The oldest articulated osteichthyan reveals mosaic gnathostome characters

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Supplementary Information 1

Phylogenetic Analysis

1. Phylogenetic methods

The matrix includes 153 morphological characters and 23 taxa. The character data entry and formatting was performed in Mesquite (version 2.5) (Maddison and Maddison 2008). *Akmonistion* (a chondrichthyan), *Acanthodes* (an acanthodian) and *Dicksonosteus* (a placoderm) were designated as the outgroup. All characters were treated as unordered, and weighted equally. The data matrix was subjected to the parsimony analysis in PAUP* (version 4.0b10) (Swofford, 2003). Tree searches were conducted using the branch-and-bound algorithm. MacClade 4.0 (Maddison and Maddison, 2000) was used to trace the character transformation in the preferred cladogram. Bremer decay indices were obtained using command files composed by TreeRot (Sorenson, 1999) in conjunction with the heuristic search algorithm in PAUP*. Bootstrap values were calculated from 1000 pseudoreplicates using the heuristic search option in PAUP* (random addition sequence with ten replicates).

Bayesian inference analyses were conducted with MrBayes 3.1.2 (Huelsenbeck and Ronquist, 2001; Ronquist and Huelsenbeck, 2003). Priors were kept at their default settings for standard (=morphological) analyses. The analysis was run for 1×10^6 generations. Samples were taken every 1×10^2 generations, resulting in a total of 1×10^4 samples for each of the parallel analyses. The first 2.5×10^3 samples for each run, representing the 'burn-in' period, were discarded. As MrBayes 3.1 only allows one single taxon as the outgroup, *Akmonistion*, *Acanthodes* and *Dicksonosteus* were designated as the outgroup, separately.

The taxon stability was assessed using RadCon (Thorley and Page, 2000). The maximum leaf stability for each terminal taxon was estimated from the topologies arising from the analysis of 1000 bootstrap pseudoreplicates. The bootstraping was performed using PAUP*.

2. Results and analysis

Results

The analysis of the data matrix found a single most parsimonious tree (MPT) of 292 steps [Consistency index (CI) = 0.5719; Homoplasy index (HI) = 0.4281; Retention index (RI) = 0.7368;

Rescaled consistency index (RC) = 0.4214; Fig. 1]. *Guiyu* is placed as the sister taxon to the clade comprising *Psarolepis* + *Achoania*. *Meemannia* and *Ligulalepis* form successively more basal taxa among the Sarcopterygii. *Lophosteus* and *Andreolepis* represent the stem osteichthyans, and *Dialipina* forms the most basal taxon among the Actinopterygii.

A branch-and-bound search made for all trees of length of 293 or less resulted in recovery of 92 trees. All these 92 trees place *Lophosteus* as a stem osteichthyan; 77 trees place *Andreolepis* as a stem osteichthyan while other 15 trees place it as an actinopterygian; 26 trees place *Ligulalepis* as a sarcopterygian and 43 trees place it as an actinopterygian; 11 trees place *Dialipina* as a sarcopterygian and 81 trees place it as an actinopterygian; 55 trees place *Meemannia* as a basal sarcopterygian and 17 tree place it as an actinopterygian (Table 1). The arrangement of the other genera is usually consistent.

Table 1. Arrangements of some taxa in the 92 trees with the length of no more than 293.

Taxon	Number of trees (length ≤ 293) which place the taxon as a sarcopterygian	Number of trees (length ≤ 293) which place the taxon as an actinopterygian	Number of trees (length ≤ 293) which place the taxon as a stem osteichthyan
Lophosteus	0	0	92
Andreolepis	0	15	77
Ligulalepis	26	43	23
Dialipina	11	81	0
Meemannia	55	17	20

The strict consensus of 92 trees does not well resolve the phylogenetic positions of some early osteichthyans (*Lophosteus*, *Andreolepis*, *Dialipina*, *Ligulalepis* and *Meemannia*), yet assigns the sarcopterygians crownward of *Meemannia*, and *Moythomasia* + *Mimia* as two monophyletic groups (Fig. 2A). A 50% majority rule consensus tree also sets the actinopterygians crownward of *Cheirolepis* and taxa crownward of *Andreolepis* as two monophyletic groups (Fig. 2B).

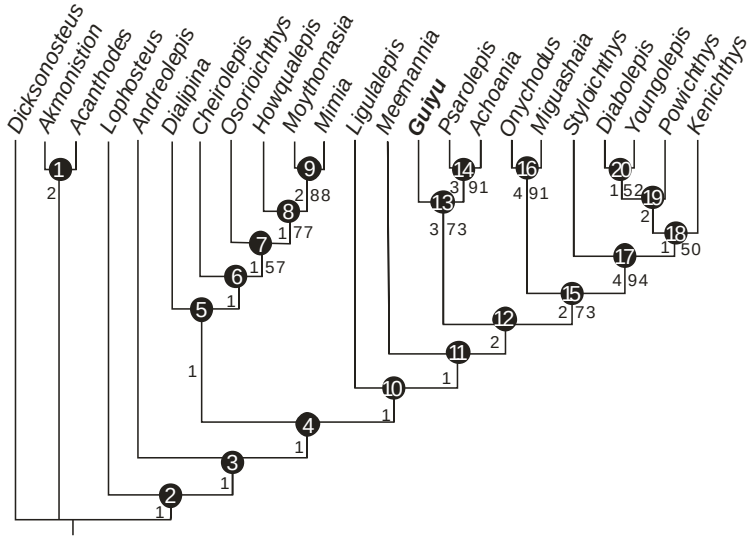


Figure 1. The single most parsimonious tree (tree length = 292; Consistency index = 0.5719; Homoplasy index = 0.4281; Retention index = 0.7368; Rescaled consistency index = 0.4214). Numbers below nodes represent Bremer decay indices and bootstrap values (where the latter are greater than 50%).

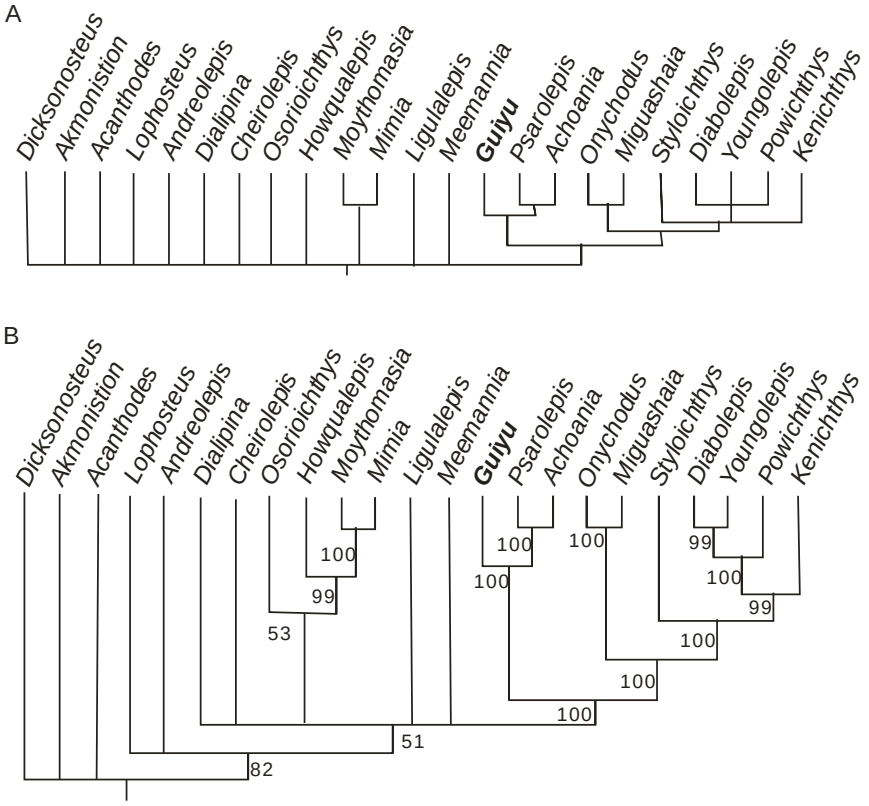
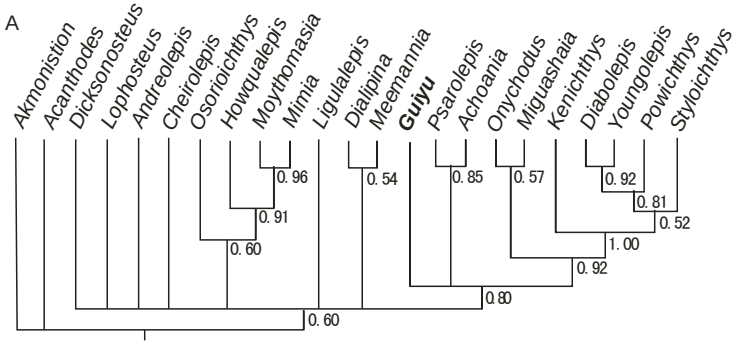


Figure 2. Strict (A) and 50% majority-rule (B) consensus tree of 92 trees with the length ≤ 293. Numbers below nodes in B represent percentage support values.

