

The presence of an orbitoantorbital fenestra: a further evidence of the anurognathid peculiarity within the Pterosauria

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Supplementary information

Here, the character states that have been modified in the nexus data matrix by Wei et al. (2021, SI) are listed. This matrix is the one that produced the strict consensus tree of fig. 7 in Wei et al. (2021). Some problems encountered in coding character states are discussed below.

The characters 10-13 regarding the antorbital fenestra have been coded as inapplicable (-) for the anurognathids, while Wei et al. (2021) coded them as "unknown" (?); the practical result is the same, anyway, and they are not reported below. This is the case also of character 64, 67-68, 70, 73-75, 77, 86, and 95. Thus, the characters states that have been modified comprise 38 of the 378 characters (10%).

Character 6 - External naris, size relative to skull openings (Lü et al. 2009): form the largest skull opening (0), smaller than the orbit or antorbital opening (1).

Batrachognathus volans 1

Sinomacrops bondei 1

Dendrorhynchoides curvidentatus 1

Luopterus mutoudengensis 1

Jeholopterus ningchengensis 1

Anurognathus ammoni 1

Vesperopterylus lamadongensis 1

Character 7 - External naris, dorsoventrally compressed: absent (0), present (1).

Batrachognathus volans 0

Sinomacrops bondei 0

Dendrorhynchoides curvidentatus 0

Luopterus mutoudengensis 0

Jeholopterus ningchengensis 0

Anurognathus ammoni 0

Vesperopterylus lamadongensis 0

Character 8 - External naris, dorsal and ventral margins, orientation (Andres et al. 2014): acute angle (0); subparallel (1).

Batrachognathus volans 0

Sinomacrops bondei 0

Dendrorhynchoides curvidentatus 0

Luopterus mutoudengensis 0

Jeholopterus ningchengensis 0

Anurognathus ammoni 0

Vesperopterylus lamadongensis 0

Character 9 - External naris (or nasoantorbital fenestra), position relative to the premaxilla: main part dorsal to the ventral margin of the premaxilla (0), main part displaced posterior to the premaxilla (1).

Batrachognathus volans 0

Sinomacrops bondei 0

Dendrorhynchoides curvidentatus 0

Luopterus mutoudengensis 0

Jeholopterus ningchengensis 0

Anurognathus ammoni 0

Vesperopterylus lamadongensis 0

State 0 is considered here as a feature shared by all anurognathids with the possible exclusion of '*Dimorphodon*' *weintraubi*.

Character 14 - Antorbital fenestra plus external naris (or nasoantorbital fenestra), extension (Dalla Vecchia 2019): under 50% skull length (0), 50% skull length or more (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

Character 15 - Antorbital fenestra and external naris, configuration: separated (0); confluent, forming a nasoantorbital fenestra (1);

Batrachognathus volans 0

Sinomacrops bondei 0

Dendrorhynchoides curvidentatus 0

Luopterus mutoudengensis 0

Jeholopterus ningchengensis 0

Anurognathus ammoni 0

Vesperopterylus lamadongensis 0

Character 16 - (Naso)antorbital fenestra, posterior margin, shape (Vidović & Martill, 2017 [recte 2018]): straight (0), convex (0), concave (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

Character 17 - (Naso)antorbital fenestra, posterior margin, orientation: posterodorsally reclined (0), perpendicular (1), anterodorsally reclined (2);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -
Luopterus mutoudengensis -
Jeholopterus ningchengensis -
Anurognathus ammoni -
Vesperopterylus lamadongensis -

Character 18 - Nasoantorbital fenestra, height (modified from Lü et al., 2009 [recte 2010]): height similar to or greater than anteroposterior length (0), elongate (1);

Batrachognathus volans -
Sinomacrops bondei -
Dendrorhynchoides curvidentatus -
Luopterus mutoudengensis -
Jeholopterus ningchengensis -
Anurognathus ammoni -
Vesperopterylus lamadongensis -

Character 19 - Nasoantorbital fenestra, anterior end (Dalla Vecchia 2019): bordered by the premaxilla (0), bordered by the maxilla (1);

Batrachognathus volans -
Sinomacrops bondei -
Dendrorhynchoides curvidentatus -
Luopterus mutoudengensis -
Jeholopterus ningchengensis -
Anurognathus ammoni -
Vesperopterylus lamadongensis -

Character 20 - Nasoantorbital fenestra, posterodorsal margin, shape: concave (0), angled (1);

Batrachognathus volans -
Sinomacrops bondei -
Dendrorhynchoides curvidentatus -
Luopterus mutoudengensis -
Jeholopterus ningchengensis -
Anurognathus ammoni -
Vesperopterylus lamadongensis -

Character 21 - Orbit, shape: subcircular (0), quadrangular (broad base) (1), piriform (dorsoventrally elongated) (2);

Batrachognathus volans 1
Sinomacrops bondei ?
Dendrorhynchoides curvidentatus ?
Luopterus mutoudengensis ?
Jeholopterus ningchengensis 1
Anurognathus ammoni 1
Vesperopterylus lamadongensis ?

This character presents three states (0 to 2) in its definition by Wei et al. (2021; doi:19.7717/peerj.11161/supp-1), but the same character has four character states in the matrix (0 to 3).

Character 22 - Orbit, size relative to antorbital fenestra: Larger than antorbital fenestra (0), Smaller than antorbital fenestra (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

Character 23 - Orbit, length relative to skull (Dalla Vecchia 2019): under half skull length (0), about or over half skull length (1);

Batrachognathus volans 1

Sinomacrops bondei 1

Dendrorhynchoides curvidentatus 1

Luopterus mutoudengensis 1

Jeholopterus ningchengensis 1

Anurognathus ammoni 1

Vesperopterylus lamadongensis 1

State 1 is considered here as a feature shared by all anurognathids with the possible exclusion of '*Dimorphodon*' *weintraubi*.

Character 24 - Orbit, supraorbital process intrudes into the orbit (Vidović & Martill, 2017[recte 2018]): present (0), absent (1);

Batrachognathus volans 1

Sinomacrops bondei ?

Dendrorhynchoides curvidentatus ?

Luopterus mutoudengensis ?

Jeholopterus ningchengensis 1

Anurognathus ammoni 1

Vesperopterylus lamadongensis ?

Character 47 - Premaxilla, posteroventral (maxillary) process bordering ventrally the external naris (Dalla Vecchia 2019): present (0), absent (1);

Batrachognathus volans 0

Sinomacrops bondei 0

Dendrorhynchoides curvidentatus 0

Luopterus mutoudengensis 0

Jeholopterus ningchengensis 0

Anurognathus ammoni 0

Vesperopterylus lamadongensis 0

The state 0 observed in *Batrachognathus volans* is considered here as a feature shared by all anurognathids with the possible exclusion of '*Dimorphodon*' *weintraubi*.

Character 48 - Premaxilla, posterodorsal margin of nasoantorbital fenestra (including nasal), width: wide (0), thin (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

Character 50 - Premaxilla, maxillary process, position (Andres et al. 2014): contacts nasal (0), reaches posterior half of external naris (1), anterior to middle of external naris (2);

Batrachognathus volans 1

Sinomacrops bondei 1

Dendrorhynchoides curvidentatus 1

Luopterus mutoudengensis 1

Jeholopterus ningchengensis 1

Anurognathus ammoni 1

Vesperopterylus lamadongensis 1

The state 1 observed in *Batrachognathus volans* is considered here as a feature shared by all anurognathids with the possible exclusion of '*Dimorphodon*' *weintraubi*.

Character 60 - Maxilla, dorsal=ascending process, shape in lateral view (modified from Dalla Vecchia 2019): short, broad and triangular (0), long, broad and arched backward (1), long, very thin and straight (2), long, thin and slightly arched backward (3);

Batrachognathus volans 2

Sinomacrops bondei 2

Dendrorhynchoides curvidentatus 2

Luopterus mutoudengensis 2

Jeholopterus ningchengensis 2

Anurognathus ammoni 2

Vesperopterylus lamadongensis 2

The state 2 observed in *Batrachognathus volans*, *Anurognathus ammoni* and *Jeholopterus ningchengensis* is considered here as a feature shared by all anurognathids with the possible exclusion of '*Dimorphodon*' *weintraubi*.

Character 61 - Maxilla, nasal process inclined backwards (modified from Unwin 2003): absent (0), present (1);

Batrachognathus volans 0

Sinomacrops bondei 0

Dendrorhynchoides curvidentatus 0

Luopterus mutoudengensis 0

Jeholopterus ningchengensis 0

Anurognathus ammoni 0

Vesperopterylus lamadongensis 0

Dorsal, ascending and nasal process of the maxilla are the same process. The state 0 observed in *Batrachognathus volans*, *Anurognathus ammoni*, and *Jeholopterus ningchengensis* is considered here as a feature shared by all anurognathids with the possible exclusion of '*Dimorphodon*' *weintraubi*.

