte paleosols. **A**. lower portion of the White Butte paleosols showing the irregular development of the IIIBCt horizon in the underlying Chalky Buttes Member sandstones and the uneven upper surface of the Chalky Buttes Member sandstones (white dashed line) within the lower-most silcrete. **B**. development of the Bt horizon in the upper portion of the lower-most silcrete, but not extending into the underlying sandstone (compare to A). **C**. isolated outcrop of the IIIBCt horizon below the lower-most silcrete displaying the characteristic 'honeycomb' erosion pattern. **D**. well-developed portion of the Bs horizon of paleosol two, with a few thin silans (white bands) present below the granular peds of the A2 horizon. Scale bar in D equals 1 inch and all others equal 1 foot.

0 in (0 cm); A1 (paleosol 4); claystone; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); strongly indurated with silica cement and more resistant than underlying horizon, creating a prominent ledge; very coarse to medium subangular blocky peds surrounded by argillans ranging from 1/8 inch thick up to 3/8 inch thick; sesquioxide concretions present up to 1/4 inch in diameter, tending to be concentrated in the lower portion (figure 5E); noncalcareous; abrupt wavy contact to

-30 in (77 cm); A2 (paleosol 4); claystone; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); weakly indurated with silica cement, creating a slope with little exposure of in situ rock; mix of granular (coarse to fine) and crumb (medium to fine) peds surrounded by curtans of similar color (unsure if clay, mineral, or a mix), making it difficult to identify isolated peds except on weathered surfaces or by microscopic examination; sparse fruit endocarps (*Celtis* sp.) present; no pedotubules noted; noncalcareous; abrupt wavy contact to

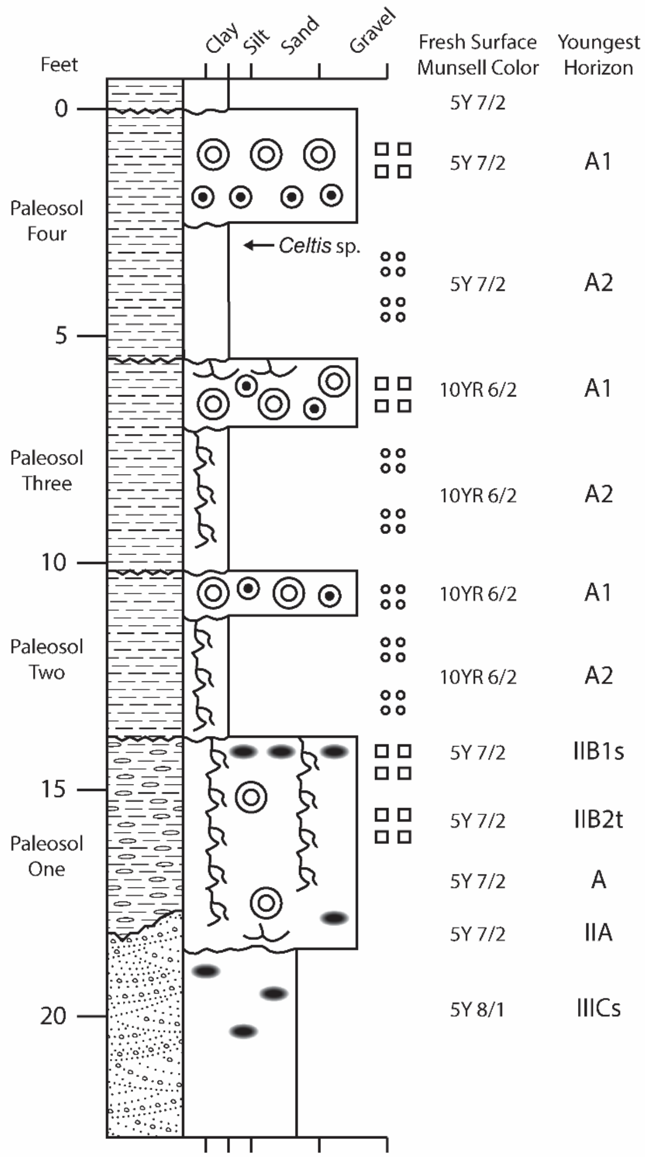

Figure 8. Diagram of White Butte paleosol at section two at White Butte (Stark County). See key to lithologic and pedogenic features in figure 3.

-65 in (165 cm); A1 (paleosol 3) and Bt (paleosol 4); claystone; pale yellowish brown (10YR6/2); weathering yellowish gray (5Y8/1); heavily bioturbated interval, with numerous ortho-isotubules up to 9/16 inch in diameter (figure 5C); strongly indurated with silica cement and more resistant than underlying horizon, creating a prominent ledge; horizon appears to have originally lacked peds (figure 6E), but was subsequently part of the Bt horizon for the overlying paleosol and was divided into coarse to very coarse, angular blocky peds with thin argillans (5Y8/1); scattered sesquioxide concretions (up to 1/8 inch in diameter) present within the peds, seeming to predate the development of the Bt horizon; noncalcareous; clear wavy contact to

-82 in (210 cm); A2 (paleosol 3) and Bt (paleosol 4); claystone; light yellowish brown (10YR6/2); weathering yellowish gray (5Y8/1); weakly indurated with silica cement, creating a slope with little exposure of in situ rock; dense networks of para-isotubules (apparent root casts) less than 1/16 inch in diameter and occasional ortho-isotubules averaging 1/4 inch in diameter; very coarse to medium granular peds with very thin (1/16 inch or less) argillans of yellowish gray (5Y8/1); appears to also form a Bt horizon for the overlying paleosol because packages of the smaller granular peds are joined together (silicified?) into coarse to very coarse angular blocky peds coated with thin argillans that are distinct from those surrounding the granular peds; noncalcareous; abrupt wavy contact to

-119 in (303 cm); A1 (paleosol 2): claystone and claystone breccia; pale yellowish brown (10YR6/2); weathering yellowish gray (5Y8/1); strongly indurated with silica cement and more resistant than underlying horizon, creating a prominent ledge; crumb (medium to very fine) and granular (very coarse to medium) peds surrounded by thin argillans; rounded sesquioxide concretions up to 5/16 inch in diameter sparsely distributed throughout horizon, either embedded within peds or eroded out as isolated pieces; noncalcareous; gradual wavy contact to

-131 in (333 cm); A2 (paleosol 2): claystone; pale yellowish brown (10YR6/2); weathering yellowish gray (5Y7/2); weakly indurated with silica cement; abundant para-isotubules of white (N9) siliceous (nonreactive to dilute acid) mineral that range from less than 1/16 inch up to 1/4 inch in diameter; very coarse to medium granular peds typically surrounded by argillans of similar minerology and color; noncalcareous; clear wavy contact to

-164 in (418 cm); IIB1s (paleosol 2) and A (paleosol 1): silicified claystone; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); many diffuse, distinct, coarse mottles of pale yellowish orange (10YR8/6); in some areas thin silans of a white (N9), siliceous mineral surround very thick to medium platy peds, while in other areas the very coarse to medium angular blocky peds surrounded by argillans typical of the underlying layer extend into this horizon; noncalcareous; gradual wavy contact to

-167 in (426 cm); IIB2t (paleosol 2) and A (paleosol 1): silicified claystone; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); very coarse to coarse peds surrounded by argillans that range in size from a 1/8 inch to up to 1 3/16 inch, with the thickest argillans tending to be horizontally oriented, making many of the peds wider than tall (but not enough to meet the classification as platy peds); occasional, thin silans present, more commonly within the upper portion of the horizon; occasional para-isotubules up to

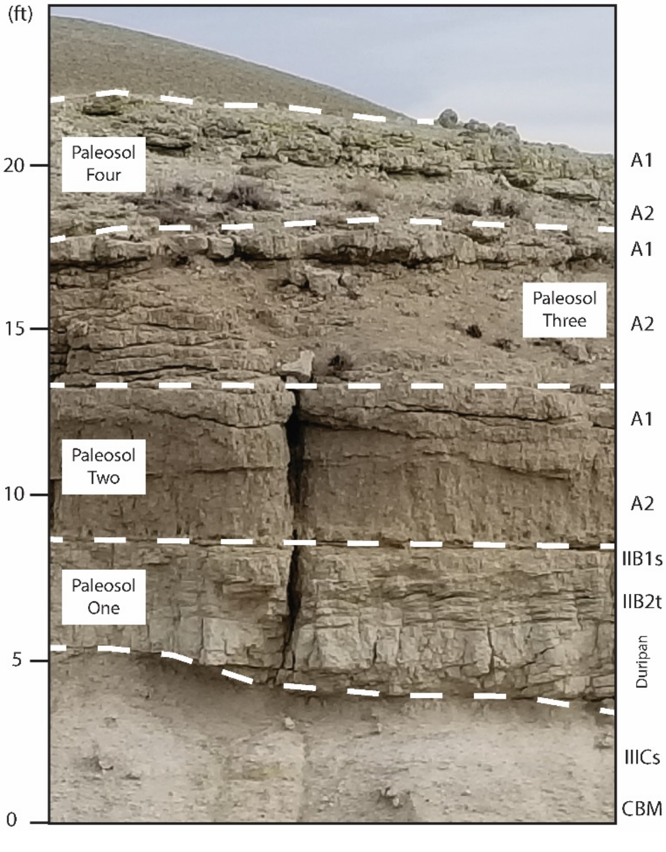

Figure 9. Photograph of the White Butte paleosol at the site of section two at White Butte (Stark County).

1/8 inch in diameter present that remain within the cutans and do not penetrate the peds; few very diffuse, distinct, coarse mottles present, often concentrated in discontinuous horizontal bands within the upper and lower portions of the horizon; parent rock (composed of an older paleosol) contains vertically oriented para-isotubules (likely root casts) and ortho-isotubules (likely burrows) within the peds that are often cut by the cutans; noncalcareous; abrupt wavy contact to

-191 in (486 cm); IIR (paleosol 2) and A (paleosol 1): silicified claystone; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); strongly indurated with silica cement; pedotubules in the overlying horizon remain within the argillans and do not penetrate into this horizon; vertically oriented ortho-granotubules (apparent burrows) averaging 3/8 inch in diameter and ortho-isotubules (apparent root casts) averaging 3/16 inch in diameter and over seven inches long are present, both of which were formed prior to silicification of rock; noncalcareous; clear wavy contact to

-208 in (529 cm); IIA (paleosol 1): silicified sandstone and pebble conglomerate; yellowish gray (5Y7/2); weathering yellowish gray (5Y8/1); strongly indurated with silica cement; composed of the upper-most portion of the underlying channel sandstone facies that was incorporated into this first silcrete; base of unit forms a prominent ledge overhanging less resistant underlying unit; ortho-granotubules (likely burrows) present that formed prior to silicification; noncalcareous; abrupt wavy contact to

-217 in (553 cm); IIICs (paleosol 1); sandstone and pebble conglomerate; yellowish gray (5Y8/1); friable; weathering to very light gray (N8); a few very diffuse, distinct, coarse mottles of sesquioxides; noncalcareous; diffuse wavy contact to

-245 in (624 cm); IIIR: sandstone and pebble conglomerate; yellowish gray (5Y8/1); weathering to very light gray (N8); friable; noncalcareous.

History of Paleosol Development

A maximum of four sets of paleosols are noted at White Butte in this study (figures 8 and 9), with the development of each successive paleosol resulting in the alteration of some features of the underlying paleosol, making it difficult to determine precisely when some of the pedogenic features first formed. The following interpretative discussion is provided to attempt to resolve this issue.

The first paleosol consists of the thick, heavily indurated silcrete present at the base of these beds (figure 7B) and an underlying Bs horizon. That silcrete incorporates two lithologies: an upper claystone portion and a lower sand/pebble conglomerate portion. The latter part is derived from incorporation of the upper-most portion of the underlying channel sandstone facies of the Chalky Buttes Member, while the former part indicates the deposition of clays in this area prior to the development of this paleosol. Both portions show evidence of bioturbation in terms of root casts (largely vertically oriented: figure 5A) and infilled burrows (averaging 3/8 inch in diameter: figure 5B) prior to silicification. The contact between these two lithologies undulates locally (figure 7A: white dotted line), indicating some degree of erosion of the upper surface of the channel sandstone facies prior to deposition of the clay facies. That interpretation is also supported by the fact that the burrows present in the sandstone portion are infilled with the same sandstone, rather than with rock from the overlying clay. Additionally, at least some of the sesquioxide accumulation (Bs horizon) in the upper portion of the underlying Chalky Buttes Member sandstones likely occurred prior to silicification of the overlying rocks because illuvial sesquioxide development is present in areas where this lower silcrete remained intact during the formation of subsequent paleosols (see description of section two above).

The second paleosol developed within a clay-dominated parent material that accumulated above the first silcrete. These clays preserve dense networks of pedotubules that are often preserved as silicified casts (figure 5F), including intricate networks of very fine, ‘hair-like’ root casts (figure 5D). Just below the A horizon there is an accumulation of sesquioxides within the upper few inches of the underlying silcrete (figure 7D), which either indicates illuvial deposition of sesquioxides in this horizon or could indicate a period of erosion and surface exposure prior to deposition of the overlying A horizon clays. The latter hypothesis is supported by the presence of small (3/8 inch to 3/4 inch) clasts of sesquioxides stained silcrete within the lower-most portion of the A horizon clays (figure 6A: black arrow). The underlying silcrete was clearly present when this second paleosol was forming, serving as a duripan. Repetitive wet/dry cycles in this soil over time fractured the underlying silcrete, and at least the upper portion in all areas observed developed into a Bt horizon where clays from the overlying A horizon were translocated down into the fractures formed within the silcrete (figure 7B). The formation of the silcrete prior to the development of this Bt horizon is inferred because the peds are more highly silicified than the surrounding argillans and that pedotubules are restricted to the argillans and do not penetrate the peds. In some areas (section one above) development of the Bt horizon extended all the way through the silcrete and into the underlying sands and pebble conglomerates of the Chalky Buttes Member. In those areas, the peds formed in the noncemented sands are less resistant than the cutans that appear to be at least partially cemented by sesquioxides and possibly some silica. As a result, erosion of those rocks results in a ‘honeycomb’ pattern on the external surface of the rocks as the peds erode, leaving behind the more resistant framework of the cutans (figures 7A and 7C). In areas where the silcrete duripan remains intact, the underlying Chalky Buttes Member rocks display only light sesquioxide staining and no trace of the development of a Bt horizon. From that evidence it is inferred that there was no Bt horizon associated with the first paleosol.

The upper-most portion of the A horizon of the second paleosol (A1 horizon) is well indurated by silica, forming a second silcrete horizon and associated resistant ledge in the weathering profile (figure 6D). The original composition of that portion of the A horizon differs from the underlying clay-dominated portion (A2 horizon) in that there are granular and crumb peds intermixed with pebbles composed of highly resistant minerologies (e.g. chert, petrified wood), as well as pebble-sized pieces of silcretes of a different color than the entombing matrix, suggesting they are reworked pieces of previously developed paleosols. Small sesquioxide concretions are present, often incorporated within silcrete fragments (figure 5E). Thus, it appears that this upper horizon was likely a stable surface for an extended period, allowing pebbles to accumulate and weather on the upper surface for long enough that they are all well rounded and only the most erosion resistant minerologies remained. Those pebbles were then mixed into the soil surface prior to or during silicification of this horizon.

The third paleosol at section two is generally similar to the second paleosol in many aspects, though there are some important differences. The upper-most horizon (A1) of the third paleosol is again a ledge-forming silcrete, but unlike in the A1 horizon of the second paleosol, this horizon was heavily bioturbated (figure 5C), includes smaller sesquioxide concretions, and lacks the pebbles of chert, petrified wood, and silcrete. Horizon A2 of the third paleosol is similar to the A2 horizon of the second paleosol, except that the pedotubules are infilled with the same clay that forms the granular peds that dominate the horizon, making them very difficult to differentiate except on fresh surfaces. This may indicate that these pedotubules were infilled prior to the silicification of the A1 horizon. Alternatively, the pedotubules in horizon A2 of the third paleosol may be burrows, while those of horizon A2 in the second paleosol may be root casts that were filled with organic material that was eventually lost and replaced by silica. The A1 horizon of the second paleosol may have acted as a duripan during the development of the third paleosol; however, there is some evidence that the A1 and A2 horizons of the second paleosol were developed into a Bt horizon during formation of the third paleosol. Evidence supporting the presence of a Bt horizon includes the development of angular blocky beds with thin argillans overprinted over the primary pedogenic features in those horizons (figure 5G). If a Bt horizon is present, it is much less well-developed (in terms of horizon depth and thickness of cutans) than the Bt horizon of the second paleosol. This difference may reflect a shorter period of formation prior to silicification of the A1 horizon of paleosol three.

The fourth paleosol is another slightly modified repetition of the general overall structure of the previous two paleosols. The A1 horizon more closely resembles the A1 horizon of paleosol two, consisting of small granular and crumb peds (absent in the A1 horizon of the third paleosol) intermixed with what appear to be rounded pieces eroded from other silcretes (figure 6F). Sesquioxide concretions are also locally present (figure 5E), typically within the lower portions of the horizon. The underlying A2 horizon is poorly exposed in section two, but where observable it is a clay-rich layer composed of granular and crumb peds with no observable pedotubules, though more detailed examination may be needed to confirm this observation as the pedotubules in the A2 horizon of the third paleosol were difficult to identify unless sufficient areas of fresh surfaces were examined. While pedotubules were not identified, an isolated endocarp was found while excavating a fresh surface, confirming the presence of plant material. Given the lack of pedotubules recognized in the fourth paleosol at section two, the identification of those horizons as a paleosol is based on the similarity to the underlying horizons, the extensive development of peds, and the presence of the endocarp in the A2 horizon. Again, the A1 horizon of the third paleosol may have formed a duripan under the fourth paleosol that was eventually breached. There appears to be a moderately developed Bt layer within the A1 and A2 horizons of the underlying paleosol, as both units tend to fracture into what appears to be very coarse angular blocky peds that are surrounded by very thin argillans. This Bt horizon would be better developed than that of the third paleosol, but much less than the second paleosol.

The uppermost A horizon identified at section one (0-54 in [0-138 cm]) is unique in that there is no associated silicified horizon capping that layer. Additionally, the color and ped size of that horizon most closely match the A2 horizon of the fourth paleosol at section two (30-65 in [77-165 cm]) rather than the third horizon. It is possible that the third paleosol either never developed at section one or was developed and subsequently eroded away. At this time the correlation of the upper-most A horizon at section one with a specific horizon (or horizons) at section two should be considered uncertain pending further study.

Sometime after the development of the fourth paleosol, the massive claystones of the South Heart Member were deposited. At White Butte there are no pebbles found within the lower portion of the South Heart Member claystones, unlike at Fitterer Ranch to the south (see below). However, the highly resistant pebbles of chert and petrified wood present in some of the horizons of these paleosols may correspond to those pebbles. Additionally, there is much local variation in whether the claystones of the South Heart Member sit atop a silcrete (A1 horizon) or the weakly silicified crumb and granular peds of an A2 horizon.

Interpretation

A few methods of silcrete formation have been identified, and they are generally divided into pedogenic and non-pedogenic categories (Nash and Ullyott, 2007; Ullyott and Nash, 2016). The silcretes at White Butte are here identified as pedogenic because they contain other pedogenic features (pedotubules, sesquioxide glaebules and mottles, and peds with associated cutans) and their positions correspond to defined horizons within these successive sets of paleosols. Additionally, the incorporation of these silcretes into the Bt horizons of overlying paleosols and the fact that pedotubules do not penetrate the silicified peds indicates these silcretes were formed close to the surface and predate the formation of the overlying paleosol. These observations rule out non-pedogenic methods of silcrete formation, such as groundwater silicification, drainage-line silcretes, sinters (silica-rich deposits that form around volcanic hot springs), ganisters (silicified sandstones that underlie coal seams), and lacustrine silcretes (Retallack, 1997; Nash and Ullyott, 2007).

Pedogenic silcretes tend to form as a result of fluctuations between wet (humid) and dry (arid) conditions, either seasonally or over longer cycles, resulting in successive periods of leaching and precipitation of silica (Nash and Ullyott, 2007). Studies have shown that evaporation is key to the formation of pedogenic silcretes (e.g. van der Graaff, 1983; Webb and Golding, 1998), with silicification beginning near the surface and successive cycles of leaching and precipitation extending the development of the silcrete deeper into the soil (Thiry and Milnes, 2016). Such a mechanism fits with the observed pattern of silcretes forming in the upper portions of the A horizons of the paleosols examined at White Butte. Pedogenic silcretes typically display a stratified distribution of silica cements that range from opal to chalcedony to microcrystalline quartz to euhedral quartz, from bottom to top (Thiry and Millot, 1987; Nash and Ullyott, 2007). Larsen (1983 examined a portion of the lower silcrete layer from the Little Badlands area (exact location uncertain) and reported the presence of chalcedony cement (and a minor amount of hematite [limonite] as a secondary cement) via petrographic and microprobe analysis. That observation fits expectations, but detailed microstratigraphic sampling would be needed to determine if the full suite of silica cements are present in the expected stratigraphic arrangement, strengthening the identification of these structures as pedogenic silcretes.

The source for the silica that cemented the silcretes was likely derived from the alteration of mineral grains, either from the siliciclastic rocks within the A horizons or from rocks in adjacent areas where the silica was then transported via surface waters into these areas (Terry and Evans, 1994; Nash and Ullyott, 2007). Specifically, kaolinization of feldspars and kaolinization or illitization of clay minerals, as in the transformation of montmorillonite to illite or kaolinite, would produce excess silica during wet cycles that could facilitate silicification during dry cycles (Nash and Ullyott, 2007). The breakdown (devitrification) of volcanic ash would also produce silica (Nash and Ullyott, 2007). Given that the overlying South Heart Member is a bentonite (as defined by Grim and Guven, 1978) that is composed of volcanic glass shards and the smectite clay montmorillonite (Larsen, 1983), it is possible that necessary amounts of these minerals were available in the region to provide the required silica. Identification of the clay minerals and their relative abundance within these paleosols would aid in determining whether these processes were major sources of silica for the development of silcretes. Larsen (1983) does note that volcanic glass is absent from within the chalcedony cemented rocks of the "silicified zone," but does not identify what clays are present in that horizon.

In addition to the silcretes, the White Butte paleosols display several important features that aid in their identification and subsequent paleoenvironment interpretation. Paleosols two through four include Bt horizons (best developed in paleosol two) that form via successive wetting and drying of well-drained soils, creating cracks in the underlying parent rock. Those cracks widen during successive wet/dry cycles, and illuviation of clays from the A horizon down into the cracks formed argillans (a clay-rich cutan) between the fractured blocks of parent rock (peds). The presence of Bt horizons indicates a well-drained soil and an environment that transitions between relatively wet and dry seasons (xeric moisture regime). This is in agreement with the vertically oriented pedotubules in paleosols one through three that also indicate moderately to well-drained soils. The presence of sesquioxide concretions and mottles, as well as the absence of original plant material, indicates oxidizing soil conditions (Retallack, 1997, 2001) and, along with the complete lack of pedogenic carbonate, also indicate acidic soil conditions. Acidic soil conditions may also explain the nearly complete lack of vertebrate fossils from the underlying Chalky Buttes Member, as also hypothesized for the Chamberlain Pass Formation elsewhere in the Great Plains region during this time (Terry and Evans, 1994).

Overall, the individual paleosols display moderate to well-drained, oxidizing, acidic soil conditions. These soils likely developed under a forested landscape (Retallack, 1997: table 3.2), which fits with traditional interpretations of late Eocene environments in the Great Plains region (e.g. Retallack, 1983). The presence of strongly developed soils with thick A horizons followed by the formation of duricrusts of silcrete on the upper surface of the A horizons indicates that relatively brief periods of siliciclastic deposition (or possibly ash falls) were followed by long intervals of nondeposition and geomorphic stability. During the periods of deposition, rocks may have gradually continued to accumulate on the soil surface, allowing thick A horizons that are bioturbated throughout their depth (at least in paleosols two and three) to develop, as opposed to a situation where the paleosol developed after a thick package of siliciclastic rock or volcanic ash was deposited. It is also possible that the A1 horizons could represent surface mantles developed over the underlying umbric epipedons (see below) of the A2 horizons, but some of the A1 horizons are too thick to fit the definition of a surface mantle and more work is needed to investigate that possibility.

Silicification is present throughout this sequence of paleosols, though the overall degree of silicification tends to decrease up section, not counting the well indurated A1 horizons (figure

9). The A2 and B horizons of the second paleosol include local development of silans between the peds, while silans are not recognized in this study in paleosols three and four. The A2 horizons also tend to become less indurated up section. It is possible that during the formation of each successive paleosol small amounts of additional silica cement was translocated into the lower-most paleosols, causing the older paleosols to be more silicified than the younger paleosols. However, it is also possible that there was an originally higher degree of silicification in the lower paleosols and that silicification lessened over time. Microscopic analysis of the silica cement across these layers could reveal the presence or absence of multiple generations of cementation, helping to resolve this question.

Identification

Two main methods of classifying paleosols are used in North America. The first, and less commonly used, is the terminology proposed by Mack et al. (1993) specifically for the identification of paleosols. This classification system takes into account only those features of paleosols most likely to survive standard diagenetic alterations and divides paleosols into nine major orders that are differentiated using a simple flow chart (Mack et al., 1993: fig. 1). Under that system, a paleosol that displays illuviation of clay into underlying horizons, like that seen in the White Butte paleosols, is classified as an Argillisol. Eighteen additional subordinate modifiers were also provided that are used to highlight important secondary features of paleosols (Mack et al., 1993: table 1). Given the prominence of silcretes in these paleosols, the final identification of the White Butte paleosols according to that classification scheme would be as silicic Argillisol.

One of the principal drawbacks of the terminology proposed by Mack et al. (1993) is that not all of their paleosol orders have modern equivalents that provide more detailed understandings of the paleoenvironment during the time of formation. For that reason, most studies of North American paleosols use the classification scheme developed for modern soils by the Soil Survey Staff (1999) at the United States Department of Agriculture. Use of the same classification scheme for modern soils and paleosols facilitates paleoenvironmental interpretations; however, it can be difficult to fully classify paleosols in some cases where either diagenesis has destroyed or altered key properties of paleosols or where paleosols display features that do not match those of any known modern soil. The latter situation is the case with paleosols that include well-developed pedogenic silcretes, which have few modern analogs. As discussed above, the silcretes in the White Butte paleosols are clearly pedogenic in origin and appear to have formed on the upper-most portions of the A horizons during periods of landscape stability. Thus, classification of the original soil can be conducted using those features that apparently formed in the paleosol prior to silicification of the upper horizon. Development of peds in the Bt horizon of paleosol two in some areas resemble lentil or wedge peds, which typically form in layers enriched in swelling clays and are characteristic of Vertisols (Retallack, 1997, 2001; Soil Survey Staff, 1999). However, ped shape is highly variable in the Bt horizon of paleosol two and it seems more likely that ped shape in that horizon is largely influenced by the conchoidal fracture pattern of silica cement of the silcrete parent rock. In general, Bt horizons are typically found in four of the twelve modern soil orders: Alfisols, Aridisols, Mollisols, and Ultisols (Retallack, 1997, 2001; Soil Survey Staff, 1999). Aridisols typically have at least one of the following horizons: calcic (Bk: subsurface horizon enriched in calcite or dolomite); gypsic (By: subsurface horizon enriched in gypsum); or, salic (Bz: subsurface horizon enriched in salts)

(Soil Survey Staff, 1999; Retallack, 2001). None of those horizons are noted within the White Butte paleosols. Additionally, Aridisols tend to be sparsely vegetated, which conflicts with the dense pedotubules of likely root casts found in paleosols two and three. The thick A horizons of the White Butte paleosols (A2 horizons are all thicker than 30 inches at section two) are composed of granular and crumb peds with heavy bioturbation by root casts, many of which are less than 1/16 inch in diameter when fresh surfaces are examined. Those features closely match the definition of an umbric epipedon (aside from color which can be modified by diagenesis [Retallack, 2001]), being more well-developed than on ochric epipedon and not developed enough to be a mollic epipedon (Soil Survey Staff, 1999; Retallack, 2001). The lack of a mollic epipedon rules out Mollisols (Soil Survey Staff, 1999), which typically develop under grasslands or dry woodlands and typically have calcic (Bk) horizons that are lacking in the White Butte paleosols.

Alfisols and Ultisols typically develop under forested environments and are composed of very similar profiles, differing mainly in their base saturation (Alfisols > 35% > Ultisols: Soil Survey Staff, 1999; Retallack, 2001). Within paleosols, Alfisols can be easily distinguished from Ultisols when they contain carbonate nodules or calcic (Bk) horizons (Retallack, 2001), though some Alfisols can be non-calcareous (Retallack, 1997). In the latter case, Alfisols can be differentiated from Ultisols by the presence of abundant base-rich clays (like smectite) or the abundance of easily weathered minerals like feldspar (Retallack, 2001). Carbonate is completely lacking in the White Butte paleosols, but the necessary tests have not been conducted to identify the clays preserved in the White Butte paleosols or to look for grain dissolution of feldspars. However, as noted above, one possible source for the silica cement observed in these paleosols could be the transformation of montmorillonite to illite or kaolinite, which are base-poor clays that are common in Ultisols (Retallack, 2001). Until further work is done to identify the clays and other minerals present in these paleosols it cannot be definitively determined if these paleosols are Alfisols or Ultisols, but the available evidence (lack of carbonate and abundance of silica cement) are here considered enough evidence to tentatively identify these paleosols as Ultisols. Among Ultisols, Xerults often have an umbric or ochric epipedon, are freely drained soils, and develop within Mediterranean climates (moist, cool winters and warm, dry summers: Soil Survey Staff, 1999), conditions that match those interpreted for the White Butte paleosols. Given the prominent presence of duripans consisting of silcrete below paleosols two through four, those paleosols are here identified as Durixerults.

The first paleosol at White Butte (lowest in section) differs from the overlying paleosols in the lack of a Bt horizon and the lack of well-developed peds in the A horizon prior to silicification. Additionally, there is some evidence that the rocks combined into paleosol one in this study actually represent two paleosols. The sandstone portion of the lower silcrete contains burrows that are infilled with sandstone, rather than with clay from the overlying layer. The upper surface is also uneven, suggesting a period of erosion and possible surface stability prior to the deposition of the overlying clay. Within the sandstone facies, clear relict structures (bedding) are still present. The clay interval also displays burrows of similar size and morphology, but also contains vertically oriented root casts that extend down into the sandstone layer. No root casts were noted that are confined to the sandstone interval. Thus, this interval may represent two weakly or very weakly developed paleosols (sensu Retallack, 1997: table 1.6). Significantly, there are no clear features indicative of a xeric moisture regime preserved within this (or these) paleosol(s). The silcrete associated with paleosol one is also much thicker than any of the successive silcretes. Those facts together suggest a much shorter duration of paleosol development followed by a much longer duration of silcrete development relative to the overlying paleosols. The initiation of the xeric moisture regime may have begun after development of the paleosol at the initiation of silcrete formation; or, the paleosol may have developed under a xeric moisture regime but had insufficient time to develop a Bt horizon, though there is a poorly developed Bs horizon.

Under the paleosol classification system of Mack et al. (1993) paleosol one at White Butte would be a silicic Protosol, given that it lacks well-developed horizonation that is unrelated to pedoturbation. Protosols include those soils typically grouped within the modern Entisols and Inceptisols soil orders (Mack et al., 1993; Soil Survey Staff, 1999). Under the modern soil classification system, paleosol one is likely an Entisols, given the poorly developed horizons and pedogenic features and the presence of some relict bedding. While there is an interval of illuvial sesquioxide concentration, it is not fully developed into an oxic horizon, precluding identification as an Inceptisols (Soil Survey Staff, 1999). Within the Entisols, paleosol one at White Butte most closely resembles Fluvents, which are weakly developed soils that form on recently water-deposited sediments (Soil Survey Staff, 1999), but are not continuously saturated with water. If this soil developed under a xeric moisture regime, which may be implied by the development of the pedogenic silcrete that tends to form during wet/dry cycles, then this soil would be a Xerofluvents.

Time for Formation

Estimating the amount of time represented by the development of the White Butte paleosols provides the best insights into the duration of the disconformity at the contact between the Chalky Buttes and South Heart Members. The White Butte paleosols have well developed Bt horizons, especially the second paleosol, where argillans up to 1 9/16 inch thick are present (figure 7B). Retallack (1997: table 3.5) states that moderately developed Bt horizons (which have abundant clay skins) develop over a span of tens of thousands of years, while strongly developed Bt horizons (which require examination of the microfabric to confirm) can represent hundreds of thousands of years of development. Individual Alfisols and Ultisols identified from the Eocene of Oregon that display similar development of their Bt horizons as the White Butte paleosols are estimated to have formed over a time period ranging from 10 ka to 300 ka (Retallack et al., 1999), though all of those paleosols lacked silcretes. The Tima paleosol from the Miocene of Oregon, which is a Natric Durixeralf developed over a silcrete, is estimated to have formed over a time span of 2 to 7 ka. However, the Bt horizon at the Tima type section is only 13 3/4 inches thick and does not reach the silcrete, while the Bt horizon of paleosol two at White Butte is 70 inches thick at section one (where the underlying silcrete duripan was breached by the Bt horizon) and 26 3/4 inches thick at section two (where the duripan remained intact, limiting formation of the Bt horizon). Therefore, use of the Tima paleosol time of formation as an estimate for the White Butte paleosols would likely provide a significant underestimate.

The formation of pedogenic silcretes in modern soils and very young paleosols is estimated to require long periods of time (>10^6 years: Thiry and Milnes, 1991; Milnes and Thiry, 1992), though those estimates are not absolutely confirmed as it is difficult to date the timing of formation of silcretes (Nash and Ullyott, 2007). Regardless, pedogenic silcretes are associated with regional unconformities and develop on stable land surfaces through the downward percolation and subsequent evaporation of silica-rich water during prolonged wet/dry cycles. That process causes silcretes to begin forming at or near the surface, progressively extending down into the soil profile as these conditions persist. This is a much slower process than the development of groundwater silcretes, where individual lenses can form in as little as 30 ka (Thiry et al., 1988; Thiry, 1999). Thus, obtaining a best estimate of how much time the White Butte paleosols took to form should take into consideration the development of the silcretes, rather than only the Bt horizons.

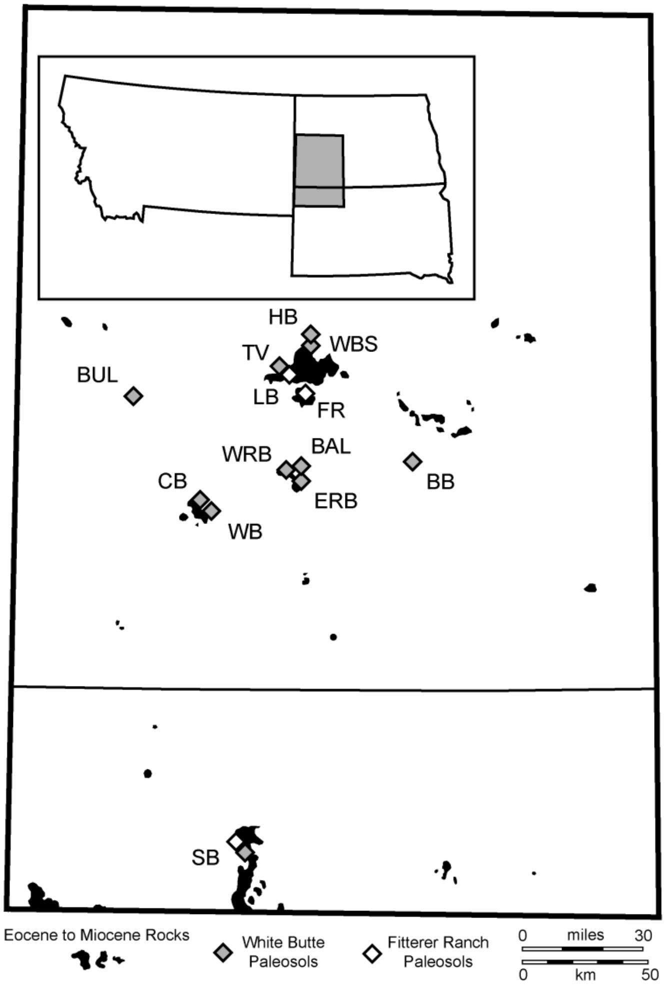

Figure 10. Geographic distribution of paleosol types observed or inferred at the contact between the Chalky Buttes and South Heart Members of the Chadron Formation (North Dakota) or their lithologic equivalents (South Dakota) within the study area. **Abbreviations**: **BAL**, Baldy Butte; **BB**, Black Butte; **BUL**, Bullion Butte; **CB**, Chalky Buttes; **ERB**, East Rainy Butte; **FR**, Fitterer Ranch; **HB**, Haystack Butte; **LB**, Little Badlands; **SB**, Slim Buttes; **TV**, Turtle Valley; **WB**, White Butte; **WBS**, White Butte (Stark County); **WRB**, West Rainy Butte.

