SUPPLEMENTARY INFORMATION

1. STRATIGRAPHY

Maastrichtian

The birds described here come from the Hell Creek Formation of Montana, North Dakota, and South Dakota, the Lance Formation of Wyoming, and the Frenchman Formation of Saskatchewan. All three formations are part of the Lancian North American Land Mammal Age (NALMA), which corresponds to the final half of the Maastrichtian.

The Saskatchewan birds can be precisely dated because the Frenchman Formation lies entirely within magnetochron c29r [(1)], and therefore represents the final 300,000 years of the Cretaceous[(2)]. Taxa occuring here include Enantiornithine A, Hesperornithiform A and Hesperornithiform B, Ornithurine A, and Ornithurine D. These five taxa can therefore be confidently shown to survive to within 300,000 years of the K-T boundary.

The age of the Lance Formation birds is not as tightly constrained, but they appear to be similar in age: a recent study suggested that they most likely correlate with c29r [(3)], which again means that these fossils were deposited within 300,000 years of the end of the Cretaceous. In the area of the Powder River Basin sites, the Lance Formation is approximately 2,500 feet thick[(4)]. All of the sites for which stratigraphic information is available lie high in section. UCMP V5620 lies about 2,100 feet above the top of the underlying Fox Hills[(4)]. The Hell Creek Formation in North Dakota spans roughly 1.3 million years of time[(2)]; assuming that the Lance was deposited over a similar period and assuming constant depositional rates, then UCMP 5620 would be from roughly 200,000 years before the K-T boundary[(4)]. *Ceramornis major*, Ornithurine F, and Ornithurine A are documented from this site. UCMP 5711 and UCMP 5003 lie somewhere in the upper half of the Lance Formation[(4)], which would put them within 650,000 years of the K-T boundary. Taxa represented in these sites include *Cimolopteryx petra*, *Cimolopteryx maxima*, Ornithurine A, and Ornithurine E. Although precise provenance data are not available for the holotype of *Palintropus*, it was collected from the same area of the Lance Formation, most likely high in section where vertebrate microfossils are most abundant, and where collecting has traditionally focused.

The Hell Creek Formation encompasses 1.3 million years[(2)] and birds from the Hell Creek can therefore be assumed to come from the latter half of the Maastrichtian. The Hell Creek exposures in Garfield and McCone counties again have been correlated with magnetochron c29r [(3)]. Birds from this area include *Avisaurus archibaldi*, Hesperornithiform A, Ornithurine B, Ornithurine C, and Ornithurine D.

Birds have also been reported from Maastrichtian and potentially Maastrichtian rocks from outside of North America (Table S1). However, we emphasize that the stratigraphic constraint of these birds is generally poor, and with the exception of a basal ornithurine and an enantiornithine from the Maastrichtian of Belgium, no archaic birds can be constrained as occurring in the final part of the Maastrichtian.

Palaeocene

We also examined collections from the Early Palaeocene of western North America to determine whether any of the taxa described here survived the K-T event. These fossils include birds from the Polecat Bench Formation of Wyoming at the Yale Peabody Museum, fossil birds from the Fort Union Formation of Wyoming, housed at the University of California Museum of Palaeontology, and fossils from the Ravenscrag Formation of Saskatchewan, housed at the University of Alberta. Bird fossils are relatively rare in these deposits compared to the Lancian; however, none of the avian remains that we studied can be referred to stem taxa such as Hesperornithes, Ichthyornithes, Palintropiformes, or Enantiornithes, and definitive remains of these taxa- or definitive remains of any stem birds- have never been documented from the Palaeogene in any locality in the world[5].

Mayr has suggested that the Palaeocene *Qinornis* may represent a stem bird on the basis of the incomplete fusion of the metatarsals[5]. It should be noted, however, that *Qinornis* could represent a juvenile neornithine in which the tarsometatarsus had not yet fully fused[5]. Furthermore, *Qinornis* lacks synapomorphies to support its referral to the Hesperornithes, Ichthyornithes, Palintropiformes, or Enantiornithes, and therefore does not alter the fact that these major clades appear to become extinct at the K-T boundary. Furthermore, the identification of *Qinornis* as a basal bird would not alter the fact that basal birds are a diverse part of the avian fauna up to the K-T boundary, nor that the fauna is dominated by Neornithes in the aftermath[5]. In short, extinction need not be total to represent a mass extinction.

While we acknowledge that further sampling could conceivably show that some basal birds survived into the Palaeocene, the available fossil record, including the fossils we examined, is entirely consistent with the mass extinction of basal birds at the K-T boundary, and in particular, it is consistent with the extinction of the four major clades of basal birds documented by fossil material in the Late Maastrichtian of western North America. A single fossil of Ornithurine C is known from the Palaeocene Fort Union Formation of Montana (seen below), and therefore represents the only avian taxon known to cross the K-T boundary.

Table S1. Maastrichtian and potentially Maastrichtian bird taxa from outside of North America

Taxon	Relationships	Locality	Formation	Age
Unnamed ornithurine (6)	Basal Ornithurae	Belgium	Maastricht Fm.	latest Maastrichtian/within 500 ka of K-T boundary (6)
Unnamed ornithurine (7)	Ornithurae	Belgium	Maastricht Fm.	latest Maastrichtian/within 500 ka of K-T boundary (6)
Unnamed enantiornithine (7)	Enantiornithes	Belgium	Maastricht Fm.	latest Maastrichtian/within 500 ka of K-T boundary (6)
Aves? (8)	Enantiornithes?	France	Auzas Marls Fm.	Late Maastrichtian (8)
Vegavis iaii (9)	Neornithes	Antarctica	Lopéz de Bertodano Fm.	middle-late Maastrichtian (9)
Polarornis gregorii (10)	Ornithurae	Antarctica	Lopéz de Bertodano Fm.	middle-late Maastrichtian (10)
Canadaga arctica (11)	Basal Ornithurae	Canada		middle Maastrichtian (11)
Asiahesperornis bazhanovi (12)	Hesperornithes	Kazakhstan	"Zhuralovskaya Svita"	Maastrichtian (12)
Lectavis bretincola (13)	Enantiornithes	Argentina	Lecho Fm.	Maastrichtian (13)
Enantiornis leali (13)	Enantiornithes	Argentina	Lecho Fm.	Maastrichtian (13)
Soroavisaurus australis (13)	Enantiornithes	Argentina	Lecho Fm.	Maastrichtian (13)
Yungavolucris brevipedalis (13)	Enantiornithes	Argentina	Lecho Fm.	Maastrichtian (13)
Vorona berivotrensis (14)	Enantiornithes	Madagascar	Maevarano Fm.	Maastrichtian (13)
Taxon B (14)	Enantiornithes	Madagascar	Maevarano Fm.	Maastrichtian (14)
Taxon C (14)	Enantiornithes	Madagascar	Maevarano Fm.	Maastrichtian (14)
Taxon D (14)	Enantiornithes	Madagascar	Maevarano Fm.	Maastrichtian (14)
Taxon E (14)	Enantiornithes	Madagascar	Maevarano Fm.	Maastrichtian (14)
Taxon F (14)	Enantiornithes	Madagascar	Maevarano Fm.	Maastrichtian (14)
Aves (15)	Aves incertae sedis	Brazil	Bauru Formation	Maastrichtian (15)
Unnamed ornithurine (16)	Basal Ornithurae	Romania	Densus-Ciula Fm.	?Maastrichtian (16)
Neogaeornis wetzeli (17)	Enantiornithes	Chile	Quiriquina Fm.	Campanian-Maastrichtian (17)
Martinavis cruzyi (18)	Enantiornithes	France		late Campanian-early Maastrichtian (18)
Gargantuavis philoinos (19)	Basal Ornithurae	France	Marnes de la Maurine Fm.	late Campanian-early Maastrichtian (19)
Limenavis patagonica (20)	Basal carinate	Argentina	Allen Fm.	middle Campanian-early Maastrichtian (20)
Teviornis gobiensis (21)	Neornithes?	Mongolia	Nemegt Fm.	late Campanian-Maastrichtian (22)
Judinornis nogontsavensis (23)	Hesperornithes	Mongolia	Nemegt Fm.	late Campanian-Maastrichtian (22)
Gobipteryx minuta (2	Enantiornithes	Mongolia	Barun Goyot Fm.	late Campanian-Maastrichtian (22)
Gurilynia nessovi (25)	Enantiornithes	Mongolia	Nemegt Fm.	late Campanian-Maastrichtian (22)
Hollanda lucera (26)	Basal Ornithurae	Mongolia	Barun Goyot Fm.	late Campanian-Maastrichtian (22)
Graculavis velox	Ornithurae	New Jersey	Hornerstown	late Maastrichtian or early Palaeocene

(27)			Fm.	(28)
Laornis edvardsianus (27)	Ornithurae	New Jersey	Hornerstown Fm.	late Maastrichtian or early Palaeocene(28)
Anatalavis rex (27)	Ornithurae	New Jersey	Hornerstown Fm.	late Maastrichtian or early Palaeocene (28)
Palaeotringa littoralis (27)	Ornithurae	New Jersey	Hornerstown Fm.	late Maastrichtian or early Palaeocene (28)
Palaeotringa vagans (27)	Ornithurae	New Jersey	Hornerstown Fm.	late Maastrichtian or early Palaeocene (28)
Tyttostonyx glauconitus (27)	Ornithurae	New Jersey	Hornerstown Fm.	late Maastrichtian or early Palaeocene (28)

Notes: *Martinavis* sp. from the Maastrichtian of Argentina may be synonymous with *Lectavis bretincola*, *Yungavolucris brevipedalis*, or *Soravisaurus australis* (18) and so it is not counted as a distinct taxon here. Similarly a number of ornithurine fossils from the Nemegt (25, 29) are not counted as distinct taxa here because the possibility exists that they represent *Teviornis* or *Judinornis*.