Character 62 - Maxilla, nasal process, backward inclination (Dalla Vecchia 2019): more than 125°(0), 125° or less (1);

Batrachognathus volans 1
Sinomacrops bondei 1
Dendrorhynchoides curvidentatus 1
Luopterus mutoudengensis 1
Jeholopterus ningchengensis 1
Anurognathus ammoni 1
Vesperopterylus lamadongensis 1

This is practically the same as character 61, but the characters of Wei et al. (2021) matrix have not been changed here, because improving that matrix is not the goal of this paper.

Character 64 - Maxilla, premaxillary process, shape in lateral view (Dalla Vecchia 2019): triangular, tapering and pointed, shorter and deeper than the jugal process (0), triangular, tapering and pointed, low and long like the jugal process (1), trapezoidal and deep trapezoidal and low (2), harpoon-shaped (3);

Batrachognathus volans ?
Sinomacrops bondei ?
Dendrorhynchoides curvidentatus ?
Luopterus mutoudengensis ?
Jeholopterus ningchengensis ?
Anurognathus ammoni ?
Vesperopterylus lamadongensis ?

The character state is considered as "unknown" for anurognathids. Alternatively, this character may be considered as "inapplicable" ("unknown" and "inapplicable" are both processed as "unknown" by the algorithm). Actually, a fifth character state should be added for the anurognathids to account for the morphology observed in *Batrachognathus volans*. This character state would have no phylogenetic importance, resulting as an apomorphy of *Batrachognathus volans*, because information on the actual shape of the processes of the maxilla is missing in the other anurognathids. Codings coincide here with those by Wei et al. (2021).

Character 66 - Maxilla, caudal ramus expands ventrally (Wang et al. 2012): present (0), absent (1);

Batrachognathus volans 1
Sinomacrops bondei ?
Dendrorhynchoides curvidentatus 1
Luopterus mutoudengensis ?
Jeholopterus ningchengensis 1
Anurognathus ammoni 1

Vesperopterylus lamadongensis ?

At least in some anurognathids, there is no particular ventral expansion of the maxilla.

Character 67 - Maxilla, dorsal process (Andres et al., 2014): broad (0), slender (thinner than the dorsal process of the jugal) (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

It is "inapplicable" because there is no dorsal process of the jugal, thus comparison for establishing the state 1 is impossible. Codings coincide here with those by Wei et al. (2021), but for different reasons (absence of the dorsal process of maxilla vs. absence of the dorsal process of jugal).

Character 68 - Maxilla-nasal contact: broad (0), narrow (1);

Batrachognathus volans ?

Sinomacrops bondei ?

Dendrorhynchoides curvidentatus ?

Luopterus mutoudengensis ?

Jeholopterus ningchengensis ?

Anurognathus ammoni ?

Vesperopterylus lamadongensis ?

We do not know whether the nasal is present or not. Wei et al. (2021) probably consider this character as "inapplicable", thus the result is the same.

Character 69 - Maxilla and internal naris, contact: absent (0), present (1);

Batrachognathus volans 1

Sinomacrops bondei ?

Dendrorhynchoides curvidentatus 1

Luopterus mutoudengensis 1

Jeholopterus ningchengensis 1

Anurognathus ammoni 1

Vesperopterylus lamadongensis ?

Because of the position of the forked palatine/ectopterygoid and according to the palate reconstruction by Bennett (2007), the "internal naris" (choana) "contacts" the maxilla, at least in those taxa where the forked palatine/ectopterygoid is preserved.

Character 70 - Nasal, contacts antorbital fenestra (Vidović & Martill, 2017 [recte 2018]): present (0), absent (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -
Luopterus mutoudengensis -
Jeholopterus ningchengensis -
Anurognathus ammoni -
Vesperopterylus lamadongensis -

The character is "inapplicable" because there is no antorbital fenestra in anurognathids (with the possible exclusion of '*Dimorphodon*' *weintraubi*). Wei et al. (2021) probably consider it "inapplicable" too, although because of the presumed presence of a nasoantorbital fenestra, thus the result is the same.

Character 72 - Nasal descending process: present (0), absent (1);

Batrachognathus volans ?
Sinomacrops bondei ?
Dendrorhynchoides curvidentatus ?
Luopterus mutoudengensis ?
Jeholopterus ningchengensis ?
Anurognathus ammoni ?
Vesperopterylus lamadongensis ?

Because it is not specified, in the formulation of the character, that the "descending process" of the nasal projects into the nasoantorbital fenestra, this character is not considered as "inapplicable" here.