Terry and Evans (1994) used estimated rates of Bt horizon genesis to estimate a minimum time of formation for each paleosol (Durixerults and Aqualfs) within the Channel Sandstone facies of the Chamberlain Pass Formation in the Weta Paleosol Series. That study determined that at least 15 ka of formation would be required for each paleosol. Given the presence of up to three stacked sets of paleosols present in a single location, as indicated by successive silcretes, those paleosols would have developed over a minimum time span of at least 45 ka (Terry and Evans, 1994). However, as noted above, such a value would seem to greatly underestimate the time required for pedogenic silcrete formation. Even using the much more conservative estimate for groundwater silcretes, a minimum of 30 ka per silcrete would be required for a total of 90 ka, though the actual amount of time was likely far longer. For the White Butte paleosols, four stacked silcretes are present (figures 8 and 9), providing a minimum estimate of 120 ka using those same assumptions. However, given that these are pedogenic silcretes and the lowermost silcrete at White Butte is well over three feet thick, the total time represented is likely several hundred thousand years.

Geographic Distribution

Paleosols similar to the White Butte paleosols are present throughout a wide area of southwestern North Dakota (figure

10). These “silicified sandy bentonite” beds (sensu Denson et al., 1965) and “silicified smectites” (sensu Murphy et al., 1993) are present at the contact between the Chalky Buttes and South Heart Members in Billings County (Bullion Butte [T137N, R102W, sections 7 and 18]: Denson et al., 1965; Murphy et al., 1993), Hettinger County (Black Butte [T135N, R95W, sections 11-12]: Denson et al., 1965; Murphy et al., 1993), Slope County (Chalky Buttes [T134N, R101W, sections 14-15, 22-23, and 26-27], White Butte [T134N, R101W, section 25], West Rainy Butte [T135N, R98W, sections 17-20 and T135N, R99W, sections 13 and 24], East Rainy Butte [T134N, R98W, sections 3-4 and T135N, R98W, sections 26-27, and 34], Baldy Butte [T135N, R98W, section 21]: Denson et al., 1965, Stone, 1972; Murphy et al., 1993), and Stark County (White Butte [T139N, R97W, sections 31-32], Haystack Butte [T139N, R97W, section 29], and Turtle Valley [T138N, R98W, section 20]: Stone, 1972; Larsen, 1983; this study). In some areas the published images and descriptions of these beds are very similar to the description of the White Butte paleosols provided above. For example, at East Rainy Butte (T153N, R98W, section 34) the basal unit of the South Heart Member is described as follows: “…very indurated, fractured, iron oxide stained, clay filled fractures…” (Murphy et al., 1993: p. 46). In that description there is evidence of Bt horizons (clay filled fractures), development of silcretes (very indurated), and the presence of sesquioxide glaebules (iron oxide stained). Photographs of those beds at East Rainy Butte and of the capping unit at nearby Baldy Butte also closely resemble the White Butte paleosols (Murphy et al., 1993: figs. 43A and 43C). Thus, the identification of all of these silicified beds at the contact between the Chalky Buttes and South Heart Members in North Dakota as paleosols similar to the White Butte paleosols appears justified, though detailed examinations of the paleosols at each of these locations could provide important information regarding geographic variation in paleoenvironment or local soil conditions.

The thickness of these beds is highly variable over short geographic distances, spanning from approximately two feet in Turtle Valley (section 8-13b-82: Larsen, 1983) to over 20 feet at White Butte in Stark County (figure 9). They also can be discontinuous within areas, like in Turtle Valley where a thin bed is present in the SE ¼ of section 20 (T138, R98W) and absent in the NE ¼ (Larsen, 1983), and in the Chalky Buttes area (Murphy et al., 1993: fig. 19h versus 19i). The presence and thickness of the White Butte paleosols seems to not be constrained by the underlying lithology, given that they do overlie mudstones in some areas (e.g. East and West Rainy Buttes: Murphy et al., 1993). Within the Little Badlands area cross sections spanning from White Butte southwest to Turtle Valley seem to indicate that the development of the White Butte paleosols is restricted to areas where the underlying Chalky Buttes Member is thicker, possibly indicating paleotopographic lows (figure 11). However, in the Rainy Buttes area these paleosols overlie portions of the Chalky Buttes Member that are approximately 10 feet thick (Denson et al., 1965; Murphy et al., 1993), similar in thickness to the section at Fitterer Ranch where the White Butte paleosols are absent (see below). Given that the White Butte paleosols are likely Ultisols that would have developed over a long period of time, their presence may be more indicative of the local area being a stable surface during the period of nondeposition and erosion that occurred between the deposition of the Chalky Buttes and South Heart Members. Those areas may be coincident with the positions of paleotopographic lows prior to the deposition of the Chadron Formation in North Dakota, but in other areas pre-Chadronian highs may have transitioned into post Chalky Buttes Member paleotopographic lows. Detailed mapping of the thickness of the Chalky Buttes Member and the presence, structure, and thickness of the White

Butte paleosols across southwestern North Dakota could provide better insights into the paleotopographic history within this region during the late Eocene.

Paleosols at Fitterer Ranch

The lithology of the Chalky Buttes Member at Fitterer Ranch varies within the area. The base of the unit through much of the area is a massive claystone layer with little observable internal structure, likely representing overbank deposits associated with the prominent channel facies found throughout the Chalky Buttes Member in the Little Badlands area. In isolated places in the Fitterer Ranch area channels of coarse, massive to cross-bedded sandstone cut several feet into these clays (figure 12A). Clasts of the underlying claystone up to several inches in diameter are present sporadically within those sands, and local lag deposits are occasionally present. These overbank muds and channel sands are truncated at their upper surface by the massive claystones of the South Heart Member. The contact between these two members is traditionally considered conformable, but close examination reveals the presence of a paleosol developed within the Chalky Buttes Member that indicates a disconformity between the Chalky Buttes and South Heart Members.

The clearest evidence of this paleosol is seen within the channel sandstone facies. The entire thickness of these sands (7.2 feet at the measured section) is fractured (pedo-brecciation) into very coarse, angular blocky peds that are surrounded by argillans that range in thickness from 1/8 inch to over 1 inch (figure 12B). These peds decrease in size at the top of the member until they are within the medium to fine size class of subangular blocky peds (Retallack, 1988: fig. 9). The repetitive wet/dry cycles, and resulting shrinking and swelling of the clays

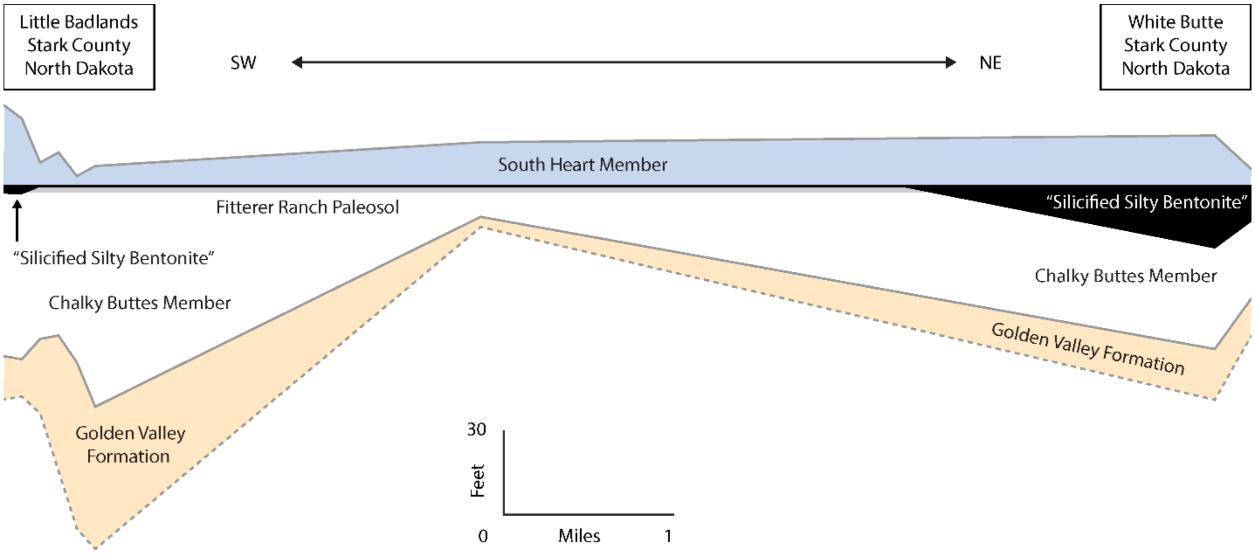

Figure 11. Fence diagram from the west margin of the Little Badlands area (138 98 20) to White Butte (139 97 32) showing the varying thickness of the Chalky Buttes Member in the region and the observed distribution of the Fitterer Ranch paleosol type and the White Butte paleosol type ("Silicified Sandy Bentonite" of Denson et al. [1965]). Based on stratigraphic sections presented in Larsen (1983:appendix A). Sections in the White Butte area were confirmed by the authors. The base of the Golden Valley Formation is not exposed in these areas. Upper surface of the South Heart Member is eroded in all areas, so thickness is preserved thickness, not original total thickness.

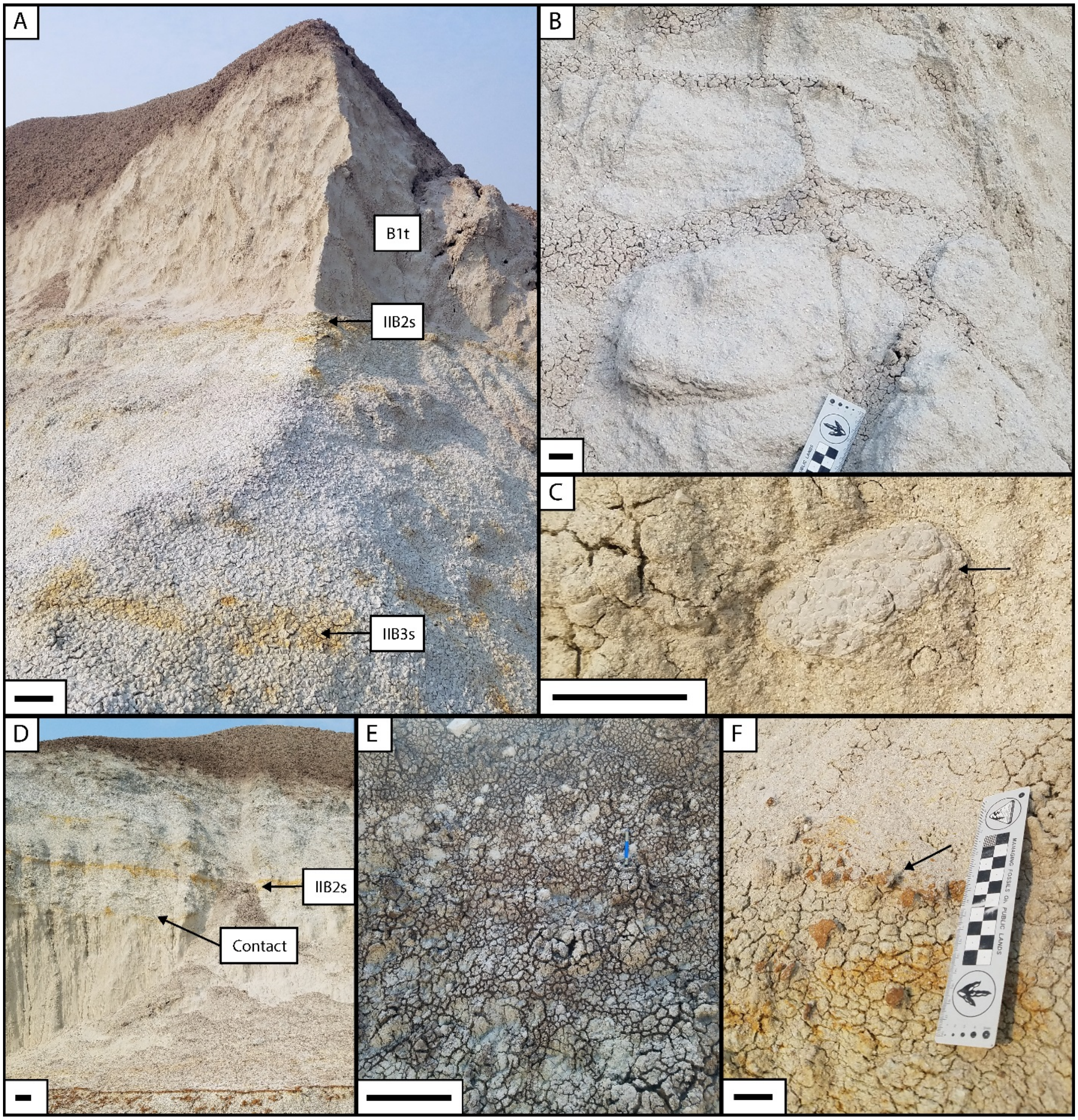

Figure 12. Pedogenic features and horizons of the Fitterer Ranch paleosol within the Chalky Buttes Member of the Chadron Formation at Fitterer Ranch (137 97 7). **A**. photograph of the Fitterer Ranch paleosol developed in the area of a channel downcut (B1t horizon). **B**. Close up of very coarse, angular blocky peds of sandstone (gray) surrounded by thick argillans (brown; desiccation cracked) in the B1t horizon. **C**. large clast of eroded claystone (black arrow) within the massive, coarse sandstone of the channel downcut in the upper portion of the Chalky Buttes Member. **D**. photograph of the full Fitterer Ranch paleosol developed within the overbank mudstones of the Chalky Buttes Member adjacent to the channel downcut (out of image to the right) above the contact with the underlying Golden Valley Formation. **E**. upper portion of Fitterer Ranch paleosol showing the peds of sandstone (gray: Chalky Buttes Member) lifted up into the South Heart Member mudstones (brown), making the exact position of the contact uncertain. **F**. thin layer of sesquioxide cemented sediment (black arrow) present at the base of the channel downcut, below the B1t horizon. Scale bar in A, D, and E equal 1 foot and in B, C, and F equal 1 inch.

within the argillans, which formed these peds resulted in the lifting of the uppermost peds up into the base of the South Heart Member. As a result, it can be difficult to identify the exact boundary between the two members on fresh surfaces, though the draping of the clays of the South Heart Member on weathered surfaces gives the appearance of an abrupt contact.

Casual inspection of the contact above the overbank mud facies gives the impression that the formation of peds is restricted to the channel sandstone facies; however, on fresh surfaces the presence of fine to coarse peds (depending on vertical distance from the upper surface) is revealed by the subtle presence of argillans of pale yellowish brown (10YR6/2) clays washed down from the South Heart Member surrounding peds composed of the light greenish gray (5GY8/1) clays of the overbank mudstone facies. The depth of these later peds into the Chalky Buttes Member is difficult to trace given the similarities in color and lithology between the peds and argillans, but they extend down at least three feet and show similar lifting into the base of the South Heart Member (figure 12E).

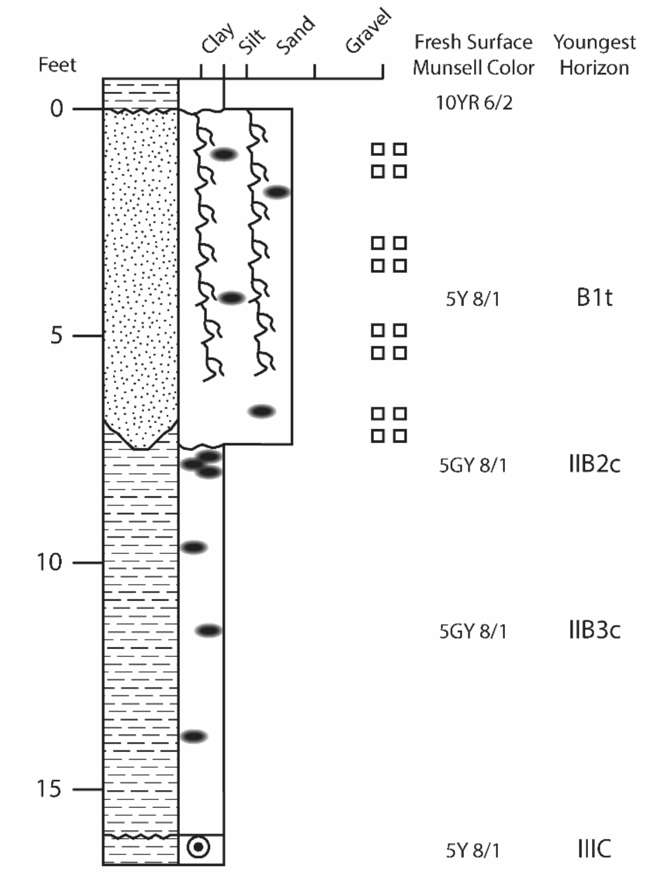

Figure 13. Diagram of the Fitterer Ranch paleosol in the southern portion of the Little Badlands area (Stark County). See key to lithologic and pedogenic features in figure 3**.**

Description of Section

This section (figure 13) was recorded on an east facing surface on a southwest to northeast trending finger of outcrop in section 7 (T137N, R97W: 13T, 655987mE, 5173559mN). The section was measured in an area where a local paleochannel downcut was present, but immediately adjacent (within 10 feet) the channel sandstone facies is absent, and claystone extends to the upper contact with the overlying South Heart Member and similar pedogenic structures are developed within that lithology as well.

+63 in (160 cm); cover; claystone; pale yellowish brown (10YR6/2); weathering same color; pebble to cobble sized inclusions of resistant lithologies (e.g. chert, quartzite, petrified wood) sparsely distributed throughout (not concentrated into a lag deposit); weathers into rounded slopes that tend to drape over underlying units; generally massive beds of smectite clays (Larsen, 1983); noncalcareous; diffuse wavy contact to

0 in (0 cm); B1t; sandstone; yellowish gray (5Y8/1); weathering same color; coarse sandstone with massive bedding and no basal lag at this location; clasts of clay up to 1 1/2 inch in maximum dimension from underlying claystone included throughout (figure 12C); entire channel sandstone facies developed into peds ranging from very coarse, angular blocky peds at the base and fine to medium, subangular blocky peds at the top (figure 12B); well-developed argillans (10YR6/2) ranging in thickness from a 1/8 inch to over 1 inch, layering is present within some argillans that may reflect successive expansion and in some areas thin laminae of a white mineral is present in the argillans that is noncalcareous (silica?); few, fine, diffuse, distinct mottles of sesquioxides, some of which surround the clay clasts; there are metatubules less than 1/16 inch thick within the argillans infilled with very similar clays, making them difficult to discern in hand sample; noncalcareous; abrupt wavy contact to

-87 in (223 cm); IIB2s; claystone; light greenish gray fresh (5GY8/1); weathering very light gray (N8); continuous, horizontal interval of translocated sesquioxides (figure 12D) developed as many, coarse, diffuse, prominent mottles through most of the area, but concentrated into thin and wide nodules along the lower surface of the paleochannel where present (figure 12F); no pedotubules recognized; noncalcareous; clear smooth contact to

-89 in (228 cm); IIB3s; claystone; light greenish gray fresh (5GY8/1); weathering very light gray (N8); zone of common, coarse, diffuse, prominent sesquioxide mottles dispersed throughout this horizon (figure 12A); no pedotubules recognized; noncalcareous; abrupt smooth contact to

-190 in (483 cm); IIIC; micaceous siltstone; yellowish gray (5Y8/1); weathering light greenish gray (5GY8/1); Bc (or possibly Btc) horizon of underlying paleosol (Yellow Mounds Paleosol Equivalent: Retallack, 1983); prominent sesquioxide mottles, nodules, and continuously cemented horizons, along with overall staining of rocks; uncertain if any of the sesquioxides result from development of the overlying paleosol; no pedotubules recognized; noncalcareous (figure 12D).

Interpretation

No clear A horizon is noted in this area, though it is not uncommon for paleosols with strongly developed Bt horizons (in excess of three feet) to lack an A horizon as a result of surficial erosion (Retallack, 2001). The Bt horizon at this location is much more deeply developed than at any place examined where the White Butte paleosols are present, suggesting a longer time of formation for this single Bt horizon than for any of the individual Bt horizons in the White Butte paleosols. That interpretation makes sense considering there is only a single paleosol developed in the Chalky Buttes Member at Fitterer Ranch, unlike the stacked series of up to four paleosols at White Butte. This paleosol seems to have developed under a land surface that was stable for an extended period of time, much like at White Butte, but lacks the silicification seen at the latter location. It may be that the area of Fitterer Ranch was a paleotopographic high during this time, and that water rich in silica from the breakdown of less resistant minerals (e.g. smectite clays, feldspars) flowed towards and concentrated in paleotopographic low areas, which may have been the areas of more extensively developed channel sandstone deposits like the White Butte area, forming silcretes. Another possibility is that silcretes may have developed in the Fitterer Ranch area at some point, but were subsequently eroded away, contributing some of the weathered pedogenic silcrete fragments found in the A1 horizons of the White Butte paleosols. Either way, the well-developed Bt horizon at Fitterer Ranch indicates an extensive period of alternating wet/dry cycles, possibly from seasonal variations in a xeric (Mediterranean) moisture regime (Retallack, 1997, 2001; Soil Survey Staff, 1999).

Other pedogenic features within the Chalky Buttes Member include the translocation of sesquioxides down into areas of the overbank mudstone facies (figure 12D) and the base of the channel scour (figure 12F). Most commonly these sesquioxides form light mottles, but within the IIB2c horizon it is concentrated along a laterally continuous horizon that seems to track at a consistent depth below the contact between the Chalky Buttes and South Heart Members over a moderate distance (figure 12D). These sesquioxides do not form distinct concretions or nodules in most places or form well-cemented, resistant horizons, all of which are present in the much better developed Yellow Mounds Paleosol Equivalent within the underlying Golden Valley Formation. However, the sesquioxide concretions in the White Butte paleosols are entirely within the silcretes, and the lack of those horizons at this location may explain the lack of concretions. The presence of these sesquioxides varies laterally and in some areas is almost entirely absent. The heaviest concentration of sesquioxides is found in locally developed layers within the lowest portions of the channel bottoms, and in general the development of sesquioxide-rich horizons appears to be greatest within the overbank mudstone facies adjacent to the channel sand facies, though sparse mottling is present within the channel sandstone facies. The presence and abundance of translocated sesquioxides suggests an oxidizing environment (Retallack, 1997, 2001). The complete lack of carbonate from this paleosol also supports an interpretation of this soil being at least slightly acidic (Retallack, 1997, 2001). In summary, the pedogenic features present in this paleosol suggest a similar environment as the White Butte paleosols but lacking in silcrete development.

Identification

The presence of a prominent, deeply developed Bt horizon with no A horizon preserved suggests this is either an Alfisols or Ultisols (Retallack, 1988: table 6). While the complete lack of calcareous nodules or cement (via the absence of a reaction with a strong acid) favors an Ultisols, there are still feldspar grains within the peds of the parent rock, some of which are up to small pebble size, which would provide support for an Alfisols (Retallack, 1988: table 6). Both of those types of paleosols are recognized in the Chamberlain Pass Formation in South Dakota, with Alfisols present on the distal (Paleudalfs) and proximal (Aqualfs) overbank facies and Ultisols (Aquults and Durixerults) on the channel sandstone facies (Terry and Evans, 1994). Redoximorphic features within the Fitterer Ranch paleosol are too poorly developed to qualify as an Aqualfs/Aquults; rather, this paleosol fits better with the properties of Xeralfs/Xerults, depending on whether this paleosol is an Alfisols or an Ultisols, which will require more detailed examinations to estimate the base saturation (Alfisols > 35% > Ultisols: Soil Survey Staff, 1999; Retallack, 2001). Under the paleosol classification system of Mack et al. (1993) this paleosol is identified as a Argillisol given the well-developed Bt horizon. No subordinate modifier is here applied to the Fitterer Ranch paleosol because no secondary feature is prominent enough to warrant recognition. If the base saturation of this paleosol is eventually determined, the proper modifier would be either eutric (if a high base status is indicated) or dystric (if a low base status is indicated).

Time for Formation

As noted above, the Bt horizon of this paleosol is more deeply developed than in any of the White Butte paleosols. Given that the Bt horizon extends down over seven feet into the subsurface, this paleosol meets the definition of a strongly developed paleosol (Retallack, 1997: table 1.6), though examination of the microfabric of the argillans would help to confirm this observation. Additionally, the presence of a well-developed Bs horizon where translocated sesquioxides are concentrated within a continuous horizontal layer supports the classification of a strongly developed paleosol (Retallack, 1997, 2001). The time of formation of strongly developed Bt horizons is on the scale of 10^5 years (Retallack, 1997: table 3.5). That general span of time is in agreement with the minimum estimated time of formation of the full set of White Butte paleosols (at least 120 ka). This agreement provides support for the interpretation that the disconformity at the contact between the Chalky Buttes and South Heart Members consistently represents a timespan of hundreds of thousands of years of missing time, regardless of geographic location or composition of the local paleosol.

Geographic Distribution

Unlike the resistant silcretes of the White Butte paleosols, the presence of the Fitterer Ranch paleosol type is difficult to discern on weathered outcrops. Where the channel sandstone facies is present, close examination typically reveals the prominent pedo-brecciation of the well-developed peds and argillans of the Bt horizon. Where mudstone or claystone directly underlie the South Heart Member mudstones or claystones, recognizing the Bt horizon is difficult unless fresh surfaces are trenched and examined. The draping of the South Heart Member rocks onto weathered surfaces also complicates recognition of this paleosol. Thus, review of published or archived images and descriptions is often insufficient for tracing the presence or absence of this type of paleosol in North Dakota. First hand examination of such outcrops is required to fully track the distribution of this paleosol. Thus far its presence is confirmed at Fitterer Ranch (section described above), within the main Little Badlands area wherever the White Butte paleosols are not present (T138N, R98W, section 23: 13T, 651215mE, 5179284mN), and in isolated outcrops situated between those two areas (e.g. T138N, R97W, section 30: 13T, 655495mE, 5178932mN). It should be noted that either the White Butte paleosols or the Fitterer Ranch paleosol type was identified everywhere at the contact between the Chalky Buttes and South Heart Members that was examined in this study (figure 10). While more detailed sampling may reveal additional paleosol types developed on this paleosurface, it is likely that the disconformity is present throughout the region at this contact.

Regional Correlations

Evans and Terry (1994) noted that the late Eocene Chamberlain Pass Formation of South Dakota is sandwiched between two paleosols. The lower paleosol (Yellow Mounds Series: Retallack, 1983) represents an extensive phase of erosion and soil development prior to the late Eocene on rocks ranging in age from Late Cretaceous (Pierre Formation) to early Eocene (Golden Valley Formation) throughout South Dakota, North Dakota, Nebraska, Montana, and Wyoming (Retallack, 1983; Terry, 1998). In South Dakota the upper paleosol is recognized as a soil catena (lateral variation in soils across a landscape) that is composed of the Interior Paleosol Series (Retallack, 1983) and the Weta Paleosol Series (Terry and Evans, 1994). Regional equivalents of the Interior and Weta paleosols were noted in Nebraska and Wyoming on top of rocks either referred to the Chamberlain Pass Formation or considered likely lithologic equivalents (Terry, 1998). Terry (1998) also notes that in Nebraska the paleosols that were identified in that study as the Interior Paleosol Equivalent and the Weta Paleosol Equivalent differ sufficiently from the formal descriptions of those units that they should be classified as their own pedotypes, though that work was beyond the scope of that study. Thus, there is precedence for there being substantial variability between paleosols formed at the top of the Chamberlain Pass Formation and its regional equivalents, in this case the Chalky Buttes Member of the Chadron Formation (Murphy et al., 1993; Hoganson et al., 1998; Terry, 1998). Terry (1998) also noted pedo-brecciation in the top of the "dazzling white" channel sandstones of the Chadron Formation at Slim Buttes, South Dakota that resembled those present at the top of the Chamberlain Pass Formation near Interior, South Dakota (further discussion below). Evans and Terry (1994) noted that more detailed study of the rocks of the Chalky Buttes Member of the Chadron Formation at White Butte in North Dakota may reveal the presence of a paleosol atop the channel sandstones, strengthening the correlation between those rocks and the Chamberlain Pass Formation. Therefore, a detailed comparison between the paleosols described in this study, the Interior and Weta Paleosol Series and their regional equivalents, and similar, undescribed paleosols in the Slim Buttes area of South Dakota is warranted.

The White Butte paleosols most closely resemble those described in the Weta Paleosol Series, specifically that portion developed over the channel sandstone facies of the Chamberlain Pass Formation. Those paleosols, also identified as Durixerults (Terry and Evans, 1994), include up to three vertically stacked, pedogenic silcretes, each of which may be up to six feet thick, similar to the pattern observed at White Butte. However, reactivation of the abandoned channels is hypothesized to have removed all but the silcretes of the Durixerults in the channel sandstone facies of the Chamberlain Pass Formation (Terry and Evans, 1994), unlike at White Butte where full soil profiles are preserved. The silcretes at these two locations are similar in that sesquioxide concretions up to 3/8 inch in diameter are only present within the silcretes, though other types of sesquioxide glaebules (mottles and nodules) are present within other horizons. The diagnostic concentric internal fabric of sesquioxide concretions indicates episodic accretion of material, supporting the hypothesis that these silcretes formed via deposition during repeated wet/dry cycles that may have been seasonal. However, several differences are present between the Durixerults of South Dakota and North Dakota. Clay-filled, drab-haloed root traces are present in the channel sandstone facies in South Dakota. While clay-filled root traces are present within the clays of the A2 horizon of paleosol three at White Butte, no drab-haloed root traces were noted anywhere within the stacked series of paleosols. Part of this difference may be lithological, given that the drab-haloed root traces in South Dakota are clay-filled root casts within sandstone, while no clay-filled root casts are present at White Butte within sands. Alternatively, one possible set of conditions for the formation of drab-haloed root traces is the presence of periodically waterlogged soils. Given that in South Dakota the channel sandstone facies was repetitively reactivated after successive paleosol development, it is possible those paleosols developed in an area where the water table was closer to the surface, especially during the wetter time of the year. The Durixerults in South Dakota also have some pedogenic carbonate present, though most of that carbonate was present as thin rims on detrital grains and within the clay-sized sediment fraction. That carbonate was interpreted as secondary- and tertiary generation lining within voids and fractures (Terry and Evans, 1994) and it is possible that such trace amounts of carbonate could be present at White Butte and would be discovered by more detailed studies of the microfabric. There is also a zone of carbonate concentration that forms a prominent horizon of large sandstone nodules that are several up to a foot in size near the base of the Chamberlain Pass Formation in some areas (Terry and Evans, 1994: fig. 14). Those carbonate cemented nodules are interpreted to be formed by translocation and precipitation of pedogenic calcrete (Evans and Terry, 1994; Terry and Evans, 1994). Similar structures are not recognized anywhere within the Chalky Buttes Member within North Dakota (Murphy et al., 1993; this study). One final difference is the presence of clay papules (maximum size 1 3/4 inch by 3/4 inch) in the Durixerults of South Dakota (possibly from the breakdown of pebble-sized clasts of feldspar), while such features are not noted in the Durixerults of North Dakota.

While the pedogenic features of these two paleosols are not identical, no other paleosol described from Eocene or Oligocene rocks of North America includes such extensive development of silcretes (Retallack, 1983, 1997, 2001; Retallack et al., 1999). The only somewhat similar paleosol is a Natric Durixeralf (Tima paleosol: Retallack, 2004) described from the upper portion of the Haystack Valley Member of the John Day Formation in Oregon. That Miocene pedotype consists of a bioturbated (drab-haloes root traces) A horizon over a Bt horizon (granular to fine blocky peds) developed over a silcrete. The entire profile is noncalcareous. That pedotype is identified as an Alfisols rather than as an Ultisols because of the thin Bt layer (13 3/4 inches at the type section), the coloration, and the base saturation (Retallack, 2004: fig. 14). The coloration is similar to that of paleosols two and three at White Butte, with only a slight difference in the chroma of the A horizon (10YR6/3 versus 10YR6/2 at White Butte), though the A horizon of paleosol 4 is yellower (5Y7/2). Additionally, the Bt horizon of the Tima paleosol does not extend down into the upper portion of the silcrete, leaving a distinct C horizon between them that is not present in the North Dakota Durixerults. The development of silcretes in the upper portion of the Haystack Valley Member is interpreted to signal the onset of a Mediterranean climate (dry summers, wet winters: Retallack, 2004), supporting a similar interpretation for the Durixerults in South Dakota and North Dakota during the late Eocene (Terry and Evans, 1994; this study).

Another important comparison that should be made to the Durixerults of South Dakota and North Dakota are the paleosols present within the Chadron Formation at the contact between the “dazzling white” channel sandstones and the overlying claystones of the “typical Chadron” in the Reva Gap area of the Slim Buttes, South Dakota (figure 14). As mentioned above, pedo-brecciation is present extensively within the upper portion of the “dazzling white” channel sandstone in much of the Reva Gap area (figures 14A-B). That pedo-brecciation represents well-developed Bt horizons that extend deep into the “dazzling white” sandstone with argillans up to and in some places exceeding 1 inch in thickness. Isolated sesquioxide mottling is present within these Bt horizons, usually spaced at least three feet or more from the upper surface. There are also large root casts (silicified) that extend vertically deep into the Bt horizons (figure 14B), supporting an inference of these soils being well-drained. Those paleosols not only closely match paleosols developed in the top of the Chamberlain Pass formation near Interior, South Dakota (Terry, 1998), but are also nearly identical to those present at the top of the Chalky Buttes Member at Fitterer Ranch and those portions of the Little Badlands area where the White Butte paleosols are not present (see above).

