PALEONTOLOGY, TAPHONOMY, AND SEDIMENTOLOGY OF THE MYGATT-MOORE QUARRY, A LARGE DINOSAUR BONEBED IN THE MORRISON FORMATION, WESTERN COLORADO—IMPLICATIONS FOR UPPER JURASSIC DINOSAUR PRESERVATION MODES

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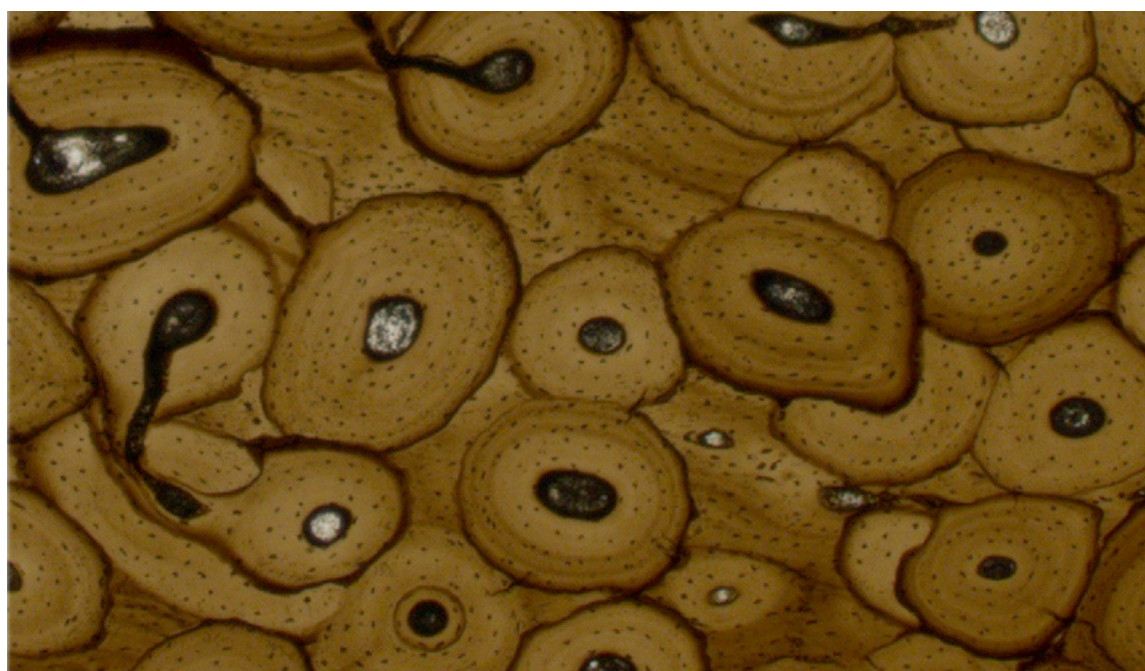
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Thin section micrograph of nearly pristinely preserved osteons from a "spongy" and almost rounded dinosaur bone fragment excavated from the Morrison Formation in the Mygatt-Moore Quarry. Micrograph image by Jane Baer (University of Utah) and John Foster (Museum of Moab).

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Paleontology, Taphonomy, and Sedimentology of the Mygatt-Moore Quarry, a Large Dinosaur Bonebed in the Morrison Formation, Western Colorado—Implications for Upper Jurassic Dinosaur Preservation Modes

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ABSTRACT

The Mygatt-Moore Quarry is a deposit of several thousand dinosaur bones in the Brushy Basin Member of the Morrison Formation in western Colorado. The site has been worked for more than 30 years and nearly 2400 mapped specimens have been collected. This study gathered data about the quarry from many sources to investigate the origin of the deposit. The Mygatt-Moore Quarry appears to be an attritional deposit of a relatively restricted diversity of dinosaurs, with few other non-dinosaurian taxa, that accumulated in a vernal pool deposit in an overbank setting. Bone modification was mostly by corrosion and breakage by trampling; scavenging was abundant. The paleofauna is dominated by *Allosaurus* and *Apatosaurus* (MNI and NIS), with the polacanthid ankylosaur *Mymoorapelta* less common. The matrix of the main quarry layer includes abundant carbonized fragments of plant material, and the mud during the time of deposition may have been often at least damp and occasionally acidic and dysoxic. The Cleveland-Lloyd Dinosaur Quarry is a close correlate of the Mygatt-Moore Quarry in terms of lithology and taphonomy, but demonstrates significant differences upon close inspection of matrix details and bone modification. Large quarries of fine-grained facies in the Morrison Formation possess a very different preservation mode as well as different taxon and relative abundance profiles from those in coarser sediments, which suggests that more may be learned in the future from taphofacies study of large quarries in mudstone beds.

INTRODUCTION

The Morrison Formation is an Upper Jurassic alluvial deposit that originally covered at least ~1,000,000 km² of what is now the western United States (Dodson and others, 1980; Turner and Peterson, 2004). The formation is well known for having produced some of the largest and most iconic dinosaurs from the Late Jurassic, and it has yielded one of the most diverse and abundant Mesozoic paleofaunas from anywhere in the world. Although forms such as *Brachiosaurus*, *Stegosaurus,* and *Allosaurus* are recognized even by non-paleontologists worldwide, the Morrison Formation's real significance lies in its preserved biota, including more than 90 vertebrate forms (more than 60 of which are not dinosaurs), plus plants, bivalves, gastropods, crustaceans, and others (Chure and others, 2006).

Dinosaur quarries in the Morrison Formation number in the hundreds and include those producing a range from a few bones of one individual up to more than 10,000 bones of multiple individuals and species (Dodson and others, 1980; Foster, 2003). Most quarries are dominated by dinosaurian remains; rare others produce almost exclusively non-dinosaur material. The diversity of preservational modes is great, particularly between those preserving mostly dinosaurs versus mostly non-dinosaurians, but several taphofacies are consistently encountered in widely scattered areas and levels. Among sites producing primarily dinosaurs, a number are considered "large," defined here as having produced multiple individuals and 500 or more mappable bones (i.e., excluding fragments unmappable at approximately 10 cm = 1 m). Among these are sites such as the Carnegie Quarry at Dinosaur National Monument, Howe Quarry, Dry Mesa Quarry, and Cleveland-Lloyd Dinosaur Quarry (Curtice and Wilhite, 1996; Miller and others, 1996; Carpenter, 2013). The greatest number of bones, individuals, and species among these sites appears to be preserved in relatively coarse sand deposits of channel sandstones. These localities also preserve relatively even numbers of each species, often reflective of the relative abundances of the species in the formation as a whole. In contrast, "large" dinosaur quarries (as defined above) preserved in drab mudstone may produce very large numbers of bones, but generally contain fewer species

than channel sandstone sites and are often dominated by one or a couple of species (e.g., Cleveland-Lloyd Dinosaur Quarry, Gates, 2005 and Peterson and others, 2017; Howe Quarry, Bird, 1985; Mygatt-Moore Quarry, Foster and others, 2016). Among the latter mudstone sites, with relatively low diversity and a predominance of just a few species, is the Mygatt-Moore Quarry in western Colorado. This site is unusual among Morrison localities in preserving a moderate diversity of plant macrofossils and palynomorphs, abundant dinosaur bones but of relatively low taxonomic diversity, and rare microvertebrate fossils, all in the same productive layer.

This study examines the general paleontology, vertebrate taphonomy, and sedimentology of the Mygatt-Moore Quarry as a large dinosaur bonebed and their implications for the origin of the deposit.

LOCALITY AND PREVIOUS WORK

The Mygatt-Moore Quarry was discovered on March 14, 1981, by J.D. and Vanetta Moore and Pete and Marilyn Mygatt (Armstrong and Perry, 1985; Armstrong and others, 1987; Mygatt, 1991; P. Mygatt, verbal communication, 2001). It is approximately 2.5 km from the Utah-Colorado state line in far western Mesa County, Colorado (figure 1), about 27 km west of Fruita. The quarry (figure 2A) is in the northwestern part of Rabbit Valley, a drainage that runs south to the Colorado River. The upper rim of the valley is composed of the Cretaceous Cedar Mountain and Naturita (formerly Dakota) Formations (figure 2B), and the floor of most of the northern part of the valley is Salt Wash Member of the Morrison Formation. Most of the hills of the valley all around are composed of partially grass-covered slopes of the Brushy Basin Member of the Morrison. The quarry has been worked every summer since 1985 and has produced more than 2300 mapped bones. The quarry has developed into a significant excavation over the years (figures 2C to 2F) but has shown no signs of playing out. In fact, results presented here suggest the bone deposit is much larger than previously suspected.

Compared to its fossil diversity, abundance, and the number of years it has been worked, relatively little has been published about the Mygatt-Moore Quarry. Plant
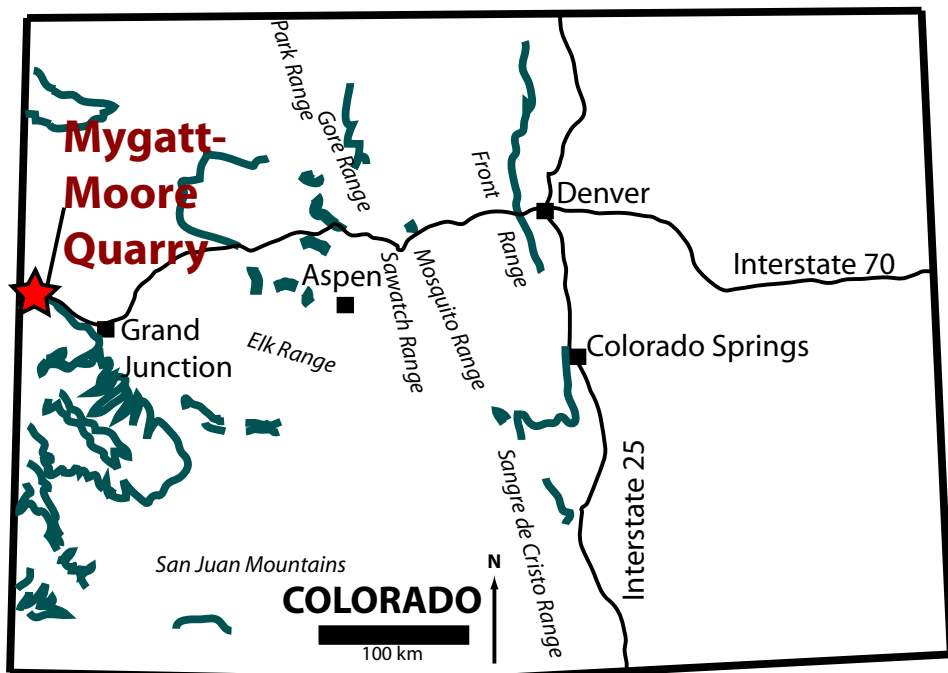
Figure 1. Location of the Mygatt-Moore Quarry in western Colorado (red star). Major outcrops in Colorado of the Morrison Formation in blue-green.

macrofossils from the Mygatt-Moore Quarry have been studied by Tidwell and others (1998) and the fossil spores and pollen by Hotton and Baghai-Riding (2010). King and Foster (2006) reported on the few non-dinosaurian vertebrates found in the quarry, whereas the ankylosaurian dinosaur *Mymoorapelta*—the first Jurassic ankylosaur in North America—was described by Kirkland and Carpenter (1994) and Kirkland and others (1998, 2010). Surprisingly, these latter two are the only papers that described any element of the dinosaur fauna exclusively. Chin and Kirkland (1998) reported possible herbivorous dinosaur coprolites from the quarry, and Bray and Hirsch (1998) described rare eggshell material from the site. The occurrence of dinosaur skin at the site, as carbonization and impressions, was reported by Foster and Hunt-Foster (2011). Only two abstracts have been produced dealing with overall site taphonomy (Kirkland and Armstrong, 1992; Foster and others, 2007), and general site characteristics have previously been covered in papers only preliminarily (Kirkland and others, 2005; Foster and others, 2016).

GEOLOGIC SETTING

Rabbit Valley (and the Mygatt-Moore Quarry) is on the northwestern edge of the Uncompahgre Plateau uplift and northwest of the local uplift of Ruby Canyon along the Colorado River; on its western edge the Uncompahgre borders the laccolithic uplift of the La Sal Mountains, which are to the southwest of Rabbit Valley. This region is on the northeastern edge of the Colorado Plateau. In Rabbit Valley, the Salt Wash Member of the Morrison Formation is about 96 m thick (Armstrong and McReynolds, 1987), and the Brushy Basin Member is about 100 to 140 m thick. The Morrison Formation in the area is underlain by what is called either the Upper Jurassic Summerville Formation (Carter and Gualtieri, 1965; Lohman, 1965; Lucas and others, 2006) or the Wanakah Formation (Scott and others, 2001) and the Entrada Sandstone (both Middle Jurassic), and is overlain by the Lower Cretaceous Cedar Mountain Formation and then the Naturita Formation (Stokes, 1952; Young, 1960; Kirkland and others, 1997; Currie and others, 2008; Sprinkel and others, 2012; Carpenter, 2014). The Cedar Mountain Formation is equivalent to the Burro Canyon Formation of the south and east side of the Colorado River in Colorado and Utah (Young, 1960); the formation is traditionally considered Cedar Mountain in Rabbit Valley only because of the valley's position north and west of the Colorado River. The Mygatt-Moore Quarry is in the upper part of the

Figure 2. Development and stratigraphy of the Mygatt-Moore Quarry in western Colorado. (A) View of the quarry from the southeast in the 1990s. (B) Stratigraphy of the uppermost Jurassic-Lower Cretaceous contact above and west of the Quarry. Jmbb = upper Brushy Basin Member of the Morrison Formation; Kcm = Cretaceous Cedar Mountain Formation; Kn = Cretaceous Naturita (formerly Dakota) Formation. (C) View of the Mygatt-Moore Quarry in September 1987, looking northeast (photo courtesy of Kay Fredette, Museums of Western Colorado). (D) Same view as C in July 2011 showing subsequent development of the quarry. (E) View of the quarry in September 1987, looking east-southeast (photo courtesy of Kay Fredette, Museums of Western Colorado). (F) Same view as E in July 2011. (G) Panorama of the Mygatt-Moore Quarry, looking southeast, in July 2011.

lower half of the Brushy Basin Member of the Morrison Formation (Turner and Peterson, 1999, also had the quarry at this approximate level; although Armstrong and McReynolds, 1987, had the quarry low in the upper half). The Morrison Formation is Late Jurassic in age, ranging from the Kimmeridgian (or possibly the latest Oxfordian) up into the early Tithonian (Turner and Peterson, 2004; Trujillo and Kowallis, 2015). At the time of quarry deposition, the Morrison Basin consisted of an alluvial plain with rivers flowing generally east out of the western mountains and across the floodplain (Turner and Peterson, 2004). Wetlands and lakes existed to the east of what is now western Colorado, and immediately to the south of the Mygatt-Moore area was "Lake T'oo'dichi'" (Turner and Fishman, 1991), a large, alkaline wetland/lacustrine complex in a hydrologically closed basin that had high evaporation rates and groundwater flow blocked to the east (Turner and Peterson, 2004). Other authors have interpreted the evidence differently and see no indication of such a complex (Anderson and Lucas, 1997; Galli, 2014).

METHODS

The Mygatt-Moore Quarry has been excavated for approximately three to four months per year since around 1990. Before that time, most seasons were approximately two weeks. Mapping of the bones in the quarry has always been from a main datum established near the original point of discovery, consisting of a survey marker-type cap, and a second marker at 40 m due north; these two markers establish the north-south coordinate axis. The grid is measured along meters approximately east-west and north-south of the datum. (It was recognized several years ago that the grid system used year to year is aligned on a bearing of approximately 350° and not true north, though the northern survey marker up slope from the quarry is correctly aligned.) Most bones have been found in an arc approximately southwest to northeast of the main quarry datum; the main quarry layer (may also be referred to as quarry layer) has already been eroded away to the south and east, and it is under the hillside to the north and west. Each bone removed was also assessed for stratigraphic

level within the quarry. The main bone layer is approximately 1 m thick in most areas; this interval is divided into lower, middle, and upper thirds (each approximately 33 cm thick), and as each bone was collected its stratigraphic interval was noted. In areas where the full bone layer is somewhat thinner, each stratigraphic level is correspondingly thinner so that the full layer was still divided visually into thirds. This system was developed a number of years ago after abandonment of a measurement of a Z-coordinate in the mapping. The Z-coordinate had been mapped off the top of the so-called "pebble layer" (see below). It was eventually discovered, however, that the "pebble layer" was indurated (and thus usable) in some areas of the quarry but not others, that where it was present its upper (and lower) boundaries undulated laterally, and that it is almost non-existent in other parts of the quarry. Thus, the simple three-part lower, middle, and upper bone layer subdivision was adopted.

Stratigraphic sections were measured in ten locations along approximately 1.62 km of strike (southwest-northeast) on the north end of Rabbit Valley. West to east, these are (1) Far West Nose, (2) West Nose, (3) Quarry, (4) Cam Stop, (5) Caudal Draw, (6) Channel Lake Traverse 1, (7) Channel Lake Traverse 2, (8) Gravel Hill, (9) East Trail Through Time, and (10) Far East Ridge (figures 3 and 4). Two sections (Quarry and Far East Ridge; figures 3 and 4) covered the complete Brushy Basin Member from the top of the Salt Wash Member of the Morrison Formation up through the Cedar Mountain Formation and into the Naturita Formation. The other stratigraphic sections were connected to at least one laterally adjacent section by traceable beds (generally the "fish layer" or various sandstone beds), so that all ten sections could be correlated. Sections were measured with a Jacob staff and Brunton compass set to the local dip of 5° northwest.

Five trenches were excavated with a backhoe (figure 5). Three sites were within the quarry excavation and two sites were excavated adjacent to the quarry on either side. These sections were also measured with a Jacob staff. Two drill holes—MM-1, which was about 87 m to the northwest of the quarry, and MM-2, which was about 95 m to the southwest—were bored with a
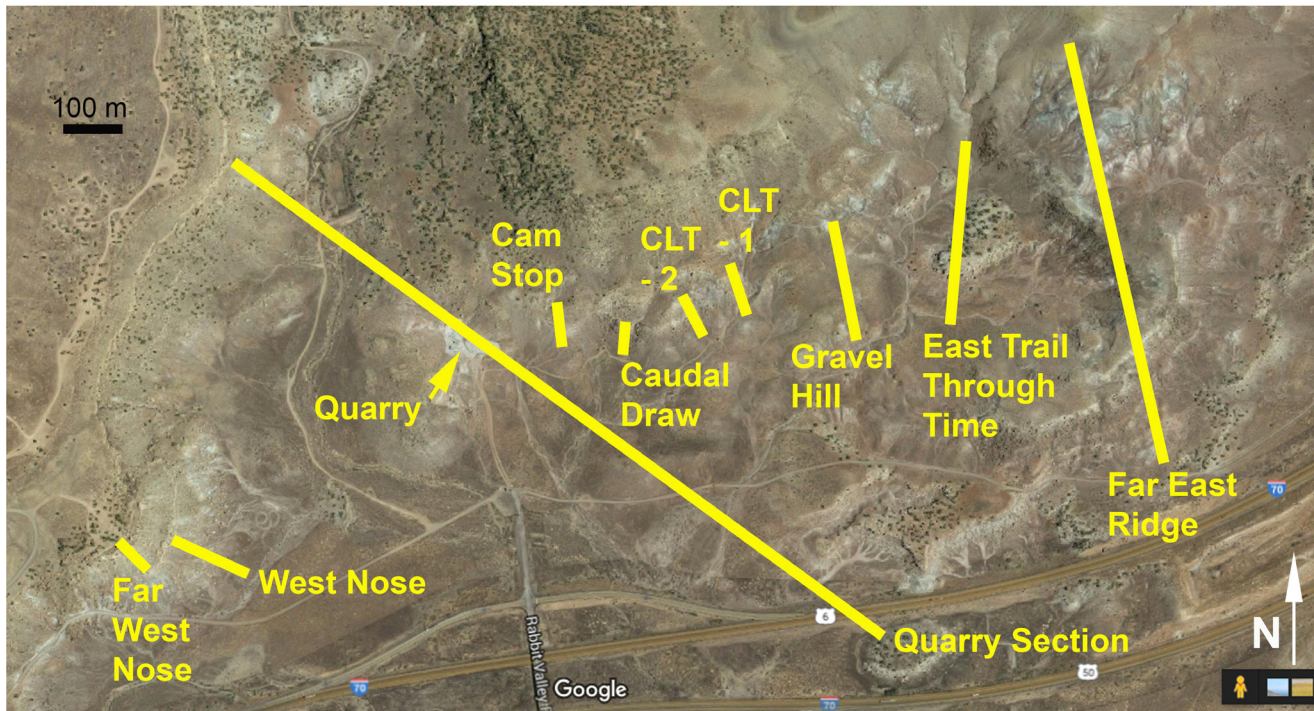
Figure 3. Map showing locations and names of the stratigraphic sections measured for this study near the Mygatt-Moore Quarry in Rabbit Valley. Quarry labeled and marked by arrow. Base from Google Earth.

track-mounted rig (figure 5). The 2.5-inch-diameter core was logged at the surface. Only 3 to 5 m of core below the "fish layer" (see below) was collected and is preserved in the Museums of Western Colorado paleontology collections. Positions of the trenches and drill holes were recorded by marking with 40 cm diameter circular orange markers and digitally photographing the whole area with a fixed-wing drone aircraft; the camera had a resolution of approximately 10 cm.

Five hand samples were collected from standard layers in each trench; the "fish layer" was sampled from all five. Two samples from the main quarry layer were collected from each trench; other samples varied between trenches. Thin sections were made from these samples. Lithologic descriptions of the trenches were recorded in the field and from the hand samples and thin sections. Thin sections were studied under a petrographic microscope and digitally photographed. In addition to the trench hand samples, numerous calcareous nodules were collected from the base of the quarry, and the five of these were thin sectioned (PB-1 through PB-5). Four

bones were also thin sectioned to compare their microstructures; two rounded, pebble-sized bone fragments (with only trabecular bone left) and two fragments containing cortical bone. All thin sections are preserved at the Museums of Western Colorado.

In addition to the thin sectioning of the calcium carbonate nodules, two of them plus three other representatives of these nodules (PB-1, PB-2, and PB-7 through PB-9) were analyzed for rare earth element ratios at the Department of Geosciences, Boise State University. Samples were crushed in a mortar and pestle to a fine powder and 125 mg of that powder was added into Teflon microwave digestion vessels. The samples were then soaked in 30% trace grade H_2O_2 for an hour to extract any trace elements from any remaining organic matter. After an hour, a 4.5:1.5:5.5 ml solution of concentrated trace grade HNO_3:HCl:DDI H_2O was added to the microwave digestion vessels. Samples were digested on a MARS microwave digester using the pre-programmed 3052XP-15min Xpress method that uses a 15 minute ramp-up time, a 15 minute hold at 190°C, and
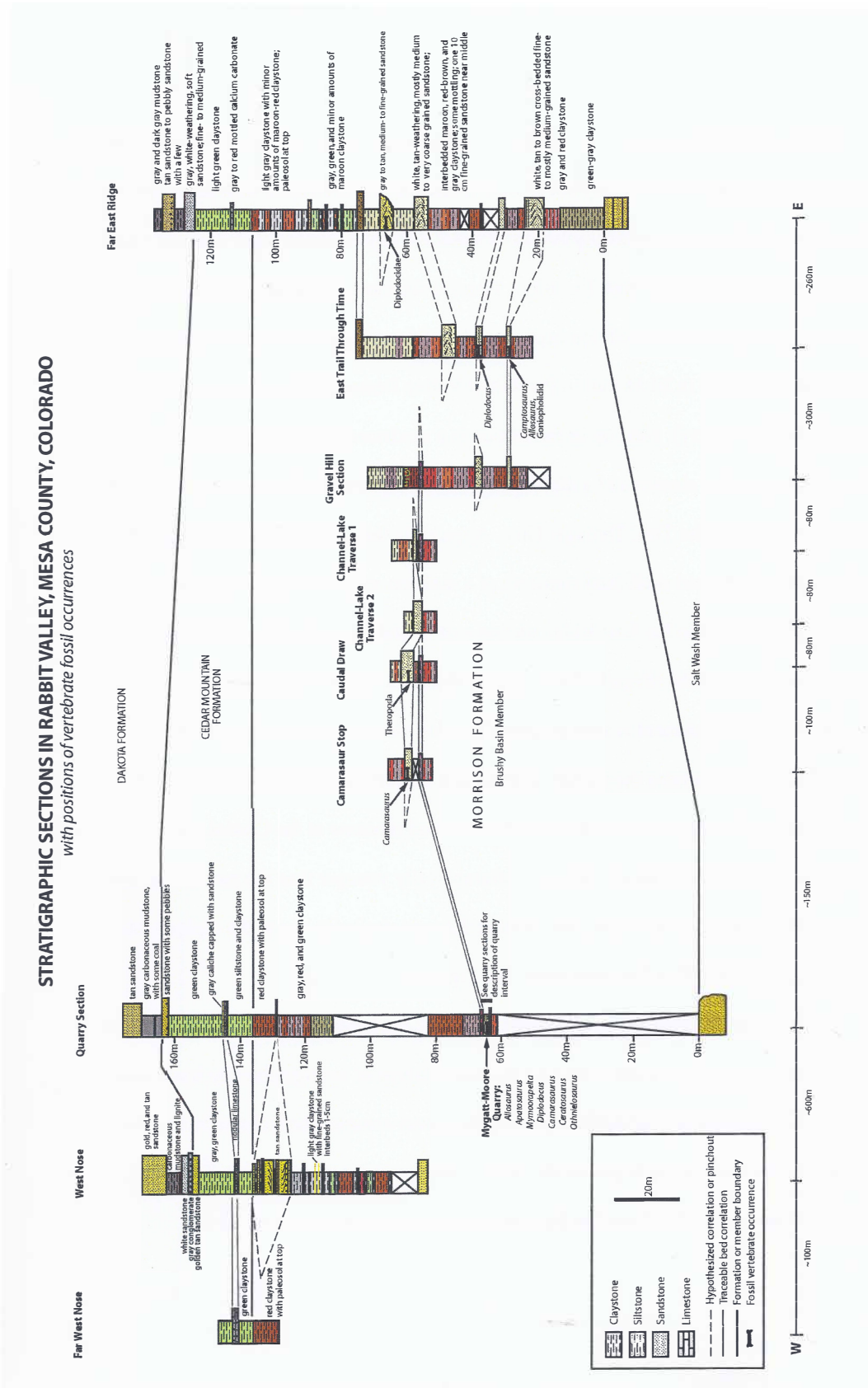
Figure 4. Stratigraphic sections measured from the top of the Salt Wash Member of the Morrison Formation (or within Brushy Basin Member) up to the base of the Naturita Formation in Rabbit Valley near the Mygatt-Moore Quarry, western Colorado. Sections anchored on the Morrison-Cedar Mountain contact. Sandstones and other marker beds tentatively correlated. Dakota = Naturita Formation. Quarry and five other fossil occurrence levels labeled and marked with arrows.
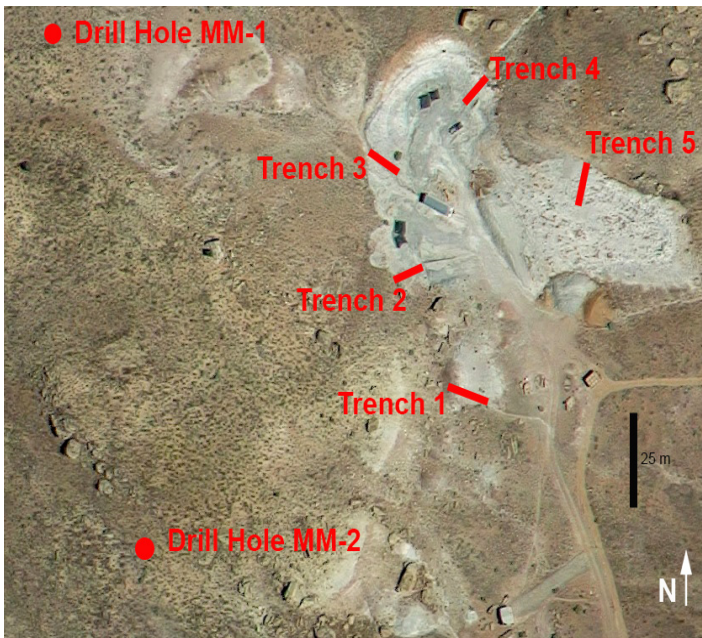
Figure 5. Close-up image of the Mygatt-Moore Quarry area showing locations of Trenches 1–5 (bars) and drill hole MM-1 and drill hole MM-2 (circles). Base is from Google Earth.

a 15 minute cool-down. Samples were then evaporated on a hot plate at 90°C and re-hydrated to 2% DDI HNO3, filtered, and analyzed using solution inductively coupled plasma mass spectrometer (ICP-MS). Samples were analyzed on a Thermo X Series 2 quadrupole ICP-MS for ^{43}Ca, ^{44}Ca, ^{66}Zn, ^{86}Sr, ^{88}Sr, ^{89}Y, ^{135}Ba, ^{137}Ba, all rare earth elements (REE), ^{208}Pb, ^{232}Th, and ^{238}U. Analysis was monitored via an internal 100 ppb (part per billion) Re standard. All REE patterns were plotted relative the NASC (Gromet and others, 1984).