Character 73 - Nasal descending process, position: placed laterally (0); placed medially (1);

Batrachognathus volans ?
Sinomacrops bondei ?
Dendrorhynchoides curvidentatus ?
Luopterus mutoudengensis ?
Jeholopterus ningchengensis ?
Anurognathus ammoni ?
Vesperopterylus lamadongensis ?

Because it is not specified, in the formulation of the character, that the "descending process" of the nasal projects into the nasoantorbital fenestra, this character is not considered as "inapplicable" here. Codings coincide here with those by Wei et al. (2021), but possibly for different reasons.

Character 74 - Nasal descending process, length: long (almost reaching the ventral margin of the skull) (0); short knob-like (extremely reduced) (1);

Batrachognathus volans ?
Sinomacrops bondei ?
Dendrorhynchoides curvidentatus ?
Luopterus mutoudengensis ?
Jeholopterus ningchengensis ?
Anurognathus ammoni ?
Vesperopterylus lamadongensis ?

Because it is not specified, in the formulation of the character, that the "descending process" of the nasal projects into the nasoantorbital fenestra, this character is not considered as "inapplicable" here. Codings coincide here with those by Wei et al. (2021), but possibly for different reasons.

Character 75 - Nasal descending process, orientation (modified from Andres et al. 2014): inclined anteriorly (0); subvertical (1), inclined posteriorly (2);

Batrachognathus volans ?

Sinomacrops bondei ?

Dendrorhynchoides curvidentatus ?

Luopterus mutoudengensis ?

Jeholopterus ningchengensis ?

Anurognathus ammoni ?

Vesperopterylus lamadongensis ?

Because it is not specified, in the formulation of the character, that the "descending process" of the nasal projects into the nasoantorbital fenestra, this character is not considered as "inapplicable" here. Codings here coincide with those by Wei et al. (2021), but possibly for different reasons.

Character 76 - Nasal descending process, lateral foramen: absent (0); present (1);

Batrachognathus volans ?

Sinomacrops bondei ?

Dendrorhynchoides curvidentatus ?

Luopterus mutoudengensis ?

Jeholopterus ningchengensis ?

Anurognathus ammoni ?

Vesperopterylus lamadongensis ?

Because it is not specified, in the formulation of the character, that the "descending process" of the nasal projects into the nasoantorbital fenestra, this character is not considered as "inapplicable" here. The position and identity of the nasal is uncertain in all anurognathids.

Character 77 - Lacrimal, shape in lateral view (Dalla Vecchia 2019): crescent-shaped (0), 'massive vertical bar' (1), 'hatched-shaped with slender jugal process' (2), 'straight slender bar' (3), 'C-shaped, arched over the antorbital fenestra' (4), 'short and quadrangular' (5), 'massive, triangular to T-shaped' (6);

Batrachognathus volans ?

Sinomacrops bondei ?

Dendrorhynchoides curvidentatus ?

Luopterus mutoudengensis ?

Jeholopterus ningchengensis ?

Anurognathus ammoni ?

Vesperopterylus lamadongensis ?

We do not know whether the lacrimal is present or not in anurognathids. Codings here coincide with those by Wei et al. (2021), but possibly for different reasons.

Character 78 - Lacrimal, foramination: absent (0), present, small present (1), enlarged (2);

Batrachognathus volans ?

Sinomacrops bondei ?

Dendrorhynchoides curvidentatus ?

Luopterus mutoudengensis ?

Jeholopterus ningchengensis ?

Anurognathus ammoni ?

Vesperopterylus lamadongensis ?

We do not know whether the lacrimal is present or not in anurognathids.

Character 79 - Lacrimal, orbital process: absent (0); present (1);

Batrachognathus volans ?

Sinomacrops bondei ?

Dendrorhynchoides curvidentatus ?

Luopterus mutoudengensis ?

Jeholopterus ningchengensis ?

Anurognathus ammoni ?

Vesperopterylus lamadongensis ?

We do not know whether the lacrimal is present or not in anurognathids. The quality of the descriptions (excluded *Anurognathus ammoni*) or the poor state of preservation prevent the identification of orbital processes, anyway.

Character 86 - Jugal, antorbital fossa (modified from Andres et al. 2014): present (0), absent (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

Codings coincide here with those by Wei et al. (2021), but for different reasons (the character is inapplicable here and "unknown" for Wei et al. 2021).

