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Depositional Model of a Late Cretaceous Dinosaur Fossil Concentration, Lance Formation

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LOMA LINDA UNIVERSITY
School of Medicine
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Depositional Model of a Late Cretaceous Dinosaur Fossil Concentration,
Lance Formation

by

Summer Rose Weeks

A Thesis submitted in partial satisfaction of
the requirements for the degree
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Each person whose signature appears below certifies that this thesis in his/her opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

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DEDICATION

To my parents who have been so loving and supportive to me throughout my life. You have encouraged me to try new things and persevere, and you have taught me to trust God with my life and all my activities.

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ABBREVIATIONS

Fm	Formation
PRB	Powder River Basin
K-T	Cretaceous – Tertiary
HRS	Hanson Research Station
RTK	Real Time Kinematic
GPS	Global Positioning System
GIS	Geographic Information System
UTM	Universal Transverse Mercator
IDW	Inverse Distance Weighted

ABSTRACT OF THE THESIS

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by

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Master of Science, Graduate Program in Geology
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Leonard Brand, PhD, Chairperson

A large Maastrichtian, nearly monospecific bonebed in the Lance Formation in eastern Wyoming has yielded 13,000 bones and fragments since 1996. Though excavation of the site continues, little is known of the circumstances and processes of deposition. This study aims to provide a depositional model for the bonebed. To accomplish this task we utilized 1D facies analysis of surrounding units and 3D analysis of the bonebed. The nature of the outcrop limited facies analysis to 1D. Four measured stratigraphic sections, each containing the bonebed unit, were taken and used in facies analysis. In addition, laterally continuous units were observed and mapped using real time kinematic (RTK) GPS equipment. For 3D analysis of the bonebed, we unitized a large GPS dataset collected over 20 years of excavation. Displaying and manipulating the points in ArcGIS allowed investigation of bone arrangement vertically and laterally within the bonebed.

Facies analysis indicates that the local sediments of the Lance Formation were deposited on a relatively flat depositional plain as part of or near a delta. Facies assemblages are compatible with both a proximal to shore delta plain distributary and

interdistributary environment and with a relatively low sinuosity meandering stream environment with periodic swampy conditions in the flood plain. The bonebed is proposed to be a result of a mass flow process resulting from the fluidization and mobilization of sediment due to seismic activity.

CHAPTER ONE

INTRODUCTION

Many workers have studied the deposits of the Late Cretaceous Lance Formation in western Wyoming near the Green River and Wind River Basins (Breithaupt, 1982; Flemings and Nelson, 1991; Gillespie and Fox, 1991; Keefer, 1965; MacLeod, 1981), however, few studies have focused attention on the deposits of the Lance Formation in eastern Wyoming. This study focuses on a portion of the Lance Formation on the southeast rim of the Powder River Basin of eastern Wyoming. For many years, researchers have found sedimentological and stratigraphic studies in the Lance Formation challenging due to the presence of vegetative cover, lack of good exposure, and shallow dip which makes measuring a complete stratigraphic section a formidable task (Connor, 1992), however, many discoveries in the realm of paleontology have been made in this area of the country (Dalman, 2013; Elzanowski et al., 2001; Gilmore, 1946; Lockley et al., 2004; Longrich, 2008; McLain et al., 2016).

Southwestern Adventist University leads an annual expedition to the Lance Fm in eastern Wyoming, about 40 km southwest of Newcastle, WY. The school's efforts have led to the discovery of ~20,000 Late Cretaceous vertebrate and invertebrate bones and fossil specimens. With the increasing number of bones available for paleontological study, a model for the genetic history of the bonebed is vital. This study proposes a depositional model consistent with the paleoenvironmental indicators at the Hanson Research Station.

This research focuses on the information gleaned from seven quarries excavated into the main bonebed on the Hanson Ranch. The main bonebed is a mostly monospecific assemblage of *Edmontosaurus annectens*, that houses an abundance of very well-preserved bones. Almost 13,000 bones and recorded fragments from the main bonebed have been discovered since the first of the quarries was opened in 1996 (Turner, 2015).

Significance

The study site is located on what used to be the western edge of the Western Interior Seaway. During the Late Cretaceous, the site underwent a dramatic environmental shift as the sea abated from the area and left the formerly marine site as a terrestrial environment. The Lance Fm records this transition from a marine to terrestrial environment making it a potential exemplar for numerous other transitional sites recorded in the geologic record. Figure 1 shows maps produced by Colorado Plateau Geosystems, Inc. that illustrate the shift of the shoreline of the Seaway during the Late Cretaceous.

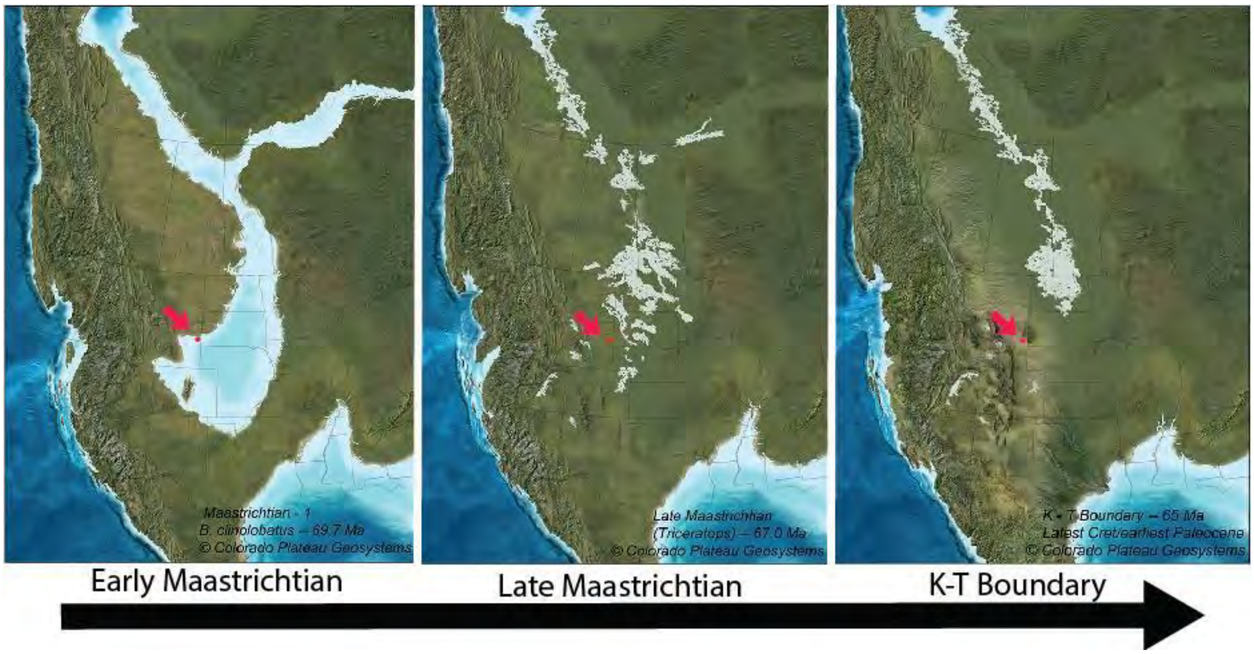

Figure 1. Paleo time slice maps of the Western Interior Seaway from early Maastrichtian up to the K-T Boundary. Red dot enhanced with red arrow indicates the study location in eastern Wyoming (Geosystems, 2012).

The Lance Formation, as a Maastrichtian (Late Cretaceous) deposit, also represents a piece of the uppermost portion of the geologic column to contain dinosaur fossils, and as such, represents some of the final records of the largest land animals to live on earth. Diverse theories for the demise of the dinosaurs have been proposed (Schulte et al., 2010), but much remains to be deciphered regarding their extinction at the K-T boundary. The sites to be studied contain dinosaur bones that may shed light on the question of why the dinosaurs went extinct.

Goal and Aims

The goal of this study is to interpret the depositional history for the main bonebed on the Hanson Ranch. In order to achieve this goal, two aims were developed.

The first aim is to determine the stratigraphic relationship between quarries on the Hanson Ranch.

The second aim is to compare facies and facies assemblages of the Lance Fm on the Hanson Ranch to facies assemblages of various paleoenvironemental models.

Background

A General Description of the Area

The study site is located in east central Wyoming in the Maastrichtian (Late Cretaceous), Lance Formation. See Figure 2 and Figure 3 for study location. In this region of the Powder River Basin of eastern Wyoming, the Lance Formation, equivalent to the Hell Creek Formation of North and South Dakota, is the uppermost formation (see Figure 4) of the Cretaceous (Connor, 1992). The Lance unconformably overlies the marginal marine Fox Hills (Dobbin and Reeside, 1929; Lloyd and Hares, 1915) and underlies the continental Fort Union Formation (Connor, 1992). It crops out in Montana, Wyoming, North Dakota, and South Dakota.

Sedimentary Description

Most of the lithologic units are siliciclastic mudstone and very-fine- to medium-grained sandstones. Lithic fragments larger than coarse sand are uncommon, but large fossil clasts are present in many localities. Occasional ochre carbonate layers appear as well as log-shaped, carbonate cemented sandstone concretions mentioned by Connor (1992) For the most part, the units show low levels of bioturbation.

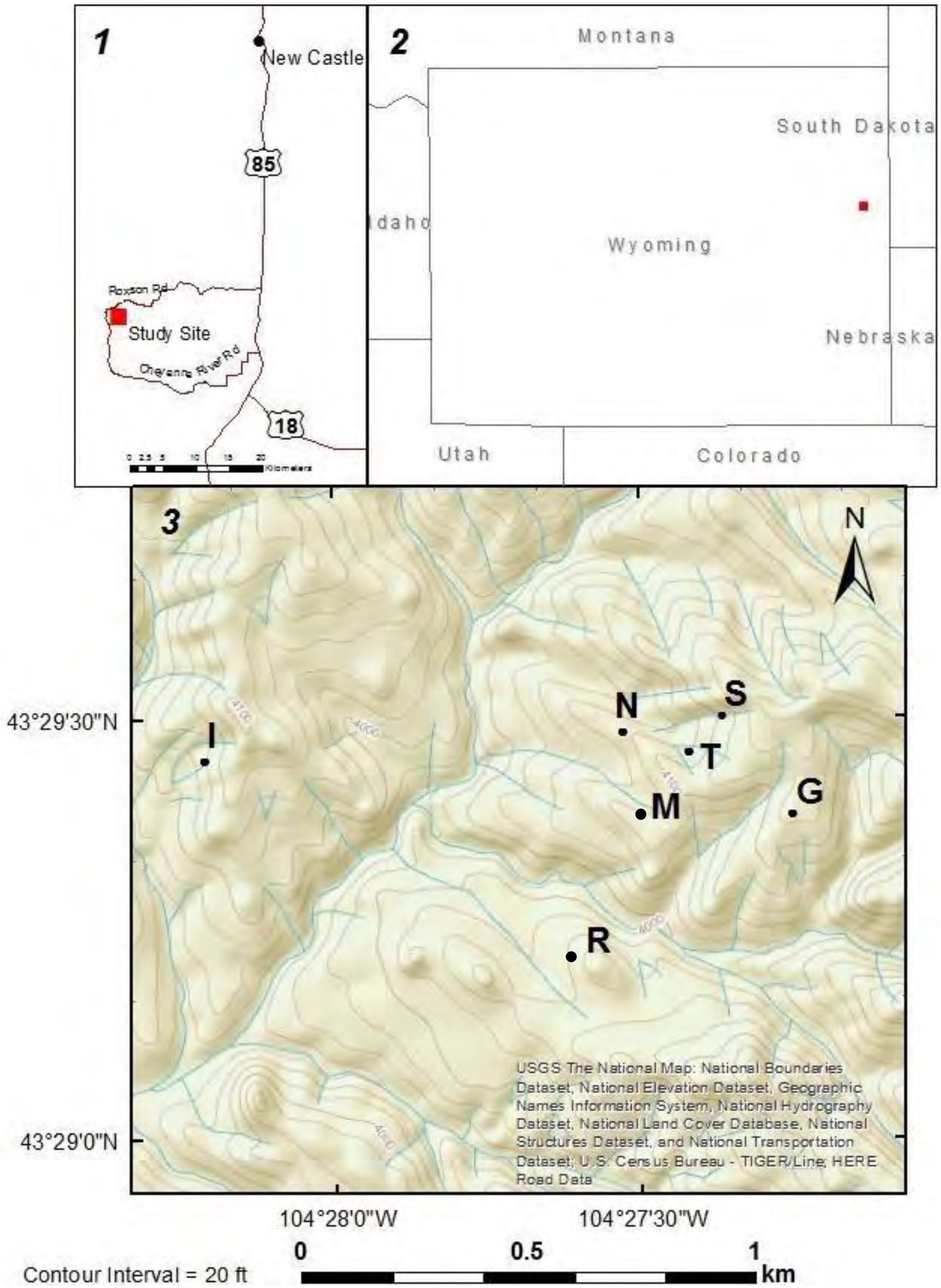

Figure 2 Location of study area. Image A: Location relative to Newcastle, Wyoming. Image B: general location in Wyoming. Image C: locations of quarries. N = Neufeld, M = Main Quarries (includes North, South, West, Southeast, and Teague Quarries), T = Toe Quarry. These are the quarries used in this study. Other quarries, which may be encountered in other studies include Iverest (I), Rose (R), Gar Ridge (G), and Stair (S). Base map accessed in ArcGIS (Program, 2015)

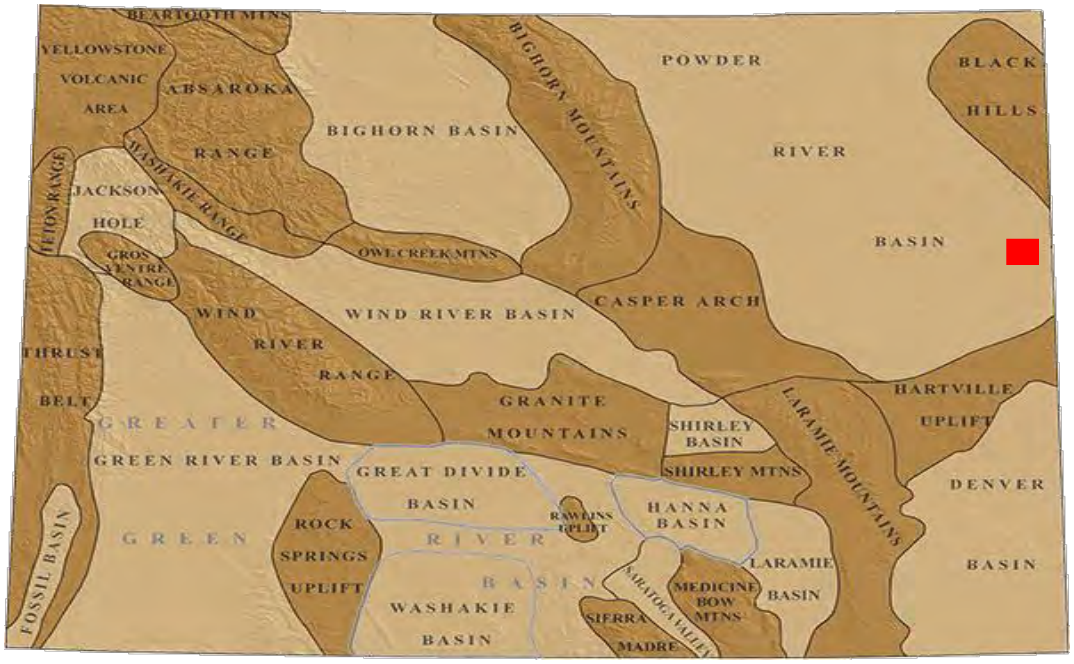

Figure 3. Modern Wyoming basins (light brown) and uplifts (dark brown). Approximate location of study site shown with red square. Image reproduced from (Survey, 2014)

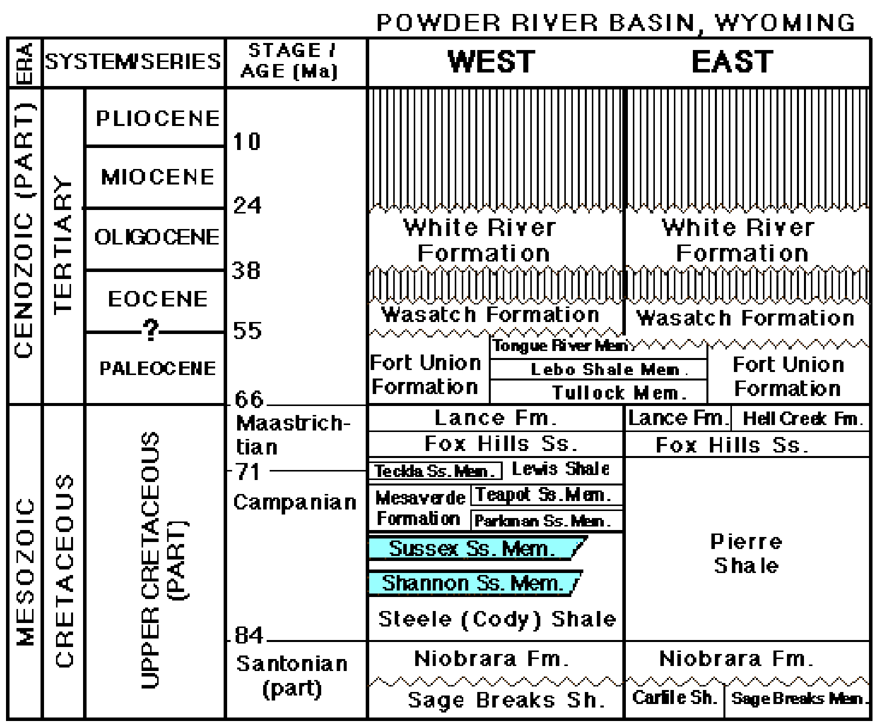

Figure 4 Stratigraphy of the PRB. The study area is located on the east side of the PRB where the Lance Fm is overlain by the Fort Union Fm. Image reproduced from the USGS digital data series (Higley et al., 1997).

Tectonic Setting

The study area in eastern Wyoming borders the Powder River Basin with the Black Hills to the northeast, the Casper Arch to the west and the Hartville Uplift to the south (see Figure 3). In the Maastrichtian, the Laramide orogeny was just beginning to make changes to the landscape of the Rocky Mountain region (Dickinson et al., 1988). Thrusting and subsequent tectonic loading caused subsidence forming basins adjacent to uplifts. The mechanism of subsidence in many of these basins is attributed to flexural deformation resulting from tectonic loading (Hagen et al., 1985). Prior to the Laramide, this region of the country was covered by more or less continuous marine facies and marginal marine facies deposited within the Western Interior Basin (Kauffman, 1977). During Mid to Late Cretaceous, this rather continuous depositional basin started to break up into smaller more isolated basins (Dickinson et al., 1988). In addition to more local episodes of subsidence and uplift, during Late Cretaceous, the Sevier orogenic thrusting on the western edge of Wyoming was still causing regional subsidence of the foreland area at large (Dickinson et al., 1988; Wiltschko and Dorr, 1983).

Sediments of the Lance Formation of southwest Wyoming originated at the Wyoming- Idaho thrust belt on the western edge of Wyoming (Montgomery and Robinson, 1997). But with the breakup of the Western Interior foreland basin, intervening uplifts between the western end of the state and the study area in eastern Wyoming might have blocked this source area. Additionally, Crowley et al (2002) noted that isopach maps and paleocurrent data from the Powder River Basin sediments indicate that the PRB was not fed by the Bighorn Mountains to the west and might not have been a separate basin in Late Cretaceous time. The prevailing paleocurrent direction recorded for the Lance in the south part of the Powder River Basin is toward the east and east-south-east farther north in the Lance (Connor, 1992). It is also reported that paleocurrents in the Lance on both the east and west of the Bighorn Mountains as well as paleocurrents measured on the east side of the Powder River Basin are to the east (Connor, 1992). This suggests that the basin and mountain range were not formed when the Lance Fm was deposited. Of all the Laramide-formed basins, the Powder River Basin was the last basin to have marine depositions occurring (Dickinson et al., 1988). Marine deposition in the Powder River Basin persisted until the latest part of the Maastrichtian.

Petrographic analysis of minerals and mineral abundances indicate multiple source areas for sediments of the Lance Fm in the Powder River Basin. The southern portion of the Lance Fm in the Powder River Basin contains abundant monocrystalline quartz (~57%), rock fragments (~34%), and variety of feldspars with higher amounts of potassium feldspars than plagioclase feldspars (Connor, 1992). This composition data, along with the paleocurrent directions, indicates a granitic source area west of the basin. The Granite Mountains (see Figure 3) are thus a likely candidate (Connor, 1992).

Isopach maps of the northern end of the Powder River Basin indicate that the Lance formation thickens dramatically (nearly doubling) from the Wyoming – Montana border to about 50 miles south of the border (Ploeg et al., 2003).

Previous Personal Experience

Prior to this study, I participated, in the summer of 2009. as an undergraduate student at the Hanson Research Station (HRS). I enrolled in the dinosaur class offered at the dig site and engaged in excavation of the dinosaur bones. The following four years, I returned in the summers to assist in and conduct research with the project director, Dr. Arthur Chadwick. The focus of my research was to decipher the local stratigraphy which led to the use of a seismite as a stratigraphic marker (Weeks and Chadwick, 2011, 2012). In addition to participating in summer research projects, I also held the position of curator for two years over the collection of fossils from the HRS housed at Southwestern Adventist University.

Stratigraphy

The stratigraphy of the Lance Formation in eastern Wyoming poses many difficulties. Beds are transient and poorly exposed with an apparent lack of stratigraphic markers. In 2011, Weeks and Chadwick started investigating the use of a seismite as a local stratigraphic marker. The perceived benefit of using a seismite as a marker bed was that it could readily be identified by the contorted bedding (Figure 3) and also that it could be recognized across facies transitions (Figure 4). With a seismite as a marker bed, we initially determined a local dip of ~2-3° and were able to plot the seismite, with a few exceptions, as a plane. However, in subsequent surveys it became apparent that more than one seismically altered layer could be present in the area. In addition, the suggestion was made, that seismic alteration may be lithologically selective (Nick, 2015); the seismite has only been observed in sandstones. Thus, the record of seismic activity might not represent a single contemporaneously exposed horizon but simply a lithology under the right conditions to be disturbed at the time of seismic activity whether or not it was at

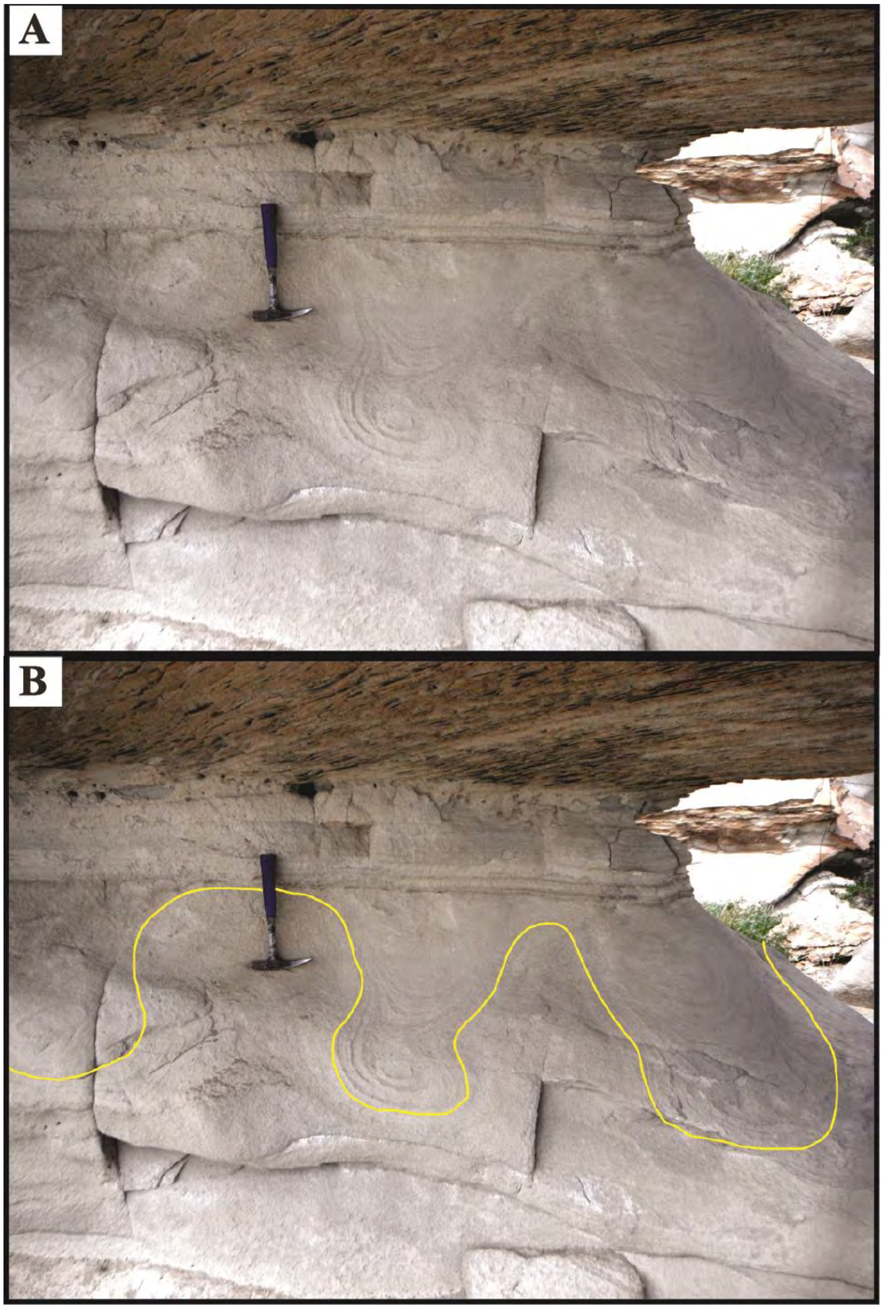

Figure 5 Seismite images showing contorted bedding. Image A is the original, and Image B shows line marking contorted sediment

the surface. Research on the seismite has been postponed for the present because of these issues. However, consideration of the flat, slightly dipping plane in which the seismite lies has led to the hypothesis that the area may represent a mostly in situ geological environment in which elevation may serve as a proxy for stratigraphic position.

Figure 6 Contorted bedding extending into a mixed sandstone and mudstone facies.

Depositional Environments Proposed for the Lance Formation

Interpretations for the depositional environment of the Lance Formation range from braided stream to marine. The following is a review of the depositional environments presented in the literature for the Lance. The interpretations are geographically organized from west to east across Wyoming.

Starting in western Wyoming in Sublette County, Montgomery and Robinson (1997) described the Lance as an "eastward-prograding wedge of siliciclastic material". Montgomery and Robinson interpret the sedimentary rocks in the area as a meandering and braided fluvial depositional environment. They also recorded a dominant flow direction of west to east. Moving farther east, past the Rock Springs Uplift in

Sweetwater County, Breithaupt (1982) reports various areas with meter-thick coal seams, rain prints, brackish oysters and dinosaur tracks in the Lance. He describes the sedimentary rocks of the Lance as riparian floodplain deposits. However, Dodge and Powell (1975) described the Lance Formation in northeastern Wyoming, Crook County, as deltaic-distributary channel sandstone and interdistributary mudstone. Moving toward eastern Wyoming and western North and South Dakota, the Lance was divided into two members by Lloyd and Hares (1915). They interpret the upper member as marine and the lower as nonmarine additionally stating that the upper marine portion is stratigraphically equivalent to a lignite member toward the west in the Lance Formation. In "A Geologic History of Powder River Basin" the Wyoming Geological Association Technical Studies Committee reports a permanent regression of the intercratonic sea in the Powder River Basin directly preceding the deposition of the Lance, thus they interpret the Lance as continental deposits of coastal plains, meandering streams, and associated flood plains (Committee, 1965). These differing interpretations are inferably due to variability in environments as the Lance changed through time or across geographic locations. This variation necessitates establishing a unique depositional model for the study area in the Lance Formation.

Facies Models

Introduction

Facies is a term used to refer to the combination of all aspects of a geologic unit or rock. Facies take into consideration the lithology, paleontology, sedimentary structures, and chemical properties of a rock unit (Dalrymple and James, 2010). Facies can suggest an aspect of the depositional history of the area, but they are not, taken individually, diagnostic of a specific paleoenvironment. To decipher the depositional environment, the unique assemblage of facies for a particular area must be considered together. Facies assemblages of associations are defined as “groups of facies genetically related to one another and which have some environmental significance (Collinson, 1969).