Matrix samples for X-ray flourescence (XRF) analysis were collected from within the quarry's main bone layer, from the same stratigraphic level (about 2 to 3 m below the "fish layer") but outside the quarry about 250 m to the east (Caudal Draw), and a bone sample from within the quarry. XRF of sediment and bone samples carried out at Indiana University of Pennsylvania using an Innov X Delta Professional handheld XRF analyzer in soil mode. Concentrations of selected elements are given in ppm (parts per million). Sediment samples were ground prior to analysis in a glass mortar and pes-

tle. Bone samples were cleaned of matrix with de-ionized water, but analyzed whole.

The U-Pb (zircon) radiometric age for the Mygatt-Moore Quarry was obtained from an ash-fall bed isolated from the quarry mudstone of the main bone layer, collected from the northern part of the quarry (quarry map coordinates 1021N, 998E) on June 6, 2011. The sample was analyzed by the University of Wyoming Geochronology Lab and reported by Trujillo and others (2014). A variety of zircon morphologies were separated from the mudstone sample; of more than 125 zircons, at least 30 demonstrated characteristics (elongate tips, longitudinal bubble trails, transverse channels) consistent with ash grains. Selected zircons were annealed at 850°C for 48 hours and then dissolved in two steps, modified from the chemical abrasion method of Mattinson (2005). The first step used concentrated HF and HNO$_3$ for 12 hours at 180°C. This removed the most metamict domains and surficial Pb. After rinsing and discarding the leachate, individual grains were completely dissolved in HF and HNO$_3$ at 240°C for 30 hours; the solutions were converted to chlorides and evaporated with 0.05N H$_3$PO$_4$ in preparation for thermal ionization mass spectrometry.

Nearly every piece of matrix from the main bone layer at the Mygatt-Moore Quarry contains carbonized plant fragments. The only plant specimens saved are those that are complete enough to be identified to some taxonomic level. Some but not all of the wood was collected as well. Plants were identified based on comparisons with publications such as Miller (1987), Tidwell (1990), Tidwell and Medlyn (1992), Ash (1994), Ash and Tidwell (1998) and Tidwell and others (1998, 2006), as well as by consultation with some paleobotanists. Mollusks were identified using Yen and Reeside (1952) and Evanoff and others (1998).

Identifications of fossil vertebrates were compared to museum collections around the country as well as many references including, but not limited to, the following: Hatcher (1901), Osborn and Mook (1921), Gilmore (1925, 1936), Madsen (1976), Galton (1980, 1981, 1983, 2007), McIntosh (1990, 2005), Carpenter and McIntosh (1994), Kirkland and Carpenter (1994), Kirkland (1998), Kirkland and others (1998), Madsen

and Welles (2000), Upchurch and others (2004), and Tschopp and others (2015).

Taphonomic scoring for bones is based on (1) the 0 to 3 scales of Fiorillo (1988) for abrasion, (2) a 0 (none) to 3 (extensive) scale for corrosion (e.g., Eberth and others, 2007), (3) Behrensmeyer's (1978) 0 to 3 scale for weathering, and (4) a 0 to 3 scale for breakage (0 = none, 3 = broken on most sides; Ryan and others, 2001). Abrasion was scored based on rounding of otherwise sharp edges, as well as on any surficial scratching. Corrosion relates to chemical or biochemical erosion of bone surfaces and was scored by the rotting of bone ends or edges that was not clearly due to abrasion. That most end and edge loss of bone surface in Mygatt-Moore material is due to corrosion rather than abrasion is evidenced by the occurrence of outer bone-surface spalling, with sediment preserved between the flaking outer surface and the spongy inner surface that is then so often found (the spalling outer surface would be long eroded away had the material been abraded). Weathering relates to degradation and cracking of bone surfaces due to surface exposure to the elements. Breakage involves pre-burial breaks in the bone that, in most cases, fragment the element. Breakage and weathering are fairly straight forward to assess, but abrasion and corrosion can be difficult to distinguish, as in either case the result is rounding of edges. These taphonomic data were collected on a randomly selected subsample of the Mygatt-Moore Quarry collections, representing approximately 23.5% of the censused collection. The randomly selected subsample of the Cleveland-Lloyd Dinosaur Quarry collection at the Natural History Museum of Utah consisted of about 289 bones including those excavated by Gates (2005).

Number of identified elements is based on a census of the collections of the Museums of Western Colorado, consisting of material prepared through 2013. Minimum number of individuals (MNI) is based on the census data sorted for element but is not based on any single element. In the case of *Apatosaurus*, for example, the MNI count is based on the presence of a juvenile, a sub-adult and, based on femora, at least two adults. In the case of *Allosaurus,* on the other hand, the number of individuals is based on femora and metatarsals of adults, plus one juvenile represented by dentaries.

A significant percentage of the bone material in the Mygatt-Moore Quarry is fragmented and mostly unidentifiable to element or taxon. Therefore, most bones used for MNI calculations were taken from a relatively small overall sample of more complete elements. A true calculation of the number of identified specimens to minimum number of skeletal elements (ratio NISP:MNE, e.g., Lyman, 1994) would be difficult, and, if knowable, the ratio would likely be rather high (although we did not attempt calculating either for this study).

Shed teeth of theropods were censused and measured for maximum basal crown length with a digital caliper. Mean and standard deviation were calculated in a spreadsheet. *Allosaurus* and *Ceratosaurus* teeth were distinguished by the more laterally compressed maxillary and dentary teeth, and smaller serrations, in *Ceratosaurus*, plus the lingual ridges of anterior dentary and premaxillary teeth in *Ceratosaurus*, as demonstrated by Madsen (1976), Madsen and Welles (2000), and Bakker and Bir (2004). Two rose diagrams for orientations of bones were constructed, one bidirectional for bones with no clearly more massive end, and a unidirectional rose diagram for those with a clearly more massive end. Bidirectional bones were measured toward the orientation between 0° and 180° and made bidirectional in representation in the computer program. Unidirectional bones were measured toward the less massive end. The rose diagrams were constructed using 30° intervals in the program Rose.Net (https://en.freedownloadmanager.org/Windows-PC/Rose-Net-FREE.html). Compass readings for the rose diagram data were taken off the quarry map.

Voorhies group analysis was based on the group I–III bone categories in Carpenter (2013, table 6), and the work of Frison and Todd (1986) on transportability of elephant bones. It is recognized that the original sheep material studied (Voorhies, 1969) may not be fully comparable to bones of large dinosaurs, as noted by Gates (2005) and Carpenter (2013); however, the analysis is carried out here to facilitate comparisons with other similar mudstone sites, such as the Cleveland-Lloyd Dinosaur Quarry, for which such analyses have also been

conducted previously. There is currently no other system available, based on flume or river studies of more appropriate (large) analogs, with which to conduct these analyses.

A randomly selected, previously unexcavated single grid square (1010 to 1011N, 1009 to 1010E) was selected to be excavated and every bone, regardless of size or preservation, was collected. This was done as a possible representation of what an unbiased square meter of the main quarry layer was like, because in the past, excavation of the quarry had been biased towards larger and/or scientifically significant specimens. The test square meter was excavated in the 2013 season and each bone, tooth, and bone fragment was collected and mapped on X, Y, and Z coordinates. The Z coordinate was taken off a datum at the top of the bone layer (below the soil layer). The bones were measured for maximum length, width, and height and identified if possible. Volume was calculated for each bone incorporating the formula for the volume of an ellipsoid cylinder, using the three dimensions measured. These volumes (as a rough approximation of overall size) were then graphed in a histogram and the mean volume calculated in a spreadsheet.

Articulation ratios for Mygatt-Moore, and other quarries used for comparison, were calculated by dividing the number of bones in articulation with at least one other bone by the total number of bones mapped from the site. These ratios were calculated by counting the bones on available quarry maps (published and unpublished). These ratios were calculated for the Mygatt-Moore, Cleveland-Lloyd, Carnegie, Howe, Howe-Stephens, Poison Creek, Little Houston, and Dry Mesa Quarries.

RESULTS

Geology

Measured Sections

The top of the Salt Wash Member of the Morrison Formation in Rabbit Valley is at the top of one or several light-brown, laterally continuous channel sandstones that can be traced across the valley. The overlying Brushy Basin Member consists of approximately 100 to 140 m of gray, maroon, and greenish-gray claystone with numerous channel sandstone and thin splay sandstone beds and only a few thin limestone beds (figure 4). The largest laterally traceable channel sandstone beds appear to be at least 250 to 500 m wide. Most channel sandstone beds are medium- to very coarse grained, contain many tabular and trough cross-beds, and basal lag deposits. Mudstone beds of the Brushy Basin appear to be smectitic and contain at least some silt-sized grains (Trujillo, 2006).

The top of the Morrison Formation was observed in four of the measured sections. In most sections, the top is recognized as a deep maroon-red paleosol overlain by light green, sometimes silty or pebbly claystone of the Cedar Mountain Formation. Approximately 6 m up into the Cedar Mountain is a 0.5- to 2.0-m-thick nodular limestone to paleosol carbonate layer similar to one often found low in the formation farther west in eastern Utah (figure 2B); this unit is consistently at this level low in the Cedar Mountain and is overlain by a thicker unit of silty light green mudstone. The top of the Cedar Mountain is formed by light green claystone or a light-brown sandstone overlain by a basal conglomerate and/or a soft white sandstone marking the base of the Naturita Formation. Immediately above this white sandstone are several meters of dark gray to black carbonaceous, and in some places coaly, mudstone characteristic of the Naturita as well. Above this first dark-gray carbonaceous mudstone is the first of two thick, yellow-brown sandstone beds that cap the ridges of Rabbit Valley to the west, north, and east. In one measured section (West Nose), the top of the Morrison Formation is at the top of a thick, pebbly and cross-bedded channel sandstone; this unit is overlain by typical light green claystone of the lower Cedar Mountain, with the caliche/nodular limestone layer approximately 5 to 6 m up section. Interestingly, this channel sandstone pinches out to the west within about 100 m from the West Nose section, so that the Morrison-Cedar Mountain contact is a red claystone and paleosol directly below the light green claystone of the Lower Cretaceous at the next section (Far West Nose) to the west (figure 2B).

The Mygatt-Moore Quarry occurs approximately 64 m above the base of the Brushy Basin Member of the

Morrison Formation, in the Quarry section (figure 4) in which the member is 135 m thick. This puts the quarry near the top of the lower half of the Brushy Basin Member (47% of the way up in the section). Galli (2014) measured a composite section of part of the Brushy Basin Member but had the quarry in a slightly lower position; Turner and Peterson (1999) had Mygatt-Moore Quarry at a slightly lower relative stratigraphic position on their master composite section. In both, however, the quarry was in the upper part of the lower half of the member.

Other vertebrate bone sites in the northern part of Rabbit Valley were tied in to the measured sections based on correlations of the channel sandstones in which they occur and were measured and correlated with the network of sections (figure 4). The stratigraphically lowest of these is a thin sandstone that contains a partial skeleton of *Camptosaurus* (Averett locality), a partial skeleton of *Allosaurus* (Under the Cedar Tree site), and a goniopholidid crocodylomorph osteoderm. These three sites are on the east end of the Trail Through Time (a BLM trail in the Rabbit Valley Research Natural Area that begins at the Mygatt-Moore Quarry). Next higher site in the Brushy Basin Member section is a sandstone that contains a proximal caudal series and several other elements of a diplodocid sauropod (probably *Diplodocus*); this is also a stop on the east end of the Trail Through Time. The stratigraphically youngest site contains a partial diplodocid skull (and elements of a skeleton still in the sandstone) collected several years ago from the Far East Ridge section east of and above the Trail Through Time. Between these sites and the Mygatt-Moore Quarry there is a channel sandstone approximately 340 m wide east to west. This channel is stratigraphically a few meters above the Mygatt-Moore Quarry. It contains the partial skeleton of a *Camarasaurus* (a stop on the Trail Through Time) and a single caudal centrum of a theropod dinosaur at the Caudal Draw section a little to the east. These latter sites are stratigraphically younger than the partial *Diplodocus* from the eastern Trail Through Time, but whether they are similar in age to the diplodocid skull, or are slightly older, is difficult to determine (see figure 4).

The "fish layer" above the quarry is a distinct marker bed that can be traced more than 500 m to the east of the quarry. Tracing the relationships of beds stratigraphically immediately adjacent to this marker bed indicates that (1) the *Camarasaurus* channel sandstone pinches out laterally to the west of the sauropod stop along the trail, before it gets to the quarry outcrop, (2) the *Camarasaurus* channel sandstone scours out the "fish layer" at the Channel-Lake Traverse 2 section, (3) the *Camarasaurus* channel sandstone pinches out on its east end, west of the Gravel Hill section, and (4) from at least the Caudal Draw section east, the stratigraphic level of the Mygatt-Moore Quarry (about 2 m below the fish layer) no longer consists of medium light-gray claystone with abundant plant debris. The Caudal Draw and sections east that level are an often dark-red mudstone devoid of any fossil content (see figure 4).

Detailed Quarry Sections

Five trenches excavated by backhoe were dug in the quarry area; three were in the back wall of the quarry itself, and one each was just outside the excavated quarry to the south and east (figures 5 and 6). These trenches were excavated from the "fish layer" down to below the main quarry layer. The base of the main quarry layer to the base of the "fish layer" is 2 to 3 m thick. The main quarry layer unit (defined as a nodule-lag based, medium light gray claystone with abundant carbonized plant debris) was approximately 70 cm (in trench 1 south of the main quarry) to 1.5 m (in trench 3 on the northwest edge of the quarry) thick. In trenches 2 and 4, also in the excavated quarry, the main quarry layer was a more typical 1 to 1.2 m thick. The main quarry layer is directly underlain by a soft, light-green silty claystone that sometimes has some white mottling and is generally devoid of fossil vertebrate material, although some specimens have been found at the very top of this layer at its contact with the overlying bone layer. Most notable, the soft, light-green claystone layer contains no carbonized plant material at all, unlike the mudstone immediately above it. The main quarry layer is a greenish-gray (5GY 6/1) to medium light-gray (N6) claystone with silt-sized clasts of quartz and minor plagioclase feldspar (in thin section), abundant carbonized plant fragments, and common greenish-colored or white clay-ball clasts that are rounded and about 2 to 5 mm in diameter (figure 6;
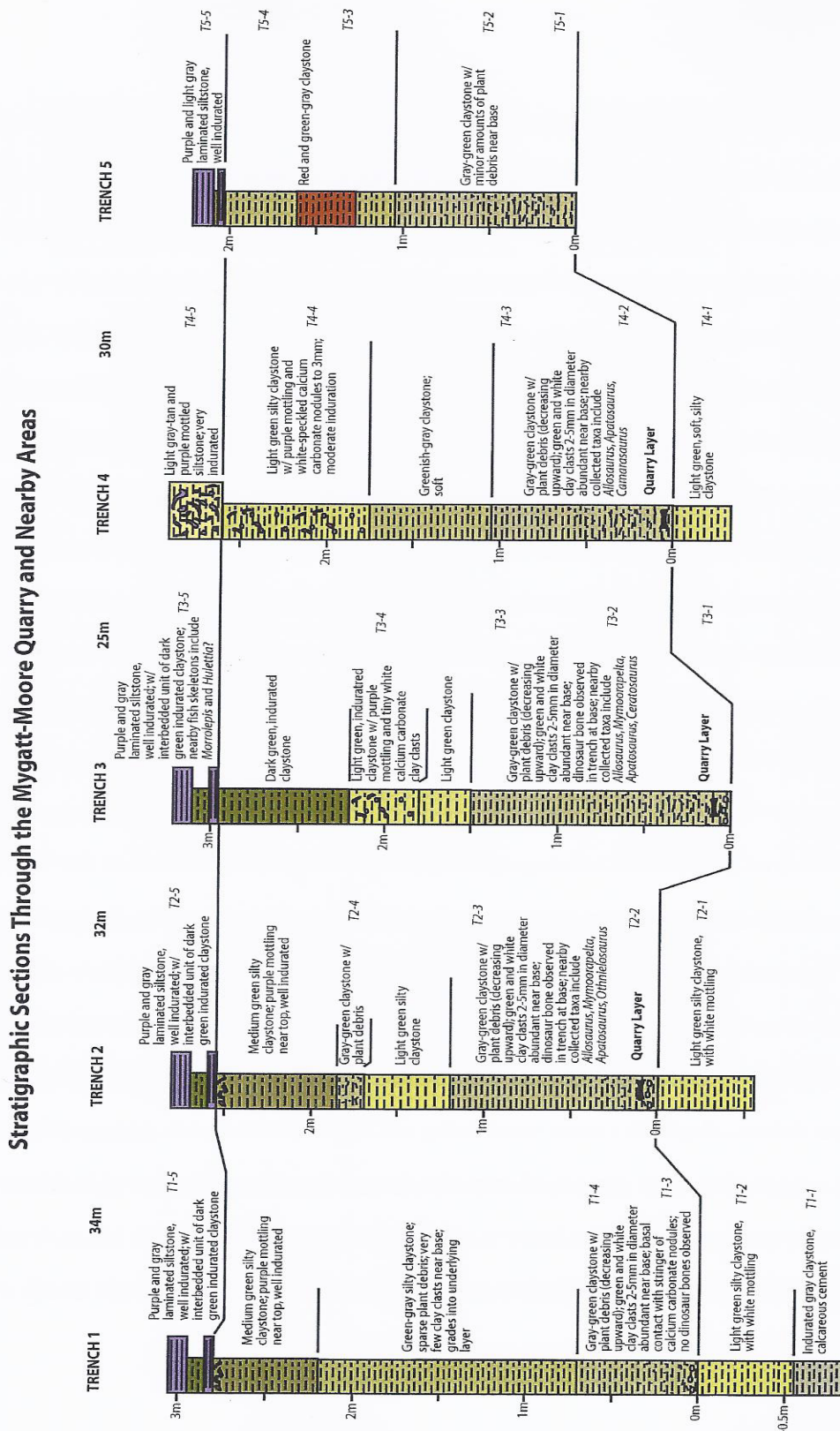
Figure 6. Stratigraphic sections of trenches 1 to 5 in and near the Mygatt-Moore Quarry. Italicized numbers to right of sections indicate thin section numbers and their sample levels.

appendix A). Trenches 2 to 4 have dinosaur bone and were in areas from which dinosaur material had been collected nearby in years past. Some of the trenches have carbonate nodules near the base of the main quarry layer (trenches 1 to 3). Above the main quarry layer is greenish-gray, light-green, and medium-green claystone with no carbonized plant fragments except in trench 2. A thin bed with minor amounts of plant debris is about 1.75 m above the base of the main quarry layer in trench 2. Other trenches were devoid of plant material above about 1 m above the base of the main quarry layer. To the east, some reddish-colored claystone was present about 1.5 m from the base of the trench 5, unlike any of the other trenches. This and the fact that the main quarry layers are thinner in trench 5 compared to the other trenches, and that the base of the main layer in trench 5 lacked clay balls, bones, or nodules, and contained fewer plant fragments, all suggest that trench 5 may be closer to the eastern edge of the bone deposit than the other trenches. The indurated, laminated silty claystone at the top of each trench (the "fish layer") was consistent except in trench 4 where the layer was mottled and laminations were less obvious.

Thin Section Micrographs

Comparison of thin section micrographs from the different layers across the five trenches indicates subtle differences in the claystone content that are not obvious in hand sample (figure 7; appendix A). The soft, light-green claystone underlying the main quarry layer appears to contain a higher percentage of larger silt-sized clasts than any of the other layers. The main quarry layer also contains a significant percentage of silt-sized grains but also has a high abundance of carbonized plant debris, clay balls (some containing silt clasts themselves), and wood fragments; these elements are missing from almost all samples from other layers (figure 7). The layer above the main quarry layer is similar in clay and silt content but is devoid of fossils and clay balls (except one sample with a single small wood fragment). The thin sections of the "fish layer" demonstrate the overall finer grained nature of the silt-sized clasts. None of the silt clasts in the "fish layer" from trenches 1 to 3 approach the size of those from underlying units. Laminations

are apparent in some of the thin section, particularly trench 1. The very different non-laminated texture of the "fish layer" thin section from trench 4 is reflected in the unusual mottled appearance in outcrop. The coarser size of the silt grains in this thin section matches that of many of the underlying layers. The "fish layer" thin section from trench 5 also has slightly coarser maximum silt grain size. The unusual texture for the "fish layer" thin sections of trench 4 (and to a lesser extent, trench 5) is somewhat unexpected because this laminated bed is traceable in outcrop for more than a half kilometer to the east. Despite the consistent appearance of the "fish layer" for hundreds of meters in outcrop, the apparent differences in the thin sections may partly explain why, to date, fish skeletons have only been found in the quarry area. In any case, the mottled, non-laminated appearance of the "fish layer" at the top of trench 4 reflected in the thin section micrograph is clearly different from the other "fish layer" thin sections. Also important to note from the thin sections (figure 7) is the somewhat different appearance of some of the trench 5 micrographs. This again may suggest that the eastern edge of the quarry deposit was near trench 5. Previous exploration excavations in this area turned up little in the way of bone (B. Britt, Brigham Young University, verbal communication, 2014), which is consistent with this interpretation.

"Pebble Bed" Nodules

A concentration of calcium carbonate nodules commonly found at the base of the main quarry layer is sometimes referred to informally as the "pebble bed." The "pebble bed" was present in trenches 1 through 3. The nodules are typically smaller and fewer in the southwestern part of the quarry and larger and more numerous in the northern part. The "pebble bed" commonly contains fragmented and heavily abraded dinosaur bone. This layer is well indurated only in some places, especially under larger sauropod bones such as a pubis and scapulae. Based on anecdotal evidence from the earlier years of the excavation, this "pebble bed" was more extensively indurated toward the southern part of the current quarry area, but in the past decade or so of excavation, only isolated spots have proved to be
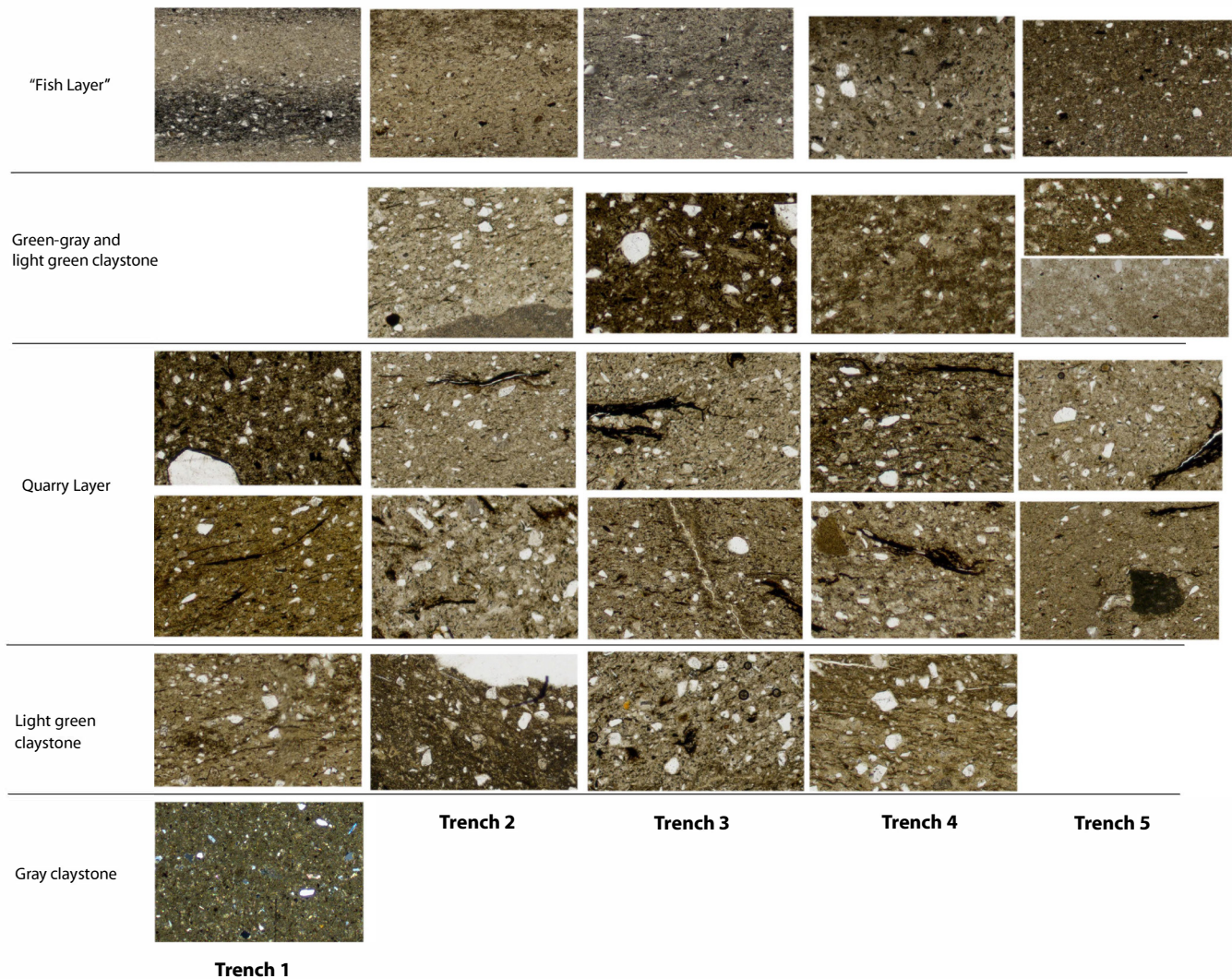
Figure 7. Thin section micrographs of samples from trenches 1–5, showing differentiation of layers and range of silt size within quarry layer. Within each trench column, thin sections are numbered in ascending order. Note plant fragments parallel to bedding in quarry layer samples; also note organics in laminations in "fish layer" samples. Each micrograph view is approximately 2000 μm across. See appendix A for descriptions.

strongly cemented. In most areas of the northern part of the quarry, the basal layer of the main quarry deposit contains abundant large dinosaur bones and bone fragments in relatively soft, plant fragment-rich claystone with a few to abundant, hard calcium carbonate nodules of irregular shape that range from 1 to 10 cm in greatest dimension. Most nodules are approximately 2 to 5 cm across and are devoid of plant material. The southwestern part of the quarry that was opened in 2005 and

worked most years since, has no well-indurated areas, and, as mentioned above, has fewer and smaller calcium carbonate nodules; however, the southwest area has a greater number of clay balls than the northern part of the quarry.

The exact source of the calcium carbonate nodules is uncertain. The calcium carbonate nodules are mostly composed of claystone with some angular to subrounded, silty to fine-grained sand grains. In hand sample

and when seen in cross section, some of the nodules appear to be laminated and some also have manganese dendrites growing in from their outer edges. Several of these nodules were thin sectioned and were found to contain silt- and fine-sand-sized clasts in a higher concentration than many of the layers sampled from the quarry (figure 8). The silt and sand clasts are not as large as the largest grains in the underlying light-green claystone. The thin sectioned nodules are perhaps most similar in texture to the main quarry layer level from trench 5 or trench 4 and possibly to the lowermost gray claystone in trench 1. The nodules are least similar in texture to the underlying light-green claystone found in the main quarry layer of trenches 1 through 3, and the "fish layer." The nodules are similar to those in the mudstone layers below, above, and lateral to the quarry, but differ from the mudstone layers in the main quarry layer. This, along with the clay balls in the main quarry layer, and very rare clasts of finely bedded, fine-grained sandstones (and sometimes a basal lag of abraded bone fragments), suggest that the calcium carbonate nodules were washed into the quarry deposits from elsewhere. Taken together, the evidence suggests that the nodules were likely formed in place as incipient soil structures outside of the quarry area but were reworked and redeposited in the Mygatt-Moore Quarry topographic low by hydraulic influence. This reworking of soil-related calcium carbonate nodules was also suggested by Kirkland and Armstrong (1992).

Total rare REE concentrations for the nodules in the "pebble bed" layer range from 74.8 to 112.5 ppm. There are two REE patterns when normalized to the North American Shale Composite (NASC) (Gromet and others, 1984). Samples PB-1, 7, and 9 exhibit a light REE pattern typical of shale, which concentrates light REE over middle and heavy REE. Samples PB-2 and 8 are middle REE depleted. This may be due to scavenging of the middle REE by Mn oxides; however, additional analysis needs to be conducted. All samples have a negative Europium (Eu) anomaly typical of a volcaniclastic source rock, consistent with the volcaniclastic nature of the sediment from the Brushy Basin Member of the Morrison Formation. The preliminary REE analysis of several of the calcium carbonate nodules also indicates
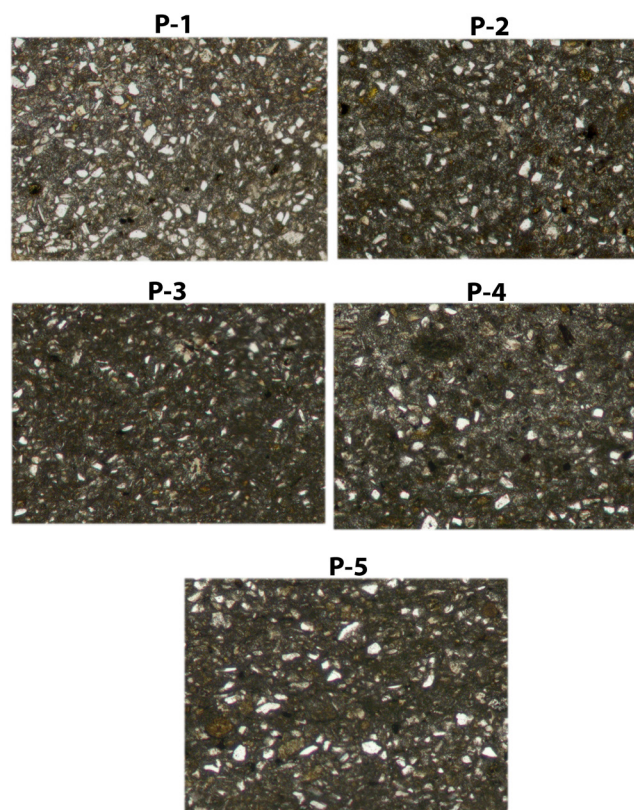

Figure 8. Thin section micrographs of calcium carbonate nodules ("pebbles") P-1 through P-5 from low in main bone layer, showing variable silty texture. Each micrograph view is approximately 2000 μm across.

that the nodules may have mixed together from two separate sources based on the two geochemical signatures (figure 9). More data on these REE signatures should be forthcoming as more nodules are analyzed in the future.

Matrix XRF Analysis

The Brushy Basin section in the Mygatt-Moore Quarry represents a mudflat deposit, which was ephemerally wetted (Foster and Hunt-Foster, 2011). The metal profile detected in the Mygatt-Moore Quarry matrix using XRF analysis is likely the result of apatite diagenesis in an ephemerally subaqueous environment. Samples analyzed from within Mygatt-Moore Quarry differ from Morrison Formation samples collected at the same stratigraphic horizon outside the bonebed. Specifically, the matrix at Mygatt-Moore Quarry contains
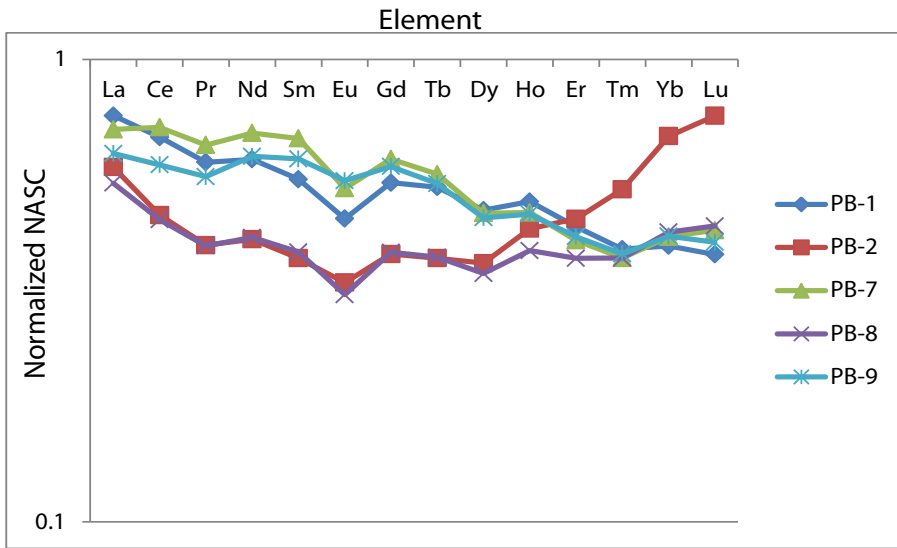
Figure 9. Rare earth element geochemistry plot of five calcium carbonate nodules (e.g., PB-1), showing two apparent signature groups and suggesting multiple sources of these "pebbles." Log-scale Y-axis.

elevated K, Ti, V, Ni, Zn, and Pb at levels at least twice those detected outside the quarry (table 1). From within this set, Ni, Zn, and Pb have been reported in obsidians, the chemical composition of which were used as proxies for volcanic ash deposited during the Jurassic (Hubert and others, 1996). Ash would have been incorporated into the sediment of Mygatt-Moore Quarry during ashfall events, resulting in these elements being found in elevated levels in the matrix and bone. Some elements detected via XRF are enriched within Mygatt-Moore Quarry bone samples relative to Mygatt-Moore Quarry matrix. Elevated levels of metals such as As, Sr, and Pb within apatite are known from other Jurassic deposits, such as the Lower Jurassic Kayenta Formation, as well as the Upper Cretaceous Prince Creek, Hell Creek, and Dinosaur Park Formations (e.g., Goodwin and others, 2007). Di- and trivalent ions substitute for Ca^{2+} in apatite during early diagenesis within bones in contact with water (Trueman and Tuross, 2002). This is one likely source of the metals, which are elevated in Mygatt-Moore Quarry bone. A second possibility is organic content within the deposit. Mygatt-Moore Quarry contains abundant plant fragments (REF), and organic-rich soil horizons have been shown to be enriched in metals, e.g., Cu, Pb, Mn, Zn, and Hg (Martí and others, 2003).

It is possible that decaying dinosaur tissue contributed to the elemental metals found within Mygatt-Moore Quarry, as has been suggested at the Cleveland-Lloyd Dinosaur Quarry (Peterson and others, 2017). However, the elemental metal profiles detected here contrast with those reported from the Cleveland-Lloyd Dinosaur Quarry in regard to the relative concentrations in bone versus matrix from Cleveland-Lloyd Dinosaur Quarry (Peterson and others, 2017). In contrast, the elemental metal profiles seen here resemble those of other Jurassic sites whose elemental metal content was determined to be diagenetic (e.g., Hubert and others, 1996; Goodwin and others, 2007). Whereas abundant sulfide minerals, such as pyrite and chalcopyrite, were detected at Cleveland-Lloyd Dinosaur Quarry, the Mygatt-Moore Quarry sediment and bone samples contain considerably lower levels of sulfides, implying a sometimes more oxygen-rich setting at Mygatt-Moore than Cleveland-Lloyd. Despite evidence from carbonized skin at Mygatt-Moore Quarry, the lower levels of sulfides imply that the levels of decay at Mygatt-Moore Quarry were not high enough to utilize the available oxygen, making it unlikely that enough dinosaur tissue was decaying to provide the observed metals. Furthermore, herbivore tissues, which dominate the Mygatt-Moore Quarry assemblage (by number of identified species and minimum number of individuals [MNI]), generally contain lower concentrations of elemental metals compared to carnivore tissues due to trophic focusing (Vijver and others, 2004). Therefore, the large amounts of dinosaur bone apatite are the most likely source of elevated el-

Table 1. X-ray flourescence (XRF) analysis results for elements in matrix samples from the Mygatt-Moore Quarry, from the same level as the quarry but about 250 m east of the quarry at the Caudal Draw stratigraphic section, and for bone from the quarry (ppm). *From main bone layer. Bolded values highlight elevated levels compared to values outside the quarry. **From about 2 m below "fish layer."

Element	Quarry Matrix* (ppm)	Caudal Draw Matrix** (ppm)	Ratio Quarry Matrix: Caudal Draw Matrix	Quarry Bone (ppm)	Ratio Quarry Matrix: Quarry Bone
P	0	0	-	253,739	0.00
S	9953	0	-	5112	1.95
K	17,129	7517	**2.28**	8636	1.98
Ca	17,128	95,736	0.18	343,740	0.05
Ti	2267	1088	**2.08**	2539	0.89
V	175	24	**7.29**	618	0.28
Cr	39	23	1.69	841	0.05
Mn	1111	1101	1.01	1204	0.92
Fe	10,354	8931	1.16	3443	3.01
Ni	45	6	**7.50**	167	0.27
Cu	17	12	1.42	48	0.35
Zn	107	26	**4.11**	86	1.24
As	58	0	-	38	1.53
Sr	150	293	0.51	4880	0.03
Mo	6	0	-	16	0.38
Pb	61	14	**4.34**	127	0.48

emental metals within the Mygatt-Moore Quarry relative to Morrison Formation sediment from the same stratigraphic horizon via diagenetic processes.

Drill Hole Cores

The cores from the two drill holes (figures 5 and 10; appendix B) demonstrated several things. First, the "fish layer," which is traceable in outcrop for more than 500 m to the east along the Trail Through Time and which is mostly covered beyond trench 1 to the southwest, was present in both drill holes. The drill holes are ~100 m apart indicating that the lake deposit extends a significant distance to the west in general. Second, the distinctive main quarry layer is also present in both cores (figures 10A and 10B); in MM-1 at 17.4 to 17.8 m and MM-2 at 15.7 to 16.6 m. More importantly, the core from MM-2 preserves an approximately 4-cm-long fragment of dinosaur bone from the 16.5 m level in the medium light gray claystone with abundant plant fragments (figure 10C).

These results indicate that the main quarry layer is geographically much larger than previously believed, especially to the southwest. The original intent of the drilling was to bracket the western and southwestern edges of the quarry in the directions the main quarry layer goes in the subsurface, but the discovery that the quarry claystone continues at least about 87 m to the northwest (drill hole MM-1) and about 95 m to the southwest (drill hole MM-2) suggests that the main quarry layer may be up to eight times larger than the area excavated so far. The area formed by a triangle linking drill holes MM-1 and MM-2 to the quarry and to each other is estimated to be approximately 4130 m². In contrast, the area of the quarry excavated so far is approximately 500 m².

Age

The age of the Mygatt-Moore Quarry has been estimated by U-Pb dating of ash-fall zircon crystals obtained from smectitic mudstone sampled from near
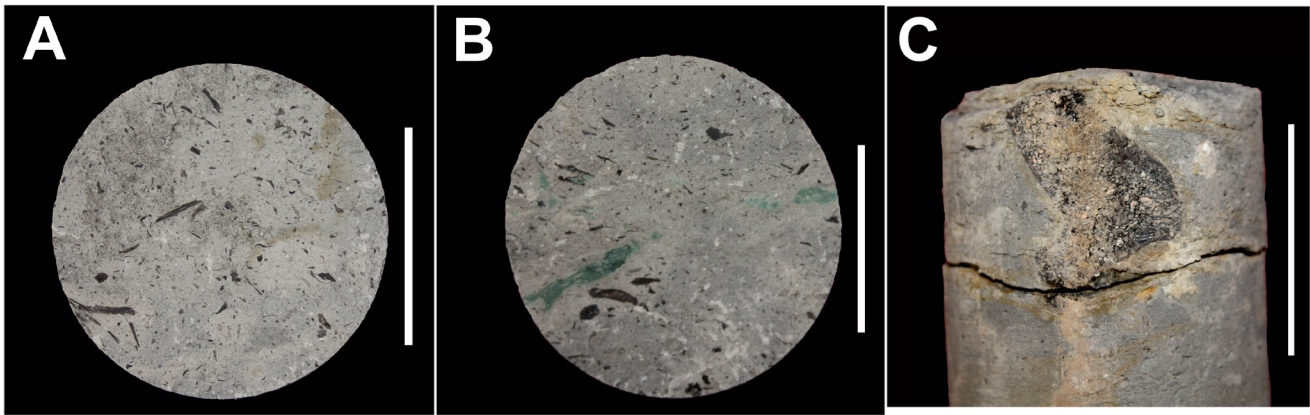
Figure 10. Drill cores from the Mygatt-Moore Quarry area. (A) View of medium light gray claystone with abundant carbonized plant fragments, characteristics of the main quarry layer, from the 17.7 m depth of drill hole MM-1. (B) View of medium light gray mudstone with abundant carbonized plant fragments from the 16.3 m depth of drill hole MM-2. (C) Side view of core section showing dark spongy-textured dinosaur bone fragment drilled through at the 16.5 m depth of drill hole MM-2, approximately 95 m southwest of the current edge of the quarry excavation. All scales bars = 5 cm.

several dinosaur bones in the main quarry layer. The calculated radiometric age for the quarry was 152.18 ± 0.29 Ma (Trujillo and others, 2014; figure 11), a date that puts the quarry at the Kimmeridgian-Tithonian boundary. This date is very close to that obtained for the famous Reed's Quarry 9 at Como Bluff, Wyoming (Trujillo and others, 2015), a site that yielded many hundreds of microvertebrates from the Morrison Formation (Carrano and Velez-Juarbe, 2006).

SYSTEMATIC PALEONTOLOGY

Preserved Taxa—Main Quarry Layer

The macrofossil record of plants from the Mygatt-Moore Quarry is unusual for the Morrison Formation in that it is found among abundant bones of sauropods and other dinosaurs. Unidentifiable plant fragments are abundant in every piece of matrix out of the quarry; in fact, as noted above, this plant-debris layer is one way to identify the quarry level even before bones have been located. Among all this preserved plant material, a small percentage is more than fragmentary and can be identified in some cases. The preserved plants from the Mygatt-Moore Quarry include at least 18 species (Tidwell and others,1998; this report), including horsetails (*Equisetum* figures 12B, 12E, and 12F) cycadophytes
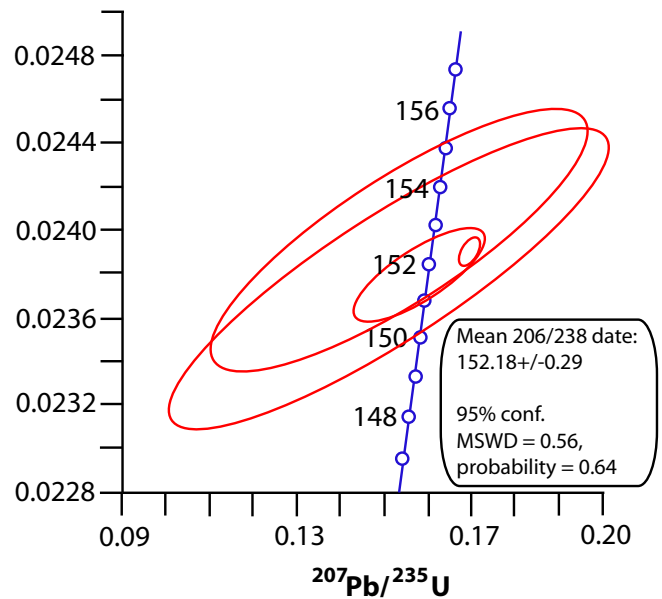

Figure 11. Concordia plot single grain, chemical abrasion, isotope dilution, thermal ionization mass spectrometric U-Pb analyses of zircon from the Mygatt-Moore Quarry, showing approximate age of ~152.2 Ma.

(*Otozamites, Cycadolepsis, Jensensispermum*), ginkgoes (*Ginkgo*; figure 12D), Czekanowskiales (*Czekanowskia*; figures 12N and 12O), and numerous conifers, based
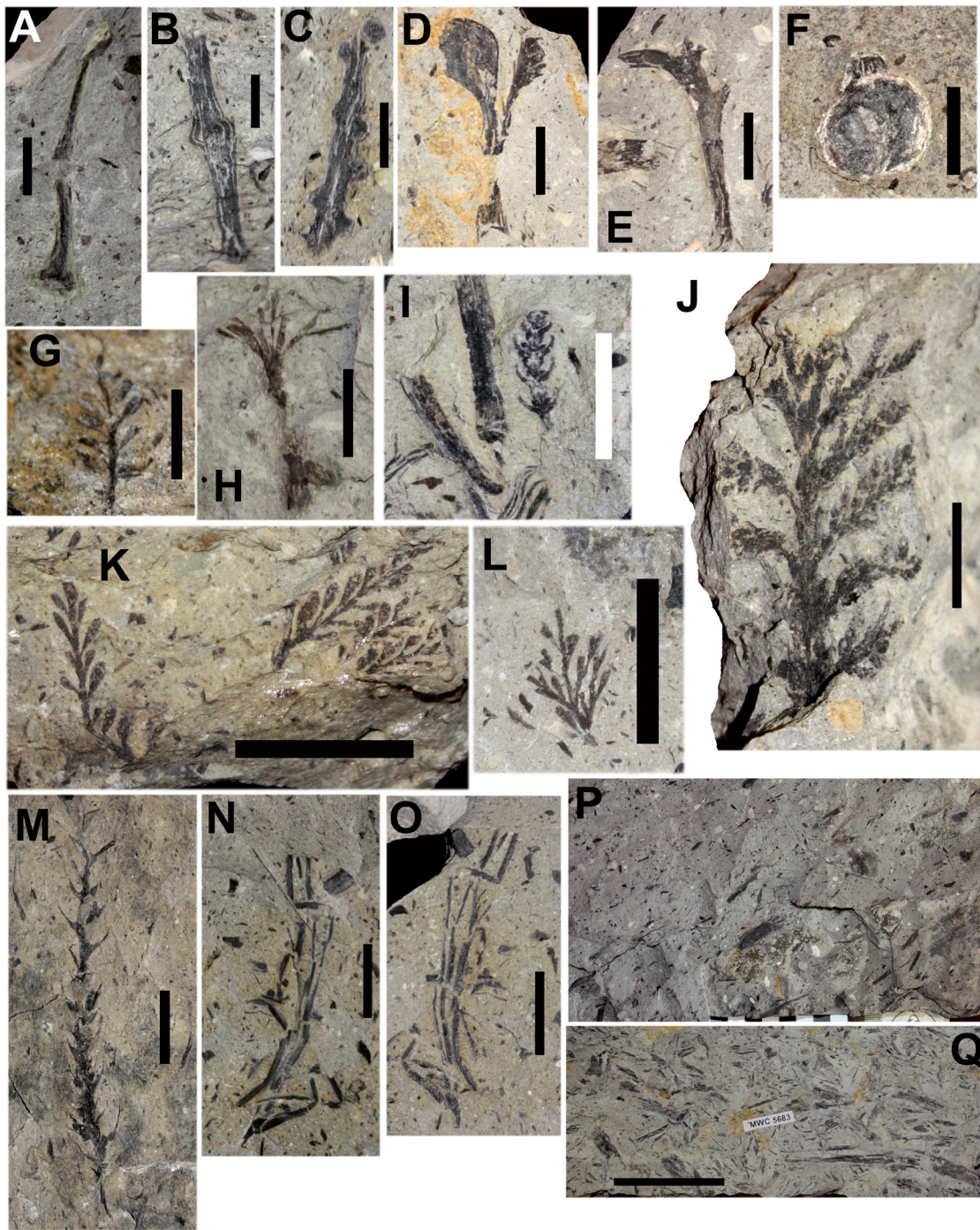
Figure 12. Plant fossils from the Mygatt-Moore Quarry. (A) Isoetaceae?, MWC uncataloged. (B) *Equisetum* sp., MWC uncataloged. (C) Indet. fern?, MWC uncataloged. (D) *Ginkgo*?, MWC uncataloged. (E) *Equisetum*?, MWC uncataloged. (F) *Equisetum* sp., isolated tuber, MWC uncataloged. (G) *Coniopteris* sp., MWC 6000. (H) Indeterminate plant, MWC uncataloged. (I) Indet. conifer, MWC 2190. (J) *Brachyphyllum* sp., MWC field number MM1205. (K) *Coniopteris* sp., MWC 2155. (L) *Sphenopteris*?, MWC field number MM1308. (M) *Pagiophyllum* sp., MWC field number MM1212. (N–O) Part and counterpart *Czekanowskia* sp., MWC uncataloged. (P) Matrix block showing aligned elongate plant fragments, MWC uncataloged. (Q) Matrix block showing aligned elongate plant fragments from southwest excavation area, MWC 5683. All scale bars = 1 cm, except P which is in cm and Q which is 5 cm.

Figure 13. Some of the fossilized wood from the Mygatt-Moore Quarry. (A) Smaller wood fragments, MWC uncataloged. (B) Larger wood piece, MWC uncataloged. Both scale bars = 10 cm.

mostly on wood, cones, and short shoots (*Steinerocaulis, Behuninia, Conites, Protocupressinoxylon, Mesembrioxylon, Xenoxylon*), but some based on small branch sections (*Pagiophyllum,* figure 12M; *Brachyphyllum*, figure 12J). Macrofossil plants reported here for the first time from the quarry include the ferns *Coniopteris* (figures 12G and 12K) and *Sphenopteris*? (figure 12L), plus a possible indeterminate Isoetaceae (figure 12A) and the conifer *Pagiophyllum* (figure 12M). These identifications are tentative, but the specimens are illustrated here to show the specimens found since the Tidwell and others (1998) publication; only Figure 12I (indet. conifer) was illustrated previously (Tidwell and others, 1998).

A palynological sample from the Mygatt-Moore Quarry, collected and studied by Hotton and Baghai-Riding (2010) along with seven other samples from the Morrison Formation from New Mexico to Wyoming, is unusual in having an abundance of lycopodiophytes (relatives of modern quillworts and clubmosses), ferns, and conifers. The conifers are mostly podocarpaceans, with a number of indeterminate bisaccate forms. It is interesting that at the nearby Fruita Paleontological Area, the conifers identified by pollen are mostly Cu-

pressaceae. The abundance of fossilized wood in the Mygatt-Moore Quarry (figure 13) was studied by Tidwell and others (1998) and includes podocarpaceous wood species, which parallels the abundance of podocarpaceous pollen found in the palynological sample (Hotton and Baghai-Riding, 2010), suggesting that the wood and pollen are of local origin and that podocarpaceous conifers grew rather close to the quarry deposit.

Several samples of abundant plant fragments in the Mygatt-Moore Quarry (figures 12P and 12Q) show a preferred alignment of long axes of elongate fragments. These have been noted particularly in the southwest part of the excavated quarry. This preferred alignment would seem to suggest orientation by gentle water action, perhaps on the edge of a pond; the plant material is small and light enough that its being aligned in such a way by unidirectional hydraulic transport seems unlikely. More likely, the water action may have been oscillatory. Such alignment seems unlikely to result from trampling by large vertebrates, which would seem more likely to produce random orientations. Trampling undoubtedly occurred at the site, however, and this plant fragment alignment simply indicates that a possibly hydrological influence was overprinting fragmentation

and possible in situ churning of the plant material.

Taxa marked with an asterisk (*) are those reported from the Mygatt-Moore Quarry for the first time here. Brief descriptions of each of the specimens are provided using the terms and architectural characteristics of Ellis and others (2009). Specimens that were previously described in alternate papers have been appropriately referenced but not formally described here.

PLANTAE
Division LYCOPODIOPHYTA
Class LYCOPODIOPSIDA
Order ISOETALES
Family ISOETACEAE INDET.?*

Single, partial, lanceolate leaf lamina specimen. Greater than 4.5 cm in length, 0.5 cm in width at the base, and less than 0.2 cm approaching the apex. The base of the specimen is lobate with a wide, obtuse angle.

One fragmentary plant specimen is believed to represent a quillwort (figure 12A), a group also identified from the site by spores. Although rare at the site as macrofossils, if correctly identified, isoetaceaeans appear to be relatively abundant in the palyonologial record (Hotton and Baghai-Riding, 2010).

Division SPHENOPHYTA
Order EQUISETALES
Family EQUISETACEAE
EQUISETUM SP. CF. *LATERALE**

Complete specimens are unknown. Internodes are long and cylindrical. The stem bulges at each node by approximately a millimeter. Leaf organization is free and whorled or occurring in a sheath. Leaves overlap nodes; course parallel; apex acute and convex.

Horsetails are represented by several macrofossil fragments (figures 12B, 12E, and 12F); as with most macrofossil plants at Mygatt-Moore, they are not particularly complete. The less typical specimens are similar to some assigned to *Equisetum* from Montezuma Creek and Dinosaur National Monument and illustrated by Ash and Tidwell (1998) and Foster (2007).

Division PTERIDOPHYTA
Order FILICALES
Family DICKSONIACEAE
CONIOPTERIS SP.*

Complete fronds are unknown and specimens at this site are fragmentary and represented by individual pinnae. The pinna is highly dissected into pinnules and appears to be odd-pinnately compound. The pinnules occur opposite along each pinna rachilla with a decurrent attachment and are obovate in shape.

This fern is represented by four fragments (figures 12G and 12K). This is the first identification of fern macrofossils from the Mygatt-Moore Quarry, although Hotton and Baghai-Riding (2010) identified fern spores in their sample from the site. Why ferns are rare as macrofossils may reflect their rarity in the original flora, but this is more likely a taphonomic artifact.

Order INCERTAE SEDIS
SPHENOPTERIS(?) *cf. METZGERIOIDES**

Complete fronds are unknown. It is unknown whether the frond is imparipinnate or paripinnate. The overall appearance is feathery and delicate with a robust and linear imparipinnate costa. Shape and course are elongate, feathery and highly dissected. The costa attachment is decurrent and alternate. The pinnules are asymmetrical and deeply dissected. The apex of the pinnules are rounded. The base of the pinnule is indistinguishable from the costa and has a decurrent attachment. This may be a new fern taxon for the Brushy Basin Member, identified based on this small piece from the Mygatt-Moore Quarry (figure 12L) and a recently discovered, more complete specimen from southeastern Utah (S. Ash, University of New Mexico, verbal communication, 2017).

Division CYCADOPHYTA
Order CYCADALES
OTOZAMITES SP.

This cycad is known from a single pinna illustrated and discussed by Tidwell and others (1998).

CYCADOLEPIS(?) SP.

Cycadolepis is represented by a single scale (Tidwell and others, 1998), but since then several more possible scale specimens of this cycad have been found.

JENSENSISPERMUM REDMONDII

This cycad was represented by a single seed in Tidwell and others (1998), and since then several more have been found at the site.

Division GINKGOPHYTA
Order GINKGOALES
GINKGO(?) SP.

A single leaf with similarities to a specimen from the Montezuma Creek locality, illustrated by Ash and Tidwell (1998), may represent *Ginkgo* (figure 12D). It is possible that this specimen instead represents the conifer *Steinerocaulis radiatus* (see below) or a single leaflet from the Bennettitalean, *Anomozamites* sp.

Order CZEKANOWSKIALES
CZEKANOWSKIA TURNERI(?)

The wet-adapted ginkgophyte *Czekanowskia* is represented by a single fragmentary fossil (figures 12N and 12O) from the quarry.

Division CONIFEROPHYTA
BRACHYPHYLLUM RECHTENII

This species was identified at Mygatt-Moore by Tidwell and others (1998) based on individual leaves; the specimen illustrated here (figure 12J) is a partial branch that appears to belong to this species of conifer.

UNIDENTIFIED CONIFER

The counterpart of the specimen illustrated here (figure 12I) was also illustrated and discussed by Tidwell and others (1998), who also noted the broad base of the leaves. This specimen remains unidentified although it was compared to *Elatides* and *Geinitzia* by Tidwell and others (1998).

BEHUNINIA PROVOENSIS

This species is represented by a short-shoot from Mygatt-Moore (Tidwell and others, 1998), and is known from several other sites in Utah and Wyoming.

STEINEROCAULIS RADIATUS

Already described from Mygatt-Moore by Tidwell and others (1998), this conifer is represented by a number of similar specimens now.

CONITES SP.

Two seed cones are known from the quarry, and they represent the largest known cones from the Morrison Formation (Tidwell and others, 1998).

PAGIOPHYLLUM SP.*

Only fragmentary specimens are known. The rachis is very thick and robust. The pinna can be arranged opposite to spirally around the rachis. The pinna is diamond shaped and comes to an acute, needle-like point at the apex. The base attachment is sessile and the pinna show a rounded attachment to the rachis. Both the base and the apex are rounded.

This new conifer identification for the Mygatt-Moore Quarry (figure 12M) was previously known only from the Belt area sites in Montana (Tidwell and others, 1998) and the Temple Canyon Locality (Gorman and others, 2008).

PROTOCUPRESSINOXYLON MEDLYNII
MESEMBRIOXYLON CARTERII
XENOXYLON MOOREI

These three types of fossil wood from the Morrison Formation were described as new species by Tidwell and others (1998). All three types of wood exhibited evidence of wood-rotting fungi that, in modern woods, most commonly function in moderately warm and wet conditions (either humidity or soil); in some cases Mygatt-Moore wood exhibited evidence of collapse, which happens in some modern woods during drying of previously soaked heartwood – this is most common in modern wetland species (Tidwell and others, 1998).

Figure 14. Gastropod *Viviparus reesidei* from the base of the Mygatt-Moore Quarry, MWC field number MM1724. Width of specimen approximately 13 mm.

METAZOA
Phylum MOLLUSCA
Class GASTROPODA
Family VIVIDPARIDAE
VIVIPARUS REESIDEI

Gastropods have been found in the "fish layer" and just below it, and well above the main bone layer. However, in 2013, several specimens of *Viviparus reesidei* were identified at the bottom of the main quarry bone layer at its contact with the underlying light green claystone. The sample included approximately eight internal shell casts and fragments of shell casts (figure 14), and all were in nodular green claystone devoid of plant material.

Phylum CHORDATA
Subphylum VERTEBRATA
Class AMPHIBIA
Clade CAUDATA
CAUDATA INDET.

Amphibians are uncommon fossils in Jurassic sedi-

ments and include only two groups: (1) the modern lissamphibians (anurans, caudatans and caecilians), and (2) the larger, brachyopoid temnospondyls. Of these groups, only anurans and caudatans are found in the Morrison Formation. Prior to the 2017 season, amphibians were unknown from the Mygatt-Moore Quarry, but a new specimen of a caudatan has since been recovered at the site. The fragile limb bone (MWC 8649) was found isolated, high in the bone-bearing horizon, just a few centimeters below the level where a rhynchocephalian was found the same season (see below). It is complete, densely mineralized (no primary bone tissue remains visible in the specimen) and is preserved as a part (figure 15A) and counterpart. There is no ossification of the epiphyses, as is typical in living caudatans, and the diaphysis is asymmetrical with a deeply concave inflection directed toward the midline of the limb. The element is 8.75 mm in length and is much longer than the 2.2 mm radius of *Iridotriton* from Dinosaur National Monument, which also has a straighter shaft than this specimen. MWC 8649 thus likely represents a different, potentially undescribed caudatan taxon. This element is strikingly similar to the morphology of the ulna in extant *Necturus* and likely represents either a forelimb (radius or ulna) or hindlimb (tibia or fibula) element in this extinct taxon. Unfortunately, as distal limb elements are not diagnostic at lower taxonomic levels, it is impossible to identify the genus to which this limb belongs or to erect a new genus based solely on this element.