2. SYSTEMATIC PALAEONTOLOGY

Although many of these taxa have previously been described (30, 31), many are not well figured, and previous descriptions have emphasized similarities with Neornithes rather than comparing these birds to a range of Mesozoic and Cenozoic taxa. For these reasons, we present a complete description for all of the Lancian birds included in this study. We refer the reader to previous descriptions for other Lancian birds. These include *Lonchodytes pterygius*, *Lonchodytes estesi*, *Potamornis skutchi*, *Graculavus augustus*, *Torotix clemensi*, a parrot-like taxon, a possible galloanserine, and a number of more fragmentary remains (30-34). Putative cormorant remains (30) most likely belong to the Hesperornithes described here. *Potamornis* may represent a member of the Hesperornithes (32), perhaps the same species as either Hesperornithiform A or Hesperornithiform B.

Institutional Abbreviations

ACM, Amherst College Museum, Amherst; AMNH, American Museum of Natural History, New York; MOR; Museum of the Rockies, Bozeman, Montana; NMC, National Museum of Canada (Canadian Museum of Nature), Ottawa, Ontario. RSM, Royal Saskatchewan Museum, Eastend and Regina, Saskatchewan; SDSM, South Dakota School of Mines, Rapid City, South Dakota; UCMP, University of California Museum of Paleontology, Berkeley, California; USNM, United States National Museum, Washington, District of Columbia; YPM, Yale Peabody Museum, New Haven, Connecticut.

Aves

Ornithothoraces

Enantiornithes Walker 1981

cf. *Avisaurus archibaldi* Brett-Surman and Paul 1985

Material. YPM 57235

Horizon and Locality. Hell Creek Formation, Montana.

Diagnosis. Enantiornithine characterized by large size, coracoid shaft lacking either a medial flange or a medial channel, absence of a supracoracoideus nerve foramen, and a shallow medial fossa of the coracoid head.

Description. This enantiornithine coracoid is provisionally referred to *Avisaurus archibaldi*[35] on the basis of its large size. The coracoid's shaft is elongate and retains a deep dorsal fossa, as is typical of Enantiornithes[13, 36, 37], and in lateral view, it is gently bowed dorsally, as in *Enantiornis*[13]. The coracoid lacks either a supracoracoideus nerve foramen or the distinctive medial flange and groove seen in other enantiornithines including *Enantiornis*[13], *Neuquenornis*[37], Enantiornithine A, and Enantiornithine B; however the lack of a medial flange and groove is similar to the condition in *Gobipteryx*[38]. The proximal end of the coracoid is worn, but the remaining parts of the scapular facet indicate that it formed a convex, caudally projecting boss, as is typical of Enantiornithes[13]. The glenoid is oriented to face dorsally, an apomorphy shared with *Enantiornis*[13] and *Gobipteryx*[38]. In contrast the glenoid faces dorsolaterally in non-enantiornithine birds. Just below the glenoid there is a prominent scar, which appears to represent the insertion of the acrocoracohumeral ligament. In dorsal view, the glenoid and scapular facet wrap around to define the lateral edge of a triosseal canal, but the triosseal canal is shallow and does not pass ventral to the scapular facet as seen in Ornithurae. The acrocoracoid process is elevated to the level of the glenoid, but is very short and does not hook medially, as is typical of enantiornithines[13, 36]. Medial and ventral to the glenoid, there is a shallow fossa bounded ventrally by a distinct lip. This is a derived feature unique to enantiornithines[36, 38].

Remarks. Referral to *Avisaurus* should be regarded as tentative given that *Avisaurus* is named on the basis of a tarsometatarsus,[35] but both come from the same formation and represent exceptionally large enantiornithines, and so it seems probable that this coracoid does belong to *Avisaurus*.

Lancian Enantiornithine A

Material. NMC 9528

Distribution. Late Maastrichtian Frenchman Formation, Saskatchewan.

Diagnosis. Medium sized enantiornithine characterized by a coracoid neck with a subtriangular shaft, a thin medial flange, and a medial fossa of the coracoid head that is developed into a deep excavation.

Description. Lancian Enantiornithine A is an enantiornithine about 2/3 the linear dimensions of *Avisaurus*. Unlike *Avisaurus* or Enantiornithine B, the neck of the coracoid has a distinctly triangular cross section, as in *Enantiornis*[13]. Medially, there is a thin medial flange running along the coracoid shaft, similar to that seen in *Enantiornis*. The glenoid is dorsally oriented and curves around a shallow triosseal canal, as in

Enantiornis[13] and *Avisaurus*. The scapular facet is typical of enantiornithines in being developed as a strongly convex, caudally projecting boss. Its dorsal surface is divided by a ridge into distinct medial and lateral facets. The acrocoracoid is relatively short and is not hooked medially, again resembling the condition in *Avisaurus* and *Enantiornis*. The most distinctive feature of this element is the medial fossa. Whereas this fossa is shallow in *Enantiornis* and *Avisaurus*, in Enantiornithine A it is developed as a pocket that extends deep into the coracoid head.

Lancian Enantiornithine B

Material. YPM 57823

Distribution. Late Maastrichtian Hell Creek Formation, Montana

Diagnosis. Small enantiornithine characterized by a coracoid neck with a subcircular section, a massive medial flange, and a scapular facet with a medial notch.

Description. Enantiornithine B is the smallest of the three enantiornithine morphotypes identified here. The neck of the coracoid has a subcircular section, which differentiates this bird from Enantiornithine A. The medial surface of the shaft has a distinct medial flange as in *Enantiornis*[13] and Enantiornithine A, however the flange is much more robustly constructed than the delicate flange in Enantiornithine A. The scapular facet has a distinctive shape; it is bulbous with a slight notch in its medial surface, a feature not seen in *Avisaurus* or Enantiornithine A. Thus, despite the fragmentary nature of this specimen it can readily be differentiated from Enantiornithine A.

Ornithurae

Palintropiformes n. tax.

Palintropiformes is defined as the stem-based clade consisting of all taxa closer to *Palintropus retusus* than to *Ichthyornis*, *Hesperornis*, or *Passer*.

Palintropus Brodkorb 1970

P. retusus Marsh 1892

Material. YPM 513, AMNH 987

Horizon and Locality. Late Maastrichtian Lance Formation, Wyoming; Hell Creek Formation, Montana

Diagnosis. Ornithurine characterized by a short and weakly hooked acrocoracoid with a knob-like end, glenoid developed as a laterally projecting, semicircular flange, scapular facet deep and bowl-like, scapular shaft with deep dorsal and lateral grooves, crescentic scar on the inside of the scapular head.

Description. The coracoid of *Palintropus* is unusual among ornithurines in having a dorsal depression as is seen in Enantiornithes:[13] the basal ornithurine *Apsaravis*[39], as well as buttonquail (Turnicidae) are the only other ornithurines with this feature. There is also a longitudinal channel on the medial surface of the coracoid shaft. Again, this feature is shared with some Enantiornithes[13] and with the basal ornithurine *Apsaravis*[39], but not with other ornithurines. The supracoracoideus nerve foramen is not preserved, but in *Palintropus* spp. from the Campanian of Alberta[40], the supracoracoideus nerve foramen passes from the dorsal depression into the medial depression, again resembling the condition in some Enantiornithes and *Apsaravis*. The scapular cotyle of *Palintropus* is deep and bowl-shaped, as is typical of basal ornithurines. A procoracoid process is absent, as in Enantiornithes[13] and *Apsaravis*[39]. The glenoid is semicircular and projects away from the body of the coracoid, forming a broad flange. This derived feature is shared with *Apsaravis* and some Neornithes, e.g. *Gallus*. The glenoid is located primarily ahead of the scapular cotyle, a derived feature absent in basal ornithurae such as *Ichthyornis*[41] and *Patagopteryx*[42], but shared with *Apsaravis,*[39] *Iaceornis*[41] and Neornithes; this most likely was acquired convergently in Palintropiformes and derived Ornithurae. The acrocoracoid is relatively short and weakly hooked medially around the triosseal canal, as is characteristic of basal Ornithurae such as *Apsaravis*[39], and *Ichthyornis*[41]; in contrast the acrocoracoid is much longer and strongly hooked medially in *Iaceornis*[41] and most Neornithes. The end of the acrocoracoid process is expanded and knob-like; in contrast the end of the acrocoracoid is weakly expanded in *Apsaravis*; this represents one of the only significant differences between the two. The triosseal canal does not pass beneath the scapular facet, again resembling the condition in *Apsaravis* and Enantiornithes; in contrast the triosseal canal passes beneath the scapular facet in *Ichthyornis*, *Iaceornis*[41], *Baptornis*, and more derived birds.

Remarks. Although *Palintropus* resembles Galliformes in its flange-like glenoid reduced procoracoid[30], our phylogenetic analysis finds that *Palintropus* is most closely related to *Apsaravis ukhaana* from the Late Cretaceous of Mongolia, as previously proposed[40]. Shared features include the strong lateral projection of the glenoid, the loss of the procoracoid process, and the deep dorsal and medial grooves connected by the supracoracoideus nerve foramen. These are here interpreted as synapomorphies of the Palintropiformes, a clade containing *Apsaravis* and *Palintropus*, and three species from the Campanian of Alberta[40].

Hesperornithes Furbringer 1888 *sensu* Clarke 2004

Hesperornithiform A

Distribution. Late Maastrichtian, Hell Creek Formation, Montana; Frenchman Formation, Saskatchewan

Diagnosis. Small hesperornithiform characterized by a short, broad metatarsus, metatarsal IV subequal in length to metatarsal III, dorsal flange of metatarsal IV does not extend the full length of the metatarsus, distal metatarsus not twisted relative to proximal metatarsus, large and proximally located depression for reception of metatarsal I.