The results of the three Bayesian analyses (Fig. 3A-C) are largely consistent with the parsimony analysis, although considerably less resolved in some places. Three monophyletic groups are recognized: actinopterygians crownward of *Cheirolepis*, sarcopterygians crownward of *Meemannia* and [*Dialipina* + *Meemannia*]. The striking difference from the MPT is the placement of *Guiyu,* which is placed as the sister group of [*Psarolepis* + *Achoania*] plus crown sarcopterygians (Node 15, Fig.1) when *Dicksonosteus* is assigned as the outgroup (Fig. 3C). In addition, *Styloichthys* rather than *Kenichthys* is assigned as a sister taxon to the Dipnomorpha, and *Dialipina* and *Meemannia* form a sister pair.



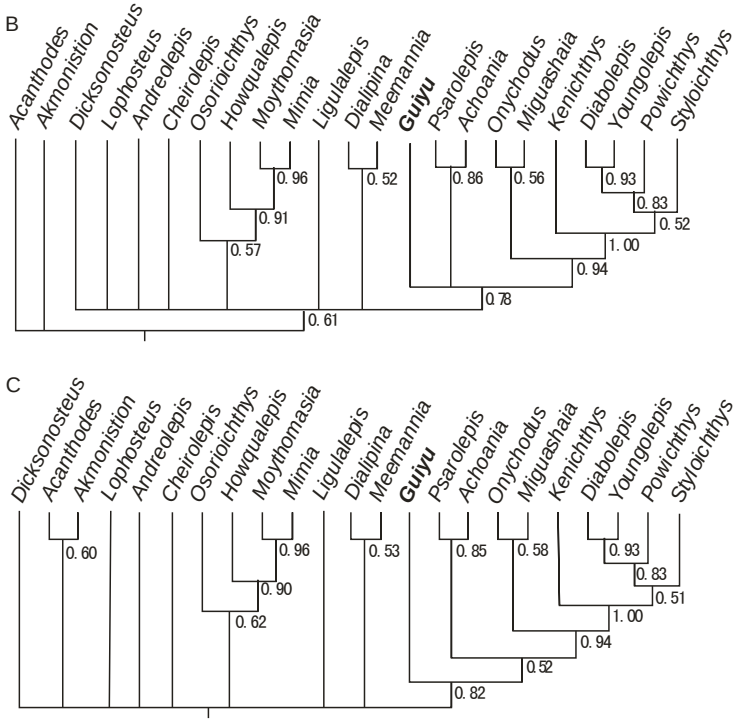


Figure 3. Bayesian analyses with *Akmonistion* (A)， *Acanthodes* (B) and *Dicksonosteus* (C) assigned as the outgroup, separately. Values associated with nodes indicate the frequency with which those bipartitions occur among sampled trees (posterior probabilities).

The influence of the taxon or character deletion on the phylogenetic topology

Areas of the disagreement on the evolution of early osteichthyans centre on the phylogenetic positions of *Lophosteus*, *Andreolepis*, *Ligulalepis* and *Dialipina* (Janvier, 1996; Basden and Young, 2001; Cloutier and Arratia, 2004; Zhu *et al.*, 2006; Botella *et al*., 2007; Friedman, 2007). Here we try to draw out the influence of the addition or deletion of these early taxa on the phylogenetic topology. Tree searches of the parsimony analysis were also conducted using the branch-and-bound algorithm in PAUP* (version 4.0b10).

(1) Deletion of *Guiyu* results in 8 MPTs with the length of 282 (Fig.4). Variants among these trees mostly arise from the arrangements of *Ligulalepis*, *Andreolepis* and *Dicksonosteus.*

All the eight trees (A1-4, B1-4) place *Ligulalepis* in a clade with *Osorioichthys*, together serving as the sister group of the clade containing *Howqualepis* plus [*Mimia+Moythomasia*] (Fig.1).

Six trees (A2-4, B2-4) place *Andreolepis* as a stem osteichthyan, while two trees (A1, B1) place *Andreolepis* as an actinopterygian.

Among four of the 8 MPTs trees (B1-4), *Dicksonosteus* is placed as the sister group of sarcopterygians, regardless of its assignment (together with *Akmonistion* and *Acanthodes*) as the outgroup.

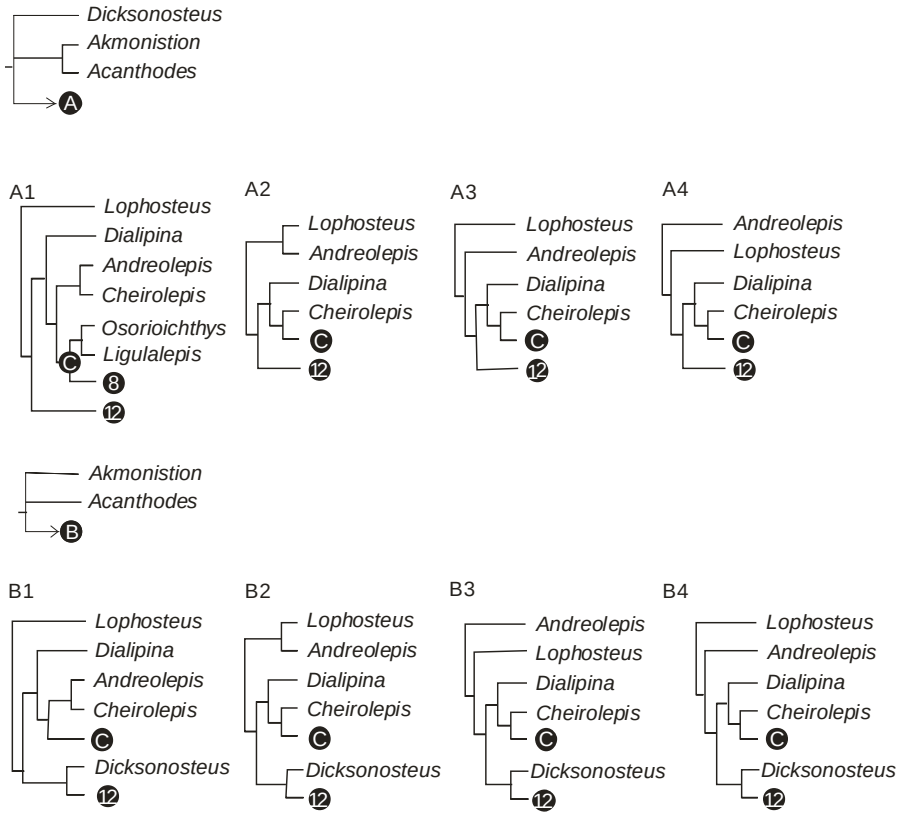


Figure 4. Eight MPTs with the deletion of *Guiyu*.

(2) Deletion of *Andreolepis* results in 15 MPTs with the length of 292. The strict consensus tree of these 15 MPTs and the arrangements of some taxa in the 15 trees are shown as follow:

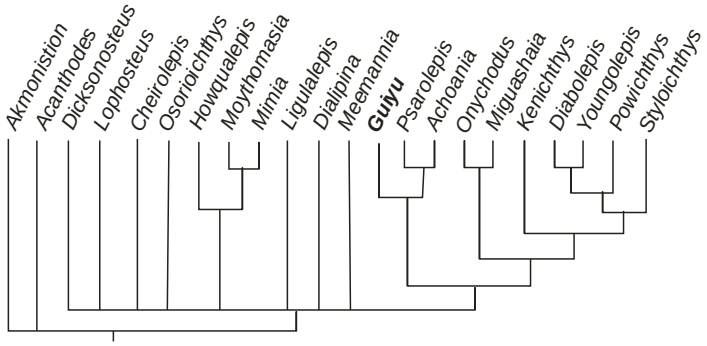


Figure 5. Strict consensus tree of 15 MPTs with the deletion of *Andreolepis.*

Table 2. Arrangements of 15 MPTs with the deletion of *Andreolepis*.

