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First confirmed identification of juvenile *Triceratops* epiparietals

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ABSTRACT

The recovery and documentation of over one hundred specimens of the ceratopsid dinosaur *Triceratops* from Upper Cretaceous (Maastrichtian) units of North America has led to what is probably the most extensive understanding of cranial ontogenetic change in a dinosaur taxon. However, gaps in knowledge persist due to the relative rarity of associated juvenile *Triceratops* remains. Like most ceratopsids, *Triceratops* possesses epiossifications on the margins of the parietosquamosal frill, termed epiparietals and episquamosals. Since parietosquamosal frill epiossifications do not fuse on to the frill margin until maturity, juvenile epiossifications are usually recovered as unfused elements which consequently lack definitive association with either the squamosal or parietal. This has prohibited identification of juvenile epiparietals and episquamosals, and subsequent comparison between epiparietals and episquamosals, which would inform on the evolution of these structures in chasmosaurine ceratopsids.

Here we report three frill epiossifications found associated with a partial isolated juvenile *Triceratops* parietal (CCM V2015.7.1), which correspondingly bears three marginal crenulations (epiparietal loci). All three epiparietals are triangular, asymmetrical, and sub-equilateral. Two of the epiparietals are nearly identical, with lateral and medial edges that are nearly straight; the third is larger and has lateral and medial edges which are more curved. These differences indicate that *Triceratops* epiparietals can be of at least two sizes and morphologies within single juvenile individuals, whereas epiparietals of mature individuals are often near-uniform in morphology and size. No squamosal remains were recovered from the site, allowing for the first confident identification and description of unfused juvenile *Triceratops* epiparietals. This is significant, as we for the first time identify hypothetical trends in the evolution of these structures, such as peramorphism within a possible *Arrhinoceratops*–*Triceratops* lineage.

1. Introduction

Triceratops is the most commonly recovered dinosaur from the Hell Creek Formation [Maastrichtian] of the northwestern United States, comprising about 40% of documented specimens (Horner et al., 2011). This incomparable dataset has allowed for one of the most extensive analyses of cranial ontogenetic change in a dinosaur taxon, and revealed an extensive suite of character development that takes place with maturation, including: postorbital horns change from posteriorly oriented in juveniles and subadults (immature) to anteriorly oriented in adults (mature), the scalloped margin of the parietosquamosal frill in juveniles and subadult flattens in adults, the epinasal increases in size then fuses to the nasals, the epijugals fuse to the jugals, and epiossifications arrayed along the frill border progressively flatten from a deltoid shape in juveniles to a low spindle shape in adults, ultimately fusing to the frill margin (Horner and Goodwin, 2006).

Historically, associated juvenile *Triceratops* remains have been collected with much less frequency than subadult or adult individuals, limiting our understanding of certain aspects of *Triceratops* ontogeny and juvenile morphology (Goodwin and Horner, 2014). Only two juvenile specimens have so far received formal descriptions ('baby' UCMP 154452 and 'juvenile' UCMP 136306; Goodwin et al., 2006; Horner and Goodwin, 2006; Goodwin and Horner, 2014, though considerably more have been included in *Triceratops* growth series (Horner and Goodwin, 2006, 2008; Scannella and Horner, 2010; Horner et al., 2011), or await description (Scannella and Fowler, 2014).

Like most other ceratopsids, *Triceratops* possesses epiossifications which line the margins of the parietosquamosal frill,

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respectively termed epiparietals for those on the parietal and episquamosals on the squamosals (Horner and Goodwin, 2008). Some specimens of *Triceratops* also possess epiossifications which straddle the parietosquamosal contacts, termed epiparietosquamosals (EPS). The number of epiparietals and episquamosals is hypothesized to increase through ontogeny and is notably variable between individuals and sometimes even between left and right sides of the same individual, such as juvenile MOR 2951, which has three epiparietal loci plus an EPS on the right side of its parietal, a single locus at the midline, and two loci plus an EPS on the left side of its parietal (Horner and Goodwin, 2008; Scannella and Horner, 2010). Published unfused *Triceratops* frill epiossifications exhibit a range of morphology that would have been dependent both on their location along the frill and ontogenetic status (Horner and Goodwin, 2008). In juvenile *Triceratops*, frill epiossifications are pointed, delta-shaped bones with an unfused and flat articular surface (Horner and Goodwin, 2008). In dorsal or ventral view, they can be either near-equilateral or asymmetrical, with straight, convex, or concave edges forming the apex. Through ontogeny, both episquamosals and epiparietals expand laterally and flatten, becoming spindle-shaped, much less pointed, and ultimately fuse to the frill margin (eventually becoming indistinguishable in some specimens).

Frill epiossifications are often found either as isolated specimens or associated with partial skulls (Horner and Goodwin, 2008). However, because the frill epiossifications originate as free and unfused bones in juveniles, previous identifications of disarticulated juvenile epiparietals or episquamosals have been inference based, rather than based on clear association with a parietal or squamosal. Fusion of the frill epiossifications to the frill margin is observed in subadults or adults (Horner and Goodwin, 2006, 2008), and thus disarticulated frill epiossifications can represent young juveniles through subadults. Disarticulated subadult epiossifications (e.g. MOR 1120; Horner and Goodwin, 2008) are sometimes identifiable as epiparietals or episquamosals because they are ontogenetically and morphologically similar to other subadult specimens with recently fused epiossifications, and/or because their articular surfaces are well enough developed that they fit to their respective loci on the frill margin. However, subadult epiossifications are morphologically different from those of juveniles (Horner and Goodwin, 2006, 2008). The ontogenetically youngest frill epiossifications are most problematic in terms of identification not only because they are found disarticulated from their in vivo position, but also because their articular surfaces have not developed the concavity and suture-like surface that in some instances allows disarticulated epiossifications (of subadult individuals) to be fit to their loci on frills. Horner and Goodwin (2008) identify two unfused juvenile epiossifications (MOR 2582) as epiparietals, though these specimens were isolated and not associated with a parietal. Horner and Lamm (2011) conducted histology on two juvenile epiossifications identified as epiparietals, one of which (MOR 3060) was isolated (and therefore could not be conclusively referred to as either an epiparietal or episquamosal), and the other (UCMP 159233) was reported in Horner and Goodwin (2008) as either an episquamosal or epiparietal (hence its precise designation is unknown). Consequently it has not been possible to definitively identify unfused juvenile *Triceratops* frill epiossifications as epiparietals or episquamosals, and previous identifications have been inference based. This has limited our ability to reconstruct and interpret any morphological differences in the epiparietals and episquamosals of young *Triceratops*, which may inform on the evolution of these structures in chasmosaurine ceratopsids.

Here we report a partial isolated juvenile *Triceratops* parietal with three associated epiossifications (collectively CCM V2015.7.1). The parietal fragment bears the remains of three marginal crenulations to correspond with the three recovered epiossifications. No remains of either squamosal were recovered from the site, allowing for the first confident identification and description of unfused juvenile *Triceratops* epiparietals associated with a parietal, and diminishing the gap in understanding of juvenile *Triceratops* cranial morphology. This is significant, as ontogenetically immature specimens like CCM V2015.7.1 can be critical in deciphering ancestral conditions and relationships.

Institutional abbreviations—**CCM**, Carter County Museum, Ekalaka, Montana; **CMN**, Canadian Museum of Nature, Ottawa, Ontario; **MOR**, Museum of the Rockies, Bozeman, Montana; **MPM**, Milwaukee Public Museum, Milwaukee; **UCMP**, University of California Museum of Paleontology, Berkeley.

2. Material, geology, and stratigraphy

CCM V2015.7.1A, partial juvenile *Triceratops* parietal with three associated unfused epiparietals: CCM V2015.7.1B; CCM V2015.7.1C; CCM V2015.7.1D, surface collected as ~50 fragments from locality 2015-FPG-023; 'Jack's Blue Juvie', Hell Creek Formation (upper Maastrichtian; Sprain et al., 2014), Valley County, northeastern Montana (Fig. 1). All fragments were recovered from the surface as float within a small area ~1 m^2 situated in the middle of a flat erosional saddle, about 12 m wide, between buttes. Excavation was conducted around the specimen but uncovered no additional material. Nearly all of the recovered fragments were reassembled, demonstrating that CCM V2015.7.1A preserves approximately half of the posterior margin of the parietal. CCM V2015.7.1 was recovered from a mudstone approximately 26 m above the uppermost surface of the basal sand of the Hell Creek Formation (Scannella and Fowler, 2014; Scannella et al., 2014), placing it in the lower part of the middle third, within the stratigraphic range of specimens that are consistent with *Triceratops horridus* morphology (Scannella et al., 2014). However, this stratigraphic position should be considered preliminary as only the lower half of the Hell Creek Formation is preserved in the area from which CCM V2015.7.1 was recovered (north of Fort Peck Lake), which is ~40–60 km northwest of the more well-known sections where the study of Scannella et al. (2014) was based. Associated fossils were limited to a fragment of a large tyrannosaurid tooth, and two fragments of ceratopsid teeth, thought to be from an individual too large to pertain to the same individual as CCM V2015.7.1. No evidence of preserved squamosals was found, allowing for the three recovered epiossifications to be identified as epiparietals.

We implement terminology that differs from previous reference to certain aspects of epiossification morphology. We refer to the surface of each epiossification which eventually fuses onto the frill margin as the articular surface, rather than the 'ventral surface' as it is called in Horner and Goodwin (2008). The broad surfaces of the epiossifications are considered the dorsal and ventral surfaces, in keeping with reference to the broad surfaces of parietals and squamosals as either dorsal or ventral.

3. Description

The frill fragment (Fig. 2A) is damaged and incomplete (25.3 cm preserved transverse width), but preserves considerable portions of both dorsal and ventral surfaces, which are completely striated with 'long-grained' texture (Sampson et al., 1997; Brown et al., 2009). Long-grained texture is indicative of particularly rapid growth, reflected in the orientation of radial vascular canals which occur parallel to growth direction (Scannella and Horner, 2010), and is exhibited in both juvenile *Triceratops* (UCMP 154452, MOR 1199, MOR 2569, MOR 2951) and during the late-stage expansion of the frill in some '*Torosaurus*'-morph mature *Triceratops* specimens