Material. RSM P 2315.1, RSM MB.AV.705, UCMP 13355

The metatarsus of Hesperornithiform A lacks a number of derived features found in the advanced members of the Hesperornithes such as *Pasquiaornis*, *Baptornis*, *Parahesperornis*, and *Hesperornis*[43-46], but closely resembles an unnamed hesperornithiform from the early Maastrichtian Nemegt Formation of Mongolia[23].

Metatarsals II-IV are completely fused to each other along their length, as is typical of Ornithurae. Metatarsal V is absent. Proximally, metatarsal III is caudally displaced relative to metatarsals II and IV, such that there is a prominent anterior depression bounded by metatarsals II and IV. The dorsal surface of metatarsal IV is developed as a prominent longitudinal flange, a feature shared with other Hesperornithes, but it is not developed to the extreme seen in *Hesperornis* and *Parahesperornis*, where it extends well beyond the midlength of the bone. Ventrally, there is a broad hypotarsal eminence, but a true hypotarsus is absent, as is typical of basal Ornithurae.

The shaft of the metatarsus is relatively short and broad, as in the Nemegt hesperornithiform. By contrast, the metatarsus is elongate and mediolaterally compressed in derived Hesperornithes. The metatarsus is untwisted along its length, a primitive feature shared with the Nemegt hesperornithiform. In contrast, the entire metatarsus is strongly twisted along its length in derived Hesperornithes such that when the toes are extended, they are directed anterolaterally instead of laterally. Distally, metatarsals II and III bound a distal vascular foramen as is typical of Ornithurae. There is a short, shallow groove proximal to this foramen, but not the deep groove seen in *Parahesperornis* and *Hesperornis*. Metatarsal II is much shorter than III. In distal view, it is shifted caudal to III and IV, a feature shared with other Hesperornithes and more derived Ornithurae. There is a prominent facet for metatarsal I on the ventral surface of metatarsal II. It is developed as a large, deep depression that extends the width of metatarsal II and extends as far as the middle of the shaft. In contrast, the facet is small and very poorly developed in derived Hesperornithes. Metatarsal IV is elongated and subequal to metatarsal III in length, a derived character shared with *Baptornis* and *Pasquiaornis*. *Hesperornis* and *Parahesperornis* also have an elongated metatarsal IV but it greatly exceeds the length of metatarsal III in those taxa. The distal articular surface of metatarsal III is tall and mediolaterally compressed as in other Hesperornithes. The distal articular surface of metatarsal IV is highly asymmetrical, being much taller medially than laterally, and is shifted dorsally relative to metatarsal III: both are derived features of Hesperornithes. The articular surface is subequal in width to that of metatarsal III, as in *Baptornis*; in contrast, the distal articular surface of IV is much broader than III in *Hesperornis* and *Parahesperornis*.

Remarks. The tarsometatarsus represents an archaic bird as evidenced by the absence of a well-developed hypotarsus. Hesperornithiform A is identified as a hesperornithiform on the basis of the following derived characters: metatarsal IV elongate, metatarsal IV dorsally shifted relative to III, distal articular surface of metatarsal II narrow relative to III and IV, distal articular surface of metatarsal IV highly asymmetrical in distal view, with a strong dorsal extension of the medial rim of the condyle. The short, broad, and untwisted metatarsus makes it more primitive than *Pasquiaornis*, Baptornithidae, and Hesperornithidae. In overall size and shape, Hesperornithiform A closely resembles a hesperornithiform from the Nemegt Formation[(23)]. *Potamornis skutchi* has been referred to Hesperornithes and it also occurs in the Lancian (32) and it therefore seems possible that Hesperornithiform A is referable to *Potamornis*; it is also possible that Potamornis corresponds to the second of the two hesperornithiform taxa identified here, Hesperornithiform B (described below).

Hesperornithiform B

Diagnosis. Differs from Hesperornithiform A in smaller adult size.

Description. A second hesperornithiform is represented by a partial tarsometatarsus approximately 2/3 the linear dimensions of Hesperornithiform A. The proximal and distal ends are broken, but the preserved parts of the tarsometatarsus are identical to those described for Hesperornithiform A.

Remarks. Despite its small size, the metatarsals are completely fused, indicating that it represents a mature individual. There is a considerable difference in size: Hesperornithiform A has an estimated mass of 3600 g vs. just 1200 g for Hesperornithiform B. This difference is too large to be explained by intraspecific variation or sexual dimorphism, so this fossil is considered to represent a separate species.

Carinatae Merrem 1813

Ichthyornithes Marsh 1873 *sensu* Clarke 2004

Lancian Ornithurine D

Material. RSM P2992.1, UCMP 187207, AMNH 22002

Distribution. Late Maastrichtian Hell Creek Formation, Montana; Frenchman Formation, Saskatchewan, Lance Formation, Wyoming

Diagnosis. Ornithurine characterized by a shallowly concave, subtriangular scapular facet, a short, deep, and weakly hooked acrocoracoid process, coracoid shaft mediolaterally compressed and bowed dorsally; procoracoid hooked ventrally around the triosseal canal, glenoid lateral to scapular cotyle.

Description. Lancian Ornithurine D represents a basal ornithurine. It is most similar to a bird described from the Campanian of Alberta, Judithian Ornithurine A[40] and to a lesser degree, it resembles *Ichthyornis*[41]. The coracoid has an elongate shaft, which is unusual in being mediolaterally compressed, such that it is much wider dorsoventrally than mediolaterally. In lateral view, the shaft is distinctly bowed, a condition shared with *Enantiornis*, *Ichthyornis*, and Judithian Ornithurine A. The scapular facet is concave but is unusual among Mesozoic ornithurines in being relatively shallow and subtriangular, a condition shared with Judithian Ornithurine A. The procoracoid is strongly hooked forward to wrap around the triosseal canal medially, a condition shared with *Ichthyornis*. The procoracoid is pierced by a supracoracoideus nerve foramen. The acrocoracoid is massive and very deep dorsoventrally, as in Judithian Ornithurine A. It is relatively short and weakly hooked inward around the triosseal canal, features that are typical of basal ornithurines. The glenoid is positioned lateral to the scapular facet, as in *Ichthyornis* and basal birds (including Judithian Ornithurine A) rather than anterior to the facet, as is typical of *Iaceornis* and Neornithes.

Remarks. Lancian Ornithurine D appears to be closely related to Judithian Ornithurine A; the primary difference is that the shaft of the coracoid is more mediolaterally compressed in the Lancian form. Both morphotypes closely resemble coracoids described from the Carrot River Formation of Saskatchewan[43] and they may represent a clade of Cretaceous stem ornithurines related to *Ichthyornis*. Longrich[40] suggested that given the association of the Carrot River coracoids with *Pasquiaornis*, they could belong to *Pasquiaornis*. However, given the close resemblance between *Pasquiaornis* and *Baptornis* it seems unlikely that *Pasquiaornis* would have differed in having such well-developed coracoids; neither do these coracoids resemble those known for *Baptornis*.

***Cimolopteryx rara* Marsh 1892**

Material. YPM 1805

Distribution. Late Maastrichtian Lance Formation, Wyoming

Diagnosis. Ornithurine with a slender, dorsoventrally compressed coracoid shaft, a weakly triangular scapular cotyle, weak medial excavation of the acrocoracoid, a prominent buttress inside the triosseal canal and below the scapular cotyle; coracoid with a lateral process.

Description. *Cimolopteryx rara* is represented by an almost complete coracoid missing only the tip of the acrocoracoid. The shaft of the coracoid is elongate as is typical of derived ornithurines, and the coracoid shaft is dorsoventrally compressed. The lateral margin of the coracoid bears a flange-like lateral process just above the sternal articulation. The sternal articulation is concave to receive the convex articular facet of the sternum, and it has a distinct dorsal facet where the sternum would have overlapped onto the coracoid. Proximally, the coracoid bears a procoracoid process, the base of which is pierced by a supracoracoideus nerve foramen. The scapular cotyle is deeply concave and slightly trihedral. The glenoid is located well anterior to the scapular facet, an apomorphy shared with *Baptornis*, *Ichthyornis*, *Iaceornis*[41] and Neornithes. The glenoid's lateral margin is strongly crescentic, giving the glenoid a semicircular shape that is not seen in any of the other Lancian birds. The acrocoracoid is elongate and strongly hooked inwards to wrap around the triosseal canal, a derived feature shared with *Iaceornis* and Neornithes. The medial surface of the acrocoracoid is excavated by a fossa, although not to the degree seen in Ornithurine F or Ornithurine C. The triosseal canal passes ventral to the scapular cotyle, a derived character shared with *Iaceornis* and Neornithes. Inside the triosseal canal there is a distinctive bony buttress that runs up towards the underside of the scapular facet; this feature is not seen in any of the other birds described here.

Remarks. A number of other specimens have been referred to *Cimolopteryx rara*[30]. These represent a distinct taxon here described as Ornithurine A; *Cimolopteryx rara* is known only from the holotype. Three other species have been referred to the genus *Cimolopteryx*: "*Cimolopteryx*" *minima*, "*Cimolopteryx*" *maxima*, and "*Cimolopteryx*" *petra*. The characters used to support this referral are widely distributed among ornithurines and monophyly is not supported by our phylogenetic analysis. The genus has been diagnosed[30] as having a robust coracoid with a subtriangular neck, a transversely elongate scapular facet, and a small lateral process. However, the coracoids of these birds are not particularly robust; the subtriangular neck of the scapula is found in a range of birds, e.g. *Enantiornis* and *Gallus*, the scapular facet is subequal in anteroposterior and transverse dimensions in *C. rara*, and the lateral process is not preserved on any specimen except for the holotype of *C. rara*. In fact, the differences in the shape of the coracoid neck, scapular facet, glenoid and acrocoracoid are more striking than the similarities and it seems unlikely that the various species actually belong to a single clade, let alone the same genus.