Taxon	Number of trees which place the taxon as a sarcopterygian	Number of trees which place the taxon as an actinopterygian	Number of trees which place the taxon as a stem osteichthyan
Lophosteus	0	0	15
Ligulalepis	3	12	0
Dialipina	0	15	0
Meemannia	6	2	7

(3) Deletion of *Lophosteus* results in 33 MPTs with the length of 292. The strict consensus tree of these 33 MPTs and the arrangements of some taxa in the 33 trees are shown as follow:

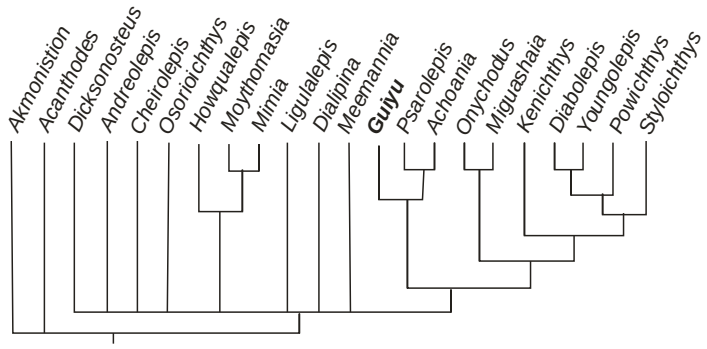


Figure 6. Strict consensus tree of 33 MPTs with the deletion of *Lophosteus.*

Table 3. Arrangements of 33 MPTs with the deletion of *Lophosteus*.

Taxon	Number of trees which place the taxon as a sarcopterygian	Number of trees which place the taxon as an actinopterygian	Number of trees which place the taxon as a stem osteichthyan
Andreolepis	0	11	22
Ligulalepis	4	17	12
Dialipina	21	12	0
Meemannia	21	2	10

(4) Deletion of *Lophosteus* and *Andreolepis* results in 18 MPTs with the length of 291. The strict consensus tree of these 18 MPTs is in accordance with the consensus trees shown in Figures 5 and 6. The arrangements of some taxa in the 18 trees are shown as follow:

Table 4. Arrangements of some taxa in 18 MPTs with the deletion of *Lophosteus* and *Andreolepis.*

Taxon	Number of trees which place the taxon as a sarcopterygian	Number of trees which place the taxon as an actinopterygian	Number of trees which place the taxon as a stem osteichthyan
Ligulalepis	3	11	4
Dialipina	7	11	0
Meemannia	11	2	5

(5) Deletion of *Meemannia* results in only one MPT with the length of 285. The topology remains intact as the MPT based on the total data set (Fig. 1).

(6) Deletion of *Ligulalepis* results in 9 MPTs with the length of 288. There are three significant differences from the MPT based on the total data set (Fig. 1): 5 of the 9 trees place *Dicksonosteus*

as the sister taxon to the sarcopterygians, two trees place *Andreolepis* as an actinopterygian, and one tree places *Dialipina* as a sarcopterygian.

(7) Deletion of *Dialipina* results in only 232 MPT with the length of 282. The strict consensus tree of these 232 MPTs is shown as follow:

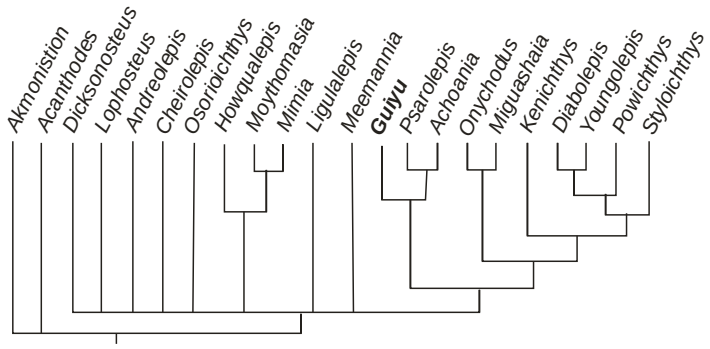


Figure 7. Strict consensus tree of 232 MPTs with the deletion of *Dialipina.*

(8) Deletion of Character 54 (endolymphatic duct of supraotic cavity). To incorporate the concerns from one of the referees, who expressed the hesitation on the definition and codings of this character, we run the character matrix to find the influence of the character deletion on the tree topology. The deletion of Character 55 results in 67 MPTs with the length of 291. The strict consensus tree of these 67 MPTs and the arrangements of some taxa in the 67 trees are shown as follow:

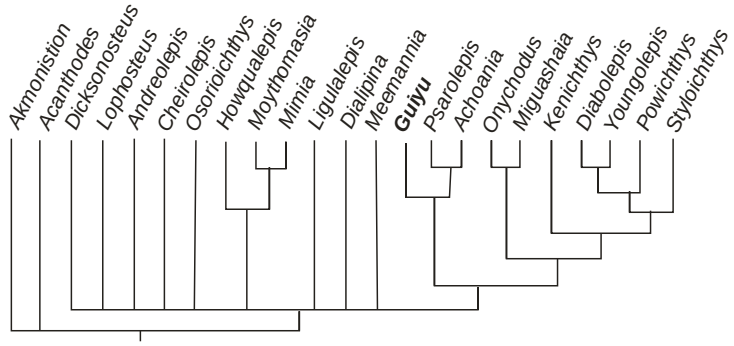


Figure 8. Strict consensus tree of 67 MPTs with the deletion of Character 54.

Table 5. Arrangements of some taxa in the 67 MPTs with the deletion of Character 54.

Taxon	Number of trees which place the taxon as a sarcopterygian	Number of trees which place the taxon as an actinopterygian	Number of trees which place the taxon as a stem osteichthyan
Lophosteus	0	0	67
Andreolepis	0	13	54
Ligulalepis	2	43	22
Dialipina	7	60	0
Meemannia	34	17	16

Comparison with previous studies

(1) Phylogenetic positions of *Lophosteus* and *Andreolepis*

Lophosteus and *Andreolepis* are only known from isolated fragments. Their affinities to, or within osteichthyans have been long debated (Gross, 1968, 1969, 1971; Schultze, 1977, 1992; Janvier, 1978, 1996; Schultze and Märss, 2004; Cloutier and Arratia, 2004; Botella *et al*. 2007). Schultze (1977) suggested that *Andreolepis* was a primitive actinopterygian and *Lophosteus* had an unresolved affinity with actinopterygians and sarcopterygians. Many authors had then assigned both genera to actinopterygians (e.g. Schultze, 1992; Janvier, 1996; Cloutier and Arratia, 2004), until Botella *et al*. (2007) placed them at the stem section of osteichthyans.

The MPT herein agrees with Botella *et al*. (2007) in placing *Lophosteus* and *Andreolepis* as stem osteichthyans. All of the 92 trees with no more than 293 steps support *Lophosteus* as a stem osteichthyan and 77 trees support *Andreolepis* as a stem osteichthyan. Placing *Lophosteus* as the sister to all other actinopterygians requires additional 5 steps.

(2) Phylogenetic position of *Ligulalepis*

Ligulalepis was referred to actinopterygians (Schultze, 1968, 1977, 1992; Chang, 2000; Schultze and Cumbaa, 2001; Basden and Young, 2001; Zhu *et al.,* 2006) or stem osteichthyans (Basden *et al*., 2000; Friedman, 2007). The MPT herein is different from the previous studies in placing *Ligulalepis* as a basal sarcopterygian. Two unambiguous apomorphies support the sister-group relationship between *Ligulalepis* and other sarcopterygians: the presence of the endolymphatic duct of supraotic cavity and the parachordal plates separated from the otic capsule by cartilage or a persistent fissure. However, 43 of the 92 trees with no more than 293 steps trees place *Meemannia* as a stem actinopterygian. Only 26 trees with 293 steps place *Meemannia* as a basal sarcopterygian and 23 trees place it as a stem osteichthyan, suggesting the future research direction on this taxon.

(3) Phylogenetic position of *Dialipina*

Dialipina has been considered a stem actinopterygian (Schultze and Cumbaa, 2001; Cloutier and Arratia, 2004; Zhu *et al*., 2006) or a stem osteichthyan (Friedman, 2007). The MPT herein resolves *Dialipina* as the most basal actinopterygian. 81 of the 92 trees with no more than 293 steps support this relationship and 11 trees place *Dialipina* as a stem sarcopterygian. Placing *Dialipina* as the stem osteichthyan requires 2 additional steps (294).

(4) Phylogenetic position of *Meemannia*

Meemannia was originally interpreted as a stem sarcopterygian (Zhu *et al.,* 2006) although the support of that node is weak. 55 of the 92 trees with no more than 293 steps trees place *Meemannia* as a basal sarcopterygian. Only 17 trees with 293 steps place *Meemannia* as a stem actinopterygian and 20 trees place it as a stem osteichthyan.