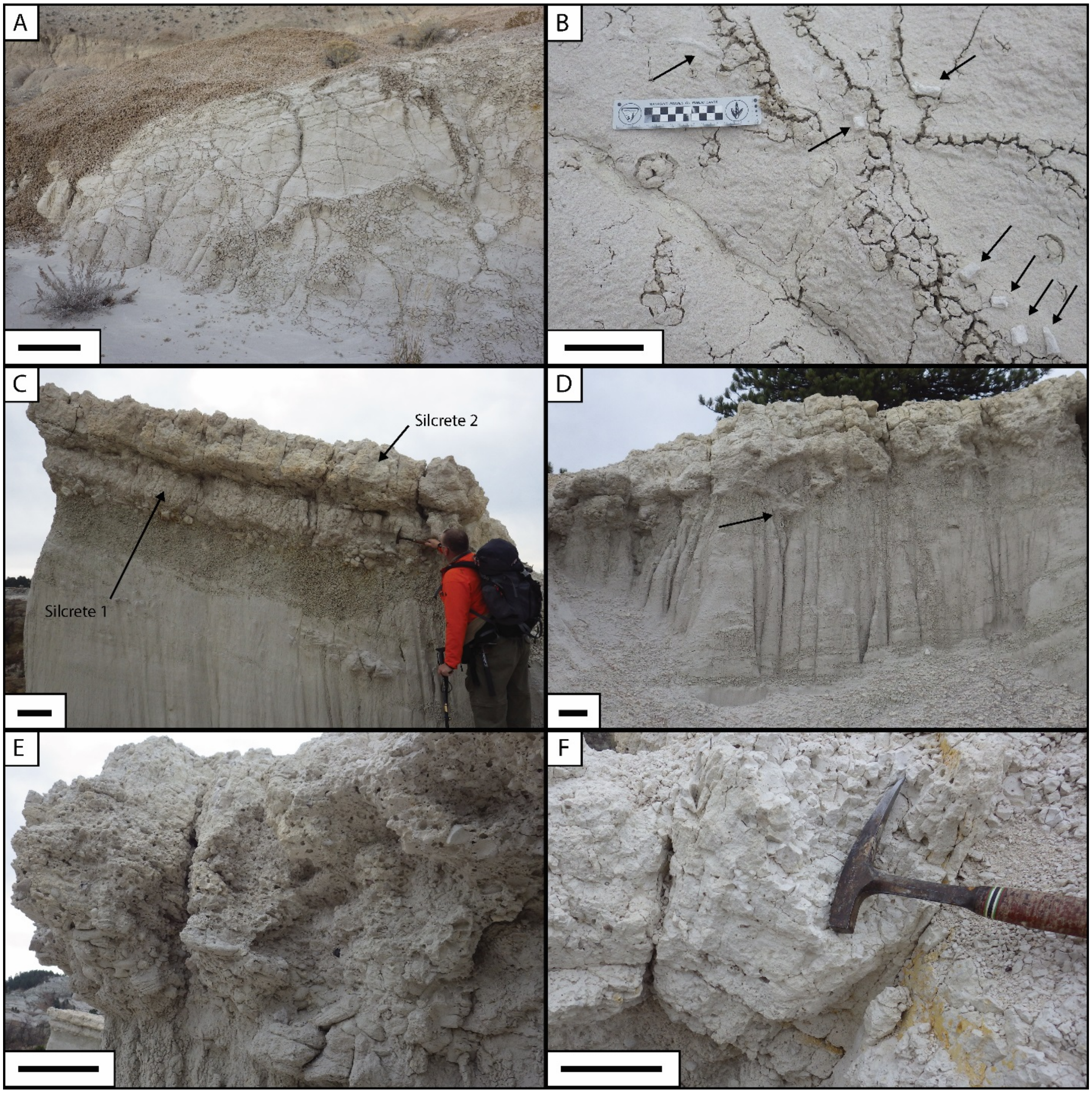

Figure 14. Paleosols developed in the upper portion of the "dazzling white" sandstone of the Chadron Formation in the Reva Gap area of the Slim Buttes (Harding County, South Dakota). **A**. well-developed Bt horizon (i.e. pedo-brecciation) in the "dazzling white" sandstone at the contact with the "typical Chadron." **B**. close up view of large peds surrounded by argillans (delineated by desiccation cracks) in the "dazzling white" sandstone with pieces of silicified pedotubules (root traces) eroded on the surface and still in situ (top left arrow). **C**. two stacked pedogenic silcretes similar to those present within the White Butte paleosols in North Dakota. **D**. area where the pedogenic silcretes at Reva Gap extend down into the in-situ channel sandstones (black arrow) rather than being confined above the conglomeratic interval. **E**. close-up view of the lower portion of the pedogenic silcrete, showing the large clasts present in the underlying conglomerate (bottom right) and the voids present in the silcrete where pebble-sized clasts have fallen out (chert, petrified wood, eroded silcretes). **F**. Close-up view of the upper portion of the silcrete, showing finer-grained texture and presence of sesquioxides along vertical joint surfaces (bottom right). Scale bars in B and F equal 4 inches and all others equal 1 foot.

At one location in Reva Gap the Bt horizon is absent and the channel sandstones of the "dazzling white" interval are overlain by well-developed silcretes (figures 14C-F). Those silcretes are formed on top of an upward fining sequence that consists of a very coarse breccia/conglomerate (clasts up to 9/16 inch in maximum diameter) at the base (figure 14C). Clasts within that conglomerate include portions of the underlying channel sandstone facies, reworked pieces of pedogenic silcrete, pieces of petrified wood, and pebble-sized clasts composed of resistant lithologies (e.g. chert). That conglomerate fines upward into sands and silts. Silicification of those rocks is best developed at the top and extends downward irregularly, in some places reaching down into the channel sandstone facies of the underlying "dazzling white" sandstone, while in other places ending within the conglomerate (figure 14D). Clasts within the conglomerate but below the level of the silcrete are coated with very thin layers of silica and sesquioxides that were translocated down through cracks. A second deposit of siliciclastic rock sits on top of the first silcrete, possibly indicating a period of channel reactivation. A second, thicker silcrete is developed in those rocks, extending down until it nearly contacts the first silcrete (figure 14C). The upper portion of that silcrete formed in a very fine-grained rock, likely a mudstone or claystone, and the bottom portion incorporated many pebble-sized clasts (figure 14F), mostly eroded pedogenic silcrete and petrified wood. The exact nature of the contact between the second silcrete and the overlying claystones of the "typical Chadron" is not well-exposed (slump covered), but it appears that in this location there were only two successive silcretes developed. It is possible additional silcretes were formed prior to the lower conglomerate deposit and were eroded away during a prior phase of channel reactivation, which would account for the large clasts of pedogenic silcrete included in those deposits. The silcretes at this location most closely resemble the silcrete of paleosol one at White Butte in that there is no associated Bt horizon and the only other pedogenic feature is light sesquioxide mottles. Detailed description, identification, and interpretation of those paleosols will have to await more detailed examinations, but there is little doubt these silcretes formed during a similar time and under somewhat similar regional paleoenvironmental conditions as the Durixerults of southern South Dakota and North Dakota, though apparently in an area that experienced higher energy fluvial events prior to the development of each of the preserved pedogenic silcretes.

Biostratigraphy of the Chadron Formation in North Dakota

Within North Dakota most outcrops of the Chadron Formation are relatively unfossiliferous (Murphy et al., 1993). To date, only a single paleontological locality is described from those rocks that includes multiple mammalian taxa: the Medicine Pole Hills local fauna (Murphy et al., 1993; Kihm, 2013; Kihm and Schumaker, 2015). Thus, there has been no way to reliably determine the relative ages of the Chalky Buttes and South Heart Members, or to determine if all the rocks referred to a single member are the same age. A newly discovered vertebrate fauna from the Chadron Formation, the Stover Site local fauna, provides a second set of biostratigraphic data to compare to the Medicine Pole Hills local fauna. This new discovery provides the first insight into the timing of deposition of the Chalky Buttes Member of the Chadron Formation in different areas of southwestern North Dakota.

New Chadron Formation Outcrops in Adams County

Discovery

In 1994 Betty J. Stover, who then lived in Bucyrus, North Dakota, made an unexpected discovery in the hills south of highway 12 between the towns of Bucyrus and Reeder (Adams County: figure 15). Betty had a long running interest in rocks, fossils, and historic artifacts, and had previously taken a weekend class in paleontology led by Mr. Dean Pearson at the Pioneer Trails Regional Museum (PTRM) in Bowman, North Dakota. She had also attended a fossil dig led by now retired North Dakota Geological Survey (NDGS) paleontologist John Hoganson and was a member of a rock and gem club in Dickinson, North Dakota. Given that background, she was well-prepared to recognize fossils when she encountered them. While hiking the hills and gravel roads in the area around Bucyrus, she and her now late husband James discovered two new late Eocene fossil localities within previously unrecognized outcrops of the Chadron Formation: the Stover Site and the Water Tower Site (figure 15). They surface collected numerous large fossils from the surface at these sites, consisting mostly of broken pieces of large mammalian postcranial bones, pieces of turtle carapace, and partial teeth. The Stovers recognized the potential importance of their discoveries and contacted several institutions in North Dakota to share this new information. They donated a portion of the fossils to the PTRM and sent another batch to the Department of Geosciences at North Dakota State University (NDSU), where their son was studying at the time.

Little work was done on those fossils for the next 20 years. In 2015, both of those sets of fossils were independently transferred to the NDGS to be accessioned into the State Fossil Collection. Those previously held at PTRM had little associated locality data, complicating efforts to relocate the site. However, the specimens held at NDSU included photographs and detailed descriptions of the original locations. Aided by those data, NDGS paleontologists relocated the sites in September of 2015. The first site is situated at the top of the highest ridge within the local area to the southeast of Reeder (T130N, R97E, sections 20 and 29). The close placement of a large water tower provided the name for this locality: the Water Tower Site (NDGS L288). A maximum of 10-20 feet of previously undocumented Chadron Formation rocks are present at the top of this ridge, all of which are referable to the Chalky Buttes Member. An old road cut is present along the east-west section fence between sections 20 and 29, exposing a few inches of gravel within the soil horizon at the crown of the hill that includes pieces of bones and teeth from brontotheriids (figure 16). That gravel is present within the grass-covered slopes across most of the upper-most surface of that ridge. On the north face of that ridge in section 20, a small amount of in situ outcrop is exposed (figure 16). The majority of that outcrop consists of a well to very-well indurated (carbonate cemented), conglomeratic sandstone. These beds appear to fine upwards, and within the basal conglomeratic intervals bone and tooth fragments are present. This site requires further study, but thus far the only taxa definitively identified are an indeterminate brontotheriid and some postcranial material from a small-bodied artiodactyl (possible leptomerycid?). Those data are sufficient to refer these rocks to the Eocene Chadron Formation, but little more can be said of their age at this time.

The second site, referred to as the Stover Site in honor of Betty and James Stover, is an old gravel pit situated on private property just east of Reeder and south of highway 12 (T130N, R97W, Section 7, SE/SE/SE: NDGS L236). That gravel pit is located two miles north and one

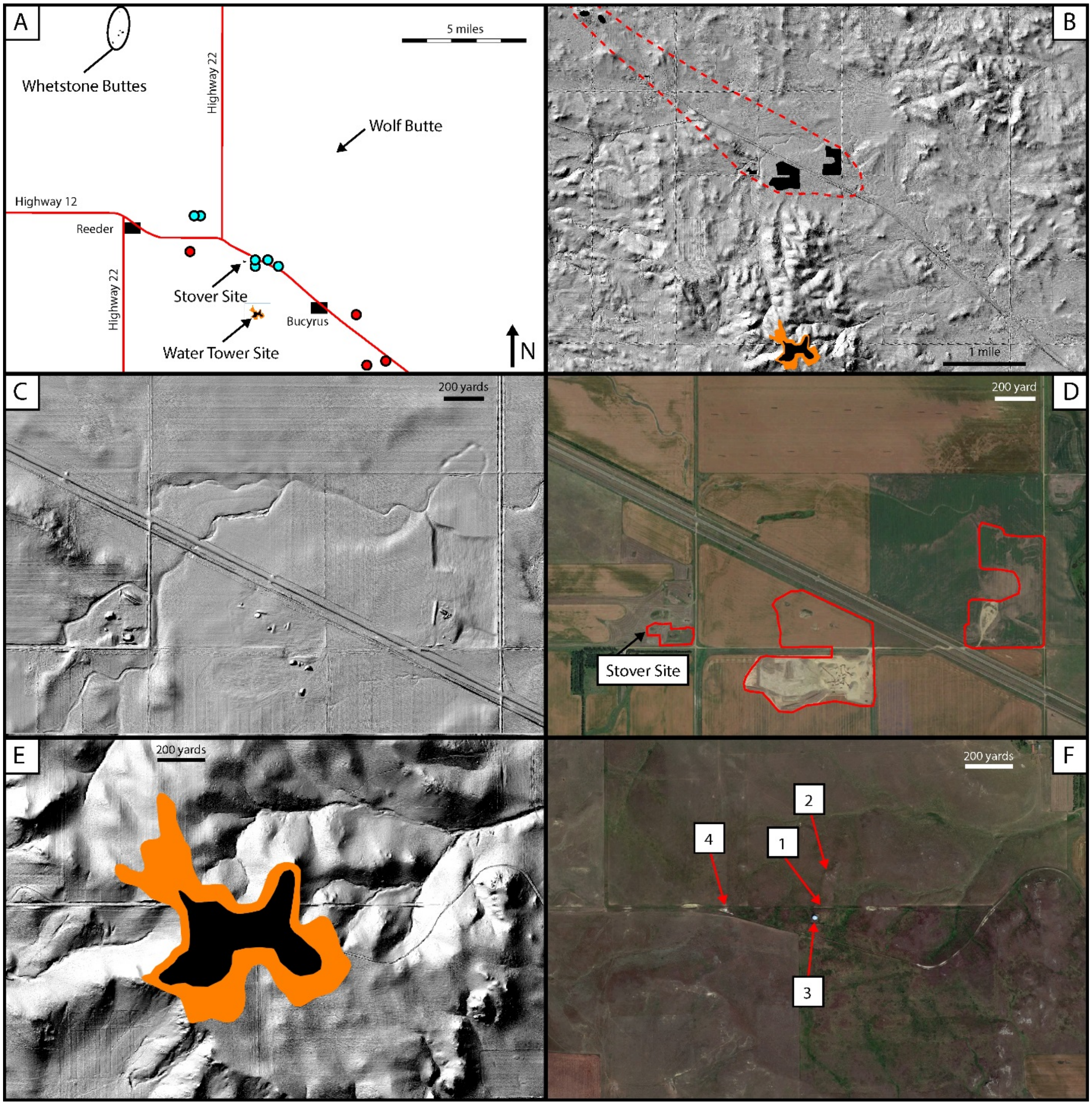

Figure 15. Geographic distribution of Chalky Buttes Member (Chadron Formation) sediments in Adams County, North Dakota. **A**. Overview of all Chalky Buttes Member sediments now recognized in Adams County. Blue circles indicate sites with sediments that match the Stover Site sandstones. Red circles are possible additional sites that still need to be assessed. **B**. LiDAR imagery of the area where newly recognized sediments of the Golden Valley Formation (orange) and Chalky Buttes Member of the Chadron Formation (black)are reported in this study. Red dashed line is the inferred distribution of the Stover Site sandstones based on field observations of exposures and gravel pits. **C**. LiDAR imagery of the area immediately adjacent to the Stover Site, revealing the extent of current and previous gravel pits in the area (compare to D). **D**. Satellite imagery of same area in C, with previously excavated areas of the Stover Site sandstone outlined in red. **E**. LiDAR imagery of the ridge that is capped by newly recognized sediments of the Golden Valley Formation (orange) and Chalky Buttes Member of the Chadron Formation (black). Extents of deposits approximated by following topographic lines based on elevation of exposed outcrops. **F**. Satellite imagery of same area in E highlighting: 1, the road cut shown in figure 16E; 2, position of in situ sediments of the Chalky Buttes Member shown in figure 16C; 3, water tower used as reference point in figure 16; and, 4, outcrop of sediments here referred to the Bear Den Member of the Golden Valley Formation.

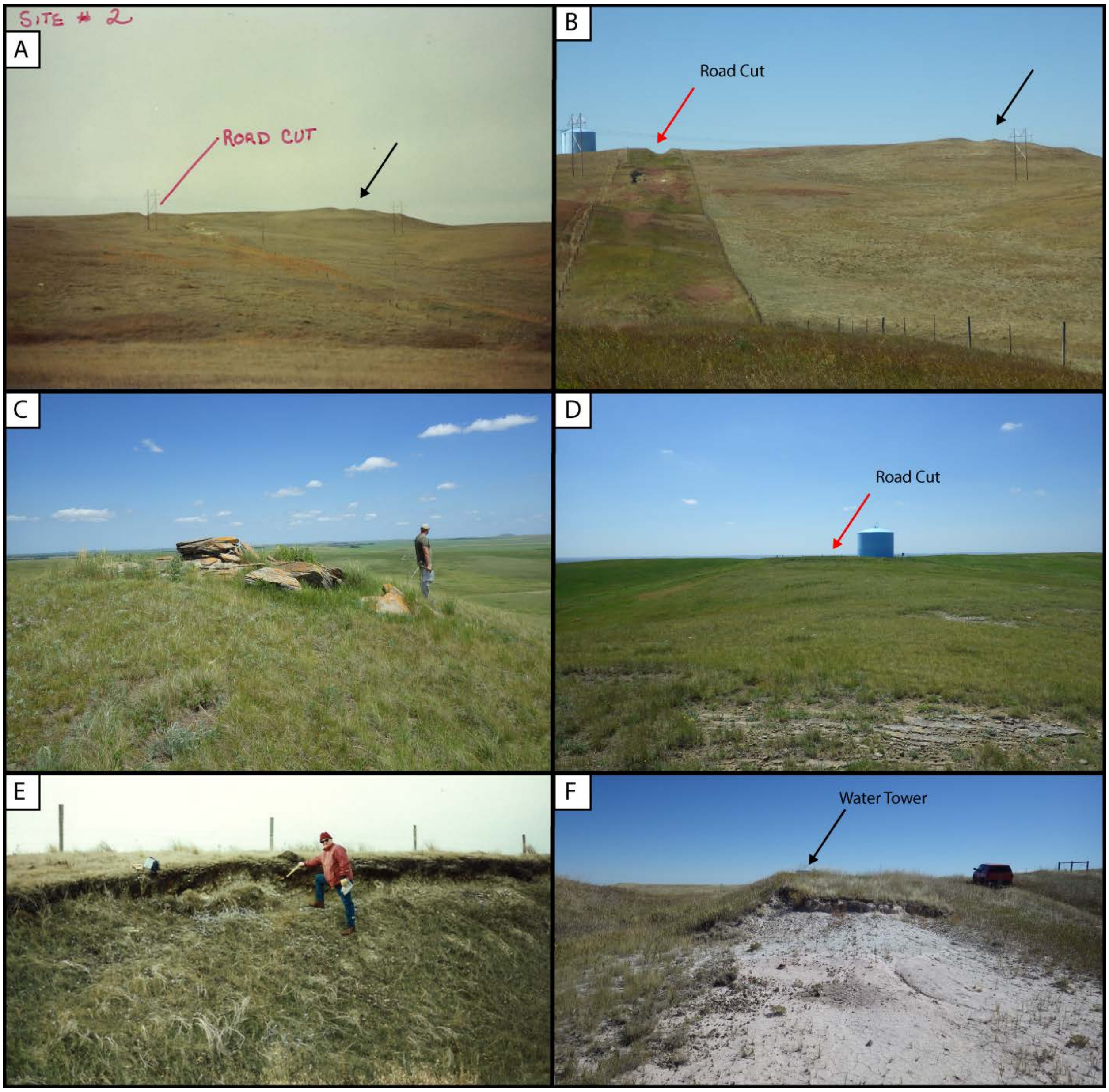

Figure 16. Photographs of the Water Tower Site in Adams County, North Dakota and nearby outcrops. **A**. Photograph from Betty and James Stover in 1994 showing the location of the road cut (red line) where they discovered fossils within gravels in the soil horizon. Black arrow shows location of in situ Chalky Buttes Member sediments. View is to the northwest. **B**. Photograph taken by NDGS paleontologists in 2015 of the same area in A, with red arrow showing the old road cut and black area showing position of in situ sediments. View is to the west. **C**. Photograph taken at the location of the black arrows in A and B. Sediments consist of conglomeratic sandstones that are well indurated by carbonate cements. **D**. Photograph taken from the location shown in C looking south towards the road cut. In situ, cross bedded sandstones of the Chalky Buttes Member can be seen in the foreground, and fossiliferous gravels are present throughout the grassy surface all the way back to the road cut. **E**. Photograph of James Stover from 1994 standing at the road cut highlighted in A, B, and D indicating the level at which they were finding fossils within the surface gravels. View is to the north. **F**. Outcrop of sediments referred to the Bear Den Member of the Golden Valley Formation west of the Water Tower Site. The old road cut is the shallow valley on the left, while the current road is on the right with the truck. The water tower is situated just behind the outcrop, as indicated by the black arrow.

mile west of the Water Tower Site, and almost two hundred feet lower in elevation (~2850 feet versus ~3040). The pit is no longer active, and most of the talus piles are overgrown with vegetation (figures 17 and 18). The rock exposed on the talus piles are highly fossiliferous. Most of the fossils thus far recovered are fragmentary pieces of bones and teeth, most of which are abraded from subaqueous transport prior to deposition, but well-preserved specimens are also present at both the macro and micro scale. Several hundred pounds of rock were collected from this site and subjected to aqueous screen washing following the methods employed at the Medicine Pole Hills fossil locality. The resulting fossils are still being separated and identified, but the portion currently identified is sufficient to provide an important biostratigraphic comparison to the Medicine Pole Hills local fauna in adjacent Bowman County.

The Stover Site Local Fauna

While less productive than the main Medicine Pole Hills site (in terms of pounds of rock washed per identifiable specimen), the Stover Site has thus far produced fossils representing at least 29 vertebrate taxa (18 mammals, 7 reptiles, and 4 fish: Table 1). The fauna as currently known is sufficient to estimate a biostratigraphic "age" for this fauna. Brontotheriid remains are relatively common at the site, especially partial and fragmentary teeth. None are complete enough to firmly support referral to a specific taxon, but their overall size and morphology is consistent with the late Eocene (Chadronian NALMA) taxon *Megacerops* (NDGS2183: Osborn, 1929; Mihlbachler, 2008). The presence of an as of yet unidentified sciurid from the site also supports a Chadronian "age" for the site (NDGS 2357). A partial lower first molar from an unidentified multituberculate (larger and morphologically distinct from *Ectypodus lovei*: NDGS 2332) is a particularly important addition to the fauna. A second, larger species of multituberculate distinct from *E. lovei* is also noted in the Medicine Pole Hills local fauna (Schumaker and Kihm, 2006) and in the Duchesnean Lac Pelletier Lower fauna from southern Saskatchewan (Storer, 1993), but in both cases a new taxon was not named owing to the scarcity of recovered material. The last appearance of multituberculate mammals in North America is within the middle Chadronian (Ch3: Weil and Krause, 2008), which helps delineate the youngest possible age of this fauna.

The most biostratigraphically informative specimens identified thus far from the Stover Site local fauna are two lower molars of the artiodactyl *Leptomeryx* (NDGS 2314 and 2315). The index taxa for the late early Chadronian (Ch2) and middle Chadronian (Ch3) NALMAs are two species of *Leptomeryx*: *L. yoderi* and *L. mammifer*, respectively. The lower dentition of these taxa are differentiated based on size (Table 2), with *L. mammifer* being on average the largest species of *Leptomeryx* present in the Chadronian (Heaton and Emry, 1996). The leptomerycids from the Medicine Pole Hills local fauna, which is hypothesized to be a late early Chadronian (Ch2) fauna (Kihm and Schumaker, 2015), fall within the size range of *L. yoderi* (Table 2). The two lower molars from the Stover Site local fauna fall within the reported size range of *L. mammifer*, are larger than the reported size range of *L. yoderi* and are clearly larger than the sample from the Medicine Pole Hills local fauna (Table 2). Together, the co-occurrence of multituberculates and *L. mammifer* in this fauna strongly imply a middle Chadronian (Ch3: 34.7-35.7 Ma) "age" for the Stover Site local fauna, making it younger than the Medicine Pole Hills local fauna. As such, further study and comparison of these two faunas could provide previously unavailable insight into the evolution of vertebrate faunas within North Dakota during the late Eocene (Chadronian). That topic will be the focus of future work on these two faunas.

Geographic Distribution

Rocks correlative with those present at the Water Tower Site are currently restricted to the top of that ridge in sections 20 and 29 (figures 15E and 15F). No other ridges or buttes in the local area reach a comparable elevation, aside from Whetstone Buttes and Wolf Butte to the north, both of which are also capped by rocks of the Chalky Buttes Member of the Chadron Formation (Murphy et al., 1993). The capping rock at Whetstone Butte (T132N, R98W, section 29) is also a well indurated, green/gray conglomeratic sandstone (Murphy et al., 1993: fig. 66), similar to the in-situ rock at the Water Tower Site. More detailed comparisons are needed, including possible heavy mineral analysis, before any direct correlations between these rocks can

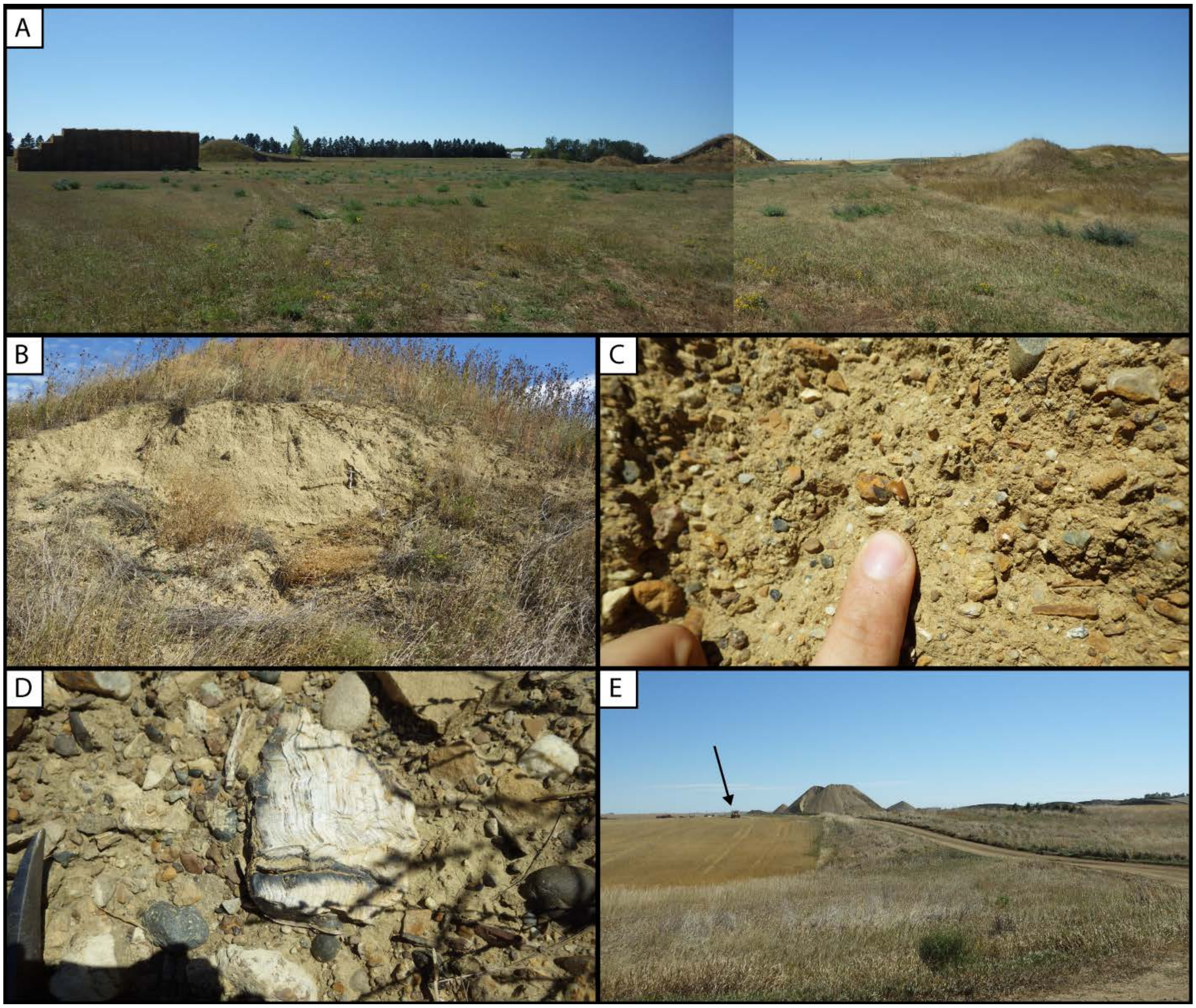

Figure 17. Photographs of the Stover Site area in Adams County, North Dakota. **A**. Overview photograph of the old gravel pit at the Stover Site. The grass covered mounds are piles of sediment left over from previous excavations. View facing southwest. **B**. Fresh face on the main sediment pile at the Stover Site where much of the sediment that was screened for fossils was collected. Rock hammer for scale. View facing east. **C**. Close up of the conglomeratic sandstone at the Stover Site with small tooth fragment exposed in center. **D**. Large piece of petrified wood on a pile of coarser material at the Stover Site gravel pit. **E**. Photograph of the gravel operation that was ongoing in the fall of 2015 to the east of the Stover Site (see figures 15C and 15D). Samples from those sediments produced fossils similar in preservation and age as those at the Stover Site, and it is presumed those sediments were a continuation of the same deposit as was excavated at the Stover Site. Black arrow highlights a gravel hauler for scale. View facing east.

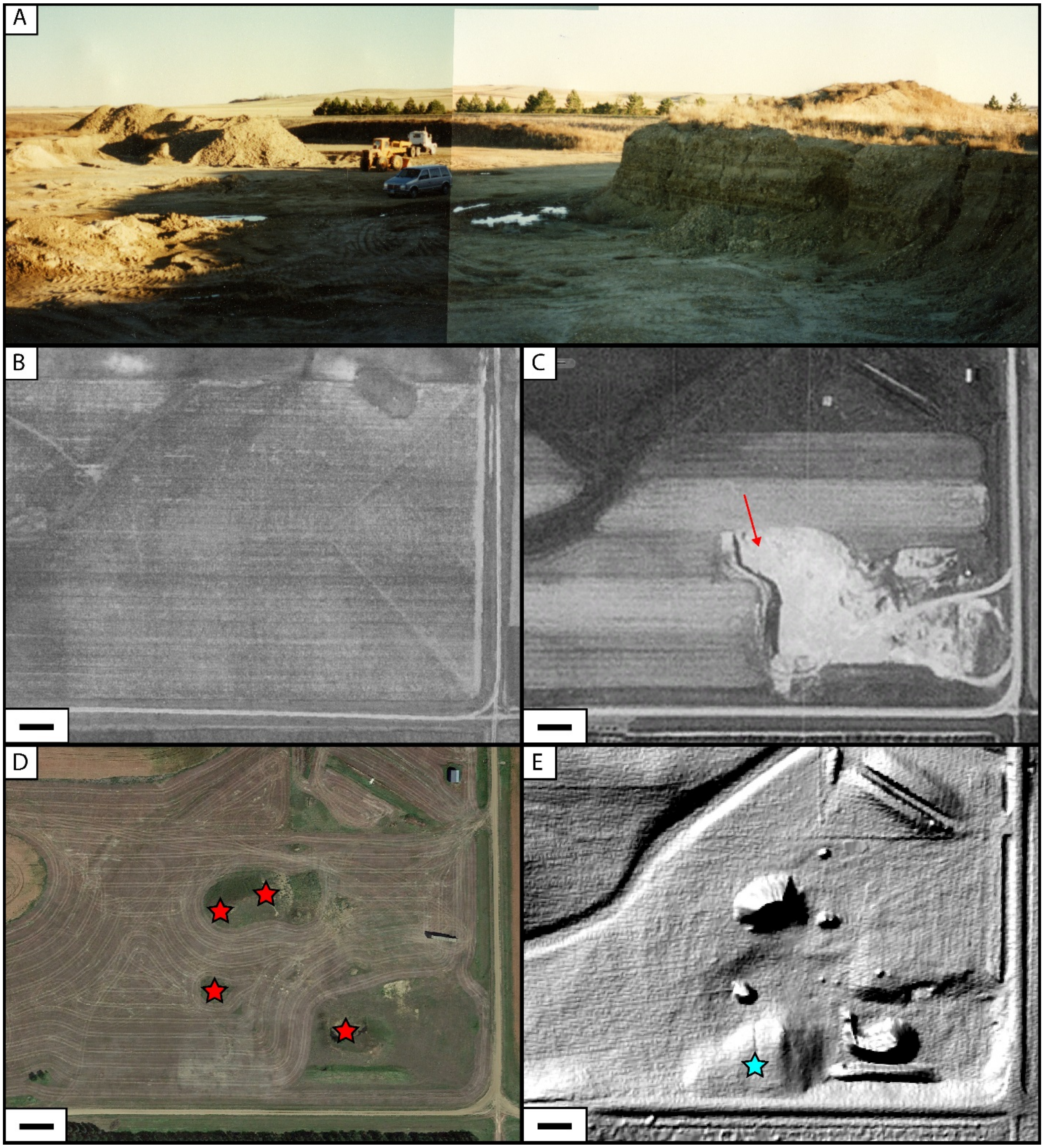

Figure 18. Historical imagery of the Stover Site highlighting the areas where the fossiliferous sediments were previously excavated. **A**. Composite of two photographs (left and right) taken by Betty and James Stover showing the sediments at the Stover Site during excavation in November of 1994. View is to the south and slightly east. **B**. Aerial photograph of the Stover Site in 1957 prior to any excavation. **C**. Satellite imagery of the same area as B taken in June of 1995, shortly after the photograph in A revealing the state of excavation. View of photograph in A shown by red arrow. **D**. Satellite imagery of same area as B taken in August of 2015, one month before NDGS collected samples from the Stover Site. Areas sampled for fossils shown by red stars. **E**. LiDAR imagery captured from NDGS 24K maps of the Stover Site. Data collected during late 2015 through early 2016. Blue star highlights a low-lying area of possible in situ, sod covered sediments (compare to extent of excavation in C). In B-E, north is oriented directly to the top of the page.

Table 1. Faunal list for the Stover Site local fauna (NDGS L236) from the Chalky Buttes Member of the Chadron Formation in Adams County, North Dakota.

- Molluska
  - Gastropoda
    - Gastropoda indet.
- Chondrichthyes
  - Myliobatiformes
    - Myliobatiformes indet.
- Osteichthyes
  - Esociformes
    - Esocidae
      - *Esox* sp.
  - Lepisosteiformes
    - Lepisosteidae
      - Lepisosteidae indet.
  - Siluriformes
    - Ictaluridae
      - Ictaluridae indet.
- Reptilia
  - Chelonia
    - Chelonia indet. [Morph 1]
    - Chelonia indet. [Morph 2]
  - Crocodylia
    - Crocodylia indet.
  - Serpentes
    - Serpentes indet.
  - Squamata
    - Anguidae
      - cf. *Helodermoides* sp.
      - cf. *Peltosaurus* sp.
    - Rhineuridae
      - ?Rhineuridae indet.
- Mammalia
  - Multituberculata
    - Neoplagiaulacidae
      - Neoplagiaulacidae indet.
  - Metatheria
    - Didelphidae
      - *Herpetotherium valens*
- Lipotyphyla
  - Micropternodontidae
    - ?*Micropternodus* sp.
- Leptictida
  - Leptictidae
    - *Leptictis* sp.
- Carnivora
  - Carnivora indet.
- Rodentia
  - Aplodontidae
    - *Prosciurus* sp.
  - Cylindrodontidae
    - Cylindrodontidae indet.
  - Eomyidae
    - *Adjidaumo* sp.
    - *Aulolithomys* sp.
    - *Paradjidaumo* sp.
  - Sciuridae
    - Sciuridae indet.
- Lagomorpha
  - Leporidae
    - Leporidae indet.
- Artiodactyla
  - Dichobunidae
    - cf. *Stibarus* sp.
  - Entelodontidae
    - Entelodontidae indet.
  - Leptomerycidae
    - *Leptomeryx mammifer*
- Perissodactyla
  - Brontotheridae
    - Brontotheridae indet.
  - Rhinocerotidae
    - Rhinocerotidae indet.

See Appendix 2 for specimen numbers supporting most taxonomic identifications.

Table 2. Measurement data for leptomerycid lower molars from the Medicine Pole Hills and Stover Site local faunas compared to reported values for the Chadronian taxa *Leptomeryx mammifer*, *Leptomeryx speciosus*, and *Leptomeryx yoderi*.

Sample		m1			m2			mx		
		L	ASW	PSW	L	ASW	PSW	L	ASW	PSW
Leptomeryx yoderi	Min	5.9	4.0	4.6	6.8	4.7	5.1			
	Mean	7.0	4.8	5.3	7.7	5.6	5.8			
	Max	8.1	5.5	6.1	8.6	6.6	6.7			
Leptomeryx mammifer	Min	7.3	4.7	5.1	8.0	5.8	5.9			
	Mean	8.4	6.0	6.6	9.4	7.0	7.1			
	Max	9.8	7.0	7.7	10.5	8.6	8.0			
Leptomeryx speciosus	Min	5.7	3.5	3.8	6.5	4.2	4.4			
	Mean	6.7	4.5	5.1	7.4	5.3	5.5			
	Max	7.9	5.5	5.7	8.4	6.1	6.5			
Medicine Pole Hills local fauna	Min							6.1	4.2	4.6
	Mean							7.7	5.2	5.7
	Max							8.4	6.3	6.7
Stover Site local fauna	Min							8.2	6.5	6.8
	Mean							8.6	6.9	7.0
	Max							9.1	7.3	7.1

Values for *Leptomeryx mammifer*, *Leptomeryx speciosus*, and *Leptomeryx yoderi* taken from Heaton and Emry (1996:table 6). All measurements are in mm to match published values. See Appendix 3 for raw measurements for the specimens from the Medicine Pole Hills and Stover Site local faunas. **Abbreviations**: **ASW**, anterior selene width; **L**, anteroposterior length; **m1**, first lower molar; **m2**, second lower molar; **mx**, unidentified lower molar (either m1 or m2); **max**, maximum reported value; **min**, minimum reported value; **PSW**, posterior selene width.

be made beyond the referral of both to the Chalky Buttes Member of the Chadron Formation.