"Cimolopteryx" minima **Brodkorb 1963**

Holotype. UCMP 53976

Distribution. Late Maastrichtian Lance Formation, Wyoming.

Diagnosis. Small ornithurine with a broad, dorsoventrally compressed coracoid shaft, a strongly triangular scapular cotyle, glenoid deflected away from the shaft in dorsal view, lateral edge of glenoid straight in lateral view.

Description. The shaft of the coracoid is unusual in being very broad transversely and strongly compressed dorsoventrally, giving it a plate-like morphology. On the medial surface of the shaft there is an anteroposteriorly elongate procoracoid process, which is pierced by a supracoracoideus nerve foramen. The scapular facet is concave as is typical of Ornithurae, but the outline is strongly triangular rather than circular in dorsal view. The glenoid is located well anterior to the scapular facet as is typical of derived ornithurines, including *Iaceornis* and Neornithes. In dorsal view, the long axis of the glenoid is angled away from the axis of the coracoid, a distinctive feature not seen in the other Lancian birds. In lateral view, the glenoid has a relatively straight lateral margin, giving the glenoid a distinctive squared-off appearance. The acrocoracoid is missing its tip, but it appears to have been typical of derived ornithurines in being elongate and strongly hooked inward around the triosseal canal. The acrocoracoid does not appear to have been excavated medially. As is typical of ornithurines, there is a well-developed triosseal canal, which passes below the scapular facet and procoracoid process.

Remarks. As discussed above, referral of this species to *Cimolopteryx* is unwarranted, particularly in light of the differences in the shape of the coracoid shaft and the shape and position of the glenoid, and this referral is not supported by phylogenetic analysis.

"Cimolopteryx" maxima Brodkorb 1963

Material. UCMP 53973

Distribution. Late Maastrichtian Lance Formation, Wyoming.

Diagnosis. Medium sized ornithurine with an ear-shaped glenoid, a shallow acrocoracoid fossa, and a tear-drop shaped scapular facet with a straight medial edge. Strong caudal extension of the glenoid around the scapular facet.

Description. "*Cimolopteryx*" *maxima* is known from a single worn and fragmentary specimen. Despite the poor preservation, it cannot be assigned to any of the other coracoid forms and appears to represent a distinct taxon. There is a deep, concave scapular facet as is typical of ornithurines. It is almost perfectly circular caudally, but has a straight medial margin, and narrows anteriorly to give it a teardrop shape. This shape is distinct from that seen in the other Lancian birds, including the similar-sized Ornithurine F. The triosseal canal passes beneath the scapular facet. The glenoid is well anterior to the scapular facet, as is typical of derived ornithurines. It has an ear-like shape, with a paddle-shaped anterior part and a narrow, tapering lobe that extends around the scapular facet. The anterior part of the glenoid is narrower than in Ornithurine F and the lobe extends further caudally, further differentiating *C. maxima* from that taxon. The acrocoracoid is broken, but it appears to have been strongly hooked inwards as is typical of derived Ornithurae. It has a shallow medial fossa.

Remarks. No features were found that support referral of this form to *Cimolopteryx* and this assignment was not supported by our analysis.

"Cimolopteryx" petra Hope 2002

Material. AMNH 21911

Distribution. Late Maastrichtian Lance Formation, Wyoming.

Diagnosis. Small ornithurine characterized by a teardrop-shaped scapular cotyle, a glenoid that is strongly angled inwards in dorsal view, and the absence of an acrocoracoid medial fossa.

Description. The coracoid has an elongate neck with a well-developed procoracoid process on its medial surface. The procoracoid process is pierced by a supracoracoideus nerve foramen. The scapular cotyle is transversely elongate and teardrop-shaped, being rounded laterally and pointed medially. The glenoid is located anterior to the scapular facet as in other derived ornithurines, and strongly canted inwards in dorsal view. The acrocoracoid is also typical of derived Ornithurae in that it is long and strongly hooked inwards around the triosseal canal. There is no acrocoracoid medial fossa. The triosseal canal passes ventromedial to the scapular cotyle as in other Ornithurae.

Remarks. As with other species referred to *Cimolopteryx*, the differences are too extensive to warrant referral to the same genus and such an assignment is not supported by phylogenetic analysis.

Ceramornis major Brodkorb, 1963

Holotype. UCMP 53959

Distribution. Late Maastrichtian Lance Formation, Wyoming.

Diagnosis. Medium sized ornithurine with a depression on lateral surface of coracoid posteroventral to glenoid, a prominent acrocoracoid medial fossa, and an ovoid glenoid.

Description. The coracoid is typical of ornithurines in having a well-developed neck and a deeply concave scapular facet. The neck of the coracoid is robust, and is unusual in having a shallow depression on its lateral surface, just behind the glenoid and below the scapular facet. Medially, the base of the procoracoid process is present but its end is missing. It is pierced by a supracoracoideus nerve foramen. The scapular facet is a bowl-shaped depression but its exact shape cannot be determined because the edges are worn. The glenoid is placed anterior to the scapular facet as is typical of derived ornithurae. The base of the acrocoracoid is preserved and suggests that the acrocoracoid was long and would have wrapped around the triosseal canal. A deep fossa excavates the medial surface of the acrocoracoid, as in Ornithurine C. The triosseal canal extends ventromedial to the scapular facet as in other derived Ornithurae.

Lancian Ornithurine A

Material. UCMP 53962, UCMP 53963, RSM P1927.936; AMNH uncatalogued.

Distribution. Lance Formation, Wyoming; Frenchman Formation, Saskatchewan.

Diagnosis. Small ornithurine with a scapular facet that is wider transversely than anteroposteriorly, acrocoracoid deep dorsoventrally, dorsal margin of acrocoracoid with a sharp ridge, procoracoid sharply hooked forwards around triosseal canal, acrocoracoid fossa absent, end of acrocoracoid blocklike.

Description. The coracoid shaft is long and straight as is typical of carinates. On its medial surface there is a small procoracoid process, which hooks upwards towards the acrocoracoid process. It extends caudally along the shaft towards the sternal end of the coracoid. Its base is pierced by a supracoracoideus nerve foramen. The scapular cotyle is ovate, being slightly wider mediolaterally than long. The glenoid is located anterior to the scapular cotyle as is characteristic of derived Ornithurae. It is broadest posteriorly and tapers anteriorly, and has a small caudal extension that wraps around the scapular facet. The acrocoracoid is long and hooks medially around the triosseal canal. Its end has an expansion that is blocklike. The dorsal edge of the acrocoracoid has a sharp ridge; its medial surface lacks a fossa.

Remarks. This form has previously been described as *Cimolopteryx rara* [30, 31], however the two are clearly distinct; referrals of this species to *Cimolopteryx* appear to have been made without comparisons to the holotype.

Lancian Ornithurine B

Material. UCMP 129143

Horizon and Locality. Hell Creek Formation, Montana.

Diagnosis. Medium sized ornithurine characterized by a shallow acrocoracoid fossa and a glenoid that is long, narrow, and anteriorly tapering in lateral view.

Desciption. Ornithurine B is represented by a single worn coracoid. The shaft of the coracoid is long and slender as is typical of carinates. It is slightly wider than tall dorsoventrally, giving it an elliptical cross section. There is a supracoracoideus nerve foramen, but it is unclear whether the procoracoid process was present or not. The scapular facet is cuplike as is typical of Ornithurae. The glenoid is located well anterior to the scapular cotyle, as is typical of derived ornithurines. The glenoid is distinctive in being long and narrow; it is widest just lateral to the scapular facet, and rapidly narrows anteriorly. This shape distinguishes Ornithurine B from any of the other birds described here. The acrocoracoid is long and strongly curved inward. These features are shared with *Iaceornis*[41] and the Neornithes. An acrocoracoid fossa is present but it is weakly developed, as in *Cimolopteryx rara*, rather than prominent as in *Ceramornis* and Ornithurine C.

Lancian Ornithurine C

Material. SDSM 64281 (2 individuals); UCMP 175251, UCMP 187208, MOR 2918, YPM PU 17020

Distribution. Late Maastrichtian Hell Creek Formation, Montana and South Dakota, Lance Formation, Wyoming; Early Palaeocene Fort Union Formation, Montana.

Diagnosis. Large ornithurine characterized by a very deep acrocoracoid fossa, acrocoracoid ending in a massive knob, deep and large scapular facet.

Description. Ornithurine C is easily the largest ornithurine in the assemblage and is rivaled in size only by *Avisaurus*. The coracoid has a relatively robust neck, the procoracoid appears to have been present but is broken off; its base is pierced by the supracoracoideus nerve foramen. The scapular cotyle is similar to that of *Ceramornis*. It is very large, deep, and bowl-shaped, and it is rounded except along the margin of the triosseal canal where its edge is straight. As is typical of derived Ornithurae, the glenoid is located well anterior to the scapular cotyle. It is generally ovate in shape, but wider posteriorly than anteriorly. As is characteristic of derived ornithurines, the acrocoracoid is elongate and strongly hooked inwards. It terminates in a large, rounded knob. The medial surface of the acrocoracoid is excavated by a deep fossa, such that the dorsal margin of the acrocoracoid strongly overhangs this fossa. The triosseal canal passes beneath the scapular cotyle as in other Ornithurae.

Remarks. Ornithurine C is the largest ornithurine known from the assemblage. The large size of the bird suggests that it may belong to *Graculavus augustus*[30]. One specimen (UCMP 187208) is known from the Palaeocene Fort Union Formation of Montana; this bird is therefore the only Late Maastrichtian avian known to cross the K-T boundary.