(5) Phylogenetic positions of *Psarolepis* and *Achoania*

Psarolepis was originally identified as the most basal 'crossopterygian', a dipnomorph more closely related to lungfishes than porolepiforms (Yu, 1998), and then interpreted as either a stem osteichthyan (Zhu *et al.,* 1999; Zhu and Schultze, 2001) or a stem sarcopterygian (Zhu *et al.,* 1999, 2001, 2006; Zhu and Yu, 2002; Botella *et al.,* 2007; Friedman, 2007). *Achoania* was placed along

the sarcopterygian stem (Zhu *et al.,* 2001, 2006; Zhu and Yu, 2002; Friedman, 2007)

Herein, *Psarolepis* and *Achoania* are resolved as a sister pair, both in the parsimonious and Bayesian trees, in agreement with Friedman (2007). This marks a departure from earlier cladograms, in which *Psarolepis* and *Achoania* are resolved as successive plesions along the sarcopterygian stem (Zhu *et al*., 2001; Zhu and Yu, 2002, 2004). The sister-group relationship between *Psarolepis* and *Achoania* is strongly supported by a Bremer decay index of 3 and a bootstrap value of 91%. 9 characters support the node [*Achoania* + *Psarolepis*] in the current study: dermintermedial process; smooth margins of postparietals and parietals participating in dermal intracranial joint; tooth-bearing median rostral; premaxillary with inturned symphysial process; large ventromesially directed flange of symphysial region of lower jaw; infradentary foramina always present; teeth of dentary not reaching anterior end of lower jaw; pore-canal network; dermal bone surface with large openings of pore canals. 8 additional steps are required to resolve *Psarolepis* and *Achoania* as successive plesions along the sarcopterygian stem crownward of *Guiyu*.

(6) Phylogenetic position of *Onychodus*

The phylogenetic position of *Onychodus* has been widely debated. *Onychodus* has been considered as the sister group of actinistians (Yu, 1990; Zhu and Schultze, 1997, 2001; Zhu *at al*., 1999, 2006), or above actinistians as the sister taxon to the dipnomorph/tetrapodomorph clade (Yu, 1990; Cloutier and Ahlberg, 1995, 1996) or tetrapodomorphs plus a subset of dipnomorphs (Schultze, 1987; Long, 1989; Young *et al.,* 1992). It has also been considered as a stem sarcopterygian (Friedman 2007; Friedman *et al*. 2007).

Onychodus is reconstructed herein as a clade with *Miguashaia*, an early actinistian, and as a crown sarcopterygian. This clade is strongly supported by a Bremer decay index of 4, and a bootstrap value of 91%. However, the Bayesian index is relatively low (0.56/0.58/0.57). Placing *Onychodus* as the immediate sister group to crown sarcopterygians takes 7 additional steps (299).

(7) Phylogenetic position of *Styloichthys*

Friedman (2007) proposed *Styloichthys* as the oldest coelacanth based on the investigation of a revised data matrix. However, the MPT herein supports the earlier arrangement that *Styloichthys* is the immediate sister taxon to tetrapodomorphs plus dipnomorphs (Zhu and Yu, 2002, Zhu *et al*., 2006). This grouping is strongly supported by a Bremer decay index of 4, 18 unambiguous and 3 equivocal synapomorphies. Noteworthy is that all of the three Bayesian solutions (Fig. 3) suggest *Styloichthys* as the sister taxon of the Dipnomorpha, although this relationship is only supported by a low Bayesian index.

Taxon stability and maximum leaf stability

We tried to plot the leaf stabilities against incompleteness to highlight the taxa that are more or less stable than would be predicted on the basis of their incompleteness alone (Friedman, 2007). There is a general trend toward decreasing stability with less complete data as shown in Figure 4A. When the residual leaf stabilities plotted against incompleteness, *Guiyu* is shown as the most unstable taxon although the incompleteness of *Guiyu* is not high (24.2%). As a whole, the stem sarcopterygians are the least stable taxa when the effects of incompleteness factored out (Friedman, 2007), suggesting the future research direction on these taxa. *Onychodus*, *Miguashaia* and the

stem actinopterygian *Dialipina* are also shown to be unstable taxa. Unlike Friedman (2007), *Styloichthys* is more stable than would be expected considering its incompleteness.

Table 6. Leaf stability measures and residuals of the taxa in the current analysis.

Taxa	Percent "?"	leaf stability	Residual
Akmonistion	82.4	0.6944	0.0243
Acanthodes	73.9	0.7021	0.01925
Dicksonosteus	62.1	0.6471	-0.05345
Lophosteus	92.2	0.6593	0.0039
Andreolepis	92.8	0.6515	-0.003
Guiyu	24.2	0.6827	-0.0747
Ligulalepis	69.9	0.6926	0.00375
Dialipina	57.5	0.6873	-0.02015
Cheirolepis	23.5	0.7546	-0.00385
Osorioichthys	45.8	0.7849	0.0599
Howqualepis	21.6	0.7970	0.0357
Mimia	3.9	0.7996	0.01175
Moythomasia	5.2	0.7997	0.0138
Meemannia	79.7	0.6350	-0.03915
Psarolepis	26.1	0.7250	-0.02955
Achoania	59.5	0.7187	0.01425
Onychodus	11.8	0.7274	-0.0486
Miguashaia	41.8	0.7094	-0.0216
Styloichthys	30.1	0.7740	0.02545
Youngolepis	14.4	0.7851	0.013
Diabolepis	39.9	0.7652	0.03135
Powichthys	14.4	0.7792	0.0071
Kenichthys	24.2	0.7758	0.0184

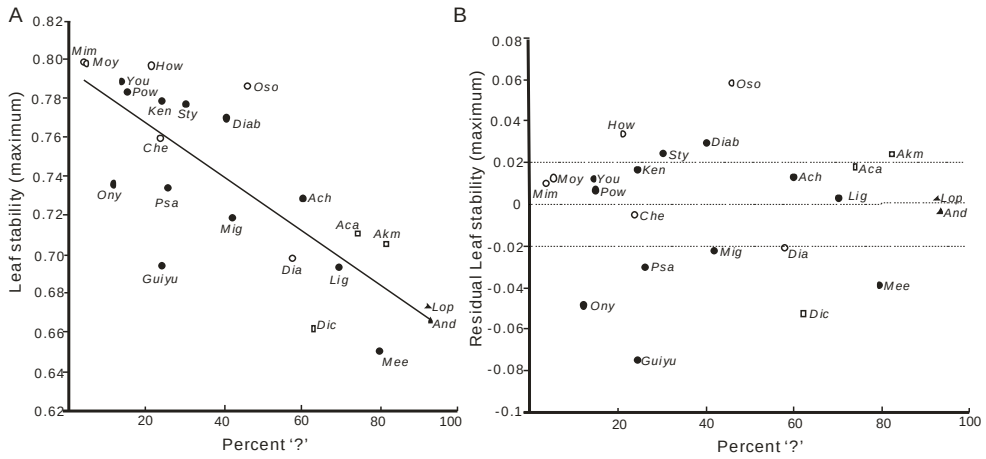


Figure 9. The maximum leaf stabilities (A) and residual leaf stabilities (B) plotted against incompleteness. The relationship in A is significant ($P = 6.127 \times 10^{-6}$). Circles represent actinopterygians; Black filled circles represent sarcopterygians and squares indicate outgroups. *Aca, Acanthodes*; *Ach*, *Achoania*; *Akm, Akmonistion*; *And*, *Andreolepis*; *Che, Cheirolepis*; *Dia*, *Dialipina*; *Diab*, *Diabolepis*; *Dic*, *Dicksonosteus*; *How, Howqualepis*; *Ken*, *Kenichthys*; *Lig*, *Ligulalepis*; *Lop*, *Lophosteus*; *Mee*, *Meemannia*; *Mig*, *Miguashaia*; *Mim, Mimia*; *Moy, Moythomasia*; *Ony*, *Onychodus*; *Oso, Osorioichthys*; *Pow*, *Powichthys*; *Psa*, *Psarolepis*; *Sty*, *Styloichthys*; *You*, *Youngolepis*.

3. Taxa and principal sources of data

Akmonistion: Coates and Sequeira (1998), Coates *et al*. (1998), Coates and Sequeira (2001a), Coates and Sequeira (2001b), Maisey (2007).

Dicksonosteus: Goujet (1975), Goujet (1984).

Acanthodes: Miles (1973), Denison (1979), Coates (1994).

Lophosteus: Gross (1968), Gross (1969), Gross (1971), Schultze (1977), Janvier (1978), Schultze (1992), Janvier (1996), Schultze and Märss (2004), Cloutier and Arratia (2004), Botella *et al*. (2007).

Andreolepis: Gross (1968), Gross (1969), Gross (1971), Schultze (1977), Janvier (1978), Schultze (1992), Janvier (1996), Schultze and Märss (2004), Cloutier and Arratia (2004), Botella *et al*. (2007).

Ligulalepis: Schultze (1968), Burrow (1994), Basden *et al.* (2000), Basden and Young (2001),.

Dialipina: Schultze (1968), Mark-Kurik (1974), Schultze (1977), Schultze (1992), Schultze and Cumbaa (2001).

Cheirolepis: Pearson and Westoll (1979), Pearson (1982), Arratia and Cloutier (1996), Arratia and Cloutier (2004).

Osorioichthys: Casier (1952), Casier (1954), Taverne (1997).

Howqualepis: Long (1988).

Mimia: Gardiner and Bartram (1977); Gardiner (1984).

Moythomasia: Gross (1950), Gross (1953), Jessen (1968), Jessen (1972), Gardiner and Bartram (1977), Gardiner (1984), Trinajastic (1999).