This section will provide background on facies assemblages considered possibilities for the study area. The sedimentary processes, structures, architectures, and facies models for each will be presented.

Deltas

Introduction

Deltas are unique geologic environments distinguished from others by exhibiting the process of sediment transport in a confined channel to an open water body within a basin. Deltas are defined as “the subaerial landforms and their subaqueous extensions produced by a river meeting a body of standing water”(Dalrymple and James, 2010). The unique depositional processes involved in the transition from confined flow to open standing or almost standing water result in unique facies and bed geometry and architecture which can be distinguished in ancient deposits.

By their very nature, deltas are progradational. Continuous deposition at the mouth of the river results in sediment accumulation at the interface between fluvial and marine environments. Consequently, deltas exhibit a coarsening up succession from marine shelf to fluvial/distributary facies. In addition, deltas produce prograding, basinward-dipping clinoforms comprised of a shallow dipping topsets, steep forests, and nearly flat bottomsets (**Error! Reference source not found.**) (Dalrymple and James, 010). Deltaic bed geometries can be identified in outcrop as well as in seismic profiles.

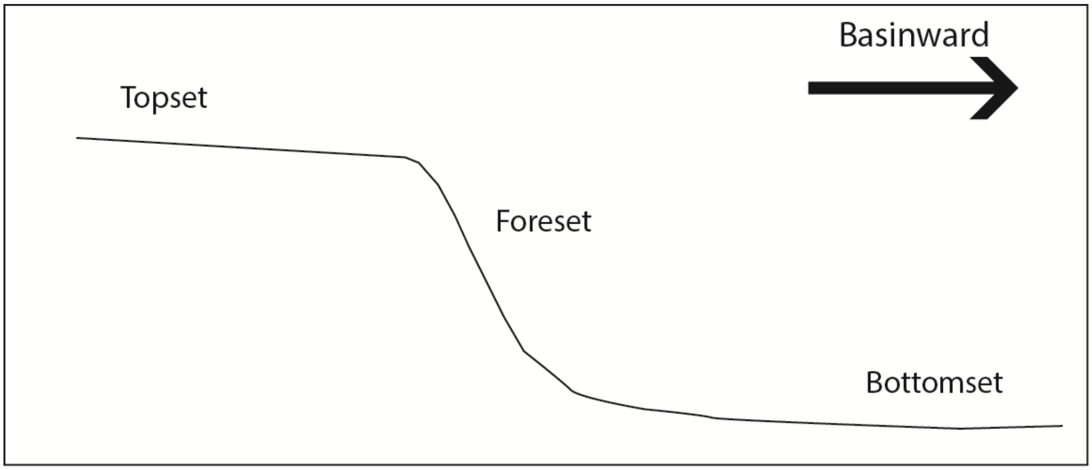

Figure 7 A diagram showing the geometrical elements of a delta.

Parts of the Delta

Three major divisions of a delta are recognized on the basis of their morphology, relation to shore (tidal shoreline, wave base, etc.), and the type of sediment deposited. These divisions are delta plain, delta front, and prodelta. Figure 8 shows a schematic of the spatial relationship between these parts.

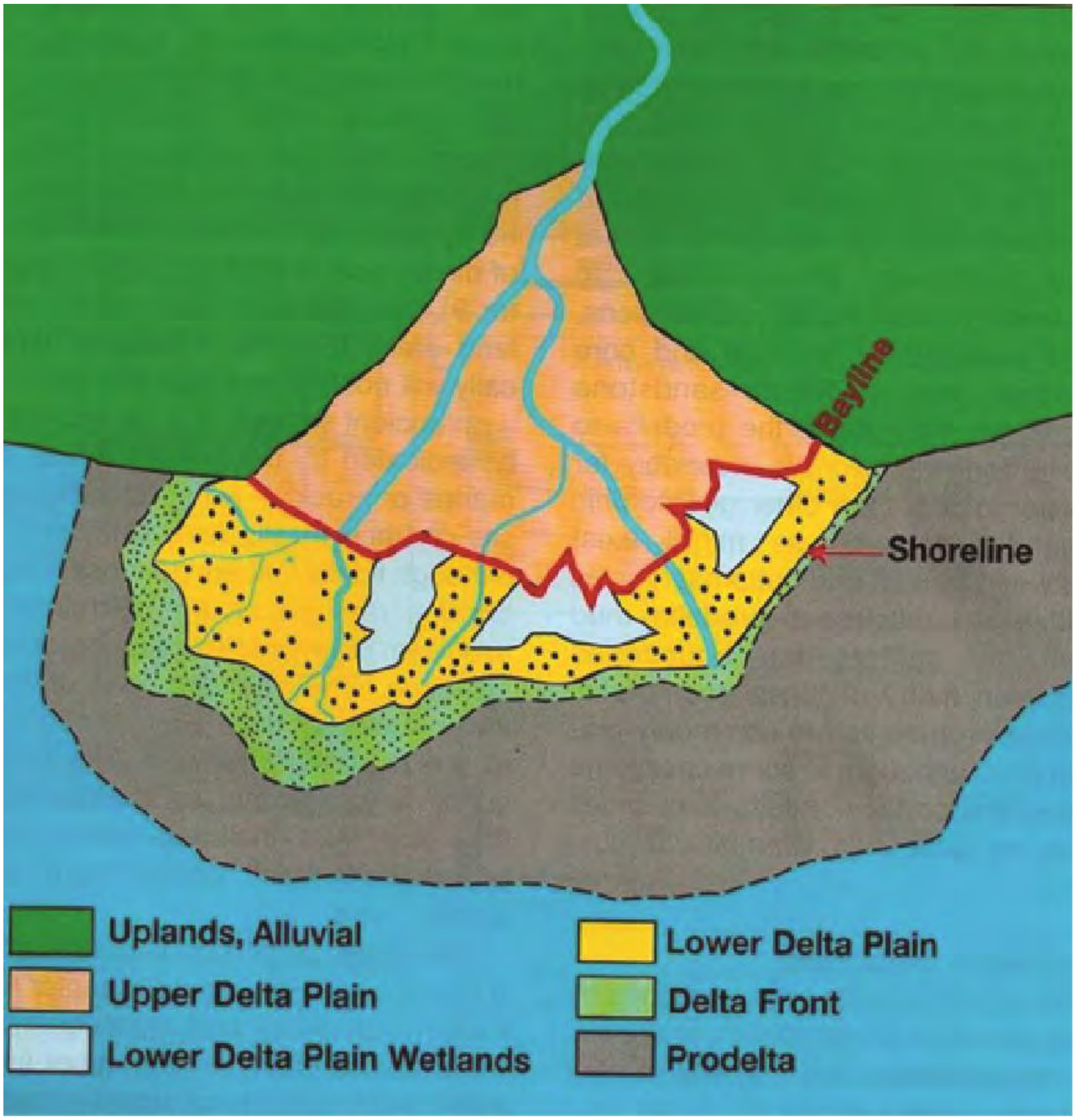

Figure 8 Schematic of deltaic divisions showing their 2-D, lateral spatial relations.

Delta Plain

The delta plain is the subaerially exposed or partially exposed, landward portion of the delta extending from point of separation in the river to the high-tide shoreline (Bhattacharya, 2010). The delta plain can be, in turn, subdivided into the upper and lower delta plains demarcated by the bayline or landward limit of bays and lagoons within the delta plain. The delta plain houses the distributary channels, inter-distributary marshes, swamps, tidal flats, lagoons, and bays. Distributary channels of the upper delta plain are essentially fluvial channels. However, the lower delta plain distributary channels exhibit varying characteristics and are affected greatly by basinal processes. These distributary channels may form from scouring and channel cutting, but they also, and perhaps more frequently, form by the coalescing of mouth bars. When this happens, a channel morphology and lag deposit may be difficult to distinguish or absent. Lower delta plain distributary channels of shoal river dominated delta systems often undergo more frequent avulsion and migration compared to deep water river dominated deltas. Also, tide and wave dominated deltas generally form longer-lived distributary channels than river dominated deltas due to the removal of sediment at the distributary mouth (Bhattacharya, 2010).

Delta Front

The delta front is the steepest portion of the delta and includes a portion of the subtidal platform between the shoreline and fair-weather wave-base. This is where the coarsest material of the delta is deposited. The deposits of river dominated systems include mouth bars and terminal distributaries extending to the lower delta front. Wave dominated delta fronts may resemble other shorefaces but will contain greater proportions of mud and less bioturbation. Tidal dominated delta fronts contain reworked mouth bar deposits elongated parallel to slope.

Prodelta

The distal portion of the delta, or prodelta region, comprises the often fine-grained deposits between the sandy delta front and the fine-grained hemipelagic sediments. The beds of the prodelta can be rhythmically deposited beds or silty to sandy graded beds depending on the dominant processes involved. Hyperpycnal flows, storm wave action, and turbidity flows can all contribute to the facies of the prodelta. Also, due to the high sedimentation rates and subsequent over pressuring by delta front sands above, the prodelta is a prime location for dewatering and soft-sediment deformation structures (Bhattacharya, 2010).

Each of the three sub-environments of the delta creates its own suite of facies, the co-existence of which make up the deltaic geologic environment which can be recognized in the ancient outcrop.

Types of Deltas

Deltas are classified, after Galloway, on the basis of the dominant process forming the framework sands of the delta (1975). Both basinal processes and fluvial processes are at play within the delta. Processes acting within the delta have been divided into two broad categories: constructive and destructive (Galloway and Hobday, 1983).

Constructive Processes

Constructive processes include deposition at the channel mouth, crevassing within the distributary portion of the delta, and channel avulsion leading to lobe formation. Deposition of sediment induces grain-size segregation as bedload is deposited as mouth bars while the suspended load is transported farther into the basin and deposited on the prodelta. Deposition of the suspended load may occur as a hyperpycnal or hypopycnal flow depending on the differential density of basin water and inflowing sediment-laden waters of the delta. Highly sediment-laden river water is likely to be denser than basin water and thus be transported as a hyperpycnal flow. Friction as a function of basin geomorphology and basin roughness helps to slow the flow and induce sedimentation. Incurrent suspended load as a hypopycnal flow is virtually independent of basin morphology. The contact of the flow with marine basinal water on the bottom of the flow helps to induce sedimentation by flocculation of clays (Prothero, 2004). The crevassing process creates a mini delta in the interdistributary embayments of the delta plain. Crevassing occurs more readily in the lower delta plain than the upper because the channel levees are less developed and even small flooding events can break the channel margins. Channel avulsion occurs as the flow seeks the steepest gradient. Multiple avulsions in turn produce a delta lobe. The geometry of the delta lobe after channel avulsion and subsequent reworking may help to identify the dominant process within the delta.

Destructive Processes

Destructive processes are the second major category of processes involved in the formation of a delta. One process is the work of wave and basinal currents acting to redistribute sediment deposited as mouth bars. This process tends to widen the delta at its seaward face as sediment is deposited in the direction of longshore drift. Another destructional process occurs as a result of rapid sedimentation in the prodelta and subsequent deposition of delta front sands on top of the uncompacted prodelta mud. This overpressuring on the prodelta induces mass gravity processes and compaction. Thus deformed sediments and growth faults are common features of the deltaic settings. These processes cause local subsidence near the loci of mouth bar formation and allow continued deposition in the area until the sediment has compacted enough to produce a stable platform. The channel can continue feeding the area until this happens. The flow then abandons that channel and seeks a location that can accept deposition. The final process discussed by Galloway and Hobday (1983) is that of lobe-abandonment and cyclic destruction. This process deals with channel migration of higher order than discussed previously. This process acts to diminish or even remove fluvial sediment supply from an area of the delta due to migration of the river to a new lobe. The abandoned lobe still experiences basin processes including tidal currents and waves which rework and destroy part or all of the mouth bar deposits.

Deltaic Facies

Depending on the type of delta or the relative proportion of processes at play, the facies within the different segments of a delta will vary. However, all delta front and prodelta facies coarsen upward while the delta plain facies fines upward. The delta front and lower delta plain portions tend to show the most variation, thus these segments may be more helpful in discriminating between delta type and determining the dominant processes that form a delta.

Delta Front Facies

Delta front facies within a fluvial dominated delta include sandstones with unidirectional ripples, trough crossbedding, planar stratification or massive graded beds. Occasionally facies may include Bouma sequences. Mud drapes and siderite nodules also occur. These delta front facies commonly have abundant macerated plant matter intermixed in the sandstones and mudstones (Bhattacharya, 2010). The more distal portion of the delta front will be more heavily bioturbated and finer grained. The distal delta front may also show evidence of storm wave action in the form of hummocky cross stratification. Organic layers will also be more numerous and thicker in the distal direction (Olariu et al., 2012). Usually river deltas form on a low gradient, and contain some evidence of oscillating current. Delta plain deposits contain interdistributary facies and distributary channel facies, which can look very similar to other fluvial facies. However, Reading (2009) states that delta distributaries differ from other fluvial channels in several ways. First they are more influenced by basinal processes than ordinary fluvial channels. Second, deltaic channels undergo more frequent avulsions. Third, the width to depth ratio is lower in deltaic fluvial settings.

Wave-influenced delta front facies may look very similar to fluvial deltas in their downdrift portions, but the succession is typically thinner. Thin, shell rich units might appear between muddy layers. On the updrift side of the wave-influenced delta, the facies typically include more mature sandy units with structures including wave ripples and a greater proportion of cross-stratification (Bhattacharya, 2010).

Tide-influenced deltas, on the other hand, appear more distinct from the other two types. Their delta front facies typically show a cyclic pattern of some kind. Beds may form tidal bundles with 14 or 28 day cyclic patterns. Mud drapes and wavy bedded mudstones are also common. Rhythmic, heterolithic strata and tidal bundles of mud draped crossbedded sandstone are thus characteristic of tide-influenced delta front facies. Tide deltas also show the lowest level of burrowing and bioturbation of all the delta types. This is a result of the harsh conditions induced by frequent environmental changes from tidal incursions of marine water followed by fresh water at low tides. Harsh, rapidly fluctuating conditions also diminishes the variety of microfossils that will be found in these facies.

Delta Plain Facies

Delta plain facies, especially those of the lower delta plain, can vary between delta types though not as much as the delta front facies. The upper delta plain looks nearly identical to a fluvial environment while the lower delta plain may show variation from fluvial character. The lower delta plain may exhibit tidal bundling of sediment or herringbone crossbedding and contain marine fossils (Galloway and Hobday, 1983).

Crevasse splays forming mini deltas are common in the lower delta plain. Crevasse splay deposits will thicken away from the main channel and will overlie embayment muds and silts. Further, these facies are often capped by a siderite rich layer. Structures vary widely in crevasse splay deposits, but climbing ripple lamination is quite common (Galloway and Hobday, 1983).

The interdistributary areas of a delta plain consist of muddy facies capped by coal, carbonaceous shales, or paleosols (Dalrymple and James, 2010). This is the facies over which crevasse splay facies lie. The marine influence, indicated by heterolithic strata and a decrease in ichnofauna variety, over the interdistributary region increases shoreward, whereas, distal to shore delta plains are far more alluvial in character.

Braided Streams

Introduction

Braided streams are distinguished from other fluvial environments by their having multiple active channels that together make up a relatively straight channel system. The formation of multiple channels or braiding is promoted by the high sediment load within the stream. Braided streams have sediment loads that exceed the competence of the stream flow, thus sediment is deposited in the channel as channel bars which split the channel and increase braiding (Prothero, 2004). These channel bars, as opposed to point bars in meandering streams, migrate in a downstream direction (Reineck, 1973) Braided streams also show constant reworking of sediments and frequent channel avulsion. This is partly a result and cause of having unstable banks which are easily erodible. In general, braided streams are shallow in comparison to other fluvial systems, but discharge may vary seasonally allowing times of deeper flow during certain parts of the year. Channel bars may be completely submerged during flooding.

Channel Bars

Channel bars in braided streams may be distilled to two main types: transverse bars and longitudinal bars (Prothero, 2004; Smith, 1970). The differences between these two types are summarized in Table 1. Bar types may be differentiated on the basis of method of formation and on the morphology and internal structures of the bar. Transverse bars are tabular in cross section and lobate in plan view. A transverse bar forms as sediment is entrained in a depression and therefore low energy point in the stream. It grows via downstream accumulation of cross bed foresets. Since the foresets build in a downstream direction, they show the flow direction perpendicular to the bed form. Longitudinal bars are more elongate in plan view and tend to form a convex bar top. This type of bar forms when a large particle in the channel becomes entrained and causes trapping of smaller particles on the downstream side of the entrained particle. As the bar continues to grow, the sediment on the upstream side of the bar is eroded, leaving coarser material behind on the upstream end. Contemporaneously, the downstream end continues to trap smaller particles. Thus the bar migrates downstream. Avalanching may create crude cross stratification on the downstream end of the bar.

Table 1 Bar characteristics of longitudinal and transverse bars (Prothero, 2004; Smith, 1970).

Bar Type	Longitudinal	Transverse
Shape	Elongate	Lobate
Cross-section shape	Convex bar top	Tabular
Other	Coarser grained upstream end	Sinuous downstream margins
Growth	Trapping of particles by larger particles; avalanches	Downstream accumulation of forests perpendicular to flow
Contributed to braiding	Aggradation	Dissection of exposed bar
Dominate Bedforms	High energy: planar bedding, sometime cross trough bedding, and imbrication	Low-velocity features: ripples cross lamination and trough cross bedding

Both types of bars contribute to braiding of the channel. Transverse bars may become exposed during periods of low discharge allowing erosion and dissection of the bar as mini channels cut through the bar. This splits the channel and increases braiding. Longitudinal bars may contribute to braiding by aggrading until the channel is split.

Facies and Occurrence of Braided Streams

Braided streams often form in mountainous areas, but they can also develop on continental plains and on deltaic plains. The South Platte River in Colorado and Nebraska is an example of a braided river formed on a plain (Smith, 1970). The Brahmaputra is cited as a braided river on a deltaic plain (Coleman, 1969; Reineck and Singh, 2012). In addition, the role of fines and the possibility of preservation of fines in braided streams has been emphasized by Bentham and colleagues (Bentham et al., 1993). Generally, however, the presence of extensive floodplain fines in a fluvial paleoenvironement is evidence against a braided stream interpretation. Typical facies present in braided stream environments is shown in Table 2.

Table 2 The expected facies in braided stream environments (Prothero, 2004; Reineck, 1973; Smith, 1970).

Location → Feature ↓	Channel	Transverse Bar	Longitudinal Bar	Flood Plain/Abandoned Channel
Grain Size	Coarse – Medium – Fine Sand	coarse to medium sand	Gravel, Coarse – Medium Sand	Fine Sand – Silt, Clay
Structures	Trough Cross Stratification, Planar Cross Stratification, Ripple Cross Lamination	Planar or Trough Cross Stratification	Cross Stratification, Massive, Planar Bedding	Bioturbation, Root Traces, Caliche, Planar Lamination, Ripple Cross Lamination, Mud Cracks

Meandering Streams with Comparison and Contrast to Braided Streams

Introduction

Meandering fluvial environments differ from braided environments in sinuosity of the channel, type of bedforms preserved, and proportion of fine-grained material present

(Bridge, 1985; Brierley and Hickin, 1991). Meandering streams typically show a high sinuosity as compared to braided stream systems. Meandering is caused by and contributes to the development of point bars, the most important depositional component of the meandering fluvial system. Though point bars occur in braided streams, mid-channel bars occur in far greater abundance (Miall, 2010). This difference in bar type for the different types of fluvial systems may be helpful in distinguishing between meandering and braided systems. Typically point bars show accretionary structures with strikes nearly parallel to the flow direction of the stream, while mid-channel bars tend to show accretionary structures with dip direction nearly parallel to flow (Miall, 1985).

Facies Model

Meandering streams, with sandy bedload and extensive floodplains, are typically finer grained environments than braided streams which are more often composed of gravely bedloads with little to no floodplain deposits (Miall, 2010). Galloway and Hobday (1983) divide fluvial facies into three broad categories based on the subenvironment: channel fill, channel margin, and flood plain.

Point Bar Facies

The channel fill facies for a meandering stream are dominated by point bars, which form by transport of finer bedload and suspended load up the slope of the inner bank of the stream. As a point bar develops, the stream floor migrates laterally and subsequently leaves behind a coarse-grained channel lag of the material which the stream was incompetent to carry. This material may be pebbles, cobbles, water saturated plant material, or mudclasts from bank collapse or rip ups. If the channel is aggrading in addition to its lateral migration, some trough cross bedded bedload may be preserved.

During flooding, a large point bar may be dissected and a second channel initiated that cuts and erodes the bar. These processes may form structures such as imbricated cobbles, planar lamination, mud lenses, and trough cross stratification. When the flow reaches the main channel again, the flow separation will cause deposition of the bedload forming a chute bar. Chute bars may be preserved as planar bedded or avalanche cross stratified bedload sediments (Galloway and Hobday, 1983).

Channel Margin Facies

Channel margin facies include facies of the natural levees and crevasse splay deposits. Natural levees form adjacent to stream margins and typically show evidence of varying flow conditions in the form of mud drapes. They also may show evidence of rapid sedimentation as a consequence of flow separation when flooding water leaves the confines of the channel and flows unconfined over the bank. Climbing ripples, small ripples, wavy, and planar lamination are common structures. Since the channel margins are subaerially exposed part of the time, soil formation and plant growth occur in both levee and crevasse splay deposits. Crevasse splay deposits also show climbing ripples, planar, wavy, and ripple laminated sedimentary structures, but additional structures that may form include trough cross bedding, scour-and-fill structures, graded beds, and mud drapes. Crevasse splay deposits often accumulate large amount of plant material, mudclasts, and other debris (Galloway and Hobday, 1983).

Flood Plain Facies

The final fluvial facies subenvironment is the flood plain. This is the location of the most plant growth, soil formation, and bioturbation due to the slow sediment accumulation rates. These processes often completely destroy the primary sedimentary structures that were present. Flood plain may also form the location for small, intermittent swampy or lacustrine environments associated with the fluvial system.

Mass Flow Processes

Introduction

Mass flow processes define those processes by which sediment is transported under the influence or by the force of gravity. In contrast, fluid flow processes are those processes by which sediment is transported by the action of a moving fluid. It is important to note that mass transport does not mean that the sediment cannot be transported in conjunction with a fluid. Two mass transport processes will be considered and compared in this section: debris flows and hyperconcentrated flows.

Hyperconcentrated flows

The term hyperconcentrated flow has sometimes been used a catch-all for flows that could not easily be classified. Here the term will be used, as described by Nemec (2009), to refer to a dense deposit with rheological characteristic between mud flows and stream flows. In particular he describes hyperconcentrated flows as a dense, terrestrial, turbulent flow which deposits non stratified beds. The fact that hyperconcentrated flows make non-stratified beds indicates that they are also non-tractional flows. Their deposits are normally graded or reverse graded (Costa, 1988; Nemec, 2009). Sedimentation is rapid, but the flow does not freeze en masse. Like normal stream flow, hyperconcentrated flow proceeds as a two phase (i.e fluid and solid) flow (Costa, 1988). Particles are thus suspended by turbulence, buoyancy, and dispersive pressure. Some hyperconcentrated flows can exhibit some sheer stress with high concentrations of fines especially with ~3-13% by volume of kaolinite and montmorillonite clays.

Characteristics of deposits made by hyperconcentrated deposits vary somewhat but in general the deposits are massive. They may display crude or faint stratification. They are clast supported, and in general show characteristic of noncohesive flow. They may be either reverse or normally graded (Costa, 1988).

Debris Flows

Debris flows act as Newtonian fluids. A debris flow may be classified as cohesive or non-cohesive based on the amount of clay within the flow. Cohesive debris flow are the focus here, but most of the following discussion could apply to any debris flow. Debris flows, in contrast to stream flows or hyperconcentrated flows, are one phase flows because the fluid and the solid flow as a single mass (Costa, 1988). In hyperconcentrated flows, fluid may flow around particles or flow at a faster rate.

The distinguishing characteristic of debris flows is a fine-grained matrix surrounding coarse clasts (Blackwelder, 1928; Crandell, 1971). They also can show uniform distribution of clast sizes since suspension of sediment is a result of cohesion, buoyancy, dispersive stresses, and structural support of the dense flow (Costa, 1988). Similarly, light weight clasts such as wood or spongy bone that might float in a stream flow or hyperconcentrated flow can be entrained in a debris flow. Elongated clasts generally show no or very poorly preferred orientation (typically with the long axis parallel to flow direction) (Lawson, 1982). Debris flows are typically cited as structureless, but they can show different types of inverse grading or normal grading (Costa, 1988).

CHAPTER TWO

METHODS

Fieldwork for this thesis was conducted in June of 2015 with several photos taken in the summer of 2016 by Michael Harriss. However, the Hanson Research Station has been actively studied and excavated since 1996, and data accumulated over that time was also used for this study. The field research area is located approximately 50 km southeast of Newcastle, Wyoming.

Stratigraphic Sections

Four stratigraphic sections (see Figure 9) (two long sections of 35 and 20 meters and two short sections each 4 meters in length) form the basic dataset of this thesis. The sections were measured within an area of 90,000 m^2. The locations for the two longer sections were chosen to obtain the largest continuous sections that also contained the bonebed. The locations of the two shorter sections were chosen to obtain information about the immediate overlying and underlying sedimentary rocks of the main bonebed at midway points between the longer sections. Each section was measured using an RTK GPS unit to obtain bed thicknesses. This method was deemed as precise as a Jacob's staff for this area due to the very low angle dip and presence of often subparallel bed surfaces. Often plants, weathering of the surface, or sediment cover hid the outcrop from view. While measuring sections, step-wise trenches were dug about 0.5m deep to obtain fresh outcrop exposures. These trenches were buried at the conclusion of the field work to ensure the safety of cattle on the ranch. Lateral movement was necessary during the measurement of sections 1 and 2 for the sake of finding the best outcrops and for the purpose of obtaining longer sections.

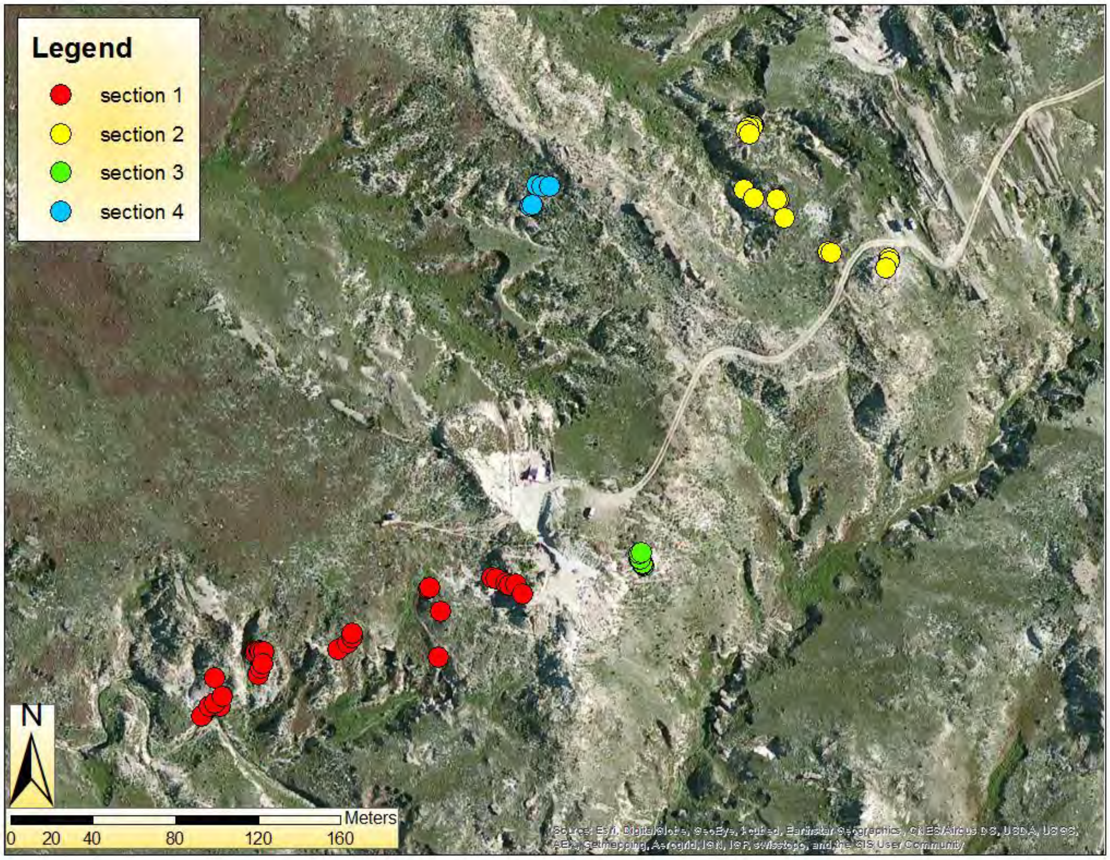

Figure 9 Map showing GPS points taken along stratigraphic sections.