Character 87 - Jugal, maxillary process: absent (0), present (1);

Batrachognathus volans 1

Sinomacrops bondei 1

Dendrorhynchoides curvidentatus 1

Luopterus mutoudengensis 1

Jeholopterus ningchengensis 1

Anurognathus ammoni 1

Vesperopterylus lamadongensis 1

As maxilla and jugal form a continuous long bar overlapping, a maxillary process of the jugal is considered to be present in all anurognathids (with the exclusion of '*Dimorphodon*' *weintraubi*).

Character 88 - Jugal, maxillary process, extension (Andres et al., 2014): posterior to nasoantorbital fenestra (or narial) (0); anterior margin same level or anterior (1);

Batrachognathus volans 0

Sinomacrops bondei 0

Dendrorhynchoides curvidentatus 0

Luopterus mutoudengensis 0

Jeholopterus ningchengensis 0

Anurognathus ammoni 0

Vesperopterylus lamadongensis 0

The maxillary process of jugal potentially does not reach the narial fenestra. This character has been coded 0 for all anurognathids excluded '*Dimorphodon*' *weintraubi*.

Character 89 - Jugal, lacrimal process base, width: broad (0), narrow (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

Character 90 - Jugal, ascending process base width (Andres et al., 2014) broad (0), narrow (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

This character is apparently redundant with character 89.

Character 91 - Jugal, lacrimal process, inclination: inclined anteriorly (0), subvertical (1), inclined posteriorly (2);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

Character 93 - Jugal, lacrimal and postorbital processes, shape (Andres et al. 2014): separated by distinct angle (0), infilled by concave flange (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

Character 94 - Jugal, rostrally expanded to overlap most of the maxilla laterally (Dalla Vecchia 2019): absent (0), present (1);

Batrachognathus volans ?

Sinomacrops bondei ?

Dendrorhynchoides curvidentatus ?

Luopterus mutoudengensis ?

Jeholopterus ningchengensis ?

Anurognathus ammoni ?

Vesperopterylus lamadongensis ?

The anterior extent of the jugal is unknown in anurognathids and dubious, in my opinion, also in *Anurognathus ammoni*.

Character 95 - Jugal, posterior process (Vidović & Martill, 2017 [recte 2018]): (tri-radiate) lacks the posterior process (0); possesses the posterior process (tetra-radiate) (1);

Batrachognathus volans -

Sinomacrops bondei -

Dendrorhynchoides curvidentatus -

Luopterus mutoudengensis -

Jeholopterus ningchengensis -

Anurognathus ammoni -

Vesperopterylus lamadongensis -

The jugal is neither triradiate nor tetraradiate. Anyway, my codings coincide with those by Wei et al. (2021) from a practical point of view.

Character 96 - Jugal, ventral margin (Andres et al., 2014): straight (0); concave (1); convex (2);

Batrachognathus volans 2

Sinomacrops bondei 2

Dendrorhynchoides curvidentatus 2

Luopterus mutoudengensis 2

Jeholopterus ningchengensis 2

Anurognathus ammoni 2

Vesperopterylus lamadongensis 2

Character 98 - Jugal/lacrimal contact (Vidović & Martill, 2017 [recte 2018]): in the ventral half of the orbit (0), approximately in the middle of the orbit (1), in the dorsal half of the orbit (2);

Batrachognathus volans -
Sinomacrops bondei -
Dendrorhynchoides curvidentatus -
Luopterus mutoudengensis -
Jeholopterus ningchengensis -
Anurognathus ammoni -
Vesperopterylus lamadongensis -

Character 100 - Jugal, if tri-radiate, ventral apex of the jugal, position (Vidović & Martill, 2017 [recte 2018]): anterior to the quadratojugal (0); posterior to the anterior margin of the quadratojugal (1);

Batrachognathus volans ?
Sinomacrops bondei ?
Dendrorhynchoides curvidentatus ?
Luopterus mutoudengensis ?
Jeholopterus ningchengensis ?
Anurognathus ammoni ?
Vesperopterylus lamadongensis ?

If the jugal is triradiate it is such because of the postorbital process. That process is missing in the reconstruction of the skull of *Anurognathus ammoni* by Bennett 2007. Unfortunately, the part of the skull with the postorbital is poorly preserved or undescribed in all anurognathid specimens.

Character 101 - Jugal, postorbital process, orbital process invading orbit (Andres et al., 2014): present (0); absent (1);

Batrachognathus volans ?
Sinomacrops bondei ?
Dendrorhynchoides curvidentatus ?
Luopterus mutoudengensis ?
Jeholopterus ningchengensis ?
Anurognathus ammoni ?
Vesperopterylus lamadongensis ?

Considerations as for character 100.

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