Meemannia: Zhu *et al*. (2006).

Psarolepis: Yu (1998), Zhu *et al*. (1999), Zhu and Schultze (2001), Zhu and Yu (2004).

Achoania:	Zhu *et al*. (2001), Zhu and Yu (2004).
Miguashaia:	Schultze (1973); Cloutier (1996), Forey (1998), Forey *et al*. (2000).
Onychodus:	Jessen (1966), Andrews (1973), Long (2001), Andrews *et al*. (2006).
Styloichthys:	Zhu and Yu (2002), Zhu and Yu (2004).
Youngolepis:	Chang (1982), Chang (1991), Chang and Smith (1992), Chang (2004).
Diabolepis:	Chang and Yu (1984), Smith and Chang (1990), Chang (1995), Campbell and Barwick (2001).
Powichthys:	Jessen (1975), Jessen (1980), Clement and Janvier (2004).
Kenichthys:	Chang and Zhu (1993), Zhu and Ahlberg (2004).

4. List of 160 characters used in the phylogenetic analysis and reference sources

1 Large consolidated dermal plates covering neurocranium and branchial arches: absent (0); present (1).

Forey (1980), Character 7; Gardiner (1984), Character 14; Zhu and Schultze (2001), Character 1; Zhu *et al*. (2001), Zhu and Yu (2002), Character 1; Zhu *et al*. (2006), Character 1; Friedman (2007), Character 1.

2 Postrostral: absent (0); postrostral mosaic of small variable bones (1); large median postrostral, with or without accessory bones (2).

Lund *et al*. (1995), Character 7; Cloutier and Ahlberg (1996), Character 23; Lund (2000), Character 6; Schultze and Cumbaa (2001), Character 9; Zhu and Schultze (2001), Characters 10-11; Zhu *et al*. (2001), Zhu and Yu (2002), Character 6; Lund and Poplin (2002), Character 7; Cloutier and Arratia (2004), Characters 47-48; Zhu *et al*. (2006), Character 7; Friedman (2007), Character 6.

Friedman (2007) altered the coding for *Kenichthys* from "2" (Zhu *et al*., 2001, Zhu and Yu, 2002) to "?". The state assessment for *Kenichthys* in Zhu *et al*. (2001) was based on the personal examination (IVPP V10493.3).

3 Mesial margin of nasal: not notched (0); notched (1).

Gardiner and Schaeffer (1989), Character A5; Lund *et al*. (1995), Character 9; Coates (1998), Character A5; Lund (2000), character 9; Schultze and Cumbaa (2001), Character 11; Lund and Poplin (2002), Character 10; Cloutier and Arratia (2004), Character 44; Zhu *et al*. (2006), Character 8.

The original formulation is modified to specify the notch for the anterior nostril.

4 Number of nasals: many (0); one or two (1).

Lund *et al*. (1995), Character 10; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 44; Ahlberg *et al*. (2000), Character 22; Lund (2000), Character 10; Poplin and Lund (2000), Character 8; Schultze and Cumbaa (2001), Character 12; Lund and Poplin (2002), Character 11; Cloutier and Arratia (2004), Character 43; Daeschler *et al*. (2006), Character 35; Long *et al*. (2006), Character 41; Zhu *et al*. (2006), Character 9.

5 Contact of nasal with premaxillary: absent (0); present (1).

Dietze (2000), Character 34; Schultze and Cumbaa (2001), Character 13; Cloutier and Arratia (2004), Character 14; Zhu *et al*. (2006), Character 10.

6 Dermintermedial process: absent (0); present (1).
Zhu and Schultze (2001), Character 37; Zhu *et al*. (2001), Zhu and Yu (2002), Character 24; Zhu *et al*. (2006), Character 29; Friedman (2007), Character 23.
The dermintermedial process is present in *Diabolepis* (IVPP V16001).

7 Position of posterior nostril: external, far from jaw margin (0); external, close to jaw margin (1).
Cloutier and Ahlberg (1996), Character 45; Schultze and Cumbaa (2001), Character 22; Zhu and Schultze (2001), Character 39; Zhu *et al*. (2001), Zhu and Yu (2002), Character 26; Zhu *et al*. (2006), Character 30; Friedman (2007), Character 24.

8 Posterior nostril: associated with orbit (0); not associated with orbit (1).
Cloutier and Ahlberg (1996), Character 46; Schultze and Cumbaa (2001), Character 23; Zhu and Schultze (2001), Character 40; Zhu *et al*. (2001), Zhu and Yu (2002), Character 27; Zhu *et al*. (2006), Character 31; Friedman (2007), Character 25.

9 Posterior nostril enclosed posteriorly by preorbital or preorbital process of premaxillary: absent (0); present (1).
New character. We suggest that the lacrimal of *Onychodus* (Andrews *et al*., 2006) corresponds to the preorbital of *Guiyu* and coelacanths. The lacrimal is absent in *Onychodus*, as well as in coelacanths. The lacrimojugal of coelacanths (Forey, 1998) is better interpreted as a single bone (jugal) since the fusion of two bones (lacrimal and jugal) involves an additional hypothesis. Zhu *et al*. (2001) suggested the posterior nostril in *Achoania* enclosed posteriorly by the lacrimal. By comparison to the condition of *Guiyu*, the bone enclosing the posterior nostril in *Achoania* should be the preorbital. The preorbital is either lost or fused to the premaxillary in *Psarolepis*, and some actinopterygians. The homology of the lacrimal in some sarcopterygians (Dipnomorpha and Tetrapodomorpha) and actinopterygians needs further clarification.

10 Supraorbital (*sensu* Cloutier and Ahlberg 1996, including posterior tectal of Jarvik): absent (0); present (1).
Gardiner and Schaeffer (1989), Character 14, E4; Lund *et al*. (1995), Character 13; Cloutier and Ahlberg (1996), Character 28; Coates (1999) Character 7; Lund (2000), Character 11; Schultze and Cumbaa (2001), Character 17; Zhu and Schultze (2001), Character 17; Zhu *et al*. (2001), Zhu and Yu (2002), Character 11; Lund and Poplin (2002), Character 12; Cloutier and Arratia (2004), Character 62; Gardiner *et al*. (2005), Character 22; Zhu *et al*. (2006), Character 12; Friedman (2007), Character 10.

11 Supraorbital, preorbital and nasal: unfused (0); fused (1).
Dietze (2000), Character 33; Schultze and Cumbaa (2001), Character 16; Zhu *et al*. (2006), Character 14.

12 Contact between parietal and supraorbital: present (0); absent (1).
Cloutier and Ahlberg (1996), Character 34; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004),

Character 57; Schultze and Cumbaa (2001), Character 63; Zhu and Schultze (2001), Character 23; Zhu *et al*. (2001), Zhu and Yu (2002), Character 16; Cloutier and Arratia (2004), Character 54; Zhu *et al*. (2006), Character 19; Friedman (2007), Character 15.

13 T-shaped dermosphenotic: absent (0); present (1).
Gardiner and Schaeffer (1989), Character A6; Coates (1998), Character A6; Schultze and Cumbaa (2001), Character 77; Cloutier and Arratia (2004), Character 65; Zhu *et al*. (2006), Character 16.

14 Intertemporal: present (0); absent (1).
Lund *et al*. (1995), Character 21; Cloutier and Ahlberg (1996), Character 36; Coates (1999), Character 4; Dietze (2000), Character 9; Ahlberg *et al*. (2000), Character 18; Schultze and Cumbaa (2001), Character 75; Zhu and Schultze (2001), Character 25; Zhu *et al*. (2001), Zhu and Yu (2002), Character 18; Cloutier and Arratia (2004), Character 71; Daeschler *et al*. (2006), Character 74; Long *et al*. (2006), Character 53; Zhu *et al*. (2006), Character 21; Friedman (2007) Character 17.

15 Tectal (*sensu* Cloutier and Ahlberg 1996, not counting the 'posterior tectal' of Jarvik): absent (0); present (1).
Cloutier and Ahlberg (1996), Character 42; Schultze and Cumbaa (2001), Character 14; Zhu and Schultze (2001), Character 15; Zhu *et al*. (2001), Zhu and Yu (2002), Character 9; Zhu *et al*. (2006), Character 11; Friedman (2007), Character 8.

16 Anterior margin of parietal: between or in front of orbits (0); slightly posterior to orbits (1); much posterior to orbits (2).
Cloutier and Ahlberg (1996), Character 31; Zhu and Schultze (2001), Character 20; Zhu *et al*. (2001), Zhu and Yu (2002), Character 14; Zhu *et al*. (2006), Character 17; Friedman (2007), Character 13.
Friedman (2007) altered the codings for *Psarolepis* and *Youngolepis* from "1" (Zhu *et al*., 2001, Zhu and Yu, 2002) to "?". The state assessment for these two taxa in Zhu *et al*. (2001) was based on the personal examination of unpublished specimens (IVPP V6795 and V16002).
Friedman (2007) cited the description of Zhu and Yu (2002) that the pineal foramen is at the anterior margin of parietals in *Styloichthys*, and changed the coding for *Styloichthys* from "0" (Zhu *et al*., 2001, Zhu and Yu, 2002) to "1". His judgement was based on his observation that the pineal foramen in *Styloichthys* lies posterior to the orbits. However, the pineal foramen in *Styloichthys* lies evidently at the level of the posterior margin of the orbits (Zhu and Yu, 2002: fig.1a), and the original coding is retained here.

