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Macroevolutionary patterns in cranial and lower jaw shape of ceratopsian dinosaurs (Dinosauria, Ornithischia): phylogeny, morphological integration and evolutionary rates

APPENDIX

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Appendix

Detailed description of phylogenetic relationships and complete literature corpus upon which we built the ceratopsian phylogeny.

Here we present a detailed summary, based on a literature review, used to build a synthetic phylogeny (Fig. 3) for all valid ceratopsian species included in this work. In order to link a particular reference to phylogenetic relationships and divergence ages among nodes (including OTUs), see Tables S4 and S5.

We first want to make a caveat here: this tree represents a phylogenetic hypothesis based on the most grounded analyses published in literature. However, the relationships among centrosaurine and chasmosaurine taxa are still debated and different phylogenies have been proposed in recent scientific contributions. The validity of some ceratopsian taxa have been debated in several systematic revisions.

Nonetheless, small changes in the tree regarding single species should not change the results showed in the "Results" section, while high level changes involving entire clades could change them. Fortunately, higher level relationships (e.g., the position of *Zuniceratops* relative to Ceratopsidae, or the compositions of Centrosaurinae and Chasmosaurinae) are quite stable within recent phylogenetic hypotheses. We feel confident that we followed the most grounded topologies found in literature in building the phylogenetic tree.

The Suborder Ceratopsia MARSH, 1890 (see also Sereno, 1986) includes six distinct clades: the Family Chaoyangsauridae (ZHAO, 1983, see also Zhao *et al.*, 2006), the Family Psittacosauridae OSBORN, 1923, the Family Leptoceratopsidae NOPCSA, 1923, the Family Protoceratopsidae GRANGER et GREGORY, 1923, the Family Ceratopsidae MARSH, 1888. Ceratopsidae includes two subfamilies: Centrosaurinae LAMBE, 1915 and Chasmosaurinae LAMBE, 1915.

Liaoceratops, *Aquilops*, *Yamaceratops*, *Auroraceratops*, *Archaeoceratops* spp., *Helioceratops*, *Koreaceratops*, Leptoceratopsidae, *Graciliceratops*, Protoceratopsidae, *Zuniceratops*, *Turanoceratops* and Ceratopsidae constitute the Infraorder Neoceratopsia (Sereno, 1986). Protoceratopsidae, *Zuniceratops*, *Turanoceratops* and Ceratopsidae constitute the Microorder Coronosauria (Sereno, 1986). *Zuniceratops, Turanoceratops* and Ceratopsidae constitute the Superfamily Ceratopsoidea (Hay, 1902; Sereno, 1986). Centrosaurinae and Chasmosaurinae constitute the Family Ceratopsidae.

The earliest representative of Ceratopsia is *Yinlong downsi* and *Hualianceratops wucaiwanensis* (Xu *et al.*, 2006; Han *et al.*, 2015), a Chinese taxa that lived in Asia during the early Late Jurassic (Oxfordian). Therefore, we placed the origin of the clade Ceratopsia at the beginning of the Late Jurassic (Oxfordian, ~163 Ma) (node 1). We followed the indications of Han et al. (2015) to estimate the age of the node 2 (162.5 Ma).

The second representatives of Ceratopsia are members of the Family Chaoyangsauridae, *Chaoyangsaurus youngi* (Zhao *et al.*, 1999) and *Xuanhuaceratops niei* (Zhao *et al.*, 2006), two Chinese taxa that lived in Asia during the end of Late Jurassic and the beginning of the Early Cretaceous. We placed the origin of Chaoyangsauridae at 152.5 Ma (middle Tithonian) (node 4) following the indications by Zhao *et al.* (1999), Xu *et al.* (2006), Zhao *et al.* (2006) and Ryan *et al.* (2012a). We placed the node 3 at 157 Ma. The divergence between Psittacosauridae and Neoceratopsia is estimated at 140 Ma following Xu *et al.* (2006) and Sereno *et al.* (2010) (node 5).

The Family Psittacosauridae includes two genera (*Hongshanosaurus* and *Psittacosaurus*) and ten valid species. The origin of the clade is estimated at 139 Ma, with the divergence of the most primitive psittacosaurid *Hongshanosaurus houi*. We basically followed You *et al.* (2003), You and Xu (2005), Tanoue *et al.* (2009) and Sun *et al.* (2011) to estimate the age of node 6. The origin of *Psittacosaurus* was placed at 138.5 Ma (node 7) with the first representative, *P. mongoliensis*. Lucas (2006) and Sereno (2010) described the phylogenetic relationships within *Psittacosaurus* and the stratigraphic range of the several psittacosaurid taxa. We followed the indications of these authors, with the addition of Sereno and Chao (1988) and Sun *et al.* (2011), to estimate the remaining nodes of the clade (node 8 to 12) and the phylogenetic relationships among psittacosaurids.

Recently, Sereno (2010) and Hedrick and Dodson (2013) addressed the systematic validity of some taxa such as *Hongshanosaurus houi* and *Psittacosaurus major* and *P. lujiatunensis*, arguing for the validity of the latter psittacosaurid only. We did not follow the revision of these authors, and we accepted the validity of ten psittacosaurid species (*H. houi*, *P. major*, *P. lujiatunensis*, *P. xinjangensis*, *P. meileyingensis*, *P. mongoliensis*, *P. neimongoliensis*, *P. sinensis*, *P. sibiricus* and *P. gobiensis*).

Mosaiceratops azumai represents the earliest neoceratopsian dinosaur (node 13). Its divergence is estimated at 133 Ma following Han *et al.* (2015). The divergence node of L*iaoceratops yanzigouensis* (node 14) has been estimated at 132 Ma following the indications of Xu *et al.* (2002, 2006), Sun *et al.* (2011)

Aquilops americanus represents the oldest neoceratopsian dinosaur from North America (node 15). We basically followed Farke and colleagues (2014) to estimate its divergence age at 131 Ma. Node 16 has been estimated at 130 Ma following Ryan *et al.* (2012a) and Farke *et al.* (2014). The *Yamaceratops dorngobiensis*/*Auroraceratops rugosus* group diverges at 127 Ma (node 17) (Makovicky and Norell, 2006; Ryan *et al.*, 2012a; Farke *et al.*, 2014). We followed Tang *et al.* (2001), You *et al.* (2005) and Farke *et al.* (2014) to estimate the age of node 18 at 128 Ma. Jin *et al.* (2009, 2010), Ryan *et al.* (2012a) and Farke *et al.* (2014) were used as references to calibrate divergence times between the *Helioceratops* + *Archaeoceratops* group and the node 19 (127 Ma). We mostly followed Tang *et al.* (2001), You and Dodson (2003) and You *et al.* (2010) to estimate the age of node 20 at 125.5 Ma, the common ancestor of *Archaeoceratops oshimai* and *A. yujingziensis*. We followed Lee *et al.* (2011), Ryan *et al.* (2012a) and Farke *et al.* (2014) to calibrate the branch length and the divergence time of *Koreaceratops hwaseongensis* at 118 Ma (node 21). The relationship between Leptoceratopsidae and *Graciliceratops* + Coronosauria has been calibrated following Ryan *et al.* (2012a) and Farke *et al.* (2014) and the divergence time estimated at 105 Ma (node 22).

For affinities within Leptoceratopsidae, we mostly followed Makovicky (2010), Ryan *et al.* (2012a), Farke *et al.* (2014) and the PaleoBiology Database (http://fossilworks.org/bridge.pl?) for the calibration of branch lengths and phylogenetic relationships among leptoceratopsid species (node 23 to 30). The ceratopsian *Asiaceratops salsopaludalis* (Nessov *et al.*, 1989) represents a controversial taxon. Its validity and phylogenetic position have been debated in the past years (Chinnery, 2004; Makovicky and Norell, 2006). In recent publications it has been included in the clade Leptoceratopsidae as the most basal representative of the group (Makovicky, 2010; Ryan *et al.*, 2012a; Farke *et al.*, 2014). It seems to be restricted to the Cenomanian stage (100.5 – 93.9 Ma), therefore we calibrated the time of divergence of the group at 101 Ma (node 23). To calibrate the branch lengths and the relationships among the several members of Leptoceratopsidae, we also followed Chinnery and Weishampel (1998), Gao and Norell (2000), Chinnery (2004), Dashzeveg *et al.* (2005), Chinnery and Horner (2007) and Hone *et al.* (2011).

Along with the description of new leptoceratopsids and revision of several leptoceratopsid material (Makovicky, 2002; Ott, 2007), new cladistic analyses have been proposed in recent publications (Chinnery, 2004; Chinnery and Horner, 2007; Makovicky, 2010; Xu *et al.*, 2010a; Ryan *et al.*, 2012a). The affinities within Leptoceratopsidae have been mostly solved in Makovicky (2010), Ryan *et al.* (2012a) and Farke *et al.* (2014) where a common vision of the evolutionary scenario have been presented, thus we followed these latter authors to build the topology of the clade.

Graciliceratops mongoliensis (Sereno, 2000) has known a tormented history both for systematic validity (Makovicky and Norell, 2006) and for the affinities with other ceratopsians. Chinnery (2004) placed this taxon within Protoceratopsidae as the sister species of *Protoceratops*. Xu *et al.* (2010a), in their phylogenetic analysis, placed this taxon as the sister species of Ceratopsoidea. Makovicky (2010), Ryan e*t al.* (2012a) and Farke *et al.* (2014) placed this taxon as the sister species of Coronosauria. In this work, the position and the branch length calibration of *Graciliceratops mongoliensis* was estimated following Sereno (2000), Ryan *et al.*, (2012a) and Farke *et al.* (2014) (100 Ma, node 31).

The divergence time of Coronosauria has been estimated at 96.5 Ma (node 32) following Sampson and Loewen (2010), Ryan *et al.* (2012a), Sampson *et al.* (2013) and Farke *et al.* (2014).

Along with the family Protoceratopsidae, the family Bagaceratopsidae has been proposed and erected by Alifanov (2003). Before the beginning of the new century, Protoceratopsidae, member of Coronosauria and sister group of Ceratopsoidea (Sereno, 1986, 1999), included the taxa *Protoceratops andrewsi*, *Bagaceratops rozhdestvenskyi*, *Protoceratops hellenikorhinus* (since 2001) and more other taxa such as *Breviceratops kozlowskii* (Maryańska and Osmólska, 1975; Kurzanov, 1990) and *Microceratops gobiensis* and *M. sulcidens* (Bohlin, 1953; Maryańska and Osmólska, 1975).

In the last ten years several systematic revisions and the description of new taxa, such as *Platyceratops tatarinovi* and *Lamaceratops tereschenkoi* (Alifanov, 2003) lead Alifanov to erect the new Family Bagaceratopsidae which included *Bagaceratops*, *Breviceratops*, *Gobiceratops minutus* (Alifanov, 2008) and *Magnirostris dodsoni* (You and Dong, 2003).

Makovicky in his Ph.D. thesis (2002) and in further publications (Makovicky and Norell, 2006) revised this bagaceratopsid material and stated that *Magnirostris, Platyceratops* and *Lamaceratops* are junior synonyms of *Bagaceratops*. Sereno (2000) and Makovicky (2002) discussed the taxonomic status of *Breviceratops* and concluded that this taxon represent a junior synonym of *Bagaceratops*. Sereno (2000) also regarded *Microceratops gobiensis* and *M. sulcidens* as nomina dubia. Sereno (2000) erected the new genus *Graciliceratops* and the new species *G. mongoliensis* to represent the material ascribed to *Microceratops gobiensis* by Maryańska and Osmólska (1975).

You and Dong (2003) and Brusatte (2012) recognized the Family Bagaceratopsidae as not valid, because it was not supported by the phylogenetic analyses (Xu *et al.*, 2002; You and Dodson, 2004; Makovicky and Norell, 2006), and only the Family Protoceratopsidae (sister group of Ceratopsoidea), which includes *Magnirostris*, *Protoceratops* spp., *Bagaceratops* and *Ajkaceratops* (Ösi *et al.*, 2010), represents the Asian taxa of the Late Cretaceous. We followed all these suggestions to build the phylogenetic tree and to calibrate the position of protoceratopsids.

We followed Lambert *et al.* (2001), Sampson and Loewen (2010), Ösi *et al.* (2010), Ryan *et al.* (2012a) and Farke *et al.* (2014) to estimate the age of the origin of Protoceratopsidae at 90 Ma (node 33). Lambert *et al.* (2001), Sampson and Loewen (2010), Ösi *et al.* (2010), Ryan *et al.* (2012a), Sampson *et al.* (2013) and Farke *et al.* (2014) were also used for the affinities and the age of nodes within Protoceratopsidae (node 34 to 36).

Zuniceratops christopheri represents the most basal member of Ceratopsoidea. We followed Wolfe and Kirkland (1998), Wolfe *et al.* (2010), Ryan *et al.* (2012a), Sampson *et al.* (2013), Farke *et al.* (2014) and Brown and Henderson (2015) to calibrate the age of node 37 at 92.5 Ma. *Turanoceratops tardabilis* is the second member of Ceratopsoidea. To calibrate the branch length and to estimate the age of node 38 at 92 Ma, we followed Sues and Averianov (2009), Ryan *et al.* (2012a), Farke *et al.* (2014) and Brown and Henderson (2015). Originally *Turanoceratops* was placed within Ceratopsidae (Sues and Averianov, 2009) but new studies (Farke *et al.*, 2009) placed this taxon outside Ceratopsidae as the sister taxon (supported by a new phylogenetic analysis). We followed this latter suggestion.

The origin of the most derived clade of Ceratopsia, Ceratopsidae, has been estimated at 83 Ma (node 39), at the beginning of the Campanian, following the indications of Kirkland and DeBlieux (2010), Xu *et al.* (2010a,b), Sampson *et al.* (2010, 2013), Hone *et al.* (2011), Fiorillo and Tykoski (2012) and Brown and Henderson (2015).

This clade traditionally includes two subclades: Chasmosaurinae and Centrosaurinae. The phylogeny of Centrosaurinae has been investigated several times in the last decades after the description of new several centrosaurines (Ryan, 2007; Currie *et al.*, 2008; Kirkland and DeBlieux, 2010; Xu *et al.*, 2010b; Farke *et al.*, 2011; Fiorillo and Tykoski, 2012; Ryan *et al.*, 2012b; Sampson *et al.*, 2013; Evans and Ryan, 2015). We basically followed Sampson *et al.* (2013) and Evans and Ryan (2015) to build the topology of Centrosaurinae. Along with the description of *Nasutoceratps titusi*, Sampson and colleagues (2013) investigated the paleobiogeography and the evolutionary implications of the basal centrosaurines as well as the evolution of the entire clade with a new phylogenetic analysis, showing different affinities among taxa as compared with previous contributions. Evans and Ryan (2015) proposed a similar phylogenetic scenario along with the description of a new centrosaurine *Wendiceratops pinhornensis* from the Oldman Formation, South Alberta, Canada.

The most basal centrosaurine is represented by *Diabloceratops eatoni* (Kirkland and DeBlieux, 2010), from the Wahweap Formation, which appeared in southern Laramidia (Utah) during the early Campanian (80 – 79.5 Ma). This leads to an estimate for the age of node 40, the origin of Centrosaurinae, at 82 Ma, in the early Campanian. We also followed the indications of Sampson and Loewen (2010), Farke *et al.* (2011) and Fiorillo and Tykoski (2012) to estimate that age. The age of node 41 has been estimated at 81.5 Ma following Sampson and Loewen (2010), Farke *et al.* (2011), Fiorillo and Tykoski (2012) and Sampson *et al.* (2013).

A basal centrosaurine subclade was recognized by Sampson *et al.* (2013). *Avaceratops* (from Montana) and *Nasutoceratops* (from Utah) constitute this subclades, both having simplified frills and long supraorbital horns. The origin of this subclade (node 42) is placed at 79 Ma following Sampson *et al.* (2013). Node 43, corresponding to the divergence of *Xenoceratops foremostensis* (from Alberta), was estimated at 81 Ma following the indications of Sampson *et al.* (2013) and Evans and Ryan (2015).

Nodes 44 and 45 were estimated at 80.5 and 80 Ma, respectively, following Sampson and Loewen (2010), Farke *et al.* (2011), Fiorillo and Tykoski (2012), Ryan *et al.* (2012b), Sampson *et al.* (2013) and Evans and Ryan (2015). Node 44 corresponds to a tricotomy where *Albertaceratops nesmoi* branches off together with additional subclades. The middle and late Campanian represent the time when several distinct centrosaurine subclades emerged in the evolutionary scenario proposed by Sampson *et al.* (2013) and Evans and Ryan (2015). *Wendiceratops* + *Sinoceratops* represents the sister group of the most derived members of Centrosaurinae, *Pachyrhinosaurus* + *Achelousaurus* + *Einiosaurus* group. This latter subclade includes centrosaurines, which possess relatively low and thickened bosses on the skull roof along with odd frill ornamentations. McDonald (2011), Farke *et al.* (2011), Fiorillo and Tykoski (2012), Ryan *et al.* (2012b), Sampson *et al.* (2013) and Evans and Ryan (2015) described the stratigraphic range and the phylogenetic relationships within this group as well as divergence dates between species (node 46 to 49). *Wendiceratops* (from Alberta) and *Sinoceratops* (from China) constitute one of them. We estimated the origin of this subclade at 79.5 (node 50) following Sampson and Loewen (2010), Farke *et al.* (2011), Fiorillo and Tykoski (2012), Ryan *et al.* (2012b), Sampson *et al.* (2013) and Evans and Ryan (2015).

The last centrosaurine subclade, characterized by the possession of elongated nasal horncores, short supraorbital horncores and typically more elaborate frills, includes a *Rubeosaurus* + *Styracosaurus* group, branching off near the node 51 estimated at 79.5 following Ryan *et al.* (2012b) and Sampson *et al.* (2013), and the remaining *Spinops* + *Centrosaurus* + *Coronosaurus* group. Node 52, corresponding to the common ancestor of *Rubeosaurus* and *Styracosaurus* (from Montana and Alberta, respectively), has been estimated at 76.2 Ma following Ryan *et al.* (2007), McDonald (2011), Farke *et al.* (2011), Fiorillo and Tykoski (2012), Ryan *et al.* (2012b) and Sampson *et al.* (2013). The relationships within *Spinops* + *Centrosaurus* + *Coronosaurus* group (nodes 53 and 54) were calibrated using Farke *et al.* (2011), Ryan *et al.* (2012b) and Sampson *et al.* (2013).

As seen above in Centrosaurinae, the phylogenetic relationships within Chasmosaurinae have been recently revised, with new cladistic analyses by several authors (Sampson *et al.*, 2010; Mallon *et al.*, 2011, 2014; Wick and Lehman, 2013; Brown and Henderson, 2015), and multiple competing evolutionary scenarios have been proposed. Sampson *et al.* (2010) conducted an exhaustive cladistic analysis for 25 ceratopsian species, including 18 chasmosaurines. The resulting analysis was compatible with previous phylogenies by Lehman (1996), Holmes *et al.* (2001) and Dodson *et al.* (2004), where *Chasmosaurus* spp. represents the most primitive taxon and *Triceratops*/*Torosaurus* the most derived chasmosaurines. A different scenario has been proposed by Mallon and colleagues (2011) after performing a similar analysis but with a slightly different character matrix. In this work, *Anchiceratops ornatus* represents the most primitive chasmosaurine, whereas *Chasmosaurus* spp. is the most derived taxon. Moreover, Mallon *et al.* (2011) identified two distinct subclades within Chasmosaurinae in a reversed stratigraphic order with respect to Sampson *et al.* (2010). In the first group, *Arrhinoceratops* is the most primitive taxon and *Triceratops* + *Torosaurus* + *Nedoceratops* (in a politomy) group represents the most derived taxon; in the second group, *Anchiceratops* is the most primitive and *Chasmosaurus* the most derived one. In a recent contribution, Mallon *et al.* (2014) partially confirmed the proposal by Mallon *et al.* (2011) of *Chasmosaurus* spp. as a derived ceratopsid group, as well as Triceratopsini, and with an unclear position for *Anchiceratops* and *Arrhinoceratops*. In 2013, Wick and Lehman described a new chasmosaurine *Bravoceratops polyphemus* and performed a new cladistic analysis using a modified version of the character matrix given by Mallon *et al.* (2011). Their result reflected the phylogenetic relationships and evolutionary scenario proposed by Sampson *et al.* (2010). Brown and Henderson (2015) proposed a new cladistic analysis, along with the description of the new chasmosaurine *Regaliceratops peterhewsi,* using a new character matrix (a combination of new characters along with those used by Sampson *et al.* (2010) and Mallon *et al*. 2014), where *Vagaceratops-Kosmoceratops* represents the basal chasmosaurine clade and *Chasmosaurus* spp. is recovered as a derived taxon.

Recent contributions have also reviewed the systematic validity of some chasmosaurines. Scannella and Horner (2010) provided evidence that *Torosaurus* represents a junior synonym of *Triceratops*. Farke (2011), Longrich and Field (2012) and Maiorino *et al.* (2013) provided new evidences on the validity of both taxa. We followed these latter indications. Longrich (2010) designated TMP 1983.25.1, previously ascribed to *Chasmosaurus russelli* (Godfrey and Holmes, 1995), as the holotype of a new chasmosaurine taxon, *Mojoceratops perifania*, recently regarded as a junior synonym of *C. russelli* by Maidment and Barrett (2011). However, Sampson *et al.* (2010), Wick and Lehman (2013) and Brown and Henderson (2015) considered this taxon as valid in their analyses. We followed these latter authors in our phylogeny. In 2011, Longrich redescribed as a new taxon, *Titanoceratops ouranos*, previously assigned to *Pentaceratops sternbergi* (Lehman, 1998) and regarded as junior synonym by Wick and Lehman (2013). We followed Wick and Lehman (2013) and we considered *Titanoceratops* as a not valid chasmosaurine in the synthetic phylogeny.

Scannella and Horner (2011) questioned the validity of *Nedoceratops hatcheri* and considered this taxon as a junior synonym of *Triceratops*. We did not accept the conclusion of this work and we followed the indications given by Sampson *et al.* (2010), Farke (2011), Wick and Lehman (2013) and Brown and Henderson (2015).

Lastly, *Ojoceratops fowleri*, a new chasmosaurine described by Sullivan and Lucas (2010) and previously assigned to *Torosaurus utahensis* (Farke and Williamson, 2006; Hunt and Lehman, 2008), has been regarded as a junior synonym of *Triceratops* by Longrich (2011). We followed Sullivan and Lucas (2010), Sampson *et al.* (2010), Wick and Lehman (2013) and Brown and Henderson (2015) concerning the validity of *Ojoceratops*.

A questionable taxon is represented by *Tatankaceratops sacrisonorum*, described by Ott and Larson (2010). Due to the paucity of the material it is difficult to establish this taxon as valid and distinct from other chasmosaurines. Moreover, *Tatankaceratops* shares with *Triceratops* several anatomical traits, and several authors suggested that it could represent an aberrant individual of *Triceratops prorsus* (Longrich, 2011; Longrich and Field, 2012). We preferred to excluded this taxon from our analyses.

We basically followed the indications given by Longrich (2010, 2011), Sampson *et al.* (2010), Wick and Lehman (2013) and Brown and Henderson (2015) to build the topology and to calibrate the branch lengths of Chasmosaurinae.

The origin of Chasmosaurinae has been estimated at 80 Ma (node 55) with the branching off of the *Vagaceratops-Kosmoceratops* group. We estimated at 77 Ma (node 56) the common ancestor of *Vagaceratops irvinensis* and *Kosmoceratops richardsoni*. Node 57 has been calibrated at 79.5 Ma, whereas node 58 was estimated at 79 Ma following Brown and Henderson (2015). Node 60, where the *Utahceratops* + *Pentaceratops* group branches off, corresponds to 78.5 Ma. The origin of *Agujaceratops mariscalensis* was estimated at 78 Ma (node 62). *Mojoceratops perifania* branches off at the node 63 with an estimated age of 77.6 Ma. The common ancestor of *Chasmosaurus belli* and *C. russelli* has been estimated at 77.3 Ma (node 64). Node 61, corresponding to the origin of the *Utahceratops* + *Pentaceratops* group, has been calibrated at 77.5 Ma. Node 59 corresponds to the common ancestor of the *Coahuilaceratops* + *Bravoceratops* group, and it has been estimated at 73.2 Ma.

Mallon and colleagues (2011), along with Longrich (2010, 2011), Sampson *et al.* (2010), Wick and Lehman (2013), and Brown and Henderson (2015) were followed to calibrate the position and age of node 65 (76 Ma) as well as the common ancestor of *Anchiceratops ornatus* and *Arrhinoceratops brachyops* (node 66: 72.3 Ma). Node 67 corresponds to an unresolved subclade with *Ojoceratops fowleri*, *Eotriceratops xerinsularis*, *Regaliceratops peterhewsi* and the *Torosaurus* + *Nedoceratops* + *Triceratops* group in a politomy. Following the authors cited above, we calibrated the node 67 at 73 Ma. The origin of the *Torosaurus* + *Nedoceratops* + *Triceratops* group has been estimated at 69 Ma (node 68).

Torosaurus spp., *Nedoceratops hatcheri* and *Triceratops* spp. are the last representatives of the clade Ceratopsia. All taxa occurred in western North America during the late Maastrichtian (67.5 – 66 Ma). *Torosaurus* includes two species: *T. latus* and *T. utahensis*. This latter taxon has been reviewed in recent contributions and accepted as valid (Sullivan *et al.*, 2005; Hunt and Lehman, 2008; see Scannella and Horner, 2010 for an opposite viewpoint) and herein accepted as well. *Torosaurus latus* is regarded a valid taxon as already argued above.

Triceratops includes two species: *T. horridus* and *T. prorsus* (Forster, 1996). Historically at least sixteen *Triceratops* species have been named by several authors (Marsh, 1889, 1890, 1891; Brown, 1933; Schlaikjer, 1935; Sternberg, 1949), most of them based on inadequate material. Forster (1996) reviewed the *Triceratops* material and, by means of cladistic and morphometric analyses as well as qualitative observations, concluded that only two of sixteen species of *Triceratops* are valid. This conclusion is largely accepted in the scientific community and herein as well. *Nedoceratops hatcheri* represents a controversial taxon. It was originally ascribed to the new genus *Diceratops* (Hatcher *et al.*, 1907), later assigned to *Triceratops* (Lull, 1933) and recently renamed as *Nedoceratops* following the discovery that the genus name *Diceratops* was preoccupied (Ukrainsky, 2007, 2009). Although some authors considered this taxon as a possible synonym of *Triceratops horridus* (Ostrom and Wellnhofer, 1986; Longrich and Field, 2012) or a transitional form between the ‘‘young adult’’ and ‘‘old adult’’ forms of *Triceratops* (Scannella and Horner, 2011), here we followed the indications given by Forster (1996), Sampson *et al.* (2010) and Farke (2011), and we accepted the validity of this ceratopsid and included it in the phylogenetic tree.

The common ancestor of *Triceratops horridus* and *T. prorsus* has been estimated at 68 Ma (node 70) following Longrich (2010, 2011), Sampson *et al.* (2010), Wick and Lehman (2013) and Brown and Henderson (2015). Similar indications were followed to calibrate the age of node 71 at 68 Ma (*Torosaurus* group).

Supplementary Tables

Table S1. List of institutional abbreviations.

AMNH, American Museum of Natural History, New York, New York, U.S.A.;
ANSP, Academy of National Science of Philadelphia, Philadelphia, Pennsylvania, U.S.A.;
BHI, Black Hills Institute of Geological Research, Hill City, South Dakota, U.S.A.;
BNHM, Beijing Natural History Museum, Beijing, China;
BSPG, Bayerische Staatssammlung für Paläontologie und historische Geologie, Munich, Germany;
CAGS-IG, Chinese Academy of Geological Science, Institute of Geology, Beijing, China;
CCM, Carter County Museum, Ekalaka, Montana, U.S.A.;
CM, Carnegie Museum of Natural History, Pittsburgh, Pennsylvania, U.S.A.;
CMN, National Museum of Canada, Ottawa, Ontario, Canada;
CPC, Coleccion Paleontologica de Coahuila, Saltillo, Mexico;
DMNH, Denver Museum of Nature and Science, Denver, Colorado, U.S.A.;
DMNH, Perot Museum of Nature and Science, Dallas, Texas, U.S.A.;
FMNH, Field Museum of Natural History, Chicago, Illinois, U.S.A.;
GMNH, Gunma Museum of Natural History, Gunma, Japan;
IGM, Institute of Geology of Mongolia, Ulan Baatar, Mongolia;
IMM, Inner Mongolia Museum, Hohhot, China;
IVPP, Institute of Vertebrate Paleontology and Paleoanthropology, Beijing, China;
LACM, Natural History Museum of Los Angeles County, Los Angeles, California, U.S.A.;
LH, Long Hao Institute for Stratigraphic Paleontology, Hohhot, China;
MNHN, Muséum National d'Histoire Naturelle, Paris, France;
MOR, Museum of the Rockies, Bozeman, Montana, U.S.A.;
MPC, Mongolian Paleontological Collection, Ulan Baatar, Mongolia;
MSM, Arizona Museum of Natural History, Mesa, Arizona, U.S.A.;
NHMUK, Natural History Museum, London, United Kingdom;
NMMNH, New Mexico Museum of Natural History and Science, Albuquerque, New Mexico, U.S.A.;
OMNH, Oklahoma Museum of Natural History, Norman, Oklahoma, U.S.A.;
PIN, Russian Academy of Sciences, Palaeontological Institute, Moscow, Russia;
PKUP, Peking University Paleontological Collections, Beijing, China;
RAM, Raymond M. Alf Museum of Paleontology, Claremont, California, U.S.A.;
ROM, Royal Ontario Museum, Toronto, Canada;
SDSM, South Dakota School of Mines and Technology, Rapid City, South Dakota, U.S.A.;
SMM, Science Museum of Minnesota, St. Paul, Minnesota, U.S.A.;
SMNH, Saskatchewan Museum of Natural History, Regina, Canada;
SMP, State Museum of Pennsylvania, Harrisburg, Pennsylvania, U.S.A.;
TCMI, Children Museum of Indianapolis, Indianapolis, Indiana, U.S.A.;
TMM, Texas Natural Science Center, Austin, Texas, U.S.A.;
TMP, Royal Tyrrell Museum of Paleontology, Drumheller, Alberta, Canada;
UALVP, University of Alberta, Laboratory of Vertebrate Paleontology, Edmonton, Alberta, Canada;
UMNH, Utah Museum of Natural History, Salt Lake City, Utah, U.S.A.;
USNM, National Museum of Natural History, Smithsonian Institution, Washington D.C., U.S.A.;
YPM, Yale Peabody Museum of Natural History, New Haven, Connecticut, U.S.A.;
ZMNH, Zhejiang Museum of Natural History, Hangzhou, China;
ZPAL, Polish Academy of Sciences, Institute of Paleobiology, Warsaw, Poland.

Table S2. List of ceratopsian material directly photographed for this study and references for those species for which we used published photos or drawings.

COLLECTION NUMBER	**TAXON**	**CLADE**	**MATERIAL**	**REFERENCES**
MOR 485	*Achelousaurus horneri*	Centrosaurinae	Skull	
MOR 591-7-15-89-1	*Achelousaurus horneri*	Centrosaurinae	Lower jaw	
TMM no code	*Agujaceratops mariscalensis*	Non-triceratopsin Chasmosaurinae	Restored skull	
CMN 8535	*Anchiceratops ornatus*	Non-triceratopsin Chasmosaurinae	Skull	
TMP 1983.01.01	*Anchiceratops ornatus*	Non-triceratopsin Chasmosaurinae	Skull + lower jaw	
OMNH 34557	*Aquilops americanus*	Neoceratopsia	Partial skull	
IVPP V11114	*Archaeoceratops oshimai*	Neoceratopsia	Skull + lower jaw	
CAGS-IG-VD-003	*Archaeoceratops yujingziensis*	Neoceratopsia	Lower jaw	
ROM 796	*Arrhinoceratops brachyops*	Non-triceratopsin Chasmosaurinae	Skull	
ROM 1439	*Arrhinoceratops brachyops*	Non-triceratopsin Chasmosaurinae	Lower jaw	
CAGS-IG-2004-VD-001	*Auroraceratops rugosus*	Neoceratopsia	Skull + lower jaw	
ANSP 15800	*Avaceratops lammersi*	Centrosaurinae	Partial skull + lower jaw	
MPC-D-100-506	*Bagaceratops rozhdestvenskyi*	Protoceratopsidae	Skull + lower jaw	
ZPAL MgD-I-126	*Bagaceratops rozhdestvenskyi*	Protoceratopsidae	Skull + lower jaw	
AMNH no code	*Bagaceratops rozhdestvenskyi*	Protoceratopsidae	Lower jaw	
ZPAL MgD-I-137	*Bagaceratops rozhdestvenskyi*	Protoceratopsidae	Lower jaw	
RAM 3679	*Centrosaurus apertus*	Centrosaurinae	Skull + lower jaw	
AMNH 5239	*Centrosaurus apertus*	Centrosaurinae	Skull	
CMN 348	*Centrosaurus apertus*	Centrosaurinae	Skull	
CMN 8795	*Centrosaurus apertus*	Centrosaurinae	Skull + lower jaw	
ROM 767	*Centrosaurus apertus*	Centrosaurinae	Skull + lower jaw	
USNM 8897	*Centrosaurus apertus*	Centrosaurinae	Skull + lower jaw	
YPM 2015	*Centrosaurus*	Centrosaurinae	Skull + lower	

	apertus		jaw	
NHMUK R4589	*Centrosaurus apertus*	Centrosaurinae	Skull	
CMN 829	*Centrosaurus apertus*	Centrosaurinae	Lower jaw	
CMN 8790	*Centrosaurus apertus*	Centrosaurinae	Lower jaw	
UALVP 11735	*Centrosaurus apertus*	Centrosaurinae	Lower jaw	
AMNH 5237	*Centrosaurus apertus*	Centrosaurinae	Lower jaw	
TMP 1981.16.355	*Centrosaurus apertus*	Centrosaurinae	Lower jaw	
UALVP 16248	*Centrosaurus apertus*	Centrosaurinae	Lower jaw	
MOR 300-7-10-84-1	*Cerasinops hodgskissi*	Leptoceratopsidae	Lower jaw	
CAGS-IG-V371	*Chaoyangsaurus youngi*	Chaoyangsauridae	Lower jaw	
CMN 2245	*Chasmosaurus belli*	Non-triceratopsin Chasmosaurinae	Skull + lower jaw	
ROM 839	*Chasmosaurus belli*	Non-triceratopsin Chasmosaurinae	Skull + lower jaw	
ROM 843	*Chasmosaurus belli*	Non-triceratopsin Chasmosaurinae	Skull	
UALVP 40	*Chasmosaurus belli*	Non-triceratopsin Chasmosaurinae	Skull	
CMN 284	*Chasmosaurus belli*	Non-triceratopsin Chasmosaurinae	Lower jaw	
CMN 8800	*Chasmosaurus russelli*	Non-triceratopsin Chasmosaurinae	Skull	
TMP 1981.19.175	*Chasmosaurus russelli*	Non- triceratopsin Chasmosaurinae	Skull	
CMN 2280	*Chasmosaurus russelli*	Non- triceratopsin Chasmosaurinae	Skull + lower jaw	
CAGS IG V371	*Chaoyangsaurus youngi*	Chaoyangsauridae	Lower jaw	
CPC 276	*Coahuilaceratops magnacuerna*	Non-triceratopsin Chasmosaurinae	Lower jaw	
TMP 2002.68.166	*Coronosaurus brinkmani*	Centrosaurinae	Lower jaw	
TMP 2002.68.168	*Coronosaurus brinkmani*	Centrosaurinae	Lower jaw	
UMNH VP 16699	*Diabloceratops eatoni*	Centrosaurinae	Skull	
MOR 456	*Einiosaurus procurvicornis*	Centrosaurinae	Restored skull + lower jaw	Sampson, 1995
MOR 373-7-15-6-13	*Einiosaurus procurvicornis*	Centrosaurinae	Lower jaw	
LACM 154904	*Einiosaurus*	Centrosaurinae	Lower jaw	

	procurvicornis			
TMP 2002.057.07	*Eotriceratops xerinsularis*	Triceratopsini	Restored skull	
IVPP V12617	*Hongshanosaurus houi*	Psittacosauridae	Skull + lower jaw	
UMNHN VP 17000	*Kosmoceratops richardsoni*	Non-triceratopsin Chasmosaurinae	Skull + lower jaw	
CMN 8887	*Leptoceratops gracilis*	Leptoceratopsidae	Skull + lower jaw	
CMN 8889	*Leptoceratops gracilis*	Leptoceratopsidae	Lower jaw	
AMNH 5205	*Leptoceratops gracilis*	Leptoceratopsidae	Lower jaw	
IVPP V12738	*Liaoceratops yanzigouensis*	Neoceratopsia	Skull + lower jaw	
IVPP V12633	*Liaoceratops yanzigouensis*	Neoceratopsia	Lower jaw	
CAGS-IG-VD-002	*Liaoceratops yanzigouensis*	Neoceratopsia	Lower jaw	
IVPP V12513	*Magnirostris dodsoni*	Protoceratopsidae	Lower jaw	
AMNH 5401	*Mojoceratops perifania*	Non-triceratopsin Chasmosaurinae	Skull	
MOR 542	*Montanoceratops cerochynchus*	Leptoceratopsidae	Lower jaw	
UMNH 16800	*Nasutoceratops titusi*	Centrosaurinae	Skull	
USNM 2412	*Nedoceratops hatcheri*	Triceratopsini	Skull	
SMP VP1875	*Ojoceratops fowleri*	Triceratopsini	Lower jaw	
TMP 2005.053.01	*Pachyrhinosaurus lakustai*	Centrosaurinae	Skull	
TMP 2001.00.33	*Pachyrhinosaurus lakustai*	Centrosaurinae	Lower jaw	
TMP 1987.55.129	*Pachyrhinosaurus lakustai*	Centrosaurinae	Lower jaw	
TMP 1989.55.78	*Pachyrhinosaurus lakustai*	Centrosaurinae	Lower jaw	
TMP 2002.76.1	*Pachyrhinosaurus sp.*	Centrosaurinae	Skull + lower jaw	
DMNH 22558	*Pachyrhinosaurus perotorum*	Centrosaurinae	Partial skull	
OMNH 10165	*Pentaceratops sternbergi*	Non-triceratopsin Chasmosaurinae	Skull + lower jaw	Lehman, 1998
AMNH 6325	*Pentaceratops sternbergi*	Non-triceratopsin Chasmosaurinae	Skull	
AMNH 1624	*Pentaceratops sternbergi*	Non-triceratopsin Chasmosaurinae	Restored skull	
NMMNH P50000	*Pentaceratops*	Non-triceratopsin	Skull	

	sternbergi	Chasmosaurinae		
NMMNH C3175	*Pentaceratops sternbergi*	Non-triceratopsin Chasmosaurinae	Lower jaw	
TCMI 2001.96.13.1	*Prenoceratops pieganensis*	Leptoceratopsidae	Restored skull + lower jaw	
AMNH 6408	*Protoceratops andrewsi*	Protoceratopsidae	Skull	
AMNH 6419	*Protoceratops andrewsi*	Protoceratopsidae	Skull	Brown and Schlaikjer, 1940
AMNH 6432	*Protoceratops andrewsi*	Protoceratopsidae	Skull	
AMNH 6434	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
AMNH 6466	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
AMNH 6438	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
AMNH 6409	*Protoceratops andrewsi*	Protoceratopsidae	Skull	
AMNH 6414	*Protoceratops andrewsi*	Protoceratopsidae	Skull	
AMNH 6418	*Protoceratops andrewsi*	Protoceratopsidae	Partial skull + lower jaw	
AMNH 6425	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
AMNH 6429	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
AMNH 6430	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
AMNH 6441	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
AMNH 6637	*Protoceratops andrewsi*	Protoceratopsidae	Skull	
AMNH 6467	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
AMNH 6460	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
AMNH 6636	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
AMNH 6471	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
UALVP 49397	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
CM 9185	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
DMNH	*Protoceratops andrewsi*	Protoceratopsidae	Skull	
DMNH 50633	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
FMNH P14046	*Protoceratops*	Protoceratopsidae	Lower jaw	

	andrewsi			
FMNH PR1135	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
MPC-D 100-522	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
MPC-D 100-502	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
MPC-D 100-502a	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
MPC-D 2006.36	*Protoceratops andrewsi*	Protoceratopsidae	Skull	
MPC-D 2006.35	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
MPC-D 100-505	*Protoceratops andrewsi*	Protoceratopsidae	Skull + lower jaw	
MSN no code	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
MPC-D 100-518	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
MPC-D 100-521	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
MPC-D 100-534	*Protoceratops andrewsi*	Protoceratopsidae	Skull	Handa *et al.*, 2012
ZPAL MgD-II-4	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
ROM 11864	*Protoceratops andrewsi*	Protoceratopsidae	Skull	
MPC-D no code	*Protoceratops andrewsi*	Protoceratopsidae	Lower jaw	
IMM 95BM1.1	*Protoceratops hellenikorhinus*	Protoceratopsidae	Skull + lower jaw	
LH PV 2	*Psittacosaurus gobiensis*	Psittacosauridae	Skull + lower jaw	
PKUP V1054	*Psittacosaurus lujiatunensis*	Psittacosauridae	Skull	Zhou *et al.*, 2007
PKUP V1060	*Psittacosaurus lujiatunensis*	Psittacosauridae	Skull	Zhou *et al.*, 2007
ZMNH M8137	*Psittacosaurus lujiatunensis*	Psittacosauridae	Skull + lower jaw	Zhou *et al.*, 2006
CAGS-IG-V004	*Psittacosaurus major*	Psittacosauridae	Skull + lower jaw	
LH PV1	*Psittacosaurus major*	Psittacosauridae	Skull + lower jaw	
IVPP V7705	*Psittacosaurus meileyingensis*	Psittacosauridae	Skull + lower jaw	
TCMI no code	*Psittacosaurus meileyingensis*	Psittacosauridae	Skull + lower jaw	
DMNH 50634	*Psittacosaurus meileyingensis*	Psittacosauridae	Skull	
AMNH 6254	*Psittacosaurus*	Psittacosauridae	Skull + lower	

	mongoliensis		jaw	
MPC-D no code	*Psittacosaurus mongoliensis*	Psittacosauridae	Skull + lower jaw	
CMN-IVPP 120888-2	*Psittacosaurus neimongoliensis*	Psittacosauridae	Skull + lower jaw	
BNHM BPV149	*Psittacosaurus sinensis*	Psittacosauridae	Skull	Sereno, 1990
IVPP V738	*Psittacosaurus sinensis*	Psittacosauridae	Skull + lower jaw	
IVPP V740	*Psittacosaurus sinensis*	Psittacosauridae	Skull + lower jaw	
TMP 2005.55.01	*Regaliceratops peterhewsi*	Triceratopsini	Skull	
AMNH 5372	*Styracosaurus albertensis*	Centrosaurinae	Skull + lower jaw	
CMN 334	*Styracosaurus albertensis*	Centrosaurinae	Skull + lower jaw	
UALVP 52612	*Styracosaurus albertensis*	Centrosaurinae	Skull	
ANSP 15192	*Torosaurus latus*	Triceratopsini	Skull	
YPM 1830	*Torosaurus latus*	Triceratopsini	Skull	
MOR 1122	*Torosaurus latus*	Triceratopsini	Skull	
USNM 15583	*Torosaurus utahensis*	Triceratopsini	Lower jaw	
BHI 4772	*Triceratops horridus*	Triceratopsini	Skull + lower jaw	
BHI 6220	*Triceratops horridus*	Triceratopsini	Skull + lower jaw	
BHI 6441	*Triceratops horridus*	Triceratopsini	Lower jaw	
DMNH 48617	*Triceratops horridus*	Triceratopsini	Skull	
FMNH P12003	*Triceratops horridus*	Triceratopsini	Skull	
MNHN F1912.20	*Triceratops horridus*	Triceratopsini	Skull	
MOR 1110	*Triceratops horridus*	Triceratopsini	Skull	
MOR 1120	*Triceratops horridus*	Triceratopsini	Skull	
MOR 1199	*Triceratops horridus*	Triceratopsini	Skull	
ROM 55380	*Triceratops horridus*	Triceratopsini	Skull + lower jaw	
SDSM 2760	*Triceratops horridus*	Triceratopsini	Skull	
TCMI 2001.93.01	*Triceratops horridus*	Triceratopsini	Skull + lower jaw	
AMNH 5116	*Triceratops horridus*	Triceratopsini	Skull + lower jaw	

USNM 1201	*Triceratops horridus*	Triceratopsini	Skull	
USNM 1205	*Triceratops horridus*	Triceratopsini	Skull	
USNM 4720	*Triceratops horridus*	Triceratopsini	Skull	
YPM 1821	*Triceratops horridus*	Triceratopsini	Skull + lower jaw	
USNM 2100	*Triceratops horridus*	Triceratopsini	Skull + lower jaw	
USNM 4726	*Triceratops horridus*	Triceratopsini	Lower jaw	
CM 1221	*Triceratops prorsus*	Triceratopsini	Skull + lower jaw	
BSPG 1964I458	*Triceratops prorsus*	Triceratopsini	Skull	
LACM 59049	*Triceratops prorsus*	Triceratopsini	Skull + lower jaw	
LACM 151459	*Triceratops prorsus*	Triceratopsini	Skull + lower jaw	
TCMI 2004.49.1	*Triceratops prorsus*	Triceratopsini	Skull + lower jaw	
YMP 1822	*Triceratops prorsus*	Triceratopsini	Skull + lower jaw	
MSM no code	*Triceratops prorsus*	Triceratopsini	Lower jaw	
SMNH P1163.4	*Triceratops prorsus*	Triceratopsini	Skull	Tokaryk, 1986
CCM 49-1	*Triceratops prorsus*	Triceratopsini	Skull	
GMNH VP124	*Triceratops prorsus*	Triceratopsini	Lower jaw	Fujiwara and Takakuwa, 2011
BHI 6409	*Triceratops prorsus*	Triceratopsini	Lower jaw	
USNM 8081	*Triceratops* sp.	Triceratopsini	Lower jaw	
USNM 508495	*Triceratops* sp.	Triceratopsini	Lower jaw	
AMNH 5039	*Triceratops* sp.	Triceratopsini	Lower jaw	
PIN 3907/11	*Udanoceratops tschizhovi*	Leptoceratopsidae	Lower jaw	Kurzanov, 1992
UMNH VP 16784	*Utahceratops gettyi*	Non-triceratopsin Chasmosaurinae	Restored skull + lower jaw	Sampson *et al.*, 2010
CMN 41537	*Vagaceratops irvinensis*	Non-triceratopsin Chasmosaurinae	Skull + lower jaw	
IGM 100-1315	*Yamaceratops dorngobiensis*	Neoceratopsia	Lower jaw	Makovicky and Norell, 2006
IVPP V14530	*Yinlong downsi*	Ceratopsia	Skull + lower jaw	
ZCDM V0015	*Zhuchengceratops inexpectus*	Leptoceratopsidae	Lower jaw	Xu *et al.*, 2010a
MSM no code	*Zuniceratops*	Ceratopsoidea	Restored skull	

	christopheri		+ lower jaw	

Table S3. Landmark definitions for the four modules (see Fig. 1 and 2, and Fig. S1). (**A**), (**B**), (**C**), (**D**), (**E**) and (**F)** in Figure S1 are subunits of skull and lower jaw configurations. Landmarks have identical definitions.

Landmark definitions for skull in lateral view	
Landmark #	**Anatomical definition**
1	lower contact of premaxilla–rostral
2	lower tip of premaxilla
3	lower contact of premaxilla–maxilla
4	upper contact of premaxilla–rostral
5	upper contact of premaxilla–nasal
6	lower contact of premaxilla–nasal
7	maximum curvature point of narial opening at caudo–dorsal edge
8	caudal contact of nasal–premaxilla
9	upper contact of maxilla–premaxilla
10	maximum curvature point of jugal
11	intersection of jugal–alveolar process of maxilla
12	lower tip of quadrate
13	epijugal tip
14	rostral tip of the orbit
15	ventral tip of the orbit
16	caudal tip of the orbit
17	dorsal tip of the orbit
18	contact of jugal–quadratojugal
19	ventral tip of infratemporal process
20	maximum curvature point of infratemporal fenestra
21	contact of quadrate–squamosal
22	lower tip of squamosal
23	parieto–squamosal contact
24	maximum curvature point of parietal
25	dorsal tip of parietal midline
26	rostral tip of supratemporal fenestra
27	projection of LM 14 on the nasal edge
28	jugal–postorbital contact at the orbit rim
Landmark definitions for lower jaw in lateral view	
1	rostral contact of dentary–predentary
2	dorsal contact of dentary–predentary
3	beginning of tooth row
4	intersection between the tooth row and the coronoid process of dentary
5	maximum curvature point of coronoid process
6	dorsal tip of coronoid process
7	dorsal contact of dentary–surangular
8	caudal tip of the lower jaw
9	ventrocaudal contact of angular–surangular
10	contact of dentary–angular–surangular
11	ventrocaudal contact of dentary–angular
12	ventral contact of predentary–dentary

Table S4. List of ceratopsian taxa, stratigraphic and geographical distribution, and references considered in this study. See Appendix for details on the phylogenetic relationships in ceratopsians.

SPECIES	CLADE	DISTRIBUTION	GEOGRAPHICAL DISTRIBUTION	REFERENCES
Achelousaurus horneri	Ceratopsidae/Centrosaurinae	74.5 - 74 Ma	Montana	Sampson, 1995; Sampson and Loewen, 2010: Sampson *et al.* , 2013
Agujaceratops mariscalensis	Ceratopsidae/Chasmosaurinae	77 - 76.8 Ma	Texas	Sampson *et al.* , 2010
Ajkaceratops kozmai	Protoceratopsidae	Santonian (86.3 - 83.6 Ma)	Hungary	Ösi *et al.* , 2010
Albertaceratops nesmoi	Ceratopsidae/Centrosaurinae	78 - 77.5 Ma	Alberta	Eberth, 2005; Ryan, 2007; Sampson and Loewen, 2010; Ryan *et al.* , 2012b; Sampson *et al.* , 2013
Anchiceratops ornatus	Ceratopsidae/Chasmosaurinae	71.5 - 69.5 Ma	Alberta	Sampson *et al.* , 2010; Mallon *et al.* , 2011
Aquilops americanus	Neoceratopsia	109 - 104 Ma	Montana	Farke *et al.* , 2014
Archaeoceratops oshimai	Neoceratopsia	Albian (106 - 104 Ma)	Mazongshan area, Gansu Province, China	Tang *et al.* , 2001; Xu *et al.* , 2006
Archaeoceratops yujingziensis	Neoceratopsia	Albian (106 - 104 Ma)	Yujingzi Basin, Mazongshan area, Gansu Province, China	Tang *et al.* , 2001; You *et al.* , 2010
Arrhinoceratops brachyops	Ceratopsidae/Chasmosaurinae	71.3 - 70.5 Ma	Alberta	Sampson *et al.* , 2010; Mallon *et al.* , 2014
Asiaceratops salsopaludalis	Leptoceratopsidae	Cenomanian (100 - 93 Ma)	Uzbekistan	PbDb*; Nessov *et al.* , 1989
Auroraceratops rugosus	Neoceratopsia	Albian (113 - 100 Ma)	Gongpoquan Basin, Gansu Province, China	PbDb; Tang *et al.* , 2001; You *et al.* , 2005
Avaceratops lammersi	Ceratopsidae/Centrosaurinae	79 - 78 Ma	Alberta	Sampson and Loewen, 2010; Sampson *et al.* , 2013
Bagaceratops rozhdestvenskyi	Protoceratopsidae	75.5 - 70.5 Ma	Nemegt Basin, Mongolia	Maryańska and Osmólska, 1975; Sampson *et al.* , 2013
Bravoceratops polyphemus	Ceratopsidae/Chasmosaurinae	72.5 - 70.5 Ma	Big Bend National Park, West Texas	Lehman, 1989; Wick and Lehman, 2013; Brown and Henderson, 2015
Centrosaurus apertus	Ceratopsidae/Centrosaurinae	77 - 76 Ma	Alberta	Eberth, 2005; Ryan and Evans, 2005; Ryan *et al.* , 2007; Sampson and Loewen, 2010; Sampson *et al.* , 2013
Cerasinops hodgskissi	Leptoceratopsidae	80 - 76.5 Ma	Montana	Chinnery and Horner, 2007
Chaoyangsaurus youngi	Chaoyangsauridae	Late Jurassic-Early Cret (148 - 140 Ma)	Liaoning Province, China	Makovicky and Norell, 2006; Xu *et al.* , 2006; Zhao *et al.* , 2006; Swisher *et al.* , 2002

Chasmosaurus belli	Ceratopsidae/Chasmosaurinae	75.8 - 75.6 Ma	Alberta	Sampson *et al.* , 2010, 2013; Brown and Henderson, 2015
Chasmosaurus russelli	Ceratopsidae/Chasmosaurinae	76.8 - 75.8 Ma	Alberta	Sampson *et al.* , 2010; Brown and Henderson, 2015
Coahuilaceratops magnacuerna	Ceratopsidae/Chasmosaurinae	71.2 - 70.3 Ma	Cohauila, Mexico	Loewen *at al.* , 2010; Sampson *et al.* , 2010; Brown and Henderson, 2015
Coronosaurus brinkmani	Ceratopsidae/Centrosaurinae	77.5 - 77 Ma	Alberta	Eberth, 2005; Ryan and Russell, 2005; Sampson and Loewen, 2010; Ryan *et al.* , 2012b; Sampson *et al.* , 2013
Diabloceratops eatoni	Ceratopsidae/Centrosaurinae	80 - 79.5 Ma	South Utah	Kirkland and DeBlieux, 2010; Sampson *et al.* , 2013
Einiosaurus procurvicornis	Ceratopsidae/Centrosaurinae	74.5 - 74.2 Ma	Montana	Sampson, 1995; Sampson and Loewen, 2010; Sampson *et al.* , 2013
Eotriceratops xerinsularis	Ceratopsidae/Chasmosaurinae/Triceratopsini	68 - 67.7 Ma	Alberta	Wu *et al.* , 2007; Sampson *et al.* , 2010; Brown and Henderson, 2015
Graciliceratops mongoliensis	Neoceratopsia	83 - 81 Ma	Gansu Province (China) and Mongolia	Sereno, 2000
Gryphoceratops morrisoni	Leptoceratopsidae	83.4 - 83.2 Ma	Writing-on-Stone Provincial Park, Alberta	Ryan *et al.* , 2012a
Helioceratops brachygnathus	Neoceratopsia	Albian/Cenomanian (106 - 96 Ma)?	Jilin Province, China	Jin *et al.* , 2009; Jin *et al.* , 2010; Ryan *et al.* , 2012a
Hongshanosaurus houi	Psittacosauridae	Barremian (ca. 127-125 Ma)	Liaoning Province, China	You *et al.* , 2003; You and Xu, 2005; Xu and Norell, 2006; Sun *et al.* , 2011
Hualianceratops wucaiwanensis	Ceratopsia	162 . 159 Ma	Junggar Basin, Xinjiang, China	Han et al., 2015
Koreaceratops hwaseongensis	Neoceratopsia	103.5 - 102.5 Ma	Tando Basin, mid-west Korea	Lee *et al.* , 2011
Kosmoceratops richardsoni	Ceratopsidae/Chasmosaurinae	76.4 - 75.8 Ma	South Utah	Sampson *et al.* , 2010; Brown and Henderson, 2015
Leptoceratops gracilis	Leptoceratopsidae	67 - 66 Ma	Alberta, Wyoming and Montana	Ott, 2007; Sampson and Loewen, 2010; Ryan *et al.* , 2012a
Liaoceratops yanzigouensis	Neoceratopsia	Valanginian/Hauterivian (133-129 Ma)	western Liaoning Province, China	Xu and Norell, 2006; You *et al.* , 2007; Sun *et al.* , 2011
Magnirostris dodsoni	Protoceratopsidae	75.5-70.5 Ma	Bayan Mandahu, Inner Mongolia, China	You and Dong, 2003; Sampson *et al.* , 2013

Mojoceratops perifania	Ceratopsidae/Chasmosaurinae	76.5 - 75.5 Ma	Alberta, Saskatchewan	Longrich, 2010; Sampson *et al.* , 2010; Brown and Henderson, 2015
Montanoceratops cerorhynchus	Leptoceratopsidae	Early Maastrichtian (69 - 68 Ma)	Montana	Chinnery and Weishampel, 1998; Makovicky, 2010; Ryan *et al.* , 2012a
Mosaiceratops azumai	Neoceratopsia	lower-middle Turonian–middle Campanian	Henan Province, China	Zheng et al., 2015
Nasutoceratops titusi	Ceratopsidae/Centrosaurinae	75.9 - 75.5 Ma	South Utah	Roberts et al., 2005; Roberts, 2007; Lund, 2010; Sampson *et al.* , 2013
Nedoceratops hatcheri	Ceratopsidae/Chasmosaurinae/Triceratopsini	Late Maastrichtian (ca. 67.5 - 66 Ma)	eastern Wyoming	Sampson *et al.* , 2010; Farke, 2011; Brown and Henderson, 2015
Ojoceratops fowleri	Ceratopsidae/Chasmosaurinae/Triceratopsini	68 - 66.5 Ma	San Juan Basin, New Mexico	Sullivan and Lucas, 2010; Sampson *et al.* , 2010; Brown and Henderson, 2015
Pachyrhinosaurus canadensis	Ceratopsidae/Centrosaurinae	72- 68.2 Ma	Alberta	Sampson and Loewen, 2010; Fiorillo and Tykoski, 2012; Sampson *et al.* , 2013
Pachyrhinosaurus lakustai	Ceratopsidae/Centrosaurinae	73.5 - 73 Ma	Grand Prairie, Alberta	Currie *et al.* , 2008; Sampson and Loewen, 2010; Fiorillo and Tykoski, 2012; Sampson *et al.* , 2013
Pachyrhinosaurus perotorum	Ceratopsidae/Centrosaurinae	70 - 69 Ma	Alaska	Fiorillo and Tykoski, 2012
Pentaceratops sternbergi	Ceratopsidae/Chasmosaurinae	74.5 - 73.5 Ma	Colorado and New Mexico	Sampson *et al.* , 2010, 2013; Brown and Henderson, 2015
Prenoceratops pieganensis	Leptoceratopsidae	78 - 77 Ma	?Alberta and Montana	Chinnery, 2004; Ryan *et al.* , 2012a
Protoceratops andrewsi	Protoceratopsidae	75 - 70.5 Ma	Gobi desert, Mongolia and China	Sampson and Loewen, 2010; Sampson *et al.* , 2013
Protoceratops hellenikorhinus	Protoceratopsidae	75-70.5 Ma	Inner Mongolia, China	Lambert *et al.* , 2001; Sampson and Loewen, 2010; Sampson *et al.* , 2013
Psittacosaurus gobiensis	Psittacosauridae	Aptian (ca. 115 Ma)	Inner Mongolia, China	Sereno *et al.* , 2010
Psittacosaurus lujiatunensis	Psittacosauridae	Hauterivian (132 - 129 Ma)	Liaoning Province, China	Zhou *et al.* , 2006; Sun *et al.* , 2011
Psittacosaurus major	Psittacosauridae	Hauterivian/Barremian (ca. 132-126 Ma)	Liaoning Province, China	Sereno *et al.* , 2007; Sereno, 2010; Sun *et al.* , 2011
Psittacosaurus meileyingensis	Psittacosauridae	120 - 117 Ma	Liaoning Province, China	Sereno *et al.* , 1988; Lucas, 2006; Sereno, 2010
Psittacosaurus mongoliensis	Psittacosauridae	125 - 105 Ma	Mongolia and China	Lucas, 2006

Psittacosaurus neimongoliensis	Psittacosauridae	Aptian (120 - 117 Ma)	Inner Mongolia, China	Russell and Zhao, 1996; PbDb; Lucas, 2006; Sereno, 2010
Psittacosaurus sibiricus	Psittacosauridae	Aptian/Albian (114 - 111 Ma)	Kemerovo Province, Russia	Averianov *et al.* , 2006; Lucas, 2006; Sereno, 2010
Psittacosaurus sinensis	Psittacosauridae	Aptian/Albian (118 - 111 Ma)	Shandong Province and Inner Mongolia, China	Lucas, 2006; Sereno, 2010
Psittacosaurus xinjiangensis	Psittacosauridae	121 - 117 Ma	Junggar Basin, Xinjiang region, China	Sereno and Chao, 1988; PbDb; Lucas, 2006; Sereno, 2010
Regaliceratops peterhewsi	Ceratopsidae/Chasmosaurinae/Triceratopsini	68 - 67.3 Ma	South Alberta	Brown and Henderson, 2015
Rubeosaurus ovatus	Ceratopsidae/Centrosaurinae	74.5 - 74.3 Ma	Montana	Sampson and Loewen, 2010; McDonald, 2011; Sampson *et al.* , 2013
Sinoceratops zhuchengensis	Ceratopsidae/Centrosaurinae	Campanian (76 - 68 Ma)	Shandong Province, China	Xu *et al.* , 2010b; Hone *et al.* , 2011; Sampson *et al.* , 2013
Spinops sternbergorum	Ceratopsidae/Centrosaurinae	78 - 77 Ma	Dinosaur Provincial Park (DPP), Alberta	Eberth, 2005; Farke *et al.* , 2011; Sampson *et al.* , 2013
Styracosaurus albertensis	Ceratopsidae/Centrosaurinae	76 - 75.5 Ma	DPP, Alberta	Eberth, 2005; Ryan and Evans, 2005; Ryan *et al.* , 2007; Sampson and Loewen, 2010; Sampson *et al.* , 2013
Torosaurus latus	Ceratopsidae/Chasmosaurinae/Triceratopsini	67.5 - 66 Ma	Montana, South and North Dakota, Colorado, Wyoming	Sampson and Loewen, 2010; Sampson *et al.* , 2010; Brown and Henderson, 2015
Torosaurus utahensis	Ceratopsidae/Chasmosaurinae/Triceratopsini	67.5 - 66 Ma	Utah and Texas	Sampson and Loewen, 2010; Sampson *et al.* , 2010; Brown and Henderson, 2015
Triceratops horridus	Ceratopsidae/Chasmosaurinae/Triceratopsini	67.5 - 66 Ma	Alberta, Montana, Wyoming, North Dakota and Colorado	Sampson and Loewen, 2010; Sampson *et al.* , 2010; Brown and Henderson, 2015
Triceratops prorsus	Ceratopsidae/Chasmosaurinae/Triceratopsini	67.5 - 66 Ma	Saskatchewan, Montana, North and South Dakota, Wyoming	Sampson and Loewen, 2010; Sampson *et al.* , 2010; Brown and Henderson, 2015
Turanoceratops tardabilis	Ceratopsoidea	91.5 - 90 Ma	Uzbekistan	Sues and Averianov, 2009
Udanoceratops tschizhovi	Leptoceratopsidae	77 - 72.1 Ma	Mongolia	Kurzanov, 1992; Gao and Norell, 2000; Dashzeveg *et al.* , 2005
Unescoceratops koppelhusae	Leptoceratopsidae	75.4 - 75.2 Ma	DPP, Alberta	Eberth, 2005; Ryan *et al.* , 2012a
Utahceratops gettyi	Ceratopsidae/Chasmosaurinae	76.3 - 75.7 Ma	South Utah	Sampson *et al.* , 2010; Brown and Henderson, 2015
Vagaceratops irvinensis	Ceratopsidae/Chasmosaurinae	75.7 - 75.5 Ma	DPP, Alberta	Sampson *et al.* , 2010; Brown and Henderson, 2015

Wendiceratops pinhornensis	Ceratopsidae/Centrosaurinae	79 - 78.7 Ma	South Alberta	Evans and Ryan, 2015
Xenoceratops foremostensis	Ceratopsidae/Centrosaurinae	79.5 - 79 Ma	South Alberta	Eberth, 2005; Ryan *et al.* , 2012a; Sampson *et al.* , 2013
Xuanhuaceratops niei	Chaoyangsauridae	145 - 140 Ma	Xuanhua Area, Hebei Province, China	Swisher *et al.* , 2002; Makovicky and Norell, 2006; Zhao *et al.* , 2006
Yamaceratops dorngobiensis	Neoceratopsia	ca. 128 Ma	Dorngobi Aimag, Mongolia	Makovicky and Norell, 2006
Yinlong downsi	Ceratopsia	163 - 157.3 Ma	Junggar Basin, Xinjiang, China	Xu *et al.* , 2006
Zhuchengceratops inexpectus	Leptoceratopsidae	80 - 77 Ma	Shandong Province, China	Prieto-Marquez, 2010; Xu *et al.* , 2010a
Zuniceratops christopheri	Ceratopsoidea	91 - 90 Ma	New Mexico	Wolfe and Kirkland, 1998; Wolfe *et al.* , 2010; Sampson *et al.* , 2013; Brown and Henderson, 2015

***PbDb =** Paleobiology Database (http://fossilworks.org/bridge.pl?)

Table S5. Age and References for Phylogenetic Positions and Stratigraphic Ranges of Nodes and OTUs on the Tree depicted in Figure 3.

NODE NUMBER	PHYLOGENY Age of nodes (Ma)	PHYLOGENY REFERENCES	TAXONOMY CLASSIFICATION	Terminal taxa from node number (INCLUDING SPECIES and higher ranks). NA when no terminal taxa descend from the node
1	163	Xu *et al.* , 2006	CERATOPSIA	Origin of Ceratopsia
2	162.5	Han *et al.* , 2015	CERATOPSIA	*Yinlong downsi-Hualicanceratops wuacaiwanensis*
3	157	Xu *et al.,* 2006; Han et al., 2015;	CERATOPSIA	NA
4	152.5	Zhao *et al.* , 1999; Xu *et al.* , 2006; Zhao *et al.* , 2006; Ryan *et al.* , 2012a; Han et al., 2015;	CHAOYANGSAURIDAE	*Chaoyangsaurus youngi -Xuanhuaceratops niei*
5	140	Xu *et al.* , 2006; Sereno *et al.* , 2010	PSITTACOSAURIDAE-NEOCERATOPSIA	NA
6	139	You *et al.,* 2003; You and Xu, 2005; Tanoue *et al.* , 2009; Sun *et al.* , 2011	PSITTACOSAURIDAE	*Hongshanosaurus houi*
7	138.5	Lucas, 2006; Sereno, 2010; Sun *et al.* , 2011	PSITTACOSAURIDAE	*Psittacosaurus mongoliensis*
8	138	Lucas, 2006; Sereno, 2010; Sun *et al.* , 2011	PSITTACOSAURIDAE	*Psittacosaurus meileyingensis*
9	137.5	Lucas, 2006; Sereno, 2010; Sun *et al.* , 2011	PSITTACOSAURIDAE	NA
10	136	Lucas, 2006; Sereno, 2010; Sun *et al.* , 2011	PSITTACOSAURIDAE	*Psittacosaurus lujiatunensis-Psittacosaurus major*
11	136	Lucas, 2006; Sereno, 2010; Sun *et al.* , 2011	PSITTACOSAURIDAE	NA
12	135	Sereno and Chao, 1988; Lucas, 2006; Sereno, 2010; Sun *et al.* , 2011	PSITTACOSAURIDAE	*P.sinensis-P.neimongoliensis-P. xinjiangensis*
13	133	Zheng et al., 2015	NEOCERATOPSIA	*Mosaiceratops azumai*
14	132	Xu *et al.* , 2002, 2006; Sun *et al.* , 2011	NEOCERATOPSIA	*Liaoceratops yanzigouensis*
15	131	Farke *et al.* , 2014	NEOCERATOPSIA	*Aquilops americanus*
16	130	Makovicky and Norell, 2006; Ryan *et al.* , 2012a; Farke *et al.* , 2014	NEOCERATOPSIA	NA
17	127	You *et al.* , 2005; Farke *et al.* , 2014	NEOCERATOPSIA	*Yamaceratops dorngobiensis-Auroraceratops rugosus*
18	128	Ryan *et al.* , 2012a; Farke *et al.* , 2014	NEOCERATOPSIA	NA
19	127	Jin *et al.* , 2009; Farke *et al.* , 2014	NEOCERATOPSIA	*Archaeoceratops* spp.-*Helioceratops brachygnathus*
20	125.5	Tang *et al.* , 2001; You and Dodson, 2003; You *et al.* , 2010; Farke *et al.* , 2014	NEOCERATOPSIA	*Archaeoceratops oshimai-Archaeoceratops yujingziensis*

21	118	Lee *et al.* , 2011; Ryan *et al.* , 2012a; Farke *et al.* , 2014	NEOCERATOPSIA	*Koreaceratops hwaseongensis*
22	105	Ryan *et al.* , 2012a; Farke *et al.* , 2014	LEPTOCERATOPSIDAE	NA
23	101	Nessov *et al.* , 1989; Nessov, 1995; Ryan *et al.* , 2012a; Farke *et al.* , 2014	LEPTOCERATOPSIDAE	*Asiaceratops salsopaludalis*
24	100	Nessov *et al.* , 1989; Nessov, 1995; Chinnery and Horner, 2007; Ryan *et al.* , 2012a; Farke *et al.* , 2014	LEPTOCERATOPSIDAE	*Cerasinops hodgskissi*
25	99	Nessov *et al.* , 1989; Nessov, 1995; Chinnery and Weishampel, 1998; Ryan *et al.* , 2012a; Farke *et al.* , 2014	LEPTOCERATOPSIDAE	*Montanoceratops cerorhynchus*
26	98	Nessov *et al.* , 1989; Nessov, 1995; Chinnery, 2004; Ryan *et al.* , 2012a; Farke *et al.* , 2014	LEPTOCERATOPSIDAE	*Prenoceratops pieganensis*
27	97	Nessov *et al.* , 1989; Nessov, 1995; Ryan *et al.* , 2012a; Farke *et al.* , 2014	LEPTOCERATOPSIDAE	NA
28	96	Nessov *et al.* , 1989; Nessov, 1995; Hone *et al.* , 2011; Ryan *et al.* , 2012a; Farke *et al.* , 2014	LEPTOCERATOPSIDAE	*Udanoceratops tschizhovi-Leptoceratops gracilis*
29	96	Nessov *et al.* , 1989; Nessov, 1995; Gao and Norell, 2000; Dashzeveg *et al.* , 2005; Xu *et al.* , 2010a; Ryan *et al.* , 2012a; Farke *et al.* , 2014	LEPTOCERATOPSIDAE	*Zhuchengceratops inexpectus*
30	95	Nessov *et al.* , 1989; Nessov, 1995; Ryan *et al.* , 2012a; Farke *et al.* , 2014	LEPTOCERATOPSIDAE	*Unescoceratops koppelhusae-Gryphoceratops morrisoni*
31	100	Sereno, 2000; Ryan *et al.* , 2012a; Farke *et al.* , 2014	NEOCERATOPSIA	*Graciliceratops mongoliensis*
32	96.5	Sampson and Loewen, 2010; Ryan *et al.* , 2012a; Farke *et al.* , 2014	CORONOSAURIA	NA
33	90	Lambert *et al.* , 2001; Sampson and Loewen, 2010; Ösi *et al.* , 2010; Ryan *et al.* , 2012a; Farke *et al.* , 2014	PROTOCERATOPSIDAE	NA
34	87	Ösi *et al.* , 2010; Ryan *et al.* , 2012a; Farke *et al.* , 2014	PROTOCERATOPSIDAE	*Ajkaceratops kozmai*
35	77	Ryan *et al.* , 2012a; Sampson *et al.* , 2013; Farke *et al.* , 2014	PROTOCERATOPSIDAE	*Bagaceratops rozhdestvenskyi-Magnirostris dodsoni*
36	78	Lambert *et al.* , 2001; Sampson and Loewen, 2010; Ryan *et al.* , 2012a; Sampson *et al.* , 2013; Farke *et al.* . 2014	PROTOCERATOPSIDAE	*Protoceratops andrewsi-Protoceratops hellenikorhinus*

37	92.5	Wolfe and Kirkland, 1998; Wolfe *et al.* , 2010; Ryan *et al.* , 2012a; Farke *et al.* , 2014	CERATOPSOIDEA	*Zuniceratops christopheri*
38	92	Sues and Averianov, 2009; Ryan *et al.* , 2012a; Farke *et al.* , 2014	CERATOPSOIDEA	*Turanoceratops tardabilis*
39	83	Kirkland and DeBlieux, 2010; Xu *et al.* , 2010b; Sampson *et al.* , 2010, 2013; Fiorillo and Tykoski, 2012; Hone *et al.* , 2011	CERATOPSIDAE	NA
40	82	Kirkland and DeBlieux, 2010; Sampson and Loewen, 2010; Farke *et al.* , 2011; Fiorillo and Tykoski, 2012; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	*Diabloceratops eatoni*
41	81.5	Sampson and Loewen, 2010; Farke *et al.* , 2011; Fiorillo and Tykoski, 2012; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	NA
42	79	Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	*Nasutoceratops titusi-Avaceratops lammersi*
43	81	Ryan, 2007; Sampson and Loewen, 2010; Farke *et al.* , 2011; Fiorillo and Tykoski, 2012; Ryan *et al.* , 2012b; Sampson *et al.* , 2013; Evans and Ryan, 2015	CERATOPSIDAE-Centrosaurinae	*Xenoceratops foremostensis*
44	80.5	Sampson and Loewen, 2010; Farke *et al.* , 2011; Fiorillo and Tykoski, 2012; Ryan *et al.* , 2012b; Sampson *et al.* , 2013; Evans and Ryan, 2015	CERATOPSIDAE-Centrosaurinae	*Albertaceratops nesmoi* + NA
45	80	Sampson and Loewen, 2010; Farke *et al.* , 2011; Fiorillo and Tykoski, 2012; Ryan *et al.* , 2012b; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	NA
46	75	Sampson and Loewen, 2010; Farke *et al.* , 2011; Fiorillo and Tykoski, 2012; Ryan *et al.* , 2012b; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	*Einiosaurus procurvicornis*
47	74.5	Sampson and Loewen, 2010; Farke *et al.* , 2011; Fiorillo and Tykoski, 2012; Ryan *et al.* , 2012b; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	*Achelousaurus horneri*
48	74	Fiorillo and Tykoski, 2012; Ryan *et al.* , 2012b; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	*Pachyrhinosaurus canadensis*
49	73.5	Fiorillo and Tykoski, 2012; Ryan *et al.* , 2012b; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	*Pachyrhinosaurus lakustai-Pachyrhinosaurus perotorum*
50	79.5	Sampson and Loewen, 2010; Farke *et al.* , 2011; Fiorillo and Tykoski, 2012; Ryan *et al.* , 2012b; Sampson *et al.* , 2013; Evans and Ryan, 2015	CERATOPSIDAE-Centrosaurinae	*Wendiceratops pinhornensis-Sinoceratops zhuchengensis*

51	79.5	Ryan *et al.* , 2012b; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	NA
52	76.2	Ryan *et al.* , 2007; McDonald, 2011; Farke *et al.* , 2011; Fiorillo and Tykoski, 2012; Ryan *et al.* , 2012b; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	*Rubeosaurus ovatus-Styracosaurus albertensis*
53	79	Farke *et al.* , 2011; Ryan *et al.* , 2012b; Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	*Spinops sternbergorum*
54	78	Sampson *et al.* , 2013	CERATOPSIDAE-Centrosaurinae	*Centrosaurus apertus-Coronosaurus brinkmani*
55	80	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	Chasmosaurinae
56	77	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	*Kosmoceratops richardsoni-Vagaceratops irvinensis*
57	79.5	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	NA
58	79	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	NA
59	73.2	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	*Bravoceratops polyphemus-Coahuilaceratops magnacuerna*
60	78.5	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	NA
61	76.8	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	*Utahceratops gettyi-Pentaceratops sternbergi*
62	78	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	*Agujaceratops mariscalensis*
63	77.6	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	*Mojoceratops perifania*
64	77.3	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	*Chasmosaurus belli-Chasmosaurus russelli*

65	76	Longrich, 2010; Sampson *et al.,* 2010; Longrich, 2011; Mallon *et al.* , 2011; Wick and Lehman, 2013	CERATOPSIDAE-Chasmosaurinae	NA
66	72.3	Longrich, 2010; Sampson *et al.* , 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	*Arrhinoceratops brachyops-Anchiceratops ornatus*
67	73	Longrich, 2010; Sampson *et al.* , 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	*Ojoceratops fowleri-Eotriceratops xerinsularis-Regaliceratops peterhewsi*
68	69	Longrich, 2010; Sampson *et al.* , 2010; Longrich, 2011; Wick and Lehman, 2013; Brown and Henderson, 2015	CERATOPSIDAE-Chasmosaurinae	*Nedoceratops hatcheri*
69	68.5	Longrich, 2010; Sampson *et al.* , 2010; Longrich, 2011; Wick and Lehman, 2013	CERATOPSIDAE-Chasmosaurinae	NA
70	68	Longrich, 2010; Sampson *et al.* , 2010; Longrich, 2011; Wick and Lehman, 2013	CERATOPSIDAE-Chasmosaurinae	*Triceratops prorsus-Triceratops horridus*
71	68	Longrich, 2010; Sampson *et al.* , 2010; Longrich, 2011; Wick and Lehman, 2013	CERATOPSIDAE-Chasmosaurinae	*Torosaurus latus-Torosaurus utahensis*

Results of analyses performed on skulls without frill and frills alone

Geometric morphometrics

Skull with the frill excluded: shape variation within Ceratopsia – The first 13 principal components of PCA, performed on the skulls without the frill (in lateral view), explain collectively 95% of total shape variance. Figure S5A shows the relationship between PC1 (38.70% of the total shape variance) and PC2 (23.47% of the total shape variance) and Figure S5B between PC1 and PC3 (7.48% of the total shape variation). Positive PC1 values are associated with a chasmosaurine-like skull bearing a nasal horn, small orbit, long circumnarial region, long maxilla and premaxilla, ventral tip of the quadrate located slightly forward respect of the jugal tip, and a rostral tip of the supratemporal fenestra located backward with respect to the quadrate. Negative PC1 values are associated with a short and deep skull having a large orbit, short premaxilla and long maxilla, ventral tip of the quadrate shifted backward with respect to the jugal tip, and a rostral tip of the supratemporal fenestra shifted forward with respect to the quadrate. This morphology is psittacosaurid-like. At negative PC2 values the skull is short and deep, having a short premaxilla and maxilla, large orbit, absence of a nasal horn, rostral tip of the supratemporal fenestra located above the quadrate, and the ventral tip of the quadrate located behind the jugal tip, whereas at positive PC2 values the skull is long. It bears a nasal horn, long maxilla and short premaxilla, a ventral tip of the quadrate shifted forward respect of the jugal tip and a rostral tip of the supratemporal fenestra located above the quadrate.

Negative PC3 values are associated with a short and deep skull bearing a nasal horn, short premaxilla and long maxilla, ventral tip of the quadrate shifted forward with respect to the jugal tip and a rostral tip of the supratemporal fenestra located above the quadrate. Positive PC3 values are associated with a low and slender skull having a short premaxilla and long maxilla, large orbit, rostral tip of the supratemporal fenestra located above the quadrate and a ventral tip of the quadrate located slightly behind the jugal tip

In summary, ceratopsids vary mainly along positive PC1 values and, in particular, centrosaurines vary mainly along negative PC3 values, whereas chasmosaurines vary along positive PC3 values. Basal centrosaurine such as *Diabloceratops eatoni* appears separated from others at small negative PC3 values and small positive PC1 values, while other centrosaurines cluster together in the morphospace. Triceratopsin morphospace partially overlaps non-triceratopsin chasmosaurine morphospace at positive PC1 and PC3 values, indicating a no clear morphological separation among each other. Leptoceratopsids, protoceratopsids and some basal ceratopsian taxa such as *Yinlong*, *Aquilops*, *Auroraceratops*, *Archaeoceratops* and *Liaoceratops* vary mainly along negative PC1 and PC2 values, while psittacosaurids are located in a distinct morphospace at negative PC1 and positive PC2 values. Figure S6 shows the 3D relationship between PC1, PC2 and PC3.

Frill shape variation within Ceratopsia – The first 6 principal components of PCA, performed on the frills in lateral view, explain collectively 95% of total shape variance. Figure S7A shows the relationship between PC1 (64.09% of the total shape variance) and PC2 (14.90% of the total shape variance) and Figure S7B between PC1 and PC3 (8.51% of the total shape variation). At positive PC1 values, the frill is incipient, with a large infratemporal fenestra and a short squamosal. This morphology is typical of psittacosaurids. At negative PC1 values the frill is dorso-caudally elongated, with a long and triangular squamosal and a small infratemporal fenestra. This morphology is typical of chasmosaurines. Negative PC2 values are associated with a caudally expanded frill, having a small infratemporal fenestra and a short squamosal, whereas positive PC2 values are associated with a centrosaurine-like frill that is moderately dorso-caudally expanded, with a larger infratemporal fenestra and a longer and sub-rectangular squamosal. At positive PC3 values the frill is elongated caudally, with a caudally elongated and sub-rectangular squamosal, and a small infratemporal fenestra. At negative PC3 values the frill is elongated dorso-caudally, with a larger infratemporal fenestra and a squared squamosal.

In summary, ceratopsids vary mainly along negative PC1 values. Within ceratopsids, centrosaurines vary mainly along positive PC2 values, whereas chasmosaurines vary along negative PC1 and PC2 values. Within Chasmosaurinae, Triceratopsins appear morphological separated from non-triceratopsin chasmosaurines at positive PC3 values. By contrast, all centrosaurine taxa cluster together indicating a similar frill morphology. *Zuniceratops* lies close to centrosaurine morphospace. Psittacosaurids cluster at extreme positive PC1 values together with *Yinlong downsi*, indicating a similar frill shape. Protoceratopsids vary mainly along positive PC1 and negative PC3 values. Frill shape of *Bagaceratops* resembles that of basal neoceratopsians. Leptoceratopsids and basal neoceratopsians vary along positive PC1 values. Basal ceratopsians lie close to the psittacosaurid morphospace, indicating a similar morphology between these taxa. Figure S8 shows the 3D relationship between PC1, PC2 and PC3.

Allometric shape variation

Figure S9 shows the relationship between the facial portion of the skull shape and size (CS). At high CS values the snout is chasmosaurine-like, having a long facial portion with a long premaxilla, a small orbit, nasal horn, a ventral tip of the quadrate located ahead of the jugal tip and a rostral tip of the supratemporal fenestra placed behind the quadrate. At low CS values the skull is psittacosaurid-like, having a short and deep snout with a short premaxilla, no nasal horn, a large orbit, a ventral tip of the quadrate located behind the jugal tip and a rostral tip of the supratemporal fenestra shifted ahead of the quadrate.

Figure S10 shows the frill shape changes associated with CS values. At high CS values the frill is dorso-caudally expanded with a triangular squamosal, a small infratemporal fenestra and a rostral tip of the supratemporal fenestra located ahead of the infratemporal fenestra. This morphological arrangement is chasmosaurine-like. At low CS values the frill is incipient with a short squamosal, a large infratemporal fenestra and a rostral tip of the supratemporal fenestra located highly ahead of the infratemporal fenestra. This morphological arrangement is typical of psittacosaurids.

Morphological covariation

Figure S11 shows the morphological covariation between the skulls without frill and lower jaws, according to the Partial Least Square analysis (PLS) performed on the pooled dataset. The first pair of singular axes (SAs) explains 55.06% of the total covariance. At negative SA1 values the skull is psittacosaurid-like, having a short and deep snout, absence of a nasal horn, short premaxilla, large orbit, all of which are associated with a lower jaw having a short and massive dentary, short coronoid process and caudally elongated angular and surangular. Positive SA1 values correspond to a ceratopsid-like skull with the frill excluded, bearing a developed nasal horn, short premaxilla and longer maxilla and ventral tip of the quadrate located slightly behind the jugal tip, associated with a lower jaw having a long and slender dentary, a dorsally developed hooked coronoid process and short angular and surangular.

Figure S12 shows the morphological covariation between the frill and the lower jaw of the pooled dataset. The first pair of singular axes (SAs) explains 72.61% of the total covariance. At positive SA1 values the frill is chasmosaurine-like and caudo-dorsally expanded. It bears an elongated and triangular squamosal, a small infratemporal fenestra and a rostral tip of the supratemporal fenestra located well forward of the infratemporal fenestra. The associated lower jaw is ceratopsid-like as well. It possesses a short angular and surangular, a dorsally elongated coronoid process and a long and slender dentary. At negative SA1 values the frill is strongly reduced, with a larger infratemporal fenestra and a rostral tip of the supratemporal fenestra located forward of the infratemporal fenestra, associated with a lower jaw having a short and massive dentary, short coronoid process, and caudally elongated angular and surangular.

Phenotypic evolutionary shifts

When exploring the evolutionary rates for shape in cranial dataset when the frill is excluded, a major phenotypic shift is identified in correspondence to Psittacosauridae along with a slowdown of the evolutionary rate. A second phenotypic rates is observable in correspondence to Ceratopsoidea, along with an acceleration of the rate. Clades such as Protoceratopsidae and Leptoceratopsidae show a moderate acceleration of the evolutionary rate (Fig. S13A). Frill shape highlights similar evolutionary rates. A deceleration of the rate characterizes psittacosaurids and a positive shift appears in correspondence to the clade Neoceratopsia (Fig. S13B).

Supplementary Figures

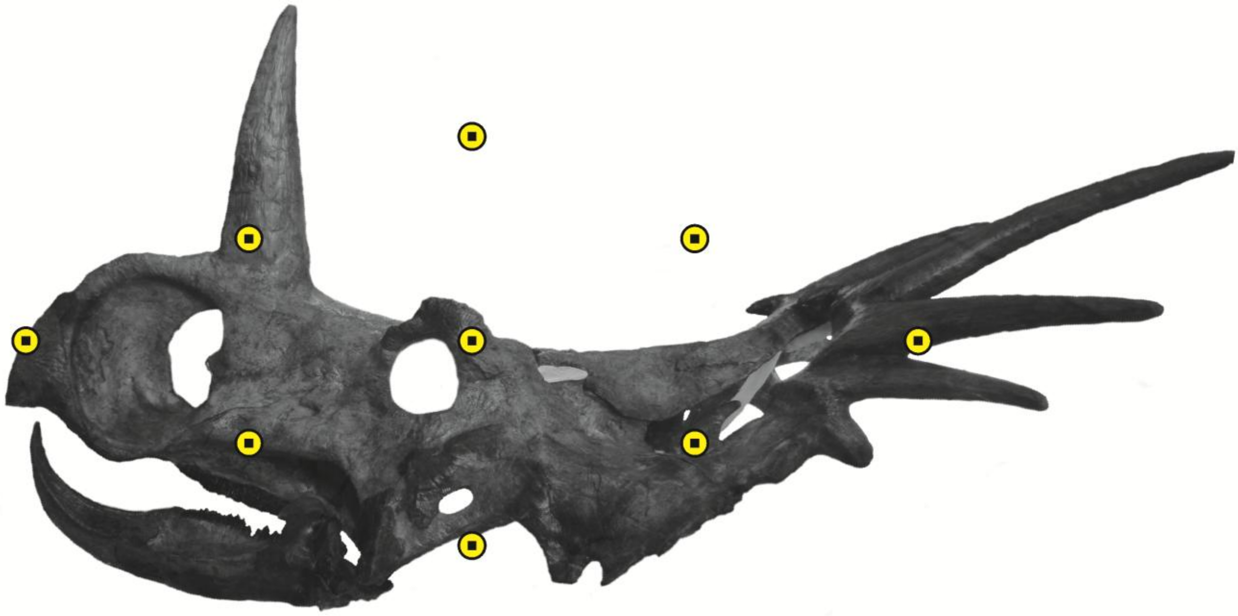

Figure S1. Rhombus distribution of focus points (yellow dots) of lens (Canon 17-85 mm f/4-5.6 IS USM) on the skull of *Styracosaurus albertensis* (AMNH 5372).

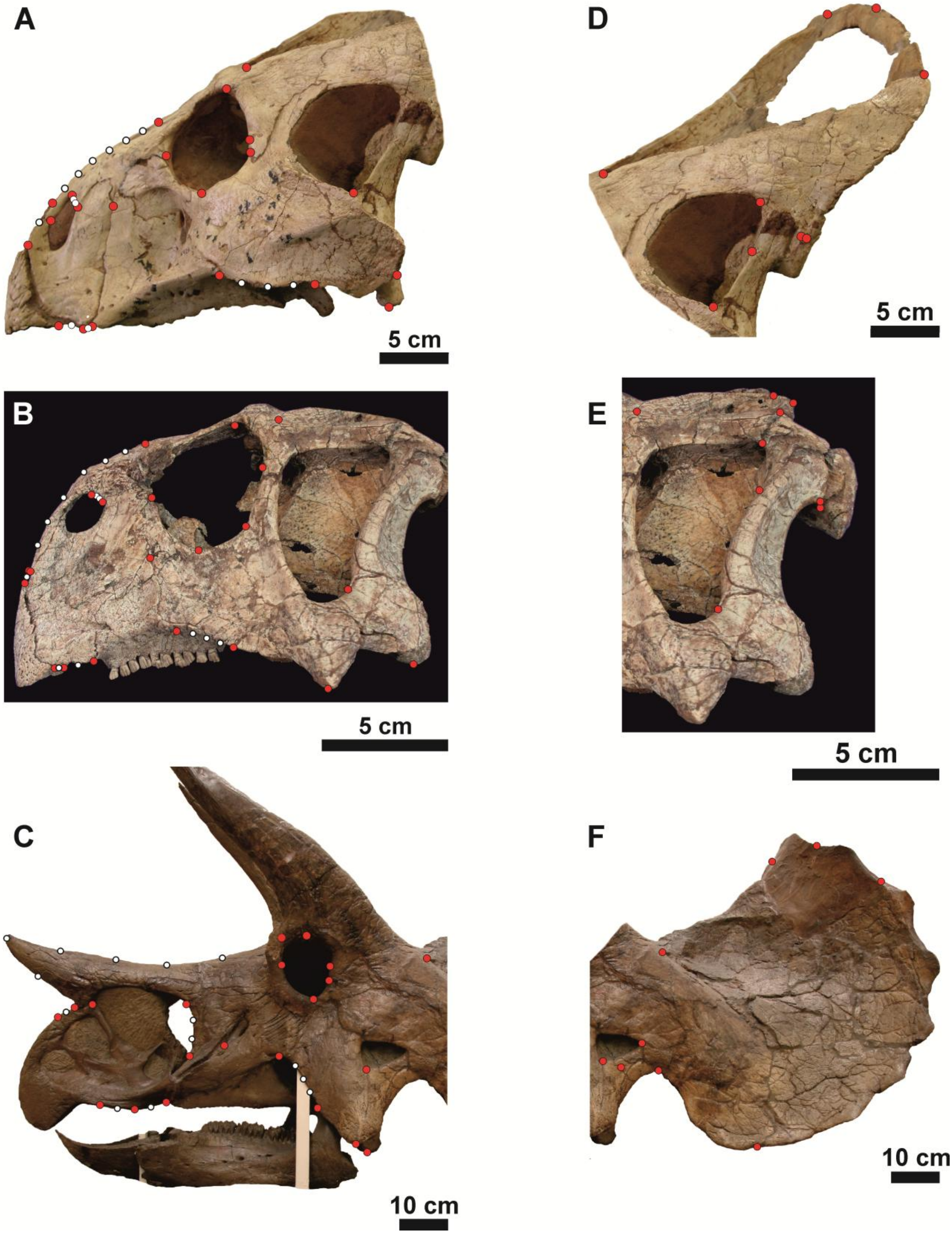

Figure S2. Subunits of skull configuration in lateral view. Landmarks have identical definitions of those found in Figure 1 (see also Table S3 in Appendix). The image of YPM 1822 (*Triceratops prorsus*) is used under the courtesy of the Peabody Museum of Natural History, Yale University, New Haven, Connecticut, U.S.A.

Figure S3. Dynamic 3D plot of Principal Component Analysis of skulls in lateral view. Hulls represent morphospaces for Triceratopsini (black); Centrosaurinae (red); non-triceratopsin Chasmosaurinae (green); Protoceratopsidae (purple) and Psittacosauridae (yellow). The light blue points represent leptoceratopsids, the grey point represents Zuniceratops, the black represents Liaoceratops, green point represents Auroraceratops, the blue represents Archaeoceratops and the red point represents Yinlong. Points dimensions are proportional to species Centroid Size.

Figure S4. Dynamic 3D plot of Principal Component Analysis of lower jaws in lateral view. Hulls represent morphospaces for Triceratopsini (green); Centrosaurinae (blue); non-triceratopsin Chasmosaurinae (red); Protoceratopsidae (grey); Leptoceratopsidae (black) and Psittacosauridae (light red). The purple point represents Zuniceratops, the black represents Chaoyangsaurus, yellow represents Liaoceratops, green point represents Auroraceratops, the light purple point represents Archaeoceratops yujingziensis, the light blue points represent Auroraceratops and Archaeoceratops oshimai, and the blue point represents Yinlong. Points dimensions are proportional to specimen Centroid Size.

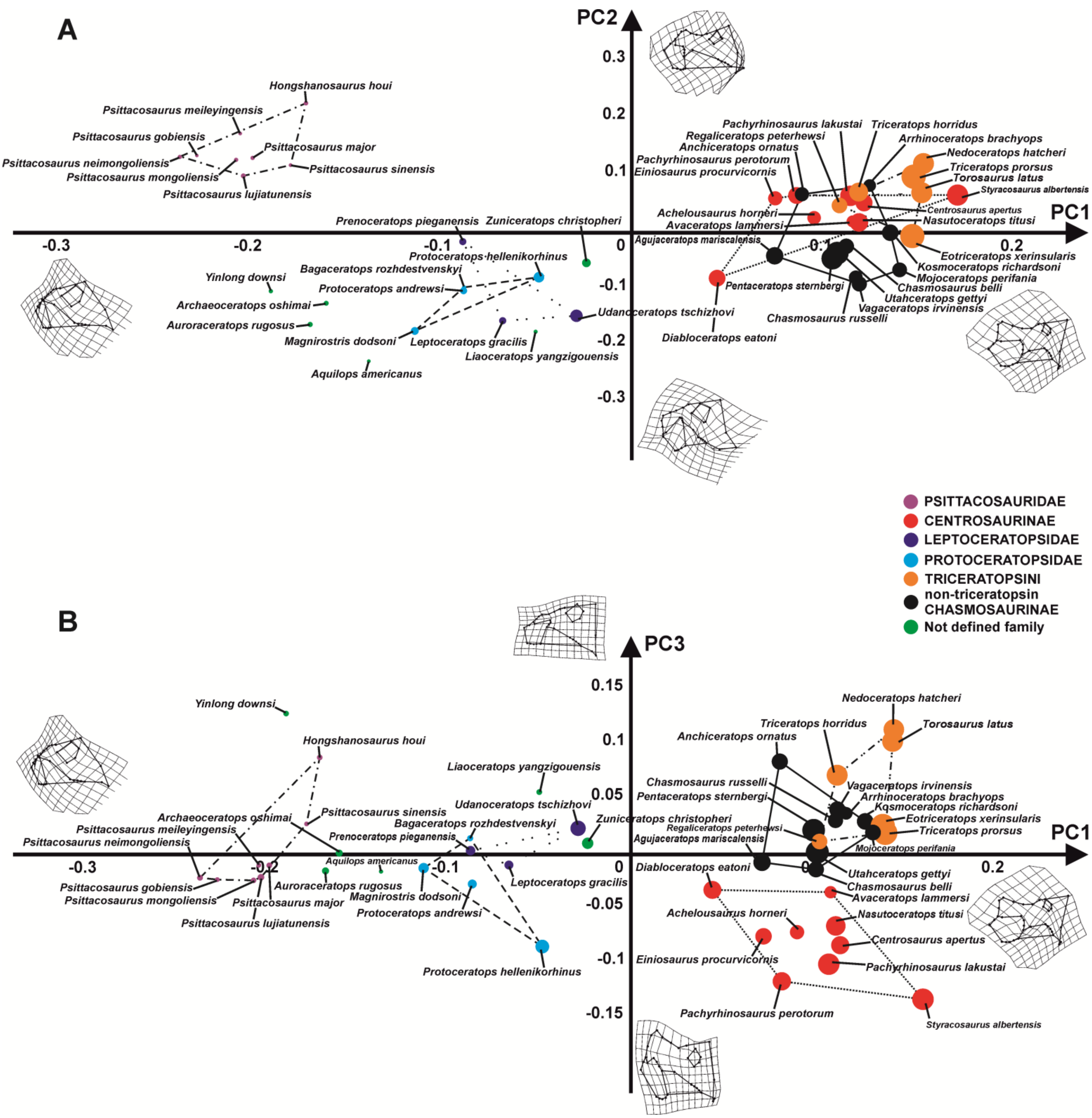

Figure S5. (**A**), Relationship between PC1 and PC2 of the cranial shape without frill. (**B**), Relationship between PC1 and PC3 of the cranial shape without frill. The continuous line represents non-triceratopsin Chasmosaurinae morphospace. The dotted line represents Centrosaurinae morphospace. The double dot-dashed line represents Triceratopsini morphospace. The dashed line represents Protoceratopsidae morphospace. The double dotted line represents Leptoceratopsidae morphospace and the dot-dashed line represents Psittacosauridae morphospace. Points dimensions are proportional to species Centroid Size.

Figure S6. Dynamic 3D plot of Principal Component Analysis of skulls without frill in lateral view. Hulls represent morphospaces for Triceratopsini (green); Centrosaurinae (red); non-triceratopsin Chasmosaurinae (black); Protoceratopsidae (purple); Leptoceratopsidae (light blue) and Psittacosauridae (yellow). The grey point represents Zuniceratops, the black represents Liaoceratops, the small blue point represents Aquilops, green point represents Auroraceratops, the large blue represents Archaeoceratops and the red point represents Yinlong. Points dimensions are proportional to specimen Centroid Size.

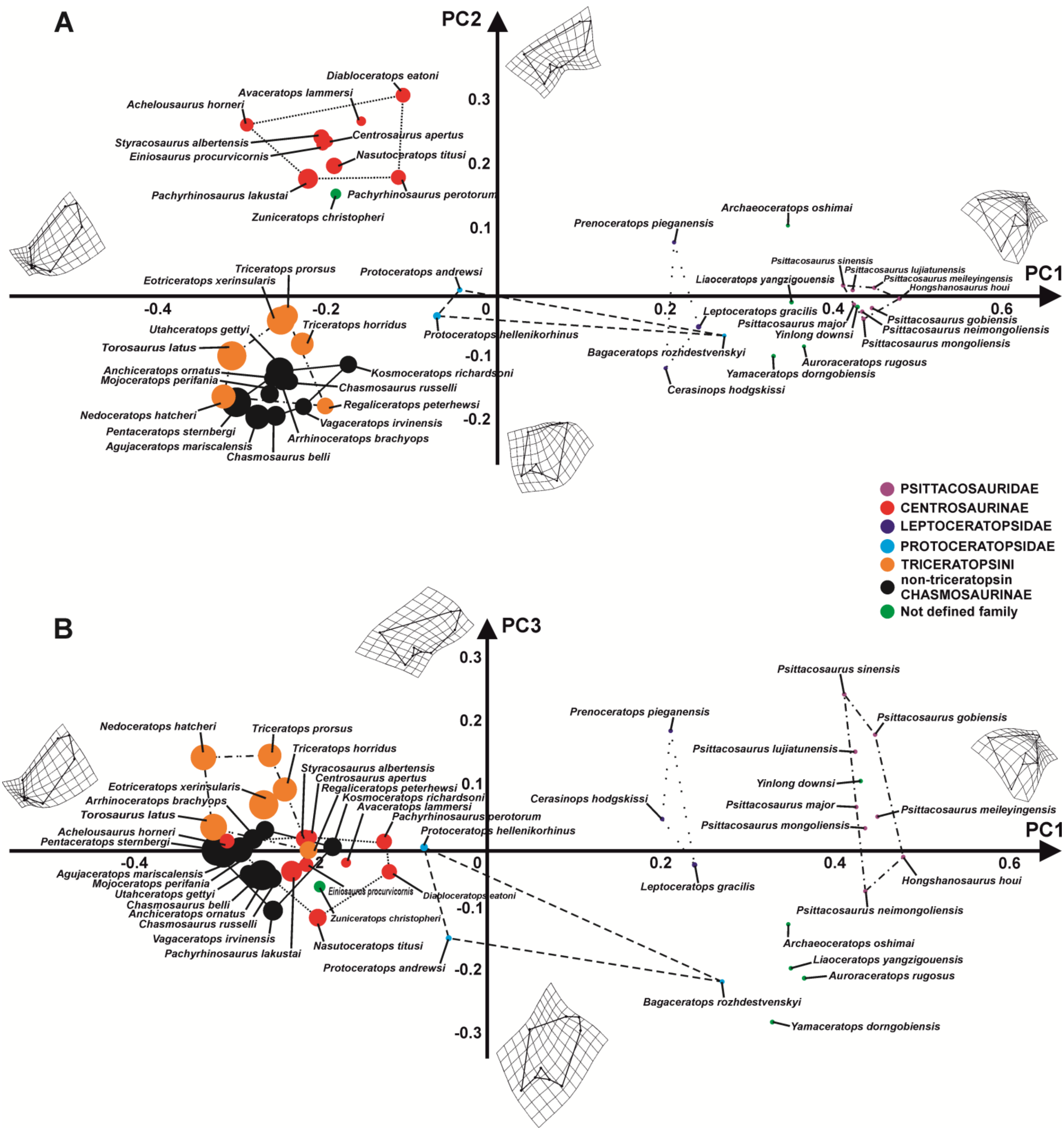

Figure S7. (**A**), Relationship between PC1 and PC2 of the frill shape. (**B**), Relationship between PC1 and PC3 of the frill shape. The dotted line represents Centrosaurinae morphospace. The continuous line represents non-triceratopsin Chasmosaurinae morphospace. The double dot-dashed line represents Triceratopsini morphospace. The dashed line represents Protoceratopsidae morphospace. The double dotted line represents Leptoceratopsidae morphospace and the dot-dashed line represents Psittacosauridae morphospace. Points dimensions are proportional to species Centroid Size.

Figure S8. Dynamic 3D plot of Principal Component Analysis of frills in lateral view. Hulls represent morphospaces for Triceratopsini (green); Centrosaurinae (red); non-triceratopsin Chasmosaurinae (black); Protoceratopsidae (purple); Leptoceratopsidae (light blue) and Psittacosauridae (yellow). The grey point represents Zuniceratops, the black represents Liaoceratops, green point represents Auroraceratops, the large blue represents Archaeoceratops, the small blue point represents Yamaceratops and the red point represents Yinlong. Points dimensions are proportional to specimen Centroid Size.

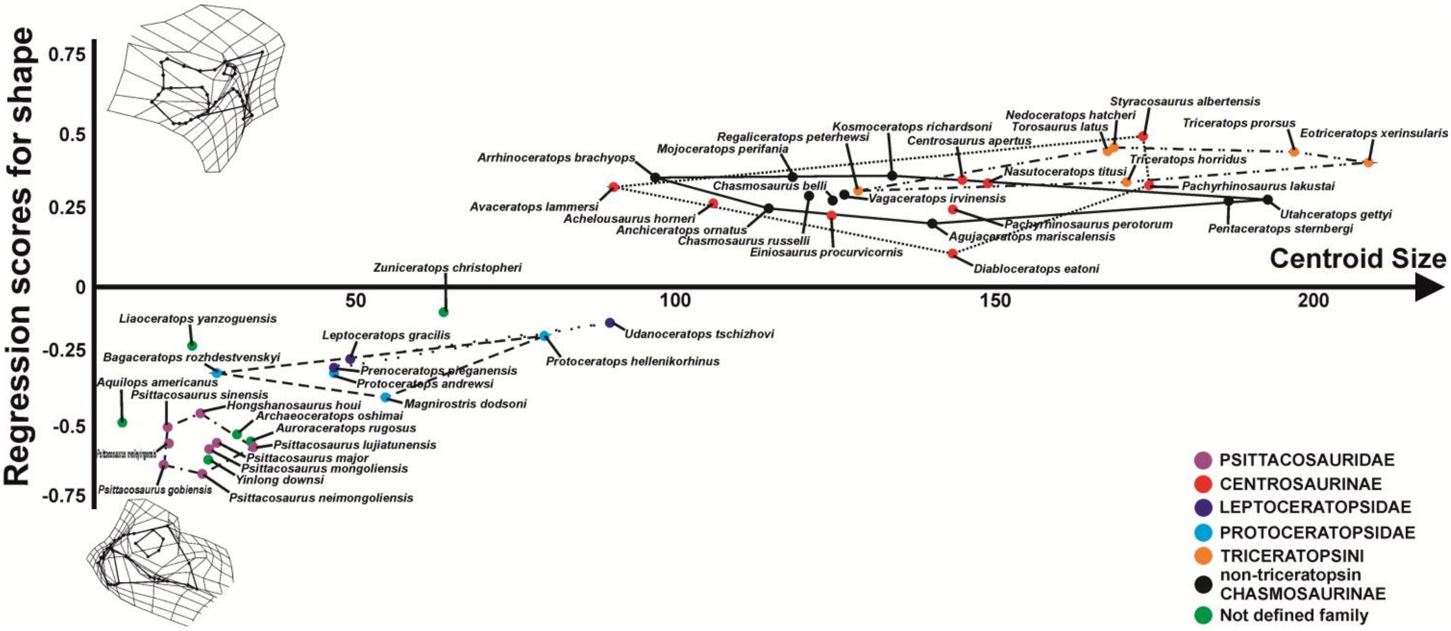

Figure S9. Relationship between the shape of skull without frill and size. The continuous line represents non-triceratopsin Chasmosaurinae morphospace. The dotted line represents Centrosaurinae morphospace. The double dot-dashed line represents Triceratopsini morphospace. The dashed line represents Protoceratopsidae morphospace. The double dotted line represents Leptoceratopsidae morphospace and the dot-dashed line represents Psittacosauridae morphospace.

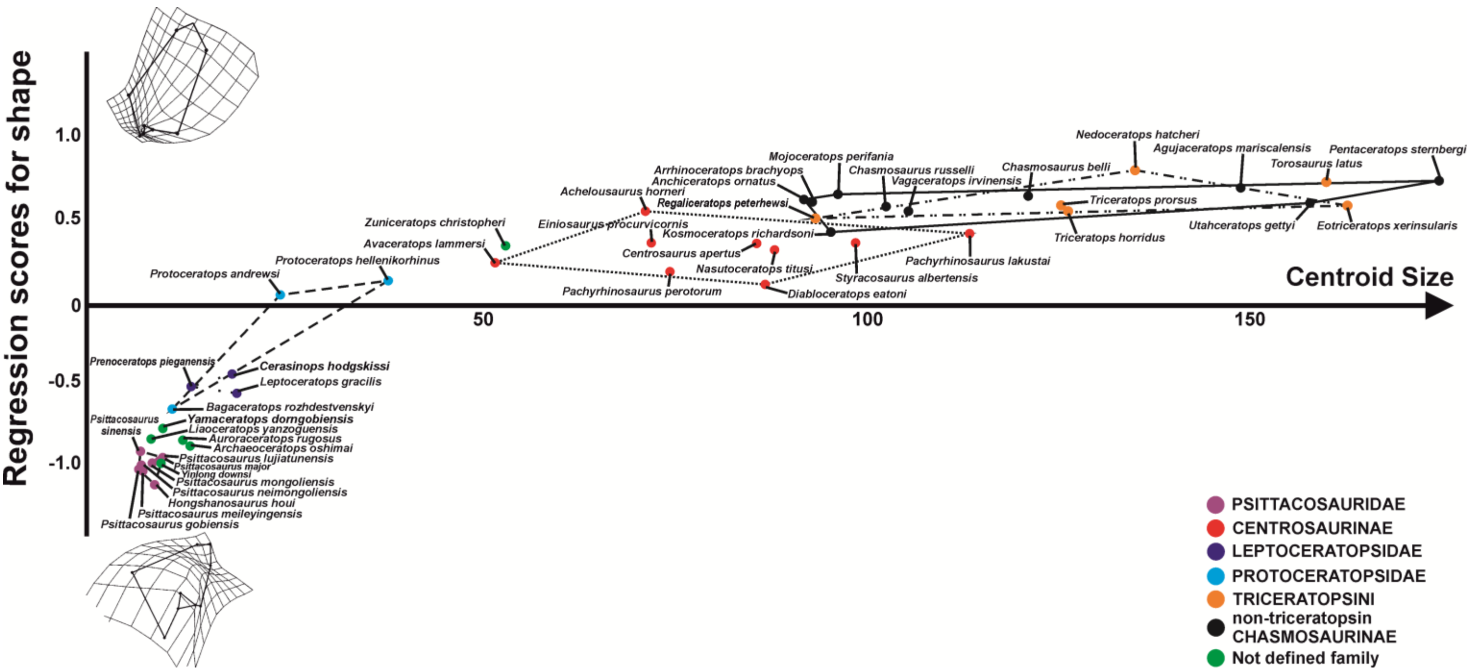

Figure S10. Relationship between frill shape and size. The continuous line represents non-triceratopsin Chasmosaurinae morphospace. The dotted line represents Centrosaurinae morphospace. The double dot-dashed line represents Triceratopsini morphospace. The dashed line represents Protoceratopsidae morphospace. The double dotted line represents Leptoceratopsidae morphospace and the dot-dashed line represents Psittacosauridae morphospace.

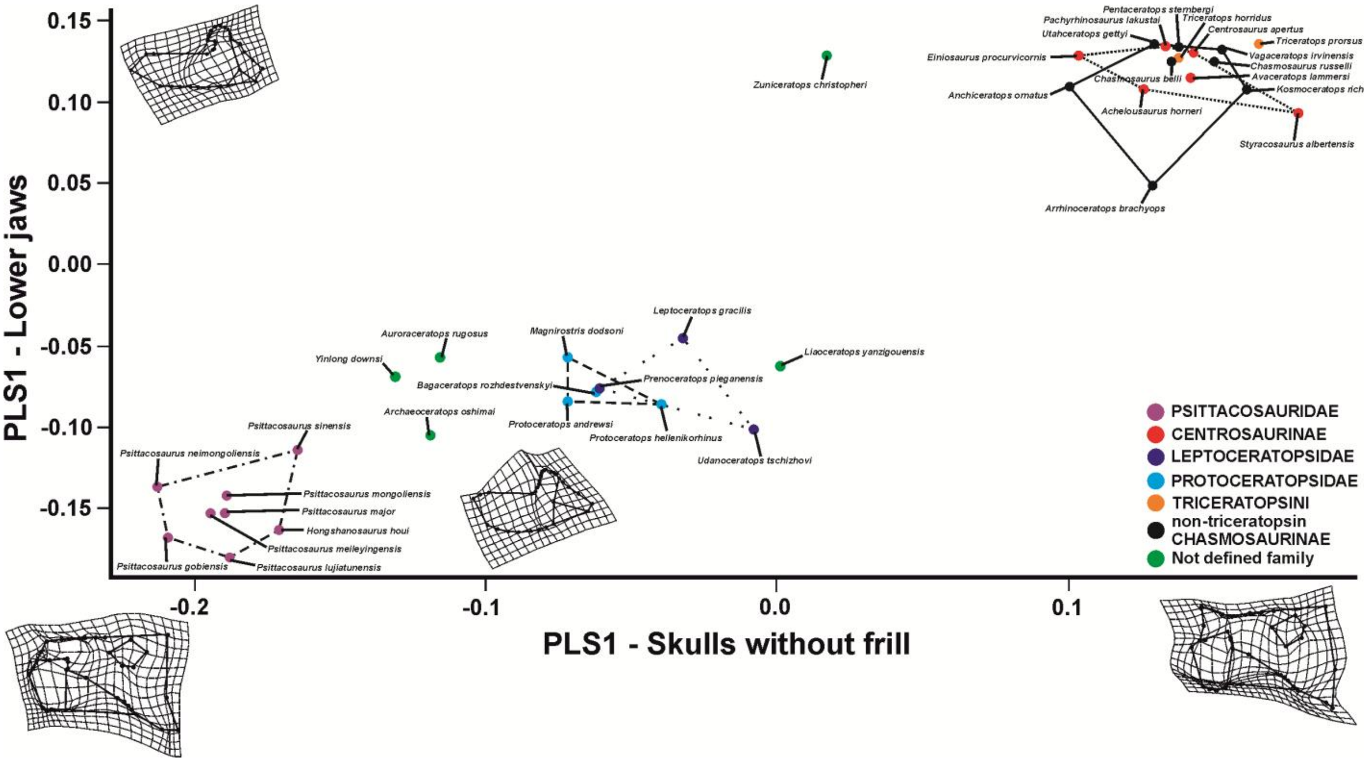

Figure S11. Morphological covariation between the skulls without frill and the lower jaws. The continuous line represents non-triceratopsin Chasmosaurinae morphospace. The dotted line represents Centrosaurinae morphospace. The dashed line represents Protoceratopsidae morphospace. The double dotted line represents Leptoceratopsidae morphospace and the dot-dashed line represents Psittacosauridae morphospace.

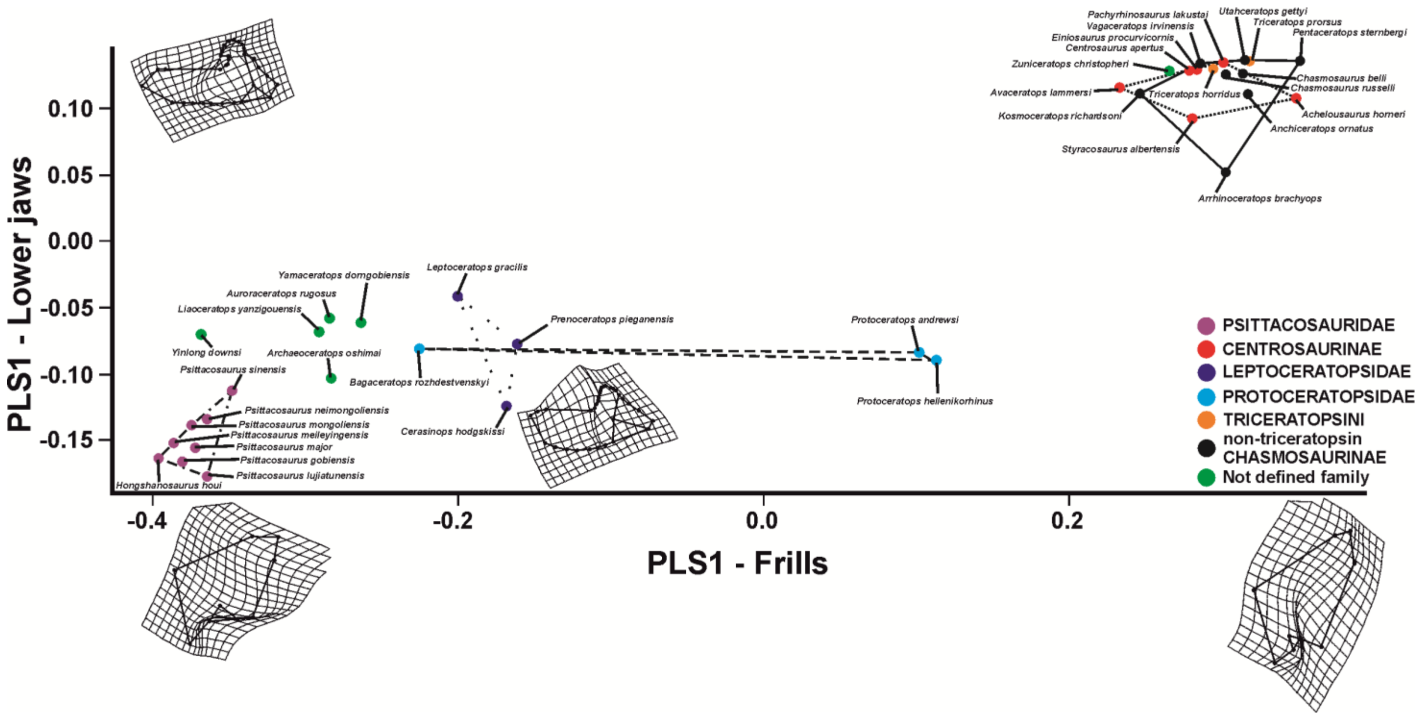

Figure S12. Morphological covariation between the frills and the lower jaws. The continuous line represents non-triceratopsin Chasmosaurinae morphospace. The dotted line represents Centrosaurinae morphospace. The dashed line represents Protoceratopsidae morphospace. The double dotted line represents Leptoceratopsidae morphospace and the dot-dashed line represents Psittacosauridae morphospace.

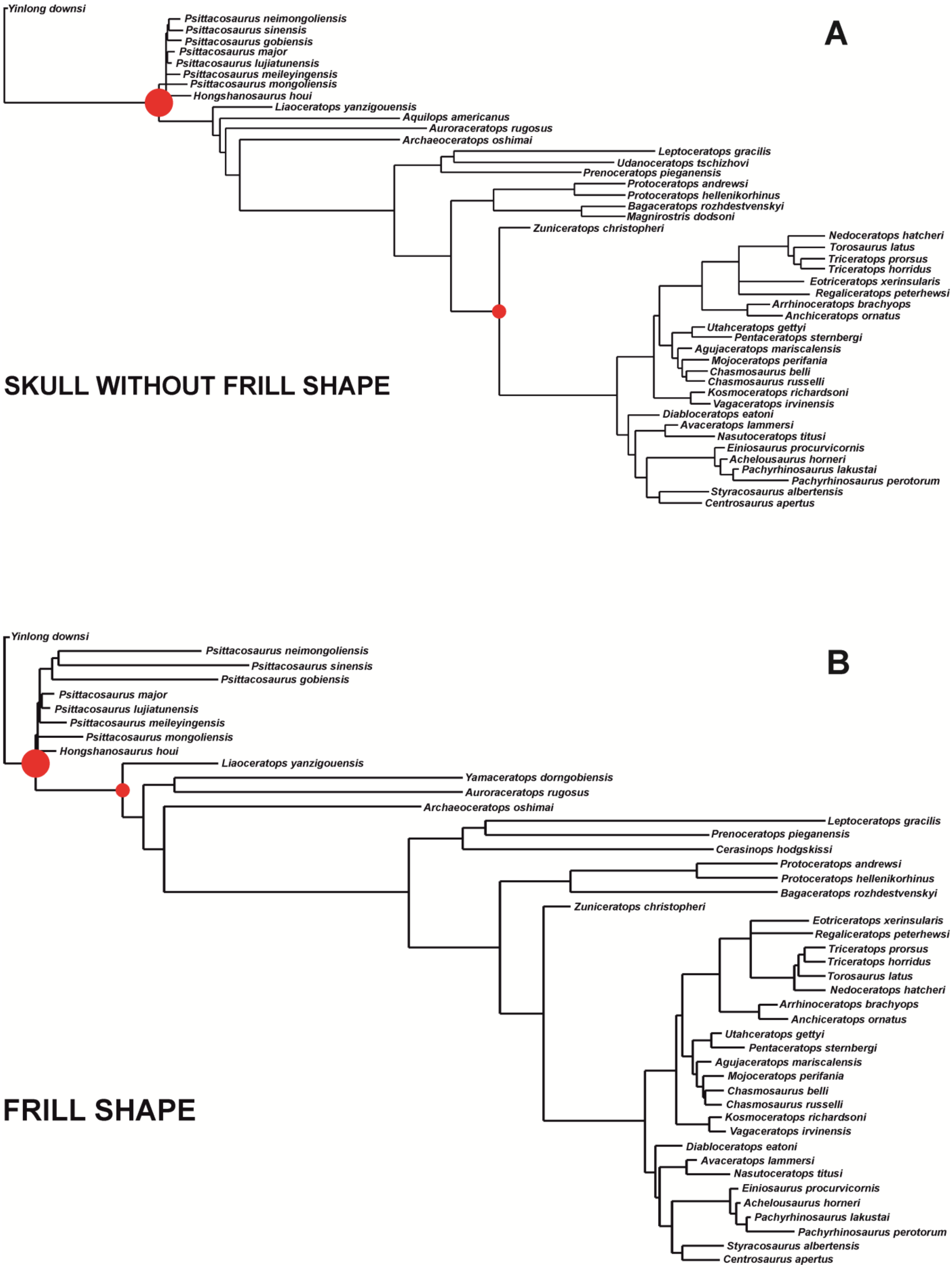

Figure S13. Phylogenetic tree with branch lengths proportional to phenotypic evolutionary rates for skull without frill shape (**A**) and frill shape (**B**). Red dots indentify the main phenotypic shifts along the phylogeny.

Supplementary Tables

Table S6. RV coefficients and the associated simulated *p*-values after 1,000 permutations for testing co-variation between entire skulls and skulls without frill and between entire skulls and frills within Ceratopsia (pooled sample) and within the clades under investigation. Significant results are shown in bold.

Clade	RV	*p*-value
Skulls and Skulls without frill		
Pooled sample	**0.85453**	**0.001**
Triceratopsini	**0.95512**	**0.015**
non-triceratopsin Chasmosaurinae	**0.95094**	**0.0009**
Centrosaurinae	**0.95081**	**0.0001**
Protoceratopsidae	0.89321	0.3288
Psittacosauridae	**0.98663**	**0.0001**
Skulls and Frills		
Pooled sample	**0.9475**	**0.001**
Triceratopsini	**0.96845**	**0.0019**
non-triceratopsin Chasmosaurinae	**0.9144**	**0.0001**
Centrosaurinae	**0.88910**	**0.038**
Protoceratopsidae	0.98623	0.1655
Psittacosauridae	0.87921	0.1385

Table S7. Pair-wise comparisons among clades of evolutionary phenotypic rates performed for shape in the four datasets. Evolutionary rate values are shown above the diagonal and *p*-values are reported below the diagonal. Significant results (*p*-value <0.05) are in bold.

SKULL shape	non-triceratopsin Chasmosaurinae	Centrosaurinae	Protoceratopsidae	Leptoceratopsidae	Psittacosauridae	Triceratopsini
Chasmosaurinae	---	**3.247/6.36**	**1.522/0.811**	**1.394/0.769**	**1.318/0.310**	**---**
Centrosaurinae	**$2.4\cdot10^{-15}$**	---	**3.449/1.638**	**3.331/1.079**	**3.237/0.318**	**3.64/1.50**
Protoceratopsidae	**0.032**	**$5.677\cdot10^{-9}$**	---	0.796/0.676	**0.803/0.271**	0.74/1.14
Leptoceratopsidae	**0.038**	**$8.507\cdot10^{-9}$**	0.352	---	**0.612/0.257**	0.63/1.01
Psittacosauridae	**0.0033**	**$6.37\cdot10^{-10}$**	**0.0091**	**0.0053**	---	**0.26/0.98**
Triceratopsini	**---**	**$1.7\cdot10^{-9}$**	0.5177	0.3254	**0.009**	---
SKULL without FRILL shape						
Chasmosaurinae	---	**2.725/5.23**	**1.423/1.113**	**1.349/0.538**	**1.296/0.358**	**---**
Centrosaurinae	**$2.1\cdot10^{-12}$**	---	**2.977/1.732**	**2.741/0.70**	**2.769/0.338**	**3.08/1.57**
Protoceratopsidae	**0.044**	**$3.574\cdot10^{-7}$**	---	0.809/0.481	**1.002/0.298**	1.01/1.30
Leptoceratopsidae	**0.026**	**$5.673\cdot10^{-7}$**	0.148	---	**0.46/0.29**	0.49/1.18
Psittacosauridae	**0.011**	**$1.195\cdot10^{-7}$**	**0.036**	**0.0093**	---	**0.31/1.16**
Triceratopsini	**---**	**$8.17\cdot10^{-8}$**	0.3139	0.1013	**0.0294**	---
FRILL shape						
Chasmosaurinae	---	**1.25/1.889**	1.182/0.297	1.116/0.694	1.062/1.175	---
Centrosaurinae	**0.034**	---	**1.608/0.367**	**1.765/1.733**	**1.727/1.22**	**1.61/0.79**
Protoceratopsidae	0.074	**0.0205**	---	**0.296/1.597**	0.295/1.133	0.37/0.84
Leptoceratopsidae	0.263	**0.0259**	**0.0356**	---	1.656/1.252	1.60/0.71
Psittacosauridae	0.701	**0.033**	0.098	0.271	---	1.02/0.70
Triceratopsini	---	**0.043**	0.1413	0.1155	0.2261	---
LOWER JAW shape						
Chasmosaurinae	---	**2.53/1.654**	**2.37/1.465**	**2.376/1.28**	**1.716/0.218**	**---**
Centrosaurinae	**$5.7\cdot10^{-5}$**	---	1.142/1.169	1.12/0.955	**0.87/0.173**	1.18/0.73
Protoceratopsidae	**0.0016**	0.272	---	1.138/0.952	**0.959/0.177**	1.21/0.71
Leptoceratopsidae	**0.0020**	0.369	0.482	---	**0.754/0.172**	1.04/0.70
Psittacosauridae	**$3.8\cdot10^{-10}$**	**$1.13\cdot10^{-9}$**	**$1.151\cdot10^{-9}$**	**$9.95\cdot10^{-10}$**	---	**0.20/0.60**
Triceratopsini	**---**	0.2399	0.2531	0.3245	**$2.32\cdot10^{-9}$**	---

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