MWC 8649 is not referable to Anura, based on its gross morphology. In anurans, the fore- and hindlimb elements are much straighter and there is notable fusion between the radius and ulna, and likewise between the tibia and fibula. No fusion is evident in this specimen. Additionally, the elongate tarsals (tibiale and fibulare) also tend to be fairly straight elements, and are inconsistent with the morphology seen in MWC 8649.

Class REPTILIA
Order RHYNCHOCEPHALIA
RHYNCHOCEPHALIA INDET.*

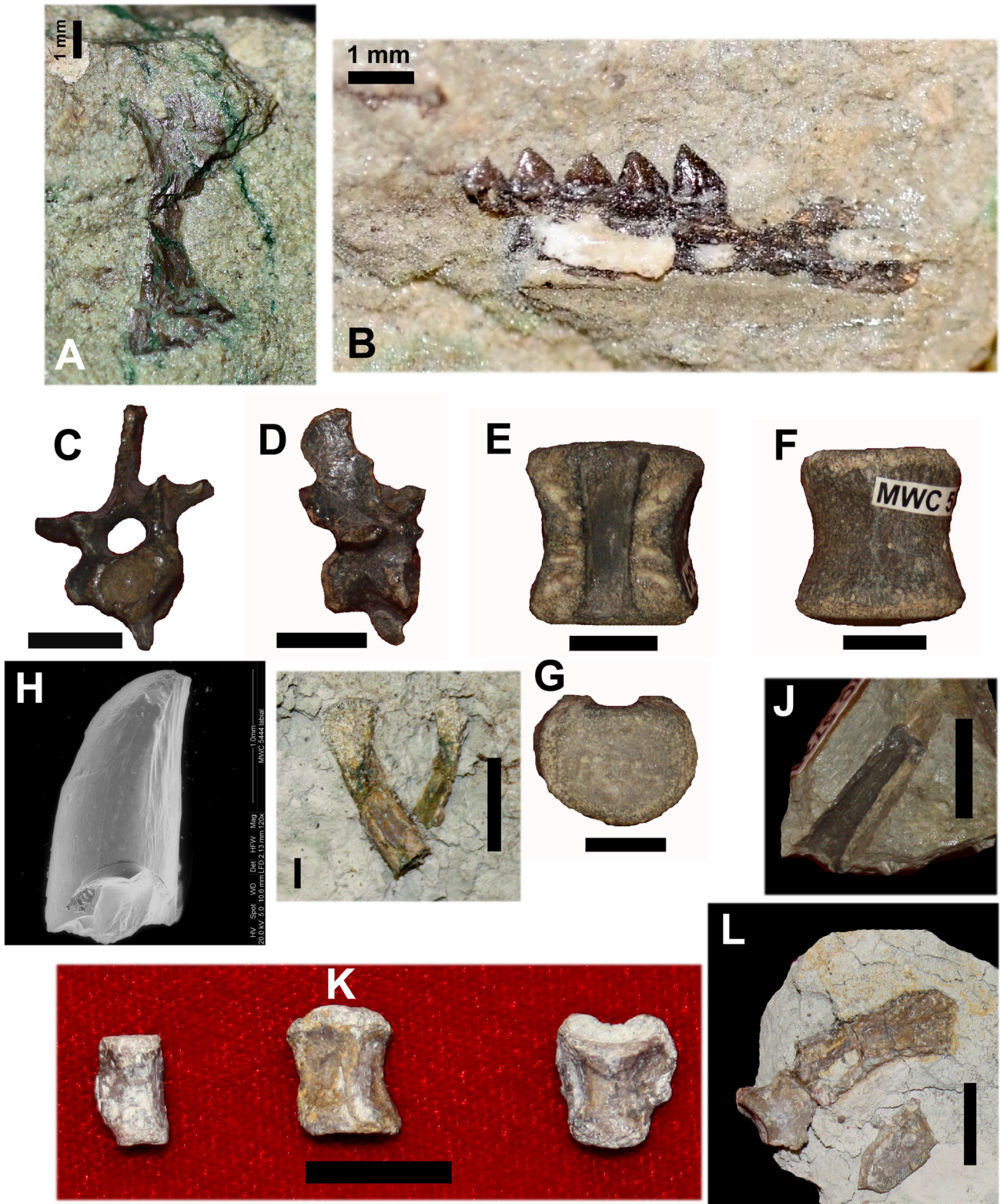In 2017, the first rhynchocephalian fossil was discovered at the Mygatt-Moore Quarry after more than three

Figure 15 caption on following page.

Figure 15 (figure on previous page). Fossils of amphibian(?) and small reptiles from the Mygatt-Moore Quarry. (A) Small limb element of Caudata(?) indet., possibly a fibula, MWC 8649. (B) Lingual view of partial right dentary(?) of rhynchocephalian, possibly *Opisthias*?, MWC 8671. (C) Small vertebra of a goniopholidid neosuchian crocodyliform in anterior view, MWC 1902. (D) Same in right lateral view. (E–G) Small vertebra (possible neornithischian or goniopholidid) in dorsal, ventral and posterior(?) views, respectively, MWC 5634. (H) Tiny reptilian tooth ~2 mm tall in mesial or distal view, MWC 5444 (image courtesy of Andy Heckert, Appalachian State University). (I) Partial limb elements of reptile?, part of MWC 5999 (associated with K and L). (J) Small hollow limb element (pterosaur?), MWC 5728. (K–L) Associated small bones of indeterminate reptile, MWC 5999. (K) Three vertebrae in ventral view. (L) Pectoral or pelvic girdle element (?). All scale bars = 1 cm, except A, B, and H which are 1 mm.

decades of excavations (figure 15B). The microfossil was found high in the bone-bearing horizon where the mudstone has a higher sand content than lower in the section. At this level, large complete vertebrate remains are not as abundant as they are lower. The element is a partial right dentary (MWC 8671) that is preserved in lingual view and contains five spade-shaped acrodont teeth, each bearing small denticles along the margins. The dentary measures 6.9 mm in length and is broken on both ends, suggesting that taphonomic factors such as trampling or predation/scavenging were at play prior to burial. Although the dentary is too fragmentary to be diagnostic at lower taxonomic levels, MWC 8671 resembles a juvenile *Eilenodon* with unworn teeth or possibly could be referred to the genus *Opisthias* (M. Jones, University of Adelaide, written communication, 2017*).

REPTILIA INDET.

A small reptilian vertebral centrum from the Mygatt-Moore Quarry (figured 15E to 15G) may belong to either a small ornithopod dinosaur or perhaps a goniopholidid neosuchian crocodylomorph, the latter of which do not have procoelous vertebrae (Steel, 1973), making identification of small reptilian vertebral centra from the Jurassic particularly difficult. This verte-

bra also has unfused neurocentral sutures so the neural arch and spine are missing.

A fragment of a very hollow limb bone (figure 15J) was found in the quarry but is too incomplete to identify. Based on the degree of hollowness, however, King and others (2006) suggested that this specimen may represent a pterosaur limb element.

A third, very small, reptilian is represented by a single, tiny conical tooth, approximately 2 mm tall (figure 15H). This specimen was found by screen washing the matrix in a jacket containing a juvenile sauropod femur. The tooth has slightly wrinkled enamel on the lingual surface and is slightly laterally compressed just at the tip, though it is mostly conical. The tooth is larger than those of most lizard specimens from the Morrison Formation, and it is not of certain crocodylomorph affinity. It is generally similar to some teeth assigned to embryonic sauropods from the Lower Cretaceous of France (Barrett and others, 2016), although even this assignment for the specimen would be tentative.

Small reptilian elements were found in 2005 in the soft green mudstone immediately below the main bone layer in the southwestern part of the quarry. These associated elements include three vertebrae, a fragmentary limb bone, a girdle bone, and several small fragments (figures 15I and 15K to 15L). The vertebrae measure 7 to 9 mm long and 4 to 7 mm in diameter; the centra have wide neural canals and laterally widely spaced pedicals with detached neural arches and exposed sutures. The girdle bone, possibly a scapula, is 30 mm long and has a somewhat blade-like shaft and a preserved "glenoid." The limb bone is preserved in several elements, approximately 42 mm long total, and appears hollow to some degree. The material suggests either a relatively large rhynchocephalian or possibly a turtle; in the latter case, the girdle bone would be an ilium, not a scapula.

Clade CROCODYLIFORMES
Family GONIOPHOLIDIDAE
GONIOPHOLIDIDAE INDET.

Goniopholidids are represented by a single vertebra at the Mygatt-Moore Quarry (MWC 1902). This vertebra is small but is very slightly procoelous and has the ventrally projecting hypapophysis typical of neosuchian
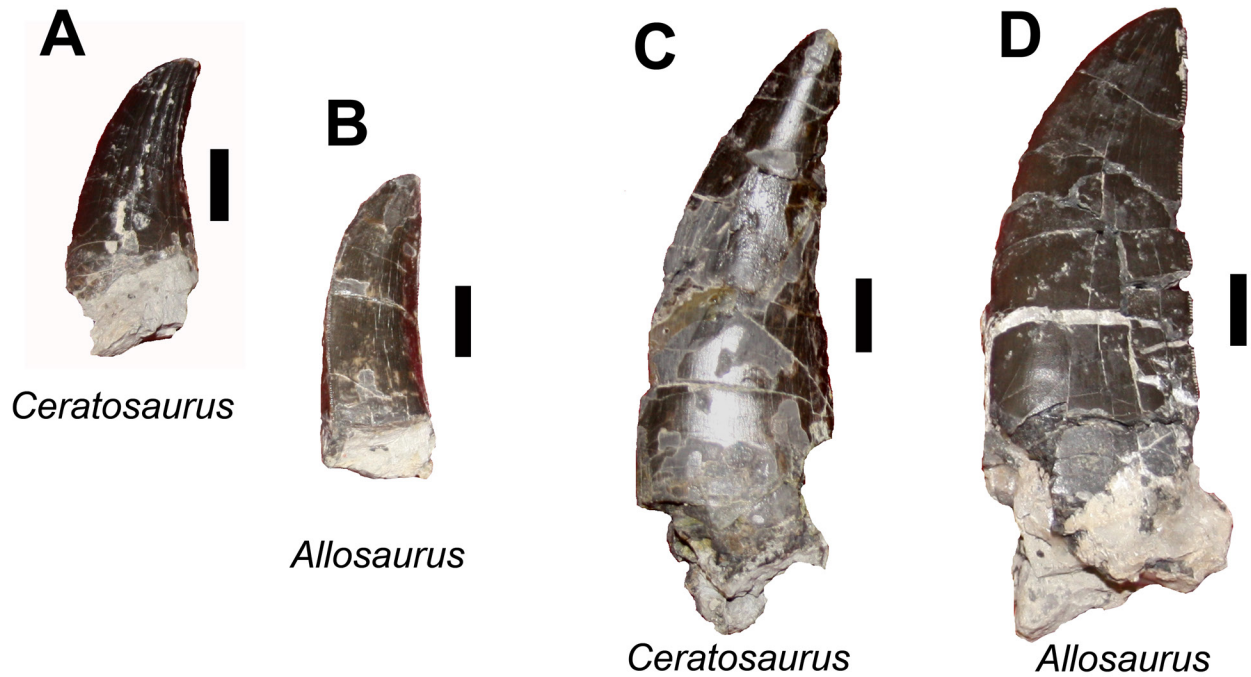
Figure 16. Theropod teeth from the Mygatt-Moore Quarry, just a few of many. (A) Anterior tooth of *Ceratosaurus*, showing lingual ridges. (B) Anterior tooth of *Allosaurus*, note lack of lingual ridges. (C) Laterally compressed and finely serrated maxilla or dentary tooth of *Ceratosaurus*. (D) Large but less laterally compressed and more coarsely serrated maxilla or dentary tooth of *Allosaurus*. All scale bars = 1 cm.

posterior cervical to anterior dorsal vertebrae (figures 15C and 15D). At least one small tooth of a goniopholidid crocodylomorph was found at the quarry as well, but no other such material has been found in nearly 30 years of excavations.

Clade DINOSAURIA
Order SAURISCHIA
Suborder THEROPODA
Family CERATOSAURIDAE
CERATOSAURUS NASICORNIS

Ceratosaurus is represented in the fauna by nine isolated shed teeth characterized by either ridged lingual enamel surfaces (in the case of mesial teeth of the dentary and premaxilla) or by large strongly laterally compressed, finely serrated distal teeth of the dentary and maxilla (figure 16A; Gilmore, 1920; Madsen, 1976; Madsen and Welles, 2000). The holotype of *Ceratosau-* *rus* (USNM 4735) is from the Marsh-Felch Quarry in Garden Park, near Cañon City, Colorado (Gilmore, 1920). *Ceratosaurus magnicornis* was named from a partial skull and skeleton from the Fruita Paleontological Area, and *C. dentisulcatus* was named from another partial skull and skeleton from the Cleveland-Lloyd Dinosaur Quarry (Madsen and Welles, 2000; Sanders and Smith, 2005). Rauhut (2003) suggested that the two more recently named species of *Ceratosaurus* from the Morrison Formation were not sufficiently differentiated from the type species, and Carrano and Sampson (2008) formally synonymized *C. magnicornis* and *C. dentisulcatus* with *C. nasicornis*. Although this taxon is only identified from teeth out of the Mygatt-Moore Quarry they are tentatively referred to *Ceratosaurus nasicornis*, because there are no differences between the Mygatt-Moore material and the other specimens.

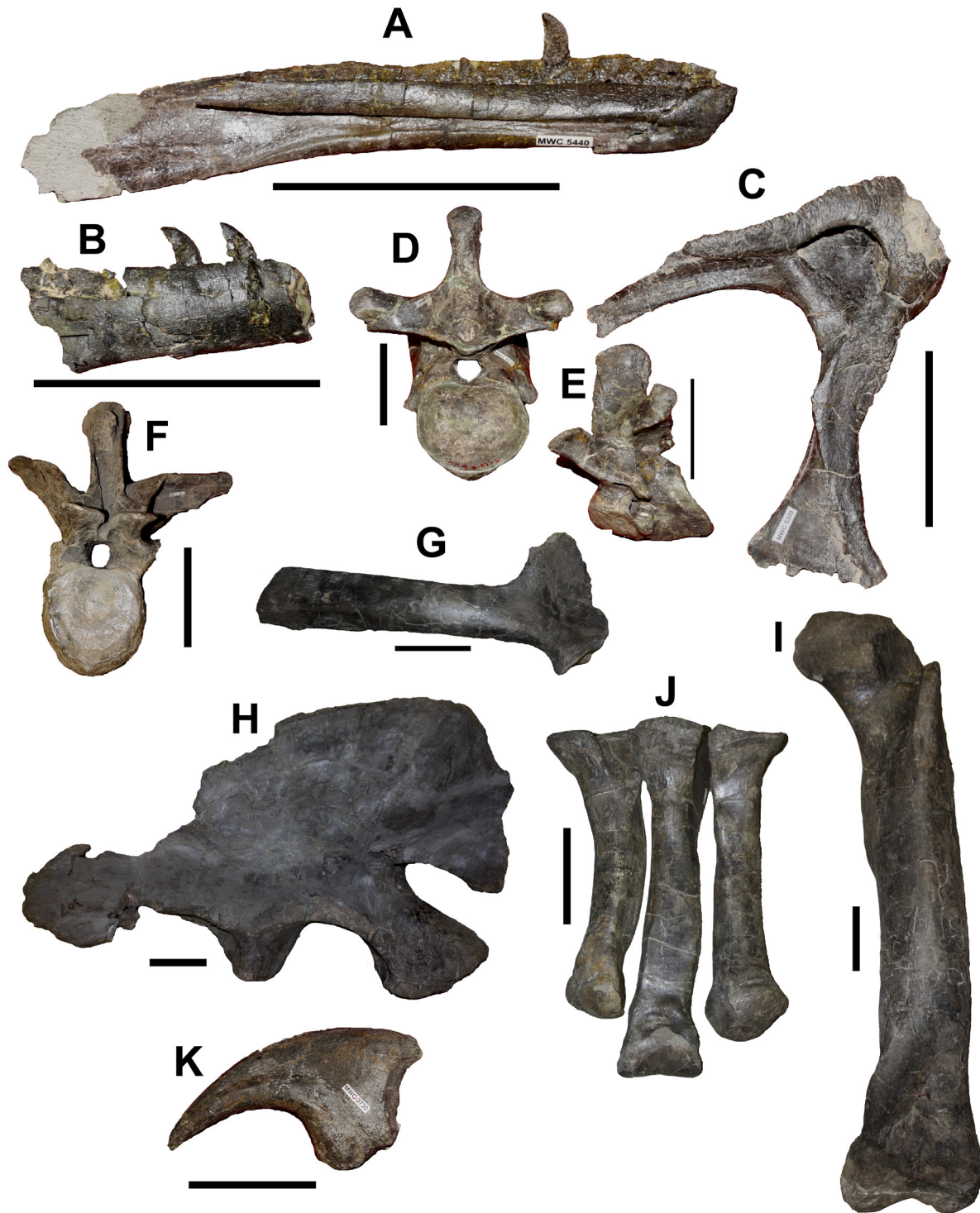*Ceratosaurus* is relatively common in the area

Figure 17. Skeletal material of *Allosaurus* from the Mygatt-Moore Quarry. (A) Left dentary of juvenile in lingual view, MWC 5440. (B) Right dentary fragment in labial view, MWC 5441, juvenile and associated with A, probably the same individual. (C) Left lacrimal in lateral view, MWC 5309. (D–E) Cervical vertebra, MWC 4010, in posterior and left lateral view. (F) Dorsal vertebra in anterior view, MWC 2861. (G) Right scapula in lateral view. (H) Right ilium in lateral view. (I) Left femur in anterior view. (J) Metatarsals II–IV. (K) Manus claw, MWC 3730. All scale bars = 10 cm.

around Mygatt-Moore, as it has been found at three other sites nearby: (1) the Twin Juniper Quarry, just 800 m south of Mygatt-Moore in Rabbit Valley, produced a partial skeleton of an articulated *Apatosaurus* and a single, large, shed tooth of *Ceratosaurus*, and (2) two sites in the nearby Fruita Paleontological Area, just 25 km to the east. These Fruita Paleontological Area specimens include the partial skeleton at the Eriksen Ceratosaur Quarry (Madsen and Welles, 2000; Sanders and Smith, 2005) and isolated teeth found at the Tom's Place Quarry (J.R. Foster, personal observation).

Clade TETANURAE
Family ALLOSAURIDAE
ALLOSAURUS FRAGILIS

Bones of *Allosaurus* are the most abundant vertebrate fossils at the Mygatt-Moore Quarry (Foster and others, 2007). This theropod is represented by more than 240 elements and at least 360 teeth in the quarry (figures 16B and 16D). Represented elements include skull, girdle, and limb elements, with dorsal and caudal vertebrae particularly abundant (figure 17). The material is identified as *Allosaurus* based on the presence of (1) a single lateral pneumatic fossa on the cervical centra (versus two in *Ceratosaurus*), (2) absence of prespinal chonos on the dorsal vertebrae (versus presence in *Ceratosaurus*), (3) tapering of neural spines of anterior- to mid-caudal vertebrae so that the distal end is narrower than the base in lateral view ("beveled cranial margin of the spine" in Holtz and others, 2004; distal end and base same width in lateral view in *Ceratosaurus*), (4) scapula with a less expanded proximal end than in *Ceratosaurus*, and (5) tibia with the astragalus contact ridge on the antero-distal surface that rises well up the shaft (versus very low in less derived theropods). None of the theropod material out of the Mygatt-Moore Quarry is referable to the Megalosauridae or *Torvosaurus*. Teeth are identified as *Allosaurus* based on the lack of lingual ridges on the anterior teeth and on the smaller size of the tooth crown, less lateral compression, and moderate-size serrations relative to *Ceratosaurus* and *Torvosaurus* (Bakker and Bir, 2004).

There are several named species of *Allosaurus*, and although few authors agree on which are valid (e.g.,

A. atrox and *A. fragilis* in Paul, 1988; *A. fragilis* and *A. maximus* in Smith, 1996, 1998), it is possible that only three species of allosaurids were present during Morrison times: the stratigraphically older-ranging *Allosaurus* n. sp. (Chure, 2000), the more common (and more robust) *A. fragilis* (Madsen,1976), and the rare and stratigraphically high *Saurophaganax maximus* (Chure, 1995; see Rauhut, 2003, and Holtz and others, 2004). Dalman (2014) named *A. lucasi* based on material from southwestern Colorado, although this taxon has not yet been addressed by others. Carpenter (2010) documented significant variation in the *Allosaurus fragilis* population from the Cleveland-Lloyd Dinosaur Quarry, which suggests that some of the variation used to define species of *Allosaurus* in the Morrison Formation may be suspect. The material of the Mygatt-Moore Quarry is not large and robust enough to be *S. maximus* but is more robust than *Allosaurus* n. sp. The complete dorsal vertebrae from Mygatt-Moore lack the accessory horizontal processes along the bases of the neural spines seen in *S. maximus* (Chure, 1995). Although autapomorphies of *Allosaurus* nov. sp. are missing from the Mygatt-Moore material due simply to lack of elemental overlap, the overall robustness of the vertebrae and girdle elements differentiates this material from that species. Additionally, a left lacrimal of *Allosaurus* from the Mygatt-Moore Quarry preserves the pneumatic recesses at the base of the cornual process; the presence of these is one of the autapomorphies of *A. fragilis* (Chure, 2000). The Mygatt-Moore Quarry material is therefore referred to this species.

Suborder SAUROPODA
Family DIPLODOCIDAE
Subfamily APATOSAURINAE
Genus *APATOSAURUS*

A large number of the sauropod elements out of the Mygatt-Moore Quarry may be referred to the diplodocid genus *Apatosaurus,* with all regions of the skeleton present and cervical and caudal vertebrae particularly abundant (figure 18). The generic identification is based on the following characters: (1) short and robust cervical ribs, (2) cervical ribs set well below and lateral to the centrum, (3) anterior caudal vertebrae have "wing-like"

Figure 18. Skeletal material of the *Apatosaurus* from the Mygatt-Moore Quarry. (A–B) Cervical vertebra MWC 1916 in left lateral and ventral views. (C–D) Cervical vertebra MWC 3829 in left lateral and anterior views. (E–F) Cervical vertebra in left lateral and dorsal views. (G) Posterior cervical vertebra in anterior view with associated dorsal rib and chevron, as preserved in quarry. (H) Close-up of cervical rib of cervical vertebra. (I–J) Caudal vertebra in anterior and right lateral views. (K) Large left femur measuring 1876 mm overall length; robusticity index for this element puts it in a range of overlap between slender *Apatosaurus* and robust *Diplodocus*, so identification is tentative. (L) Right tibia in posterior view. All scale bars = 10 cm except for K which is 25 cm.

caudal ribs (similar to *Diplodocus* and *Barosaurus*) but generally lack well-developed lateral pneumatic fossae (pleurocoels) in the centra, (4) coracoids with roughly quadrangular lateral profile, and (5) proximal condyles of the ulna sub-equal in length (Upchurch and others, 2004).

The material from the Mygatt-Moore Quarry may be referred to Apatosaurinae based on the following synapomorphies of Tschopp and others (2015; numbers in parentheses refer to their synapomorphy identifiers): (1) cervical ribs project well beneath centrum so that the diapophysis/tuberculum is approximately the same length as the posterior process, (2) no paired pneumatic fossae on the ventral surface of anterior cervical vertebrae, and (4) anterior process of posterior cervical ribs is absent or reduced to a short bump-like process. Because we treat the clade Apatosaurinae of Tschopp and others (2015; *Apatosaurus* + *Brontosaurus*) as consisting of several species but all within *Apatosaurus* (Foster and Peterson, 2016), we identify the Mygatt-Moore material as belonging to *Apatosaurus*.

APATOSAURUS CF. *LOUISAE*

By Upchurch and others (2004) criteria, the *Apatosaurus* material from the Mygatt-Moore Quarry may best be referred to the species *A.* cf. *louisae,* first identified from Dinosaur National Monument (Gilmore, 1936). Among the recognized species of Morrison apatosaurs, *A. ajax* and *A. parvus* may be ruled out as candidate species for the Mygatt-Moore material due to the cervical vertebrae not having a width:height ratio of 1.5 or greater and to the scapular acromial ridge being at less than a 90-degree angle to the long axis of the scapular blade, respectively. Foster (2015), however, noted that the interspecific variation in these characters among apatosaurines was slight and that, regardless, the small sample size left the characters potentially statistically insignificant. The Mygatt-Moore material is in some respects similar to *A. excelsus* by Upchurch and others' (2004) criteria but bears greater similarity to material of *A. louisae.* As in *A. excelsus,* the cervical ribs terminate anterior to the posterior end of the centrum; as in *A. louisae,* the proximal ends of the sacral ribs are on the anterior part of their respective centra, the ante-

rior caudal centra are ventrally keeled (a "ventral midline ridge"), and the beveled glenoids of the scapulae face anteriorly, ventrally, and medially (Upchurch and others, 2004). The Mygatt-Moore material is thus tentatively assigned to *Apatosaurus* cf. *louisae.*

Identifying the Mygatt-Moore material to species based on synapomorphies identified by Tschopp and others (2015) is more ambiguous. The quarry's apatosaurine material includes few skull elements, but of four autapomorphies of *A. ajax*, three are in the skull; the fourth, "elliptical depression between the lateral spinal lamina of caudal neural spines and the postspinal lamina," is true of most anterior caudal vertebrae from the site. (A possible juvenile apatosaur basioccipital-basal tubera, figures 21A and 21B, does not seem to match autapomorphy 3 for *A. ajax*.) However, there are 28 autapomorphies for *A. louisae* (Tschopp and others, 2015) and of these the Mygatt-Moore material is clearly lacking characters 11 and 12 (the rest of them are unclear in the preserved material or cannot be confirmed because the material was found disarticulated). Of seven autapomorphies of *Brontosaurus excelsus* listed by Tschopp and others (2015), most are ambiguous regarding the disarticulated Mygatt-Moore material, but character 1 does not match the type and referred material (some Mygatt-Moore cervical vertebrae do have median tubercles) and character 3 is highly variable within the Mygatt-Moore material. The Mygatt-Moore apatosaurine material does not match characters 5, 8, or 9 for *B. parvus* (Tschopp and others, 2015; character 1 is true only of a few anterior cervical vertebrae, but not most cervicals among Mygatt-Moore material), and it matches character 5 but not character 2 for *B. yahnahpin* (Tschopp and others, 2015).

Based on these results, it is difficult to assign the Mygatt-Moore material with confidence to any one apatosaurine species defined in Tschopp and others (2015). Most elements out of the quarry either lack the right data for most characters or their disarticulated condition prevents certainty when characters depend on skeletal position. Most importantly, for many characters for which we can identify their states, the material is contradictory by matching some autapomorphic characters, but not matching others. This would not be
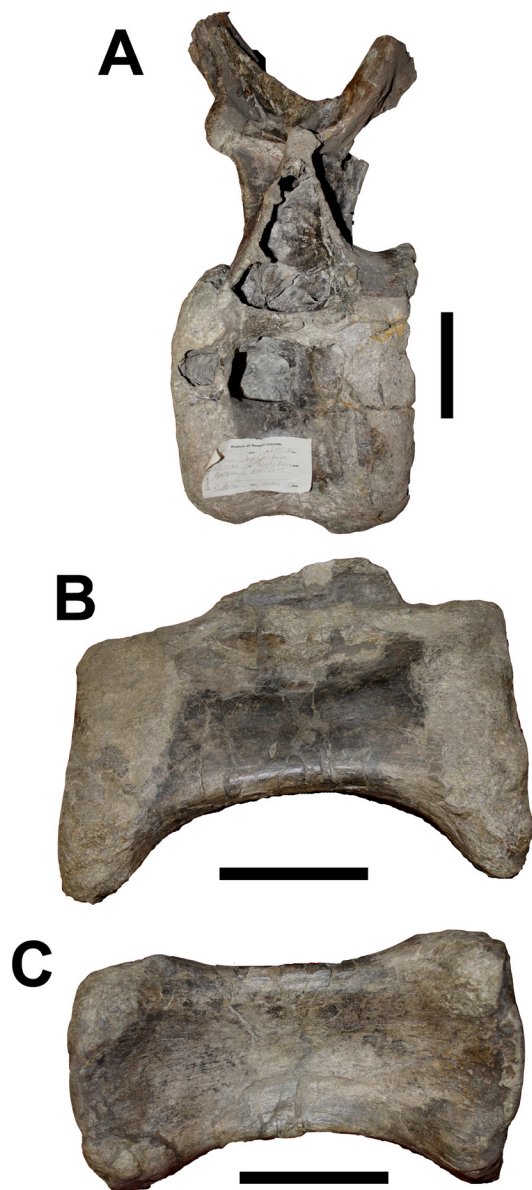
We therefore are relying, until contradictory evidence is found, on the autapomorphies of Upchurch and others (2004) and identify the Mygatt-Moore apatosaurine material as *A.* cf. *louisae*.

Discussion – Some of the material assigned to *Apatosaurus* consists of juvenile elements, including at least one cervical rib, a femur and a scapula (see SAUROPODA MISC. section for figures). Juvenile elements have been recognized from the Mygatt-Moore Quarry for some time, and juvenile material in general is not especially rare in the Morrison Formation (Foster, 2005a). A very large, complete femur from the quarry (1876 mm in length) may belong to *Apatosaurus* (figure 18K) and represents the second longest complete femur ever found in the formation (after the type specimen of *Brachiosaurus* FMNH 25107). In 2016, Museums of Western Colorado crews collected the nearly complete skull of an apatosaurine (with cervicals 1–3 nearly in articulation) from Mygatt-Moore (McHugh and others, 2017); this specimen is still being prepared.

Subfamily DIPLODOCINAE
DIPLODOCINAE INDET.

Eight elements, all caudal vertebrae, may be referred to non-apatosaurine diplodocids based on the "wing-like" caudal ribs, deep pleurocoels, and ventral excavations of the anterior caudal vertebrae. The mid-caudal vertebrae are elongate with small pleurocoels and groove-like ventral excavations (figure 19). These caudals are distinct from those of *Apatosaurus* and are similar to *Diplodocus* and *Barosaurus* (Hatcher 1901; McIntosh, 1990; Ostrom and McIntosh, 1999). Distinguishing caudals of *Diplodocus* and *Barosaurus* is rather difficult, as most of the differences between these two Morrison diplodocines are in the cervical vertebrae and the number of dorsals (Curtice, 1996; McIntosh, 2005). *Barosaurus* may have mid-caudal centra that are relatively shorter and less deeply excavated ventrally than in *Diplodocus* (McIntosh, 1990; Foster, 1996), but quantifying these differences is difficult. The material from the Mygatt-Moore Quarry is therefore identified only as Diplodocinae indet. Numerous isolated teeth of diplodocids are found in the quarry, and some of them may have belonged to *Diplodocus* or *Barosaurus* individuals, but

Figure 19. Elements of Diplodocinae indet. from the Mygatt-Moore Quarry. (A) Right lateral view of an anterior caudal vertebra collected in 1989, MWC uncataloged. (B–C) Mid-caudal vertebra in lateral and ventral view, MWC 3707. All scale bars = 10 cm.

unexpected if there are multiple species in the sample, but we assume the Mygatt-Moore apatosaurine material represents a single species because most other large dinosaur quarries in the Morrison Formation contain a single species of each genus of sauropod (Foster, 2003).

Figure 20. Posterior dorsal vertebra of *Camarasaurus* from the Mygatt-Moore Quarry. (A) Anterior view. (B) Posterior view, MWC 2864. Scale bars = 10 cm.

the teeth cannot be distinguished from *Apatosaurus*.

Clade MACRONARIA
Family CAMARASAURIDAE
CAMARASAURUS SP. CF. *LENTUS*

Camarasaurus sp., the most abundant dinosaur in the Morrison Formation overall (Foster, 2003), is rare at the Mygatt-Moore Quarry. It is represented by 23 bones, mostly caudal vertebrae, a braincase, two dorsal vertebrae, a scapula (distally expanded), three pelvic elements, several limb elements, a dentary fragment with teeth of a juvenile, and 35 shed teeth, mostly of adults, but with some juveniles represented. These elements are characteristic of *Camarasaurus* within the Morrison Formation in having (1) anterior caudals with simple caudal ribs, no pleurocoels, rounded unexcavated ventral outlines, and short transversely expanded dorsal ends of the neural spines, (2) dorsal vertebrae with transversely expanded ("fan-shaped") neural spines (figure 20), (3) particularly elongated metacarpals, (4) robust, spoon-shaped teeth, and (5) antero-posteriorly

narrow, transversely elongate supratemporal fenestra, compared with diplodocids (Osborn and Mook, 1921; Gilmore, 1925; Berman and McIntosh, 1978; Madsen and others, 1995). The two dorsals do not preserve the neurocentral sutures well enough to determine if they are the high-pedicel-bearing type of *Camarasaurus grandis* or the low morphology of *C. lentus* (McIntosh, 1990), but all specimens are smaller than those assigned to *C. supremus*. The caudal neural spines appear to be gradually transversely expanded near the distal ends, in the manner of *C. lentus* and not like *C. grandis* or *C. supremus* (Ikejiri, 2005).

SAUROPODA MISC.

Many specimens cannot be assigned to lower taxonomic levels but are clearly sauropod elements. Most of these belong to adult sauropods, but a number of juveniles are represented, some of them very young. Juvenile sauropod elements represented in the quarry include a diplodocid basioccipital (figures 21A to 21C), a *Camarasaurus* dentary fragment (figure 21D), a possible *Apatosaurus* cervical (figure 21E), a possible *Camarasaurus* dorsal (figure 21G), and several *Apatosaurus* elements (figures 21H to 21J). The sample represents at least three juvenile sauropods (MNI).

Order ORNITHISCHIA
Clade ANKYLOSAURIA
Family POLACANTHIDAE
MYMOORAPELTA MAYSI

The polacanthid ankylosaurian *Mymoorapelta* is represented by more than 160 elements from all parts of the skeleton (figure 22; Kirkland and Hunt-Foster, in preparation), making this genus the third most abundant vertebrate in the Mygatt-Moore Quarry. Particularly abundant are lateral spines, osteoderms, dorsal and caudal vertebrae. Based on comparative size of elements, there are at least two individuals present; occurrence of some ankylosaurs osteoderms stratigraphically high within the quarry suggests that more than two individuals may in fact be represented. *Mymoorapelta* was the first Jurassic ankylosaur identified in North America (Kirkland and Carpenter, 1994). Polacanthid anky-
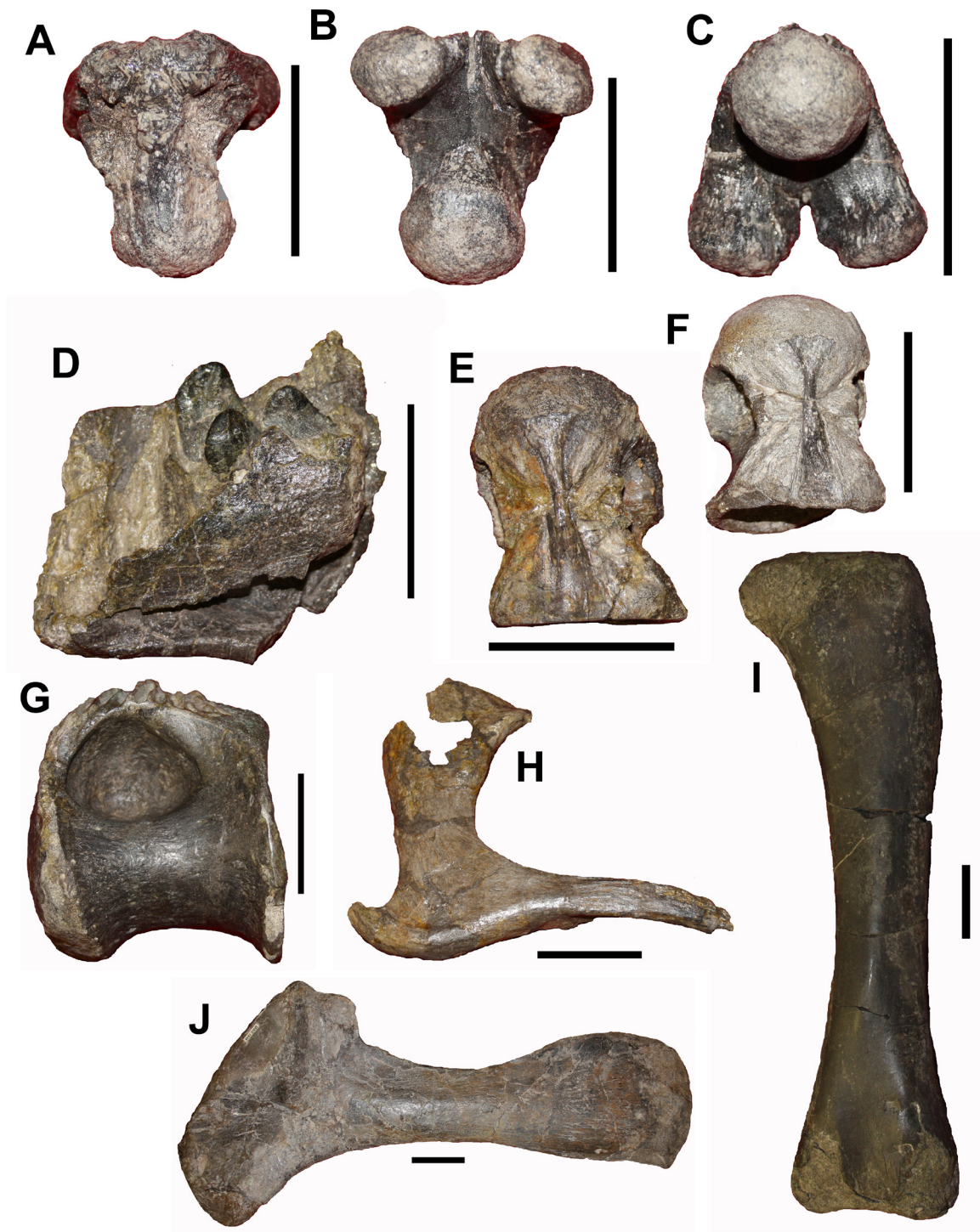
Figure 21. Juvenile sauropod specimens from the Mygatt-Moore Quarry. (A–C) Basioccipital of a juvenile diplodocid in dorsal, ventral, and posterior view, MWC 7224. (D) Fragment of right dentary of sub-adult *Camarasaurus* with several teeth in lingual view, MWC 5009. (E–F) Two cervical vertebrae of very young indeterminate sauropods in dorsal view, MWC 1917 and MWC 3828. (G) Dorsal vertebra of indeterminate juvenile sauropod (possibly *Camarasaurus*) in left lateral view, MWC 3630. (H) Left cervical rib of young *Apatosaurus*, MWC 1925. (I) Left femur of juvenile *Apatosaurus* in anterior view, MWC 5439. (J) Left scapula of juvenile *Apatosaurus* in lateral view, MWC 1848. All scale bars = 5 cm.
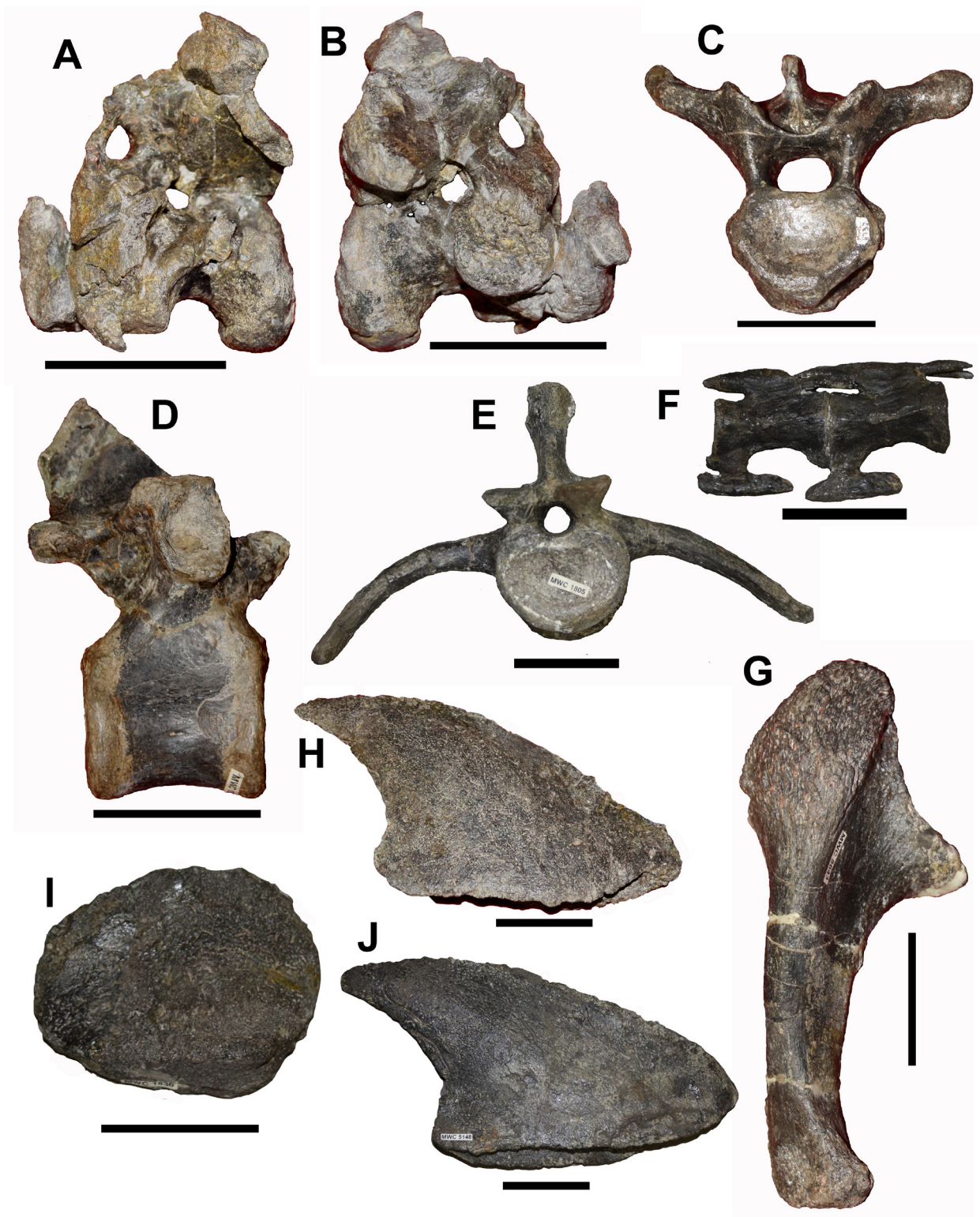
Figure 22. *Mymoorapelta* elements from the Mygatt-Moore Quarry. (A–B) Braincase fragment in left lateral (internal) and right lateral views, MWC 5435. (C) Cervical vertebra in anterior view, MWC 6737. (D) Dorsal vertebra in right lateral view, MWC 1801. (E) Anterior caudal vertebra in anterior view, MWC 1805. (F) Two distal caudal vertebrae. (G) Ulna, MWC 5643. (H) Lateral spine, MWC 2678. (I) Osteoderm. (J) Lateral spine. All scale bars = 5 cm.

losaurs have since been found at a number of other sites in other areas of the Morrison Formation, including western Colorado, Utah, and Wyoming (e.g., Kirkland and others, 1998; Tremaine and others, 2015).

Clade NEORNITHISCHIA
OTHNIELOSAURUS CONSORS

Othnielosaurus was found in the quarry in 2008, the first new dinosaur taxon for the quarry in 18 years at the time. It is represented by a small maxilla or dentary fragment with three teeth in matrix (figure 23; MWC 5966). The teeth are tiny (0.9–1.4 mm in mesiodistal length), diamond-shaped, and contain two to four denticles each, characteristic of some *Othnielosaurus* from other localities (Galton, 1983, 2007) and perhaps distinct from other small neornithischians of the Morrison Formation such as *Drinker* (Bakker and others, 1990), and very distinct from *Dryosaurus* (Galton, 1981). The teeth also lack the cingula of *Stegosaurus* and ankylosaurs. Carpenter and Galton (in press) suggest that *Othnielosaurus* is a junior synonym of *Drinker nisti*.

DINOSAURIA? INDET.
Eggshell
Angustiprismatic Morphotype

A 43 x 34 mm fragment of what was estimated to have been an originally 10 cm diameter egg was found in the Mygatt-Moore Quarry during the 1990s (figure 24). This calcitic eggshell is of an unnamed type that is considered a dinosauroid-prismatic basic type, and is also unique to the Mygatt-Moore Quarry within the Morrison Formation (Bray and Hirsh, 1998).

Preserved Taxa—"Fish Layer"
Phylum MOLLUSCA
Class GASTROPODA

Several indeterminate gastropods have been identified in the "fish layer" beds. These are not well preserved and are difficult to identify.

Phylum ARTHROPODA
Clade CRUSTACEA
Class BRANCHIOPODA
Order DIPLOSTRACA

A number of "conchostracans" have been found in the claystone just below the "fish layer" (Kirkland and Carpenter, 1994) (figure 25). All are in light gray mudstone devoid of plant material. The term conchostracan has been abandoned after determination that the group was paraphyletic. The taxa formerly within "Conchostraca" are now placed within several families within the Diplostraca (Martin and Davis, 2001).

Figure 23. Neornithischian jaw fragment with three teeth, MWC 5966, probably *Othnielosaurus*. Scale bar = 1 cm.

Figure 24. Dinosaur egg in the Mygatt-Moore Quarry, photo taken in the field. Counterpart in upper left; egg still in situ in lower right below U.S. nickel, MWC 1900 and 1901. Photo courtesy of Jim Kirkland, Utah Geological Survey.
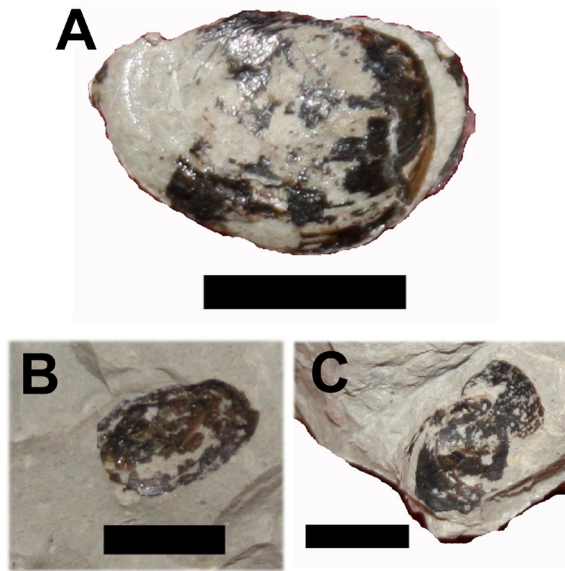
Figure 25. Diplostracan arthropods ("conchostracans") from the Morrison Formation, including the upper part of the Mygatt-Moore Quarry just below the "fish layer" in gray claystone matrix without plant material. (A) *Lioestheria* sp., MWC 1854, from the Wolny Site near Grand Junction, Colorado (Lucas and Kirkland, 1998). (B) Unidentified diplostracan from upper levels of Mygatt-Moore, MWC 1862. (C) Unidentified diplostracan from upper levels of Mygatt-Moore, MWC 1865. All scale bars = 5 mm.

These bivalve crustaceans are capable of dormancy in dry habitats and are thus able to survive in ephemeral wetlands.

<div align="center">

Class MALACOSTRACA
Order DECAPODA
Unnamed crayfish

</div>

A nearly complete crayfish fossil was found in the "fish layer" during the 1990s, and this specimen has not yet been described or named. A second fragmentary crayfish specimen was discovered at the site in 2005 (figure 26I).

<div align="center">

Phylum CHORDATA
Superclass OSTEICHTHYES
Clade PALAEONISCOIDEA
MORROLEPIS SCHAEFFERI

</div>

Several specimens of the coccolepid palaeoniscoid *Morrolepis* have been found since the description of the type specimen by Kirkland (1998) (figures 26B to 26D). Some of these specimens show details of caudal and dorsal fin morphology better than the type, due to better preservation. Another specimen preserves a skull, possibly of *Morrolepis* (figure 26G).

<div align="center">

Class ACTINOPTERYGII
Subclass NEOPTERYGII
Order INDET.
"HULETTIA" HAWESI

</div>

The type specimen of *"Hulettia" hawesi* is from the Fruita Paleontological Area, but the species was soon after identified from the "fish layer" at the Mygatt-Moore Quarry. There are now at least five specimens known from the "fish layer," including a scale patch, two scale patches with partial caudal fins, an anterior third of a fish with the skull, and a nearly complete fish except for the skull (figure 26A). The latter two specimens have been found since 2005. This species probably belongs in a separate genus from *Hulettia*, from the marine Sundance Formation (J. Kirkland, Utah Geological Survey, verbal communication, 2003), which is why the generic name is in quotations here.

<div align="center">

Infraclass TELEOSTEI
Order LEPTOLEPIFORMES
Family LEPTOLEPIDAE
CF. *LEPTOLEPIS*

</div>

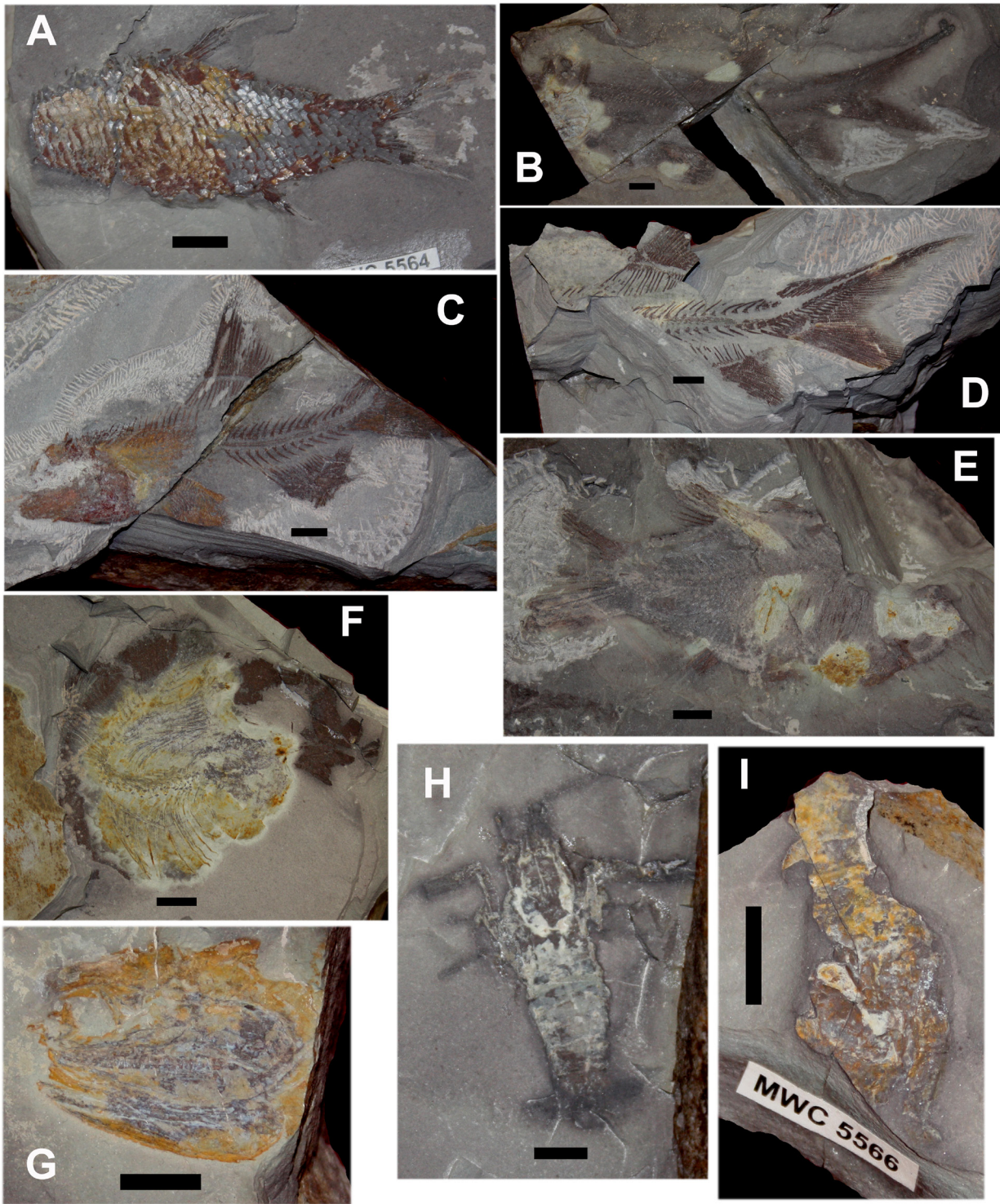A partially complete teleost fish was described by

Figure 26. Species from the "fish layer" above the Mygatt-Moore Quarry. (A) The possible semionotid fish "*Hulettia*" *hawesi*, MWC 5564. (B) The coccolepid fish *Morrolepis schaefferi*, holotype, MWC 440. (C–D) Referred specimens of *Morrolepis*, MWC 5306 and MWC 5305. (E) Teleost cf. *Leptolepis*, MWC 3722. (F) Actinopterygii indet., MWC 5941. (G) Skull of possible *Morrolepis*, MWC 5307. (H) Undescribed crayfish. (I) Partial crayfish, MWC 5566. All scale bars = 1 cm.

Kirkland (1998) out of the "fish layer" (figure 26E). This specimen is missing most of the skull and is the only confirmed teleost from the site.

ACTINOPTERYGII INDET.

Several other specimens are known from the "fish layer," most consisting of partial or isolated fins, and these generally cannot be identified to a lower taxonomic level. One partial fish skeleton, preserved in the left lateral view in its posterior portion and in oblique right-dorsal view in its anterior portion (figure 26F), is somewhat more complete but still awaits identification.

TAPHONOMY

Sample Size

Over 30 years of work at the Mygatt-Moore Quarry, several thousand bones have been collected and mapped. The quarry map contains nearly 2400 mapped elements, whereas the census of the data in the Museums of Western Colorado collections consists of more than 900 elements.

Relative Abundances of Fossil Vertebrates

The sample of 897 identifiable bones indicates that the Mygatt-Moore Quarry is dominated by sauropod dinosaurs and the theropod *Allosaurus fragilis* (figure 27). By number of elements, the most abundant vertebrate taxa by far are indeterminate sauropods and *Apatosaurus* cf. *louisae*, followed by *Allosaurus* and then *Mymoorapelta* (figure 27A). All other taxa are rare, including the otherwise common Morrison sauropod *Camarasaurus*. By minimum number of individuals, *Allosaurus* is most abundant followed by *Apatosaurus* and then indeterminate sauropods (figure 27B).

Allosaurus is also particularly abundant based on the tooth sample out of the quarry (figure 28). The tooth sample indicates a normal distribution of basal crown length of *Allosaurus* teeth and a larger sample, contrary to what was found previously with a smaller example from the quarry by Foster (2005b).
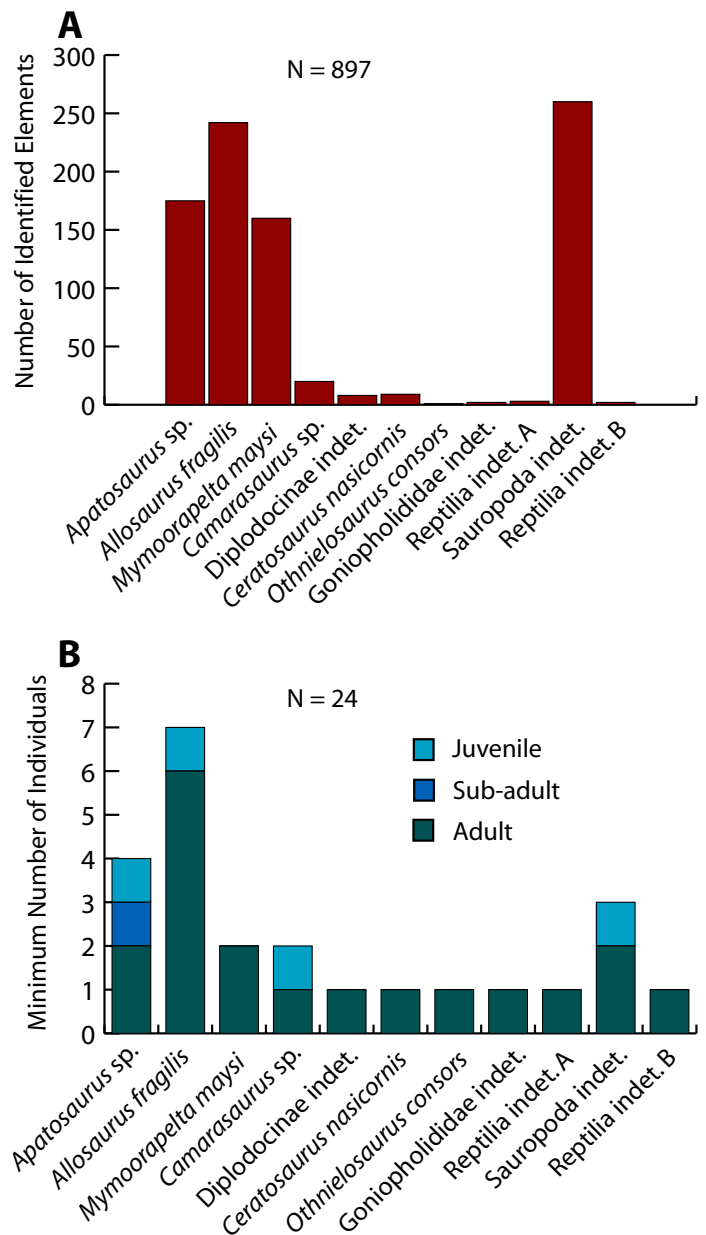
Figure 27. Relative abundances of vertebrate taxa from the main quarry layer at the Mygatt-Moore Quarry. (A) By number of identified elements. (B) By minimum number of individuals and with relative age designated.