The rocks at the Stover Site differ significantly from those at the Water Tower Site, most obviously in their lack of cementation and their relatively low stratigraphic position. Brief surveys of the local area reveal the presence of several other gravel pits within a few miles of the Stover Site at a similar elevation (figure 15). In the fall of 2015, a gravel operation was underway in the adjacent NW ¼ of section 17 (figures 15C and 15D). The rock at that site closely resembles that at the Stover Site, and samples collected with the operator’s permission from that site produced Chadronian fossils that matched the preservation noted at the Stover Site. Immediately to the north in the SW ¼ of section 8, leftover piles of sand and gravel are present from a previously operated gravel pit. Samples from those piles also match those from the Stover Site. Less than two miles to the northwest along the same low-lying hills that run through the Stover Site, two old gravel pits are present (T130N, R98W, sections 1 [NW ¼] and 2 [NE ¼]. The rock in those pits is also similar to that present at the Stover Site. More importantly, the gravel pit in section 1 contains large (>3 inches) cobbles of quartz latite porphyry, which were previously only reported from the Chalky Buttes Member of the Chadron Formation within North Dakota and are considered unique markers of that lithostratigraphic unit (Murphy et al., 1993:p. 100). That discovery supports the referral of those rocks to the Chalky Buttes Member. Former or current gravel pits are also present east and south of the Stover Site (figure 15), but those sites have yet to be examined. At the least, these new Chalky Buttes Member deposits extend over several miles in the area of Reeder, making them by far the most extensive Chadron Formation deposits within Adams County (figure 15). Additional work is needed to survey gravel pits and road cuts in this area of Adams County to determine the full extent of these deposits.

Stratigraphic Relationships

The presence of Chadron Formation rocks at the Water Tower Site and especially at the Stover Site at first consideration seems an unexpected occurrence; however, detailed review of the distribution and stratigraphic relationships of other exposures of the Chadron Formation in the southern region of North Dakota provides some clarity regarding the presence of those deposits and some hypotheses for their deposition. The lowest exposed rocks of the Chadron Formation at South Whetstone Butte (T132N, R98W, section 32, NW/NE) are at an elevation of approximately 3072 feet, though the base of the Chadron Formation is not exposed on that butte (Murphy et al., 1993:p. 70). At North Whetstone Butte (T132N, R98W, section 20, SE/SE) rocks of the Fort Union Group are exposed along the south and east slopes, separated by about ten feet of cover from overlying rocks of the Chadron Formation. Those relationships place the basal contact of the Chadron Formation at North Whetstone Butte between an elevation of 3040 and 3050 feet (Murphy et al., 1993:fig. 69). To the east at Wolf Butte, very thin (<1 foot) lenses of Chalky Buttes Member sandstones are also present at an elevation between 3040 and 3050 feet (Murphy et al., 1993:fig. 71). At the Water Tower site, the base of the Chadron Formation is not exposed, but the position of that contact seems to also be situated between 3040 and 3050 feet. That interpretation is based on the lowest exposure of in situ Chadron Formation rocks just below an elevation of 3050 feet on the north face of the ridge (T130N, R97W, section 20, SW/SE) and the presence of older rocks at an elevation of 3040 feet to the west (T130N, R97W, section 29, NE/NW: Murphy, 2013). Thus, the elevation of the base of the Chadron Formation at the Water Tower Site is consistent with that observed at other locations in Adams County, not including the Stover Site.

At Wolf Butte and the Whetstone Buttes, the Chadron Formation sits on top of the Sentinel Butte Formation of the Fort Union Group (Murphy et al., 1993). The highest exposed rocks underlying the Chadron Formation at the Water Tower Site are exposed at the intersection between an abandoned, east-west section line road and a more recently established road that curves to the south around the water tower before curving north and rejoining the east-west section line road to the east of the Water Tower Site (T130N, R97W, section 29, NE/NW). Those rocks do not match the Sentinel Butte Formation, which is exposed at lower elevations on that same ridge. A prior study investigating the alumina content of the Bear Den Member of the Golden Valley Formation and the Rhame Bed of the Slope Formation in North Dakota examined the dull white to light pink mudstones exposed at that intersection. That study noted that while those rocks were similar to those of the Rhame Bed, they were approximately 300 feet higher in elevation than nearby outcrops of the Rhame Bed (Murphy, 2013:p. 52). As there were no prior reports of Golden Valley Formation in the region and the upper and lower contacts were not exposed, this outcrop was very tentatively identified as the Rhame Bed. However, the rocks at that outcrop are highly micaceous, a characteristic feature of the Golden Valley Formation (Hickey, 1977), which would suggest a referral to the Bear Den Member of the Golden Valley Formation rather than the Rhame Bed.

Support for the referral of those rocks to the Bear Den Member of the Golden Valley Formation can be found in southwestern Grant County. In that area, the southern-most outcrops of Golden Valley Formation rocks are present at the top of Pretty Rock Butte (T131N, R89W, sections 27, 33, and 34: Murphy, 2013). At that location the lowest exposed portion of the Bear Den Member is at approximately 2770 feet (Murphy, 2013:p. 68), though the lower contact with the Sentinel Butte Formation is not exposed. Nearby, a small outcrop of the Rhame Bed is exposed at a roadcut (T131N, R89W, section 13, NW/SW/SW) that ranges from approximately 2485 to 2500 feet in elevation (upper and lower contacts not exposed: Murphy, 2013:p. 69). Thus, in that area of North Dakota the difference in elevation between the Rhame Bed of the Slope Formation and the Bear Den Member of the Golden Valley Formation is slightly less than 300 feet, unlike the thicker section present in more western portions of North Dakota. Given the similar stratigraphic patterns in these two areas and the position of the outcrop directly below newly recognized rocks of the Chadron Formation, the rocks at the outcrop in section 29 (T130N, R97W, NW/NE/NW) are tentatively assigned to the Bear Den Member of the Golden Valley Formation. Rocks of the Sentinel Butte Formation are exposed just down slope to the west of this outcrop at an elevation of 3030 feet, indicating that the preserved thickness of the Bear Den Member at this site is between 10 and 15 feet, and suggesting that the Camels Butte Member is likely absent at this location.

It should be noted that it is possible those rocks here identified as the Bear Den Member may represent a local weathered horizon developed below the disconformity at the base of the Chadron Formation. Under that scenario these rocks would not be correlative with either the Rhame Bed or the Bear Den Member. Additional study is needed on these rocks before that possibility can be either confirmed or refuted.

The presence of the Golden Valley Formation in the area of the Water Tower Site and its absence at both Wolf and Whetstone Buttes to the north can also be better understood by examining outcrops in Grant County where a similar relationship is seen between the Chadron, Golden Valley, and Sentinel Butte Formations. Outcrops of the Chadron Formation are present at the top of the Coffin Buttes (T132N, R90W, section 34; T131N, R90W, sections 2, 3, 10, and 11: Murphy et al., 1993), and a drill core taken 500 feet to the east of South Coffin Butte revealed the basal contact was at 2671 feet and sits unconformably on the Bullion Creek Formation (Murphy et al., 1993:p. 88), indicating that localized erosion prior to the deposition of the Chadron Formation at this location completely removed several hundred feet of the Golden Valley and Sentinel Butte Formations. Six miles to the southeast, the tops of Pretty Rock Butte (T131N, R89W, sections 27, 33, and 34) are capped by up to 90 feet of the Golden Valley Formation, with both the Bear Den and Camels Butte Members present in the thickest sections and no evidence of the Chadron Formation (Murphy, 2013). The lowest exposed rocks of the Golden Valley Formation on Pretty Rock Butte are at approximately 2770, approximately 100 feet higher than the Chadron-Bullion Creek contact at Coffin Buttes. These lithostratigraphic differences over the relatively short distance between the Coffin Buttes and Pretty Rock Butte demonstrate the localized nature of the late Eocene erosion and subsequent deposition of the Chadron Formation in southwestern North Dakota and help to explain the lack of Golden Valley Formation rocks at both Whetstone Butte and Wolf Butte despite their presence as a thin layer at the Water Tower Site.

The above example also demonstrates how Chadronian localized paleotopographic lows downcut several hundred feet into underlying rock while adjacent areas a few miles away experienced far less erosion, as also seen in the elevation differences between the Stover Site and surrounding outcrops in Adams County. Given these observations, the channel sandstones at the Stover Site and adjacent gravel pits were likely deposited within a local paleotopographic low compared to surrounding deposits at the Water Tower Site, Whetstone Butte, and Wolf Butte. The deposits at the Water Tower Site, the Whetstone Buttes, and Wolf Buttes may have been formed on the broad, relatively shallow limbs of the paleovalley containing the Stover Site after the deeper portions were infilled or may represent older deposits that were subsequently cut by the Stover Site paleovalley. However, it is also possible the rocks present at the Stover Site are relatively recently deposited colluvium or alluvium derived from the erosion of topographically higher Chadron Formation rocks (see heavy mineral section below).

Medicine Pole Hills Local Fauna

The presence of fossiliferous White River Group rocks at the Medicine Pole Hills was first reported nearly a century ago by Leonard (1922). Subsequent investigators working in the area agreed with that referral and noted additional fossil discoveries in the area (Hares, 1928; Benson, 1952; Denson et al., 1959). Despite the scarcity of fossils in North Dakota from what is now recognized as the Chadron Formation, detailed investigations into the fossils present at the Medicine Pole Hills did not begin until the 1990's (Pearson, 1993; Pearson and Hoganson, 1995a; Pearson, 1998). Those studies used aqueous screen washing to separate the abundant microvertebrate fossils (largely disarticulated bones and isolated mammal teeth) from the poorly indurated rock. Research on this fauna began as cooperation between the NDGS and the PTRM in Bowman, North Dakota (Pearson, 1993; Pearson and Hoganson, 1995a, 1995b; Pearson, 1998) and was eventually expanded upon by Dr. Allen Kihm and students at Minot State University (MSU) in partnership with the PTRM. To date, work at the main fossil site (PTRM V89002) has processed several tonnes of rock, resulting in the recovery of thousands of identifiable fossils, making the Medicine Pole Hills local fauna one of the most diverse and productive Chadronian fossil localities in North America. Those results are in stark contrast to the majority of the Chadron Formation in North Dakota, which is typically unfossiliferous (figure 19).

Faunal lists for the Medicine Pole Hills local fauna have been briefly outlined in conference abstracts (Pearson, 1993; Pearson and Hoganson, 1995a, 1995b); however, only a small portion of the overall fauna has been studied and described in detail (Smith, 2006, 2011a, 2011b, 2013; Schumaker and Kihm, 2006; Kihm and Schumaker, 2008, 2015; Kihm, 2011, 2013; Kihm and Tornow, 2014). Detailed description of the remainder of that fauna is well beyond the scope of this study and that work is ongoing by several researchers, including paleontologists at the NDGS. However, a full faunal list based on currently identified specimens is included in this study for the first time in over two decades (Appendix 1), demonstrating the high diversity of this fauna. Overall, the well-studied portion of the fauna reveals a unique mix of typical early and middle Chadronian taxa along with several holdovers from older Duchesnean (e.g. the marsupialiform *Herpetotherium* sp. cf. *H. marsupium*) and Uintan faunas (e.g. the sciuravid rodent *Prolapsus*: Kihm, 2013). When compared to other Chadronian local faunas from North America, the Medicine Pole Hills local fauna best fits with the late early Chadronian NALMA (Ch2: 35.7 – 36.5 Ma: Prothero and Emry, 2004; Kihm and Schumaker, 2015). That conclusion is best supported by the presence of the basal ruminant *Leptomeryx yoderi* (as outlined above), which is an index taxon for the late early Chadronian NALMA. That occurrence contrasts with the Stover Site local fauna where the dominant leptomerycid is *Leptomeryx mammifer*, the index taxon for the middle Chadronian NALMA (Ch3: Prothero and Emry, 2004), and *L. yoderi* is absent. The relative biostratigraphic "ages" of these two faunas provide crucial evidence for interpreting the results of heavy mineral analyses on Chadron Formation rocks presented later in this study.

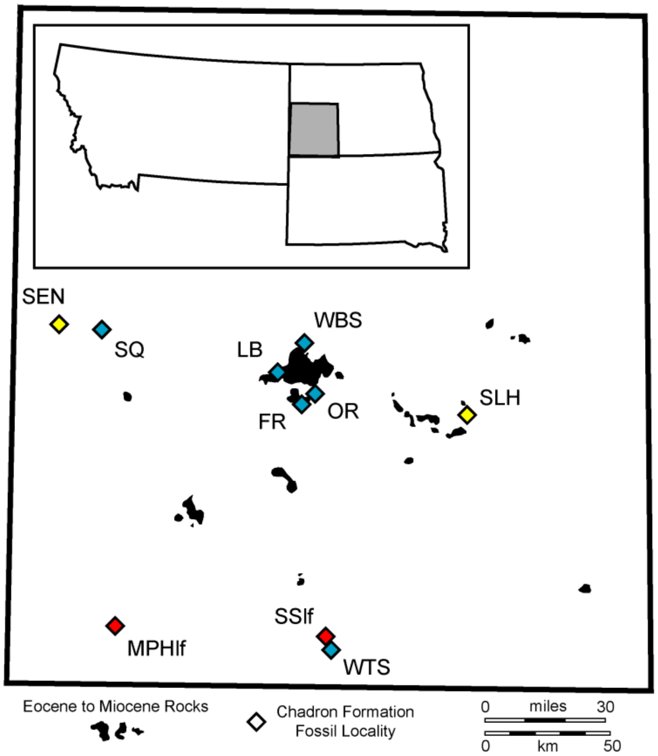

Figure 19. Paleontological localities within the Chadron Formation in southwestern North Dakota. Blue diamonds indicate brontotheriid remains, yellow diamonds equal freshwater fish and associated plants and invertebrates; and, red diamonds indicate the presence of a diverse vertebrate fauna. **Abbreviations**: **FR**, Fitterer Ranch; **LB**, Little Badlands proper; **MPHlf**, Medicine Pole Hills local fauna; **OR**, Obritsch Ranch; **SEN**, Sentinel Butte; **SLH**, South Lime Hills; **SQ**, Square Butte; **SSlf**, Stover Site local fauna; **WBS**, White Butte (Stark County); **WTS**, Water Tower Site.

Other Fossils from the Chalky Buttes Member

Remains of brontotheriids are the most frequently discovered vertebrate fossils from the Chalky Buttes Member of the Chadron Formation in North Dakota (Figure 19), reported from at least eight different areas (Lammers and Hoganson, 1988; Murphy et al., 1993; this study). Aside from material from the Medicine Pole Hills local fauna, brontotheriid remains from the Chadron Formation of North Dakota are highly fragmentary and typically cannot be identified beyond Brontotheriidae indet. However, one specimen discovered by an amateur fossil collector from the Little Badlands area and subsequently donated to North Dakota State University is of additional taxonomic value. That specimen, which has since been transferred to the North Dakota State Fossil Collection (NDGS 2727), is a deciduous upper third premolar (dP3) with part of the unerupted P3 crown and a small piece of the maxilla attached (Figure 20). The size and morphology of that tooth conforms with the taxon *Megacerops* (Osborn, 1929:plate 25, fig. A1). *Megacerops* is restricted to the Chadronian NALMA (Mader, 1998; Mihlbachler, 2008), fitting with the other biostratigraphic evidence recovered from the Chadron Formation of North Dakota. While the exact stratigraphic position of this specimen was not recorded, rock still attached to the specimen matches the channel sandstones of the Chalky Buttes Member found throughout much of the Little Badlands area, rather than the bentonitic claystones of the South Heart Member.

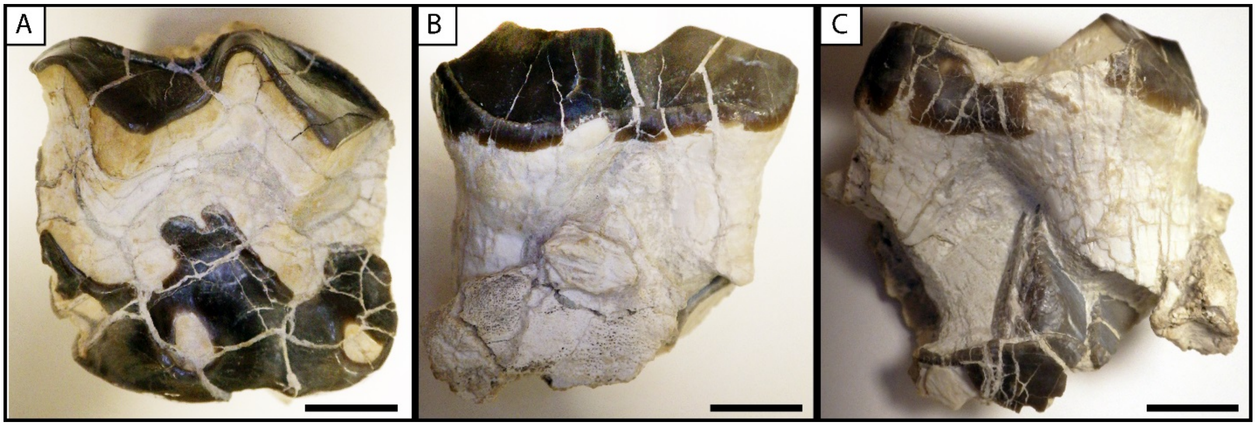

Figure 20. Photographs of brontotheriid (*Megacerops* sp.) dP3 (NDGS 2727) collected from the Chalky Buttes Member of the Chadron Formation within the Little Badlands area of Stark County, North Dakota (NDGS L269). **A**. Tooth crown in occlusal view. **B**. Tooth in labial view with small fragment of maxilla attached to base of the root. **C**. Tooth crown in posterior view with partial crown of the unerupted P3 exposed below. Crown measures 2 inches (51.12 mm) in anteroposterior length and 2 3/16 inches (55.24) mm in transverse width. All scale bars equal 1/2 inch.

The only other mammalian taxon previously reported from the Chadron Formation of North Dakota is single horse (Equidae) specimen referred to *Miohippus assiniboiensis* (Prothero and Shubin, 1989). That specimen (F:AM 116407: a partial palate and mandible) was reportedly collected from the Little Badlands area of Stark County, and is listed as either middle or late Chadronian, suggesting the inference that it was collected from the Chadron Formation (Prothero and Shubin: 1989). However, the shipping inventory for the specimen provided by the American Museum of Natural History lists that specimen (field number 78 from box 8 sent on July 21, 1944) as being collected 14 miles south and 8 miles west of Dickinson, North Dakota, which would be within the area currently known as Fitterer Ranch (broadly considered part of the Little Badlands area). The stratigraphic information is listed as above the nodules in a channel deposit. In the stratigraphic column provided with the shipment, which closely resembles the stratigraphic section of Skinner (1951) the nodular layer is indicated to end at a one to two foot thick white marker zone, which matches the description and stratigraphic position of the Antelope Creek Tuff (Murphy et al., 1993). The “Fitterer Channel” is a prominent channel deposit situated above, and often downcuts through, the Antelope Creek Tuff (Skinner, 1951; Murphy et al., 1993). Thus, it is likely F:AM 116407 was collected from the Brule Formation at Fitterer Ranch, and not from the Chadron Formation. A similar referral to this same taxon of material from Anxiety Butte (Saskatchewan) is now recognized as being from Oligocene (Whitneyan) rocks rather than Eocene (Chadronian) rocks. As a result, *M. assiniboiensis* is removed from the faunal list of the Chadron Formation of North Dakota.

Fossils from the South Heart Member

Few vertebrate fossils are known from the South Heart Member of the Chadron Formation in North Dakota. A similar situation is present in the lithologically equivalent Peanut Peak Member of the Chadron Formation in the Big Badlands area of South Dakota, where fossils are very sparsely present within the bentonitic claystones. In the Big Badlands area, vertebrate fossils tend to be concentrated within or adjacent to well-indurated channel sandstones that are occasionally present within the bentonitic claystones (Figure 21). Those channel sandstones are

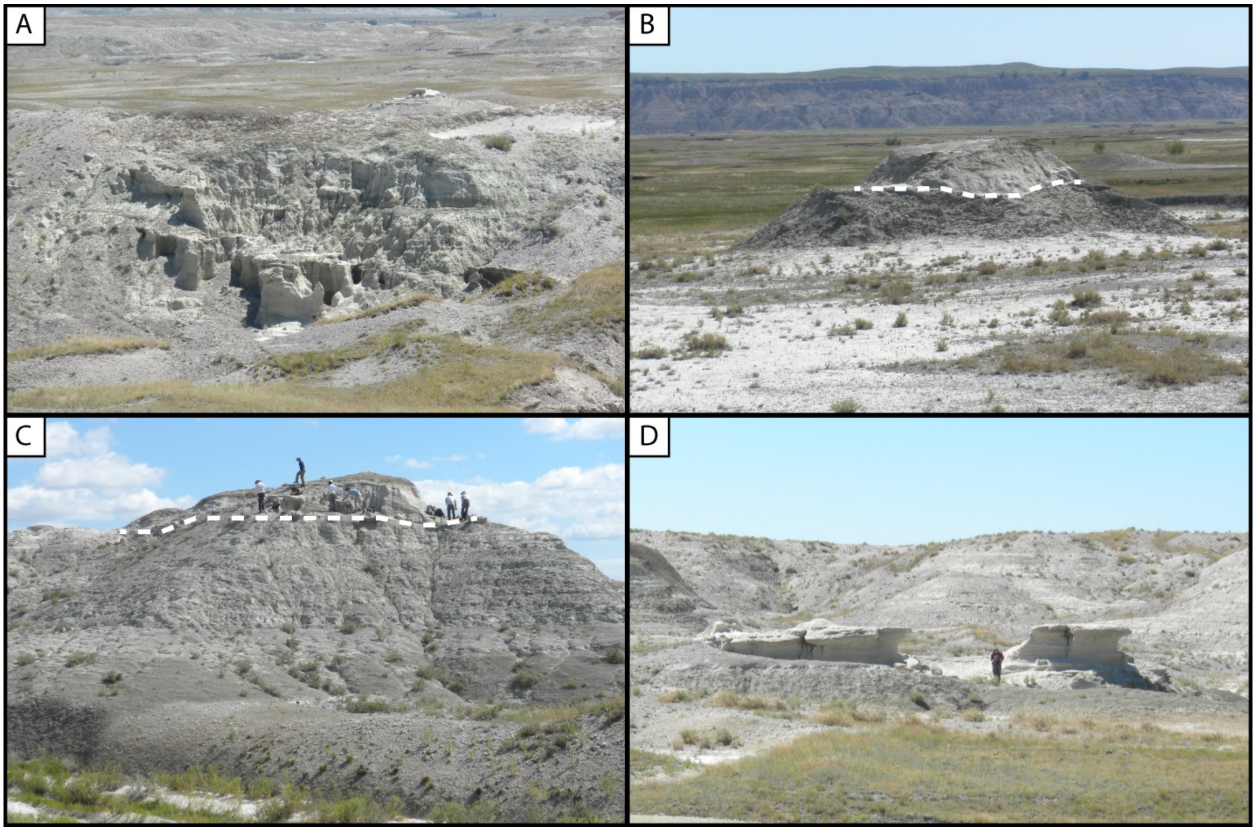

Figure 21. Photographs of channel sandstones situated within the mudstones and claystones of the Peanut Peak Member of the Chadron Formation within the North Unit of Badlands National Park. **A**. Channel sandstone within the Peanut Peak Member. Photograph taken from top of hill shown in C. **B**. Small outcrop of Peanut Peak Member sediments with sandstones sitting on top of typical Peanut Peak Member mudstones. Dashed line highlights the contact between the two lithologies. **C**. Channel sandstone capping a hilltop above typical mudstones of the Peanut Peak Member. Dashed line highlights the contact between the two lithologies. People for scale at top of hill. **D**. Small outcrop channel sandstone in the floor of an erosional valley. Person for scale in center. All photographs provided courtesy of Badlands National Park.

distinct from the sandstones of the underlying Crazy Johnson Member of the Chadron Formation, which are restricted to within the Red River Paleovalley farther to the south and west (Clark et al., 1967; Terry, 1998). Channel sandstones similar to those found within the claystones of the Peanut Peak Member in South Dakota are currently unknown from the South Heart Member of North Dakota, possibly explaining the paucity of fossils recovered from this unit.

The most noteworthy fossils known from rocks referred to the South Heart Member are found within lacustrine limestone beds present within the bentonitic claystone at some locations (Figure 19). Those limestones preserve fossils of freshwater snails, terrestrial snails, charophyte oogonia, ostracods, and several different types of fish (Cope, 1883; White, 1883); Hansen, 1953; Feldmann, 1962; Boyer, 1981; Murphy et al., 1993). These limestones are best studied at Sentinel Butte in Golden Valley County, North Dakota (e.g. Cope, 1883; Feldmann, 1962; Boyer, 1981). At that location, 50 feet of green, calcareous claystone that contains at least three carbonate beds sit directly on top of sandstones of the Golden Valley Formation. Those claystones are referred to the South Heart Member based on similarity to claystones containing limestone beds of variable thickness in eastern Hettinger and Stark Counties (North Dakota) that sit on top of claystones, mudstones, and sandstones referred to the Chalky Buttes Member (Murphy et al., 1993). That makes Sentinel Butte the only site yet known in North Dakota where the South Heart Member sits directly upon pre-Chadronian rocks. However, at nearby Square Butte (approximately six miles east) ten feet of Chalky Buttes Member sandstones sit above Golden Valley Formation sandstones and below South Heart Member claystones that contain carbonate lenses, providing additional support for the referral of the Sentinel Butte claystones to the South Heart Member.

Most of the fish identified from the limestones at Sentinel Butte are referred to two species of centrarchids (sunfishes) that were first named from specimens collected from that location: *Plioplarchus sexspinosis* and *Plioplarchus whitnei* (Cope, 1883; White, 1883). In the Big Badlands area of South Dakota, a prominent limestone bed in the White River Group (Bloom Basin limestone bed) preserves partial centrarchid skeletons that have at least 5 dorsal and anal spines, suggesting they also represent either *P. sexspinosis* or *P. whitnei* (Smith and Miller, 1985; Evans and Welzenbach, 1998). The Bloom Basin limestone bed is situated immediately above rocks that preserve an earliest Orellan fauna (Boyd and Welsh, 2014), indicating it was deposited during the early Oligocene, as opposed to the late Eocene age suggested by other studies (Evans and Welzenbach, 1998). At this time there is no biostratigraphic evidence for deposition of the South Heart Member in North Dakota extending into the early Oligocene (Orellan NALMA), but the similarity between the fish at Sentinel Butte and the Bloom Basin limestone bed may provide support for a late Chadronian “age” for at least some of the South Heart Member.

Heavy Mineral Analysis of the Chadron Formation in the Williston Basin

Denson et al. (1965) reported average heavy mineral compositions of samples collected from Tertiary rock units and the Cretaceous Hell Creek Formation in the Williston Basin region. Raw data from the very fine sand portions of those samples were reported in Denson and Gill (1965), including 23 samples from the late Eocene Chadron Formation. Based on stratigraphic positions and lithologies reported in Denson et al. (1965) and identifications of regional lithologic equivalents to the Chalky Buttes and South Heart Members reported by various authors (e.g. Murphy et al., 1993; Terry, 1998), 16 of the 23 samples were collected from what would now be considered the Chalky Buttes Member (North Dakota) or equivalent rocks in South Dakota and Montana, while five samples were from the South Heart Member (North Dakota) or equivalent rocks (Denson et al., 1965:plates 3 and 4). The remaining two samples from Taylor and Coal Buttes in South Dakota are of uncertain stratigraphic position within the Chadron Formation because Denson et al. (1965) did not provide stratigraphic sections of those locations and attempts to obtain that data from other sources has thus far been fruitless. Stratigraphic sections recorded at the nearby Signal Butte/Fox Ridge and Bison City Dump areas (Denson et al., 1965:plate 4) record only a few feet of sandstone equivalent to the Chalky Buttes Member. Given that the samples at Taylor and Coal Buttes were recovered at a height of 20 and 25 feet above the basal contact, respectively, it is very plausible that those samples were collected from rocks equivalent with the South Heart Member. Therefore, those last two samples were treated as South Heart Member samples for the purpose of this study.

Webster et al. (2015) combined 18 of the above-mentioned samples (the 16 from the Chalky Buttes Member or equivalent rocks and the Taylor Butte and Coal Butte samples) with 18 new heavy mineral samples (grain sizes ranging from very fine to medium sand) from the same stratigraphic interval in the Williston Basin to assess the source areas and stratigraphic relationships of the sandstones at the Medicine Pole Hills (MPH) paleontological locality in Bowman County, North Dakota. The exact stratigraphic relationships of the MPH sandstones have been problematic given that they sit unconformably on the Bullion Creek Formation of the Fort Union Group with no overlying rocks at that location or in the adjacent region. A late Eocene (late early Chadronian NALMA) age is indicated by the fossils preserved at that locality (see biostratigraphy section above), and prior studies (e.g. Murphy et al., 1993) referred the MPH sandstones to the Chalky Buttes Member of the Chadron Formation, which is a sandstone dominated series of fluvial deposits in southwestern North Dakota (Murphy et al., 1993). Analysis of the heavy minerals from the MPH sandstones and comparison to other samples throughout the Williston Basin demonstrated that the MPH heavy mineral assemblage is quite distinct from all other Chalky Buttes Member samples. While the heavy minerals from the MPH sandstones are dominated by amphibole, epidote, and diopside, the dominant heavy mineral assemblages at other localities are either zircon, staurolite, aluminosilicates, and tourmaline or epidote, garnet, zircon, and staurolite, indicating a different source area for the MPH sandstones. As a result, it was suggested that either the MPH sandstones should not be referred to the Chalky Buttes Member of the Chadron Formation, or they should be considered a distinct facies within that lithostratigraphic unit (Webster et al., 2015).

The newly discovered Stover Site paleontological locality in Adams County, North Dakota is also difficult to place in stratigraphic context relative to other rocks in the Williston Basin. Like the MPH sandstones, there are no overlying rocks to provide stratigraphic context and all currently exposed rocks at the gravel pit containing the Stover Site are out of original context. While the recovered Stover Site local fauna indicates a late Eocene (middle Chadronian NALMA) age that is likely slightly younger than the Medicine Pole Hills local fauna (see biostratigraphy section above), the exact relationships to other Chadron Formation rocks in the region is uncertain. Thus, heavy minerals were here used to compare the Stover Site sandstones to other samples from the Chadron Formation within the Williston Basin (figure 2) to address that question and provide better insights into depositional patterns within the Chadron Formation in this region.

Sampling Locations

While much of the heavy mineral data used in this study come from Denson and Gill (1965), data from very fine sand fractions of 13 of the 36 samples analyzed in this study were generated at MSU. Of those 13 samples, two were previously used in a prior analysis of heavy minerals from the Chadron Formation (samples RSB and MPH-F*: Webster et al., 2015), but the raw data from the RSB sample were not included in that study. A third very fine sand sample used in Webster et al. (2015) from the Slim Buttes in South Dakota (Slim Buttes [vf]) is now recognized as coming not from the Chadron Formation, but from an underlying unit that may be equivalent to the Golden Valley Formation. As a result, that sample, which was dominated by micas, is excluded from this study. Most of the 13 new samples were first analyzed by undergraduate students at MSU. Those samples were later checked (and corrected as necessary) by one of us (JRW) prior to use in this study. A quick discussion of the geographic locations and stratigraphic positions of those 13 MSU very fine sand fractions of samples is warranted so that their positions relative to samples from Denson and Gill (1965) can be properly understood.

Five of the very fine sand samples come from the Medicine Pole Hills paleontological locality in Bowman County, North Dakota (T130N, R104W, section 2, NE1/4: 13T, 604716mE, 5107687mN). At that locality, rocks previously referred to the Chalky Buttes Member of the Chadron Formation (Murphy et al., 1993) sit unconformably on the lower portion of the Bullion Creek Formation. Those rocks consist of seven successive sets of fluvially deposited conglomeritic sands and muds that are identified as layers B-H, from bottom to top (Webster et al., 2015:fig. 4). For this study, very fine sand fractions of heavy minerals from layers E, G, H, and F were used, with two samples coming from layer F (MPH-F* and KS-3).

Rattlesnake Butte is one of the prominent buttes that form the Chalky Buttes in Slope County, North Dakota. Denson et al. (1965) based the lower portion of their section number six in the Chalky Buttes on exposures on the east side of Rattlesnake Butte (T134N, R100W, section 31, SW1/4,SE1/4), and the four heavy mineral samples they report from the Chadron Formation at the Chalky Buttes likely came from that area as well. The new sample (RSB) also comes from that same general area of Rattlesnake Butte. Within the collection area, 78 feet of sandstone was recorded, likely corresponding to the conglomeratic sandstone recorded from 20 feet to 107 feet above the base of the Chadron Formation by Denson et al. (1965). In the area where the new sample was collected, two distinct sandstones were noted: a basal gray sandstone (50 feet) and an upper yellowish sandstone (28 feet). Thus, that sandstone interval was about ten feet shorter than that reported for the conglomeratic sandstone by Denson et al. (1965:plate 3). The upper two heavy mineral samples of Denson and Gill (1965: GND-9 and GND-18) were collected 15 and 25 feet from the base of the conglomeratic arkose, respectively, which would correspond to the gray sand interval noted at the new collection site. The new sample was collected from the yellow sandstone between five and ten feet above the contact with the underlying gray sandstone. That position would correspond to approximately 75-80 feet above the base of the Chadron Formation, for comparison to the Denson and Gill (1965) samples.

The Whetstone Buttes include five buttes in Adams County, North Dakota, that are capped by rocks referred to the Chalky Buttes Member of the Chadron Formation (Murphy et al., 1993). Denson and Gill (1965) report two heavy mineral samples from these buttes, but Denson et al. (1965) did not provide a stratigraphic section indicating the exact positions and collection sites of those samples. The lower sample (GND-6) is reported to have been collected ten feet above the base of the Chadron Formation, while the upper sample (GND-8) is reported from 55 feet above that contact. The basal contact between the Chadron Formation and the underlying Sentinel Butte Formation is not currently exposed in the Whetstone Buttes area. Additionally, at no place in the Whetstone Buttes are more than 37 feet of Chadron Formation rocks exposed (Murphy et al., 1993:figs. 66 and 69), so it is likely these two samples were not collected on the same butte. However, rocks of the Sentinel Butte Formation on the south and east slopes of North Whetstone Butte (T132N, R98W, section 20, SE1/4) are separated by about ten feet of covered slope from rocks of the Chadron Formation (Murphy et al., 1993:fig. 69). Therefore, Denson and Gill (1965) could have estimated the height above the base of the Chadron Formation if they had collected the lower sample from North Whetstone Butte. They could have then used the elevation of the contact at North Whetstone Butte to estimate the height above the basal contact of the rocks exposed at the top of the tallest butte in the area, Whetstone Butte (T132N, R98W, section 29, SE1/4). Such an estimate would likely place sample GND-8 at the top of the lower sandstone and claystone interval reported by Murphy et al. (1993:fig. 66). The new sample (WST-2) was also collected from Whetstone Butte, about 13 feet below the base of the coarse conglomerate capping the butte, roughly corresponding to a position about 11 feet below the upper Denson and Gill (1965) sample and 44 feet above the base of the Chadron Formation. These positions are all estimates, but it seems clear that, at the least, sample WST-2 was collected from a position that was between the two samples reported by Denson and Gill (1965).