Quarries and Bones

Seven quarries have been excavated into the main bonebed. These quarries were all utilized in this study. Figure 10 shows the location of each of these quarries. Other quarries are active at the Hanson Research Station, but their stratigraphic relationship to the main bonebed has yet to be established. Most of them also show very different sedimentological characteristics than the main bonebed. Only the quarries known to be from the main bonebed are shown in Figure 10 and included in this study.

Bones from the Hanson Research Station are curated for study and storage at the Drake Paleontology Museum on the campus of Southwestern Adventist University in Keene, Texas.

Excavation at the Hanson Research Station takes place for one month each year with an average of 1000 elements recovered during that month. The recovered bones and fragments are measured and identified in the field and cleaned and re-identified at the preparatory lab at Southwestern Adventist University. With the use of RTK GPS technology, the 3D position, and thus orientation, of each element is recorded along with a photograph for curation into the online database at fossil.swau.edu. The *in situ* photograph and GPS points are combined into a 3D virtual quarry for future study. Photographs of specimens used in this thesis were obtained from the online database of the Drake Paleontology Museum. Information concerning the taphonomic condition and weathering of fossil specimens was gleaned from and can be accessed at the online museum database (Chadwick et al., 2016). Personal experience handling the bones in the quarries as well as in the museums was also useful in understanding the preservation of fossil specimens.

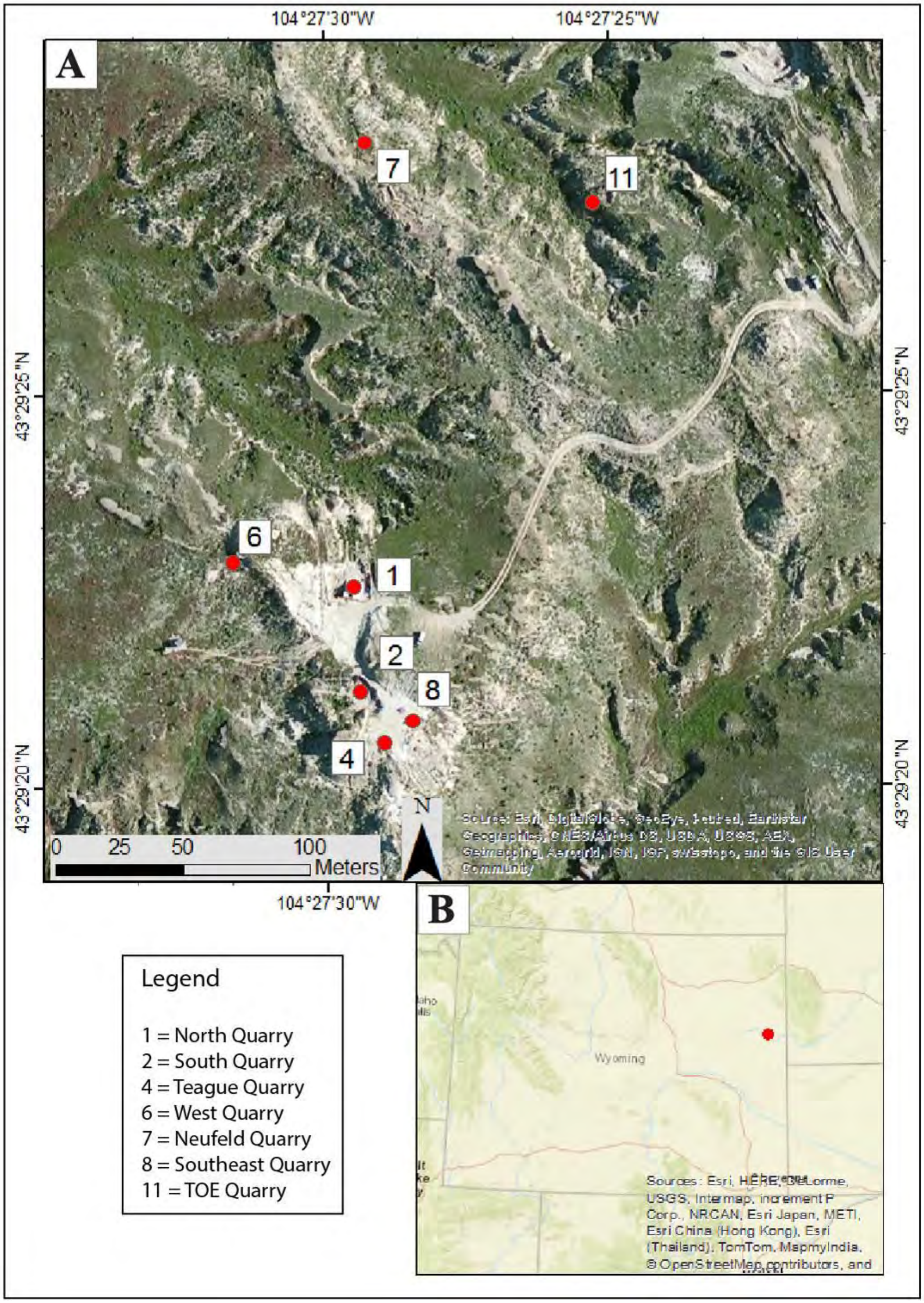

Figure 10 Map showing numbered quarry locations.

Samples of bonebed matrix were taken from each quarry to use for grain size analysis. These samples were collected from fresh surfaces of the quarry at vertical intervals of 10 cm. The samples from South Quarry were analyzed with a Beckmam Coulter LS 13-320 Particle Size Analyzer. The samples showed a bimodal distribution, thus the modal peaks from each grain size were plotted separately in Excel to determine vertical grain size variations within the matrix of the bonebed.

Paleocurrent Measurements

Paleocurrent measurements were taken on various structures throughout the study area. The measurements taken within the 90,000 m^2 study area include measurements from cross beds as well as ripple structures. Care was taken to ensure quality of measurements. Outcrops with three dimensional exposures of structures or clear plan views were utilized for current measurements while those with only two dimensional, vertical exposure, or poorly preserved structures were not used.

Lithologic Facies

In the determination of facies, grain size was the primary criteria for delineating different facies. Sedimentary structures may vary within a particular facies with the exception of facies 3 which is defined on the basis of sedimentary structure.

Several line drawings were made to illustrate the sedimentary history of a sandstone hoodoo directly above the bonebed. These were rendered on Abobe Illustrator referencing field marked photographs of the hoodoos.

Maps

ArcGIS was used to make most of the maps in this thesis. Elevation maps for different stratigraphic units were created with the raster interpolation method of inverse distance weighting (IDW). This method of interpolation determines the cell value based on a specified number of nearest neighbor data points weighted as a function of inverse distance. The data points for these maps were obtained by walking out certain beds with a roving GPS unit. For beds that cropped out and were easily visible, the GPS was set to automatically take readings at specified distances while in motion. For beds that were not easily seen in outcrop, readings were manually taken where the bed cropped out. The top of the bonebed was approximated by taking readings of the highest stratigraphic occurrences of in situ bones and fragments on the hillsides.

CHAPTER THREE

RESULTS

This study aimed to answer how a unique layer of dinosaur bones was deposited in the Lance Formation. The proposed model should be consistent with the characteristics of the bone bearing layer itself as well as with the determined paleoenvironment of the local area. The results presented here contain information about these two avenues of research: the sedimentological surroundings of the bonebed and the bonebed facies itself.

Sedimentology

Sedimentological aspects to be presented include facies analysis, paleocurrent information, and stratigraphic sections.

Facies Analysis

Facies analysis of the study area in the Lance Fm indicate six distinct lithologic facies: planar and cross bedded sandstone, interlaminated mudstone and sandstone, climbing ripple sandstone, brown-grey mudstone, red shale, and bonebed facies. Facies are defined primarily on the basis of lithology. Sedimentary structures were used to distinguish two sandstone facies. Two fine-grained facies are distinguished partly on the basis of sediment size (facies 5 is generally more silty than facies 4), and partly on the basis of color, which reflects abundance of organic content or chemical composition.

Facies 1: Planar and Cross Bedded Sandstone

Facies 1 consists of white, very fine- to medium-grained, cross bedded, planar laminated, or ripple cross laminated sandstone. Mudclasts and mud rip ups as well as rare small bones, fish scales, teeth, or wood fragments may be found at the base of some cross bedded sets. On well exposed outcrops, channel scouring may be observed.

Few large-scale cross bed units were observed in the study area, but many sandstone units, equivalent of facies 1, in the vicinity around the study area show successions of large scale trough cross stratification (Figure 11). Paleocurrent data for one of these large cross bedded sandstone units is given in Appendix F but was considered beyond the scope of this research because the location could not be stratigraphically correlated with the study area. Ripples, where outcrop allows identification, are mainly linguoid ripples with rare straight crested to undulatory ripples. Planar and very low-angle cross bedding is also apparent.

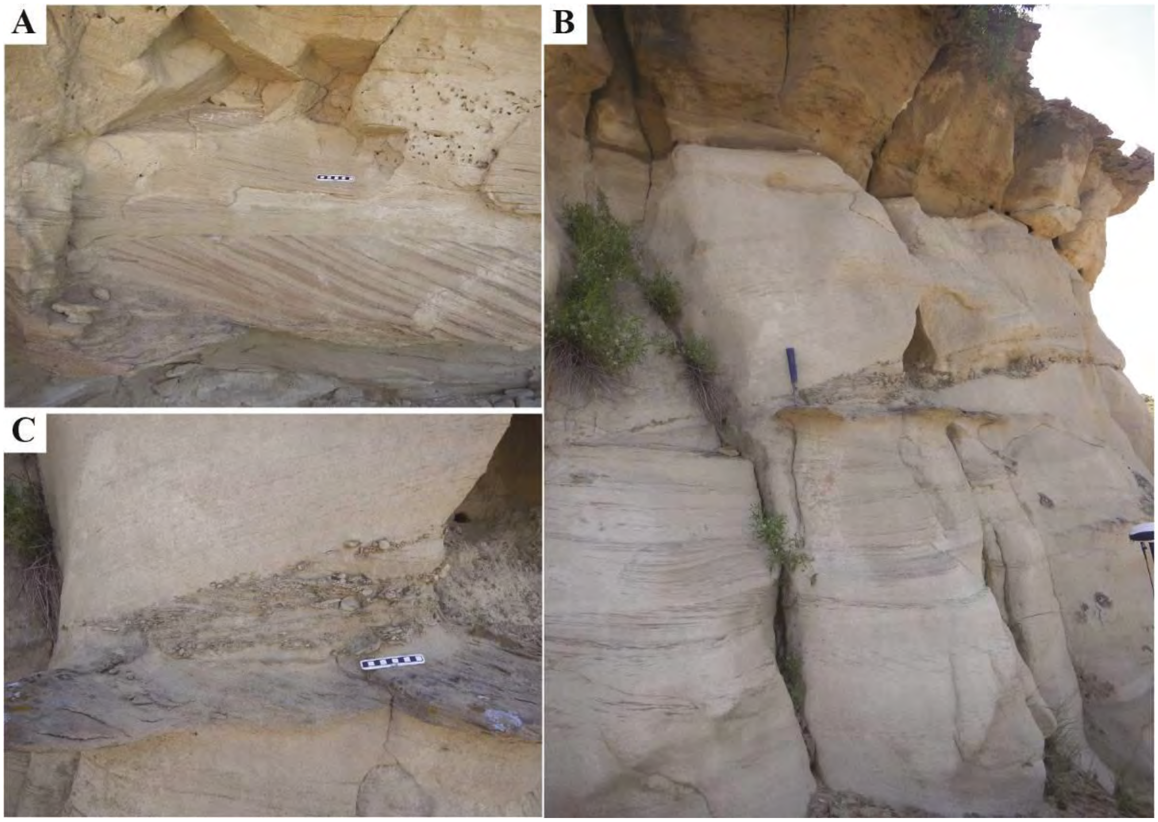

Figure 11 Facies 1 sandstone from northeast of section 2 shows well developed tabular cross stratification (image A) and cross trough stratification (images B and C). C is a close up of the center of image B. Abundant mudclasts appear at the base of trough cross beds.

Faint climbing ripples are sometimes present within these sandstones, however, they are not classified as facies 3 for three reasons. First, they appear sandwiched between sandstones clearly identified as facies 1. Second, no break in sedimentation seems to have separated them from the surrounding sandstone, and third, the appearance of the sandstone, in terms of cementation and color, is the same as the rest of facies 1.

In some locations, beds of facies 1 show large scale deformations, which have been identified as seismites (Figure 12) and previously utilized as stratigraphic markers (Weeks and Chadwick, 2011, 2012).

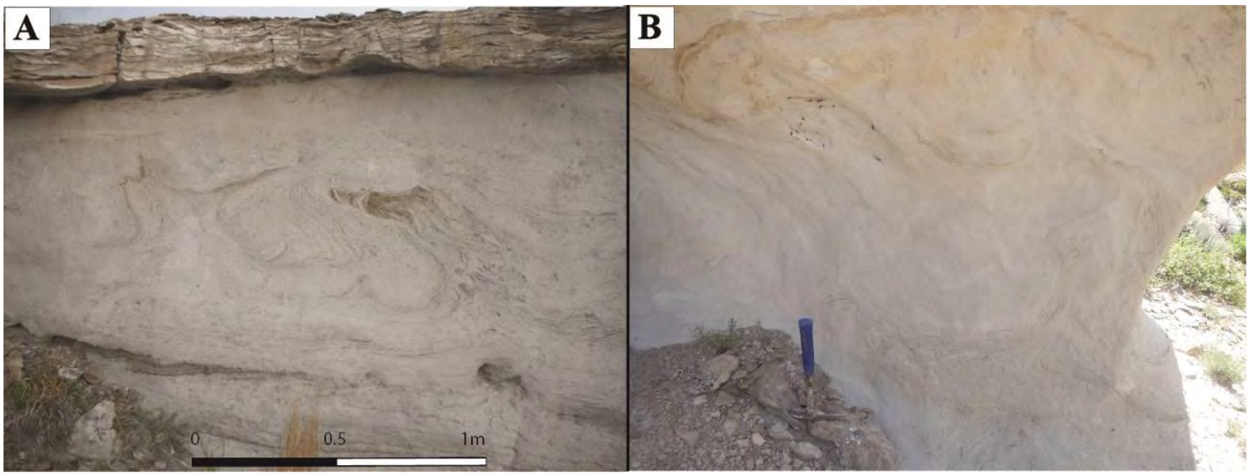

Figure 12 Contorted bedding. Image A is located outside the study area but is from a nearby location on the ranch. Image B shows contorted bedding of facies 1 sandstone seen in section 1. Refer to measured section #1 for specific stratigraphic location.

Much of facies 1 sandstone is soft and easily weathered, but many outcrops are protected by a hard, carbonate cemented cap which typically ranges in thickness between 20cm and 40cm. These carbonate cemented caps are typically of facies 1 but also may be carbonate mudstones classified under facies 4.

Some outcrops of facies 1 sandstone show convex up scoured surfaces and structural features. Figure 13 shows a panoramic picture of an outcrop of facies 1 sandstone with several low relief convex up structures.

Figure 13 Stitched photo of the lowest facies 1 interval in stratigraphic section 1. Several convex up, channel-like structures.

Large exposures of facies 1 show both vertical and lateral sedimentary structural transitions often depicting an upward decrease in energy of flow. Figure 14 to Figure 16 show different angles of the same sandstone hoodoo, which lies directly over the bonebed between Quarries 2 and 4 (i.e. South and Teague Quarries). They depict typical facies 1 sandstone with various structures of planar bedding, cross bedding, and ripple cross lamination. Figure 16 especially shows an ideal vertical succession of facies 1 sedimentary structures from planar bedding to cross bedding to ripple cross lamination. Figure 15 clearly shows the relationship of this outcrop of facies 1 sandstone to the bonebed below. A 20-30cm bed of mudstone and sandstone with 10cm clasts of mud, sand and bones and fragments separates the bonebed from the overlying sandstone. An erosional surface half way up the outcrop contains abundant mudclasts at its base.

Facies 1: Interpretation of Processes

Sandstones of facies 1 represent mostly continuous episodes of deposition with varying flow energy, which produced different sedimentary structures.

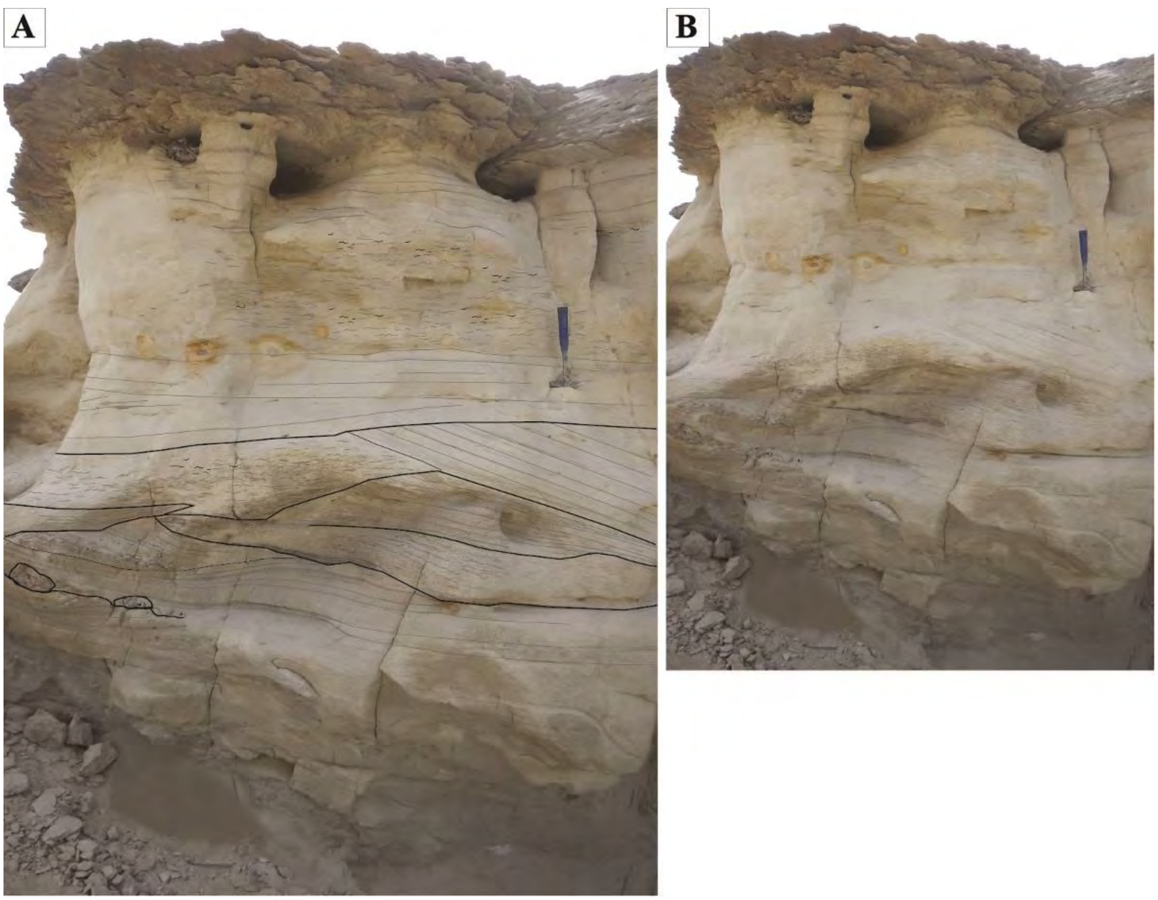

Figure 14 Line Drawing of hoodoo above the bonebed shows several sedimentary transitions in depositional structures in the sandstone. Original photo is shown to the right (image B) of the line drawing for comparison.

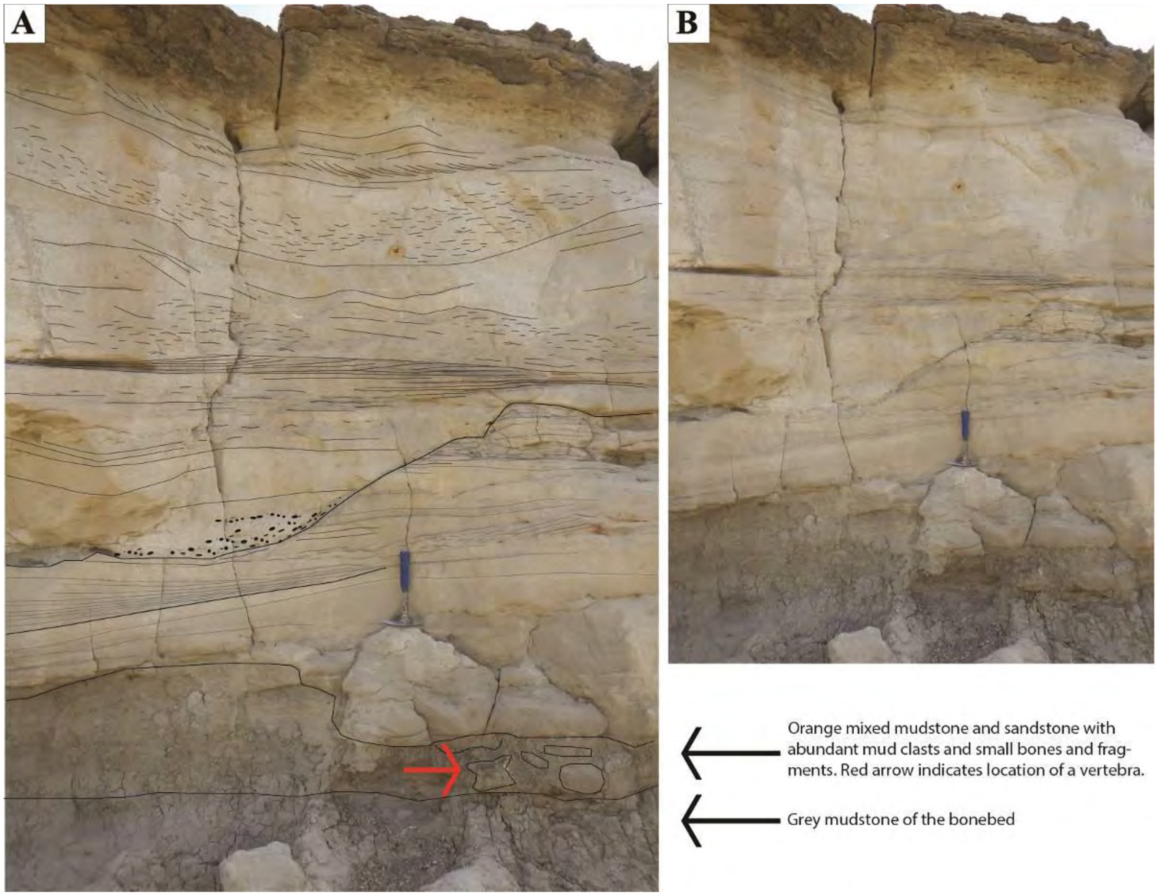

Figure 15 Line Drawing of hoodoo above the bonebed shows a mudclast and bone fragment conglomerate deposit just above the bonebed. Subsequent eroded depositional surface is seen halfway up the photo with another lag of mudclasts at its base. Original photo is given on the right (Image B).

Figure 16 Photograph of sandstone hoodoo above the bonebed. Image A has lines drawn illustrating structures seen during field observations. The bonebed is the lowest unit visible. Image B is the photograph without lines for comparison.

Facies 2: Interlaminated Mudstone and Sandstone

Mud is incorporated into the sandstone as broken muddy layers or stringers or as mud drapes over ripple cross lamination or small scale cross beds. Mud drapes occur over small scale cross bedding and ripple cross lamination. Facies 2 sediments give the appearance of flaser bedding. This facies exhibits pervasive soft sediment deformation structures in some localities while it appears undisturbed in other locations. Some of the deformation may be due to bioturbation (burrowing or trackways). Macro-scale fossils are not a defining element of this facies, and micro-fossils have not been studied.

Facies 2: Interpretation of Processes

Facies 2 represents periods of high suspended load such that even small changes in the energy of flow allowed clays to settle out of suspension. Fine sediment settled either by flocculation of clays or, in some cases, sufficient time elapsed for clays and silt to settle by the slow action of gravity.

Facies 3: Climbing Ripple Sandstone

Facies 3 comprises relatively pure tabular sandstone bodies with climbing ripple lamination. Facies 3 typically occurs as carbonate cemented, ~30 cm thick sandstone beds. Generally the climbing ripples preserve the lee side as well as most of the stoss side forming Type 1 ripple laminae-in-drift climbing ripples (Reineck and Singh, 2012).

Facies 3: Interpretation of Processes

Sandstones of facies 3 preserve a record of periods of high sedimentation rate with water depth and velocity appropriate for formation of ripple cross lamination. Sedimentation rates were high enough to allow upward aggradation of ripple structures. Sedimentation rate exceeded the rate of erosion.

Facies 4: Brown-Grey Mudstone

Facies 4 is a sticky, clay-rich mudstone. It often appears structureless, but structures might be lost due to diagenetic alteration or bioturbation. Facies 4 contains sparse root traces (Figure 18 image B) and macerated plant material. In the beds with root traces, often larger (10-20 cm long) plant fragments are nearby. Orange laminations are present in some beds and may be a result of diagenetic processes or reflect primary sedimentary structures (see Figure 18 image C). The mudstone breaks apart in chunks with orange stain on the surfaces of natural blocks though the inside is gray. Iron staining surrounding grey mud balls, which may or may not be cemented hard, are common. Small dipping coal veins are locally present. One facies 4 bed contains an interval of *Unio* bivalves preserved as closed, whole shells. The bivalves form a one-shell thick horizon at the base of a mudstone bed.

Facies 4: Interpretation of Processes

Facies 4 represents locations or episodes of quiet, standing water. The water was saturated with suspended clays and tiny, macerated plant fragments which settled out. Coalified plant roots are very rare but, when present, appear in living position indicating that some areas or periods had conditions suitable for plant growth. No mud cracks were evident indicating the environment stayed near saturation or episodes of prolonged subaerial exposure did not occur or were not preserved.

Facies 5: Red Shale

Facies 5 is a distinctly red silty to muddy shale which sometimes appears as a bed of very thin flakey siltstone or as a blockier mudstone. A thin (~0.5cm), almost continuous layer of coal often forms the upper contact of the beds of this facies. Compared to facies 4, the red shale contains higher concentrations of macerated plant debris. Though this facies is repeated in the measured section, it serves as a very local stratigraphic marker bed occurring approximately 2m below the bonebed. Its distinct red color allows it to be spotted on the hillsides.

Facies 5: Interpretation of Processes

Sediments of facies 5 are slightly coarser than that of facies 4, but the two facies probably represent similar conditions. Quiet water allowed small suspended particles and plant material to settle out of the water. The coal at the upper contact may indicate a small amount of plant growth at this interval. The presence of this plant material may contribute to the red color, or the coal may be from influx of plant material as an event over the top of a siltstone bed. Since no root traces were discovered, the latter interpretation may be more likely.

Facies 6: Bonebed

Facies 6 is a unique facies occurring only once in the entire length of section measured. Its characteristics will be presented in more detail later. It is a 1m thick bed of mudstone with abundant dinosaur bones, some plant material, and coal pieces. The bones are arranged in a normally graded distribution. Specific information on fossil species found in the bed are available in the online database provided by Southwestern Adventist University (Chadwick et al., 2016). A list of species is also provided in Appendix D.

Table 3 gives a summary of the information presented above as well as some information about facies 6 that will be given in greater detail later in this thesis.

Table 3 Summary of Facies

Facies	Lithology	Inorganic Sedimentary Structures	Biofacies	Distribution and vertical facies transitions
1	Sandstone	Ripples: straight crested to linguoid ripples Cross bedding: trough cross bedding and planar cross bedding Mudclasts	Rare bone fragments, various tetrapod teeth, and wood fragments	Within facies vertical transition from high to low energy.
2	Heterolithic; sandstone and mudstone	Mottled textures Abundant mud drapes Ripple cross lamination Trough cross bedding	Possible bioturbation causing mottled texture	Within facies vertical succession generally fine upward
3	Sandstone	Climbing Ripples: Type 1 in-drift	None	Rare, typically appears above facies 4
4	Mudstone to Claystone	Ochre colored laminations rare	Macerated plant material *Unio* bivalves	
5	Mudstone to Siltstone	None apparent	Leaf imprints Capping coal vein Root traces Macerated plant material	
6	Mudstone	Structureless, bones are normally graded	Dinosaur bones and teeth Crocodile teeth and small bones Fish scales and teeth Turtle scouts and rare bones Skate and Ray teeth Seeds	Unique facies Flat upper contact and sharp lower contact in places where sandstone is in contact with bonebed

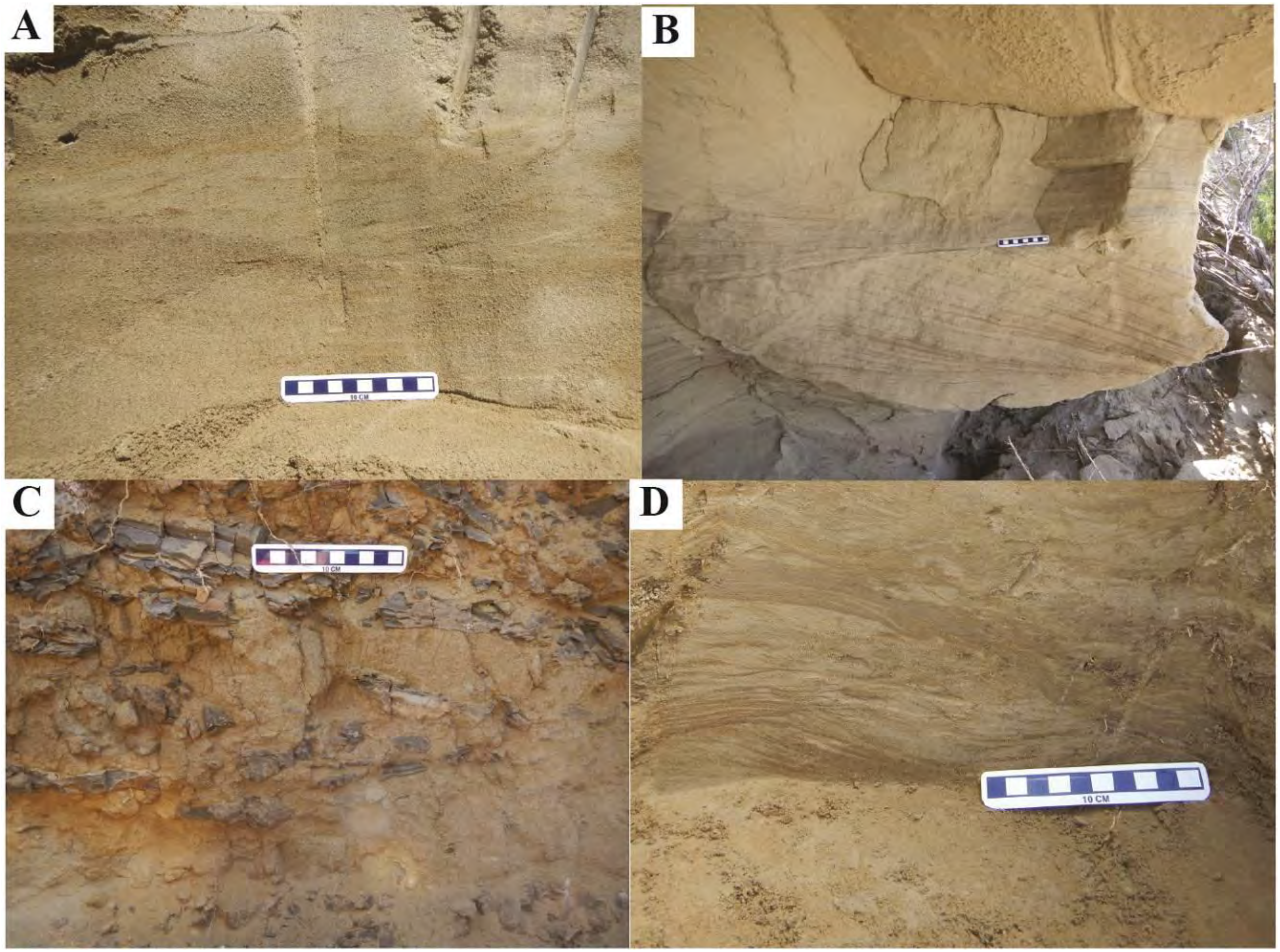

Figure 17 Facies photos. A: facies 1, clean sandstone showing small-scale, low-angle cross-bedded lamination; B: Facies 1, large scale cross-bedding in a clean sandstone; C: facies 2, mud-rich sandstone showing mud in the form of clasts and thick, brecciated, mud drapes; D: facies 2, muddy sandstone with ripple lamination and small-scale cross-bedding with mud drapes and ~2cm thick mud intervals.

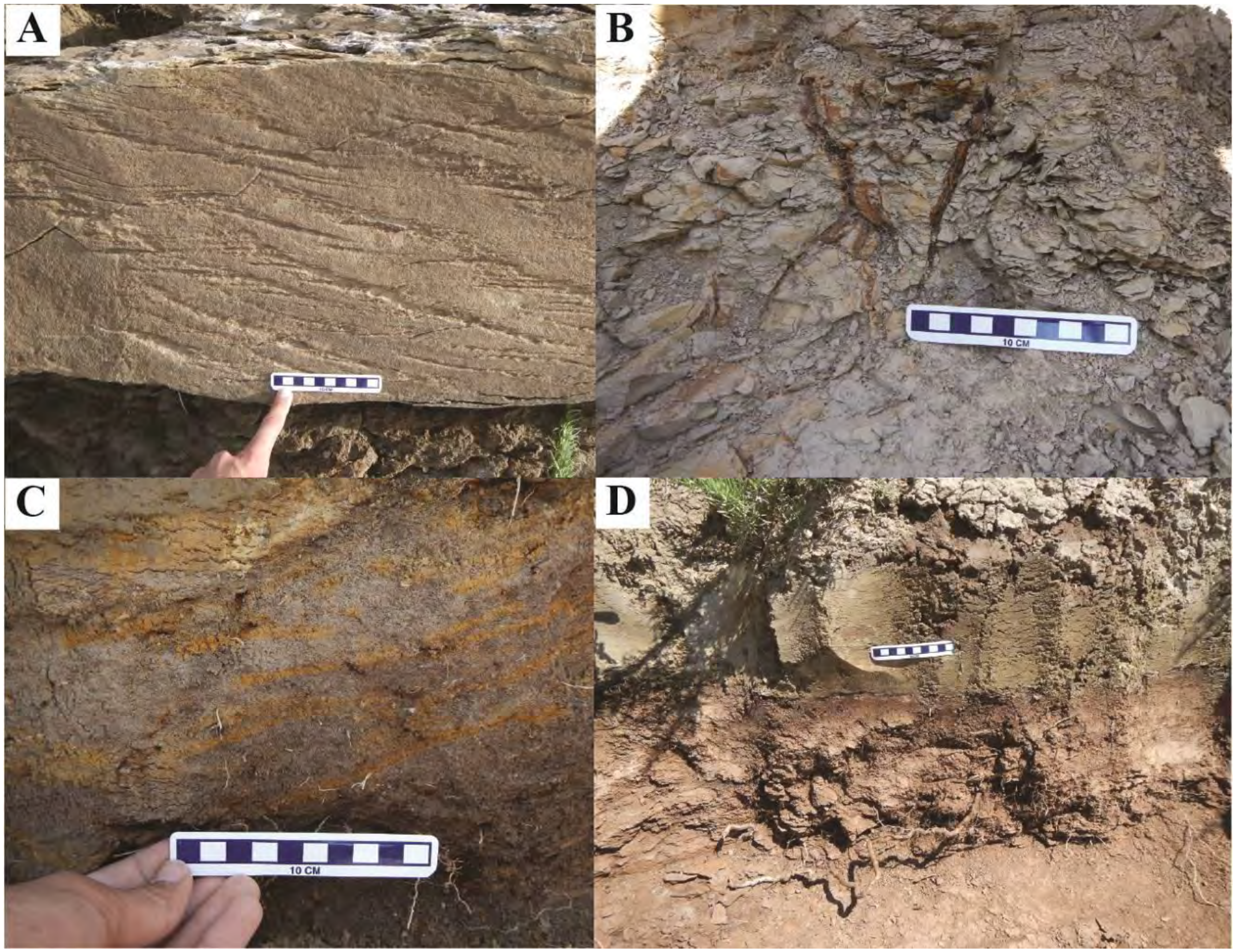

Figure 18 Facies photos. A: facies 3, super critically-climbing ripples in a very clean, carbonate cemented sandstone; B: facies 4, rare, coalified roots in growth position within a drab-grey mudstone; C: facies 4, drab-grey mudstone with orange laminations possibly indicating primary structure; D: facies 5, red, shaley siltstone with abundant macerated plant material and a thin <1 cm coal lamination at the upper contact (visible ~4 cm below the scale)

Paleocurrent Data

Paleocurrent measurements from ripples and dunes are plotted in Figure 19 on separate rose diagrams. The rose diagrams indicate a mostly unidirectional flow to the southeast for the area. Comparison of this flow direction with the maps of the Western Interior Seaway of Figure 1 show that the determined paleocurrent of the Lance Fm here is toward the center of a water inlet of the Western Interior Seaway.

Paleocurrent data were obtained mostly from ripples and dunes of facies 1 sandstones. A few measurements were obtained from facies 3 climbing ripples, and one measurement was taken in facies 4 mudstone of several coal and orange dipping laminations that resemble cross bedding. The laminations showed a direction consistent with other measurements. The measurements that were taken from beds during the logging of sections are indicated on the stratigraphic columns of

Figure 22- Figure 24.

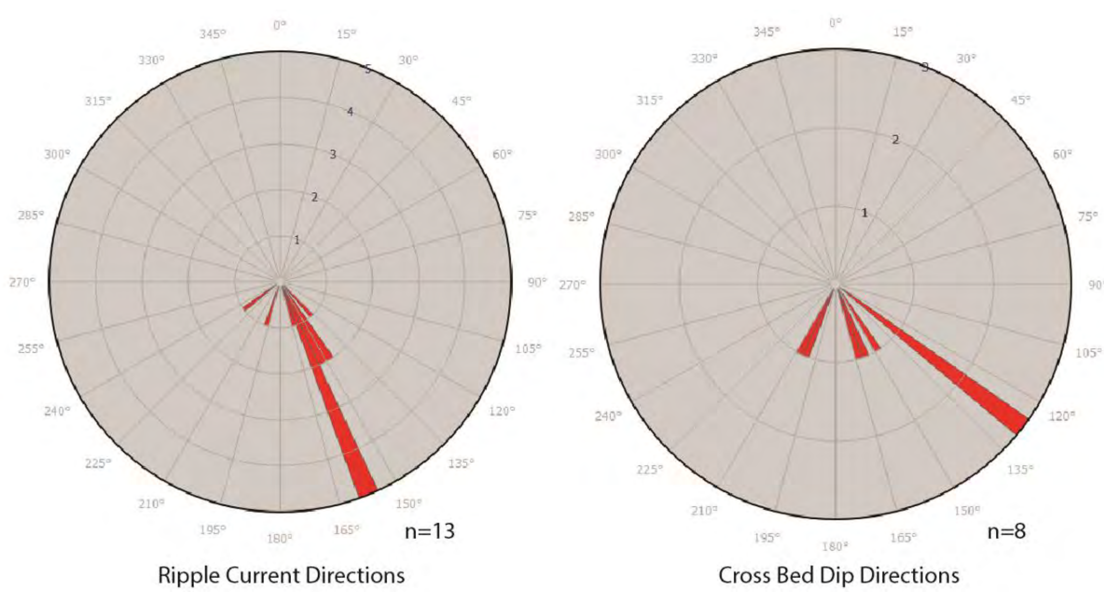

Figure 19 Rose diagrams of paleocurrent indicators depict a mostly unidirectional flow. Measurements on ripples and dunes are plotted separately. n=21

Stratigraphic Sections

Four stratigraphic sections were measured (Figure 21- Figure 25). Table 4 shows the UTM coordinates for each section. Sections 1 and 2 are each fairly long (section 1 = 35m and section 2 = 19 m) while sections 3 and 4 are shorter (~4 m each). Figure 20 shows the outcrop on which section 1 was measured. This photo typifies the outcrop of the Lance Fm in the study area.

Table 4 UTM Zone 13N coordinates for beginning and end of each stratigraphic section.

Section No.	**1**	**2**	**3**	**4**
Start (Northing Easting)	4815209 543649	4815496 543912. 9	4815283 543860	4815457 543804.8
End (Northing Easting)	4815269 543802.7	4815427 543977.3	4815289 543858.8	4815467 543814.2

Figure 20 Typical Lance Fm outcrop. Section 1 was measured from the bottom left side of this photo to the upper right.

The legend for all stratigraphic sections is given in Figure 21. The Four sections were correlated (see Figure 25) using the bonebed and a carbonaceous, red, flakey shale (facies 5) which lies ~2m below the bonebed. The combined, nonoverlapping length of Lancian section measured totals ~45.5m. Over the area studied, no faults were evident, however, lateral variations in sedimentary structure, lithology, and thickness of beds are apparent.

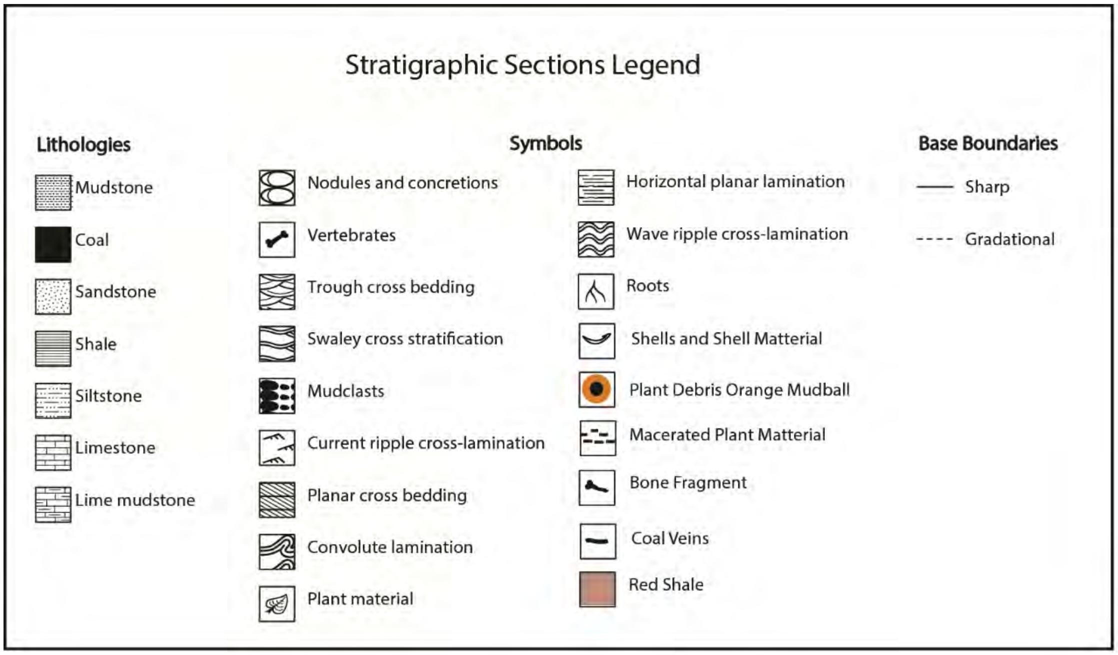

Figure 21 Legend for all four stratigraphic sections.

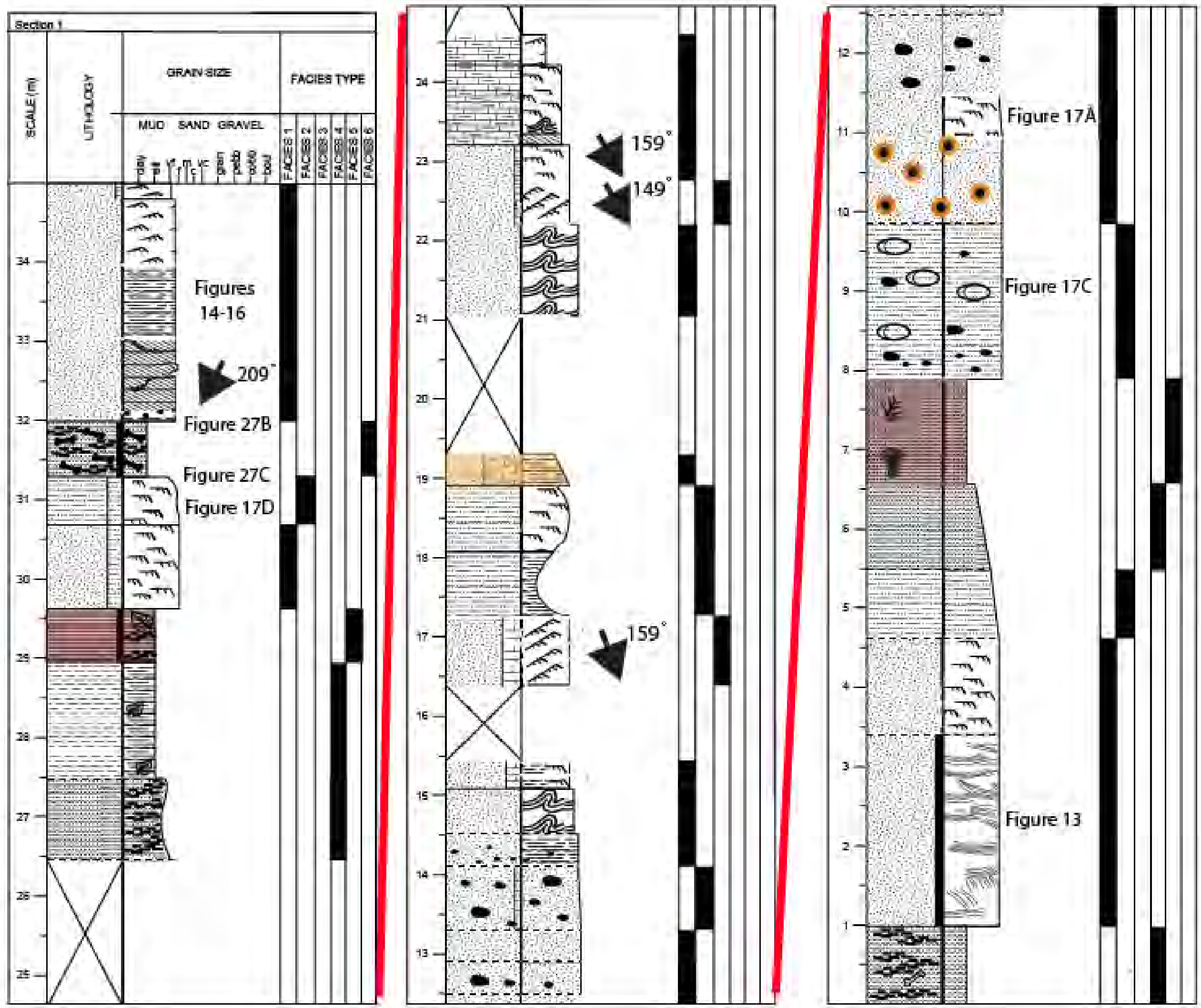

Figure 22 Stratigraphic section 1 split into three columns for ease of viewing. Legend is in Figure 21.

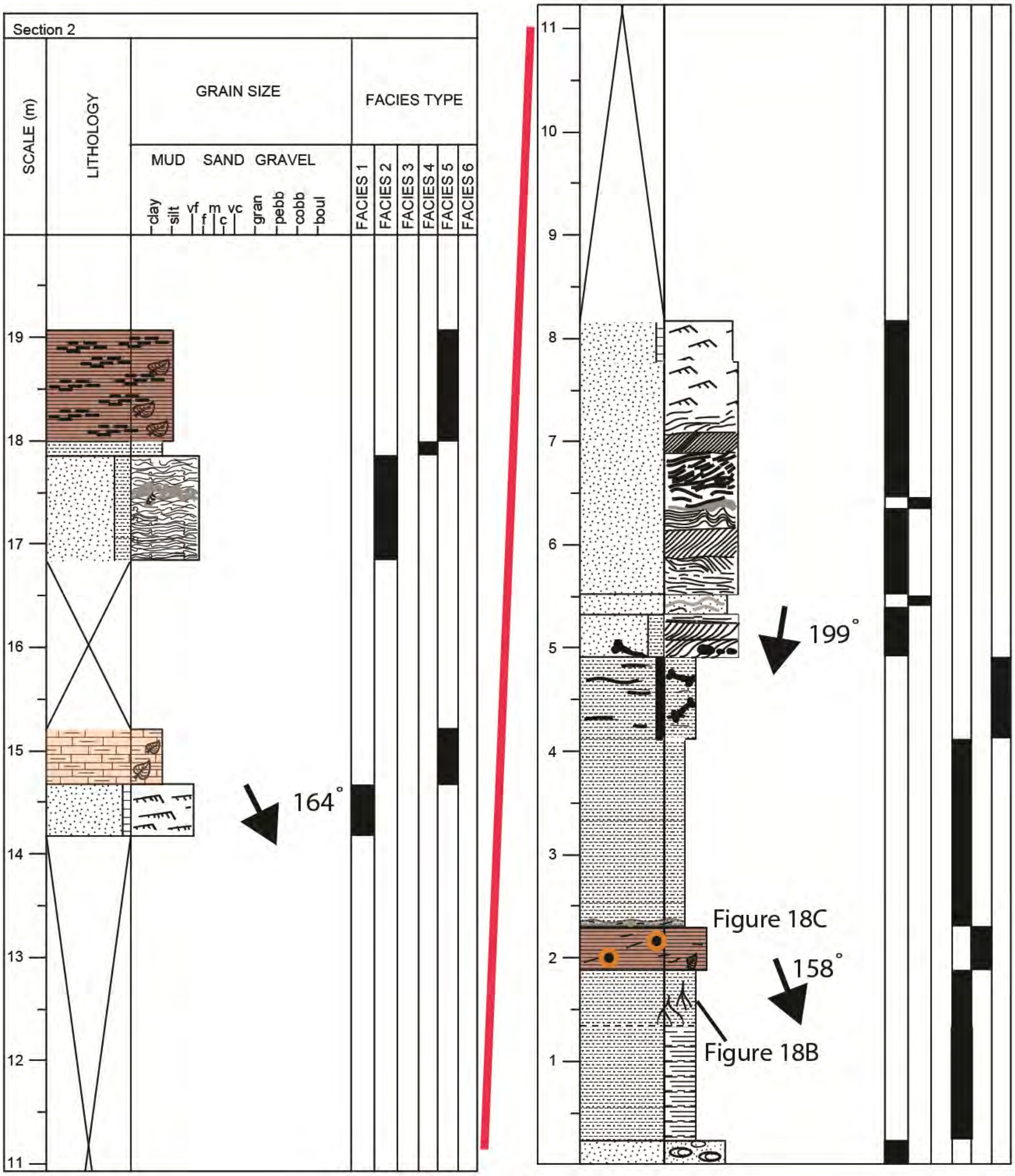

Figure 23 Stratigraphic section 2 is shown in two panels for ease of viewing Legend is in Figure 21..

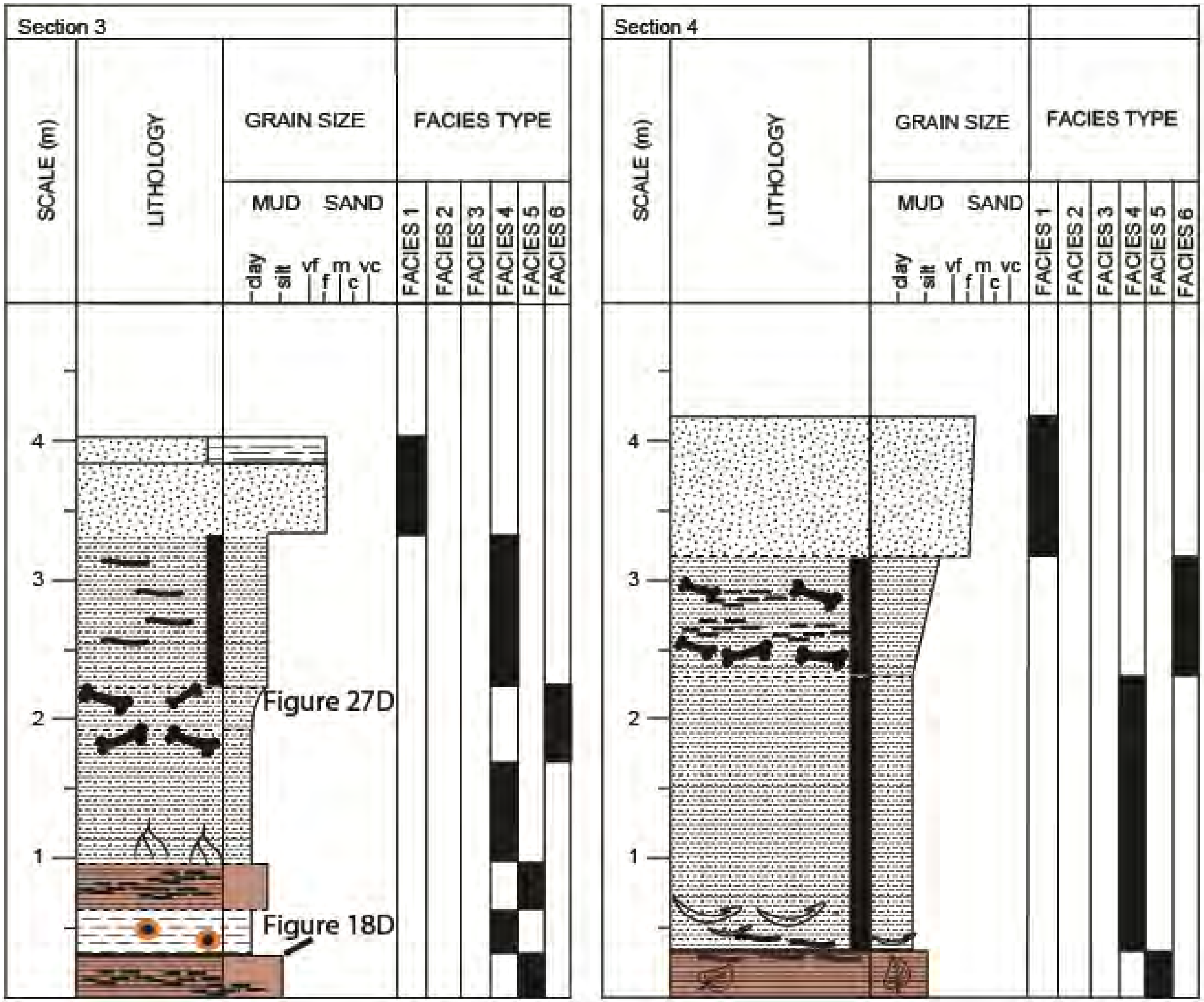

Figure 24 Stratigraphic sections 3 and 4. Legend is on Figure 21.

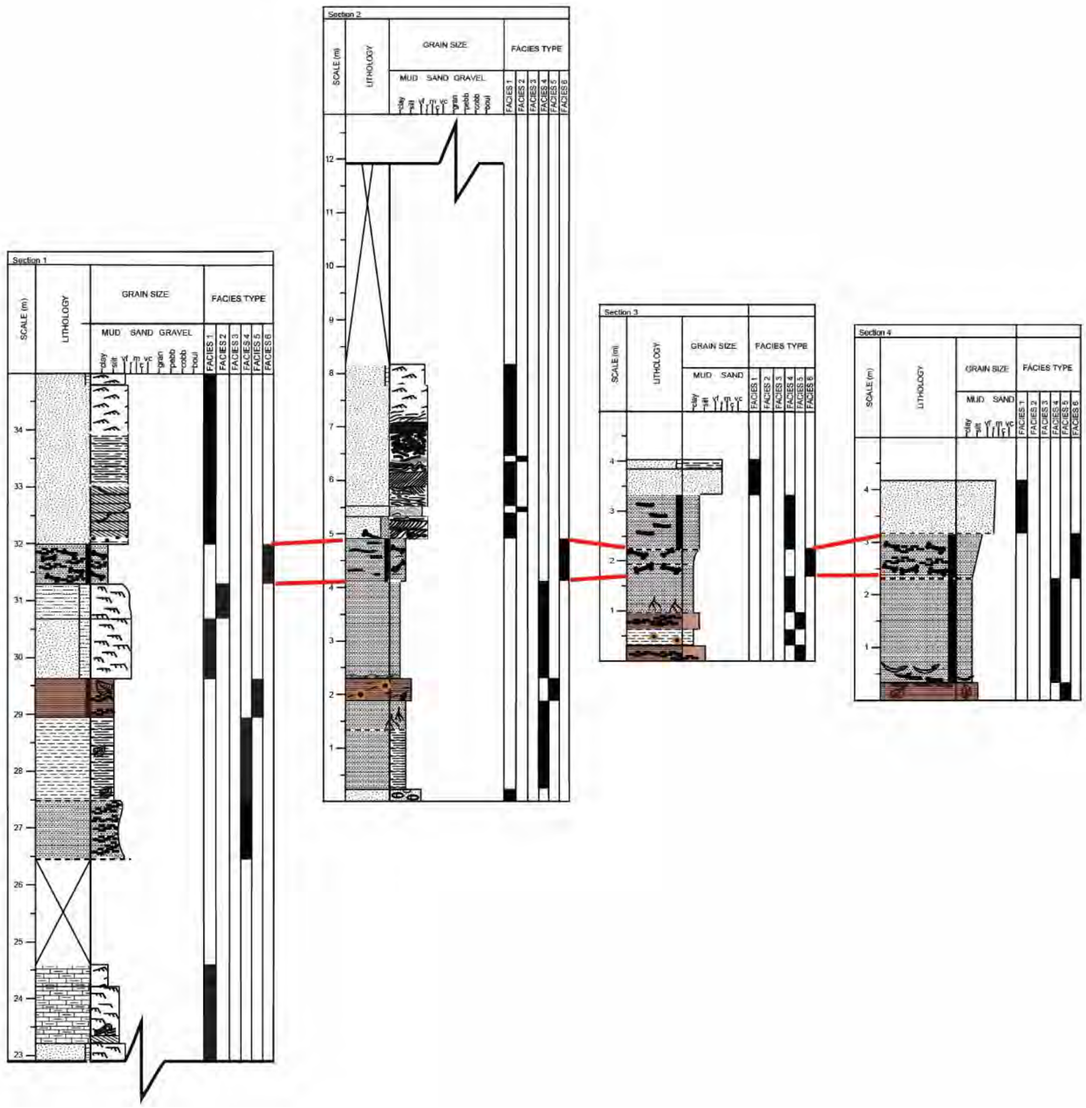

Figure 25 Stratigraphic sections correlated with the bonebed. Complete versions of sections 1 and 2 can be found in previous figures.

Bonebed Facies

The bonebed is a unique facies. The other five facies occur repeatedly throughout the observed portion of the Lance, but the bonebed facies appears only once. The bonebed, except for short intervals where Quaternary alluvium covers the hill, crops out continuously around several fingers of a large hill. The bonebed can be observed in these outcrops as well as from several quarries probing into the bonebed.

There are many active quarries on the Hanson Ranch, but, for the purposes of this study, only seven of these quarries have been included. Figure 26 is a map that shows the position of the quarries used in this study. Other quarries not utilized in this study are located some lateral distance away from the studied quarries. The excluded quarries did not crop out in the study area, and thus, they are not in the presented stratigraphic columns. Most of the seven studied quarries have been under excavation for many years. They represent the totality of quarries, to date, dug into the main bonebed. These seven quarries were correlated by walking out the bonebed. The bed is easily identified by the presence of abundant dinosaur bones lying on the surface of the hillside. The sedimentology and spatial data of the bonebed are presented below.

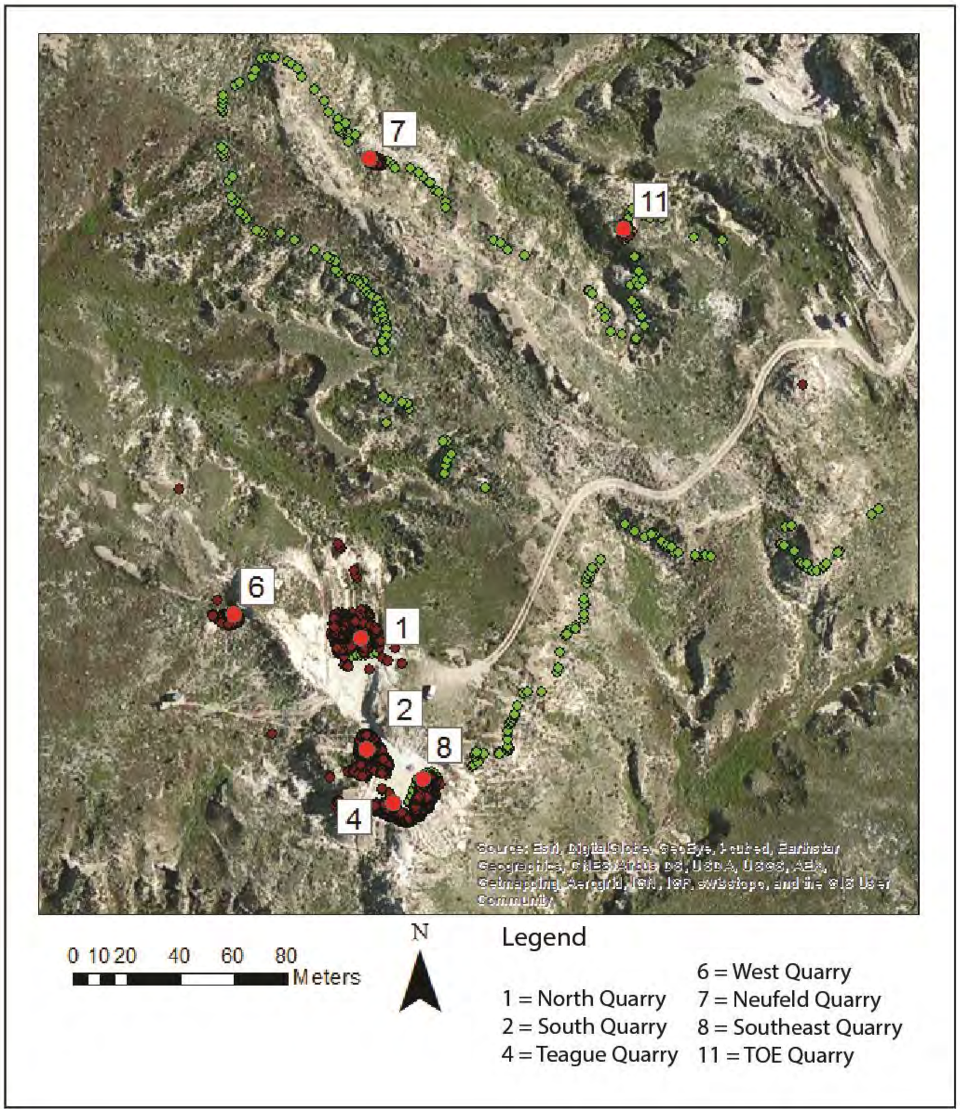

Figure 26 Map showing location of bonebed. Bright red dots indicate quarry locations. Dark red dots indicate position of bones found in quarries. Green dots indicate location of bones in outcrop.

Sedimentology

The bonebed, studied from seven quarries, is a 0.5 to 1.5 meter thick bed of structureless mudstone with abundant dinosaur bones and teeth and small bones of other animals. On the south end, it is bounded on the bottom by a muddy sandstone (facies 2) and on the top by a fine-grained ripple cross laminated and cross-bedded sandstone (facies 1). On the north end, it is bounded by a mudstone (facies 4) on the bottom and a fine-grained, ripple cross laminated and small-scale cross bedded sandstone (facies 1) on the top. The contact between the bonebed and the overlying sandstone is sharp and flat (Figure 27 images A, B and D).

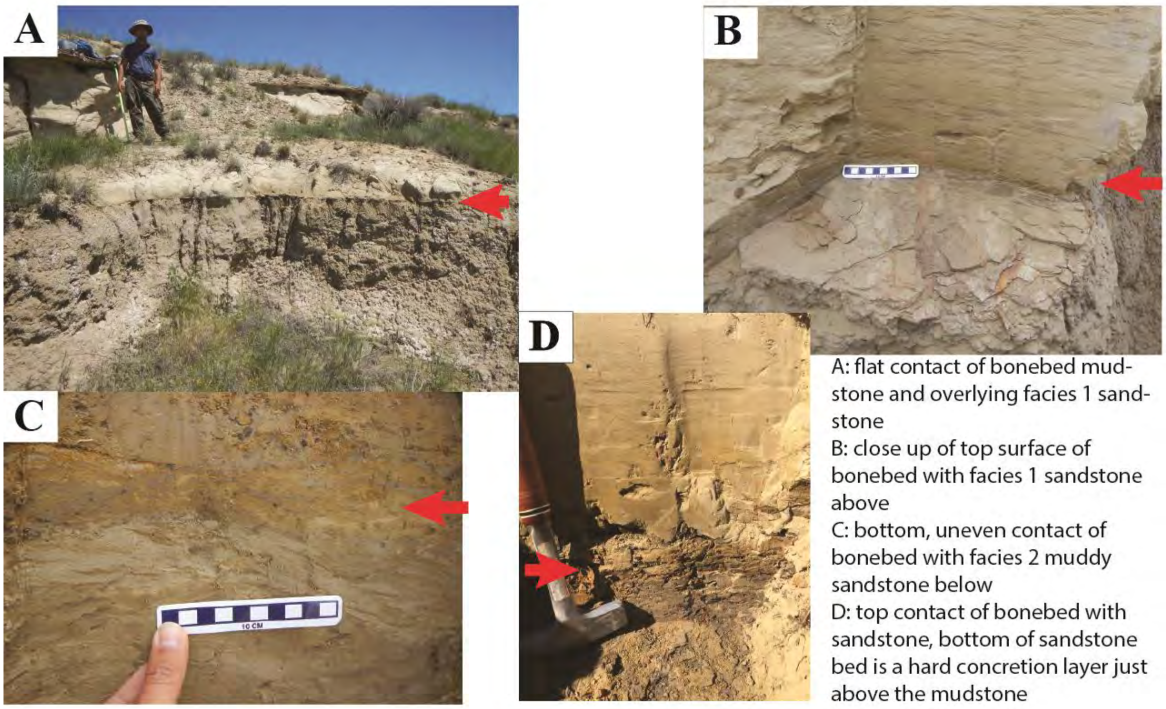

Figure 27 Bonebed Contacts. The contact between the bonebed and overlying sandstone is a flat contact. Small mudclasts and concretions sit just above the mudstone in some locations. The basal surface of the bonebed makes a sharp contact where it meets underlying sandstone (image C), but where it overlies mudstone toward the north, a contact is indistinguishiable.

The upper contact of the bonebed, though flat, contains concentrations of mudclasts in the immediately overlying sandstone. In some locations, there are sparse bone fragments, and teeth incorporated in the overlying sandstone. These are mostly restricted to the ~20-30cm of sediment directly above the bonebed. However, a few fragments may appear 1-2m above the bonebed incorporated in mudclast-rich intervals at the base of cross bed sets or individual cross beds. No bone material has been observed in the underlying sandstone when it is present, and when the bonebed is underlain by mudstone, the basal contact is imperceptible.

Where sandstone underlies the bonebed, the basal contact is uneven and less distinct than the top, but a sharp, dark line marks the boundary between sandstone and mudstone. This contact shows some possible small scours or tool marks indicated by short breaks in the dark demarcating line of the contact.

Vertical Distribution of Bones

It is evident from excavating the bonebed and from observing the 3-D generated quarry images of the bed (see Figure 28), that the bones appear in a normally graded distribution with the largest bones resting on the floor of the bed and smaller bones suspended in the matrix. Most of the bonebed is matrix supported, but in Southeast Quarry (Quarry 8), bones at the bottom of the bed are in contact with each other and might represent a clast supported area of the bed or at least a more densely populated area of the bed forcing larger bones to be in contact.

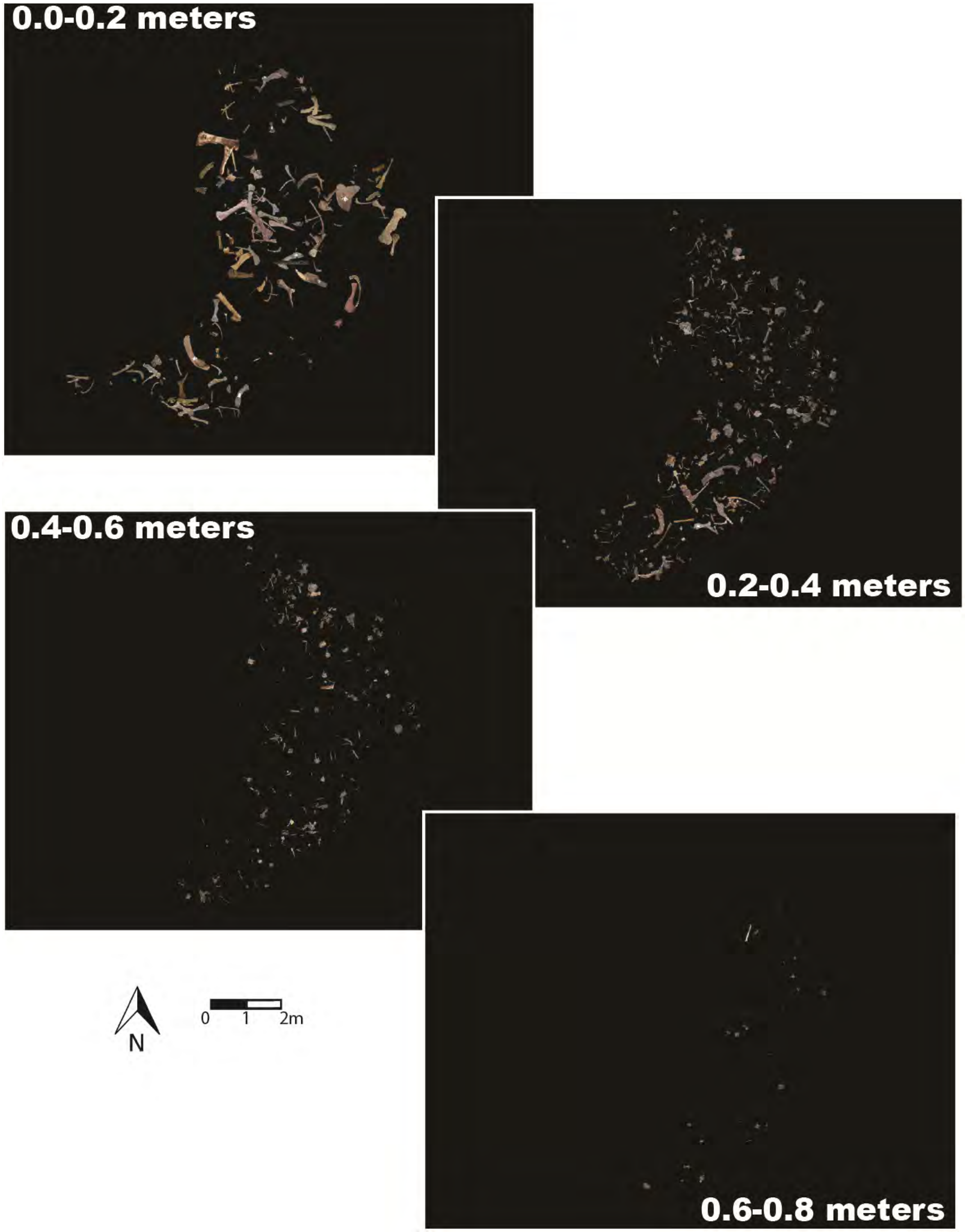

Figure 28 Horizontal slices of a portion of the bonebed showing vertical distribution of bones. The basal most 0.2m is shown at the top followed by successive 0.2m slices.

Matrix Grain Size Analysis

The mudstone matrix of the bonebed exhibits no apparent grading. Figure 29 shows the vertical distribution of grain sizes of clay and silt within the matrix. The graph in Figure 30 was generated from the size analysis of the lowest matrix sample taken from South Quarry. The majority of particles in the matrix are silt with ~20-25% clay and a small fraction of very fine-grained sand.

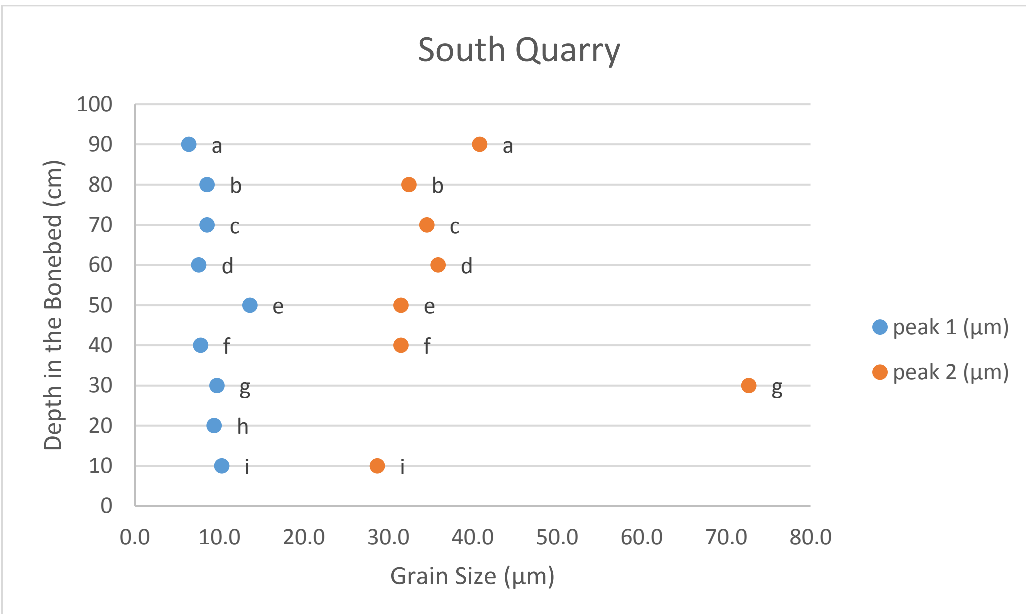

Figure 29 Grain size analysis of mudstone matrix from South Quarry shows little apparent vertical size variation.

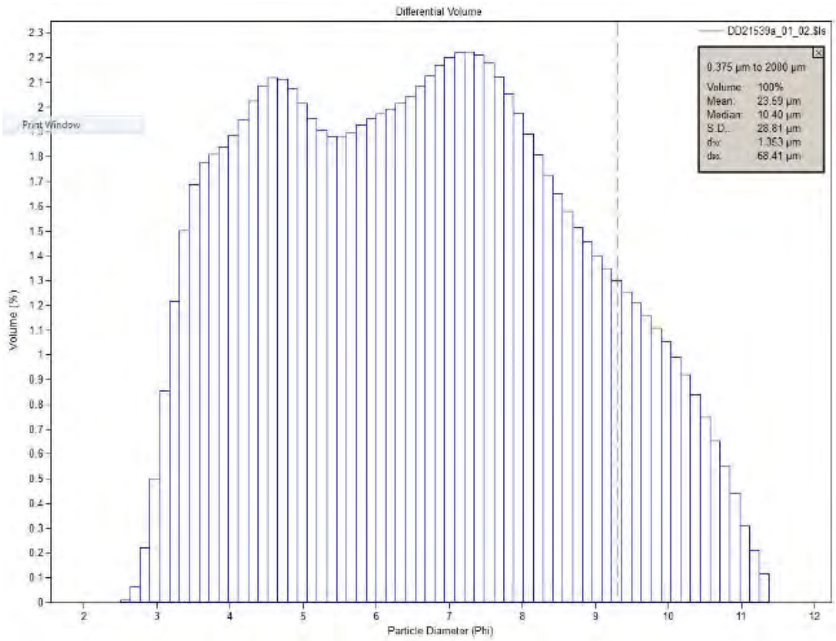

Figure 30 Sample grain size analysis graph showing obvious bimodal distribution.

Bone Orientation

Elongated bones (i.e. limb bones, ribs, meta carpals, etc.) show no preferred orientation. Figure 31 shows long bone orientations. No imbrication of bones has been observed, nor does the bed show any sedimentary structures. The matrix appears structureless with the exception of a horizontal color difference between top and bottom half of the quarry seen in South Quarry. This may be due to recent water movement in the quarry or may represent primary structure.

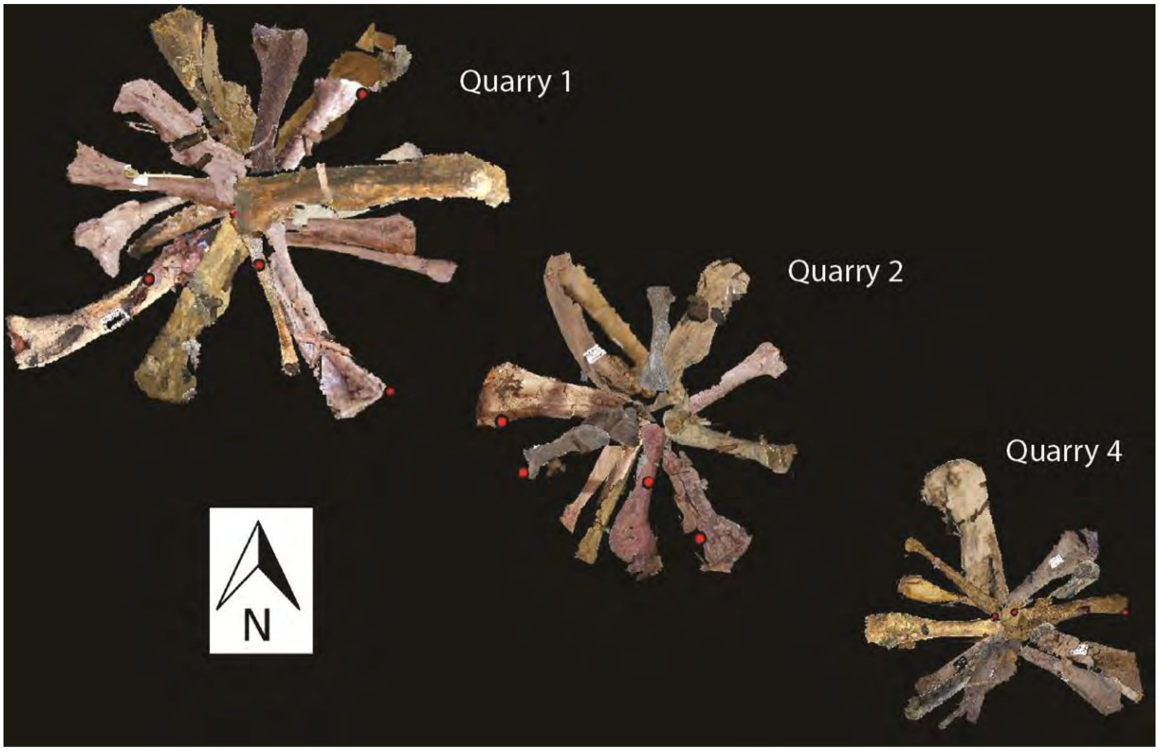

Figure 31 Pictorial rose diagrams showing long bone orientation from three quarries. No preferred orientation is evident.

Spatial Data

The bonebed has been sampled from 7 quarries within an area of ~ 0.1 km^2. The average thickness of the bed is 1m. The bonebed thickens to the south (see Figure 32). At its thinnest it is ~0.5-0.6m, and at its thickest it is ~1.5m. The lateral distribution of bones shows that bone concentrations increases slightly toward the south, (Figure 32-Figure 34) while the vertical distribution is normally graded. The quantity of bone material in the bottom 0.5m of the bonebed in quarries 1, 2, 4, and 8 is far greater than in the top 0.5m (Figure 35).

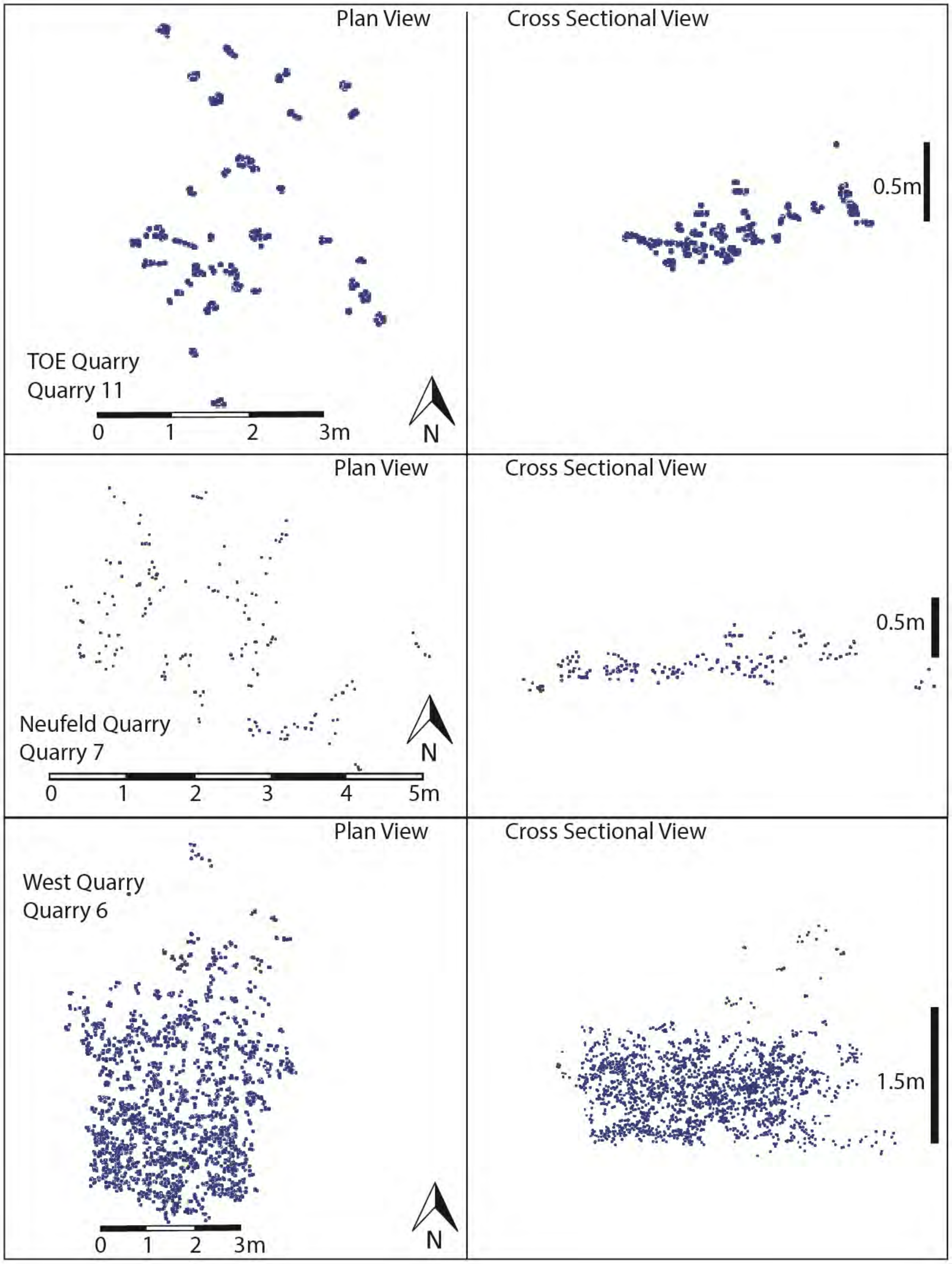

Figure 32 Plan and cross sectional view of three quarries illustrating thickness differences and variation of bone concentration from quarry to quarry.

The bonebed, though fairly planar, exhibits a dip of approximately 3° to the NW (dip measured from GPS data of the top of the bonebed). This is roughly 180° opposed to the average paleocurrent direction of surrounding beds. Relief within the bed is minimal. Figure 36 shows an IDW elevation map of the bonebed. Within the study area, the maximum and lowest elevation difference of the top of the bonebed is ~11m. Figure 37 shows the elevation map of a red shale layer (facies 5) that lies ~2m below the base of the bonebed. It is the most prominent, mappable layer in the vicinity of the bonebed. Both beds appear to have nearly the same topographic architecture.

Modern drainages truncate the bonebed on the southwest, southeast, and northwest. (See Figure 26 for a map of GPS points taken on the bonebed.) It is possible but unknown whether the same bonebed may crop out on other hills at more distant localities. The northeastern edge of the bonebed becomes untraceable where Pleistocene alluvium covers the outcrop. However, another bonebed, not included in this study, appears north of the Pliestocene cover at approximately the same elevation. It may eventually be shown to correlate with the main bonebed. The fossil assemblage of this northern bonebed is more articulated and contains remains of taxa which are scarce to absent in the main quarries.

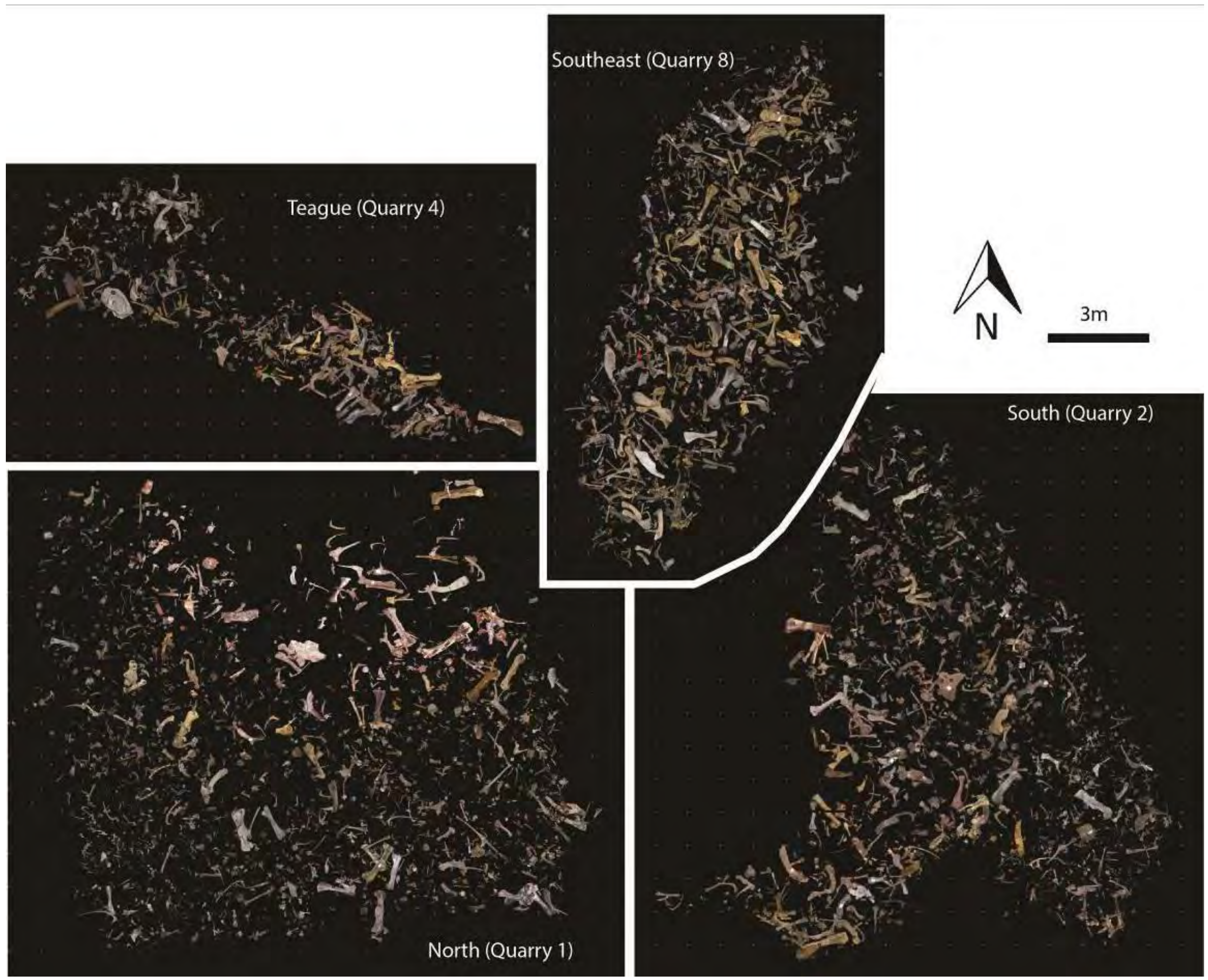

Figure 33 Georeferenced images of bones from each quarry show the lateral distribution of bones within the bed. Where bones are exposed, the height of the bed has been excavated. Black areas are either unexcavated or eroded portions of the bonebed due to modern drainages.

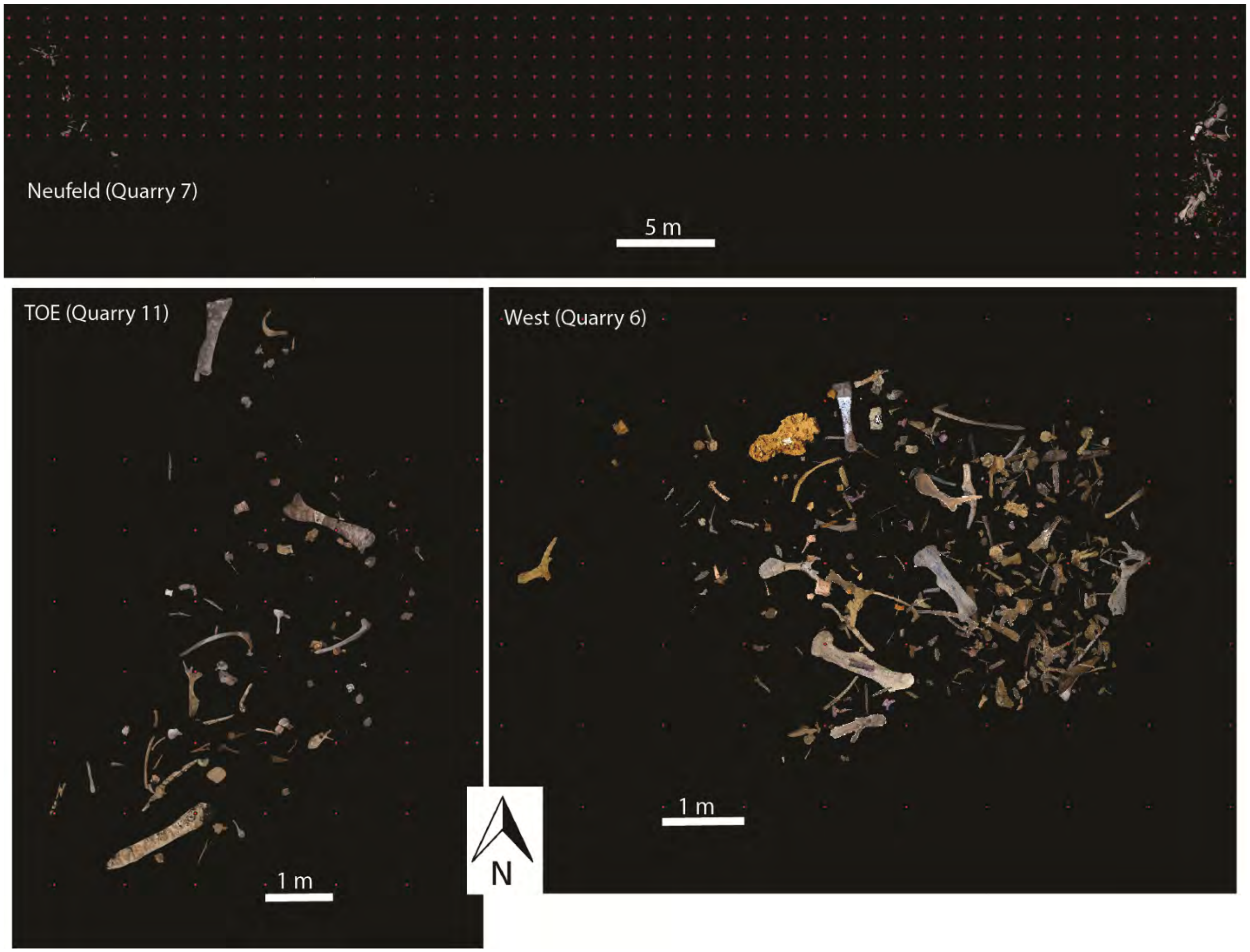

Figure 34 Georeferenced bone images from each quarry, quarries 6, 7, & 11.

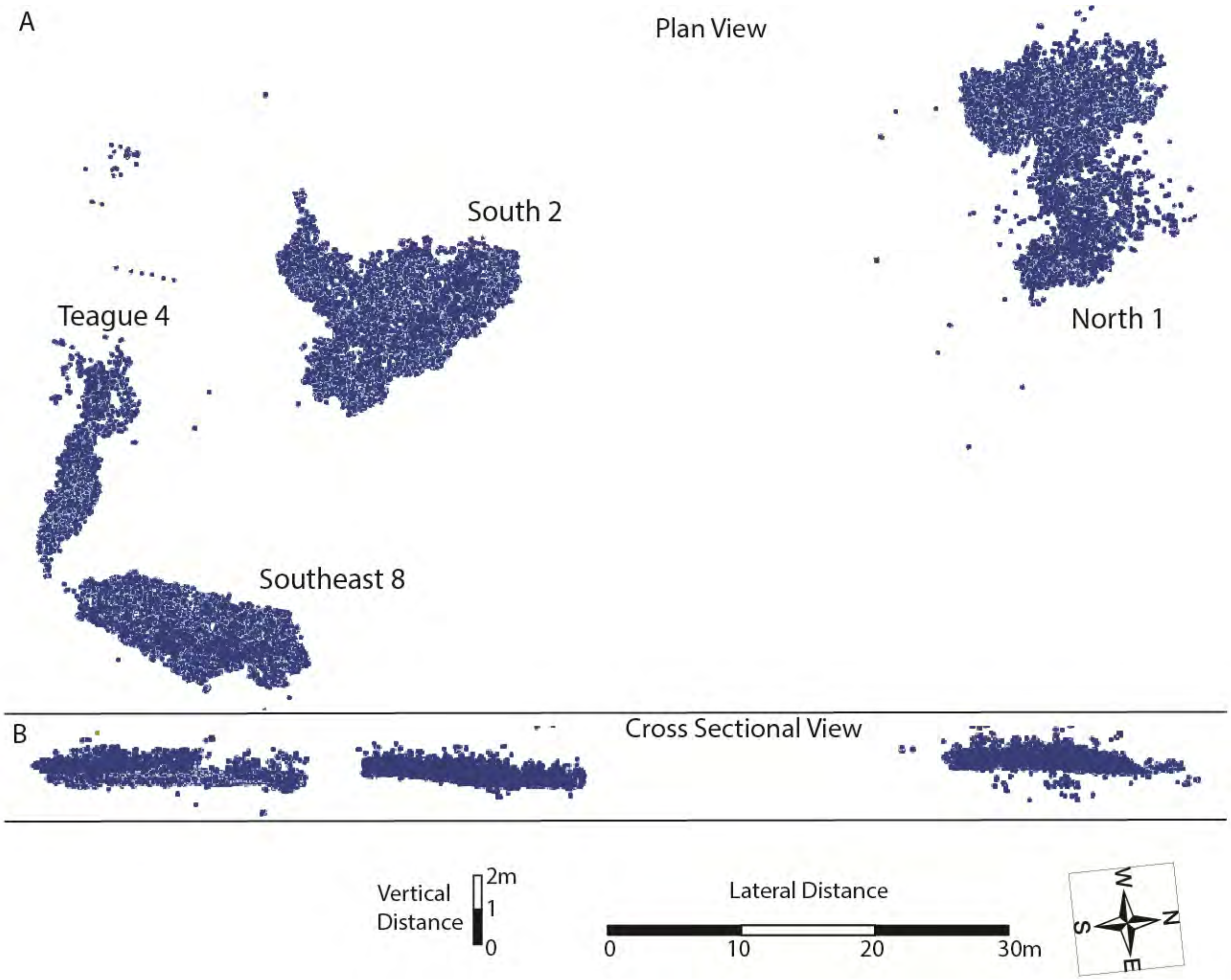

Figure 35 Diagrams generated from accumulated GPS data points taken on the periphery of each excavated bone. A is an aerial view, and B is a cross sectional view of the same quarries.

Mapping Data

Several lithologic units were mapped during field research. Units mapped are presented in Appendix E. To establish the dip and learn about the topographic relief of the bonebed, the bonebed and uppermost mappable unit below the bonebed were mapped and displayed below (Figure 36 and Figure 37). Though initially the goal was to map the bottom of the bonebed, this was deemed impractical because of the obscurity of the bottom contact of the bonebed mudstone with the underlying mudstone. Instead, the highest stratigraphic occurrence of *in situ* bone material was mapped as a proxy for the top of the bonebed. An easily identified, mappable unit below the bonebed was mapped in order to compare its relief to that of the bonebed.

The dip of both beds, the bonebed and the red shale, is very shallow (~2-3°) to the NW. They also show very similar patterns in terms of topographic relief. Both beds have fairly low topographic relief. Based on this evidence, it seems reasonable to say that the bottom of the bonebed displays little topographic relief.

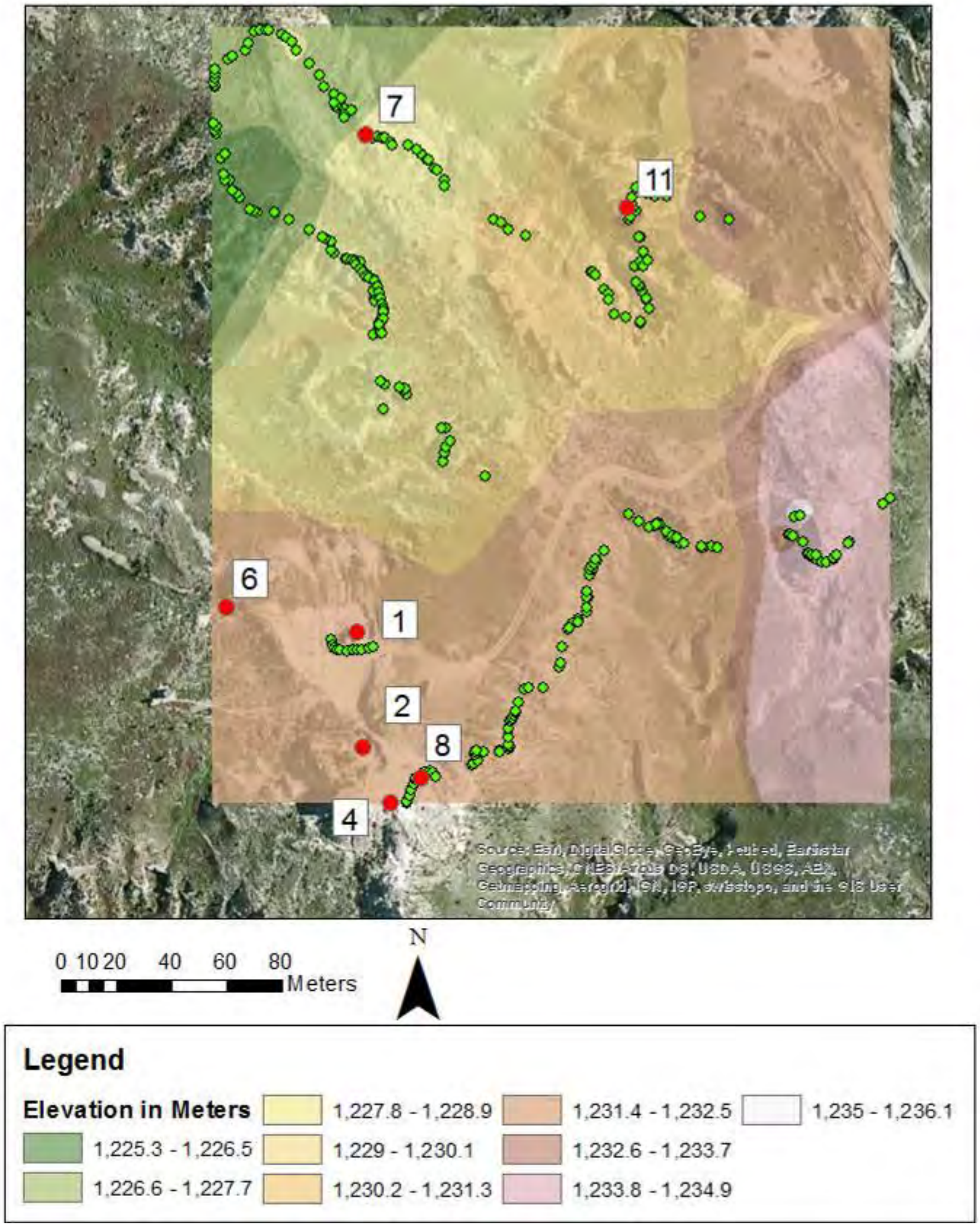

Figure 36 Elevation contour map of the bonebed. Quarries are indicated by red dots. GPS points used to make the IDW are indicated by green dots.

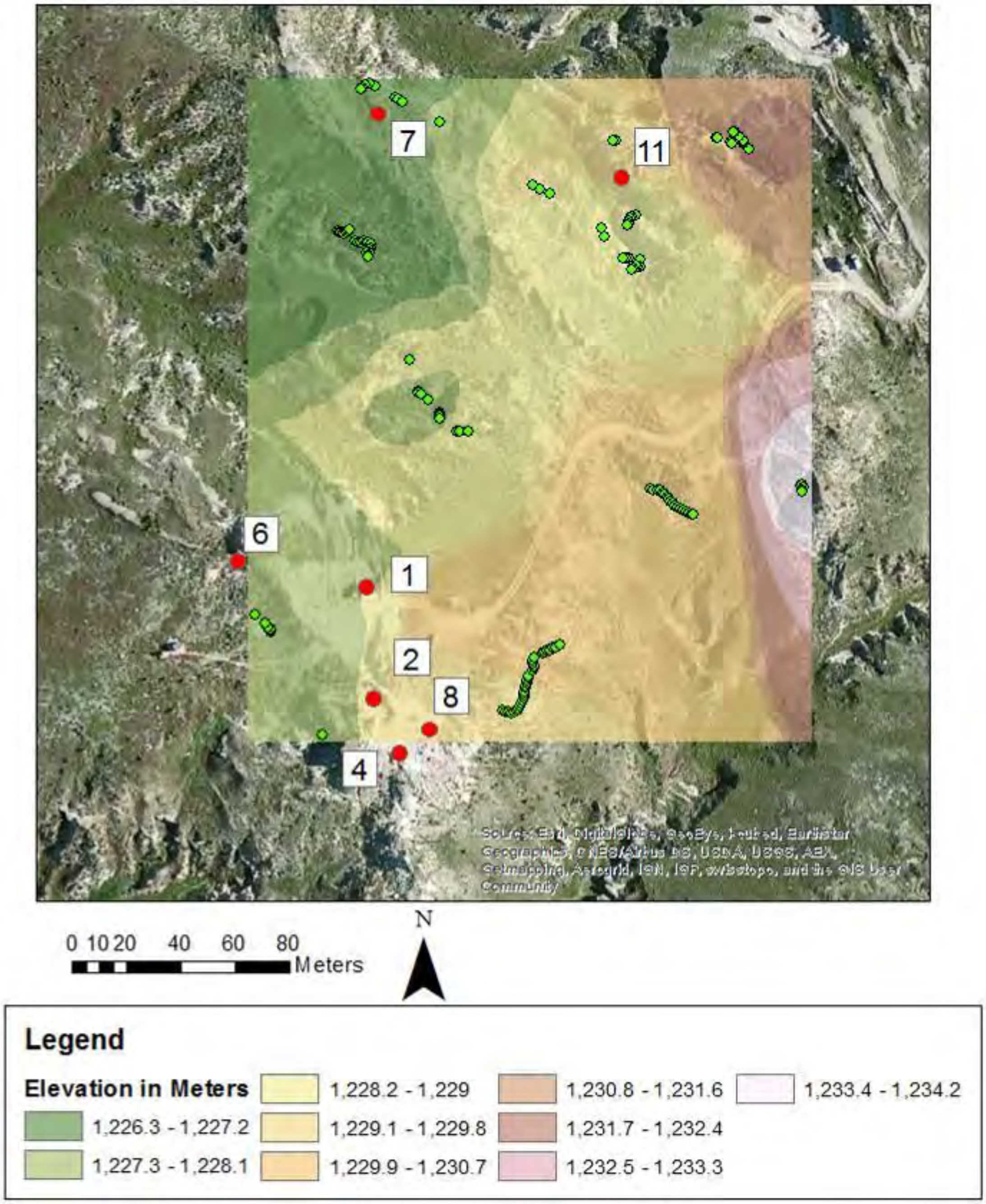

Figure 37 Elevation contour map of red shale (facies 5) layer below the bonebed. Quarries are indicated by red dots. Data points used to create the IDW are green.

CHAPTER FOUR

DISCUSSION

Interpretation of Depositional Environment

Introduction

One of the aims of this research was to determine the paleoenvironment of the study area so that the depositional history of the bonebed could be discussed in the light of the determined paleoenvironment. The tools utilized in determining the depositional environment are the four stratigraphic sections (Figure 22-Figure 24), which helped to define facies present in the study area, and published facies models for environments similar to what might have created the Lance Fm. The facies models are discussed in detail in Chapter One.

Facies Analysis

Interpreting the facies assemblage yields one piece of the puzzle. A single facies alone is not indicative of a specific environment, but the association of individual facies may lead to a unique paleoenvironmental interpretation.

Fossil Assemblages from Mudstone Facies

Most fossils are restricted to mudstone facies (facies 4, 5, and 6) with rare fragments in facies 1. The fossils in the area indicate that the environment was freshwater and not marine, assuming these fossils are in place. *Unio* bivalves are known from terrestrial fluvial, lacustrine, lagoonal, and flood plain environments as well as from marginal marine settings (Fossilworks, 2016). This is probably the best fossil indicator for environment because these bivalves appear to be an autochthonous concentration. Most of the bivalves are found in the closed position indicating they were not dead long enough before burial to allow decaying of soft tissue because the relaxed position of the bivalve is open (Ray, 2008). They are found at one horizon of a muddy bed and are in exceptional condition with the mantle still intact and whole shells present. The bivalves are in a one bivalve-thick, sparse concentration but confined to a single stratigraphic horizon, whereas the bonebed, as a fossil concentration, is a thicker, deposit of disarticulated fossils. To have a thicker or more concentrated deposit indicates preferential accumulation of animal material compared to inorganic sediments. Most fossil material, excluding the bivalves, was likely transported at least some distance from its original habitat. Whether transport was long distance or short, is not determined for the other deposits. The presence of articulated skeletons or at least partially articulated skeletons would give evidence of an accumulation of fossils buried soon after death, but the bonebed contains only a small number of articulated artifacts of two or three bones and no articulated skeletons. This fact, in addition to the lack of disarticulated but associated skeletons, indicates that sufficient time elapsed for disarticulation of skeletons, and also the material was transported a distance sufficient to disassociate the skeletal elements.

The crocodiles, turtles, rays, and fish (pieces of which are found in the main bonebed) are also known from freshwater environments but might be consistent with a marginal marine environment such as a delta, delta distributaries, or estuary. The dinosaur assemblage points to a terrestrial environment, probably low elevation alluvial or marginal marine. A more comprehensive list of taxa present in the study area is given in Appendix D.

Interpretation of Facies 1

Facies 1, planar and cross bedded sandstone, is a clean, fine-grained sandstone occasionally housing mudclasts and bone fragments. Facies 1 sandstone beds show varying sedimentary structures produced by traction transport processes. Longer vertical successions of facies 1 sediment show structures indicative of waning flow conditions (i.e. changes in sedimentary structures from planar bedding to cross bedding to ripple cross lamination up section). Vertical grain size variations are not evident within these successions. This may be an artifact of the limited variety of grain sizes available. The convex up structural features of Figure 13 suggest channel margin scouring, and the outcrop of facies 1 sandstone directly overlying the bonebed shows evidence of erosional scouring by channel cutting processes (see Figure 15).

Large clasts in the sandstones of facies 1, when they appear, are likely due to undercutting of muddy banks and subsequent bank collapse into a channel. Some small mudclasts could be a result of erosion of larger mudclasts or traction transport and aggregation of tiny particles which pick up mud from the channel floor. Sometimes mudclasts are entrained in the flow for a while allowing the edges of the clasts to become rounded. Some mudclasts show lamination, an indication of primary structure in the original mud layer. The mudclasts deposited and buried in the channel allowed the lamination to be preserved while the original remaining mudstone layer was bioturbated or diagenetically altered to the point of becoming mostly structureless (see discussion of facies 4 below).

The structures and motifs of facies 1 sandstone are compatible with channel fill sandstones. Planar bedding might indicate the top of a transverse bar form or a very low angle point bar. Mudclasts make up the channel lag deposits in some locations and are found at the base of cross bed sets. Most cross beds show paleocurrent directions comparable to directions measured on ripples suggesting they are within channel bedforms instead of point bar deposits. They are either avalanche surfaces of longitudinal bars or forward migrating, lobate transverse bars. Ripple cross lamination might form on the tops of these bars or on the channel floor during low energy flow conditions.

Though channel fill seems a good interpretation of this facies, channel architectural elements are scarce to absent in the study area. Lens-shaped channel fills are either not present or obscured by modern vegetation.

Interpretation of Facies 2

Facies 2, interlaminated mudstone and sandstone, is a heterolithic facies indicating fluctuation in flow velocity or energy. The alternating deposition of clay and sand is reminiscent of flaser to wavy bedding but may not be representative of implied tidal influence that the term flaser carries. This facies does, however, indicate periods of slack water.

It is possible facies 2 indicates tidally forced fluctuation in flow conditions, however, the alternation between sand and mud does not give the appearance of rhythmic fluctuations or cyclicity as might be expected for a tidally influenced facies. Other processes may complicate an otherwise regular cycle of sedimentation enforced by tidal currents.

Another possibility for this facies is that it represents the flood plain deposits of an alluvial fluvial system. Both levee and crevasse splay deposits have heterolithic bedded units due to the fluctuation between flowing water during flooding and standing water or arid conditions between flooding events. Some of the beds of facies 2 show a mottled texture that may be partially due to bioturbation, which would be expected to occur between flooding events in the flood plain deposits of a fluvial environment. However, facies 2 outcrops generally show preservation of much, if not all, of the primary structures indicating that bioturbation plays only a minor role. In addition, plant material is not present in facies 2. Deposits proximal to fluvial environments should contain plant material if enough time elapses between flooding events. Thus, if facies 2 represents natural levees or distal crevasse splay deposits, not much time elapsed between flooding events.

Facies 2 represents fairly rapid deposition of both sand and mud indicating highly saturated water that deposits mud fairly quickly as soon as slack water conditions occur. Rapid deposition is indicated by the often complete lack of bioturbation, and saturated water is indicated because mud drapes over sand occur at such small scale as the ripple. These conditions might occur in either proximal flood plains of alluvial fluvial channels where crevassing produces rapid deposition and fluctuating conditions or in distributary channels of deltas where deposition often occurs rapidly and tidal influence produces fluctuations in flow conditions.

Interpretation of Facies 3

Facies 3, climbing ripple sandstone, is the least abundant of the facies identified. It represents periods of rapid sedimentation. This facies is interpreted as proximal crevasse splay deposits of some kind of channel. It often appears above mudstones indicating deposition on overbank fines, which is consistent with crevasse splays.

Interpretation of Facies 4

Facies 4, brown-grey mudstone, makes up the bulk of the fines in the stratigraphic sections. Concretions, iron stained lamination, and macerated plant material characterize this facies. Delta front deposits often contain abundant macerated plant material and siderite nodules (Bhattacharya, 2006).This facies may fit well within a delta interpretation, but it could also represent channel plugs, however, there is no reason to suspect this because no channel architectural elements indicate facies 4 was deposited within abandoned channels.

One facies 4 bed contains a concentration of bivalves at its base which points to an interchannel lagoon or embayment depositional environment. This facies could be produced in either a meandering stream flood plain or deltaic interdistributary environment. The absence of strictly marine fossils indicates that, if the environment was deltaic, this location was a more distal to shore location.

Interpretation of Facies 5

Facies 5, red shale, warrants a different classification from facies 4 due to its appearance and weathering. Red shale weathers as a papery or blocky shale. It often contains more organic material in the form of macerated plants and occasional tiny, well-preserved leaves. It very rarely contains root traces. Red shale often underlies mudstone of facies 4 with a thin, prevalent but discontinuous coal seam ~0.5cm thick forming the contact between facies. The thin coal above this facies indicates the growth of plant material at this horizon, or that plant material was washed in at this horizon.

This facies could represent a paleosol which was subaerially exposed for long enough to accumulate plant material in growing position. The papery weathering of some of these units could be a result of higher concentrations of plant matter than facies 4, however, facies 5 contains, in general, less clay than facies 4. Interdistributary environments of delta plains are noted to contain fine-grained facies capped by coals or paleosols (Dalrymple and James, 2010). However, this facies is not incompatible with a more alluvial meandering stream environment.

Interpretation of Facies 6

Facies 6, bonebed facies, will be considered in more depth later, but it can be noted here that the bonebed represents a unique mass transport facies.

Interpretation of Paleoenvironment

The facies assemblage is compatible with either a meandering fluvial environment or delta plain distributary environment. The absence of coarse material and the abundance of fine material precludes interpretation as a braided stream system. The sandstone facies indicates that channel fill deposition was more prominent than bar accretion and migration. The setting was highly aggradational. The fossil assemblage is compatible with either terrestrial alluvial or marginal marine environments. Channel cutting and channel lens formation are not a major feature of the environment. This fact gives credence to the deltaic distributary hypothesis since channels can form from coalescing of mouth bars instead of by channel cutting. However, several places indicate scouring and lag deposits. The facies are characterized by low levels of bioturbation also pointing to a fast sedimentation rate. Soft sediment deformation is present in small scale and large scale. This might be due to seismic activity, or, if this is a deltaic environment, to slumping as a result of over pressuring unconsolidated, rapidly deposited sediment that may also be seismically triggered or induced (Weeks and Chadwick, 2012).

Either a delta plain or alluvial fluvial environment of a coastal plain fit very well in the historical geological setting of the Powder River Basin of the Late Cretaceous. As the Seaway regressed, the landscape transitioned from marine to terrestrial. The Lance Fm was deposited during this transitional period. Flow directions of the Lance Fm indicate drainage into the marine basin toward the east.

Depositional Model for Bonebed

Perhaps the most obvious and intriguing aspect of the bonebed is the number of large herbivorous dinosaurs preserved in the layer. Based on the number of curated left surangulars, a minimum number of individuals of *Edmontosaurus*, is 28 (Siviero, 2016), and the bonebed is minimally sampled to date. The question immediately arises, "How did these bones get here?" A discussion of the evidence presented in Chapter Three will hopefully yield a satisfactory answer to this question.

Elements excavated from the seven quarries considered in this study number ~13,000 bones, fragments, teeth, and tendons measuring more than 10cm. (Tendons smaller than 10cm are discarded from the quarry.) Bones are almost exclusively from adult *Edmontosaurus annectens* while teeth from scavengers such as *Tyrannosaurus rex*, *Troodon*, *Dromaeosaurus*, and *Nanotyrannus* are common in the bonebed (Chadwick, 2016). The assemblage of *Edmontosaurus* bones are primarily sub adult to adult – very few bones are from juvenile *Edmontosausus* – however, this data has not been quantified and is beyond the scope of this project. Bones, teeth, and scutes appear in pristine condition; bones show minimal surface abrasion, rounding, or weathering (Chadwick et al., 2016). However, many ribs and spinal processes are broken possibly from trampling, and caudal vertebrae and ribs have occasional tooth marks from predation or aggression. The bones display similar weathering characteristics across the bonebed as well as across skeletal types indicating that this is an event concentration.

Also of interest, is that teeth and bones of the skull and mandible are found in the same deposit along with vertebrae, ribs, and sacra. These two groups of bones are in different Voorhies categories (Voorhies, 1969). The first set of bones are thought to form a lag-type deposit if transported and deposited in stream flow. The second group is less dense and typically are transported easily or perhaps even float.

Skeletal elements from the entire animal are distributed in the deposit such that taking only a portion off the top of the bonebed would not yield all the bones of the animal. Theoretically, to construct a dinosaur from the bones in the bonebed, the whole vertical depth of the bed would need to be excavated. This offers a unique look into the mode of deposition in the quarry. It indicates that the deposit represents a single event.

From the previous discussion of facies and paleoenvironment, the model for bonebed deposition must fit within the broad picture of a terrestrial deltaic or coastal plain fluvial environment, and, based on the distribution of bones in the quarry, it appears obvious that the deposit represents a single event. The bones are distributed with the largest bones at the base of the deposit and successively smaller bones are found higher in the bed. If this were a multiple event bed, it is expected that bones of several animals might be found in the top portion of the bed and then the bones of several more animals would be found below that, but instead, the bones that comprise all the bones of a dinosaur skeleton are distributed throughout the vertical depth of the quarry.

Also, bones are matrix supported which indicates that some mass transport mechanism deposited these bones. Two likely candidates for mass transport are debris flow and hyperconcentrated flow.

The bonebed rests on mudstone or heterolithic mudstone and sandstone (facies 2 and 4 respectively). These are flood plain or interdistributary facies. The lateral transition from facies 2 to facies 4 might indicate distance from the channel. Heterolithic, facies 2, deposits could be the medial portion of a crevasse splay which transitions distally to mudstone, facies 4. The sediments directly above the bonebed are facies 1, channel sandstone. Directly on top of the bonebed is a lag-like deposit of mudclasts and bone fragments. It might be suggested that the bonebed represents a lag deposit, but instead, the lag deposit sits directly on top of the bonebed, and a lag deposit would not be expected to contain so much mud.

It is difficult to determine whether the base of the bonebed is erosional or not. It does seem to have some very shallow divots or scours, but these may be a result of tool marking along the base of the flow. Debris flows typically don't show erosional bases simply because they are non-turbulent flows. Hyperconcentrated flows are more turbulent and can cause erosion along the base of the flow. The underlying sediment changes lithology from one quarry to the next, but within a quarry, the base of the bonebed appears fairly flat. These transitions in lithology have not yet been excavated and studied.

Hyperconcentrated flows are expected to deposit clasts differentially based on size. This means that a hyperconcentrated deposit should be clast supported. The flow should not freeze *en-masse* with bones suspended in the matrix. However, a debris flow acts as a one phase flow and can freeze with clasts suspended in the matrix. This points to a debris flow mechanism of deposition. But debris flows typically require steep slopes to initiate and continue movement. Based on paleotopographic literature review, there were no uplifts in the vicinity of the study area. Perhaps an erosional escarpment could be invoked that would provide the relief necessary for initiation of a debris flow.

Other lines of evidence point to a debris flow process of deposition. One evidence is that the bones do not show preferential orientation. Though some debris flows can induce orientation in elongated clasts, it is not always present or may be poorly preserved. However, the two phase flow of a hyperconcentrated flow often induces preferred orientation in elongated clasts. Another evidence is that debris flows can entrain light weight or low density clasts in the same flow as heavy or high density clasts. Objects like wood and light weight, spongy bone might float in a hyperconcentrated flow and would not be preserved in the deposit or at least not below the surface of the deposit, but in the bonebed we have found many fragments of wood, seeds, vertebrae, and ribs.

Figure 38 Large wood fragment found within the bonebed.

There are a few pieces of evidence that point away from a debris flow interpretation. For instance, debris flows typically show a uniform distribution of grain sizes. The bonebed is made up of a very fine matrix of silt and clay with large bone clasts many orders of magnitude larger than the matrix particles. There are, of course, very small (millimeter-sized) teeth and bones also present as clasts in the bonebed. But sediment of intermediate size, fine-medium sand which is abundant in the surrounding units, is absent in the bonebed. Another more glaring evidence against a debris flow is that the bones are arranged in a normally graded distribution. Debris flows typically show either no grading or inverse grading. However, hyperconcentrated flows often show normal grading, but their depositional mechanisms shouldn't produce a bed with a matrix supported framework.

The model proposed for the deposition of the bonebed is as follows, and Figure 39 displays a diagram of the proposed depositional setting of the Lance Formation. Large, local accumulations of dinosaur bodies rested subaerially for a time during which the flesh decayed, but before sun bleaching and surface weathering could take place, the bones were entrained in a mud slurry which could be classified as a pseudoplastic debris flow. Likely this slurry was initiated by an earthquake which caused liquefaction and mobilization of fluid-rich mud of a local escarpment left from stream erosion. The clay rich matrix was diluted with water enough to make a viscous style of flow. Yield strength is relatively low providing enough lift for smaller bones but inadequate for the largest bones. The viscous style of flow kept the bones from making many collisions, thus keeping the bones in pristine condition during transport. Though the flow moved as a viscous, dominantly one phase flow, the fine-grained matrix and relatively low concentration of clasts failed to provide the inertial forces to cause kinematic sieving to occur. Thus the large bones were allowed to migrate down to the bottom of the flow while smaller bones remained higher in the flow. The slurry traveled over the level terrain of the interchannel flood plain until liquefaction ceased and frictional forces brought the slurry to rest, freezing it mid flow with many bones suspended in the matrix. Subsequent aggradation and migration of streams eroded the very top of the bonebed creating a flat upper surface to the deposit. Some of the eroded material was consolidated and left as a lag on top of the bonebed.

Observations of a similar deposit have been published by Shultz for the Cutler Fm of western Colorado (1984). He describes a normally graded, matrix supported diamictite. The bed is less than a meter in thickness with a fine-grained matrix and coarse grained clasts, most of which are not larger than cobbles. The interpretation for this bed is a pseudoplastic debris flow which has relatively low shear strength due to high water content, thus the matrix supports only the smaller clasts which the others being moved during periods of high velocity flow in which turbulence provides the means of movement.

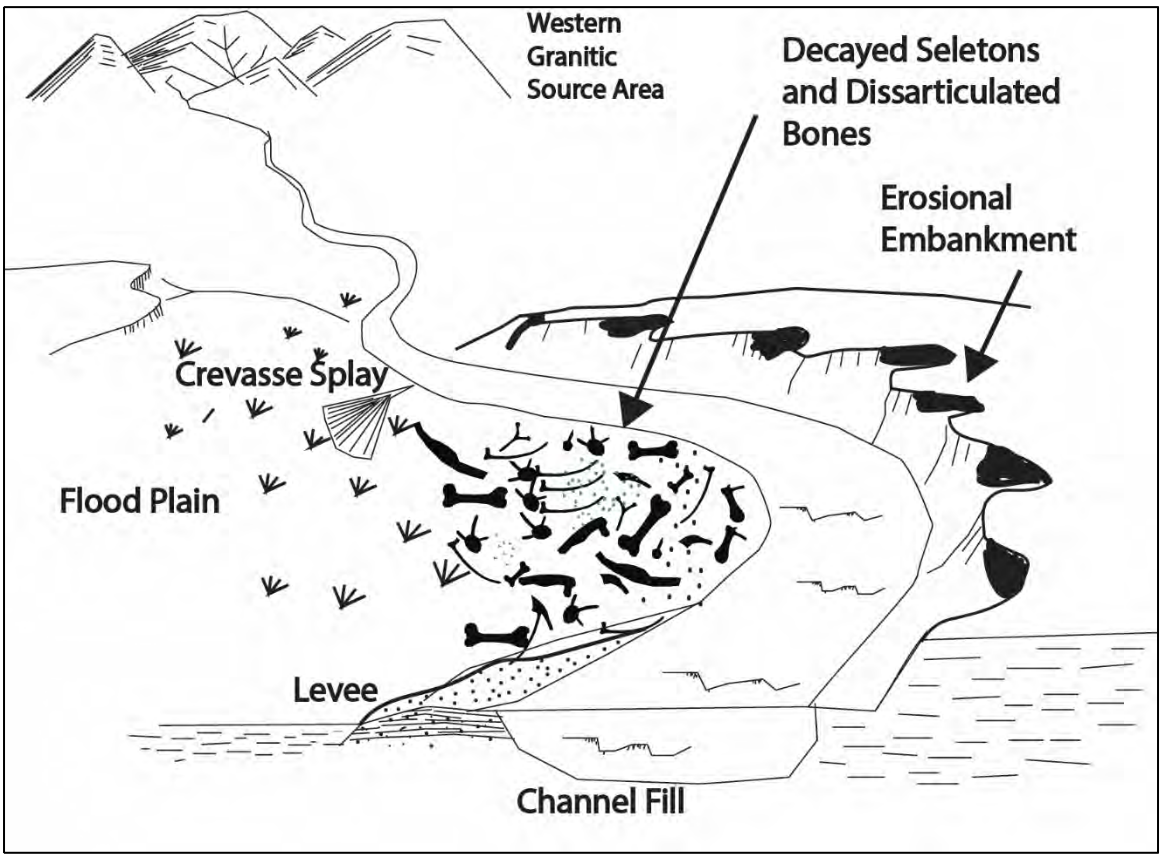

Figure 39 Depositional model of the Lancian landscape prior to proposed mobilization and final deposition of dinosaur bones.

The bonebed on the Hanson Ranch displays many of the same characteristics of Shultz's graded matrix-supported diamictite. The bonebed provides further support for the flow mechanism and rheological properties Shultz proposed.

CHAPTER FIVE

CONCLUSIONS

The goal of this project was to determine a depositional model for the main bonebed at the Hanson Research Station. To achieve this goal, two main avenues of research were pursued: the paleoenvironment of the area and the specific depositional indicators of the bonebed itself.

In light of the geologic setting, it was expected that the depositional environment would show indications of a transitional environment between the marine setting of the Western Interior Seaway and the terrestrial environment that followed the regression of the Seaway. The sedimentological evidence was not extremely conclusive. Facies analysis showed that either an alluvial fluvial environment or a marginal marine deltaic distributary environment is compatible with the evidence. However, several environments, which were cited as possibilities for the Lance, have been ruled out. These include marine and braided stream environments. The former is ruled out because of the lack of marine fossils and apparent subaerial exposure of sediments for the growth of plants. The latter is ruled out based on the absence of coarse-grained material and presence of abundant fine material indicating overbank deposits. Braided streams are well known for their general lack of fine material.

With these paleoenvironmental limits in mind, the deposition of the bonebed was considered. The bonebed’s characteristics are indicative of mass transport processes. Mass transport deposits having a structureless, fine-grained matrix with large clasts suspended by the matrix indicates a debris flow-type of deposition, however, the tectonic setting yields no topographic relief which might have induced the sediment gravity flow. Hypothesizing a local erosional relief solves this problem for the moment until further investigation can be done. The presence of multiple layers showing large scale deformation indicates the area was plagued by earthquakes, which may have helped to trigger a sediment gravity flow on a shallow slope that otherwise might not have initiated a depositional event.

This area is still a rich research ground and can support many more projects including supplementary projects to this thesis.

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APPENDIX A

LIST OF FACIES

Facies 1	Traction Sandstone
Facies 2	Heterolithic Mudstone and Sandstone
Facies 3	Climbing Ripple Sandstone
Facies 4	Green/Grey Mudstone
Facies 5	Red Shale
Facies 6	Bonebed

APPENDIX B

LIST OF QUARRIES

Quarry 1	North Quarry
Quarry 2	South Quarry
Quarry 4	Teague Quarry
Quarry 6	West Quarry
Quarry 7	Neufeld Quarry
Quarry 8	Southeast Quarry
Quarry 11	TOE Quarry

APPENDIX C

GRAIN SIZE ANALYSIS

The following graphs are grain size plots for South Quarry. Each sample (a-i) were taken from one vertical section of the quarry. Sample *a* was taken at the base of the quarry followed by sample *b* taken 10 cm above sample *a* and so on till sample *i* which was taken at the top of the quarry.

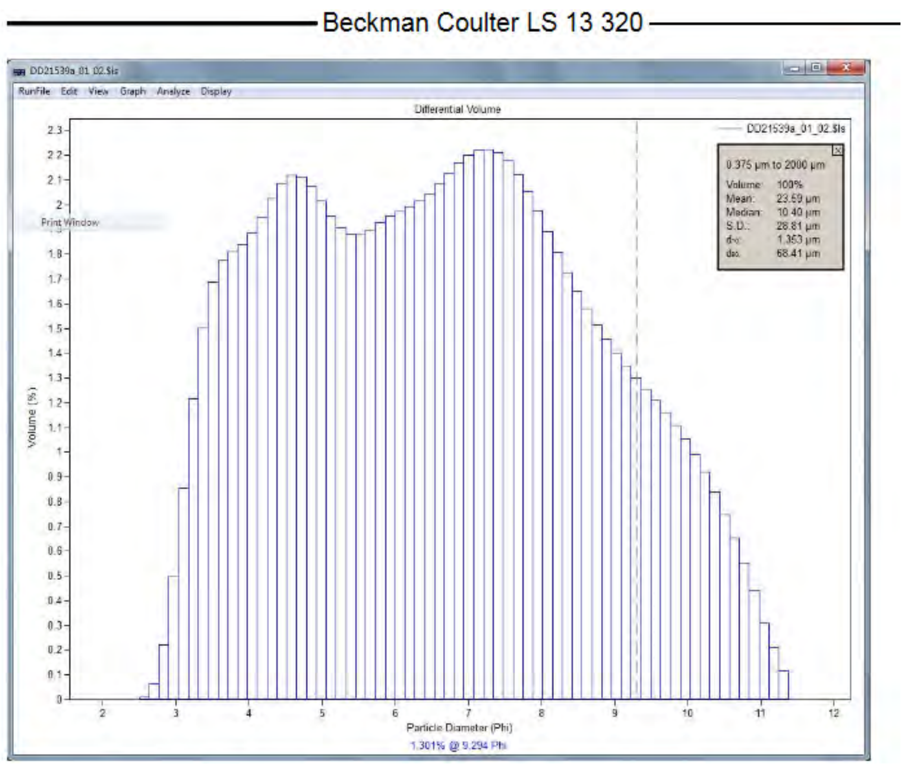

Figure 40 Sample a

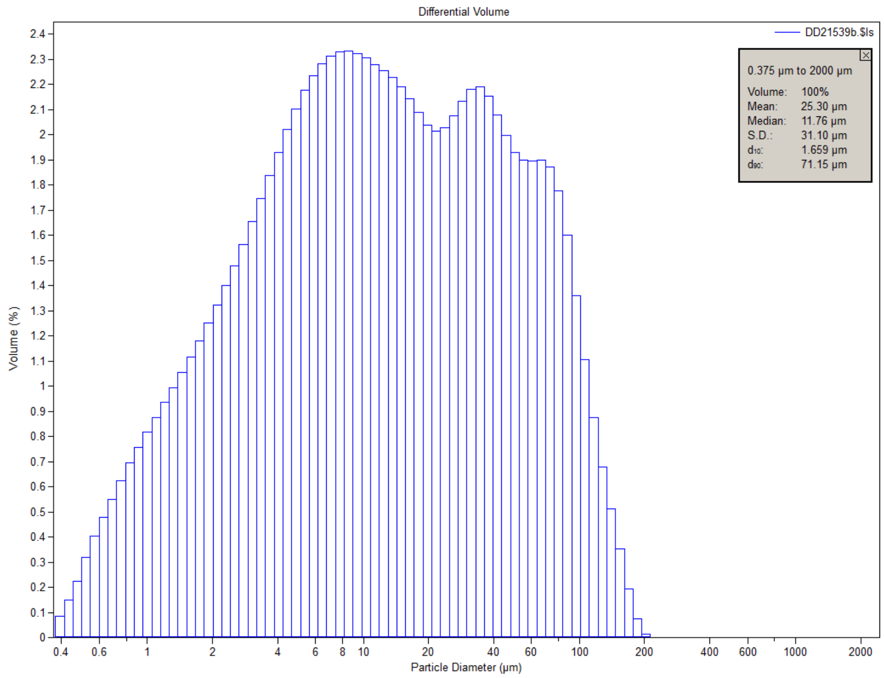

Figure 41 Sample b

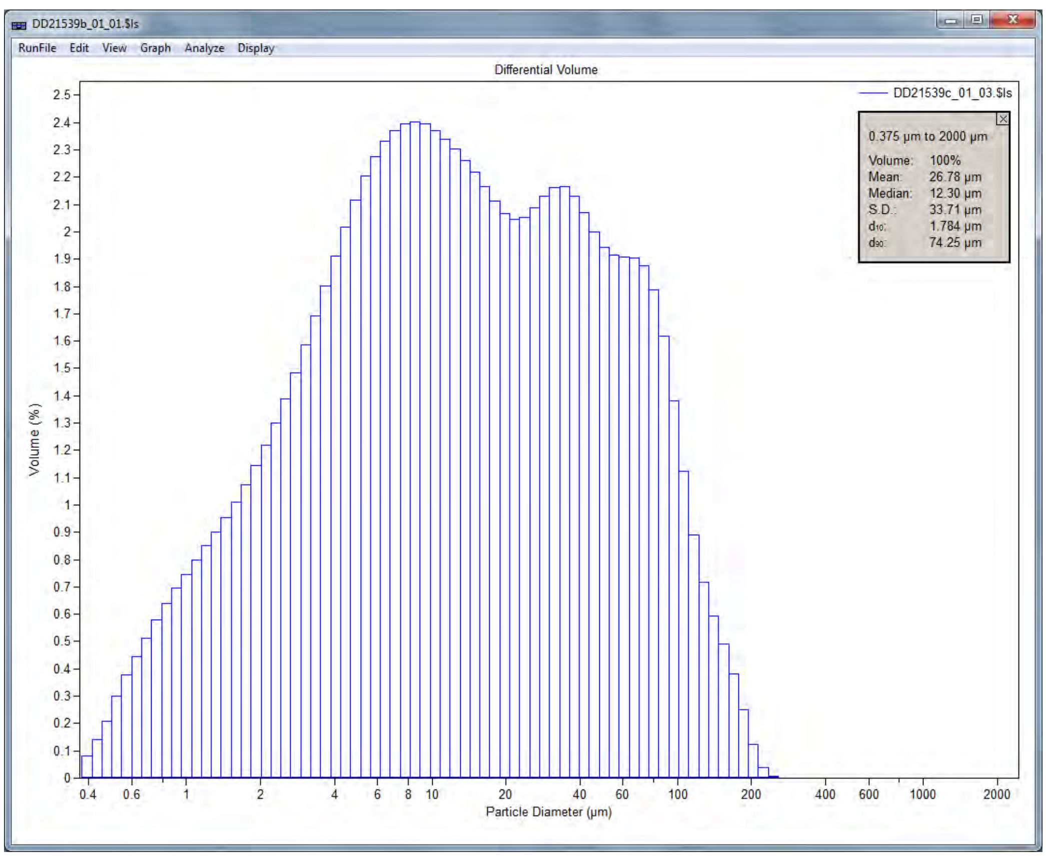

Figure 42 Sample c

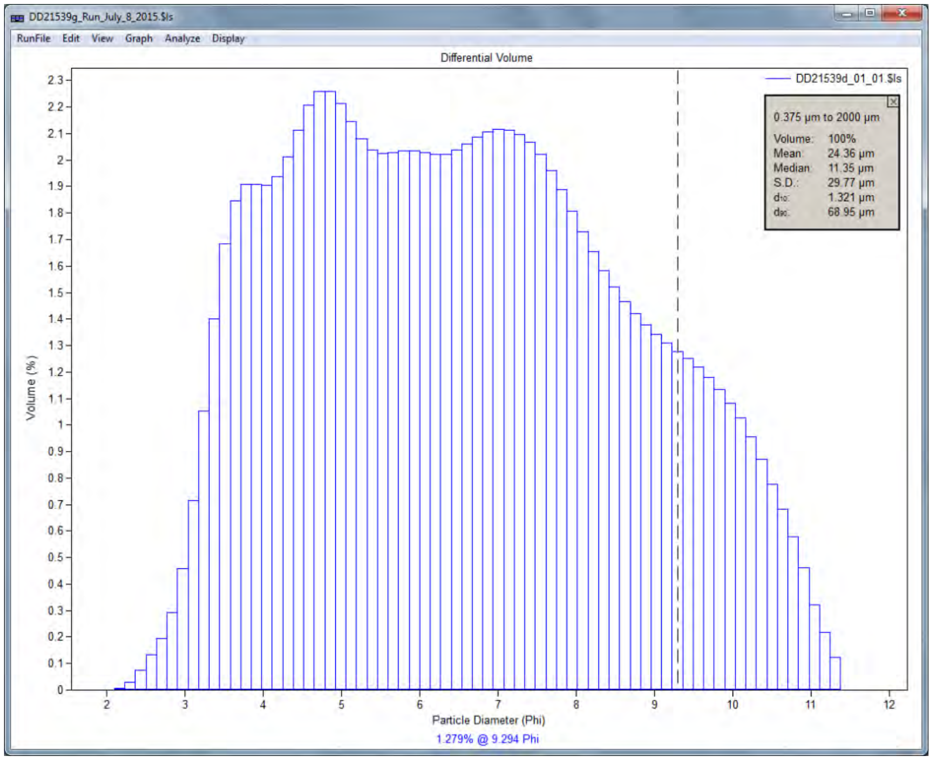

Figure 43 Sample d

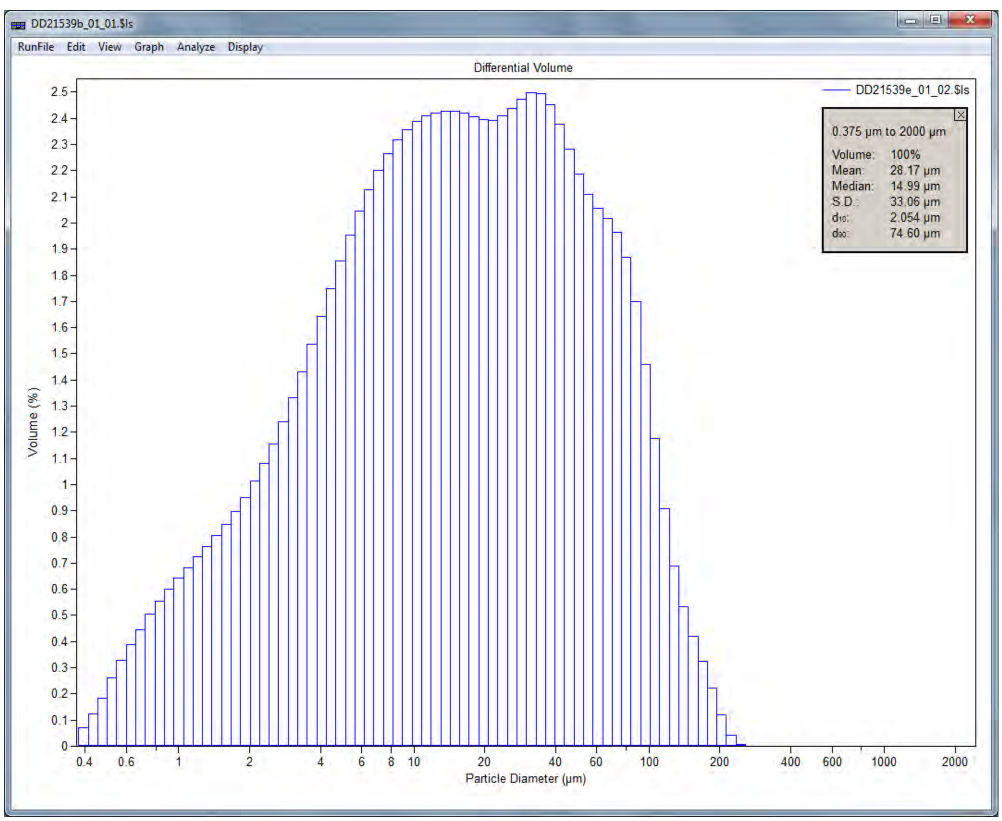

Figure 44 Sample e

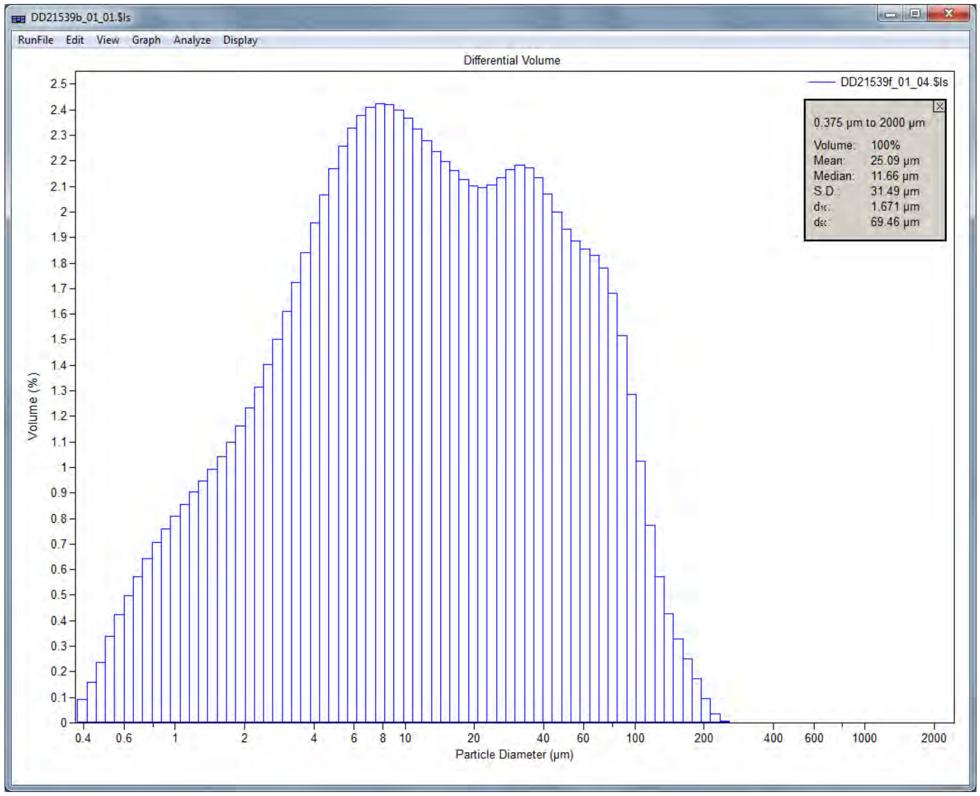

Figure 45 Sample f

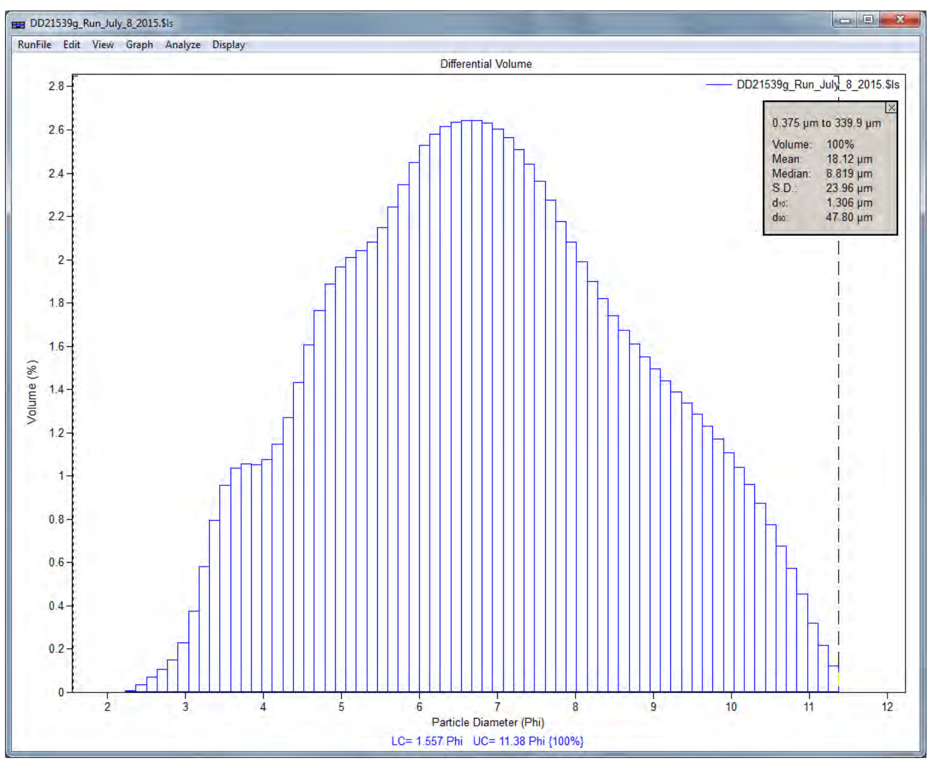

Figure 46 Sample g

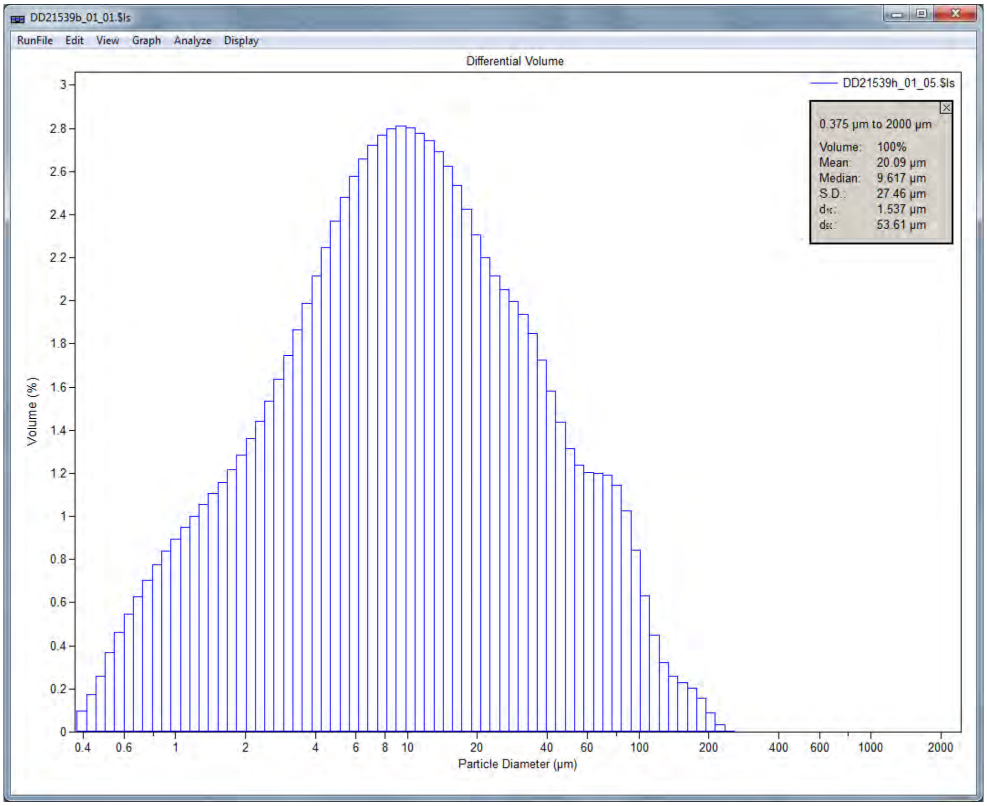

Figure 47 Sample h

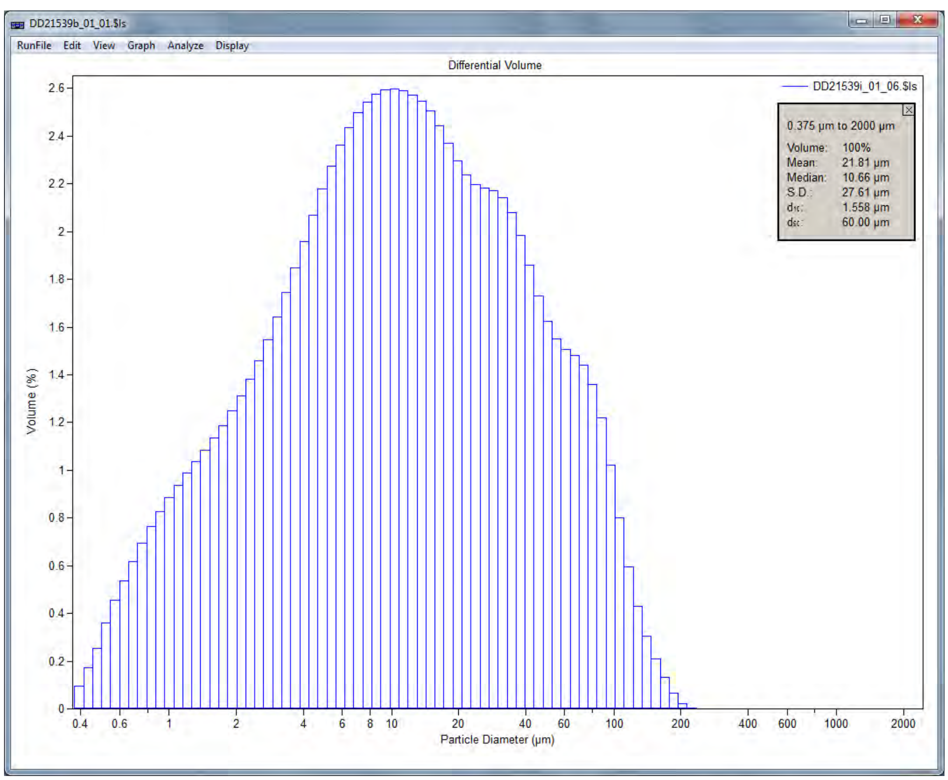

Figure 48 Sample i

APPENDIX D

TAXONOMIC ASSEMBLAGE

Taxonomic information presented in this appendix was obtained from Southwestern Adventist University's online fossil museum (Chadwick et al., 2016) and from personal communication with Arthur Chadwick (Chadwick, 2016). Information concerning weathering status of fossil specimens can also be found on the online fossil museum.

The most abundant fossils in the study area are from hadrosaurids (*Edmontosaurus*), duckbilled dinosaurs. These are ~12m long herbivorous archosaurs. The quarries also yield teeth, bones, and fragments from other archosaur genera such as *Tyrannosaurus, Triceratops, Pachycephalosaurus, Dromaeosaurus, Nanotyrannus,* and *Nodosaurus.* Non-archosaur taxa include *Rhombodus* (stingray, teeth found), Rajiformed (ray, teeth found), *Brachychampsa* (crocodilian; teeth, skull fragments, and other small bones found), Actinopterygii (ray-finned fish, teeth and scales found), *Myledaphus* (guitar fish, teeth found), Testudines (plastron and carapace fragments and small bones), and several genera of Chondrichthyes (teeth found). Several small mammalian teeth have also been recovered from the bonebed and surrounding anthills. In addition to the animal fossil remains, fossil plant material is also abundant. Plant material, in the form of coal, is present in small pockets in the bonebed, as well as, in small veins in surrounding mudstones. Leaf impressions and seeds have been recovered from the quarries and surrounding units as well. Fragments of fossil wood are present in mudstones and sandstones in the area.

Freshwater bivalves (family Unionidae and likely genus *Unio*) have been found in the quarries as well as in the surrounding layers. The bottom of a mudstone bed approximately 1.5m below the bonebed houses a small concentration of these bivalves in good condition (Figure 49). Complete shells with mantle material still intact appear as a sparse, one bivalve thick interval just above a red shale (facies 5) layer.

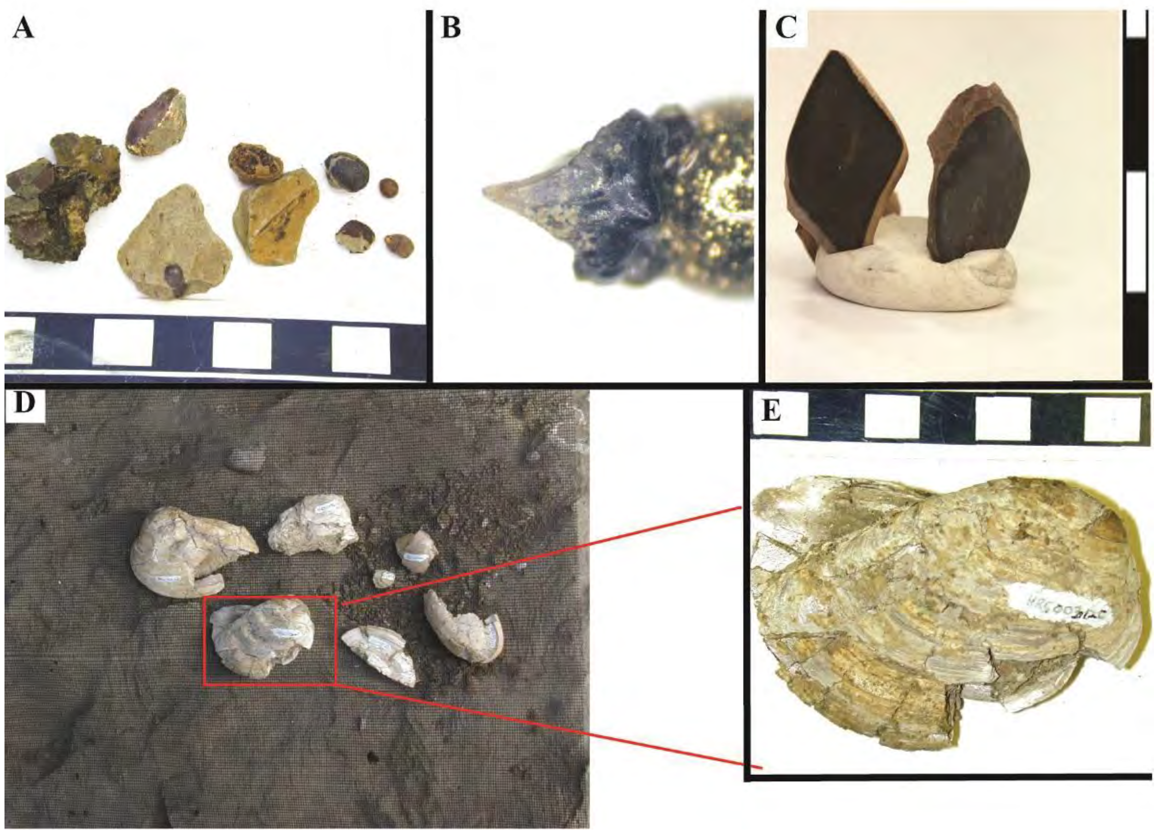

Figure 49 Fossils excavated from the bonebed and surrounding layers show good preservation. A shows several seeds from the bonebed. B shows a tooth from a cartilagenous fish (shiney gold pin head for scale). C shows 2 gar fish scales. D and E show several *Unio* bivalves.

APPENDIX E

MAPPED LITHOLOGIC UNITS

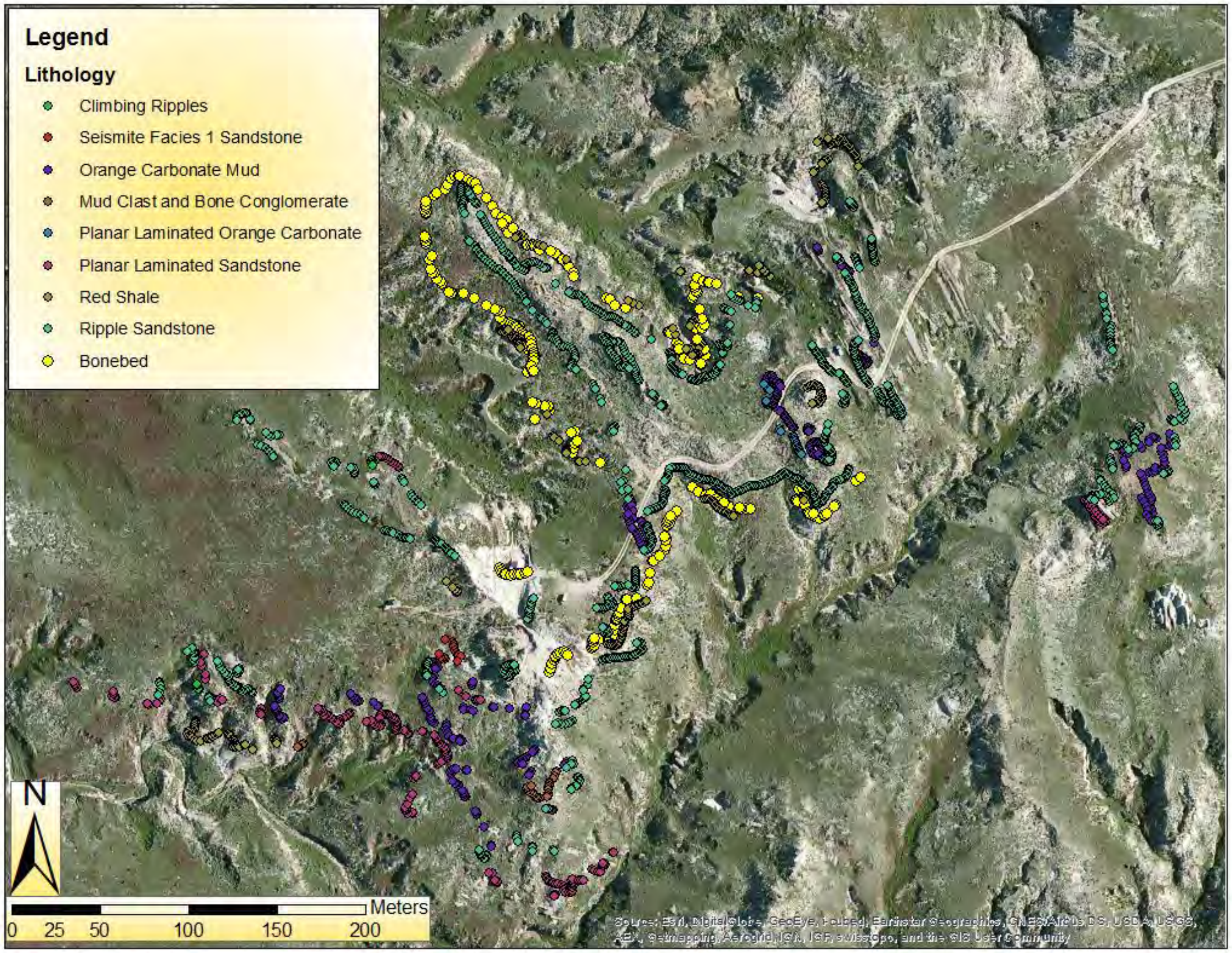

Figure 50 Map of GPS data points taken on prominent lithologic units within the study area.

APPENDIX F

ADDITIONAL PALEOCURRENT DATA

Figure 51 shows paleocurrent data taken from large cross beds located roughly at UTM 13N 544590.28m E 4816468.879m N.

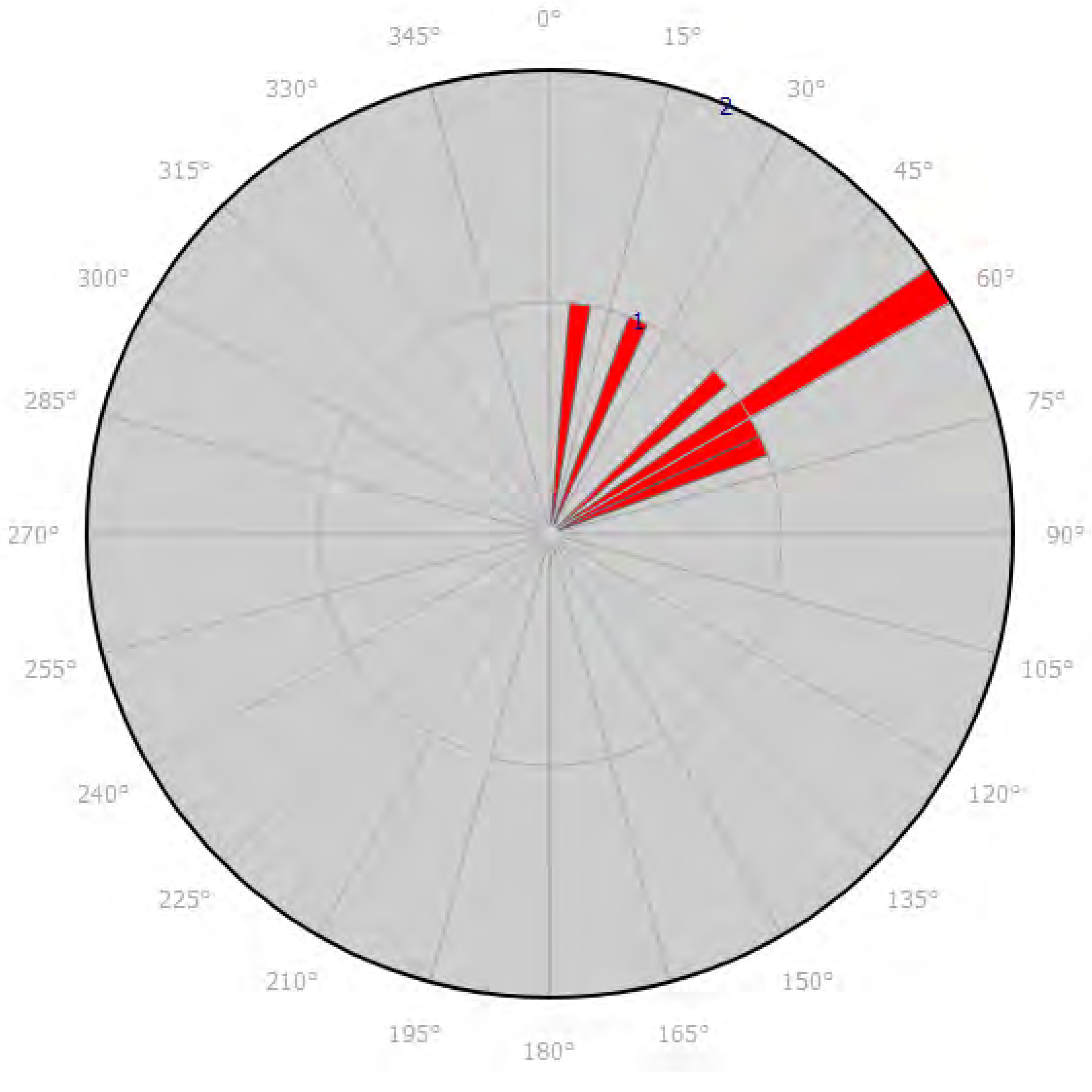

Figure 51 Paleocurrent data from large cross beds located outside the study area show a mostly unidirectional current but roughly perpendicular to other paleocurrent data presented. N=7

APPENDIX G

BURROWS

Surrounding sediments exhibit minimal to no bioturbation. However, one sandstone unit contains several burrow structures (Figure 52). Due to the difficulty in tracing layers in the Lance Formation, the vertical and temporal relationship between this unit and the bonebed has not been determined. However, it does crop out below the elevation of the bonebed and could represent a penecontemporaneous event with the deposition of the bonebed.

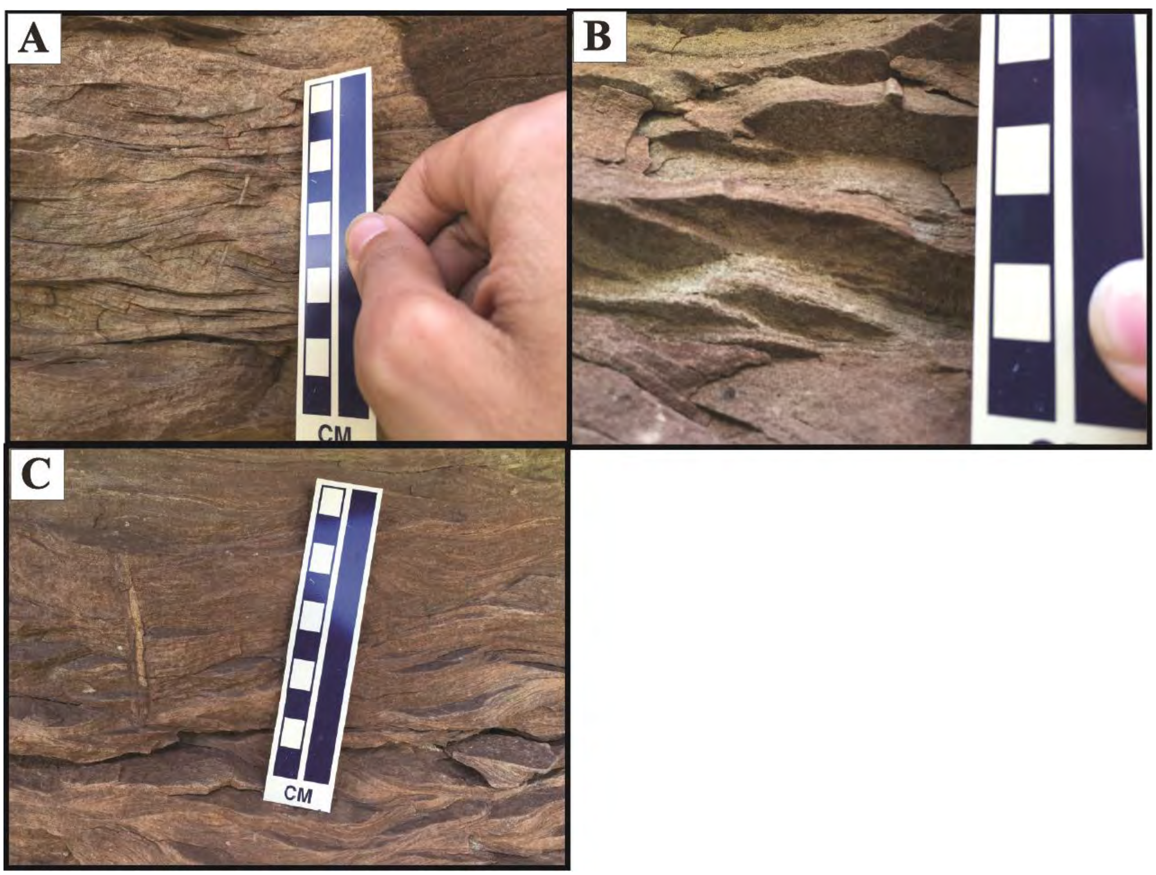

Figure 52 Photo plate of rare burrows. Stratigraphic position is uncertain, but position is lower in elevation than main bonebed. A-C were taken in the same ripple cross laminated sandstone.

APPENDIX H

EXAMPLE DINOSAUR BONES

The state or conditions of fossil elements is beyond the scope of this thesis, but Figure 53 shows four example bones from the main bonebed that, at first glance, appear in good preservation condition.

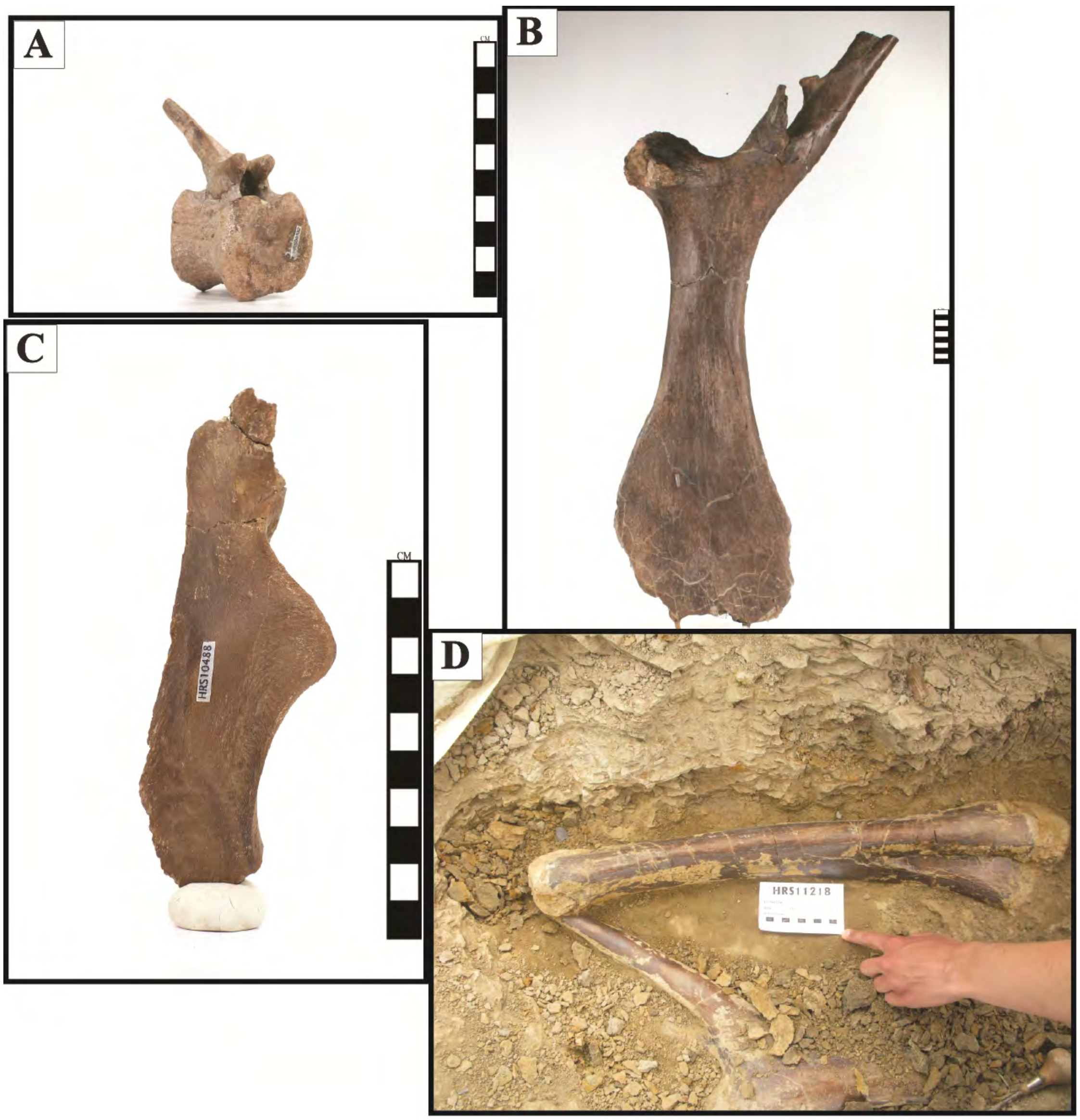

Figure 53 Example bones found in the main quarries. Image A: caudal vertebra; Image B: pubis; Image C: surangular; Image D: ulna. All scales in cm. All bones from *Edmontosaurus.*