Anurans from the Lower Cretaceous Jehol Group of Western Liaoning, China

Liping Dong1*, Zbyněk Roček2, Yuan Wang1, Marc E. H. Jones3

1 Key Laboratory of Vertebrate Evolution and Human Origin of Chinese Academy of Sciences, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China, 2 Institute of Geology, Department of Palaeobiology, Academy of Sciences of the Czech Republic, Prague, Czech Republic, 3 Research Department of Cell and Developmental Biology, University College London, London, United Kingdom

Abstract

Background: To date, the Lower Cretaceous Jehol Group of western Liaoning, China has yielded five monotypic genera of anurans, including Liaobatrachus grabai, Callobatrachus sanyanensis, Mesophryne beipiaoiensis, Dalianbatrachus mengi, and Yizhoubatrachus macilentus. However, the validity and distinctness of these taxa have been questioned.

Methodology/Principal Finding: We provide a comprehensive analysis of the Jehol frogs that includes a re-examination of the published taxa as well as an examination of a number of new specimens that have been collected over the past 10 years. The results show that the five previously named taxa can be referred to three species of one genus—Liaobatrachus grabai, L. beipiaoiensis comb. nov., and L. macilentus comb. nov.. The diagnosis of Liaobatrachus is revised, and a new diagnosis is provided for each species of this genus. We also establish Liaobatrachus zhaii sp. nov., on the basis of a dozen well-preserved specimens from a new locality. This taxon is distinguished by a unique combination of characteristics, including relatively long hind limbs, a rounded rather than triangular acetabulum, and a gradually-tapering cultriform process of the parasphenoid. In addition, an unnamed frog from a higher horizon, which has narrow sacral diapophyses and particularly long legs, is different from Liaobatrachus and represents another form of anuran in the Jehol Biota.

Conclusion/Significance: Comparisons with other Mesozoic and extant anurans and the primary phylogenetic analysis both suggest that Liaobatrachus is a member of the anuran crown-group and forms a polytomy with leiopelmatids (Ascaphus and Leiopelma) and the remaining crown-group anurans (Lalagobatrachia).

Introduction

The Jehol Biota represents an Early Cretaceous lacustrine terrestrial ecosystem with a high degree of diversity and endemism [1,2]. It contains a variety of Mesozoic taxa including the early bird Confuciusornis and its relatives [3], the feathered tyrannosaurid Yixianrannus huailu [4], and the early eutherian Acriatherium yanensis [5]. The Jehol Biota is best known from the Jehol Group, which is exposed in western Liaoning, northern Hebei and southeastern Inner Mongolia. The Jehol Group consists of, in ascending order, the Dabeigou Formation, the Yixian Formation, the Jiufotang Formation, the Dabin’ergou Formation, the Qingshankou Formation, and the Qingshankou Group. Its age has been estimated as ascending order, the Dabeigou Formation, the Yixian Formation [6], the Jiufotang Formation, and the Dabin’ergou Formation [7].

Liaobatrachus grabai, Ji and Ji 1998 [8], and Callobatrachus sanyanensis Wang and Gao 1999 [9], Mesophryne beipiaoiensis Gao and Wang 2001 [10], Dalianbatrachus mengi Gao and Liu 2004 [11], and Yizhoubatrachus macilentus Gao and Chen 2004 [12]. Because each taxon was based on a single specimen, some anatomical characters were ambiguous or even incorrectly interpreted. For example, Liaobatrachus grabai was reported to have no ribs [8], the centra of Mesophryne beipiaoiensis were reported to be procoelous [10], and Dalianbatrachus mengi was considered to have fused frontoparietals [11]. Some revisions have been made [13], but many problems and uncertainties remain unresolved. Based on new fossil discoveries and a re-examination of all reported taxa, this paper provides the first comprehensive study of the Jehol anurans, including revisions of established taxa and erection of a new taxon.

Materials and Methods

Institutional Abbreviations

CYH, Chaoyang Bird Fossil National Geopark, Chaoyang, Liaoning; DNM D, Dalian Natural History Museum, Dalian,
Localities and Materials

We examined 25 specimens from eight fossil localities in the area around Yixian, Beipiao and Chaoyang in western Liaoning (Fig. 1). The anuran-bearing horizons are the Lujiatun, Jian- shangou and Dawangzhangzi Beds of the Yixian Formation, and the Jiufotang Formation (Fig. 2) [14]. There are not anurans currently known from the Dabeigou Formation. The localities and their anuran fossil content are as follows (also see Table 1):

1. Lujiatun Locality: near Lujiatun Village, 25 km northwest of Beipiao City, Liaoning Province; Lujiatun Bed, Yixian Formation; Barremian. Specimen IVPP V13245 (a three-dimensionally preserved incomplete skeleton) was excavated here.

2. Qianyangou Locality: about 1.5 km west of Qianyangou Village, Shangyuan Town, Beipiao City, Liaoning Province; Lujiatun Bed, Yixian Formation; Barremian. All of the specimens from this locality are three-dimensionally preserved. They include IVPP V13236 (a partial skeleton with part of the skull and most of the postcranial bones preserved), IVPP V13239 (a partial skeleton lacking the urostyle, ilia, and hind legs), IVPP V13300 (a partial skeleton with the skull and pectoral girdle preserved), IVPP V14203 (a nearly complete skeleton missing only some limb bones), IVPP V14206 (the smaller of two frogs preserved on one slab, with the upper and lower jaws and most of the postcranial bones preserved), IVPP V14270 (the larger on the slab that also bears specimen IVPP V14269, a partial skeleton with part of the skull, part of the appendicular skeleton and nearly all of the vertebral column preserved), IVPP V13238 (a partial skeleton with part of the vertebral column, the pelvis and the hind limbs preserved), IVPP V13379 (a partial skeleton with most of the cranial bones missing), and IVPP V14608 (a partial skeleton consisting of the posterior portion of the vertebral column, the pelvis and the hind limbs). Specimen IVPP V14979, which represents several frogs preserved on two associated slabs, was also recovered from this locality. Some of the skeletons are nearly complete, with only a few bones disarticulated and displaced. The first slab bears two adult skeletons (IVPP V14979.1 and IVPP V14979.2) and two juvenile skeletons (IVPP V14979.3 and IVPP V14979.4), whereas the second slab (not considered in the paper as they are the young individuals of IVPP V14979.1) bears two frogs: IVPP V14979.5 and IVPP V14979.6 [15].

3. Sihetun Locality: 1.5 km southwest of Sihetun Cunminzu (a “Cunminzu” is a subdivision of a village), Chaomidianzi Village, Shangyuan Town, Beipiao City, Liaoning Province; Jianshangou Bed, Yixian Formation; Barremian/Aptian. Specimens found here include GMV2126 (see Ji and Ji, 1998 [8]), IVPP V11525 (see Wang and Gao, 1999 [9]), MV 77 (a nearly complete skeleton with a slightly displaced pelvis), IVPP V12717 (a nearly complete skeleton with part of the vertebral column displaced and the limbs not preserved), and CYH 004 (a nearly complete skeleton).

4. Heitizigou Locality: 0.5 km east of Libalanggou Village, Zhangjiying Township, Beipiao City, Liaoning Province; Jianshangou Bed, Yixian Formation; Barremian/Aptian. Specimen LPM 0030 (see Gao and Wang, 2001 [10]) was found here.

5. Huangbanjigou Locality: near Huangbanjigou Village, Shangyuan Town, Beipiao City, Liaoning Province, 3 km northeast of the Sihetun Locality; Jianshangou Bed, Yixian Formation; Barremian/Aptian. Specimen DNM D2166/7 (see Gao and Liu, 2004 [11]) was found here.
6. Hejiaxin Locality: near Hejiaxin Village 15 km west of the Yixian County, Jinzhou City, Liaoning Province; Dawangzhangzi Bed, Yixian Formation; Aptian. Specimens ZMNH M8621 (see Gao and Chen, 2004 [12]) and IVPP V12510 (a nearly complete skeleton) were found here.

7. Wangjiagou Locality: about 20 km northeast of Yixian, Jinzhou City, Liaoning Province; Dawangzhangzi Bed, Yixian Formation; Aptian. Specimen IVPP V12541 (a nearly complete skeleton with disarticulated and displaced cranial bones) was found here.

8. Xierhuqiao Locality: 6 km southwest of Yixian, Jinzhou City, Liaoning Province; Jiufotang Formation; Aptian. Specimen IVPP V13235 (see Wang et al., 2007 [16]) was recovered here.