17 Pineal foramen: present (0); absent (1).
Lund *et al*. (1995), Character 20; Cloutier and Ahlberg (1996), Character 32; Taverne (1997), Character 2; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 36; Dietze (2000), Character 1; Schultze and Cumbaa (2001), Character 1; Zhu and Schultze (2001), Character 21; Zhu *et al*. (2001), Zhu and Yu (2002), Character 15; Cloutier and Arratia (2004), Character 50; Daeschler *et al*. (2006), Character 27; Long *et al*. (2006), Character 36; Zhu *et al*. (2006), Character 18; Friedman (2007), Character 14.

18 Pineal eminence (in those taxa with no pineal foramen): absent (0); present (1).
Friedman (2007), Character 146.

19 Location of pineal foramen/eminence: level with posterior margin of orbits (0); well posterior of orbits (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 37; Daeschler *et al*. (2006), Character 28.

20 Parietals surround pineal foramen/eminence: yes (0); no (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 38; Daeschler *et al*. (2006), Character 29.

21 Dermal intracranial joint: absent (0); present (1).
Cloutier and Ahlberg (1996), Character 81; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 71; Zhu and Schultze (2001), Character 31; Zhu *et al*. (2001), Zhu and Yu (2002), Character 20; Daeschler *et al*. (2006), Character 50; Long *et al*. (2006), Character 3; Zhu *et al*. (2006), Character 24; Friedman (2007), Character 19.

22 Margins of postparietals and parietals participating in dermal intracranial joint: smooth (0); jagged (1).
Friedman (2007), Character 147.

23 Length of parietal versus postparietal: equal or Ppa longer than Pa (0); Pa up to 2 times Ppa (1).
Lund *et al*. (1995), Character 19; Taverne (1997), Character 3; Dietze (2000), Character 7; Lund (2000), Character 14; Poplin and Lund (2000), Character 10; Schultze and Cumbaa (2001), Character 70; Lund and Poplin (2002), Character 15; Cloutier and Arratia (2004), Character 57; Zhu *et al*. (2006), Character 25.

24 Parietal portion of skull roof relative to postparietal portion in length: parietal portion roughly as long as postparietal portion (0), parietal portion much longer postparietal portion (1), parietal portion much shorter than postparietal portion (2).
Schultze and Cumbaa (2001), Character 68; Zhu and Schultze (2001), Character 5; Zhu *et al*. (2006), Character 26.

25 Complete enclosure of spiracle by bones bearing otic and infraorbital canals: absent (0); present (1).
Friedman (2007), Character 148.

26 Posterior margin of skull roof: embayed (0); straight or convex (1).
Zhu *et al*. (2006), Character 27.

27 Number of marginal bones alongside postparietal and posterior to the intertemporal: single (0); two or more (1).
Lund *et al*. (1995), Character 21; Cloutier and Ahlberg (1996), Character 37; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 49; Schultze and Cumbaa (2001), Character 74; Zhu and Schultze (2001), Character 27; Zhu *et al*. (2001), Zhu and Yu (2002), Character 19; Cloutier and Arratia (2004), Character 75; Daeschler *et al*. (2006), Character 39; Zhu *et al*. (2006), Character 22; Friedman (2007) Character 18.

28 Extratemporal: absent (0); present (1).
Cloutier and Ahlberg (1996), Character 35; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 47; Zhu and Schultze (2001), Character 24; Zhu *et al*. (2001), Zhu and Yu (2002), Character 17; Daeschler *et al*. (2006), Character 37; Long *et al*. (2006), Character 44; Zhu *et al*. (2006), Character 20; Friedman (2007), Character 16.

29 Number of extrascapulars: uneven (0); paired (1).
Gardiner and Schaeffer (1989), Character A8; Lund *et al*. (1995), Character 30; Cloutier and Ahlberg (1996), Character 40; Coates (1998), Character A8; Dietze (2000), Character 2; Lund (2000), Character 20; Poplin and Lund (2000), Character 12; Schultze and Cumbaa (2001), Character 73; Zhu and Schultze (2001), Character 34; Zhu *et al*. (2001), Zhu and Yu (2002), Character 21; Lund and Poplin (2002), Character 21; Cloutier and Arratia (2004), Character 60; Zhu *et al*. (2006), Character 28; Friedman (2007), Character 20.

30 Endochondral bone: absent (0); present (1).
Forey (1980), Character 27; Gardiner (1984), Character 20; Zhu and Schultze (2001), Character 202; Zhu *et al*. (2001), Zhu and Yu (2002), Character 147; Zhu *et al*. (2006), Character 114; Friedman (2007), Character 130.

31 Co-mineralised ethmosphenoid region: present (0); absent (1).
Friedman (2007), Character 171.

32 Interorbital space: broad (0); narrow (1).
Friedman (2007), Character 174.

33 Internasal pits: undifferentiated or anterior palatal fossa (0); shallow paired pits with strong midline ridge (1); deep pear-shaped pits (2); absent (3).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 25; Daeschler *et al*. (2006), Character 19; Long *et al*. (2006), Character 28.

34 Fenestra ventralis: absent (0); present (1).
Schultze and Cumbaa (2001), Character 61; Zhu and Schultze (2001), Character 143; Zhu *et al*. (2001), Zhu and Yu (2002), Character 107; Zhu *et al*. (2006), Character 82; Friedman (2007), Character 93.

35 Ethmoid articulation for palatoquadrate: placed on postnasal wall (0); extends posteriorly to the level of N.II (1).
Friedman (2007), Character 172.

36 Eye stalk or unfinished area for similar structure: absent (0); present (1).
Zhu and Schultze (2001), Character 147; Zhu *et al*. (2001), Zhu and Yu (2002), Character 109; Zhu *et al*. (2006), Character 83; Friedman (2007), Character 95.

37 Postorbital pillar: absent (0); present (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 75; Zhu *et al*. (2001), Zhu and Yu (2002), Character 112; Zhu *et al*. (2006), Character 86; Friedman (2007), Character 98.

38 Basipterygoid process: small knob-like process (0); developed as a broad platform (1).
Long *et al*. (2006), Character 33.

39 Position of exit of pituitary vein: in front of basipterygoid process (0); dorsal to vertical portion of basipterygoid process (1); posterior to basipterygoid process (2).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 79; Zhu and Schultze (2001), Character 151; Zhu *et al*. (2001), Zhu and Yu (2002), Character 113; Zhu *et al*. (2006), Character 87; Friedman (2007), Character 99.

40 Unconstricted cranial notochord: absent (0); present (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 77; Schultze and Cumbaa (2001), Character 62; Zhu and Schultze (2001), Character 153; Zhu *et al*. (2001), Zhu and Yu (2002), Character 115; Zhu *et al*. (2006), Character 88; Friedman (2007), Character 101.

41 Descending process of sphenoid (with its posterior extremity lacking periostegeal lining): absent (0); present (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 78; Zhu and Schultze (2001), Character 135; Zhu *et al*. (2001), Zhu and Yu (2002), Character 102; Zhu *et al*. (2006), Character 78; Friedman (2007), Character 89.

42 Endoskeletal intracranial joint: absent (0); present (1).
Cloutier and Ahlberg (1996), Characters 82-83; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 72; Zhu *et al*. (2001), Zhu and Yu (2002), Characters 98-99; Daeschler *et al*. (2006), Character 51; Long *et al*. (2006), Character 32; Friedman (2007), Character 86.

43 Orientation of intracranial joint: vertical or anteroventrally slanting (0); posteroventrally slanting (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 73; Zhu and Schultze (2001), Character 133; Zhu *et al*. (2001), Zhu and Yu (2002), Character 100; Zhu *et al*. (2006), Character 77; Friedman (2007), Character 87.

44 Articulation facet with hyomandibular: single-headed (0), double-headed (1).

Cloutier and Ahlberg (1996), Character 88; Zhu and Schultze (2001), Character 128; Schultze and Cumbaa (2001), Character 53; Zhu *et al*. (2001), Zhu and Yu (2002), Character 96; Zhu *et al*. (2006), Character 73; Friedman (2007), Character 84.

45 Hyomandibular facet: on lateral commissure (0); posterior to lateral commissure (1).
Friedman (2007), Character 177.

46 Position of the lateral commissure: overlying root of N.V (0); posterior to root of N.V (1).
Friedman (2007), Character 178.

