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Title: Description of a Juvenile Triceratops Skull and Lower Jaw

and Comparison of Juvenile Ceratopsian Characteristics

Thesis Chair: Michael Morales

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A juvenile *Triceratops* partial skull and lower jaw from the Upper Cretaceous (66 million years) Hell Creek Formation near Jordan, Montana, was collected in 2014. Having been collected near the top of the upper third of the Hell Creek, the fossil material likely belonged to *Triceratops prorsus*. Main elements from the skull (Emporia State University Paleontology Collection specimen number ESU 2014-1) include the parietal, the right postorbital horn, partial left postorbital horn, the right maxilla, a partial left maxilla, a left nasal, and a rostral. Both left and right dentaries and the predentary were collected. Growth stages of *Triceratops* are: baby, juvenile, subadult, and adult. The size of the skull material and the posteriorly-curving brow horn indicate that this was an older, medium-to-large sized juvenile specimen, with a snout-to-occipital condyle length of about 65 cm.

Comparisons among *Triceratops* juveniles and between juveniles of other ceratopsian species focused on ontogenetic features. Characteristics of juvenile *Triceratops* are posteriorly curving brow horns, large orbits in comparison to skull size, delta shaped epoccipitals that are not fused to the frill, and unfused nasals. In babies, the brow horn was straight, but in subadults it angled forward. ESU 2014-1 shows individual variation from other *Triceratops* of the same growth stage in the shorter length of the postorbital horns, the larger size of the bony prominence along the parietal midline, and the shallow scalloping of the frill.

A survey of ceratopsian literature revealed that besides the size of the individual, common characteristics for juvenile ceratopsians of several genera include proportionally larger orbits, unfanned and/or scalloped frills, amount of striated bone texture, unfused nasals, lack of horn core sinuses, and unfused skull sutures. Identification of the juvenile growth stage of ceratopsians must be based on the observation of multiple juvenile traits in the individual specimen.

Keywords:
Triceratops, Ceratopsians, Juveniles, Hell Creek Formation, Growth Stages

Description of a Juvenile *Triceratops* Skull and Lower Jaw and Comparison of Juvenile Ceratopsian Characteristics

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Chapter 1: Introduction

In the summer of 2014, Carlton Laird, from St. Louis, Missouri, discovered a fragmentary and disarticulated skull and related mandible fragments of the ceratopsian dinosaur *Triceratops* in deposits of the upper Hell Creek Formation, of Late Cretaceous age (66 million years). The small size of the bones indicated that they represented a juvenile individual, which is rare for the genus (Goodwin et al., 2006). Laird and Dave Lukens excavated the skull, and then they collected it with the help of Mark Fedde and Carl Campbell (St. Louis Community College), all from the St. Louis, Missouri area. Laird, Fedde, and Campbell worked to remove the rock from the fossilized bones at the St. Louis Science Center. In 2017, Campbell and crew reopened the site and found and collected the right postorbital (brow) horn of the skull. The site (Figure 1) was opened once again in 2018, and a fragment of the left postorbital horn was found and collected. Dr. Michael Morales, Matt Mers, Nick Thurber, and I, all from Emporia State University, measured a stratigraphic section of the site with the help of Carl Campbell. The rock at the site where the fossil was collected was a light gray siltstone. The site was located about 48 feet below the Cretaceous-Paleogene boundary.

The purpose of this MS research were (1) to describe this rare and significant skull and lower jaws specimen, (2) to compare it to the few other known juvenile *Triceratops* skulls to document similarities and differences, and (3) to compare its juvenile traits with juvenile traits of other ceratopsians. Results of these analyses and the stratigraphic level of the specimen’s site should provide information about the species

Figure 1. Excavation site of ESU 2014-1. Looking to the north. The fossils were found in the gray and orange mudstone in the shadows.

identification within the genus. In addition, the fossil material allowed for investigation of changes in skull morphology and proportions through ontogeny in the genus (Horner and Goodwin, 2006). Compared to adult *Triceratops*, the number of juveniles that have been uncovered and collected are far fewer. Juveniles of any ceratopsian are a significant find. Juvenile ceratopsians, including *Triceratops*, look distinctive from adults, so these fossils offer insight into changes that occur during ontogeny.

The fossil material is stored in the Johnston Geology Museum of Emporia State University as ESU 2014-1. The material (Figure 2) is comprised of a partial skull, including the parietal section of the frill, a complete right postorbital horn and the base and a section of the left postorbital horn, a portion of the right maxilla and a smaller piece of the left maxilla, a partial piece of the left nasal, and many small skull fragments. In addition to the skull, there are also incomplete portions of the left and right sides of the lower jaw. The skull has been repaired, with cracks in the frill being filled in with epoxy putty, and portions of the lower jaws have been reconstructed based on symmetry.

Figure 2. Reconstruction of the skull of ESU 2014-1 based on MOR 2951. The fragments of ESU 2014-1 are shown in red.

Triceratops was a dinosaur from the Late Cretaceous epoch, most iconic for the three horns and frill adorning its skull. The appearance of its young is not as well known --nor are the changes they went through as they matured into an adult. The skull material described in this thesis will add to the better understanding of juvenile *Triceratops.* The skull of ESU 2014-1 is larger than the smallest known (baby stage) skull of *Triceratops* UCMP 154452, which is housed at the University of California Museum of Paleontology (Goodwin et al., 2006) but smaller than that of typical adult and subadult stages of the genus. The ESU material was compared to juveniles of other ceratopsians, noting differences and similarities between skull features.

Numerous studies of adult *Triceratops* have been completed over the years since discovery of the genus in 1889, but very few studies of young *Triceratops* exist. Horner et al. (2006) described the growth stages of *Triceratops.* Based on ontogenetic trends, they categorized *Triceratops* into four growth stages: baby, juvenile, subadult, and adult. According to their study, the specimen discussed in this thesis would be categorized as a juvenile. Goodwin et al. (2014) described a juvenile *Triceratops* of similar size, albeit slightly larger than ESU 2014-1. Based on the characteristics of each stage, this would put both *Triceratops* individuals on the older side of juvenile. The smallest *Triceratops* described by Goodwin et al. (2006) is representative of the baby stage. Their paper also reviewed the cranial ornamentation in ceratopsians and how it applies to their specimen, as young as it was.

Chapter 2: Previous Work

Introduction

The first section of this chapter focuses solely on *Triceratops*. The chapter begins with an overview of *Triceratops* and leads into specimen description. The descriptions of *Triceratops* are ordered by growth stage. In the second section of the chapter, growth stages and juveniles of other ceratopsians are discussed.

Triceratops

The first *Triceratops* fossils ever found were mistaken as remains of a fossil bovid, originally described as *Bison alticornis* (Marsh, 1887). The pair of horn cores were thought to have come from late Pliocene sandstone deposits. In 1889, Marsh published a paper attributing the horn cores to a new dinosaur species, *Triceratops horridus*, which he included in the newly named family of dinosaurs Ceratopsidae. *Triceratops horridus* was described as having a pair of massive horns on top of the skull, a third horn on the nose, a huge occipital crest, and a bone in front of the premaxillaries named the rostral (Marsh, 1889).

Sixteen species of *Triceratops* were named in the late 1800s and early 1900s. In modern times, however, only two species, *Triceratops horridus* and *Triceratops prorsus*, were recognized by Forster (1996), who concluded that all sixteen *Triceratops* species could be divided into only two groups, with most of the species being assigned to *T. horridus*. Display and defensive features, such as horn curvature and frill size and shape, vary between individuals, and some of these features had been used to classify

Triceratops into the sixteen species. Forster and Dodson (1990) and Forster (1996) listed some of those adult varying characteristics as being the suture between the squamosal, jugal, and postorbital horn, the postorbital horn length and orientation, the absence of frontal fontanelle, the rostrum shape, and nasal horn length.

Gilmore (1905) described a mounted *Triceratops prorsus* in the United States National Museum, Washington, D.C., which became known as the Arts and Industries Building. The individual mounted for display was mostly complete, with the missing elements being substituted from individuals of similar size (Figure 3). The skeleton was positioned such that its legs were splayed similar to a turtles, rather than being placed directly beneath the body. Its overall length was stated to be 19 feet and 8 inches. Gilmore stated that the skull alone was nearly one-third the length of the entire body. Characteristics used to determine *T. prorsus* in general are closed frontal fontanelle, relatively short postorbital horns and a shorter, convex rostrum (Forster, 1996.)

Scannella et al. (2014) discussed trends of skull characteristics based on stratigraphic placement. *Triceratops* found in the lowest portions of the Hell Creek Formation, the same formation from which ESU 2014-1 was collected, were listed as having small nasal horns or a low nasal boss, a narrow nasal process of the premaxilla that is strongly posteriorly inclined, a pronounced anteromedial process on the nasal, and a frontoparietal fontanelle that remained open until late in ontogeny. *Triceratops* from the middle third of the Hell Creek were stated as having a mean nasal horn increase in length throughout the section. Specimens at this level were noted as sometimes having a pronounced projection on the posterior surface of the epinasal (Scannella et al., 2014).

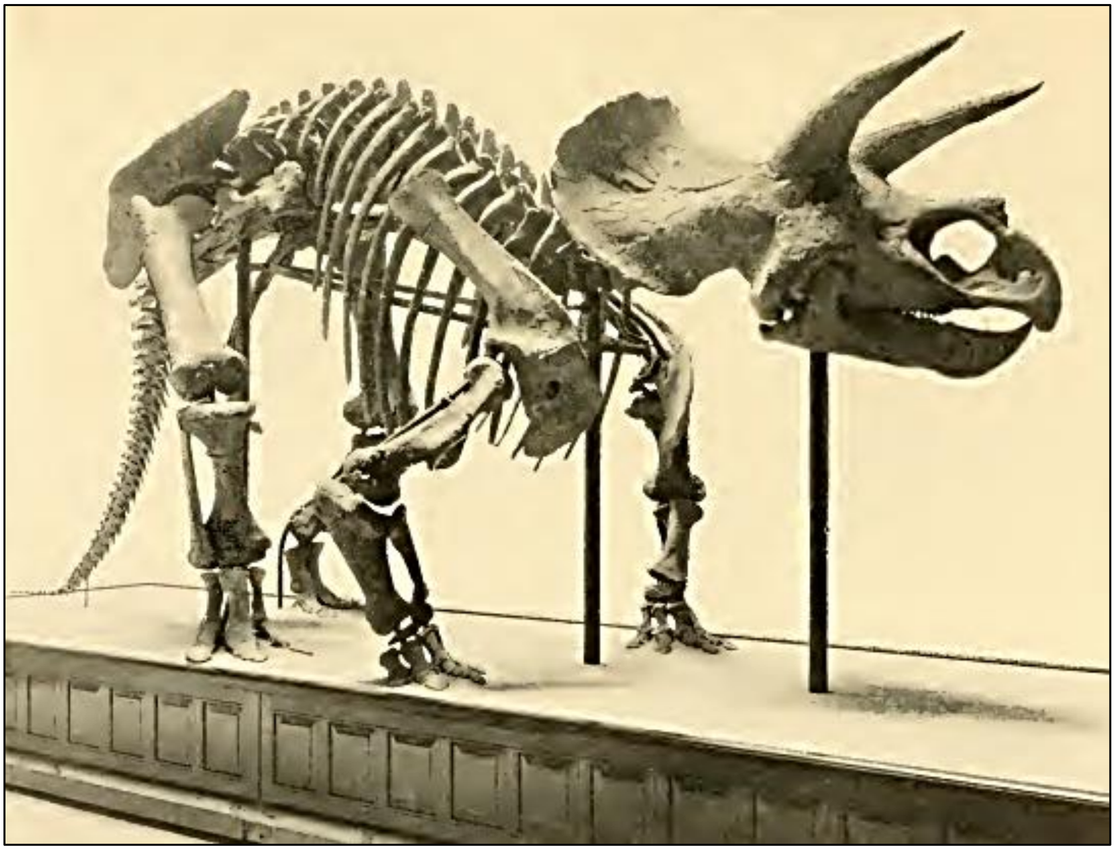

Figure 3. Mounted specimen of *Triceratops prorsus.* (Gilmore, 1905)

It was also stated that *Triceratops* from this middle section have a pronounced anteromedial process on the nasal horn, and the rostrum is more convex in specimens from the upper part of this section. In the upper third of the Hell Creek, *Triceratops* were said to possess elongated and narrow nasal horns, a convex rostrum, a reduced anteromedial process of the nasal, a closing of the frontoparietal fontanelle in subadults, and shorter postorbital horn cores. Scannella et al. (2014) concluded that *Triceratops* underwent an anagenetic (gradual) evolution in which *T. horridus* specimens of the bottom third evolved slowly into *T. prorsus* transitioning in the upper part of the middle third and the upper third of the Hell Creek Formation.