Lancian Ornithurine E

Material. USNM 181923, AMNH 13011

Distribution. Late Maastrichtian, Lance Formation, Wyoming.

Diagnosis. Small ornithurine characterized by an ovate scapular facet and a glenoid that is laterally deflected in dorsal view.

Description. The coracoid neck is elongate, as is typical of derived ornithurines, and lacks a dorsal fossa. The procoracoid process is large and its base is pierced by a supracoracoideus nerve foramen. The scapular facet is deeply concave, and slightly wider than tall. The glenoid is angled away from the scapular facet in dorsal view, a feature seen only in "*C.*" *minima* among the Lancian birds.

Remarks. The phylogenetic position of this species is uncertain because the acrocoracoid is missing; however, it probably represents a derived ornithurine.

Lancian Ornithurine F

Material. UCMP 53957, ACM 12359

Distribution. Late Maastrichtian Lance Formation, Wyoming.

Diagnosis. Ornithurine characterized by a paddle-shaped glenoid, a massive medial edge to the glenoid, a large scapular facet, and a large scapular facet that is wider mediolaterally than long anteroposteriorly.

Description. The type and referred specimens are very fragmentary but comparisons indicate that they cannot be referred to any of the other coracoid morphs described here and in particular, close inspection suggests that referral to "*Cimolopteryx*" *maxima* is not warranted. As is typical of Cretaceous ornithurines, the scapular facet is deep and bowl-shaped. It is very large, to a greater degree than in "*Cimolopteryx*" *maxima*, and its anteromedial edge along the border of the triosseal canal is straight, as in Ornithurine C and *Cimolopteryx maxima*. Medially the scapular facet narrows to a point, giving it a teardrop shape. The scapular facet is wider mediolaterally than long anteroposteriorly, which differentiates this morph from the similar-sized "*Cimolopteryx*" *maxima*. The glenoid is positioned well anterior to the scapular facet, as is typical of derived ornithurines. The glenoid resembles *Ceramornis* in being paddle-shaped, but it is broader anteriorly than posteriorly. It lacks the long caudal extension of the glenoid seen in *Cimolopteryx maxima*. The acrocoracoid is broken, but there appears to have been a modest acrocoracoid fossa.

Remarks. This form was originally refered to "*Cimolopteryx*" *maxima* by Brodkorb (31). Here it is recognized as a separate species, on the basis of the large scapular facet, the fact that the scapular facet is wider than long, the anteriorly broad glenoid, the limited caudal extension of the glenoid around the scapular facet, and the massive medial margin of the glenoid.

Table S2. List of specimens included in this study.

Taxon	Specimen	Locality	Site
Avisaurus archibaldi	YPM 57235	Hell Creek Formation, MT	
Enantiornithine A	NMC 9528	Frenchman Formation, SK	
Enantiornithine B	YPM 57823	Hell Creek Formation, ND	
Hesperornithiform A	RSM P 2315.1	Frenchman Formation, SK	
Hesperornithiform A	UCMP 13355	Hell Creek Formation, MT	UCMP V82052
Hesperornithiform A	RSM MB.AV.705	Frenchman Formation, SK	
Hesperornithiform B	RSM P2604.1	Frenchman Formation, SK	
Palintropus retusus	YPM 2076	Lance Formation, WY	
Palintropus retusus	AMNH 987	Hell Creek Formation, MT	
"*Cimolopteryx*" *petra*	AMNH 21911	Lance Formation, WY	UCMP V5711
"*Cimolopteryx*" *maxima*	UCMP 53973	Lance Formation, WY	UCMP V5711
Ornithurine F	UCMP 53957	Lance Formation, WY	UCMP V5620
Ornithurine F	ACM 12359	Lance Formation, WY	
"*Cimolopteryx*" *minima*	UCMP 53976	Lance Formation, WY	UCMP V5003
Cimolopteryx rara	YPM 1805	Lance Formation, WY	
Ceramornis major	UCMP 53959	Lance Formation, WY	UCMP V5620
Ornithurine A	UCMP 53962	Lance Formation, WY	UCMP V5620
Ornithurine A	UCMP 53963	Lance Formation, WY	UCMP V5620
Ornithurine A	AMNH uncatalogued	Lance Formation, WY	UCMP V5711
Ornithurine A	RSM P1927.936	Frenchman Formation, SK	
Ornithurine B	UCMP 129143	Hell Creek Formation, MT	UCMP V75178
Ornithurine C	SDSM 64281A	Hell Creek Formation, SD	
Ornithurine C	SDSM 64281B	Hell Creek Formation, SD	
Ornithurine C	UCMP 175251	Hell Creek Formation, MT	UCMP V93126
Ornithurine C	MOR 2918	Hell Creek Formation, MT	
Ornithurine C	YPM PU 17020	Lance Formation, WY	
Ornithurine D	UCMP 187207	Hell Creek Formation, MT	UCMP V84145
Ornithurine D	RSM P2992.11	Frenchman Formation, SK	
Ornithurine E	USNM 181923	Lance Formation, WY	UCMP V5622
Ornithurine E	USNM 13011	Lance Formation, WY	UCMP V5711

2. Diversity

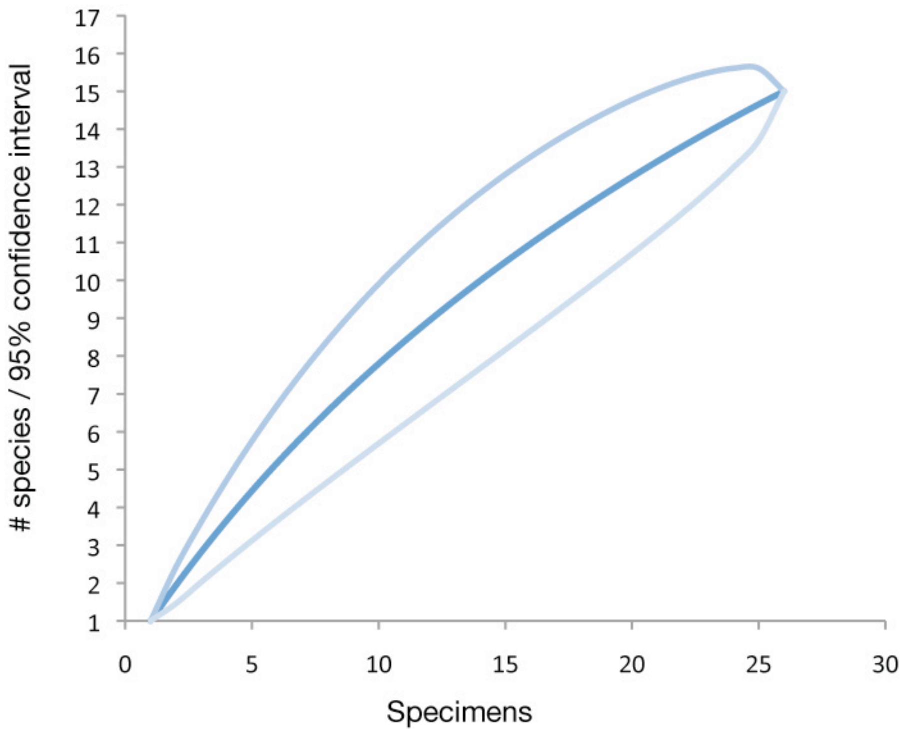

Figure S1. Rarefaction curve for 26 coracoids representing 14 species.

Rarefaction analysis[47] was performed using PAST software[48] to determine how well-sampled the Lancian avian assemblage is. Coracoids were exclusively considered in this study to compare taphonomically comparable elements. Only 26 coracoids were available but these represent 15 distinct taxa, many of which are represented by just a single specimen, which suggests that the assemblage is severely undersampled. As predicted, the rarefaction analysis produces a curve that continues to climb rather than leveling out as would be predicted for a well-sampled assemblage. Although far more species (39) are known from the Jehol Biota[49], the number of specimens from the Jehol exceeds that of the Lancian assemblage by orders of magnitude, and the Jehol biota also spans roughly 11 million years[50], and therefore represents a succession of faunas rather than a single fauna. Taking into the account the limited number of specimens and the narrower interval of time represented by the Lancian biota, it therefore seems likely that the true diversity of the Lancian birds was much higher than that of the Jehol.

3. PHYLOGENETIC ANALYSIS

Methods

The phylogenetic analysis used a modified version of the matrix employed by Zhou et al.[51]. 22 characters from the coracoid and tarsometatarsus were added to the matrix to elucidate the phylogenetic position of the taxa described here, for a total of 46 taxa and 227 characters.

The resulting matrix combines a large number of taxa with a large amount of missing data, because all of the taxa described from the Late Maastrichtian of North America are known from single skeletal elements. Furthermore, most of the ornithurines described here code similarly for most of these characters.

As a result, it is impossible to produce a fully resolved tree, and there is a very large number of most parsimonious trees. Rather than attempt to locate all most parsimonious trees, which would then simply need to be collapsed into a consensus, we estimated the consensus by using the heuristic search algorithm of PAUP* 4.0 b10 [52] to find a subsample of the most parsimonious trees (arbitrarily set at 100,000) and then construct a consensus. The resulting strict and Adams consensus trees (Figure S1) are each the consensus of 100,000 trees with a treelength of 512 steps, consistency index (excluding uninformative characters) of .5558, a retention index of .8107, and a rescaled consistency index of .4576 (supplementary figure 2).

