

GEOLOGY, TAPHONOMY, AND PALEOECOLOGY OF A UNIQUE UPPER
CRETACEOUS BONEBED NEAR THE CRETACEOUS-TERTIARY BOUNDARY IN
SOUTH DAKOTA

By

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ABSTRACT

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This research examines a Konzentrat-Lagerstätte, the Bone Butte site, in the Upper Cretaceous Hell Creek Formation of South Dakota. Field data from a diverse multispecific bonebed in Harding County, South Dakota, including sedimentologic, stratigraphic, taphonomic, floral, and faunal observations, are used to reconstruct the depositional history, depositional environment, and paleoecology of the site, while comparing it to other sites within the Hell Creek Formation.

Taphonomic analyses of bone completeness, abrasion, and sorting reveal the presence of autochthonous and allochthonous faunas, and demonstrate the heterogeneity of the Hell Creek dinosaurian fauna. Particularly noteworthy components of the Bone Butte ecology are undescribed insect and ornithurine bird faunas. Also, a rare instance of dinosaur predation is evidenced by theropod tooth marks and an embedded tooth found in two fused proximal hadrosaur vertebrae.

The precise temporal resolution of the site, less than 7 years as indicated by sedimentologic, paleobotanical, and vertebrate ontogenetic data, provides the basis of a reconstruction of the local climate and ecology. Finely preserved clay-pebble laminae show evidence of annual rainfall magnitude, and pyroclastic-enriched laminae may indicate a chronology of significant local forest fires. The optimum temperature requirements for plants at Bone Butte, for example the gymnosperm *Taxodium*, give a rough estimation of annual temperature variation. Thousands of collected vertebrate specimens provide a means of tracking ontogenetic ratios from hatchlings to adulthood in the local stratigraphic column. In some of the

dinosaur specimens, the presence of medullary bone allowed estimation of their seasonal nesting habits.

Laboratory experiments and examination of modern fluvial analogs augmented the analysis of data from the Bone Butte site. A reconstruction of the Bone Butte river system and site-forming events are presented in this work. In particular, the presence of marine organisms at Bone Butte indicates the river system's close proximity to the paleoshoreline.

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CHAPTER 1

INTRODUCTION

The Bone Butte Site is an area enriched by a diverse multispecific bonebed in Upper Cretaceous strata of Harding County, South Dakota. The study area contains Upper Hell Creek strata close to the Cretaceous-Tertiary boundary (Rothrock, 1937; Cox, 1962; Bjork, 1964; Philip Bjork, pers. comm.) and is composed of sandstones, siltstones, and clay-pebble conglomerates overlying siltstone and mudstone floodplain deposits, formed during an active fluvial episode (Fig. 1.1). Depositional settings comprising crevasse-splays, an oxbow lake, and a stream channel, are immediately adjacent to each other at Bone Butte and provide an opportunity to compare the discrete preservational characteristics of different depositional settings. Furthermore, the stream deposits at Bone Butte, as indicated by vertebrate ontogenetic and floral evidence, preserve a finely detailed chronology of less than three years of deposition. The extraordinary time resolution of Bone Butte, coupled with the profusion of diverse vertebrate and invertebrate remains, enables this study to examine aspects of the Upper Hell Creek depositional environments and paleoecology at an unprecedented level of detail.

This study uses detailed geologic and microstratigraphic data coupled with taphonomic, floral, and faunal data from Bone Butte to answer the following questions:

- How were the sediments at Bone Butte deposited and what depositional environments characterize the site?
- What was the structure of the Bone Butte biocoenosis and how does it compare to previous characterizations of the Hell Creek paleocommunities?
- How can taphonomic evidence help elucidate the history of the Bone Butte thanatocenosis and resolve discrete localized paleocommunities?

-How can the extremely detailed microstratigraphic framework, floral, and faunal evidence from Bone Butte help reconstruct new and previously undocumented aspects of Upper Hell Creek animal behavior and climate?

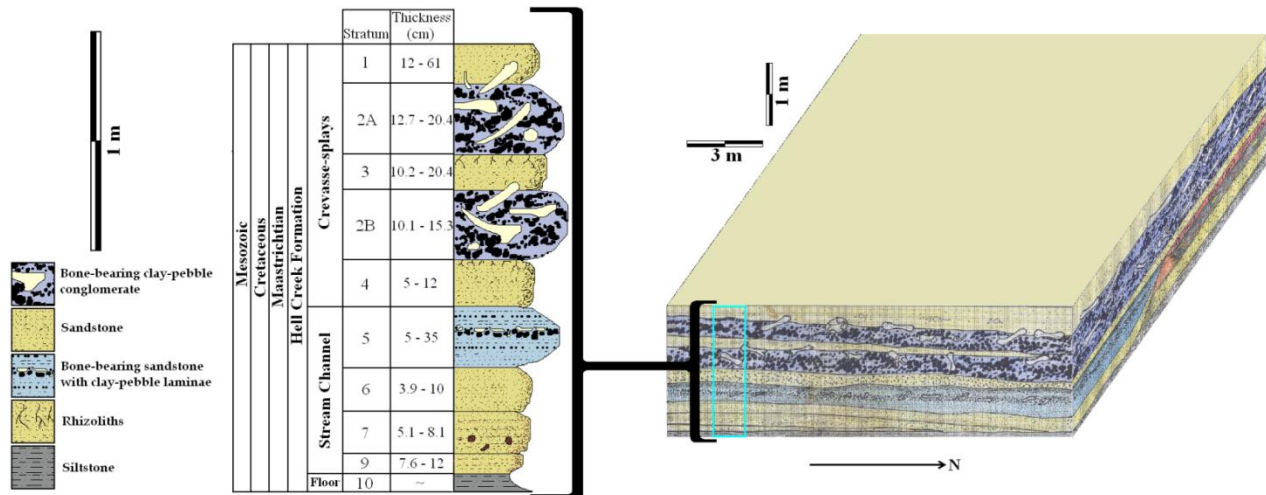


Figure 1.1. Stratigraphic column and fence diagram depicting the alternating sandstones and clay-pebble conglomerates of Bone Butte.

1.1. *Description and Site History*

The alternating rolling prairies and badlands of Harding County South Dakota offer exposures of the Upper Cretaceous Fox Hills and Hell Creek Formations, and Lower Tertiary Fort Union Formation (Bjork, 1964; Agnew et al., 1965; Johnson et al., 2002). The abundance of Upper Cretaceous vertebrate fossils in Harding County was first documented by Lt. Colonel George A. Custer's reconnaissance of the Black Hills region in the 1870's (Grafe and Horsted, 2003) and the area has been searched by fossil hunters and researchers ever since. The well exposed Upper Cretaceous strata in Harding County's badlands permit extensive opportunities for the recovery of fossil vertebrates and invertebrates (Fig. 1.2). Consequently, Harding County



Figure 1.2. Hell Creek badlands, composed of siltstones, mudstones, and sandstones, provide an excellent sampling ground for Upper Cretaceous fossils, and have become a locus for Upper Cretaceous field research.

has become a destination for those wishing to study the Upper Cretaceous and Lower Tertiary periods (Triebold, 1995; Bartlett, 1999; Larson, 2002; Larson and Carpenter, 2008).

Between 1997 and 2000, my late colleague Terry Smith and I engaged in work on Wyoming's Upper Cretaceous Lance Formation and coeval Hell Creek deposits in South Dakota and Montana for the Graves Museum of Archaeology and Natural History. After the Graves Museum's Wyoming expeditions ceased in 2000, Terry and I continued to conduct field research, primarily concentrating on the Hell Creek deposits of South Dakota and Montana. The harsh badlands of Harding County yielded fossils and bonebeds of varying significance over the ensuing years, Bone Butte being one of the more notable discoveries. In 2003, in a sandy exposure of Hell Creek strata perched atop a hillside that overlooked a vast valley network of badlands, we discovered what appeared to be a single bone-bearing clay-pebble conglomerate within a sandy fluvial sequence, overlying 70 m of alternating mudstones and siltstones. There was some evidence that others had extracted bones from the locality in previous years, although

judging by the size of weeds and sage growing on the small ($<1\text{ m}^2$) excavation platform, the site had been abandoned for years. After a brief survey of landmarks in the area, the locality bore close resemblance to a collecting spot Terry and I were invited to visit in 2000 (but regrettably had not been able to attend) by a vocational part-time fossil collector from Nebraska. After the landowners were notified of the new discovery, permission previously granted to collect specimens was re-confirmed and Terry and I began systematically mapping the area in preparation for excavation. A suitable area of exposure along the valley rim was chosen and excavation commenced shortly thereafter.

Initial excavation of the site produced dozens of bones, ranging in size from 4 mm to 1 m in length, representing a diverse vertebrate fauna of both dinosaurian and non-dinosaurian components. Not long after excavation began, it was evident that several bone-bearing strata were present, each with unique directions of bone orientation, variable bone sizes, and sediment types. The site was dubbed “Bone Butte” and between the years of 2003 and 2009, systematic excavation produced nearly 3000 vertebrate specimens and innumerable examples of petrified wood, fossil leaves, ichnofossils, invertebrate animals, and amber, making it one of the most prolific and diverse Hell Creek dig sites for its size (Triebold, 1997; Bartlett, 1999, 2004).

1.2. Spatiotemporal Setting

Bone Butte is located in the southeastern corner of Harding County, near the northern border of the Burke Ranch, whose more than 20,000 acres of land provide extensive exposures of the Hell Creek Formation (Fig. 1.3). Hell Creek sediments are exposed in washouts, isolated buttes that rise up to 75 m from the surrounding prairie, and valleys associated with tributaries of the Moreau River. No exposures of the underlying marine Fox Hills Formation have thus far been found on the ranch, although remnants of the Paleocene Fort Union Formation exist as

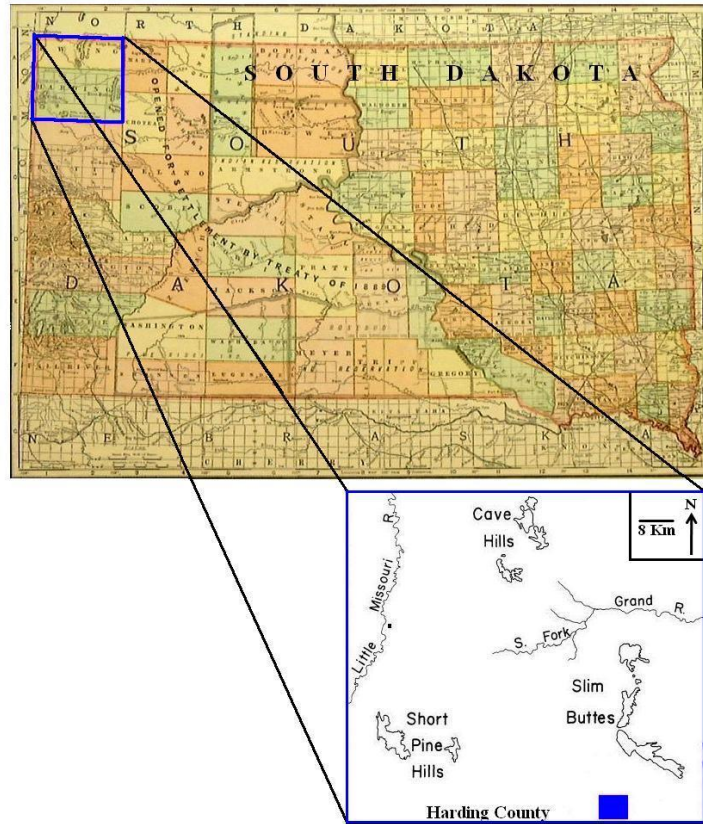


Figure 1.3. The location of the Bone Butte study area (solid blue square) within Harding County, South Dakota.

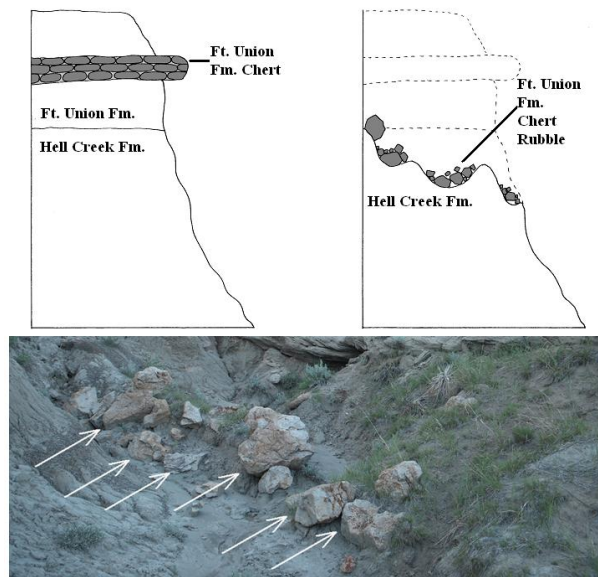


Figure 1.4. Chert boulders from the Paleocene Fort Union Formation resting unconformably atop Cretaceous Hell Creek Formation strata (bottom). The deposition of the chert boulders, as a result of the erosion of overlying Paleocene strata, is outlined in the top two diagrams.

fields of weathered chert boulders resting unconformably atop the Hell Creek strata (Fig. 1.4). Ranches to the immediate north of Bone Butte have abundant intact Paleocene exposures conformably overlying the Hell Creek strata, and preserved at elevations just slightly higher than Bone Butte.

The Bone Butte site is located on a topographically high projection along the south rim of Petra Valley, a valley complex situated around the Mary L. tributary of the Moreau River, in the northwest corner of the Burke Ranch (Fig. 1.5). At an elevation of 920 m above sea level, Bone Butte and correlating strata in nearby buttes are the highest points on the ranch. The alternating

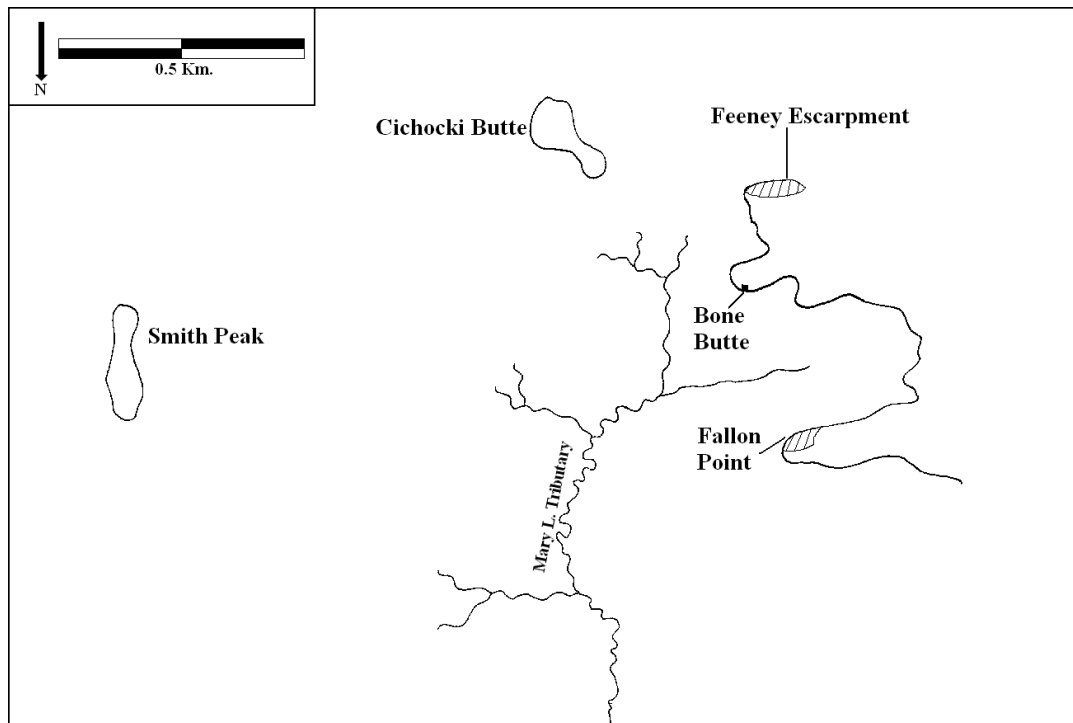


Figure 1.5. The Bone Butte study area, including the Bone Butte site proper, and adjacent sampling localities.

sandstones and conglomerates of Bone Butte, the massive and cross-bedded sandstones above Bone Butte, and the siltstones below Bone Butte, form a continuous stratigraphic section of the

Hell Creek Formation measuring 70 m in thickness. The ~2 m thick section of crevasse-splay, stream, and oxbow lake deposits that comprise Bone Butte is overlain by ~2 m of massive sandstones alternating with thin bands of cross-bedded sandstone, and capped by patches of cherty Fort Union rubble. Cretaceous strata from Bone Butte have been traced along the rim of Petra Valley to Fallon Point, northeast to Smith Peak, southeast to Cichocki Butte, and south to the Feeney Escarpment. The Feeney Escarpment consists of a ~0.75 m thick stratum of well indurated, often cross-bedded sandstone that exhibits primary sedimentary structures such as ripples. The orientation of ripples varies throughout the Feeney Escarpment sandstone, although they frequently indicate an eastward flow. This sandstone bench caps the hillside and overhangs by as much as 2 m. Distal fragments of the Feeney Escarpment have broken off during weathering and litter the southwestern side of the hillside (Fig. 1.6), covering much of the underlying strata.

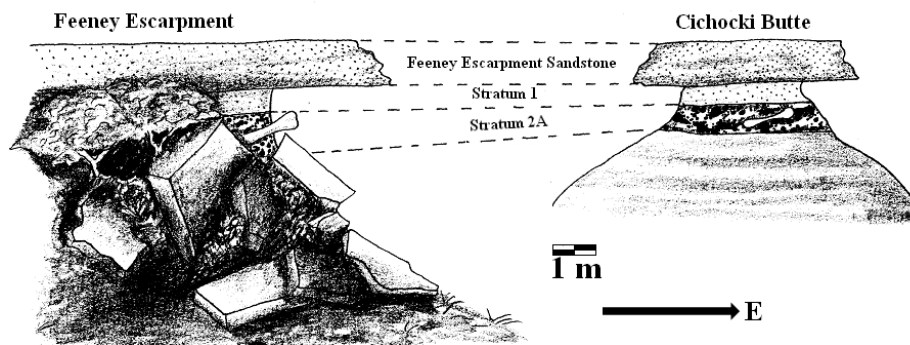


Figure 1.6. A profile of the Feeney Escarpment shows the vegetated hillside and debris field composed of weathered cross-bedded sandstone that obscures much of the underlying strata. The cross-bedded sandstone of the Feeney Escarpment, and the unconsolidated sandstone and clay-pebble conglomerate beneath, can be correlated with Cichocki Butte to the east.

The debris field from the Feeney Escarpment, the slumping of the soft hillside, and overgrowth of vegetation, preclude detailed observations of underlying strata; however, it is at least evident

that bone-bearing clay-pebble conglomerates from Bone Butte crop out immediately below the sandstone bench of the Feeney Escarpment. A similar situation is present at the top of Cichocki Butte, although weathering has progressed to an extent that limits the Bone Butte equivalent strata to a lateral extent of about 20 m, which is capped by a small portion of Feeney Escarpment equivalent sandstones (Fig. 1.6).

The Bone Butte excavations covered an area approximately 15 m long (north to south) by 12 m wide (east to west) and with an average depth of 6 m. Laminated sandstone and clay-pebble conglomerates containing abundant vertebrate remains represent a paleo stream channel (Fastovsky, 1987) and are found eastwardly adjacent to sandstone and siltstone deposits of a penecontemporaneously formed oxbow lake. The stream channel and oxbow lake deposits are, in turn, overlain by two crevasse-splay deposits consisting of coarse-grained sandstone and conglomerate composed of mudclasts and vertebrate remains.

Whereas the Cretaceous-Tertiary (K-T) Boundary is not preserved on the Burke Ranch, there is evidence that can help bracket the Bone Butte site in a temporal framework and estimate its proximity to the contact between the Cretaceous and Paleocene sediments. The Bone Butte site rests atop 70 m of exposed Hell Creek deposits, with an indeterminate number of additional meters of Hell Creek deposits separating it from the Fox Hills Formation below. The Hell Creek Formation is known to have averaged 100 m in thickness at the Sandy site (Bartlett, 2004), which is less than 64 km west of Bone Butte, and that average thickness decreases to the east (Winchester et al., 1916; Murphy et al., 2002; Bartlett, 2004). If the Fox Hills contact was immediately below the floor of Petra Valley, Bone Butte would be at least 70 m above the contact with the Fox Hills Formation and no more than 30 m below the contact with the Fort Union Group. Trenches excavated in the valley floor, however, show that the Hell Creek

Formation persists for at least 3 m below the valley floor, placing Bone Butte an absolute maximum of 27 m below the Fort Union contact. The contact between the Hell Creek Formation and Fort Union Group has been surveyed in numerous locations immediately to the north and northeast of Bone Butte (Hares, 1928; Bjork, 1964; Agnew, 1965), and gives a more accurate estimate of Bone Butte's stratigraphic position. The closest areas in which the contact is preserved are: 8.7 miles N, elevation 940 m; 7.4 miles N 51 E, elevation 930 m; 9.3 miles N 106 W, elevation 930 m; 11 miles N 39 E, elevation 935 m. Since the Hell Creek Formation has a negligible angle of dip in this area (Leonard, 1908; Hares, 1928; Krumbein & Sloss, 1963), and Bone Butte has an elevation of 920 m, the contact between the Hell Creek Formation and Fort Union Group can be estimated to be less than 20 m above Bone Butte (Fig. 1.7). This estimate is supported by the Bone Butte angiosperm flora that matches the HC III floral zone of Johnson (2002), which occurs in the upper 20 m of the Hell Creek Formation.

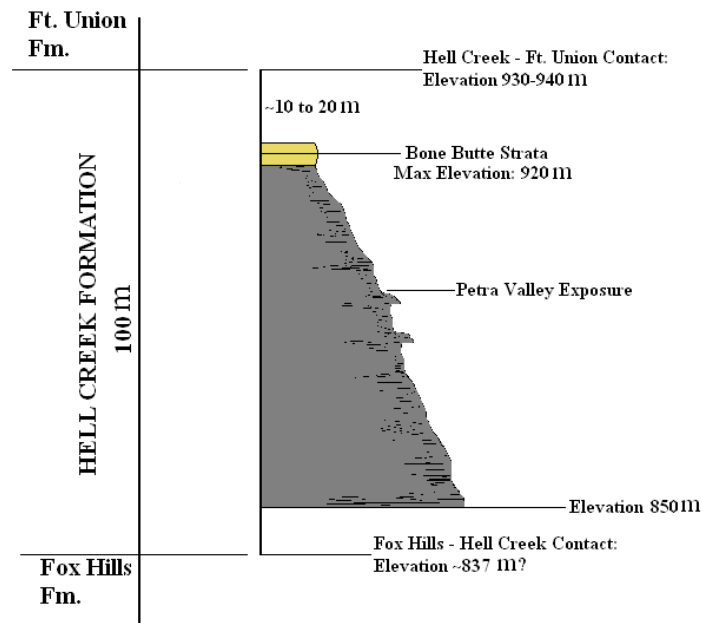


Figure 1.7. Using the known thickness of the Hell Creek Formation, the thickness of Hell Creek exposure in Petra Valley, and elevations of the Hell Creek – Fort Union contact, it is possible to estimate that Bone Butte's proximity to the Fort Union contact is between 10 and 20 m.

1.3. *Focus of the Study*

The focus of the Bone Butte study is directed toward the depositional context of the site, the local paleoenvironment, and the dynamics of the Upper Hell Creek paleoecology as represented by evidence from Bone Butte. The sedimentologic and geologic data collected from Bone Butte is used to reconstruct the series of events leading to the formation of the Bone Butte strata. In addition to comparison with modern analogs and direct experimentation using stream tables and tumblers, data from the Bone Butte oxbow lake and stream deposits is compared to Bone Butte equivalent strata in the immediate area and used to reconstruct the paleo river tract that formed Bone Butte. Through a fortuitous set of depositional circumstances and detailed field data collection, the well preserved stream channel and oxbow lake deposits at Bone Butte provide vertebrate remains in progressive ontogenetic stages, preserved within their original stratigraphic context, and demonstrate a progressive cycle from hatchling to adult. Plant fossils in the strata exhibiting growth stages corresponding to particular times of the year estimate the annual time of deposition to within several months. Additionally, microstratigraphic examination of conglomerate laminae in the stream and oxbow lake strata provides a cyclic record of storm magnitudes for a ~2.5 year period of the stream's history. The extraordinarily detailed stratigraphic data from the oxbow lake and stream deposits, coupled with vertebrate ontogenetic and floral data, places the sedimentologic processes within a temporal framework, and permits a detailed reconstruction of the paleoclimate at the time of deposition. Examination of the Bone Butte sediments and the remains of life preserved within, as well as interpretations of the facies represented at the site, elucidate the detailed environmental context and provide a paleoecological reconstruction.

A most fortuitous discovery of medullary bone in some dinosaurian remains from the site (Fig. 1.8) gives significant clues for the recognition of dinosaur behavior and reproduction. Medullary bone is a form of specialized bony growth within the medullary cavities of birds and some dinosaurs, and serves as a calcium reservoir for egg shell production during their reproductive cycle (Lee et al., 2007; Schweitzer et al., 2008). Medullary bone has been well

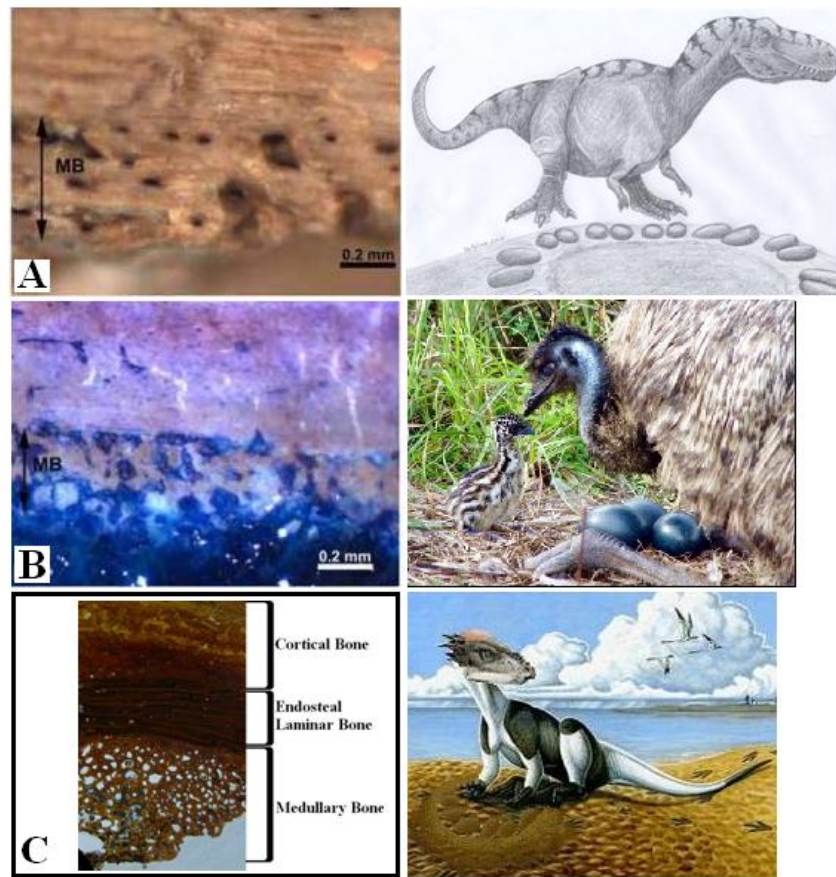


Figure 1.8. (A) Medullary bone from a *Tyrannosaurus rex* (Schweitzer et al., 2008) compared with (B) medullary bone from a modern Emu (Schweitzer et al., 2008), and (C) medullary bone from a pachycephalosaur bone collected at Bone Butte.

documented in both saurischian and ornithischian dinosaurs (Lee et al., 2007) and, as medullary bone is only present in birds within a ~1-month period during mating and egg-laying, it has been

used as an indication of the reproductive status of dinosaurs whose bones possess medullary bone (Lee et al., 2007; Schweitzer et al., 2007, 2008). Medullary bone has been documented in three dinosaur taxa from Bone Butte, representing members of both the saurischia and ornithischia, and is used to infer new aspects of dinosaurian reproduction, such as preferred breeding seasons and possibly seasonal nesting sites in circum-riparian environments.

The thousands of vertebrate specimens collected from Bone Butte provide a wealth of taphonomic data on the history of Bone Butte's thanatocenosis and ancient biocenosis. Clues such as bone abrasion, cracking, completeness, surface etching by roots and fungi, orientation, sorting, and signs of predation or scavenging are extremely valuable in reconstructing a bone's journey from the biosphere to the lithosphere (Behrensmeyer, 1991). Discrete taphonomic characteristics such as level of abrasion, completeness, and bone sorting, assist in separating the bones into what are interpreted as allochthonous and autochthonous assemblages, each possessing a distinct faunal composition (Fig. 1.9). Although over one hundred twenty years of

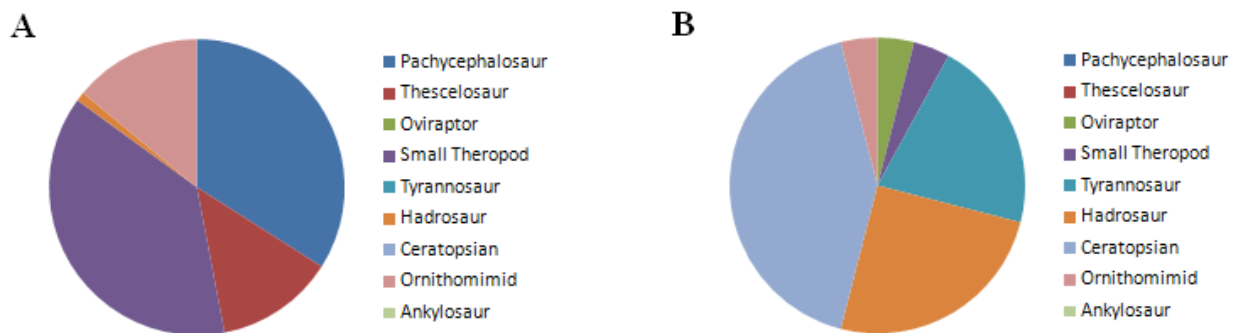


Figure 1.9. The allochthon and autochthon from Bone Butte vary significantly in their compositions. The autochthonous fauna (A) is dominated by small theropods, pachycephalosaurs, ornithomimids and thescelosaurus, while the allochthonous fauna (B) is dominated by ceratopsians, hadrosaurs, and tyrannosaurs.

study have produced a general consensus that the Hell Creek Formation represents an angiosperm-dominated, fluvial environment with a ubiquitous dinosaurian megafaunal assemblage comprised mainly of ceratopsians, hadrosaurs, and tyrannosaurs (Lehman, 1987; White et al., 1998; Russell and Manabe, 2002), recent studies have begun to challenge previous interpretations of the Hell Creek Formation, recognizing a rough differentiation between upland and lowland paleofaunas and latitudinal zonation. Recent studies, such as the Bartlett (2004) study of Mike Triebold's Sandy Site and the Holroyd and Hutchinson (2002) study on Late Cretaceous turtles, have demonstrated that the Hell Creek fauna was much more heterogeneous than previously thought, existing as a rich mosaic of distinct faunal communities. Bartlett (2004) provided a breakdown of the Hell Creek Fauna different from previous views, showing two distinct dinosaurian assemblages, one local and another, closer in composition to traditional reconstructions of Hell Creek fauna that was transported from further west in the river system.

This study further reinforces Bartlett's findings by elucidating the presence of two faunas at Bone Butte – one which was a local fauna dominated by ornithischians and small theropods, distinct in composition from Bartlett's, and an exotic fauna closer to traditional reconstructions of the Hell Creek Formation – and helps to emphasize the extremely diverse, heterogeneous nature of Hell Creek paleocommunities. Furthermore, the excellent sampling of dinosaur taxa from Bone Butte demonstrates that dinosaur diversity, contrary to some researchers' opinions (Sloan et al., 1986; Williams, 1994), remained high until the very end of the Cretaceous. Ultimately, a cohesive picture of distinct faunal associations, their respective paleoenvironmental settings, and their variation with proximity to the paleoshoreline, is formulated. This study uses a research site of exquisite quality and an extensive dataset to provide information critical to the understanding of the dynamics of vertebrate life in the Upper Hell Creek Formation immediately before the K-T extinction.

CHAPTER 2

METHODS

The plethora of information contained within Bone Butte and the surrounding territory necessitated a multi-level approach to collection and analysis of data. The scope of this study spans the sedimentology, depositional history, taphonomic history, and paleoecology of the Bone Butte site, and a variety of methods were employed in collecting and analyzing data.

A general reconnaissance and mapping of Bone Butte and the vicinity preceded more invasive physical work at the site. Systematic mapping and excavation of bones were carried out concomitantly with efforts to record detailed stratigraphic and sedimentologic data. Taphonomic data was collected both in the field and following the subsequent return of fossil specimens to the laboratory. In addition, hypotheses regarding the formation of the Bone Butte oxbow lake, stream channel, and crevasse-splays were tested in laboratory experiments, the data from which were compared with data from the field and modern analogs. Fossil specimens from Bone Butte were repositied in the Palm Beach Museum of Natural History in Florida (PBMNH) and the University of Kansas (KUPV).

2.1. Fieldwork

Data collected through field expeditions included observations on geologic and taphonomic details, as well as the occurrence of vertebrate, invertebrate, floral, and trace fossils. Fieldwork led by me was carried out at the Bone Butte site, with a core team consisting of two individuals and an additional rotating group of seven personnel.

Because the secluded nature of the Bone Butte site precluded access by most vehicles, ground reconnaissance was carried out by several teams of two people each, who ventured out on foot. Teams disbursed from the central Bone Butte location and scoured the surrounding

outcrops, searching for correlating units, body fossil evidence, and trace fossils. The teams covered an area corresponding to approximately 5 km² (Fig. 2.1) and encountered a series of floodplain, channel, crevasse-splay, and back swamp deposits that reflected a number of

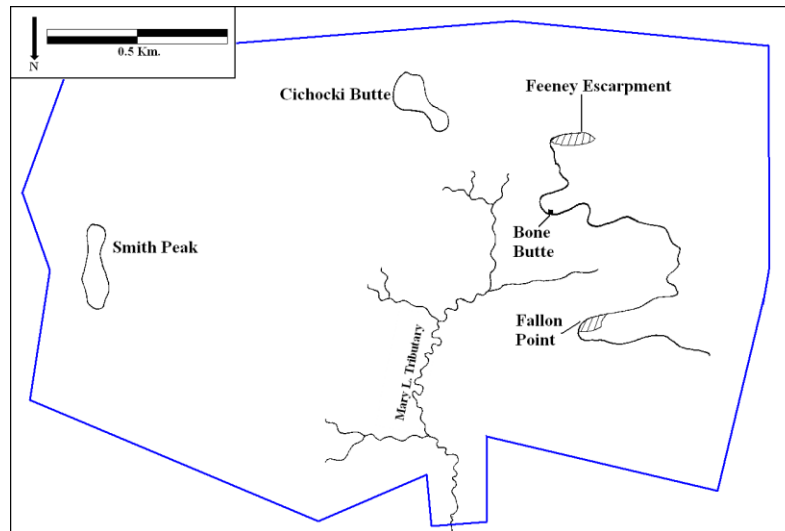


Figure 2.1. A generalized map of the Bone Butte area, depicting the area of main reconnaissance (blue polygon).

typical Hell Creek fluvially dominated facies and paleoenvironments (Lehman, 1987; Fastovsky, 1987 a, b; Behrensmeier et al., 1992). The study area consisted of both *in situ* Hell Creek deposits and weathered chert boulder remnants of the now-absent Paleocene Fort Union Formation. As the Hell Creek deposits are the focus of the present study, Paleocene remnants were noted but not investigated. Areas of interest were flagged and subjected to more intensive investigation.

Before formal excavations at the site began, the Bone Butte location and areas flagged during preliminary ground reconnaissance were scrutinized. Locations surrounding the Bone Butte site, specifically Fallon Point to the north, Smith Peak to the northeast, Cichocki Butte to the southeast, the Feeney Escarpment to the south, and the rim of Petra Valley adjacent to Bone

Butte, were closely examined and mapped. Using traditional surveying techniques (Rayner, 1943; Krumbein & Sloss, 1963), the areas of interest were mapped and plotted on a USGS topographical map of the local area. Elevations of the primary Bone Butte site and peripheral study areas measured with a GPS were recorded and, when necessary, localized stratigraphic maps were generated for target areas. The supplementary stratigraphic maps were deemed necessary in order to document the strata to a greater degree of detail (15 cm contour intervals) than the USGS 1:24000 topographic maps. In addition to mapping the strata and ground surface at selected locations around Bone Butte, samples of strata that correlated with Bone Butte were collected for further analysis. The strata were documented with respect to color (both fresh and weathered), their stratigraphic relationships, internal structures, thickness, strike/dip, fossil content, gross composition, and (later in the lab) sediment grain size and composition. Representative samples of body fossils and ichnofossils were also collected.

Detailed excavation of the Bone Butte dig site, ultimately resulting in an area approximately 15 m long (north to south) by 12 m wide (east to west) by 2.5 m deep, commenced following the survey of the surrounding area. The extent and condition of initial outcrop exposures at the site were recorded before the excavation took place. Excavation began with the systematic removal of approximately 1 m of a massive sandstone unit above the uppermost bone-bearing stratum. An ongoing effort to systematically map the site's strata began immediately after excavation was initiated, and the site's primary strata were given numbers. A 1 m grid system, aligned north to south, was tied into a main site datum point. This grid was used both in mapping the strata of the site and the orientation of the bones. Some bone-bearing strata, such as Strata 5, 11, and 15, having well-formed, distinct laminae of variable thickness, were mapped with a very detailed (6 cm interval) vertical control, which formed a highly detailed record of bone orientation and occurrence in three dimensions (Fig. 2.2). Each of

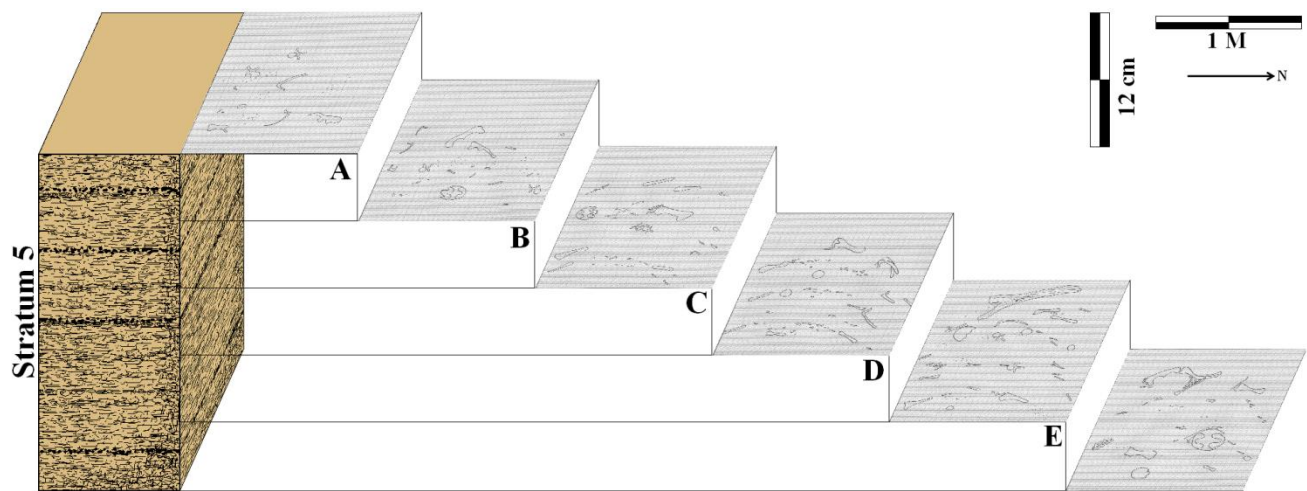


Figure 2.2. In Strata 5, 11, and 15, bone maps were generated at 6 cm vertical intervals, producing highly detailed, three-dimensional records of bone orientation. The level of detail was sufficient to trace turtle and crocodilian ontogenies from hatchling to adult. In this figure, a section of Stratum 5 is used as an example; letters designate each of the 6 cm-thick subsets.

the 6 m subsets were designated a letter from A to J. After exposure, each bone was tied into the site's base line, and both horizontal and vertical orientations were recorded. In addition, clay-pebble laminae in Strata 5, 11, and 15 were documented with respect to their average clast size and bone content. The presence of burnt wood (pyrofusain) was noted and its abundance was quantified by estimating the pyrofusain to matrix ratio within a 10 cm x 10 cm grid placed over the laminae. In instances where pyrofusain comprised less than 1% of a lamina, its presence was not noted. As excavation progressed, the dig site wall was planed smooth vertically (to the greatest extent the matrix would allow) at 60 cm intervals and stratigraphic sections of the entire thickness of the dig site were measured. During the 6-year course of excavation, over 100 stratigraphic sections were amassed in this fashion, producing a high-resolution stratigraphic reconstruction of the site (Fig. 2.3). Additionally, fence diagrams were created using stratigraphic sections measured at Bone Butte, Petra Valley, Fallon Point, Smith Peak, Cichocki

Butte, and the Feeney Escarpment, and enabled a three dimensional stratigraphic reconstruction of the entire Bone Butte area.

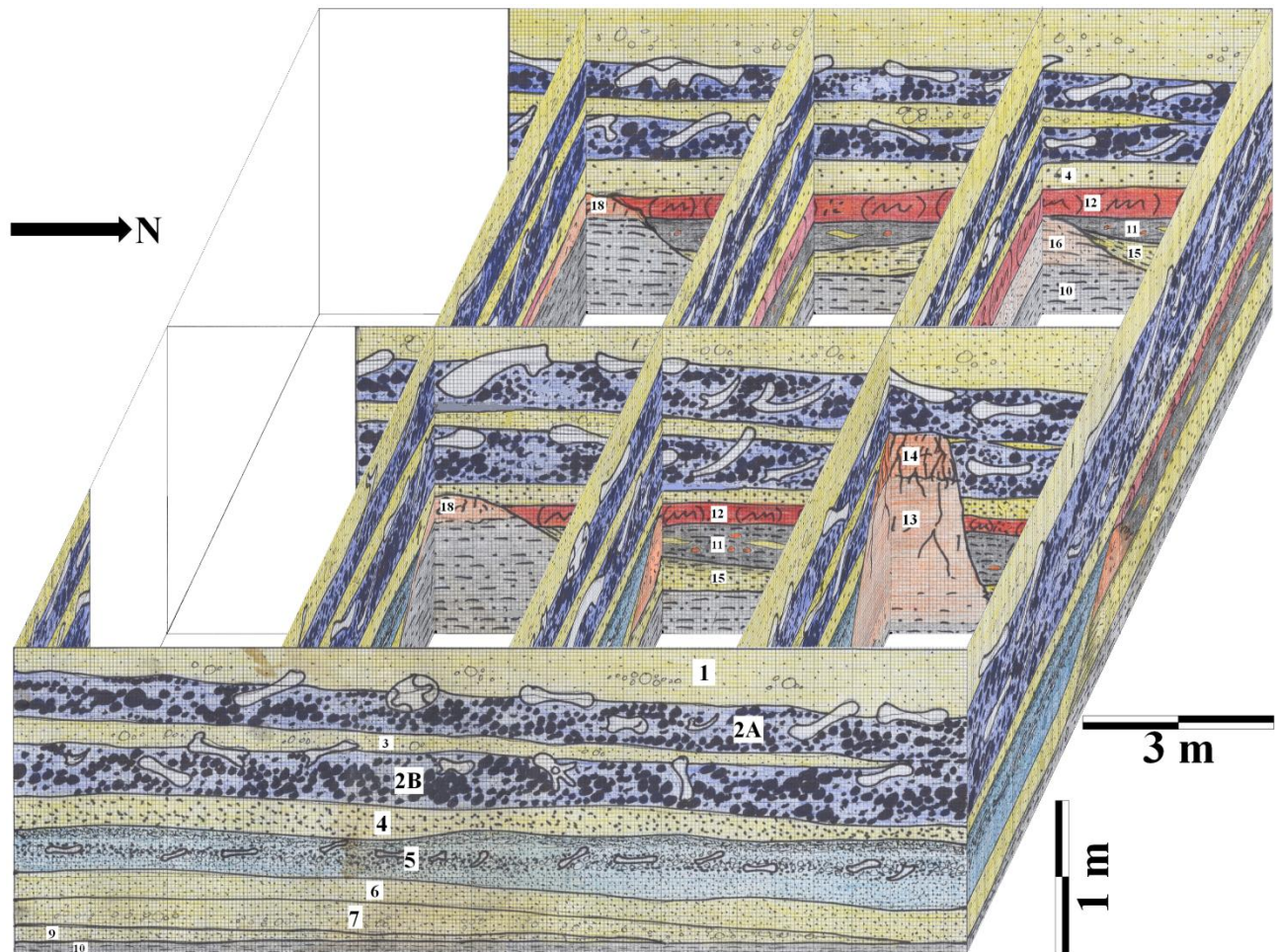


Figure 2.3. A fence diagram of the Bone Butte site, created by correlating over 100 stratigraphic columns that were generated during the 6 years of excavation.

Since details of bone orientation can be critical to the reconstruction of a site's formation and depositional history (Behrensmeyer, 1991; Aslan and Behrensmeyer, 1996), the bones discovered at Bone Butte were mapped concomitantly with the strata. Initial reconnaissance of Bone Butte revealed what appeared to be a single bone-bearing stratum, however additional bone-bearing strata were discovered soon after excavation began. The main bone-bearing

conglomerate was, in fact, divisible into two distinct strata. In addition, three more bone-bearing strata – one from a small channel and another two from an oxbow lake – were discovered.

Because documenting the bones of all bone-bearing strata on a single quarry map would have provided facies-averaged data that were minimally informative, bones from the different strata – the two conglomerate strata, the channel, and the oxbow lake – were recorded in separate quarry maps. Mapping the orientations and distributions of bones in these four strata was a critical step in reconstructing the depositional scenario, paleoenvironment, and paleoecology of Bone Butte. As excavation at the site progressed, the orientation and, when applicable, the plunge of the bones were recorded and tied into the main site datum. Each bone was given a catalog number that remained with it during excavation and subsequent transport back to the laboratory.

Before excavation began and, when necessary, as excavation progressed, the different strata of Bone Butte, both bone-bearing and barren, were photo-documented and geologic samples were removed for further study. After notes were taken on the gross appearance and composition of the matrix, as well as color, thickness, strike/dip, fossil content, and gross composition/grain size estimates, samples were removed with new X-acto blades and placed either in glass specimen tubes or larger rigid plastic containers. These specimens were later analyzed in the laboratory to extract additional information about their composition, grain size, and depositional environment (Krumbein & Sloss, 1963).

2.2. Excavation and Collection of Fossils

Upon initial examination of the Bone Butte site, it was immediately clear that the site contained a profuse amount of dinosaur and turtle remains. Over the course of excavation more than 50 vertebrate taxa were recorded, in addition to fossil plants and wood, amber, invertebrate

animals, and ichnofossils produced by vertebrates and invertebrates. The collection of fossils was carried out systematically and in such a way that limited damage to the specimens during removal from the ground and subsequent transport back to the laboratory. Because of the nature and variable fragility of the various forms of fossils discovered, the different categories of fossils, vertebrate or invertebrate, trace fossils, fragile and delicate or large and stable, demanded unique collection protocols. The different fossil types were often found in close association with one another, so employment of many of these collection protocols was often carried out at the same time.

The protocol during excavation of fossil bone did not vary appreciably among the different animal taxa, with the exception of bones larger than 30 cm, which required substantial reinforcement before their removal. Meticulous excavation of the bone-bearing strata typically employed the use of nothing larger than a #22 X-acto blade. Quite frequently, the bones were so tightly packed and interwoven that small dental instruments were required in order to excavate small spaces between bones. Removal of bulk matrix from the periphery of skeletal elements was typically conducted using an X-acto blade or bayonet, and loosened matrix fragments and debris were carefully whisked away with a camel-hair brush. As necessary, cyanoacrylate glue was applied to cracks in the bone to maintain cohesion, limiting possible damage to the bone during exhumation. As each bone was exposed, details concerning the specimen's taxonomic affinity, age category based on bone size, completeness, abrasion, and mode of life (carnivore vs. herbivore), were recorded. Once a bone was isolated, identified and documented, mapping of the bone's location commenced and the bone was prepared for removal. For bones over approximately 30 cm, plaster field jackets were constructed. In such cases, a narrow trench was excavated around the periphery of the bone, thereby creating a pedestal for the specimen. A separating medium, usually heavy-duty aluminum foil, was wrapped around the bone and affixed

there with fiberglass-reinforced packing tape. Strips of burlap permeated with plaster of paris were placed over the foil-wrapped bone (Fig. 2.4).



Figure 2.4. Photographs depicting the process of bone removal: (A) A bone was first uncovered using standard excavation instruments, stabilized, and (B) trenches were circumscribed around the bone, leaving only a supporting pedestal of matrix beneath. (C) An aluminum foil separating medium was placed around the bone and (D) successive layers of plaster bandages were placed on the bone to ensure its safe transfer back to the laboratory.

After the first layer, a wooden or metal reinforcing rod was placed against the long axis of the bone, along with a set of rope handles, and subsequently locked in place by more layers of plaster bandages. After the plaster had thoroughly set, the jacketed bone was rolled off of its pedestal, any excess matrix of the pedestal still adhering to the bone's undersurface was removed, and the underside of the bone was stabilized with more cyanoacrylate glue. Smaller bones were excavated in the same fashion, with the exception of plaster jacketing; smaller bones were jacketed in foil only.

Progressively throughout the course of excavation, sediments from the site's talus pile were screened for micro fossils. Screen-washing produced only a miniscule amount of additional fossil material, a testament to thorough collecting during primary excavation. During the study period, however, presumed fossil poachers visited the site at least twice and left their own talus piles. Sediment screened from these talus piles produced a greater abundance of microfossils.

Plant fossils from the site typically occurred as whole, carbonized leaves, fragmented plant parts, amber, seeds, and wood ranging from 5 - 150 cm. After excavation, the location and stratum from which the plant material originated was noted, however the specimens were not given catalog numbers. Exhumation of most leaves and larger plant parts was often problematic due to the friable nature of the matrix and because future laboratory examination of the plant material required the absence of adhesive stabilizers. Because many leaves had a number of joints running through them, and the matrix became more friable after drying, it was impossible to collect many large, intact leaves. In many cases, the matrix block surrounding a leaf was stabilized with glue, leaving the leaf free of detail-obscuring preservative and allowed safe removal. Some plant detritus was stable enough to be removed in small matrix blocks without the aid of glue. Such specimens were permitted to dry, then wrapped in foil and packed for transport.

Amber at the site was, in some strata, quite profuse. The fissile nature of the amber-bearing strata allowed many sheet-like fragments of matrix to be removed, leaving amber specimens safely cradled in the original matrix for transport. In cases where amber was dislodged from the matrix, the amber was placed in large glass vials that were cushioned at both ends. In all cases, freshly-exposed amber specimens were immediately taken out of direct contact with sunlight and allowed to dry for a single day before packing. Although amber from Bone

Butte is larger and more stable than amber from most sites in the Hell Creek Formation, rapid changes in temperature and exposure to sunlight dramatically accelerate the amber's degradation and internal fracturing. Because of this, the specimens were stored in opaque, insulated containers to shield them from both natural light and temperature change.

Petrified wood at the site typically was represented by one of three modes of preservation, most of which preserved the wood in three dimensions: 1) solid, ironstone-replacement of the wood, 2) mudstone or silt-replaced wood with black organic film on outer surface, and 3) flattened lignite, preserving surface details but no internal structure. The former two were the only forms collected, and most specimens were treated sparingly with cyanoacrylate before packing. The lignite-preserved wood specimens were noted and photographed in many cases, but the nature of preservation did not allow safe exhumation.

In the lab, additional work was carried out on fossil specimens if necessary. Preparation of selected fossil bones using hand tools, air scribes, and micro air-abrasion with a sodium bicarbonate powder revealed certain taphonomic data, such as surface modification, that had been obscured by adhering matrix. Amber specimens were initially examined for any obvious signs of inclusions. Those specimens that showed the greatest promise of producing inclusions were the first to be processed further. Amber collected at Bone Butte was generally large (from 1 to 5 cm) and the majority was stable enough to be polished - a condition that has thus far not been reported in any Hell Creek Amber. Polishing the amber was first done by abrading the specimens with 150-grit sandpaper to remove several mm of the outer surface. Successively finer-grained sandpaper (250-grit, 400-grit, 600-grit, 1200-grit, 1500-grit) was used to further polish the specimens, and ultimately a final polish on a cotton buffing wheel rendered the specimens ready for microscopic examination for any inclusions (Fig. 2.5). The inclusions

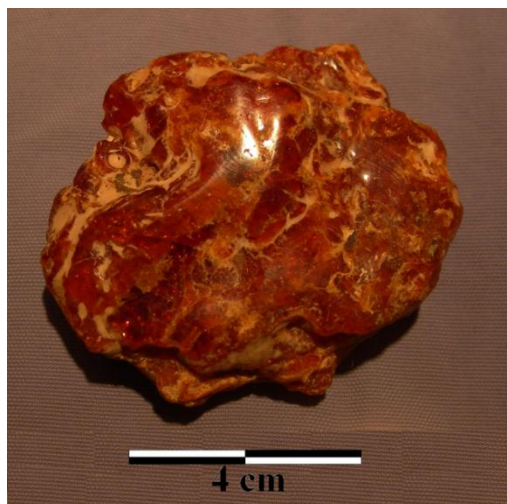


Figure 2.5. An example of the unusually large and well-preserved amber found at Bone Butte. Unlike most Hell Creek Amber, the Bone Butte specimens are stable enough to be polished before searching for inclusions.

observed were recorded and specimens that contained exceptional insect inclusions were scanned using ultra high resolution Micro-Computed Tomography (Micro-CT) and Environmental Scanning Electron Microscopy (ESEM).

2.3. Taphonomic Data

Recovering good taphonomic data was crucial to studying and reconstructing the depositional history, paleoenvironment and paleoecology of the Bone Butte area (Behrensmeyer, 1991, Behrensmeyer et al., 1992). A taphonomic chart following one used by Behrensmeyer (1991), (Appendix B 4) was used to record details including bone completeness, abrasion, sorting, orientation, sample size, assemblage size, ratios of juveniles to adults, number of species, degree of articulation, spatial density, and diversity (Table 3.1). Whenever possible, data was recorded in the field, and the remainder was collected subsequently in the laboratory. Using this data, the accumulation of bones at Bone Butte can be demonstrated to be the result of a

unique history and set of depositional events, in which elements such as bioturbation, transport along river channels, crevasse-splays, and *in situ* deposition of faunal assemblages all combined to form the fossil assemblage at Bone Butte. Examining the taphonomic clues left behind was necessary to tease apart the details that led to this particular taphocoenosis and to recognize the allochthonous and autochthonous elements of the Bone Butte fossil assemblage (Behrensmeyer, 1991; Behrensmeyer and Hook, 1992; Lyman, 1994; Bartlett, 2004).

In fluvially dominated systems, abrasion on bones and other hard-parts can be a significant indicator of the energy of the depositional environment as well as the distance the bone has travelled since it entered the system (Krumbein & Sloss, 1963; Behrensmeyer, 1991; Behrensmeyer and Hook, 1992). In this study, abrasion of fossil bones was estimated on a point-based scale from 1 to 6, with 6 representing maximal abrasion. Point-based systems have been used previously in taxonomic studies of bone abrasion (Behrensmeyer, 1991; Varricchio, 1995; White et al., 1998; Bartlett, 2004), and have proven useful in quantifying the degree of bone abrasion seen in bonebed studies. The completeness of bones was treated as a separate category from abrasion, as completeness and abrasion may not always be related. Bone completeness can be (and is) affected by much more than simply abrasion (Behrensmeyer, 1991; Lehman, 1987; White et al., 1998) and it is important to make that distinction, especially when the data is to be used in postulating the origin of bone assemblages. In this study, bone completeness was

Taphonomy Chart used in Bone Butte Study (Modified from Behrensmeyer, 1991)

Variable	Possible manifestations at a fossil site
<u>Assemblage Data</u>	
Sample size	-----10-----100-----1000-----10,000
Number of species	1-----10-----100-----
Diversity	low-----moderate-----high
Age spectrum	juveniles only-----50/50-----adults only
Medullary bone	absent-----present but rare-----abundant
Bone articulation	articulated-----disarticulated-----associated-----isolated but associated & dispersed & dispersed
Skeletal parts	unsorted-----sorted-----one part only
<u>Quarry Data</u>	
Size of accumulation	-----1 m ² -----100 m ² -----1000m ² -----
Spatial density	-----0.1/m ² -----1/m ² -----10/m ² -----100/m ² -----
Spatial arrangement	
In plan view	random-----preferred orientation
In profile	high dips-----horizontal
Patchiness	even-----uneven-----highly patchy
<u>Bone Modification</u>	
Breakage	complete-----broken-----fragments
Cracking [Weathering according to Behrensmeyer (1978)]	(Stage 0)----- (Stage 1)----- (Stage 0-3)
Abrasion/polish	unabraded-----abraded-----highly abraded
Surface marks	none-----present-----extensive

Table 3.1. Taphonomic details examined in the Bone Butte study.

calculated on a percent-based scale from 1% to 100% and provided more accuracy than the gradational scale suggested by Behrensmeyer (1991). Very few of the bones showed deterioration due to subaerial weathering and only a very slight fraction showed spiral fracture, damage that would have occurred before fossilization. Bone was used to estimate maturity of individuals at the time of death, as well as the carrying capacity of the fluvial system. Sorting of

fossil specimens can be a good indicator of transportation, and higher degrees of sorting are generally associated with greater distances of transport (Behrensmeyer, 1991; Behrensmeyer and Hook, 1992; Lyman, 1994). The degree of sorting of Bone Butte fossils was quantified on a scale of 1 to 5, with 5 representing the highest degree of sorting. The collective data on abrasion, completeness, sorting, and bone size were later analyzed, providing compelling evidence for local (autochthonous) and exotic (allochthonous) assemblages. In addition, taphonomic data including details of root etching on bone surfaces, “sun cracks” resulting from prolonged subaerial exposure, tooth marks from predator-prey interaction or scavenging, and evidence of etching due to partial digestion were collected and used to further resolve the paleoecology of the area and taphonomic history of the fossil assemblage.

In taphonomic studies there are a number of different methods for calculating the number of specimens collected, and which method is employed is at the researcher’s discretion (Behrensmeyer, 1991). In this study, recognizable individual skeletal elements and teeth were figured into the calculation of overall specimen number. At the minimum, bones had to be identifiable as dinosaurian or non-dinosaurian in order to be included in the faunal percentage comparison; worn fragments of bone that could not be assigned with confidence to at least the level of class were not included. Weathered bone fragments that could not be identified beyond the level of family were tagged as “unidentified vertebrate remains” and not included in the faunal percentage comparison, however they were included in the gross specimen number. Animals that replaced their dentition throughout life or had an overabundance of bony scales prone to fossilization created a risk of overrepresentation depending on what skeletal elements were included in the final total. In the case of scaly animals, such as fish, only bones and teeth were used. The use of shed teeth in specimen calculation is common practice and teeth have been included in the calculations of faunal abundance in virtually all Hell Creek publications

(Lehman, 1987; White et al., 1998; Russell and Manabe, 2002; Bartlett, 2004), despite the fact that shed teeth can overrepresent animal taxa. In this study however, shed teeth were used to enable the comparison of faunal data from Bone Butte with other studies of the Hell Creek fauna. (For a calculation using only skeletal elements, see Appendix B 1).

During the course of fossil excavation, the condition of fossil plant material, more specifically fossil leaves and amber, was closely monitored and documented. Especially in fluvial systems, leafy plant detritus and erosionally sensitive parts such as amber can be significantly (and rather quickly) affected by transport and their conditions can be an indicator of the distance they traveled before deposition, and of the temporal resolution of the particular stratum being examined (Spicer, 1991; Wing & DiMichelle, 1992). The condition of leaves, including the presence of wear, breakage, degradation, and the position of the leaves in the matrix (such as lying horizontally in a mat or oriented chaotically at a multitude of angles) was recorded. Surface morphology of amber was examined, as amber that has been transported appreciable distances will show significant rounding and loss of primary surface structures such as evidence of drips and runnels.

2.4. Experimentation, Laboratory Preparation, and Analysis

Grain size analyses, taphonomic analyses, physical experimentation, and examination of modern fluvial analogs augmented the geologic, taphonomic, and faunal data collected at Bone Butte. Taphonomic data regarding bone completeness, sorting, and degree of abrasion, was used to group bones together into smaller units of comparable condition. Bones grouped based on taphonomic characteristics modified from Behrensmeyer et al. (1992) were graphically represented in tables and charts. Groupings based on taphonomic data enabled the reconstruction

of their pre-depositional history and revealed a distinction between allochthonous and autochthonous sets. Assemblages of taxa in these sets were compared against each other and against other faunal assemblages tabulated in recent Hell Creek studies (Lehman, 1987; White et al., 1998; Russell and Manabe, 2002; Bartlett, 2004) in the vicinity. Furthermore, the entire collection of fossil bone, represented by an allochthonous and autochthonous group, was analyzed with respect to ratios of adult:subadult:juvenile:hatchling animals, predator to herbivore, and dinosaurian to nondinosaurian. Because of a fortuitous occurrence of natural breaks in the bones, it was possible to examine gross cross-sections of bone specimens for all dinosaur groups. Through this line of study, medullary bone was reported in several dinosaur groups. As medullary bone is known to occur only immediately before, during, and immediately after egg-laying in birds and dinosaurs (Lee et al., 2007; Schweitzer et al., 2007, 2008), dinosaurs at the Bone Butte site that possessed medullary bone died during a period of active egg-laying or brooding. The presence of medullary bone provided an additional ratio, comparing dinosaurs that were actively egg-laying vs. non-egg-laying, in the allochthonous and autochthonous dinosaur groups.

Direct experimentation involving stream tables and tumblers has proven useful in the reconstruction of ancient fluvial sequences (Voorhies, 1969; Korth, 1979; Tokaryk and Storer, 1991; Bartlett, 2004), and data collected in the field was complemented by data from experiments and grain size analyses following Krumbein & Sloss (1963). Hypotheses regarding the formation of the Bone Butte oxbow lake, features of the small stream channel, and formation of the crevasse splays were tested using a standard stream table setup. In addition, tumbler experiments were carried out to study changes in the morphology of rip-up mudclasts in order to resolve the distances they traveled before being deposited.

Over one hundred individual stratigraphic columns recorded in the field were correlated and three-dimensional fence diagrams and stratigraphic profiles were generated for Bone Butte and the surrounding area. Matrix collected from each stratum at Bone Butte and correlating strata in the surrounding area was brought back to the laboratory and passed through a nested set of sieves. The breakdown of grain size frequency and sediment composition provided valuable information regarding depositional energy and flow magnitude.