In the area of Black Butte in Hettinger County, North Dakota, where Denson et al. (1965) measured their stratigraphic section (T135N, R95W, section 12, SW1/4, SW1/4) exposures of the Chadron Formation are very poor. The new sample (BB-1) was collected between one and two feet above the base of the Chadron Formation, comparable to the level where Denson and Gill (1965) collected their sample.

Good exposures of the Chadron Formation were present in the area of White Butte in Hettinger County, North Dakota, where Denson et al. (1965) recorded their stratigraphic section (T136N, R93W, section 16, NE1/4, NW1/4). The new sample (WB-3) was collected between one and two feet above the base of the Chadron Formation at that location. By comparison, the Denson and Gill (1965) sample (GND-54) was collected eight feet above the basal contact.

The South Cave Hills in Harding County, South Dakota, received the densest sampling of heavy minerals of any location included in this study. Denson and Gill (1965) reported five samples from the area of the Denson et al. (1965) stratigraphic section (T20N, R5E, section 5, NW1/4, NW1/4). The new sample (SCH-2) was collected from arkosic sandstones about five feet above the base of the Chadron Formation in that same area, but in a location where the basal conglomeratic sandstone reported by Denson et al. (1965:plate 4) is absent. Field observations of the area by one of us (JRW) indicate that the relative thickness of that arkosic sandstone is variable in that area owing to its apparent cut and fill relationship with the underlying conglomeratic sandstone. The lower two samples reported by Denson and Gill (1965) come from the basal conglomeratic sandstone, the upper two come from the upper bentonites and bentonitic claystones, while the middle sample (CSD-31) was collected from the arkosic sandstone (Denson et al., 1965). Given these facts, sample SCH-2 is here considered to have come from an equivalent stratigraphic level as CSD-31.

The final collection area was in the Long Pine Hills of Carter County, Montana. The stratigraphic section of this area provided by Denson et al. (1965:plate 4) is a composite section from multiple areas (T3S, R62E, section 16, SE1/4, SE1/4; section 17, E1/2; and section 8, W1/3), with no indication of what portions of the section were recorded in which areas. The two new samples in this study (LPH-1 and LPH-4) were collected in the SW ¼ of section 16 at ten feet and one foot above the base of the Chadron Formation, respectively. Denson and Gill (1965) reported two heavy mineral samples from this area. The lower-most sample (GM-345) was collected from the basal sandstone interval 15 feet above the base of the Chadron Formation, and the upper-most sample (GM-347) was collected from the nodular claystone interval 30 feet above the basal contact (Denson et al., 1965). However, the exact collection locations are unknown and the top of the Fort Union Formation in that area is undulatory, making it difficult to place the new heavy mineral samples into exact stratigraphic position relative to the Denson and Gill (1965) samples. The best practice in this case is to conclude that the two new samples likely came from below GM-345, though the exact vertical distance between the new samples and GM-345 is uncertain.

Methodology

Unless otherwise specified, sample processing and data analysis methods follow those used in Webster et al. (2015). Efforts were made to ensure the new data produced in this study were as comparable as possible to the work of Denson and Gill (1965).

Disaggregation and Cleaning

Samples selected for analysis were disaggregated initially by gentle hammering with a three-pound sledge. The smaller pieces were ground against a hardened countertop using the same sledge. Disaggregated samples were soaked in water with a small amount of Calgon detergent for two to three days in a 15-quart plastic tub. After soaking, samples were wet-sieved on a four phi (0.063 mm) sieve to remove the mud fraction. Some samples contained significant amounts of composite grains. Those samples were disaggregated further using a blender. That process involved placing small batches (100-150 mL) of each sample in a blender and running them for four minutes on the “blend” setting (a moderate to low setting). After blending each batch was again wet-sieved to remove the mud fraction. Recovered sand samples were placed back in their respective tubs and dried in an oven.

Grain-size Separation

Dried sand samples were separated into ¼ phi size fractions using eight-inch sieves. The sieves were first cleaned in an ultrasonic bath to remove any grains from prior samples. The 21 sieves needed were used in three sets of seven sieves each. Samples were run through a set of sieves in approximately 100-gram batches for 10 minutes using a tilted shaker machine. For very fine sand samples, sieving was started through the middle set of sieves to save time. Any material collected in the coarsest sieve was then run through the coarser set of sieves. Each size fraction was stored in an appropriate plastic bag, and the weight of each size fraction was measured and recorded.

Heavy-liquid Separation

Selected size fractions were transferred to beakers for ultrasonic bath cleaning to loosen and remove mud particles adhering to grains. Each sample was run 10 times for four minutes each in distilled water. Water was decanted after each run through a four phi (0.063 mm) sieve to avoid loss of sand-sized grains. Samples were then rinsed with distilled water three times, again decanting through the sieve. As much water as possible was decanted after the last rinse, and a minimal amount of water was used to transfer grains from the sieve back into the beaker. Cleaned samples were put in an oven at 60 °C to dry.

Separations were done using a lithium heteropolytungstate solution (known as LST) that had been adjusted to a density of 2.85 g/cm^3. A centrifuge was used at 2500 rpm for 30 minutes. Samples were run in either a 500 mL centrifuge bottle or 50 mL centrifuge tubes. Heavy minerals were extracted from the bottom of the centrifuge bottles/tubes using a syringe with an attached Teflon tube. A glass tube was first inserted through the layer of light minerals that had the bottom capped to prevent entry of light grains. A glass rod was used to remove the cap, and the Teflon extraction tubing was inserted through the glass tube. The syringe was used to extract heavy minerals, taking care to avoid removing too much heavy liquid. Recovered heavy mineral grains were filtered and then rinsed several times with distilled water. They were transferred to a beaker and dried in an oven at 60 °C. Light minerals were also recovered by filtering, rinsing, and drying. Dried heavy minerals were transferred to a small labeled and weighed glass vial. Light minerals were stored in small plastic bags for possible future work.

Grain-mount Preparation

Grain mounts for each sample were prepared on one-inch round glass slides. Slides were frosted on one side by hand-lapping with silicon carbide grit. A small amount of epoxy was then placed on the frosted side, and heavy mineral grains were sprinkled onto the epoxy with a spatula. A rectangular cover slip was placed on top and pressed down to spread the epoxy and grains in order to arrange the grains into a single layer as much as possible. After the epoxy cured (at least 24 hours), the excess cover slip was broken off and the edge ground smooth using the grinding wheel on a thin-section machine. Some grain mounts were polished and coated with carbon for microanalysis (spot chemical analysis of grains) using a scanning electron microscope equipped with an energy dispersive spectrometer system (SEM-EDS). These grain mounts were partially ground with a thin-section machine to partially expose grains and then polished using Buehler Metaserve 2000 polishing machine with a series of five diamond and alumina polishes. Polished sections were coated with carbon using a Denton Vacuum Desk 2 sputter coater equipped with a carbon coating accessory.

Grain mounts selected for optical microscopy work (and possibly SEM-EDS analysis) were scanned using a 35-mm slide scanner. The digital images were imported into Adobe Illustrator, which was used to divide the image into quarters (A-D) and sub-sections (labeled with lower-case letters) with polygon lines. Within each sub-section (drawn to contain approximately 40–50 grains each), grains were numbered. Each grain could then be individually referenced by quarter, sub-section, and grain number (e.g., Ac38).

Heavy Mineral Analysis

A polarized-light microscope was used to describe and identify approximately 550-650 grains. More grains were counted in samples in which more opaque grains were found, so that a sufficient number of non-opaque grains were identified (ideally around 500, but at minimum several hundred). The main properties described for each grain were color and pleochroism, birefringence, cleavage, and degree of transparency (clear vs turbid). For hornblende grains, the pleochroic formula was recorded. Grain identifications were tabulated in an Excel spreadsheet.

These raw heavy mineral data from the non-opaque grains were then modified in the following ways prior to analysis. Muscovite and apatite/bone were excluded to allow comparison with data from Denson and Gill (1965), which excluded white mica because it was typically found in both the light and heavy mineral fractions and excluded apatite because their samples were treated with acid, which can dissolve apatite. Calcite was also excluded as carbonates are typically not included in heavy mineral analysis and its presence in the Denson and Gill (1965) samples likely would also have been impacted by the acid treatment. Remaining non-opaque heavy minerals were normalized to 100 percent.

A series of cluster analyses (details below) were conducted to compare heavy mineral samples from the Chadron Formation of North Dakota and the surrounding region (Montana and South Dakota). Unless otherwise state below, methods for the cluster analyses follow those reported by Webster et al. (2015). In preparation for cluster analysis, some very similar minerals reported by Denson and Gill (1965), Webster et al. (2015), and this analysis were combined prior to analysis (Appendix 4). Andalusite, kyanite, and sillimanite were combined into an aluminosilicate group (Al-silicates). Epidote, clinozoisite, and zoisite were combined into an epidote group. Actinolite and hornblende were combined into an amphibole group. Abundances of 14 heavy minerals were used in carrying out cluster analysis calculations: aluminosilicates, amphibole, augite, biotite, diopside, epidote, garnet, hypersthene, monazite, rutile, sphene, staurolite, tourmaline, and zircon. Only three heavy minerals with very infrequent occurrences and/or very low abundances were excluded: chlorite, allanite, and goyazite.

Results

A large number of heavy mineral grains had to be counted and identified from the Stover Site sample in order to obtain data on a sufficient number of non-opaque grains. In the very fine sand fraction (3.5–3.25 phi: 0.090–0.106 mm), 2,086 grains were counted and identified, yielding 463 non- opaque grains. In the medium sand fraction (2–1.75 phi: 0.25–0.30 mm), 1,596 grains were counted and identified, yielding 370 non-opaque grains. The two size fractions had very similar and high percentages of opaque grains (Table 3). Those opaque grains were dominated by ferruginous aggregate grains, some of which had fairly large grains within them (often calcite and quartz/feldspar). Among the non-opaque grains (normalized to 100%), in both size fractions bone fragments were the most common grains identified, especially in the medium size fraction (Table 3). The very fine sand fraction also had a high percentage of calcite, which was lacking in the medium sand fraction. The calcite grains frequently had a coating of ferruginous material, similar to what made up the majority of opaque grains.

Normalized percentages of the analyzed non-opaque heavy minerals for the Stover Site are shown in Table 3, while those from all other very fine sand fractions of samples used in this study are provided in Appendix 4, and those from medium sand fractions of samples are provided in Appendix 5. The former values are based on a total of 206 grains in the 3.5–3.25 phi (0.090–0.106 mm: very fine sand) fraction and 202 grains in the 2.0–1.75 phi (0.25–0.30 mm: medium sand) fraction. The very fine sand fraction showed more diversity in its assemblage of heavy minerals, with epidote > hornblende, garnet > diopside. Other minerals with > 1% were sphene, zircon, tourmaline, actinolite, and biotite. The medium sand fraction was dominated by diopside > hornblende, epidote > garnet.

The diopside (calcic pyroxene) in the Stover Site samples looks very similar to what was called augite in Brule Formation samples (Webster, unpub. data), and similar to diopside in MPH sandstone samples (Webster et al., 2015). It should be noted that with regards to the Brule Formation samples (Webster, unpub. data), the name augite was applied to the calcic pyroxene minerals identified in those samples in order to maintain consistency with the minerals reported in Denson and Gill (1965) from the Brule Formation. One difference in the diopside grains from the Stover Site compared to those from the MPH samples is that denticulated terminations were

Table 3. Heavy minerals identified (raw and normalized values) from the two grain size fractions from the Stover Site sample STOV-3.

		All Heavy Minerals		Select Heavy Minerals [a]	
Grain Size		VF	M	VF	M
Total Heavy Mineral Grains		2086	1596		
Non-opaque Grains		463	370	206	202
Percent Opaque Grains		77.8	76.8		
Percent Non-opaque Grains		22.2	23.2		
Normalized Non-opaque					
Diopside		3.9	21.1	8.7	38.6
Augite		0.2	0	0.5	0
Hypersthene		0.2	0.5	0.5	1.0
Biotite		0.6	0	1.5	0
Amphiboles	Hornblende	6.7	11.9	15.0	21.8
	Actinolite	0.9	0.3	1.9	0.5
Epidote (Epi-Cz)		19.0	11.9	42.7	21.8
Garnet		6.9	6.8	15.5	12.4
Staurolite		0.2	0.3	0.5	0.5
Al-silicates		0	0	0	0
Sphene		1.9	0.8	4.4	1.5
Monazite		0	0	0	0
Zircon		1.7	0	3.9	0
Tourmaline		1.1	0.3	2.4	0.5
Rutile		0	0	0	0
Allanite		0	0.3	0	0.50
Chlorite		0.9	0.3	1.9	0.5
Apatite		2.4	0		
Bone		29.8	45.1		
Muscovite		0.4	0.3		
Calcite		22.9	0		
Unknown		0.2	0.3	0.5	0.5
Total		100.0	100.0	100.0	100.0

Notes: Data shown for heavy minerals are grain percentages. **Abbreviations**: **Epi-Cz**, epidote-clinozoisite; **M**, medium sand fraction; **vf**, very fine sand fraction.

[a] = Normalized excluding non-opaque minerals that were also excluded by Denson and Gill (1965).

less abundant, and when present were not as well-developed (more similar to what was found in Brule Formation samples). Hornblende grains showed a variety of pleochroic types, as found in the MPH and Brule Formation samples (Webster et al., 2015; Webster, unpub. data). Epidote grains varied in their appearance, ranging from clean light green to yellow-green grains to turbid grains, often multi-crystalline or fine-grained.

Interpretation of Grain Size Differences in Heavy Minerals

The medium size fraction yielded a heavy mineral assemblage that was very similar to analyses of the same size fraction from the MPH samples, which were also dominated by hornblende, epidote, and diopside, with some garnet and biotite (Webster et al., 2015). The one big difference between the Stover Site and MPH samples was the much higher percentage of opaque grains in the former (76.8%). Opaque grains in the medium size fraction of MPH samples ranged from 0.8% to 15.6%, with an average of 5.3%.

The very fine sand fraction appeared to be a mixture of a typical Chalky Buttes Member sandstone heavy mineral assemblage (CBM-type) and a Medicine Pole Hills sandstone assemblage (MPH-type). Diopside in particular was much less abundant in the very fine sand fraction compared to the medium sand fraction. Hornblende was somewhat lower, epidote was higher (about twice as much as the medium size fraction), and garnet was slightly higher than in the medium sand fraction. These data indicate that the CBM-type assemblage was epidote-garnet-rich, most similar to Long Pine Hills (Montana) samples (Appendix 4).

The ability to produce the assemblage of the Stover Site very fine sand fraction through mixing was tested using least-squares mass-balance mixing calculations. These were carried out using software written by JRW for testing crystal fractionation and magma mixing hypotheses. The software was adapted for use here by using heavy mineral abundances in place of major element oxide weight percentages. The calculations used a combination of two of the Long Pine Hills (LPH) samples (LPH-4 and LPH-1: Appendix 4) and a combination of MPH samples to determine the mixture that yielded the best fit with the observed non-opaque heavy mineral assemblage of the Stover Site very fine sand fraction. The results showed that the best match was obtained with a mixture consisting of 65% LPH assemblage (approximately 5:4 LPH-4 to LPH-1) with 35% MPH-type assemblage.

Cluster Analyses of Chalky Buttes Member Samples

Cluster analysis was used to compare the results for both size fractions of the Stover Site sample with available heavy-mineral data from Chalky Buttes Member samples. Chadron Formation heavy mineral samples of very fine sand fractions were taken from Denson and Gill (1965), Webster et al. (2015), Klingbeil (2017), and the new samples reported in Appendix 4. Samples of medium sand fractions were taken from Webster et al. (2015) and from preliminary data of JRW (some from undergraduate student studies: Appendix 5).

A dendrogram was produced based on the results of a cluster analysis of only the very fine sand fractions of samples from the Chalky Buttes Member or equivalent rocks (figure 22). In that dendrogram the Stover Site sample clusters most closely with two samples from the Long Pine Hills (LPH-1 and LPH-4), as part of sub-group B1. That sub-group also includes another

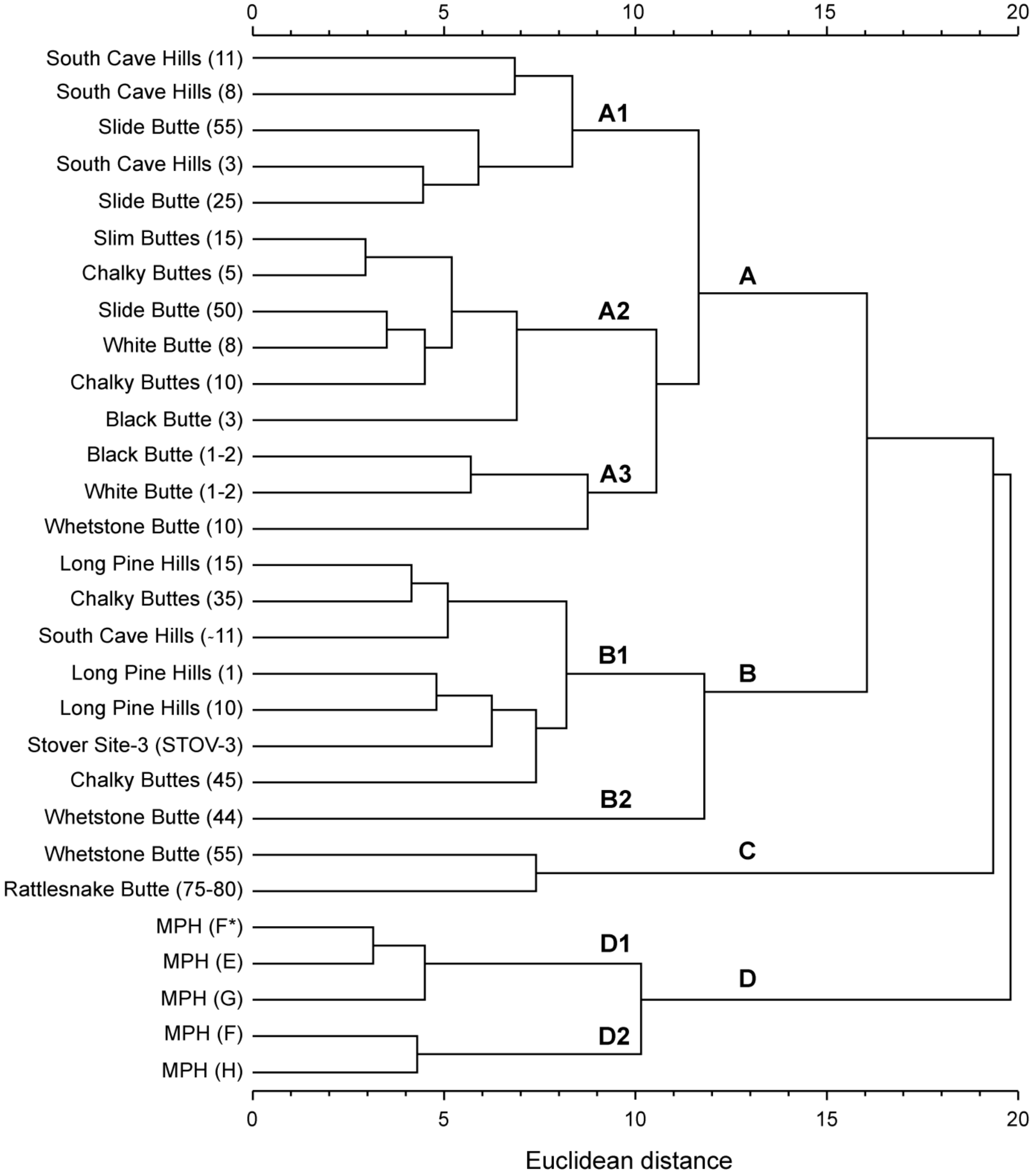

Figure 22. Dendrogram based on cluster analysis of heavy mineral analyses of very fine sand fractions from the Chalky Buttes Member (North Dakota) or lithologic equivalents (Montana and South Dakota). Numbers in parentheses indicate how many feet above the base of the Chadron Formation the sample was collected. See Appendix 4 for raw values and Appendix 6 for group and sub-group averages.

sample from the Long Pine Hills (GM-345), a sample from the lower part of the Chadron Formation in the South Cave Hills (SCH-2) and the upper two (of four) Chalky Butte area samples reported by Denson and Gill (1965: GND-9 and GND-18). Average heavy mineral abundances of the groups and sub-groups are shown in Appendix 6. Despite the presence of diopside and hornblende in the Stover Site sample, the abundances of epidote and garnet were apparently the dominant factors that caused that sample to cluster with sub-group B1, which is overall dominated by the latter two minerals.

A second dendrogram was produced based on the results of cluster analysis of medium sand fractions (figure 23). The Stover Site sample in this case clusters with MPH samples, and most closely with the very diopside-rich sample MPH-F* as part of sub-group D2. Aside from the Stover Site sample, group D consisted only of MPH samples. Average heavy mineral

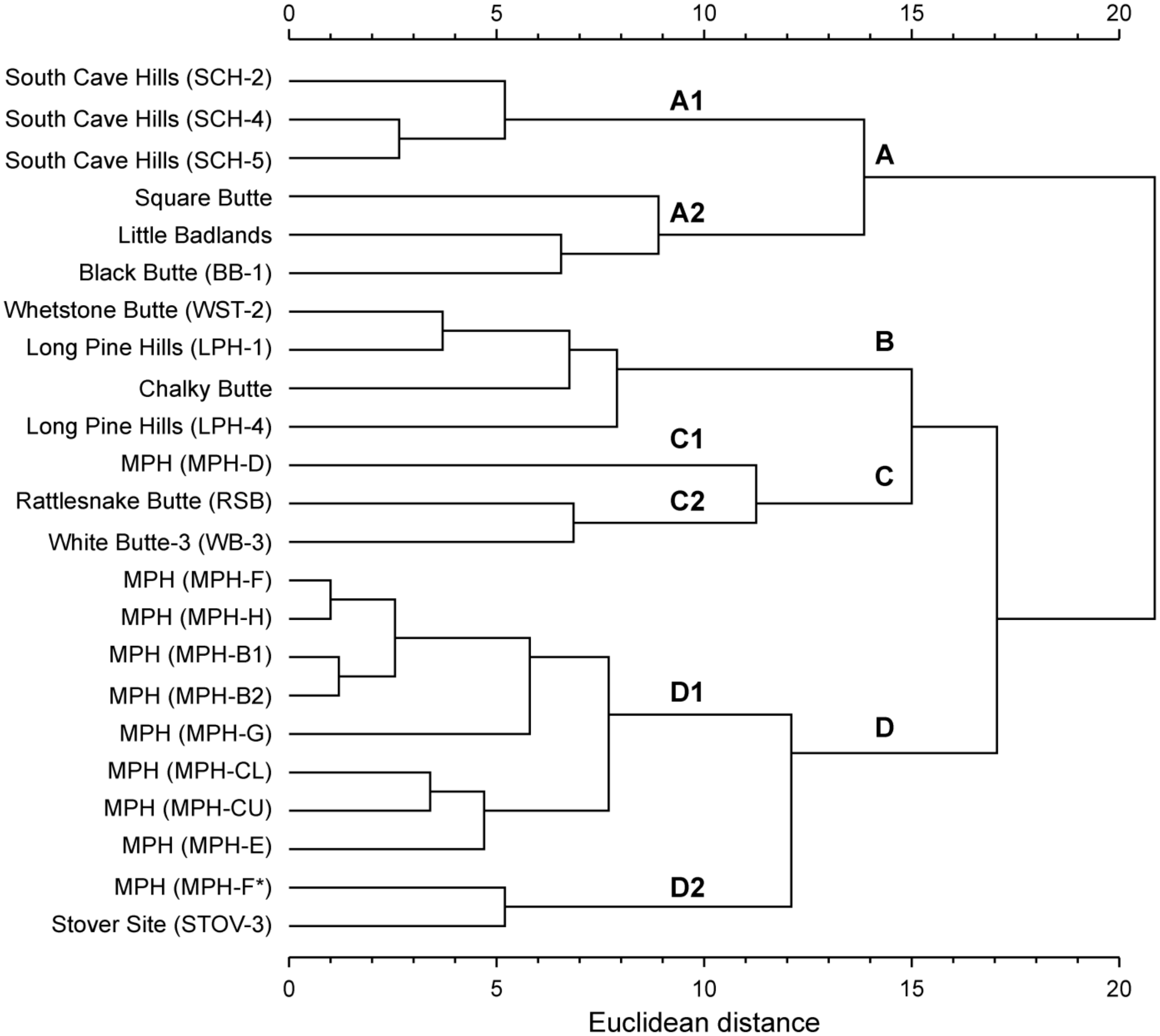

Figure 23. Dendrogram based on cluster analysis of heavy mineral analyses of medium sand fractions from the Chalky Buttes Member (North Dakota) or lithologic equivalents (Montana and South Dakota). Sample identifications provided in parentheses. Raw values are given in Appendix 5. Group and sub-group averages provided in Appendix 7.

abundances of the groups and sub-groups are shown in Appendix 7. Sub-group D2 consisted of samples with higher diopside and lower amphibole and garnet compared to the sub-group D1 samples.

Cluster Analysis Including South Heart Member Samples

Another cluster analysis was conducted using all 36 available samples of very fine sand fractions from the Chadron Formation, including seven samples likely collected from the South Heart Member and equivalent rocks. Adding the South Heart Member samples into the analysis does change things slightly, but overall the same basic heavy mineral assemblage types are found (figure 24). Average heavy mineral abundances of the groups and subgroups are provided in Appendix 8 and summarized generally in Table 4. The Stover Site sample is again part of sub-group B1 along with the same six samples discussed above in the prior analysis of very fine sand fractions. The only change to group B is one sample from Whetstone Butte (GND-6) that moves from group A into Group B to form a new sub-group B2. All of the newly included samples from the South Heart Member (or equivalent rocks) are recovered within group A, and there is some rearrangement of samples within group A compared to the dendrogram produced using only Chalky Buttes Member samples (figure 22 versus 24).

Subsequent cluster analyses in this study use this set of 36 very fine sand fraction analyses to investigate how samples cluster when a certain mineral (or minerals) is (are) excluded. When discussing those results, the designations of groups and sub-groups shown in figure 24 are maintained as much as possible to facilitate comparisons between analyses.

Cluster Analysis Without Biotite

Biotite is a mineral that has a significant effect on how these samples cluster. This is most obvious in the case of group C (figure 24), which consists of two very biotite-rich samples. This biotite is volcanic in origin, and its deposition may have been rather “sporadic” in that its source does not seem to be tied to other volcanic sources (which produced diopside and hornblende). Given that biotite would not be (as intimately) controlled by fluvial transportation systems, it is useful to look at how heavy mineral assemblages compare when biotite is excluded. To test this concept, a cluster analysis was carried out with biotite removed and the percentages of remaining heavy minerals normalized to 100%.

With biotite excluded, group C was no longer recovered (figure 25; Appendix 9). The two biotite-rich samples that were previously in group C, one from Rattlesnake Butte (RSB) and another from Whetstone Butte (GND-8), joined group B and group D, respectively. The Rattlesnake Butte sample became part of sub-group B3 along with one sample from Long Pine Hills (LPH-4), which was previously part of Group B1. The Whetstone Buttes sample (GND-8) became part of group D2. The only other change is that another sample from the Whetstone Buttes (GND-6) moved from sub-group B2 to sub-group B1. Removing biotite had no effect on clustering in Group A. Other than the addition of the Whetstone Butte sample (GND-8) to D2, the group D sub-groups remained the same.

These results highlight that when the biotite source excluded, the Rattlesnake Butte sample (RSB) is most similar to group B (B3) given the abundance of epidote and garnet in that

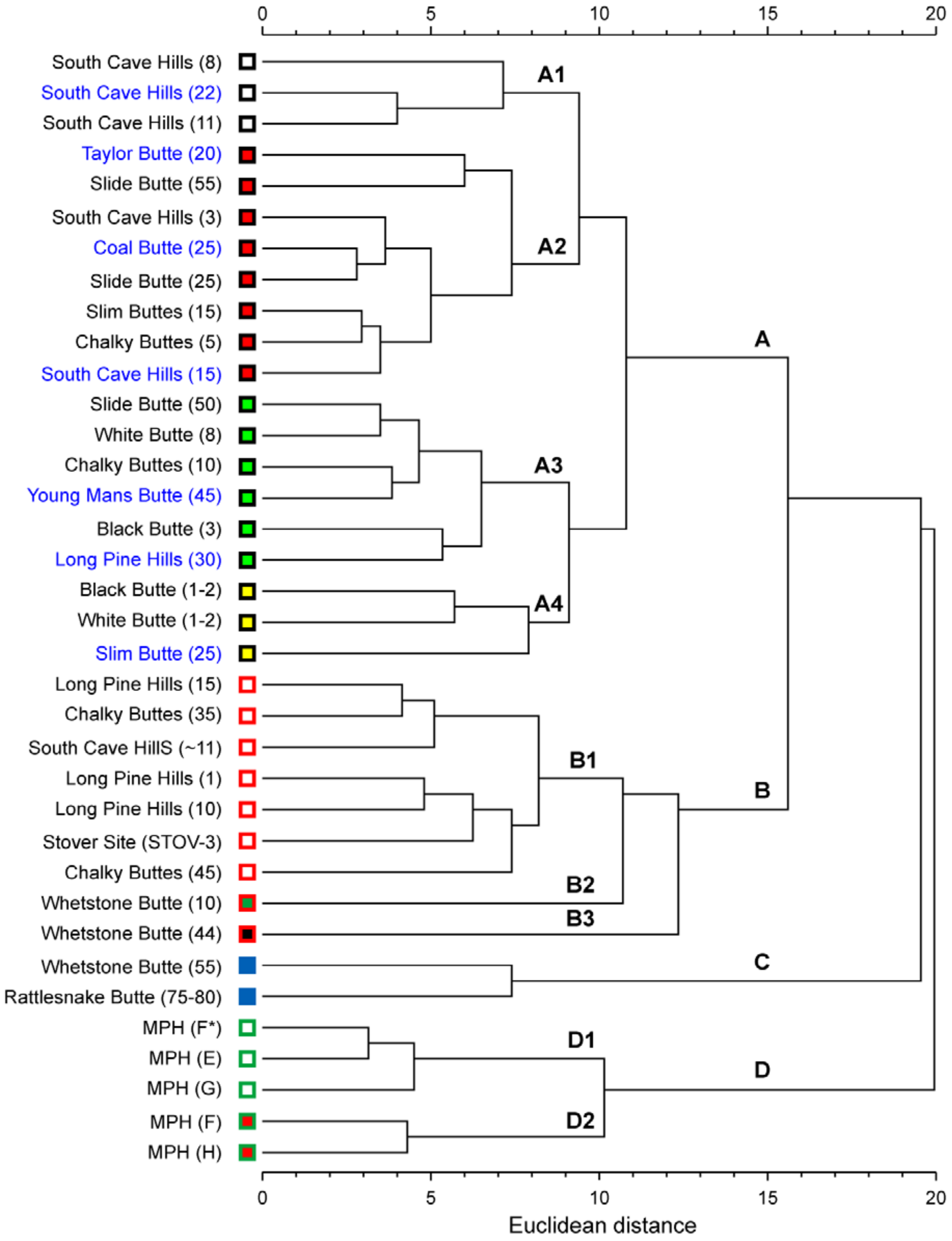

Figure 24. Dendrogram based on cluster analysis of heavy mineral analyses of very fine sand fractions from the Chadron Formation in the Williston Basin. Samples listed in blue are from the South Heart Member (North Dakota) or lithologic equivalent (Montana and South Dakota), while all the others are from the Chalky Buttes Member (North Dakota) or lithologic equivalents (Montana and South Dakota). Numbers in parentheses indicate how many feet above the base of the Chadron Formation the sample was collected. See Appendix 4 for raw values and Appendix 8 for group and sub-group averages.

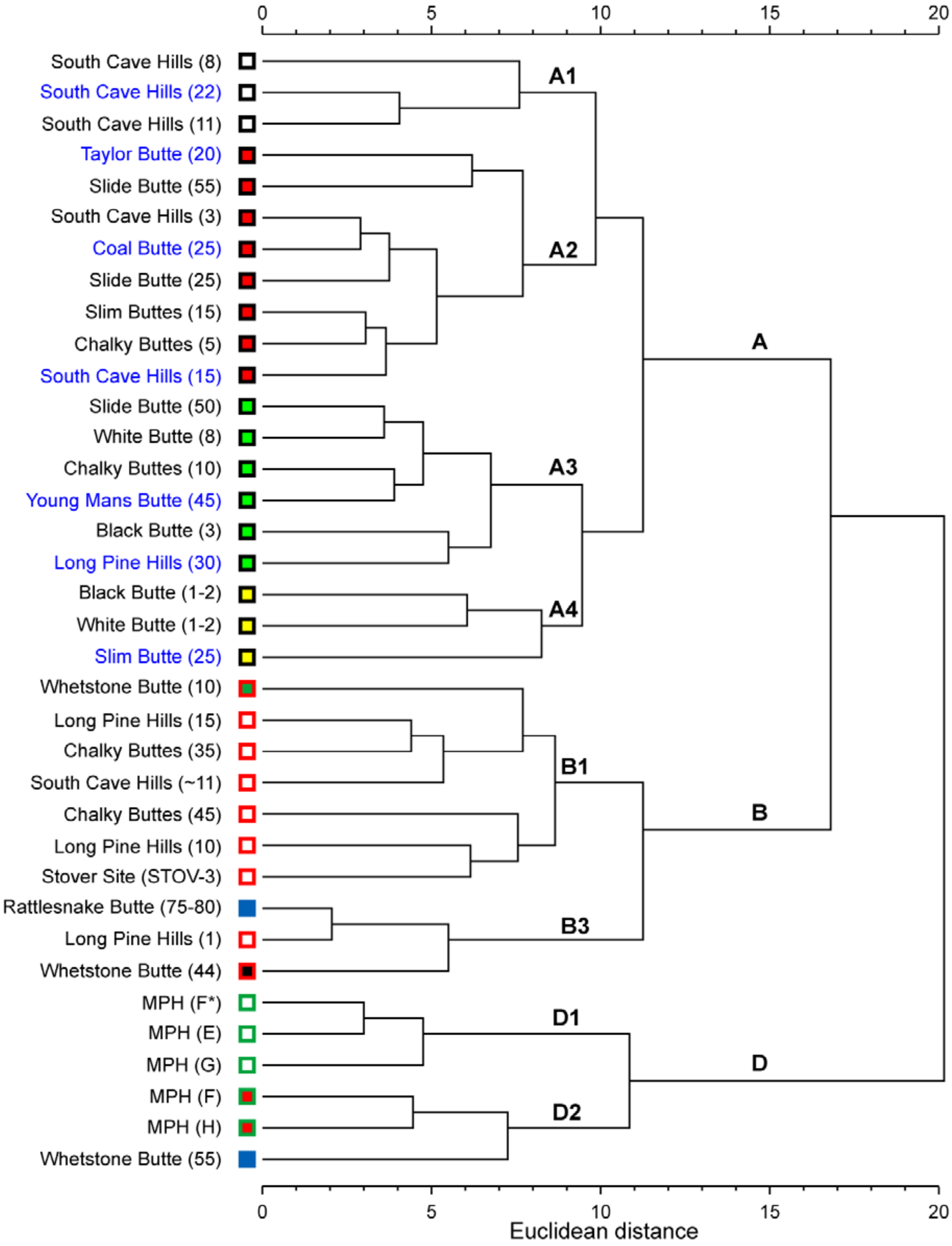

Figure 25. Dendrogram based on cluster analysis of heavy mineral analyses of very fine sand fractions excluding biotite. Colored squares correspond to the groups recovered in figure 24 when all minerals are included. Samples listed in blue are from the South Heart Member (North Dakota) or lithologic equivalent (Montana and South Dakota), while all others are from the Chalky Buttes Member (North Dakota) or lithologic equivalents (Montana and South Dakota). Numbers in parentheses indicate how many feet above the base of the Chadron Formation the sample was collected. See Appendix 4 for raw values and Appendix 9 for group and sub-group averages.

Table 4. Summary of dominant and minor heavy minerals by group and sub-group resulting from the analysis of all 36 Chadron Formation samples.

	Groups			Sub-groups	
	Dominant minerals	Minor minerals		Dominant minerals	Minor minerals
A	Zir > St > As, Tml	Epi > Rut, Gt	**A1**	As > St, Tml > Epi	Zir > Gt > Rut
			A2	St > Zir > As > Tml	Epi > Rut, Gt
			A3	Zir > St	Tml, As > Epi > Rut, Gt
			A4	Zir, Tml > St	Epi > Rut > As > Gt, Sph
B	Epi > Gt > Zir	Hb, Tml, Biot, St, As	**B1**	Epi > Gt > Zir	Sph, Tml, Hb, St, As
			B2	Epi = Zir = Biot	As, Hb > Gt, St, Tml
			B3	Epi	Gt > Sph > Zir
C	Biot > Epi	Hb > Gt > Zir			
D	Hb > Di > Epi	Gt	**D1**	Hb > Di > Epi	Gt, Biot
			D2	Hb > Epi	Di, Gt

Abbreviations: **As**, aluminosilicates; **Biot**, biotite; **Di**, diopside; **Epi**, epidote; **Gt**, garnet; **Hb**, hornblende; **Rut**, rutile; **Sph**, sphene; **St**, staurolite; **Tml**, tourmaline; **Zir**, zircon.

sample. Alternatively, the Whetstone Buttes sample (GND-8) is most similar to some Medicine Pole Hills samples (D2) because of its amphibole content. Thus, the recovery of those two samples within their own group (group C: figure 24) was influenced solely by the high biotite content and not on broad similarities between their entire heavy mineral assemblages.

Cluster Analysis Without Epidote

One problem that might be implied by comparing heavy mineral data produced at MSU and the data of Denson and Gill (1965) is that epidote-rich samples are common in MSU data, and not common in the Denson and Gill (1965) data. Only two MSU samples group into the epidote-poor group A (figure 24). There are some consistencies when comparing data from these two sources collected from similar geographic areas. For example, samples collected from the Chalky Buttes Member equivalent at Long Pine Hills, samples collected from the upper portions of the Chalky Buttes (including Rattlesnake Butte), and samples collected from the Whetstone Buttes are all in the epidote-rich groups. Additionally, all samples from White Butte and Black Butte fall into group A. However, the MSU South Cave Hills sample (SCH-2) falls into group B, while all of the South Cave Hills samples reported by Denson and Gill (1965) fall into group A (figure 24). It is possible that the lack of epidote-poor samples among MSU samples is coincidence; however, the nature of epidote grains raises the possibility that they were treated differently by these two sets of researchers. Many of the epidote grains recorded in this study are turbid to some extent. It is possible that Denson and Gill (1965) omitted the more turbid grains as opaque or rock fragment grains given that the most turbid grains tend to be fine-grained intergrowths of epidote and quartz/feldspar. That decision could result in very different counts of epidote grains from otherwise similar samples.

To see what effect epidote has on the grouping of heavy mineral samples, the raw data were normalized to 100% with epidote excluded (in the case of those data from Denson and Gill [1965], epidote, clinozoisite, and zoisite were excluded). Those results are shown in figure 26 and summarized in Appendix 10. Surprisingly, there were few changes in the way samples clustered (figure 24 versus 26). Two samples changed from one major group to another: one sample from Whetstone Butte (GND-6) moved from group B to (marginally) part of group A (A5), and one sample from White Butte (WB-3) moved from group A to group B (B1). There were also some changes within some sub-groups. Five samples from sub-group A2 joined with group A1 to form a new subgroup A1/2, while three other sub-group A2 samples (GND-3, CSD-66, and ZD-31) joined with sub-groups A3 and A4 to form the subgroup A3/4. The Stover Site sample formed its own sub-group (B4) outside of sub-group B1, and one Chalky Buttes sample (GND-18) formed its own sub-group (B5). Sub-groups D1 and D2 did not change. In the absence of epidote, most group B samples are still well separated from group A samples by higher amounts of garnet and sphene, and relatively lower amounts of zircon, staurolite, and aluminosilicates (Appendix 10). Thus, the differences between most group B and group A samples extends throughout the heavy mineral assemblage and is not solely influenced by how epidote is treated.

Despite the fact that epidote does not have significant control over how most samples cluster, the effect of including or excluding epidote from heavy mineral analyses is something that should perhaps be kept in mind when comparing individual samples For example, Whetstone Buttes sample GND-6 and White Butte sample WB-3 switch groups based on whether or not epidote is included, perhaps indicating low support for their inclusion in either group, or indicating the presence of a transitional heavy mineral assemblage in those samples.

Cluster Analysis Without Epidote and Biotite

Given the differences between the dendrogram produced by analysis of the full suite of heavy minerals and those produced after removing either biotite or epidote, another analysis was run with both of those minerals excluded to determine if their combined absence produced any additional changes to the recovered groups. The results of that analysis are shown in figure 27 and summarized in Appendix 11. Group C, which was based largely on high biotite content, is lost again. The Rattlesnake Butte sample (RSB) again groups with the same Long Pine Hills sample (LPH-4) as in the no-biotite analysis, but now also groups with an upper Chalky Buttes sample (GND-18) to form sub-group B3 instead of with a Whetstone Buttes sample (WST-2). The Whetstone Buttes sample previously in group C (GND-8) once again in situated in sub-group D2 as in the no-biotite analysis. The Stover Site sample is also placed in group D, within its own sub-group (D3). That sample differs from the others within group D in having less amphibole and more garnet. This is the only analysis of very fine sand fractions where the Stover Site sample is placed in a group with the MPH samples.

While groups B and D most closely resemble their counterparts in the no-biotite analysis (figure 27 versus 25), group A more closely resembles the no-epidote analysis (figure 27 versus HME). Sub-group A1/2 is identical to that in the no-epidote analysis. However, sub-group A3/4 in this analysis is larger than in any other analysis, including 13 samples. In the no-epidote analysis, one Whetstone Buttes sample (GND-6) was placed at the base of group A (sub-group

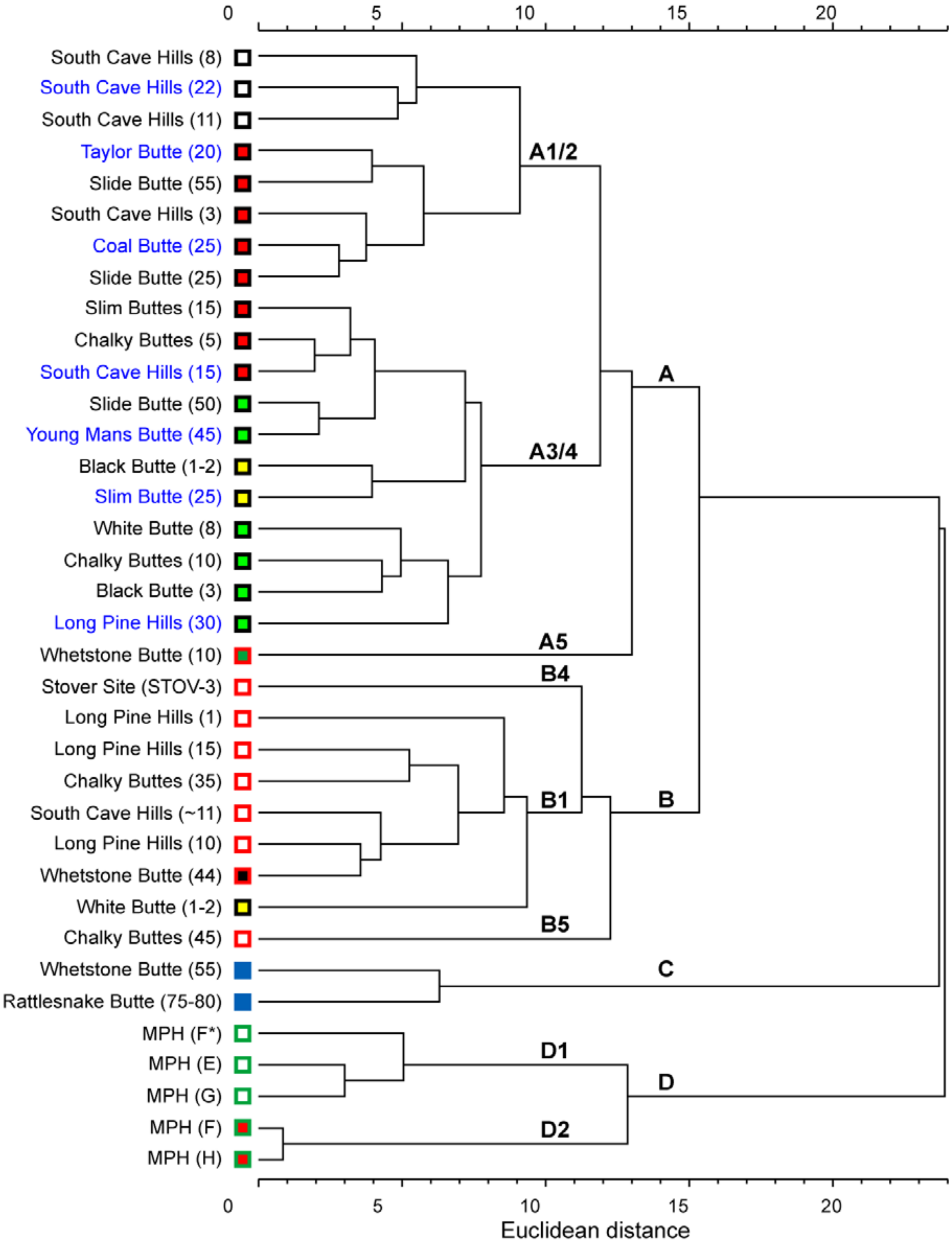

Figure 26. Dendrogram based on cluster analysis of heavy mineral analyses of very fine sand fractions excluding epidote. Colored squares correspond to the groups recovered in figure 24 when all minerals are included. Samples listed in blue are from the South Heart Member (North Dakota) or lithologic equivalent (Montana and South Dakota), while all others are from the Chalky Buttes Member (North Dakota) or lithologic equivalents (Montana and South Dakota). Numbers in parentheses indicate how many feet above the base of the Chadron Formation the sample was collected. See Appendix 4 for raw values and Appendix 10 for group and sub-group averages.

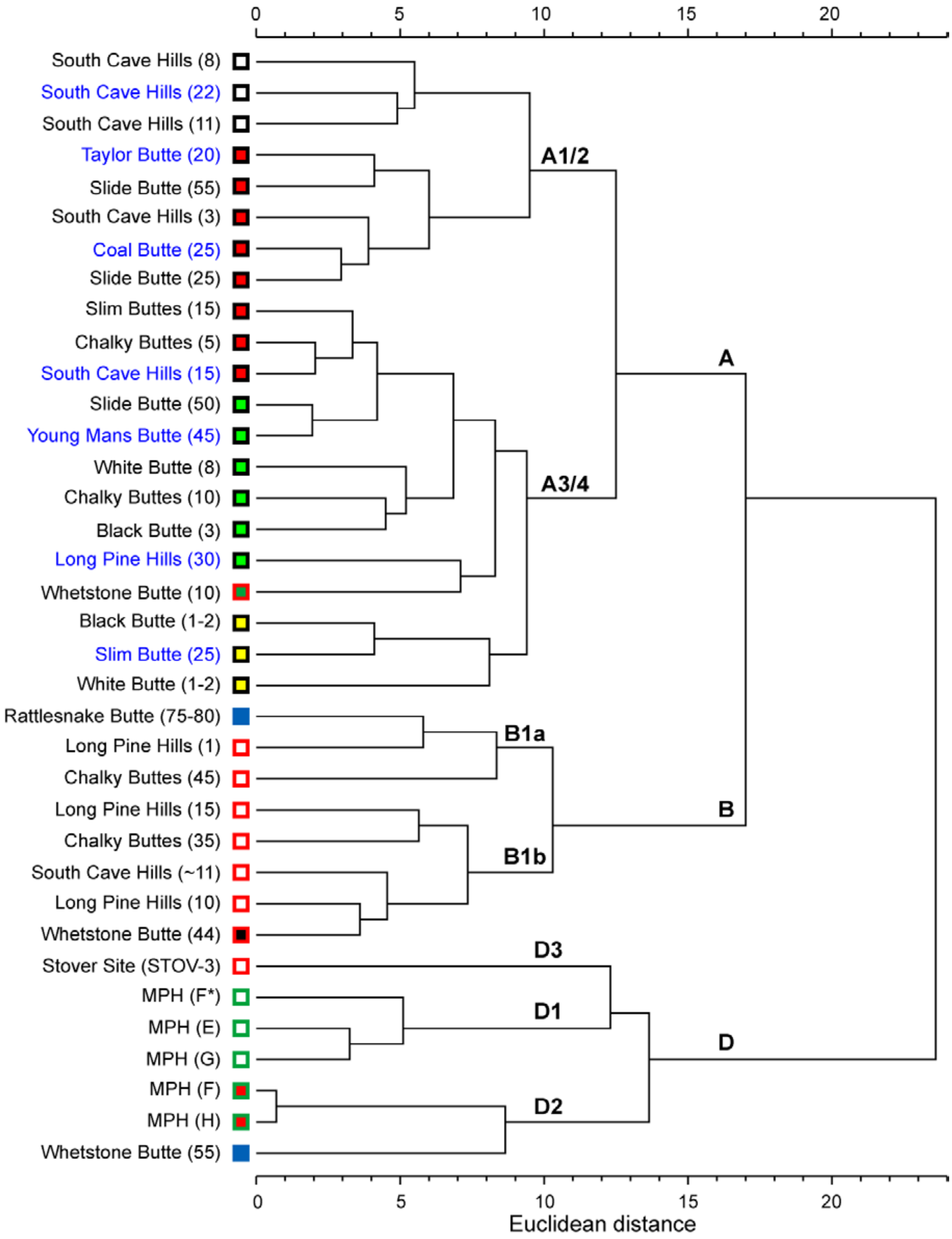

Figure 27. Dendrogram based on cluster analysis of heavy mineral analyses of very fine sand fractions excluding biotite and epidote. Colored squares correspond to the groups recovered in figure 24 when all minerals are included. Samples listed in blue are from the South Heart Member (North Dakota) or lithologic equivalent (Montana and South Dakota), while all others are from the Chalky Buttes Member (North Dakota) or lithologic equivalents (Montana and South Dakota). Numbers in parentheses indicate how many feet above the base of the Chadron Formation the sample was collected. See Appendix 4 for raw values and Appendix 11 for group and sub-group averages.

A5) based on its high biotite content (Appendix 10). When only biotite is removed, GND-6 is placed into sub-group B1. When both epidote and biotite are removed, that sample falls into sub-group A3/4 (figure 27; Appendix 11). One final sample of note is WB-3 from White Butte. In this analysis that sample is in the A3/4 sub-group, in a similar position to where it is in the full analysis (figure 24) and the no-biotite analysis (figure 25) but differing from the placement in the no-epidote analysis where it moves to group B1 (figure 26).

Cluster Analysis Without Volcanic Minerals

As was done by Webster et al. (2015), a final cluster analysis was carried out after removing volcanic-source heavy minerals and normalizing to 100%. The minerals excluded were pyroxenes (diopside, augite, and hypersthene), biotite, and the volcanic portion of amphiboles (primarily hornblende). The blue-green varieties of hornblende, interpreted to be metamorphic in origin, were retained, while green/brown/reddish-brown hornblendes, interpreted to be volcanic in origin, were excluded (following Sato and Denson [1967] and Denson and Chisholm [1971]). The percentage of hornblende retained was 57% for the MPH samples (based on detailed analysis of two samples in Webster et al. [2015]). In the other (Chalky Buttes Member) samples, 41% of the hornblende was retained based on counting of pleochroic color types in the Stover Site sample. The resulting cluster analysis dendrogram is shown in figure 28, and group averages are given in Appendix 12.

With volcanic minerals excluded, samples clustered much the same as before (figure 24 versus 28). Group A, and each of its subgroups, are exactly the same. That result is not surprising given the paucity of volcanic minerals in those samples (Appendix 4). Group B without volcanic minerals was roughly the same, except that sub-group B1 split into two sub-groups, here termed B1a and B1b. The two biotite-rich samples of the former group C became part of group B; Whetstone Buttes sample GND-8 became part of sub-group B1a and Rattlesnake Butte sample RSB became part of sub-group B1b. Those two sub-groups differ largely in that sub-group B1a contains a relatively high percentage of zircon and a lower percentage of epidote, while sub-group B1b is epidote-rich and zircon-poor (Appendix 12). Group D (all five MPH samples) remained the same, but with no clear sub-groups identified when volcanics are removed.

Discussion

Overall, the results of analyses using the very fine sand fractions of samples seem rather robust. Leaving out various minerals or mineral combinations did not result in many significant changes in the way that samples cluster; changes were mostly at the sub-group level. The exceptions are the five samples highlighted in Table 5, which were the only ones to move between groups when different sets of minerals were included in the analyses. Of those samples, the White Butte sample (WB-3) was fairly stable, staying in sub-group A4 or A3/4 in all analysis except when epidote was excluded, where it moved to sub-group B1, possibly owing to a higher garnet content than most other group A samples. The Stover Site sample was also fairly stable, remaining in group B in all analyses except when both biotite and epidote were removed, where it moved over to group D with the MPH samples, matching its position when the medium sand fraction was analyzed. The two biotite-rich samples were also fairly stable, with their positions mostly only influenced by the presence or absence of biotite in each analysis, though sample GND-8 from the Whetstone Buttes moved from group D to group B when volcanics were excluded. The most unstable sample in these analyses was GND-6 from the lower portion of the

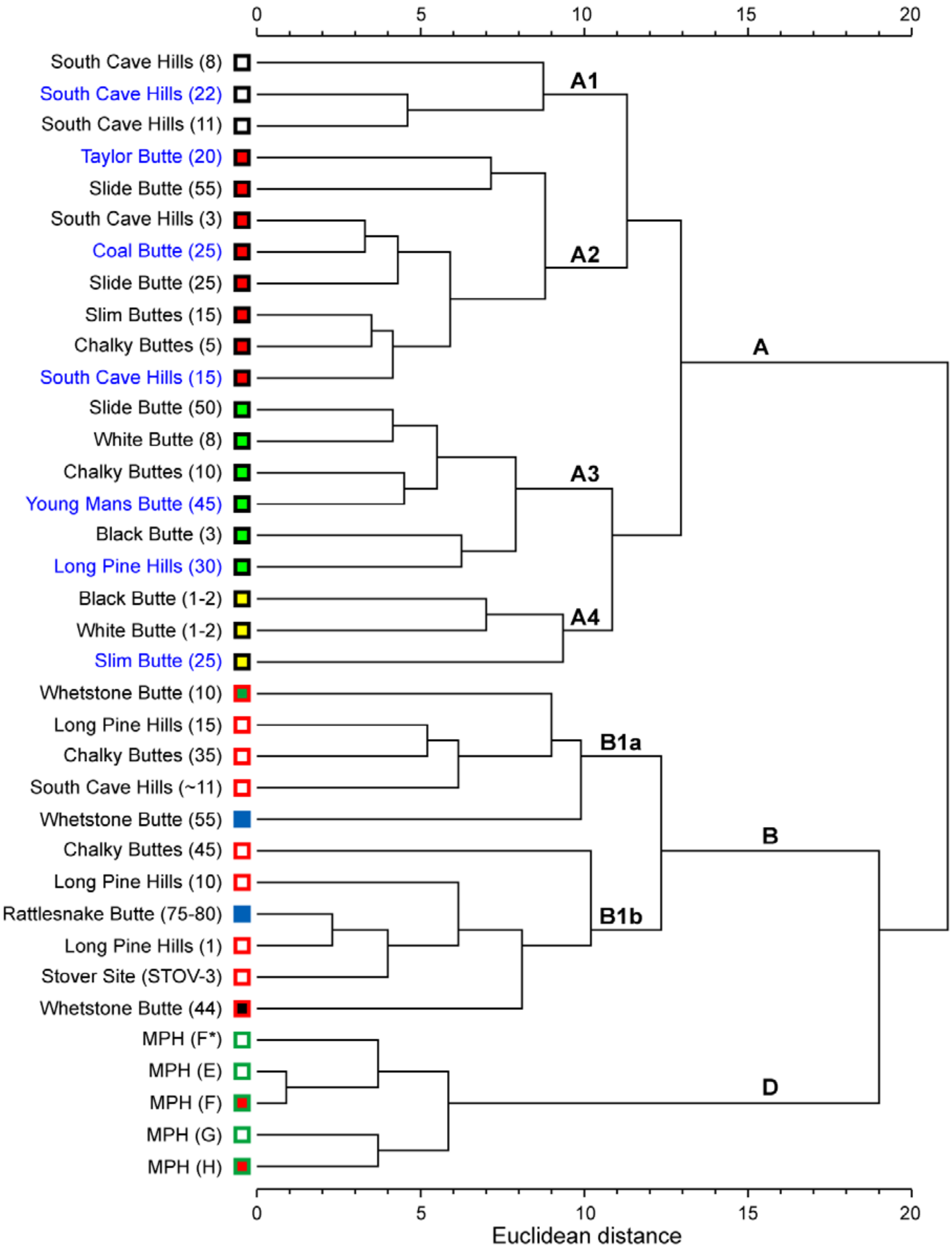

Figure 28. Dendrogram based on cluster analysis of heavy mineral analyses of very fine sand fractions excluding volcanic minerals. Colored squares correspond to the groups recovered in figure 24 when all minerals are included. Samples listed in blue are from the South Heart Member (North Dakota) or lithologic equivalent (Montana and South Dakota), while all others are from the Chalky Buttes Member (North Dakota) or lithologic equivalents (Montana and South Dakota). Numbers in parentheses indicate how many feet above the base of the Chadron Formation the sample was collected. See Appendix 4 for raw values and Appendix 12 for group and sub-group averages.

Table 5. Tracking the various positions of heavy mineral samples that move between groups in the cluster analyses depending on what minerals are included.

Sample	Location	All	Biotite Removed	Epidote Removed	Biotite & Epidote Removed	Volcanics Removed
GND-6	Whetstone Butte, ND	B2	B1	A5	A3/4	B1a
GND-8	Whetstone Butte, ND	C	D2	C	D2	B1b
RSB	Rattlesnake Butte, ND	C	B3	C	B1a	B1b
STOV-3	Stover Site, ND	B1	B1	B4	D3	B1b
WB-3	White Butte (Hettinger), ND	A4	A4	B1	A3/4	A4

Notes: See figures 24 through 28 for groups cited.

Whetstone Buttes, which moved between groups A and B depending on which minerals were included in the analysis. That sample had equal amounts of biotite, epidote, and zircon (24% each); therefore, when epidote is excluded that sample falls into the zircon-rich group A (sometimes in its own biotite-rich sub-group), while it falls into group B when epidote is included. That sample also was based on a very small number of non-opaque grains (n=25: Denson and Gill, 1965), and that insufficient sampling may be impacting the results.

Implications for the Stover Site Heavy Mineral Sources

Samples from the MPH sandstone showed no evidence of CBM-type heavy minerals in either the very fine sand (Table 4) or medium sand fractions (figure 23: Webster et al., 2015). In the Stover Site sample, the medium sand fraction has a MPH-type heavy mineral assemblage (figure 23; Table 3) while the very fine sand fraction represents a mixture of CBM-type and MPH-type assemblages (figure 22; Table 3). One possible explanation for these differences is that the CBM-type heavy mineral assemblage in the very fine sand fraction of the Stover Site sample was derived from erosion and inclusion of sediment grains from previously deposited rocks. That erosion could have occurred during the late Eocene as a small stream or river downcut into previously deposited rocks of the Chalky Buttes Member that contained a CBM-type heavy mineral assemblage. That scenario could also explain another point of conflict between the MPH sandstone samples and the Stover Site sample: the low abundance of opaque grains in the MPH sample and the relatively high abundance of those grains in the Stover Site sample (Appendix 4). Most of the opaque grains noted in the Stover Site sample are ferruginous aggregate grains and not grains of individual opaque heavy minerals. The source of those grains could also be the erosion of local rocks, especially if a paleosol that included sesquioxide cementation of original grains was developed on the upper surface of those rocks prior to erosion. A pedogenic source for those ferruginous aggregate grains may also be supported by the significant abundance of calcite in the very fine sand fraction of the Stover Site sample (Table 3). Many of those calcite grains were coated to various degrees with ferruginous material, and it was also common to find grains that were dominantly opaque but had recognizable calcite within them. Based on those observations, the aggregate grains and the isolated calcite grains were likely derived from the same source, and the development of both ferruginous material and carbonates in paleosols is common (Retallack, 2001). Calcite grains are completely lacking from the medium sand fraction in the Stover Site sample (Table 3), suggesting that they were derived from the same source as the CBM-type heavy minerals present in the very fine sand fraction. Thus, the ferruginous aggregate grains, the calcite grains, and the CBM-type heavy minerals may be derived from previously deposited rocks in the local area, while the MPH-type heavy minerals were transported via the stream or river from more distant source rocks.

An alternative, but somewhat similar explanation for the mixed heavy mineral assemblage noted at the Stover Site is that those rocks represent a colluvium or alluvium deposit formed via the relatively recent (last several thousand years) erosion of Chadron Formation rocks situated in the topographically higher area to the south, the same ridgeline that includes the Water Tower Site. Under that scenario, Chadron Formation sediments may have been present to the south that preserved distinct CBM-type and MPH-type heavy mineral assemblages, and those heavy minerals were then mixed together at the Stover Site. That scenario would account for the lower topographic position of the Stover Site compared to other Chadron Formation rocks in Adams County. It could also account for the ferruginous aggregate grains and the calcite grains, as rocks at the Water Tower Site do appear to contain both iron-rich and carbonate cements, and iron cementation is noted in sediments at the top of the Whetstone Buttes to the northwest (Murphy et al., 1993). The rocks at the Water Tower Site are also fossiliferous, potentially supporting this scenario, though the age of those fossils currently cannot be refined beyond the Chadronian. More work needs to be done on the heavy mineral assemblage in the rocks preserved at the Water Tower Site as well as the fauna from that site to determine if it is plausible for those sediments to have produced the heavy mineral assemblage and the fauna recorded at the Stover Site. Additional work also needs to be conducted to located in situ rocks at the Stover Site so that the mode and timing of deposition can be accurately determined.

A third possible explanation for the differences between the Stover Site sample results and those of the MPH samples is based on paleogeography. Both areas could have been receiving sediment from similar source rocks that provided diopside, hornblende, epidote, and garnet. However, the Stover Site was possibly in a location that was also receiving sediment from other source rocks that provided the CBM-type heavy minerals; sources that were not contributing to the MPH sandstones. The fact that the CBM-type heavy minerals from these additional sources were nearly absent from the medium sand fraction of the Stover Site sample could be explained by grain-size limitations in the sources; they were not providing large enough grains to show up in the coarser fraction.

A final possibility is similar to the third, but is based on time rather than paleogeography, or perhaps both time and paleogeography. In this case, the differences in heavy minerals between the Stover Site and the MPH sandstones are explained by changes in sources over time. If the Stover Site sample represents a somewhat younger deposit than the MPH sandstone (see biostratigraphic section), it suggests that the sources of diopside, hornblende, epidote, and garnet that contributed to the MPH deposits were still contributing to deposition later at the Stover site, but that additional sources were also contributing (providing the CBM-type assemblage).

Implications for Relative Ages of Chadronian Deposits

While the presence of three main groups of heavy mineral assemblages seems well-supported by these data, the question remains as to what factors may be influencing these groups. To investigate that question, a summary of the stratigraphic and geographic distributions of samples and their group designations is given in figure 29 (South Heart Member samples excluded). This figure reveals a few interesting temporal and geographic patterns within the Chalky Buttes Member (and lithologic equivalents). A clear stratigraphic shift in heavy minerals is seen in the five samples from the Chalky Buttes area of North Dakota (Table 6). Samples lower in section are rich in zircon and staurolite, placing them in group A. Moving up through the section, a shift away from those two minerals and towards an epidote- and garnet-rich assemblage is noted, with those samples clustering in group B. More specifically, a sub-group B1a sample is overlain by a sub-group B1b sample. The upper-most sample (RSB) is placed in group C because it is enriched in biotite, but when biotite is removed it is consistently placed in group B (Table 5). The upper portion of that sequence matches the sequence found at the nearby Whetstone Buttes, where a sub-group B1a sample is overlain by a sub-group B1b sample, and finally by a group C sample (figure 29). Based on those observations, group A rocks are

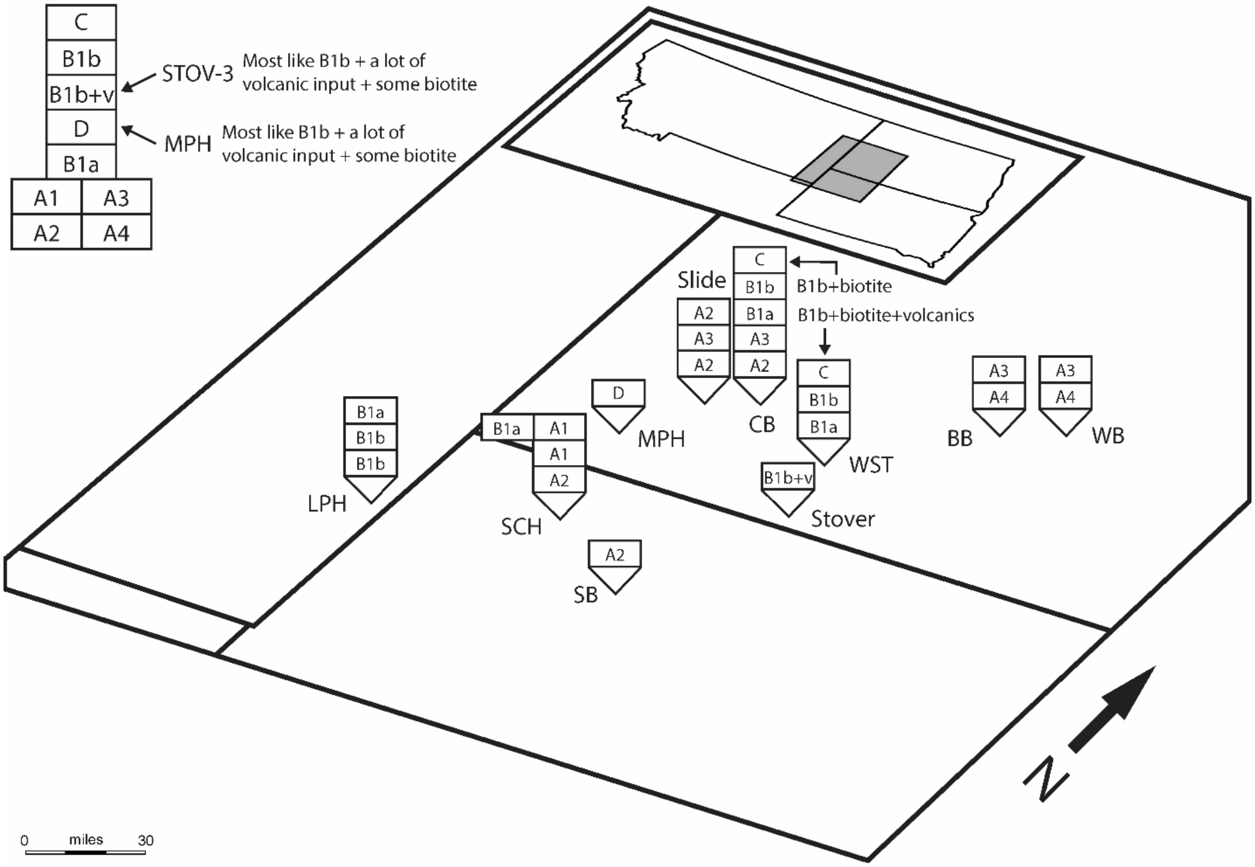

Figure 29. Geographic and stratigraphic distribution of heavy mineral groups and sub-groups. All groups taken from dendrogram shown in figure 24, except sub-groups within group B, which are based on the dendrogram in figure 28. The triangle at the base of each stratigraphic column indicates the location of the sample area. A hypothesized stratigraphic sequence of heavy mineral assemblages based on observed patterns and biostratigraphic information is provided in the upper left corner. **Abbreviations**: **BB**, Black Butte; **CB**, Chalky Buttes; **LPH**, Long Pine Hills; **MPH**, Medicine Pole Hills; **SB**, Slim Buttes; **SCH**, Short Cave Hills; **Slide**, Slide Butte; **Stover**, Stover Site; **WB**, White Butte (Hettinger County); **WST**, Whetstone Buttes.

Table 6. Stratigraphic pattern of heavy minerals in the Chalky Buttes area (including Rattlesnake Butte) of North Dakota.

Sample	Member	Position	Biotite	Epidote	Garnet	Staurolite	Al-silicates	Zircon
RSB	Chalky Buttes	75-80	**52.9**	**29.9**	10.6		0.6	1.4
GND-18	Chalky Buttes	45		**40**	**35**	12	7	
GND-9	Chalky Buttes	35		**24**	**28**	8	8	21
GND-5	Chalky Buttes	10		8	9	**15**	6	**49**
GND-3	Chalky Buttes	5		2	2	**29**	15	**38**

Notes: Only heavy minerals that made up a minimum of ten percent of at least one sample are shown. For full data see Appendix 4. Position is reported in feet above the base of the Chadron Formation.

interpreted to represent the oldest deposits laid down within the Chadron Formation in the Williston Basin, with group B rocks following thereafter, and an increase in biotite noted in the upper-most samples. Rocks from group B, seemingly from sub-group B1b (figure 28), were also deposited at the Medicine Pole Hills and the Stover Site. At the Medicine Pole Hills, that rock was joined and largely overwhelmed by volcanic input (pyroxenes, amphibole, and some biotite), forming group D. At the Stover Site, group B1b rock was joined by a more modest contribution of volcanic material, at least in the very fine fraction. In the medium sand fraction from the Stover Site the B1b rocks are also overwhelmed by volcanic input, as happens at Medicine Pole Hills

While there appears to be some stratigraphic (=temporal?) pattern among samples at the group level, variations among sub-groups do not show a consistent stratigraphic pattern. At the Long Pine Hills locality, a sub-group B1a sample overlies two sub-group B1b samples, the reverse pattern seen in the Chalky Buttes area and at Whetstone Buttes. Within group A, sub-group variations are more complex. In the area of Slope County (North Dakota) that includes the Chalky Buttes, Rattlesnake Butte, and Slide Butte, a sub-group A2 sample is overlain by a sub-group A3 sample, although there is a return to a sub-group A2 sample in the upper-most portion of Slide Butte (GND-131). At the South Cave Hills locality, a sub-group A2 sample is overlain by two sub-group A1 samples. At both White Butte and Black Butte, a sub-group A4 sample is overlain by a sub-group A3 sample. While stratigraphic patterns seem absent, there is some geographic partitioning of group A samples from the Chalky Buttes Member and equivalent rocks, with sub-group A1 and A2 samples present in the southern areas, sub-group A3 and A4 samples present in more northern areas, and a transition within the Chalky Buttes Area (including Slide Butte) with sub-group A2 and A3 samples present. This sub-group distribution appears to reflect a north-south gradient of heavy mineral assemblages, with southern group A samples (A1 and A2) enriched in both staurolite and aluminosilicates relative to other minerals, and northern group A samples (A3 and A4) dominated by zircon.

Table 7. Stratigraphic pattern of heavy minerals at South Cave Hills in South Dakota.

Sample	Member	Position	Epidote	Garnet	Staurolite	Al-silicates	Sphene	Zircon	Tourmaline
CSD-6	South Heart	22	**16.0**	10.0	10.0	**31.0**	2.0	8.0	13.0
CSD-66	South Heart	15	11.0	5.0	**28.0**	12.0		**30.0**	9.0
CSD-31	Chalky Buttes	11	15.0	8.0	**22.0**	**28.0**	1.0	11.0	15.0
SCH-2	Chalky Buttes	~11	**25.5**	**20.1**	4.1	2.7	11.8	17.9	12.1
CSD-38	Chalky Buttes	8		1.0	**22.0**	**46.0**		5.0	18.0
CSD-50	Chalky Buttes	3	2.0	1.0	**30.0**	**24.0**		**24.0**	16.0

Notes: Only heavy minerals that made up a minimum of ten percent of at least one sample are shown. For full data see Appendix 4. Position is reported in feet above the base of the Chadron Formation. Bold values are the dominant minerals from that sample.

Some of the stratigraphic inconsistencies noted at the sub-group level may be the result of sampling from different stratigraphic sections. Although stratigraphic positions of samples from Denson and Gill (1965) and this study are fairly well known (see above), in terms of height above the base of the Chadron Formation, the exact geographic locations of the sections of Denson et al. (1965), and thus the heavy mineral samples, are not known. It could also be that variations inherent in the heavy mineral data simply don't support interpretation of stratigraphic positions at the sub-group level.

Assessing heavy mineral assemblages in stratigraphic context may also explain some of the other issues encountered in this study. For example, differences in mineral abundance between samples reported by Denson and Gill (1965) and those conducted at MSU do not appear to be the result of methodological differences or in the treatment of a single mineral group (i.e. epidote) given the overall stability of the groups regardless of which subsets of minerals are included. In fact, when the samples are examined in stratigraphic context, some of the samples that look like outliers begin to make more sense. Of the 36 samples included in the most comprehensive cluster analysis (figure 24), the sample that seems the most out of place at first glance is the one sample from the South Cave Hills that was processed at MSU (SCH-2). That sample is the only sample of the six total South Cave Hills samples that falls into group B (figure 24). Sample SCH-2 differs from the other five samples in that is has relatively high amounts of epidote, garnet, and sphene and very low amounts of aluminosilicates and staurolite. However, when you look at these six samples in stratigraphic order (Table 7), it is apparent that sample SCH-2 seems to mark a transition point in the heavy mineral assemblage at that geographic location. Samples below SCH-2 are almost completely lacking in epidote (0-2%) and garnet (1%), while those at approximately the same level or above SCH-2 have higher levels of both minerals (11-16% and 5-10%, respectively), though not as high as in SCH-2 (25.6% and 20.1%, respectively). It should also be noted that SCH-2 was likely not collected along precisely the same stratigraphic section as the five samples from Denson and Gill (1965), so there could be some lateral variation at work here as well. Regardless, sample SCH-2 appears to be less of an outlier when samples are examined in stratigraphic context, revealing a clear pattern of increasing epidote and garnet content at South Cave Hills that may signal the addition of new sediment source areas in the upper portion of the section.

Reinterpretation of the Deposition of the Chadron Formation in North Dakota

Those data presented above enhance our knowledge of patterns of late Eocene deposition in North Dakota. Those insights enhance lithologic and biostratigraphic correlations with other deposits in the Great Plains region, necessitating a revision of several prior interpretations of those rocks referred to the Chadron Formation in North Dakota.

The Chalky Buttes Member

Rocks of the Chadron Formation rest unconformably upon Paleocene (Fort Union Group) or Eocene (Golden Valley Formation) rocks in North Dakota, depending on the degree of erosion that occurred locally prior to deposition. The majority of that erosion occurred during a period of prolonged surface stability across the Great Plains region and a prominent paleosol, the Yellow Mounds Paleosol Equivalent (sensu Terry, 1998), is developed upon those rocks. In South Dakota, the earliest phase of deposition following that period of erosion and surface stability is represented by the Slim Buttes Formation, which is restricted to the southern portion of the Slim Buttes (Malhotra and Tegland, 1959; Bjork, 1967), though some rocks within the northern Slim Buttes positioned below the “dazzling white” channel sandstones of the Chadron Formation may also be referable to the Slim Buttes Formation (Lillegraven, 1970). Those rocks preserve a late middle Eocene fauna (Duchesnean NALMA [40.1-36.9 Ma]: Bjork, 1967). No comparable rocks or Duchesnean fossils are currently recognized in North Dakota.

Localized deposition of the Slim Buttes Formation mudstones and sandstones was followed by region-wide deposition of channel sandstones and associated overbank mudstones. In southern South Dakota, Nebraska, and parts of Wyoming, those rocks are referred to the Chamberlain Pass Formation, including those rocks previously referred to the Chadron A bed of the Chadron Formation (Schultz and Stout, 1955; Terry, 1998). Those rocks contain a fauna that is either late middle Eocene (Duchesnean) or late Eocene (earliest Chadronian: Terry, 1998; Benton et al., 2015). In northwestern South Dakota and southeastern Montana, the “dazzling white” channel sandstones of the Chadron Formation are considered correlative with the Chamberlain Pass Formation (Terry, 1998). The Chalky Buttes Member of the Chadron Formation in North Dakota is also typically correlated with those rocks (Murphy et al., 1993; Evans and Terry, 1994; Hoganson et al., 1998; Terry, 1998). While we agree with that correlation in part, the data in this study suggests there may be a more complicated pattern of deposition of Chalky Buttes Member rocks in North Dakota than is traditionally recognized. Specifically, we hypothesize that two phases of deposition are represented by rocks of the Chalky Buttes Member.

The first phase of deposition began with those Chalky Buttes Member rocks in Golden Valley, Hettinger, Slope, and Stark Counties that contain the group A heavy mineral assemblage (zircon > staurolite > aluminosilicates, tourmaline: figure 29 and Table 4). Those rocks closely resemble the “dazzling white” channel sandstones of the Chadron Formation at the Slim Buttes (South Dakota), which also contain the group A heavy mineral assemblage. In the Chalky Buttes area, rocks containing the group B heavy mineral assemblage (epidote>garnet>zircon: figure 29 and Table 4) overlay rocks containing group A heavy minerals, suggesting that rocks with group B heavy minerals within the Williston Basin are younger relative to those with group A heavy minerals. The White Butte and Fitterer Ranch paleosols overlie those group A and group B rocks throughout much of the area studied (figure 10), indicating the cessation of most deposition and development of a stable land surface after deposition of those rocks containing the group B heavy mineral assemblage.

In the Big Badlands of southern South Dakota, a period of erosion and surface stability also followed deposition of the Chamberlain Pass Formation (Terry, 1998). In that area, the most striking evidence of that erosion was the development of the Red River Paleovalley (Clark et al., 1967), a broad paleovalley that cut down through the Chamberlain Pass Formation and deep enough into the underlying rocks of the Pierre Shale to remove all traces of the Yellow Mounds Paleosol (Terry and Evans, 1994; Terry, 1998). During that period of erosion and surface stability a second paleosol developed within the central Great Plains either on top of the Chamberlain Pass Formation or overprinted on the Yellow Mounds Paleosol where that formation is absent. Those paleosols, termed the Interior Paleosol Series and the Weta Paleosol Series (and their regional equivalents: Terry, 1998) were likely formed at the same time as the White Butte and Fitterer Ranch paleosols described in this study (figure 9), as were similar silcrete-bearing paleosols noted in this study in the Slim Buttes of South Dakota (figure 14). Terry and Evans (1994) suggested that the pedogenesis of the Chamberlain Pass Formation may indicate a period of regional geomorphic stability that is marked by deposition of similar lithologies and stratigraphic successions across the Great Plains. Based on the data presented in this study, we concur with those inferences. As a result, it seems likely that most if not all of those Chalky Buttes Member rocks that are overlain by either the White Butte or Fitterer Ranch paleosol (figure 10) do correlate with the Chamberlain Pass Formation and the “dazzling white” channel sandstones of the Chadron Formation in the Great Plains region (figure 30).

In the Big Badlands of southern South Dakota, the second phase of deposition began in the Red River Paleovalley with the Ahearn Member and was followed by the channel sandstones of the Crazy Johnson Member (figure 30). The Ahearn Member is reported to contain an earliest Chadronian fauna (Ch1: 36.5-37.0 Ma: Janis et al., 2008), while the Crazy Johnson Member contains a middle Chadronian fauna (Ch3: 34.7-35.7 Ma: Janis et al., 2008). Presumably, development of the Interior and Weta Paleosol Series (and their regional equivalents) continued during much of that time adjacent to the paleovalley, until infilling of the Red River Paleovalley was largely completed and deposition spilled out of the paleovalley. We suggest that during this period of time spanning the early and middle Chadronian, a series of streams and/or rivers were also locally present within Adams and Bowman Counties (North Dakota) that resulted in localized downcutting of underlying rocks and eventually deposition of the Medicine Pole Hills and Stover Site sandstones. A few lines of evidence are cited in support of this hypothesis. At the Medicine Pole Hills, there is no trace of the Yellow Mounds Paleosol developed at the top of the underlying Bullion Creek Formation (Webster et al., 2015:fig. 4), similar to the condition in the area of the Red River Paleovalley (Terry, 1998). It is currently unknown if this condition is also present at the Stover Site. Second, the Medicine Pole Hills and Stover Site local faunas are early to middle Chadronian (Ch2 and Ch3, respectively), matching those preserved within the base of

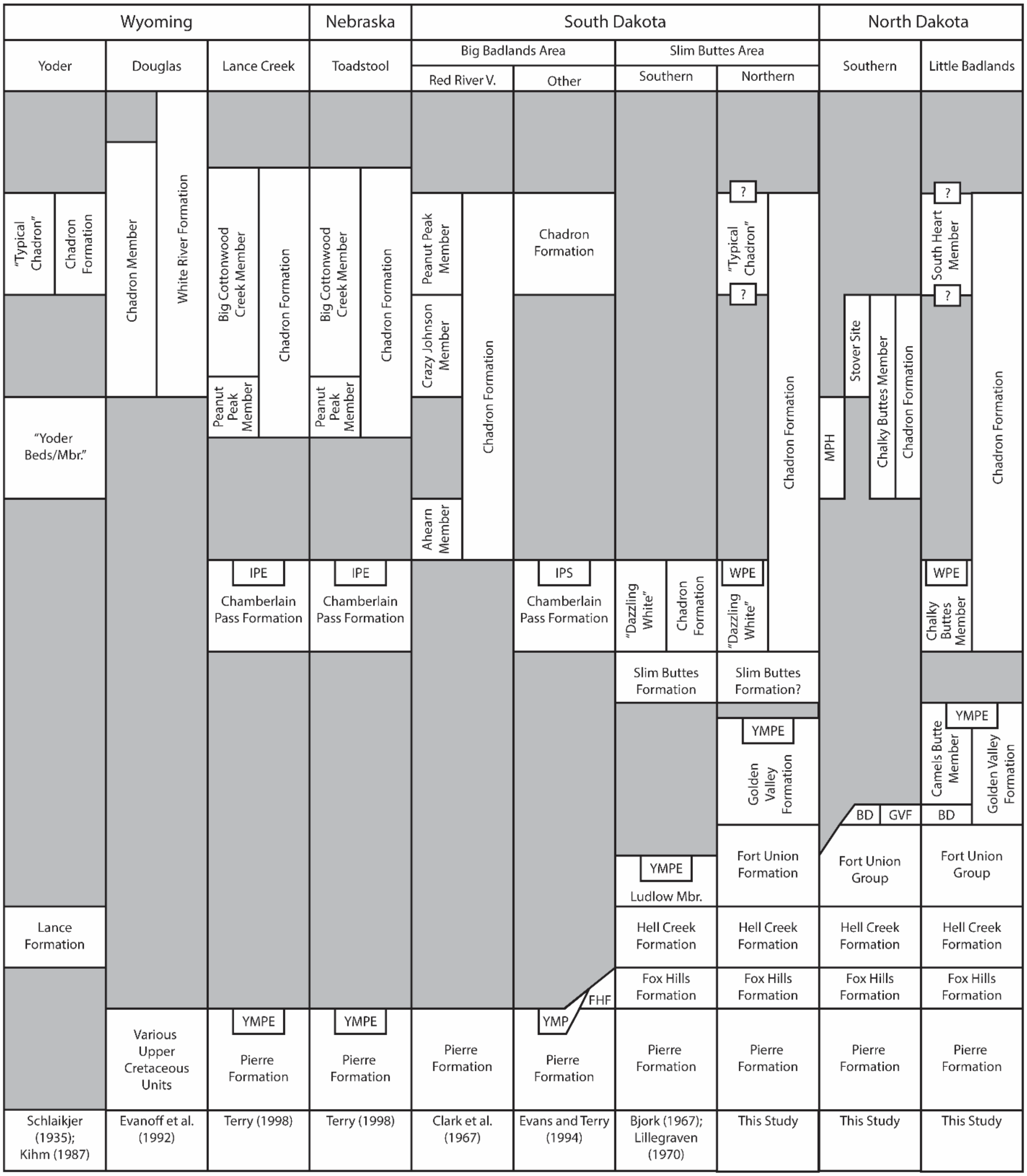

Figure 30. Biostratigraphic correlation of sediments across Nebraska, North Dakota, South Dakota, and Montana. Vertical position within columns indicates approximate biostratigraphic "age" of faunas within those sediments. Modified from Terry (1998:fig. 10). **Abbreviations**: **BD**, Bear Den Member; **FHF**, Fox Hills Formation; **GVF**, Golden Valley Formation; **IPS**, Interior Paleosol Series; **IPE**, Interior Paleosol Equivalent (sensu Terry, 1998); **MPH**, Medicine Pole Hills sandstones; **Red River V.**, Red River Paleovalley; **WPE**, Weta Paleosol Equivalent (sensu Terry, 1998); **YMP**, Yellow Mounds Paleosol Series; **YMPE**, Yellow Mounds Paleosol Equivalent (sensu Terry, 1998); **?**, age of boundary is uncertain, and when present at both the upper and lower contact the age of the entire unit is uncertain.

the Red River Paleovalley, indicating deposition of these rocks in both areas was largely synchronous.

The most convincing evidence supporting the presence of a second phase of deposition of Chadronian sandstones in North Dakota comes from the heavy mineral data reported for the Medicine Pole Hills and the Stover Site. Cluster analysis of the medium sand fraction of the heavy mineral samples from the Chalky Buttes Member and lithologic equivalents resulted in a dendrogram that grouped together the Medicine Pole Hills and Stover Site samples to the exclusion of all other samples (group D [hornblende>diopside>epidote]: figure 23 and Table 4), indicating the rocks at those two sites are distinct from all other Chalky Buttes Member rocks sampled in this study. At the Stover Site, the very fine sand fraction of the heavy minerals is a mix of group B and group D heavy mineral assemblages (approximately 65% to 35%, respectively). As discussed above, the presence of group B heavy minerals in the very fine sand fraction of the heavy mineral sample from the Stover Site and their absence in the medium sand fraction may be the result of group B heavy minerals being released during the mechanical breakdown of the abundant ferruginous aggregate grains that dominate the abundant opaque heavy minerals in the Stover Site sample (Table 3). Those ferruginous aggregate grains are also likely the source of the abundant calcite grains that are common within the non-opaque heavy mineral grains in the very fine sand fraction (22.9%: Table 3) but are completely absent from the medium sand fraction. Those ferruginous aggregate grains were likely derived from erosion of previously deposited Chalky Buttes Member rocks that had a paleosol developed within the upper portion, providing pedogenic carbonate and sesquioxide cementation around group B rocks that would match the hypothesized composition of the ferruginous aggregate grains within the Stover Site sample.

Examination of Chadron Formation rocks in adjacent areas of Adams County reveals that those eroded group B rocks were likely locally derived. The very fine sand fraction of the heavy minerals from the upper-most sample analyzed to the north at the Whetstone Buttes (GND-8) is more similar to the Stover Site sample than the lowest Whetstone Buttes sample (GND-6) despite the fact that the Stover Site sits at a much lower elevation than the Whetstone Buttes. The upper-most preserved rocks at the Whetstone Butte are well-indurated and at least partially cemented by iron-rich minerals (Murphy et al., 1993). The upper-most preserved rocks at the Water Tower Site to the south are also well-indurated, and there is a large quantity of carbonate cementation as evidenced by a strong reaction with dilute acid. Thus, it is quite possible that the eroded ferruginous aggregate grains that seem to have contributed the group B heavy minerals to the very fine sand fraction of the heavy mineral sample from the Stover Site were derived from older Chalky Buttes Member rocks equivalent with those that cap the Water Tower Site to the south and the Whetstone Buttes to the North. If the presence of group B heavy minerals in the very fine sand fraction of the sample from the Stover Site can be explained in this way, then the group D heavy mineral assemblage from the Medicine Pole Hills and Stover Site sandstones is distinct from all other Chalky Buttes Formation rocks in the region of the Williston Basin sampled in this study (figure 23). Given all of that evidence, it is here suggested that rocks which contain the group D heavy mineral assemblage represent a second phase of deposition within the Chalky Buttes Member in North Dakota, occurring after the onset of the period of relatively stable surfaces that led to the development of the White Butte and Fitterer Ranch paleosols on top of group A and group B rocks. These group D rocks would also be contemporaneous with at least a portion of the second phase of deposition of coarse-grained rocks within southern South Dakota in the Red River Paleovalley (Crazy Johnson Member). The interpretations outlined above support the conclusion of Webster et al. (2015) that the Medicine Pole Hills sandstones represent a facies or depositional event that is distinct from the rest of the Chalky Buttes Member rocks. Specifically, the Medicine Pole Hills and Stover Site sandstones represent a second phase of deposition of coarse rocks within North Dakota during the late Eocene.

The stratigraphic and temporal relationships of these group D rocks of the Chalky Buttes Member with the finer-grained rocks of the South Heart Member are uncertain (figure 30). Biostratigraphic data is largely lacking for the South Heart Member in North Dakota (see below) and there are no exposures of the South Heart Member within the southern areas of North Dakota where these group D rocks are exposed (Adams and Bowman Counties) that would facilitate an interpretation of superpositional relationships. It appears that both the group D rocks of the Chalky Buttes Member and the South Heart Member were deposited after the onset of the development of the White Butte and Fitterer Ranch paleosols. However, at this time it cannot be determined if the downcutting of the channels that deposited the group D rocks of the Chalky Buttes Member occurred before, during, or after the deposition of the South Heart Member in North Dakota. We think it is likely that the same superpositional relationships present in southern South Dakota in the Red River Paleovalley, where the Peanut Peak Member overlies the Crazy Johnson Member, would also be present in North Dakota, but until additional evidence is brought to bear on this question the answer remains uncertain.

The South Heart Member

The extensive presence of paleosols at the contact between the Chalky Buttes and South Heart Members as well as their local equivalents in the Slim Buttes area documented in this study reveals that contact to be unconformable, contrary to prior reports. There has also been some disagreement on whether the rocks of the paleosols themselves (=”silicified sandy bentonite” or “silicified smectites:” Denson et al., 1965; Murphy et al., 1993) should be placed within the Chalky Buttes or South Heart Members. Examination of those rocks reveals support for the latter option. In areas where relatively thick sections of the White Butte paleosols are present, beds of fine-grained muds and clays are present between the well-developed silcretes (figure 9). Additionally, well-rounded pebbles within some of the A horizons of the White Butte paleosols at White Butte (Stark County) resemble those present within the lower-most portion of the South Heart Member at Fitterer Ranch, where silcretes are absent. Alternatively, the basal conglomeratic sandstone portion incorporated into the silcrete of paleosol one within the White Butte paleosols displays clear evidence of erosion and bioturbation on the upper surface prior to the development of the silcretes, indicating deposition of those coarser rocks had ceased prior to the formation of the silcretes. All of that evidence suggests that the silcretes of the White Butte paleosols formed within basal mudstones and claystones deposited during the gradual onset of deposition of the South Heart Member, supporting their referral to that unit as suggested by most prior studies (e.g. Stone, 1973; Murphy et al., 1993).

Biostratigraphic data for the South Heart Member is extremely poor, and all that can be said of those rocks in North Dakota is that they were deposited during the late Eocene (Chadronian). Equivalent rocks referred to the Peanut Peak Member of the Chadron Formation in South Dakota typically contain a late Chadronian fauna (Ch4: 34.7-33.7 Ma: Janis et al., 2008);

however, in Nebraska the lowermost rocks previously referred to the Chadron B bed at now included within the Peanut Peak Member (Terry, 1998) and they contain a middle Chadronian fauna (Ch3: Janis et al., 2008).Those differences highlight the fact that onset of deposition of these finer-grained rocks within the Great Plains region was diachronous and biostratigraphic data from one area cannot solely be used to infer the age of rocks in different areas. Given that the only biostratigraphic data available in North Dakota for Chalky Buttes Member rocks that directly underlie rocks of the South Heart Member indicates a general Chadronian "age," the South Heart Member could represent deposition during any portion of the Chadronian depending on when local deposition of fine-grained rock began in North Dakota. More detailed study of the South Heart Member is needed before those questions can be properly addressed.

The upper contact between the Chadron and Brule Formations is placed either at the highest limestone bed (where present) or at the transition from non-calcareous clays below to calcareous clays above (Stone, 1973; Murphy et al., 1993). Though there is little overt evidence for either erosion or long-term nondeposition at that contact in most areas, biostratigraphic data suggest this contact is unconformable. Brontotheriid remains are known from the South Heart Member within North Dakota, indicating a Chadronian NALMA for the faunal component, providing a youngest possible age of 33.7 Ma for the top of Chadron Formation (Murphy et al., 1993; Prothero and Emry, 2004). Detailed biostratigraphic work currently ongoing at the NDGS in collaboration with Dr. Bill Korth (University of Rochester) and Dr. Robert Emry (National Museum of Natural History) on the Brule Formation at Fitterer Ranch within the Little Badlands area (Stark County) indicate that the lowest beds of the Brule Formation at that location contain a latest Orellan fauna (Or4), which at its oldest would be 32.6 Ma (Prothero and Emry, 2004). Thus, at least 1.1 million years is missing from the rock record across this contact at Fitterer Ranch. While the span of time represented by this unconformity could vary geographically within North Dakota, given that detailed biostratigraphic work is not yet available for other locations, it is likely that this contact is unconformable across all of North Dakota and local variation would simply reduce or extend the span of time represented by that unconformity. Similar lithologic criteria define the contact between the Chadron and Brule Formations in southern South Dakota, and a more abbreviated unconformity is also present in much of South Dakota between the Chadron and Brule Formations (Boyd and Welsh, 2014; Benton et al., 2015). Therefore, we interpret the contact between the Chadron and Brule Formations as a disconformity in North Dakota.

Future Research Directions

Moving forward, one of the main goals is to expand the heavy mineral work on the Chalky Buttes Member (and lithologic equivalents) through greater geographic coverage and more detailed stratigraphic sampling at individual locations. Increased geographic coverage could be obtained via analysis of samples already processed (e.g. disaggregated, sieved) but not yet studied, and via processing and analysis of additional samples that were collected in the fall of 2017. Additional samples should also be collected farther to the east/northeast (e.g. Schultz, Young Mans, Long, and/or Coffin Buttes in North Dakota), to the east/southeast (e.g. Taylor Butte and Coal Butte, South Dakota), and to the southwest (e.g. East Short Pine Hills, South Dakota). Detailed sampling and analysis of the Chalky Buttes Member at a locality showing diversity in heavy mineral assemblages would help to reveal more details about temporal variations in source contributions. The Chalky Buttes–Rattlesnake Butte area seems like an excellent choice for such work given that current sampling shows substantial variation in sample composition through time even though all currently processed samples come from the bottom two-thirds of the section.

Another goal of future heavy mineral work is to extend work stratigraphically through detailed studies of the Golden Valley Formation, the Slim Buttes Formation, the South Heart Member of the Chadron Formation (and lithologic equivalents), and the Brule Formation. Initially, this goal is being addressed by focusing on samples already collected from those rocks at Fitterer Ranch (Stark County, North Dakota), White Butte (Stark County, North Dakota), the Slim Buttes (Harding County, South Dakota), and the Long Pine Hills (Carter County, Montana). The purpose of that work is to better understand how rock sources varied prior to and following deposition of the Chalky Buttes Member. That work could also assist with lithostratigraphic referral of previously unidentified rocks within the Williston Basin, like the "golden brown" rocks of the Chadron Formation and possible lithologic equivalents of the Golden Valley Formation in the Slim Buttes area of South Dakota.

Continued study is planned for the newly discovered Chadron Formation rocks in Adams County (North Dakota). Further elucidation of the Stover Site local fauna will improve comparisons to the Medicine Pole Hills local fauna and other Chadronian faunas from North America. Field surveys of the area around Reeder and Bucyrus will continue in order to identify the full geographic extent of Stover Site equivalent rocks in Adams County and better understand the depositional history of those rocks. Special focus will be placed on finding in situ rocks in that area that will allow for more detailed study of those deposits and their stratigraphic context.

Attempts to discover additional faunas from the Chadron Formation in North Dakota will also continue, especially in areas where those biostratigraphic data can be tied into the heavy mineral data. The paleontology program at the NDGS continues to collect and screen wash test samples of sandstones from the Chadron Formation in search of microvertebrate fossils, though such tests at White Butte (Stark County) have thus far been unproductive. One discovery from this study that may assist in locating additional Chadronian faunas was the relatively high abundance of bone fragments among the non-opaque heavy mineral grains at locations where microvertebrate fossils were abundant (e.g. Table 3). During the processing of heavy mineral samples in this study, the medium sand fraction of the heavy minerals from two samples in the Long Pine Hills were found to have abundant amounts of bone fragments (LPH-1: 44%; LPH-4: 22%). Those values are on par with those reported herein from the Stover Site (Table 3), indicating that microvertebrate sampling at those two sample sites may be productive. Future heavy mineral work within the Chadron Formation in the Williston Basin may be useful in identifying other areas where microvertebrate sampling should be conducted using these same criteria. Macrovertebrate fossils were also previously noted at Square Butte (Golden Valley County, North Dakota: Murphy et al., 1993), but have not been heavily sampled or studied in detail. That site will be one of the focuses of additional collecting efforts in the near future.

Finally, the geographic distribution, identification, and composition of paleosols developed in the upper portion of the Chalky Buttes Member needs to be studied in more detail within the Williston Basin. That work would include conducting necessary microscopic and geochemical analysis of the White Butte and Fitterer Ranch paleosols at the sections described in this study as well as similar paleosols reported in this study in the Reva Gap area of the Slim Buttes in South Dakota. Better understanding of the distribution of these paleosols and the paleoenvironments they represent will greatly enhance reconstructions of North Dakota during the Late Eocene.

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Appendices

Appendix 1. Updated faunal list for the Medicine Pole Hills local fauna from the Chalky Buttes Member of the Chadron Formation in Bowman County, North Dakota.

Class	**Order**	**Family**	**Taxon**	**Citation/Specimen**
Osteichtheys	-	-	Osteichthyes indet.	3
Osteichthyes	Amiiformes	Amiidae	Amiidae indet.	1
Osteichthyes	Amiiformes	Amiidae	*Amia* cf. *scutata*	3
Osteichthyes	Amiiformes	Amiidae	*Kindleia fragosa*	3
Osteichthyes	Lepisosteiformes	Lepisosteidae	*Lepisosteus* sp.	1,3
Osteichthyes	Siluriformes	Ictaluridae	*Ictalurus* sp.	1.3
Amphibia	Anura	-	Anura indet.	1,3
Amphibia	Caudata	-	Caudata indet.	3
Reptilia	Chelonia	-	Chelonia indet.	1,3
Reptilia	Chelonia	Testudinidae	*Stylemys* sp.	1,3
Reptilia	Chelonia	Testudinidae	*Stylemys nebrascensis*	20
Reptilia	Chelonia	Trionychidae	*Trionyx* sp.	1
Reptilia	Chelonia	Trionychidae	cf. *Trionyx* sp.	3
Reptilia	Crocodylia	-	Crocodylia indet.	1,3,23
Reptilia	Squamata	Agamidae	*Tinosaurus* sp.	10, PTRM 19515
Reptilia	Squamata	Anguidae	Anniellinae indet.	13, PTRM 19129
Reptilia	Squamata	Anguidae	Diploglossinae indet.	10, PTRM 19207
Reptilia	Squamata	Anguidae	Gerrhonotinae indet.	13, PTRM 19025
Reptilia	Squamata	Anguidae	*Helodermoides* sp.	10, PTRM 19028
Reptilia	Squamata	Anguidae	cf. *Peltosaurus* sp.	10, PTRM 19211
Reptilia	Squamata	Iguanidae	*Tuberculacerta pearsoni*	10, PTRM 5296

Appendix 1. Continued.

Class	**Order**	**Family**	**Taxon**	**Citation/Specimen**
Reptilia	Squamata	Iguanidae	*Oreithyia oaklandi*	13,14, PTRM 5198
Reptilia	Squamata	Iguanidae	*Cypressaurus* sp.	10, PTRM 19063
Reptilia	Squamata	Iguanidae	*Quironius praelapsus*	13, PTRM 19499
Reptilia	Squamata	Polychrotidae	*Sauropithecoides charisticus*	13, PTRM 1841
Reptilia	Squamata	Rhineuridae	cf. *Spathorhynchus* sp.	10, PTRM 19160
Reptilia	Squamata	Rhineuridae	cf. *Rhineura* sp.	10, PTRM 19128
Reptilia	Squamata	Varanidae	*Saniwa edura*	10, PTRM 19036
Reptilia	Squamata	Xantusiidae	*"Palaeoxantusia" borealis*	10, PTRM 19024
Reptilia	Squamata	Anguimorpha	Anguimorpha indet.	10, PTRM 19212
Reptilia	Ophidia	Boidae	*Calamagras weigeli*	16, PTRM 19710
Reptilia	Ophidia	Colubridae	Colubridae indet.	16, PTRM 19641
Reptilia	Ophidia	Loxocemidae	*Ogmophis compactus*	16, PTRM 19724
Reptilia	Ophidia	Ophidia incertae sedis	*Coniophis* sp.	16, PTRM 19595
Mammalia	Mammalia incertae sedis	-	*Idiogenomys* sp.	X, PTRM 6266
Mammalia	Multituberculata	Neoplagiaulacidae	*Ectypodus lovei*	9, PTRM 1962
Mammalia	Multituberculata	Neoplagiaulacidae	?Neoplagiaulacidae indet.	9, PTRM 7812
Mammalia	Metatheria	Didelphidae	*Herpetotherium valens*	3,6,7,8,18, PTRM 1953
Mammalia	Metatheria	Didelphidae	*Herpetotherium* cf. *fugax*	7,8,18, PTRM 5778
Mammalia	Metatheria	Didelphidae	*Herpetotherium* cf. *marsupium*	18, PTRM 4745
Mammalia	Metatheria	Didelphidae	*Peratherium* sp.	1,Z
Mammalia	Metatheria	Peradectidae	*Didelphidectes* cf. *pumilis*	3,18, PTRM 7855

Appendix 1. Continued.

Class	Order	Family	Taxon	Citation/Specimen
Mammalia	Metatheria	Peradectidae	*Peradectes* cf. *californicus*	7,8,18, PTRM 1343
Mammalia	Cimolesta	Apatemyidae	*Sinclairella* sp.	3,8, PTRM 2080
Mammalia	Soricomorpha	Soricidae	*Domnina sagittariensis*	11, PTRM 7890
Mammalia	Soricomorpha	Soricidae	*Domnina* cf. *thompsoni*	11, PTRM 5831
Mammalia	Soricomorpha	Soricidae	cf. *Domnina*	11, PTRM 14680
Mammalia	Leptictida	Leptictidae	*Leptictis* sp.	1,3, PTRM 7271
Mammalia	Leptictida	Leptictidae	*Leptictis* cf. *acutidens*	8, PTRM 1374
Mammalia	Eulipotyphla	Apternodontidae	*Apternodus* sp.	8, PTRM 5768
Mammalia	Eulipotyphla	Geolabididae	*Centetodon chadronensis*	3,8, PTRM 1331
Mammalia	Eulipotyphla	Geolabididae	*Centetodon magnus*	3,Z
Mammalia	Eulipotyphla	Micropternodontidae	*Micropternodus* cf. *borealis*	8, PTRM 10489
Mammalia	Eulipotyphla	Oligoryctidae	*Oligoryctes* cf. *cameronensis*	8, PTRM 1999
Mammalia	Eulipotyphla	Proscalopidae	*Cryptoryctes* sp.	X, PTRM 10279
Mammalia	Erinaceomorpha	-	Erinaceomorpha indet.	X, PTRM 6267
Mammalia	Macroscelidea	Amphilemuridae	cf. *Ankylodon* sp.	3
Mammalia	Chiroptera	-	Chiroptera indet.	3, PTRM 5488
Mammalia	Creodonta	Hyaenodontidae	*Hemipsalodon? grandis*	20
Mammalia	Creodonta	Hyaenodontidae	cf. *Hyaenodon* sp.	1
Mammalia	Creodonta	Hyaenodontidae	*Hyaenodon* sp.	21,22
Mammalia	Primates	Paromomyidae	cf. *Ignacius* sp.	17, PTRM 17483
Mammalia	Primates	Microsyopidae	Uintasoricinae indet.	17, PTRM 10401

Appendix 1. Continued.

Class	**Order**	**Family**	**Taxon**	**Citation/Specimen**
Mammalia	Carnivora	Amphicyonidae	*Brachyrynchocyon dodgei*	X, PTRM 1416
Mammalia	Carnivora	Amphicyonidae	*Daphoenus* sp.	3,Z
Mammalia	Carnivora	Canidae	*Hesperocyon gregarious*	1,3, PTRM 10215
Mammalia	Carnivora	Nimravidae	*Dinictis* sp.	21,22, USNM V 18597
Mammalia	Carnivora	Subparictidae	*Subparictis parvus*	X, PTRM 1358
Mammalia	Rodentia	Cylindrodontidae	*Cylindrodon collinus*	12, PTRM 2615
Mammalia	Rodentia	Cylindrodontidae	*Pseudocylindrodon silvaticus*	12, PTRM 5010
Mammalia	Rodentia	Cylindrodontidae	*Ardynomys saskatchewensis*	12, PTRM 11023
Mammalia	Rodentia	Eomyidae	*Adjidaumo* sp.	PTRM 14575
Mammalia	Rodentia	Eomyidae	*Aulolithomys* sp.	PTRM 14262
Mammalia	Rodentia	Eomyidae	*Centimanomys* sp.	3
Mammalia	Rodentia	Eomyidae	*Metanoiamys* sp.	PTRM 4879
Mammalia	Rodentia	Eomyidae	*Paradjidaumo* sp.	PTRM 5106
Mammalia	Rodentia	Eomyidae	*Paradjidaumo* cf. *trilophus*	3
Mammalia	Rodentia	Eomyidae	*Paradjidaumo* cf. *hansonorum*	3
Mammalia	Rodentia	Eomyidae	*Yoderimys* cf. *stewarti*	3, PTRM 2063
Mammalia	Rodentia	Eutypomyidae	*Eutypomys parvus*	12, PTRM 1364
Mammalia	Rodentia	Pipestoneomyidae	*Pipestoneomys* sp.	12, PTRM 6167
Mammalia	Rodentia	Ischyromyidae	*Ischyromys junctus*	15, PTRM 11042
Mammalia	Rodentia	Ischyromyidae	*Ischyromys* cf. *veterior*	15, PTRM 11038
Mammalia	Rodentia	Ischyromyidae	*Metaparamys* cf. *dawsonae*	15, PTRM 8349

Appendix 1. Continued.

Class	Order	Family	Taxon	Citation/Specimen
Mammalia	Rodentia	Sciuravidae	*Prolapsus* sp.	15, PTRM 7298
Mammalia	Rodentia	Aplodontidae	*Prosciurus vetustus*	15, PTRM 5037
Mammalia	Rodentia	Aplodontidae	Prosciurinae indet.	15, PTRM 4901
Mammalia	Rodentia	Sciuridae	*Douglassciurus jeffersoni*	15, PTRM 2607
Mammalia	Rodentia	Heliscomyidae	*Heliscomys* cf. *vetus*	15, PTRM 4881
Mammalia	Lagomorpha	Leporidae	*Palaeolagus* sp.	1
Mammalia	Lagomorpha	Leporidae	*Palaeolagus* cf. *temnodon*	3
Mammalia	Lagomorpha	Leporidae	*Megalagus* cf. *brachyodon*	3, PTRM 1977
Mammalia	Artiodactyla	Anthracotheriidae	Bothriodontinae indet.	3, PTRM 1975
Mammalia	Artiodactyla	Camelidae	cf. *Poebrotherium* sp.	1,3,21,22
Mammalia	Artiodactyla	Dichobunidae	cf. *Stibarus* sp.	1, PTRM 5764
Mammalia	Artiodactyla	Dichobunidae	*Stibarus montanus*	3
Mammalia	Artiodactyla	Entelodontidae	Entelodontidae indet.	X, PTRM 10526
Mammalia	Artiodactyla	Leptomerycidae	*Leptomeryx* sp.	1,3,20,21,22
Mammalia	Artiodactyla	Leptomerycidae	*Leptomeryx yoderi*	3, 4, PTRM 10534
Mammalia	Artiodactyla	Merycoidodontidae	Merycoidodontidae indet.	PTRM 15017
Mammalia	Artiodactyla	Merycoidodontidae	*Merycoidodon* sp.	1
Mammalia	Artiodactyla	Oromerycidae	Oromerycidae indet.	PTRM 1415
Mammalia	Artiodactyla	Protoceratidae	cf. *Leptotragulus* sp.	X, PTRM 1524
Mammalia	Artiodactyla	Protoceratidae	Protoceratidae indet.	X, PTRM 1524
Mammalia	Artiodactyla	Tayasuidae	cf. *Perchoerus* sp.	1

Appendix 1. Continued.