All of the specimens mentioned above are owned by and deposited in museums or research institutes, and access to them was granted through proper official channels.

**Nomenclatural Acts**

The electronic edition of this article conforms to the requirements of the amended International Code of Zoological Nomenclature, and hence the new names contained herein are available under that Code from the electronic edition of this article. This published work and the nomenclatural acts it contains have been registered in ZooBank, the online registration system for the ICZN. The ZooBank LSIDs (Life Science Identifiers) can be resolved and the associated information viewed through any standard web browser by appending the LSID to the prefix “http://zoobank.org/”. The LSID for this publication is: urn:lsid:zoobank.org:pub:8C96D835-EB8F-4664-9CA1-99A0E2CDAA4B. The electronic edition of this work was published in a journal with an ISSN, and has been archived and is available from the following digital repositories: PubMed Central, LOCKSS.

**Phylogenetic Analysis**

To determine the systematic positions of the Jehol frogs studied in this paper, we conducted a phylogenetic analysis of 25 taxa and 65 characters in PAUP 4.0b10 using the Branch-and-Bound search option. All characters were unordered and equally weighted, and ACCTRAN optimization was used to minimize the possibility of parallelisms. The resulting trees were rooted by using Caudata as an outgroup. The taxon-character matrix (see

![Figure 2. Stratigraphic distribution of Jehol anurans described in this paper.](http://zoobank.org/)

1. basalt and andesite with volcanic breccia (lava); 2. conglomerate with volcanic breccia; 3. sandstone and conglomerate; 4. tuffaceous sandstone and tuff; 5. shale and tuff.

doi:10.1371/journal.pone.0069723.g002
Table 1. List of anuran specimens examined in this paper (arranged according to geological age).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Age</th>
<th>Horizon</th>
<th>Locality</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVPP V13245</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Lujijatun</td>
</tr>
<tr>
<td>IVPP V13236</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V13239</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V13380</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V14203</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V14269</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V14270</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V14979.1</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V14979.2</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>*IVPP V14979.3</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>*IVPP V14979.4</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V13328</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V13379</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>IVPP V14068</td>
<td>Barremian</td>
<td>Lujijatun Bed</td>
<td>Qianyangou</td>
</tr>
<tr>
<td>GMV2126</td>
<td>Barremian/Aptian</td>
<td>Jianshangou Bed</td>
<td>Sihetun</td>
</tr>
<tr>
<td>IVPP V11525</td>
<td>Barremian/Aptian</td>
<td>Jianshangou Bed</td>
<td>Sihetun</td>
</tr>
<tr>
<td>IVPP V12717</td>
<td>Barremian/Aptian</td>
<td>Jianshangou Bed</td>
<td>Sihetun</td>
</tr>
<tr>
<td>MV 77</td>
<td>Barremian/Aptian</td>
<td>Jianshangou Bed</td>
<td>Sihetun</td>
</tr>
<tr>
<td>CYH 004</td>
<td>Barremian/Aptian</td>
<td>Jianshangou Bed</td>
<td>Sihetun</td>
</tr>
<tr>
<td>LPM 0030</td>
<td>Barremian/Aptian</td>
<td>Jianshangou Bed</td>
<td>Sihetun</td>
</tr>
<tr>
<td>DNM D2166/7</td>
<td>Barremian/Aptian</td>
<td>Jianshangou Bed</td>
<td>Huangbanjigou</td>
</tr>
<tr>
<td>ZWNH M6821</td>
<td>Aptian</td>
<td>Dawangzhangzi Bed</td>
<td>Hejiaxin</td>
</tr>
<tr>
<td>IVPP V12510</td>
<td>Aptian</td>
<td>Dawangzhangzi Bed</td>
<td>Hejiaxin</td>
</tr>
<tr>
<td>*IVPP V12541</td>
<td>Aptian</td>
<td>Dawangzhangzi Bed</td>
<td>Wangjiagou</td>
</tr>
<tr>
<td>*IVPP V13235</td>
<td>Aptian</td>
<td>Jiufotang Formation</td>
<td>Xieruqiao</td>
</tr>
</tbody>
</table>

*juvenile individual.
doi:10.1371/journal.pone.0069723.t001

Table S1 was adapted from Wang, 2006 [13] with some amendments to the character descriptions and coding. We exclude the invalid taxa “Callobatrachus”, “Mesophyne”, and “Tzihoubatrachus” from the Jehol Biota of China, as well as the disarticulated material from Japan (the Teto frog). The amended matrix also reflects our revised view, described below of the species-level taxonomy of Liaobatrachus. Character definitions mainly follow Gao and Chen, p. 762, figs 2–3.

Character 3: Medial contact between nasals: contact present, or nasals slightly separated medially (0); nasals widely separated medially (1); or nasals fused medially (2).

Character 31: Parahyoid: plate-shaped (circular or triangular plate) (0); V-shaped splint (1); absent (2).

Character 50: Shape of coracoid: medial end of coracoid very broadly expanded (0); medial end of coracoid moderately expanded, about as wide as distal end (1); medial end of coracoid slightly expanded (2).

Systematic Paleontology

Amphibia Gray, 1825

Anura Fischer von Waldheim, 1813

Family incertae sedis Liaobatrachus Ji and Ji, 1998

1998 Liaobatrachus Ji and Ji, p. 39, fig. 1
1999 Callobatrachus Wang and Gao, p. 637, fig. 1
2001 Mesophyne Gao and Wang, p. 461, figs 2–4
2004 Delianobatrachus Gao and Liu, p. 2, fig. 1; pl. 1, fig. 1
2004 Tzihoubatrachus Gao and Chen, p. 762, figs 2–3

Type species: Liaobatrachus grabaus Ji and Ji, 1998

Revised diagnosis. A crown-group anuran having the following unique combination of characteristics: medium body size (snout-vent length [SVL] 62–94 mm, with location of vent in living animal considered to correspond to that of posterior end of ischium); skull wider than long; dermal roofing bones unsculptured; maxilla deep and bifurcated anteriorly; quadratojugal present; nasals with extensive midline contact; a large fontanelle between paired frontoparietals; squamosal with short zygomatic ramus that does not contact maxilla; vomer with dentigerous portion bearing 6–10 teeth arranged in single row and long postchoanal process (as long as, or longer than prechoanal process), which forms narrow angle with prechoanal process; parabovoid V-shaped; columella present; nine amphicoelous presacral vertebrae; atlas with type II coyles (located ventral to the foramen magnum and adjacent to each other [17]); three pairs of recognizable ribs on presacrals II–IV (either unfused with corresponding transverse processes, or coalesced with transverse processes but with boundary recognizable in each case as thickened or unossified seam); sacral diapophyses broadly dilated and fan-like with convex lateral edges; sacro-urostyal articulation monocondylar; urostyle with one pair of transverse processes; scapula short and discoglossid-like whose anterior margin is straight and whose anteromedial margin is overlapped by distal end of clavicle; cleithrum not bifurcated medially; ilium with no dorsal protuberance or dorsal crest.

Comparisons (with leioleptomatsids, discoglossids, and other Jurassic and Cretaceous anurans). In contrast to extant leioleptomatids [18–22], Liaobatrachus has nasals that contact one another medially (instead of lacking midline contact), a quadratojugal and columella (bones that absent in leioleptomatids), neural arches that are imbricated (instead of non-imbricated with the spinal canal partially exposed), sacral diapophyses that are fan-like (instead of rod-like), and a monocondylar sacro-urostyal articulation (instead of a non-condylar one). Liaobatrachus is similar to leioleptomatids in lacking dermal sculpture on the cranial roofing bones, having paired frontoparietals that bound a fontanelle, lacking a free palatine, and having nine amphicoelous presacral vertebrae, a cleithrum that is not distally bifurcated, and recognizable ribs present on presacral II–IV.

Liaobatrachus differs from discoglossids [23–26] in having a maxilla with a bifurcated anterior end (instead of an unbifurcated one), a cleithrum that is not distally bifurcated, nine amphicoelous presacral vertebrae (instead of eight opisthocoelous ones), a monocondylar sacro-urostyal articulation (bicondylar in most discoglossids, although monocondylar in Barbouriule), and an ilium that lacks a dorsal protuberance and dorsal crest. Liaobatrachus and discoglossids share many characteristics, such as: free palatine absent, paired frontoparietals with fontanelle present, quadratojugal present, anteromedial margin of scapula overlapped by distal end of clavicle, second through fourth presacral vertebrae bear recognizable ribs, and rib on third presacral with uncinate process, sacral diapophyses dilated, one pair of transverse processes on urostyle.

Liaobatrachus differs from Prosaliurus Shubin and Jenkins 1995 [27] from the Lower Jurassic of Arizona in having a simplified
A1, skeleton of the holotype, GMV2126. A2, enlargement of the left radioulna, carpals and hand. The carpals are arranged in three rows: a proximal one containing the radiale and ulnare, a middle one containing distal carpal V and element Y, and a distal one containing distal carpals II-IV. There is one prepollex element situated medial to element Y (indicated by arrow). B1, skeleton of the referred specimen IVPP V11525. B2, enlargement of part of the skull. The long postchoanal process of the vomer is marked by a white arrow, and the short, free zygomatic ramus of the squamosal by a black arrow. C1, skeleton of the referred specimen MV 77. C2, enlargement of the premaxilla and the anterior end of the maxilla. The arrow marks the bifurcated anterior end of the maxilla. C3, enlargement of the vertebral column. There are 10 presacrals and the last one is partially fused with the sacrum, a condition that probably represents a developmental anomaly. D, ilium of the referred specimen CYH 004. The round acetabulum is marked by an arrow.

doi:10.1371/journal.pone.0069723.g003

Liaobatrachus is distinguished from Vieraella by being larger (SVL = 33 mm in Vieraella), and by having a fused prootic and exoccipital, a cultriform process of the parasphenoid that is long and reaches the level of the vomers (rather than relatively short as in Vieraella), fewer presacral vertebrae (10 in Vieraella) and fan-like sacral diapophyses (instead of rod-like). However, Liaobatrachus has a greater number of similarities with Vieraella than with Prosalirus. For example, both Liaobatrachus and Vieraella are characterized by extensive contact between the nasals, and by having a fontanelle between the frontoparietals.

Liaobatrachus is different from Notobatrachus Reig 1956 [28,29] from the Middle to Upper Jurassic of Argentina, in being smaller (SVL: 120–140 mm in Notobatrachus), lacking dermal sculpture on the cranial roofing bones, displaying contact between the nasals and between the frontoparietals, having a single well-ossified
sphenethmoid (instead of a pair of ossification centers, sometimes called “orbitosphenoids”), having a fused prootic and exoccipital, having a V-shaped parahyoid (rather than crescent shaped), having fan-like sacral diapophyses (instead of rod-like), lacking discrete postsacral vertebrae (one discrete postsacral vertebra is present in most Notobatrachus specimens), and having a mono-condylar sacro-urostylar articulation (rather than a non-condylar one). The two taxa are similar in having nasals with an extensive midline contact, paired frontoparietals surrounding a fontanelle, a vomer with a dentigerous portion, nine amphicoelous presacral vertebrae, imbricated neural arches, an atlas with type II cotyles, recognizable ribs, and an ilium without a dorsal protuberance or dorsal crest.

Liaobatrachus differs from Eodiscoglossus Villalta 1957 [30,31] from the Middle and Upper Jurassic of Europe in having nasals with an extensive midline contact (midline contact absent in Eodiscoglossus), nine amphicoelous presacral vertebrae (instead of eight opisthocoelous ones), and an ilium without a dorsal protuberance or dorsal crest (both present on the ilium of Eodiscoglossus). Liaobatrachus is similar to Eodiscoglossus in lacking dermal sculpture on the cranial roofing bones, bearing a fontanelle between the paired frontoparietals, and having a low and long coronoid process on the angulosplenial,
recognizable ribs only on presacrals II–IV, imbricated neural arches, fan-like sacral diaphyses, and one pair of transverse processes on the urostyle.

*Liaobatrachus* differs from *Wealdenbatrachus* Fey 1988 [32], a supposedly *Endosigophorus*-like taxon from the Lower Cretaceous of Spain, in at least two respects: the ilium lacks a dorsal crest (strong dorsal crest present in *Wealdenbatrachus*) and the sacral diaphyses are fan-like (rather than rod-like).

*Liaobatrachus* differs from *Gobiates* Șpinar and Tatarinov 1986 [33,34] and *Cretasalia* Gubin 1999 [34,35] from the Upper Cretaceous of Central Asia in the following respects: (1) cranial dermal sculpture; in *Gobiates* pit-ridge sculpture is present on all dermal roofing cranial bones, dermal sculpture in *Cretasalia* is limited to the maxilla, and *Liaobatrachus* lacks dermal sculpture; (2) morphology of maxilla: in *Gobiates* this bone is not bifurcated anteriorly and has a small facial process, whereas in *Liaobatrachus* the facial process is proportionally larger and the anterior end is bifurcated into dorsal and ventral rami (unknown in *Cretasalia*); (3) contact between nasals: the nasals of *Gobiates* and *Cretasalia* are in contact anteriorly, but not in *Liaobatrachus* which has extensive midline contact; (4) squamo-maxillary contact: in *Gobiates* and *Cretasalia* the zygomatic ramus of the squamosal is long in and contact with the maxilla, whereas in *Liaobatrachus* it is short and does not contact one another; (5) morphology of vomer: the vomer of *Gobiates* has no postchoanal process, whereas that of *Liaobatrachus* bears a long postchoanal process (unknown in *Cretasalia*); (6) cultriform process of parasphenoid: the cultriform process of *Gobiates* does not reach the level of vomers, whereas that of *Liaobatrachus* does (unknown in *Cretasalia*); (7) fusion of the urostyle: in *Gobiates* and *Cretasalia* the two bones are separated by a suture, instead of fully fused as in *Liaobatrachus*.

However, these three anurans also share many similarities. For example, the frontoparietals of all three bound a large fontanelle; the presacrals are amphicoelous; the neural arches are strongly imbricated; the urostyle has one pair of transverse processes; and the ilium lacks a dorsal crest.

*Liaobatrachus* also differs from *Cordicephalus* Nevo 1968 and *Thoraciliacus* Nevo 1968 [36–38] from the Lower Cretaceous of the Middle East in a number of respects. These include (1) vertebral number: seven or eight presacral vertebrae present in *Cordicephalus* and *Thoraciliacus*, compared to nine in *Liaobatrachus*; (2) vertebral structure: episthochelicous with well developed transverse processes in *Cordicephalus*, but amphicoelicous with short transverse processes in *Liaobatrachus* (unknown in *Thoraciliacus*); (3) vomerine teeth: absent in *Cordicephalus* (unknown in *Thoraciliacus*), but present and arranged in a single row in *Liaobatrachus*; (4) parashenophoid shape: lateral wings absent in *Cordicephalus* and *Thoraciliacus*, but present in *Liaobatrachus*; (5) frontoparietal morphology: broad and axygnous in *Cordicephalus* and *Thoraciliacus*, but paired in *Liaobatrachus*; and (6) size: *Cordicephalus* and *Thoraciliacus* small-bodied (SVL: 30–40 mm), but *Liaobatrachus* large-bodied (SVL: 62–94 mm).

*Liaobatrachus* differs from *Aygroua* Jones, Evans and Sigogneau-Russell 2003 [39] from the Lower Cretaceous of Morocco with respect to iliac structure: the ilium of *Aygroua* has a strong dorsal crest, flared ventral acetabular rim, and prominent medial buttress, whereas the ilium of *Liaobatrachus* has none of these features.

**Remarks.** *Callobatrachus*, *Mesophryne*, *Dalibatrachus* and *Yichuanbatrachus* are re-assigned to *Liaobatrachus* based on thorough examination of their holotypes and newly collected fossils from Sihetun, Qianyangou, and Hejixian localities. All of the latter fossils can also be referred to this genus as detailed below.

**Liaobatrachus grabaui** Ji and Ji, 1998

Figure 3A–D

1998 *Liaobatrachus grabaui* Ji and Ji, p. 39, fig. 1

1999 *Callobatrachus sanyanensis* Wang and Gao, p. 637, fig. 1

**Holotype.** GMV2126, incomplete skeleton in dorsal view, with vertebral column and pelvis articulated but skull and limbs disarticulated and displaced.

**Type locality and horizon.** Sihetun Locality; Jianshangou Beds, Xian Formation, Barremian/Aptian (125±1 Ma) [40–42].

**Referred specimens.** IVPP V11525 (holotype of "*Callobatrachus sanyanensis*" [Fig. 3B], MV 77 (Fig. 3C), CYH 004 (Fig. 3D).

**Revised diagnosis.** The type species of *Liaobatrachus* differs from other species referred to this genus in having the following unique combination of features: relatively short hind limbs, tibiofibula and femur subequal in length, maxilla with palatine process, and only one prepollex element present.

**Description.** CYH 004 (SVL = 78.6 mm), IVPP V11525 (SVL = 94 mm) and MV 77 (SVL = 83.5 mm) represent adult frogs. However, GMV2126 (SVL~73 mm) probably represents a young adult, judging by the absence of ossified epiphyses on the long bones.

The skull is wider than long. No sculpture is present on the dermal roofing bones, maxilla, or squamosal (IVPP V11525, MV 77). The nasals are in extensive contact with each other medially (IVPP V11525, MV 77), and each nasal possesses an obvious rostral process which extends to the distal end of the alary process of the premaxilla (MV 77). The anterolateral margin of the nasal is moderately concave, and a low parochoanal process is present halfway along its length (IVPP V11525, MV 77). The paraorbital process is long and directed laterally, forming the anterior margin of the orbit together with the maxilla (CYH 004, MV 77). The paired frontoparietales are separated by a suture along the posterior portion (GMV2126), and anteriorly they bound a large fontanelle that extends for more than half the total length of the frontoparietales (GMV2126, IVPP V11525, MV 77). The orbital margin is straight, and a frontoparietal shelf is present (IVPP V11525). The structure of the alae of the parashenophoid is unknown due to poor preservation. The prootic and exoccipital are fused in adults (GMV2126, CYH 004, IVPP V11525, MV 77). The columella (IVPP V11525, MV 77) has a swollen footplate and bar-like shaft. The squamosal (IVPP V11525) is T-shaped, with three rami. The zygomatic ramus is short and does not contact the maxilla. The otic ramus articulates with the otic capsule, but does not contact the frontoparietal. The ventral ramus is the longest of the three, and extends ventrally to articulate with the quadratojugal.

The premaxilla (IVPP V11525, MV 77) bears about 24 tooth positions. The base of the alary process is perpendicular to the main body, but the distal end of the process is directed laterally. The development of the horizontal lamina is unknown due to the fact that the premaxillae are exposed only in dorsal view. The posterior process is absent (CYH 004). The maxilla bifurcates anteriorly into ventral and dorsal rami (GMV2126, IVPP V11525, MV 77), and the ventral ramus articulates with the premaxilla (MV 77). In life, the longer dorsal ramus likely had a ligamentous connection with the alary process of the premaxilla (MV 77). The facial process (GMV2126, MV 77) is prominent, and perpendicular to the main body of the maxilla. The disarticulated right maxilla of GMV2126, exposed in ventral view, reveals the presence of a palatine process and also shows that the zygomatico-maxillary process is less well developed than the facial process (GMV2126). The maxilla extends posteriorly to the level of the otic capsule (IVPP V11525, MV 77). The number of maxillary teeth is unknown, but exceeds 30. The quadrate is
ossified and fused with the quadratojugal, completing the maxillary arch (CYH 004, IVPP V11525, MV 77).

The vomer bears a plate-like anterior portion located just posterior to the articulation between the premaxilla and maxilla (IVPP V11525, MV 77). The prominent prechoanal and postchoanal processes of the vomer are directed laterally and define a narrow angle (IVPP V11525, MV 77). The morphology of the ventral aspect of the vomer is unknown, as this bone is exposed dorsally in all specimens in which it is preserved. A short ossified portion of the nasal septum projects from the sphenethmoid (IVPP V11525, MV 77). The pararenalis is exposed only in IVPP V11525 and MV 77, in both cases through the frontotemporal fontanelle, and the important feature of the lateral portion cannot be observed in either specimen. The pterygoid is triradiate (CYH 004, GMV2126, IVPP V 11525, MV 77); the anterior ramus is the longest of the three and articulates with the posterior portion of the maxilla, the medial ramus partially overlaps the anterior surface of the otic capsule, and the posterior ramus articulates with the quadratojugal.

The lower jaw is composed of a dentomaxillary bone (MV 77), dentary and angulosplenial (CYH 004, IVPP V11525). The angulosplenial bears a low coronoid process. A notch is not present on the coronoid process. Only the postcoronoid process of the hyoid plate can be observed (CYH 004, IVPP V11525).

The vertebral column generally consists of nine clearly amphicoelous presacral vertebrae (IVPP V11525), the sacral vertebra, and the urostyle. However, there are 10 presacral vertebrae in MV 77, and the last presacral vertebra of this specimen is partially fused to the sacral vertebra. The left transverse process of the tenth presacral and the left sacral diaphysis are distally fused to form an enlarged sacral diaphysis, but remain separated proximally. We regard this occurrence as a developmental anomaly, as is true of a similar morphological pattern that has previously been reported in extant anurans [43]. The neural arches are imbricated (GMV2126, IVPP V11525, MV 77), and bear low spines which probably do not extend posteriorly beyond the posterior margins of the neural arches (MV 77). Presacrals II–IV possess recognizable ribs that are either free from the transverse processes of the vertebrae (IVPP V11525, MV 77) or fused with them (GMV2126, MV 77). The ribs of presacral II are “hatchet-like”, each bearing an uncinate process at the distal end. The ribs of presacral III are longer than those associated with presacral II, and each bears an uncinate process located at the midlength. The ribs of presacral IV lack uncinate processes. The posterior presacrals of the vertebral column have transverse processes that are either nearly perpendicular to the body axis (GMV2126) or only slightly inclined anteriorly (CYH 004, IVPP V11525, MV 77). The sacral diaphyses are dilated and fan-like, with convex lateral margins (GMV2126, CYH 004, IVPP V11525, MV 77). The urostyle is long, and a pair of short transverse processes is present on the anterior part of this bone (GMV2126, IVPP V11525).

The clavicle is strongly curved (GMV2126, CYH 004, IVPP V11525), with a finger-like lateral end that partially overlaps the anterior surface of the pars acromialis of the scapula (CYH 004, IVPP V11525). The sulcus for the pectorocaudal cartilage can be seen in IVPP V11525 and MV 77. The medial and lateral ends of the coracoid are nearly equal in width (IVPP V11525, MV 77). The short scapula has a straight or slightly concave anterior margin (GMV2126, CYH 004, IVPP V11525, MV 77), and a deep interglenoidal sinus between the pars acromialis and pars glenoidealis (GMV2126, IVPP V11525). The clithrum has a nearly straight anterior margin (GMV2126, CYH 004, IVPP V11525, MV 77) and is not distally bifurcated (GMV2126, CYH 004, IVPP V11525).

The humerus bears a well developed ventral crest proximally (GMV2126, MV 77), and a deep cubital fossa (MV 77). The radial epicondyle is poorly developed whereas the ulnar one is moderately well developed. The medial and lateral crests are absent (MV 77), suggesting that the skeleton probably belongs to a female. The radioulna bears a well developed olecranon process (GMV2126, CYH 004, IVPP V11525, MV 77). The carpals are arranged in three rows: a proximal one containing the radiale and ulnare, a middle one containing distal carpal V and element Y, and a distal one containing distal carpals II–IV (GMV2126, CYH 004, MV 77) [44]. One large prepollex element is located medial to the second finger (GMV2126, CYH 004 MV 77) [45]. The phalangeal formula of the manus is 2-2-3-3 (IVPP V11525, MV 77).

The ilium does not have a dorsal crest or dorsal protuberance, and is slightly swollen where the acetabular region meets the shaft (GMV2126, IVPP V11525, MV 77). No further morphological details can be discerned, due to poor preservation. The ischium is kidney-shaped (CYH 004, IVPP V11525, MV 77), and the pubis is unossified.

The femur is sigmoid in shape, and its proximal portion bears a weak femoral crest (CYH 004, IVPP V11525, MV 77). The tibiofibula is slightly shorter than the femur and shows a nutrient foramen at the midlength (CYH 004, IVPP V11525, MV 77). The tibiae and fibulae are free from one another (GMV2126, IVPP V11525, MV 77). The distal tarsals are unossified and the phalangeal formula of the pes is 2-2-3-4-3 (IVPP V11525, MV 77).

Remarks. The holotype of Liaobatrachus grabaui (GMV2126) was first described in 1998. At that time Liaobatrachus was mistakenly assigned to the family Pelobatidae based on the supposed presence of several characteristics [8], including: frontoparietals fused together, procoelous presacrals, presacrals II–IV with long diapophyses (but no ribs), and fan-like sacral diaphyses. However, re-examination of GMV2126 reveals that this specimen has three pairs of recognizable ribs rather than long presacral transverse processes, and that the frontoparietals are paired. The type of the centrum in GMV2126 cannot be determined due to poor preservation of the specimen. Therefore, referral of Liaobatrachus grabaui to the Pelobatidae is not supported.

“Callobatrachus sanyanensis” (IVPP V11525) was the second named Jehol anuran, and this specimen is better preserved than the holotype (GMV2126) of Liaobatrachus grabaui. In previous studies [9,10,13], IVPP V11525 was assigned to the Discoglossidae based on the supposed presence of opisthocoelous presacral centra and a bicondylar sacro-urostylar articulation. However, more thorough preparation of the fossil and re-interpretation of its osteology suggest that the presacral centra are in fact amphicoelous and that the sacro-urostylar articulation cannot be referred to as bicondylar. Furthermore, this specimen differs from GMV2126 only in the degree of ossification of the olecranon process of the radioulna, a difference that is probably ontogenetic. Therefore, “Callobatrachus sanyanensis” is here considered to represent a junior synonym of Liaobatrachus grabaui.

**Liaobatrachus beipiaoensis** (Gao and Wang, 2001) comb. nov.

**Figure 4A–C**

2001 Mesophytyne beipiaoensis Gao and Wang, p. 461, figs 2–4

2004 Dalianbatrachus mengi Gao and Liu, p. 2, fig. 1, pl. 1, fig. 1

**Holotype.** LPM 0030, a nearly complete skeleton exposed on part and counterpart slabs, with the skull slightly distorted.
Type locality and horizon. Heitizigou locality; Jianshangou Bed, Yixian Formation, Barremian/Aptian (125±1 Ma).

Referred specimens. DNM D2166/7 (holotype of “Dalibatrachus mengi”) (Fig. 4B), IVPP V12717 (Fig. 4C).

Revised diagnosis. This species differs from other Liaobatrachus species in having the following unique combination of characteristics: relatively long hind limbs, femur slightly longer than tibiofibula, ilium with subcircular acetabulum, and two prepollex elements present.

Description. LPM 0030 (SVL = 69 mm), DNM D2166/7 (SVL = 73.5 mm), and IVPP V12717 (SVL = 83 mm) are all adults.

As in the type species of Liaobatrachus, the skull is relatively wide and lacks sculpture on the cranial bones (LPM 0030, DNM D2167). Medial contact between the nasals is extensive (LPM 0030, DNM D2167, IVPP V12717), and the paracranial process is present but relatively weakly developed (LPM 0030, IVPP V12717). The paraorbital process extends laterally, but fails to reach the maxilla and thus leaves the anterior orbital margin incomplete (LPM 0030, DNM D2167). The paired frontoparietals are in contact with each other posteriorly, but bound a large fontanelle anteriorly (IVPP V12717). The lateral edges of these bones are straight, and each bears a shelf (DNM D2167, IVPP V12717). Behind the orbit the frontoparietals expand laterally but do not form prominent alae (IVPP V12717). Specimen IVPP V12717 shows that the prootic and exoccipital are fused, and that the columella is composed of a swollen footplate and bar-like shaft. The T-shaped squamosal (IVPP V12717) has a short zygomatic ramus that does not contact the maxilla; the ventral ramus is the longest of the three, and extends ventrally to articulate with the ossified quadrates.

There are about 23 tooth positions on the dental lamina of the premaxilla (LPM 0030). The anterior portion of the maxilla is dorsoventrally bifurcated (LPM 0030), and the ventral ramus articulates with the premaxilla. The dorsal ramus is longer than the ventral one, and is directed anterodorsally (LPM 0030). The maxilla extends posteriorly to the level of the otic capsule (IVPP V12717). The number of tooth positions on the maxilla cannot be determined. The quadratogular, together with the premaxilla and maxilla, completes the maxillary arch (IVPP V12717).

The vomer has a plate-like anterior portion (DNM D2166), and prominent prechoanal and postchoanal processes which are directed laterally and define a narrow angle between them (LPM 0030, DNM D2167). The dentigerous area is not preserved. The cultriform process of the paraprosphenoid has a rounded tip (IVPP V12717) and reaches the level of the vomer (DNM D2166). The paraprosphenoid alae are narrow (their anteroposterior length being less than 1/3 of the distance between their lateral ends); the lateral and posterior margins of the alae are obscured by postcranal bones in available specimens. Thus, whether the paraprosphenoid bears a posteroalatal notch and posterior process is unknown. The pterygoid is triradiate (LPM 0030, DNM D2167, IVPP V12717), and articulates with the maxilla, otic capsule, and quadratojugal.

The lower jaw is formed by the coalesced dentomaxillarian bone and dentary (LPM 0030, DNM D2167), and by the angulosplenial. The angulosplenial (LPM 0030, DNM D2167) has a low coronoid process, but it is not possible to assess whether notches are present on the anterior and posterior margins of the process.

There are nine presacral vertebrae. The centra of the presacra are clearly amphicoelous (DNM D2167, IVPP V12717). The neural arches are imbricated and bear low spines (IVPP V12717). The atlantal cotyles (IVPP V12717) are ventrally located and close to each other, and can be recognized as type II of Lynch (1971).

Recognizable ribs are associated with presacra II–IV. These may be free (LPM 0030, IVPP V12717) or fused to the transverse processes (DNM D2167). The ribs of presacral II bear uncinate processes at their tips (LPM 0030, DNM D2167, IVPP V12717), whereas those of presacral III have uncinate processes at the midlength (LPM 0030, IVPP V12717). The transverse processes of the posterior presacra are generally anteriorly inclined (DNM D2167, IVPP V12717), but in some cases extend straight laterally (LPM 0030). As in the type species, the sacral diapophyses are fan-like (LPM 0030, DNM D2167, IVPP V12717). The sacro-urostyal articulation is clearly monocoondylar (IVPP V12717). The urostyle bears a pair of short transverse processes (LPM 0030) and a spinal nerve foramen, but no dorsal crest is present (IVPP V12717).

The curved clavicle (DNM D2167) has a finger-like lateral end that partially overlaps the anterior surface of the pars acromialis of the scapula (DNM D2167, IVPP V12717). The medial end of the bar-like coracoid is slightly wider than the lateral end (CVH 004, IVPP V12717). The scapula is short, with a slightly concave anterior margin (LPM 0030, DNM D2167, IVPP V12717) and an interglenoideal sinus separating the pars acromialis and pars glenoideal (DNM D2167). The cleithrum is not distally bifurcated (LPM 0030, IVPP V12717), and the anterior margin of this bone is nearly straight (IVPP V12717).

The humerus has a well developed ventral crest (LPM 0030, DNM D2167, IVPP V12717). In specimen IVPP V12717 this bone lacks radial and ulnar epicondyles in addition to medial and lateral crests, probably reflecting sexual dimorphism and indicating a female individual. The cubital fossa is deep (IVPP V12717). The radioulna has a well developed olecranon process (LPM 0030, IVPP V12717). The carpus is configured as in the type species (DNM D2166, IVPP V12717). Two prepollex elements, of which the distal one is the larger, are located medial to the second finger (LPM 0030, DNM D2167). The phalangeal formula of the manus is 2-2-3-3 (DNM D2167, IVPP V12717). The ilium has neither a dorsal crest nor a dorsal protuberance (IVPP V12717). The pars ascends is moderately developed (IVPP V12717) but the pars descendens (IVPP V12717) is barely discernible. The ischia are fused (LPM 0030, IVPP V12717) and the pubes are unossified.

The proximal portion of the sigmoid femur bears a crest (IVPP V12717). The tibiofibula, which is nearly as long as the femur, shows a nutrient foramen (IVPP V12717). The tibiofibula, which is nearly as long as the femur, shows a nutrient foramen (IVPP V12717). The tibial crest and fibular crest are free from one another (LPM 0030, DNM D2166/7, IVPP V12717), and articulates with the maxilla, ilium with subcircular acetabulum, and two prepollex elements present. The proximal portion of the sigmoid femur bears a crest (IVPP V12717). The dens of the tibia is large (IVPP V12717). The distal margins of the tibia and fibula are free from one another (LPM 0030, DNM D2167). The urostyle bears a pair of short transverse processes (LPM 0030, IVPP V12717) and a spinal nerve foramen, but no dorsal crest is present (IVPP V12717).

The ilium has neither a dorsal crest nor a dorsal protuberance (IVPP V12717). The pars ascendens is moderately developed (IVPP V12717) but the pars descendens (IVPP V12717) is barely discernible. The ischia are fused (LPM 0030, IVPP V12717) and the pubes are unossified.

The proximal portion of the sigmoid femur bears a crest (IVPP V12717). The dens of the tibia is large (IVPP V12717). The distal margins of the tibia and fibula are free from one another (LPM 0030, DNM D2167). The urostyle bears a pair of short transverse processes (LPM 0030, IVPP V12717) and a spinal nerve foramen, but no dorsal crest is present (IVPP V12717).

Remarks. LPM 0030 was catalogued as IVPP V11721 when it was made the holotype of the new putative “Mesophryne beipiaonis” [10], but was subsequently returned to the municipal government of Beipiao and catalogued in the Liaoning Paleontological Museum under its present specimen number. Only the part slab [published as IVPP V11721A, now LPM 0030], which preserves less of the skull than the counterpart, is currently available. The counterpart slab was probably lost after being returned to Liaoning. Contrary to the original description of the specimen [10], the carpus of LPM 0030 does not contain an intermedium and the presacral centra cannot be determined to be prococelous. The specimen has the general characteristics of the genus Liaobatrachus, including a bifurcated maxilla, a nasal and vomer of the appropriate shape, recognizable ribs on presacra II–IV, fan-like sacral diapophyses, and transverse processes on the urostyle, and is reassigned to Liaobatrachus in this paper to form the new combination L. beipiaonis.
Different catalogue numbers (DNM D2166, DNM D2167) have been given to the part and counterpart of the holotype of "Dalianbatrachus mengi", even though both components belong to the same individual [11]. DNM D2166/7 has paired frontoparietals and an amphicoelous presacral centrum, and displays virtually no differences from LPM 0030. Thus we regard "Dalianbatrachus mengi" as a junior synonym of Liaobatrachus beipiaensis.

Liaobatrachus macilentus (Gao and Chen, 2004) comb. nov

Figure 5A, B
2004 Yizhoubatrachus macilentus Gao and Chen, p. 762, figs 2–3

Holotype. ZMNH M8621, nearly complete skeleton with some cranial bones slightly displaced, and metacarpals and phalanges of left forelimb preserved as imprint.

Type locality and horizon. Hejiacin locality; Dawangzhangzi Bed, Yixian Formation, Aptian (122 Ma) [2].

Referred specimens. IVPP V12510 (Fig. 5B), IVPP V12541.

Revised diagnosis. This species differs from other species of Liaobatrachus in having the following unique combination of features: femur slightly longer than tibiofibula, maxilla bearing a palatine process, cultriform process of parasphenoid ending in slender needle-like tip (tapering abruptly at a point located about 1/3 of the skull length posterior to the rostrum), anterior
acetabular margin of ilium pointed anteriorly, and two prepollex elements present.

**Description.** IVPP V12510 (SVL = 62 mm) is an adult, but is not fully grown, and ZMNH M8621 (SVL = 56 mm) is a juvenile.

As in the type species of *Liaobatrachus*, the skull is relatively wide. The nasal has a long paraorbital process which is directed laterally and forms the orbital margin together with the maxilla (ZMNH M8621). The frontoparietals are paired and border a large anterior fontanelle (IVPP V12510). The orbital margin is straight and a frontoparietal shelf is present (ZMNH M8621, IVPP V12510). In ZMNH M8621, the medial margin of the anterior portion of the frontoparietal is thickened. The posterior portions of the frontoparietals are sutured together, and extend slightly laterally behind the orbits (IVPP V12510). The otic capsules are nearly completely overlapped in ventral view by the alae of the parasphenoid (IVPP V12510), and a faint suture can be recognized between the prootic and exoccipital. The columella (ZMNH M8621, IVPP V12510) has a swollen footplate and bar-like shaft, and the T-shaped squamosal (IVPP V12510) has a short zygomatic ramus that does not contact the maxilla.

There are 18–20 tooth positions on the dental lamina of the premaxilla (IVPP V12510, ZMNH M8621). The alary process extends dorsally, but the distal end of the process is laterally inclined. The anterior portion of the maxilla is thick, and probably bifurcated (ZMNH M8621). The facial process is prominent and nearly perpendicular to the main body of the maxilla. The palatine process is well developed, and positioned anterior to the facial process (ZMNH M8621). The horizontal lamina widens posteriorly (ZMNH M8621), and thus probably possesses a pterygoid process. The posterior end of the maxilla reaches the level of the otic capsule, and is obtuse and rounded (IVPP V12510). The maxilla bears 41 tooth positions (ZMNH M8621, IVPP V12510), and the tooth row extends beyond the level of the pterygoid process. The quadratojugal is present, and is fused with the ossified quadrate (IVPP V12510).

The vomer has prominent prechoanal and postchoanal processes, which diverge laterally at a narrow angle from one another (ZMNH 8621, IVPP V12510). A dentigerous area with about 6 tooth positions arranged in a single row is present close to the midline, medial to the choana. The sphenethmoid has a prominent anterior process, representing the ossified part of the nasal septum. The parasphenoid has a cultriform process that reaches the level of the vomer. The process is slightly constricted at its base, and widens gradually up to its midpoint before tapering to a slender and needle-like tip (ZMNH M8621, IVPP V12510). The nature of the alae and posterior margin is unknown. The pterygoid (ZMNH M8621, IVPP V12510) is triradiate: the anterior ramus is the longest of the three and extends anteriorly to articulate with the maxilla, whereas the medial ramus contacts the otic capsule.

The lower jaw is formed mainly by the coalesced mentomeckelian bone and dentary (ZMNH M8621, IVPP V12510), and the angulosplenial. The angulosplenial has a low but distinct coronoid process, with a smooth posterior margin and an anterior margin that is probably interrupted by a notch (ZMNH M8621). A V-shaped parahyoid and bar-like posteromedial process of the hyoid plate are preserved (ZMNH M8621, IVPP V12510).

The axial column is comprised of nine presacral vertebrae, the sacral vertebra, and the urostyle. The atlas and presacral II are nearly completely overlapped in ventral view by the alae of the parasphenoid (IVPP V12510), and a faint suture can be recognized between the prootic and exoccipital. The columella (ZMNH M8621, IVPP V12510) has a triradiate: the anterior ramus is bifurcated (ZMNH M8621). The facial process is prominent and nearly perpendicular to the main body of the maxilla. The palatine process is well developed, and positioned anterior to the facial process (ZMNH M8621). The horizontal lamina widens posteriorly (ZMNH M8621), and thus probably possesses a pterygoid process. The posterior end of the maxilla reaches the level of the otic capsule, and is obtuse and rounded (IVPP V12510). The maxilla bears 41 tooth positions (ZMNH M8621, IVPP V12510), and the tooth row extends beyond the level of the pterygoid process. The quadratojugal is present, and is fused with the ossified quadrate (IVPP V12510).

The ilium does not have a dorsal crest or dorsal protuberance, and is somewhat rugose at the point of transition between the acetabular portion and the shaft (ZMNH M8621, IVPP V12510). The anterior margin of the acetabulum (ZMNH M8621, IVPP V12510) is pointed anteriorly rather than rounded, and the anterior and ventral margins both rise to form crests. The pars ascendens is moderately well developed, but the pars descendens is nearly lacking (ZMNH M8621, IVPP V12510). The ischia are fused, and kidney-like (IVPP V12510). The pubes were cartilaginous.

The femur is slightly longer than the tibiofibula (ZMNH M8621, IVPP V12510), and the latter bone bears a nutrient foramen at its midpoint (IVPP V12510). The tibiale and fibulare are not fused together (ZMNH M8621, IVPP V12510). The distal tarsals were cartilaginous. The phalangeal formula of the pes is 2-2-3-3 (IVPP V12510).

**Remarks.** Wang (2006) pointed out that the holotype of “*Tzouhaitrachus macilentus*” (ZMNH M8621) actually represents a medium-sized subadult frog (SVL: 56–62 mm) rather than a large frog as reported in the original paper (SVL = 115 mm according to Gao and Chen, 2004, page 766), so the lack of an ossified mesopodium in both the fore- and hind limbs is likely a non-diagnostic subadult feature. This conclusion is further supported by discovery of a larger specimen (IVPP V12510) from the same locality and closely resembling ZMNH M8621, which does have ossified carpals and probably represents an adult. Moreover, whether the parasphenoid of ZMNH M8621 has a posterior process is uncertain, because the posterior margin is obscured in the available specimens. The presacral centrum are amphicoelous, not opisthocoelous as previously reported. This degree of conformity with the diagnosis of *Liaobatrachus* indicates that “*Tzouhaitrachus*” is a junior synonym of *Liaobatrachus*.
Etymology. The species name honors Professor Ermi Zhao, a prominent Chinese herpetologist.

Holotype. IVPP V14979.1, a nearly complete, three-dimensionally preserved skeleton exposed in ventral aspect, the largest and most complete of four specimens preserved on a single block of silty sandstone.

Paratypes. IVPP V14979.2, a nearly complete, three-dimensionally preserved skeleton in ventral aspect. IVPP V14203, a nearly complete, three-dimensionally preserved skeleton in ventral aspect, with only the distal parts of the forelimbs missing. IVPP V13239, a partial, three-dimensionally preserved skeleton in dorsal aspect, retaining the skull, the presacral section of the vertebral column and parts of the forelimbs but lacking the pelvic and hind limbs.

Type locality and horizon. Qianyangou locality; Lujiatun Bed, Yixian Formation, Barremian (slightly older than 125 Ma) [2,42,46].

Referred specimens. IVPP V13236, IVPP V13245 (Fig 7C), IVPP V13380, IVPP V14269, IVPP V14270, IVPP V14979.3, IVPP V14979.4, probably IVPP V13238, IVPP V13379, and IVPP V14608. All are from the type locality and surrounding area (Lujiatun Village).

Diagnosis. This new species of Liaobatrachus differs from other members of the genus in having the following unique combination of characteristics: relatively long hind limbs, tibiofibula nearly as long as femur, parasphenoid with cultriform process that tapers gradually beginning at the midpoint, maxilla without palatine process, ilium with round acetabulum, and pubis ossified in fully grown adults.

Description. (based on type specimens) IVPP V14979.1 (SVL = 73.8 mm), IVPP V13239, and IVPP V14203 (SVL = 80.5 mm) are fully grown adults, whereas IVPP V14979.2 (SVL = 73 mm) is an early adult.

The skull is wider than long. No sculpture is present on the dermal roofing bones, maxilla, or squamosal (IVPP V 13239, IVPP V 14203). The nasals contact one another extending along
their medial margins (IVPP V13239) and each possesses an obvious rostral process, which extends as far as to the level of the alary process of the premaxilla (IVPP V14979.1, IVPP V13239). The anterolateral margin is moderately concave (IVPP V14979.1, IVPP V13239), and a low parachoanal process is present at the midpoint of the margin (IVPP V13239). The paraoideal orbital process (IVPP V13239) is long and laterally directed, forming the anterior margin of the orbit together with the maxilla. The paired frontoparietals are sutured together posteriorly, and their anterior portions border a large fontanelle that is more than half as long as the frontoparietal (IVPP V13239). The orbital margin is straight, and a frontoparietal shelf is present. The posterior portion of the frontoparietal extends laterally but is not developed as wing-like process, and the lateral process, paraoccipital process, posterior process and posterolateral canthus can all be seen (IVPP V13239). The prootic and exoccipital are completely fused with each other on both sides of the skull (IVPP V13239). The supracondylar crest extends from the posterolateral canthus of the frontoparietal to the torus terminalis. The two occipital condyles, located near each other, are mainly ventral to the foramen magnum. A columnella (IVPP V13239) is present. The squamosal (IVPP V13239) is T-shaped. The short zygomatic ramus does not contact the maxilla, and is directed anteriorly and medially. The vomer has a plate-like anterior portion (IVPP V14203), and the prominent premaxillary and postmaxillary processes of this bone are directed laterally and define a narrow angle (IVPP V13239, 14203). The vomer bears about 20 tooth positions (IVPP V14329). The alary process (IVPP V13239) is short. The basal portion of the alary process is perpendicular to the main body of the premaxilla, and the distal portion is directed laterally. The horizontal lamina of the premaxilla (IVPP V14203) has a poorly developed palatine process but no posterior process. The maxilla bifurcates into ventral and dorsal rami anteriorly, and only the ventral ramus articulates with the premaxilla (IVPP V14203). The dorsal ramus is the longer of the two, and probably had a ligamentous connection with the alary process of the premaxilla in the living animal (IVPP V13239). The maxilla bifurcates into ventral and dorsal rami anteriorly, and only the ventral ramus articulates with the premaxilla (IVPP V14203). The dorsal ramus is the longer of the two, and probably had a ligamentous connection with the alary process of the premaxilla in the living animal (IVPP V13239). The maxilla bears at least 48 tooth positions (IVPP V14979.2). The facial process (IVPP V13239, IVPP V14203) is prominent, and perpendicular to the main body of the maxilla. The palatine process is absent (IVPP V14979.2), and the zygomatico-maxillary process is small (IVPP V13239). The facial process (IVPP V14203) is prominent, and perpendicular to the main body of the maxilla. The palatine process is absent (IVPP V14979.2), and the zygomatico-maxillary process is small (IVPP V13239). The maxilla extends posteriorly to the level of the otic capsule (IVPP V13239, IVPP V14979.2). The quadratojugal, which articulates with the posterior end of the maxilla (IVPP V13239, IVPP V14203, IVPP V14979.2). The vomer has a plate-like anterior portion (IVPP V14203), and the prominent premaxillary and postmaxillary processes of this bone are directed laterally and define a narrow angle (IVPP V13239, 14203).
IVPP V14203, IVPP V14979.1. The dentigerous portion is located medial to the choana, and bears 10 teeth arranged in a single row. The sphenethmoid is long in fully grown adults (IVPP V14203, IVPP V14979.1) but poorly developed in young adults, in which the nasal septum is cartilaginous (IVPP V14979.2). The cultriform process of the parahyoid bone, whose base is slightly constricted, extends anteriorly to the level of the vomer (IVPP V13380). The cultriform process is widest at the midpoint, and tapers gradually as it continues anteriorly. The alae are long and narrow, their anteroposterior width being less than 1/3 of the distance between their lateral ends. There is no notch (IVPP V14979.1) in the postero-lateral margin of the ala, but a distinct posterior process (IVPP V14979.2) is present in the middle of the posterior margin. The anterior ramus of the pterygoid articulates with the pterygoid process of the maxilla (IVPP V14203, IVPP V14979.1, IVPP V14979.2). The medial ramus of the pterygoid (IVPP V13239) partially overlaps the anterior surface of the otic capsule, and the posterior ramus (IVPP V14979.1, IVPP V14979.2) contacts the ventral ramus of the squamosal.

The lower jaw is comprised of a mentomeckelian bone (IVPP V14203), a dentary (IVPP V14203, IVPP V14979.1), a prearticular (IVPP V14203, IVPP V14979.1, IVPP V14979.2), a dentary (IVPP V14203, IVPP V14979.1, IVPP V14979.2), and the cubital fossa is deep (IVPP V14203). The humeral condyle may be either ossified (IVPP V13239, IVPP V14979.1) or unossified (IVPP V14203), due to developmental variation. The radial epicondyle is less well developed than the ulnar one. Medial and lateral crests are not present (IVPP V13245, IVPP V14203). The radius and ulna bears a well developed olecranon process (IVPP V14979.1, IVPP V14979.2). Ossified carpals are present, but the arrangement of the carpals and the phalangeal formula of the manus are both unknown due to incomplete preservation.

In young adults (IVPP V14203, IVPP V14979.2) the pubis was still cartilaginous, as indicated by the presence of an empty gap where the pubis would be expected to occur. The fused ischia are 'T'-shaped in dorsal view (IVPP V14979.1, IVPP V14979.2). The femur is sigmoid in shape and bears a crest on the proximal section (IVPP V14203, IVPP V14979.1, IVPP V14979.2). The tibia and fibula are fused at their proximal and distal ends in fully grown adults (IVPP V14979.1, but unfused in younger adults (IVPP V14979.2). Similarly, the distal tarsals are ossified in fully grown adults (IVPP V14979.1), but not in younger ones (IVPP V14979.2). The phalangeal formula of the pes is unknown due to poor preservation.
Anura genus and species indet

**Material.** IVPP V13235, part and counterpart of a partial skeleton.

**Horizon and locality.** Jiufotang Formation (Aptian, 120.3 ± 0.7 Ma) [40]; Xierhuqiao Locality.

**Description.** Each vertebra has an unfused neural arch and centrum, and the long bones lack epicondyles. These features indicate that the individual is surely a juvenile (for detailed description see Wang et al., 2007 [16]).

The frontoparietals are paired, and their anterior portions border a large fontanelle whose anteroposterior length exceeds 1/2 the length of the frontoparietals. The squamosal is T-shaped, with short zygomatic ramus that does not contact the maxilla. The postorbital bone is very short and lacks contact between the nasals and in lacking both a squamosal-maxillary contact and dermal sculpture on the bones of the skull. The urostyle bears a pair of short, expanded. As in leiopelmatids, nine presacral vertebrae are present and the distal end of the cleithrum is unbifurcated. The anterior margin of the pars acromialis of the scapula is overlapped by the distal end of the clavicle, and the sacral diapophyses are present and the distal end of the clavicle is unbifurcated.

A ternary diagram was used to analyze the hind limb proportions of anurans and two outgroup taxa [16], and this frog from the Jiufotang Formation was well separated on the diagram from a cluster of Jehol anurans from the underlying Yixian Formation. In fact, the Jiufotang frog fell amongst extant hylids, leptodactylids, and discoglossids. The precise phylogenetic position of this small frog remains uncertain, but the specimen differs from *Liaobatrachus* in having a greater degree of ossification. For example, the young adult of *L. macilentus* has unossified carpals and a poorly developed radioulna that lacks a prominent olecranon; the fully grown adult of *L. zhaoi* has distinct epicondyles at the ends of the long bones, an ossified pubis and distal tarsals, and a proximally and distally fused tibia and fibula. Further examples of inferred developmental anomalies include the presence, in some specimens, of an additional presacral (presacral X) in *L. grabaudi*, of the fusion between presacras I and II in *L. macilentus*, and of the fusion between the last presacral and the sacral vertebra in *L. grabaudi* and *L. zhaoi*.

**Discussion.** All fossil anuran specimens that belong to the Jehol Biota come from the Yixian Formation, with the exception of one specimen IVPP V13235 that comes from the Jiufotang Formation. It is clear that, with respect to osteological characters, the Xianan frogs are homogeneous and should be referred to the single genus *Liaobatrachus*.

Within *Liaobatrachus* we distinguish four species according to body proportions, the shape of the cultriform process of the parasphenoid, the shape of the acetabulum, and the number of prepollex elements. The relative length of the hind limb (femur, tibiofibula, and fibulare) is greater in *L. beijioaniensis* and *L. zhaoi* than in *L. grabaudi* (see Table S2). However, in *L. beijioaniensis* the femur is slightly longer than the tibiofibula, as opposed to nearly the same length as the tibiofibula in *L. zhaoi*. The acetabulum is triangular in *L. macilentus* but more circular in other species of *Liaobatrachus*. The cultriform process of the parasphenoid is anteriorly needle-like in *L. macilentus*, but tapers gradually anteriorly in *L. zhaoi* and comes to a rounded anterior tip in *L. beijioaniensis*. *Liaobatrachus grabaudi* possesses only one prepollex element whereas *L. beijioaniensis* and *L. macilentus* have two. Other differences among the specimens exist, but can be explained as intraspecific variations or developmental anomalies. The intraspecific differences are mainly ontogenetic variations in the degree of ossification. For example, the young adult of *L. macilentus* has unossified carpals and a poorly developed radioulna that lacks a prominent olecranon; the fully grown adult of *L. zhaoi* has distinct epicondyles at the ends of the long bones, an ossified pubis and distal tarsals, and a proximally and distally fused tibia and fibula. Further examples of inferred developmental anomalies include the presence, in some specimens, of an additional presacral (presacral X) in *L. grabaudi*, of the fusion between presacras I and II in *L. macilentus*, and of the fusion between the last presacral and the sacral vertebra in *L. grabaudi* and *L. zhaoi*.

*Liaobatrachus* exhibits several derived character states not seen in Prosalinus, Notobatrachus and Vieraella from the Jurassic deposits of the Americas. These include a reduced number of presacras, a complete urostyle, and a monocondylar sacro-urostylar articulation as opposed to a non-condylar joint between the sacrum and urostyle. However, *Liaobatrachus* does not appear to be as derived as the European Jurassic-Cretaceous *Eodiscoglossus*, as the presacras of *Liaobatrachus* are amphicoelous and also more numerous. *Gobitara* and Cretasalia from the Upper Cretaceous of Central Asia resemble *Liaobatrachus* more closely than American and European taxa in possessing an ilium that lacks a dorsal crest and having at least some contact between the nasals. However, *Liaobatrachus* differs from these Central Asian taxa in having a greater degree of contact between the nasals and in lacking both a squamosal-maxillary contact and dermal sculpture on the bones of the skull roof. *Liaobatrachus* does not resemble the Early Cretaceous frogs known from the Middle East or North Africa, which are pipoids. Among extant anurans, *Liaobatrachus* resembles leiopelmatids in some features and discoglossids in others. As in discoglossids, the anterior margin of the pars acromialis of the scapula is overlapped by the distal end of the clavicle, and the sacral diapophyses are expanded. As in leiopelmatids, nine presacral vertebrae are present and the distal end of the cleithrum is unblutricated. However, the combination of amphicoelous centra and a monocondylar sacro-urostylar articulation suggests that *Liaobatrachus* is likely more derived than leiopelmatids. In our phyloge-
ngetic analysis (Fig. 8), *Liaobatrachus* is clustered together with leiopelmatsids and the Lalagobatrachia (of Frost et al., 2006 [49]). *Liaobatrachus* is more deeply nested than most previous analyses have indicated [10,12,13,50]. The frog from the Jiufotang Formation of Aptian age is about 5 million years younger than the known specimens of *Liaobatrachus*, and differs from them in having rod-like sacral diapophyses and larger ratio of tibiofibula to femur. This frog provides evidence of the presence of another anuran genus in the Jehol Biota, but we prefer not to erect a new taxon on the basis of a single juvenile specimen.

**Conclusion**

Most known Jehol anurans can be referred to the genus *Liaobatrachus* (Table 2) on the basis of osteological characters. The five previously named taxa, *Liaobatrachus grabaui* Ji and Ji 1998, *Callobatrachus sanyanensis* Wang and Gao 1999, *Mesophryne beiptoana-sis* Gao and Wang 2001, *Dalianbatrachus mengi* Gao and Liu 2004 and *Zhoubatrachus macilentus* Gao and Chen 2004, are consolidated into three species of *Liaobatrachus: L. grabaui, L. beiptoana-sis* comb. nov. and *L. macilentus* comb. nov.. A new species, *Liaobatrachus zhaoi* sp. nov., is established based on a dozen three-dimensionally preserved specimens from the Lujiautun Bed of the Yixian Formation. Nevertheless, the known taxonomic diversity of the Jehol anurans is significantly less than previously believed. Comparisons with fossil and extant anurans, and a phylogenetic analysis, suggest that *Liaobatrachus* is a member of the anuran crown-group.

**Supporting Information**

Table S1 Taxon-character data matrix used in our phylogenetic analysis. Character description is as in Gao and Wang (2001) and Wang (2006) with amendments mentioned in the Material and Method section. Letters in bold indicate the character states that are resolved in this paper. The letters in the matrix represent the states shown below: A, (0&1); B, (1&2); C, (0 or 1); D, (0&2); E, (1 or 2).

**Table S2 Morphometric data of Jehol anurans.** Abbreviation: SVL, snout-vent length; PsC, presacral column; LS, length of skull; LsS, width of skull; H, humerus; R, radulina; F, femur; Tf, tibiofibula; Fb, fibular; I, ilium; U, Urostyle; Mt4, metatarsal IV.

**Acknowledgments**

We are very grateful to Liwu Lu (China Geological Museum), Chunling Gao and Fengjiao Zhang (Dalian Natural Museum), Xiaodong Wang, Wanxiang Zhang and Jun Ye (Liaoning Normal University, China). Zheng (Zhengjiu Museum of Nature and History) for greatly facilitating our visits to their institutions to examine specimens. Thanks are also due to Yinfang Guo and Wei Gao (Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences) for specimen preparation and photography, respectively. We also appreciate the kind help of Corwin Sullivan (IVPP) in the language of the manuscript. Amy Henrici and Zoltán Szentesi deserve our gratitude for their kind help in reviewing the manuscript.

**Author Contributions**

Analyzed the data: LD YY. Wrote the paper: LD. Examined the specimens: LD ZR YY MEHJ. Constructed figures: LD MEHJ. Contributed significantly to editing/revision of the submitted manuscript: ZR MEHJ YY.

**References**