Preserved Elements

The total sample inventoried in the Museums of Western Colorado, including taxonomically unidentifiable material, consisted of nearly 1900 elements (table 2). Although fragmentary bones were most abundant,
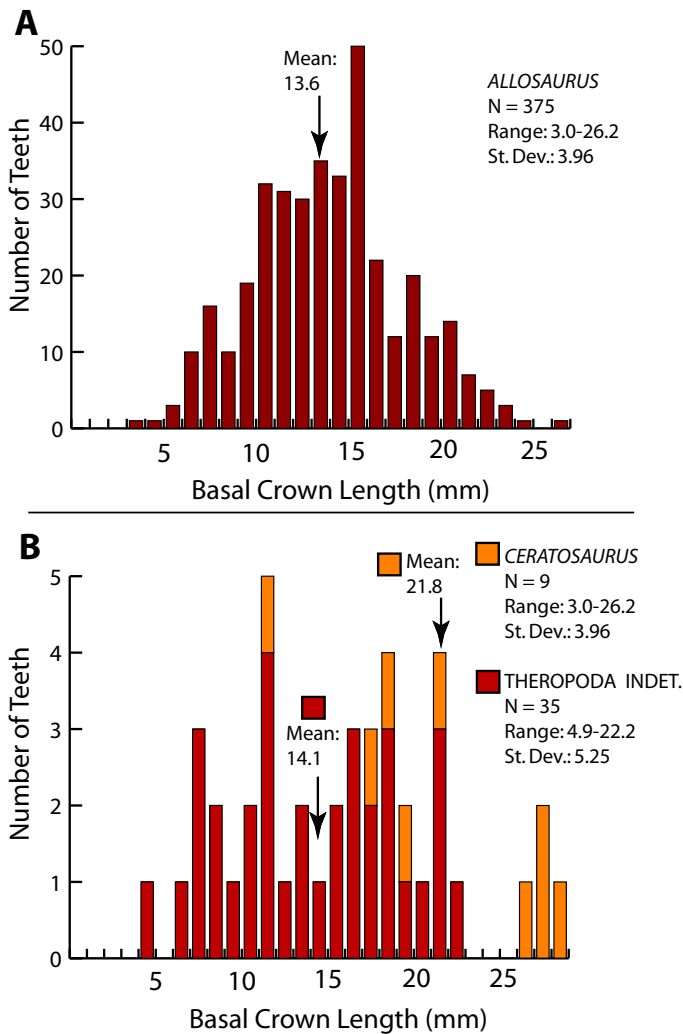
MYGATT-MOORE QUARRY THEROPOD TEETH

Figure 28. Size distributions of theropod dinosaur teeth from the Mygatt-Moore Quarry, measured along the basal crown length. (A) *Allosaurus*. (B) Theropoda indet. plus *Ceratosaurus*.

teeth, vertebrae, and ribs were well represented (figure 29). Girdle, limb, and dermal bones were about equally represented, and skull elements were comparatively rare.

An analysis of the preserved elements by modified Voorhies bone distribution groups (Voorhies,1969; Carpenter, 2013; see Methods) for the sauropods and *Allosaurus* subsamples of the inventoried collection (figure 30) indicates that the percentage representation of elements in highly transportable (Group 1) to trans-

Table 2. Mygatt-Moore Quarry bone sample by element. All taxa combined.

Element	Number of Identified Specimens
Cranial	
Braincases	4
Dentaries	4
Other skull elements	7
Teeth	438
Axial	
Cervical vertebrae	56
Cervical ribs (isolated)	5
Dorsal vertebrae	75
Dorsal ribs	86
Rib fragments	192
Sacra	6
Caudal vertebrae	190
Chevrons	54
Appendicular	
Scapulae	10
Coracoids	6
Humeri	10
Radii	4
Ulnae	3
Carpals	3
Metacarpals	15
Ilia	5
Pubes	7
Ischia	9
Femora	17
Tibiae	14
Fibulae	11
Astragali	4
Metatarsals	38
Phalanges	56
Unguals	22
Other	
Dermal spines	20
Osteoderms	70
Miscellaneous elements	25
Fragments	869
Total:	1897 bones
	438 teeth

port resistant (Group 3) categories closely matches the representation of the elements in the respective (sauropod and *Allosaurus*) skeletons. This suggests that the better-preserved, identifiable material from the quarry was not likely transported into the quarry area as an assemblage nor winnowed to its current condition with
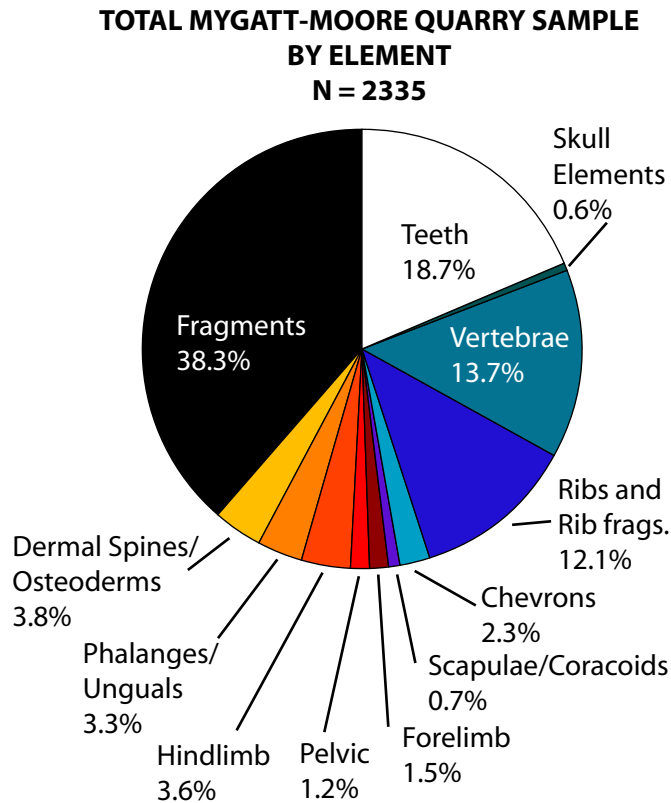
Paleontology, Taphonomy, and Sedimentology of the Mygatt-Moore Quarry, a Large Dinosaur Bonebed in the Morrison Formation, Western Colorado–Implications for Upper Jurassic Dinosaur Preservation Modes
Foster, J.R., Hunt-Foster, R.K., Gorman, M.A., II, Trujillo, K.C., Suarez, C.A., McHugh, J.B., Peterson, J.E., Warnock, J.P., and Schoenstein, H.E.

Figure 29. Frequency of bones from the Mygatt-Moore Quarry sample by element.

highly transportable elements washed elsewhere. Rather, the Voorhies element analysis results seem to indicate that at least the identifiable material was essentially autochthonous to the local quarry area (fragmentary and rounded; i.e., transported allochthonous material, however, is also abundant in the quarry).

Age Distribution

The main bone layer sample includes, by minimum number of individuals of dinosaurs and other vertebrates, four juveniles, one sub-adult, and 17 adult-sized animals (figure 31). Such a distribution with many adults, fewest number of sub-adults, and moderate representation of juveniles is suggestive of an attritional morality assemblage with delayed burial (Eberth and others, 2007, their figure 5.7). This argues against a non-selective catastrophic mortality for the animals preserved and indicates that the skeletal material was
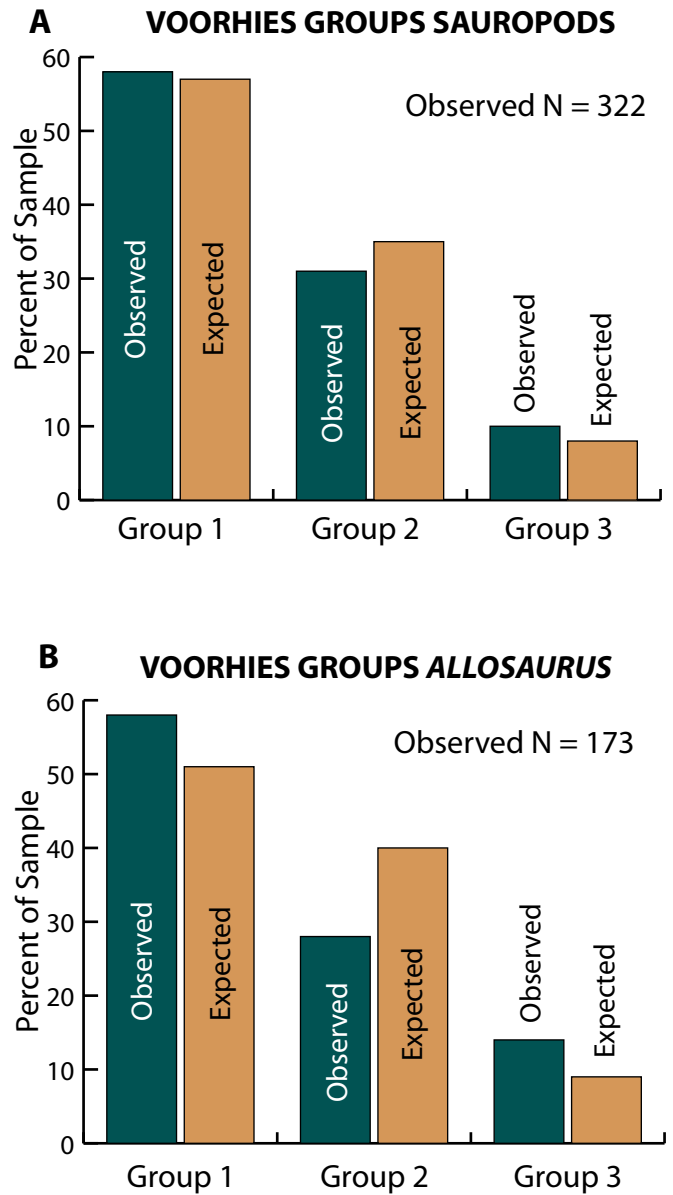
Figure 30. Voorhies group analysis for sauropod and *Allosaurus* bones from the Mygatt-Moore Quarry. Group 1 is highly transportable, Group 2 less so, and Group 3 is least transportable. Observed is the percentage of elements within each group actually preserved in the sample; Expected is the percentage of elements in the respective skeletons. Samples unusually high in Group 1 elements would be expected to have been perhaps washed into the area, whereas a Group 3-dominated sample suggests a lag deposit in which only the most transport-resistant elements are left in a winnowed assemblage. The fact that in both cases here, the observed distribution of elements is similar to what would be expected out of a skeleton suggests the bones are essentially autochthonous and are neither significantly transported in nor winnowed.
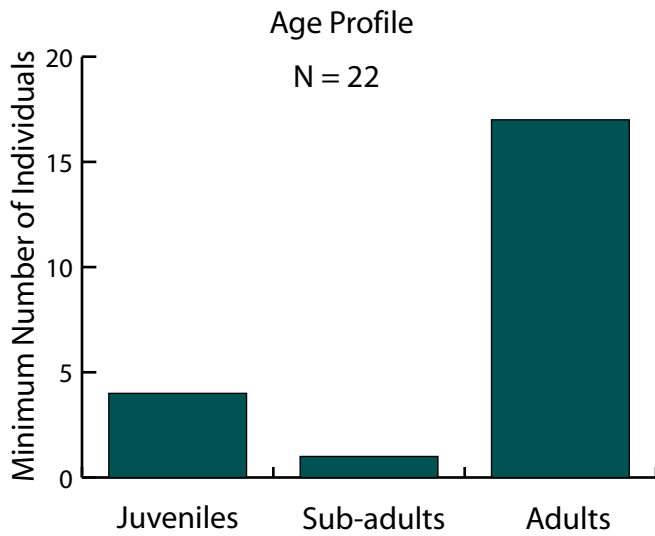
Age Profile

N = 22

Figure 31. Age profile of the vertebrates out of the Mygatt-Moore Quarry, discounting indeterminate reptiles. Sample is high in adults, lower in juveniles, but is mostly missing mid-sized animals.

exposed for some time before burial, which is consistent with other taphonomic factors noted about the site (see below).

Bone Distribution

The nearly 2400 mapped bones from the Mygatt-Moore Quarry show a pattern of disarticulation and only slight association in rare instances (figure 32). Of the entire mapped sample only eight bones are in articulation with at least one other one (three pairs of dorsal vertebrae and one pair of cervical vertebrae, all of *Apatosaurus*; two of the three dorsal pairs appear to be from the same sub-adult individual). This ratio of articulated bones to the total number (0.00337) is lower than for any other major quarries of the Morrison Formation studied here (table 3). The almost totally disarticulated nature of the sample out of the Mygatt-Moore Quarry has been one of its notable features since it was first worked. From the quarry map (figure 32) it is also apparent that the orientation and distribution of material in the quarry is random (see below); bones are scattered in all parts of the quarry, lightly in some areas but clustered in some others.

The main bone layer is approximately 1 m thick and the occurrences of bones within this interval are concentrated near the basal 33 cm or so. More than half of the bones collected from the 2000–2013 seasons were found in that lower third of the deposit (figure 33). Elements from the upper third accounted for only a little more than 15% of the sample. The vertical distribution of fossils in the quarry area was also illustrated qualitatively in sections by Kirkland and Carpenter (1994) and Kirkland (2006).

Based on the number of mapped bones to mapped area, there appear to be approximately 4.9 mapped bones per square meter of the quarry. This density, however, is based on the bones large enough to map and record. Because very small and fragmentary bones have been noted as common in the quarry, but have not historically been documented, an unexcavated square meter was selected from the eastern part of the quarry to excavate and collect everything found to record the density of material within this test area. This nearly cubic meter (m³) of matrix contained about 100 randomly distributed bones (figure 34); mostly these are small fragments, but the sample also included four theropod teeth. The results showed a relatively random orientation within the meter but concentrated in the lower portion. The fragments were mostly unidentifiable and small, with a mean volume of 6.78 cm³ and a maximum volume of about 47 cm³ (figure 35). The excavated m³ is thought to be typical of the deposit overall because it is from an area close to where large dinosaur bones have been excavated. It is from neither within the current excavation nor close to what appears to be the edge of the deposit to the east. The material was found within typical medium light-gray claystone containing abundant carbonized plant fragments. If the many small bone fragments randomly distributed within this 1 m³ indicate what is typical of the quarry, there may have been approximately 50,000 individual bone pieces within the about 500 m² of the quarry excavated so far. Extrapolated to the potential area of the quarry demonstrated by the drill coring (see above), the entire deposit may contain as many as 463,000 bones, based on the fully sampled single m³, and as many as 23,150 mappable bones, based on the density demonstrated by the quarry map (figure

MYGATT-MOORE QUARRY

Figure 32. Quarry map of Mygatt-Moore Quarry main quarry layer, through the 2013 season. Scale bars marked in meters.

Table 3. Articulation ratios for several larger quarries in the Morrison Formation.

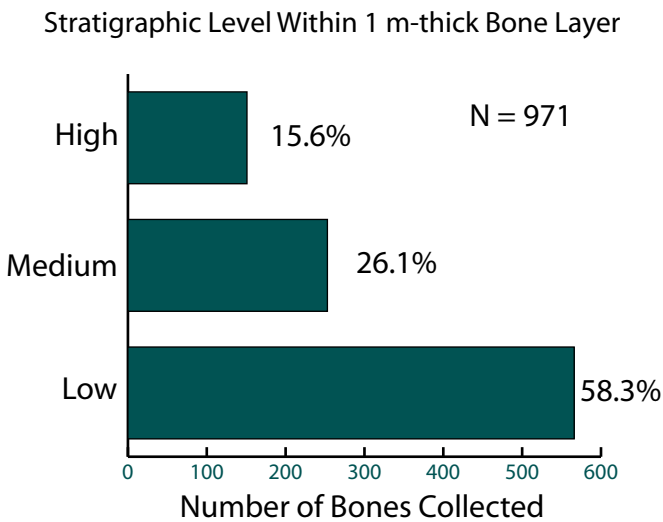| Quarry	State	Lithology	Number of Mapped Bones	Bones in Articulation	Articulation Ratio	Map Reference
Mygatt-Moore Quarry	CO	Mudstone	2372	8	0.00337	This paper
Cleveland-Lloyd Quarry	UT	Mudstone	6197	123	0.01984	Miller and others (1996)
Carnegie Quarry, DNM	UT	Sandstone	2993	1848	0.61744	G. York; Carpenter (2013)
Howe Quarry	WY	Siltstone	1668	644	0.38609	Bird (1985)
Howe-Stephens Quarry	WY	Mudstone	649	217	0.33436	Ayer (1999)
Poison Creek Quarry	WY	Mudstone	469	127	0.27079	Erickson, unpublished (1984)
Dry Mesa Quarry	CO	Sandstone	416	33	0.07933	Miller and others (1991)
Little Houston Quarry	WY	Siltstone	255	65	0.25490	Pagnac, unpublished (2014)

Figure 33. Stratigraphic distribution of vertebrate material within the main quarry layer showing concentration of most elements in the lower and middle thirds of the deposit. Each level is approximately 33 cm thick. (There is no correlation between bone size or volume and level at which they occur; large bones have been found high in the deposit, and many small ones are found low.)

32). The abundance of small fragmentary bones, along with larger better preserved bones and more complete dinosaur elements in the same deposit, may suggest two sources for the material.

As mentioned above, the quarry map (figure 32) appears to show a random orientation of the bones at Mygatt-Moore. Azimuth orientations of bones from the quarry, measured off the map and categorized as either bidirectional or unidirectional, suggest that indeed the orientation is random. Neither bidirectional bones nor those that are unidirectional demonstrate any strongly preferred azimuth orientation (figure 36) such as would be expected if there were current influence on the material (Toots, 1965). Random orientations of bones as demonstrated by figure 36 suggest scattering by scavenging and other process other than hydraulic current influence.

Bone Preservation and Modification

A large number of bones in the quarry are fairly well preserved and complete. Most of the identifiable elements that have been collected over the years are nearly complete, with only moderate degradation by abrasion, corrosion, weathering, and breakage. Among the bone modifications are green fractures that appear to have occurred when the bones were in or on the muddy matrix near the surface, well before lithification. Examples of these breaks include splintered, broken sauropod ribs (figures 37A and 37B), a broken and displaced *Allosaurus* metatarsal (figures 37E and 37F), and an *Allosaurus* distal tibia broken off before burial. A random survey of a subsample of the total collections inventory (446 specimens, or about 23.5% of the bone collection) indicates that approximately 61.6% of bones have post-mortem, pre-burial breaks that in many cases probably resulted from trampling. Only about 0.46% of the bones have pathologies (table 4). One of these includes a sauropod ulna with a slightly forked, distally-pointing bone spur along the shaft near the distal end of the element (MWC 5044).

Another common modification on bones is tooth marks left by carnivorous theropod dinosaurs. Approximately 4.62% of the bones out of the quarry have some
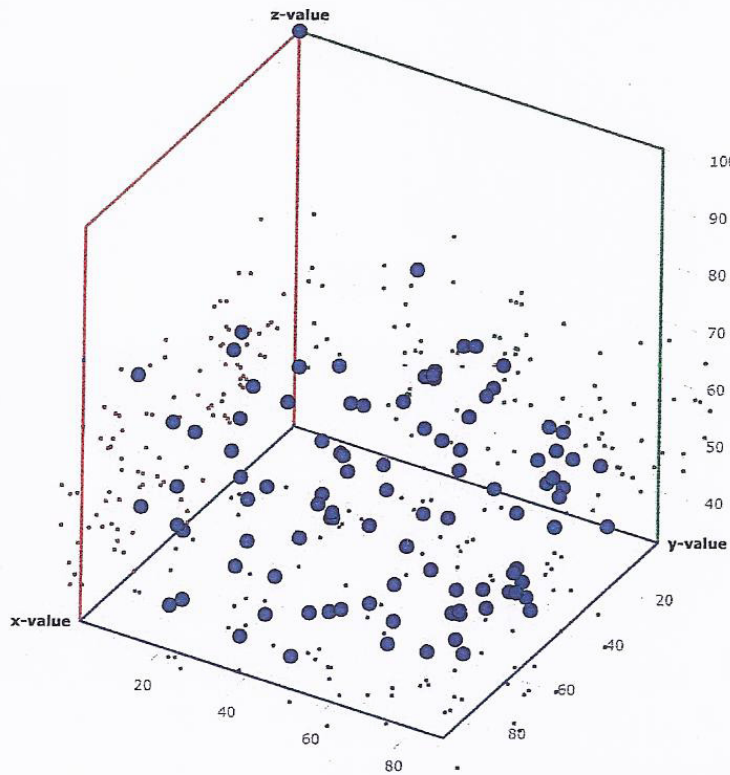
Figure 34. X-, Y-, and Z-coordinate plot of 98 bone positions within the square-meter test pit in the Mygatt-Moore Quarry, showing the density of distribution and the material's concentration lower in the main quarry layer. This may be typical of most of the quarry.

indication of tooth marks (table 4), which is perhaps not surprising given the more than 400 teeth of theropods that have been found in the deposit (98.3% of these teeth appear to be shed and were probably lost during scavenging, as only a few percent of the 419 teeth counted for this study had intact roots). These teeth are so abundant that they are often found in close association with bones of herbivores. One tooth was found in close proximity to the pleurocoel of an *Apatosaurus* cervical vertebra (figure 37G), and in another case nine teeth were excavated in 2005 from around a single sauropod femur. Among the distinctly tooth-marked bones from the quarry are an *Apatosaurus* ischium (figure 37D), an *Apatosaurus* pubis, and the type ilium of *Mymoorapelta* (Kirkland and Carpenter, 1994).

Abrasion of bones was noted in about 24.5% of the bones surveyed. It was characterized commonly by single, small, shallow, and randomly oriented scratches on the bone surface in some cases, but most often by rounding of originally sharp edges of bones or broken elements of them, a common characteristic of transport modification. In some cases, abrasion was difficult to distinguish from corrosion. If a bone was not significantly broken otherwise, it was assumed that most wearing of edges was more likely due to corrosion than transport abrasion.

The corrosion of bone from Mygatt-Moore was found to be concentrated on the edges of vertebral centra and on the ends of long bones such as limb elements and ribs (figure 37C), where cortical bone is thin and trabecular bone close to the surface. Most limb bone-shafts, for example, where cortical bone is thick, are unaffected by corrosion. The nature of this bone loss is confirmed as corrosion rather than abrasion by the documentation of thin and delicate spalled outer bone surfaces separated from trabecular bone in cross sections of several Mygatt-Moore bones collected and thin sectioned in the 1990s (J. Kirkland, Utah Geological Survey, verbal communication, 2013).

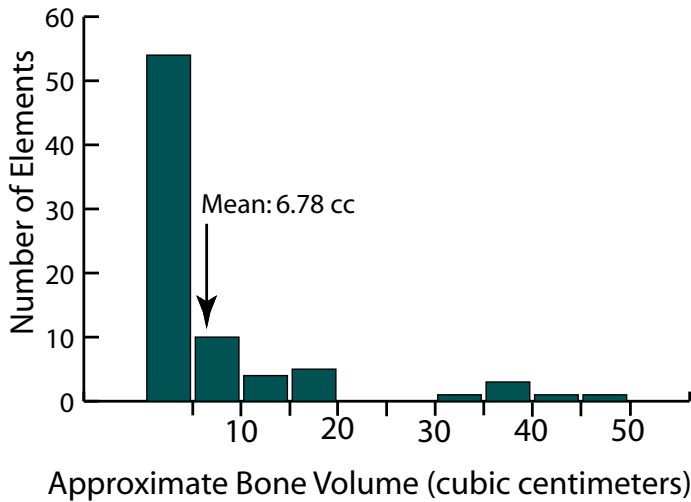Weathering was noted in 25.2% of bones from the

Paleontology, Taphonomy, and Sedimentology of the Mygatt-Moore Quarry, a Large Dinosaur Bonebed in the Morrison Formation, Western Colorado–Implications for Upper Jurassic Dinosaur Preservation Modes
Foster, J.R., Hunt-Foster, R.K., Gorman, M.A., II, Trujillo, K.C., Suarez, C.A., McHugh, J.B., Peterson, J.E., Warnock, J.P., and Schoenstein, H.E.

MYGATT-MOORE QUARRY TEST METER

Figure 35. Histogram showing the size distribution of bone pieces collected from the test pit square-meter, measured by calculated bone volume. Most pieces are small and fragmentary.

sample and was generally characterized by cracking and decay of the outer surface of the bone. The degree of weathering (i.e., average weathering stage) of bones from the quarry, however, was generally low.

The majority of bones surveyed were either un-abraded (0) or only slightly so (1, figure 38A). A number of bones demonstrated an abrasion condition of 1 to 2 and none was at 3. Similarly, most surveyed bones were unweathered (0) and none reached class 3. Corrosion and breakage were much more common (figures 38B and 38D), and for both of these a number of bones were in classes 2 and 3. In contrast, a surveyed subsample of the collection from the Cleveland-Lloyd Dinosaur Quarry (at the Natural History Museum of Utah) indicates much less modification in all four categories (figure 39); none of those elements reached class 3 (in case of weathering, class 1 was the highest recorded for any bone). Although the degree of corrosion and breakage within the Cleveland-Lloyd subsample was higher than it was for abrasion and weathering, all were lower than for the Mygatt-Moore Quarry subsample. The Cleveland-Lloyd Dinosaur Quarry sample was, however, museum-based, meaning that there was a collecting
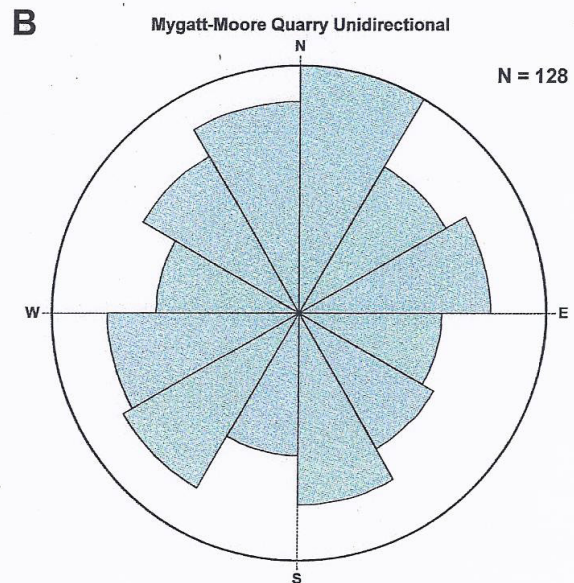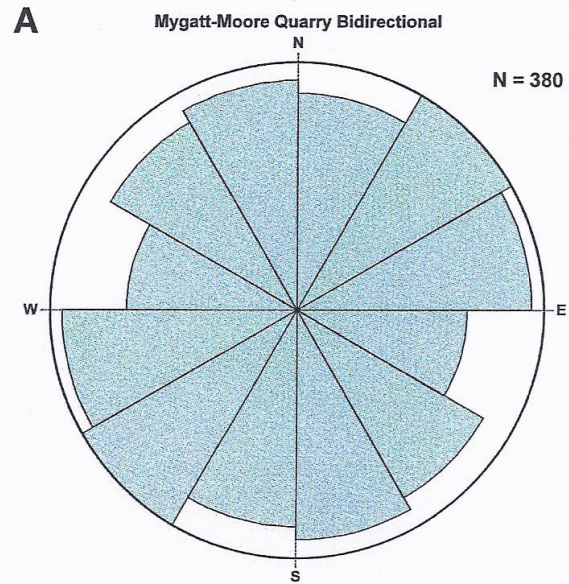
Figure 36. Rose diagrams of bone azimuth orientations in the Mygatt-Moore Quarry. (A) Bidirectional plot for long bones with no heavier end. (B) Unidirectional plot for long bones with a heavier end. Both distributions show no strong preferred orientation. Weak lower frequency in west-north-west–east-southeast orientation in both.

Table 4. Comparison of percentage occurrence of tooth marks, pathologies, juveniles, and subadults among museum collections from Mygatt-Moore and Cleveland-Lloyd Dinosaur Quarries. Percentages after N values indicate approximately how much of full museum sample was surveyed for this study.

	Mygatt-Moore Quarry Collections (N=446; ~23.5%)	Cleveland-Lloyd Dinosaur Quarry Collections (N=282; ~4.6%)
Tooth marks	4.62%	0.73%
Pathologies	0.46%	1.82%
Juveniles	1.61%	6.72%
Sub-adults	1.16%	16.42%

bias in favor of better preserved material from the start.

The sample studied from the single test meter in the Mygatt-Moore Quarry, interestingly, showed a different pattern from the collection inventory subsample. The test meter consisted of a full recording of every bone piece within a square meter, regardless of size or identification potential. Because of that fact, we perhaps should not be surprised that the results for the test meter (figure 40) are quite different from the quarry collections subsample, and from the Cleveland-Lloyd Dinosaur Quarry subsample, for that matter. In fact, recent detailed work at the Cleveland-Lloyd Quarry indicates a similar pattern in that most bones in the matrix (generally uncollected) are small and fragmentary (Gates, 2005; Peterson and others, 2017), and thus the collections sample surveyed here is skewed in favor of better preservation by collection bias. Many bones at Mygatt-Moore are abraded, more are corroded, a number are lightly weathered, and a large majority are broken quite badly, many rounded into a "bone pebble" shape. The test meter results may indicate that numerous allochthonous, fragmentary bones were transported into the site, although these were not necessarily transported long distances, nor out of the home ranges of the animals they belonged to (see Behrensmeyer and Rogers, 2017).

Histological slides of two very rounded bone "pebbles" (containing no outer bone surface), and of two bone fragments containing sections of the outer surface of the elements as well, indicate very different states of preservation at a microscopic scale. Whereas at fine scale, some bone specimens appear nearly pristine (figure 41C), and others are very well preserved (figure 41B), others have some or a great number of micro-fractures in the bone cell structure (figures 41A and 41D). The range of preservation of these elements suggests that these apparently allochthonous bone fragments may come from several different source areas. Especially interesting is that most rounded and abraded bone "pebble" specimens (figures 41C and 41D) are, respectively, the best and worst preserved pieces at a microscopic scale among the four that were thin sectioned; there was no way to predict this prior to sectioning. The nearly perfect preservation of the osteons in one specimen (figure 41C) and the heavily fractured nature of the same in another (figure 41D) suggest very different pre-burial (or possibly digenetic) histories of these elements and perhaps a complex set of origins for the "background" majority of small bone fragments that comprises the bone sample out of the quarry.

Dinosaur Skin

At least two patterns of dinosaur skin have been found in the Mygatt-Moore Quarry (Foster and Hunt-Foster, 2011), one identified as that of a sauropod consists of ~30 mm diameter hexagonal scales (figure 42A) and another consisting of much smaller polygonal scales (figures 42B and 42D) that belongs to an indeterminate dinosaur. These skin sections are preserved as either carbonized patches or similarly partially carbonized impressions of scales in matrix. In some cases, the

Figure 37. Examples of taphonomic modifications of bones from the Mygatt-Moore Quarry. (A) Sauropod rib with splintered fracture, MWC field number MM1260. (B) Close up of splintered fracture in A. (C) Corrosion of the end of a long bone, MWC 2882. (D) Distal end of theropod tibia with fresh break of lower half of shaft; break surface was surrounded by matrix when found. (E) Deeply gouged tooth marks on distal end of a sauropod ischium (arrow), MWC 4011. (F–G) Fractured *Allosaurus* metatarsal as found, MWC field number MM1398. (H) Theropod tooth preserved in matrix almost in a pleurocoel of an *Apatosaurus* cervical vertebra (upside down), showing the often close association of sauropod material and shed theropod teeth, MWC 5046. All scale bars = 10 cm.

MYGATT-MOORE QUARRY COLLECTION
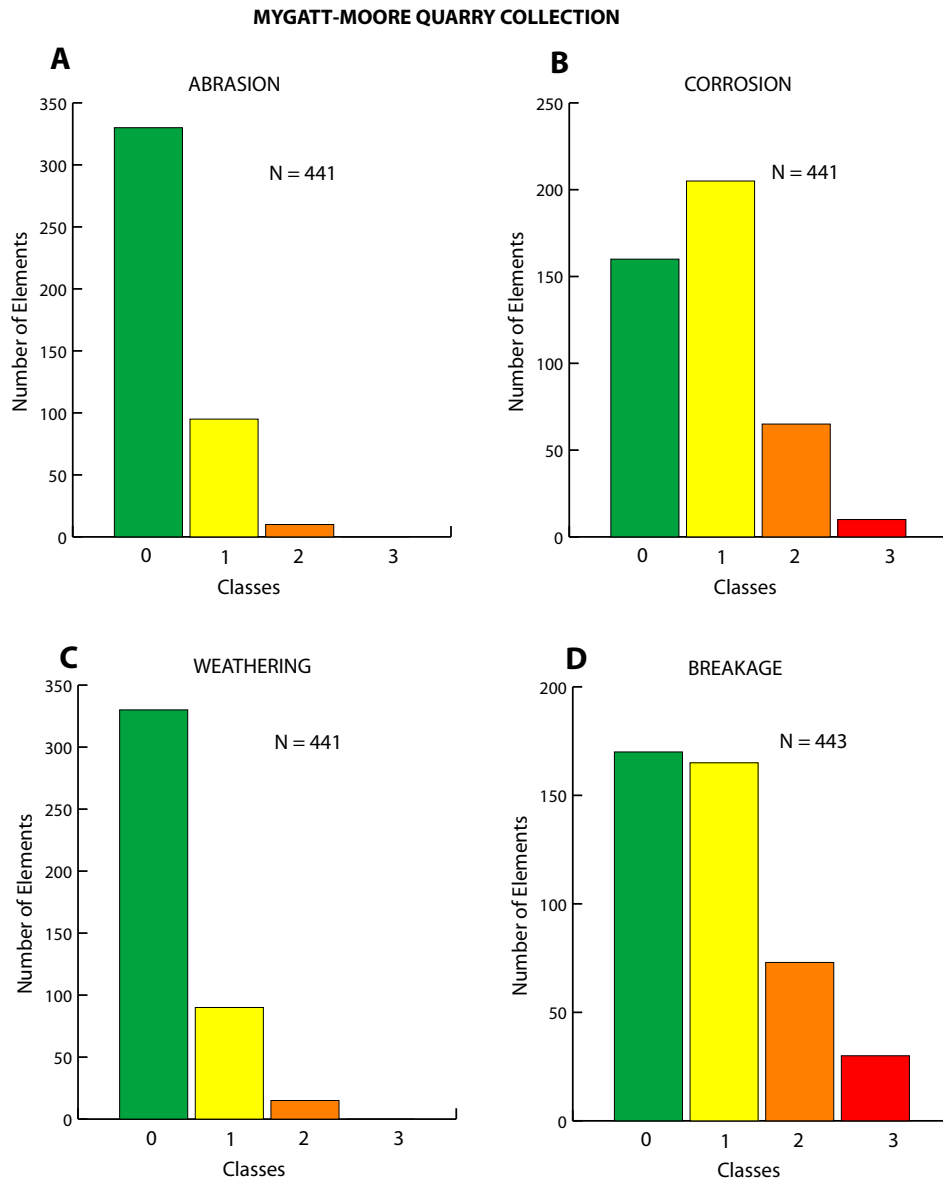
Figure 38. Bone modification of material from the Mygatt-Moore Quarry collections inventory, by classes and type of modification. Generally, the severity of modification goes up from classes 1 to 3; 0 = no modification. Modification less than average for whole quarry due to this being a collected museum sample of better material.

skin pieces are folded over within the matrix and are separated by up to 1 cm of matrix.

DISCUSSION

Paleoenvironmental Setting

The stratigraphic sections around Rabbit Valley suggest that the quarry area itself was surrounded by an alluvial system of poorly-drained to well-drained floodplains and sandy to very gravelly river channels. These channels may have been meandering to anastomosing (e.g., Cooley and Schmitt, 1998), as they are only traceable laterally for at most several hundred meters and are noticeably less laterally extensive than the channel sandstones of the underlying Salt Wash Member. The sections also indicate a great degree of lateral variability within the Brushy Basin Member strata as mudstone

CLEVELAND-LLOYD QUARRY COLLECTION
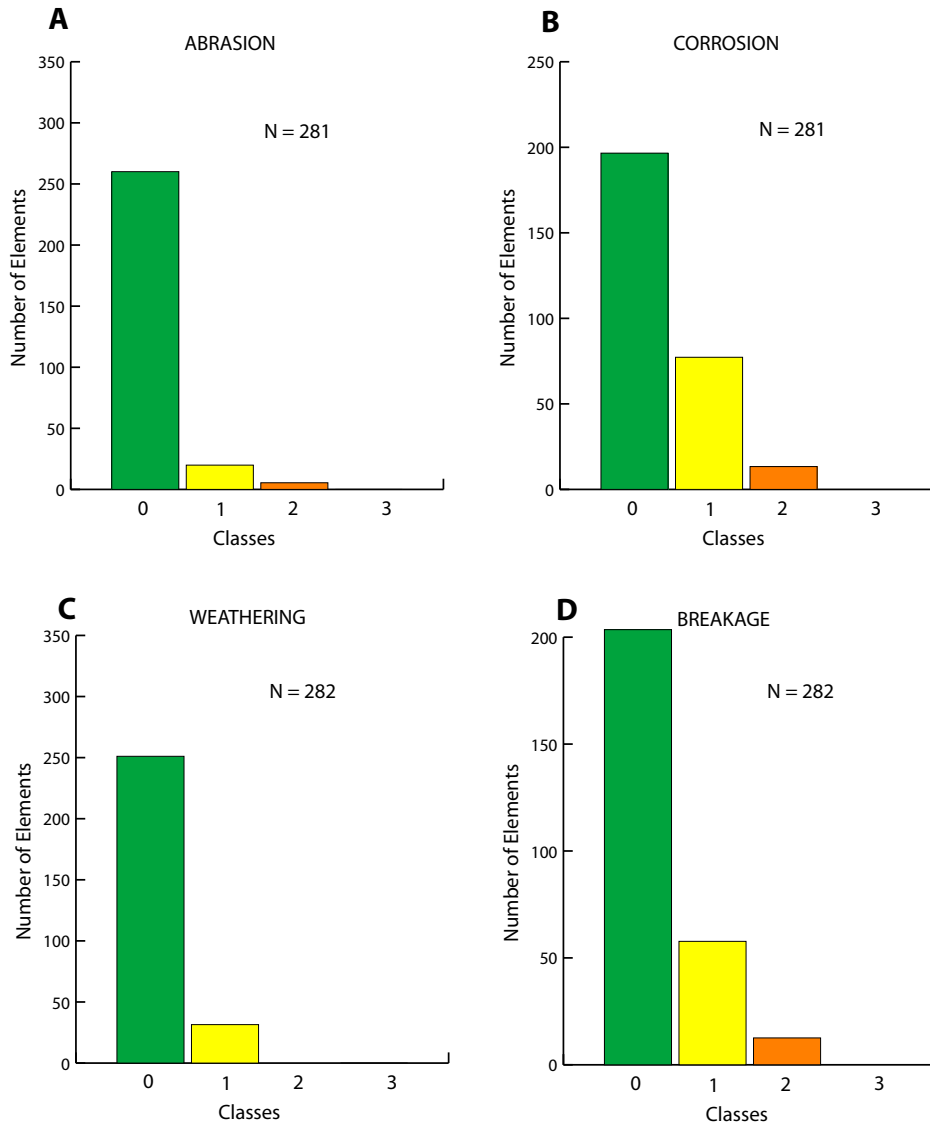
Figure 39. Bone modification of material from the Cleveland-Lloyd Dinosaur Quarry collections survey, by classes and type of modification. Generally, the severity of modification goes up from classes 1 to 3; 0 = no modification. Modification less than average for whole quarry due to this being a collected museum sample of better material.

bed, channel sandstone, and the "fish layer" beds were all documented to change or pinch out laterally within tens to hundreds of meters.

The lateral variability is matched by almost universal changes in the vertical stacking patterns (figure 4). These vertical components document changing paleoenvironments over time, and within the quarry area itself we can document several changes. A transition from a permanent or ephemeral overbank topographic low into an ephemeral pond and then to a permanent but small (and probably shallow) lake is indicated by the lithologic variability of the quarry interval. Later, a return to floodplain deposition with a nearby river represented by the channel sandstone at the Camarasaur Stop.

The main quarry layer demonstrates features of a pond or pool. The lack of bones east of trench 5 and the reddish-colored mudstone at the quarry level at the

MYGATT-MOORE QUARRY TEST METER
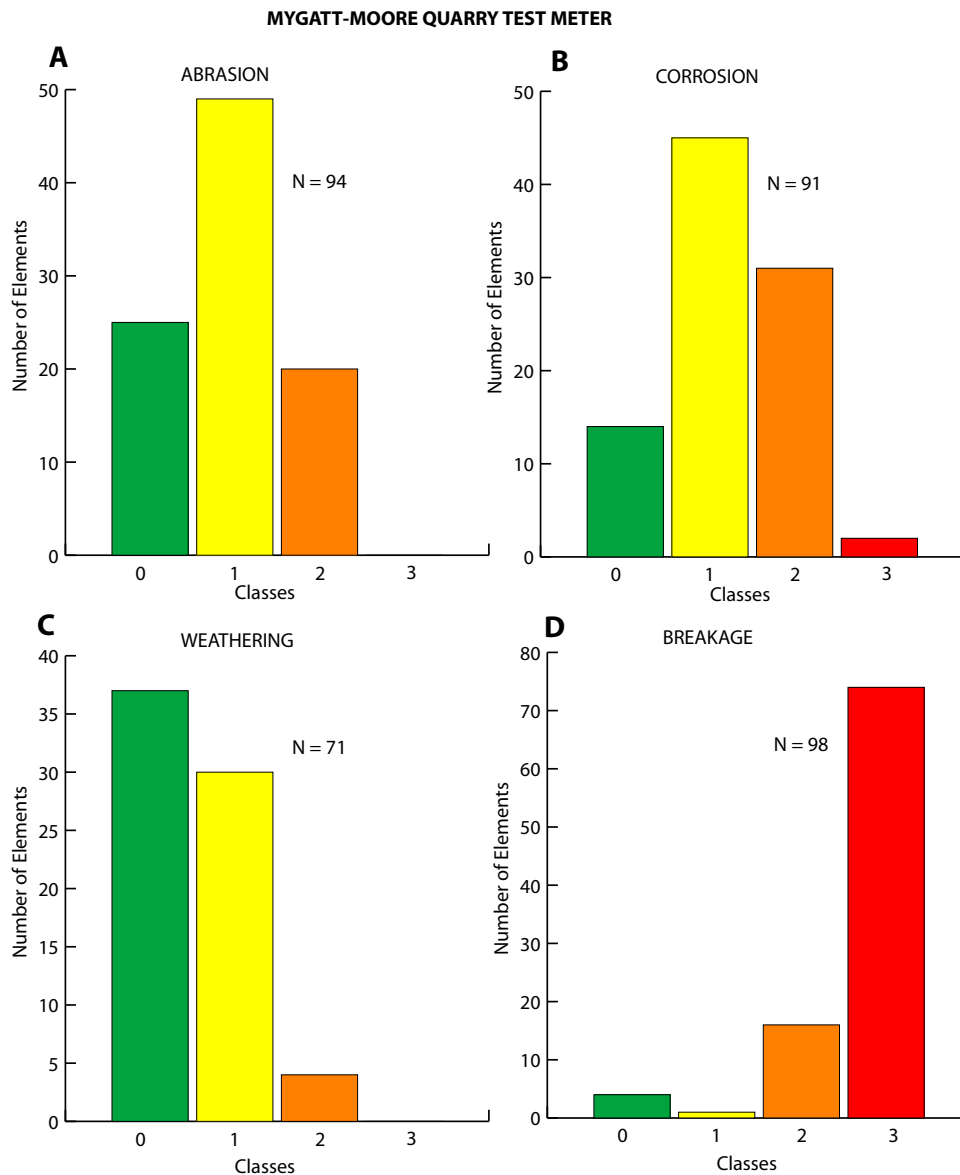
Figure 40. Bone modification of material from the Mygatt-Moore Quarry test pit square-meter. Generally, the severity of modification goes up from classes 1 to 3; 0 = no modification.

Caudal Draw stratigraphic section, the different character of trench 5 in both trench stratigraphy and thin sections, and the fact that drill holes MM-1 and MM-2 showed that the main quarry layer is thinner and slightly higher stratigraphically, all suggest that the quarry layer is a convex-bottomed, laterally restricted lens. The minimum area of the deposit is approximately 18,200 m² and may be the deepest near the present northern part of the quarry (dimensions about 130 x 140 m, mea-sured drill hole MM-1 to trench 5 and drill hole MM-2 to trench 4). Although this is an approximately rectangular area, the actual deposit is probably roughly oval.

Paleoenvironment of the Main Quarry Layer

The base of the main quarry layer (with abundant plant debris and bone) appears to begin with deposition in a quiet, perennial pond, in that the very base of the

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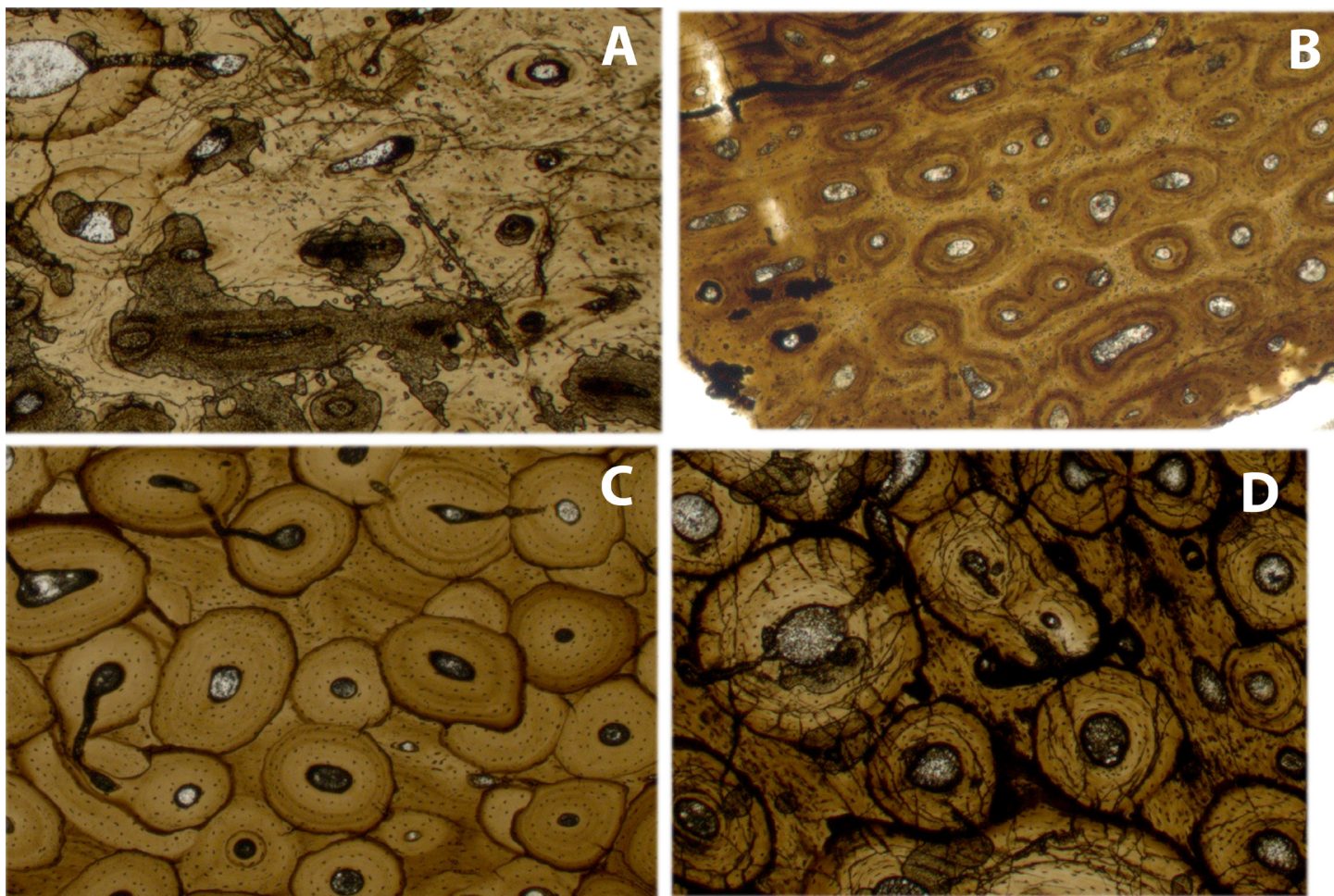
Figure 41. Thin section micrographs of samples from bone fragments out of the Mygatt-Moore Quarry. (A) Relatively well preserved bone fragment, BG-1, nevertheless showing some micro-fracturing. (B) Well preserved bone fragment, BG-2, showing fairly good preservation even at microscopic scales. (C) A "spongy" and almost rounded bone fragment, BP-1, that preserves nearly pristine osteons. (D) Another poorly preserved, rounded bone fragment, BP-2, with highly micro-fractured osteons. All thin section micrograph views are approximately 2000 μm across.

quarry (at the contact with the underlying light-green silty claystone) is a layer that contains several viviparid gastropods. The sediments that contain these gastropods, however, do not have any plant fragments. So, these gastropods occur in a basal layer or unit rather different than the actual main bone layer just a few centimeters higher in the section.

The main quarry layer has some seemingly contradictory taphonomic characteristics. Some characteristics suggest very wet conditions, possibly perennial standing water; others suggest wet or damp conditions but only ephemeral water. Some evidence suggests the

bones in the quarry are locally autochthonous, whereas other rounded and abraded elements seemingly indicate transport a moderate distance; it is unlikely even heavily modified bones were transported great distances or mixed into areas outside the ranges of the animals they derive from (Behrensmeyer and Rogers, 2017). Although there is no clear evidence of miring of dinosaurs at the Mygatt-Moore Quarry as there is at some other sites (e.g., Howe Quarry, Farlow *in* Bird, 1985), the abundance of theropod material might at first suggest a predator trap. Even though the sample is dominated by just two of the present dinosaur taxa, the age profile
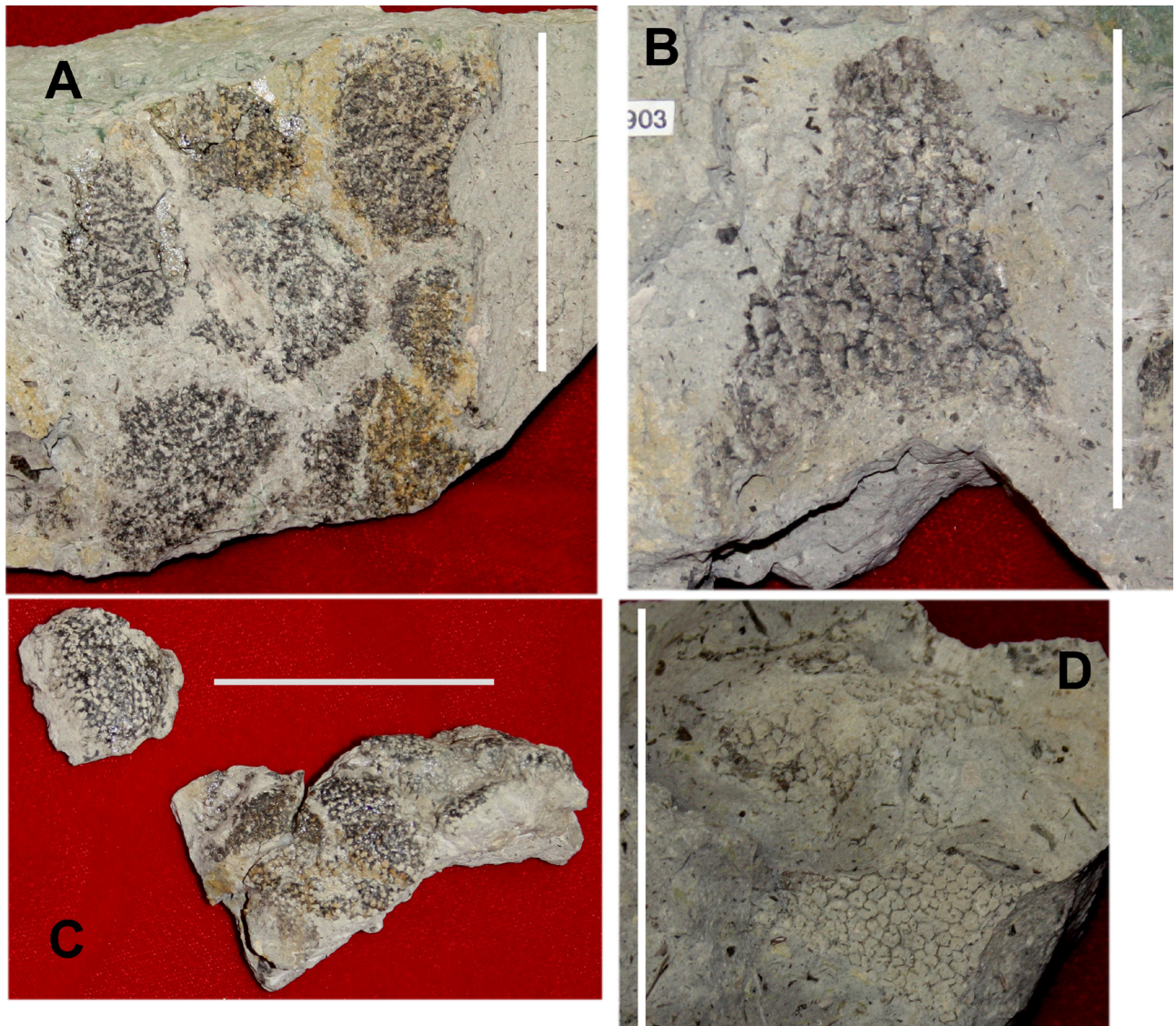
Figure 42. Dinosaur skin specimens from the Mygatt-Moore Quarry. (A) Sauropod skin patch with large hexagonal scales, MWC 6718. (B) Patch of smaller scales belonging to an indeterminate dinosaur, MWC 1903. (C) Pattern of very small tubercles, possibly superimposed on larger hexagonal pattern, MWC 5537. (D) Another patch, partly carbonized but also preserved as impression; this specimen is also folded over on itself, discovered during the 2013 season, MWC field number MM1687.

suggests an attritional assemblage (see below).

The Mygatt-Moore Quarry "bone layer" may represent an ephemeral pond surrounded by conifers, similar to a wooded vernal pool, although there is a paucity of direct evidence to confirm this. Amphibians, often characteristic of modern vernal pools may be very rare at the site due to taphonomic bias. The unit geometry (see above) and the mudstone (with some silt) lithology indicate that it is not a channel and is likely some type of overbank deposit. The presence of many bone fragments (almost a 'background' of small, nearly rounded fragments), calcium carbonate "pebbles," and small clayballs indicates that a significant portion of the material was washed in, probably during flooding of a nearby channel. The range of micro-preservation characteristics in the histological bone samples, the appearance of two

distinct geochemistry signals in the calcium carbonate nodules, and the different colors and range of the silt and clay content in the clayballs, all in the lower main quarry layer, suggest that there were multiple sources for the allochthonous bones, "pebbles," and clay clasts in the quarry. In addition, these sources mixed during a single phase of emplacement, though probably not a single episode. Variation in clay clast, nodule, and bone characteristic does not appear to stratigraphically correlate. Despite the "background" of small fragmentary bones (allochthonous), a significant number of nearly complete, well-preserved, but often rotted (corroded), bones are present in the main quarry layer, which probably represent an autochthonous component.

Small, elongate plant debris that is often aligned might indicate light (possibly oscillatory) water influence during deposition of the bone layer. The fact that the rose diagrams both show no preferred orientation suggests that whatever current there was, it was not a unidirectional current and not strong enough to align dinosaur skeletal material.

The total lack of fish from the main quarry layer, the fact that not a single turtle element has ever been confirmed from the layer, and the extreme paucity of neosuchian material all suggest that permanent water was probably not present at the site at the time of deposition of the main bone layer. The restriction of "prosobranch" gastropods to layers above and below the main bone layer indicates that the quarry area was a locality of perennial water, but there is no direct evidence to indicate this with certainty from the bone layer itself. That "conchostracans" are present just below the "fish layer" suggests that the area may have been an ephemeral water hole at times, but again there is no direct evidence of these ephemeral pond inhabitants in the bone layer. Actinopterygian fish are restricted to the overlying "fish layer" and indicate perennial water with certainty, but only well after dinosaur quarry (bone layer) deposition was over.

In addition, the fact that other sites such as the Small Quarry (Garden Park), Quarry 9 (Como Bluff), and the Little Houston Quarry (Black Hills) seem to represent ponds, and also preserve abundant turtles, neosuchians, and fish (Foster, 2001, 2003), suggests that

if these aquatic and semi-aquatic taxa were present at the Mygatt-Moore Quarry at the time, they would have been preserved. Their absence may be due to a mechanical taphonomic bias that filtered out smaller animals (Behrensmeyer and others, 1979), but this bias seems unlikely for taxa as robust as turtles. If these animals were present in large numbers at the Mygatt-Moore Quarry, it would seem at least a few would be preserved.

The abundance of plant material and carbonized plant fragments throughout the main quarry layer at the Mygatt-Moore Quarry suggest that the soil was acidic. The high degree of corrosion (or "rot" along with resulting spalling) in the quarry is also probably indicative of acidic conditions in the quarry mud at the time, as bone preservation can deteriorate in lower-pH conditions (Baxter, 2004). The effects of low pH on bones can sometimes be quite variable even between samples in the same soil, however (Nicholson, 1996). Preservation of dinosaur skin, not just as impressions in matrix, but more often as carbonization, suggests occasional dysoxia in the mud of the deposit, if not necessarily in any standing water that may have been present. Dysoxic or anoxic conditions may have enhanced the frequency of plant preservation also (Briggs, 1999). The presence of contemporary wood-rotting fungi in a number of the wood specimens from the quarry (Tidwell and others, 1998) would also seem to suggest that the environmental setting was wet and possibly humid.

Like the Cleveland-Lloyd Dinosaur Quarry, the Mygatt-Moore Quarry bone layer matrix is elevated in several elements such as Pb, As, Mn, K, and S (Peterson and others, 2017). It is unknown if this phenomenon is due to original conditions in the deposit, diagenetic factors, or perhaps is a result of decomposition of carcasses at the site (Peterson and others, 2017). As discussed above (matrix XRF analysis), it seems more likely that the elevation of several elements is the result of diagenetic processes at the Mygatt-Moore Quarry.

Perhaps perennial water was present at the Mygatt-Moore Quarry during deposition of the bone layer, but were there environmental conditions that kept smaller aquatic and semi-aquatic animals out? The acidic soils and dysoxic conditions apparent at the site during deposition of the main quarry layer might have been

such factors to make the area unappealing to these taxa. However, the fact that turtles, crocodylians, and fish are abundantly preserved in the dark, carbonaceous (presumably somewhat acidic) mudstone and the (sometimes dysoxic; mummifying) sandstone beds of Late Cretaceous deposits suggest that such conditions were neither always avoided by the animals nor detrimental to their preservation. The paucity of neosuchians and the lack of fish and turtles from the main quarry layer may well be a paleobiological pattern then, and the possibility remains that the mud that now comprises the main quarry layer was only seasonally under water.