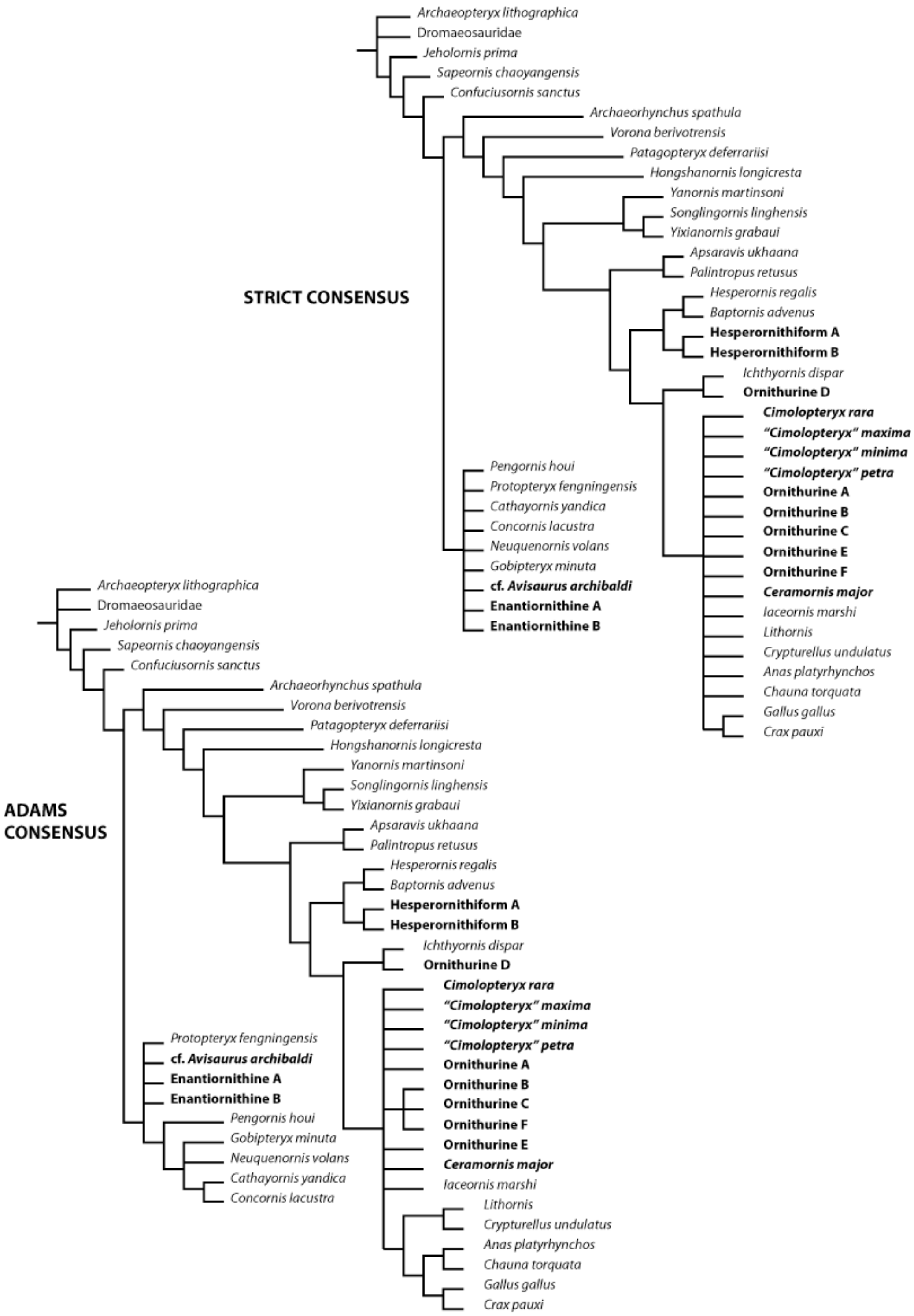

Figure S2. Strict and Adams consensus of 100,000 most parsimonious trees.

Character List

Characters added to the matrix of Zhou et al. [51]

206. Coracoid, glenoid lateral to scapular articulation 0) anterolateral 1) or anterior 2) Ordered)

207. Coracoid, acrocoracoid projecting anteriorly or weakly hooked medially 0) strongly hooked medially 1)

208. Coracoid, procoracoid process: medially projecting 0) or strongly hooked forward and wrapping around the triosseal canal in dorsal view 1)

209. Coracoid, triosseal canal passing ventromedial to scapular articulation: absent 0) or present 1)

210. Coracoid, glenoid projects laterally from body of coracoid as a broad flange: absent 0) present 1)

211. Coracoid, shaft straight in lateral view 0) or bowed dorsally 1)

212. Coracoid, acrocoracoid medial fossa absent 0) or present 1)

213. Coracoid, margin of sternal articulation convex 0) straight or concave 1)

214. Coracoid, acrocoracoid with a facet for articulation with the furcula: absent 0) or present 1)

215. Coracoid, acrocoracohumeral ligament scar on top of acrocoracoid: absent 0) or present 1)

216. Coracoid, medial margin with a continuous sheet of bone extending from the sternum to the scapula 0), reduced to a procoracoid process or lost 1)

217. Coracoid, simple tab-and-slot articulation with sternum 0, or articulation with a tongue-like dorsal process of the sternum 1)

218. Coracoid, medial surface of triosseal canal with a prominent crescentic scar ventrally bounding a fossa: absent (53) or present (1)

219. Coracoid, glenoid laterally or dorsolaterally oriented (53) or dorsally oriented, lying directly atop the head of the coracoid (1)

220. Tarsometatarsus: metatarsal IV shorter than metatarsal III 0) at least as long as

metatarsal III 1)

221. Tarsometatarsus, metatarsal II lies in the same plane as metarsal III 0) or distal articular surface of metatarsal II shifted posteriorly relative to metatarsal III 1)

222. Tarsometatarsus, metatarsal IV lies in the same plane as metatarsal III 0) or distal articular surface of metatarsal IV shifted anteriorly relative to metatarsal III 1)

223. Tarsometatarsus, tarsometatarsus broad 0) or mediolaterally compressed 1)

224. Tarsometatarsus, straight 0) or distal tarsometatarsus twisted laterally relative to proximal end 1)

225. Tarsometatarsus, metatarsal III distal articular surface approximately as wide as or wider than tall 0) or distal articular surface much taller than wide in distal view 1)

226. Tarsometatarsus, metatarsal I articulates with posteromedial surface of metatarsal II 0) or posterior surface of metatarsal II 1)

227. Metatarsal IV: anterior flange absent 0) present along proximal end of bone 1)

Character-Taxon Matrix

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Archaeopteryx_lithographica
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Dromaeosauridae
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3. MASS ESTIMATION

Skeletal preparations of 141 extant volant avian species (representing 100 families) were examined to provide mass estimates from dimensions of coracoids and tarsometatarsi for Lancian birds (Table S4). Only specimens possessing sex identification data were examined. These specimens were obtained from the Yale Peabody Museum's Vertebrate Zoology collection.

Mean body mass estimates and corresponding sex information for each of the bird species were obtained from the CRC Handbook of Avian Body Masses, 2nd edition[54]. A matrix containing the coracoid, tarsometarsus and body mass measurements was constructed, and can be found below (table). In the sex column, M signifies male, F signifies female, B signifies both, and U signifies that the bird's sex was unidentified.

The anteroposterior length of the coracoid's glenoid fossa was measured with digital calipers sensitive to 0.01mm, as pictured below (Fig. S3A). Mediolateral midshaft tarsometarsus width was also measured for these taxa (Fig. S3B). Two reduced major axis regression lines with their 90% confidence intervals were constructed using JMP: Log(mass) vs. Log(anteroposterior glenoid length), and Log(mass) vs. Log(midshaft tarsometatarsus width) (Figs. S4A and S4B, respectively). These regressions were then used to provide mass estimates for the fossil avian taxa examined in this study.

Table S3. Mass estimates and 90% confidence intervals for Lancian birds. Data for AMNH 291911 and USNM 181923 from Hope (2002).

Specimen	Taxon	Anteroposterior glenoid fossa length (mm)	Mass estimate	Upper bound mass estimate	Lower bound mass estimate
RSM P2315.1	Hesperornithiform A	8.7	3580	9490	1372
RSM P2604.1	Hesperornithiform B	5.5	1246	3303	477
YPM 57235	cf. *Avisaurus archibaldi*	16	5388	13157	2234
MOR 2918	Ornithurine C	12.2	2872	7013	1191
SDSM 64281A	Ornithurine C	11.4	2454	5992	1018
NMC 9528	Enantiornithine A	9.2	1492	3643	619
UCMP 53973	*"C." maxima*	8.7	1310	3200	544
UCMP 53957	Ornithurine F	8.7	1310	3200	544
UCMP 53959	*Ceramornis major*	7.8	1017	2484	422
YPM 2076	*Palintropus retusus*	7.4	900	2198	373
RSM P2992.1	Ornithurine D	6.8	740	1807	307
YPM 2012	*Cimolopteryx rara*	5.9	532	1300	221
UCMP 129143	Ornithurine B	5.8	512	1249	212
UCMP53963	Ornithurine A	5.3	415	1013	172
UCMP 53962	Ornithurine A	4.9	346	845	143
UCMP 53976	"*C.*" *minima*	3.8	192	468	80
AMNH 21911	*Cimolopteryx petra*	4.4	269	658	112
USNM 181923	*Ornithurine E*	4.4	269	658	112

Figure S3. A, example of anteroposterior glenoid length measurements made on extant and fossil bird coracoids in this study. B, Example of mediolateral midshaft tarsometatarsus width measurements made on extant and fossil bird material in this study. Bones of *Larus atricilla*.

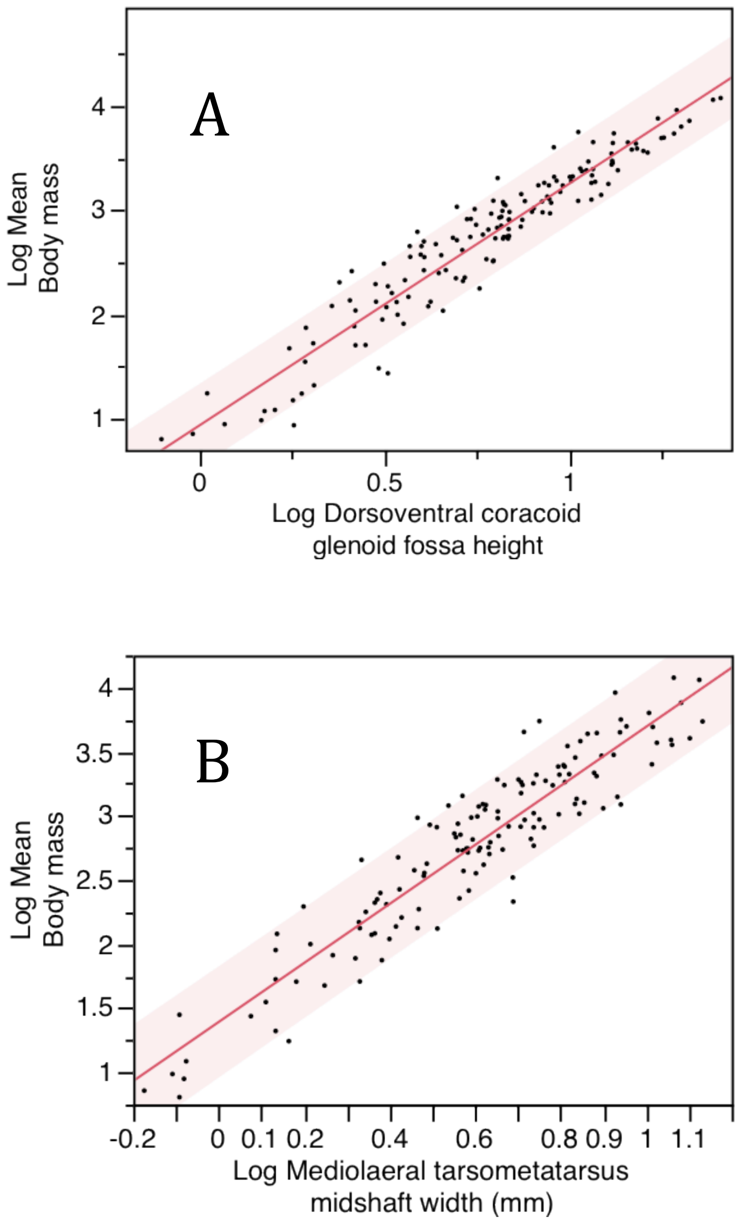

Figure S4. Body mass, in grams, versus glenoid fossa length, in mm (A) and mediolateral midshaft tarsometatarsus width (B). The following reduced major axis regression lines with their 90% confidence limits are drawn: y=0.937454 + 2.3203189*(log glenoid length), R^2=0.904368 (Fig. S4A); y=1.3919324 + 2.3011483*(log midshaft tarsometatarsus width), R^2=0.867408 (Fig. S4B).

Table S4. Masses and linear dimensions used for mass estimates.

Species	Common name	Sex	Yale Peabody Museum collection number	Log mean body mass	Log anteroposterior coracoid glenoid fossa length	Log mediolateral tarsometatarsus midshaft width (mm)
Crypturellus undulatus	Undulated Tinamou	F	109106	2.7930916	0.588831726	0.635483747
Eudromia elegans elegans	Elegant Crested Tinamou	M	104454	2.832508913	0.804139432	0.555094449
Gavia immer	Common Loon	M	103838	3.737192643	1.119255889	0.750508395
Gavia immer	Common Loon	F	102648	3.653212514	1.063333359	0.71432976
Podilymbus podiceps	Pied-billed Grebe	M	102643	2.675778342	0.638489257	0.419955748
Podilymbus podiceps	Pied-billed Grebe	F	107558	2.553883027	0.56937391	0.481442629
Podiceps auritus	Horned Grebe	U	102663	2.656098202	0.568201724	0.33243846
Podiceps auritus	Horned Grebe	U	102645	2.656098202	0.599883072	0.334453751
Aechmophorus occidentalis	Western Grebe	M	104291	3.155032229	0.86923172	0.57054294
Aechmophorus occidentalis	Western Grebe	F	104290	3.078819183	0.820201459	0.537819095
Diomedea exulans	Wandering Albatross	M	102981	3.959518377	1.288919606	0.92788341
Phoebastria albatrus	Short-tailed Albatross	U	106517	3.644537058	1.116607744	0.884795364
Thalassarche bulleri platei	Buller's Albatross	M	110721	3.45331834	1.115943177	0.834420704
Thalassarche cauta cauta	Shy Albatross	M	110722	3.638489257	1.178976947	0.86332286
Pachyptila vittata	Broad-billed Prion	U	110705	2.292256071	0.475671188	0.198657087
Procellaria aequinoctialis	White-chinned Petrel	U	111041	3.083860801	0.925312091	0.625312451
Calonectris diomedea	Cory's Shearwater	U	109740	2.728353782	0.820201459	0.571708832
Calonectris diomedea	Cory's Shearwater	U	109739	2.728353782	0.833784375	0.608526034
Puffinus gravis	Greater Shearwater	U	109773	2.92890769	0.810232518	0.494154594
Phaethon rubricauda	Red-tailed Tropicbird	B	110024	2.818885415	0.835056102	0.730782276
Pelecanus onocrotalus	Great White Pelican	M	102106	4.058805487	1.3872118	1.124504225
Pelecanus onocrotalus	Great White Pelican	F	105864	3.880241776	1.238297068	1.082066934
Pelecanus rufescens	Pink-backed Pelican	F	105865	3.691965103	1.247727833	1.015778756
Pelecanus erythrorhynchos	American White Pelican	M	107559	3.801335096	1.301247089	1.006893708
Pelecanus erythrorhynchos	American White Pelican	F	110867	3.696356389	1.254306332	0.954242509
Pelecanus occidentalis	Brown Pelican	M	102105	3.568436414	1.19893187	1.025305865
Morus bassanus	Northern Gannet	M	111192	3.467163966	1.050379756	0.895974732
Sula nebouxii	Blue-footed Booby	M	109112	3.108226656	0.944975908	0.85308953
Phalacrocorax auritus auritus	Double-crested Cormorant	M	107561	3.31993844	0.958085849	0.797267541
Phalacrocorax auritus auritus	Double-crested Cormorant	F	107560	3.262688344	0.931457871	0.810232518
Phalacrocorax melanoleucos	Little Pied Cormorant	M	110792	2.914871818	0.722633923	0.706717782

Phalacrocorax africanus	Long-tailed Cormorant	B	103559	2.736396502	0.684845362	0.664641976
Anhinga anhinga	Anhinga	B	105119	3.091666958	0.793790385	0.833784375
Fregata magnificens	Magnificent Frigatebird	M	105483	3.102090526	1.058805487	0.855519156
Ardea herodias	Great Blue Heron	M	109114	3.394451681	1.062957834	0.80685803
Ardea herodias	Great Blue Heron	F	110364	3.324282455	1.008174184	0.820201459
Ardea goliath	Goliath Heron	U	106132	3.650113164	1.15715444	0.939019776
Ardea alba	Great Egret	M	102532	2.970811611	0.946943271	0.750508395
Ardea alba	Great Egret	F	102531	2.909556029	0.836956737	0.737192643
Egretta tricolor	Tricolored Heron	M	107575	2.618048097	0.710117365	0.620136055
Egretta thula	Snowy Egret	U	105829	2.56937391	0.653212514	0.572871602
Butorides virescens	Green Heron	B	107569	2.271841607	0.509202522	0.46834733
Nycticorax nycticorax	Black-crowned Night-Heron	B	102316	2.908485019	0.872156273	0.761175813
Tigrisoma mexicanum	Bare-faced Tiger-Heron	F	105901	3.019531685	0.903089987	0.737192643
Botaurus poiciloptilus	Australasian Bittern	M	110759	3.131297797	0.939519253	0.837588438
Mycteria americana	Wood Stork	F	105903	3.382917135	1.045322979	0.809559715
Ciconia ciconia	White Stork	M	102549	3.55278985	1.210586025	1.06069784
Theristicus caudatus	Buff-necked Ibis	B	104522	3.237040791	0.981365509	0.781755375
Eudocimus albus	White Ibis	M	103257	3.015359755	0.900367129	0.843855423
Phoenicopterus ruber	Greater Flamingo	M	102097	3.543198586	1.112939976	0.8162413
Phoenicopterus minor	Lesser Flamingo	F	111198	3.176091259	0.974511693	0.707570176
Cygnus buccinator	Trumpeter Swan	M	140398	4.075546961	1.407730728	1.06483222
Cygnus columbianus	Tundra Swan	M	109899	3.857332496	1.3232521	
Chen caerulescens	Snow Goose	M	143700	3.438384107	1.113274692	
Chen canagica	Emperor Goose	M	103109	3.374748346	1.033021445	
Branta bernicla nigricans	Brant	F	105115	3.089905111	1.022840611	0.618048097
Branta canadensis canadensis	Canada Goose	M	112318	3.581380689	1.167612673	0.846337112
Branta leucopsis	Barnacle Goose	M	103490	3.252367514	1.104487111	0.736396502
Chloephaga rubidiceps	Ruddy-headed Goose	U	105106	3.319314304	1.000434077	0.743509765
Alopochen aegyptiana	Egyptian Goose	M	109245	3.272537777	1.068927612	0.764922985
Anas strepera	Gadwall	M	109124	2.985875357	0.898176483	0.591064607
Anas strepera	Gadwall	F	101923	2.937517892	0.815577748	0.559906625
Somateria mollissima	Common Eider	F	102622	3.282168778	1.004321374	0.701567985
Clangula hyemalis	Long-tailed Duck	F	109701	2.910624405	0.835690571	0.51054501
Melanitta nigra	Black Scoter	M	109916	3.048053173	0.82672252	0.62324929
Melanitta nigra	Black Scoter	F	110999	2.994317153	0.818225894	0.605305046
Melanitta fusca deglandi	White-winged Scoter	M	102112	3.282622113	0.964730921	0.652246341
Melanitta fusca deglandi	White-winged Scoter	F	105120	3.238547888	0.943988875	0.668385917
Bucephala clangula	Common Goldeneye	F	109902	2.851869601	0.814913181	0.565847819
Pipra filicauda	Wire-tailed Manakin	B	109087	1.187520721	0.250420002	
Todirostrum cinereum	Common Tody-Flycatcher	B	105875	0.806179974	-0.102372909	-0.091514981
Menura alberti	Albert's Lyrebird	M	110047	2.967547976	0.788168371	0.716003344
Geothlypis trichas	Common Yellowthroat	M	103495	0.986771734	0.167317335	-0.107905397
Emberiza rutila	Chestnut Bunting	B	107444	1.243038049	0.276461804	0.164352856
Icterus icterus	Troupial	M	102633	1.888740961	0.418301291	0.320146286
Acanthorhynchus tenuirostris	Eastern Spinetail	M	110127	1.075546961	0.176091259	
Paradisaea raggiana	Raggiana Bird-of-paradise	M	104938	2.424881637	0.606381365	
Cyanocorax yucatanicus	Yucatan Jay	B	103072	2.071882007	0.505149978	0.357934847