Baby *Triceratops*

The smallest *Triceratops* skull known belongs to a baby (but not hatchling), and some of the distinctive features are its relatively (compared to an adult) large orbits, foreshortened face, small postorbital horns, and short frill which is deeply scalloped along the posterior margin (Figure 4) (Goodwin et al., 2006). The entire skull of this small *Triceratops* specimen, UCMP 154452 (University of California Museum of Paleontology), is 30 cm long. This baby was collected in the upper Hell Creek Formation near Garfield County, Montana, which is the latest Cretaceous (Maastrichtian: 66 million years) in age (Cohen et al., 2018).

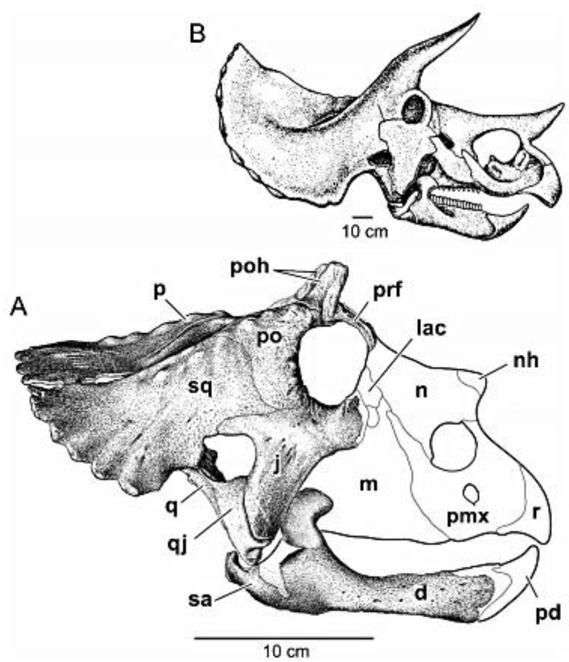

Figure 4. Comparison of the smallest (baby) *Triceratops* skull with that of an adult. Legend: d - dentary; j - jugal; lac - lacrimal; m - maxilla; n - nasal; nh - nasal horn; p - parietal; po - postorbital; poh - postorbital horn; pd - predentary; pfr - prefrontal; pmx - premaxilla; q - quadrate; qj - quadratojugal; r - rostral; sa - surangular; and sq - squamosal. (Goodwin et al., 2006)

Juvenile *Triceratops*

Goodwin and Horner (2014) described a juvenile *Triceratops* skull similar in size to the ESU specimen (Figure 5). Found in the upper Hell Creek Formation of McCone County, Montana, this nearly complete *Triceratops* skull is Late Cretaceous in age. At this growth stage, it was noted that the orbits were still large, the postorbital horns curved caudally, and that the frill had not fanned out. The epinasal had not fused to the nasals yet. The basal skull length (from tip of rostral to occipital condyle) was estimated to be 64 cm (Goodwin and Horner, 2014).

Figure 5. Reconstruction of the juvenile *Triceratops.* (Goodwin and Horner, 2014)

Postorbital horn curvature changes through ontogeny, with the horns growing straight as a baby, curving posterior as a juvenile, transitioning to an anterior curve as a subadult, and anterior curvature as an adult (Figure 6) (Horner and Goodwin, 2006). Characteristics of the juvenile growth stage were posteriorly curving postorbital horns, delta shaped epoccipitals, unfused but paired nasals, and with horn excavation (cornual sinus) present in large juveniles but not present in smaller ones (Horner and Goodwin, 2006). Horner and Goodwin (2006) included a table detailing ontogenetic trends throughout all *Triceratops* growth stages (Table 1).

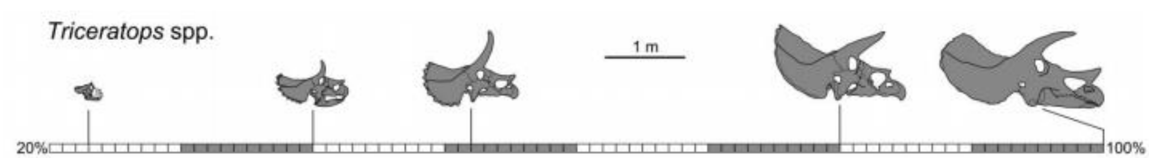

Figure 6. *Triceratops* growth stages. Scale is the percent of adult skull size, with largest adult skull = 100%. (Mallon et al., 2015)

Two juvenile left postorbital horn cores were discovered in late Maastrichtian (66 million years) deposits of southern Saskatchewan, Canada, a first known occurrence in the Frenchman Formation (Tokaryk, 1997). The small chasmosaurine horn cores, likely from *Triceratops* or *Torosaurus*, lack the curvature seen in larger individual juveniles and adults. The larger of the two left postorbital horns measured 95 mm and the shorter was 65 mm.

			ontogenetic trends									
Triceratops	element	growth stage	A	B	C	D	E	F	G	H	I	J
UCMP 154452	skull	baby	x								x	
MOR 652	squamosal	baby	x									
MOR 1098	postorbital horn	baby										
MOR 1053	postorbital horn	baby										
UCMP 158441	postorbital horn	baby										
UCMP 399749	postorbital horn	baby										
MOR 1199	skull	juvenile		x			x					
UCMP 136306	skull	juvenile		x			x					
MOR 1110	skull	juvenile		x			x	x				
UCMP 159233	partial skull	juvenile										
MOR 1129	partial skull	juvenile										
UCMP 139292	postorbital horn, maxillary, braincase	juvenile										
UCMP 150234	parietal	juvenile		x			x					
MOR 539	postorbital horns	juvenile					x					
UCMP 186583	epinasal	juvenile										
MOR 989	epinasal	juvenile										
MOR 1167	epinasal	juvenile										
UCMP 137263	skull	subadult		x		x						x
MOR 1120	skull	subadult		x	x	x		x	x	x	x	x
MOR 699	skull	subadult		x		x					x	x
UCMP 136092	skull	subadult		x		x					x	
UCMP 137266	partial skull and skeleton	subadult										x
UCMP 173739	postorbital horn	subadult										x
MOR 1604	skull	adult			x				x	x		x
MOR 004	skull	adult			x	x			x	x		x
MOR 1625	skull	adult			x				x	x		x
UCMP 113697	skull	adult			x	x		x	x			x
UCMP 174838	skull	adult			x				x	x		x
UCMP 136589	partial skull	adult			x							x
UCMP 140416	partial skull	adult				x						x
UCMP 129205	premaxillae, nasals, nasal horn	adult				x						
			A	B	C	D	E	F	G	H	I	J

Table 1. Ontogenetic trends in *Triceratops* specimens. A - parietal–squamosal frill with scalloped posterior margin, B - posterior frill margin less scalloped to wavy, C - epoccipitals merged onto smooth caudal frill margin, D - fan-shaped frill, E - posterior postorbital horn curvature, F - excavation of postorbital horn internally, G - fusion of nasals, H - fusion of nasal horn onto the nasals, I - supraoccipital present between the exoccipitals, J - anterior postorbital horn recurvature (Horner and Goodwin, 2006).

A partial parietal frill with epiossifications (epiparietals and episquamosals) from a juvenile *Triceratops* was described by Wilson and Fowler (2017). The specimen was Maastrichtian in age and found in the Hell Creek Formation in Valley Country, Montana. The three unfused epiparietals were recovered with the frill, which was stated as having a striated texture.

Subadult *Triceratops*

A *Triceratops* was described by Schlaikjer (1935) as being a subadult. This specimen was uncovered from Upper Cretaceous deposits of the Lance Formation in Goshen Hole of southeast Wyoming. The fossils were the skull, jaws, and some skeletal material. Schlaikjer described some of the pertinent characteristics as being an elevated orbit, horns being long and slender, and still having open sutures. Schlaikjer interpreted this specimen as being an immature individual and as a new species, *Triceratops eurycephalus.* However, that species is considered to be a *nomen dubium* as the characteristics used to define it as its own species were, in fact, not unique (Forster 1996). Forster (1996) did not place this specimen in either *T. horridus* or *T. prorsus*, as some skull material and the mandibles were described as not resembling those of *Triceratops.*

A feature seen in late juvenile and older *Triceratops* is the presence of cornual sinuses, or excavations of the horn cores (Farke, 2006). In *Triceratops*, the cornual sinus is an extension of the frontal sinus into the center of the postorbital horn core. The development of the cornual sinus was observed in many ceratopsian species. Farke (2006) described the cornual sinuses as likely having multiple purposes, which may include shock absorption, mass reduction, and thermoregulation.

Triceratops, among many other ceratopsians, had frills and horns that differed from other ceratopsian species. Farlow and Dodson (1975) discussed the purpose of frill and horn shape and stated that both were likely very significant in display and combat. They wrote that ceratopsians can be classified as either short-frilled or long-frilled, with *Triceratops* falling into the short-frilled category. In combat with other *Triceratops*, the frill would act as a shield to the neck (Farlow and Dodson, 1975).

Other Non-Adult Ceratopsian Specimens

Introduction

Other taxa included here are phylogenetically basal ceratopsians and those from the more advanced subfamilies of Centrosaurinae and Chasmosaurinae. The specimens reviewed are ordered into basal ceratopsians, chasmosaurines, and centrosaurines. The best examples of juvenile specimens are discussed first for each group.

Basal Ceratopsians

***Liaoceratops*.** Xu et al. (2002) described *Liaoceratops yanzigouensis*, a basal ceratopsian from western China of Lower Cretaceous age. A juvenile specimen had fewer teeth, vaulted frontals, a weaker jugal horn, and a shorter and narrower frill than that of adult specimens. The squamosals were stated as growing to form half the frill margin as an adult. Xu et al. (2002) mentioned that this arrangement is different in *Protoceratops,* where the squamosals contribute to less of the overall frill size in adults, and they noted that *Liaoceratops* was the oldest known neoceratopsid.

Psittacosaurus. Two juvenile specimens of *Psittacosaurus* were described by Coombs (1982) (Figure 7). The specimens were from the Early Cretaceous Oshih Formation in western Mongolian Peoples' Republic. The material of one specimen was composed of a partial skull and jaws, and the other was an almost complete skull and jaws with numerous postcranial elements from at least seven individuals. Both specimens are very small, with the larger of the two having a total estimated body length of 340-390 mm and the smaller at 230-265 mm. The skulls have short snouts, orbits with a diameter 33-38% of the cranial length, lateral temporal fenestrae smaller than the orbits, and small jugal spines. It was stated that their large brains (relative to body size) were a juvenile characteristic. Some other juvenile features listed were the skull roof having more curvature than in adults, rostral close to or touching maxilla, a lack of sagittal crest, and a slender suborbital bar.

Protoceratops. Multiple papers include discussion of juvenile *Protoceratops*, either as their primary focus or secondarily. Dodson (1976) discussed multiple specimens, categorized into groups of males, females, and juveniles. Two of the variables used in the study (height of the posterior region of the skull and height of the frill) are noted as relatively increasing in size during ontogeny, along with development of the coronoid process of the jaw. These details indicate that it was unlikely that the frill evolved for strengthening muscles of the jaw. Mature individuals of *Protoceratops* were sexually dimorphic, with features of the skull and jaws being different between adult males and females. Although males and females reached about the same adult size, the frill and nasal horn differed in their prominence between the two sexes and were likely used for display rather than function (Dodson, 1976).

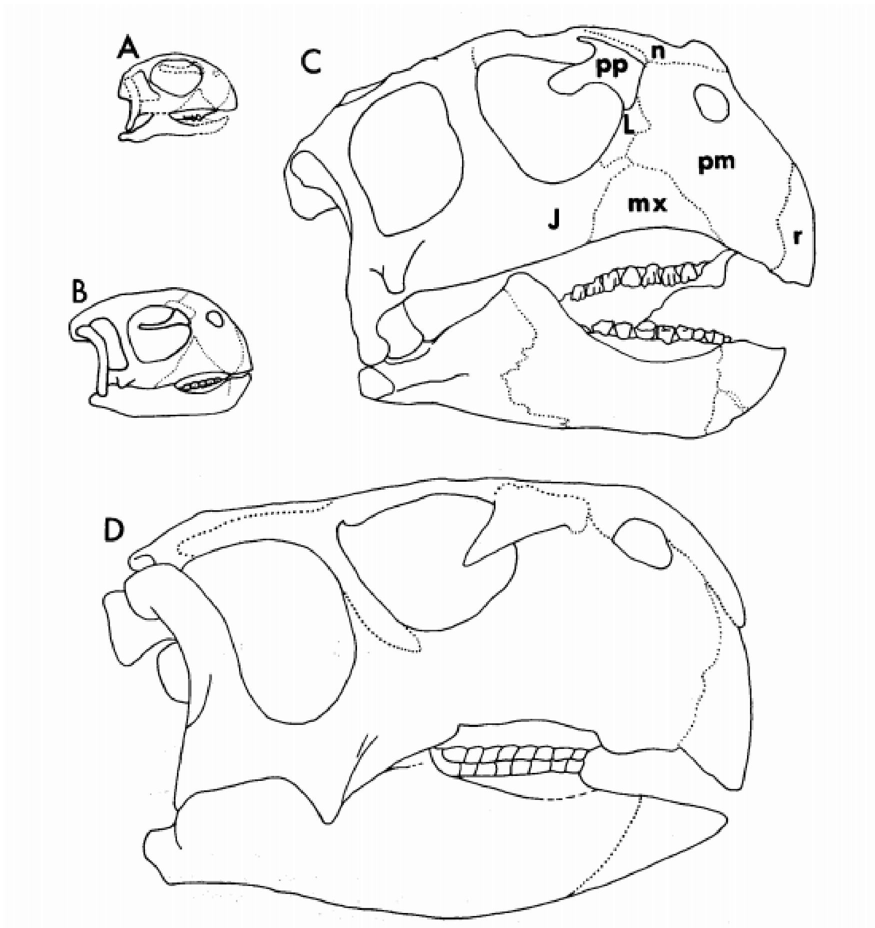

Figure 7. Skull comparison of *Psittacosaurus*. A and B are the described juveniles. (Coombs, 1982)

Hone et al. (2014) discussed an aggregation of four juvenile *Protoceratops* from the Central Gobi region of Cretaceous deposits in Mongolia. Most of the four were nearly complete, with each being similar in size and approximately one-quarter size of the largest adult *Protoceratops* found (Hone et al. 2014). The juveniles were noted as having unfused skull sutures, large orbits relative to the skull, and proportionately small frills. It was noted that they died simultaneously and were likely alive at the time of burial. Near the same stratigraphic level, a pair of subadults were found. One of the subadults was nearly complete, with the second being poorly preserved. The pair of *Protoceratops* were determined to be subadult based on size and skull development. Frill and nasal ornamentation had yet to develop distinctly as seen with full grown adults (Figure 8).

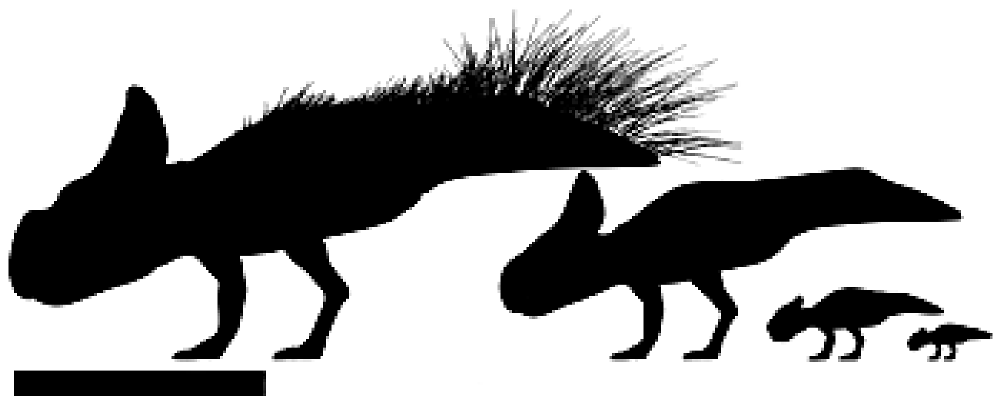

Figure 8. Body silhouettes of *Protoceratops*. The figures represent an adult, subadult, a midsize juvenile, and a very small juvenile. The subadult and midsize juvenile are based on specimens from Hone et al. (2014). Scale bar is 1 m.

Zuniceratops. The holotype of *Zuniceratops*, a ceratopsian from the Turonian (Late Cretaceous) Moreno Hill Formation near the Arizona-New Mexico border, was likely a younger (juvenile or subadult) specimen based on larger horn cores being found in another specimen (Wolfe and Kirkland, 1998). The authors stated that the holotype specimen has, in comparison with adults of the same species, large orbits and a smaller brow horn of 88 mm. Striated bone texture is considered to be a juvenile feature, but the holotype of *Zuniceratops* lacks evidence for this. Adults were noted as having well-developed brow horns and frills with large fenestra (Wolfe and Kirkland, 1998).

Chasmosaurines

Chasmosaurus. A mostly complete juvenile *Chasmosaurus* from the Late Cretaceous Dinosaur Park Formation of Alberta, Canada was described by Currie et al. in 2016 (Figure 9). Their paper described the characteristics of the juvenile *Chasmosaurus* and compared those traits to adults. In juveniles, the nares, orbits, and lower temporal fenestrae were large, the snout was short, the horns were poorly developed, the maxillary tooth count was less than in adults, and the frill was short and narrowed posteriorly. Currie et al. (2016) also stated that this chasmosaurine was smaller than the smallest, i.e., baby, *Triceratops* described by Goodwin et al. (2006), which has a basal skull length of only 272 mm.

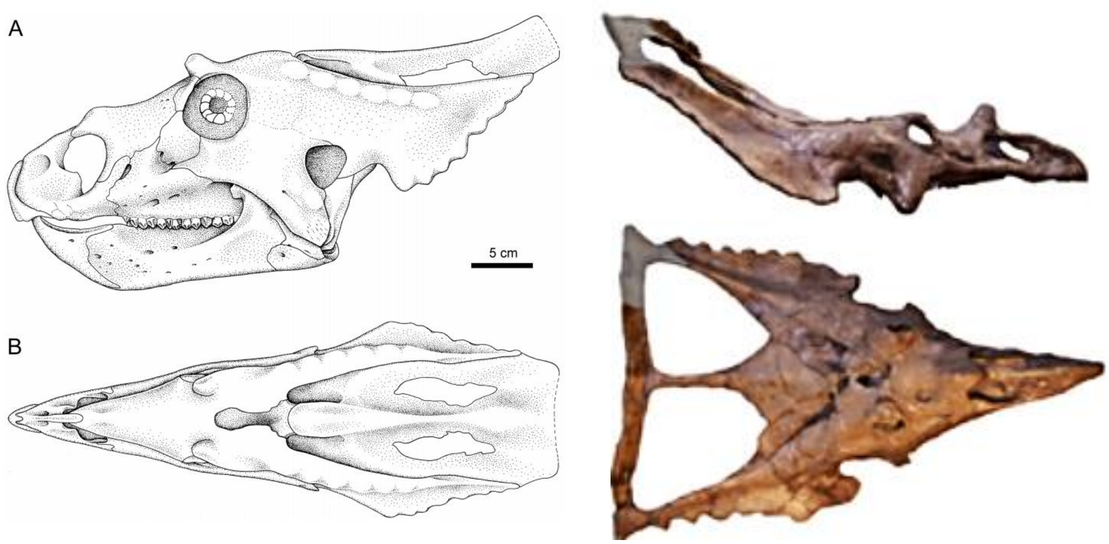

Figure 9. The juvenile *Chasmosaurus* skull compared to an adult. (Left – Currie et al., 2016; Right – Campbell et al., 2016)

Campbell et al. (2016) discuss similarities of ontogeny between *Chasmosaurus belli* and *Chasmosaurus russelli*. *Chasmosaurus* growth stages were defined as baby, juvenile, subadult and adult (Figure 10). Based on these stages, juvenile characteristics were listed as having a rostral-to-epijugal length between 250 mm and 550 mm, and having open sutures and unfused epiparietals. Both juveniles and subadults have postorbital horn cores, whereas in adults this feature is reabsorbed into the base. The orientation of postorbital horns varied between immature individuals.

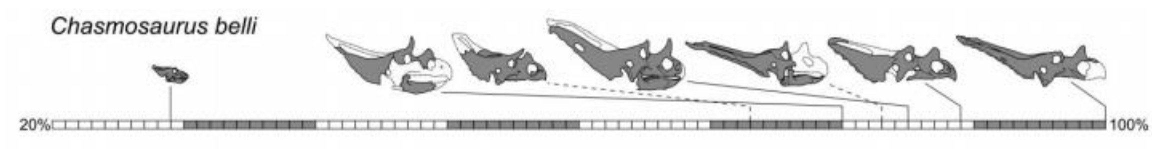

Figure 10. Growth series of *Chasmosaurus*. Percentage based on largest skull specimen. (Mallon et al., 2015)

Arrhinoceratops. Mallon et al. (2015) discussed ontogeny in *Arrhinoceratops*. A juvenile, specimen CMN 8882 (Canadian Museum of Nature), collected in 1925 from the Upper Cretaceous Horseshoe Canyon Formation in Alberta, Canada, was described (Figure 11). The juvenile *Arrhinoceratops* had an approximate basal skull length of 465 mm. The specimen is a partial skull and jaws and some postcranial elements. Included with the skull is the right posteriorly-curving postorbital horn. The squamosal and parietal fragments were stated as having a long-grained (= striated) bone texture, indicative of a juvenile.

Figure 11. Growth series of *Arrhinoceratops*. Based on largest basal skull length percentage. The described *Arrhinoceratops* is the leftmost juvenile skull. (Mallon et al., 2015)

Centrosaurines

Sampson et al. (1997) discussed ceratopsian ontogeny, listing juvenile and subadult features with a focus on skeletal bone textures and centrosaurine skull ornamentation. Surface bone texture was determined to be an indicator of position in the growth series a ceratopsian may be. A striated texture indicates rapid bone growth as seen in juveniles and portions of subadults, with adult ceratopsians lacking this bone texture. Adult bone texture is smooth, with a transition between this adult texture and the juvenile striated being a mottled texture, seen in juveniles and subadults. Brown et al. (2009) noted a step-like interface between striated and mottled textures (Figure 12). Centrosaurine juveniles and subadults have nasal horn cores that overlay most of their narial openings and that are divided longitudinally, for these would fuse from the tip down and grow to cover only the posterial margin of the narial opening. In the case of postorbital horns, juveniles and subadults possess low, rounded horn cores which were modified into adult horn cores or pachyostotic (thick dense bone) bosses as adults. In centrosaurine species that lacked postorbital horns as adults, the postorbital horn core was either resorbed by the body or eroded into paired left and right pits. The frill of juveniles and subadults of different centrosaurines were similar in appearance in that they were thin and scalloped. As an individual grew into an adult, the epoccipitals would fuse to the frill and would develop ornamentation characteristic to its species (Sampson et al., 1997).