47 Single posterior foramen for jugular canal and ramus hyomandibularis N.VII: absent (0); present (1).
Friedman (2007), Character 179.

48 Vestibular fontanelles: absent (0); present (1).
Friedman (2007), Character 180.

49 Accessory fenestration in otic capsule: absent (0); present (1).
Friedman (2007), Character 181.

50 Parachordal plates: separated from the otic capsule by cartilage or a persistent fissure (0); sutured or co-mineralised with the otic capsule (1).
Friedman (2007), Character 182.

51 Enclosed canal for dorsal aorta within basioccipital region: absent (0); present (1).
Friedman (2007), Character 183.

52 Basicranial fenestra: absent (0); present (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 76; Zhu *et al*. (2001), Zhu and Yu (2002), Character 114; Daeschler *et al*. (2006), Character 52; Long *et al*. (2006), Character 34; Friedman (2007), Character 100.

53 Otical process (an outgrowth from the lateral wall of the braincase penetrated by the branches of the r. oticus lateralis): absent (0); present (1).
Chang and Smith (1992), Character A3, Chang (2004), Character 145.

54 Endolymphatic duct of supraotic cavity: absent (0); present (1).
Zhu *et al*. (2006), Character 90.

55 Lateral cranial canal: absent (0); present (1).
Gardiner and Schaeffer (1989), Character 5, C1; Coates (1999), Character 32; Cloutier and Arratia (2004), Character 1; Zhu *et al*. (2006), Character 91.

56 Foramina (similar to infradentary foramina) on cheek bones: absent (0); present (1).

Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 63; Zhu and Schultze (2001), Character 70; Zhu *et al*. (2001), Zhu and Yu (2002), Character 53; Zhu *et al*. (2006), Character 50; Friedman (2007), Character 47.

57 Number of sclerotic plates: four or less (0); more than four (1).
Cloutier and Ahlberg (1996), Character 49; Zhu and Schultze (2001), Character 41; Schultze and Cumbaa (2001), Character 20; Zhu *et al*. (2001), Zhu and Yu (2002), Character 29; Zhu *et al*. (2006), Character 33; Friedman (2007), Character 27.

58 Lacrimal posteriorly enclosing posterior nostril: absent (0); present (1).
Zhu *et al*. (2001), Zhu and Yu (2002), Character 28; Long *et al*. (2006), Character 2; Zhu *et al*. (2006), Character 32; Friedman (2007), Character 26.

59 Most posterior major bone of cheek bearing preopercular canal ('preopercular') extending forward, close to orbit: absent (0); present (1).
Zhu and Schultze (2001), Character 58; Zhu *et al*. (2001), Zhu and Yu (2002), Character 44; Zhu *et al*. (2006), Character 45.

60 Number of cheek bones bearing preopercular canal posterior to jugal: one (0); two (1).
Friedman (2007), Character 41.

61 Bone bearing both quadratojugal pit-line and preopercular canal: absent (0); present (1).
Friedman (2007), Character 42.

62 Dermohyal: absent (0); present (1).
Patterson (1982), Character 8; Gardiner and Schaeffer (1989), Character A2; Lund *et al*. (1995), Character 48; Cloutier and Ahlberg (1996), Character 52; Coates (1998), Character A2; Dietze (2000), Character 41; Lund (2000), Character 44; Schultze and Cumbaa (2001), Character 2; Zhu and Schultze (2001), Character 60; Zhu *et al*. (2001), Zhu and Yu (2002), Character 45; Lund and Poplin (2002), Character 41; Cloutier and Arratia (2004), Character 95; Gardiner *et al*. (2005), Character 24; Zhu *et al*. (2006), Character 46; Friedman (2007), Character 40.

63 Vomerine fangs: absent (0); present (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 24; Zhu *et al*. (2001), Zhu and Yu (2002), Character 90; Friedman (2007), Character 78.

64 Vomeral area with grooves and raised areas: absent (0); present (1).
Zhu and Schultze (2001), Character 142; Zhu *et al*. (2001), Zhu and Yu (2002), Character 106; Zhu *et al*. (2006), Character 81; Friedman (2007), Character 92.

65 Parasphenoid: protruding forward into ethmoid region of endocranium (0); behind ethmoid region (1).
Zhu and Schultze (2001), Character 124; Zhu *et al*. (2001), Zhu and Yu (2002), Character 93; Zhu *et al*. (2006), Character 71; Friedman (2007), Character 81.

66 Denticulated field of parasphenoid: without spiracular groove (0); with spiracular groove (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 26; Zhu and Schultze (2001), Character 121; Zhu *et al*. (2001), Zhu and Yu (2002), Character 94; Zhu *et al*. (2006), Character 72; Daeschler *et al*. (2006), Character 20; Long *et al*. (2006), Character 29; Friedman (2007), Character 82.

67 Ascending process of parasphenoid: absent (0); present (1).
Patterson (1982), Character 9; Dietze (2000), Character 54; Schultze and Cumbaa (2001), Character 52; Zhu and Schultze (2001), Character 125; Cloutier and Arratia (2004), Character 123; Zhu *et al*. (2006), Character 70.

68 Shape of parasphenoid: lozenge-shaped (0); broad, splint-shaped (1); slender, splint-shaped (2).
Friedman (2007), Character 168.

69 Parasphenoid denticle field with multifid anterior margin: absent (0); present (1).
Friedman (2007), Character 167.

70 Parasphenoid denticle field with anteriorly divergent lateral margins: absent (0); present (1).
Friedman (2007), Character 169.

71 Parasphenoid denticle field: terminates at or anterior to level of foramina for internal carotid arteries (0); extends posterior to foramina for internal carotid arteries (1).
Friedman (2007), Character 170.

72 Fenestra in palatoquadrate marking position of basal articulation: absent (0); present (1).
Friedman (2007), Character 162.

73 Dermal bone forming outer dental arcade: absent (0); present (1).
New character.

74 Large monolinear tooth row of outer dental arcade: absent (0), present (1).
Botella *et al*. (2007).

75 Tooth-bearing median rostral: absent (0), present (1).
Cloutier and Ahlberg (1996), Character 22; Schultze and Cumbaa (2001), Character 28; Zhu and Schultze (2001), Character 9; Cloutier and Arratia (2004), Character 38; Zhu *et al*. (2006), Character 6; Friedman (2007), Character 143.

76 Premaxillaires with inturned symphysial processes: absent (0); present (1).
Friedman (2007), Character 149.

77 Premaxillary forming part of orbit: absent (0); present (1).

Cloutier and Ahlberg (1996), Character 18; Schultze and Cumbaa (2001), Character 27; Zhu and Schultze (2001), Character 7; Zhu *et al*. (2001), Zhu and Yu (2002), Character 4; Cloutier and Arratia (2004), Character 12; Zhu *et al*. (2006), Character 3; Friedman (2007), Character 4.

78 Preorbital process of premaxillary: absent (0); present (1).
Zhu and Schultze (2001), Character 8; Zhu *et al*. (2001), Zhu and Yu (2002), Character 5; Zhu *et al*. (2006), Character 4; Friedman (2007), Character 5.

79 Posterior expansion of maxilla (maxilla cleaver-shaped): present (0); absent (1).
Lund *et al*. (1995), Character 52; Lund (2000), Character 31; Poplin and Lund (2000), Character 18; Schultze and Cumbaa (2001), Character 31; Zhu and Schultze (2001), Character 54; Zhu *et al*. (2001), Zhu and Yu (2002), Character 42; Lund and Poplin (2002), Character 30; Cloutier and Arratia (2004), Character 18; Zhu *et al*. (2006), Character 43; Friedman (2007), Character 39.

80 Ventral margin of maxilla: straight (0), curved (1).
Dietze (2000), Character 26; Poplin and Lund (2000), Character 19; Schultze and Cumbaa (2001), Character 32; Cloutier and Arratia (2004), Character 19; Zhu *et al*. (2006), Character 44.

81 Contribution by maxilla to posterior margin of cheek: present (0); absent (1).
Friedman (2007), Character 151.

82 Strong ascending flexion of symphysial region of mandible: absent (0); present (1).
Friedman (2007), Character 155.

83 Large ventromesially directed flange of symphysial region of mandible: absent (0); present (1).
Friedman (2007), Character 156.

84 Flange-like extension composed of Meckelian ossification and prearticular that extends below ventral margin of infradentaries: absent (0), present (1).
Friedman (2007), Character 159.

85 Infradentary foramina: always present (0); variable (1); always absent (2).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 15; Schultze and Cumbaa (2001), Character 42; Zhu and Schultze (2001), Character 98; Zhu *et al*. (2001), Zhu and Yu (2002), Character 76; Daeschler *et al*. (2006), Character 11; Zhu *et al*. (2006), Character 62; Friedman (2007), Character 64.

86 Length of dentary; long (0); short with lip fold (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 10; Zhu *et al*. (2001), Zhu and Yu (2002), Character 58; Friedman (2007), Character 50.