Corvus brachyrhynchos	American Crow	M	103225	2.730782276	0.799340549	0.559906625
Actophilornis africanus	African Jacana	M	103783	2.136720567	0.40654018	0.414973348
Rostratula benghalensis	Greater Painted-Snipe	B	105558	2.08278537	0.357934847	0.365487985
Haematopus bachmani	Black Oystercatcher	B	109185	2.744292983	0.822168079	0.579783597
Himantopus himantopus	Black-winged Stilt	B	104799	2.206825876	0.519827994	0.428134794
Burhinus capensis	Spotted Thick-knee	U	111287	2.626340367		0.487138375
Pluvialis apricaria	Eurasian Golden-Plover	U	111350	2.330413773	0.555094449	0.689308859
Pluvialis squatarola	Black-bellied Plover	U	102854	2.397940009	0.646403726	0.378397901
Thinocorus rumicivorus	Least Seedsnipe	B	104153	1.725094521	0.307496038	0.133538908
Stercorarius antarcticus	Brown Skua	M	110731	3.239299479	0.915399835	0.710963119
Larus marinus	Great Black-backed Gull	M	109861	3.262213705	1.058805487	0.707570176
Larus glaucescens	Glaucous-winged Gull	M	109211	3.071882007	0.949877704	0.608526034
Anous stolidus stolidus	Brown Noddy	M	102601	2.250420002	0.756636108	0.344392274
Sterna hirundo	Common Tern	U	112355	2.079181246	0.618048097	0.136720567
Uria lomvia	Thick-billed Murre	U	109225	2.984077034	0.837588438	0.465382851
Alca torda	Razorbill	U	111017	2.860936621	0.747411808	0.551449998
Aethia psittacula	Parakeet Auklet	F	111907	2.426511261	0.665580991	0.423245874
Fratercula corniculata	Horned Puffin	F	112022	2.713490543	0.695481676	0.583198774
Columba livia	Rock Pigeon	F	107621	2.531478917	0.77524626	0.480006943
Columbina inca	Inca Dove	U	105877	1.67669361	0.243038049	0.247973266
Ducula poliocephala	Pink-bellied Imperial-Pigeon	B	103079	2.744292983	0.731588765	0.583198774
Hemiphaga novaeseelandiae	New Zealand Pigeon	B	110710	2.814913181	0.780317312	0.59439255
Dumetella carolinensis	Gray Catbird	U	105843	1.547774705	0.285557309	0.11058971
Terpsiphone rufiventer	Black-headed Paradise-Flycatcher	U	107086	1.178976947	0.252853031	
Cacatua sulphurea	Yellow-crested Cockatoo	M	109927	2.51054501	0.7930916	
Trichoglossus haematodus	Rainbow Lorikeet	B	103743	2.123851641	0.624282096	0.465382851
Nestor notabilis	Kea	M	110766	2.980457892	0.926856709	0.653212514
Eclectus roratus	Eclectus Parrot	B	109602	2.748962861	0.831229694	0.611723308
Amazona leucocephala	Cuban Parrot	B	102305	2.356025857	0.716837723	0.563481085
Tauraco corythaix	Knysna Turaco	U	105024	2.488550717	0.498310554	
Coccyzus erythropthalmus	Black-billed Cuckoo	U	112021	1.706717782	0.421603927	0.181843588
Crotophaga ani	Smooth-billed Ani	M	103238	2.039346	0.421603927	0.399673721
Geococcyx californianus	Greater Roadrunner	U	110410	2.575187845	0.597695186	0.457881897
Tyto alba alba	Barn Owl	M	111167	2.51851394	0.794488047	0.688419822
Bubo virginianus pallescens	Great Horned Owl	F	112030	3.057666104	0.822168079	0.899820502
Asio otus	Long-eared Owl	M	104526	2.416640507	0.411619706	0.58546073
Podargus ocellatus plumiferus	Marbled Frogmouth	F	110392	2.309630167	0.378397901	0.392696953
Caprimulgus carolinensis	Chuck-will's-widow	B	110392	2.037426498	0.658011397	
Cypseloides senex	Great Dusky Swift	B	104165	1.999130541	0.53529412	0.214843848
Colius striatus	Speckled Mousebird	U	103480	1.7084209	0.44870632	0.330413773
Trogon viridis	White-tailed Trogon	B	110029	1.952792443	0.494154594	0.133538908
Ceryle alcyon	Belted Kingfisher	U	111019	2.170261715	0.564666064	0.328379603
Momotus momota lessonii	Blue-crowned Motmot	B	103071	2.123851641	0.477121255	0.330413773
Aceros undulatus	Wreathed Hornbill	M	107215	3.400537989	1.028571253	1.013679697

Pteroglossus aracari aracari	Black-necked Aracari	F	110031	2.348304863	0.692846919	0.371067862
Melanerpes formicivorus	Acorn Woodpecker	M	103894	1.912753304	0.551449998	0.267171728
Phylloscopus trochilus	Willow Warbler	U	107095	0.939519253	0.255272505	
Coragyps atratus atratus	Black Vulture	U	111066	3.334252642	1.060320029	0.878521796
Pandion haliaetus	Osprey	M	104411	3.147057671	1.084933575	0.932980822
Milvus migrans	Black Kite	B	104087	2.753583059	0.836324116	0.631443769
Gyps africanus	White-backed Vulture	U	109139	3.735039705	1.28171497	1.13225969
Accipiter novaehollandiae	Gray Goshawk	M	104650	2.551449998	0.607455023	0.602059991
Buteo jamaicensis	Red-tailed Hawk	F	111065	3.087781418	0.87909588	0.941014244
Aquila chrysaetos	Golden Eagle	M	102002	3.591064607	1.181843588	1.058426024
Sagittarius serpentarius	Secretarybird	B	111126	3.603901832	0.957128198	1.102433706
Leipoa ocellata	Malleefowl	M	137673	3.308564414	0.805500858	0.88422877
Ortalis vetula	Plain Chachalaca	M	102075	2.766412847	0.765668555	0.737192643
Opisthocomus hoazin	Hoatzin	U	109946	2.84260924	0.868056362	0.655138435
Anthropoides virgo	Demoiselle Crane	B	111249	3.38327665	1.13001195	0.794488047
Grus canadensis canadensis	Sandhill Crane	F	102539	3.474507639	1.114944416	0.924279286
Aramus guarauna	Limpkin	U	102828	3.033423755	0.695481676	0.653212514
Psophia crepitans	Gray-winged Trumpeter	B	102505	3.011147361	0.743509765	0.795880017
Porzana carolina	Sora	U	109051	1.873901598	0.28780173	0.382017043
Gallicrex cinerea	Watercock	M	107198	2.701567985	0.606381365	0.633468456
Fulica cristata	Red-knobbed Coot	U	105277	2.916980047	0.733197265	0.678518379
Heliornis fulica	Sungrebe	B	102505	2.120573931	0.532754379	0.511883361
Eurypyga helias	Sunbittern	B	104542	2.322219295	0.711807229	0.365487985
Ardeotis kori	Kori Bustard	F	105280	3.749736316	1.02325246	0.941014244
Wilsonia pusilla	Wilson's Warbler	B	103585	0.857332496	-0.017728767	-0.173925197
Dendroica coronata	Yellow-rumped Warbler	M	103759	1.086359831	0.204119983	-0.075720714
Piranga ludoviciana	Western Tanager	B	103927	1.44870632	0.506505032	-0.091514981
Parus major	Great Tit	F	107236	1.245512668	0.021189299	
Troglodytes troglodytes	Winter Wren	B	105036	0.949390007	0.068185862	-0.080921908
Sitta carolinensis	White-breasted Nuthatch	B	106968	1.322219295	0.309630167	0.133538908
Bombycilla cedrorum	Cedar Waxwing	M	110272	1.485721426	0.484299839	
Passer domesticus	House Sparrow	F	109463	1.437750563	0.509202522	0.075546961

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