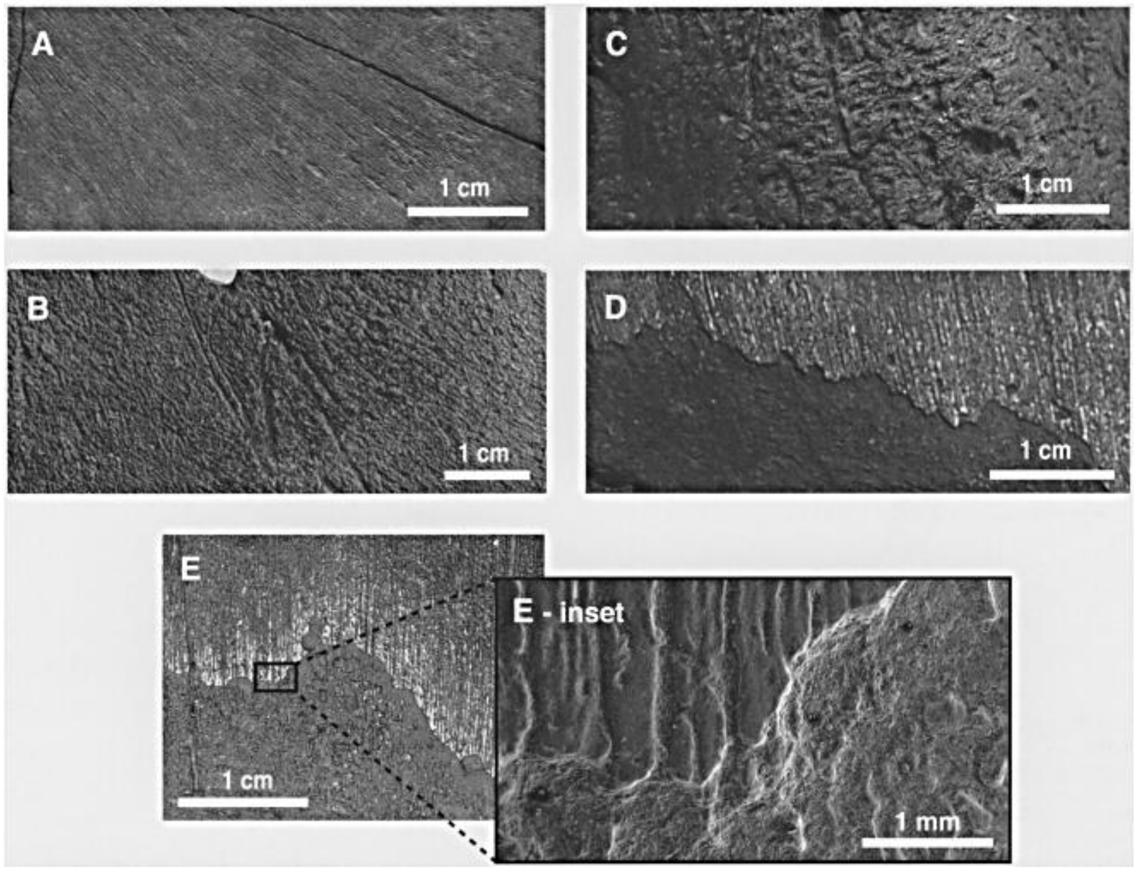

Figure 12. Centrosaurine bone texture. A – long-grained texture. B – mottled. C – smooth. D – long-grained and mottled. E – long-grained and mottled with step-like contact. (Brown et al., 2009)

Centrosaurus. Ryan et al. (2001) discussed a centrosaurine bone bed and *Centrosaurus.* Centrosaurine material was divided into only three groups, juvenile, subadult, and adult (no baby category) (Figure 13). Bones that were less than one-half the size of a typical adult were categorized as juvenile, bones that were between one-half and two-thirds were subadult, and bones in the largest one-third size range were categorized as adult. This differs from the growth stage of *Triceratops* and *Chasmosaurus*, in which size and skull characteristics divide them into baby, juvenile, subadult, and adult. Postorbital horns in centrosaurines, as in chasmosaurines, could be used as an immature characteristic. As the individual matures, the postorbital horn was reabsorbed, leaving either bony mounds, ridges, or pits. The formation of pits indicated reabsorption had or was occurring (Figure 14). Ryan et al. (2001) stated that pitting occurs after horn suture fusion, when the animal has reached maturity. The development of pitting is variable among individual mature animals. A *Centrosaurus* specimen was described as having a low, right horn with pits, while the left remained unmodified.

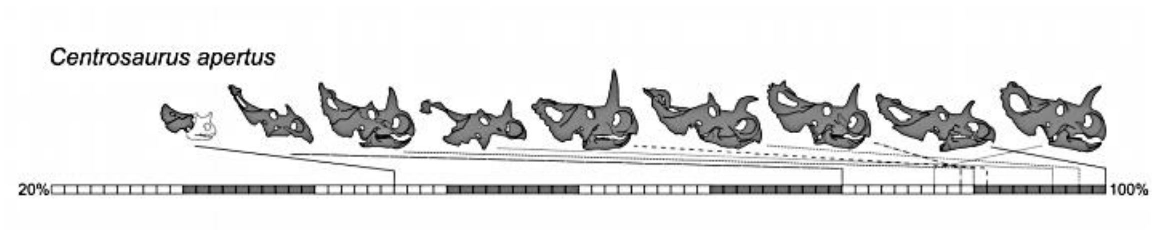

Figure 13. Growth series of *Centrosaurus*. Percentage based on largest skull size. (Mallon et al., 2015)

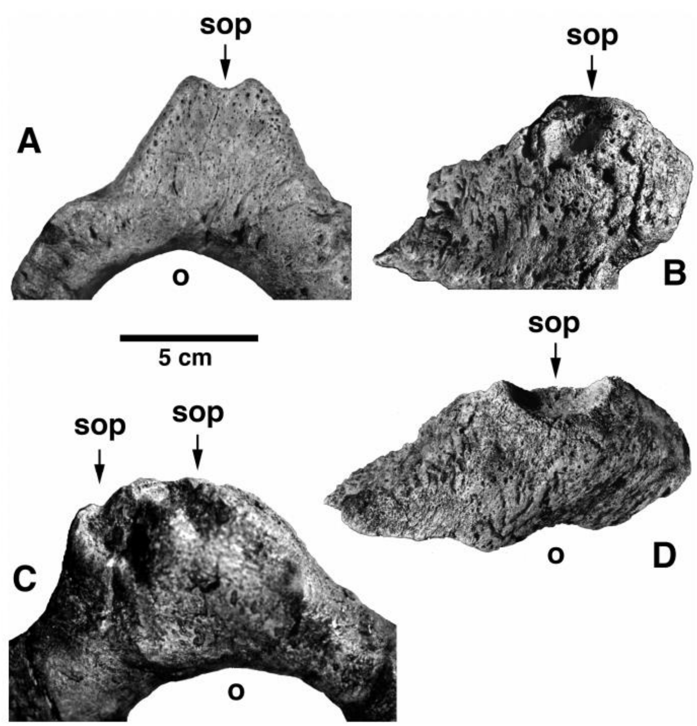

Figure 14. Pitting in adult horn cores. (Ryan et al., 2001). Legend: o – orbit; sop – supraorbital pit.

Pachyrhinosaurus. Fiorillo and Tykoski (2013) discussed an immature *Pachyrhinosaurus perotorum* from the Late Cretaceous Kikak-Tegoseak Quarry in Alaska. The specimen's main element was composed of parts of both fused nasals and it was likely a subadult. Multiple stages were noted in *Pachyrhinosaurus* ontogeny, with the youngest being to Stage 1 and the adults being Stage 6. The described specimen is represented in Figure 15 below as the Stage 4 skull.

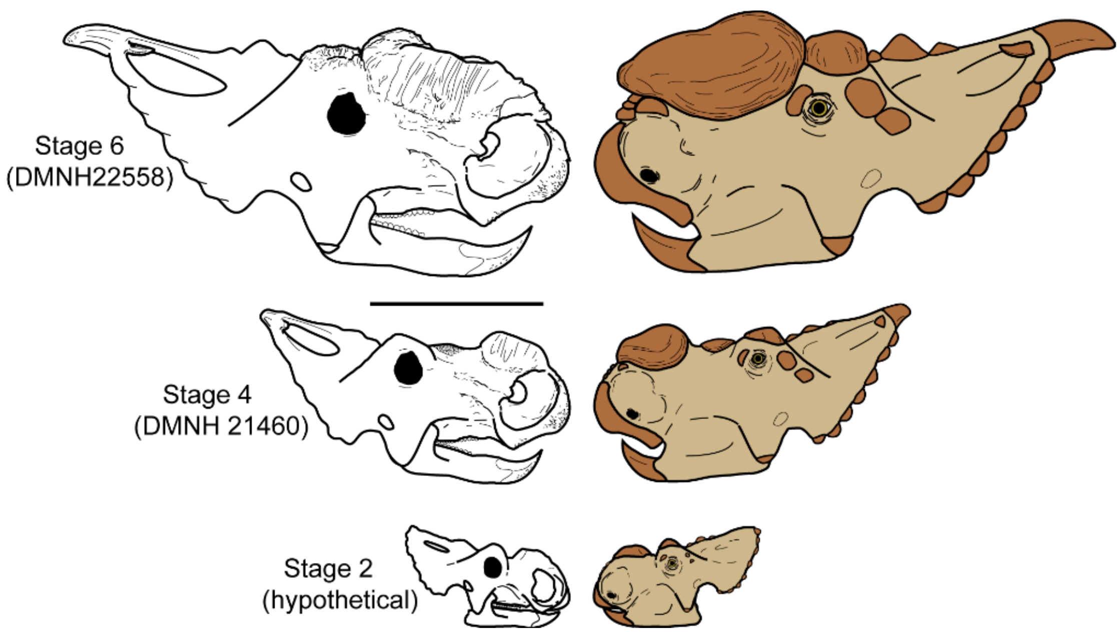

Figure 15. Ontogenetic stages of *Pachyrhinosaurus*. Scale bar is 50 cm (Fiorillo and Tykoski, 2013).

Albertaceratops. This basal centrosaurine from Alberta, Canada was described as having slight excavation at the base of the horn like that seen in chasmosaurines but unlike other centrosaurines (Ryan, 2007). The fossil was found in the lower Oldman

Formation near the Alberta-Montana border and was Late Cretaceous (middle Campanian) in age. Ryan stated that the large postorbital horns of *Albertaceratops* are plesiomorphic characters shared with almost all chasmosaurines as well as *Zuniceratops*, which would be the first occurrence in centrosaurines. An adult size nasal horncore was found unfused to the nasal bone, indicating those elements did not fuse until later in life in *Albertaceratops* (Ryan, 2007).

Nasutoceratopsini. A ceratopsian belonging to the subfamily Centrosaurinae, and likely representing a new taxon of the tribe Nasutoceratopsini, was described by Ryan et al. (2017). This specimen was discovered in the Oldman Formation of southeastern Alberta and is Late Cretaceous (mid-Campanian) age. Features from this ceratopsian included a scalloped frill and a lack of epoccipitals (Figure 16). Striated bone texture was found on some of the fossil elements, but adult bone texture was also noted in places on the skull.

Figure 16. Skull from the Nasutoceratopsini specimen. (Ryan et al., 2017)

Avaceratops. In the same paper by Ryan et al. (2017), the holotype of *Avaceratops* was discussed. *Avaceratops*, described by Dodson (1986) and Penkalski and

Dodson (1999), was from the Upper Cretaceous deposits of the Judith River Formation of Montana. A scalloped parietal and squamosals were uncovered, along with the jugal, quadratojugal, quadrate, maxilla, premaxilla, dentary and other skeletal elements. Ryan et al. (2017) state that *Avaceratops* was only represented by one immature specimen and that diagnosing it as a seperate taxon is problematic.

Brachyceratops. This genus is a *nomen dubium* as only juveniles have been found (Gilmore, 1917; Sampson et al., 1997). The type material is composed of juvenile and/or possible subadult remains. It was collected in 1913 from the Late Cretaceous Two Medicine Formation on the Blackfeet Indian Reserve in Montana. The specimens collected in 1913 were small and generally about the same size. The frill of *Brachyceratops* has small parietal fenestration and lacks epoccipitals. Sutures on the skull and some post-cranial elements were described as being open. The nasal horn core was longitudinally separated into two halves and was an outgrowth of the nasals rather than being an epinasal.

Chapter 3: Methods

Multiple steps were needed to propose, conduct, and write up this research project. During the comprehensive literature review, a compilation of data on juvenile ceratopsians was made and analyzed, and a standard vertebrate paleontological description of fossil specimens was produced. The specific steps taken for this thesis were: (1) gathering, reading, summarizing, and organizing relevant literature; (2) measuring the fossil material and making qualitative observations; (3) photographing the new fossils and other fossils used for comparison; (4) measuring the rock section where the new fossils were collected; (5) describing the new material with text, photographs, and tables; (6) making osteological comparison of the new material with similar fossils from the literature and from the Museum of the Rockies (MOR), Bozeman, Montana, and University of California Museum of Paleontology (UCMP), Berkeley, California; (7) describing the fossils; (8) analyzing the data; and finally (9) writing up the project.

Literature Review

The first step taken when starting this research project was to gather and read material about juvenile *Triceratops*. The literature gathered was mainly through online resources. Gathering of relevant literature began during the spring of 2018, with most of the reading and studying done during the summer and fall of 2018. If the sources were not readily available, then the ESU library allowed access through their database. Literature discussing juvenile *Triceratops*, as well as juveniles of other ceratopsians, was studied and compiled, and digital copies of each publication were stored.

Observations and Measurements of the Fossils

The fossils had been collected and prepared before being sent to ESU in the spring of 2018. Each fossil was then identified to element and degree of completeness. Specimens included the parietal frill, the right horn and some of the left, partial maxillae, the left nasal and a few smaller, unidentifiable fragments. Both sides of the mandible were found as well as the predentary. Observations of juvenile characteristics and other qualitative features of the skull and mandibles were recorded. The more complete specimens were measured using a GPM brand (Swiss made) anthropometer for accuracy.

Photography

Pictures of each fossil element were taken with a Canon EOS Rebel T6 35mm digital camera. Each element was placed on a white background under the camera stand, and multiple views were photographed with a centimeter scale. Every fossil had at least the top and bottom or left and right sides photographed.

Stratigraphic Section of the Fossil Locality

In the summer of 2018, I travelled to the location of the site where the fossil material was found. The site is located northeast of Jordan, Montana, in the upper Hell Creek Formation. With the help of Dr. Michael Morales and Professor Carl Campbell, and Emporia State University students Matt Mers and Nick Thurber, a stratigraphic section of the site was measured. A Jacob’s staff, measuring tape, and hand level were used, starting from where the juvenile *Triceratops* was collected, into the coal beds where the K-Pg boundary clay layer was located, and up to the overlying Tullock Member of the Fort Union Formation. Samples from each of the section's nine layers were collected, consisting of various forms of mudstone, sandstone, and coal.

Museum Trips

In mid-October, 2018, I visited the University of California Museum of Paleontology to examine, photograph, and measure material from three separate juvenile-sized *Triceratops.* The material from the first juvenile, UCMP 150324, included a parietal frill and was smaller than that of the juvenile in this project. The second set of material was UCMP 128562, which included a horn and a left dentary. The UCMP’s last juvenile specimen was that described by Goodwin and Horner in 2014, i.e., UCMP 136306. It is a more complete skull and is almost the same size, if slightly larger, than the ESU specimen. Notes and measurements were taken on similarities and differences between the UCMP material and the ESU fossils.

The second museum I visited, at the end of the fall semester 2018, was the Museum of the Rockies in Bozeman, Montana. There, I had the opportunity to see *Triceratops* specimens of similar size to the ESU specimen. Dr. John Scannella helped me to identify to element some of the fossils from the ESU material, and I learned more about *Triceratops*. On the day before and then again after seeing the MOR juvenile material, I toured the museum to see their displays, including the growth series of *Triceratops*. In the museum’s collections were several juvenile fossils, which I was able to see and compare the features to that of the ESU *Triceratops*. A replica of UCMP 154452, the smallest (baby) *Triceratops,* which had not been available to see at the time at UCMP, was available for me to take measurements from and look for comparative features.

Chapter 4: Results

Introduction

Fossil Material

Specimen ESU 2014-1 is a medium to large size juvenile *Triceratops prorsus*. The fossil material includes many skull fragments and incomplete left and right lower jaws (Figures 2 & 17).

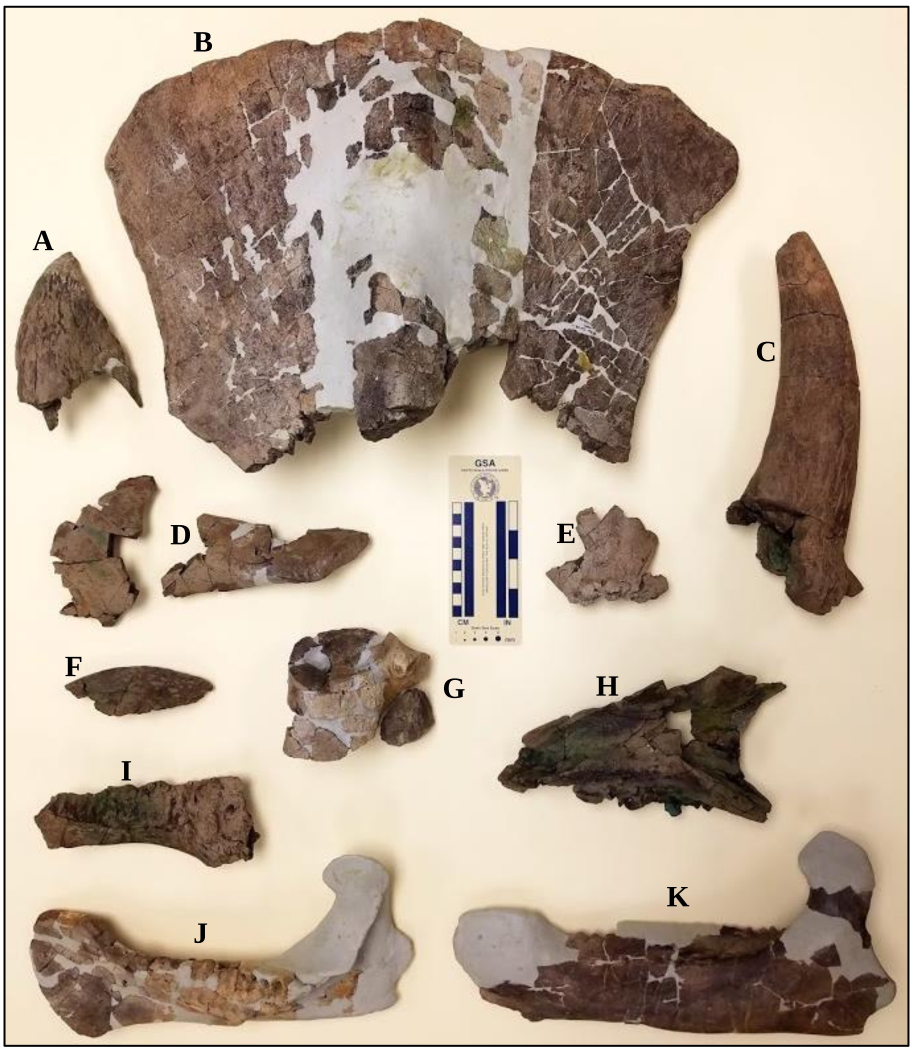

Figure 17. Overview of major fossil elements. A – predentary. B – parietal. C – right postorbital horn. D – left nasal. E – postorbital. F – rostral. G – left postorbital horn. H – right maxilla. I – left maxilla. J – right dentary. K – left dentary. Left column on scale bar is 10 cm total length.

Geographic Location, Stratigraphic Position, and Age

The fossil material was found in upper Hell Creek deposits in Garfield County, Montana. The locality is 14-1 Baby Tric (*sic*) Cross Road Area. The exact location of the site is in the records of the Bureau of Land Management (BLM) Montana district office in Billings and the BLM repository at Emporia State University, Emporia, Kansas.

The material was found in the upper Hell Creek Formation, which is of Maastrichtian age, Late Cretaceous (66 million years). The locality is 14.7 meters below the bottom of the Tullock Member of the Fort Union Formation, of early Paleogene age (Figures 18 & 19). The fossil site was located at the 0 cm mark in the stratigraphic section.

Figure 18. Location of the excavation site of ESU 2014-1. The broken sediment in red ellipse indicates where the *Triceratops* was excavated. The K-Pg layer is located within the black coal layers.

Depositional Environment

The fossils were buried a floodplain fluvial environment. The excavation site was in gray and orange overbank mudstone in an area of alternating channel sandstone and floodplain mudstone.

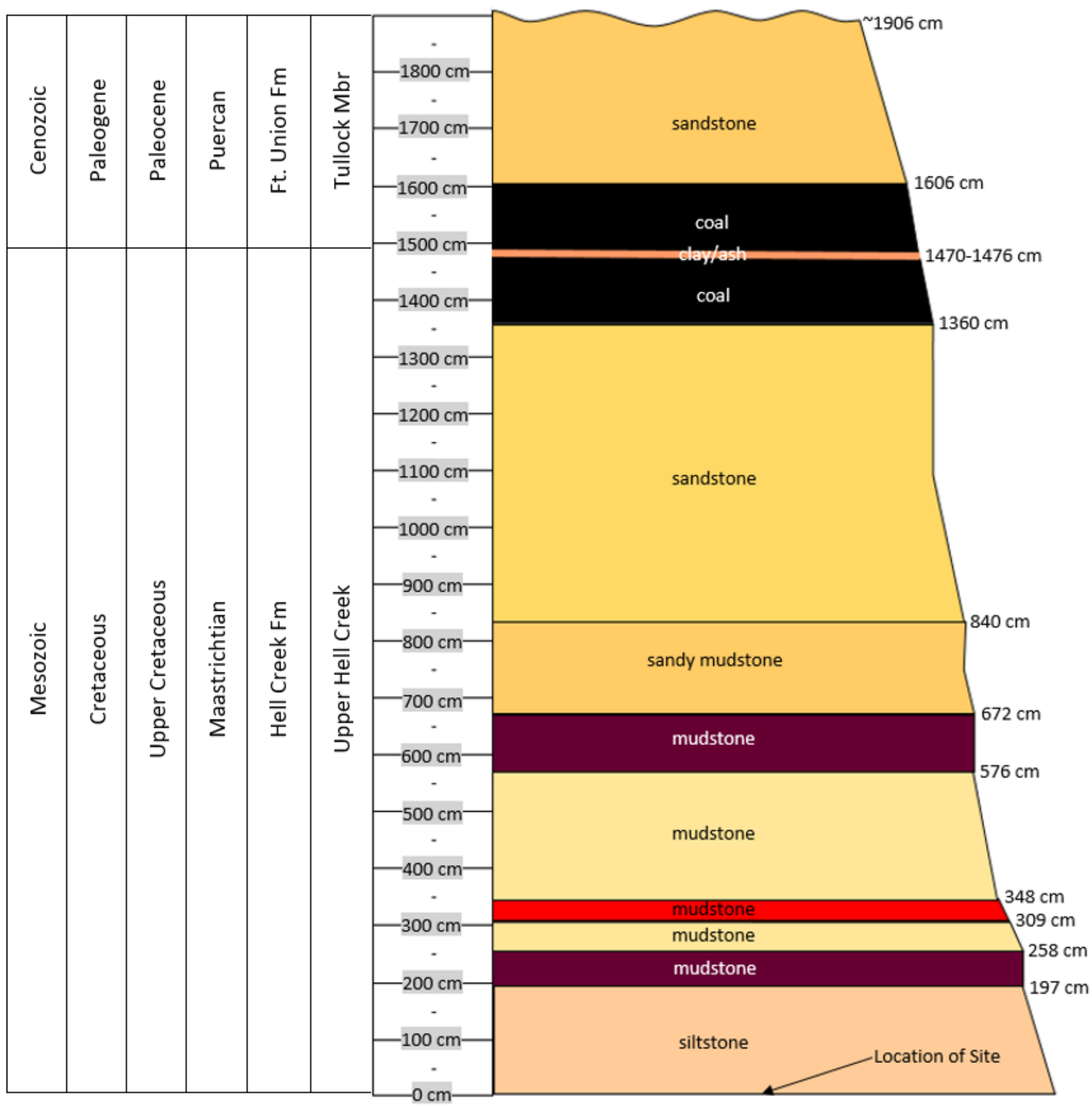

Figure 19. Stratigraphy of the fossil excavation site. Measurement began at 0 cm (Hell Creek Formation) and ended at the top of the butte (Tullock Member of the Fort Union Formation). The Cretaceous-Paleogene boundary is located at the clay/ash layer.