The presence of trampled bones suggests that living animals frequented the deposit area, stepping on bone already in the mud during times of low (or no) water. This trampling is evidenced by many bones broken clearly after the element was in the mud but still exposed at or near the surface; unhealed, splintered fractures are relatively common and were documented in the field as having occurred prior to collection by matrix adjacent to broken surfaces. Documented field evidence, such as vertical changes in mudstone bedding within the quarry and post-depositionally broken bones, also suggests that many bones were churned in the soft mud, again presumably by trampling. Among observed elements that seem to have been preserved in soft wet mud were multiple bones preserved at an angle to horizontal, thin bones with fresh unabraded edges preserved in the matrix on edge, and at least one shed theropod tooth found on end (vertically) with the tip down in the matrix (no associated skull material).

The frequent presence of carnivores and abundant scavenging in the quarry area are indicated by the abundance of *Allosaurus* bones, the abundance of shed theropod teeth, and the moderate amount of tooth marks on bones. The extremely high rate of disarticulation and significant disassociation compared with other large quarries in the Morrison Formation may be due to trampling by dinosaurs (as with scatter of modern elephant bones by elephants; Haynes and Klimowicz, 2015) and scattering by scavenging theropods. Some modern bones, however, can also be found scattered by lake waters, surface sheet flow, and possibly wind along lacustrine margins in autochthonous deposits (Co-

bo-Sánchez and others, 2014). Therefore, a number of factors may have been acting in scattering the material at the Mygatt-Moore Quarry.

Several of the plant types preserved in the quarry are associated with wet environments, including horsetails, *Czekanowskia* (Tidwell and others, 1998), and lycopodiophytes. Lycopodiophytes today are common elements of some vernal pools (Keeley, 1990) and, in some settings, live in slightly acidic water (Wang and others, 2002). Ferns and conifers are also particularly abundant, and plenty of ginkgoes and cycadophytes are also present. The fact that podocarpaceous wood and pollen are both found in the quarry (Tidwell and others, 1998; Hotton and Baghai-Riding, 2010) indicates that some of the abundant fossil wood at Mygatt-Moore is almost certainly local and therefore that the surrounding area was probably wooded. Among the plants common at the Mygatt-Moore Quarry, *Equisetum* and ginkgoes are two of the better candidates for plant fodder for herbivorous dinosaurs, whereas Podocarpaceae were probably less appealing (Gee, 2010).

Vertebrate age profiles in hypothetical standing populations would have many juveniles and fewer adults, and non-selective catastrophic mortality would result in a similar profile (Eberth and others, 2007). Attritional mortality could result in an age profile with many juveniles and adults and fewer mid-age classes. Rapid burial of such a profile would result in a similar distribution, whereas delayed burial would favor preservation of adult-size classes (although Myers and Storrs, 2007, noted that with sauropod remains, rate of burial may have less influence on preservation effects than with smaller taxa). Still, delayed burial of an attritional assemblage may result in an age profile with few mid-sized animals, more juveniles, and an abundance of older animals (Eberth and others, 2007) and this is what is observed at the Mygatt-Moore Quarry. The extremely high degree of disarticulation of the material seen at the quarry (lowest measured articulation radio among large Morrison sites) is also consistent with delayed burial (Myers and Fiorillo, 2009). Despite the unusual abundance of two taxa (*Allosaurus* and *Apatosaurus*) in the quarry, the age profile seems to indicate an attritional assemblage with non-rapid burial. Therefore,

the deposit does not appear to be the result of a catastrophic mortality of dinosaurs.

The slow burial would seem support the existence of an ephemeral overbank pond, but the high abundance of just two taxa is harder to explain. Among several scenarios, it is possible that the deposit built up over multiple environmental stresses (e.g., occasional droughts), with the high abundance of *Apatosaurus* resulting from a population frequenting the water source repeatedly during times when the rest of the floodplain was drying out. That apparently-shed sauropod teeth (mostly Diplodocidae but with a number of camarasaurids) are relatively abundant at the site suggests that in fact the animals were feeding nearby, and it is estimated that population densities on the Morrison landscape would have allowed for a handful of individuals of each sauropod species per km^2 (Farlow and others, 2010). Possibly, a regional apatosaur population tended to frequent the area seasonally, coincidentally when stresses on the herd were highest, while other sauropod taxa migrated through during other, less stressful times (J. Kirkland, Utah Geological Survey, verbal communication, 2013). There seems to be some evidence of regional migration among sauropods from the Morrison (Fricke and others, 2011). At times when the population was in the area it may have had higher densities of animals because the group was absent at other times, and because presumably at times when the apatosaurs were there, the other sauropods were away. An alternative hypothesis is that a local apatosaur population frequented the area year-round, preferring an environmental or dietary aspect of the surrounding area, to the general competitive exclusion of other sauropods. In this scenario, the attritional assemblage would also have been built up over time as the area was populated long-term by a high percentage of *Apatosaurus.* Although we were able to discern an attritional versus catastrophic origin for the bone assemblage, distinguishing between the two above scenarios to explain the abundance of *Apatosaurus* relative to *Camarasaurus* and Diplodocinae indet., may be difficult. The facts that the macro-plant and pollen-spore assemblages are thus far almost unique among plant sites in the Morrison (Hotton and Baghai-Riding,

2010), and that the Mygatt-Moore Quarry is one of the only apatosaur-dominated sites in the formation, suggest that perhaps something about the flora of the local habitat was attractive to these particular sauropods. Still, determining whether this attraction was seasonal or perennial may be impossible.

Comparison to Other Quarries

Cleveland-Lloyd Dinosaur Quarry

The major quarry to which the Mygatt-Moore Quarry compares most closely is the Cleveland-Lloyd Dinosaur Quarry in the Morrison Formation of the San Rafael Swell of east-central Utah (Stokes, 1985; Miller and others, 1996; Bilbey, 1999; Gates, 2005; Peterson and others, 2017). Similarities to the Mygatt-Moore Quarry include mudstone matrix, many disarticulated bones, highly mixed arrangements of the bones, many *Allosaurus* elements (MNI = 49), and a relatively thin bone layer (Richmond and Morris, 1996; Gates, 2005; Hunt and others, 2006; Foster and others, 2016). Differences of Cleveland-Lloyd Dinosaur Quarry compared to Mygatt-Moore Quarry include (1) lack of carbonized plant material in the mudstone, (2) higher degree of articulation, and (3) greater dominance by *Allosaurus* primarily. Additionally, as found in this study, the Mygatt-Moore Quarry has a much higher percentage of shed carnivore teeth (versus rooted), has slightly more tooth marked bones, has more fragmented, weathered, abraded, and corroded bone, and has more allochthonous clasts and bone fragments. Mygatt-Moore Quarry also demonstrates less evidence of hydraulic sorting and more random azimuth orientations of the bones as compared to the Cleveland-Lloyd Dinosaur Quarry (see Gates, 2005). The Cleveland-Lloyd Dinosaur Quarry has only a single *Apatosaurus* element (Foster and Peterson, 2016), whereas the Mygatt-Moore Quarry has no elements clearly belonging to *Stegosaurus*; the reasons for these taxa being rare or missing are unclear, as they are otherwise very common overall in the Morrison Formation. The Mygatt-Moore Quarry also has a lower percentage of juveniles and sub-adults than does the Cleveland-Lloyd Dinosaur Quarry.

Howe Quarries

The Howe Quarry (Bird, 1985) and the Howe-Stephens Quarry (Ayer, 1999) are large, multi-taxic sites in the Morrison Formation of northern Wyoming. Both differ from the Mygatt-Moore Quarry in that the matrix is a silty to slightly sandy mudstone with more direct evidence of fluvial influence (more so at Howe-Stephens). The Howe Quarry contains an abundance of diplodocine sauropod material relative to other taxa, and in this sense, it is similar to the Mygatt-Moore and Cleveland-Lloyd Dinosaur Quarries. The Howe Quarry also preserve a relative abundance of dinosaur skin (Czerkas, 1992).

Little Houston Quarry

The Little Houston Quarry is in the thin Morrison Formation of the Black Hills in northeastern Wyoming (Foster and Martin, 1994; Foster, 2001). This quarry is in a laterally restricted, ribbon-like abandoned channel deposit with interbedded green claystone and laminated gray-green siltstone. Articulation of dinosaur bones is moderate, density of the bone material is high, and microvertebrate material is very abundant, even in among the sauropod bones in some levels. This site preserves a diversity of large dinosaurs and especially small reptiles, mammals, and fish, along with an abundance of turtles and neosuchian crocodyliforms. This preservation mode is common in the northern and eastern parts of the Morrison Formation (Foster and McMullen, 2017) and is characteristic of the Small Quarry and Quarry 9 as well (Foster, 2001, 2003). This mode is taphonomically very different from the Mygatt-Moore and Cleveland-Lloyd mode of preservation.

Carnegie Quarry, Dinosaur National Monument

The Carnegie Quarry at Dinosaur National Monument in Utah is a good representative of the taphonomic mode of preservation so common among large dinosaur quarries in the Morrison Formation in that it occurs in a thick, pebbly sandstone (Lawton, 1977; Carpenter, 2013). The site preserves a diversity of dinosaurs, most of the reasonably common ones in the formation, in fact, and in high numbers. There are thousands of bones in this quarry and probably more than 120 individuals represented. The degree of articulation is the highest measured for this study. Sedimentologically and taphonomically channel sandstone deposits like the Carnegie Quarry are very different from large sites in mudstone like Mygatt-Moore and Cleveland-Lloyd Dinosaur Quarries.

Preserved Diversity by Site

One interesting aspect of the preservation of dinosaur taxa at some of the large quarries in the Morrison Formation is the variation in the relative abundance of the most common dinosaur taxa. For example, within the Morrison overall, the most abundant dinosaurs are, in descending order, *Camarasaurus*, *Allosaurus*, *Stegosaurus*, *Apatosaurus*, and *Diplodocus*. Each of these is slightly less abundant than the next highest in rank abundance. If we look at large quarries in mudstone and siltstones (fine-grained sites), we notice that (1) this pattern does not hold up and that the relative abundances among these five taxa are highly uneven, with some quarries missing one genus entirely, (2) one or two taxa often dominate, with the other taxa rare, and (3) the dominant taxon or taxa are variable (figure 43; Foster and others, 2016). Although the Mygatt-Moore Quarry has a number of *Allosaurus* individuals, it is dominated by *Apatosaurus* by number of identified elements (as opposed to MNI). Cleveland-Lloyd Dinosaur Quarry is even more dramatically dominated by *Allosaurus*, and the Howe Quarry is dominated by diplodocines. The pattern demonstrated by large quarries in channel sandstones, however, more closely reflects the pattern in the Morrison Formation overall (figure 43). All of the "big five" dinosaur genera are present at all sites, relative abundances are much more even, and no site is dominated by one taxon to the degree that the fine-grained sites are. These different relative abundances probably reflect the relative size of the sampled geographic area and the amount of time averaging within each deposit. The geographic area from which large Morrison river channels were drawing skeletons could well have been rather extensive, particularly considering the possible areas of the individual drainage basins on a relatively
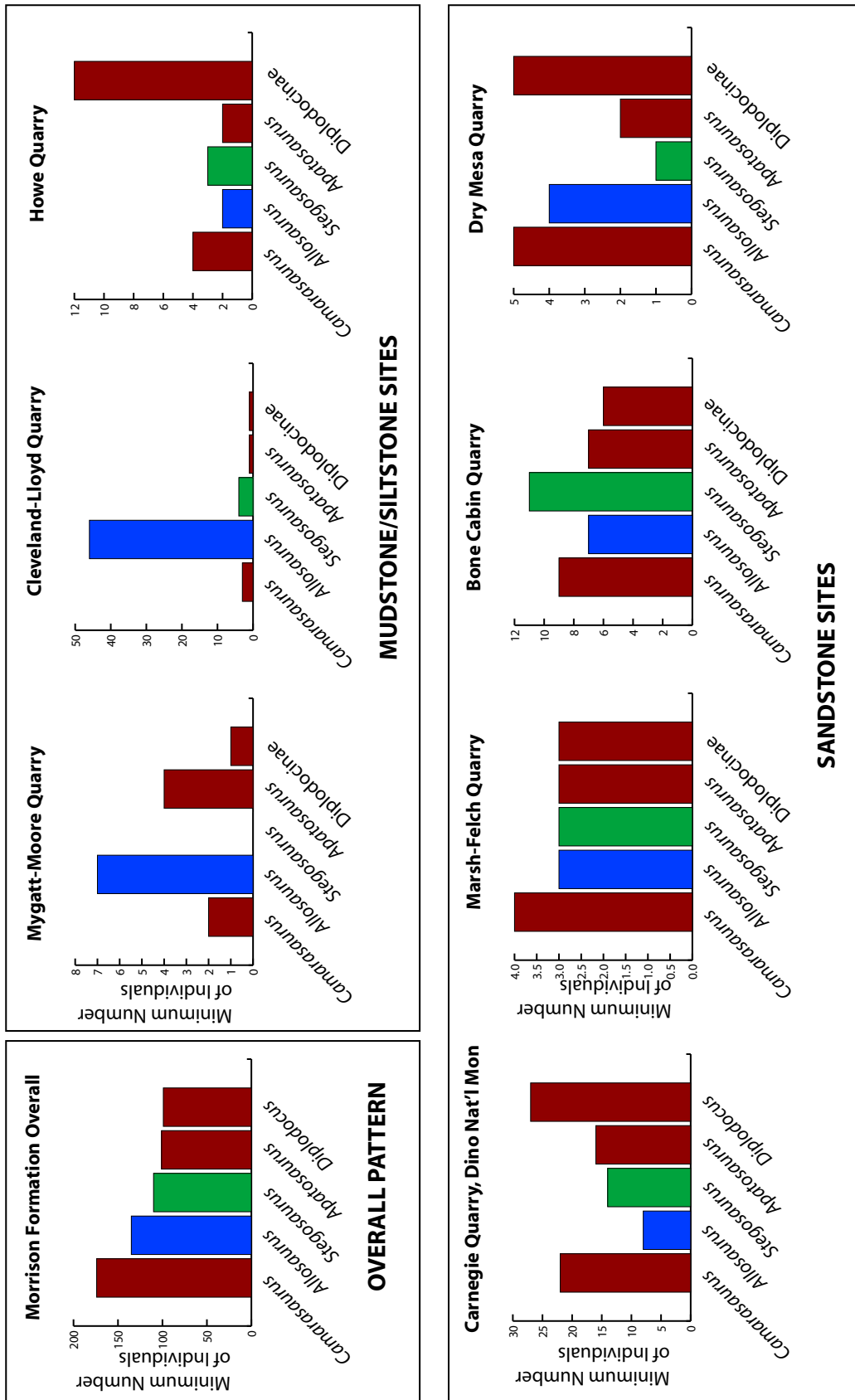
Figure 43. Comparison of relative abundance (by MNI) of the five most common dinosaurs of the Morrison Formation at each of three fine-grained (mudstone/siltstone) facies quarries and each of four sandstone facies quarries, with comparison to the Morrison Formation overall sample. Representation and relative abundances of taxa in sandstone facies are more representative of the formation overall than the often very uneven representation and relative abundance in large mudstone facies sites.

Figure 44. Reconstruction of the Mygatt-Moore Quarry, 152 million years ago. An *Allosaurus* feeds on the carcass of an *Apatosaurus*. Shed teeth and tooth marks of carnivores suggest that theropod dinosaurs regularly concentrated their feeding on the large muscles of the hind limbs and pelvis. ©Todd Marshall

flat floodplain at the time (Behrensmeyer, 1982). Although sauropod bones and carcasses probably would not have been transported great distances in recognizable form (Myers and Storrs, 2007), it would not be surprising if the area from which a dinosaur deposit in a channel sandstone was drawn was in fact far broader than that of a local pond or overbank topographic low. There is variation in the amount of time represented by different sites within the fine-grained site subsample, with the Mygatt-Moore Quarry perhaps representing an attritional and possibly more time-averaged sample than Cleveland-Lloyd Dinosaur Quarry, for example. The amount of time-averaging in an attritional mudstone site was probably still far less than that of a channel sandstone deposit like the Carnegie Quarry, which appears to include several lag beds superimposed in a thickness of several meters. Both Mygatt-Moore and Cleveland-Lloyd Dinosaur Quarries are much thinner beds of about 1 m thickness.

This pattern of uneven relative abundances at mud-stone sites and more diverse and evenly represented taxa at sandstone sites (figure 43) suggests that large quarries of dinosaur bones in the Morrison Formation fall into at least two major taphonomic modes. Many sites in the Morrison consist of paucispecific deposits of a few individuals and up to a few hundred bones, sometimes also dominated by one or a few taxa, in poorly drained floodplain mudstones (e.g., Tucker, 2011). Very large deposits of multiple hundreds or thousands of bones are often either (1) diverse sandstone quarries with relatively even abundance distributions among the most common dinosaurs, or (2) less diverse fine-grained (mudstone or siltstone) quarries with sometimes wildly uneven abundance distributions among the most common dinosaurs (some missing entirely). There are undoubtedly a number of the former deposits in the Morrison Formation channel sandstone beds with many bones and many taxa (e.g., Carnegie Quarry, Dry Mesa Quarry), and undeveloped examples can be seen in the Morrison Formation at least in Colorado and Utah

(e.g., Split Rock, Mill Canyon). Perhaps there are yet undiscovered deposits of the latter kind, large potential quarries in mudstone that sampled a *Camarasaurus*- or ankylosaur-dominated fauna, for example. These sites have the potential to tell us a little more about the vagaries of preservation and dinosaur paleobiology than do more time-averaged and geographically blended sites.

CONCLUSIONS

The Mygatt-Moore Quarry is Late Jurassic in age (152.18 +/-0.29 Ma), very close to the Kimmeridgian-Tithonian boundary. The Mygatt-Moore Quarry is in a claystone that has slightly higher (and coarser) silt content than the surrounding claystone beds. Claystone beds that are lateral to the quarry deposit are different in color and silt content and, in some cases, include sandstone beds near quarry level away from the site. The bones were probably deposited on a topographically low part of the floodplain, possibly within 800 to 1000 m of a river channel to the east (figure 4).

The quarry was at least about 130 m by 140 m across, possibly an oval shape. The area may be as much as 18,200 m^2 as currently known from excavations, trenches, and drill cores. The thickest part of the quarry is in the northern area of the current excavation; it thins to the east, southwest, and northwest. The base slopes upward in those latter directions as well, so that the bone layer is somewhat lens-shaped (convex down).

The quarry preserves both autochthonous and allochthonous bone components. There is a group of mostly fragmented and almost rounded bones that was probably washed in early in the deposit's history from a significant distance and a second group of more intact bones that were sourced from skeletons of animals that died near or at the point of deposit itself.

As a probably perennially damp to seasonally flooded low area of the floodplain, the quarry area was very likely occupied and immediately surrounded by a greater abundance of conifers, horsetails, and, to a lesser degree, ferns than the next most outlying areas. Abundant plant material in the quarry bone layer matrix was likely preserved due to acidic soil conditions, which are conductive to plant preservation. Relatively low pH during

deposition of the bone deposit seems likely, although at the earliest stages when the "pebble layer" was deposited, pH may have been higher. Dampness from high moisture content in conifer wood in the quarry area led to rotting of wood by fungi. Preservation of carbonized skin of dinosaurs (and plant material) suggests the mud of the deposit may have been dysoxic to anoxic.

The calcium carbonate nodules that are abundant near the base of the bone layer appear to be washed in from at least two different source areas, but how far they were transported is difficult to assess. They formed in place as incipient soil nodules but were then reworked and deposited at the quarry after transport. Their origin could be from a different area than the rock clasts and clayballs in the matrix of the main bone layer. Much of the initial input to the bone layer (basal portion) thus appears to have been from elsewhere.

The abundance of *Allosaurus* bones and teeth is almost certainly a result of a combination of environmental stresses on the animal (drought?) causing slightly higher mortality of the population and increase in the number of individuals in the area, probably drawn in to scavenge on carcasses of both herbivorous and carnivorous dinosaurs (figure 44). Although the abundance of shed teeth and tooth-marked bone clearly indicates scavenging, there is no direct evidence of predation occurring at the site.

The abundance of *Apatosaurus* appears to be from attritional mortality of a resident population of animals that frequented the area either year-round or seasonally. If these animals were around all year, it may have been due to an affinity for the Mygatt-Moore Quarry area's unique mix of plant types. Other sauropods like *Camarasaurus* were probably competitively excluded or simply did not like the fodder in the area and so would be preserved less frequently.

Although it is possible that acidity or oxygen-poor conditions excluded small aquatic taxa or caused them not to be preserved, this is not the case at other, very wet sites in the Morrison Formation (e.g., Little Houston, Quarry 9). We believe the near total lack of aquatic and semi-aquatic animals represents their actual rarity during deposition of the deposit due to infrequent (possibly only seasonal) presence of standing water at

the site.

The extremely high degree of disarticulation of bones in the quarry appears to be a result of scavenging of carcasses by predators, trampling and churning of the bones in mud by living animals, and relatively long exposure before the bones were locked in the sediment and fully buried. Still, the exposure time was not long enough for there to be significant weathering of the bone material.

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APPENDIX A – GEOLOGIC THIN SECTIONS

Descriptions of hand samples and thin sections made from them. Specimens numbered within each trench from stratigraphically lowest upward.

Trench 1
#5 – Clay (90–95%) with black mineral or organic carbon laminations; 5–10% angular to subrounded quartz silt; less silt and smaller grains than main quarry layer; "fish layer."
#4 – Clay (80%) and silt to fine sand (20%) that is sub-angular to subrounded and mostly quartz; few clayballs and mostly without silt; some carbonized plant fragments.
#3 – Clay (80–85%) and silt to fine sand (15–20%) that is sub-angular to subrounded and mostly quartz; angular to sub-angular clayball clasts of various colors, some purely clay, some with minor amounts of silt grains within them; many carbonized plant fragments; "Main bone layer."
#2 – Clay (80–85%) and silt to fine sand (15–20%) angular to subrounded; silt grains mostly quartz but with at least one plagioclase feldspar.
#1 – Clay and mostly angular to some rounded silt, mostly quartz with a few non-quartz, non-feldspar silt grains; tiny amounts of detrital micas; 85–90% clay and about 10–15% silt.

Trench 2
#5 – Clay (90–95%) with black mineral laminations; 5–10% angular to subrounded quartz silt; less silt and smaller grains than main quarry layer; "fish layer."
#4 – Clay (95%) and silt to fine sand (5%) that is sub-angular to subrounded and mostly quartz; few clayballs and mostly without silt; some carbonized plant fragments and at least one small plant stem or woody plant fragment.
#3 – Clay (95%) and silt to fine sand (5%) that is sub-angular to subrounded and mostly quartz; no clayballs; some carbonized plant fragments.
#2 – Clay (85–90%) and silt to fine sand (10–15%) sub-angular to subrounded; silt grains mostly quartz but with at least one plagioclase feldspar; rounded to sub-angular clayballs of various colors to 9 mm diameter, some with and some without internal silt grains; many carbonized plant fragments and one small wood fragment; "Main bone layer."
#1 – Clay and mostly sub-angular to subrounded silt, mostly quartz; 80–90% clay and about 10–20% silt, no clayballs.

Trench 3
#5 – Clay (90–95%) with black mineral laminations; 5–10% angular to subrounded quartz silt; less silt and smaller grains than main quarry layer; "fish layer."
#4 – Clay (95%) and silt to fine sand (5%) that is angular to subrounded and mostly quartz with at least one plagioclase feldspar; some light hematite mottling.
#3 – Clay (90–95%) and silt to fine sand (5–10%) that is sub-angular to subrounded and mostly quartz; no clayballs; some carbonized plant fragments.
#2 – Clay (90–95%) and silt to fine sand (5–10%) angular to subrounded; silt grains mostly quartz and minor amounts of plagioclase feldspar; carbonized plant fragments; one bone fragment.
#1 – Clay (90–95%) and silt to fine sand (5–10%), angular to subrounded; silt grains quartz and minor amounts of plagioclase feldspar; abundant carbonized plant fragments; some clayballs; "Main bone layer."

Trench 4

#5 – Clay (90–95%) and silt to fine sand (5–10%); angular to subrounded quartz and minor amounts of rock fragments as silt grains; mottled but no laminations; "fish layer."

#4 – Clay (95%) and silt to fine sand (5%) that is angular to subrounded and mostly quartz with minor plagioclase feldspar grains; single carbonized plant fragment; mottled; no clayballs.

#3 – Clay (95%) and silt to fine sand (5%) that is angular to rounded and mostly quartz; no clayballs; very rare carbonized plant fragments.

#2 – Clay (90–95%) and silt to fine sand (5–10%) angular to rounded; silt grains mostly quartz; some carbonized plant fragments; one clayball; "Main bone layer."

#1 – Clay (85–90%) and silt to fine sand (10–15%), angular to subrounded; silt grains quartz and minor amounts plagioclase feldspar; no plant material; no clayballs.

Trench 5

#5 – Clay (90–95%) and silt to fine sand (5–10%) with dark laminations; angular to subrounded quartz silt grains; "fish layer."

#4 – Clay (95%) and silt (5%) that is angular to subrounded and mostly quartz with minor plagioclase feldspar grains.

#3 – Clay (95%) and silt to fine sand (5%) that is sub-angular to rounded and mostly quartz.

#2 – Clay (90–95%) and silt to fine sand (5–10%) sub-angular to subrounded; silt grains mostly quartz with some minor amounts of plagioclase feldspar; some carbonized plant fragments.

#1 – Clay (95%) and silt to fine and medium-fine sand (5%), sub-angular to subrounded; silt grains quartz and minor amounts plagioclase feldspar and rock fragments; some carbonized plant material; one clayball; "Main bone layer."

Pebbles (P-1 through P-5)

Clay (90–95%) and silt (5–10%); silt grains angular to subrounded and mostly quartz; silt grains finer grained but more numerous than some in-place silty claystone; edges of pebbles same as center; dendrites growing in from some edges; P-5 is laminated but otherwise no different from the others. P-1 is somewhat laminated, too. All appear to be calcite cemented nodules, no chert nor rock fragments.

APPENDIX B − CORE DESCRIPTIONS

Mygatt-Moore Quarry Drill Hole MM-1
June 25, 2013
Logged by J. Foster
UTM: 12S 0670796E, 4340409N
105m ~WNW of 1000, 1000 quarry datum cap

Top

107 cm	soil
274 cm	light gray claystone
25 cm	darker gray claystone
107 cm	light gray claystone
180 cm	maroon to brick-red, slightly silty mudstone (some minor light gray mottling)
140 cm	light gray to light green claystone
134 cm	gray mudstone, becomes silty near base
173 cm	deep red silty mudstone
36 cm	light gray mudstone
33 cm	silty gray and purple mudstone
127 cm	light gray silty mudstone
13 cm	deep red to purple and green-gray mottled and laminated siltstone
13 cm	deep red mudstone
33 cm	silty gray mudstone, with black and white (dentritic?) staining in bottom half
228 cm	light gray silty mudstone
18 cm	purple and light gray laminated siltstone ("fish layer")
8 cm	very dark gray, crumbly mudstone
8 cm	light gray and purple mottled mudstone
84 cm	light gray and light greenish-gray mudstone
38 cm	light gray mudstone with abundant carbonized plant fragments (**main quarry layer**)
8 cm	green mudstone
137 cm	light gray to greenish-gray slightly silty mudstone
71 cm	gray, silty mudstone
30 cm	light gray and greenish-gray very fine grained sandstone

Bottom

Mygatt-Moore Quarry Drill Hole MM-2
June 25–26, 2013
Logged by J. Foster and H. Schoenstein
UTM: 12S 0670809E, 4340274N
118m ~SW of 1000, 1000 quarry datum cap
Top

---	loose gravel
23 cm	green and red mottled mudstone
61 cm	maroon-red mudstone

Paleontology, Taphonomy, and Sedimentology of the Mygatt-Moore Quarry, a Large Dinosaur Bonebed in the Morrison Formation,
Western Colorado–Implications for Upper Jurassic Dinosaur Preservation Modes
Foster, J.R., Hunt-Foster, R.K., Gorman, M.A., II, Trujillo, K.C., Suarez, C.A., McHugh, J.B., Peterson, J.E., Warnock, J.P., and Schoenstein, H.E.

20 cm	green-gray mudstone
23 cm	gray siltstone to very fine grained sandstone
25 cm	dark gray mudstone
25 cm	green-gray crumbly mudstone with yellow staining of the cracks
97 cm	light gray claystone
41 cm	dark reddish gray mudstone
145 cm	light gray to light greenish-gray mudstone and siltstone
51 cm	dark gray mudstone, some reddish mudstone near base
221 cm	light greenish-gray mudstone, with golden-tan mineralization in cracks near the base
48 cm	red and light greenish-gray mottled mudstone
183 cm	dark red mudstone, with some light gray mottling
71 cm	light greenish-gray mudstone
51 cm	red mudstone mottled with light gray
129 cm	light gray to white siltstone and slightly silty mudstone
30 cm	green-gray mudstone
165 cm	light gray to white, finely laminated silty mudstone with some very fine grained sandstone
8 cm	light gray siltstone with thicker, slightly purple laminations ("fish layer")
13 cm	dark gray mudstone
8 cm	light green siltstone, slightly laminated purple ("fish layer")
33 cm	light green mudstone
48 cm	medium green mudstone
94 cm	medium greenish-gray to gray mudstone with moderate to abundant carbonized plant fragments; some layers of light green, rounded clayballs to 5 mm diameter; **dinosaur bone fragment** in
core	at 16.5 m down (**main quarry layer**)
33 cm	light green, soft mudstone ("clay layer")
33 cm	light green mudstone
38 cm	medium green mudstone
15 cm	medium green to reddish mudstone
299 cm	medium to light green and maroon-red mottled, silty mudstone
Bottom	