In order to test hypotheses regarding the formation of the oxbow lake, fining-upward stream channel sequence and several crevasse-splays at Bone Butte, a stream table, measuring 2.5 m x 2 m, was constructed. The table dipped 1 degree downstream and was filled with fine-grained sand to an even depth of 5 cm. The goals of the stream table experiments were: 1) to examine the changes in morphology of an oxbow lake when the parent channel is a) unimpeded and b) flowing around a weather-resistant obstacle; 2) to test the effects on a tributary channel when a portion of it contacts the main trunk channel upstream from the tributary's main outflow; 3) to test the spatial trends of levee breach and resultant crevasse-splays when a) tributary channels empty into the main channel, and b) no tributary channels are present (Fig. 2.6).

For stream table experiment number 1, standard meanders created from water flowing at a rate of 0.5 gallons per minute were observed during their recumbent stages and eventual formation of oxbow lakes. Two sets of ten runs were carried out, one set in which oxbow lakes formed unimpeded and the other in which a clay obstacle was placed in the stream's path. Powdered organic carbon and plant detritus were introduced into the water flow in this and the two following experiments in order to trace the areas of preferential deposition of fine-grained sediments and organics. The resultant changes in oxbow lake morphology were recorded and compared to field data.

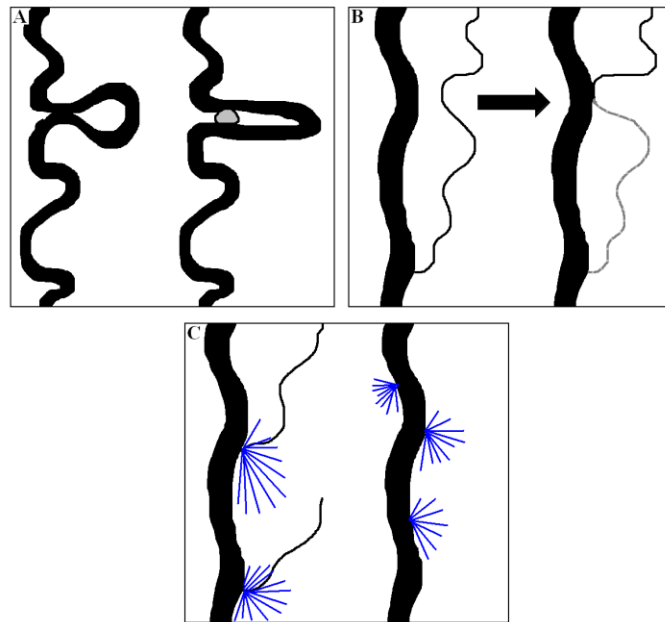


Figure 2.6. The stream table experiments sought to answer three primary questions: (A) How could an obstruction have affected the morphology of the Bone Butte oxbow lake? (B) How would a secondary connection between a tributary and the main channel affect the tributary's flow? And (C) How would the presence of a tributary affect the spatial occurrence of crevasse-splays in a main channel?

Stream table experiment number 2 called for a trunk channel and a tributary to be created. A main channel with a water flow of 1.5 gallons per minute was intersected by a tributary channel with a water flow of 0.5 gallons per minute. Flow meters were placed in the main channel upstream and downstream of the tributary outflow, and additional flow meters were placed in the tributary channel, one 10 cm from its source and a second 10 cm from its contact with the main channel. Meanders in the tributary channel were observed as they became recumbent and drifted toward the main channel. Invariably, a large meander from the tributary would contact the main channel upstream from the tributary's primary outflow point. The resultant flow differential in the upstream and downstream portions of the tributary was noted.

The third stream table experiment called for a trunk channel and tributary to be created in an identical fashion to experiment number 2. In this experiment, three conditions were tested with regard to the formation of crevasse splays: 1) a main channel with no tributaries in proximity; 2) a main channel being intersected by a normal tributary, 3) a main channel being intersected twice by the same tributary (both at the normal outflow point and a secondary contact upstream). Ten runs were carried out for each of these conditions, in which water flow in the main channel was momentarily increased to 3 gallons per minute and the tributary was momentarily increased to 1.5 gallons per minute. The spatial formation of crevasse splays in each of the three conditions was observed and noted.

Tumbler experiments were devised to test the effects of fluvial transport on rip-up mudclasts, in an effort to estimate the distance traveled by mudclasts uncovered at Bone Butte. Mudclasts at the Bone Butte site typically exist as angular to subangular clasts that range from 1 to 15 cm in diameter, and primary bedding structures, invertebrate burrows, and rhizoliths are still present within them. Three types of matrix – pieces of Bone Butte mudclasts, clay clasts from Clinton Lake in Douglas County, Kansas, and clay clasts from Okeechobee County, Florida were selected for use in the tumbler experiments. Five separate experimental batches were created for each clay type, consisting of mudclasts measuring 0.5 cm, 1 cm, 5 cm, 10 cm, and 20 cm. Mudclasts were graded on a scale of 1 to 5, with 5 corresponding to maximally angular and 1 corresponding to nearly spherical or no angularity. All mudclasts in the experiment initially possessed an angularity of 5. Mudclasts and medium-grained sand corresponding to Bone Butte sandstone were placed in tumblers with an internal circumference of 100 cm. The tumblers were switched on and left for one day, revolving at a rate of one complete revolution per minute. The condition of mudclasts was checked every 30 minutes and recorded. The change in size and

angularity of the mudclasts with respect to the number of revolutions made by the tumbler gave a rough estimate of the mudclasts' changes over a given distance of transport (Fig. 2.7), each

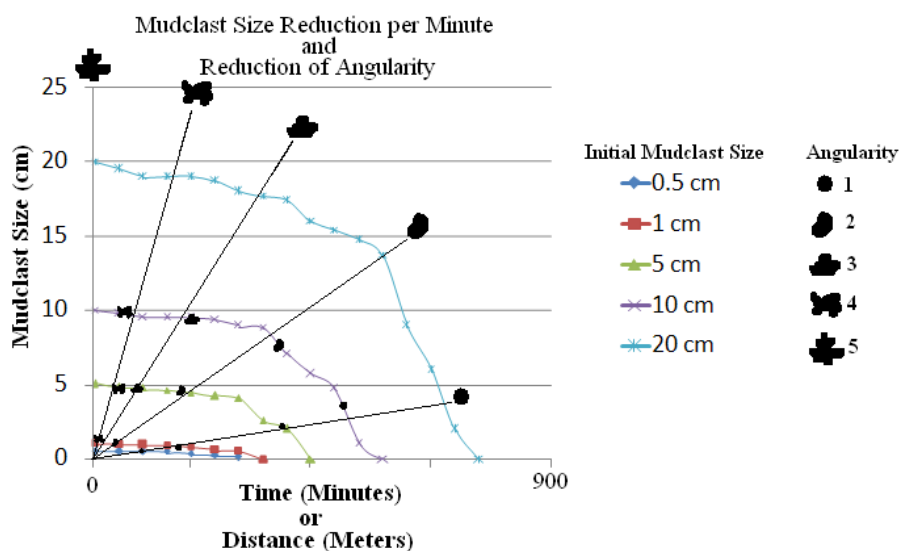


Figure 2.7. Bone Butte tumbler experiment graph. Each minute in the tumblers equaled one meter of distance traveled. Thus, the tumbler experiments enabled mud clast size and angularity to be measured and correlated with their minimum estimated distance traveled in a fluvial system. Changes in angularity and size over estimated distance was relatively constant over the 5 initial mudclast sizes, forming a roughly linear relationship between clast angularity and size, and distance traveled.

minute in the tumbler equaling one m of transport. These estimates were plotted on a graph and enabled theoretical distance estimates to be assigned to mudclasts encountered in the field.

CHAPTER 3

RESULTS

3.1. *Geology*

3.1.1 *Areal Geology*

Sediments encountered at Bone Butte are a combination of sandstones, siltstones, ironstones, and mudstones that are typical of the Hell Creek Formation (Knowlton, 1909; Johnson et al., 2002; Murphy et al., 2002; Bartlett, 2004). The majority of sediments (upwards of 70%) are composed of fine, medium, and coarse-grained sandstone, representing a predominantly high-energy environment (Krumbein and Sloss, 1963). Clay-pebble conglomerates comprise an important part of the total Bone Butte deposits, while finely laminated, highly organic-rich siltstones are found in localized deposits. Concretionary nodules composed of manganese oxide and iron oxide occur randomly throughout the strata.

3.1.2. *Sandstones and Siltstones*

The majority of sandstones at Bone Butte are composed of medium to coarse grains that possess subangular surface morphology. Color typically ranges from light yellow-tan to orange due to different degrees of iron staining. With the exception of some finely laminated, dense point-bar deposits, nearly all sandstones at the site are poorly cemented and unconsolidated. Sorting of grains is generally very poor in the massive-bedded sandstones and much greater in the bedded laminae. A large variety of structures are present in the sandstone, including ichnofossils, cross-bedding, and lamination of medium to fine-grained sandstone strata. At least half of the sandstone strata are part of fining-upward sequences, in which coarse-grained sandstones grade vertically into medium and fine-grained sandstone and, in some cases, into siltstone that has begun to undergo pedogenesis. In a number of sandstone strata, mostly those that exhibit massive bedding, rip-up mudclasts of various sizes are present in great quantities. The mudclasts are almost universally subangular in their surface morphology and all retain traces of their original bedding and evidence of prior pedogenic processes, such as rhizoliths, blocky pedogenic structures, greenish-gray and red mottling, and slickensides. Also present in the

sandstone and siltstone strata are concretionary nodules composed of siderite and iron-manganese. Vertebrate remains are quite common along the lower bounding surfaces of several sandstone strata.

Siltstones are less common than sandstones, and are generally more localized in the study interval. All siltstones exhibit fine, laminar bedding traces and contain more organic material than the sandstones. Because most siltstones at the site are found at the top of fluvial-to-terrestrial fining-upward sequences, their upper portions commonly exhibit insipient pedogenic structures such as rhizoliths, invertebrate burrows, and slickensides. Fewer vertebrate remains were recovered from the siltstone than the sandstone and clay-pebble conglomerates. Plant remains in most of the siltstones are typically severely degraded and present as small, taxonomically unidentifiable fragments. Identifiable specimens are found densely packed in laminae occurring at various intervals, mainly consisting of gymnosperm plants. Amber ranging in size from 0.25 - 5 cm, however, is quite prevalent in much of the siltstone and exhibits almost pristine, unmodified surface morphology. In some instances, localized lenses of fine-grained sandstone and gray sandy-siltstone are found in the dark, organic-rich siltstone deposits. These lenses contain abundant plant material, consisting primarily of well-preserved angiosperm leaves and wood fragments.

3.1.3. *Mudstones and Ironstones*

With the exception of the quarry floor, mudstones are not common at the Bone Butte site. The quarry floor is composed of dark gray-green to black mudstone that is generally very thinly laminated (with laminae often 1mm thick or less) and overall homogenous in composition and structure. An unconformity exists between the quarry floor and the overlying Bone Butte strata, and consequently most portions of the floor that once contained abundant rhizoliths, invertebrate

burrows, and pedogenic structures had been scoured away by stream channels, leaving behind only limited traces of subaerial exposure and soil formation. Some rhizoliths, iron staining, and invertebrate burrows exist in patches at the upper bounding surface, however all have been cross-cut and scoured.

Some thin mudstone lenses can be found within the main Bone Butte strata, mainly in association with the siltstone deposits. Thin mudstone laminae grade into organic-rich siltstone in some areas as sediment grain size varies from silt-dominated to mud-dominated. Thin mudstone laminae also occasionally are found associated with the fine sandstone lenses that occur within organic-rich siltstone deposits. As with the fine-grained sandstone lenses, these mudstone laminae contain fantastically preserved plant remains, predominantly angiosperm in origin.

In localized areas of the site, tabular sheets of dark red ironstone are found, usually lying atop organic-rich siltstone deposits. Unlike ironstone concretions that have been attributed to subaerial exposure and soil-formation (Krumbein and Sloss, 1963; Fastovsky, 1987 b; Behrensmeyer and Hook, 1992), these ironstone sheets typically are of uniform thickness and contain no rhizoliths or obvious pedogenic structures. In addition, the surface morphology commonly contains undulating ripple marks found in various orientations and occasionally mud cracks. Similar ironstone structures have been associated with low-lying, shallow bodies of stagnant water that contain abundant microbes and organic mats (Krumbein and Sloss, 1963; Behrensmeyer and Hook, 1992; Harrison and Henderson, 2002).

3.1.4. *Bone Butte Stratigraphy*

At the east end of the Bone Butte quarry, a series of fine to medium-grained sandstones and interbedded clay-pebble laminae lie atop the gray mudstone quarry floor (Fig. 3.1 A).

Adjacent to these strata, on the west end of the quarry, a series of fine-grained sandstones, siltstones, and ironstones lie atop the quarry floor (Fig. 3.1 B). These sequences of strata are separated by a narrow band of moderately oxidized, highly bioturbated, organic-rich siltstone (Fig. 3.1 C). Above these adjacent strata rest several massive beds of medium to coarse-grained sandstone and clay-pebble conglomerate composed of coarse-grained sandstone, vertebrate remains ranging from 1 cm to 1 m, and large clay rip-up clasts ranging from 6 to 18 cm (Fig. 3.1 D). The uppermost massive sandstone stratum is bounded on the top by a zone rich in organic

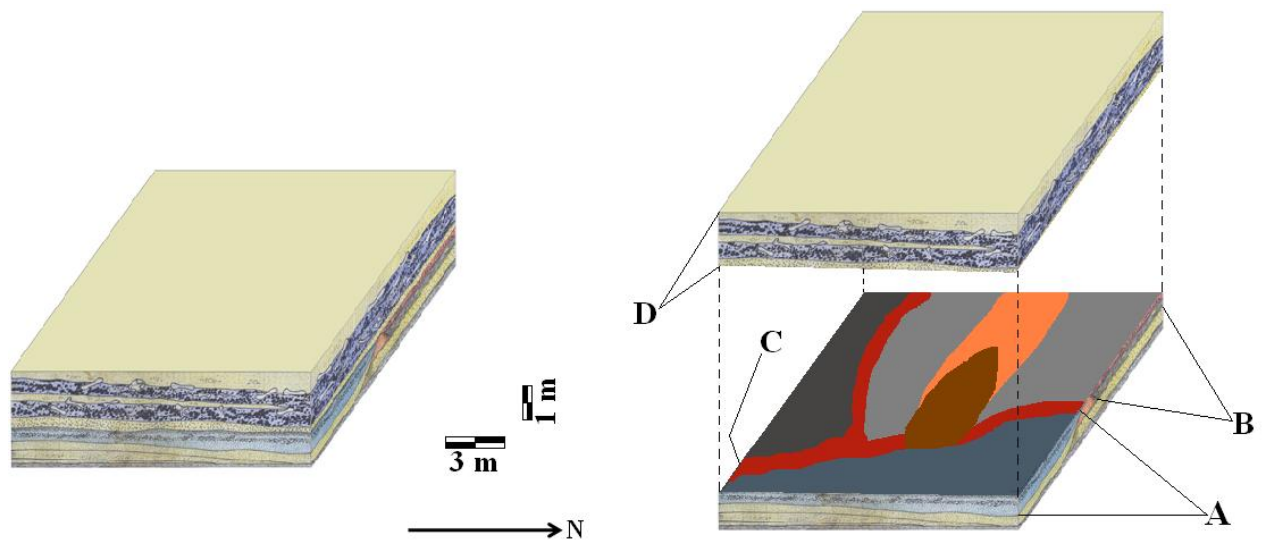


Figure 3.1. A dissected fence diagram of Bone Butte reveals the primary subdivisions of the sediments: (A) stream channel, (B) oxbow lake, (C) levee, and (D) crevasse-splay.

debris and carbonized plant matter, as well as rhizoliths. Above this lies a thin (~1.5 m thick) series of horizontal beds composed of massive and weakly bedded coarse-grained sandstones and massive cross-bedded sandstones that are not included within this study. The microstratigraphy of Bone Butte has been documented in extensive detail and provides a high-resolution record of the ~2 m thick interval studied.

Stratum 1: Massive Sandstone. This massive sandstone stratum is the uppermost unit of the study. The stratum averages 12 - 61 cm in thickness. Both weathered and fresh samples are light yellow-tan in color. Overall, the stratum undulates to a small degree and dips very slightly, between 2 and 3 degrees to the north. Grains are moderately to poorly sorted, and size ranges from medium to coarse-grained sand. The majority of the sediment, however, consists of medium-grained sand. Grain size decreases slightly toward the top of the stratum, where some discontinuous bands of silt appear. No bedding traces were noted, and the entire stratum is largely homogenous in its composition. Occasional subangular to subround clay rip-up clasts averaging 8 cm in diameter occur near the lower bounding surface (Fig. 3.2 D). The rip-up clasts are composed of light gray-green and orange, finely laminated mudstone that contains fossil plant material and primary pedogenic structures such as rhizoliths, slickensides, and invertebrate burrows (Fig. 3.2 D). Both the rhizoliths and walls of the burrows are stained red due to oxidation of iron. Upon microscopic inspection, it was noted that the majority of invertebrate burrows are filled with the same sediment as Stratum 1, indicating they were filled after they were removed from their initial area of deposition. Fossil material in Stratum 1 is generally restricted to plant matter. Whole leaves, plant sprigs, and pieces of petrified wood up to 90 cm in length are distributed chaotically and at various orientations throughout the stratum. The frequency of smaller plant matter (from 3 - 15 cm in length) increases toward the upper bounding surface of the stratum. Petrified wood is generally preserved as either lignite or silt-filled casts of the wood and, more infrequently, as three-dimensional ironstone casts. Sections of wood greater than 15 cm in length generally are oriented subhorizontally and point, on average, in the direction of N 44 E. The largest sections of wood also tend to concentrate around the upper bounding surface of the stratum. Vertebrate remains from Stratum 2A protrude up to 15 cm into

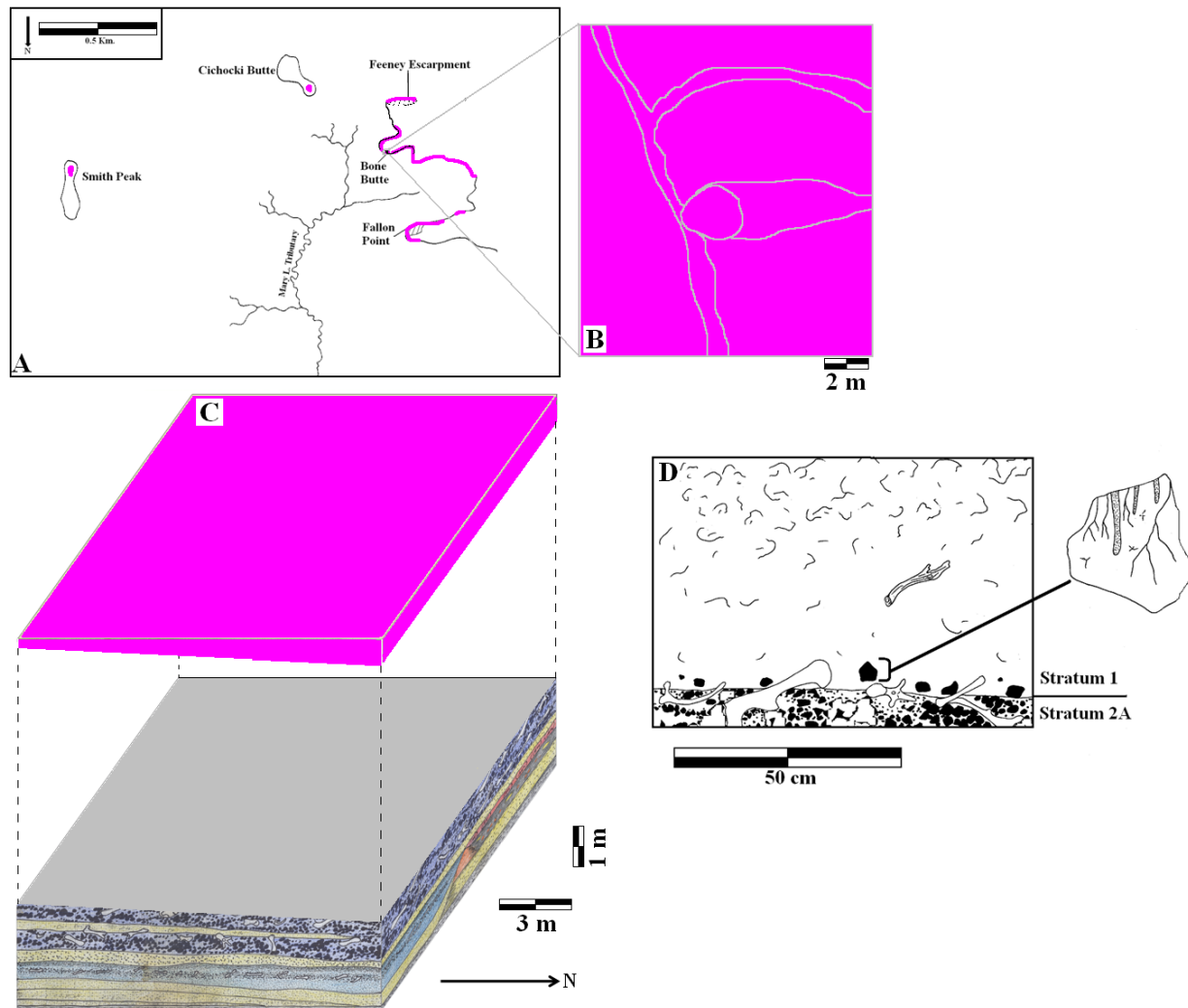


Figure 3.2. Data for Stratum 1. The lateral extent of Stratum 1 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C). The chaotic orientation of Stratum 1 plant debris, and the mudclasts composed of bioturbated paleosols, can be observed in (D).

the lower section of Stratum 1, but no bones are ever found completely encased within Stratum 1. Stratum 1 overlays the entire extent of Stratum 2A and its lateral extent was traced around the rim of Petra Valley, to the tip of Fallon Point to the north, to Smith Peak to the northeast, Cichocki Butte to the southeast, and the Feeney Escarpment to the southwest (Fig. 3.2).

Stratum 2A: Clay-pebble Conglomerate #1. Stratum 2A is a clast-supported, clay-pebble conglomerate composed of clay rip-up clasts, vertebrate remains, and coarse-grained sand that

directly underlay Stratum 1. This stratum ranges from 12.7 - 20.4 cm in thickness and dips 2 to 3 degrees north in the same fashion as Stratum 1. The stratum typically appears dark reddish-brown overall, due to the large number of iron-stained mudclasts, fossil bones, and limonite nodules. The sandy matrix of the stratum is typically buff-tan to orange in color. This stratum is composed primarily of subangular clay rip-up clasts averaging 10 - 15 cm in diameter. The rip-up clasts are typically light gray-green with red mottling. Thin laminae representing original bedding traces are present in the mudclasts, as well as pedogenic structures such as rhizoliths, invertebrate burrows, and slickensides. As with Stratum 1, the rhizoliths and interior walls of the burrows are stained red and most burrows are filled with coarse-grained sediment identical to the matrix of Stratum 2A. Limonite and siderite nodules are common in this stratum and occur in clusters associated with mudclasts and bones. Coarse, buff-tan to orange sandstone composes the matrix of Stratum 2A and is relatively equally dispersed throughout the stratum. The sand comprises less than 23% of the stratum, and grains are subangular in surface morphology. No bedding traces are present, though the tightly packed mudclasts, bones, and limonite and siderite nodules generally restrict the sand to a series of thin, undulating, frequently interconnected lenses. No burrows, rhizoliths, or other obvious structures are observed in Stratum 2A. Fossil vertebrate remains are distributed throughout the stratum and their vertical orientation is chaotic, sometimes protruding into Stratum 1 above. Lateral orientation of the bones has more structure, however. Observations of bones in the field and on the quarry maps reveal elongated clusters of bones, petrified wood and debris that point, on average, in the direction of N 43 E. Petrified wood is preserved primarily three-dimensionally in ironstone and ranges from 5 cm to over 2 m in length. Other than the wood, no plant matter was recovered from Stratum 2A. At its lower bounding surface, Stratum 2A contacts Stratum 3 over the majority of the dig site area, except where Stratum 3 pinches out in the last 1.5 m to the north (Appendix A 1). Where Strata 2A and

2B contact each other at the northern end of the site, no bones from Stratum 2B protrude into 2A. On the contrary, some bones in Stratum 2B are sheared off and broken at the boundary between the two strata (Appendix A 1). The nearly identical nature of Strata 2A and 2B, and the fact that on the north end of the site they are in direct contact with each other, led to the initial incorrect hypothesis that they were a single stratum. As excavations progressed, Stratum 3 was discovered between them, and other details (such as sheared-off bones) support the fact that Stratum 2 is not a single unit. Hence, Stratum 2 was labeled as two distinct strata, 2A and 2B respectively, each deposited during similar, yet separate and distinct, events. Stratum 2A covers the extent of the Bone Butte dig site and, as with Stratum 1, was traced around the rim of Petra Valley, to the tip of Fallon Point to the north, to Smith Peak to the northeast, Cichocki Butte to the southeast, and the Feeney Escarpment to the southwest (Appendix A 1).

Stratum 3: Massive Sandstone. This massive sandstone stratum is similar in overall composition to Stratum 1. Stratum 3 ranges in thickness from 10.2 - 20.4 cm and is light yellow-tan in color. The stratum dips 2 to 3 degrees to the north in the same fashion as Strata 1 and 2A. The poorly sorted sediment is predominantly composed of medium-grained sand exhibiting subangular surface morphology. As with Stratum 1, discontinuous bands of silt occur along the upper bounding surface, but are limited to the southern portion of the quarry, where Stratum 3 is thickest. Rip-up mudclasts are virtually absent from this stratum and consist of gray-green subround to subangular mudclasts with red mottling and rarely exceed 2 - 3 cm. Mudclast surface morphology is subangular to subround and mudclasts possess nearly identical internal structures to those seen in mudclasts from the previously mentioned strata. No bedding traces are apparent, although intermittent clusters of *in situ* rhizoliths and invertebrate burrows are present at the upper bounding surface near the south end of the quarry. The few plant remains present are comprised of smaller leaves and twig fragments in the 1 - 8 cm range. Fossil bones are not

present in this stratum except for those that protrude up from Stratum 2B. In a similar situation to Stratum 1, bones protrude upward from Stratum 2B through the lower bounding surface of Stratum 3, to an extent of 9 cm in some cases (Appendix A 2). Stratum 3 extends over virtually the entire area of the dig site, except for a 1-m patch that is interrupted by an erosionally resistant paleosol (Stratum 14), and the last 1.5 m to the north, where Stratum 3 pinches out (Appendix A 2). The lateral extent of the stratum was traced westward along the rim of Petra Valley but pinches out after less than 12 m (Appendix A 2). Tracing the stratum south to the Feeney Escarpment proved impossible due to slumping in that area obscuring positive identification.

Stratum 2B: Clay-pebble Conglomerate #2. Stratum 2B is a clast-supported, clay-pebble conglomerate composed of clay rip-up clasts, vertebrate remains, and coarse-grained sand that virtually duplicates Stratum 2A in composition and appearance. As mentioned previously, Stratum 2B was never a part of Stratum 2A, and was formed during a separate depositional event. Stratum 2B ranges from 10.1 - 15.3 cm in thickness and dips 2 to 3 degrees north in the same fashion as Strata 1, 2A, and 3. As with Stratum 2A, this stratum typically appears dark reddish-brown overall, due to the large number of iron-stained mudclasts, fossil bones, and limonite nodules. The sandy matrix of the stratum is typically buff-tan to orange in color. This stratum is composed primarily of subround to subangular clay rip-up clasts averaging 5 - 6 cm in diameter. The clasts, as with the previous strata, are composed of gray-green mudstone with red mottling and are subangular to subround in surface morphology. Internal structure is identical to the previously mentioned mud clasts. Framework matrix is composed of both medium and coarse-grained sand, although medium-grained sand is more prevalent. The sand exists as a series of thin, often interconnecting lenses between tightly packed mud clasts, fossil bones, limonite and siderite nodules, and plant debris. Vertebrate remains are nearly as prevalent as they are in Stratum 2A, though frequency and average size is slightly lower. Petrified wood is almost

exclusively represented by three-dimensional ironstone castings and average sizes present are between 2 cm and 1.5 m. Vertebrate remains and petrified wood are distributed throughout the stratum, even protruding into Stratum 3 above. Vertical orientation of bones and wood specimens is chaotic, although field observations and examination of the quarry maps revealed that the specimens are arranged in elongated clusters that point, on average, N 39 E, a similar condition to that seen in Stratum 2A. Stratum 2B covers the extent of the dig site area and was traced along the rim of Petra Valley but pinches out before it reaches Fallon Point to the north (Appendix A 3). As with Stratum 3, tracing the stratum south to the Feeney Escarpment proved impossible due to slumping in that area. Stratum 2B is also interrupted by the same erosionally resistant paleosol (Stratum 14 and the upper part of Stratum 13) that interrupts Stratum 3.

Stratum 4: Massive Sandstone. Stratum 4 is a thin 5 - 12 cm-thick deposit of massive sandstone directly underlying Stratum 2B. Color of Stratum 4 varies from light yellow-tan to light orange. The sediment is poorly sorted, and is comprised of medium to fine-grained sandstone. The upper bounding surface of Stratum 4 dips slightly north by 2 to 3 degrees, as did all of the previously described strata, and contains a thin ~2 cm thick cap of silt, as well as intermittent invertebrate burrows and rhizoliths preserved *in situ*. Attached to the rhizoliths are portions of plants, bent horizontally to rest against the bedding surface. The direction of orientation for such plants varies, but averages N 43 E. No obvious bedding traces are present and the stratum is virtually absent of any sedimentary structure. Small angiosperm leaves and some gymnosperm material are oriented chaotically throughout the stratum, showing no obvious orientation. Mud clasts are absent and there are no traces of fossil bone. Stratum 4 covers the entire extent of the dig site, except for a small area interrupted by Strata 13 and 14, and was traced westward along the rim of Petra Valley for 7 m before pinching out (Appendix A 4). It, as well as Strata 1, 2A, 2B, and 3, most likely extend as far south as the Feeney Escarpment but

positive identification to differentiate between the different sandstones and conglomerates was not possible due to slumping in the area.

Stratum 5: Clay-pebble Conglomerate #3; Bird and Mammal Zone. Stratum 5 is a clay-pebble conglomerate composed of multiple alternating laminae of fine to medium-grained

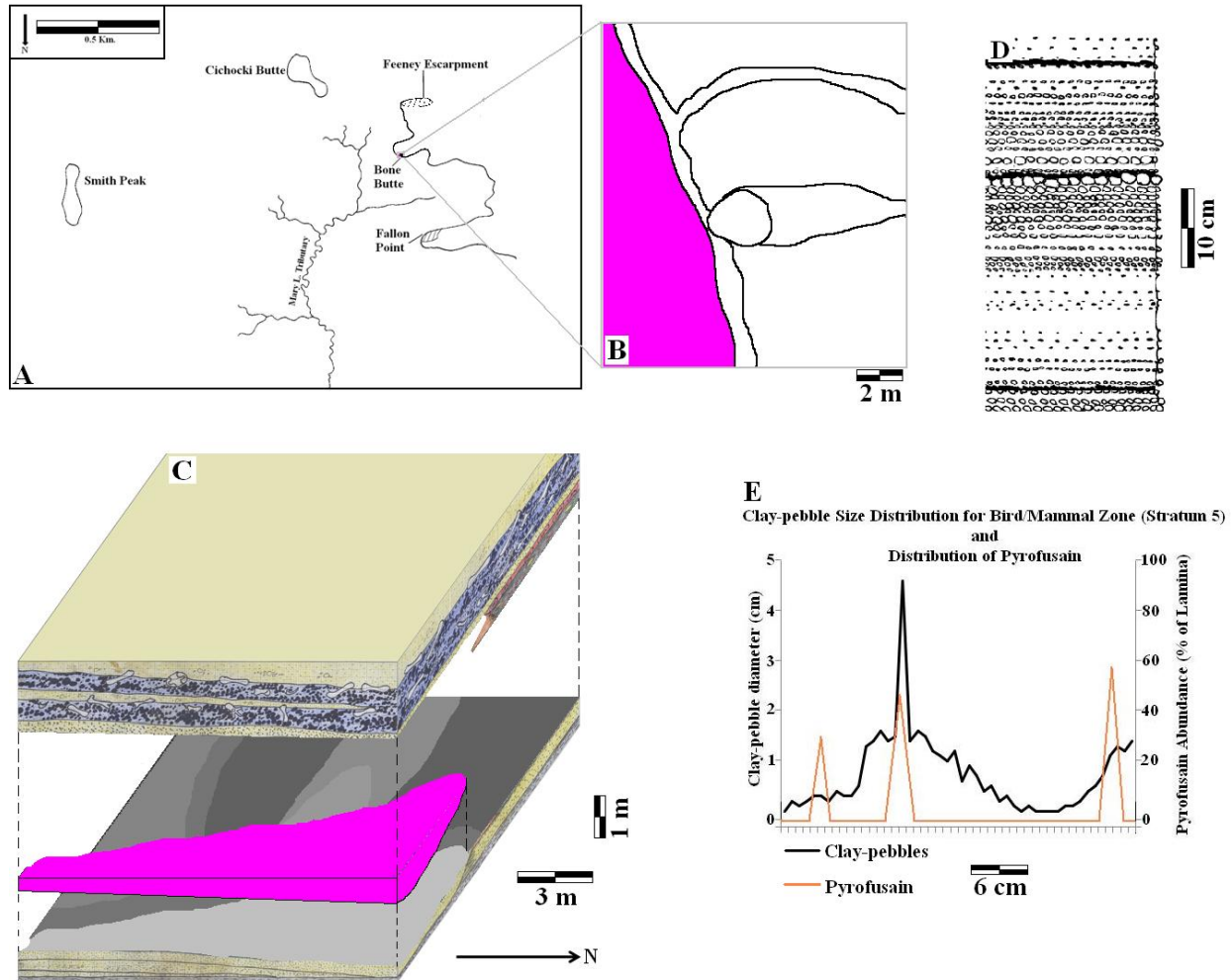


Figure 3.3. Stratum 5 data. The lateral extent of Stratum 5 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C). A generalized stratigraphic column for Stratum 5 can be observed in (D), and a graph of clay-pebble size variation and the presence of pyrofusain is depicted in (E).

sandstone and small (0.3 - 5 cm) clay pebbles (Fig. 3.3 D). This stratum is horizontal and has a thickness of 15 - 35 cm. The color ranges from light gray-green to buff-tan depending on the ratio of mud clasts to sand grains. Laminae composed of sand average 0.8 cm in thickness and are composed of micro-laminae of alternating fine and medium-grained sand. Grains are subround and generally well-sorted. The sand laminae are interbedded with laminae composed almost exclusively of small clay pebbles that range in size from 2 - 50 mm. The clay-pebble laminae contain a small (<6%) amount of sand, all of which is medium-grained, and laminae with larger clay-pebbles generally contain larger bone fragments as well as seeds, charcoalfied wood preserved as pyrofusain, and plant material. The majority of fossil bones in Stratum 5 are complete and well-preserved. Pyrofusain is present in greatest abundance at specific stratigraphic intervals (Fig. 3.3 E), but is otherwise virtually absent from the rest of the stratum. Each of the clay-pebble laminae were examined with respect to the average size of their constituent clay-pebbles, revealing an overall pattern in clay-pebble size (Fig. 3.3 E). The alternating clay-pebble and sand laminae, in addition to occasional limonite nodules, comprise virtually the entire stratum except for one interval, approximately two-thirds below the upper bounding surface, in which a clay pebble lamina comprised of significantly larger 0.5 - 7 cm clay pebbles occurs. This robust lamina is enriched with pyrofusain, vertebrate remains in greater abundance than the other Stratum 5 laminae, lignified plant material, and seeds. In the portions of Stratum 5 above the robust clay-pebble lamina, especially in the upper 5 - 10 cm, overall grain size steadily decreases, while organic content markedly increases. Lamina thickness and grain size decrease upward until the upper 3 - 5 cm are composed entirely of light brownish-black, finely bedded organic-rich silt punctuated by regularly spaced clay-pebble laminae (Fig. 3.3 D). Other than some "*Ficus*" *ceratops* horsetail rhizomes (Brown, 1937) in the upper 3 cm of the stratum, no root traces, bioturbation, or other sedimentary structures were observed in Stratum 5. Fossil bone

is common throughout Stratum 5, with brief increases in the clay-pebble laminae. The single robust clay-pebble lamina contains the greatest abundance of bone, more notably a higher frequency of bird and mammal bones than in any other stratum. The Small 1 - 10 mm pieces of amber are common in the dark, organic-rich siltstones near the upper bounding surface of Stratum 5. The stratum exists as a narrow strip along the northeast corner of the dig site and persists along virtually the entire north-south extent of the site. Stratum 5 abuts against the erosionally resistant paleosol of Stratum 13 to the west, and grades into parts of the highly bioturbated and oxidized Stratum 18, which runs as a strip in a roughly north-south direction (Fig. 3.3). No other strata could be correlated with Stratum 5.

Stratum 6: Sandstone. Stratum 6 is approximately 3.9 - 10 cm in thickness, underlays Stratum 5, and is composed of intermittent finely cross-bedded sandstone lenses and massive sandstone. This stratum is light yellow-tan in color and contains a minimal number of mudclasts. Grains range from fine to very fine-grained sand. The stratum's upper bounding surface is equally horizontal to Stratum 5, though the lower bounding surface dips approximately 2 to 3 degrees north, following the contours of the underlying Stratum 7. Clusters of fossil plant material are periodically found but are poorly preserved, occur as impressions and carbon films, and are oriented chaotically throughout the stratum. Plant preservation is good enough, however, to note that both angiosperms and gymnosperms are present in relatively equal abundance. Fossil vertebrate material is not common and consists of tiny, unidentifiable bone fragments. Stratum 6 extends over the full lateral area of Stratum 5, abuts against Stratum 15 to the west, and upper portions of its western margin grade into Stratum 18 (Appendix A 5).

Stratum 7: Nodular Sandstone. Stratum 7 consists of medium-grained sandstone with a high content of siderite and limonite nodules. This stratum is between 5.1 and 8.1 cm thick and

underlays Stratum 6. The entire stratum dips slightly to the north, by approximately 2 to 3 degrees. Stratum 7 is medium to dark tan in color, appearing darker due to the abundance of ironstone nodules. Concretionary nodules ranging from 3 to 5 cm comprise approximately 60% of the stratum, with the remainder comprised of medium-grained, well-sorted sandstone. No obvious sedimentary structures are visible and no fossil material was observed. Stratum 7 extends the majority of Stratum 5's lateral area, though Stratum 7 pinches out within 90 cm of the site's north boundary (Appendix A 6).

Stratum 9: Fine-grained Sandstone. Stratum 9 underlays Stratum 7 and is comprised of fine-grained sandstone. Thickness is between 7.6 and 12 cm and sediment grain size is consistently in the fine-grained range. The upper bounding surface dips 2 to 3 degrees to the north but the lower bounding surface is relatively horizontal. Color of this stratum is uniformly light yellow-tan. No obvious sedimentary structures are present, although occasional limonite nodules occur. No fossils of any sort were observed. Stratum 9 follows the course of Stratum 5, but pinches out nearly 5 m south of the north boundary of the site (Appendix A 7).

Stratum 10: Mudstone; Quarry Floor. Stratum 10 comprises the floor of the Bone Butte quarry. This stratum is between 30 and 100 cm thick and is composed entirely of finely-laminated mudstone. Color ranges from light gray to dark gray and black with some reddish mottling, and fissility is variable. Plant fossils are present and preserved as numerous, small fragments and carbon films, none of which reveal any taxonomically valuable information. Patches of ichnofossils such as rhizoliths and invertebrate burrows, as well as blocky pedogenic structures and slickensides, are occasionally present at various locations across the upper contact between Stratum 10 and the overlying Bone Butte strata, however all such structures are incomplete and are cross-cut at Stratum 10's upper bounding surface. This stratum extends

laterally for tens of meters and is close in composition to the majority of the additional strata below it in Petra Valley. Stratum 10 was only examined with respect to its contact with the main Bone Butte strata and was not subjected to further investigation.

Stratum 11: Organic-rich Siltstone (Oxbow upper portion). Stratum 11 is a localized

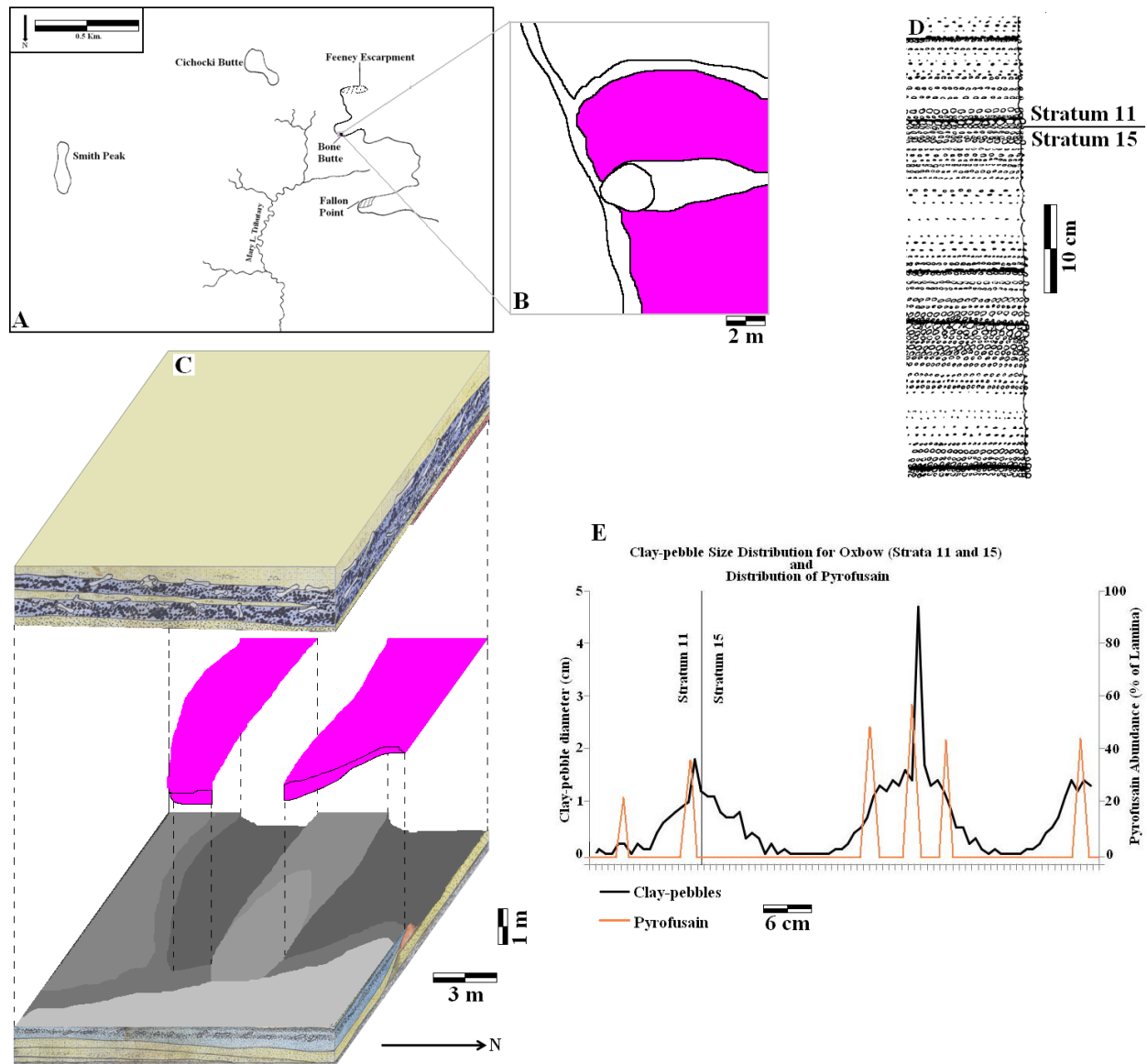


Figure 3.4. Stratum 11 data. The lateral extent of Stratum 11 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C). A generalized stratigraphic column for Strata 11 and 15 can be observed in (D), and a graph of clay-pebble size variation and the presence of pyrofuosain in Strata 11 and 15 is depicted in (E).

organic-rich siltstone deposit that exists directly atop Stratum 15, flanking the north and south sides of Stratum 16 point-bar deposits. This stratum is between 10 and 25 cm thick and is dark brown to black in color. Highly fissile, organic-rich, fine-grained siltstone punctuated by periodic clay-pebble laminae comprise the entire stratum (Fig. 3.4 D). The average size of constituent clay-pebbles of the laminae was recorded and graphed to reveal a similar pattern to that seen in Stratum 5 (Fig. 3.4 E). The pattern of clay-pebble size variation in Stratum 11 correlates with that seen in the upper portion of Stratum 5 (Fig. 3.4 F). Periodic lenses of medium to fine-grained sandstone mixed with mudstone exist throughout. Grain size and coloration of the stratum remain relatively consistent throughout and few sedimentary structures other than bedding traces were observed. In the upper 2 cm occasional “*Ficus*” *ceratops* horsetail rhizomes, rhizoliths, and invertebrate burrows were observed. Vertebrate fossils in this stratum consist primarily very complete, well-preserved, and sometimes articulated bones of turtles, fish, dinosaurs, and aquatic reptiles of various sizes. Plant fossils are not well preserved although they are profuse. Certain laminae are densely packed with well-preserved plant material, virtually all of which are gymnosperms, the aquatic plant *Pistia corrugata*, and *Equisetum* horsetail fossils. Conversely, the sandstone lenses all contain extremely well-preserved examples of fossil leaves and sprigs, most of which are angiosperms. Amber is profuse in the organic siltstone and pieces exceeding 3 cm in diameter are common. Insect inclusions and plant debris were recovered from amber specimens from this stratum. Stratum 11 directly underlays Stratum 12 and abuts against Stratum 16’s north and south margins. Stratum 16’s western margin has been removed by modern erosion, so no data is available for that area. The southernmost margin of Stratum 11 contacts Stratum 10, and Stratum 11’s eastern margin interfingers with Stratum 18 (Fig. 3.4).

Stratum 12: Tabular Sheet of Ironstone. Stratum 12 is a broad, dense sheet of ironstone that overlays Strata 11 and 16. This stratum is consistently 10 - 12 cm in thickness and nearly horizontal in nature. The color is dark reddish-brown and does not vary appreciably. The ironstone is homogenous and does not contain any visible internal structures or bedding traces. Occasional fragments of plant matter were observed within the concretion but otherwise no fossils are preserved. The surface morphology exhibits an undulating rippled texture in many areas and occasionally traces of lithified mud cracks are visible (Appendix A 8). Small U-shaped burrows are preserved as convex hypichnal traces on the lower bounding surface of Stratum 12, incised less than 1 cm into the underlying strata. Stratum 12 completely covers Strata 11 and 16, and extends from Stratum 11's southernmost margin all the way to the northern border of the site (Appendix A 8).

Stratum 13: Erosionally Resistant Paleosol (Lower). Stratum 13 is a relatively vertical section of paleosol that interrupts Strata 2B, 4, 11, 12, and 15 (Fig. 3.5 A - C). Stratum 13 is approximately 90 cm in thickness and is composed of highly bioturbated mudstones and siltstones. This stratum is generally greenish-gray in color with extensive red mottling. A mixture of siltstone and mudstone comprise the stratum, and sediment grain size varies in patches. The entire stratum is very well indurated and problematic to break apart. No bedding traces are visible, as the entire stratum is highly bioturbated by invertebrate burrows and rhizoliths. Some remnant bedding traces are present at the lower bounding surface where Stratum 13 grades into Stratum 10. Near the contact between Stratum 13 and 14, many invertebrate burrows are present, the interior walls of which are always stained dark red from oxidation. The matrix filling the burrows is coarse-grained, yellow-tan sand. Root traces are present in the upper 50 cm, nearly all of which could be traced into the overlying Stratum 14. Within the stratum are many pieces of petrified wood, preserved as three-dimensional ironstone castings with outer

lignite crusts. The wood frequently exceeds 15 cm in diameter and a significant proportion extends into Stratum 14. Other than petrified wood, no additional fossils were recovered. Stratum 13 exists as a vertical structure, approximately centered in the dig site and nearly 2 m from the site's north border. The stratum is elongated to the west and continues westward for approximately 7 m. Portions of Stratum 13's westward "tail" are overlaid by Strata 12 and 16 (Fig. 3.5).

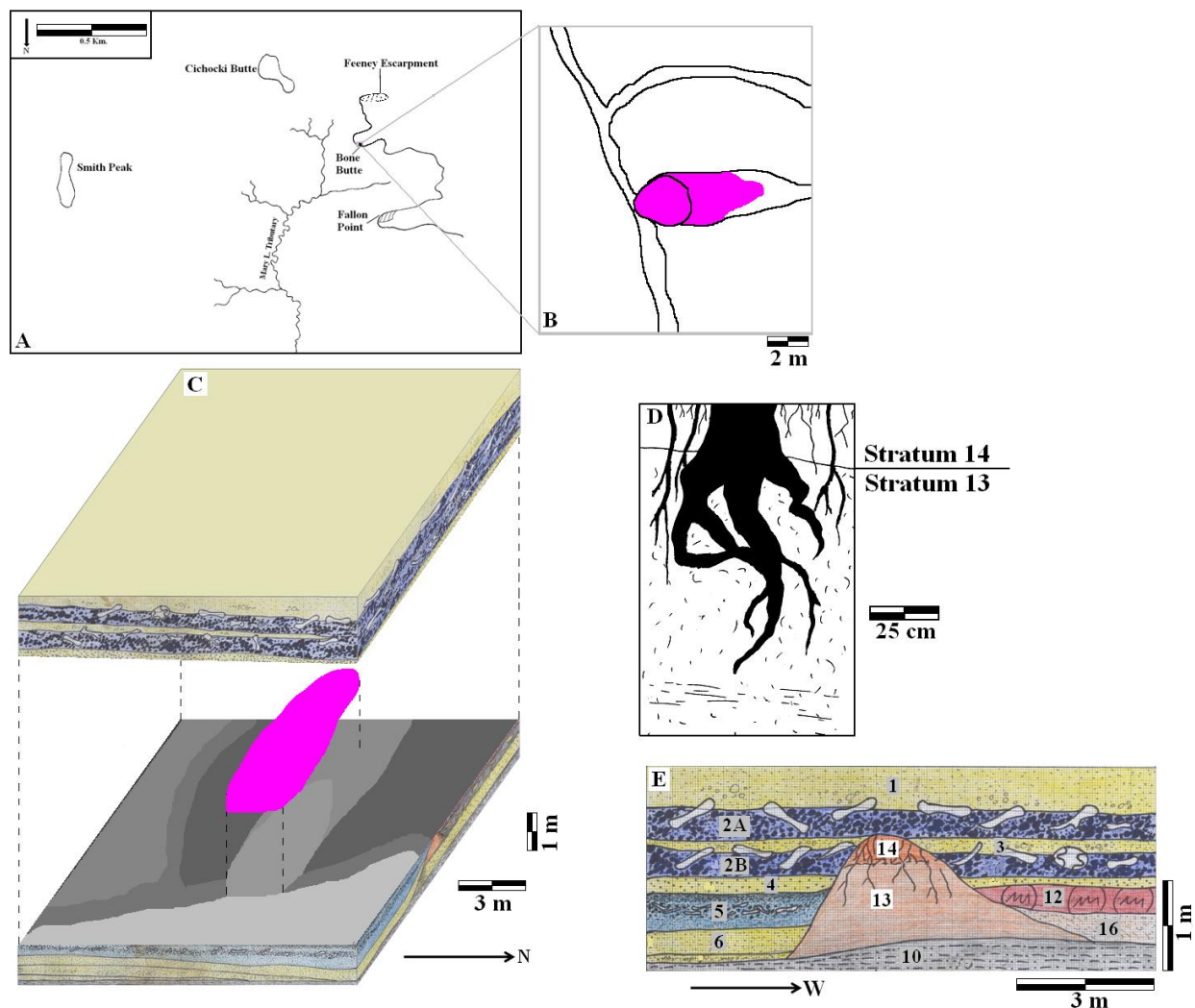


Figure 3.5. Stratum 13 data. The lateral extent of Stratum 13 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C) and (E). A lateral cutaway diagram of the stratum (D) shows the pervasive rhizoliths and plant material present in Strata 13 and 14.

Stratum 14: Erosionally resistant Paleosol (Upper). Stratum 14 is a second component of the erosionally resistant paleosol structure, and overlays Stratum 13. Stratum 14 is approximately 25 cm in thickness and is dark reddish-orange in color with patches of gray-green mottling. Similar in overall composition to Stratum 13, Stratum 14 contains a higher clay content and is much more heavily bioturbated. The stratum, overall, is extremely hard and indurated. Pedogenic structures such as rhizoliths, slickensides, invertebrate burrows, and blocky pedogenic structures are common. Rhizoliths are much more abundant than those seen in Stratum 13; while some rhizoliths continue from Stratum 14 down into Stratum 13, additional groups of rhizoliths terminate at Stratum 14's lower bounding surface and do not cross over into Stratum 13. Stratum 14's rhizoliths, in contrast to those in Stratum 13, are greenish-gray in coloration, in a dark red matrix. As with Stratum 13, the burrows in Stratum 14 are filled with coarse-grained, yellow-tan sand. Pieces of intertwined petrified wood of substantial diameter (up to 25 cm in diameter) and length (up to 40 cm long) extend from Stratum 14 into Stratum 13. No additional fossils were recovered. Stratum 14 is a small remnant of paleosol that sits atop Stratum 13 and interrupts Strata 2B and 3 (Appendix A 9).

Stratum 15: Thinly bedded Sandstone (Oxbow lower portion). Stratum 15 underlays Strata 11 and 18, and measures between 20 and 25 cm thick. Overall, the stratum is buff-tan in color and consists of medium to fine-grained sandstone punctuated at semi-regular intervals by laminae composed of clay-pebbles. Laminae of medium and fine-grained sandstone, and others composed of clay-pebble conglomerate, generally do not exceed 1 cm in thickness and alternate to form a stratum of relatively consistent appearance. The average size of clay-pebbles comprising the regularly spaced clay-pebble laminae was recorded and forms a record of clay-pebble size variation continuous with that of Stratum 11. A similar pattern in clay-pebble size variation to that seen in Stratum 5 is evident, with a regularly fluctuating increase and decrease

of clay-pebble size (Appendix A 10). The pattern of variation in clay-pebble size for the upper portion of Stratum 15 correlates with the pattern observed in the lower portion of Stratum 5. In the portion of Stratum 15 on the south side of Stratum 16, Stratum 15's laminae dip slightly to the west. Conversely, in the portion of Stratum 15 to the north of Stratum 16, Stratum 15's laminae dip slightly to the east. In addition, as the laminae come in contact with Stratum 16, they follow Stratum 16's gradual incline. In a similar condition to Stratum 5, Stratum 15's overall grain size decreases toward its upper bounding surface, as it vertically grades into Stratum 11. The fining-upward sequence exhibits progressively finer sediments and thinner laminae until, at its upper contact with Stratum 11, there is almost no way to distinguish Stratum 15 from Stratum 11 (Appendix A 10). Vertebrate fossils recovered from Stratum 15 are plentiful and they follow a rough horseshoe-shaped pattern around Stratum 13 and the Stratum 16 point bar. "*Ficus*" *ceratops* rhizomes and *Equisetum* shafts are present in the upper portions of Stratum 15. The stratum has a lateral extent that matches that of Stratum 11 (Appendix A 10).

Stratum 16: Fine-grained Sandstone. Stratum 16 is a rather small, localized patch of thinly laminated, sometimes cross-bedded, sandstone. Thickness of this stratum averages 9 - 25 cm. Coloration is typically light to dark tan-orange, darkening upward. Stratum 16 is composed almost exclusively of fine-grained, well-sorted sandstone. Laminae are numerous and generally flat, dipping slightly to the west. Occasionally some cross-bedding is present, but is not common. The upper 4 cm is generally bioturbated and much of the bedding traces are lost. In addition, rhizoliths, "*Ficus*" *ceratops* rhizomes, and *Equisetum* horsetail shafts occur in the upper portion, sometimes in abundance. Rhizoliths in Stratum 16 are always stained green-gray. Invertebrate traces such as *Cochlichnus* were observed, in addition to two examples of bird tracks. No vertebrate fossils were found. Stratum 16 is flanked to the north and south by Stratum 15, and

overlays the “tail” of Stratum 13 to the east. Stratum 16 is bounded at the top by Stratum 12, and at the bottom by Stratum 10 (Appendix A 11).

Stratum 17: Lenticular Ironstone. Stratum 17 consists of several small patches of lenticular ironstone, all of similar morphology. The lenses are dark reddish-brown in coloration and typically do not exceed 8 cm in thickness. Similar in composition to Stratum 12, Stratum 17 is composed of homogenous, fine-grained ironstone that is exceedingly hard and well-cemented. No traces, burrows, rhizoliths, pedogenic structures, or fossils are present. The surface of Stratum 17 is occasionally undulatory and contains a few traces of mud cracks, but otherwise exhibits no unique morphology. Stratum 17 exists as several localized lenses resting atop Strata 10 and 18 in the southwest section of the dig site (Appendix A 12).

Stratum 18: Bioturbated Siltstone. Stratum 18 exists as a narrow strip of highly bioturbated siltstone that runs roughly down the center of the dig site. Stratum 18 varies in color from light tan-orange to deep reddish-brown, and is generally not more than 23 cm in thickness. The stratum is composed entirely of siltstone, and clay content varies from low to moderate. Bioturbation is extensive and no original bedding traces are evident. Invertebrate burrows are prevalent, many times cross-cutting each other. Burrow walls are stained greenish-gray and the interiors are filled with coarse-grained, yellow-tan sand. Rhizoliths are common and are stained greenish-gray. No vertebrate fossils occur in Stratum 18. The stratum runs roughly north to south through the middle of the site, resting atop Stratum 15 to the north and Stratum 10 to the south. Stratum 18 interfingers with Stratum 11 and appears to grade into Strata 5 and 6 to the east (Fig. 3.6).

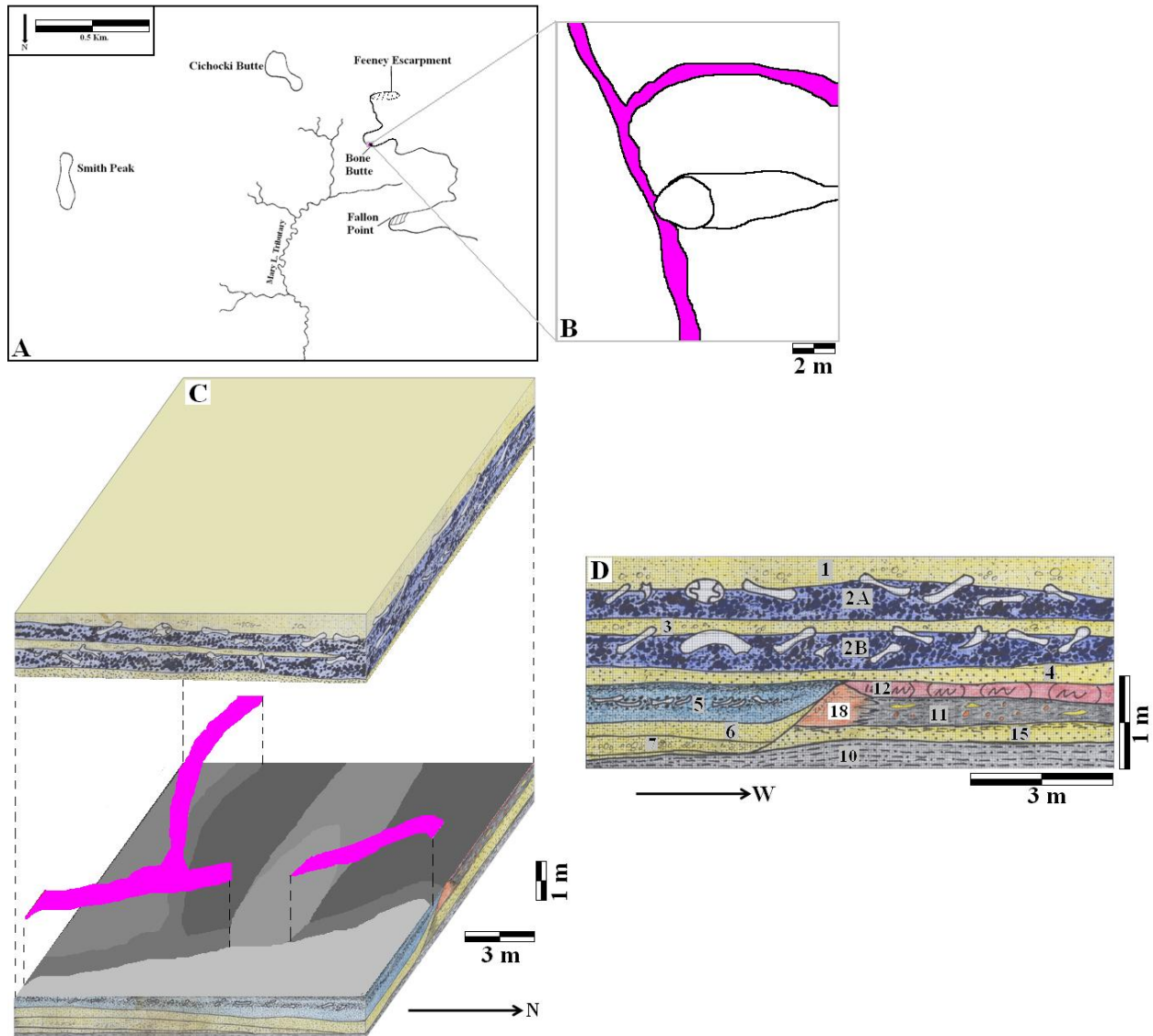


Figure 3.6. Stratum 18 data. The lateral extent of Stratum 18 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C) and (D).

3.2 Experiments

3.2.1 Stream Table Experiments

Questions regarding the effect of weather-resistant obstructions on oxbow morphology, the effects of a tributary coming into contact with its destination channel upstream of the tributary's primary outflow point, and the effects of a tributary on the spatial occurrence of

crevasse splays produced by a main channel were all addressed through direct experimentation utilizing a stream table apparatus. Results from the stream table experiments were augmented with satellite photos and ground reconnaissance of modern analogs of Hell Creek river systems.