Class	**Order**	**Family**	**Taxon**	**Citation/Specimen**
Mammalia	Perissodactyla	Amynodontidae	*Toxotherium* sp.	3, PTRM 8205
Mammalia	Perissodactyla	Brontotheriidae	*Megacerops* sp.	1, 3, 19, 20, 21, 22, 23, PTRM 10419
Mammalia	Perissodactyla	Equidae	*Mesohippus* sp.	14, PTRM 1405
Mammalia	Perissodactyla	Equidae	*Mesohippus* cf. *propinquus*	3
Mammalia	Perissodactyla	Equidae	*Mesohippus* cf. *westoni*	3
Mammalia	Perissodactyla	Rhinocerotidae	*Hyracodon* sp.	21,22, PTRM 10216
Mammalia	Perissodactyla	Rhinocerotidae	*Trigonias* sp.	3
Mammalia	Perissodactyla	Rhinocerotidae	cf. *Subhyracodon* sp.	1
Mammalia	Perissodactyla	Tapiridae	cf. *Colodon* sp.	1
Mammalia	Perissodactyla	Tapiridae	cf. *Protapirus* sp.	1

Citations: **1**, Pearson (1993); **2**, Pearson and Hoganson (1995a); **3**, Pearson and Hoganson (1995b); **4**, Heaton and Emry (1996); **5**, Pearson (1998); **6**, Kihm et al. (2001); **7**, Kihm et al. (2003); **8**, Kihm and Schumaker (2004); **9**, Schumaker and Kihm (2006); **10**, Smith (2006); **11**, Kihm and Schumaker (2008); **12**, Kihm (2011); **13**, Smith (2011a); **14**, Smith (2011b); **15**, Kihm (2013); **16**, Smith (2013); **17**, Kihm and Tornow (2014); **18**, Kihm and Schumaker (2015); **19**, Leonard (1922); **20**, Hares (1928); **21**, Benson (1952); **22**, Denson et al. (1959); **23**, Murphy et al. (1993).; **X**, new report in this study; **Z**, prior report that appears to be in error based on subsequent studies.

Appendix 2. Faunal list with specimen citations for the Stover Site local fauna from the Chalky Buttes Member of the Chadron Formation in Adams County, North Dakota.

Class	**Order**	**Family**	**Taxon**	**Citation/Specimen**
Molluska	Gastropoda	-	Gastropoda indet.	NDGS 2319
Chondrichthyes	Myliobatiformes	-	Myliobatiformes indet.	*
Osteichthyes	Esociformes	Esocidae	*Esox* sp.	*
Osteichthyes	Lepisosteiformes	Lepisosteidae	Lepisosteidae indet.	*
Osteichthyes	Siluriformes	Ictaluridae	Ictaluridae indet.	*
Reptilia	Chelonia	-	Chelonia indet. [Morph 1]	*
Reptilia	Chelonia	-	Chelonia indet. [Morph 2]	*
Reptilia	Crocodylia	-	Crocodylia indet.	NDGS 2182
Reptilia	Serpentes	-	Serpentes indet.	NDGS 2319
Reptilia	Squamata	Anguidae	cf. *Helodermoides* sp.	NDGS 2320
Reptilia	Squamata	Anguidae	cf. *Peltosaurus* sp.	NDGS 2180
Reptilia	Squamata	Rhineuridae	?Rhineuridae indet.	NDGS 2181
Mammalia	Multituberculata	Neoplagiaulacidae	Neoplagiaulacidae indet.	NDGS 2332
Mammalia	Metatheria	Didelphidae	*Herpetotherium valens*	NDGS 2333
Mammalia	Lipotyphyla	Micropternodontidae	?*Micropternodus* sp.	NDGS 2337
Mammalia	Leptictida	Leptictidae	*Leptictis* sp.	NDGS 2335
Mammalia	Carnivora	-	Carnivora indet.	NDGS 2341
Mammalia	Rodentia	Aplodontidae	*Prosciurus* sp.	NDGS 2356
Mammalia	Rodentia	Cylindrodontidae	Cylindrodontidae indet.	NDGS 2343
Mammalia	Rodentia	Eomyidae	*Adjidaumo* sp.	NDGS 2346
Mammalia	Rodentia	Eomyidae	*Aulolithomys* sp.	NDGS 2354

Appendix 2. Continued.

Class	**Order**	**Family**	**Taxon**	**Citation/Specimen**
Mammalia	Rodentia	Eomyidae	*Paradjidaumo* sp.	NDGS 2349
Mammalia	Rodentia	Sciuridae	Sciuridae indet.	NDGS 2357
Mammalia	Lagomorpha	Leporidae	Leporidae indet.	NDGS 2338
Mammalia	Artiodactyla	Dichobunidae	cf. *Stibarus* sp.	NDGS 2359
Mammalia	Artiodactyla	Entelodontidae	Entelodontidae indet.	NDGS 2317
Mammalia	Artiodactyla	Leptomerycidae	*Leptomeryx mammifer*	NDGS 2314
Mammalia	Perissodactyla	Brontotheridae	Brontotheridae indet.	NDGS 2183
Mammalia	Perissodactyla	Rhinocerotidae	Rhinocerotidae indet.	NDGS 2318

* = material not yet cataloged, so no specimen number information is available at this time.

Appendix 3. Raw measurements of leptomerycid lower molars from the Medicine Pole Hills and Stover Site local faunas.

Site	Specimen Number	Tooth Position	L	ASW	PSW
MPH	PTRM 686	mx	6.8	4.2	4.6
MPH	PTRM 1525	m1	7.3	4.8	5.5
MPH	PTRM 1525	m2	7.3	5.2	5.5
MPH	PTRM 1556	mx	8.2	5.3	6.5
MPH	PTRM 1558	mx	7.9	5.2	6.0
MPH	PTRM 1797	mx	7.2	4.3	4.7
MPH	PTRM 2733	mx	7.8	5.8	6.2
MPH	PTRM 7445	mx	8.4	5.9	6.4
MPH	PTRM 10234	m2	8.0	6.2	6.1
MPH	PTRM 10575	mx	8.0	5.2	5.7
MPH	PTRM 10578	mx	8.1	5.5	5.8
MPH	PTRM 10579	mx	7.8	6.3	6.7
MPH	PTRM 10582	mx	8.4	5.9	6.3
MPH	PTRM 10583	mx	7.9	5.0	5.5
MPH	PTRM 10586	mx	7.7	4.8	5.3
MPH	PTRM 15010	mx	7.7	4.9	5.5
MPH	PTRM 15013	mx	7.5	5.4	6.1
MPH	PTRM 15014	m1	6.1	4.3	4.7
MPH	PTRM 16027	mx	8.3	5.7	5.8
MPH	PTRM 16040	mx	7.4	4.9	5.2
SS	NDGS 2315	mx	8.2	6.5	6.8
SS	NDGS2314	mx	9.1	7.3	7.1

Measurements were only recorded from well-preserved specimens. All measurements in mm. **Abbreviations**: **ASW**, anterior selene width; **L**, anteroposterior length; **m1**, first lower molar; **m2**, second lower molar; **mx**, unidentified lower molar (either m1 or m2); **max**, maximum reported value; **min**, minimum reported value; **MPH**, Medicine Pole Hills local fauna; **PSW**, posterior selene width; **SS**, Stover Site local fauna.

Appendix 4. Heavy mineral data for the 36 very fine sand fractions of samples from the Chadron Formation in Montana, North Dakota, and South Dakota.

Geographic Location	BB	BB	CB	CB	CB	CB	Coal	LPH	LPH	LPH
Member Equivalent	CBM	CBM	CBM	CBM	CBM	CBM	CBM	CBM	CBM	CBM
Sample	GND-58	BB-1	GND-18	GND-3	GND-5	GND-9	SD-5	GM-345	LPH-1	LPH-4
Feet Above Basal Contact	3	1-2	45	5	10	35	25	15	10	1
Percent Opaque Grains	78	70.3	69	87	80	72	87	75	44.5	56.0
Percent Non-opaque Grains	22	29.7	31	13	20	28	13	25	55.5	44.0
# of Non-opaque Grains	129	272	124	92	117	106	156	131	333	292
Diopside	0	0.0	0	0	0	0	0	0	0.0	0.0
Augite	0	0.0	0	0	0	0	0	0	0.0	0.0
Hypersthene	0	0.4	0	0	0	0	0	0	0.0	0.7
Biotite	0	1.8	0	0	0	0	0	2	0.9	6.8
Amphibole	2	1.8	1	0	1	4	0	8	1.2	0.0
Monazite	0	0.0	0	0	0	0	0	0	0.0	0.0
Sphene	1	5.9	3	1	0	4	0	3	7.8	5.8
Epidote	1	16.9	40	2	8	24	2	33	44.4	56.8
Staurolite	15	9.6	12	29	15	8	37	0	1.5	0.7
Al-silicates	7	5.5	7	15	6	8	19	0	1.8	0.3
Garnet	2	0.7	35	2	9	28	1	27	21.0	17.5
Zircon	65	32.7	0	38	49	21	27	24	11.7	1.4
Tourmaline	3	17.6	1	9	7	1	11	2	8.4	6.2
Rutile	4	6.3	1	4	5	2	3	1	0.6	3.1

Appendix 4. Continued.

Geographic Location Member Equivalent Sample Feet Above Basal Contact	LPH SH GM-347 30	MPH CBM KS-3 F	MPH CBM MPH-E E	MPH CBM MPH-F* F	MPH CBM MPH-G G	MPH CBM MPH-H H	RSB CBM RSB 75-80	SB CBM ZD-31 15	SB SH CSD-44 25	SCH CBM CSD-31 11
% Opaque Grains	75	18	9.0	8.1	6.2	6.4	24.7	95	79	72
% Non-opaque Grains	25	82	91.0	91.9	93.8	93.6	75.3	5	21	28
# of Non-opaque Grains	146	353	415	397	445	422	348	80	95	140
Diopside	0	8.7	34.9	44.7	25.6	5.2	0.0	0	0	0
Augite	0	0	0	0	0	0	0.3	0	0	0
Hypersthene	0	0	0	0.5	0	0	0.0	0	0	0
Biotite	1	0	5.1	1.0	2.7	0.9	52.9	0	1	0
Amphibole	5	66.5	43.9	40.4	44.5	57.1	0.0	0	0	0
Monazite	0	0.3	0	0	0	0	0	7	0	0
Sphene	1	0	0.7	1.0	0.9	1.2	2.9	0	1	1
Epidote	6	16.9	11.1	11.7	17.3	29.1	29.9	5	0	15
Staurolite	3	0	0.2	0.5	0.7	0.2	0	25	15	22
Al-silicates	6	0	0	0	0.4	0	0.6	17	7	28
Garnet	1	7.3	3.6	0	7.2	5.2	10.6	5	0	8
Zircon	58	0	0	0	0	0	1.4	35	39	11
Tourmaline	16	0	0	0	0	0	0.6	6	33	15
Rutile	3	0	0.5	0.3	0.4	0.9	0.9	0	4	0

Appendix 4. Continued.

Geographic Location	SCH	SCH	SCH	SCH	SCH	Slide	Slide	Slide	SS	TB
Member Equivalent	CBM	CBM	CBM	SH	SH	CBM	CBM	CBM	CBM	CBM
Sample	CSD-38	CSD-50	SCH-2	CSD-6	CSD-66	GND-131	GND-133	GND-134	STOV-3	SD-2
Feet Above Basal Contact	8	3	~11	22	15	55	50	25	-	20
% Opaque Grains	84	94	60.9	72	69	69	-	76	77.8	83
% Non-opaque Grains	16	6	39.1	28	31	31	-	24	22.2	17
# of Non-opaque Grains	81	246	364	52	123	144	102	158	463	57
Diopside	0	0	0.0	0	0	0	0	0	8.7	0
Augite	0	0	0.0	0	0	0	0	0	0.5	0
Hypersthene	0	0	0.8	0	0	0	0	0	0.5	0
Biotite	0	1	0.5	4	0	0	0	0	1.5	0
Amphibole	1	0	0.5	0	0	5	0	0	17.0	0
Monazite	0	0	0.3	0	0	0	0	0	0	2
Sphene	0	0	11.8	2	0	0	0	0	4.4	0
Epidote	0	2	25.5	16	11	2	1	0	42.7	19
Staurolite	22	30	4.1	10	28	42	25	41	0.5	37
Al-silicates	46	24	2.7	31	12	23	10	12	0	19
Garnet	1	1	20.1	10	5	1	0	0	15.5	4
Zircon	5	24	17.9	8	30	7	46	26	3.9	12
Tourmaline	18	16	12.1	13	9	17	11	17	2.4	7
Rutile	4	2	3.6	6	5	3	7	4	0	0

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Appendix 4. Continued.

Geographic Location	WB	WB	WST	WST	WST	YMB
Member Equivalent	CBM	CBM	CBM	CBM	CBM	SH
Sample	GND-54	WB-3	GND-6	GND-8	WST-2	GND-35
Feet Above Basal Contact	8	1-2	10	55	44	45
% Opaque Grains	75	77.0	79	67	64.5	84
% Non-opaque Grains	25	23.0	21	33	35.5	16
# of Non-opaque Grains	109	296	25	89	357	127
Diopside	0	0.0	0	0	0.0	0
Augite	0	0.0	0	0	0.0	0
Hypersthene	0	0.3	0	0	0.0	0
Biotite	0	3.4	24	62	1.4	2
Amphibole	1	0.7	8	16	0.8	2
Monazite	0	0	0	0	0	0
Sphene	1	5.4	0	1	5.3	1
Epidote	5	12.5	24	11	75.9	12
Staurolite	28	7.1	4	2	0.3	18
Al-silicates	5	5.4	8	1	0.3	11
Garnet	0	12.5	4	3	8.7	2
Zircon	52	17.9	24	4	4.2	39
Tourmaline	2	18.6	4	0	2.0	9
Rutile	6	14.5	0	0	0.6	4

Notes: Data shown for heavy minerals are grain percentages. For Medicine Pole Hills samples, the unit number is provided rather than a measured height above the basal contact (see Webster et al., 2015). **Abbreviations**: **BB**, Black Butte; **CB**, Chalky Buttes; **CBM**, Chalky Buttes Member; Coal, Coal Butte; **LPH**, Long Pine Hills; **MPH**, Medicine Pole Hills; **RSB**, Rattlesnake Butte; **SB**, Slim Buttes; **SCH**, South Cave Hills; **SH**, South Heart Member; **Slide**, Slide Butte; **SS**, Stover Site; **TB**, Taylor Butte; **WB**, White Butte; **WST**, Whetstone Buttes; **YMB**, Young Mans Butte.

Appendix 5. Heavy mineral data for the 23 medium sand fractions of samples from the Chadron Formation in Montana, North Dakota, and South Dakota.

Geographic Location	BB	CB	LB	LPH	LPH	MPH	MPH	MPH	MPH	MPH
Member Equivalent	CBM	CBM	CBM	CBM	CBM	CBM	CBM	CBM	CBM	CBM
Sample	BB-1	CB-L	LB	LPH-1	LPH-4	MPH-B1	MPH-B2	MPH-CL	MPH-CU	MPH-D
Feet Above Basal Contact	1-2	unkn.	unkn.	10	1	B	B	C	C	D
Percent Opaque Grains	74.7	17.3	28.9	29.5	87.5	3.3	3.2	3.0	6.7	3.1
Percent Non-opaque Grains	25.3	82.7	71.1	70.5	12.5	96.7	96.8	97.0	93.3	96.9
# of Non-opaque Grains	138	495	224	101	52	494	564	390	497	272
Diopside	0.0	0.0	0.0	0.0	0.0	1.2	0.9	22.6	20.3	0.0
Augite	0.7	0.0	14.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hypersthene	0.0	0.0	4.0	1.0	0.0	0.2	0.0	0.0	0.0	0.4
Biotite	2.9	18.2	2.2	9.9	0.0	0.4	2.0	0.5	0.0	47.4
Amphibole	7.2	0.6	0.9	0.0	9.6	57.1	54.1	43.6	53.5	31.6
Monazite	5.8	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sphene	0.0	1.0	0.0	1.0	0.0	0.6	0.2	0.0	0.2	0.0
Epidote	11.6	61.8	3.1	77.2	59.6	36.6	39.5	22.8	24.1	19.9
Staurolite	34.1	3.0	22.8	4.0	9.6	0.2	0.0	0.5	0.0	0.0
Al-silicates	10.9	0.6	12.1	0.0	13.5	0.8	0.7	0.0	0.0	0.0
Garnet	3.6	11.7	3.6	1.0	0.0	2.8	2.7	9.2	1.8	0.7
Zircon	13.8	0.0	3.6	0.0	7.7	0.0	0.0	0.0	0.0	0.0
Tourmaline	5.1	2.2	13.8	2.0	0.0	0.0	0.0	0.0	0.0	0.0
Rutile	4.3	0.2	2.7	3.0	0.0	0.0	0.0	0.3	0.0	0.0

Appendix 5. Continued.

Geographic Location	MPH	MPH	MPH	MPH	MPH	RSB	SCH	SCH	SCH	SQB
Member Equivalent	CBM	CBM	CBM	CBM	CBM	CBM	CBM	CBM	CBM	CBM
Sample	MPH-E	MPH-F	MPH-F*	MPH-G	MPH-H	RSB	SCH-2	SCH-4	SCH-5	SQB
Feet Above Basal Contact	E	F	F	G	H	75-80	~11	3	3	4-5
% Opaque Grains	3.0	8.2	0.8	15.6	5.8	7.4	62.9	85.8	91.7	62.0
% Non-opaque Grains	97.0	91.8	99.2	84.4	94.2	92.6	37.1	14.2	8.3	38.0
# of Non-opaque Grains	486	358	484	346	440	689	97	250	204	181
Diopside	30.5	2.5	51.9	11.6	0.9	0.1	0.0	0.0	0.0	0.0
Augite	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0
Hypersthene	0.0	1.1	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0
Biotite	0.0	4.2	0.0	5.5	4.5	33.4	0.0	0.0	0.0	0.0
Amphibole	35.6	47.5	29.8	35.8	49.3	0.4	2.1	0.4	0.0	0.0
Monazite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7
Sphene	0.0	0.3	0.4	0.9	0.5	0.4	2.1	0.0	0.0	1.1
Epidote	29.2	43.6	13.4	35.5	42.0	41.4	7.2	1.2	0.0	34.3
Staurolite	0.0	0.6	0.6	0.6	0.0	0.3	67.0	69.2	77.5	21.0
Al-silicates	0.0	0.0	0.0	0.0	0.0	0.6	3.1	20.0	14.7	14.9
Garnet	4.7	0.3	3.5	9.0	2.3	21.5	7.2	0.4	0.0	3.9
Zircon	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.4	0.0	3.9
Tourmaline	0.0	0.0	0.0	0.0	0.2	0.4	6.2	5.6	4.9	16.6
Rutile	0.0	0.0	0.0	0.0	0.0	0.6	5.2	2.8	2.0	0.6

Appendix 5. Continued.

Geographic Location	SS	WB	WST
Member Equivalent	CBM	CBM	CBM
Sample	STOV-3	WB-3	WST-2
Feet Above Basal Contact	–	1-2	44
% Opaque Grains	76.8	36.4	15.2
% Non-opaque Grains	23.2	63.6	84.8
# of Non-opaque Grains	202	121	347
Diopside	38.6	0.0	0.0
Augite	0.0	0.0	0.0
Hypersthene	1.0	0.0	0.0
Biotite	0.0	40.5	0.0
Amphibole	22.3	0.0	0.6
Monazite	0.0	0.0	0.0
Sphene	1.5	0.0	1.2
Epidote	21.8	36.4	84.4
Staurolite	0.5	5.0	4.9
Al-silicates	0.0	10.7	0.3
Garnet	12.4	0.8	6.3
Zircon	0.0	0.8	0.9
Tourmaline	0.5	5.0	1.4
Rutile	0.0	0.8	0.0

Notes: Data shown for heavy minerals are grain percentages. For Medicine Pole Hills samples, the unit number is provided rather than a measured height above the basal contact (see Webster et al., 2015). **Abbreviations**: **BB**, Black Butte; **CB**, Chalky Buttes; **CBM**, Chalky Buttes Member; **LB**, Little Badlands; **LPH**, Long Pine Hills; **MPH**, Medicine Pole Hills; **RSB**, Rattlesnake Butte; **SCH**, South Cave Hills; **SQB**, Square Butte; **SS**, Stover Site; **unkn**; unknown stratigraphic position; **WB**, White Butte; **WST**, Whetstone Buttes.

Appendix 6. Group and sub-group averages of 29 very fine sand fractions of heavy mineral samples from the Chalky Buttes Member (and lithologic equivalents) in Montana, North Dakota, and South Dakota.

	Group A				Group B			Group C	Group D		
Subgroup	Full	A1	A2	A3	Full	B1	B2	Full	Full	D1	D2
# of Samples	14	5	6	3	8	7	1	2	5	3	2
Diopside					1.1	1.2			**23.4**	**35.1**	5.9
Augite					0.1	0.1		0.1	0.1		0.2
Hypersthene	0.1			0.2	0.2	0.3			0.1	0.2	
Biotite	2.2	0.2		9.7	1.6	1.7	1.4	**57.4**	1.9	2.9	0.5
Amphibole	1.5	1.2	0.7	3.5	4.1	4.5	0.8	8.0	**50.8**	**43.0**	**62.6**
Monazite	0.5		1.2		0.0	0.0			0.0		0.1
Sphene	1.1	0.2	0.5	3.8	5.6	5.7	5.3	1.9	0.7	0.9	0.6
Epidote	6.7	3.8	3.7	**17.8**	**42.8**	**38.1**	**75.9**	**20.4**	**17.4**	**13.4**	**23.4**
Staurolite	**22.5**	**31.4**	**22.8**	6.9	3.4	3.8	0.3	1.0	0.3	0.5	0.1
Al-silicates	**15.1**	**26.6**	**10.0**	6.3	2.5	2.8	0.3	0.8	0.1	0.1	
Garnet	3.3	2.2	3.0	5.7	**21.6**	**23.4**	8.7	6.8	4.5	3.6	5.8
Zircon	**30.9**	14.6	**47.5**	**24.9**	**10.5**	**11.4**	4.2	2.7	0.1		0.2
Tourmaline	11.5	**16.6**	6.3	**13.4**	4.4	4.7	2.0	0.3	0.0		0.0
Rutile	4.3	2.6	4.3	6.9	1.5	1.6	0.6	0.4	0.4	0.4	0.5
Total	99.6	99.4	100	99.2	99.4	99.4	99.4	100	99.9	100	99.8

Notes: Data shown for heavy minerals are grain percentages. Amphibole includes hornblende and actinolite. Totals may be less than 100% as a result of rounding differences and the exclusion of unidentifiable and select low-abundance mineral grains. Bold values highlight the dominant minerals in each group and sub-group.

Appendix 7. Group and sub-group averages of 23 medium sand fractions of heavy mineral samples from the Chalky Buttes Member (and lithologic equivalents) in Montana, North Dakota, and South Dakota.

	Group A			Group B	Group C			Group D		
Subgroup	Full	A1	A2	Full	Full	C1	C2	Full	D1	D2
# of Samples	6	3	3	4	3	1	2	10	8	2
Diopside					0.1		0.1	**18.1**	**11.3**	**45.2**
Augite	2.3		4.6		0.1		0.1			
Hypersthene	0.7		1.3	0.2	0.1	0.4		0.3	0.3	0.5
Biotite	0.9		1.7	7.0	**40.5**	**47.4**	**37.0**	1.7	2.1	
Amphibole	1.8	0.8	2.7	2.6	**10.6**	**31.6**	0.1	**42.8**	**47.1**	**25.7**
Monazite	1.6		3.2							
Sphene	0.5	0.7	0.4	0.8	0.1		0.2	0.4	0.3	1.0
Epidote	9.6	2.8	**16.3**	**70.8**	**32.6**	**19.9**	**39.0**	**30.9**	**34.2**	**17.6**
Staurolite	**48.6**	**71.2**	**25.9**	5.4	1.8		2.6	0.3	0.2	0.6
Al-silicates	**12.6**	**12.6**	**12.6**	3.5	3.8		5.7	0.2	0.2	
Garnet	3.1	2.5	3.7	4.8	7.7	0.7	**11.2**	4.9	4.1	7.9
Zircon	3.6	0.1	7.1	2.1	0.3		0.5			
Tourmaline	8.7	5.6	11.8	1.4	1.8		2.7	0.1		0.3
Rutile	2.9	3.3	2.5	0.8	0.3		0.4			
Total	96.8	99.7	93.9	99.5	99.9	100	99.8	99.7	99.9	98.7

Notes: Data shown for heavy minerals are grain percentages. Amphibole includes hornblende and actinolite. Totals may be less than 100% as a result of rounding differences and the exclusion of unidentifiable and relatively rare (e.g. goyazite) mineral grains. Bold values highlight the dominant minerals in each group and sub-group.

Appendix 8. Group and sub-group averages of 36 very fine sand fractions of heavy mineral samples from the Chadron Formation in Montana, North Dakota, and South Dakota.

	Group A					Group B				Group C	Group D		
Subgroup	Full	A1	A3	A3	A4	Full	B1	B2	B3	Full	Full	D1	D2
# of Samples	20	3	8	6	3	9	7	1	1	2	5	3	2
Diopside						1.0	1.2				**23.4**	**35.1**	5.9
Augite						0.1	0.1			0.1	0.1		0.2
Hypersthene					0.2	0.2	0.3				0.1	0.2	
Biotite	0.7	1.3	0.1	0.5	2.1	4.1	1.7	**24.0**	1.4	**57.4**	1.9	2.9	0.5
Amphibole	1.0	0.3	0.6	1.8	0.8	4.5	4.5	8.0	0.8	8.0	**50.8**	**43.0**	**62.6**
Monazite	0.5		1.1	0.0									0.1
Sphene	1.0	1.0	0.1	0.7	4.1	5.0	5.7		5.3	1.9	0.7	0.9	0.6
Epidote	6.8	10.3	5.4	5.5	9.8	**40.7**	**38.1**	**24.0**	**75.9**	**20.4**	**17.4**	**13.4**	**23.4**
Staurolite	**22.9**	**18.0**	**33.6**	**17.3**	**10.6**	3.5	3.8	4.0	0.3	1.0	0.3	0.5	0.1
Al-silicates	**15.4**	**35.0**	**17.6**	7.5	6.0	3.1	2.8	8.0	0.3	0.8	0.1	0.1	
Garnet	3.3	6.3	2.4	2.3	4.4	**19.6**	**23.4**	4.0	8.7	6.8	4.5	3.6	5.8
Zircon	**31.1**	8.0	**24.9**	**51.5**	**29.9**	**12.0**	**11.4**	**24.0**	4.2	2.7	0.1		0.2
Tourmaline	12.8	**15.3**	11.5	8.0	**23.1**	4.3	4.7	4.0	2.0	0.3			
Rutile	4.2	3.3	2.6	4.8	8.3	1.3	1.6		0.6	0.4	0.4	0.4	0.5
Total	99.7	99.0	100	100	99.2	99.5	99.4	100	99.4	100	99.9	100	99.8

Notes: Data shown for heavy minerals are grain percentages. Amphibole includes hornblende and actinolite. Totals may be less than 100% as a result of rounding differences and the exclusion of unidentifiable and relatively rare (e.g. goyazite) mineral grains. Bold values highlight the dominant minerals in each group and sub-group.

Appendix 9. Group and sub-group averages of 36 very fine sand fractions of heavy mineral samples from the Chadron Formation in Montana, North Dakota, and South Dakota with biotite removed and values within each sample normalized to 100%.

	Group A					Group B			Group D		
Subgroup	Full	A1	A3	A3	A4	Full	B1	B3	Full	D1	D2
# of Samples	20	3	8	6	3	10	7	3	6	3	3
Diopside						0.9	1.3		**20.0**	**36.1**	4.0
Augite						0.1	0.1	0.2	0.1		0.1
Hypersthene					0.2	0.2	0.2	0.2	0.1	0.2	
Amphibole	1.0	0.3	0.6	1.8	0.9	4.4	6.2	0.3	**50.2**	**44.3**	**56.0**
Monazite	0.5		1.1								0.1
Sphene	1.0	1.0	0.1	0.7	4.2	5.2	4.9	5.9	1.1	0.9	1.3
Epidote	6.9	10.6	5.4	5.6	10.2	**44.7**	**34.9**	**67.5**	**19.6**	**13.8**	**25.3**
Staurolite	**23.1**	**18.4**	**33.7**	**17.4**	**10.8**	3.2	4.5	0.3	1.2	0.5	1.8
Al-silicates	**15.6**	**35.9**	**17.7**	7.5	6.1	3.2	4.3	0.6	0.5	0.1	0.9
Garnet	3.3	6.5	2.4	2.3	4.6	**20.4**	**21.9**	**16.8**	5.2	3.8	6.6
Zircon	**31.3**	8.2	**24.9**	**51.7**	**30.6**	**12.0**	**15.9**	2.9	1.8		3.6
Tourmaline	12.9	**15.7**	11.5	8.1	**23.7**	4.2	4.6	3.3			
Rutile	4.3	3.5	2.6	4.9	8.6	1.4	1.2	1.9	0.4	0.4	0.3
Total	100	100	100	100	100	100	100	100	100	100	100

Notes: Data shown for heavy minerals are grain percentages. Amphibole includes hornblende and actinolite. Bold values highlight the dominant minerals in each group and sub-group.

Appendix 10. Group and sub-group averages of 36 very fine sand fractions of heavy mineral samples from the Chadron Formation in Montana, North Dakota, and South Dakota with epidote removed and values within each sample normalized to 100%.

	Group A				Group B				Group C	Group D		
Subgroup	Full	A1/2	A3/4	A5	Full	B1	B4	B5	Full	Full	D1	D2
# of Samples	20	8	11	1	9	7	1	1	2	5	3	2
Diopside					1.8		**15.9**			**27.2**	**40.3**	7.7
Augite					0.1		0.9		0.2	0.1		0.2
Hypersthene					0.4	0.4	0.9			0.1	0.2	
Biotite	2.2	0.7	0.6	**31.6**	3.8	4.5	2.7		**72.5**	2.3	3.3	0.7
Amphibole	1.5	0.8	1.3	**10.5**	6.3	3.5	**31.0**	1.7	9.0	**62.6**	**49.7**	**81.8**
Monazite	0.5	0.3	0.7			0.1				0.0		0.1
Sphene	0.8	0.4	1.2		**10.6**	**11.8**	8.0	5.0	2.6	0.9	1.0	0.8
Staurolite	**24.4**	**32.3**	**20.3**	5.3	5.6	4.3	0.9	**20.0**	1.1	0.4	0.5	0.1
Al-silicates	**16.9**	**27.5**	9.8	**10.5**	4.2	3.7		11.7	1.0	0.1	0.2	
Garnet	3.2	3.8	2.6	5.3	**35.7**	**33.6**	**28.3**	**58.3**	9.3	5.6	4.3	7.6
Zircon	**33.7**	**16.0**	**46.7**	**31.6**	**17.5**	**21.5**	7.1		3.3	0.1		0.2
Tourmaline	12.9	15.3	**11.9**	5.3	9.6	11.5	4.4	1.7	0.4			
Rutile	3.8	2.9	4.7		4.2	5.2		1.7	0.6	0.5	0.5	0.6
Total	100	100	100	100	100	100	100	100	100	100	100	100

Notes: Data shown for heavy minerals are grain percentages. Amphibole includes hornblende and actinolite. Bold values highlight the dominant minerals in each group and sub-group.

Appendix 11. Group and sub-group averages of 36 very fine sand fractions of heavy mineral samples from the Chadron Formation in Montana, North Dakota, and South Dakota with epidote and biotite removed and values within each sample normalized to 100%.

	Group A			Group B			Group D			
Subgroup	Full	A1/2	A3/4	Full	B1a	B1b	Full	D1	D2	D3
# of Samples	21	8	13	8	3	5	7	3	3	1
Diopside							**22.4**	**41.6**	5.2	**16.4**
Augite				0.2	0.6		0.2		0.2	0.9
Hypersthene			0.1	0.4	0.6	0.2	0.2	0.2		0.9
Amphibole	1.7	0.8	2.3	3.2	0.6	4.9	**58.6**	**51.5**	**74.7**	**31.8**
Monazite	0.5	0.3	0.6	0.0		0.1			0.1	
Sphene	1.1	0.5	1.6	**12.8**	**12.7**	**12.9**	2.4	1.0	1.8	8.2
Staurolite	**23.8**	**32.4**	**18.5**	5.3	7.3	4.0	1.5	0.6	2.6	0.9
Al-silicates	**16.8**	**27.8**	10.1	4.3	5.3	3.8	0.6	0.2	1.2	
Garnet	3.9	3.9	4.0	**44.1**	**56.4**	**36.7**	9.9	4.5	8.8	**29.1**
Zircon	**34.0**	**16.0**	**45.0**	**17.7**	4.1	**25.9**	3.2		5.1	7.3
Tourmaline	13.6	15.4	**12.5**	8.4	7.4	9.0	0.7			4.5
Rutile	4.5	3.0	5.4	3.5	5.1	2.5	0.4	0.5	0.4	
Total	100	100	100	100	100	100	100	100	100	100

Notes: Data shown for heavy minerals are grain percentages. Amphibole includes hornblende and actinolite. Bold values highlight the dominant minerals in each group and sub-group.

Appendix 12. Group and sub-group averages of 36 very fine sand fractions of heavy mineral samples from the Chadron Formation in Montana, North Dakota, and South Dakota with volcanic minerals removed (augite, biotite, diopside, hypersthene, and the volcanic portion of amphiboles).

	Group A					Group B			Group D
Subgroup	Full	A1	A2	A3	A4	Full	B1a	B1b	Full
# of Samples	20	3	8	6	3	11	5	6	5
Amphibole	0.5	0.1	0.3	1.0	0.4	3.9	6.6	1.7	**54.8**
Monazite	0.5	0.0	1.1				0.1		0.1
Sphene	1.1	1.0	0.1	0.7	4.3	5.2	4.6	5.8	1.6
Epidote	7.0	10.6	5.4	5.6	10.3	**45.8**	**31.6**	**57.5**	**33.3**
Staurolite	**23.2**	**18.4**	**33.8**	**17.5**	**10.9**	3.7	5.0	2.5	0.7
Al-silicates	**15.7**	**36.0**	**17.7**	7.6	6.2	3.3	5.1	1.8	0.2
Garnet	3.3	6.5	2.4	2.4	4.7	**20.2**	**18.8**	**21.3**	8.3
Zircon	**31.5**	8.2	**24.9**	**52.3**	**30.8**	**12.6**	**22.6**	4.3	0.1
Tourmaline	13.0	**15.7**	11.6	8.2	**23.8**	4.0	4.2	3.8	
Rutile	4.3	3.5	2.6	4.9	8.7	1.3	1.4	1.2	0.8
Total	100	100	100	100	100	100	100	100	100

Notes: Data shown for heavy minerals are grain percentages. Amphibole includes hornblende and actinolite. Bold values highlight the dominant minerals in each group and sub-group.