Measurements

Measurements of the major fossil elements are shown in Figure 20. Partial measurements of the remaining fragments are as follows: Left nasal (rostral end piece) – maximum length 18.2 cm long, maximum perpendicular height 7.4 cm. Postorbital – maximum length 8.1 cm long, maximum width 10.4 cm wide. Left Postorbital horn – maximum width 8.9 cm wide, maximum height 8.6 cm tall, maximum length 11.8 cm long. Left maxilla – maximum length 18.1 cm long, maximum height 7.2 cm tall. Rostral – maximum length 12.2 cm long, maximum height 4.8 cm tall, maximum width 3.6 cm wide.

Description of the Elements

Parietal

The middle section of the frill of *Triceratops* specimen, ESU 2014-1, is composed of the parietal (Figure 21). It is mostly complete, with the center area having been restored with a light grey epoxy putty and cracks filled with glue and epoxy putty. There are five, gently sloping scallops where epoccipitals would have fused with it into adulthood. Along the midline ridge, there are three bony prominences and a missing section where there had likely been a fourth. The last prominence extends nearly to the frill margin. The frill has a striated bone texture, which is indicative of rapid growth (Brown et al., 2009; Sampson et al., 1997). The edges of the parietal where they would come in contact with the missing squamosals are unfused. The parietal frill measures 53.1 cm along the marginal end and 30.4 cm towards the frontal. The length measured along the midline was 31 cm, the left 27.6 cm, and the right at 31 cm. The thickness of the frill was 2 cm along the sutural edges, and at the thickest along the midline, it measured 5.8 cm thick.

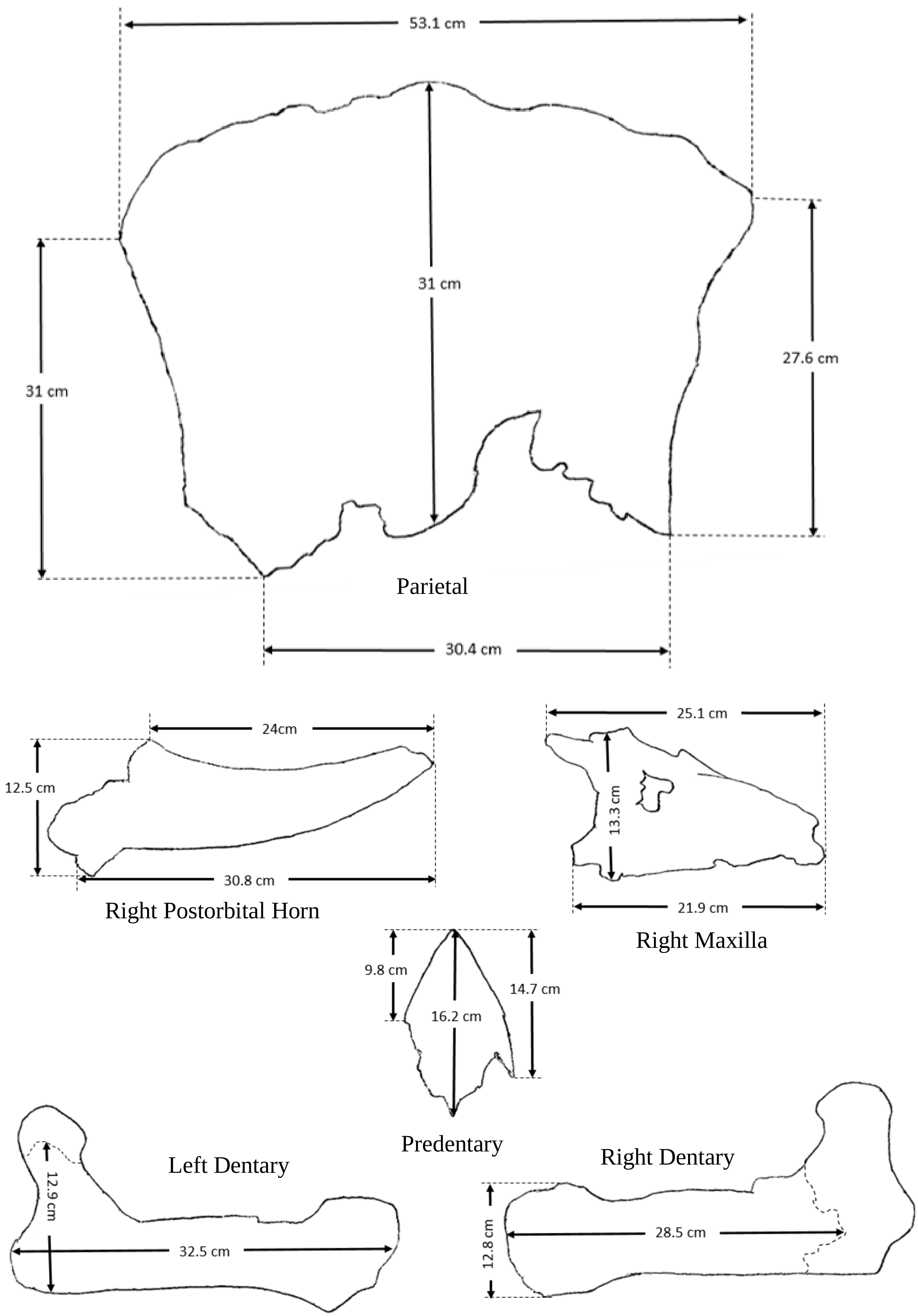

Figure 20. Measurements of major elements of the juvenile *Triceratops,* ESU 2014-1.

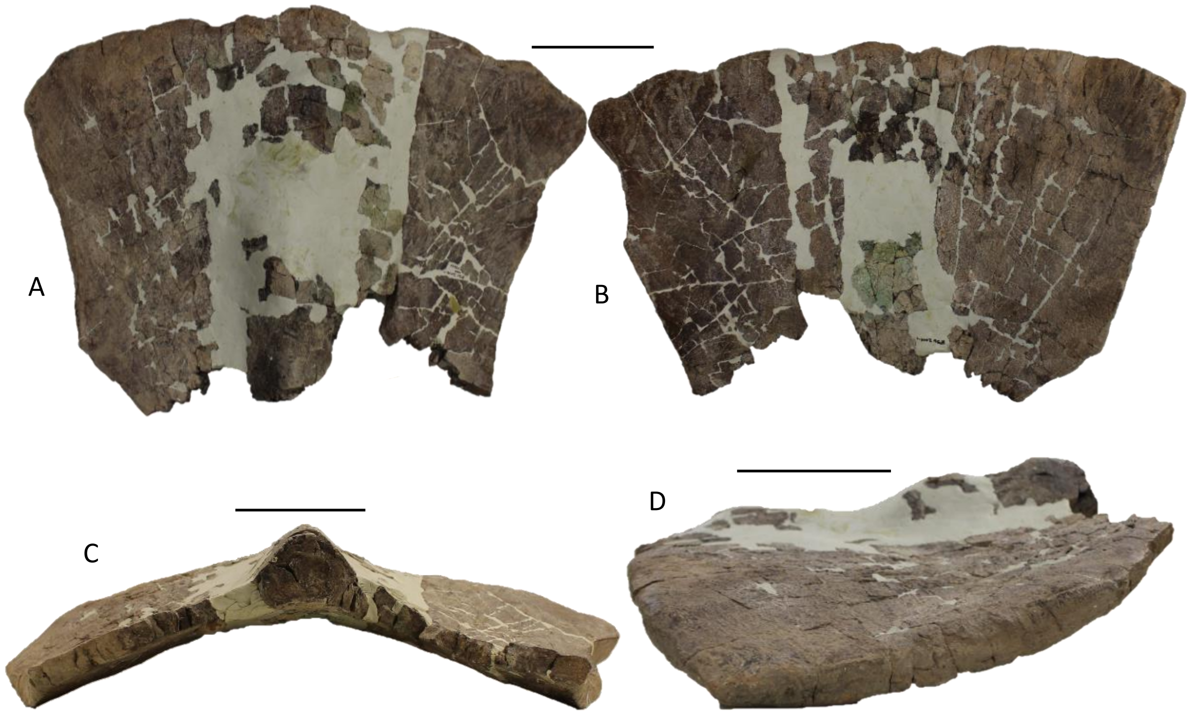

Figure 21. Parietal frill. A – Dorsal view. B – Ventral view. C – Left-right cross-section view. D – Lateral view. Scale bars are 10 cm.

Postorbital

Horns. The right postorbital horn is nearly complete, missing only the very tip (Figure 22). The horn has a gentle posteriorly oriented curve. Grooves from blood vessels indicate it had been covered in a keratinous sheath. The horn becomes more porous towards the center of the core. Some edges towards the base are rugose along sutural edges. The horn had been broken into segments which were repaired with glue and epoxy putty by those at the St. Louis Science Center. At the base, the horn measured 12.5 cm thick. From base to tip on the dorsal side, the horn measured 24 cm. On the rostral side from base to tip, it measured 30.8 cm. There is no rugose surface on this side, indicating the prefrontal had fused to the postorbital horn (Goodwin et al., 2006).

All that remains of the left postorbital horn is the base and a segment closer to the tip (Figure 23). The base is slightly porous towards the center, and along the anterior edge has a rugose surface. Multiple cracks and several sections have been filled in with glue and epoxy putty. At the top of the base, the horn measures 7.3 cm wide and 8.9 cm at the bottom. The longest section of the bone is 11.8 cm, and the tallest is 8.6 cm.

Orbital rim. A small section of the right postorbital near the orbital rim remains (Figure 24). The edge of the rim is very rugose and chipped in some places. It is 8.1 cm at its longest and 10.4 cm at its widest.

Figure 22. Right postorbital horn. Scale bar is 10 cm.

Figure 23. Left postorbital horn base. A – Dorsal view. B – Ventral view. Scale bar is 10 cm.

Figure 24. Right postorbital. Scale bar is 10 cm.

Maxilla

The right maxilla is mostly complete, with edges worn away and a missing piece in the middle (Figure 25). Striated bone texture can be found on nearly every visible, unbroken surface. There is some distortion and breakage along the tooth sockets. The multiple cracks have been glued back together. The maxilla is 21.9 cm long at the tooth battery side, and at the dorsal side it is 25.1 cm long. At the thickest point, it is 6.5 cm wide, and at the tallest point it is 13.3 cm. A tooth and several tooth fragments remain.

Figure 25. Right maxilla. Scale bar is 10 cm.

Only a small portion of the left maxilla with an empty row of tooth sockets remain (Figure 26). Most of the bone is missing, and the remainder is worn and slightly distorted. Some cracks have been repaired with glue. The remaining bone is 18.1 cm long and 7.2 cm at the tallest. At the thickest, the bone is 4.9 cm.

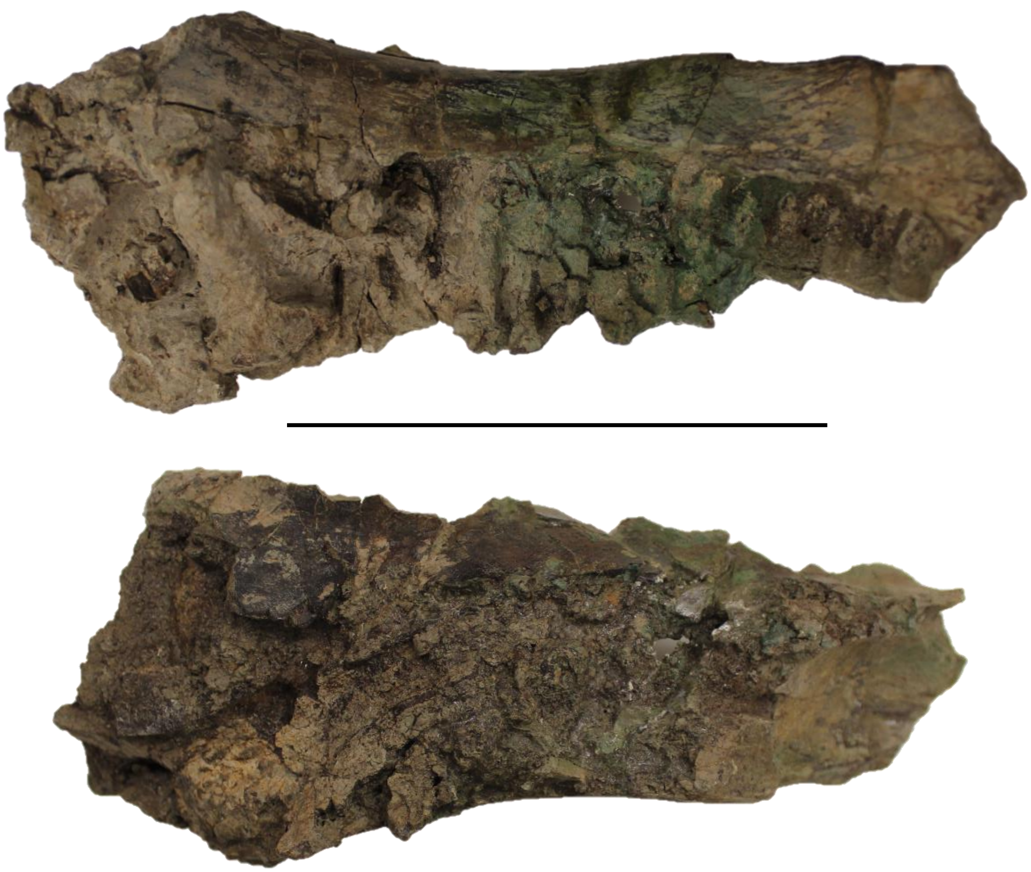

Figure 26. Left maxilla. Scale bar is 10 cm.

Nasal

The left nasal is mostly complete, with a few broken sections along the dorsal and ventral edges (Figure 27). A portion between the anterior and posterior end was broken and missing. Cracks and a few missing sections of bone were filled in with glue and epoxy putty. Striated bone texture could be found along portions of the bone. Some areas of the bone appear to show a transition between mottled and striated texture (Figure 28). The rostral piece is 18.2cm long and 7.4 cm tall.

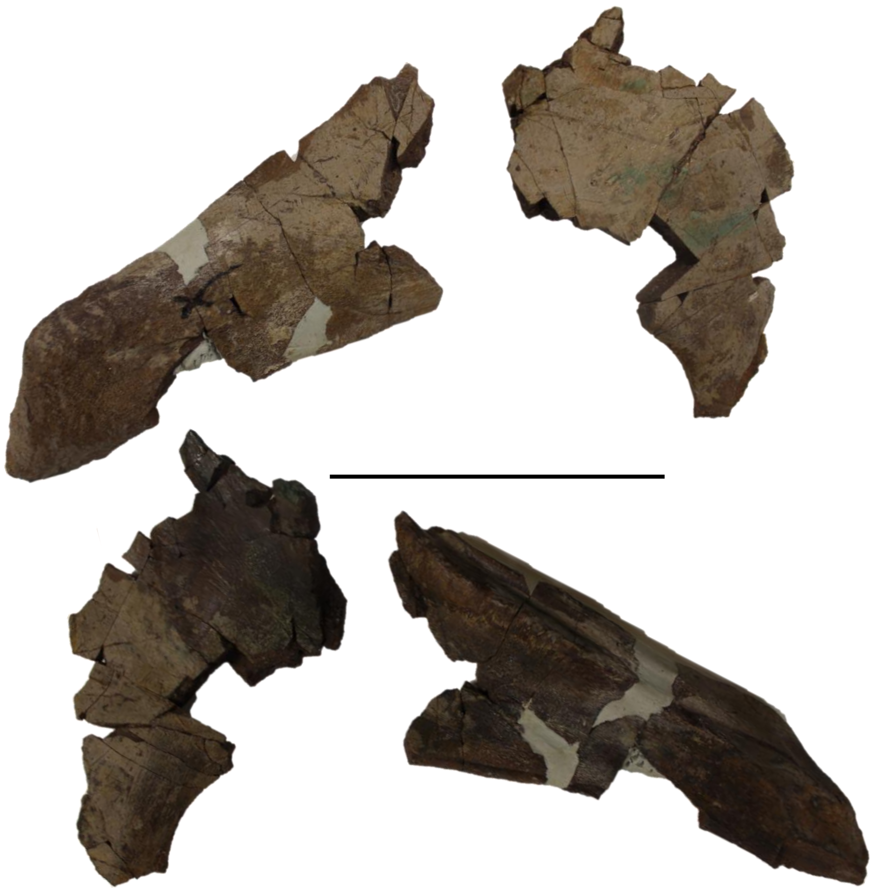

Figure 27. Left nasal. Scale bar is 10 cm.

Figure 28. Transition between striated [bottom] and mottled textures [top].

Rostral

Only a portion of the rostral bone remains (Figure 29). A large portion of the tip and ventral side were not recovered. Towards the dorsal end, the bone becomes well vascularized. The bone is 12.2 cm long. At the tallest, it is 4.8 cm, and at the thickest it is 3.6 cm.

Figure 29. Rostral. Scale bar is 10 cm.

Dentary

The right dentary is mostly complete, only missing the end toward the coronoid process (Figure 30). The bone was repaired along cracks and restored at the posterior end with glue and epoxy putty. Striated and mottled bone texture can be found along the bone. No teeth were found with the dentary, just empty tooth sockets. The right dentary is 28.3 cm long. Towards the predentary end, where the bone is the tallest and most complete, it is 12.8 cm tall. At the thickest, the right dentary is 4.7 cm.

Figure 30. Right dentary. Scale bar is 10 cm.

The left dentary is slightly more complete than the left (Figure 31). It was restored with epoxy putty toward the predentary end, along with several cracks repaired with glue. No teeth were found with the dentary, just empty tooth sockets. Striated and mottled bone texture can be found along the bone. The left dentary is 30.3 cm long. The tallest portion of the bone is towards the end, where the tip of the coronoid process has broken off. The bone here is 12.9 cm tall. At the thickest, it measures 7.8 cm wide.

Figure 31. Left dentary. Scale bar is 10 cm.

Predentary

The predentary is nearly complete, with only sections near where it would attach to the right dentary missing (Figure 32). There are several cracks, which have been repaired with glue and epoxy putty. Striated bone texture can be seen on either side of the predentary. Along the midline of the ventral side, the bone measures 16.2 cm long. From the tip to most posterior portion, the predentary measures 14.7 cm long on the left side and 9.8 cm on the right. At the thickest, it measures 9.7 cm and at the tallest, 7.2 cm.

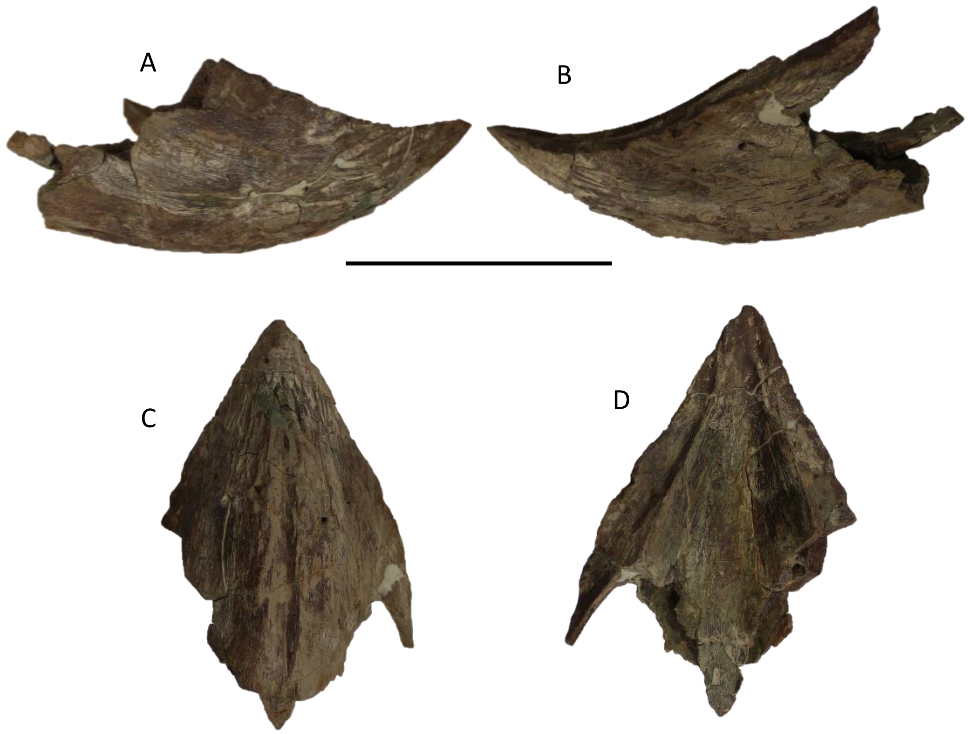

Figure 32. Predentary. A and B – Lateral views. C – Ventral view. D – Dorsal view. Scale bar is 10 cm.

Miscellaneous Bones

Many of the fossils collected from ESU 2014-1 were small fragments. Empty tooth sockets in some of the pieces indicate either maxilla or dentary, but they are too fragmentary to identify with certainty.

Chapter 5: Discussion, Conclusions, and Future Work

Discussion

Introduction

This chapter discusses the juvenile traits seen in *Triceratops* and in other ceratopsians. The first section begins with comparisons between ESU 2014-1 and other *Triceratops*, and the section after that discusses juvenile traits of ceratopsians in general.

Juvenile Features in *Triceratops*

There are multiple features of ceratopsians that can indicate the age of an individual. The *Triceratops* specimen, ESU 2014-1, displays multiple juvenile features despite missing several skull elements. The postorbital horn curves in a posteriorly-facing direction. There were no signs of epoccipitals fusing with the parietal. The fossils had evidence of striated bone texture. Sutures on the available elements had no apparent signs of fusion. These are traits shared with other juvenile *Triceratops*.

Size can be a good indicator of age if the adult species is known. The supplementary data in Scanella et al. (2014) provide the formulas to find the basal skull length (from the tip of the rostral to the occipital condyle) based on what elements are available. In the case of ESU 2014-1, the left dentary was the most complete element from which to calculate the basal skull length. The formula for this calculation is:

$$y = 2.1918x – 10.298$$

With a jaw length of 34.6 cm, the estimated basal skull length of the juvenile *Triceratops* is 65.5383 cm.

UCMP 136306 has an estimated basal skull length of 64 cm (Figure 33). Another juvenile *Triceratops*, MOR 2951, has a dentary length of 31 cm and a basal skull length of 58.6 cm (Figure 34). MOR 2951 is considered a medium sized juvenile, and ESU 2014-1 is very similar in size, if only slightly larger.

Figure 33. Three *Triceratops* skulls of different ontogenetic age. UCMP 136306 skull juvenile skull (left) compared to an adult (middle) and baby (right) from University of California Museum of Paleontology. ESU 2014-1 is approximately the same size as the left juvenile.

Traits of *Triceratops* can vary among individuals. Compared to other juvenile *Triceratops*, ESU 2014-1's major differences in the known elements would be the shape of the postorbital horns and the length and prominence of the midline ridge of the parietal.

Figure 34. Skeletons of a juvenile and large subadult *Triceratops* in the Museum of the Rockies. Juvenile is specimen MOR 2951. ESU 2014-1 is slightly bigger than the juvenile's skull.

UCMP 136306 is close in size to ESU 2014-1's estimated basal skull length, but the postorbital horns appear to be more elongate than the stouter horns of ESU 2014-1. In younger juveniles and babies, the prefrontal extends over the base of the postorbital but remains unfused. This leaves a rough patch at the sutural surface, which ESU 2014-1 does not have--indicating that this sutural surface has fused (Figure 35). Most juvenile *Triceratops* usually have four bony prominences along the midline of the parietal, which smooth out towards the posterior margin of the frill. This ridge in ESU 2014-1 ends comparatively closer to the posterior margin.

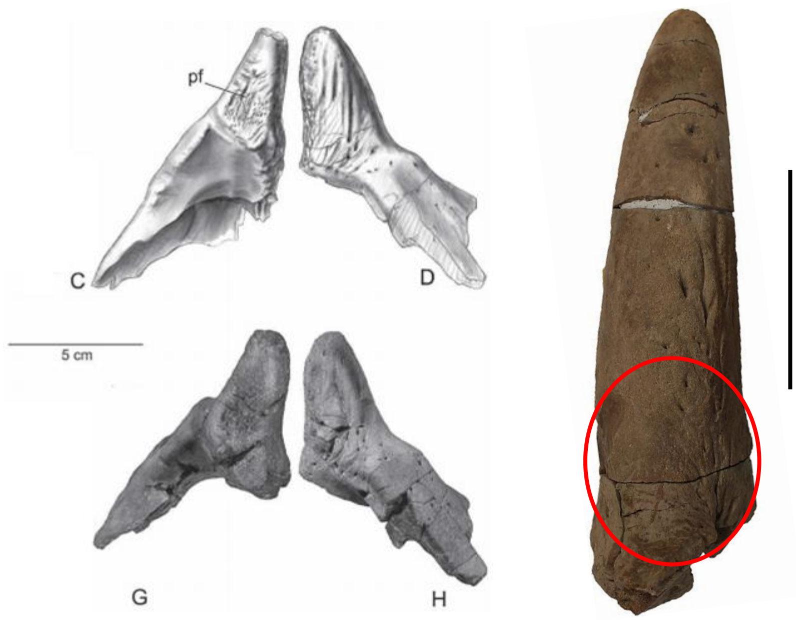

Figure 35. Comparison of unfused prefrontal and postorbital bones. C, D, G, H - UCMP 154452, the baby *Triceratops* showing unfused bones (Goodwin et al., 2006); Right - ESU 2014-1 with fused bones (in red ellipse). pf – prefrontal sutural surface. Dark lines in right photo are cracks and chips. Right scale bar is 10 cm.

Juvenile Features in Ceratopsians

Not all ceratopsian taxa have the same adult features. Horns and frills vary very greatly. Chasmosaurine postorbital horns tended to increase in size, whereas in centrosaurines the horns tend to be reabsorbed. Orbits are often oversized, and skull sutures had yet to fuse in many specimens. The snouts are often short and nasals and nasal horns unfused. Juveniles and subadults tended to exhibit a striated bone texture or a mix of striated and smooth. A compilation of general juvenile ceratopsian trends found throughout the literature can be seen in Table 2. Papers used to produce this compilation include: Coombs, 1982; Currie et al., 2016; Dodson, 1993; Gilmore, 1917; Goodwin et al., 2006; Goodwin and Horner, 2014; Horner and Goodwin, 2006; Hone et al., 2014; Mallon et al., 2015; Ryan, 2007; Ryan et al., 2017; Schlaikjer, 1935; Wilson et al., 2014; Wolfe and Kirkland, 1998; and Xu et al., 2001.

	Relatively Narrow/ Short Frill	Post. Dir. or Straight Horns	Unfused Epocc-ipitals	Lack of Horn Core Sinus	Relatively Large Orbits	Unfused Nasals	Relatively Short Snout	Unfused Sutures	Juvenile Bone Texture
Basal Ceratopsian									
(juvenile) *Liaoceratops* – IVPP V12633	Yes	-	-	-	Yes				
(juvenile) *Psittacosaurus* – AMNH 6535-6536	-	-	-	-	Yes		Yes	No	
(juveniles) *Protoceratops* – MPC-D 100/526 (A-D)	Yes	-	-	-	Yes			Yes	
(subadults) *Protoceratops* – MPC-D 100/534	No	-	-	-					
(juvenile?) *Zuniceratops* – MSM P2101	N/A	+	N/A		Yes	N/A	N/A		
Centrosaurinae									
(juvenile) *Brachyceratops* – Type Material			Yes					Yes	Yes
(subadult-adult) Nasutoceratopsini – CMN 8804			Yes						Yes
(juvenile) *Avaceratops* – ANSP 15800		N/A	Yes	N/A		N/A		Yes	
Chasmosaurinae									
(Juvenile) *Arrhinoceratops* – CMN 8882	Yes	Yes	Yes			N/A	+	Yes	Yes
(baby) *Chasmosaurus* – UALVP 52613	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes
(baby) *Triceratops* – UCMP 154452	Yes	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes
(juvenile) *Triceratops* – ESU 2014-1	Yes	Yes	Yes	Yes	N/A	Yes	N/A	Yes	Yes
(juvenile) *Triceratops* – UCMP 136306	Yes	Yes	Yes	Yes	Yes	N/A	N/A	Yes	Yes
(juvenile) *Triceratops* – CCM V2015.7.1	N/A	N/A	Yes	N/A	N/A	N/A	N/A	N/A	Yes
(subadult) *Triceratops* – MCZ 1102	No	No					No	Yes	

Table 2. Features of Juvenile Ceratopsians. Yes = feature is present, No = feature is not present, N/A = material not available, (–) = feature does not occur in species, (+) = feature remains unchanged as adult, blank = not mentioned in the literature.

In Table 2, institutional abbreviations are as follows:

AMNH, American Museum of Natural History, New York

ANSP, Academy of Natural Sciences, Philadelphia, Pennsylvania

CCM, Carter County Museum, Ekalaka, Montana

CMN, Canadian Museum of Nature, Ottawa, Ontario

ESU, Emporia State University, Emporia, Kansas

IVPP, Institute of Vertebrate Paleontology and Paleoanthropology, Beijing, China

MCZ, Museum of Comparative Zoology, Cambridge, England

MOR, Museum of the Rockies, Bozeman, Montana

MPC, Mongolian Paleontological Center, Mongolian Academy of Sciences, Mongolia

MSM, Mesa Southwest Museum, Mesa, Arizona

UALVP, University of Alberta Laboratory for Vertebrate Paleontology, Alberta, Canada

UCMP, University of California Museum of Paleontology, Berkeley, California

From the table, it is clear that common traits seen in juvenile ceratopsians include: (1) possession of narrow frills, which would fan out as the individual grew older; (2) orbits that tend to be overly large for the skull size; (3) striated (long-grained) bone texture; (4) sutures of the skull had yet to fuse; (5) nasals and epinasals not yet fused; (6) epoccipitals, if present in the species, typically were unfused to the frill in younger specimens. Individually, these traits would not necessarily indicate that a specimen was a juvenile as some of these traits can be seen through the subadult stage. It is the observation of multiple juvenile traits in an individual that can indicate its age.

Narrowness and/or Shortness of the Frill. Juvenile ceratopsians had shorter and narrower frills in comparison to adults. In *Triceratops,* babies had a very short, boxy frill. As the *Triceratops* would grow, this frill would expand in breadth, fanning out more and more until it reached adulthood. Other chasmosaurines and centrosaurines would undergo a similar change. *Chasmosaurus* had a narrow and boxy frill as a juvenile, and the fenestration of the frill was slender. As adults, *Chasmosaurus* would have a very broad and long frill, with an expansion of the fenestration as the frill fanned out.

Relative Size of Orbits. The orbits in juvenile ceratopsians were often large in comparison to the skull size. In the juvenile *Chasmosaurus*, the diameter of the orbits were 18% of the basal skull length (Currie et al., 2016). A *Chasmosaurus* tentatively identified as adult *Chasmosaurus*, CMN 8802, has an estimated total skull length of around 200 cm and orbits about 100 mm long (Campbell et al., 2018). This measurement is only twice as large as the 50 mm orbits of the juvenile *Chasmosaurus* on an animal with a skull around 4-5 times larger.

Bone Texture. Long-grained, or striated, bone texture has been observed in both centrosaurines and chasmosaurines. Striated bone texture is seen in ceratopsians as young as the smallest *Triceratops*, UCMP 154452. However, striated bone texture can also be seen in adult sized animals, with the striations occurring in tandem with the adult, smooth texturing. In subadults, bone texture varies, with a mix of striations, mottled, and/or smooth texturing (Sampson et al. 1997).

Fusing of Skull Elements. The state of suture closure on an animal can help determine that animal's age. In juveniles, the sutures are usually visible or open. For adults, sutures are generally fully closed and not visible. Sampson et al. (1997) studied sutures from the palpebrals, frontals, postorbitals, squamosals, and parietals and divided the state of the sutures into three categories. The first was the juvenile state, where sutures are fully visible. In the second category, skull sutures are partially obscure. The third category included sutures that were fully obscure. Sampson et al. (1997) noted that fully obscure skull sutures are not necessarily indicative of a mature animal as sutures may become obscured due to remodeling.

Fusing of Nasals. This characteristic includes the fusion of the epinasal to the nasals in ceratopsians like *Triceratops*. The epinasal began in *Triceratops* as an isolated element resting on the anterior tip of the juvenile’s paired, but unfused, nasals. As *Triceratops* reached the subadult stage, the epinasal would fuse with the nasals to become the nasal horn, and into adulthood the nasals would fuse along the midline (Horner and Goodwin, 2006).

Fusing of Epoccipitals. If the ceratopsian had epoccipitals, then they would remain disarticulated from the skull in their juvenile stages. Basal ceratopsians, such as *Protoceratops* and *Liaoceratops*, whose frills already lacked the expansiveness seen in chasmosaurines and centrosaurines, did not have epoccipitals to begin with. Juvenile ceratopsians had highly scalloped frills, and while the frill expanded the scallops would shallow out and fuse with the epoccipitals.

Postorbital Horns. Between centrosaurines and chasmosaurines, chasmosaurines generally had more prominent brow horns. The change in postorbital horn growth throughout ontogeny is best documented in *Triceratops* and *Chasmosaurus*. *Triceratops,* as babies, have very short, straight horns. These horns curve posteriorly as the baby enters the juvenile stage. Into the subadult stage, they begin to angle into an anterior position (Horner and Goodwin, 2006). *Chasmosaurus,* although a chasmosaurine ceratopsian, had similar horn development as what is seen in centrosaurines (Campbell et al., 2016). In centrosaurines, the postorbital horns of juveniles and subadults tended to be similar across all taxa. It is only in animals reaching adulthood that the characteristics of the horns are specific enough to differentiate between taxa (Sampson et al. 1997).

Reabsorption of the postorbital horns is only seen in adult specimens. Seen in many centrosaurines and some chasmosaurines, the reabsorption of the horn begins with pits developing at or near the tip. Sampson et al. (1997) listed possible reasons that adult ceratopsians reabsorbed their postorbital horn cores. They were stated as periodic resorption and regrowth, age-related resorption, periodic or seasonal replacement, pathology, loss due to lack of use, or even resorption for calcium required in egg-laying.

Conclusions

The juvenile *Triceratops* specimen, ESU 2014-1, composed of partial skull and mandible material, was mostly recovered in 2014, and its right postorbital horn was recovered in 2017. This individual was likely a medium to large size juvenile *Triceratops prorsus*, based on its stratigraphic location. It exhibits multiple juvenile characteristics, including posteriorly curving postorbital horns, unfused skull sutures, and large areas of striated bone texture.

Common traits shared by ceratopsian juveniles include (compared to adults): relatively narrow or short frills, posteriorly directed (or straight horns in babies), epoccipitals that are not fused with the frill bones, a lack of horn core sinuses, relatively large orbits, unfused nasals, relatively short snouts, unfused skull sutures, and a large amount of striated bone texture.

Multiple papers have been published about individual ceratopsian juveniles and their ontogeny. However, the papers discuss juvenile traits only for their specific specimen, not for ceratopsians as a group. This thesis presents, for the first time, a compilation of the general juvenile traits for basal ceratopsians, centrosaurines, and chasmosaurines. The table of general juvenile ceratopsian characteristics details the data and trends seen in the literature and places them all together.

Future Work

Fossils of juvenile ceratopsians are not very common, so any specimen discovered is significant. Future work could involve in-depth investigation of any new juvenile traits found, including species-specific ones. Juvenile specimens of *Triceratops* are currently under study, and publications involving them should be coming in the future. *Triceratops* fossils of juveniles were at both museums that I travelled to while conducting research. Small pieces, such as parietals and horns, were at the University of California Museum of Paleontology and had not yet been described. At the Museum of the Rockies, several juvenile *Triceratops* fossils are currently under research for publication.

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Description of a Juvenile *Triceratops* Skull and Lower Jaw and Comparison of Juvenile Ceratopsian Characteristics

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