During the first run of experiments, a series of 20 meanders were allowed to form, which became recumbent and eventually cut off to form oxbow lakes (Fig. 3.7). The first 10 meanders



Figure 3.7. Bone Butte stream table experiment results for meander formation. When an obstruction was not present, meanders formed in perfect, textbook fashion, with a teardrop shape (G – L). However, the presence of an obstruction altered the morphology of developing meanders, generally forming an elongated head (A – F). Arrow in (B) points to an obstruction, and arrow in (C) points to back-filled portion of the stream as the meander migrated to the right.

were formed with no obstructions impeding the stream flow. In each of the 10 runs, virtually perfect, textbook examples of oxbow lakes were produced, in which the point bar “head” of the oxbow expanded distally and formed a teardrop shape (Fig 3.7 G – L). An additional 10 experimental runs were carried out in the same sediment, under identical conditions, save for the fact that an erosionally resistant obstruction composed of compressed clay was placed along the bank near an insipient meander. As the meander produced by the stream grew and matured, the

channel encountered the clay obstacle and initially formed a small erosional embayment in the bank on the upstream-side of the obstacle (Fig. 3.7 B). As the meander continued to grow, it eventually circumvented the clay obstacle, thereby forming a temporary island in the stream (Fig. 3.7 C). The meander continued to grow, progressing laterally past the obstacle, until the original course of the stream was filled in by point bar deposits and the loop of the meander circled around the clay obstacle (Fig. 3.7 D). Contrary to what was observed in the first experimental runs, the stream current was deflected off of the clay obstacle, forming a narrow, elongated point bar between the meander horns rather than a short, teardrop-shaped one (Fig. 3.7 E). Eventually the horns of the recumbent meander contacted each other at the meander's neck, breaching the previously formed point bar deposits and forming a relatively straight channel once again. The cut-off meander continued to receive water flow from the stream until it progressively filled with silt, and laterally accreting sediments from the active channel formed levees that completely cut the meander off, forming an oxbow lake (Fig. 3.7 F). The presence of an obstruction did, indeed, have an effect on the overall morphology of the meanders and oxbow lakes, and consistently produced elongated oxbows (Fig. 3.7).

The second suite of experimental runs tested the condition in which a tributary stream, emptying into a larger trunk channel, eventually contacted the channel upstream of the tributary's main outflow point. In each instance, as a meander contacted the main channel upstream of the tributary's primary juncture with the channel, flow in the downstream portion of the tributary immediately decreased while flow in the upstream portion remained the same (Fig. 3.8 B, D, E). More notably, the decreased flow in the downstream portion of the tributary deposited lag sediments and bars, further decreasing its flow (Fig. D, E). The downstream portion of the tributary progressively filled with finer sediments until it was completely abandoned (Fig. 3.8 B). As the total volume of water entering the main channel never changed,

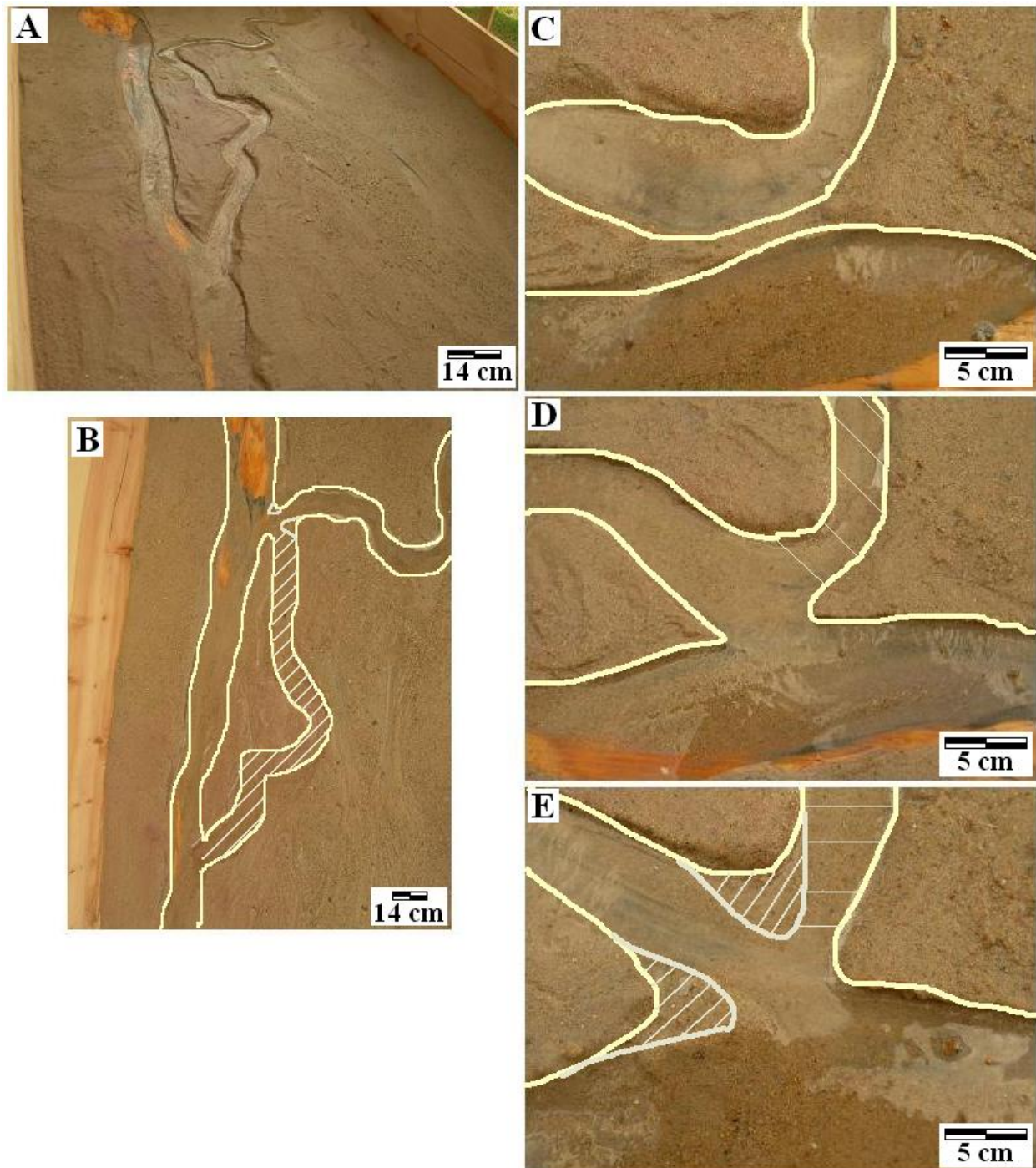


Figure 3.8. Bone Butte stream table experiment results for secondary connection of a tributary. A tributary's meander migrates close to a larger trunk channel (A, C). After the meander contacts the trunk channel and merges with it (B, D), water flow in the downstream portion of the tributary immediately begins to decrease, and fine sediments are deposited. Eventually, point bars begin to form (E), excluding the downstream portion of the tributary, and leading to the eventual abandonment of the downstream portion (B, E).

the flow of the main channel was not affected during the course of the experimental runs. The tributary, however, consistently demonstrated a decrease in flow and eventual abandonment of the downstream portions of its course after meanders came into secondary contact with the main channel.

The third suite of experiments was carried out in an attempt to observe the effects of tributary placement on crevasse-splay formation. Three stream conditions were tested in this experiment, in which: 1) a main channel was intersected by a tributary, 2) a main channel being intersected twice by the same tributary (both at the normal outflow point and a secondary contact upstream), and 3) a main channel with no tributaries intersecting it. For condition 1, the main channel breached and formed a crevasse-splay in the vicinity of the tributary's juncture with the channel in 9 out of 10 runs (Fig. 3.9 A). Condition 2 had similar results, although the majority of

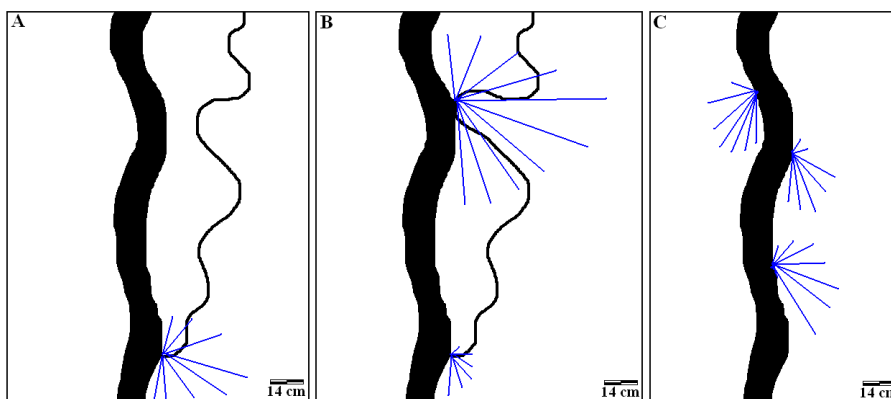


Figure 3.9. Bone Butte stream table experiment crevasse-splay formation results. When a trunk channel is intersected by a tributary, crevasse-splays frequently occurred at the tributary-channel junction (A). In cases where a tributary made a secondary connection with the trunk channel, crevasse-splays more frequently occurred at the upstream junction than the downstream junction (B). In instances where no tributaries intersected the trunk channel, crevasse-splay formation was random and displayed no obvious preference for location (C).

main channel breaches formed at the upstream juncture between the tributary's meander and the main channel (Fig. 3.9 B). The primary juncture between the tributary and main channel,

downstream of the secondary contact, saw far fewer breaches. It is notable that all breaches occurred at points in which the tributary intersected the main channel, and a direct correlation was observed between crevasse-splays and tributary-channel intersection. Condition 3, in which no tributary intersected the main channel, produced the most random results. In nearly all 10 runs for condition 3, the main channel was breached at different, apparently random, locations along its course (Fig. 3.9 C).

In all cases the experimental stream table results reinforce original notions regarding the formation and morphology of the particular fluvial structures tested: ¹⁾obstructions in a stream's path can create similar elongated oxbow morphology to that seen at Bone Butte, ²⁾tributaries with secondary connections with their destination channel will tend to abandon the downstream portion, and ³⁾crevasse-splay formation is definitely more prone to occur at the juncture between tributaries and their destination channels than at random. The experimental results were augmented by examination of satellite images of modern fluvial analogs and ground reconnaissance. Locations along the Suwannee River in Florida and Big Creek in Georgia were explored in person, and satellite images of those and other river systems around the world were examined using Google Earth, providing multiple corroborative examples of oxbow lakes formed by partially obstructed meanders, tributaries contacting a main channel in multiple areas due to migrating meanders, and crevasse-splays affected and influenced by junctures with tributaries (Fig. 3.10).

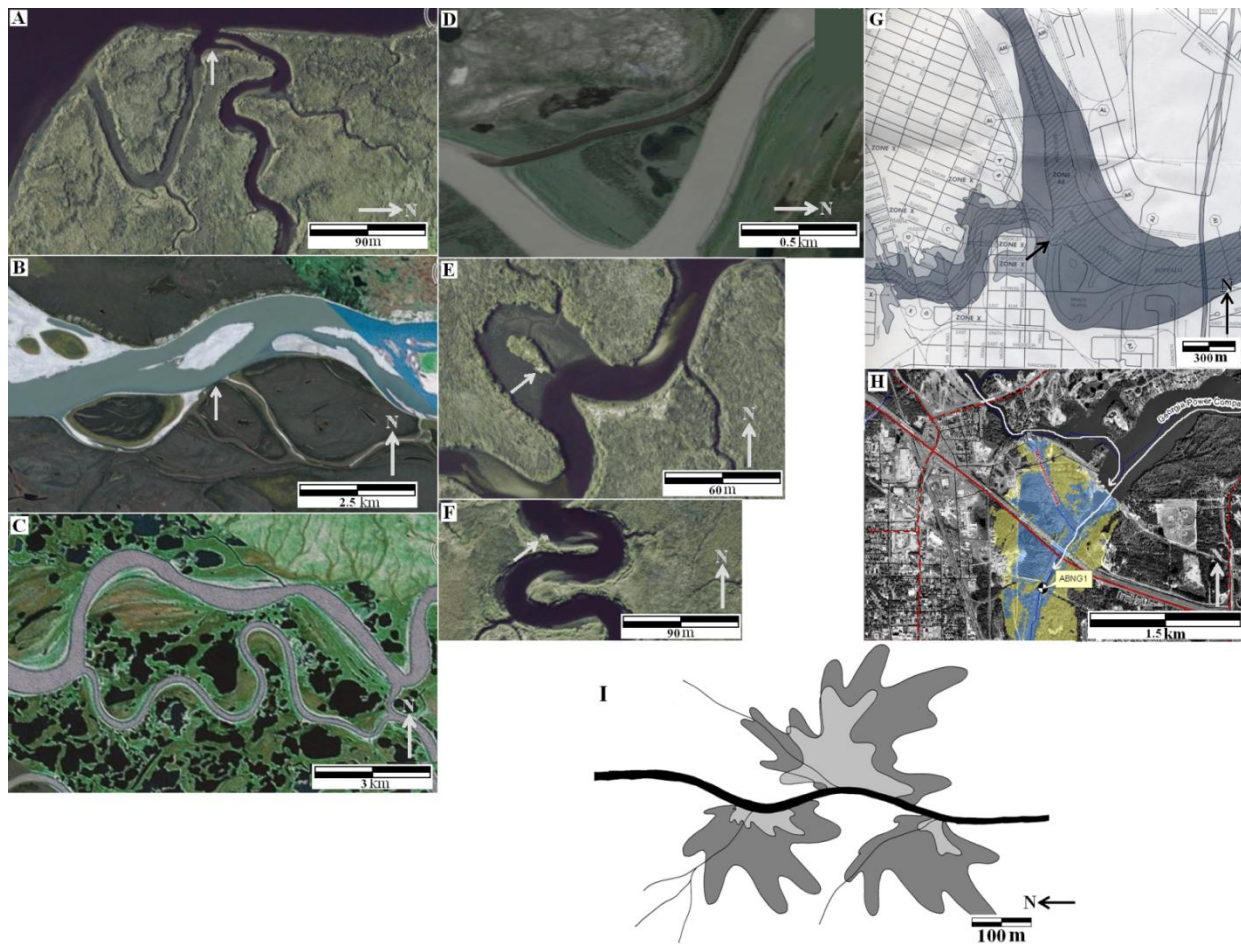


Figure 3.10. Real-world examples of the fluvial conditions tested in the stream table experiments. Secondary connections of tributaries in (A) the Suwannee River in Florida, and (B) the Mackenzie River in Canada, both resulted in the abandonment of the tributary's downstream portion (White arrows point to the secondary connections). Secondary connections between tributaries and trunk channels are not uncommon, and other cases involving insipient secondary connections are shown in (C) the Mackenzie River and (D) Suwannee River. (E, F) Obstructions in the vicinity of meandering tributaries (white arrows) appear to have led to the formation of elongated meander heads. In (F), a normal meander head is seen immediately south of the elongated meander head. (G) A secondary connection between a tributary and trunk channel in Houston, Texas, is the primary locus of flooding, a similar condition to the tributary-channel junction of the Chattahoochee River in Georgia (H). Crevasse-splays formed multiple times at the same tributary-creek junctions over a period of years at Big Creek in Georgia (I). (Images A-F courtesy Google Earth; image (G, H) courtesy FEMA.)

3.2.2. Tumbler Experiments

The study of rip-up mudclasts at the Bone Butte site was augmented by experiments conducted on the surficial morphology of simulated rip-up clasts. The experimental material, consisting of natural clay from the Bone Butte dig site, Clinton Lake in Douglas County, Kansas, and Lake Okeechobee in Florida, was subjected to simulated fluvial erosion in sediment tumblers. The clay clasts of all five sizes responded to the experiment almost identically and to similar degrees (Fig. 3.11). Regardless of initial clast size, all clasts exhibited roughly equivalent

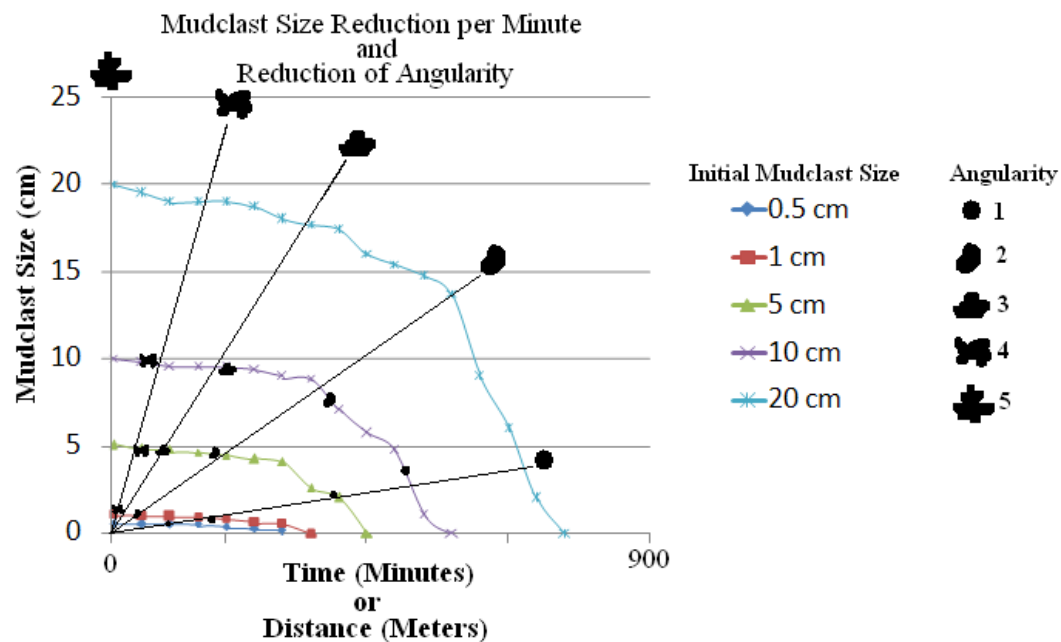


Figure 3.11. Results of the Bone Butte tumbler experiments. A roughly linear relationship exists between mudclast angularities and sizes over time for the different mudclast sizes tested. This enables the graph to be used to test mudclasts found in the field and estimate their distance from origin.

rates of rounding and decrease in diameter. Clasts began with maximal angularity, rounding slowly within the first quarter and more quickly after that point. After achieving a subspherical surface morphology, angularity was at its minimal extent, and the clasts continued to decrease in size until they eventually disintegrated entirely. It was possible to plot on a graph the points at

which clasts shifted from one level of angularity to another. Since the rates of angularity and diameter change were roughly the same for each initial mudclast size, only differing in magnitude, a virtually linear relationship exists between diameters and levels of angularity for the 5 sizes of clasts with respect to time (Fig. 3.11). The tumblers used in the experiments had an internal circumference of 100 cm, hence, by substituting the time lapsed in the experiments with the corresponding number of revolutions made by the tumbler, a maximal theoretical distance traveled was calculated for the corresponding levels of angularity and diameters of the different clasts. This theoretical distance was tested on mud clasts in crevasse-splays along Big Creek and the Chattahoochee River in Georgia, where mudclasts from modern crevasse-splay deposits were observed. In one field test, mudclasts collected from crevasse-splay deposits near the Chattahoochee River in Georgia that possessed a diameter of 4 cm and an estimated angularity of 3 were compared to the graph produced by Bone Butte tumbler experiments. Based on the tumbler experiment graph, the mudclasts should have originated from a point between 50 and 60 m from the point of deposition. The actual measured distance from the river to the point of

Field Test of Tumbler Graph Estimates

Sample origin	Big Creek, GA	Chatt. Riv., GA	Chatt. Riv., GA	Chatt. Riv., GA
Mudclast diameter	2 cm	5 cm	6 cm	4 cm
Mudclast angularity	4	4	2	3
Estimated distance from origin (based on tumbler graph)	20 - 25 m	48 - 54 m	290 - 310 m	50 - 60 m
Actual distance from origin	22 m	51 m	305 m	56.25 m
range of accuracy	10 - 12%	5.5 - 6.2%	1.6 - 5.2%	6.2 - 12.5%

Table 3.2. Field test results for the tumbler graph. Mudclasts from crevasse-splays at Big Creek and the Chattahoochee River in Georgia were examined and the estimated distances from their point of origin were based upon the Bone Butte tumbler experiment graph. Estimated distances traveled were compared with actual measured distances, and the % accuracy of the tumbler graph estimates was calculated.

deposition was 56.25 m, indicating that the graph produced estimates that were consistently accurate to within 10 percent. Additional field tests at the Chattahoochee River and at Big Creek produced similar results that confirmed the graph's level of accuracy to be within 10 percent in estimating the distance traveled by rip-up mudclasts (Table 3.2).

3.3 Fossil Collection

3.3.1 Vertebrates

Over 2000 vertebrate specimens recovered from Bone Butte provide a basis for numerous taphonomic and paleontological analyses of Late Cretaceous vertebrate communities. The overall vertebrate diversity at Bone Butte surpasses many other Hell Creek sites (Pearson et al., 2002; Russell, 1984; Bartlett, 2004) and includes over 67 genera of vertebrates. Bone Butte vertebrates include a diverse assortment of terrestrial and aquatic reptiles, amphibians, fish, mammals, dinosaurs, and birds. Vertebrate remains were recovered from four distinct fossil-bearing strata and represent examples of nearly all major taxa in the Hell Creek Formation. The fact that the relatively small site ($\sim 360 \text{ M}^3$) produced so many specimens is remarkable, making the site one of the most prolific vertebrate localities reported in published work on the Hell Creek Formation (Bartlett, 2004).

The bones recovered from Bone Butte were not significantly distorted during diagenesis and are generally well permineralized, although medullary cavities and marrow remains free of crystal growth and mineral in-filing. Complete turtle shells consisting of fully fused carapaces and plastrons were commonly found inflated and uncrushed. Delicate, hollow bones of small theropods and ornithurine birds are also typically preserved with little to no crushing. Abrasion and completeness of individual bones is variable, although a high percentage of bones recovered, especially from Stratum 5, the lower portion of Stratum 11, and Stratum 15, have minimal to

negligible amounts of abrasion. The integrity of the bones and above-average quality of preservation is shared among both the macro and microfossil assemblages. Even the heavily worn bones are dense and not friable. A small percentage (<5%) of bones were encased in dense ironstone concretions or have significant damage due to the breakdown of iron pyrite crystals that precipitated in their medullary cavities of the bones.

The majority of large fossil bones were recovered from Strata 2A and 2B clay-pebble conglomerates, where bone abundance peaked at 50/m³. It should be noted that, whereas the majority of large bones from the site emanated from Strata 2A and 2B, the bones from those strata are not limited to macrofossils. A diverse assortment of microfossils, including those of fish, turtles, small theropods, and mammals are also common in Strata 2A and 2B, providing a wide variety of bone sizes. However, larger animal taxa are represented primarily by the smaller elements of their skeletons (such as distal phalanges, distal caudal vertebrae, teeth, and individual skull bones). The bones recovered from Strata 2A and 2B were oriented quite chaotically in the vertical aspect and mapping at various vertical intervals within the two strata was deemed to be unnecessary. The bones are, however, strongly oriented in the horizontal aspect. In both strata the majority of bones pointed in a direction of N 43 E and it was not uncommon for groupings of bones to form elongated tapered masses that frequently interconnected with each other. Large petrified logs and smaller pieces of petrified wood shared the same general directional orientation as the bones. Quite frequently, clusters of smaller bones were found on the up-current side of larger bones, while the down-current side of the large bones remained free of small bone accumulation (Fig. 3.12 A). Similarly, in an area of Stratum 2B that is interrupted by Strata 13 and 14, fossil bones were found in tangled masses on the up-current side and were absent for slightly over one m from the down-current side (Fig. 3.12 B). Although less than 3% of all bones recovered from the site were articulated (not counting the partially

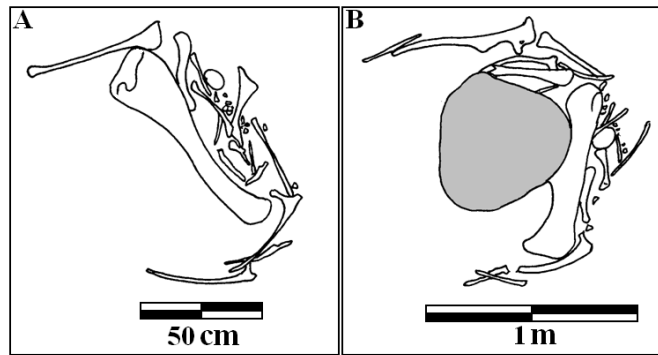


Figure 3.12. Small bones were frequently observed clustering on one side of larger bones (A) or other obstructions (B). These examples are from the Stratum 2B bone maps.

articulated bird skeleton), and despite the chaotic nature of deposition for Strata 2A and 2B, a number of articulated elements, including several limb elements of thescelosaurus and turtles, were recovered from those strata.

On average, Strata 5, 11, and 15 were quite productive, with a maximum bone density of $20/\text{m}^3$, but have a lower bone density than Strata 2A and 2B. Bone distribution in Strata 5, 11, and 15 is somewhat more complex and provides additional information regarding the deposition of sediments and bone, as well as information on faunal communities and time resolution of the site. Stratum 5, unlike the homogenous Strata 2A and 2B, consists of a series of sandstone and clay-pebble conglomerate laminae. Because of the ordered stratigraphy of the stratum, and the fact that bones within it appear to have both ordered vertical and horizontal orientation, the vertical distribution and horizontal distribution of the bones were mapped. Vertebrate material from Strata 5, 11, and 15 is plentiful, particularly in the 0.2 - 40 cm range, and several taxa are represented by an entire suite of ontogenetic stages, from hatchling to adult. The majority of fossil material from these three strata is disarticulated, however it contains a higher percentage of articulated specimens (~5%) than Strata 2A and 2B. Fossils from Stratum 5 and the lower portions of Stratum 15 also have strong directional orientation. Bones in Stratum 5 tend to follow

a gradually curving arc that mirrors the contour of the stratum's western margin. Similarly, bones in the lower portion of Stratum 15 follow the stratum's lateral margin and curve around Strata 13 and 14 in a horseshoe-shaped arc. Bones in the upper portion of Stratum 15, however, are situated more randomly and do not exhibit any obvious directional orientation. The random lateral orientation of bones persists into Stratum 11.

In most cases, even the most heavily weathered bones were identifiable to the family or generic level, and the majority of bones could be identified to the species level. For purposes of analyzing faunal composition and comparison with data from other studies, certain taxa were combined into broader categories, for example, troodontids and dromaeosaurs are included in the category "small theropods".

Dinosaurs

Carnivorous dinosaurs are well represented at the Bone Butte site and consist of a wide assortment of well preserved skeletal elements. Small theropods such as dromaeosaurs and troodontids are more common than larger theropods such as tyrannosaurids, and are represented by a greater assortment of bones. Small theropods recovered thus far include the dromaeosaurids *Dromaeosaurus* and *Saurornitholestes*, and the troodontid *Troodon formosus*, which are represented by teeth and skeletal elements, and the maniraptorans *Paronychodon*, *Pectinodon*, and *Richardoestesia*, which are represented only by teeth. Skeletal elements of small theropods tend to be well preserved and exhibit little crushing, despite their hollow, fragile nature. Among the theropod dinosaurian remains recovered, the only articulated bones consist of limb, foot, and vertebral elements; the rest are disarticulated and disbursed. The presence of shed teeth increases the small theropods count slightly, although small theropods are represented by examples of virtually every skeletal element. Large theropod dinosaurs, such as the tyrannosaurids, are not as

well represented, and their remains consist mainly of teeth and smaller skeletal elements, such as distal caudal vertebrae, chevrons, phalanges, and small skull elements. Among the tyrannosaurids, *Tyrannosaurus rex*, *Aublysodon*, and *Nanotyrannus* have been identified. The latter two could be debated, however, as *Aublysodon* is a taxon represented solely by teeth and has been considered to be synonymous with *T. rex* (Carr and Williamson, 2004). Similarly, although *Nanotyrannus* was initially described as a distinct genus (Bakker et al., 1988), it has been argued that *Nanotyrannus* might represent a juvenile stage of *T. rex* and is not a separate taxon (Henderson, 2005). In terms of this study, however, the three tyrannosaurids are treated as separate, discrete taxa.

Omnivorous dinosaurs were sampled from all bone-bearing strata and include the oviraptorids *Caenagnathus* and *Chirostenotes*, the ornithomimids *Ornithomimus* and *Struthiomimus*, and the thescelosaurids *Thescelosaurus neglectus*, *Thescelosaurus garbanii* and *Bugenasaura*. All omnivorous dinosaur taxa except the oviraptorids are represented by a diverse assortment of skeletal material and very few teeth. The omnivores that possessed teeth, the thescelosaurids, are represented primarily by skeletal elements and only a small percentage of shed teeth. Interestingly, most thescelosaurid teeth were recovered from intact jaw sections. Some ornithomimid bones exhibit crushing and distortion although the majority of bones are uncrushed. A small number of omnivore bones were found articulated. Such finds consist of two partial *Thescelosaurus* legs and one partial *Thescelosaurus* arm, both from Stratum 5. A high percentage of ornithomimid and thescelosaur bones contain medullary bone (Appendix B2), which is produced only during breeding season (Schweitzer et al., 2007; Schweitzer et al., 2008). This is the first time medullary bone has been reported in any ornithomimids or thescelosaurus.

Herbivorous dinosaurs at Bone Butte primarily consist of smaller animals, although a wide range of Hell Creek herbivores was sampled. The most common herbivores represented are the pachycephalosaurids *Pachycephalosaurus* and *Stygimoloch*, and the hadrosaurids *Edmontosaurus annectens*, *Anatotitan*, and hip elements of a more robust hadrosaur consistent in morphology with bones of crested hadrosaurs such as *Parasaurolophus*, which could have been present in the Hell Creek Formation (Weishampel and Jensen, 1979). A high percentage of the pachycephalosaur bones from Bone Butte contain medullary bone (Appendix B2). As with the ornithomimids and thescelosaurus, this is the first time medullary bone has been reported in pachycephalosaurs. A set of articulated metatarsals and several sets of articulated vertebrae of a pachycephalosaurid are the only articulated herbivorous dinosaurian remains found; the metatarsals were found in Stratum 5 and the vertebral sets were found in Stratum 15. Other less well represented herbivores include the ceratopsids *Triceratops prorsus*, *Triceratops horridus*, and *Torosaurus latus*, and the ankylosaurids *Edmontonia* and *Ankylosaurus*. The frequency of herbivores is, in some cases, such as the ceratopsians and hadrosaurs, strongly influenced by the presence of shed teeth. The total percentages of dinosaurian fauna were calculated using data from both shed teeth and bones to enable the comparison of Bone Butte with other Hell Creek studies, as the same criteria were used in the calculation of faunal percentages by other researchers (Lehman, 1987; White et al., 1998; Russell and Manabe, 2002; Bartlett, 2004); See Appendix B1 for faunal percentages comparing skeletal percentages with combined skeletal and tooth percentages.)

At Bone Butte, several small pieces of dinosaur eggshell were also collected. The eggshell fragments are approximately 1 cm in diameter, 1 mm thick, have ramotuberculate ornamentation, and prolatocanaliculate pore morphology. The shell microstructure was of the

prolatospherulitic shell morphotype, which has been associated with non-theropod dinosaurs (Carpenter, 1999). The broken margins of the shell fragments are very angular and unworn.

Non-dinosaurian Vertebrates

Non-dinosaurian vertebrates are very common and are represented by both articulated and disarticulated skeletal elements. A fairly diverse fauna of turtles, fish, amphibians, and aquatic reptiles comprise the majority of non-dinosaurian vertebrates, with mammals and birds being the least common.

Fish remains recovered from the Bone Butte site consist primarily of scales, teeth, vertebrae, and skull elements, and are common in all bone-bearing strata. The scales nearly all from the gar *Lepisosteus* and are well preserved. A small percentage (<30%) of the scales exhibit surface etching that is indicative of consumption and partial digestion. The majority of fish remains collected belong to *Lepisosteus* and the freshwater batoid *Myledaphus*. Other fish recovered include remains of the amiids *Melvius* sp., and *Kindleia fragosa*, and the acipenseriform fish *Paleopsephurus wilsoni*. Some fish material (<30%) could be identified as belonging to the actinopterygii but is too fragmentary to make a more specific identification. Whereas *Myledaphus* is a freshwater-tolerant marine fish, other fish more commonly associated with a fully marine or brackish environment (Wroblewski, 2004), including teeth of *Ischyrhiza avoncola*, *Lissodus selachos*, *Squatirhina americana*, and unidentified orectolobid shark teeth, are also represented at Bone Butte.

Reptile and amphibian remains are also common, especially the aquatic forms (turtles and aquatic reptiles are listed in two separate groups in this study to enable comparison of the data with other Hell Creek studies). Reptiles and amphibians are present in all bone bearing strata, although crocodilians and turtles are most common in Stratum 15. A wide variety of

skeletal elements were recovered for all reptiles and amphibians. Bones from a wide variety of age groups were uncovered as well; crocodilians and turtles were the most common and represent ontogenetic stages from hatchling to adult (Fig. 3.13).



Figure 3.13. An example of crocodilian femora from Bone Butte demonstrates the wide range of ontogenetic stages present at the site. Missing areas were lost due to modern weathering.

Borealosuchus and *Brachychampsia* are the only two freshwater crocodilians identified, and are represented by elements of the entire skeleton. Another crocodilian found at Bone Butte, *Thoracosaurus neocesariensis*, is represented primarily by skull material, and is generally regarded as a marine or semi-marine animal (Jouve et al., 2008). Also fairly common is the choristoderan crocodile ecomorph *Champsosaurus*, although the remains are less common than actual crocodilians. The remains consist of teeth, vertebral centra and some disarticulated limb elements.

The majority of the turtle fauna is represented by aquatic forms, with *Plesiobaena* and *Trionyx* being the most common. Less common were *Compsemys*, “*Clemmys*” *backmani*, and kinosternid remains. A large proportion of the turtle fossils are very well preserved, showing

little to no crushing and sometimes exhibiting limb articulation. Often, whole shells were recovered intact and uncrushed. Fragmentary shells consist primarily of unbroken, disarticulated segments of the carapace and plastron. Partial turtle limbs were found articulated within Strata 5, 15 and 11. In addition, shell, limb, and neck portions of the terrestrial dermatemydid tortoise ecomorph *Basilemys sinuosa* were recovered from Stratum 15.

Pterosaur remains were extremely rare and were recovered from Stratum 5. Although the material is too fragmentary to provide any specific taxonomic information, azhdarchid pterosaur specimens have been previously reported from the Hell Creek Formation (Harrison and Henderson, 2002; Henderson and Peterson, 2006). The material from Bone Butte is similar and consists of one partial claw and one partial proximal phalangeal wing element.

Amphibians are moderately well represented at the site by vertebrae and skull elements, and include the salamanders *Scapherpeton*, *Opisthotriton*, and an anuran of indeterminate taxonomic affinity (possibly *Scotiophryne pustulosa*). The majority of amphibian material is well preserved, although sufficiently fragmentary to limit taxonomic identification beyond the level of amphibia.

As with the amphibians, lizard material is disarticulated and somewhat fragmentary. Lizards including *Palaeosaniwa*, *Chamops segnis*, and *Parasaniwa* have been identified based on skull material, however much of the lizard specimens could not be identified beyond the order Squamata.

Bone Butte mammals are represented most commonly by teeth, skull bones, and some hip and limb elements. The majority of mammal specimens were recovered from Strata 5, 15, and 11. A wide variety of mammals were found, including two of the three species of *Didelphodon* (*D. vorax* and *D. padanicus*), *Alphadon*, *Meniscoessus*, and fragmentary remains of

least six additional taxa (Fig. 3.14). Teeth tend to be excellently preserved and bones generally exhibit minimal damage. Recovered specimens include members of the eutheria, metatheria and multituberculata and represent approximately 30% of the total known mammal diversity in the Hell Creek Formation.



Figure 3.14. Much of the mammal material from Bone Butte is in excellent condition, as the mandible of *Didelphodon vorax* (top) demonstrates. The other two jaw sections (left) are from *D. padanicus*, and the pelvis (right) is from *Didelphodon* sp. A life reconstruction of *Didelphodon* can be seen below. (Diagram © Robert A. DePalma II.)

Bird material is surprisingly common in Stratum 5 and consists of both isolated and semi-articulated skeletal elements. Over 47 bird bones were recovered, including a semi-articulated skeleton consisting of 27 bones. The bones are all in relatively good condition with negligible crushing (Fig. 3.15). At least three taxa of birds were recovered from the site, all of which are

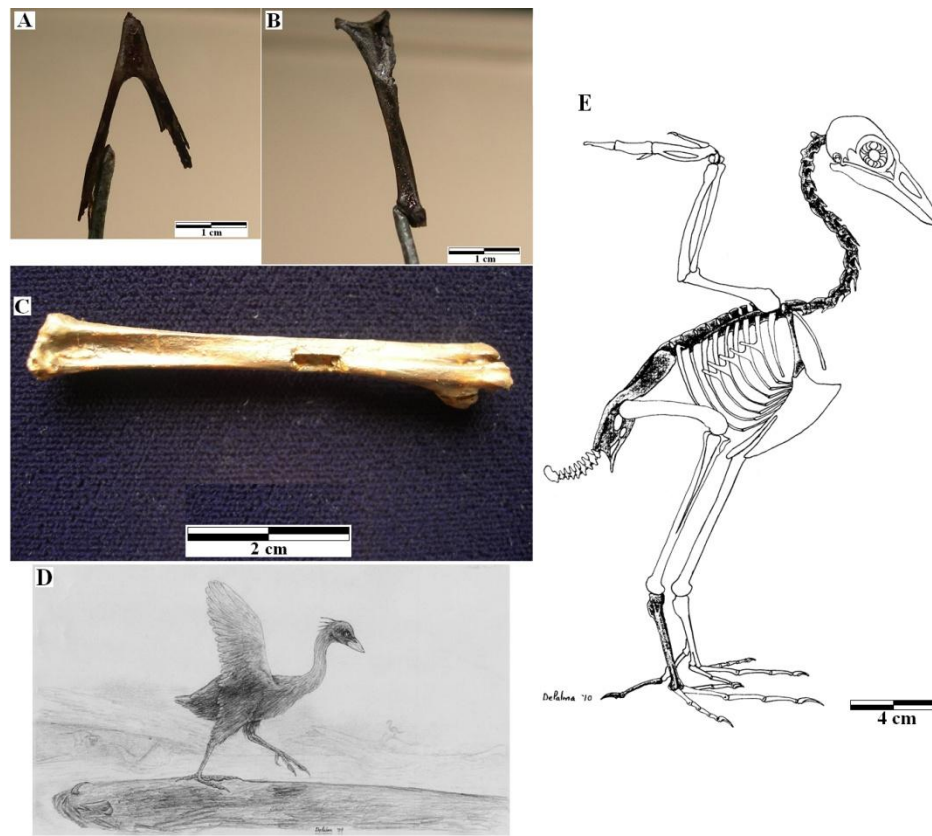


Figure 3.15. An example of the exquisite ornithurine bird bones from Bone Butte can be seen in (A – C). A pair of fused dentaries (A) and a coracoid (B) are from a small taxon of bird, while the larger tarsometatarsus (C) is from another taxon, and is part of the most complete bird skeleton ever recovered from the Hell Creek Formation. The tarsometatarsus belonged to a water-marginal bird similar to the reconstructions in (D - E). Shaded areas in (E) represent recovered bones from a single skeleton. (Diagrams D, E © Robert A. DePalma II.)

undescribed members of the ornithurae. The semi-articulated ornithurine bird specimen was found in Stratum 5 and consists of a nearly complete, articulated cervical series, a nearly complete, partially articulated dorsal vertebral series, associated right scapula and coracoid, partial hips articulated with a fragmentary synsacrum, one pedal claw, one pedal phalanx, and a right tarsometatarsus. The long, slender legs and large feet are reminiscent of water-marginal birds. The bird would have been about the size of a small duck in life, and is currently under further study in preparation for being described.

3.3.2 *Non-vertebrates*

Paleobotanical

Plant fossils vary in abundance and preservation but overall the Bone Butte site is rich in fossilized leaves and wood (Fig. 3.16). The plant taxa recovered are consistent with the HC III floral zone of Johnson (2002). Petrified wood was found in Strata 1, 2A, 2b, 3, 5, 11, and 15 and is preserved as compressed lignite, compressed silty clay with carbon film, and three-dimensionally as ironstone castings. The majority of leaves and needles are well preserved and occur in abundance in Strata 15 and 11, and, to a lesser degree, Strata 1 and 3. At their highest abundance, clusters of leaves in sandstone lenses in Stratum 11 reached approximately 900/m². Angiosperm and gymnosperm trees are common at the site, in addition to *Equisetum* horsetail shafts and *Pistia* water lettuce.

The needles and sprigs of gymnosperms are found in varying abundance throughout all bone bearing strata, especially the upper, organic-rich shaley portions of Strata 5 and 15, and all of Stratum 11. The organic-rich, upper 10 cm of Stratum 5 contain abundant gymnosperm needles, at least six morphotypes of seeds, and a fair amount of amber. Except for isolated, elongate, fine-grained sandstone lenses containing angiosperm leaves, plant fossils in Stratum 11 consists almost entirely of gymnosperm needles, sprigs, and a profusion of amber. The leaves of angiosperms are present primarily in Strata 1, 3, and 11. In Strata 1 and 3, leaves are oriented erratically, sometimes oriented perfectly vertically, folded, and even pressed in masses around dinosaur bones. Angiosperm leaves in Stratum 11 are present in mats preserved in fine-grained sandstone lenses, where incredibly dense accumulations of leaves sometimes even obscure

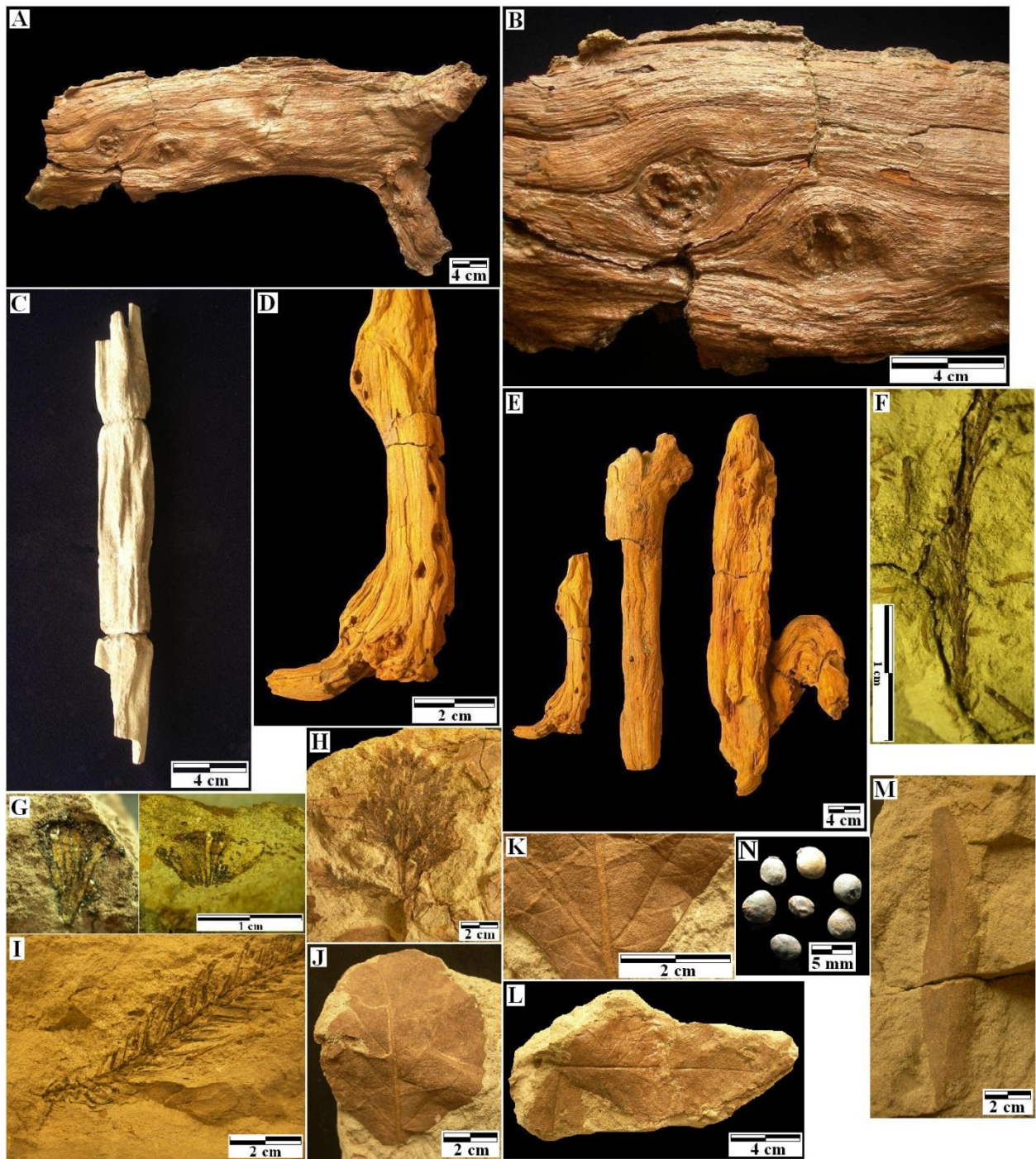


Figure 3.16. The plants from Bone Butte represent a wide variety of gymnosperms and angiosperms (A – N). Examples of petrified wood replaced by ironstone can be seen in (A, B, D, E). (C), A well-preserved *Equisetum* shaft. (F), *Glyptostrobus* sp. (G), Two *Dammarites* gymnosperm cone scales, with parallel resin tracts preserved. (H), *Fokieniopsis*. (I), A sprig of the gymnosperm *Cunninghamia*. (J), “*Ficus*” *planicostata*. (K), A close-up view of the leaf in (J). (L), *Liriodendron*. (M), *Dryophyllum*. (N), An assortment of seeds from Bone Butte.

individual detail. Amber is virtually absent from the sandstone lenses. Carbonized films are present on nearly all of the plant material, and preserved cuticle is common.

Whereas angiosperms would be expected to be the dominant flora in such an Upper Cretaceous environment, gymnosperms are incredibly prevalent at the Bone Butte site and angiosperms are limited to the sandstones of Strata 1 and 3 and the sandstone lenses in Stratum 11. *Taxodium*, *Cunninghamia*, *Sequoia*, and *Metasequoia* appear to have been the dominant gymnosperms, and gymnosperm needles, sprigs, buds, and cones are common. Numerous small *Taxodium* branches with attached needles and buds were recovered from Stratum 15. Amber commonly co-occurred with wood and within cone specimens (Fig. 3.17).

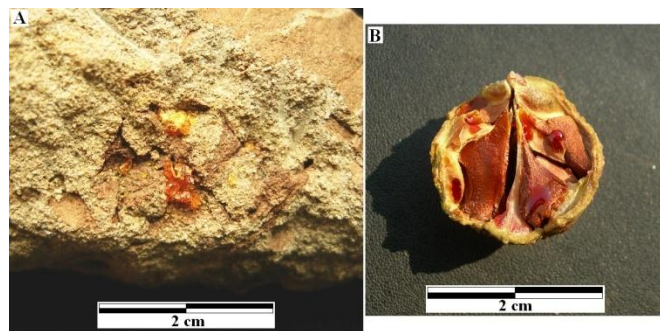


Figure 3.17. A fossil gymnosperm cone from Bone Butte with fossil resin inside (A) and a modern Bald Cypress cone with a similar occurrence of internal resin (B).

Taxonomically identified members of the angiosperm leaf diversity include *Dryophyllum*, *Cinnamomum*, *Liriodendrites*, *Marmarthia*, *Platanites*, and *Erlingdorfia*. At least 16 angiosperm leaf morphotypes were observed, with ovate, elongate and palmate leaf morphotypes among the most prevalent. Toothed leaf margins are not common although elongated, acuminate drip tips were encountered regularly.

Especially abundant in Stratum 15 and portions of Stratum 11 are “*Ficus*” *ceratops* horsetail rhizomes (Brown, 1937) and shafts of *Equisetum* horsetails. “*Ficus*” *ceratops* specimens are most often preserved three dimensionally, with an outer carbonized film, whereas the *Equisetum* shafts are rarely preserved in such a manner, most often existing as impressions in the silty shale. Also in Stratum 11 are abundant examples of the aquatic plant *Pistia corrugata*.

Amber is extremely common at the site and was found in abundance in Stratum 11 and, to a lesser extent, the upper portions of Strata 5 and 15. Occasionally, pieces of amber were found within carbonized limb fragments or within cones and resin tracts, but the specimens were nearly always found as isolated pieces that ranged in size from 0.4 cm to 5 cm in diameter. The majority of amber has original surface morphology, such as elongated runnel shafts and teardrop-shaped droplets, preserved in great detail (Fig. 3.18), and many preserve the surface morphology of the wood upon which the amber exuded before hardening.



Figure 3.18. Amber droplets from Bone Butte with their original surface morphology perfectly preserved, and not abraded by transport or reworking.

Amber is reddish-yellow to yellow in coloration and is quite transparent. Microfractures and swirls of opaque bubbles make some of the amber appear less transparent, although only about 10% of the specimens are truly opaque. Unlike typical amber from the Hell Creek

Formation, which is small, rather crumbly, quite friable, and cannot be readily sanded or modified, amber from Bone Butte is cohesive, stable, and able to hold a high polish. Because the amber recovered is larger and more stable than most Hell Creek amber, the specimens enable polishing and microscopic examination.

Examination of amber specimens has revealed a host of inclusions that have never been reported from the Hell Creek Formation. Inclusions take one of several forms: botanical fragments, bubbles/clouds of bubbles, organic smears, insects, and two bird feathers (Fig. 3.19), all of which are currently undergoing further study. Botanical remains are not uncommon inclusions and consist of splinters of wood, needle fragments, pollen, and an assortment of unidentifiable plant debris (Fig. 3.19 E). The majority of botanical remains are not of much taxonomic use, although some wood splinters could have originated from the amber-bearing trees. Pollen and spores in Bone Butte amber specimens have thus far not been examined in detail.

Swirling clouds of microbubbles are quite common and indicate the direction of resin flow in amber specimens (Fig. 3.19 B). Clouds of bubbles and larger, isolated bubbles all appear to be air-filled and bear no indication of being filled with fluid or other substances. In some instances, large accumulations of dark, reddish-brown spheres occur in the amber. Fractured surfaces of the amber reveal these spheres to be solid, although no obvious ordered structure is evident in their cross sections (Fig. 3.19 F). Another form of dark reddish-brown sphere that was encountered exhibits signs of having previously been filled with a fluid substance. Unlike the previously mentioned dark spheres, these spheres are completely hollow except for a dark, reddish-brown residue on their interior surface. The residue exhibits cracks consistent with desiccation, and indicate that the spheres have been depleted of their liquid contents over time.

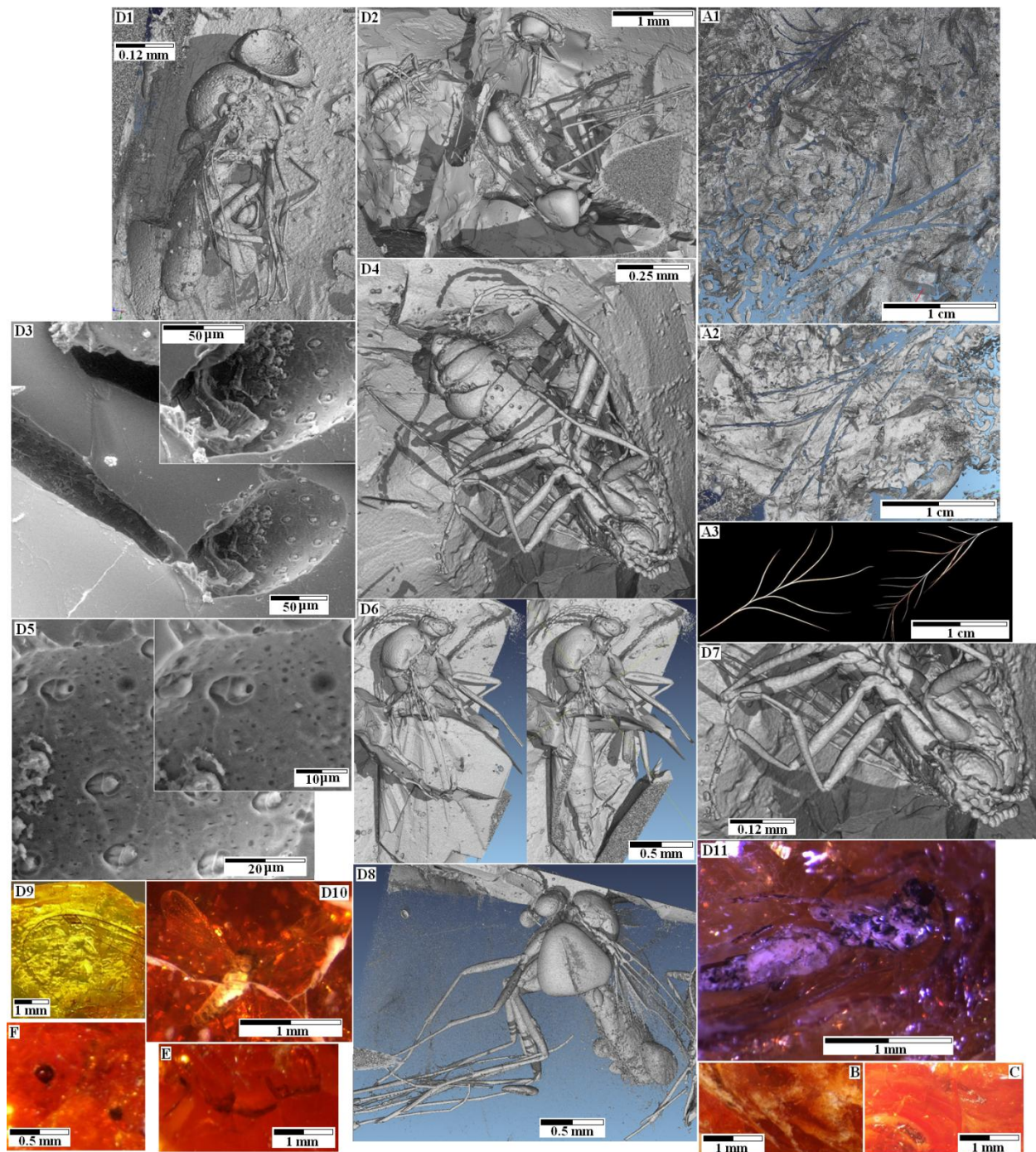


Figure 3.19. Amber inclusions from Bone Butte. A pair of feathers from the Bone Butte amber are seen in Micro-CT images (A1, A2) and compared with modern emu feathers (A3). Swirling clouds of microbubbles (B) and organic smears (C) are common in the Bone Butte amber. Insect inclusions (D1-11) have been examined using traditional microscopy, (ESEM), and Micro-CT. (D1, 2, 4, 6, 7, 8), Dipterans imaged using Micro-CT. (D3, 5), ESEM images of a leg from the nematoceran fly pictured in (D11), showing muscle fibers (D3) and internal anchoring points of the setae (D5). A wing of the dipteran imaged in (D6) was digitally dissected away from the insect, revealing an intact abdomen (right image). Among the insect inclusions was the wing of a hemiphebiid damselfly (D9). Plant fragments (E) and dark, solid spherical inclusions (F) are more common than insect inclusions, however are typically not well preserved.

Taking on a similar shape as the clouds of bubbles, cream-colored and light brown organic smears occur in over half the amber specimens studied (Fig. 3.19 C). The smears appeared to have been formed as the newly-exuded resin ran down the tree's trunk, and the direction of resin flow is preserved in the smears' morphology. Details of the exact composition of the smears remain unknown.

Considering the comparatively small number of amber specimens (<500), and the absence of insect body fossils from previous published Hell Creek studies, the number of insect inclusions observed is remarkable. The amber specimens from Stratum 11 produced over 19 insect inclusions, 10 of which are complete or nearly complete insects (Fig. 3.19 D). The majority of insects belong to the Nematocera, although one hemiphlebiid damselfly wing was recovered. Considering that at least 11 distinct species and numerous genera are present in the 19 insect specimens recovered, the diversity of recovered insects is noteworthy.

Two bird feathers were discovered in one amber specimen (Fig. 3.19 A). The feathers are very simple in morphology and consist of a central rachis with long, intermittent barbs. As these are the first feathers reported from the Hell Creek Formation, there are no other specimens to form a basis for comparison, however the Bone Butte feathers are nearly identical in size and morphology to feathers from a juvenile emu (Fig. 3.19 A3).

Mollusks

While marine mollusk remains occur with varying frequency in the Hell Creek Formation, concentrating in near-shore and marine environments such as the Hell Creek marine

Breien Member (Murphy et al., 2002), freshwater mollusks have been reported with some regularity in quiescent backwater areas such as oxbow lakes and tributary deposits (Harrison and Henderson, 2002). At Bone Butte, mollusk remains are rare but much more common than at the Sandy Site (Bartlett, 2004). Steinkerns of unionid bivalves averaging 6 cm in length are the most common mollusk, and over 40 specimens were uncovered in the Oxbow and Bird & Mammal Zone deposits. Several steinkerns of the gastropod *Pachymelania* sp., an animal associated with brackish to marine environments (Hartman and Kirkland, 2002), were uncovered in the Bird & Mammal Zone. The only other mollusk remains found were several small (3 cm diameter) steinkerns of the gastropod *Campeoloma* sp.

Trace Fossils

Ichnofossils at Bone Butte are not as common as fossil bone, however a variety of organisms produced a diverse assortment of traces. Traces formed by vertebrates, invertebrates, and plants are represented by dozens of recovered specimens.

Vertebrate trackways are not common in the Hell Creek Formation and it was not until recently that any had been found (Lockley et al., 2001; Manning et al., 2008; Falk, 2009). Consequently, the discovery of two isolated anisodactyl bird tracks in the thinly bedded laminae of Stratum 16 is notable. One track is preserved as a concave epichnal trace and the other is preserved as a convex hypichnal trace (Fig. 3.20). Both tracks measure approximately 1.5 cm

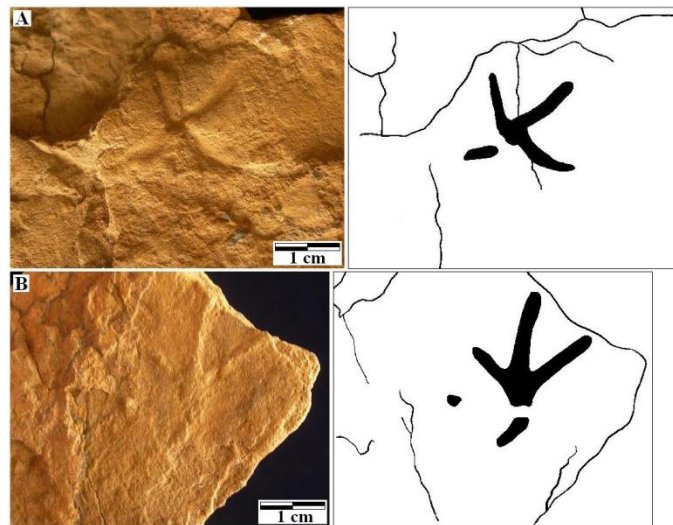


Figure 3.20. Bird tracks from Bone Butte with accompanying schematic drawings. One track is preserved as a concave epichnal trace (A) and the other is preserved as a convex hypichnal trace (B). Both tracks are likely from ornithurine birds, and the small raised area to the left of the second track (B) could represent a probe mark from the bird's beak.

across and exhibit an angle of divarication between digits II and IV well over 100 degrees (111 degrees and 150 degrees). The angle of divarication of dinosaur tracks is below 100 degrees, whereas bird track angle of divarication exceeds 100 degrees, generally ranging from 110 to 170 degrees (Lockley, 1992), not counting the curious toe arrangement in zygodactyls. As such, the two tracks from Bone Butte were undoubtedly produced by a Cretaceous bird. No webbing is apparent in either track, however the preservation is not superb, and the angle of divarication is consistent with water-marginal shorebirds. Furthermore, digit IV is not reduced in either track, supporting evidence that the tracks were made by ornithurine birds (Lim et al., 2002).

Bird tracks have not been reported from the Hell Creek Formation, however they are prevalent in some areas of the slightly older Cretaceous Lakota Sandstone (Lockley et al., 2001). At present, documented Mesozoic bird tracks are not common in North America and only 3 ichnogenera have been established: *Ignotornis* (Mehl, 1931), *Aquatilavipes* (Currie et al., 1981),

and *Koreanaornis* (Anfinson, 2009). The tracks from Bone Butte exhibit morphology almost identical to Upper Cretaceous bird tracks of the ichnogenus *Aquatilavipes* (Currie et al., 1981).

Several morphologies of invertebrate burrows were recovered from Bone Butte. One of the most common traces is a vertical tube, similar in morphology to *Skolithos* (Hasiotis 2002, 2003), that penetrates siltstones and mudstones of Strata 10, 14, 16, and 18 (Fig. 3.21). The burrows are consistently between 5 and 8 mm in diameter, approach lengths of 12 cm and are

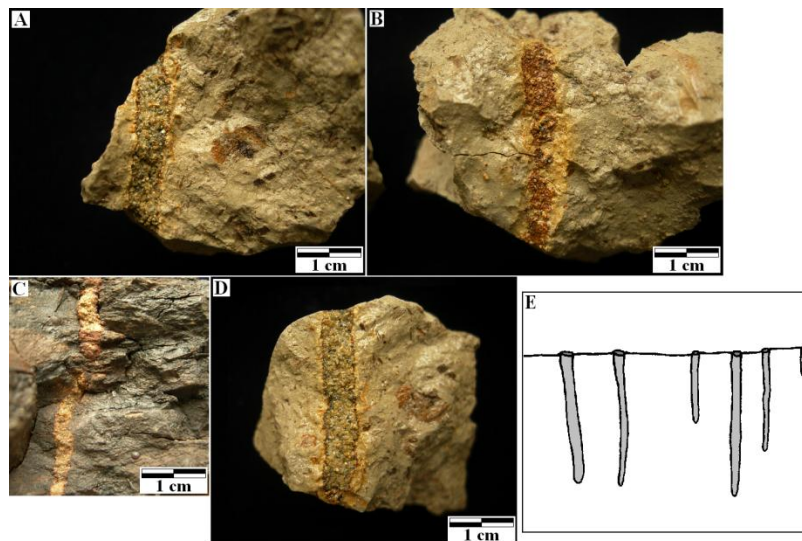


Figure 3.21. Vertical burrows resembling *Skolithos* are common at Bone Butte, especially within rip-up mudclasts (A – D). A comparative drawing of actual *Skolithos* burrows (E) was modified from Hasiotis (2002).

preserved in full relief. The burrow walls are commonly stained orange-red, although the walls of vertical burrows in the tan-reddish Strata 16 and 18 are stained gray-green. All of the vertical burrows are filled with yellow-tan medium to coarse-grained sandstone.

Meandering, concave epichnal traces resembling *Cochlichnus* (Hasiotis 2002, 2003) are common in some areas of Stratum 16 (Fig. 3.22). *Cochlichnus* traces are known to co-occur with bird tracks (Falk, 2009), and while the *Cochlichnus* traces are not prevalent in the specific slabs

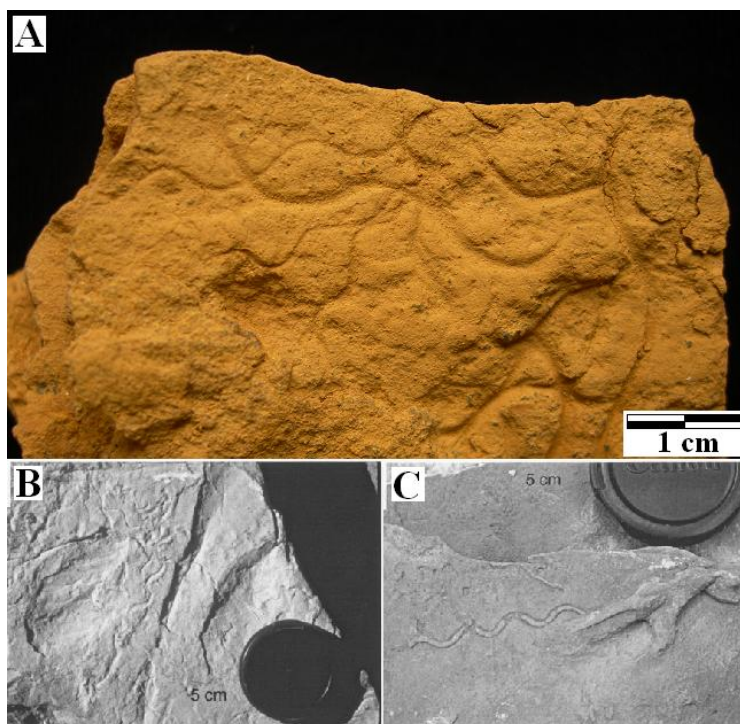


Figure 3.22. Sinuous *Cochlichnus* traces produced by ambulating worms are common in the Stratum 16 deposits at Bone Butte (A), and bear a close resemblance to *Cochlichnus* traces from the Jurassic of Colorado (B, C). Photos in (B, C) courtesy of Hasiotis (2002).

containing the bird tracks at Bone Butte, other portions of Stratum 16 contain multitudes of the sinuous traces. Trails have a width of approximately 2 mm and appear interwoven, cross-cutting each other frequently.

A densely packed assemblage of cross-cutting U-shaped burrows was observed at the contact point between Strata 11 and 12. The burrows strongly resemble *Arenicolites* traces (Hasiotis, 2002, 2003), although they are much shallower excavations and do not possess mounds of built-up sediment at the aperture (Fig. 3.23). The U-shaped burrows are composed of ironstone and are preserved as convex hypichnal traces on the lower margin of Stratum 12, protruding down into Stratum 11. Burrow diameter is 4 mm on average and length between apertures is typically less than 4 cm.

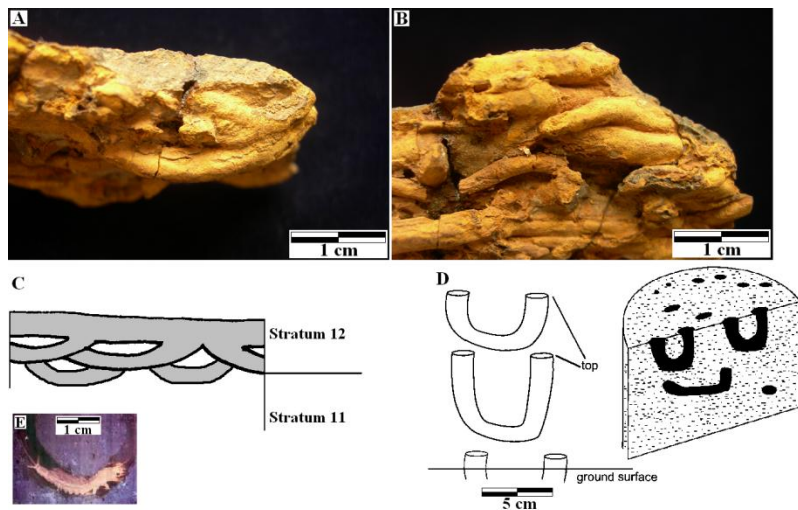


Figure 3.23. U-shaped burrows similar to *Arenicolites* traces are common at the lower bounding surface of Stratum 12 at Bone Butte (A – C). In the continental realm, such burrows are commonly produced by the nymphs of insects such as mayflies (D, E). Photo in (E) courtesy Calvin Fremling. Diagram in (D) modified from Hasiotis (2002).

A curious burrow complex was discovered in the paleosol of Stratum 14. The burrow complex consists of a series of laterally curved tubes, each of which terminates in an ovoid capsule. The tubes are approximately 1 cm in diameter and the terminal galleries were between 3 and 4 cm in diameter (Fig. 3.24). The structures are incised into the reddish paleosol of Stratum

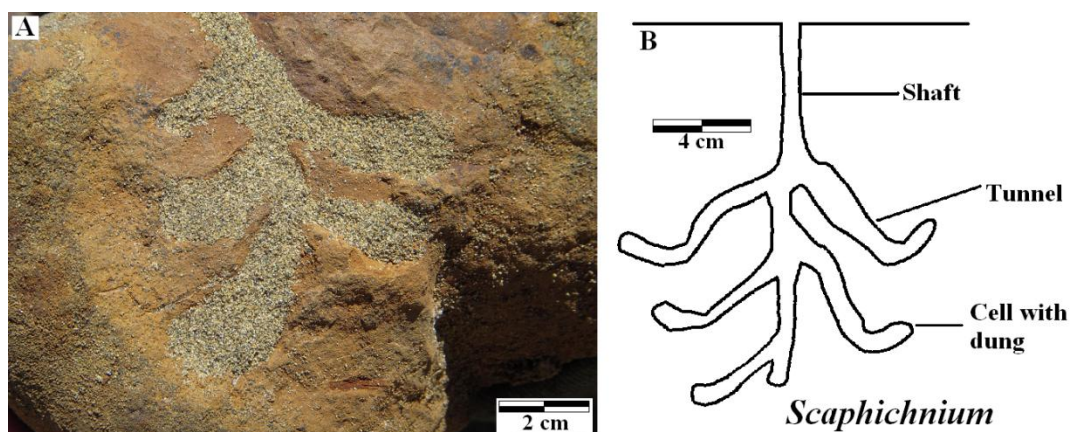


Figure 3.24. A burrow complex from paleosol deposits at Bone Butte (A) most closely resembles a *Scaphichnium* dung beetle burrow complex (B) and was likely produced by dung beetles. Diagram in (B) modified from Hasiotis (2002).

14 and are filled with tan-yellow medium-grained sandstone. The burrow complex is consistent in morphology with *Scaphichnium* traces produced by dung beetles (Hanski and Cambefort, 1991; Hasiotis, 2002).

Rhizoliths are the most common ichnofossils present at the site and consist mainly of short (~7 cm long) clusters of branching root traces. Such rhizoliths are common in Strata 14, 16 (sparsely), and 18. In these strata, the rhizoliths are predominantly preserved gray-green in color. Longer, thicker rhizoliths are present in Stratum 14 and penetrate down into Stratum 13. These rhizoliths are rather large in diameter (between 4 cm and 10 cm), mottled green and dark red in color, and are frequently found intertwined with other pieces of petrified wood.

3.4. *Taphonomy*

Multivariate approaches to taphonomic data collection help to elucidate the various phases bones undergo as they transfer from the biosphere to the lithosphere, and assist in the reconstruction of depositional scenarios, depositional settings, and the composition of paleo ecosystems (Behrensmeyer, 1991, Behrensmeyer and Hook, 1992). The taphonomic data collected from Bone Butte followed methods modified from Behrensmeyer (Behrensmeyer, 1991) and includes aspects of quarry data, bone assemblage data, and bone modification (Table 3.1).

3.4.1. *Quarry Data*

Size of Accumulation

The extent of the Bone Butte bone-bearing strata was estimated using visual reconnaissance and examination of correlative strata in the field. The only stratigraphic package

that could be correlated over significant distances is that consisting of Strata 1 and 2A. The bone-bearing Strata 1 and 2A were correlated with strata along the rim of Petra Valley, North to Fallon Point, Northeast to Smith Peak, and Southeast to Cichocki Butte. Bones in the stratigraphic package vary in abundance over the total area, decreasing with distance from Bone Butte, toward the North, East and Southeast. The total estimated area of bone-bearing portions of Strata 1 and 2A is 2 km². This minimum estimation of area is large but was within the limits of typical bonebeds, especially bonebeds associated with fluvial systems, which generally range in size from a few square m to many square km (Anita, 1979; Bown and Kraus, 1981; Bown and Beard, 1990; Behrensmeyer, 1991). Strata 2B and 3 were only traced a short distance along the rim of Petra Valley before they pinched out; consequently, their known area, 0.5 km², is much smaller than that of Strata 1 and 2A. Strata 11 and 15 occupy the same horseshoe-shaped area, each approximately occupying 40 m². These two strata are localized and not continuous with any other strata in the area, although were once part of a stream system of unknown total area. Stratum 5, though part of a channel, is localized due to erosion of the hillside and only about 72 m² of bone-bearing sediment is preserved.

Spatial Density

The spatial density of bones did not vary appreciably at the Bone Butte site, itself, however over large distances (>0.5 km), significant variability was observed. As mentioned, Strata 5, 11, and 15 are only locally preserved, so it is not surprising that their small area does not show significant variability in bone density (Behrensmeyer, 1991). Strata 2B and 3 showed very slight variation in bone density, varying from 50/m² at the Bone Butte site to only 4/m² toward the Northwestern extent along the rim of Petra Valley. With the largest preserved lateral

extent, Strata 1 and 2A display the greatest variety of spatial density of bones. Bones in these strata occur at a maximum of $50/\text{m}^2$ at the Bone Butte site, to $4/\text{m}^2$ at Fallon Point, $1/\text{m}^2$ at Smith Peak, $1/\text{m}^2$ at Cichocki Butte, and $55/\text{m}^2$ at trenched areas along the Feeney Escarpment. A general increase in bone density is seen with closer proximity to the Feeney Escarpment.

Spatial Arrangement

Virtually all bones recovered display a form of directional orientation. The lateral orientation of bones was mapped for all bone-bearing strata (Strata 2A, 2B, 5, 11, 15) and vertical orientation was mapped for those strata that exhibited some sense of vertical organization (Strata 5, 11, 15). Bones in Strata 2A and 2B have a chaotic and unordered vertical arrangement and so there was no benefit in creating a structured vertical bone map.

Bones in Strata 2A and 2B nearly always have a strong orientation in the direction N 43 E (Fig 3.25). Large bones commonly bear accretions of smaller bones on their southwestern edges and complete vertebrae are nearly always oriented with their centra pointing to the southeast and their dorsal processes/neural arches pointing N 43 E. Accumulations of bones tend to cluster in elongated lenses with tapered ends, often coming into contact with one-another, forming masses of intertwined bone. Petrified branches and logs follow the same directional orientation as the bones (Fig. 3.25). In one instance, in which Stratum 2B is interrupted by the upper margin of Stratum 13, bones tend to cluster along the southwestern margin of Stratum 13 and no bones rest atop Stratum 13 (Fig. 3.25 B). In cases where bones are asymmetrical, with one end more massive than the other, the more slender or gracile end almost always points N 43 E. As previously mentioned, vertical orientation in Strata 2A and 2B is chaotic and there is no observable vertical order beyond the fact that the bones are clustered in elongated, tapered, intertwined lenses.

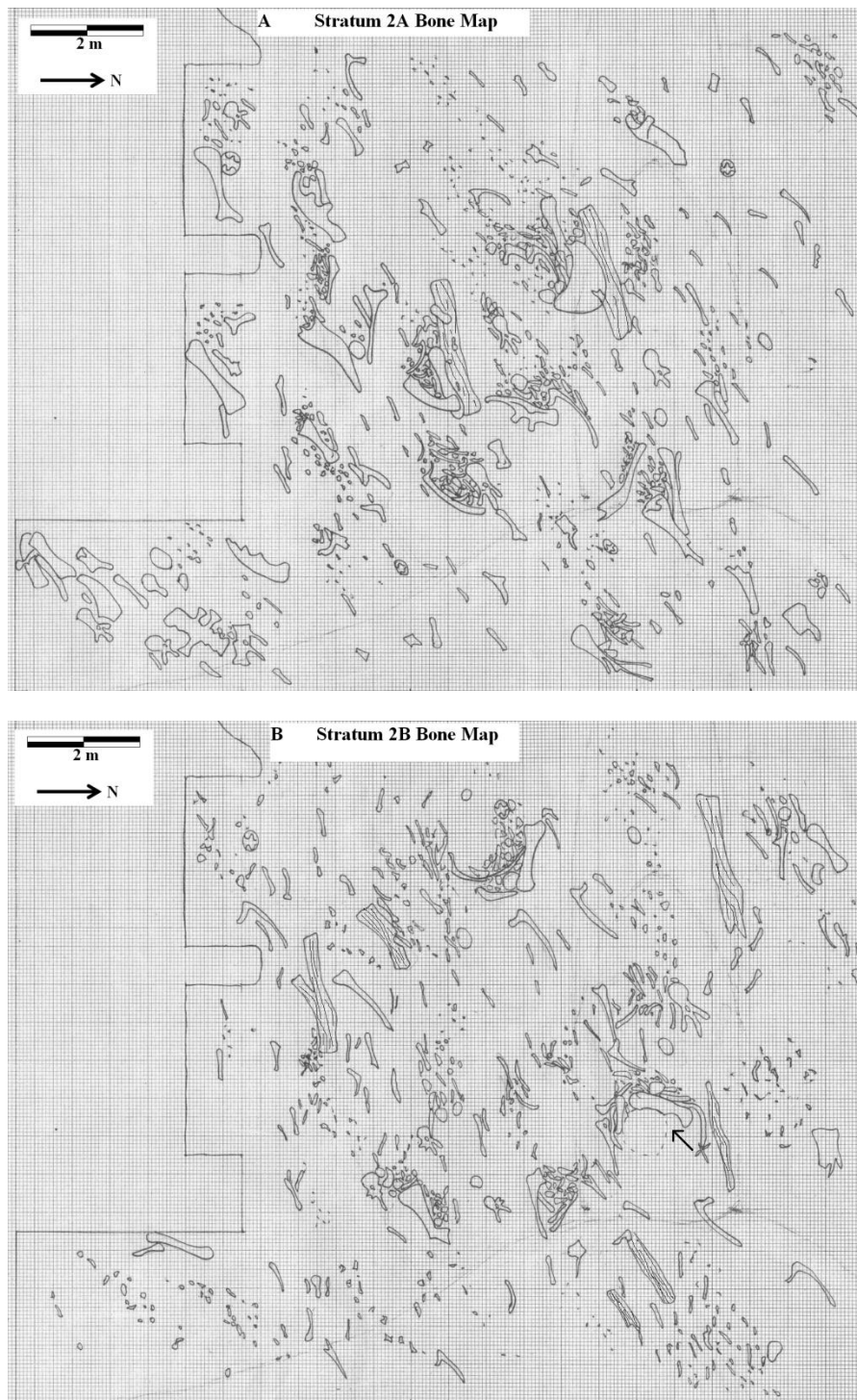


Figure 3.25. A strong directional orientation and elongated clusters of bones can be seen in the bone maps of Strata 2A (A) and 2B (B). Smaller bones tend to cluster on one side of larger bones and obstructions, such as near the bold arrow in (B).

Bones in Stratum 5 show a lateral orientation distinct from that of the other strata, in which bones form a gentle arc with the bones at the South end of Stratum 5 pointing roughly N 12 W and bones at the North end pointing N 30 E (Fig. 3.26). Stratum 5 is very thinly laminated

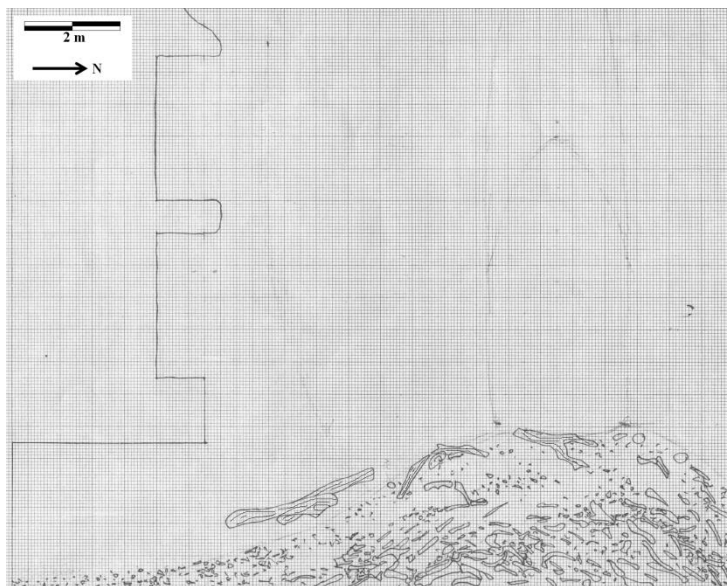


Figure 3.26. Stratum 5 bone map. The bone orientation curves from the northwest to the northeast, following the lateral margin of Stratum 5.

and bones are always situated horizontally on the bedding planes of the laminae. The vertical distribution of bones in Stratum 5 was mapped every 6 cm, producing roughly 6 individual bone maps (Fig. 3.27). The excellent vertical control of Stratum 5, and the abundant remains of certain vertebrate species there (such as turtles, crocodilians, ornithomimids, pachycephalosaurs, and thescelosaurus), made it possible to calculate ratios of adult:subadult:juvenile:hatchling individuals at each of the 6 subsets.

Bones in Strata 11 and 15, which grade into each other, have a lateral orientation distinct from all previous strata. In the lower, sandy portions of Stratum 15, bones are arranged in a

broad horseshoe-shaped arc that follows the lateral margins of the stratum and arcs around Strata 13, 14, and 16 (Fig. 3.28). The greatest concentration of bones is situated along the inside edge

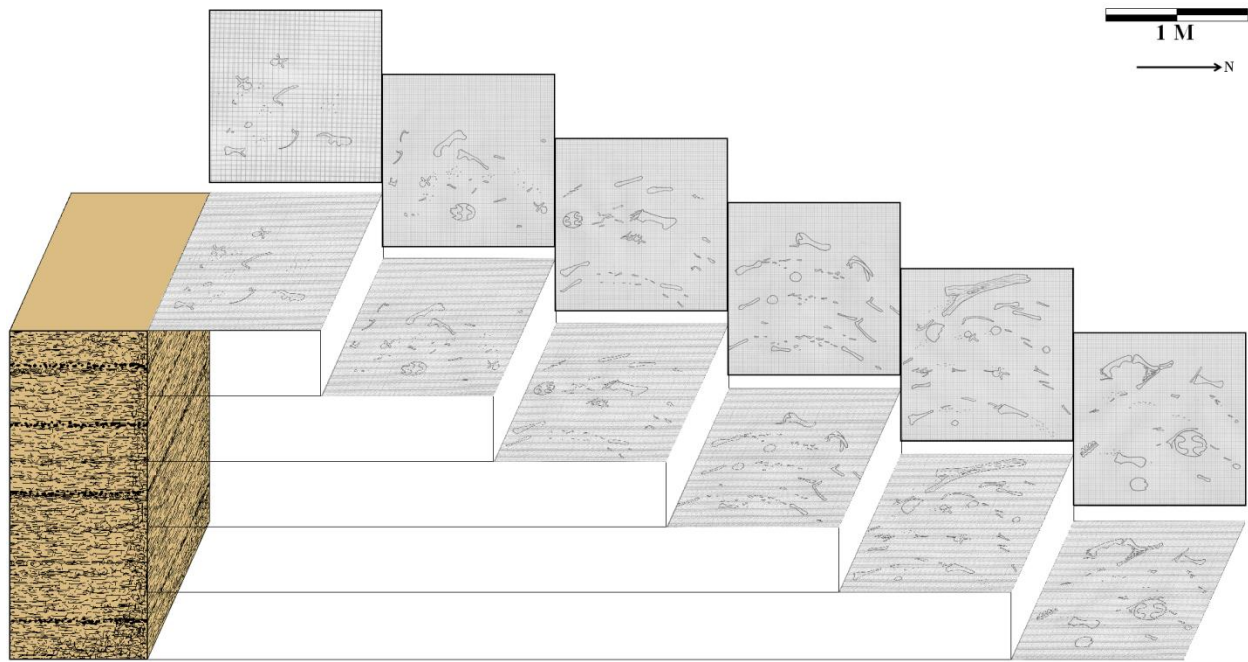


Figure 3.27. Progressive bone maps at 6 cm intervals for a section of Stratum 5.

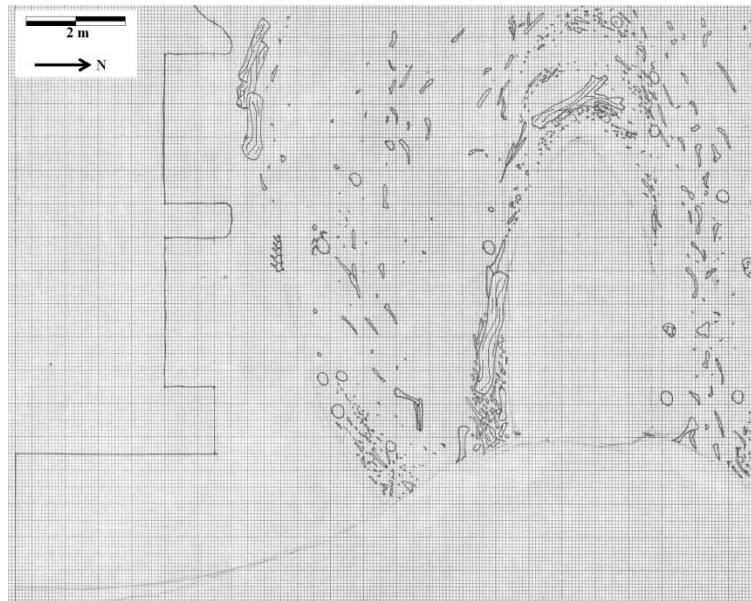


Figure 3.28. Stratum 15 bone map. The bone orientation in Stratum 15 follows a horseshoe-shaped arc around Strata 13 and 14. Bones at the Stratum 5-15 margin are sheared off.

of the arc. The bones in the uppermost portion of Stratum 15, in which sediments become increasingly finer-grained and silty, are more randomly oriented in the lateral aspect, although a vague sense of directionality mirrors the orientation of bones in the lower portion of Stratum 15. All lateral orientation is lost as Stratum 15 grades upward into Stratum 11, and bones in Stratum 11 do not preserve any sense of directionality. The vertical orientation, however, was mapped for Strata 11 and 15 in the same manner as Stratum 5. As with Stratum 5, the thinly laminated strata preserve the vertical distribution of bones on individual laminae and it was possible to calculate ratios of adult : subadult : juvenile : hatchling individuals at 6 cm intervals.

3.4.2. Plant Modification

Leaves and Sprigs

Leaves, needles and sprigs representing both angiosperms and gymnosperms display a wide spectrum of preservation, from pristine and unweathered to damaged nearly beyond recognition. The occurrence of the various degrees of preservation follows a fairly consistent pattern in the Bone Butte strata and enabled a prediction of plant types and condition of preservation even before a particular stratum was formally excavated. For example, strata composed of massive sandstone, such as Strata 1, 3, and 4, and the sandstone lenses of Strata 11 and 15, tend to contain the well preserved leaves of angiosperms oriented in a chaotic fashion both in the lateral and vertical aspects, and few gymnosperm remains (Fig. 3.29). Leaves in these strata are always either complete or minimally torn, with well preserved leaf margins, and virtually never occur as macerated smears of unidentifiable plant matter. In some instances, such as the sandstone lenses within Strata 11 and 15, the leaves are so abundant as to form densely

packed mats (Fig. 3.30) that were deposited horizontally and not twisted or folded over in three dimensions as is the case with leaves from Strata 1, 3, and 4. The majority of all angiosperm

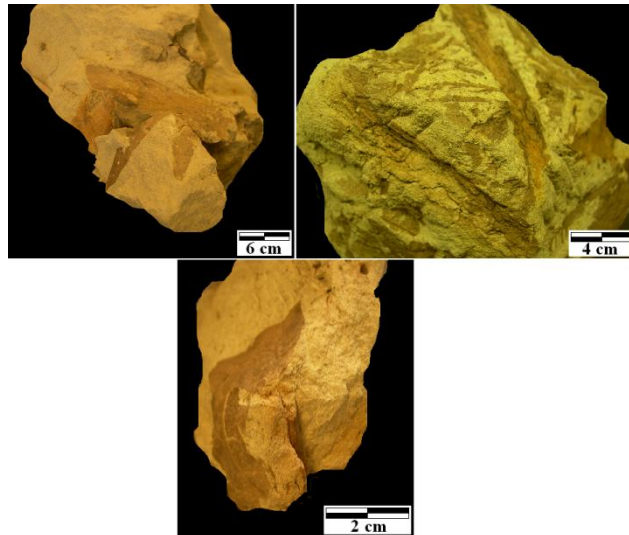


Figure 3.29. Samples of leaves from Stratum 1, photographed in their original orientation. The leaves are chaotically distributed throughout the sandstone and virtually never lay horizontally. Each block is vertically oriented as it was in the field.



Figure 3.30. Densely packed horizontal mats of angiosperm leaves from the sandstone lenses in Stratum 11.

leaves from the site are well preserved and either occur as densely packed mats in sandstone lenses or chaotically oriented in massive sandstone.

The gymnosperm needles and sprigs display a wider range of preservation than the angiosperms, and are consistently found in separate locations. The best preserved gymnosperm

needles, sprigs, strobili, and buds, which are often found attached to small twigs (Fig. 3.31), were uncovered in regularly occurring laminae in Strata 11 and 15 (the Oxbow) and the upper portion of Stratum 5 (Bird & Mammal Zone). In these instances, gymnosperm remains are well

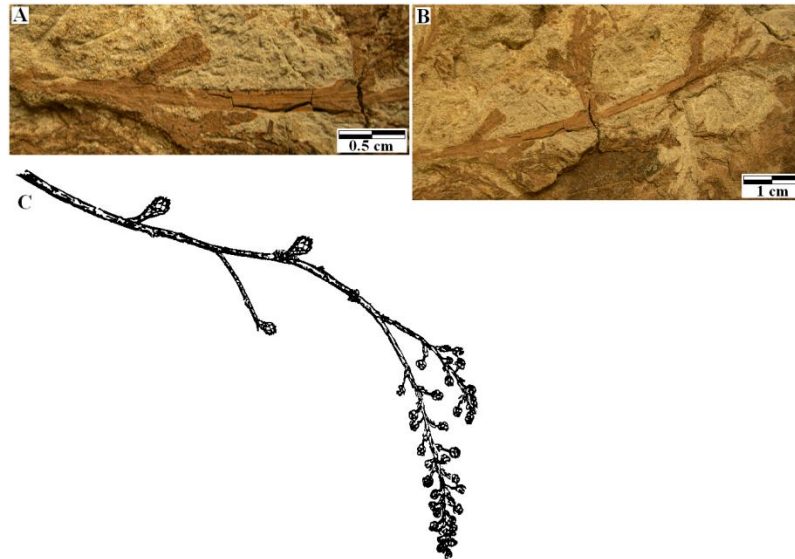


Figure 3.31. Two views of a gymnosperm sprig with attached buds from Stratum 11 (A, B) compared to a *Taxodium* sprig during spring months (C). Drawing in (C) modified from Elias (1989).

preserved and occur as dense mats with few to no angiosperm leaves present. The spatial distribution of mats of well preserved gymnosperm remains, as well as occurrences of gymnosperm twigs with preserved buds, indicates a cyclic pattern (Fig. 3.32). Except for the well preserved mats of gymnosperm remains within the intermittent laminae of the Bird & Mammal Zone and Oxbow, many of the gymnosperm fossils are fragmentary, partially decayed, and in moderate condition. This is not surprising, considering the fragile nature of most gymnosperm plant material and the short time they last in an active fluvial setting (Wing and DiMichelle, 1992).

Charcoal

Charcoalified wood, or pyrofusain, is quite common in certain laminae at Bone Butte (see Stratum 5 description in section 3.1.4.). Pyrofusain occurs as small fragments (3 mm to 40 mm)

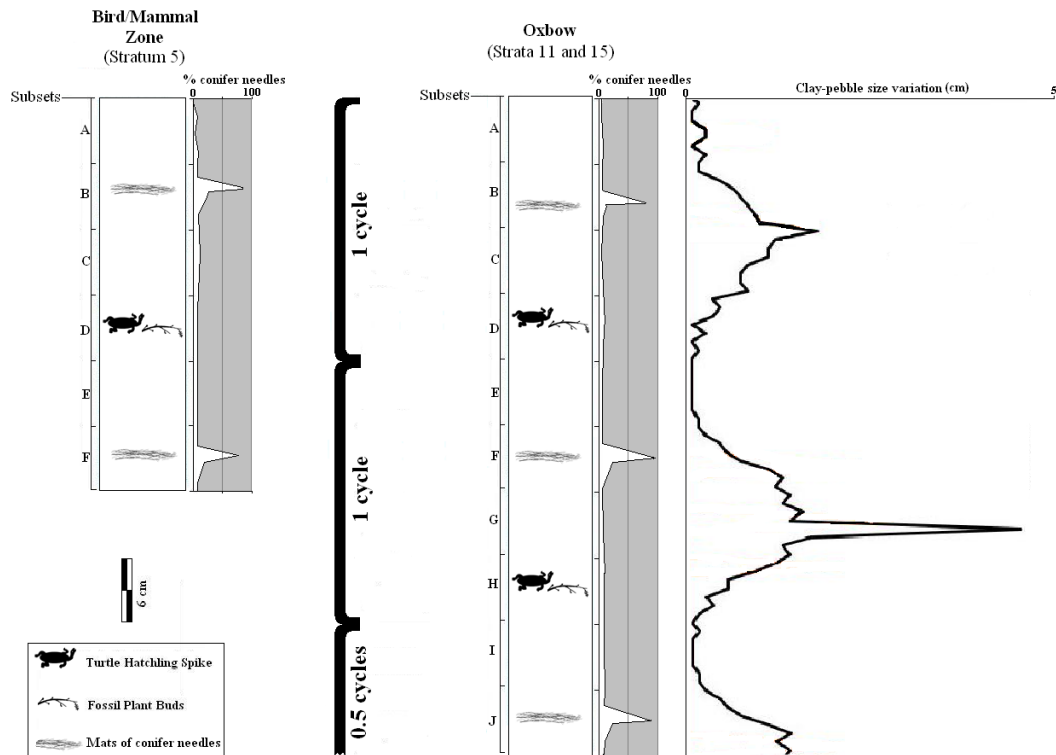


Figure 3.32. The stratigraphic occurrence of plant sprigs with attached buds and dense mats of dropped gymnosperm needles at Bone Butte reveals an evenly spaced, cyclic pattern that repeats about 2.5 times.

of well preserved burnt wood, unmineralized, and displays excellent internal structure. Although large fragments of pyrofusain were uncovered in Strata 1, 3, and 4, the majority of pyrofusain from the site is limited to thin charcoal-enriched laminae regularly occurring in the Bird & Mammal Zone and the Oxbow (Fig. 3.33). Only a small percentage (<15%) of pyrofusain fragments are round or subround in morphology; the majority are overtly angular or subangular. The tree taxa that burned to produce the pyrofusain are as yet unidentified and it is unknown if they were angiosperms, gymnosperms, or a mix of the two.

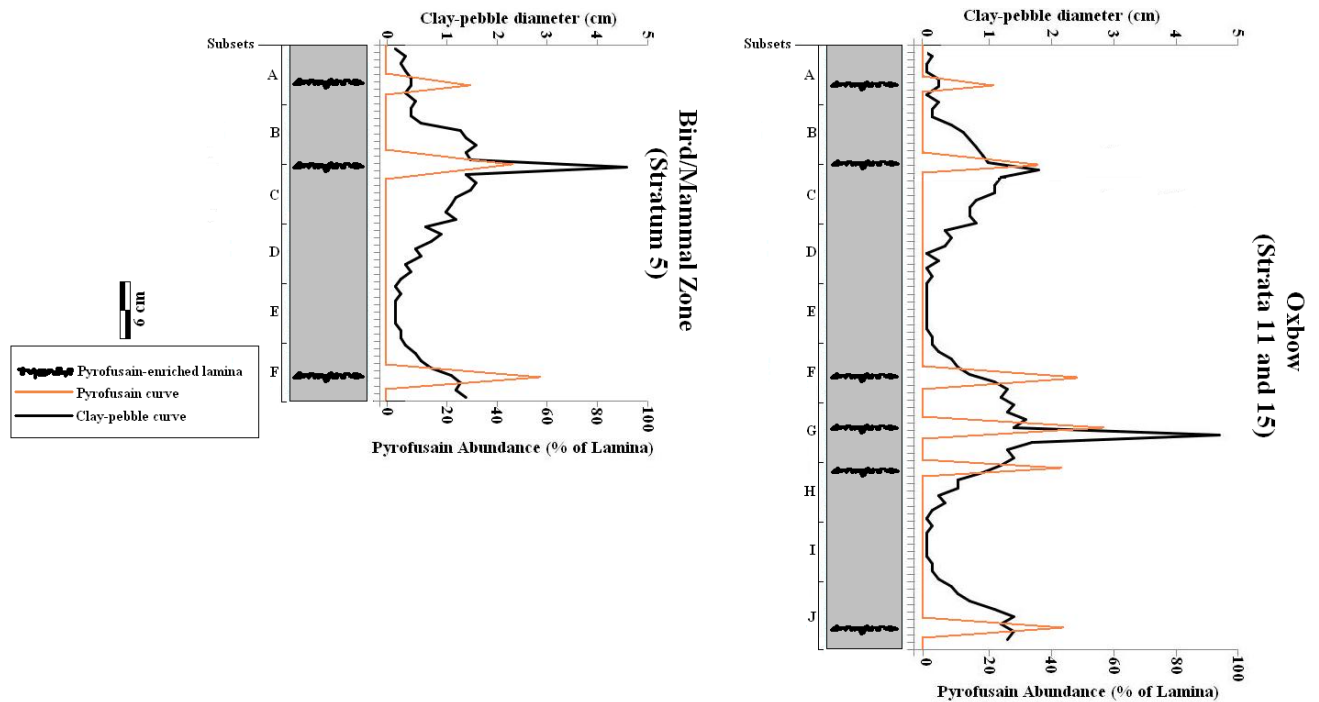


Figure 3.33. Pyrofusain-enriched laminae in Stratum 5 can be correlated with laminae in Stratum 11 and the upper portions of Stratum 15.

3.4.3. Bone Modification

Abrasion

The degree of abrasion varies among the different taxa discovered at Bone Butte and the percentage of abraded versus unabraded bones varies between Stratum 2 (combined Strata 2A and 2B), the Bird & Mammal Zone, and the Oxbow. The degree of abrasion was quantified on a scale of 1 to 6, with 1 representing zero or negligible abrasion and 6 representing maximal abrasion. A number of groups, such as aquatic and terrestrial reptiles, amphibians, turtles, and fish, display an evenly distributed range of abrasion, with ratings spread consistently between 1 and 6. Among these groups, there is no obvious clustering at any particular degree of abrasion. The birds, mammals, and all dinosaurian groups do, however, display a clustering trend on the abrasion scale. These animals are divided primarily into two groups (Fig 3.34), one with high to

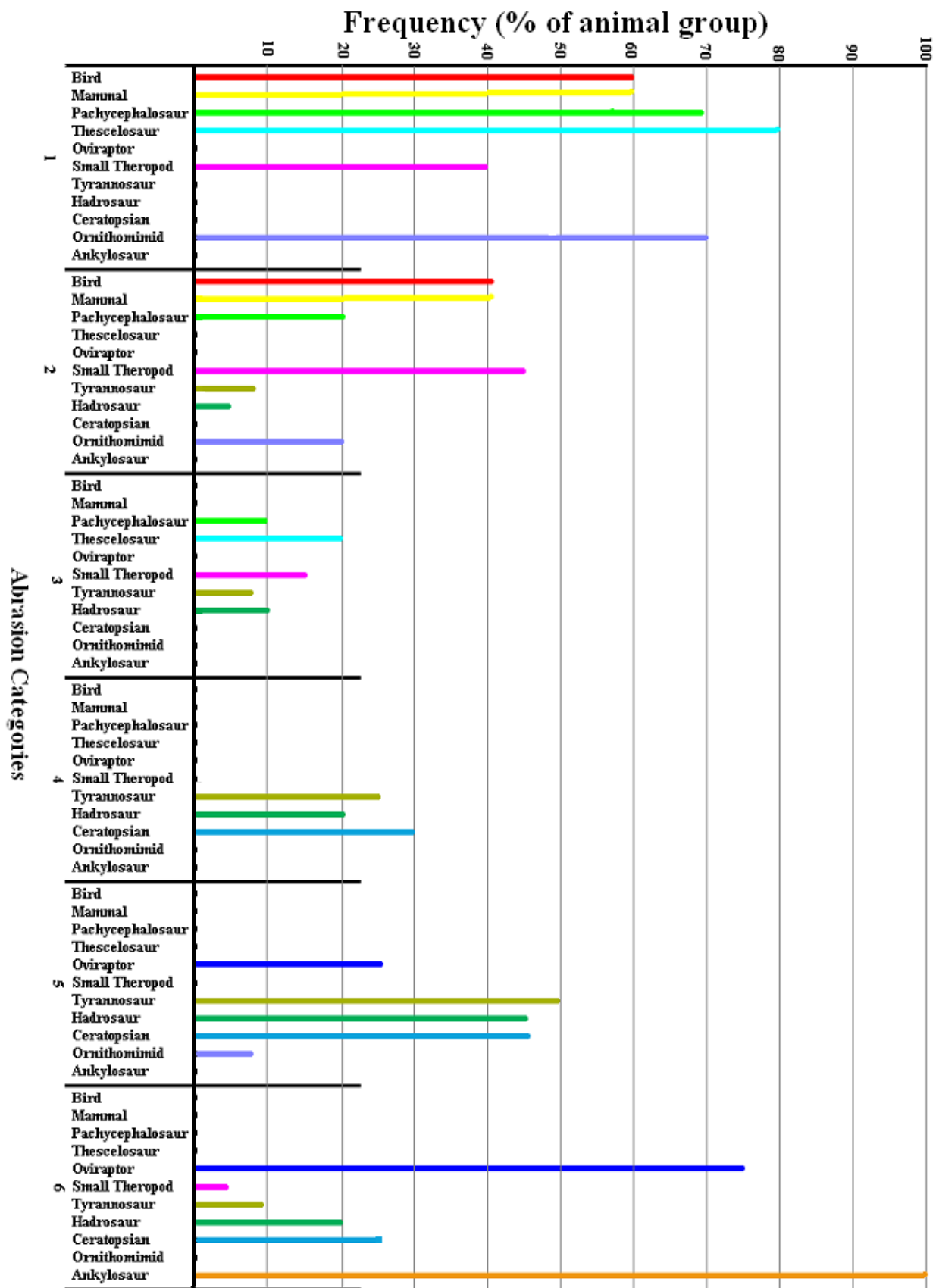


Figure 3.34. Graph of frequency of animal groups falling within one of 6 abrasion categories.

moderate abrasion (Level 4, 5, and 6), and the other with low to no abrasion (Level 1, 2, and 3). Animals such as oviraptorids, ceratopsians, and ankylosaurs cluster only in the high abrasion range. Other animals, such as tyrannosaurs and hadrosaurs clustered mainly in the high abrasion range but some are found in the moderate to low abrasion category. Some animals, such as birds, pachycephalosaurs, and thescelosaurs, score only in the low abrasion range. A large portion of the birds, mammals, and dinosaurs of Stratum 2 (approximately 87%) fall in the high abrasion range, whereas the animals in the Bird & Mammal Zone and Oxbow fall mainly in the low abrasion range (approximately 75%).

Completeness/Breakage

As with the abrasion observed on Bone Butte specimens, the completeness of bones also varies among groups and among the three primary bone-bearing zones (Stratum 2, the Bird & Mammal Zone, and Oxbow). The completeness of bones was measured on a percentage scale from 1% - 100%, corresponding to the percentage of the bone remaining intact (Fig. 3.35). Bones from Bone Butte are generally very complete and few fall below the 40% - 60% complete range. Even fewer fall below the 20% - 40% complete range, and virtually none fall within the 1% - 20% range. As with the abrasion study, the percentage of very complete bones among the birds, mammals, and dinosauria vary between Stratum 2, the Bird & Mammal Zone and the Oxbow; the majority of bones in Stratum 2 are lower on the completeness scale and the bones in the Bird & Mammal Zone and Oxbow are predominantly high on the completeness scale. Animals that are in the low abrasion categories also tend to cluster in the completeness range of

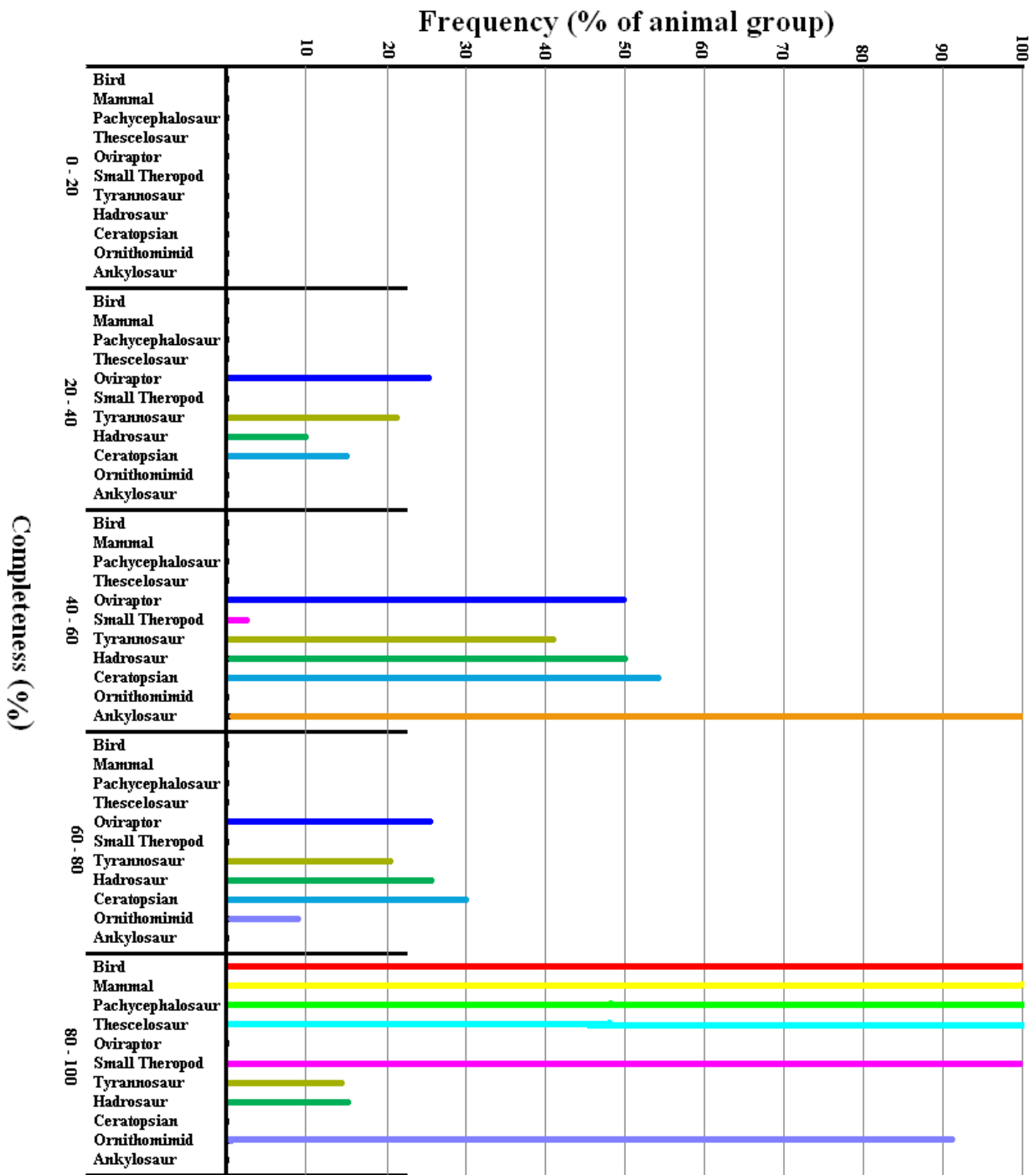


Figure 3.35. Graph of frequency of animal groups falling within completeness percentage brackets.

80% -100%. Conversely, animals that rank high on the abrasion scale tend to cluster between 20% and 80% completeness.

Sorting

To help ascertain the overall distance of transport of bones, the sorting of recovered specimens was ranked based on the diversity of skeletal elements present. The different animal groups from Bone Butte were ranked with respect to the variety of different skeletal elements by which they were represented. A scale of 1 to 5 was used, with 1 corresponding to animals represented by a wide spectrum of skeletal elements, and 5 corresponding to animals represented by a minimal number of different skeletal elements (Table 3.3).

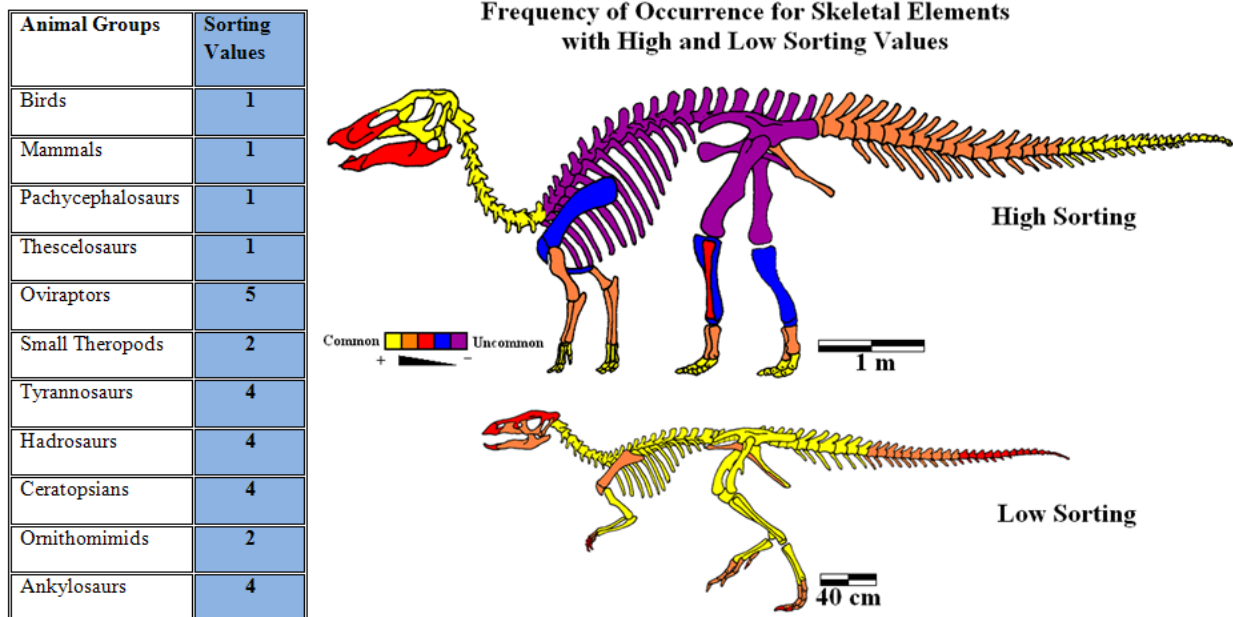


Table 3.3. Sorting values for the different animal groups at Bone Butte (left). The sorting scale is from 1 to 5, with 1 representing the lowest degree of sorting. The frequency of skeletal elements encountered in animals with high and low sorting values can be seen in the figure at right, which uses a hadrosaur (top) and thescelosaur (bottom) as an example. Animals with low sorting values are represented by a wide range of skeletal elements, whereas animals with high sorting values are represented primarily by bones from the periphery of the skeleton.

The animal groups that display the least variation between the different abrasion and sorting categories rank at the middle of the scale, between 2 and 3. Animal groups such as birds,

mammals, pachycephalosaurs, and thescelosaurus, which are represented by examples of virtually every skeletal element, exhibit no sorting and are ranked 1. Other groups, such as small theropods and ornithomimids, exhibit moderate sorting, rank at 2. Interestingly, these two animal groups also straddle the abrasion and completeness groups and are present in both high and low abrasion and completeness categories. The animal groups with highest degrees of sorting, represented by a very narrow fraction of smaller skeletal elements, are the oviraptorids, tyrannosaurs, hadrosaurs, ceratopsians, and ankylosaurs. These groups also happen to correlate with high abrasion and low completeness percentages.

Surface Marks

Surface modification such as root etching, dissolution pits, carnivore bite marks, and sun cracks can be common taphonomic traces and their presence or absence can be important clues to reconstructing a particular taphocoenosis (Behrensmeyer, 1991; Behrensmeyer and Hook, 1992; Lyman, 1994). Surface modification other than abrasion is not especially common in the fossils from Bone Butte and less than 5% of all bones collected exhibit any of the above mentioned surface modifications.

Root etching traces on bone surfaces are the most common surface modifications observed. Dendritic patterns caused by dissolution of bone by plant roots occur in about 3% of all bones uncovered. The occurrence of such traces does not follow any obvious pattern or affinity for particular taxa except that root etching is not observed on the bones of fully aquatic or partially aquatic organisms. Root etchings are only observed on the bones of terrestrial organisms, in both dinosaurian and non-dinosaurian groups.

Dissolution pits were observed in a smaller portion of bones (~2%) and are evenly distributed among all taxa uncovered. Such surface marks have been attributed to dissolution due to algae growth, soil acidity, and partial digestion (Behrensmeyer, 1991; Lyman, 1994; Denys et al., 1995; Bartlett, 2004), however the lack of root etching on the majority of bones with dissolution pits does not support the contribution of soil forming processes, and the extreme size (up to 1 m in length) and completeness of many affected bones rules against their consumption by predators or scavengers. The most likely causative agent is erosion due to aquatic algae and microorganisms (Behrensmeyer, 1991).

Bite marks created by carnivores or scavengers were observed on only 1% of the bones recovered and are present only on dinosaurian and turtle bones. Raking tooth marks and parallel grooves on turtle leg bones, turtle shell fragments, and small dinosaur bones are consistent with the spacing of serrations on *Troodon* or small dromaeosaurid teeth. Other, conical tooth punctures in turtle shells and small dinosaur bones are consistent in size and morphology with crocodilian teeth recovered from the site. Tooth marks consistent in size with large tyrannosaurs were observed in medium to large-sized dinosaur bones, the most striking examples occurring in a large hadrosaur ilium and a set of fused hadrosaur caudal vertebrae. The hadrosaur ilium was punctured, forming an open 11 cm hole in the bone. Evidence of bone healing around the margins of the puncture indicates that the wound had become inflamed, and the animal lived for some time after being attacked. The set of two fused hadrosaur caudal vertebrae were found approximately 4 m away, and provide the clearest evidence of theropod predation (Fig. 3.36). The vertebrae, fused together by an extensive mass of rugose bone growth caused by infection,



Figure 3.36. Two fused hadrosaur caudal vertebrae from Bone Butte are a striking example of predatory behavior. A theropod tooth embedded in the vertebrae (white circle) is encircled by healing bone.

preserves the embedded tip of a theropod tooth. As with the ilium, the growth of healed bone around the tooth indicates the hadrosaur lived for a period of time after the attack.

Cracks formed in bones before fossilization, resulting from subaerial exposure and drying due to sunlight, are present in less than 1% of the specimens. All of the “sun cracks” are small, resembling the Stage 1 cracks of Behrensmeyer (1978). The occurrence of “sun cracks” follows the same pattern as root etching; sun cracks are only observed on the bones of terrestrial organisms at Bone Butte (Fig. 3.37). No other pattern was seen in the distribution of sun cracks and they are rather evenly distributed among the different taxa and strata.

3.4.4. *Correlated Similarities in Taphonomic Data*

Correlated similarities in taphonomic results on abrasion, completeness, and sorting elucidate a trend that bird, mammal, and dinosaur fossils among the Bone Butte specimens fall



Figure 3.37. These two *Didelphodon* jaws from Bone Butte bear different taphonomic characteristics. Whereas the surface of one jaw is smooth and pristine (A), the surface of the other jaw bears parallel “sun cracks” formed while the unfossilized bone was subaerially exposed (B).

within two taphotypes (Table 3.4 A, B). It is evident that the group of fossils with high levels of abrasion (Level 3-5) correlates with the group of fossils that has lower levels of completeness (1% - 80%) and high levels of sorting (4-5). This group of bones, termed Group A, was calculated individually for Stratum 2, the Bird & Mammal Zone, and Oxbow. It was also observed that another group of bones, which possesses low levels of abrasion (Level 1-3), correlates with the group that has higher levels of completeness (80% - 100%) and low/negligible levels of sorting (1-2). This group, termed Group B, was calculated for stratum 2, the Bird & Mammal Zone, and Oxbow (Table 3.5).

The percentage of each animal group comprising Group A and Group B was calculated for each of the three bone-bearing zones, the results of which show that the ratios of animals in each Group A are nearly identical and those in each Group B vary only slightly between Stratum 2, the Bird & Mammal Zone, and Oxbow (Table 3.6). The Group A taphotype is comprised mainly of ceratopsians, hadrosaurs and tyrannosaurs, with a smaller component of oviraptorids,

A	Dinosaurs, Birds, and Mammals	Abrasion	Completeness	Sorting
	Birds	Low	High	Low
	Mammals	Low	High	Low
	Pachycephalosaurs	Low	High	Low
	Thescelosaurs	Low	High	Low
	Oviraptors	High	High	High
	Small Theropods	Moderate/ Low	High	Moderate/ Low
	Tyrannosaurs	High	Low	High
	Hadrosaurs	High	Low	High
	Ceratopsians	High	Low	High
	Ornithomimids	Moderate	Moderate/High	Moderate
	Ankylosaurs	High	Low	High

B	Group A	Group B
	High Abrasion	Low Abrasion
	Low Completeness	High Completeness
	High Sorting	Low Sorting
	Oviraptorids	Pachycephalosaurs
	Small Theropods	Thescelosaurs
	Tyrannosaurs	Small Theropods
	Hadrosaurs	Tyrannosaurs
	Ceratopsians	Hadrosaurs
	Ornithomimids	Ornithomimids
	Ankylosaurs	

Table 3.4. (A) Comparison of relative abrasion, completeness and sorting scores among the animal groups. (B) Animals divided into Group A and Group B based on correlated taphonomic characteristics.

ornithomimids, small theropods, mammals, and ankylosaurs. The Group B taphotype, however, is comprised mainly of small theropods, pachycephalosaurs, ornithomimids, and thescelosaurs, with a smaller component of mammals, birds, tyrannosaurs, and hadrosaurs. Group B animal ratios vary slightly between Stratum 2, the Bird & Mammal Zone, and Oxbow, with an increased abundance of birds and mammals in the Bird & Mammal Zone, and an increased abundance of pachycephalosaurs and small theropods in the Oxbow.

The compositions of the Group A and Group B faunas from each of the three bone-bearing zones were combined to form a single Group A and Group B (Table 3.7). An additional set of calculations separate the bird and mammal components from the groups and allow a Group A and Group B composed solely of dinosaurs to be examined (Table 3.8).

	<u>Stratum 2</u>		<u>Bird & Mammal Zone</u>		<u>Oxbow</u>	
	<u>Group A</u> (87% of specimens)	<u>Group B</u> (13% of specimens)	<u>Group A</u> (25% of specimens)	<u>Group B</u> (75% of specimens)	<u>Group A</u> (29% of specimens)	<u>Group B</u> (71% of specimens)
	% of specimens in Group A	% of specimens in Group B	% of specimens in Group A	% of specimens in Group B	% of specimens in Group A	% of specimens in Group B
Dinosaurs, Birds, and Mammals						
Birds	0%	0%	0%	100%	0%	100%
Mammals	66%	34%	0%	100%	0%	100%
Pachycephalosau rs	0%	100%	0%	100%	0%	100%
Thescelosaurs	0%	100%	0%	100%	0%	100%
Oviraptors	100%	0%	100%	0%	100%	0%
Small Theropods	15%	85%	2%	98%	4%	96%
Tyrannosaurs	100%	0%	86%	15%	100%	0%
Hadrosaurs	99%	1%	85%	15%	85%	15%
Ceratopsians	100%	0%	100%	0%	100%	0%
Ornithomimids	67%	33%	8%	92%	11%	89%
Ankylosaurs	100%	0%	100%	0%	0%	0%

Table 3.5. Percent of each animal group falling into either Group A or Group B, calculated for Stratum 2 (2A and 2B), the Bird & Mammal Zone, and Oxbow.

Relative Abundance of Taxa/Faunal Percentages in Group A and Group B						
Calculations for Stratum 2, Bird/Mammal Zone, Oxbow						
	Stratum 2		Bird/Mammal Zone		Oxbow	
	Group A (87% of specimens)	Group B (13% of specimens)	Group A (23% of specimens)	Group B (73% of specimens)	Group A (29% of specimens)	Group B (71% of specimens)
	% of Group A	% of Group B	% of Group A	% of Group B	% of Group A	% of Group B
Dinosaurs, Birds, and Mammals						
Birds	0%	0%	0%	10%	0%	2%
Mammals	1%	1%	0%	16%	0%	3%
Pachycephalosaurs	0%	23%	0%	26%	0%	32%
Therapsids	0%	21%	0%	9%	0%	12%
Oviraptors	7%	0%	6%	0%	4%	0%
Small Theropods	1%	32%	1%	22%	4%	35%
Tyrannosaurs	16%	0%	17%	1%	21%	0%
Hadrosaurs	24%	2%	25%	1%	23%	2%
Ceratopsians	43%	0%	46%	0%	42%	0%
Ornithomimids	6%	19%	4%	15%	4%	14%
Ankylosaurs	1%	0%	1%	0%	0%	0%

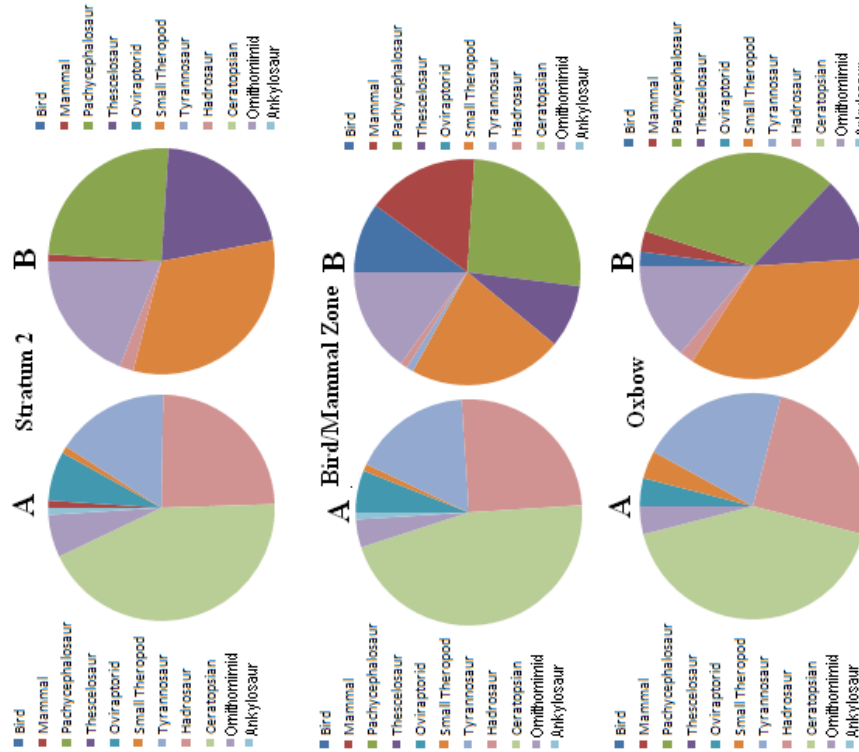


Table 3.6. Relative abundance of each animal group present in Group A and B for the 3 stratigraphic packages.

Relative Abundance of Taxa/Faunal Percentages in Group A and Group B		
Calculations Combined all Group A and Group B Animals into Two Groups		
	Group A (61% of specimens)	Group B (39% of specimens)
	% of Group A	% of Group B
Dinosaurs, Birds, and Mammals		
Birds	0%	6%
Mammals	1%	11%
Pachycephalosaurs	0%	27%
Thescelosaurus	0%	12%
Oviraptors	6%	0%
Small Theropods	1%	26%
Tyrannosaurs	17%	1%
Hadrosaurs	24%	2%
Ceratopsians	44%	0%
Ornithomimids	6%	15%
Ankylosaurs	1%	0%

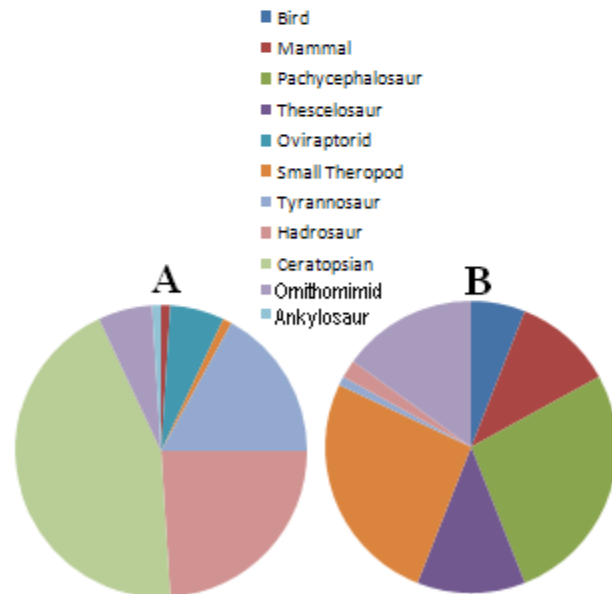


Table 3.7. Group A and Group B from Stratum 2, Bird & Mammal Zone, and Oxbow, combined to form a single Group A and Group B. Compositions of the groups are represented by percentages and pie charts.

Relative Abundance of Dinosaurian Faunal Percentages in Group A and Group B		
Calculations Combined all Group A and Group B Animals into Two Groups		
	Group A (% of specimens)	Group B (% of specimens)
	% of Group A	% of Group B
Dinosaurs		
Pachycephalosaurs	0%	32%
Thescelosaurs	0%	15%
Oviraptors	6%	0%
Small Theropods	1%	32%
Tyrannosaurs	17%	1%
Hadrosaurs	25%	2%
Ceratopsians	44%	0%
Ornithomimids	6%	18%
Ankylosaurs	1%	0%

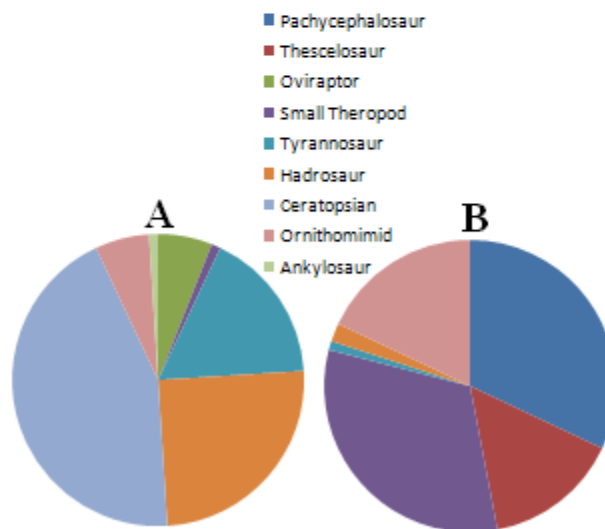


Table 3.8. The faunal composition of dinosaurian components of Groups A and B.

3.4.5. Assemblage Data

Sample Size

The total number of specimens collected from Bone Butte, including teeth, is 2799, far above the minimum of 100 samples necessary to perform an effective comparative analysis (Behrensmeyer, 1991). In fact, Bone Butte has proven to be one of the most prolific and diverse Hell Creek sites of its size, as compared to previously reported sites (Bartlett, 2004). Of the 2799

specimens collected, 1231 are from dinosaurs. Group A consists of 743 dinosaurian specimens and 8 mammal specimens. Group B consists of 398 dinosaur specimens, 29 bird specimens, and 53 mammal specimens. 1568 additional fossils of aquatic and terrestrial reptiles, amphibians, turtles, and fish comprise the remainder of vertebrate specimens from Bone Butte.

Number of Species and Diversity

The calculation of vertebrate species richness at Bone Butte was facilitated by the generally superior preservation of the fossil material. In most cases fossils could be identified to the generic and specific levels and, with more fragmentary remains, to the ordinal and familial levels. The vertebrate faunal list for Bone Butte as of 2009 was calculated at 53, close to the maximum expected for the sample size collected (Bartlett, 2004, Fig. 3.38), and ranking the site as one of the most diverse in published work on the Hell Creek Formation (Pearson et al., 2002; Bartlett, 2004). Vertebrate remains are clustered into three groups – Stratum 2 (Strata 2A and 2B combined), Stratum 5 (Bird & Mammal Zone), and Strata 11 and 15 (Oxbow) – corresponding to strata that represent different depositional settings. Dinosaurian remains comprise between 44% and 32% of the overall vertebrate assemblage, comparable to other Hell Creek studies (Lehman, 1987; White et al, 1998; Russell and Manabe, 2002; Bartlett, 2004), and contain a wide assortment of carnivores, herbivores and omnivores. The dinosaurian percentage varies between the different strata, decreasing in abundance from Stratum 2A and 2B, to Stratum 5, and to Strata 11 and 15. The abundance of crocodilian and turtle remains increases in Stratum 5 and especially in Strata 11 and 15. Bird and mammal abundance increases in the same strata, although they reach maximum abundance in Stratum 5, earning that stratum the name “Bird and Mammal Zone”.

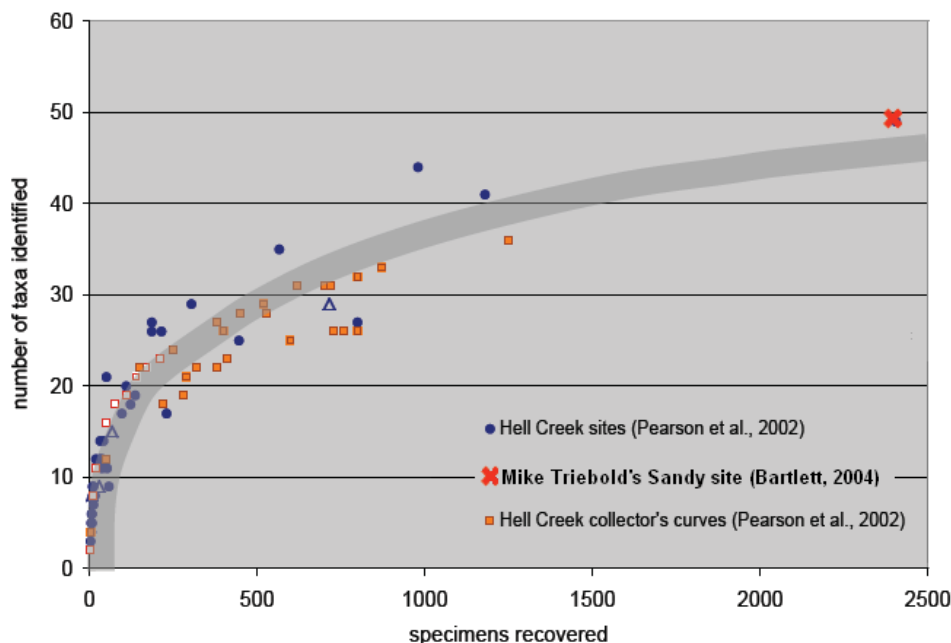


Figure 3.38. This chart, modified from Bartlett (2004), shows a relationship between the number of collected specimens and number of taxa discovered. The curve plateaus at about 2500 collected specimens, after which the expectancy to find additional taxa decreases. With nearly 3000 specimens collected from Bone Butte, it is likely that the majority of taxa present in the Bone Butte area have been sampled during the course of this study.

Dinosaurian diversity is high in both Group A and Group B bonesets and overall diversity does not vary appreciably between the two groups (Table 3.9). Group A dinosaurs total 20 species and 19 genera, while Group B dinosaurs total 14 species and 16 genera. The tyrannosaurs and hadrosaurs, which have representatives in both Group A and Group B, have a much higher occurrence and higher diversity in Group A. Overall, the diversity of dinosaurs in Group A and Group B, and among both dinosaurian and non-dinosaurian vertebrates at Bone Butte, is high.

Dinosaurs Total genera: 25 Total species: 27					
Group A	Genera: 19	Species: 20	Group B	Genera: 14	Species: 16
<u>Oviraptorids</u> <i>Chirostenotes</i> <i>Caenagnathus</i> <u>Small Theropods</u> <i>Richardoestesia</i> <i>Troodon formosus</i> <i>Dromaeosaurus</i> <i>Sauromitholestes</i> <i>Paronychodon</i> <u>Tyrannosaurids</u> <i>Tyrannosaurus rex</i> <i>Aublysodon</i> <i>Nanotyrannus lancensis</i> <u>Hadrosaurs</u> <i>Edmontosaurus annectens</i> <i>Anatotitan</i> Crested hadrosaur (gen. et. spec. indet.) <u>Ceratopsians</u> <i>Triceratops horridus</i> <i>Triceratops porosus</i> <i>Torosaurus latus</i> <u>Ornithomimids</u> <i>Struthiomimus</i> <i>Ornithomimus</i> <u>Ankylosaurs</u> <i>Edmontonia</i> Ankylosauria indet.			<u>Pachycephalosaurs</u> <i>Pachycephalosaurus wyomingensis</i> <i>Stygimoloch spinifer</i> <u>Thescelosaurs</u> <i>Thescelosaurus neglectus</i> <i>Thescelosaurus garbanii</i> <i>Bugenasauria</i> <u>Small Theropods</u> <i>Richardoestesia</i> <i>Troodon formosus</i> <i>Dromaeosaurus</i> Dromaeosaurid indet. <i>Sauromitholestes</i> <i>Paronychodon</i> <i>Pectinodon</i> <u>Tyrannosaurids</u> <i>Tyrannosaurus rex</i> <u>Hadrosaurs</u> <i>Edmontosaurus annectens</i> <u>Ornithomimids</u> <i>Struthiomimus</i> <i>Ornithomimus</i>		

Table 3.9. The genera and species of dinosaurs recorded for Group A and Group B.

Age Spectrum and Medullary Bone

Bone Butte is unique in that it contains a wide spectrum of age groups for many of its taxa. The aquatic reptiles, terrestrial reptiles and turtles all contain representatives of various age groups. Terrestrial reptiles are the most limited in this respect, containing about 90% adult and 10% subadult individuals. Aquatic reptiles, especially crocodilians, possess a whole suite of

different age groups, from hatchling to adult. Crocodilians are comprised of approximately 50% adults, 23% subadults, 18% juveniles, and 10% hatchlings. Champsosaur remains also contain juvenile material, although juvenile champsosaurs make up only about 5% of the total champsosaur remains recovered. Turtles, like the crocodilians, are represented by every age group: approximately 47% are adults, 30% are subadults, 18% are juveniles, and 5% are hatchlings.

Many dinosaurian groups are also represented by a multitude of age groups, however dinosaurs in the Group A taphotype tend to have fewer subadults and juveniles than those in the Group B taphotype and no dinosaurian hatchling bones were recovered. Among the Group A dinosaurs, the small theropods, hadrosaurs, ceratopsians, and ornithomimids all have subadult representatives, but juvenile and hatchling remains are lacking. Group B dinosaur remains have a higher incidence of immature remains, with the pachycephalosaurs, thescelosaurs, small theropods, and ornithomimids all having a strong component of subadult and juvenile individuals. A few subadult hadrosaur bones are also part of the Group B dinosaur assemblage, however the percentage is miniscule. Also, one juvenile theropod tooth assigned to *Tyrannosaurus rex* is part of the Group B assemblage, the only juvenile tyrannosaur bone recovered from the site.

A highly detailed excavation of the Bird & Mammal Zone and Oxbow enabled an extremely accurate calculation of ontogenetic ratios through time for certain well represented taxa. The Bird & Mammal Zone and Oxbow strata were excavated in 6 cm vertical increments, each subset with its own separate tally of bones. For the Bird & Mammal Zone, there are 6 such subsets, and for the Oxbow there are 10. Calculating the ratios of adult:subadult:juvenile:hatchling for each of the increments reveals a cyclic pattern in

ontogenetic ratios through time (Fig 3.39 – 3.40). Using this method, it was possible to trace the growth and development of some of the best represented taxa, such as the crocodilians, turtles, ornithomimids, and thescelosaurus.

Whereas no hatchling bones were recovered for any of the dinosaur taxa, the presence of medullary bone and several fragments of pristine eggshell suggest that hatchling dinosaurs were in the vicinity (Fig. 3.41). The distribution of medullary bone, an indicator of dinosaurian and avian breeding status (Schweitzer, 2008), is limited almost entirely to the Group B bones, where it is present in approximately 59% of pachycephalosaur bones, 45% of thescelosaur bones, and 58% of ornithomimid bones. Curiously, very few examples of medullary bone are present in the Group A taphotype. In Group A, only about 1% of ornithomimid bones contain medullary bone, and medullary bone is otherwise absent from all Group A bones.

Dinosaur eggshell has not been reported from the Hell Creek Formation in decades (Jepsen, 1931) and discovery of North American dinosaur eggshell has been limited primarily to the Upper Cretaceous of Utah (Zelenitsky et al., 2000) and Montana (Hirsch and Quinn, 1999).

Articulation

Overall, the incidence of articulated specimens at Bone Butte is low. Among non-dinosaurians, the only articulation observed is among the turtles, crocodilians, and a single avian. Articulation of turtle bones was found in at least ten cases. Turtle feet, limb elements, and partial necks were found in all three bone-bearing zones: Stratum 2, the Bird & Mammal Zone, and Oxbow. Ironically, one of the best articulated animals in the entire site belongs to the rarest organism: an ornithurine bird. This is the best-preserved example known from the Hell Creek

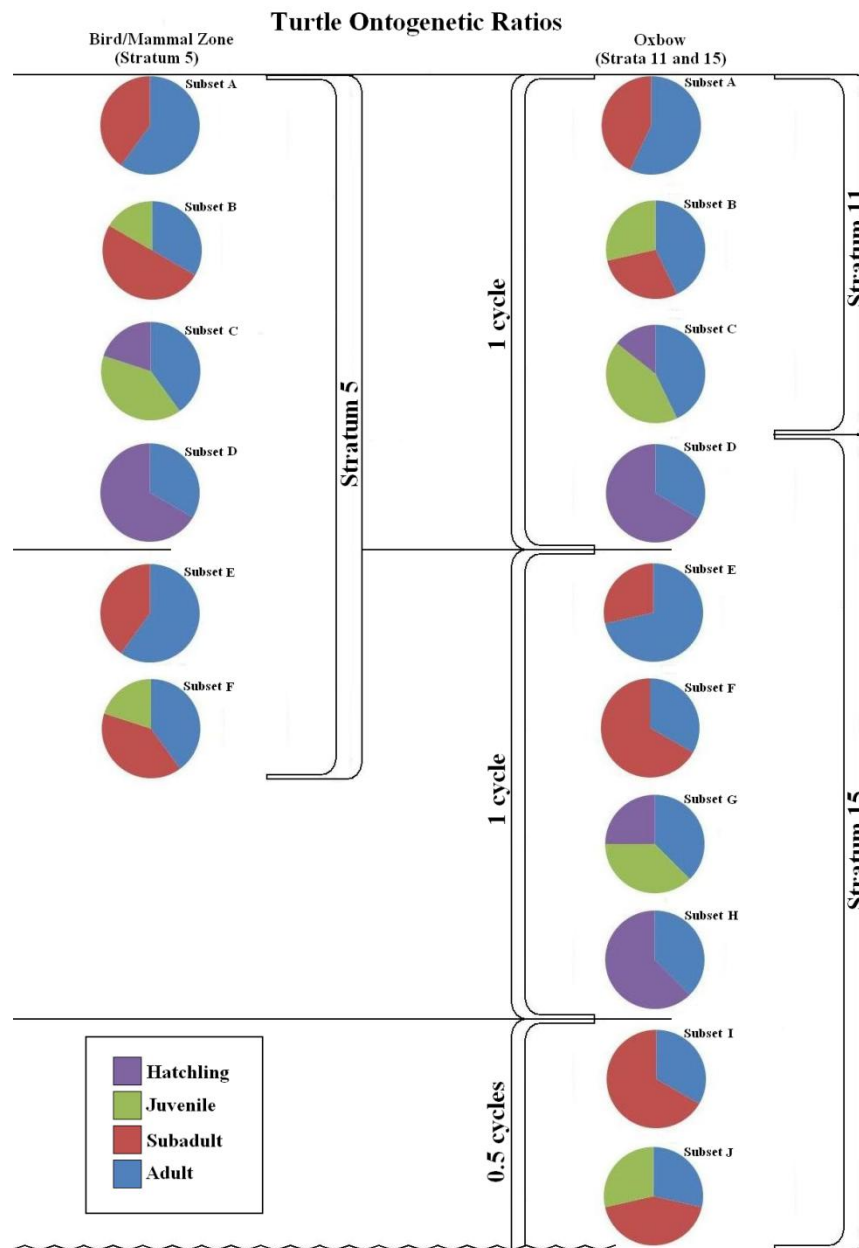


Figure 3.39. Succession of pie charts depicting the shift in frequency of turtle ontogenetic stages in the Bird & Mammal Zone (left) and Oxbow (right). A repeating pattern of ontogenetic stages is evident, indicating approximately 2.5 cycles. Also, ontogenetic ratios in overlapping portions of the Bird & Mammal Zone and Oxbow correlate with each other.

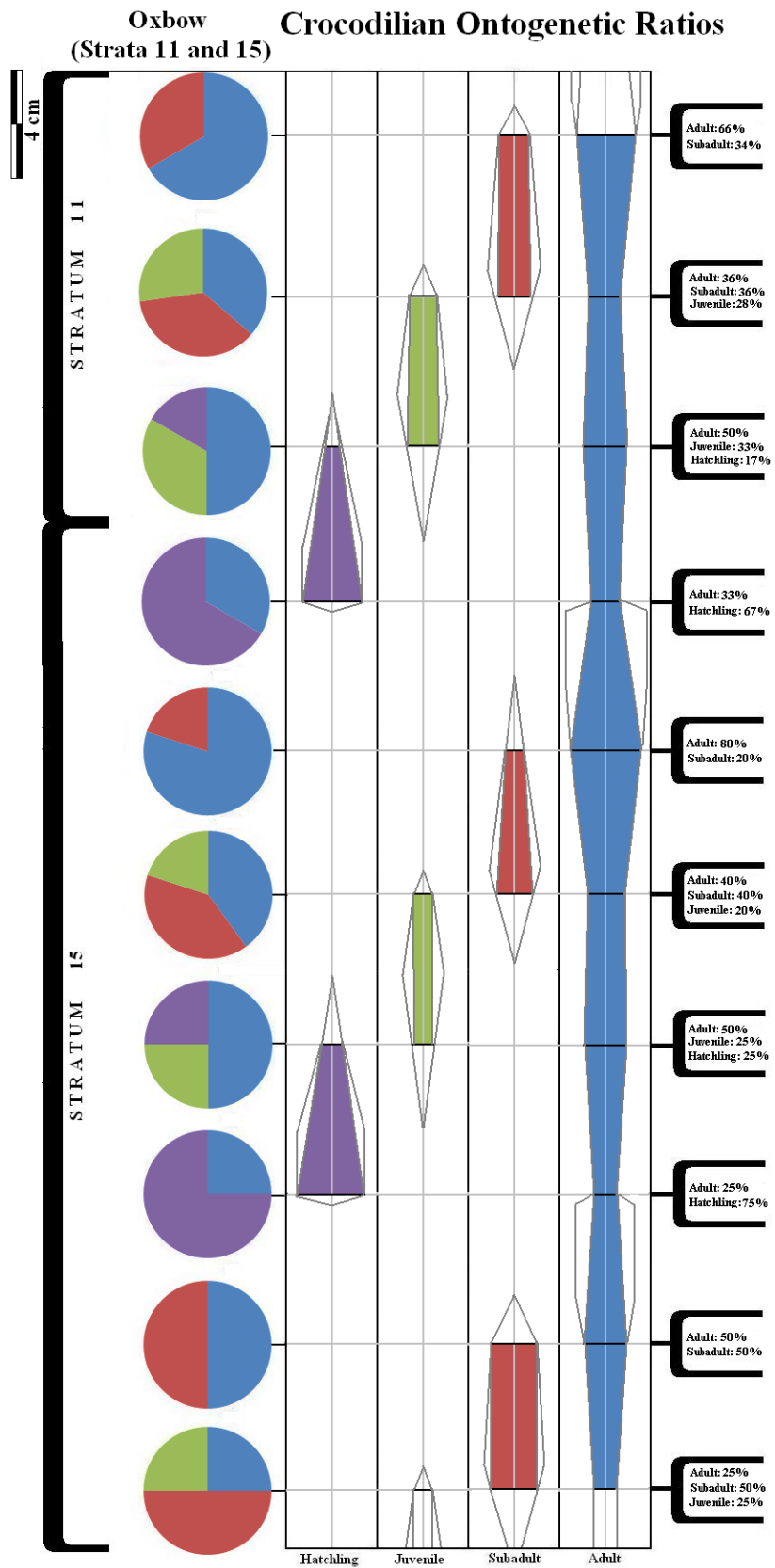


Figure 3.40. Graphical representation of crocodilian ontogenetic data from the Oxbow. The crocodilian population can be seen maturing over time, with new pulses of hatchlings at regular intervals.

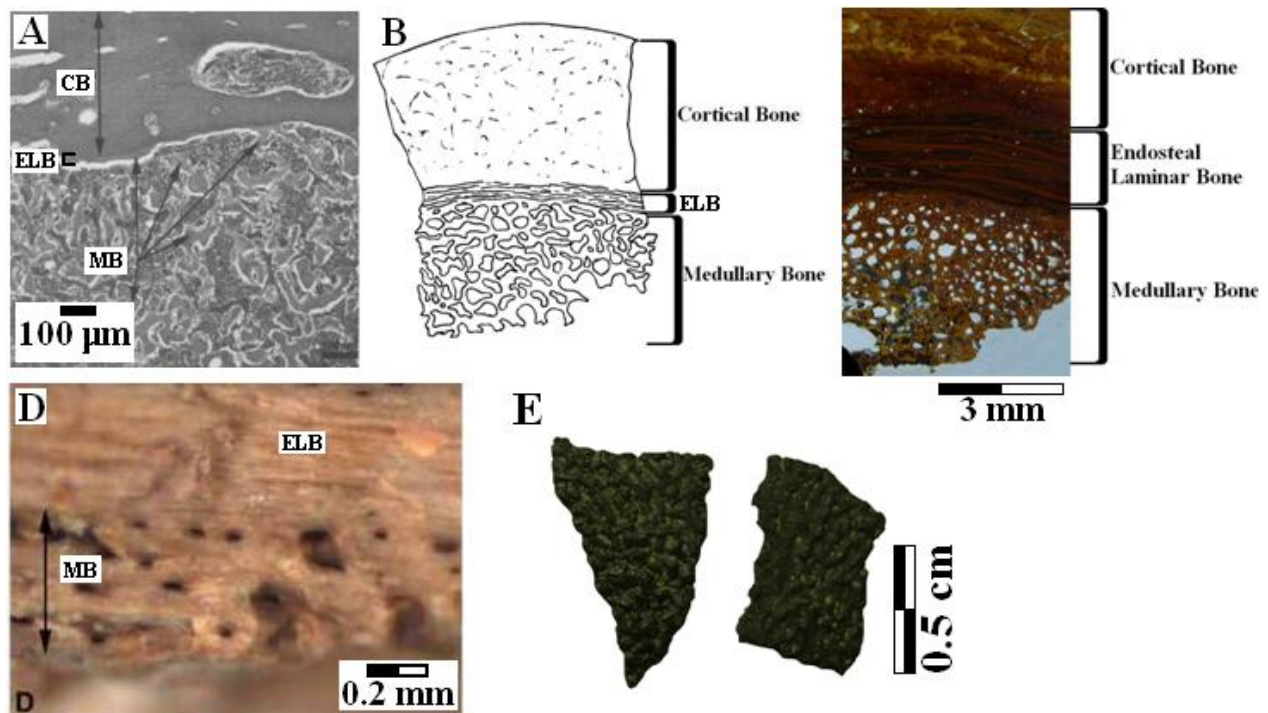


Figure 3.41. Medullary bone from a pachycephalosaur at Bone Butte (C) is compared to a diagram of dinosaur medullary bone modified from Lee and Werning, 2007 (B), medullary bone from a modern laying hen (A; Schweitzer et al., 2008), and medullary bone from a tyrannosaur reported by Schweitzer (D; photo credit NCSU). Fossil dinosaur eggshell with ramotuberculate ornamentation and prolatospherulitic shell morphology (E) was also found at Bone Butte. Abbreviations: CB = cortical bone; ELB = endosteal laminar bone; MB = medullary bone.

Formation and was found beside a partially articulated juvenile *Trionyx* turtle in the Bird & Mammal Zone.

Articulation of dinosaurian remains was observed only among Group B bones, and is confined to the pachycephalosaurs, thescelosaurs, small theropods, ornithomimids, and a single hadrosaur (not including the pathological fused caudal vertebrae). Articulated elements of pachycephalosaurs, thescelosaurs, and small theropods consist of partially articulated limbs without feet, articulated thoracic vertebral sections, and partially articulated feet consisting of proximal phalanges articulated with metatarsals. Ornithomimids possess the same suite of articulated elements, with the addition of two small sections of articulated caudal vertebrae with

chevrons. Articulation was observed among the above mentioned dinosaurian groups in all three bone-bearing zones, however the incidence of articulated specimens increased in the Bird & Mammal Zone and the Oxbow.

Skeletal Elements Present

As previously mentioned, significant levels of sorting are primarily limited the Group A bones from Bone Butte. In general, Group A specimens tend to be comprised of smaller bones originating from distal parts of the animals, such as distal caudal vertebrae, phalanges, and skull bones, whereas Group B bones tend to be comprised of a wider variety of skeletal elements (Table 3.10). The tyrannosaurs, hadrosaurs, and ceratopsians are all represented by a

Representation of Skeletal Elements							
	Manus/Pes Elements	Limb Bones	Shoulder and Hip Elements	Cervical and Caudal Elements	Thoracic Vertebrae and Ribs	Skull Elements	Teeth
Pachycephalosaurs	Many	Many	Many	Many	Many	Many	Many
Thescelosaurus	Many	Many	Many	Many	Many	Many	Many
Oviraptorids	/	Moderate	/	Many	/	/	n/a
Small Theropods	Few	Many	Moderate	Few	Many	Few	Many
Tyrannosaurs	Few	/	/	Few	/	/	Many
Hadrosaurs	Many	Moderate	Few	Many	/	Few	Many
Ceratopsians	Many	Few	Moderate	Many	Few	Few	Many
Ornithomimids	Many	Many	Many	Many	Many	Many	n/a
Ankylosaurs	/	/	/	/	/	/	Many

Table 3.10. Relative frequency of various skeletal elements from the different dinosaurian groups.

preponderance of teeth, distal caudal elements, phalanges, cervical ribs, and in the case of hadrosaurs and ceratopsians, occasional skull and limb bones. Oviraptorids are represented by only distal caudal and rear limb elements, and ankylosaurs are represented by teeth, scutes, and a single left quadrate. Small theropods and ornithomimids are represented by a wider range of skeletal elements, although some sorting was evident. The small theropods and ornithomimids are represented by examples of nearly every skeletal element, although caudal elements, cervical elements, skull bones, and phalanges are not especially common for these animal groups. Pachycephalosaurs and thescelosaurs, however, exhibit virtually no sorting at all and multiple examples of every part of their skeletons were found.

The mammals and birds have extremely low sorting scores and are represented by a wide variety of skeletal elements including skull bones, phalanges, claws, ribs, vertebrae, hip elements, and, in the case of mammals, many teeth. Other non-dinosaurs such as aquatic and terrestrial reptiles, amphibians, turtles, and fish are represented by examples of nearly every kind of skeletal element, however there is a general overabundance of teeth, vertebrae, scales, fish fin elements, and tetrapod phalanges which cause their sorting level to be scored higher.

CHAPTER 4

DISCUSSION

4.1. Taphonomy, Paleoenvironment, and Paleoecology

4.1.1 Temporal Resolution

Establishing the temporal resolution of a bonebed is a critical step in the interpretation of paleoecosystem structure (Behrensmeyer and Hook, 1992). Ideally, the rock unit being examined

will preserve a snapshot of the local paleoecology, unbiased by the effects of time-averaging. Unfortunately, the sedimentologic record is incomplete, punctuated by periods of nondeposition or erosion, and the degree of its incompleteness affects the temporal resolution of any given rock stratum. Rock units can frequently consist of 10^3 to 10^6 years of time-averaged sediment (Krumbein and Sloss, 1963; Behrensmeyer and Hook, 1992), blurring the relationships between animal groups, paleo-faunal assemblages, and ecosystems. Fossil assemblages can be regarded as contemporaneous only within the context of a bracketed time interval assigned to a particular rock stratum (Behrensmeyer and Hook, 1992), and as such, the higher temporal resolution of a stratum can enable the formulation of more accurate paleoecological reconstructions.

In establishing the temporal resolution of fluvial deposits, researchers have used a variety of methods, including radiometric dating, magnetostratigraphy, and observations of modern fluvial settings, concluding that stream channel deposits typically represent between 10^2 and 10^4 years of continuous sediment accumulation (Grabau, 1932; Behrensmeyer and Hook, 1992). Whereas such estimates can be helpful in paleontological studies, a wide range of potential error can prove problematic in establishing an accurate estimate (Behrensmeyer and Hook, 1992). In instances where magnetostratigraphic and radiometric dating techniques cannot be applied, other methods, including the examination of internal features of fossil-bearing units, have been suggested as reliable guides to calculating temporal resolution (Behrensmeyer and Hook, 1992). Examination of internal features of the Bone Butte strata, including the cyclic clay-pebble laminae and pedogenic structures, coupled with observations on paleobotanical data and the ratios of vertebrate ontogenetic stages, have enabled temporal resolution of the Bone Butte site to be calculated with some confidence. Furthermore, ratios of ontogenetic stages of certain taxa sampled at regular intervals in the Bird & Mammal Zone and Oxbow indicate that the effects of time-averaging on Bone Butte strata are exceptionally low.

Bone maps generated at 6 cm intervals for the Bird & Mammal Zone and the Oxbow indicate a trend in ontogenetic ratios of vertebrate taxa. The trend, most clearly exemplified by the turtle and crocodilian groups, is a repeating cycle beginning with a spike in hatchling individuals, followed by a reduction in hatchling percentage and concomitant increase in juvenile percentage, followed by a reduction in juvenile percentage and concomitant increase in subadult percentage, and terminating in a reduction in subadult percentage and increase in adult percentage (Fig. 4.1). As can be seen, the relative percentage of adults stays constant until the subadult portion begins to wane; only at this point does the adult portion begin to significantly increase. The percentage of adults stays high until the next peak in hatchlings, at which time the entire cycle begins anew. Although the ratios of ontogenetic stages collected were undoubtedly affected to a certain degree by varying mortality rates and modes of death, such as consumption by carnivores, leading to dispersal of partially digested bones elsewhere, or even total destruction of the bones during digestion, the overall progression from hatchling to juvenile to subadult to adult is clearly evident and can be compared with more refined data from extant taxa (Fig. 4.2).

The above mentioned pattern is observed in the 6 datasets taken from the Bird & Mammal Zone (B/M subsets A through F), in which it completes approximately 1.5 cycles (Fig. 4.3 A). The Bird & Mammal Zone datasets are nearly identical to datasets from the correlating upper portion of the Oxbow (Fig 4.3 B). Fortuitously, the Oxbow contains a thicker section of undisturbed sediments and provides 10 datasets of ontogenetic ratios (Oxbow subsets A through J) which contain nearly 3 complete cycles of turtle and crocodilian development. Hatchling spikes occur at the same stratigraphic intervals for both crocodilians and turtles, indicating a common breeding season. Breeding seasons of modern subtropical and tropical turtles and

crocodilians typically last for several months, between April and June (Staten and Dixon, 1977; Gorzula and Seijas, 1989; Gibbons and Greene, 1990; Dunham and Gibbons, 1990; Mitchell and Pague, 1990; Moll and Moll, 1990). Assuming the breeding season of ancestral Cretaceous reptilian taxa also occurred once per year, the Bird & Mammal Zone and Oxbow data indicate a period of relatively continuous sedimentation over a ~2.5 year period. This estimate of temporal resolution, based on data from a continuous record of turtle and crocodilian maturation, falls far below the typical estimated 10^1 to 10^4 years of sediment accumulation for this thickness of sediment as suggested by the literature (Grabau, 1932; Behrensmeyer and Hook, 1992). Furthermore, based on the vertebrate ontogenetic data and time between hatching periods, each of the mapped 6 cm subsets of the Bird & Mammal Zone and Oxbow represents approximately 3 months of sediment. In terms of paleontological studies, time-averaging commonly ranges between 10^3 to 10^6 years (Krumbein and Sloss, 1963; Behrensmeyer and Hook, 1992), which can limit the effectiveness of paleoecological studies. The 3-month time-averaging of the Bird & Mammal Zone and Oxbow strata provides a clear window into a ~2.5 year period in the Upper Cretaceous and enables the examination of truly time-synchronous assemblages.

Plants, Buds, and Leaf Litter

The paleobotanical material recovered from Bone Butte also provides clues as to the temporal resolution of the site. Fossil conifer fragments are found in distinct sandstone laminae (Fig. 4.4), layered horizontally atop each other and not oriented chaotically as in the crevasse-splays, suggesting that large quantities from an autochthonous source were periodically

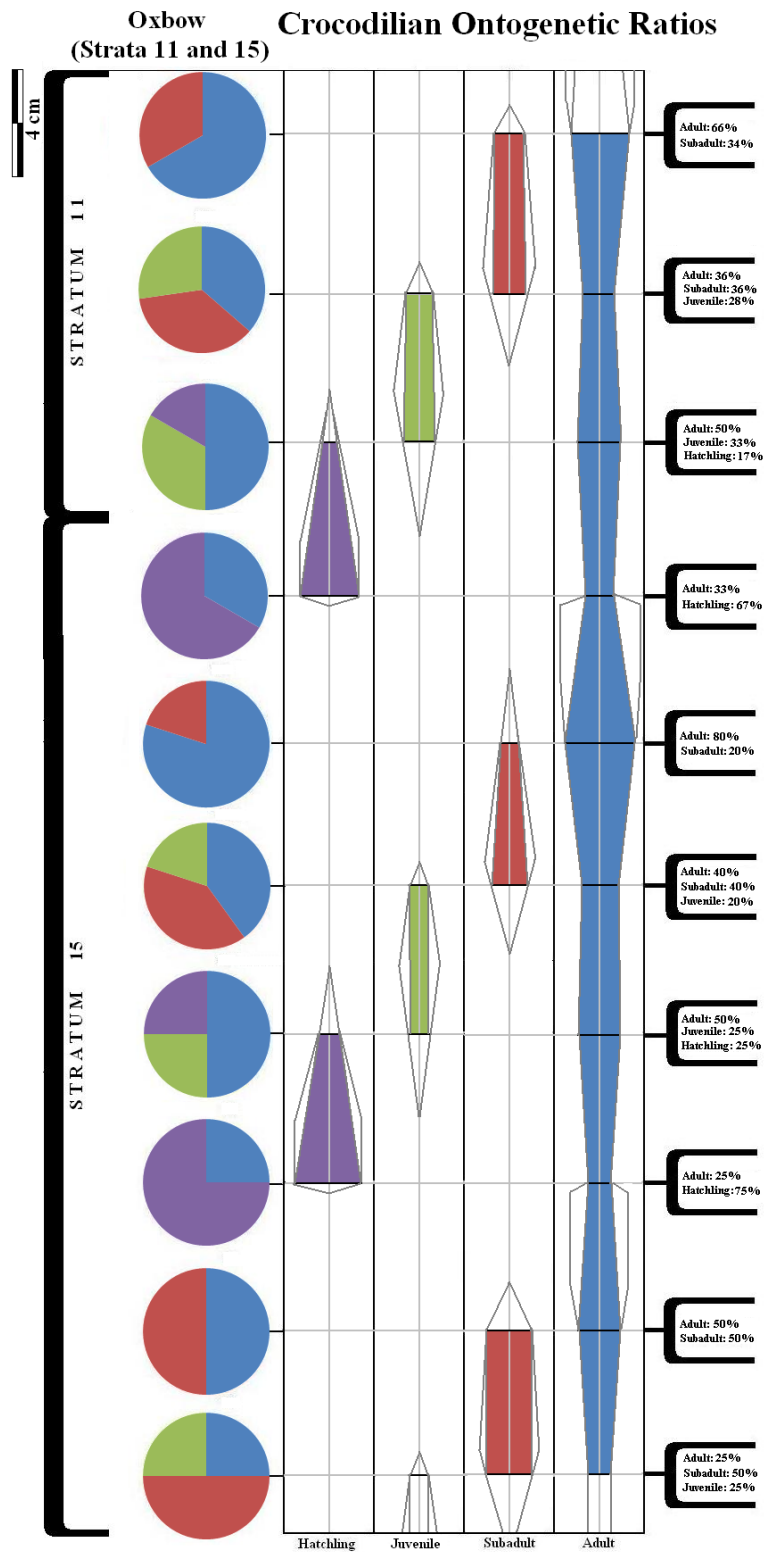


Fig. 4.1. Ratios of crocodilian ontogenetic stages for the 10 sampled intervals of the Oxbow strata. The series of pie charts records the ontogenetic ratios for each sampled interval, while the graph at center extrapolates changes in ontogenetic ratios over time. Colored polygons represent actual data, and gray lines were extrapolated. At right, the numerical percentages of the constituent ontogenetic stages are listed.

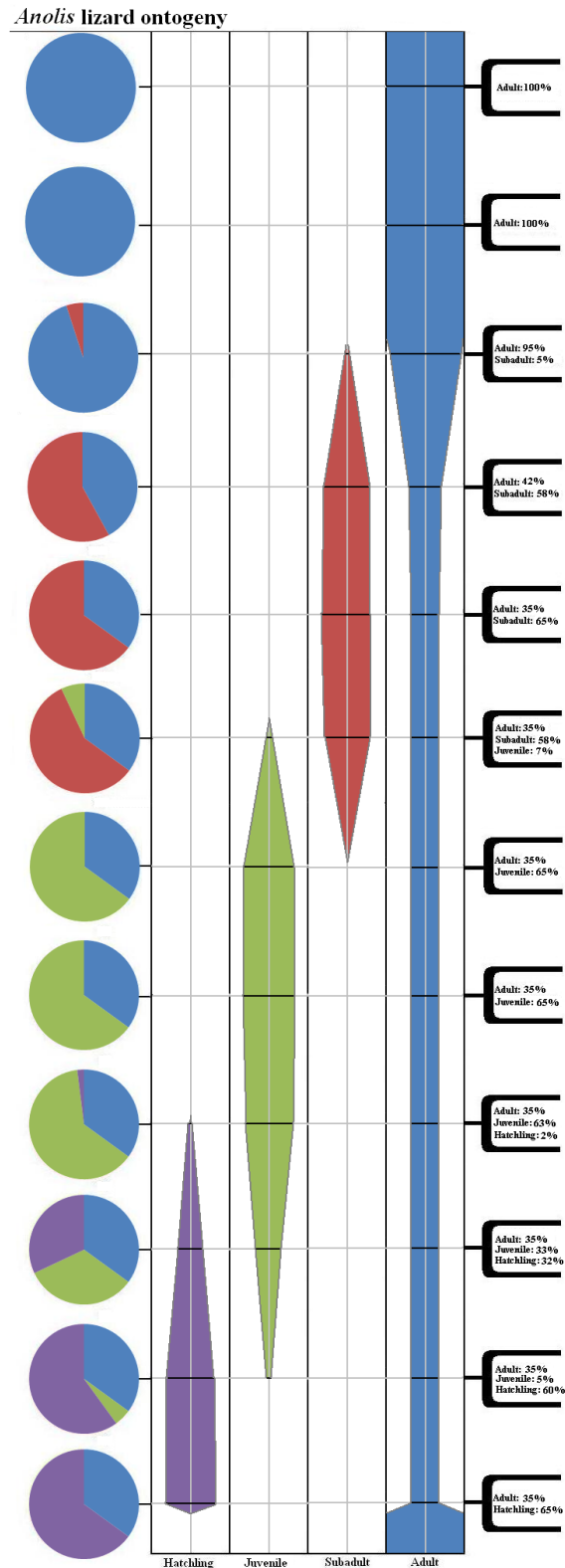


Fig. 4.2. A maturation graph for the *Anolis* lizard, from an experiment carried out by Terry Smith and I in 1998 - 99. One pie chart was generated each month, for a total of 12 months. The maturation of the hatchling *Anolis* lizards is traced until the group is incorporated into the adult category. This modern maturation graph bears close resemblance to the graph generated for Bone Butte crocodilians.

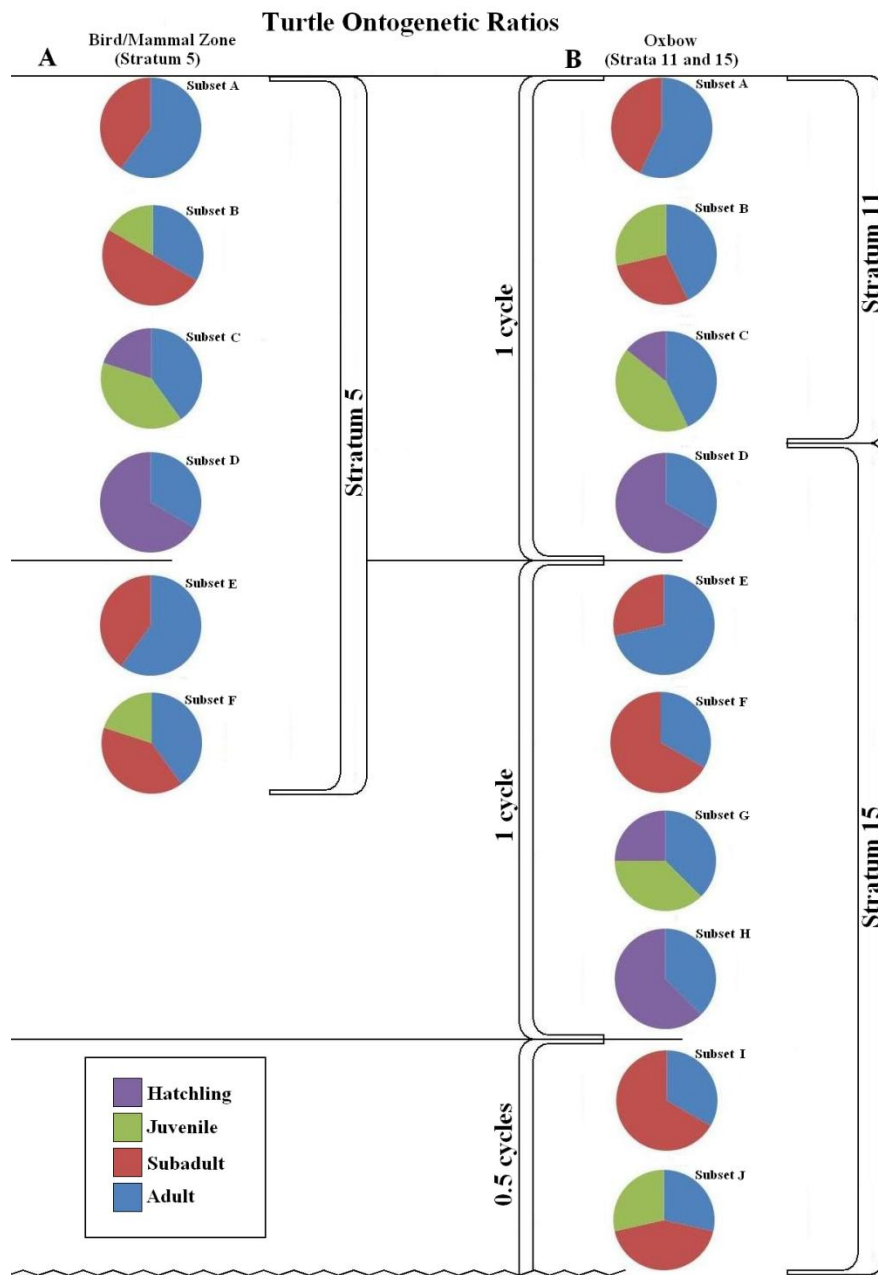


Fig. 4.3. Ratios of turtle ontogenetic stages taken at 6 cm intervals from (A) the Bird & Mammal Zone and (B) the Oxbow. Notice the nearly perfect correlation between the ontogenetic ratios of the Bird & Mammal Zone and the upper 6 intervals of the Oxbow.

deposited quickly in a quiescent environment (Burnham, 1989; Spicer, 1991; Behrensmeyer and Hook, 1992; Burnham et al., 1992; Wing and DiMichelle, 1992; Gastaldo et al., 1996). The regularly occurring dense mats of conifer needles and conifer twigs with attached buds found in the Bird & Mammal Zone and the Oxbow show traces of a cyclical pattern similar in timing to that seen in the repeating spike in reptilian hatchlings and are further evidence of a yearly cycle (Fig. 4.4). The elevations of conifer mats and twigs with attached buds in the Bird & Mammal Zone roughly correlate with similar occurrences in the upper portion of the Oxbow (Fig. 4.4). Twigs with attached buds and nearly mature strobili are found in the same laminae as turtle hatchling bones (Bird & Mammal Zone subset D; Oxbow subsets D and H), and overlies dense mats of well-preserved conifer needles, which occur 6 to 12 cm below in Bird & Mammal Zone subset B and F, and Oxbow subsets B, F, and J (Fig. 4.4 B). The mats of conifer needles are similar in appearance to those produced by deciduous conifer trees such as *Taxodium distichum* (Bald Cypress) and *Metasequoia glyptostroboides* (Dawn Redwood), which shed their foliage during mid to late fall and live in subtropical to temperate regions (Dallimore, 1948; Dennis, 1988; Middleton and McKee, 2004). Using the spike in turtle and crocodilian hatchlings as a guide to estimate a range of months represented by the strata, one would expect to find twigs with buds as well as maturing strobili present in the D and H subsets of the Bird & Mammal Zone and the Oxbow, which correspond to spring months. The twigs with buds do, in fact, occur in the D and H subsets, suggesting an annual cycle consistent with that of extant deciduous conifers and a climate with noticeable seasonality (Fig. 4.4). The occurrence of twigs with buds is also consistent with the timing of turtles and crocodilians hatching in a subtropical climate (Staten and Dixon, 1977; Gorzula and Seijas, 1989; Dunham and Gibbons, 1990; Gibbons and Greene, 1990; Mitchell and Pague, 1990; Moll and Moll, 1990).

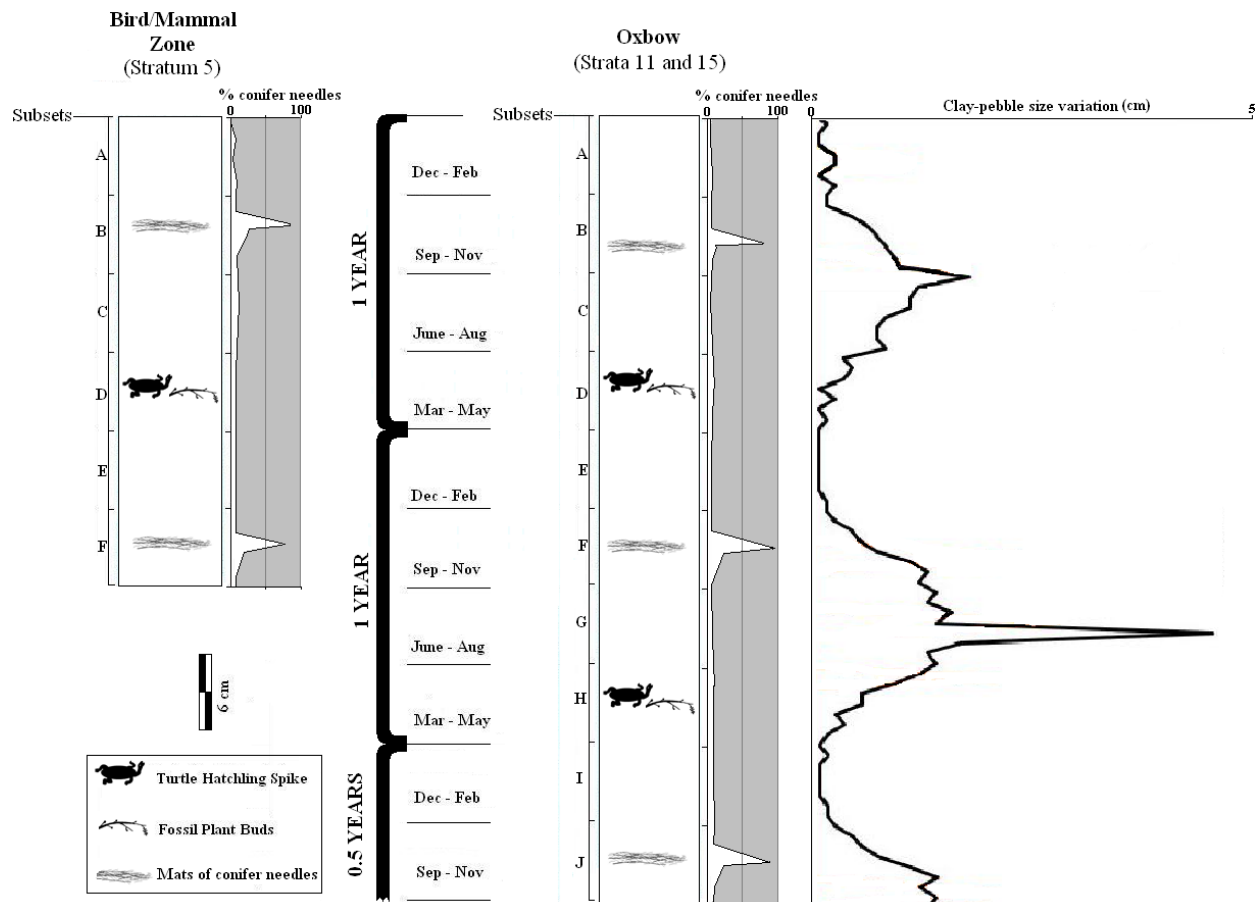


Fig. 4.4. Distribution of conifer needle mats, conifer twigs with attached buds, and hatchling turtles within the Bird & Mammal Zone (left) and the Oxbow (right). Spacing between occurrences of leaf mats and between turtle hatchling spikes is nearly equal (about 24 cm), supporting an annual occurrence. The spacing of the turtle hatchling spikes, twigs with attached buds, and mats of conifer needles enables a rough approximation of the months represented by the strata (center).

The cyclic nature of plant material in the Bird & Mammal Zone and Oxbow is not reflected in Strata 1 through 4. Recognizable leaves are only present in Strata 1 and 3, preserved in chaotic orientations that suggest rapid burial (Spicer, 1991). The leaves in Strata 1 and 3, almost entirely consisting of angiosperms, tend to increase slightly in abundance and exhibit more horizontality toward the upper margins of the strata, however no horizontally stacked beds of leaves exist (Fig. 4.5). No observable directional orientation of the leaves exists, however their chaotically bent, folded, and sometimes tattered appearance, and burial within crevasse-splays, is

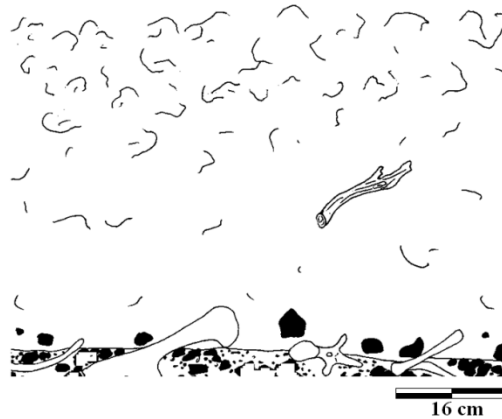


Fig. 4.5. Graphic approximation of leaf distribution within Stratum 1. Notice the chaotic orientation of leaves throughout the stratum and the increase in leaf abundance toward the stratum's upper margin.

indicative of moderate transport distance and fast burial (perhaps 1 to 5 days) (Spicer, 1991; Behrensmeyer and Hook, 1992; Wing and DiMichelle, 1992; Battle and Golladay, 2001). The presence of minimal rhizoliths and invertebrate burrows along the upper margins of Strata 3 and 4 suggest that they were not subaerially exposed for a long duration between deposition events, probably less than one year.

Mudclasts and Rain Cycles

Regularly spaced clay-pebble laminae found in the Bird & Mammal Zone and the Oxbow provide further evidence of the fine temporal resolution at Bone Butte. The laminae, composed chiefly of subround to round clay-pebble rip-up clasts, represent brief periods of increased carrying capacity due to greater flow velocity (Grabau, 1932; Krumbein and Sloss, 1963). The clay-pebbles of each lamina were measured and compared to one-another, forming a graph of comparative flow increases that elucidates an oscillating cycle of increasing and decreasing flow

velocity (Fig. 4.6). The mudclast values for the Oxbow, the thickest contiguous set of laminated strata, produce approximately 2.5 cycles. At the peak of each cycle there is typically a single

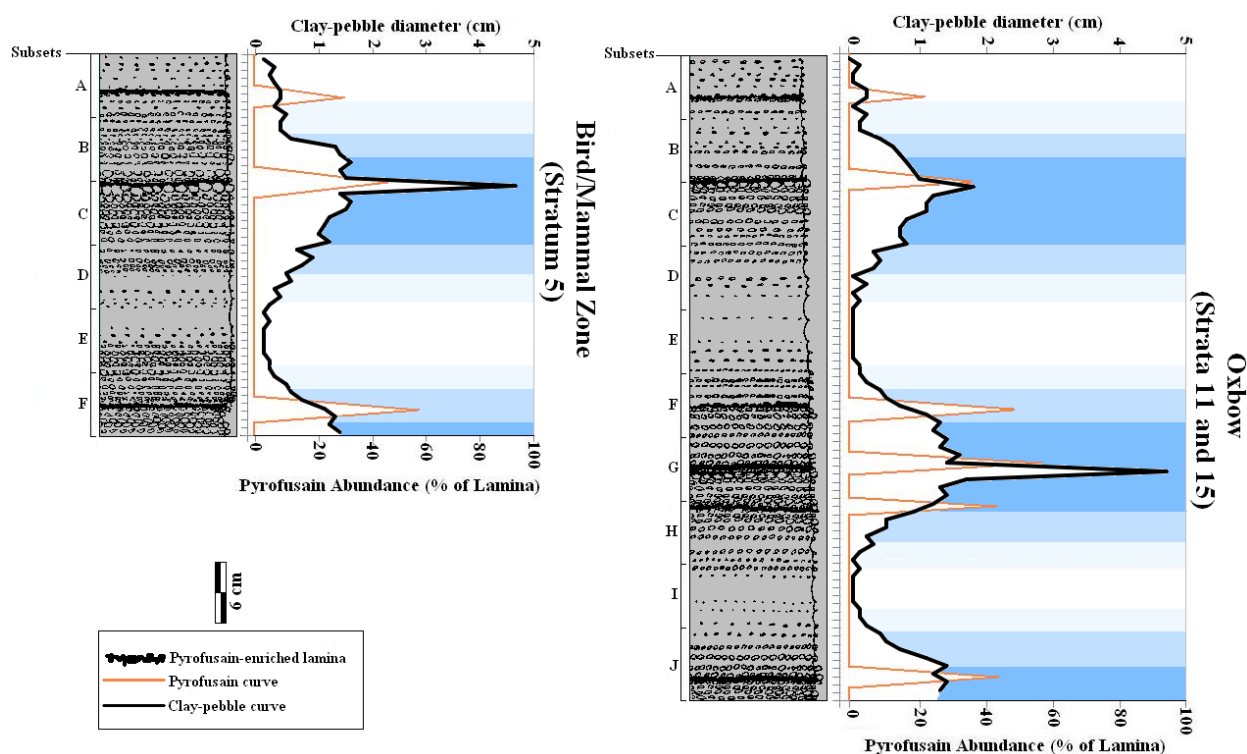


Fig. 4.6. Graphic depiction of clay-pebble laminae in the Bird & Mammal Zone (left) and the Oxbow (right), and accompanying graphs of clay-pebble diameters. Notice the cyclic pattern of large and small clay-pebbles which corresponds to waxing and waning flow velocity. A significant spike is seen at the apex of each wave of large clay-pebble diameters.

event with significantly larger mudclasts, after which clast size diminishes, bottoms out, and begins to rise again (Fig. 4.6 A). The Bird & Mammal Zone possesses a nearly identical curve to that of the correlating upper portion of the Oxbow. The curve tracks abrupt, punctuated changes in flow velocity similar to rainfall graphs for subtropical areas with a slight monsoonal component (Fig. 4.7), and is nearly identical to the rainfall curve for Corpus Christi, Texas (Hu and Feng, 2007; NWS Internet Services Team, 2009). The individual clay-pebble laminae are interpreted as the result of periodic increases in flow velocity caused by individual rainstorms

throughout the year. Cyclicity in this curve represents a “wet” and “dry” period of the year and the repetition of the cycle (approximately 2.5 times) corroborates the previous evidence that the Bird & Mammal Zone and Oxbow sediments represent roughly 2.5 years of deposition.

Modern Precipitation Curves Compared to Clay-pebble Curve from Bone Butte

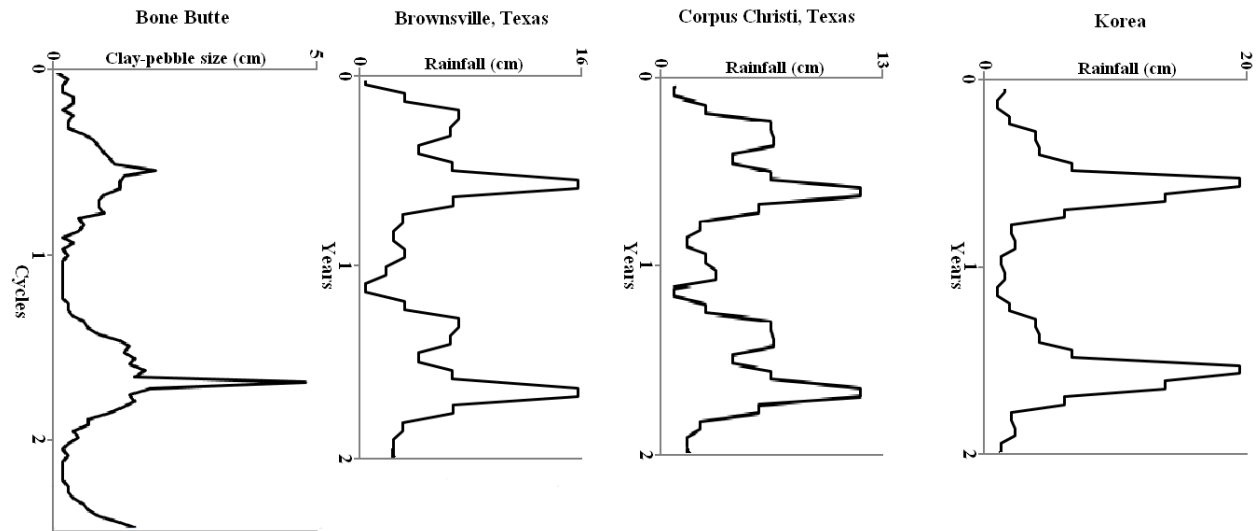


Fig. 4.7. Graph of clay-pebble diameters in Bone Butte’s Oxbow strata (left) compared with 2.5-year rainfall curves for (from left to right) Brownsville, Texas; Corpus Christi, Texas; and Korea. Bone Butte’s clay-pebble curve matches very well with the subtropical, basal-monsoonal climates of Brownsville and Corpus Christi, Texas, and does not match as well with the fully monsoonal rain curve of Korea. (Rainfall data courtesy National Weather Service).

The evidence provided by vertebrate ontogenetic ratios, paleobotanical data, and the cyclicity of annual precipitation, indicates that the lower strata at Bone Butte were deposited over a relatively short, ~2.5 to 3 year time period. Furthermore, reptilian ontogeny and paleobotanical evidence enable the time of year during which sediments were deposited to be estimated to within several months, providing a temporal resolution of incredible detail. The near absence of rhizoliths, invertebrate traces, and other pedogenic structures along the contact surfaces of overlying crevasse-splay deposits indicates that likely very little time (<2 years; Grabau, 1932; Krumbein and Sloss, 1963; Behrensmeier, 1991) lapsed between crevasse-splay

formation. As such, the entire stratigraphic package of Bone Butte is estimated to represent no more than 7 years of total sediment accumulation (Fig. 4.8).

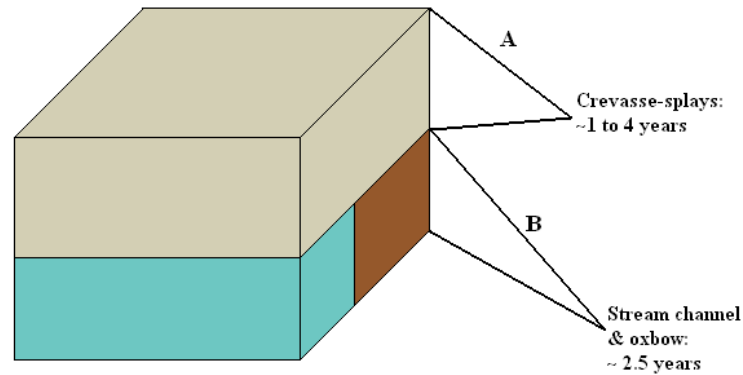


Fig. 4.8. A simplified graphic depiction of the Bone Butte strata, indicating (A) the ~1 to 4 years represented by the upper crevasse-splay deposits and (B) the ~2.5 years represented by the Bird & Mammal Zone and Oxbow strata. In total, the Bone Butte Strata represent between 3.5 and 6.5 years of sediment accumulation.

It should be noted that careful excavation and documentation of the strata at very small ~ 6 cm increments enabled the discovery of such time resolution. Had the Bird & Mammal Zone or Oxbow been excavated and documented *in toto* as single units, the information contained within would have been averaged, thereby obliterating the patterns observed in this study, and possibly leading researchers to incorrectly deduce a lengthier representative temporal estimate closer to that seen in the literature.

4.1.2. Group A and Group B Taphotypes; Allochthony vs. Autochthony

Taphonomic characteristics of bone assemblages can be instrumental in determining whether an assemblage was transported, and in reconstructing the provenance of an assemblage (Behrensmeyer et al., 2000). In the case of Bone Butte, the presence of a locally derived

autochthonous fauna, and an exotic allochthonous fauna transported from afar, is elucidated by a taphonomic study similar to that carried out by Bartlett (2004). Taphonomic characteristics of the Bone Butte fossils enable the separation of bones into two distinct groups: the Group A taphotype, consisting of highly abraded, well-sorted, and generally less complete skeletal elements, and the Group B taphotype, consisting of virtually pristine, very complete, and poorly sorted skeletal elements. Group A bones dominate the crevasse-splay deposits of Stratum 2 (combined Strata 2A and 2B), whereas the Bird & Mammal Zone and Oxbow are dominated by the Group B taphotype. As indicated by other studies, the first bones transported from the site of an animal's death are generally from the periphery of the skeleton: phalanges, unguals, claws, distal caudal elements, anterior cervical elements, teeth, and skull elements (Behrensmeyer, 1991; Behrensmeyer and Hook, 1992; Aslan and Behrensmeyer, 1996; Behrensmeyer et al., 2000; Bartlett, 2004; Behrensmeyer, 2007). As a result of transport, bones are subjected to breakage and bone surfaces become increasingly abraded (Behrensmeyer, 1991; Behrensmeyer, 2000; Coulson et al., 2002; Bartlett et al., 2003). The increased abrasion and breakage associated with Group A bones, coupled with the high degree of sorting, indicate that the bones entered the river system from a single point and were transported an appreciable distance before being deposited at Bone Butte (Behrensmeyer, 1991; Behrensmeyer and Hook, 1992; Behrensmeyer, 2000). Their comprising animal taxa, distinct from those of Group B, suggest Group A was part of a separate, allochthonous population (Damuth, 1982; Behrensmeyer and Hook, 1992; Bartlett, 2004). The exact distance traveled by the Group A assemblage remains unknown, however it has been demonstrated that bones transported by fluvial systems, bearing similar taphonomic characteristics to those in Group A, can travel significant distances (Behrensmeyer, 1991; Aslan and Behrensmeyer, 1996). The Group B bones bear independent taphonomic signatures of virtually no transport – negligible sorting, low breakage, and essentially no abrasion – and

indicate a local, autochthonous population (Krumbein and Sloss, 1963; Damuth, 1982; Behrensmeyer, 1991; Bartlett, 2004; Behrensmeyer, 2007). Others have previously asserted that crevasse-splay deposits are enriched with allochthonous material, whereas slow-moving tributaries, abandoned channels, and oxbow lakes tend to hold almost exclusively autochthonous material (Krumbein and Sloss, 1963; Burnham, 1989; Spicer, 1991; Wing and DiMichelle, 1992; Behrensmeyer, 2007). The Group A (allochthonous) bones are found in highest abundance in the crevasse-splay deposits of Strata 2A and 2B, whereas the Group B (autochthonous) bones are most common in the more quiescent stream channel of the Bird & Mammal Zone, and Oxbow deposits, supporting the interpretation of the allochthony and autochthony for the respective Group A and Group B bone assemblages. In addition, the dinosaurian constituents of Group A and Group B are distinct from each other, with very few dinosaurian groups belonging to both the Group A and Group B taphotypes. Group A, interpreted as the allochthon, was transported to the Bone Butte site primarily by a series of avulsive events, while the Group B autochthon was a local fauna that was deposited relatively *in-situ*.

The allochthonous component preserved at Bone Butte is similar in overall composition to typical Hell Creek faunal reconstructions (Lehman, 1987; White et al., 1998; Russell and Manabe, 2002; Bartlett, 2004), composed of a high percentage of ceratopsians, followed by a smaller percentage of hadrosaurs, tyrannosaurs, ornithomimids, and oviraptorids and a minimal number of small theropods, ankylosaurids, and mammals (Fig. 4.9). The Bone Butte autochthonous component is composed of a very different set of animals, dominated by small theropods and pachycephalosaurs, with a smaller component of ornithomimids, thescelosaurus, mammals, and birds, and minimal tyrannosaur and hadrosaur components (Fig. 4.9). Interestingly, animals common in the autochthon are very rare in traditional reconstructions of the Hell Creek Fauna. For example, pachycephalosaurs and thescelosaurus, the two most common

ornithischians in the Bone Butte autochthon, are two of the least represented taxa reported in the Hell Creek Formation (White et al., 1998; Russell and Manabe, 2002; Bartlett, 2004), and are not even included in the faunal list of Lehman (1987). Ornithomimids and small theropods are

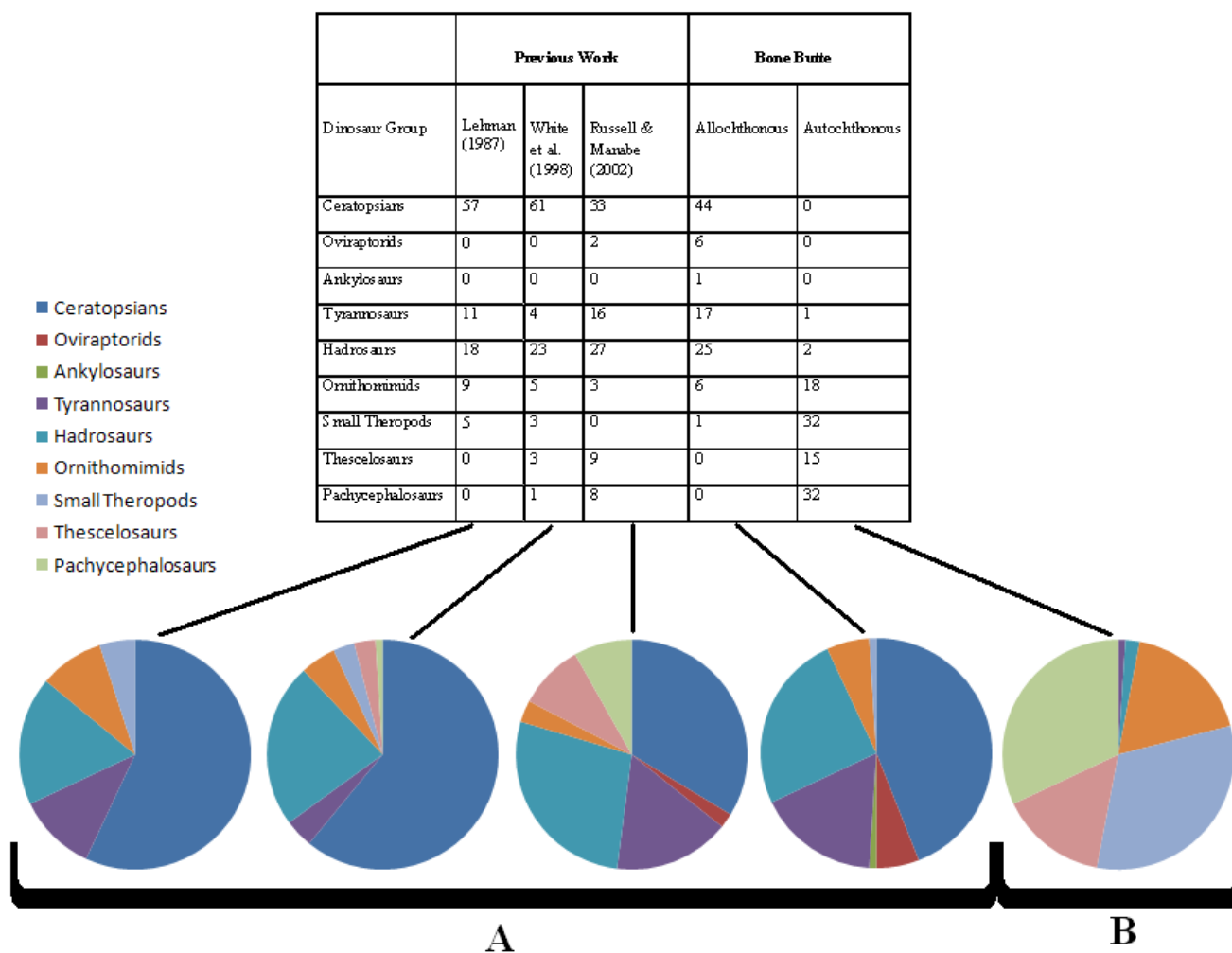


Fig. 4.9. Bone Butte's fauna compared with other Hell Creek faunal lists from recent studies. (A) The allochthonous fauna is very close in composition to traditional calculations of the Hell Creek Fauna. (B) The autochthonous assemblage from Bone Butte is strikingly different in composition from the allochthonous component, and contains many taxa that are rare or absent in traditional studies of the Hell Creek Formation.

additional dinosaurs common in the Bone Butte autochthon, but quite rare in traditional reconstructions of the Hell Creek fauna (Lehman, 1987; White et al., 1998; Russell and Manabe, 2002; Bartlett, 2004).

Certain dinosaur groups exist in both the allochthon and autochthon, although in such cases, the group's presence is more strongly represented in either the allochthon or autochthon

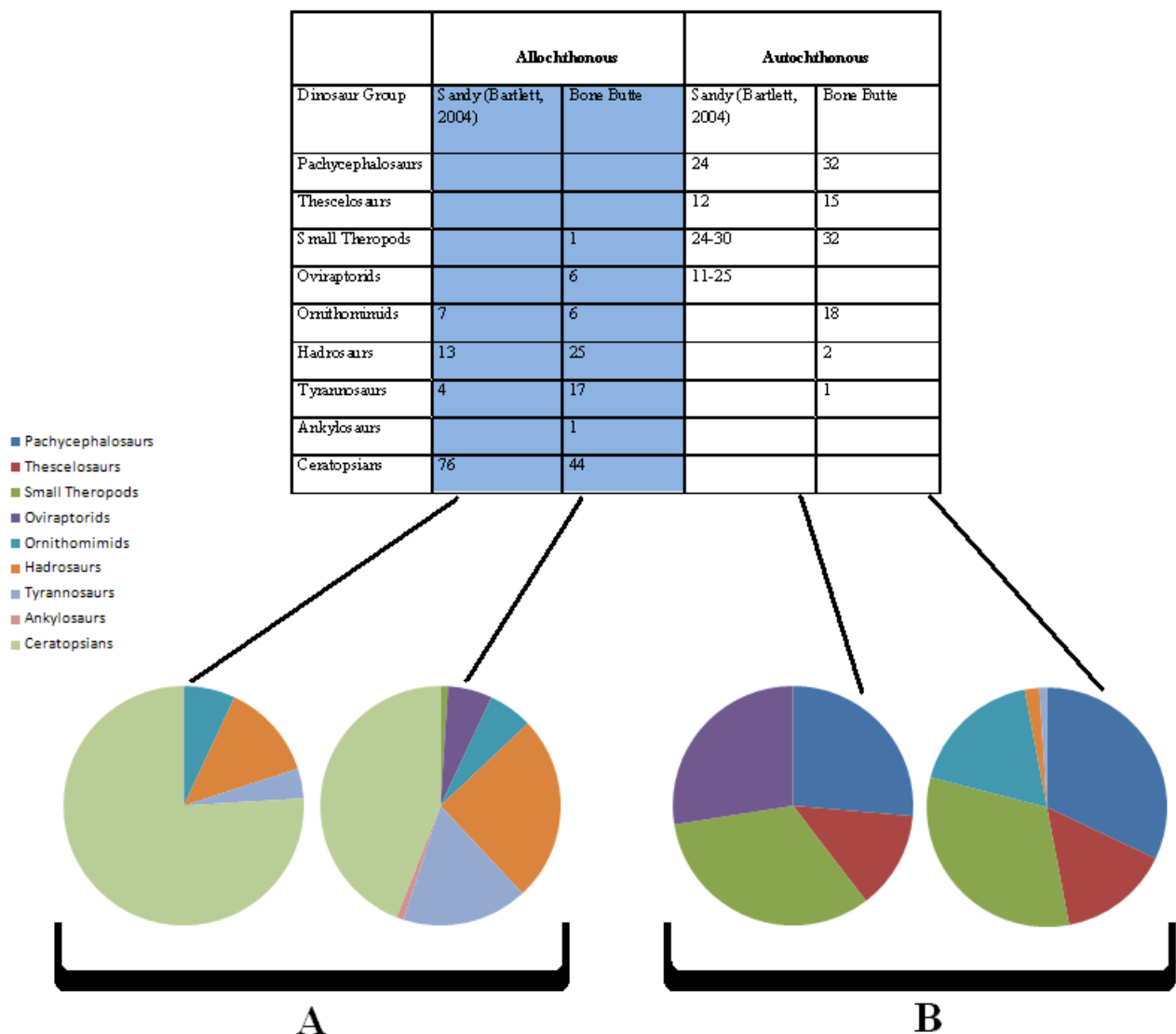


Fig. 4.10. The Bone Butte assemblage compared with that of the Sandy site (Bartlett, 2004). The Sandy site proved the closest comparison to the allochthonous and autochthonous assemblages at Bone Butte. Interestingly, the oviraptorid component of Sandy's autochthon is replaced by ornithomimids in Bone Butte's autochthon (B).

and no group is evenly distributed between the two. Small theropods and ornithomimids, for example, have a very minimal representation in the allochthon, however are extremely abundant in the autochthon (Figs. 4.9, 4.10). Conversely, the tyrannosaurs and hadrosaurs, well-represented in the allochthon, are almost nonexistent in the autochthon (Figs. 4.9, 4.10). Certain vertebrate groups are of mixed provenance and do not specifically fall within the Group A or Group B taphotypes; these groups include the aquatic reptiles, terrestrial reptiles, turtles, and fish. These animals are evenly distributed across the spectrum of abrasion, completeness, and other taphonomic modifications and exhibit poor sorting, indicating entry of material into the river system from multiple points along its course as opposed to a single point of entry, and represent groups that were spread throughout the Hell Creek Formation (Behrensmeyer, 1991), spanning the boundary separating the allochthonous and autochthonous assemblages at Bone Butte.

The proportions of animals in the Bone Butte allochthon and autochthon most closely resemble those reported in a study by Bartlett (2004), in which a local autochthonous fauna and exotic allochthonous fauna were identified at Mike Triebold's Sandy site less than 64 km west of Bone Butte (Fig. 4.10). The Bartlett study used taphonomic characteristics of the bones to elucidate a heterogeneous pattern in the distribution of Hell Creek vertebrates, contrasting with the traditional homogenous reconstruction of the Hell Creek fauna. Whereas the Bone Butte allochthon and autochthon are very close in composition to those discovered by Bartlett, the shifts in composition between the Bone Butte fauna and Bartlett's Sandy fauna indicate that not only was the faunal mosaic of the Hell Creek vertebrates more complex and varied than previously thought, but also that the compositions of the background and localized faunas varied

eastwardly, with proximity to the paleoshoreline. The Bone Butte and Sandy autochthonous faunas have nearly identical animal percentages (Fig. 4.10), however the oviraptorid component of the Sandy autochthon is replaced by a nearly identical percentage of ornithomimids in the Bone Butte autochthon (Fig. 4.10 B). In addition, several groups not present in the Sandy autochthon – tyrannosaurs, hadrosaurs, and ornithomimids – appear in the Bone Butte autochthon. The Bone Butte and Sandy allochthonous populations exhibit a similar trend, with all Sandy taxa crossing over to Bone Butte in similar proportions. As with the Bone Butte autochthon, the allochthon has several taxa not present in that of Sandy: oviraptorids, small theropods, and ankylosaurids. Unfortunately, the studies by Lehman (1987), White et al. (1998), and Russell and Manabe (2002) treated the Hell Creek fauna as a homogenous unit and did not analyze taphonomic data in such a way that could elucidate its allochthonous and autochthonous components, as the Bartlett (2004) and Bone Butte studies do. As such, results from the Lehman (1987), White et al. (1998), and Russell and Manabe (2002) studies are only of limited comparative use with the Sandy or Bone Butte data and the full extent and complexity of the Hell Creek faunal mosaic remains unknown, however further research should help to resolve the matter.

The allochthonous and autochthonous vertebrate assemblages observed at Bone Butte likely represent variations in the ecologies and ecological preferences of the constituent animal groups. Modern examples exist in which a largely homogenous background fauna and intermittent localized faunas vary in composition with proximity to the seashore (Fig. 4.11). The predominant fauna of central Florida, for example, consists of a wide assortment of mammals, reptiles, and birds, which are present throughout the majority of the central portion of the state (National Coastal Ecosystems Team, 1984; Dennis, 1988; Wolfe et al., 1988; Best et al., 1990; Flynn, 1990). This background fauna is typically punctuated by localized faunas (Fig. 4.11), the

constituents of which exhibit a much greater degree of variation in their abundance and representative taxa with proximity to the coastline (National Coastal Ecosystems Team, 1984; Dennis, 1988; Wolfe et al., 1988; Best et al., 1990; Flynn, 1990). Data from Bone Butte and the Sandy site indicate that the Hell Creek faunas were structured in a similar fashion to what is seen in Florida and other areas today, existing as a mosaic of localized ecology incised upon a

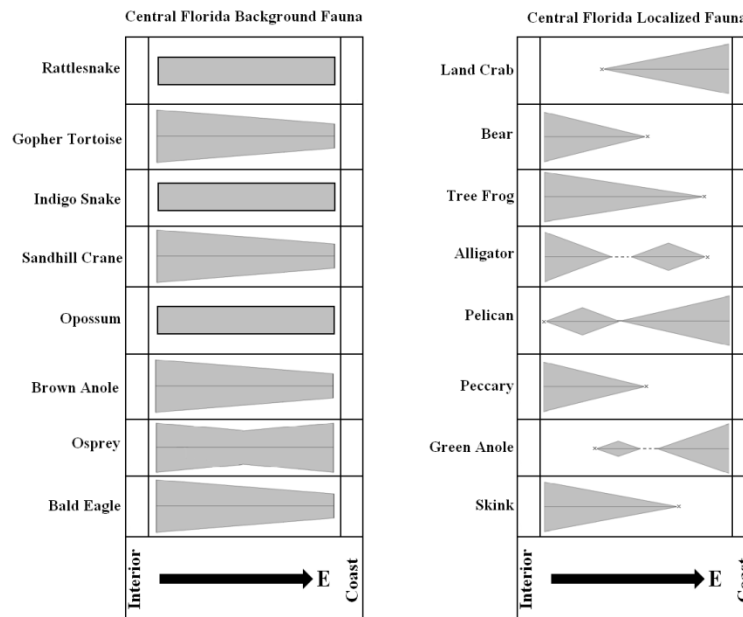


Fig. 4.11. A pattern observed in the ecology of Central Florida includes a more widespread background fauna (left) and a series of more isolated localized faunas (right). Both the background and localized faunas vary with proximity to the shoreline.

broader, more universal background fauna, and percentages of constituent animal groups shifted with proximity to the paleoshoreline.

The allochthonous vertebrate fauna of Bone Butte, consisting primarily of dinosaurian megafauna such as ceratopsians, hadrosaurs, and tyrannosaurs, is associated with an abundance of angiosperm plants and virtually no gymnosperms. The autochthon largely resembles the Type II animal communities outlined by Olson (1966), in which terrestrial plants provide the main

source of energy, which is consumed by terrestrial herbivorous vertebrates and, in turn, by terrestrial carnivorous vertebrates (Fig. 4.12). It has been suggested that the evolution and diversification of large Cretaceous browsing herbivores, such as the hadrosaurs and ceratopsians, was driven by the appearance and evolution of angiosperms (Bakker, 1978; Wing and Tiffney, 1987; Weishampel and Norman, 1989; Wing and Sues, 1992), on which the herbivores subsisted. This view is consistent with the connection between the angiosperms and herbivorous megafauna

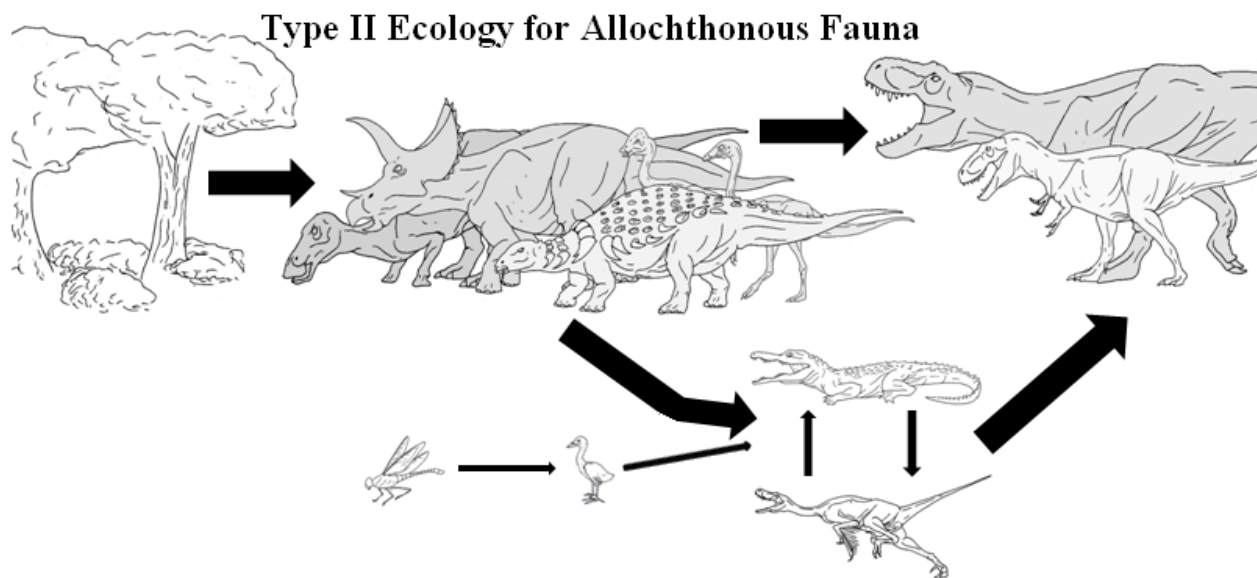


Fig. 4.12. The Type II ecological aspect of the Bone Butte allochthonous fauna, following Olson (1966). Bold arrows indicate the primary transfers of energy. In the Type II ecology, terrestrial plants (in this case, angiosperms) provide energy to the terrestrial herbivores, which are consumed by carnivores. Crocodilians and small theropods invariably consumed each other and are interchangeable in this food web. (Diagram © Robert A. DePalma II.)

of the Bone Butte allochthon. Megacarnivores, such as the large tyrannosaurids, were most likely ecologically suited to subsist on the late Cretaceous megaherbivores, as fossil evidence at Bone Butte and elsewhere (Holtz, 2008; Paul, 2008) has suggested. Small herbivorous dinosaurs such as the pachycephalosaurs and thescelosaurus of the autochthon, as well as the small theropods, did not play a significant role in the allochthonous fauna. The Sandy allochthon, which originated

from a point of unknown distance west of its location of deposition at the Sandy site, forms a basis for comparison of changes in the Hell Creek background fauna as it neared the paleoshoreline. Variations in the composition of the allochthon can be traced between the Sandy site, which is roughly 170 km from the paleoshoreline, and the Bone Butte site, which is roughly 110 miles from the paleoshoreline (Kennedy et al., 1998; Murphy et al., 2002, Cochran et al., 2003; Bartlett, 2004; The estimated distance to paleoshoreline is probably far less, as indicated by data from Bone Butte). It can be observed that, although the proportions of the different animal taxa stayed similar, their percentages varied as one progressed eastward from Sandy toward Bone Butte (Fig. 4.13 A). Ceratopsian and ornithomimid percentages decrease, while hadrosaur and tyrannosaur percentages increase. With proximity to Bone Butte, and the paleoshoreline, three new groups – oviraptorids, small theropods, and ankylosaurs – are added to the allochthon (Fig. 4.13 B).

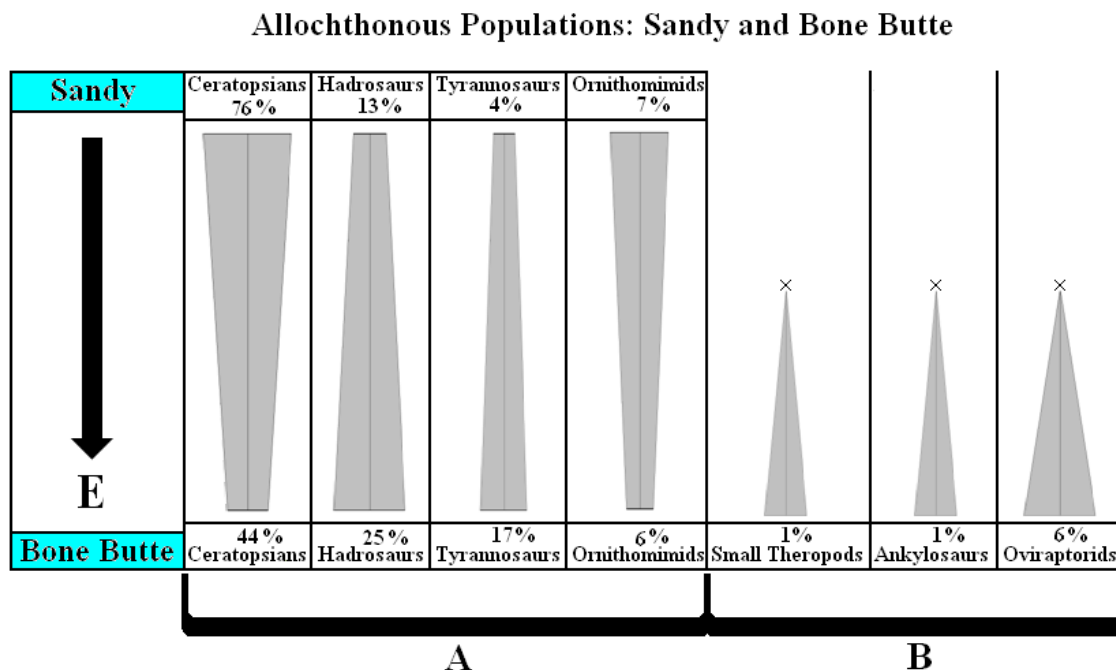
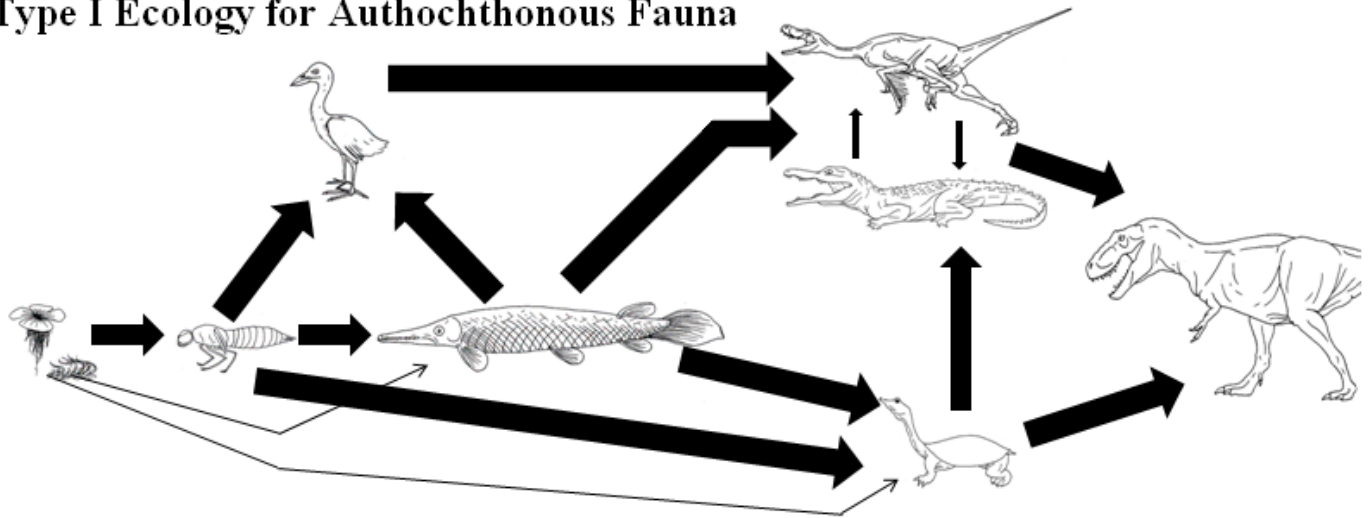


Fig. 4.13. The Sandy allochthonous fauna compared to that of Bone Butte. The Sandy percentages vary eastward toward Bone Butte (A), although ratios of animals remain similar. Three additional animal groups appear in Bone Butte’s allochthon (B), although their percentages are so low they could have been present at Sandy as well but never been discovered.

The Bone Butte autochthonous fauna, rather than being associated with a typical late Cretaceous preponderance of angiosperms (Johnson et al., 2002, Johnson, 2002), is associated almost exclusively with gymnosperms, horsetails, and aquatic plants, and is composed primarily

A

Type I Ecology for Autochthonous Fauna



B

Type II Ecology for Autochthonous Fauna

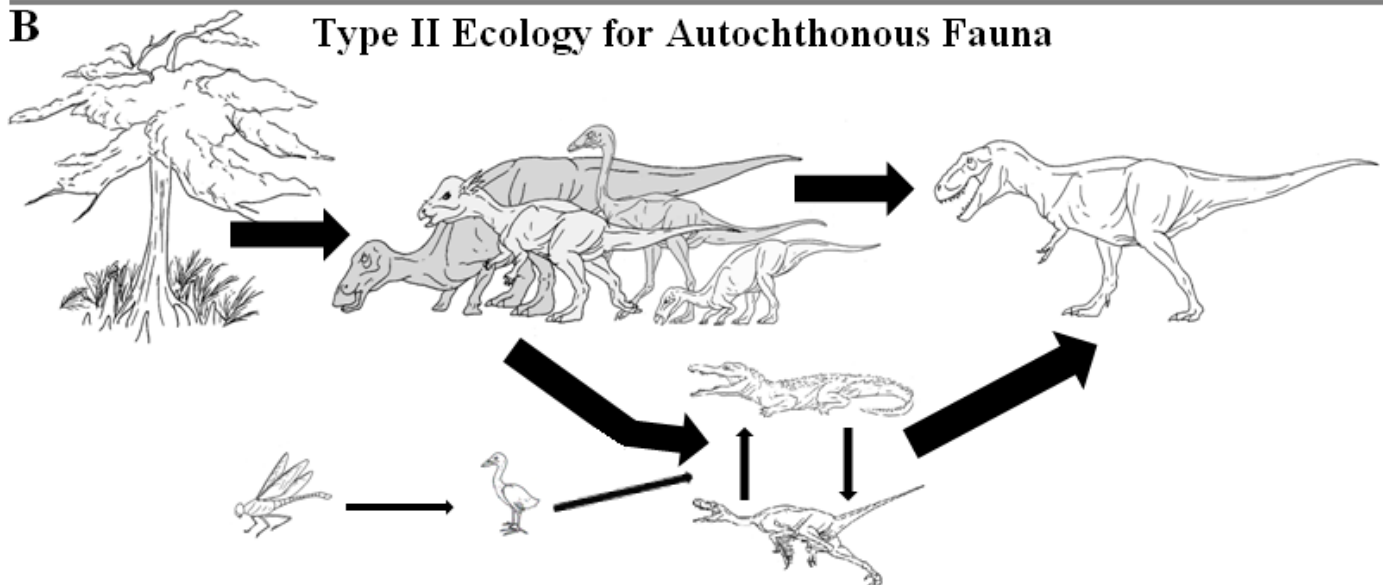


Fig. 4.14. The Type I and Type II ecological aspects of the Bone Butte autochthonous fauna, following Olson (1966). Bold arrows indicate the primary transfers of energy. In the Type II ecology, terrestrial plants (in this case, gymnosperms) provide energy to the terrestrial herbivores, which are consumed by carnivores. Crocodilians and small theropods invariably consumed each other and are interchangeable in this food web. In the Type I ecology, aquatic plants are the basal source of energy, which is passed on to aquatic invertebrates, and on to aquatic, semi-aquatic, and terrestrial vertebrates. (Diagram © Robert A. DePalma II.)

of smaller dinosaurs, birds, and mammals. Whereas the allochthon appears to have resembled a Type II terrestrial plant-based ecology, the Bone Butte autochthon consists of associations resembling a Type II ecology in addition to a prevalent Type I ecology (Fig. 4.14), in which aquatic plants formed the basis of energy, which was passed on to aquatic vertebrates and invertebrates, and on to terrestrial vertebrates (Olson, 1966). Greater variation was observed in the autochthon between Sandy and Bone Butte (Fig. 4.15 A). The ratios between small theropods, pachycephalosaurs, and thescelosaurus at Sandy are relatively consistent with those observed at Bone Butte, however their percentage of abundance increases eastward. The oviraptorid component of the Sandy autochthon disappears to the east, and three groups – the tyrannosaurs, hadrosaurs, and ornithomimids – are added to the Bone Butte autochthon (Fig. 4.15 B).

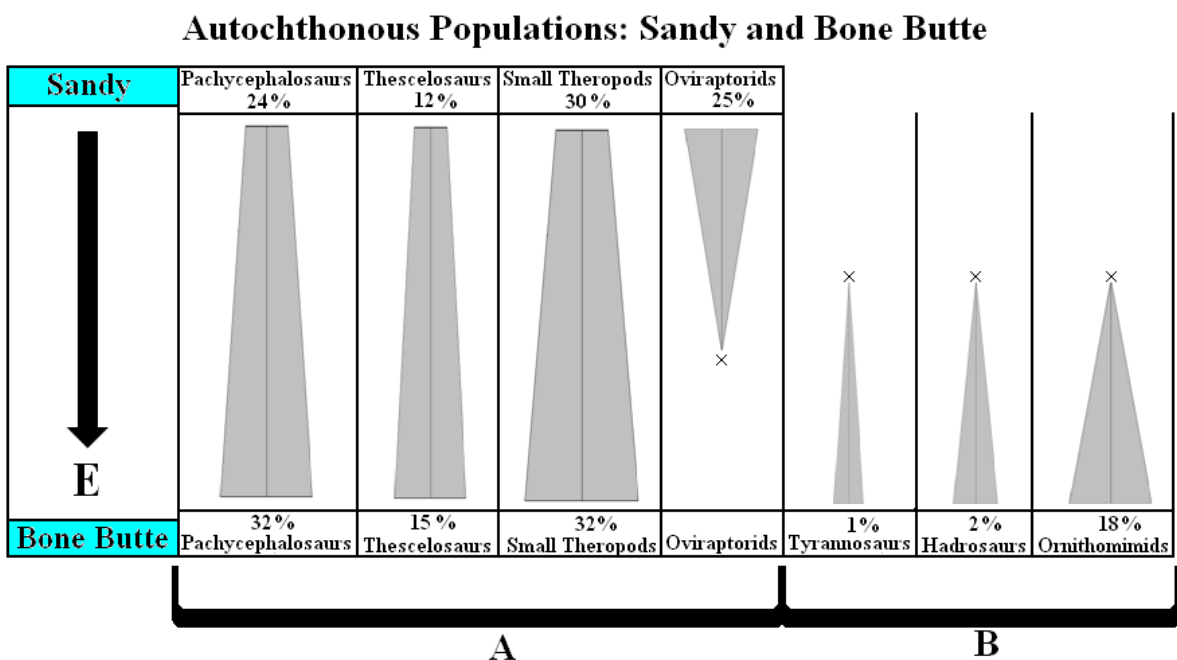


Fig. 4.15. The Sandy autochthonous fauna compared to that of Bone Butte. With the exception of oviraptorids, which disappear from the autochthon, all animals in Sandy's autochthon increase in abundance at Bone Butte (A). Three additional groups not present in Sandy's autochthon appear in Bone Butte's autochthon (B).

The widespread angiosperm and megafauna-dominated allochthonous assemblages and the localized gymnosperm and small theropod-dominated autochthonous assemblages likely formed the basic template of Hell Creek life. As indicated by the shifts in composition between the Bone Butte and Sandy site allochthonous and autochthonous assemblages, variations of these ecologies existed with proximity to the seashore (Fig. 4.16). As with the shifts in broad and localized ecologies in Florida (National Coastal Ecosystems Team, 1984; Wolfe et al., 1988; Dennis, 1988; Best et al., 1990; Flynn, 1990), the Hell Creek faunas likely varied in composition as a result of changes in ground cover due to variations in the water table or soil composition, the spatial occurrence of preferred hunting territories of certain predatory taxa, the proximity to saltwater sources, density or sparseness of forest growth, composition of forest growth (angiosperm vs. gymnosperm), stability of the ground/substrate, proximity to freshwater sources, or any combination thereof.

Diversity among the allochthonous and autochthonous groups of Bone Butte is comparable to that of other studies (Lehman, 1987; White et al., 1998; Russell and Manabe, 2002; Bartlett, 2004) and indicates a strong, robust dinosaurian presence. The allochthonous group, with 19 dinosaur genera and 20 species, has a slightly higher diversity than the autochthonous group, which contains 14 genera and 16 species of dinosaurs, however both groups are within a typical level of diversity for the Late Cretaceous (Russell 1984; Lehman, 1987; White et al., 1998; Russell and Manabe, 2002; Bartlett, 2004). Overall, both groups yield a grand total of 25 dinosaur genera and 27 species. In addition to the raw numbers of genera and species, the dinosaurs at Bone Butte consist of a wide variety of herbivores and carnivores, of both large and small body size. Theories regarding the end-Cretaceous dinosaur extinction have suggested that dinosaurian diversity was already in severe decline by the end of the Cretaceous and that, rather than driven to extinction by a catastrophic extinction event, dinosaurs simply

faded out of existence (Williams, 1994; Sloan et al., 2009). The diversity of dinosaurs uncovered at Bone Butte does not support such a theory and, in fact, supports quite the opposite:

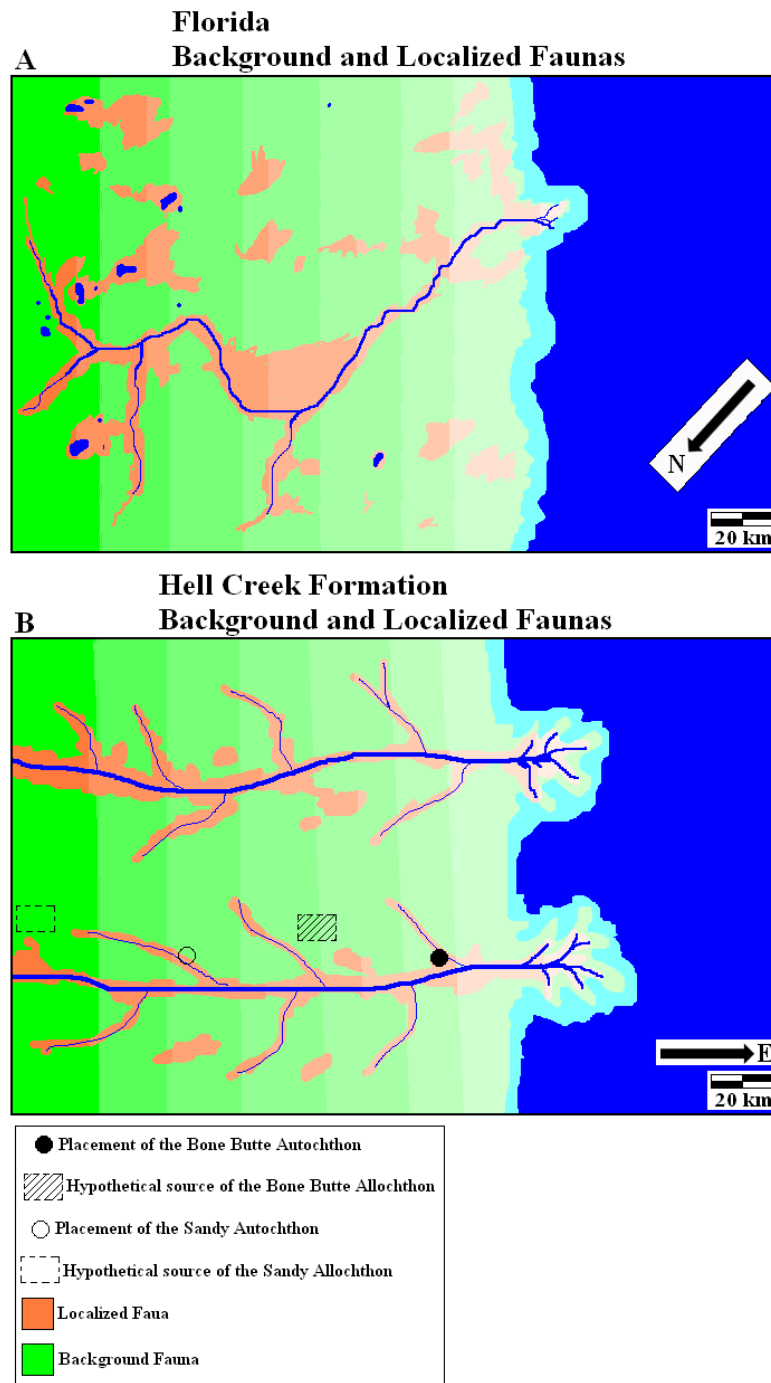


Fig. 4.16. A stylized depiction of variations in the background fauna and localized fauna in Florida (A) and in the Hell Creek Formation as suggested by data from the Sandy site and Bone Butte (B). The background fauna (green) and the localized faunas (orange) gradually vary in composition toward the shoreline. Approximate positions of Bone Butte and the Sandy site, as well as hypothetical origins of their respective allochthonous material, are included.

dinosaurian diversity and abundance in the American West was high immediately before the K-T extinction event and evidence shows that dinosaurs did not gradually wink out of existence.

4.1.3. Medullary Bone, Growth Rates, and Nesting Behavior

In addition to assisting in the establishment of temporal resolution for the Bird & Mammal Zone and Oxbow, the ratios of hatchling, juvenile, subadult, and adult vertebrates, calculated at 6 cm stratigraphic intervals, helped to track nesting seasons of various animal taxa. Repeating spikes in hatchling abundance for turtles coincide with hatchling spikes for crocodilians, both occurring at the onset of a period of prolonged increase in storm intensity (Fig. 4.17 A). The periods of increased storm intensity at Bone Butte lasted for roughly one half of the

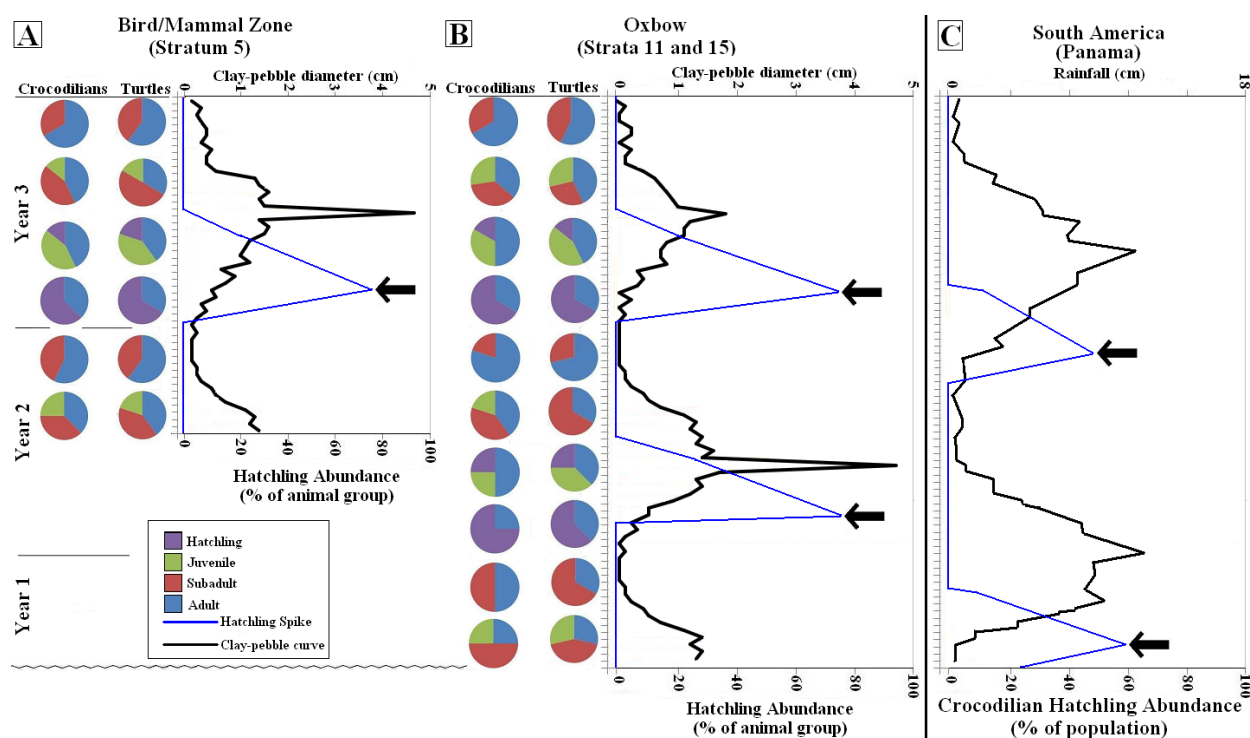


Figure 4.17. Ontogenetic ratios of turtles and crocodilians that were recorded at 6 cm intervals in the Bird & Mammal Zone and Oxbow, compared to seasonal hatching times of the black caiman. Turtle and crocodilian ontogenetic ratios from the Bird & Mammal Zone (A) and the Oxbow (B) show an almost identical, repeating pattern of succession. The graph of storm intensity is shown to the right of ontogenetic ratio charts. Notice how the spikes in hatchlings (black arrows) coincide with the onset of the rainy season. (C) A rain curve for a ~2.5 year period in South America, with arrows pointing to the hatching season of the black caiman. As with Bone Butte's crocodilians and turtles, the black caiman's eggs hatch at the onset of the rainy season. (Rainfall data courtesy National Weather Service.)

yearly rain cycle and are consistent with a rainy season in a tropical to subtropical environment (Whigham, 1990; Adler et al., 2003; Murphy and Lugo, 2003; Love-Brotak, 2007). Although the breeding and hatching seasons for modern turtles and crocodilians can vary, the timing of hatchling spikes at Bone Butte coincides with what can presently be seen in the breeding behavior of many subtropical and tropical reptiles. Egg clutches of the black caiman and many other South American crocodilians and turtles, for example, are laid during the dry season and hatch at the onset of the wet season (Fig. 4.17 B) (Staten and Dixon, 1977; Gorzula and Seijas, 1989; Gibbons and Greene, 1990; Moll and Moll, 1990). This timing of egg-laying protects the nests from the stormy weather of the wet season and increases nest success, as is the case with many tropical ground-nesting birds, which also lay their eggs during the dry months for this reason (Nice, 1957).

Although dinosaurian ontogenetic data from the Bird & Mammal Zone and Oxbow is generally not as ideal as that of the crocodilians and turtles due to smaller sample size, a trend in ontogenetic ratios comparable to that of the turtles and crocodilians can be seen. Data from the Bird & Mammal Zone is the most complete and of greatest use in tracking dinosaurian ontogenetic ratios, and the following references to stratigraphic subsets refer to those of the Bird & Mammal Zone. The ornithomimids, a particularly well represented group, show a general pattern in the progression of ontogenetic ratios that closely mirrors that seen in the crocodilians and turtles (Fig. 4.18). Although no ornithomimid hatchling bones were found, the patterns of progressive ratios of juveniles, subadults, and adults in the stratigraphic subsets indicate a

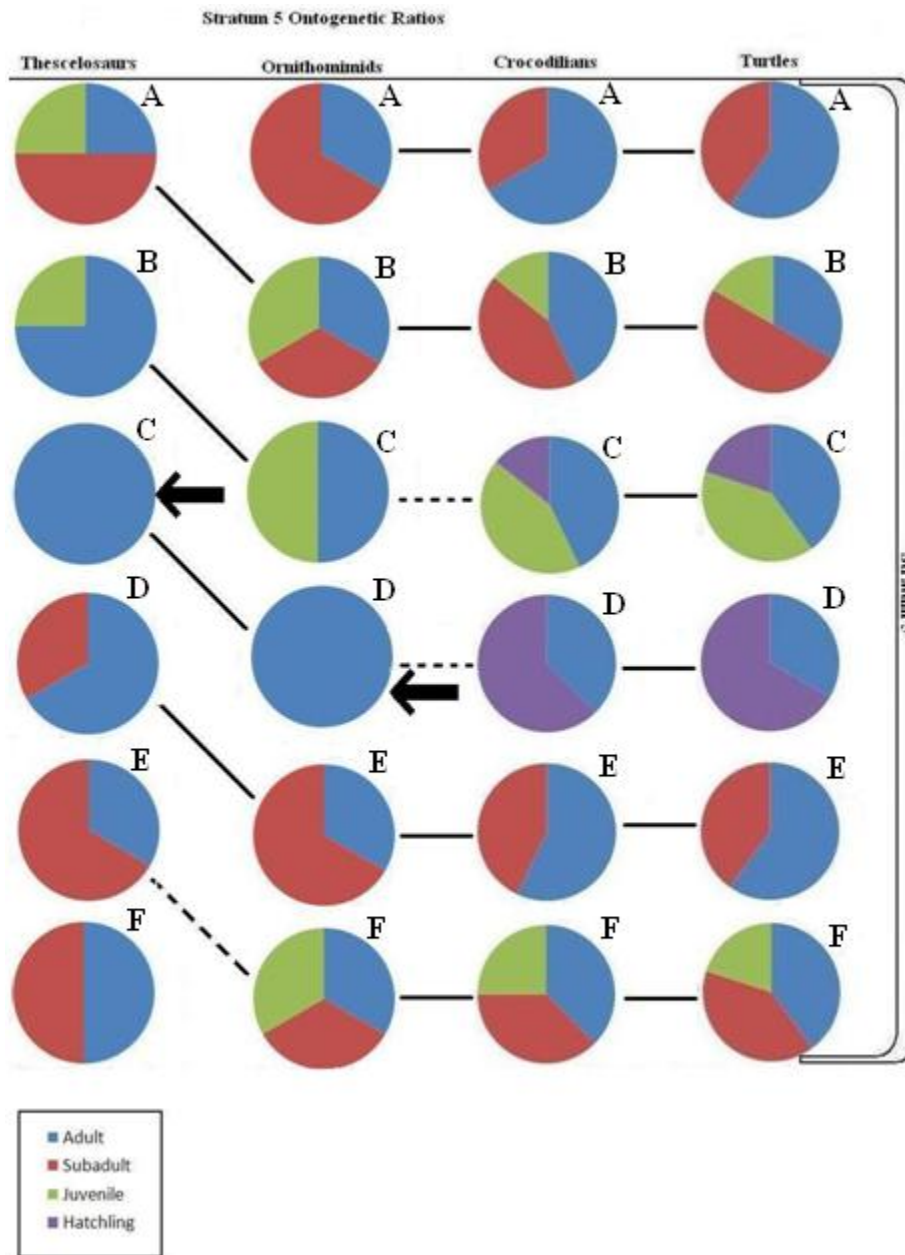


Figure 4.18. Ontogenetic ratios of thescelosaurus, ornithomimids, crocodilians, and turtles from the Bird & Mammal Zone; letters indicate stratigraphic subsets at 6 cm intervals. The ornithomimids, turtles, and crocodilians have a nearly identical progression of ontogenetic ratios. A discrepancy in the ornithomimids includes the absence of hatchlings in subsets C and D. The occurrence of medullary bone in the dinosaurs is indicated by black arrows and indicates that medullary bone is present at points where hatchling bones would have been expected. Although the hatchling bones are absent, the medullary bone indicates the timing of the breeding season. Dashed lines indicate discrepancies between ontogenetic ratio pie charts.

common hatching period to that of the crocodilians and turtles – at the onset of the rainy season. Because of a lower sample size than the crocodilians and turtles, the data from thescelosaurus is not as well resolved (particularly in the Oxbow), however it is still indicative of a cycle. In the six stratigraphic subsets of the Bird & Mammal Zone, some dinosaurian ontogenetic ratios are perfect matches to those seen in the crocodilians and turtles while others are incomplete, owing to the incompleteness of fossil representation. The subset A ontogenetic ratios of thescelosaurus, for example (composed of juveniles, subadults, and adults), is very similar in composition to the subset B composition of ornithomimids, turtles, and crocodilians (also composed of a mixture of juveniles, subadults and adults). Conversely, less-complete animal representation at certain stratigraphic intervals produces less-refined ontogenetic ratios: whereas the subset E thescelosaurus ontogenetic ratios do not contain any ontogenetic stages that contradict what is seen in the equivalent ontogenetic ratios of crocodilians (in subset F), the thescelosaurus juvenile component is absent, precluding the perfect comparative match between ontogenetic ratios that was expected based on patterns already observed in the two taxa (Fig. 4.19).

As can be seen, the ontogenetic ratios of thescelosaurus nearly mirror those seen in the ornithomimids, but are shifted one subset up; subsets A through E of the thescelosaurus match subsets B through F of the ornithomimids (Fig. 4.20). The shift in timing between thescelosaurus and ornithomimid ontogenetic ratio patterns, while maintaining an equal duration of each repeated cycle, indicates that thescelosaurus had a later hatching season than the ornithomimids, and reached adult size at nearly the same rate as ornithomimids (less than two years as indicated by Bone Butte ontogenetic rates).

One of the most obvious differences between the ontogenetic ratio charts of the crocodilians/turtles and dinosaurs is the absence of dinosaurian hatchling remains. Based on

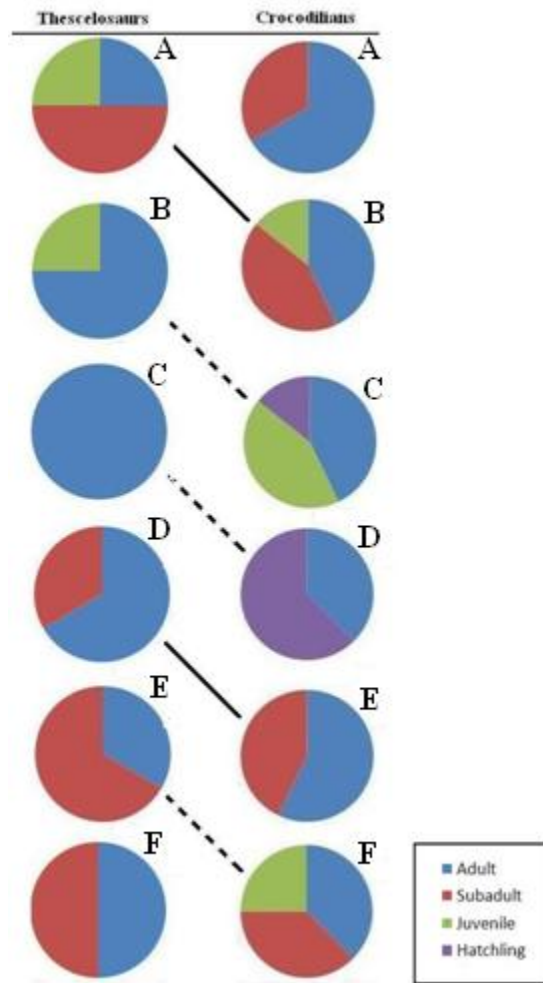


Figure 4.19. Thescelosaur and crocodilian ontogenetic ratios; letters indicate stratigraphic subsets at 6 cm intervals. The thescelosaur ontogenetic ratios, although containing no ontogenetic stages that contradict what is seen in the crocodilian and turtle patterns, contain some discrepancies due to incompleteness of representation in the strata. Correlations already observed between the dinosaurian and crocodilian/turtle ontogenetic ratios, for example, indicate that a juvenile component should exist in thescelosaur subset E, however the juvenile component is absent. Dashed lines indicate discrepancies between ontogenetic ratio pie charts.

trends seen in the crocodilian and turtle graphs, one would expect to see hatchling spikes in the ornithomimids in subset D, and in thescelosaurus in subset C, preceding the appearance of juveniles. Rather than seeing hatchling spikes at these subsets, the dinosaurian graphs show a purely adult population with no other ontogenetic stages present. The absence of hatchling remains might otherwise have proven problematic to the hypothesis that subsets C and D

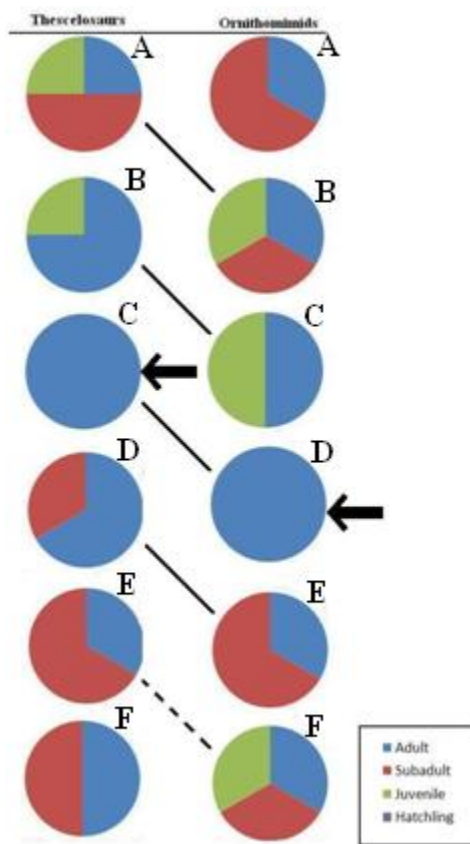


Figure 4.20. Ornithomimid and thescelosaur ontogenetic ratios; letters indicate stratigraphic subsets at 6 cm intervals. Black arrows indicate points at which medullary bone is present, a sign of breeding season. Notice the excellent correlation between the progression of ontogenetic ratios of the two dinosaur groups, with the exception of thescelosaur subunit E and ornithomimid subunit F. Thescelosaur ontogenetic ratio progression, although nearly identical to the ornithomimids, is shifted one subunit up, indicating a later breeding season while retaining a similar rate of maturation. Dashed lines indicate discrepancies between ontogenetic ratio pie charts.

represent hatching seasons for the thescelosaurs and ornithomimids, however data from medullary bone distribution among the dinosaur taxa retains a signature of their reproductive activity (Fig. 4.18). The occurrence of medullary bone within the thescelosaur and ornithomimid bones indicates that medullary bone was only present in these groups in subset C (for thescelosaurs) and subset D (for ornithomimids). Medullary bone is unique in that it is produced by birds only during breeding season (one week prior to and several weeks following egg-laying), and not at any other time of the year (Lee et al., 2007; Schweitzer et al., 2007, 2008).

The presence of medullary bone in the thescelosaurs and ornithomimids at stratigraphic intervals at which hatchling spikes were expected indicates that hatchlings (or at the very least, pregnant dinosaurs) existed at the specific intervals, supporting the hypothesis of an annual breeding season for thescelosaurs and ornithomimids. The medullary bone discovered in pachycephalosaurs, thescelosaurs, and ornithomimids at Bone Butte also provides a unique observation that dinosaurian medullary bone is physiologically similar to that of birds. Whereas dinosaurian ontogenetic ratio data is spotty at best in the Oxbow, ontogenetic and medullary bone data from the Oxbow support what is shown by equivalent Bird & Mammal Zone laminae, and indicate that spikes in ontogenetic stages, and breeding seasons, followed a cyclic pattern.

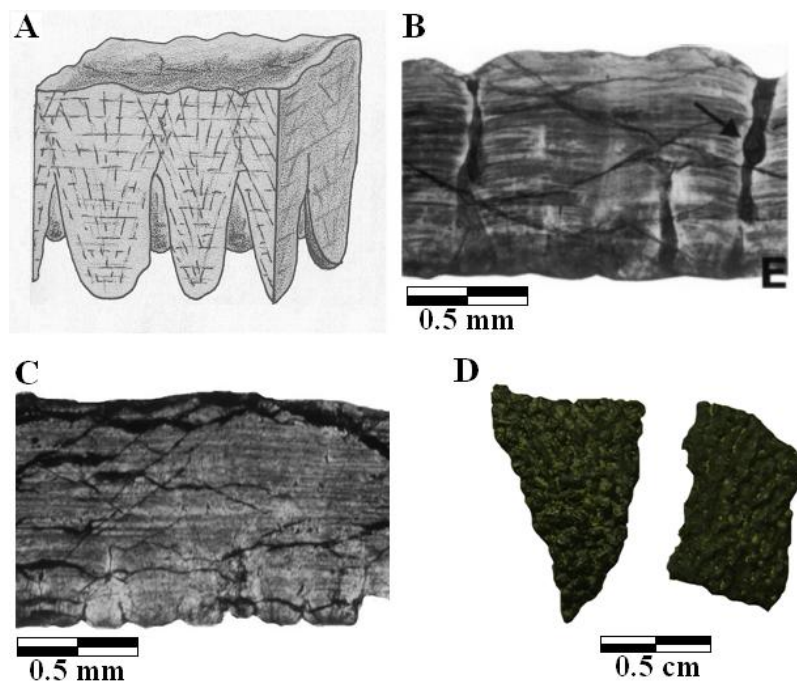


Figure 4.21. A thin section of prolatospherulitic eggshell from Bone Butte (C) compared to a thin section of prolatospherulitic eggshell from Canada (B) and a schematic diagram of prolatospherulitic eggshell (A). A view of the eggshell surface can be seen in (D). Diagram in (A) modified from Carpenter (1999), and thin section in (B) modified from Zelenitsky and Hills (1997).

Further evidence that hatchling dinosaurs existed in the vicinity of Bone Butte comes in the form of eggshell fragments. Several eggshell fragments discovered in subset C of the Bird &

Mammal Zone (Fig. 4.21) have been identified as belonging to the spherulitic shell morphotype – a morphotype associated with non-theropod dinosaurs (Carpenter, 1999). Medullary bone from pachycephalosaurs and thescelosaurs, both non-theropod dinosaurs, has been discovered in subset C, however, since no eggshell has ever been definitively attributed to either of those groups, it is unclear which produced the shell, or if the shell was produced by another different herbivorous dinosaur group. Although experiments have shown that modern eggshell can travel considerable distances before showing significant signs of abrasion (Carpenter, 1999; Tokaryk and Storer, 1991), the Bone Butte specimens do not show any indication of being transported and most likely originated from the vicinity of Bone Butte. The fact that eggshell has been found in association with multiple examples of medullary bone indicates that dinosaur breeding may have occurred at or near Bone Butte. However, the absence of hatchling bones remains problematic. Hatchling bones tend to have a lower preservation potential than adult bones, however the presence of reptilian hatchling bones and other very delicate specimens otherwise not readily preserved (including lizard, amphibian, and articulated bird remains), and the presence of low-energy environments that favor the preservation of infant bones (Russell and Manabe, 2002), indicate that the conditions at Bone Butte were, in fact, favorable to the preservation of hatchlings, and the absence of hatchling bones is not due to preservational phenomena. It is possible that dinosaurs with exceptionally small clutch sizes would produce fewer offspring per season and, consequently, fewer hatchlings would be preserved, or perhaps the dinosaurian hatchlings had a low mortality rate. A low mortality rate for dinosaur hatchlings is unlikely, however, considering the universally high mortality rate of extant ground-nesting bird hatchlings (Nice, 1957; Jaroslav, 1988; Mankin and Warner 1992). It is more probable that the nesting sites were sufficiently distanced from Bone Butte to preclude the deposition of hatchlings and copious amounts of eggshell in the Bone Butte sediments, yet close enough to still be considered part of

the autochthonous fossil assemblage. Studies of modern ground-nesting birds have shown that, whereas the density of nests or their proximity to each other do not affect their protection from predators, the effective concealment of nests within particular types of vegetation offers some of the best protection from predation (Mankin and Warner, 1992). In addition to nesting in areas of abundant vegetation favorable to the concealment of their nests, it is possible that some Bone Butte autochthonous dinosaurs (such as small theropods) nested in marshier areas as opposed to meadows or thickets. Studies of ground-nesting birds have shown that the success of the nests made in or near marshes is much higher than nests in thickets or meadows, due to the inability of many predators to reach the nests and young (Jaroslav, 1988). Other modern animals are known to spawn in marginal, less-hospitable areas to provide a safer environment for reproduction and rearing of young. The bighorn sheep, for example, live in rocky, isolated areas already considered to be rather inhospitable. However, when giving birth and initially rearing lambs, the females will leave the flock and seek even rockier and more isolated areas to deter predators (Spencer, 1943). A similar approach is taken by blue-footed boobies and other coastal birds, which utilize unwelcoming, isolated rocky cliffs as rookeries because fewer predators can reach the eggs and young (Goss, 1888; Bancroft, 1927). If the dinosaur hatchlings at Bone Butte were altricial, as are many extant ground-nesting birds (Nice, 1957; Picman, 1988; Mankin and Warner 1992), they would leave the protection of the nest only after they had reached a sufficient level of maturity beyond the hatchling phase. In this were the case at Bone Butte, it would further demonstrate the unlikelihood that hatchling bones would be found anywhere other than the specific location of the nests.

Whereas it is improbable that the pachycephalosaur, thescelosaur, and ornithomimid nesting areas were located specifically at Bone Butte, taphonomic signatures suggest that these dinosaur groups lived in the Bone Butte area and were not transported from a distant location. It

is likely that nesting took place nearby and, as is the case with many modern animals, the parents could have chosen areas that were safe, secluded, less prone to attack by predators, and less likely to experience rapid sediment deposition that could have smothered the eggs. The Bone Butte herbivorous dinosaurs could have employed an approach to nesting practices similar to that of extant ground-nesting birds, and selected an area close to the Bone Butte site that would have been more isolated or otherwise inhospitable, in an attempt to ward off potential predators.

4.1.4. *Paleoenvironment*

The Bone Butte sediments were deposited during a period of time characterized by a gradual progression from a heavily forested, nearly globally tropical environment to a cooler climate, characterized by patchy stands of forest punctuated by meadows, and a shift from gymnosperm plants to angiosperms (Crabtree, 1987; Lindgard and Crane, 1990; Wing and Sues, 1992). Evidence from Bone Butte can be used to produce a reconstruction of the Hell Creek paleoenvironment, providing a context for its vertebrate inhabitants.

The sediments at Bone Butte indicate a moist, low-lying environment. Poorly drained, unoxidized, organic-rich sediments enriched by gleys and pseudogleys, such as the floor of the Bone Butte site (Stratum 10), and surrounding strata, were deposited in a low-lying, circum-seashore floodplain environment reminiscent of the modern Mississippi River delta (Farrell, 1987; Behrensmeyer et al., 1992; Aslan, 1998; Bartlett, 2004). Seasonal wetting and drying is suggested by pedogenic structures such as slickensided blocky peds and the oscillating wet and dry cycles depicted by the laminae of the Bird & Mammal Zone and Oxbow (Aslan, 1998; Bartlett, 2004). Laminae in the Bird & Mammal Zone and Oxbow indicate annual wet and dry periods, characterized by a dry period of intermittent low-intensity storms, followed by a wet period with an increased frequency of high-intensity storms. Deposits of burnt wood, or

pyrofusain, frequently occur within periods of greater rainfall and storm intensity, and are probably related to fires initiated by lightning strikes. The rain cycle is not abrupt or intense enough to characterize as fully monsoonal, however the mild monsoonal component to the rainfall graph is supportive of the Pangean monsoonal climate suggested for the time period (Parrish et al., 1986; Parrish and Peterson, 1988; Wing and Sues, 1992), and is similar to modern semi-monsoonal climates (Ogawa et al., 1965; Bullock, 1985; Murphy and Lugo, 1986).

By the time Bone Butte was forming, vegetation had already begun to make its shift from gymnosperm-dominated to angiosperm-dominated, and densely packed forests began to thin out in a Late Cretaceous cooling trend (Crabtree, 1987; Lindgard and Crane, 1990; Wing and Sues, 1992). Although the Bone Butte climate was cooler by Early Cretaceous standards, global temperatures were warmer than at present, to an extent that likely precluded the formation of polar icecaps (Hallam, 1985). The majority of the Hell Creek Formation was dominated by patches of angiosperm forest, which were visited by herds of dinosaurian megaherbivores including hadrosaurs, ceratopsians, and ankylosaurs. The weedy nature of many angiosperms and their association with disturbed ground reinforce their connection with the megaherbivore component of the Bone Butte allochthonous fauna (Bakker, 1978; Tiffney, 1984; Wing and Tiffney, 1987; Weishampel and Norman, 1989; Wing and Sues, 1992). The angiosperms from crevasse-splay deposits at Bone Butte were adapted to a warm, moist environment, and frequently have broad leaves and drip-tips. Many have a close taxonomic affinity to angiosperms in temperate and subtropical areas today. In localized groupings, dense stands of gymnosperms, such as *Metasequoia* and *Cunninghamia*, lived in low-lying areas and in circum-riparian environments, punctuating the ubiquitous stands of angiosperms. Seasonality in the weather is made evident not only by the oscillating rain cycle and soil structure, but also by the deciduous nature of cupressaceous trees at Bone Butte, which were observed to have formed extensive mats

of dropped needles probably on an annual basis. The presence of immature strobili, attached to twigs associated with the needle mats, indicates the needles were dropped in the fall, just as with the modern Bald Cypress trees (Dallimore, 1948; Dennis, 1988). Temperatures likely did not fall low enough to form ice, which is injurious to cupressaceous trees and limits their range (Middleton and McKee, 2004), however enough of a temperature gradient existed to form well defined seasons. Using the optimum temperature ranges of modern deciduous conifers as a guide (Dallimore, 1948; Middleton and McKee, 2004), annual temperature at Bone Butte could have ranged from 13° C to 36° C while still maintaining a productive cupressaceous component. Temperature ranges and precipitation cyclicity suggest that the Bone Butte forested areas could have been similar to the semi-deciduous, dry-monsoonal, or monsoonal forest-savanna areas today, all of which can be found between the present 16° N and 17° N latitudes (Ogawa et al., 1965; Bullock, 1985; Murphy and Lugo, 1986).

Although very little is presently known about Hell Creek insects due to the rarity of specimens, those from Bone Butte offer some evidence for the paleoenvironment. Eleven different insect taxa are represented by the 19 insect specimens thus far recovered from Bone Butte amber, making diversity among the collected specimens rather high. Virtually all insect taxa recovered from amber (primarily dipterans) required standing or flowing water at some point in their life cycle, consistent with the interpretation of a wet Hell Creek environment. Dung beetles (represented at Bone Butte by preserved burrows), burrow in subaerially exposed sediment (Halffter and Edmonds, 1982; Hanski and Cambefort, 1991), and areas around Bone Butte must have remained sufficiently dry even in the wet season to ensure the beetles' survival. Insects no doubt played an important role in the Hell Creek ecology, as has previously been suggested (Wing and Sues, 1992), and the diversity of Bone Butte insects, coupled with previous

knowledge of additional Hell Creek insect taxa, helps to reveal a wide variety of Hell Creek insects and their potential to interact with and affect other members of the ecology.

4.2. *Geology and Site Formation*

Although Bone Butte and its correlating strata are a small part of the entire study area, they provide a suite of sedimentologic, taphonomic, and paleontologic clues that enable a reconstruction of local paleo-river tracts and Bone Butte site-forming events. Bone Butte's stream channel and oxbow lake deposits were once part of tributary system that fed a larger river channel. Interactions between the tributary and the main trunk channel influenced the spatial arrangement and occurrence of multiple crevasse-splays that subsequently covered the Bird & Mammal Zone and Oxbow. The main trunk channel emptied into the Western Interior Seaway a short distance east of Bone Butte. Recent studies have suggested that the Western Interior Seaway persisted, and that its shore during the late Maastrichtian was situated about 100 km east of Harding County, South Dakota (Gill and Cobban, 1973; Kennedy et al., 1998; Murphy et al., 2002; Cochran et al., 2003; Bartlett, 2004), or approximately 110 km east of Bone Butte. The Bone Butte study confirms the persistence of the Western Interior Seaway, while providing evidence that the paleoshoreline was much further west than previously suggested. The presence of several genera of orectolobid sharks, the hybodont shark *Lissodus selachos*, and the "sawfish" *Ischyrrhiza avoncola*, organisms associated with fully marine and occasionally brackish water (Estes, 1964; Wroblewski, 2004), indicates that the paleoshoreline was perhaps 10 km from Bone Butte, rather than 110 km. The presence of *Thoracosaurus*, a marine crocodile, and the marine gastropod *Pachymelania*, provide further evidence of Bone Butte's close proximity to the paleoshoreline (Hartman and Johnson, 2002; Jouve et al., 2008), and of the persistence of the Western Interior Seaway into the latest-Cretaceous.

4.2.1. Tributary and Oxbow

The floor of Bone Butte (Stratum 10) is composed of alluvial floodplain mudstones, siltstones, and paleosols, sediments that are common elsewhere in the Hell Creek Formation (Fastovsky, 1987 a, b; Bartlett, 2004). The Stratum 10 sediments were eroded and incised by a small stream, labeled Stream A, which is estimated from the width of the channel deposit to have been about 5 m wide at the study area (Fig. 4.22 A). At the same time, small, localized, shallow

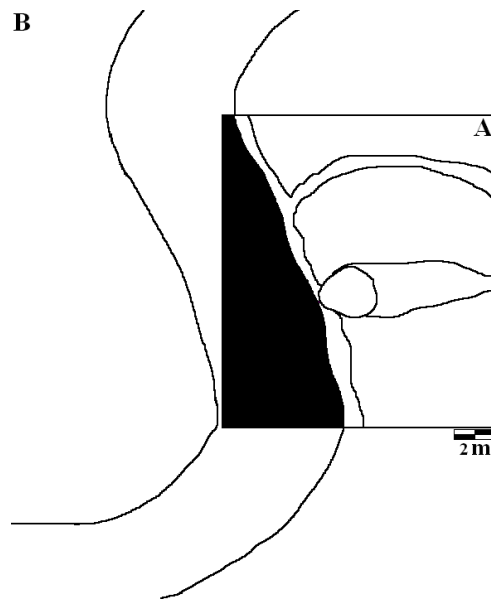


Figure 4.22. The “Stream A” sediments of Bone Butte, in black (A) and a theoretical continuation of portions of the stream course not preserved at Bone Butte (B). The circular object in (A) represents the erosionally resistant paleosol deposits of Strata 13 and 14.

pools laden with algae and microbial mats formed atop Stratum 10, resulting in the ironstone lenses of Stratum 17 (Behrensmeyer and Hook, 1992). The presence of rhizoliths, patches of paleosol, and invertebrate burrows at the contact between Stratum 10 and Stream A, indicate that the Stratum 10 floodplain deposits were mature and subaerially exposed for an appreciable period of time before being incised by the stream (Fastovsky, 1987 a, b; Retallack, 1987). At the north end of the Bone Butte site, Stream A’s direction curves at approximately N 30 E, and is

traced by the overlying Bird & Mammal Zone. Highly bioturbated, phytodebris-enriched, reddish-orange mottled siltstones (Stratum 18) flank the western margin of Stream A and the subsequent oxbow meander, and represent a levee system (Fastovsky, 1987 a; Retallack, 1987; Bartlett, 2004; Fig. 4.24 A-B). As the stream deposits at Bone Butte cannot be correlated with sediments in any surrounding butte, it is impossible to trace the exact stream course, however the gentle curve toward the northeast suggests that Stream A meandered to a certain extent, as do most tributaries, and was in the process of turning toward the east (Fig. 4.22). The coarse to medium-grained sandstone of Strata 7 and 9 were deposited as Stream A followed this course. As a meander of Stream A grew and migrated westward, it encountered a localized mass of

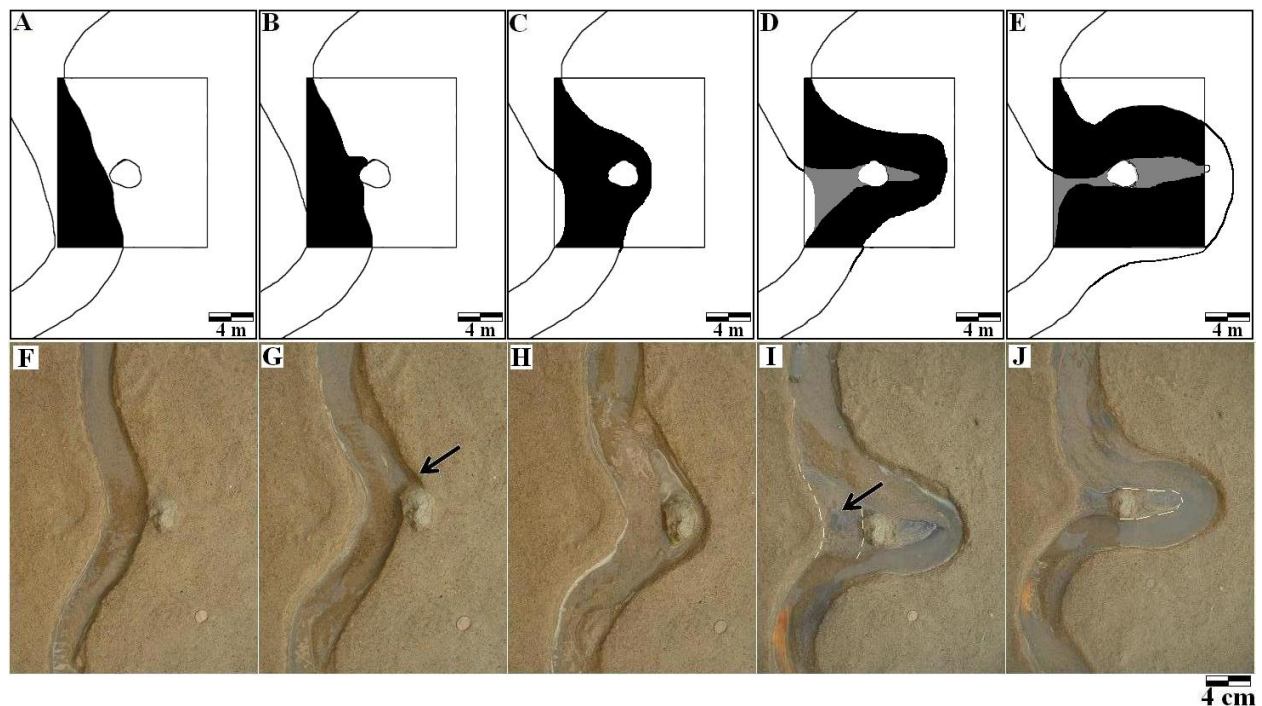


Figure 4.23. Theoretical evolution of the Bone Butte meander and oxbow (A-E) compared with images from the stream table experiments (F-J). As Stream A contacted the erosionally resistant paleosols of Strata 13 and 14, westward migration would temporarily have been halted (A, F), after which a small embayment would have formed on the upstream side (arrow in G). The meander would have continued around the obstruction, circumscribing it (C, H), and then continuing west (D, I). Arrow in (I) indicates back-filled portion of stream as the meander migrated westward. Eventually, an oxbow loop would have formed and become increasingly recumbent (E, J).

erosionally resistant soil (Strata 13 and 14) that was perhaps once part of Stratum 10 (Fig. 4.23 A). Plant rhizoliths extending from the reddish, highly bioturbated Stratum 14 into the greener Stratum 13 below suggest that Strata 14 and 13 could represent A and B soil horizons that were

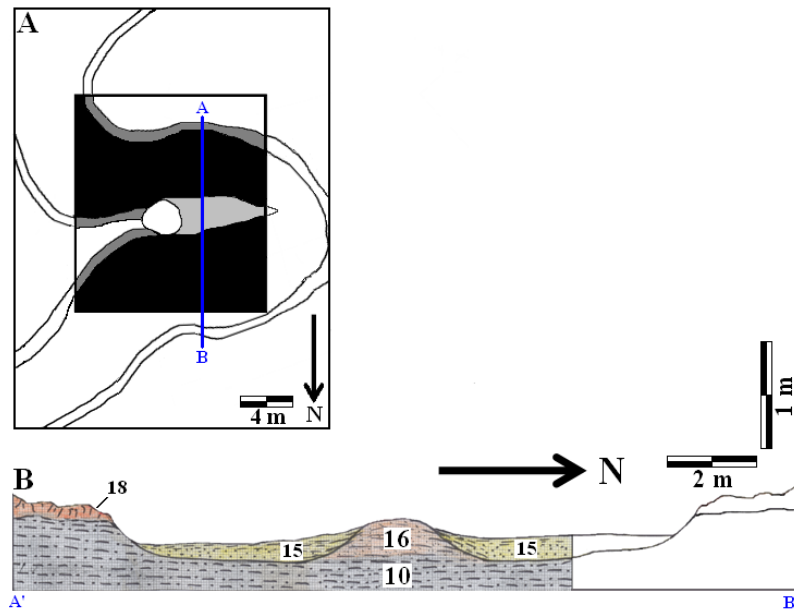


Figure 4.24. A schematic of the Bone Butte oxbow loop in map view (A) and sectioned profile (B). The band that follows the banks of the stream and oxbow loop are levee deposits (Stratum 18). Point bar deposits are represented by Stratum 16. Over time, the Stratum 15 deposits were laid down by the stream flow.

formed prior to the appearance of Stream A (Fastovsky, 1987 a; Retallack, 1987). Extending downward from Stratum 14 into the center of the Stratum 13 mass of sediment is a tangle of large (>10 cm diameter) rhizoliths that at first appeared to be pieces of petrified branches. These large rhizoliths bear close resemblance to tree roots and suggest that a tree (with a trunk diameter 120 cm or less based on Stratum 14's size) was growing in the Strata 13-14 sediment mass. It is possible that, as occurs with many cypress trees today, the tree growing in Strata 13 and 14 helped to reinforce the surrounding sediments and increase their resistance to erosion. As no portions of the trunk are preserved in the overlying crevasse-splay deposits, it is possible that

either the tree was felled by one of the crevassing events, or it died and fell apart some time before deposition of the crevasse-splay sediments.

Stream table experiments conducted earlier in the Bone Butte study show that as the Stream A meander contacted the erosionally resistant Strata 13 and 14, its westward migration was likely temporarily halted. A slight erosional embayment in the stream bank would have formed on the upstream side of Strata 13 and 14 (Fig. 4.23 B), which would have grown, and eventually formed an oxbow channel that circumvented Strata 13 and 14's western margin (in this paper, the proper noun Oxbow refers to the combined oxbow channel and oxbow lake deposits of Strata 15 and 11, whereas the common noun usage of the word shall refer collectively to oxbows in the geomorphologic sense). Unlike the typical, teardrop-shaped recumbent meanders seen in today's rivers, the morphology of the Stream A oxbow channel is narrow and elongate (Fig. 4.23 E). Stream table experiments from this study show that the presence of an obstacle in a developing meander's path can affect the morphology of the meander and oxbow, and can form an elongated oxbow rather than a teardrop-shaped one as the water is deflected off the obstacle (Fig. 4.23 F-J). The presence of Strata 13 and 14 appears to have created such a deflection and promoted the formation of an elongated oxbow at Bone Butte (Fig. 4.23 A-E). The sediments of Stratum 15 were deposited in the oxbow channel while the Stratum 16 point-bar deposits (also known as an oxbow "head") were laid down between the horns of the oxbow (Fig. 4.23 C-E). Over time, *Equisetum* horsetail plants commonly found along the banks began to grow on the point bar, and ornithurine birds frequented the area, perhaps to feed upon the invertebrate creatures that formed the Stratum 16 *Cochlichnus* and *Arenicolites* traces. Periodic rain storms created temporary increases in stream velocity, which deposited clay-pebble laminae in Stratum 15. The bones of various autochthonous dinosaurs, birds, mammals, reptiles, amphibians, and fish were deposited throughout Stratum 15, and follow the contours of the

oxbow. Some bones from an allochthonous source – mainly small, easily transported items such as teeth, claws, and distal skeletal elements – were also deposited in Stratum 15.

In oxbow lake formation, the “neck” of the oxbow channel can be breached at virtually any time once it is maximally reduced, at which time the recumbent oxbow meander will be incorporated into the newly straightened channel as a side loop, and eventually will be entirely isolated from the channel, forming an oxbow lake (Schumm et al., 1987; Leopold et al., 1995; Fig. 4.25 A-D). The abandonment of the oxbow meander is always characterized by a fining-upward sequence of sediment (Reineck and Singh, 1973; Behrensmeier and Hook, 1992; Miall, 1992; Bartlett, 2004). After about a year, as indicated by sedimentologic, paleobotanical, and

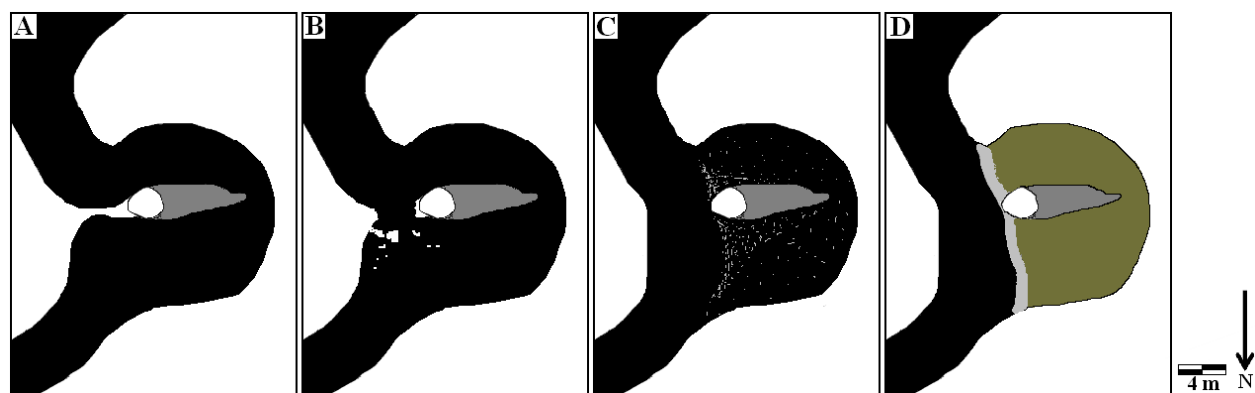


Figure 4.25. The formation of an oxbow lake. The highly recumbent oxbow loop forms a constricted “neck” (A), which is susceptible to erosion and breaches (B). The stream channel follows a straighter path, as the oxbow loop fills with sediments (C). Eventually, sediment “plugs” form, excluding the oxbow loop from the stream, forming an oxbow lake (D).

vertebrate ontogenetic data (see section on temporal resolution), the oxbow meander at Bone Butte would have become so recumbent that its neck would have been reduced to a narrow spit of land. In Stratum 15, a lamina of particularly large clay-pebbles – representing a large storm event during the summer months– immediately precedes a fining-upward sequence of sediment. The fining-upward sequence represents the first stages of decreased water flow and isolation of

the oxbow channel as it became an oxbow lake. It is likely that the large storm provided the final “push” that breached the oxbow’s neck, allowing the channel to straighten, and also contributed to depositing the chaotic sediments of Stratum 6. Stratum 6 forms a unit of equal thickness and elevation to the lower portions of Stratum 15 that precede Stratum 15’s fining-upward sequence. At the time Stratum 6 was being deposited, portions of Strata 7 and 9, as well as Stratum 15-equivalent sediments from Stream A, were eroded away and reworked.

The newly straightened channel of Stream A, composed of Stratum 5, shall simply be referred to as the Bird & Mammal Zone. Clay-pebble laminae resulting from storms in the lower half of the Bird & Mammal Zone correlate with those in the upper portion of Stratum 15, the only difference being that the equivalent Stratum 15 sediments are characterized by a fining-upward sequence while the Bird & Mammal Zone sediments remain steady and consistent (Fig. 4.26 A). This shift in Stratum 15’s grain size is due to decreased flow into the oxbow loop caused by accretionary sediment plugs deposited by the active Bird & Mammal Zone stream (Fig. 4.25 C). The oxbow loop was still connected to the Bird & Mammal Zone stream at this point, and fish and other fully aquatic organisms were allowed ingress and egress, as supported by the wide size range of both freshwater (gar and other teleost fish) and partially marine aquatic organisms (sharks, rays, and marine crocodiles). The stands of gymnosperm trees that characterize the habitat of Bone Butte’s autochthonous fauna dropped needles, branches, and copious amounts of amber into the oxbow loop, which are preserved in Strata 15 and 11. Whereas the upper portion of Stratum 15 contains some fine-grained sand mixed with silt and organics, the overlying sediments of Stratum 11 are composed solely of siltstone and abundant organics. Stratum 11 was deposited after sediment plugs fully excluded the oxbow loop from the Bird & Mammal Zone stream sometime during the summer months, forming an isolated oxbow lake (Fig. 4.27 A-C). Clay-pebble laminae in the upper portion of the Bird & Mammal Zone

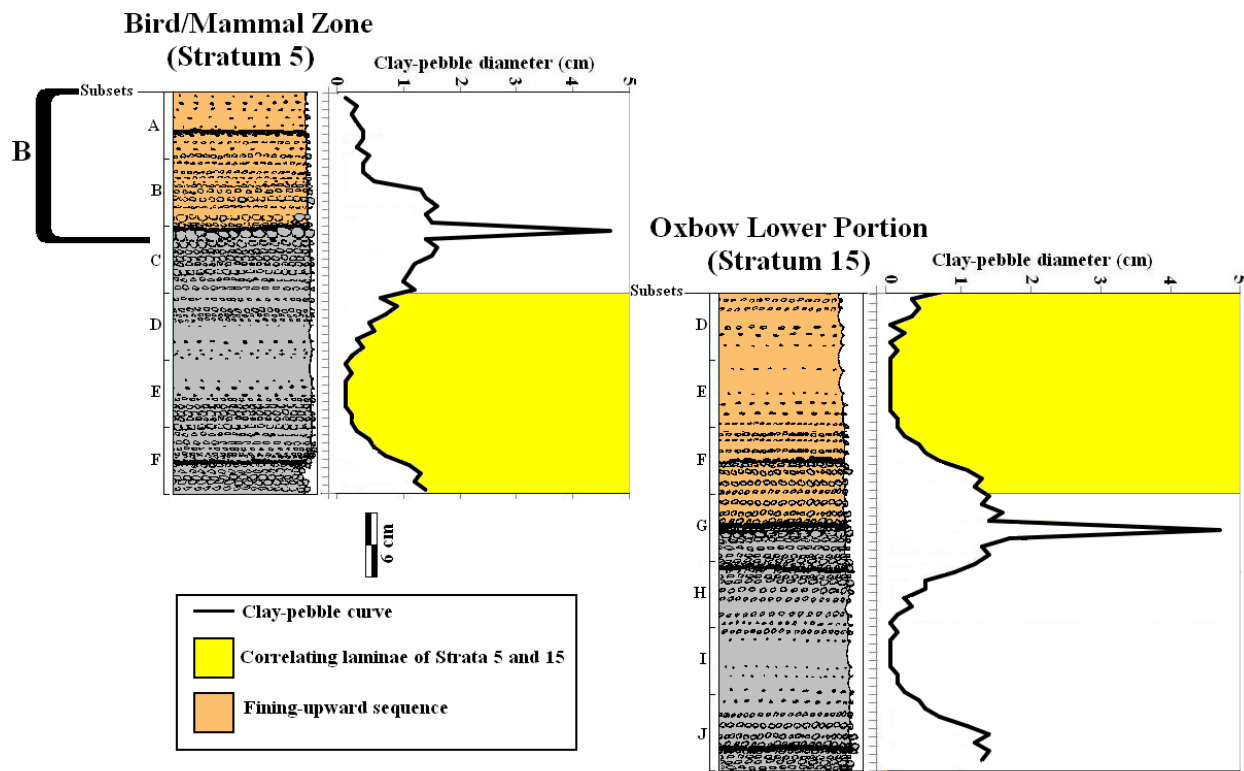


Figure 4.26. The Bird & Mammal Zone strata (left) compared with Stratum 15 (right). Clay-pebble laminae in the lower Bird & Mammal Zone correlate with laminae in the upper portion of Stratum 15, however the upper portion of Stratum 15 exhibits a fining-upward pattern (tan). A similar fining-upward pattern to that of Stratum 15 is present in the Bird & Mammal Zone (B), both of which follow a large storm (spike in clay-pebble graph).

correlate with clay-pebble laminae and fine-grained sandstone lenses in Stratum 11, which were deposited as stream flooding caused by storms overshoot the bank and entered the oxbow lake (Fig. 4.26). Vertebrate bones were still being deposited in the isolated oxbow lake, however large fish were absent, as were any partially marine organisms such as selachians or marine crocodiles. The quiescent environment of the oxbow lake was an ideal breeding environment for certain varieties of insects (Hunt, 1951), as supported by ichnofossils from Stratum 11, and the insects would have provided a viable food source for fish, turtles, birds, small theropods, and small mammals (Fig. 4.28). The occurrence of “*Ficus*” ceratops horsetail rhizomes and horsetail shafts was highest near Stratum 11’s upper bounding surface, a sign that horsetails colonized the

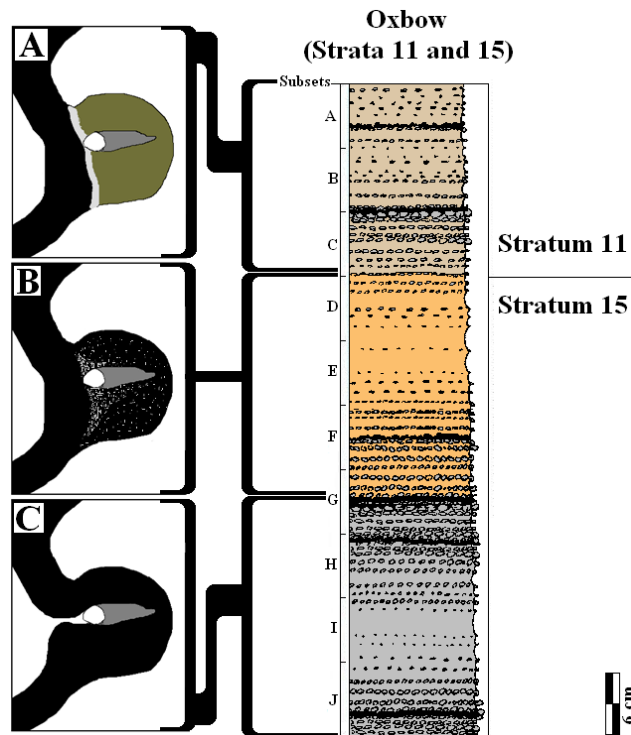


Figure 4.27. Sediments from the Oxbow (Strata 11 and 15) with interpretive diagrams (left). The lower portion of Stratum 15 was deposited in the active oxbow loop (C). The upper portion of Stratum 15 exhibits a fining-upward trend and represents the gradual abandonment of the oxbow loop after the stream channel straightened (B). Stratum 11's highly organic siltstone was deposited after the oxbow loop was completely isolated from the stream, forming an oxbow lake (A).

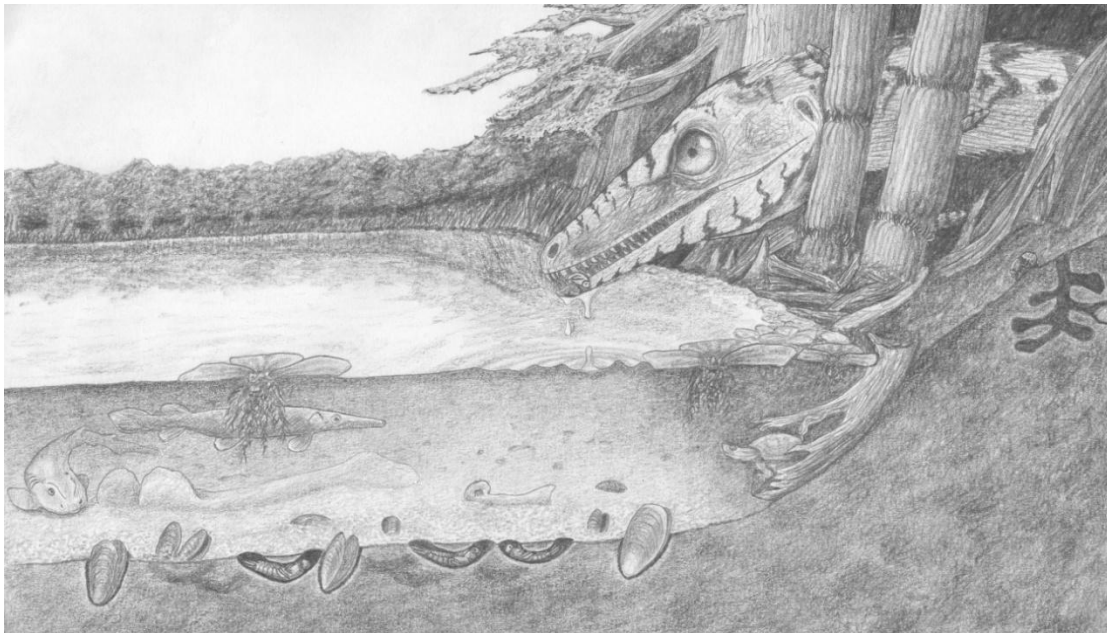


Figure 4.28. The quiet waters of the oxbow lake at Bone Butte would have provided an ideal environment for insect larvae, which would have been an important component of the local ecology. (Diagram © Robert A. DePalma II.)

majority of the oxbow lake as it gradually filled with sediment and shallowed. The oxbow lake accumulated sediment and vertebrate bones for slightly less than a year before it was reduced to little more than a shallow, algae-infused puddle, which was preserved as Stratum 12. Stratum 12, which caps Strata 11 and 16, was deposited at the same time as the upper ~10 cm of the Bird & Mammal Zone. Clusters of U-shaped burrows that are seen at Stratum 12's lower margin attest to the fact that life was still supported at the time Stratum 12 was deposited, however the absence of vertebrate remains suggests that vertebrate life had largely vacated the pond by that time.

In the upper 1/3 of the Bird & Mammal Zone, a similar fining-upward trend to that of Stratum 15 attests to an abrupt change in the stream's flow patterns, in which deposits from a large storm precede the fining-upward sequence (Fig. 4.26 B). The storms preceding the fining-upward sequences of the Bird & Mammal Zone and Stratum 15 both occurred at the height of the rainy season, toward the end of summer/beginning of fall, but occurred during subsequent years (the Bird & Mammal Zone experienced its fining-upward trend one year following Stratum 15). The fining-upward sequence of the Bird & Mammal Zone is typical of those seen in abandoned channels (Reineck and Singh, 1973; Behrensmeyer and Hook, 1992; Miall, 1992; Bartlett, 2004), however the cause of the Bird & Mammal Zone stream's abandonment is not directly evident at Bone Butte. Channels can become abandoned if precipitation and water level decrease to an extent that lowers the overall water outflow of the stream (Horton, 1945; Schumm et al., 1987; Leopold et al., 1995), however evidence for regular rain storms in the area demonstrates that precipitation was not atypically low, and the presence of many horizontal rhizoliths are indicative of a high water table (Behrensmeyer and Hook, 1992). Stream channels can also become abandoned via other events, including a change in stream course due to landslide or other obstruction, or a large recumbent meander forming a giant oxbow lake (Horton, 1945; Schumm et al., 1987; Leopold et al., 1995). Since the Bird & Mammal Zone and Oxbow deposits

are covered by several crevasse splays far larger than the Bird & Mammal Zone stream could ever have been capable of producing, we know that a larger river channel was in close proximity to Bone Butte. In modern fluvial systems, a meander from a tributary will sometimes migrate toward a large river channel and make contact with the river upstream of the tributary's primary outlet point. In these cases, the portion of the tributary downstream of the secondary contact with the main river will eventually become completely abandoned (Fig. 4.29 A-C).

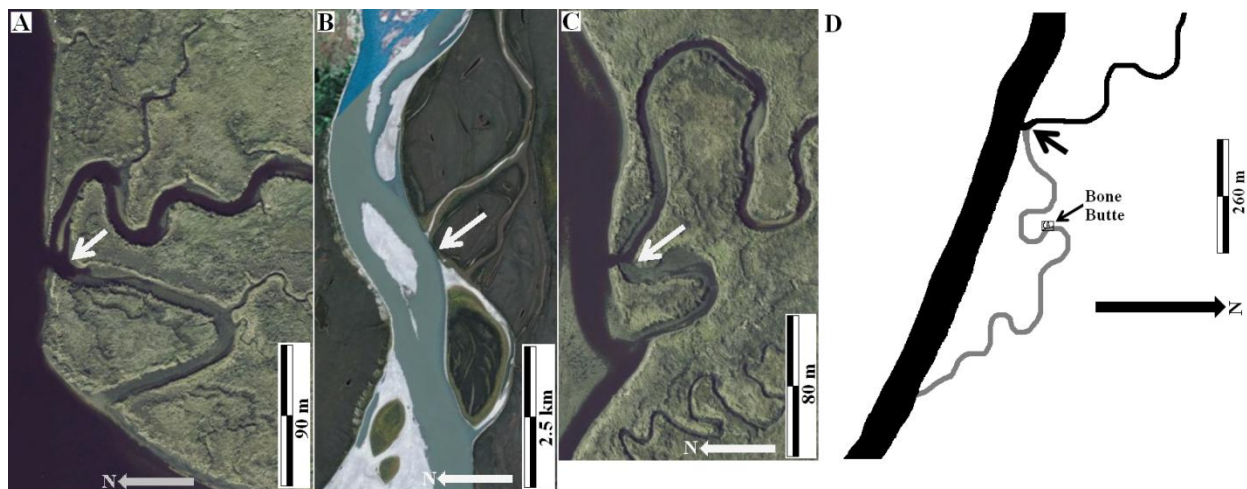


Figure 4.29. Examples of modern rivers (A-C) compared with a possible scenario for Bone Butte (D). In the Suwannee River (A, C) and Mackenzie River (B), tributaries often make secondary connections with the trunk stream (white arrows), causing downstream portions of the tributaries to become abandoned. Such a secondary connection with a trunk stream is a plausible reason for the Bone Butte stream's abandonment (D). (A-C Courtesy Google Earth.)

Personal observation of modern analogs has revealed that in some instances, such as with certain tributaries near Big Creek in Georgia, the time lapsing between initial abandonment and a transition to fully terrestrial deposits can be as little as 2 years. Stream table experiments in the Bone Butte study consistently showed an abandonment of the downstream portions of tributaries following the formation of secondary connections with their destination rivers. It is probable that, since a large river channel was in the vicinity of Bone Butte, the Bird & Mammal Zone

stream was one of its tributaries and that a secondary connection with the river channel caused the Bird & Mammal Zone stream's abandonment (Fig. 4.29 D). Other evidence, from the location of several crevasse-splay formations that will be discussed in the next section, further supports the formation of a secondary contact between a tributary and main river channel. Curiously, the fining-upward sequence in the Bird & Mammal Zone immediately succeeds a lamina produced by a large storm, similar to the fining-upward sequence of Stratum 15, which also succeeds a large storm. If a tributary's meander grew close to the main river channel and began eroding the levee, the increased water volume created by a large storm event could have exacerbated the situation and caused the meander to unite with the river channel. This notion is supported by evidence from stream table runs, in which a momentary pulse of increased water flow hastened the secondary connection of a tributary's meander with the main river channel. This scenario supports the fining-upward sequence preceded by a major storm event that is seen in the Bird & Mammal Zone.

4.2.2. Crevasse-Splays and Main River Channel

Crevasse-Splay # 1

Neither the Bird & Mammal Zone nor the Oxbow made the full transition from fully aquatic to fully terrestrial before being covered by crevasse-splay deposits, although the Oxbow was in the most advanced stage of transition. The first crevasse-splay deposit, Stratum 4, is the most diminutive of the three crevasse-splays preserved at Bone Butte. The sediments of this stratum thin to the north, east, and southeast of Bone Butte, indicating a point of origin somewhere to the southwest. The lack of rip-up mudclasts diminishes the ability to estimate the distance traveled by the Stratum 4 sediments, however intermittent occurrences of rhizoliths near

the upper bounding surface are connected to plant remains bent at a 90° angle, and laid horizontally against the upper bedding plane (Fig. 4.30). They typically point between N 41 E

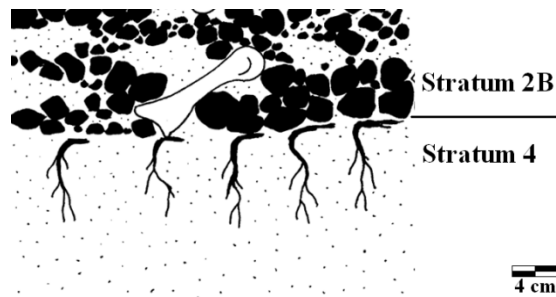


Figure 4.30. A schematic of Stratum 4 and overlying Stratum 2B. Rhizoliths along the upper bedding plane of Stratum 4 frequently were connected to plants that had been bent over and laid flat against the bedding plane. The bent plants frequently pointed between N 41 E and N 45 E.

and N 45 E, reinforcing a point of origin to the southwest (Fig. 4.31 A). The paucity of rooted plant remains and invertebrate burrows indicates that Stratum 4 was not subaerially exposed very long before being covered by additional crevasse-splay deposits (Bown and Kraus, 1981). Water flow velocity was great enough to carry medium-grained sediment and leaves, but apparently not animal bones.

Crevasse-Splay # 2

After a short duration, perhaps a year or less considering how few plant remains took root in Stratum 4, another crevasse-splay, consisting of Strata 3 and 2B, came to rest atop Stratum 4. This second crevasse-splay was massive by comparison, and had enough carrying capacity to transport large dinosaur bones and tree logs exceeding 2 m in length. Sediments from the second

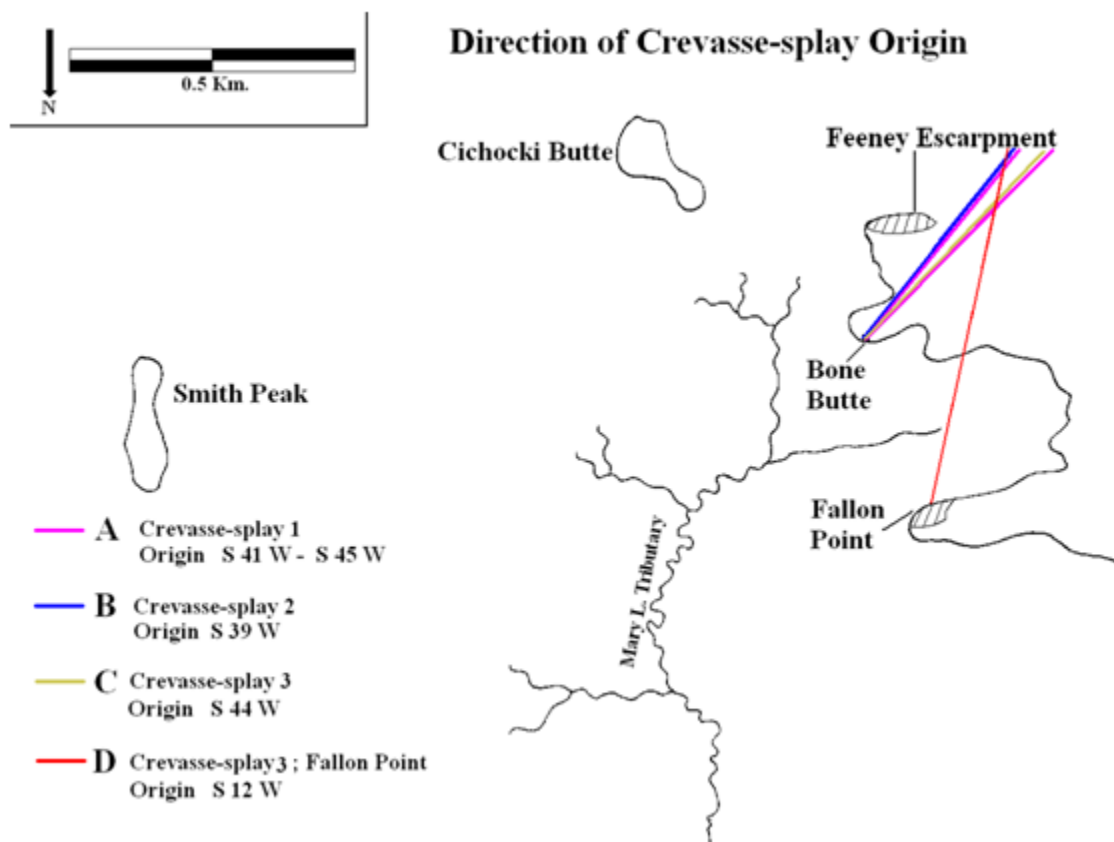


Figure 4.31. Based on the orientation of fossils, the direction of origin for the three crevasse-splays was calculated. Crevasse-splay 3 (Stratum 2A) originated from a direction of roughly S 44 W, crevasse-splay 2 (data from Stratum 2B) originated from a direction of roughly S 39 W, and crevasse-splay 1 (Stratum 4) originated from between S 41 W and S 45 W. All three crevasse-splays originated from the same approximate direction. Additional data from Stratum 2A from Fallon Point corroborates the evidence collected at Bone Butte.

crevasse-splay thin to the north, east, and southeast of Bone Butte, and the majority of fossils deposited are oriented roughly N 39 E, similar to the first crevasse-splay, and indicate a similar direction of origin (to the southwest; Fig. 4.31 B). “Logjams” of bones pressed against the southwestern side of Stratum 14, a structure that projected above the second crevasse splay, are further evidence of the direction of flow. The sandy upper portion of the second crevasse-splay (Stratum 3) preserves several isolated occurrences of rhizoliths, although none are connected to plants bent against the bedding plane, as seen in Stratum 4.

Crevasse-Splay # 3

As with Stratum 4, sediments from the second crevasse-splay were subaerially exposed for a minimal amount of time, perhaps a year, as indicated by the infrequency of rhizoliths and invertebrate burrows (Bown and Kraus, 1981), before being covered by the third crevasse-splay. The most massive of the three crevasse-splays, the third event (Strata 1 and 2A) covered all previous crevasse-splay deposits and could be traced to nearby buttes up to 1.5 km to the northeast. The intensity of the flow was sufficient to scour away some of Stratum 3 and disrupt some of the bones in underlying Stratum 2B. As with the other two crevasse-splays, sediments from the third event thin to the north, east, and southeast and the orientation of the fossils (roughly N 44 E on average) indicates a nearly identical point of origin to those of the first two crevasse-splays (Fig. 4.31 C). As Stratum 1 contacts overlying sandstone strata unconformably, it is unknown how much time lapsed before these crevasse-splay deposits were covered by additional fluvial sediments.

Distance to Origin

Whereas the direction of origin for the three crevasse-splays was calculated at between S 39 W and S 44 W based on the direction of fossil orientation, such information is of only limited value if the distance to the point of origin is unknown. A comparison between the results of the mudclast tumbler experiments carried out in this study, and the abundant rip-up mudclasts from the second and third crevasse splays, enable a theoretical minimum distance traveled by the Bone Butte crevasse-splay mudclasts to be calculated. Quantified values of angularity follow the scale used in the Bone Butte tumbler experiments. Mudclasts from the second crevasse-splay average 5 - 6 cm in diameter and have an average angularity of 2.2 (subround to subangular), making

their estimated distance from origin approximately 253 - 263 m based on the tumbler experiment data (Fig. 4.32 B, E, F). Similarly, mudclasts from the third crevasse-splay, with an average diameter of 10 - 15 cm and average angularity of 3.4 (subangular to angular), are estimated to have traveled approximately 250 - 265 m from their point of origin, showing that both the second

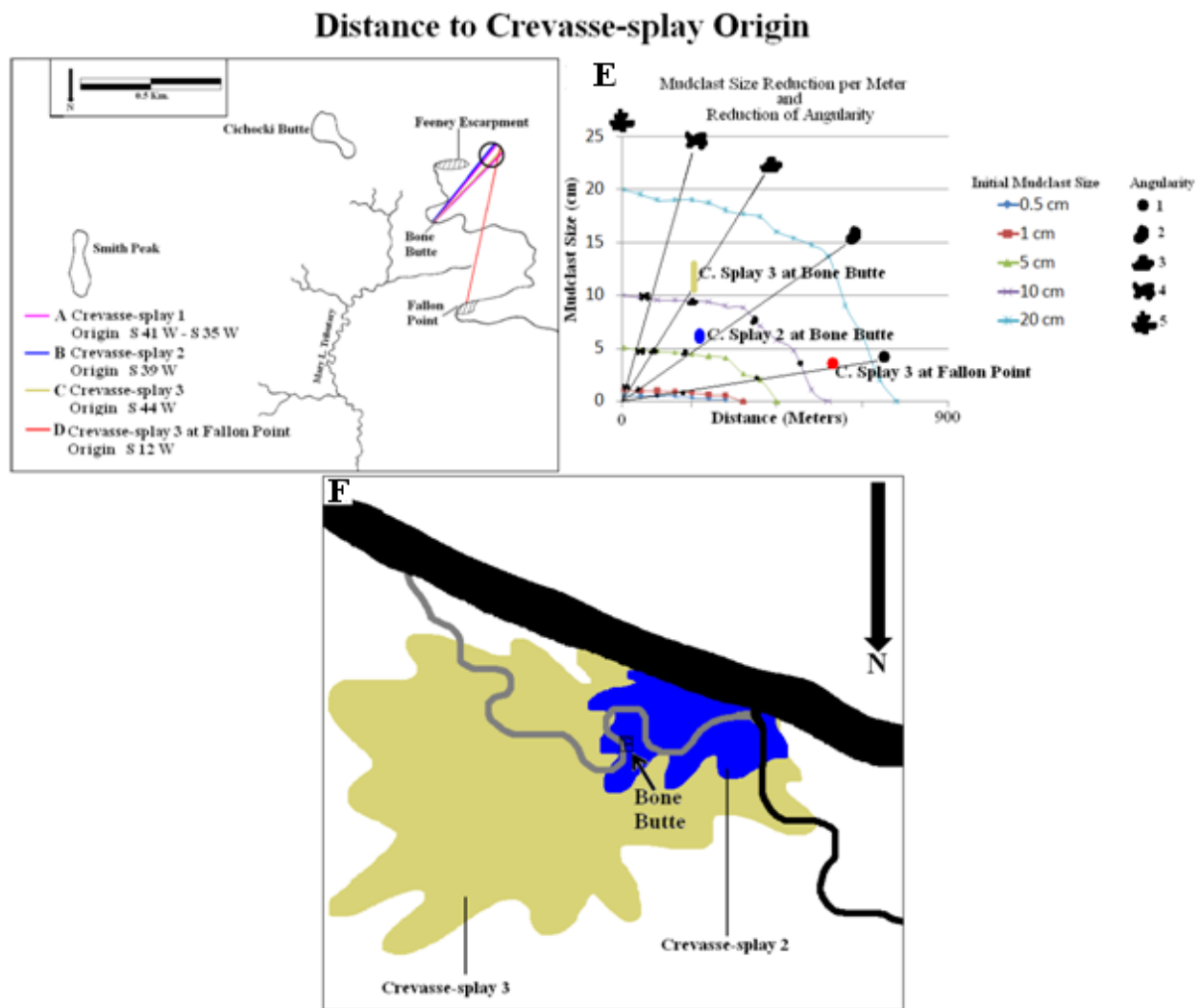


Figure 4.32. The distance to the point of origin for the crevasse-splays was estimated based on the mudclast graph generated by the Bone Butte tumbler experiments. The estimated distance of mudclast transport (E), combined with the direction of fossil orientation, enables the point of origin for crevasse-splay deposits to be estimated (A-D). The crevasse-splays all share a common point of origin. Crevasse-splay #'s 2 and 3 can be seen superimposed on each other in (F).

and third crevasse-splays originated from the same general area of 250 - 265 m S 43 W of Bone Butte (Fig. 4.32 C, E, F). Field observations of modern crevasse-splays show that estimated distances of mudclast transportation based on the tumbler experiment data can be consistently accurate to within about 10 percent (see results section), however the estimated distances traveled by Bone Butte mudclasts were tested through additional means. Bone samples recovered from Stratum 2A equivalent sediments from Fallon Point, 420 m north of Bone Butte, had an average orientation of N 12 E, indicating a direction of origin roughly S 12 W (Fig. 4.32 D). A line drawn in the direction of S 12 W from Fallon Point and a line drawn in the direction of S 44 W from Bone Butte's Stratum 2A sediments triangulate the point of sediment origin to an area roughly 260 m S 44 W from Bone Butte (Figure 4.32 bold circle), the same general point of origin estimated by the tumbler experiment graph. As an additional means of calculating the point of crevasse-splay origin, mudclasts collected from Stratum 2A-equivalent sediments from Fallon Point were compared with the tumbler experiment data and estimated to be 590 - 620 m of their point of origin, confirming the previously calculated point of origin (Fig. 4.32 D, E, F). Unfortunately, sediments from the first crevasse-splay lack the mudclasts needed to estimate the distance from their point of origin, however the direction of origin remains constant with the second and third crevasse-splays, and the first crevasse-splay likely emanated from the same location as the second and third.

Spatial Arrangement of Crevasse-Splays

The fact that three crevasse-splays, formed at three distinct points in time, originated from the same geographic point, initially seems somewhat dubious. In one of the first stream table experiments carried out in the Bone Butte study, the spatial distribution of crevasse-splays

along a simulated river was largely random and seldom repeated more than once at the same location. This experiment initially reinforced the unlikelihood of a hypothesis that all three crevasse-splays shared one point of origin on three separate occasions. However, subsequent stream table experiments that included tributaries feeding into the simulated rivers showed that crevasse-splays were more frequently formed at the juncture between a tributary and the simulated river. During the course of the experiment, crevasse-splays were formed numerous times at the same tributary-river junction (Fig. 4.33 A). Personal observations of modern

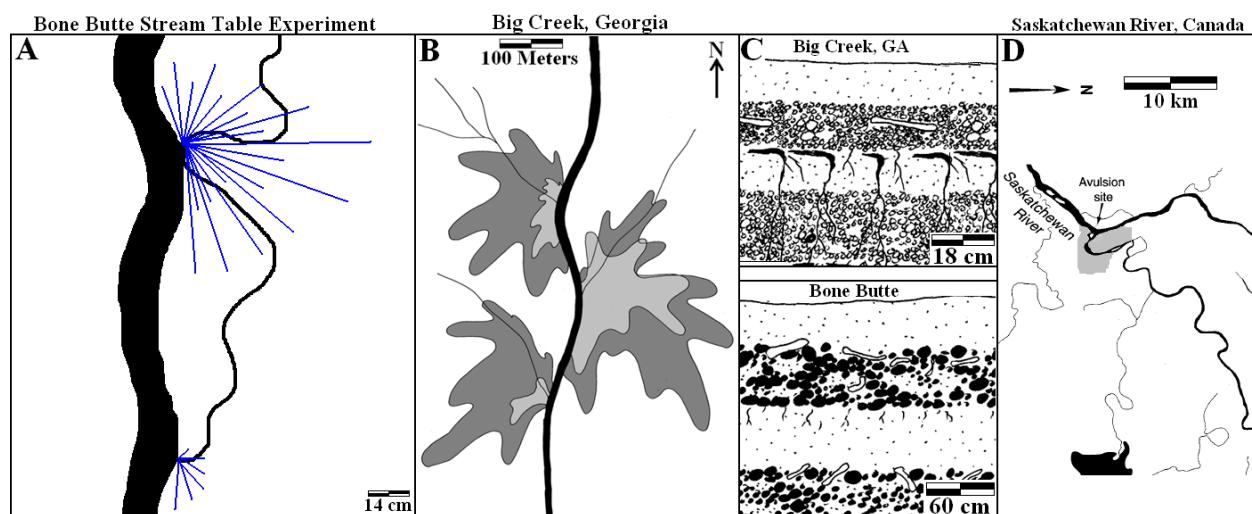


Figure 4.33. Crevasse-splay formation as affected by tributaries. Bone Butte stream table experiments (A) and observations of modern streams (B, Big Creek in Georgia; D, Saskatchewan River modified from Pérez-Arlucea and Smith, 1999) show that crevasse-splays can be prone to forming multiple times at the juncture between a tributary and river channel. An examination of sediments from two episodes of crevassing at Big Creek (C, top) shows a nearly perfect miniature version of Bone Butte crevasse-splay deposits (C, bottom).

avulsive events along Big Creek in Georgia confirm that the frequency of crevasse-splay occurrence can be higher where a tributary meets a larger channel, as crevasse-splays formed at the same tributary-creek junctions during two separate flooding events (Fig. 4.33 B). The crevasse-splay deposits from both events rested atop each other and were a nearly perfect miniature model of what was observed at bone Butte (Fig. 4.33 C). Big Creek's levees were

interrupted by the tributaries, which formed an area of weak resistance to flooding, and promoted the repeated formation of crevasse-splays during times of increased water flow. A similar situation is seen along the Saskatchewan River in Canada, in which an avulsive event in the 19th century produced a crevasse-splay at the juncture between the river's active channel and one of its former channels (Pérez-Arlucea and Smith, 1999; Fig. 4.33 D).

Experimental and real-world observations demonstrate that a tributary's junction with a larger river channel likely was the cause of repeated crevasse-splays from the same point of origin in the Bone Butte area. As Stream A, already known to have been present in the area, is suspected to have made a secondary connection with a larger river (see Tributary and Oxbow section above), the most parsimonious theory would posit that Stream A's breach of the river channel levee created an area of weak resistance that led to multiple successive crevasse-splays over time.

4.2.3. Sequence of Site-Forming Events

The formation of Bone Butte began as rivers from the western upland Lancian deposits, transporting water eastward toward the remnants of the Western Interior Seaway, were met by smaller southeast-flowing streams draining water from the northern territories (Belt et al., 1997; Murphy et al., 2002; Bartlett, 2004). A main river channel just south of Bone Butte ran in an easterly direction toward the seaway. As indicated by selachian fossils and other partially marine vertebrates from Bone Butte, the seashore was very close to the Bone Butte locality (Wroblewski, 2004), probably not farther than 16 km, much closer than the ~110 km suggested by some previous studies (Gill and Coban, 1973; Kennedy et al., 1998; Murphy et al., 2002; Cochran et al., 2003; Bartlett, 2004). Stream A, a tributary of the river, ran in a southeasterly

direction and contacted the river some distance downstream of Bone Butte (Fig. 4.34 A). A localized autochthonous fauna lived in the circum-riparian gymnosperm-dominated environment

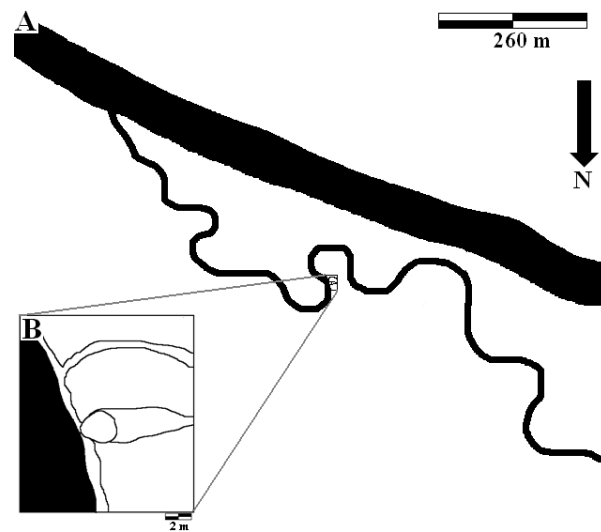


Figure 4.34. A reconstruction of the Bone Butte river system, showing a meandering tributary feeding into a larger river. The area represented by the Bone Butte site is shown enlarged in (B).

associated with the tributary and river, while a separate allochthonous fauna, situated upstream, occupied a more widespread angiosperm-dominated landscape. Over time, the recumbent meanders of the tributary formed oxbows and oxbow lakes, one of which existed at the Bone Butte site (Fig. 4.34 B). Hydrophilic plants such as horsetails and *Pistia sp.* “water lettuce” formed ideal habitats for the small reptiles, amphibians, birds, mammals, and small dinosaurs that lived near the tributary and oxbow regions, while larger gymnosperms provided cover and food for the larger vertebrates in the local assemblage. One of the tributary’s meanders migrated toward the main river channel southwest of Bone Butte, nearly isolating Bone Butte in a large tract of land between the river and tributary, and forcing terrestrial animals to use a narrow spit of land for ingress and egress (Fig. 4.35 A, Fig. 4.36 A). Just as the quasi-quiescent tributary and isolated oxbow at Bone Butte were ideal places for turtles and crocodilians to breed, the isolated

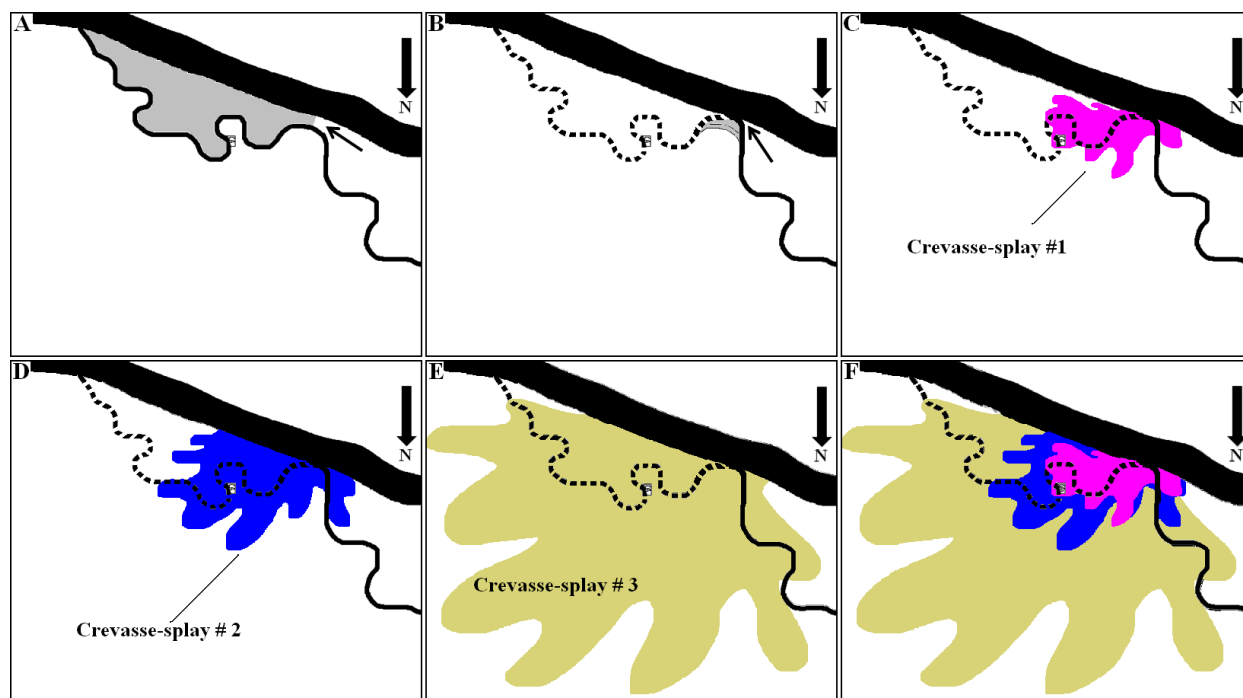


Figure 4.35. A sequence of site-forming events at Bone Butte. A meander from the tributary migrated close to the main river (A), isolating a tract of land (gray shaded area) and allowing access to it only via a small spit of land (bold arrow). The meander migrated closer to the river until they merged (B), making a secondary connection between the tributary and river (bold arrow), which initiated the abandonment of the tributary's downstream portion (dashed line). The first crevasse-splay event occurred at the area of the river weakened by the tributary's secondary connection (C). Two additional crevasse-splays (D, E) emanated from the same weakened point. The three crevasse-splays are seen superimposed upon each other in (F).

tract of land between the tributary and river could have provided a somewhat isolated and safe environment to small dinosaurs during nesting season. At some point, perhaps influenced by increased water flow created by a storm event, the meander fully eroded away a portion of the river's levee and the tributary joined with the river upstream of the tributary's primary outflow point. This event caused a gradual abandonment of the tributary downstream (Fig. 4.35 B, Fig. 4.36 B), and also weakened the river's levee system. Less than a year later, the first of three crevasse-splays emanated from the new juncture between the tributary and river, covering the abandoned section at Bone Butte in a layer of sediment that extended at least 260 m from its

point of origin at the river (Fig. 4.35 C, Fig. 4.36 C). At a later point in time, short enough to preclude soil formation but long enough to permit the growth of sparse vegetation, an even larger crevasse-splay, originating from the same point as the first, covered Bone Butte with sediment and extended at least 280 m from its point of origin (Fig. 4.35 D, Fig. 4.36 D). The second crevasse-splay carried with it vertebrate remains that were primarily allochthonous in origin, representing animals and plants that were transported from upstream in the river system. The composition of this assemblage varied slightly from the composition of the allochthon described from the coeval Sandy site (Bartlett, 2004), situated less than 64 km to the west, and the Bone Butte allochthon likely originated from some area between the Sandy and Bone Butte localities. Sediments from the second crevasse-splay rested undisturbed for a period of time comparable to that between the first and second crevasse-splays, after which a third crevasse-splay, larger than either of the previous two, covered Bone Butte with additional sediment and bones (Fig. 4.35 E, Fig. 4.36 E). An additional assortment of vertebrate and plant fossils, similar in composition to that in the second crevasse-splay, was left by the third. This final crevasse-splay emanated from the same point as the first two and extended the furthest, at least 1.7 km. Other massive cross-bedded fluvial deposits that were beyond the temporal limits of this study were eventually deposited atop the last crevasse-splay sediments.