87 Teeth of dentary: reaching anterior end of dentary (0); not reaching anterior end (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 11; Zhu *et al*. (2001), Zhu and

Yu (2002), Character 60; Daeschler *et al*. (2006), Character 7.

88 Splenial: absent (0); present (1).
Cloutier and Ahlberg (1996), Character 93; Schultze and Cumbaa (2001), Character 34; Zhu and Schultze (2001), Character 85; Zhu *et al*. (2001), Zhu and Yu (2002), Character 64; Cloutier and Arratia (2004), Character 26; Zhu *et al*. (2006), Character 55.

89 Postsplenial: present (0); absent (1).
Cloutier and Ahlberg (1996), Character 93; Ahlberg and Clack (1998), Character 33; Zhu *et al*. (2001), Zhu and Yu (2002), Character 65; Zhu and Schultze (2001), Character 86; Zhu *et al*. (2006), Character 56.

90 Surangular: absent (0); present (1).
Cloutier and Ahlberg (1996), Character 93; Taverne (1997), Character 4; Coates (1999), Character 18; Zhu and Schultze (2001), Character 87; Zhu *et al*. (2001), Zhu and Yu (2002), Character 66; Cloutier and Arratia (2004), Character 27; Zhu *et al*. (2006), Character 57.

91 Parasymphysial plate: detachable tooth whorl (0); long with posterior corner, sutured to coronoid, denticulated or with tooth row (1); absent (2).
Cloutier and Ahlberg (1996), Character 11; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 1, Character 7; Ahlberg *et al*. (2000), Character 7; Schultze and Cumbaa (2001), Character 37; Zhu and Schultze (2001), Character 81; Zhu *et al*. (2001), Zhu and Yu (2002), Character 61; Daeschler *et al*. (2006), Character 1; Long *et al*. (2006), Character 5, Zhu *et al*. (2006), Character 53.

92 Coronoids (*sensu stricto*, excluding parasymphysial dental plate or foremost bone of the coronoid series): present (0); absent (1).
Schultze and Cumbaa (2001), Character 46; Zhu and Schultze (2001), Character 89; Zhu *et al*. (2001), Zhu and Yu (2002), Character 68; Zhu *et al*. (2006), Character 58; Friedman (2007), Character 56.

93 Number of coronoids: more than three (0); three (1).
Ahlberg and Clark (1998), Character 4; Daeschler *et al*. (2006), Character 5; Long *et al*. (2006), Character 11; Friedman (2007), Character 158.

94 Fangs of coronoids (*sensu stricto*): absent (0); present (1).
Ahlberg *et al*. (2000), Character 15; Zhu and Schultze (2001), Character 90; Zhu *et al*. (2001), Zhu and Yu (2002), Character 69; Zhu *et al*. (2006), Character 59; Daeschler *et al*. (2006), Character 71; Long *et al*. (2006), Character 18; Friedman (2007), Character 57.

95 Marginal denticle band on coronoids: broad band, at least posteriorly (0); narrow band with 2-4 denticle rows (1).
Cloutier and Ahlberg (1996), Character 10; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 9; Schultze and Cumbaa (2001), Character 47; Zhu and Schultze (2001), Character 91;

Zhu *et al*. (2001), Zhu and Yu (2002), Character 70; Cloutier and Arratia (2004), Character 30; Friedman (2007), Character 58.

96 Anterior end of prearticular: far from jaw symphysis (0); near jaw symphysis (1).
Schultze and Cumbaa (2001), Character 38; Zhu and Schultze (2001), Character 93; Zhu *et al*. (2001), Zhu and Yu (2002), Character 71; Cloutier and Arratia (2004), Character 28; Zhu *et al*. (2006), Character 60; Friedman (2007), Character 59.

97 Linear, subparallel ridges of remodeled denticles on dermal bones lining the oral cavity: absent (0); present (1).
Friedman (2007), Character 161.

98 Prearticular-dentary contact: present (0); absent (1).
Cloutier and Ahlberg (1996), Character 96; Schultze and Cumbaa (2001), Character 39; Zhu and Schultze (2001), Character 94; Zhu *et al*. (2001), Zhu and Yu (2002), Character 72; Cloutier and Arratia (2004), Character 29; Zhu *et al*. (2006), Character 61; Friedman (2007), Character 60.

99 Meckelian bone exposed immediately anterior to first coronoid: yes (0); no (1).
Ahlberg and Clack (1998), Character 22; Ahlberg *et al*. (2000), Character 4; Zhu *et al*. (2001), Zhu and Yu (2002), Character 63; Daeschler *et al*. (2006), Character 65; Long *et al*. (2006), Character 12; Friedman (2007), Character 53.

100 Foramen in hyomandibular: absent (0); present (1).
Friedman (2007), Character 163.

101 Number of branchiostegal rays per side: ten or more (0); two to seven (1); none (2).
Lund *et al*. (1995), Character 61; Cloutier and Ahlberg (1996), Character 63; Coates (1999), Character 12; Dietze (2000), Character 39; Schultze and Cumbaa (2001), Character 87; Zhu and Schultze (2001), Characters 105-106; Zhu *et al*. (2001), Zhu and Yu (2002), Characters 81-82; Cloutier and Arratia (2004), Character 114; Zhu *et al*. (2006), Character 65; Friedman (2007), Character 70.

102 Median gular: present (0); absent (1).
Lund *et al*. (1995), Character 64; Cloutier and Ahlberg (1996), Character 66; Coates (1999), Character 11; Lund (2000), Character 49; Schultze and Cumbaa (2001), Character 84; Zhu and Schultze (2001), Character 109; Zhu *et al*. (2001), Zhu and Yu (2002), Character 85; Lund and Poplin (2002), Character 47; Cloutier and Arratia (2004), Character 115; Zhu *et al*. (2006), Character 67; Friedman (2007), Character 73.

103 Size of lateral gular: lateral gular and branchiostegal rays of similar size (0); lateral gular covering approximately half the intermandibular space (1).
Lund *et al*. (1995), Character 65; Cloutier and Ahlberg (1996), Character 69; Lund (2000), Character 50; Schultze and Cumbaa (2001), Character 85; Zhu and Schultze (2001), Character 112; Zhu *et al*. (2001), Zhu and Yu (2002), Character 86; Cloutier and Arratia (2004), Character 119;

Zhu *et al*. (2006), Characters 68-69; Friedman (2007), Character 74.

104 Submandibulars: absent (0); present (1).
Cloutier and Ahlberg (1996), Character 64; Ahlberg *et al*. (2000), Character 29; Schultze and Cumbaa (2001), Character 86; Zhu and Schultze (2001), Character 107; Zhu *et al*. (2001), Zhu and Yu (2002), Character 83; Cloutier and Arratia (2004), Character 120; Daeschler *et al*. (2006), Character 80; Long *et al*. (2006), Character 63; Zhu *et al*. (2006), Character 66; Friedman (2007), Character 71.

105 Course of ethmoid commissure: middle portion through median rostral (0); sutural course (1); through bone center of premaxillary (2).
Lund *et al*. (1995), Character 5; Schultze and Cumbaa (2001), Character 6; Zhu and Schultze (2001), Character 43; Zhu *et al*. (2001), Zhu and Yu (2002), Character 31; Cloutier and Arratia (2004), Character 126; Zhu *et al*. (2006), Character 34; Friedman (2007), Character 29.

106 Position of anterior pit-line: on postparietal (0); on parietal (1).
Cloutier and Ahlberg (1996), Character 103; Zhu and Schultze (2001), Character 50; Zhu *et al*. (2001), Zhu and Yu (2002), Character 38; Zhu *et al*. (2006), Character 40; Friedman (2007), Character 36.

107 Middle and posterior pit-lines on postparietal: posteriorly situated (0), mesially situated (1).
Zhu *et al*. (2001), Zhu and Yu (2002), Character 39.

108 Position of middle and posterior pit-lines: close to midline (0); near the central portion of each postparietal (1).
Zhu *et al*. (2006), Character 41.

109 Course of supraorbital canal: between anterior and posterior nostrils (0); anterior to both nostrils (1).
Lund *et al*. (1995), Character 14; Cloutier and Ahlberg (1996), Character 98; Schultze and Cumbaa (2001), Character 18; Zhu and Schultze (2001), Character 44; Zhu *et al*. (2001), Zhu and Yu (2002), Character 32; Cloutier and Arratia (2004), Character 128; Zhu *et al*. (2006), Character 35.

110 Course of supraorbital canal: straight (0); lyre-shaped (1).
Zhu *et al*. (2001), Zhu and Yu (2002), Character 33; Zhu *et al*. (2006), Character 36; Friedman (2007), Character 31.

111 Posterior end of supraorbital canal: in postparietal (0); in parietal (1); in intertemporal (2).
Schultze and Cumbaa (2001), Character 64; Zhu and Schultze (2001), Character 48; Zhu *et al*. (2001), Zhu and Yu (2002), