Supplymentary. Affinities and age of *Labocania anomala*.

As part of this project we undertook a preliminary restudy of the holotype of *Labocania anomala*, IGM 5307, formerly LACM 20877. A full redescription of *Labocania* is currently underway and so complete redescription of this animal is beyond the scope of the present work, but a few issues are worth clarifying here, in terms of the affinities of *Labocania* and its age.

I. ***Systematics of*** **Labocania anomala.**

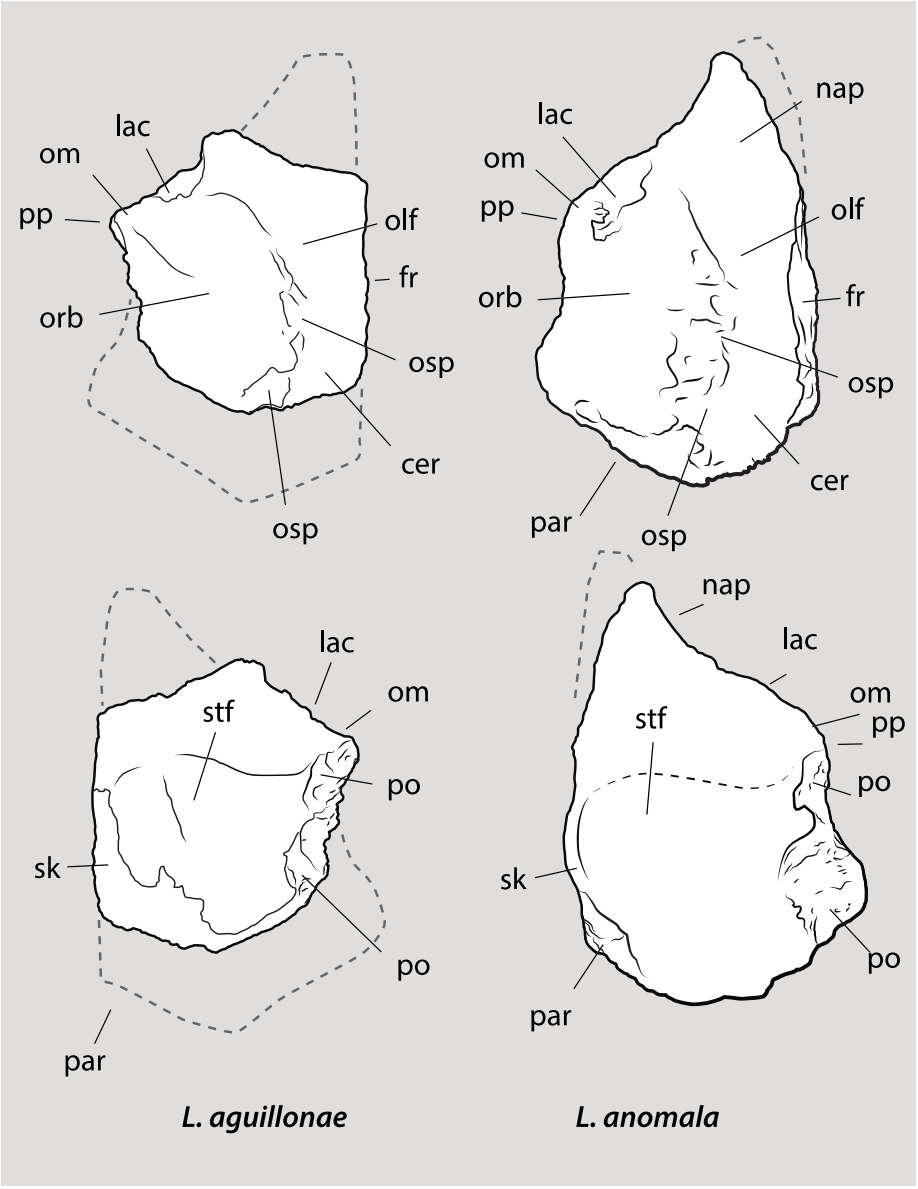


Figure S1. Frontals of *Labocania aguilloni* CPC 2974 and *Labocania anomala* IGM 5307 in ventral view (top) and dorsal view (below). Abbreviations: fr, frontal articular facet; lac, lacrimal articular facet; nap, narial process; om, orbital margin; orb, orbital fossa; osp, orbitosphenoid articular facet; par, parietal articular facet; po, postorbital articular facet; pp, postorbital process; sk, sagittal keel; stf, supratemporal fossa.

The affinities of *Labocania* have been debated since its original description. *L. anomala* was originally described and named by Molnar [1], who was

uncertain of the animal's affinities, and compared it to tyrannosaurids and a variety of other theropods [1]. Since then, it has been suggested to possibly represent a tyrannosaur;l it has also been claimed to show similarities to non-tyrannosaurs such as an abelisaurids [2] or to represent a carcharodontosaurid [3].

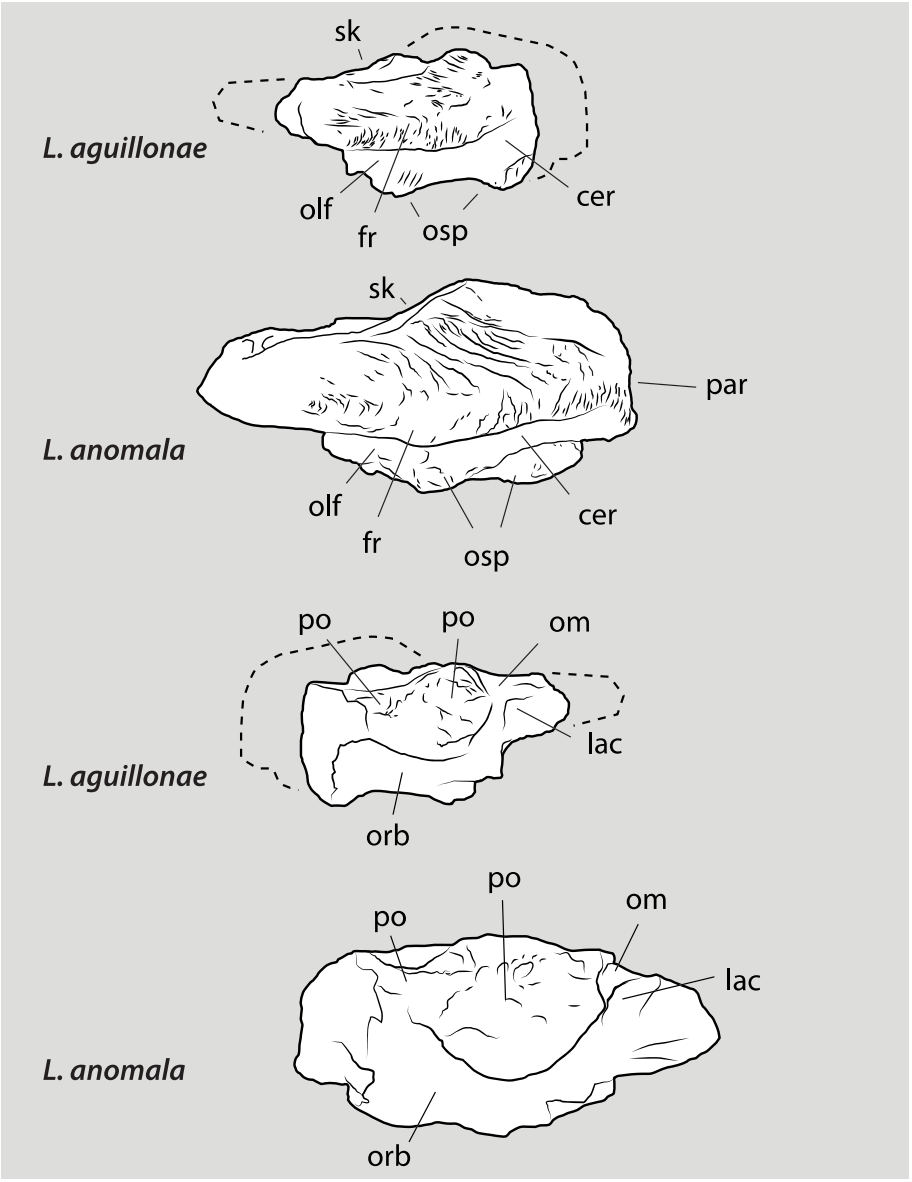


Figure S2. Frontals of *Labocania aguilloni* CPC 2974 and *Labocania anomala* IGM 5307 in medial view (top) and lateral view (below). Abbreviations: fr, frontal articular facet; lac, lacrimal articular facet; om, orbital margin; orb, orbital fossa; osp, orbitosphenoid articular facet; par, parietal articular facet; po, postorbital articular facet; pp, postorbital process; sk, sagittal keel.

Based on our restudy of the holotype, IGM 5207, the anatomy of *Labocania* clearly and definitively establishes its affinities with Tyrannosauridae and specifically suggests affinities with teratophonein tyrannosaurines. Of the elements preserved- the frontals, maxillae, quadrate, teeth, ischia, and metatarsals, each shows tyrannosaurid features and lacks features supporting referral to another theropod. Many of the supposedly anomalous features of the animal are either found in

tyrannosaurids or based on misinterpretations of the anatomy. We do not believe that affinities with either Abelisauridae or Carcharodontosauridae are possible in light of the anatomical evidence.

Frontals. Frontals do not resemble either Carcharodontosauridae [4,5] or Abelisauridae [6] as is sometimes claimed. Instead the frontals are virtually identical to those of *L. aguilloni* (Appendix Figs. 1, 2) and *Bistahieversor sealeyi* [7], and to a lesser degree, tyrannosaurids such as *Teratophoneus* [8], *Dynamoterror* [9], *Lythronax* [8], and *Gorgosaurus* [10].

Lack of fusion between the frontals differentiates *Labocania anomala* animal from carcharodontosaurines [4,5] and most abelisaurids [6]. The interfrontal suture also has a horizontal ridge or shelf, and above and below this ridge, a series of oblique "<" shaped ridges that would have interlocked with the opposite frontal. This suture pattern is characteristic of tyrannosaurids [10,11].

Molnar argued that the frontal is unusually thickened [1] but similar thickening is seen in other tyrannosaurines, e.g. *Tarbosaurus* [11] and *Dynamoterror* [9]; it is simply the result of the large size of the animal. Frontal thickening is seen in some carcharodontosaurs, e.g. *Sauroniops* [12] but not others, e.g. *Eocarcharias* [13], in which it is much thinner than in *Labocania* or other tyrannosaurines.

Molnar furthermore argued that the frontal "lacked the anterior shelf of the supratemporal fossa", i.e. the scar marking the anterior border of the supratemporal fossa. In fact, the dorsal surface of the bone is weathered, such that the thin outermost layer of the cortex has peeled away in all but a few places. The scar for the supratemporal fossa appears to have simply been eroded away. However, the shape of the frontal is identical to other teratophoneins here, and shows that the supratemporal fossae are broadly extended anteriorly and medially onto the postorbital process and the midline sagittal crest, as in other tyrannosaurids [8,10]. This is unlike the condition in carcharodontosaurids, in which the supratemporal fossae are restricted to the back of the parietal and tend to be widely separated [4,5], or abelisaurids [6,14], where again the supratemporal fossae are posteriorly located, and widely separated.

The frontal also shares the typical tyrannosaurid morphology in which the lacrimal articular facet closely approaches the postorbital facet, but a small gap exists so that the frontal participates in the orbit [8,10]. Again, this is inconsistent with referral to either carcharodontosaurids [4,5,13] or abelisaurids [6,14], where a broad postorbital-lacrimal contact excludes the frontal from the lateral margin of the orbit.

The postorbital facet is also typical of tyrannosaurids. There is a large, dorsoventrally expanded postorbital facet on the frontal's postorbital process, which contacted the postorbital laterally. Below and behind this facet is a second facet which is expanded onto the dorsal surface of the frontal, such that the postorbital would have overlapped onto the frontal. This articulation is characteristic of tyrannosaurs [10] and differs from the laterally abutting contact seen in carcharodontosaurs [13] and abelisaurids [14].

Ventrally, there is a massive orbital rim with a broad contact for the orbitosphenoid, as in other tyrannosaurids [11,15]; the orbital rim is much narrower in carcharodontosaurs [13] and abelisaurids [16].

Maxillae. Maxillae have weak sculpturing, as in most tyrannosaurs [8,10,17]. This contrasts with the heavy sculpturing of both carcharodontosaurs [18], and abelisaurids [6,14] (no dentary is present, the element identified as the dentary being the other maxilla). Interdental plates appear to be present, unlike the condition in carcharodontosaurs [18] or abelisaurids [6].

Quadrate. The quadrate is poorly preserved. We were unable to identify any features that preclude referral to Tyrannosauridae.

Teeth. Teeth are typical of tyrannosaurids [19,20]. Features shared with tyrannosauroids include broad, ovoid cross-sections, anterior carinae that twist onto the anteromedial surface of the tooth at the base of the crown, blunt denticles separated by blood grooves. The teeth lack the hooked denticles of abelisaurids [21] or the enamel wrinkles [18,22] of carcharodontosaurs. As discussed above, the pinched crown bases are uniquely shared with tyrannosaurid teeth from the Cerro del Pueblo Formation among Tyrannosauridae.

Ischium. The ischium is typical of tyrannosaurids [23] and Coelurosauria in general in having a large, triangular obturator process. It is further characteristic of Tyrannosauridae in having an enlarged proximodorsal process or scar [1], and resembles Tyrannosaurinae [23] in that the scar/process is very large. The curvature of the ischial shaft is a derived feature shared with Teratophoneini [8].

Tibia. The distal end of a tibia is preserved. The scar for the ascending process of the astragalus is broad, covering almost the entire anterior face of the tibia, and tall. This is characteristic of Coelurosauria, and differs from the low, narrow astragalus of Carcharodontosauria [22] and Abelisauridae [24].

In summary:

1. The holotype of *Labocania anomala*, IGM 5307, exhibits numerous characters seen in Tyrannosauridae, many of which are seen only in Tyrannosauridae;
2. We were unable to verify the presence of any characters in IGM 5307 that were inconsistent with assigning *Labocania anomala* to Tyrannosauridae, and the supposedly unusual features of *Labocania* are all either present in Tyrannosauridae (thickened frontals) or do not appear to be present in *Labocania* (absence of supratemporal fossae);
3. Neither could we find any characters that supported placement in Carcharodontosauridae or Abelisauridae (e.g. thickened frontals) that were not also found in Tyrannosauridae.

In all observable features the anatomy of *Labocania anomala*, IGM 5307, is wholly consistent with referral to Tyrannosauridae, and specifically to Tyrannosurinae and the tribe Teratophoneini. Referral to another clade

such as Abelisauridae or Carcharodontosauria is not supported by any available evidence, and would be inconsistent with the known distribution of these groups, abelisaurids not being known from North America, and carcharodontosaurids not known from the Late Cretaceous of North America. We do not believe that such referrals are plausible.

2. Age of *Labocania anomala*

The age and stratigraphic position of IGM 5307 are not well-constrained. The specimen is reported as coming from the La Bocana Roja Formation [1], but its stratigraphic position has not been published, and the age of La Bocana Roja Formation is poorly understood, with ages estimated from a maximum of 94.7 Ma (late Cenomanian — early Turonian) [25] to a minimum of 75.79 Ma (Late Campanian) [26].

Data from radiometric dating of ash beds, detrital zircons, microfossils, invertebrate fossils and vertebrates provide different and often conflicting information [1,25-27]. We do not believe it is possible to constrain the age of *Labocania anomala* with confidence based on the available data, but note that the anatomy of *Labocania anomala* and associated lambeosaurine fossils are most consistent with a mid-late Campanian age.

Locality and Horizon. Molnar [1] reported that the bones of were found in association in a small area about 2 meters square "near the top of the shoulder of a hill, and trailing down the side". With respect to the stratigraphy, it is reported only that "The lithological unit from the theropod remains were recovered is that designated by Kilmer as the 'La Bocana Roja Formation' ... red mud- stones and tuffs unconformably underlying 'El Gallo Formation.' The locality is on the north side of the unimproved road from El Rosario to Punta Baja, about 3 miles north of Cerro Rayado. The locality is that recorded in the Los Angeles County Museum files as LACM Locality #7257: no maps showing the area are available, since the area has not been
mapped."

Unfortunately, no map or stratigraphic column of the site have been published, nor have subsequent studies of the area attempted to place the type locality in section. Molnar suggested the specimen is Late Campanian or older based on the age of the overlying El Gallo Formation [1]. The basal unit of the overlying El Gallo Formation is constrained by radiometric dating to the Late Campanian [1].

Dated ash beds. Recalibrated radiometric dates of ashes in the overlying El Gallo Formation, in the La Escarpa member, suggest an age of 75.84 +/- .05 near the base of the El Gallo Formation [26]. This suggests a minimum age of ~76 Mya for the La Bocana Roja Formation and *Labocania anomala*. However, the El Gallo Formation meets the La Bocana Roja Formation in an angular unconformity; a period of erosion therefore separates the two formations but it is unclear how much time is missing, and it could therefore be significantly older than 76 Ma.

Detrital zircon dating. Recently, Kane et al. [25] attempted to constrain the age of the La Bocana Roja Formation using radiometric dating of detrital zircons [25]. Detrital zircons provide a maximum depositional age (MDA) of 93.6 +/- 1.1 Ma, i.e. early Cenomanian to even latest Cenomanian in age. Using the same method, the beds of the incising and interfingering Punta Baja Formation were dated as having an MDA of 87.1±1.5 Ma to 84.9±2.0 Ma, i.e. Coniacian to basal Campanian. Again using detrital zircons, the base of the El Gallo Formation was dated to an MDA 86.8±1.8 Ma, i.e. Coniacian, inconsistent with the much younger, late Campanian ages derived from radiometric dating of ash beds [26].

It is important to consider that the MDA represents the *maximum* age of the sediments, not the true depositional age, or TDA [28]. Since detrital zircons are reworked from older volcanic rocks into the host rocks, the host rocks must be younger than the zircons they contain. Therefore, existence of a zircon dating to 93 Ma in a host rock means that the host rocks must be younger than 93 Ma, but *how much younger* is unclear. Using the MDA as a proxy for TDA assumes that there are nearby sources of zircon formed at about the same time as the host rocks, and that they are transported to the host rock [28]. However, studies of Recent and Holocene sediments suggest that these sediments are dominated by older zircons, with over 99% of zircons being at least two million years older than the host rocks [28]. In theory the MDAs could be far older than the TDA of these rocks, although it would require a substantial gap to consistently exist between TDA and MDA for both the La Bocana Roja and the Punta Baja Formation.

Radiometric dates derived from ashes in the El Gallo Formation suggest the gap between TDA and MDA could be considerable. The El Gallo Formation is dated to 75.84 +/- 0.05 near the base, to 75.43 +/- .08 Ma near the top of the La Escarpa member, and 75.17 +/- .15 Ma just above the La Escarpa member, in the overlying El Disecado Member [26]. This suggests the basal La Escarpa Member of the El Gallo was deposited relatively rapidly, over a period of around a million years, in the Late Campanian. If the Coniacian MDA of 86.8 Ma is correct for the base of the La Escarpa Member is correct, then this would imply that 11 million years of sedimentation occurred in the very base of the La Escarpa member, followed by a million years of sedimentation forming the rest of the member. This demands either a dramatic change in the rate of deposition through the La Escarpa Member and/or a significant depositional hiatus. Alternatively, the Coniacian MDA overestimates the age of the basal El Gallo Formation.

Microfossils. Another source of data are the fossils of the La Bocana Roja Formation and of the Punta Baja Formation, which cuts down into the El Gallo. The microfossils of the interfingering Punta Baja Formation have wide stratigraphic ranges, but one species ranges from the Cenomanian to Santonian [25], suggesting a minimum age of Santonian for the Punta Baja Formation, and an older age for the La Bocana Roja Formation.

Invertebrate fossils. However, invertebrate fossils suggest a younger age for the Punta Baja Formation. The bivalves have been used to suggest a late middle Campanian age, and the ammonites suggest a middle Campanian

age [25]. Based on invertebrates, the La Bocana Roja Formation could therefore be as young as late middle Campanian.

Dinosaur fossils. Finally, the dinosaurs themselves provide information on the age of the fauna. As discussed here, *Labocania* is closely related to- and almost indistinguishable from- *Bistahieversor sealeyi* from the late Campanian of the Kirtland Formation, and *L. aguilloni* from the latest Campanian of the Cerro Del Pueblo Formation. This suggests a Late Campanian age.

The hadrosaurs found in the formation have been identified as Lambeosaurinae, with the oldest lambeosaurs in North America being early Campanian in age [29]. An ischium reported from the La Bocana Roja Formation, LACM 28990 [27], can be referred to Lambeosaurinae based on the large distal boot. It is a relatively large animal, comparable in size to the holotype of *Magnapaulia*. Although distinct from *Magnapaulia*, it shares with *Magnapaulia* a derived morphology of the ischium, with the iliac peduncle being elongate and strongly hooked back, a robust shaft, and an anteriorly hooked pubic boot [27]. Based on this limited information it can be confidently identified as a member of Lambeosaurini and appears to be closely related to or congeneric *Magnapaulia*, from the Campanian of the El Desicado Member, which has a maximum age of 75.43 My [26]. Again, this suggests a Late Campanian age.

The dinosaur fauna reported from the La Bocana Roja Formation is therefore inconsistent with a Turonian age, and strongly suggests a younger, mid-to-late Campanian age. The presence of *Labocania* in the Turonian would be highly anomalous, just as it would be extraordinary to find highly derived, Late Campanian taxa like *Albertosaurus sarcophagus*, *Pachyrhinosaurus canadensis*, *Edmontosaurus regalis*, or *Parasaurolophus walkeri* in the Turonian.

Summary of stratigraphic and chronostratigraphic data.

Data	Age
Radiometric dating of ash beds	75.84 +/- 0.05 (minimum)
Radiometric dating of detrital zircons	93.6 +/- 1.1 (maximum)
Microfossils	Santonian (minimum)
Fossil invertebrates	Middle Campanian (minimum)
Fossil vertebrates	Late Campanian

The various age constraints are contradictory and can be used to assign an age of anywhere from Cenomanian to Late Campanian age for *Labocania anomala*. The dinosaurs themselves show close affinities with Late Campanian forms.

It is also worth noting that the stratigraphy of the El Rosario area and especially the La Bocana Roja Formation / El Gallo Formation contact are extremely complicated [25,30]. The contact between the La Bocana Roja Formation and the overlying El Gallo Formation is an angular uncomformity; in places the beds dip by approximately 30 degrees or

more [25] such that the age of the top of the El Gallo Formation presumably differs from north to south.

In other areas, blocks have been thrust up or faulted downwards; where blocks have slipped downwards the top of the La Bocana Roja Formation will be younger. The substantial thrusting and faulting, the emplacement of the Punta Baja Formation above and interfingering with the La Bocana Roja Formation, and the erosive contact at the top all complicate the stratigraphy, although they do tend to imply a significant period of time passed between the emplacement of the La Bocana Roja Formation and the El Gallo Formation.

Last, given the contradictory nature of the evidence and the highly derived nature of *Labocania anomala*, it is worth considering whether the stratigraphic data itself might be in error, and if *Labocania* might in fact come from the base of the overlying El Gallo Formation.

In recent years, restudy of a number of dinosaurs has shown that their original stratigraphic assignment was incorrect; *Naashoibitosaurus ostromi* for example was originally believed to come from the Maastrichtian of the Naashoibito Member of the Kirtland, but was later found to come from the lower, Late Campanian part of the Kirtland [31]. Recently, the stratigraphy of *Coahuilaceratops* was revised and the specimen was argued as coming from the Cerro Huerta Formation rather than the underlying Cerro Del Pueblo Formation [32]. Such mistakes are not common but do happen. In general the published stratigraphic assignments should probably be trusted, but in the current situation the highly discordant constraints on age suggests a conflict that needs to be resolved.

Curiously, the data on file for the holotype site of Labocania and the site of the lambeosaurine, LACM 7257, "El Rosario", is given as " 'La Bocana Roja Formation' 10 miles south of El Rosario. Massive fine grained red sandstone. Former LACM loc. 6755 is now incorporated into this locality. Theropoda and HAdrosauridae."

The data for LACM loc 6755, "Arroyo del Rosario", is in turn given as "Purple and red mudstone mapped by Kilmer 1963 El Gallo Fm. (El Diseado member [sic]) south side of Arroyo del Rosario along road to Punta San Antonio, 7.4 miles S 4 deg East of main crossroads in El Rosario Arriba. On west side of road immediately south of small normal fault (approximately 100 ft. West of road). [See LACM loc. 7257]."

The reason for incorporating LACM 6755 into LACM 7257 is not clear, but if the two sites are redundant, then it would seem the locality was originally assigned to the El Gallo Formation and only later reassigned to the La Bocana Roja Formation. This implies that the outcrops of the La Bocana Roja Formation and the El Gallo Formation are not always easily distinguished in this area, and the reassignment of this locality could be in error.

In light of the anatomy of the fossil, the associated lambeosaurs, and the potential for a significant gap between age of detrital zircons and true age of the host rocks, we regard a Turonian age as highly unlikely for *Labocania anomala*. Resolving this issue is not possible with the available data and will likely require further fieldwork on the stratigraphy of the site and/or the age of the La Bocana Roja Formation.

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