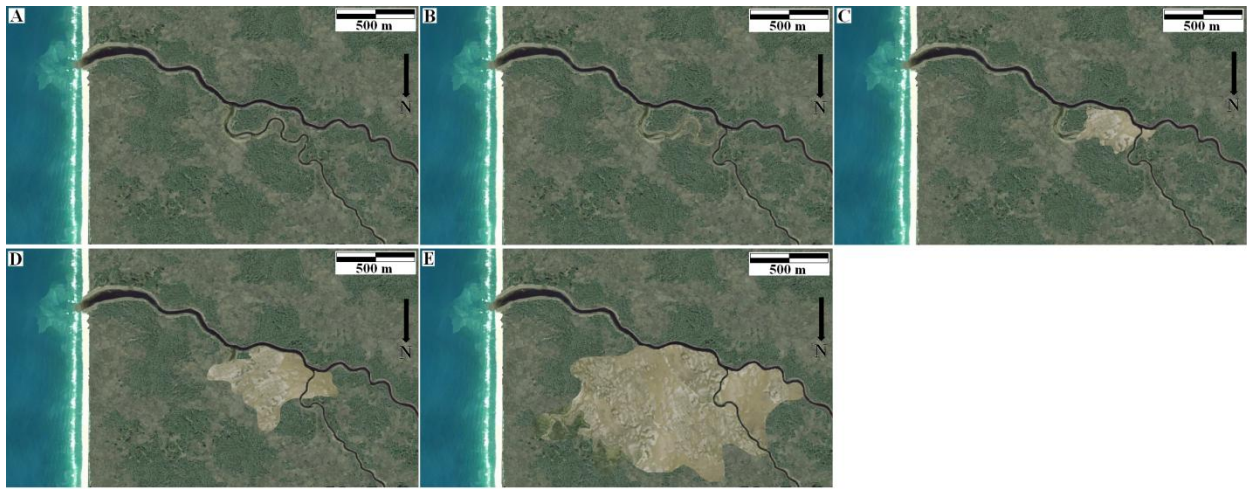


Figure 4.36. Simulated aerial views of the Bone Butte area, depicting the tributary feeding the main channel (A), abandonment of a portion of the tributary following a secondary connection with the main channel (B), and three successive crevasse-splays that originated at the point of the tributary's secondary connection (C-E).

CHAPTER 5

CONCLUSION

5.1 The Bone Butte Strata and Fossil Assemblage

The formation of the Bone Butte fossil assemblage is the result of geomorphologic processes in an ancient fluvial system that emptied into the Western Interior Seaway. A small tributary feeding a larger trunk channel was the setting in which a local, autochthonous dinosaur fauna existed. Although the trunk channel was not preserved at Bone Butte, its signature, in the form of multiple crevasse-splays, was evident. Based on the presence of organisms normally associated with marine deposits, such as orectolobid sharks and marine crocodiles, the shoreline of the Western Interior Seaway was recognized to be significantly closer to Bone Butte than estimated by previous studies (perhaps less than 10 km). Bones from a more ubiquitous,

allochthonous dinosaur fauna of distinct composition were introduced into the river system some distance upstream from Bone Butte. Massive flooding events caused the formation of crevasse-splays, bringing a huge volume of sediment and bones from the trunk channel to the northeast, covering the tributary and adjacent oxbow lake deposits, and introducing exotic organisms to the Bone Butte local fauna.

5.2 The Bone Butte Biocoenosis and Paleoenvironment

Taphonomic characteristics, including levels of bone abrasion, completeness, and sorting, revealed the distinction between allochthonous bones transported from upstream, and a more pristine autochthonous group of bones that was deposited more or less *in situ*. The autochthonous group is different in composition than the usual faunal reconstructions of the Hell Creek fauna, characterized by animals that are typically uncommon in the Hell Creek Formation – small herbivorous dinosaurs such as pachycephalosaurs and thescelosaurus, small theropods, and a higher percentage of ornithurine birds. The autochthons lived in a localized circum-riparian habitat that was overgrown with gymnosperm trees and hydrophilic plants such as horsetails and water cabbage. The allochthons, however, lived in an area rich in angiosperms, and comprised of a more traditional fauna common in previously described reconstructions of the Hell Creek Formation – the most common of which were ceratopsians, tyrannosaurs and hadrosaurs. Bartlett (2004) examined taphonomic characteristics of fossil assemblages, revealing the presence of a heterogeneous faunal mosaic in the Hell Creek Formation, as opposed to a homogenous blanket fauna suggested by previous workers. Bartlett (2004) speculated that the Hell Creek Formation could have been composed of a broad, background fauna typical in composition to traditional reconstructions, which was punctuated by a number of localized faunas, forming a faunal mosaic. The Bone Butte study reinforces the validity of Bartlett's speculation and, furthermore,

demonstrates an eastward variation in the background and localized faunas with proximity to the paleoshoreline.

Laminae in the stream channel and oxbow lake deposits indicate an annual oscillation in rainfall consistent with a submonsoonal, subtropical environment, and paleobotanical data indicates that the wettest time of the year was between the mid-summer and fall, followed by seasonal fires. Mats of deciduous conifer needles (found at regular intervals) were formed during the coldest months and are further indication that the Bone Butte paleoenvironment was seasonal. The finely detailed chronology of the site also enabled the reconstruction of vertebrate breeding seasons and maturation rates. Spikes in the abundance of turtle and crocodilian hatchlings were observed at regular intervals and indicate a common breeding season toward the height of the dry season and beginning of the wet season. Although no dinosaurian hatchling bones were recovered, a similar trend in breeding seasons was observed among the dinosaurs. The presence of medullary bone, a type of bone present in birds and some dinosaurs only during breeding season, was observed in pachycephalosaurs, thescelosaurs, and ornithomimids – the first time reported in these three dinosaur taxa. Medullary bone deposits occurred in bones at specific stratigraphic intervals roughly coinciding with the turtle and crocodilian breeding seasons, indicating that breeding and egg-laying for the dinosaurs was occurring at the same general time of year. Dinosaurian eggshell fragments suggest that nesting was occurring near Bone Butte, although far enough from the site that eggs and hatchling bones were not found at this site. Tracking the ratios of the ornithomimid and thescelosaur ontogenetic stages present at various stratigraphic intervals allowed a reconstruction of the maturation process, showing that adult sizes were attained in a little over one year.

In addition, dinosaur diversity at Bone Butte was high, similar to that seen in the Bartlett (2004) study, and demonstrates that dinosaurian diversity was not in decline at the end of the Cretaceous. Evidence of flourishing plant life, insects, and vertebrates at Bone Butte is suggestive of a thriving ecosystem that was not impoverished or struggling. The data collected demonstrate that the environment did not undergo gradual deterioration with proximity to the K-T extinction, thereby making a cataclysmic event a more likely explanation.

5.3 Future Work

The Bone Butte study has increased our understanding of animal behavior, the composition of paleocommunities, and the paleoenvironments during the Late Cretaceous. Efforts to augment the results of the Bone Butte study, and the engagement in new, innovative studies of the Hell Creek Formation, are essential to better understanding the last moments of the Maastrichtian and the transition into the Tertiary.

In the Bartlett (2004) study of the Sandy site, it was suggested that the conditions leading to good preservation and the ability to differentiate between allochthonous and autochthonous assemblages, such as those encountered in his study, were repeatable. Furthermore, it was postulated that additional examination of similar deposits could augment the results of his study, and help provide a more detailed view of the Hell Creek Formation. The Bone Butte study demonstrates this, and used data from a site with a similar depositional history to that of Sandy, revealing a similar yet not identical set of dinosaur populations. The Bone Butte study has confirmed some of Bartlett's suppositions about the existence of a Hell Creek faunal mosaic, while revealing the variation in background and localized faunal composition that occurred with proximity to the paleoshoreline. Further examination of similar deposits can help to refine our current knowledge and provide a more detailed paleoecological reconstruction for the Upper

Cretaceous of North America. Bone Butte has also demonstrated that certain stream channel and oxbow lake deposits can preserve an unprecedented level of temporal resolution, and the location and examination of similar deposits, in a manner similar to that carried out in the Bone Butte study, could have a profound effect on our understanding of the Late Cretaceous and other time periods. Such a study would be of particular importance if it sampled across the Cretaceous-Tertiary boundary, recording virtually moment-by-moment detail over a short period of time during the end Cretaceous extinction, and perhaps increasing our knowledge of circumstances surrounding this transition.

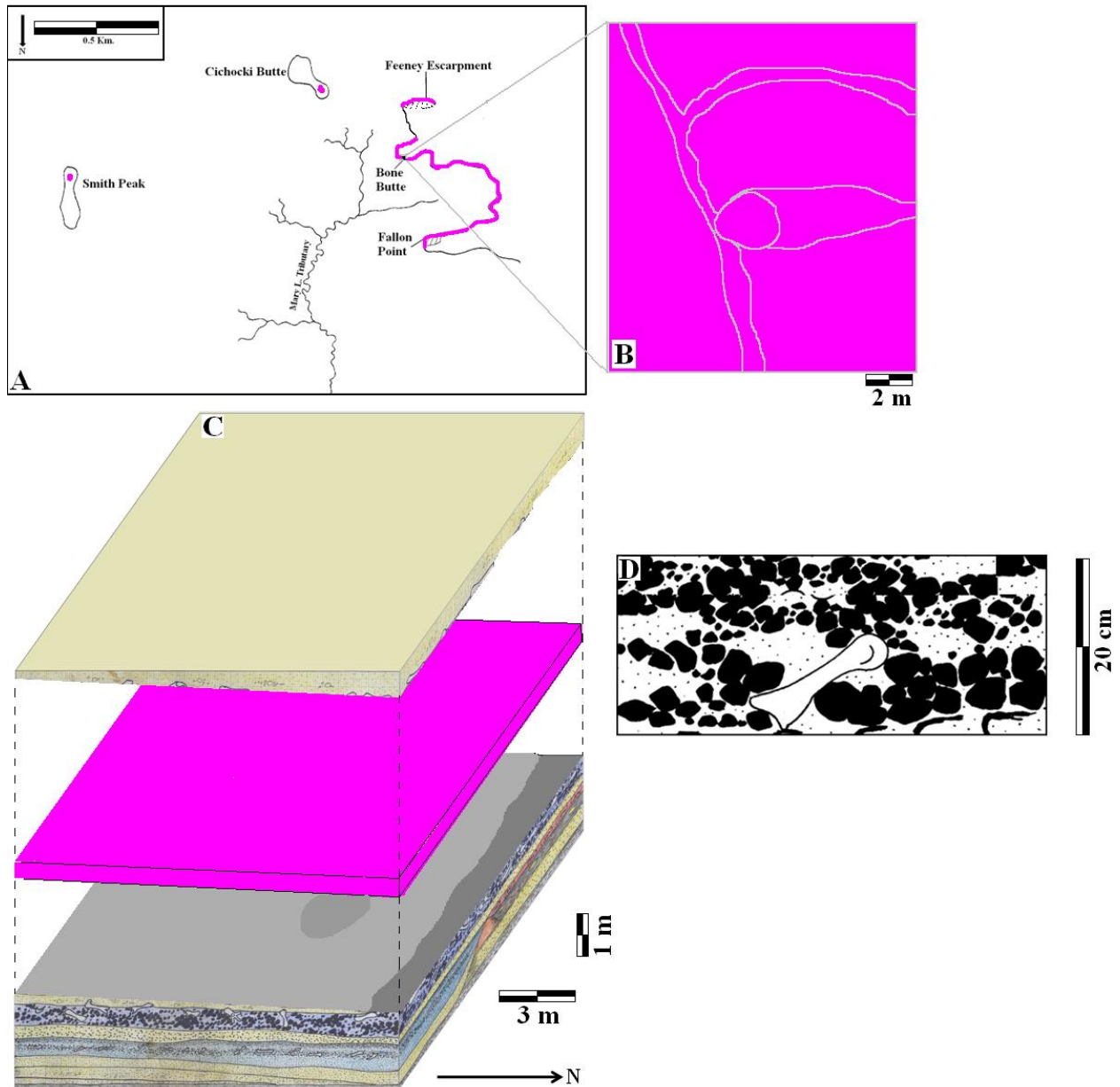
Discoveries in Bone Butte amber have added to the list of Hell Creek insects by an order of magnitude. Future studies may uncover additional information that would have an impact on our understanding of insect-plant and insect-animal interactions, as well as the paleoclimate. New methods of processing the amber, such as embedding the specimens in epoxy resin before polishing, should minimize damage to the specimens and increase their durability. Further study of the Bone Butte insects is recommended, in addition to bulk collection of amber specimens from the study area in an effort to locate more specimens.

The Bone Butte study has demonstrated that it can be possible to study the relative magnitude of individual paleo-rainstorms, and possibly storm-associated seasonal fires, by examining stream channel deposits that exhibit good temporal resolution. Further analysis of the annual rain cycle at Bone Butte, as well as locating a similar record at other locations, can provide insight into minute details of paleoclimatology and paleometeorology. The information gained from such studies could significantly fine-tune our knowledge of climates millions of years before the present.

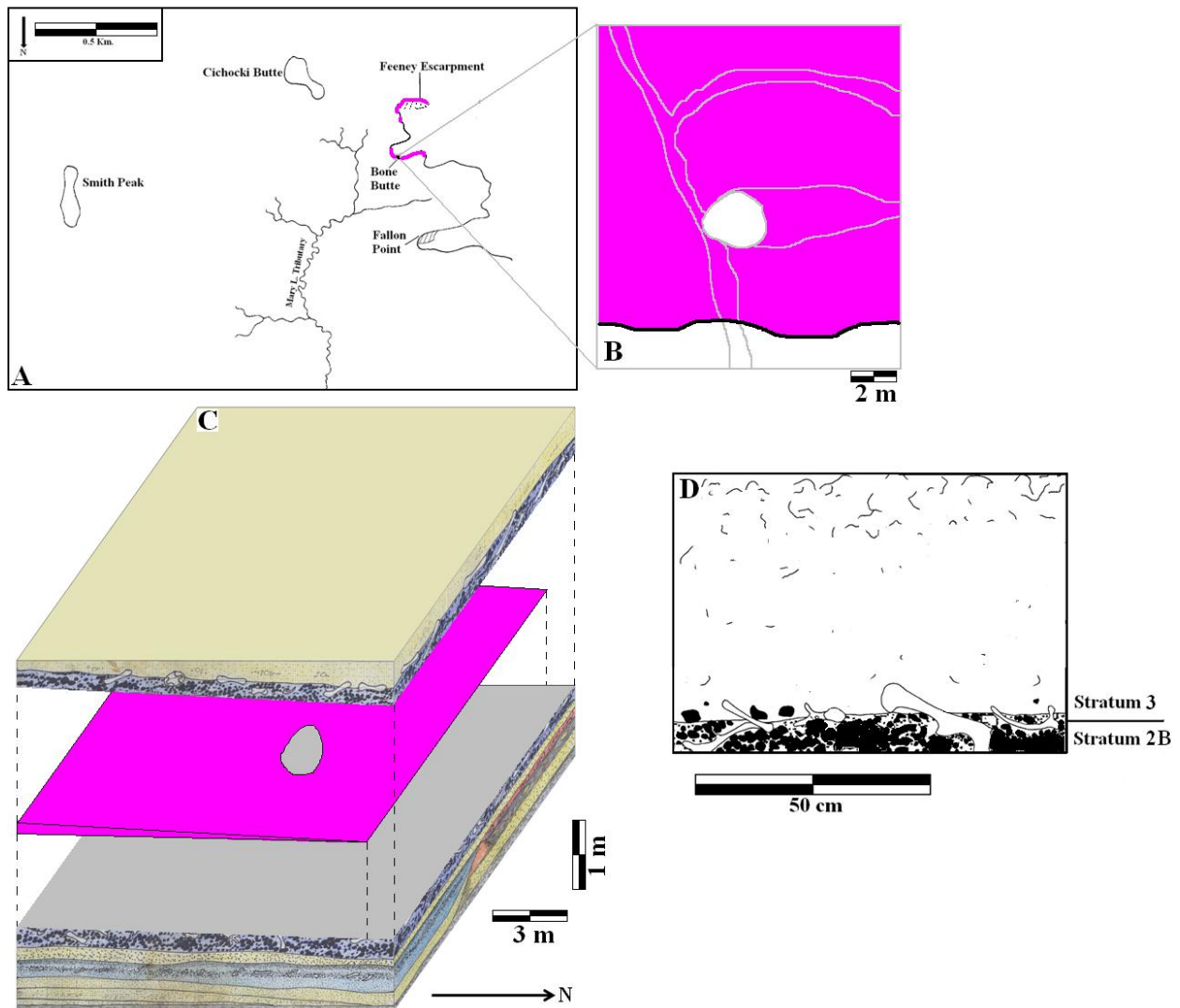
APPENDICES

Appendix A

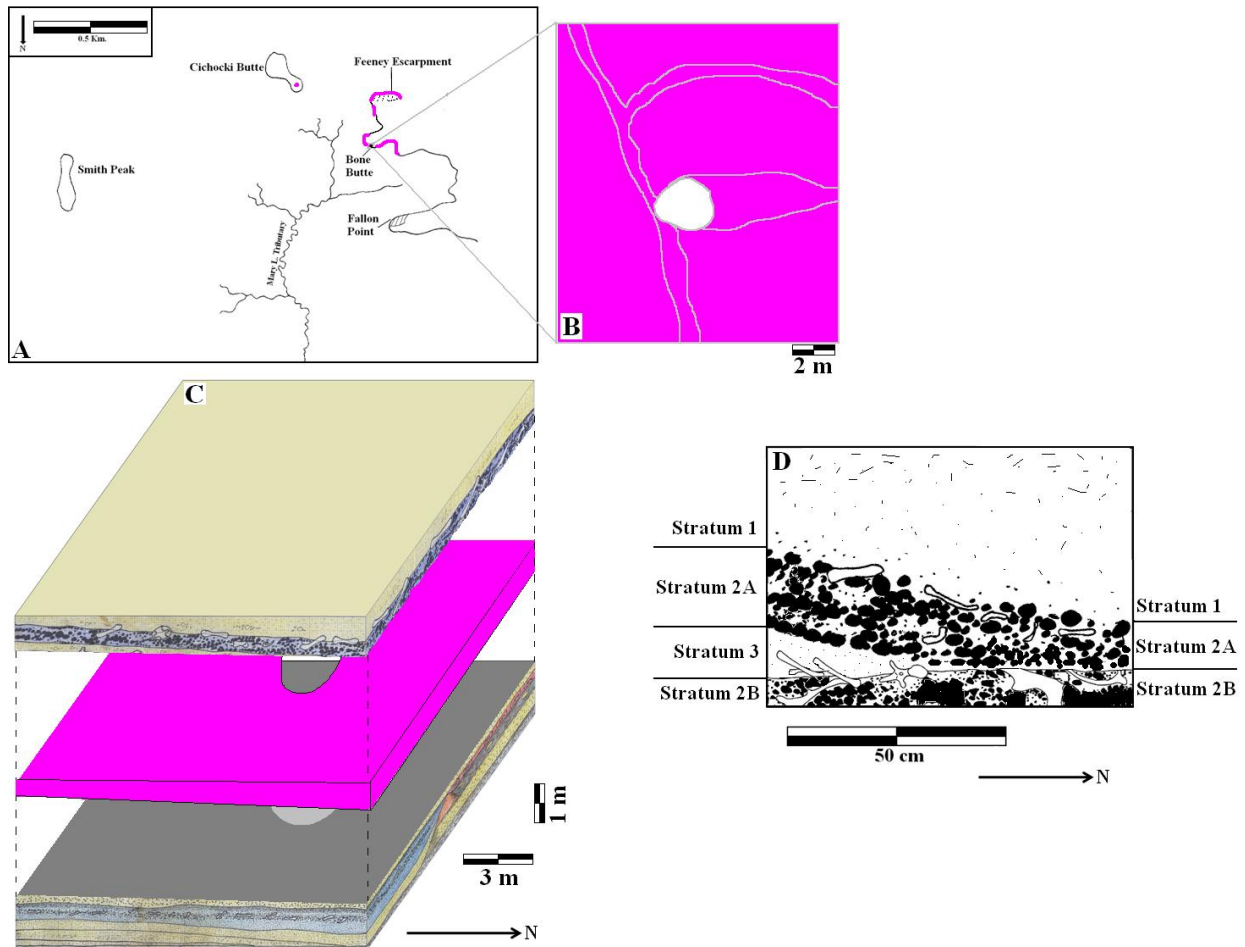
Appendix A1. Data for Stratum 2A. The lateral extent of Stratum 2A can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C). A profile of the stratum can be seen in (D).



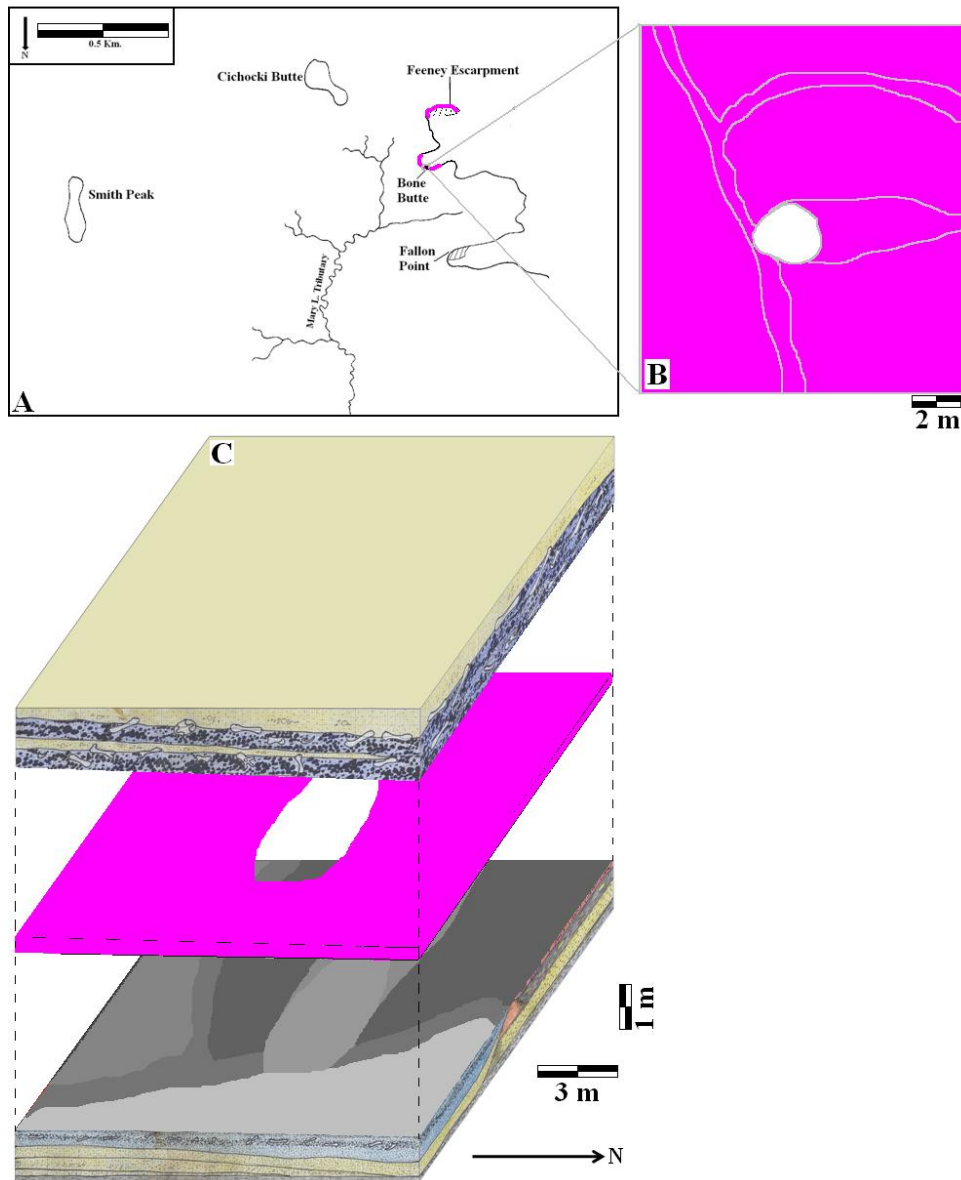
Appendix A2. Data for Stratum 3. The lateral extent of Stratum 3 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C). A profile of the stratum can be seen in (D).



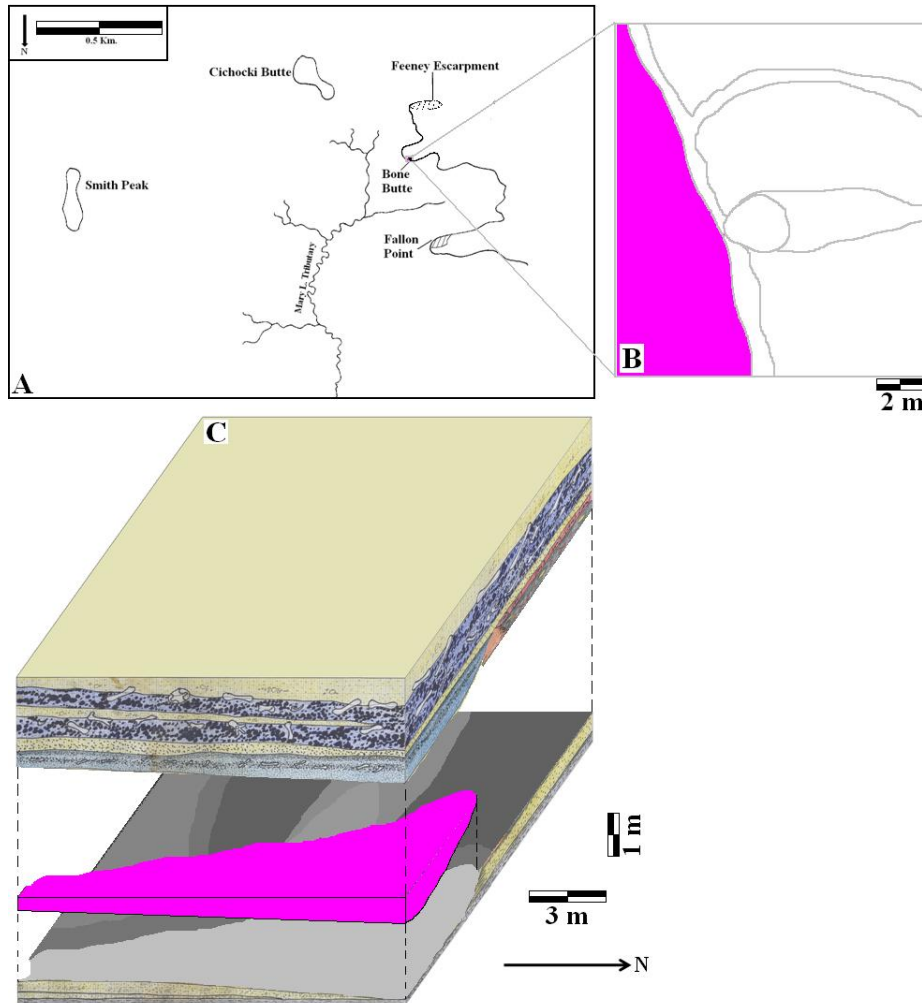
Appendix A3. Data for Stratum 2B. The lateral extent of Stratum 2B can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C). A profile of the stratum in (D) shows how bones protruding from the upper margin of Stratum 2B were sheared off when in contact with Stratum 2A.



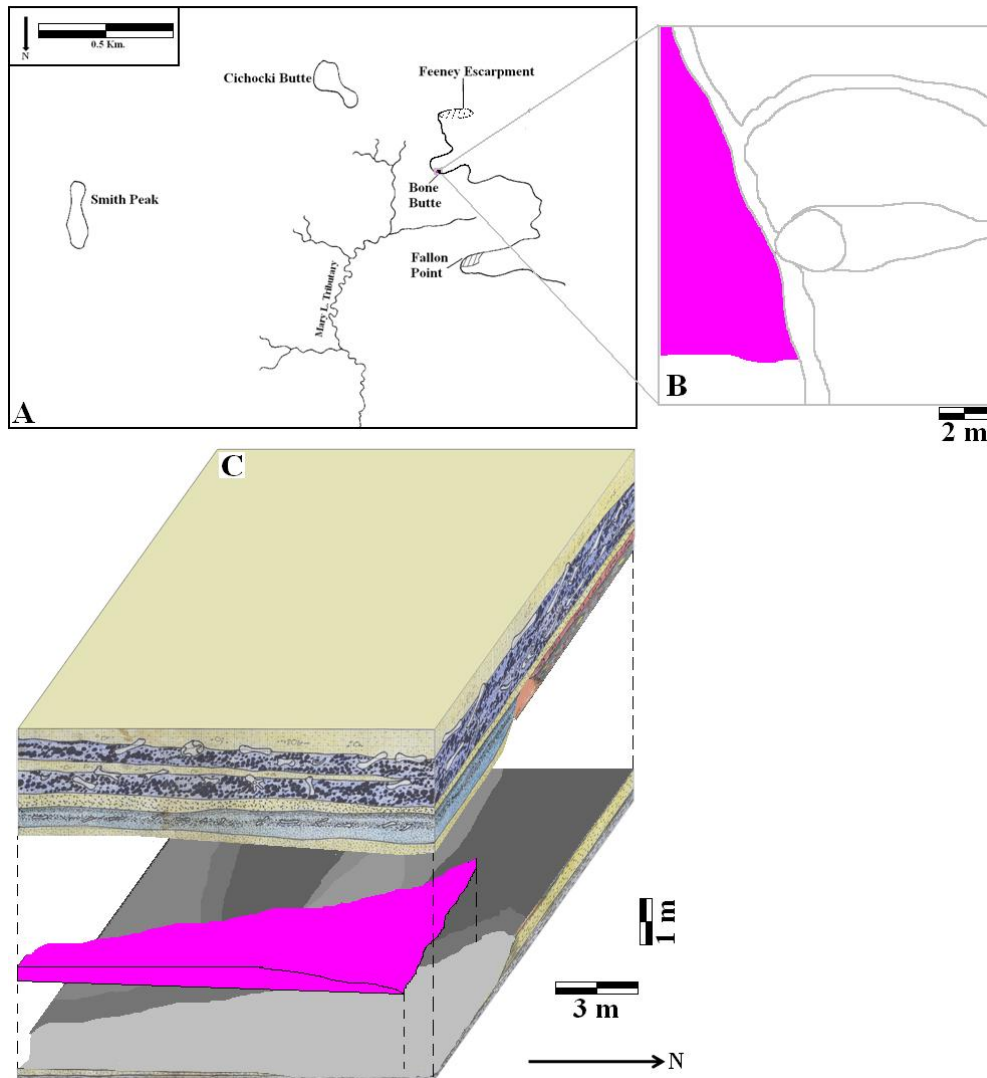
Appendix A4. Data for Stratum 4. The lateral extent of Stratum 4 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C).



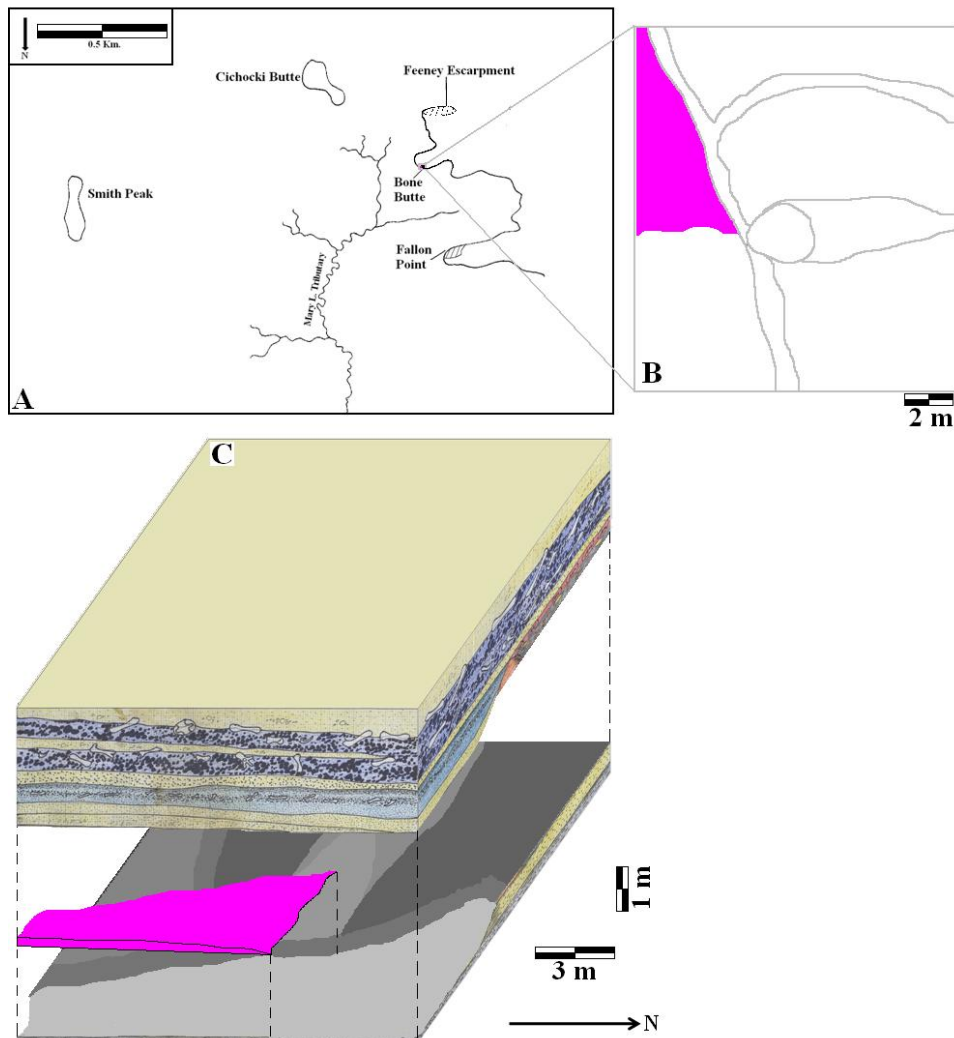
Appendix A5. Data for Stratum 6. The lateral extent of Stratum 6 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C).



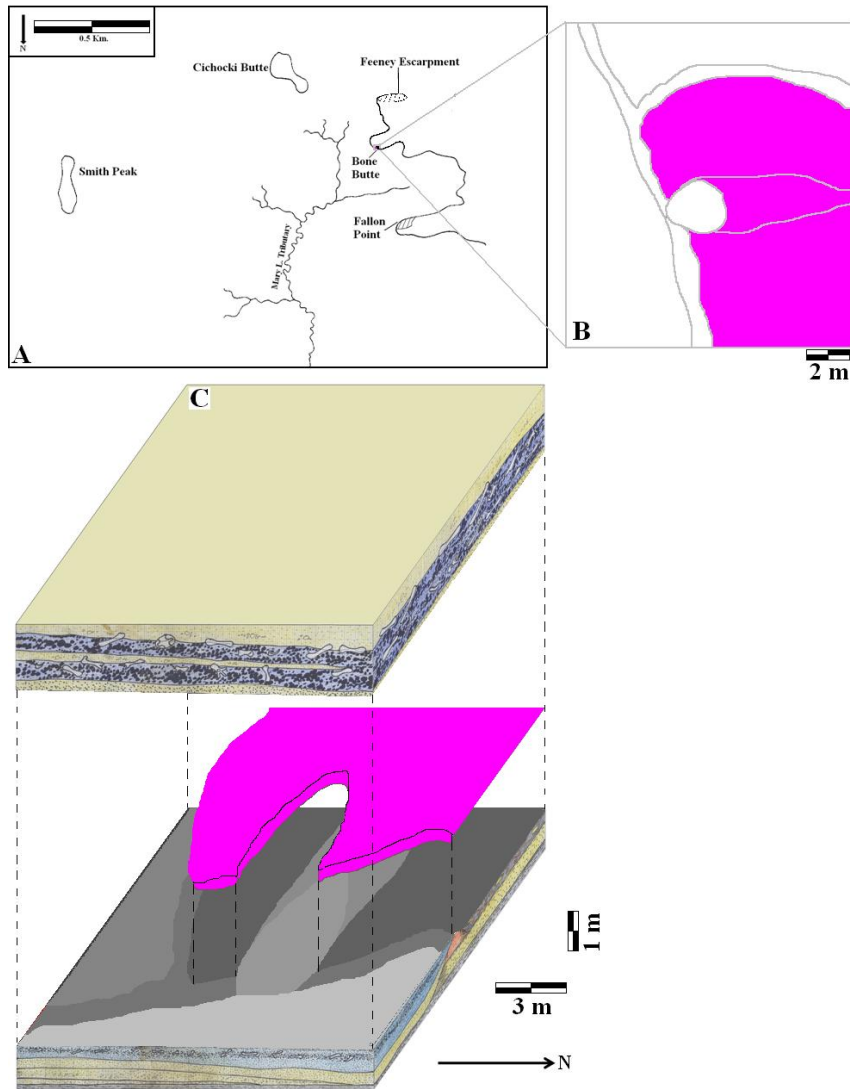
Appendix A6. Data for Stratum 7. The lateral extent of Stratum 7 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C).



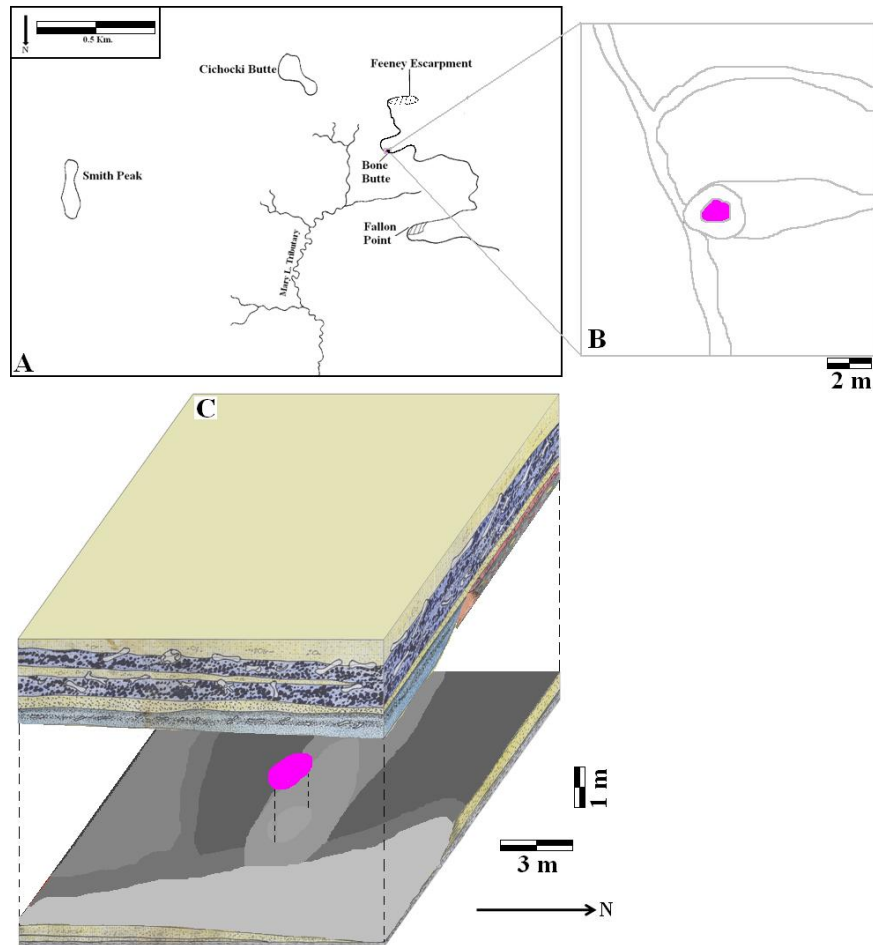
Appendix A7. Data for Stratum 9. The lateral extent of Stratum 9 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C).



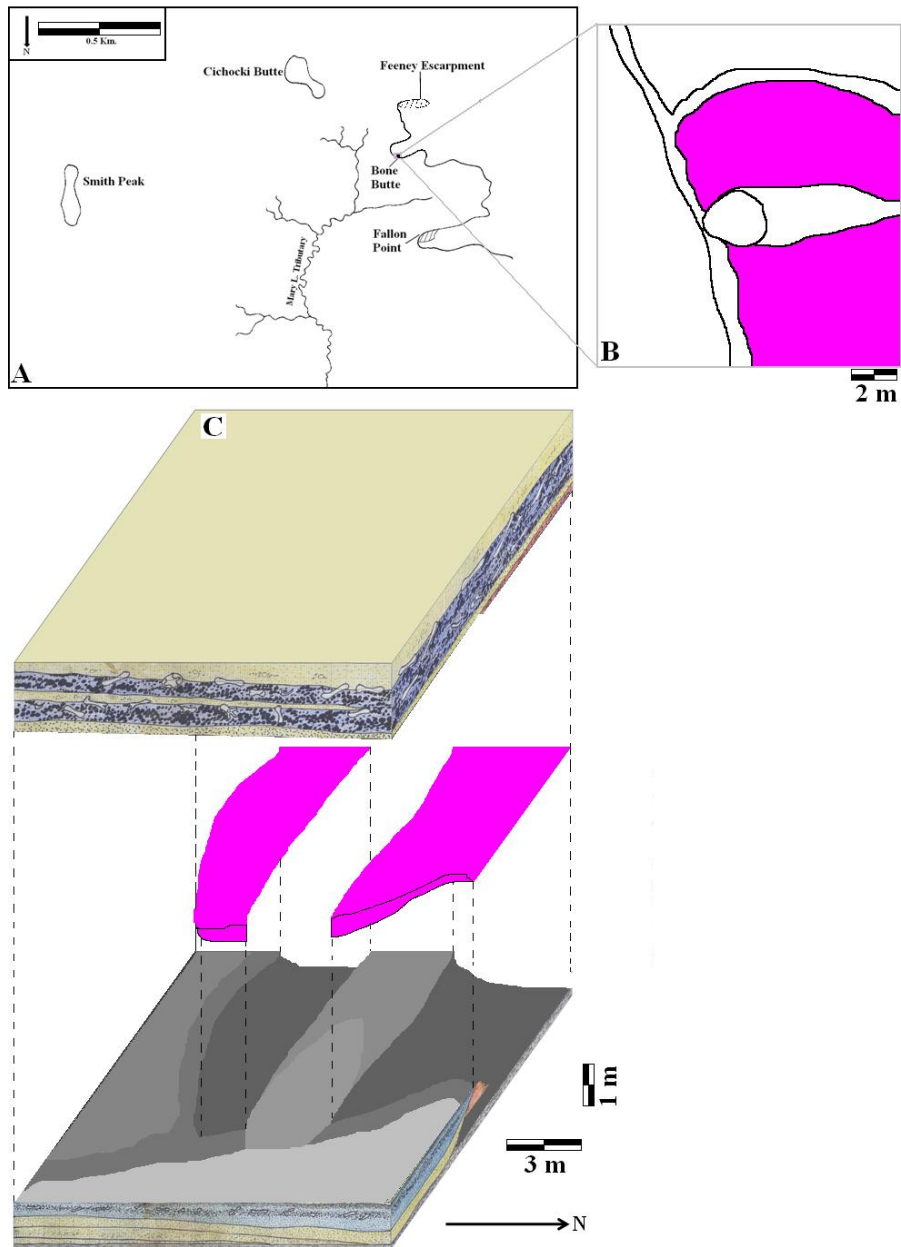
Appendix A8. Data for Stratum 12. The lateral extent of Stratum 12 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C).



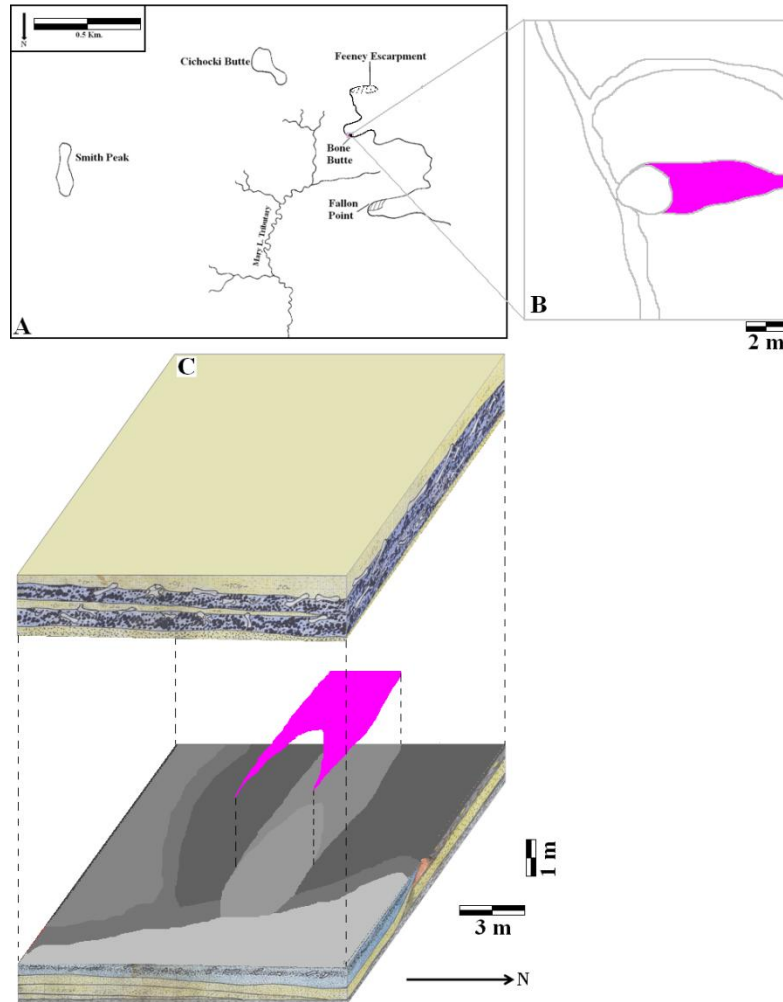
Appendix A9. Data for Stratum 14. The lateral extent of Stratum 14 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C).



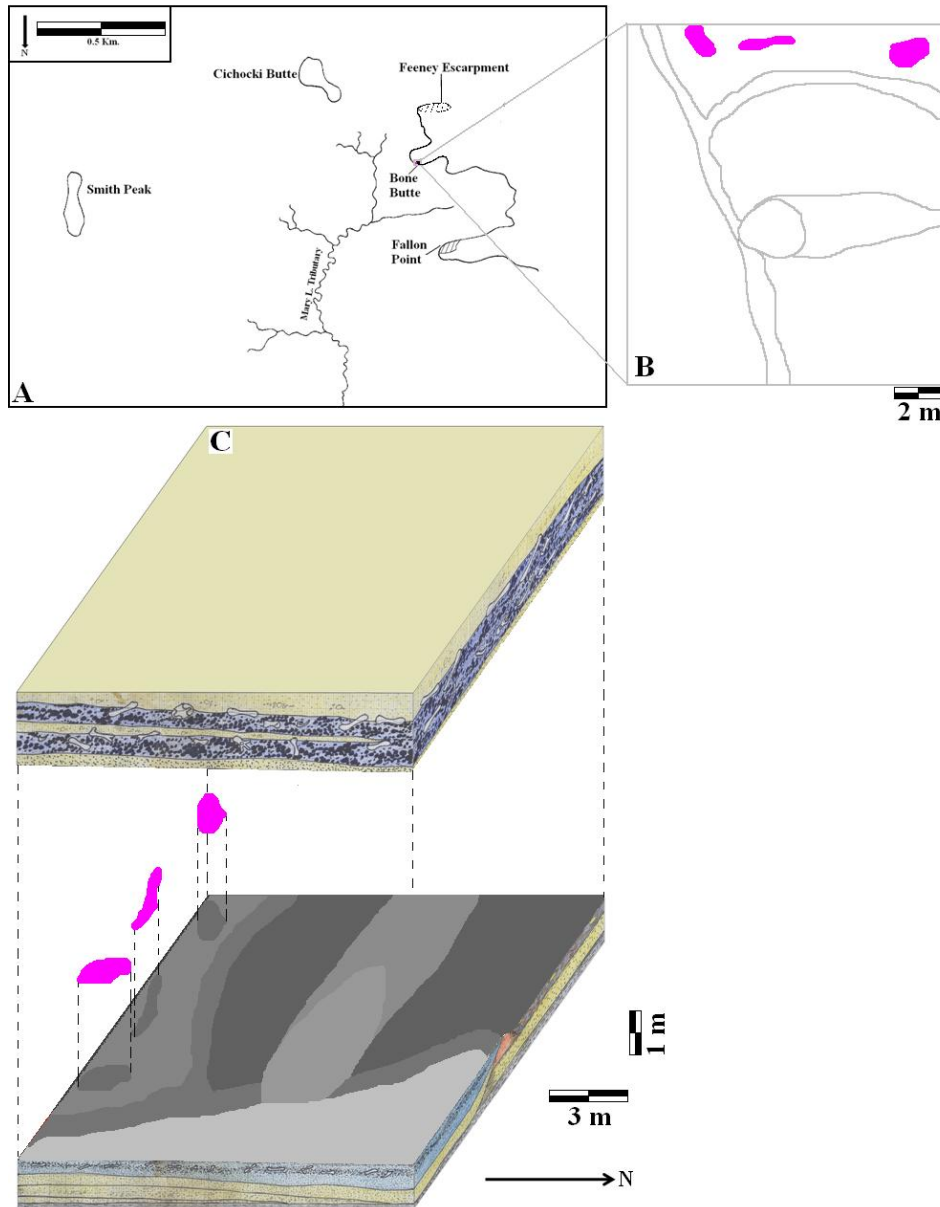
Appendix A10. Data for Stratum 15. The lateral extent of Stratum 15 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C).



Appendix A11. Data for Stratum 16. The lateral extent of Stratum 16 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C).



Appendix A12. Data for Stratum 17. The lateral extent of Stratum 17 can be traced in (A) and (B), and its position in the Bone Butte stratigraphic column can be observed in (C).



Appendix B

Appendix B1. Faunal percentages at Bone Butte calculated using only skeletal elements (left side of column), and with teeth included in the calculation (right side of column).

	<u>Stratum 2</u>		<u>Bird/Mammal Zone</u>		<u>Oxbow Lake</u>	
	<u>Alloch.</u> (87% of stratum total)	<u>Autoch.</u> (13% of stratum total)	<u>Alloch.</u> (25% of stratum total)	<u>Autoch.</u> (75% of stratum total)	<u>Alloch.</u> (29% of stratum total)	<u>Autoch.</u> (71% of stratum total)
	% of Alloch.	% of Autoch.	% of Alloch.	% of Autoch.	% of Alloch.	% of Autoch.
Dinosauria	45%	38%	43%	35%	45%	18%
Other	40%	47%	45%	55%	44%	72%
Unidentified	15%	15%	12%	10%	11%	10%
Dinosaurs						
	NT ----- T	NT ----- T	NT ----- T	NT ----- T	NT ----- T	NT ----- T
Pachycephalosaurs	/ - /	24% - 25%	/ - /	30% - 35%	/ - /	32% - 34%
Thescelosaurs	/ - /	19% - 21%	/ - /	20% - 13%	/ - /	18% - 13%
Oviraptors	11% - 7%	/ - /	11% - 6%	/ - /	6% - 4%	/ - /
Small Theropods	<1% - 1%	29% - 32%	/ - 1%	24% - 29%	/ - 4%	29% - 38%
Tyrannosaurs	15% - 16%	/ - /	14% - 18%	/ - 1%	19% - 21%	/ - /
Hadrosaurs	23% - 24%	/ - 2%	25% - 24%	<1% - 2%	25% - 25%	/ - 1%
Ceratopsians	36% - 43%	/ - /	42% - 46%	/ - /	44% - 42%	/ - /
Ornithomimids	10% - 6%	28% - 19%	8% - 4%	26% - 20%	6% - 4%	21% - 14%
Ankylosaurs	<1% - 1%	/ - /	/ - 1%	/ - /	/ - /	/ - /

Appendix B2. Percentages of adults, subadults, and juveniles among dinosaur taxa at Bone Butte. The percentages of dinosaurs that had medullary bone are also shown.

	<u>Stratum 2</u>		<u>Bird/Mammal Zone</u>		<u>Oxbow Lake</u>	
	<u>Alloch.</u>	<u>Autoch.</u>	<u>Alloch.</u>	<u>Autoch.</u>	<u>Alloch.</u>	<u>Autoch.</u>
% Adult						
Dinosaurs						
Pachycephalosaurs	/ - /	63%	/ - /	63%	/ - /	62%
Thescelosaurus	/ - /	64%	/ - /	62%	/ - /	65%
Small Theropods	72%	74%	70%	73%	74%	71%
Tyrannosaurs	100%	/ - /	100%	50%	100%	/ - /
Hadrosaurs	61%	64%	63%	64%	62%	66%
Ceratopsians	89%	/ - /	85%	/ - /	88%	/ - /
Ornithomimids	69%	66%	65%	65%	100%	64%
Ankylosaurs	100%	/ - /	100%	/ - /	/ - /	/ - /

	<u>Stratum 2</u>		<u>Bird/Mammal Zone</u>		<u>Oxbow Lake</u>	
	<u>Alloch.</u>	<u>Autoch.</u>	<u>Alloch.</u>	<u>Autoch.</u>	<u>Alloch.</u>	<u>Autoch.</u>
% Subadult						
Dinosaurs						
Pachycephalosaurs	/ - /	24%	/ - /	25%	/ - /	21%
Thescelosaurus	/ - /	25%	/ - /	28%	/ - /	14%
Small Theropods	28%	26%	30%	27%	26%	29%
Tyrannosaurs	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /
Hadrosaurs	39%	36%	37%	36%	38%	20%
Ceratopsians	11%	/ - /	15%	/ - /	12%	/ - /
Ornithomimids	31%	20%	35%	21%	/ - /	14%
Ankylosaurs	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /

	<u>Stratum 2</u>		<u>Bird/Mammal Zone</u>		<u>Oxbow Lake</u>	
	<u>Alloch.</u>	<u>Autoch.</u>	<u>Alloch.</u>	<u>Autoch.</u>	<u>Alloch.</u>	<u>Autoch.</u>
% Juvenile	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /
Dinosaurs						
Pachycephalosaurs	/ - /	13%	/ - /	12%	/ - /	17%
Thescelosaurs	/ - /	11%	/ - /	10%	/ - /	21%
Small Theropods	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /
Tyrannosaurs	/ - /	/ - /	/ - /	50%	/ - /	/ - /
Hadrosaurs	/ - /	/ - /	/ - /	/ - /	/ - /	14%
Ceratopsians	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /
Ornithomimids	/ - /	14%	/ - /	14%	/ - /	22%
Ankylosaurs	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /

	<u>Stratum 2</u>		<u>Bird/Mammal Zone</u>		<u>Oxbow Lake</u>	
	<u>Alloch.</u>	<u>Autoch.</u>	<u>Alloch.</u>	<u>Autoch.</u>	<u>Alloch.</u>	<u>Autoch.</u>
% with medullary bone						
Dinosaurs						
Pachycephalosaurs	/ - /	59%	/ - /	61%	/ - /	58%
Thescelosaurs	/ - /	45%	/ - /	43%	/ - /	49%
Small Theropods	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /
Tyrannosaurs	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /
Hadrosaurs	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /
Ceratopsians	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /
Ornithomimids	/ - /	58%	<1%	56%	/ - /	60%
Ankylosaurs	/ - /	/ - /	/ - /	/ - /	/ - /	/ - /

Appendix B3. Complete faunal and floral list for Bone Butte.

Flora and Fauna from Bone Butte		
Major clade	Genus and species	Comments
Pelecypoda	<i>Sphaerium beckmani</i>	“Pill clam”
Gastropoda	<i>Campeloma</i> sp.	Fresh water snail
	<i>Pachymelania</i> sp.	Marine snail
Mammalia	<i>Mesodma</i> sp.	Multituberculate mammal
	<i>Cimolodon</i> sp.	Multituberculate mammal
	<i>Cimolomys gracilis</i>	Multituberculate mammal
	<i>Meniscoessus robustus</i>	Multituberculate mammal
	<i>Alphadon</i> sp.	Metatherian mammal
	<i>Glasbius twitchelli</i>	Metatherian mammal
	<i>Pedimys</i> sp.	Metatherian mammal
	<i>Didelphodon vorax</i>	Metatherian mammal
	<i>Didelphodon padanicus</i>	Metatherian mammal
	<i>Cimolestes</i> sp.	Eutherian mammal
Elasmobranchii	<i>Lissodus selachos</i>	Hybodont shark
	<i>Squatirhina americana</i>	Orectolobid shark
	<i>Cretorectolobus</i> sp.	Orectolobid shark
	Orectolobidae indet.	
	<i>Ischyrhiza avoncola</i>	Sawfish ecomorph
	<i>Myledaphus bipartitus</i>	Batoid shark
Osteichthyes	<i>Paleopsephurus wilsoni</i>	Paddlefish

	<i>Melvius thomasi</i>	Amiid
	<i>Kindleia fragosa</i>	Amiid
	<i>Phyllodus paulkatoi</i>	
	<i>Lepisosteus occidentalis</i>	Gar
Amphibia	<i>Albanerpeton nexuosus</i>	Salamander
	<i>Opisthotriton kayi</i>	Salamander
	<i>Scapherpeton tectum</i>	Salamander
	<i>Lisserpeton bairdi</i>	Salamander
	<i>Habrosaurus dilatus</i>	Salamander
	<i>Scotiophryne pustulosa</i>	Frog
Reptilia	<i>Plesiobaena antiqua</i>	Baenid turtle
	" <i>Clemmys</i> " <i>backmani</i>	Turtle
	<i>Basilemys sinuosa</i>	Dermatemydid, tortoise ecomorph
	Kinosternidae indet.	Turtle
	<i>Trionyx</i> sp.	Trionychid turtle
	<i>Compsemys victa</i>	Baenid turtle
	<i>Champsosaurus</i> sp.	Choristoderan crocodile ecomorph
	<i>Leptochamops denticulatus</i>	Teiid lizard
	<i>Chamops segnis</i>	Teiid lizard
	<i>Parasaniwa wyomingensis</i>	Necrosaurid lizard
	" <i>Leidyosuchus</i> " <i>sternbergi</i>	Crocodylian
	<i>Brachychampsia montana</i>	Crocodylian
	<i>Thoracosaurus</i>	Marine crocodylian

	Pterosauria gen. et sp. indet.	Pterosaur
Aves	Ornithurae indet.	Ornithurine shorebird
	Ornithurae indet.	Ornithurine bird
	Ornithurae indet.	Ornithurine bird
Dinosauria	<i>Tyrannosaurus rex</i>	Tyrannosaurid
	<i>Aublysodon mirandus</i>	Tyrannosaurid
	<i>Nanotyrannus lancensis</i>	Tyrannosaurid
	<i>Ricardoestes</i>	Small theropod
	<i>Troodon formosus</i>	Small theropod
	Troodontidae indet.	Small theropod
	<i>Dromaeosaurus sp.</i>	Small theropod
	Dromaeosauridae indet.	Small theropod
	<i>Paronychodon lacustris</i>	Small theropod
	<i>Pectinodon</i>	Small theropod
	<i>Saurornitholestes</i>	Small theropod
	<i>Ornithomimus sp.</i>	Ornithomimid
	<i>Struthiomimus sp.</i>	Ornithomimid
	<i>Chirostenotes sp.</i>	Oviraptorid
	<i>Caenagnathus</i>	Oviraptorid
	<i>Thescelosaurus garbanii</i>	Thescelosaurid
	<i>Bugenasaura infernalis</i>	Thescelosaurid
	<i>Thescelosaurus neglectus</i>	Thescelosaurid
	<i>Edmontosaurus annectens</i>	Hadrosaurid
	<i>Anatotitan copei</i>	Hadrosaurid

	Hadrosauridae indet.	Crested hadrosaur
	<i>Pachycephalosaurus wyomingensis</i>	Pachycephalosaurid
	<i>Stygomoloch spinifer</i>	Pachycephalosaurid
	<i>Edmontonia</i> sp.	Ankylosaurid
	Ankylosauridae indet.	
	<i>Triceratops horridus</i>	Ceratopsian
	<i>Triceratops prorsus</i>	Ceratopsian
	<i>Torosaurus latus</i>	Ceratopsian
Plantae	<i>Cinnamomum</i> sp.	
	<i>Dryophyllum</i> sp.	
	" <i>Ficus</i> " <i>artocarpoides</i>	<i>Equisetum</i> rhizome
	" <i>Ficus</i> " <i>planicostata</i>	
	" <i>Ficus</i> " <i>ceratops</i>	<i>Equisetum</i> rhizome
	<i>Liriodendrites bradacii</i>	
	Cannabaceae indet.	
	<i>Cissites acerifolia</i>	
	<i>Erlingdorgia montana</i>	
	" <i>Zizyphus</i> " <i>fibrillosus</i>	
	<i>Marmarthia pearsonii</i>	
	<i>Metasequoia</i> sp.	
	<i>Cunninghamia</i>	
	<i>Sequoia</i> sp.	
	<i>Taxodium</i> sp.	

	<i>Dammarites</i> sp.	
	<i>Glyptostrobus</i> sp.	
	<i>Fokienopsis catenulata</i>	
	<i>Plantanites marginata</i>	
	<i>Pistia corrugata</i>	Water lettuce
	<i>Equisetum</i>	

Appendix B4.

Taphonomy Chart of Behrensmeyer (1991)

Variable	Possible manifestations at a fossil site
<u>Assemblage Data</u>	
Sample size	-----10-----100-----1000-----10,000
Number of individuals	1-----10-----100-----1000-----
Number of species	1-----10-----100-----
Relative abundance	all individuals/one species-----equal no. of individuals/species
Body size (kg)	-----5-----100-----500-----1000-----
Age spectrum	juveniles only-----50/50-----adults only
Bone articulation	articulated-----disarticulated-----associated-----isolated but associated & dispersed & dispersed
Skeletal parts	unsorted-----sorted-----one part only
<u>Quarry Data</u>	
Size of accumulation	-----1 m ² -----100 m ² -----1000m ² -----
Spatial density	-----0.1/m ² -----1/m ² -----10/m ² -----100/m ² -----
Spatial arrangement	
In plan view	random-----preferred orientation
In profile	high dips-----horizontal
Patchiness	even-----uneven-----highly patchy
<u>Bone Modification</u>	
Breakage	complete-----broken-----fragments
Cracking [Weathering according to Behrensmeyer (1978)]	(Stage 0)----- (Stage 1)----- (Stage 0-3)
Abrasion/polish	unabraded-----abraded-----highly abraded
Surface marks	none-----present-----extensive

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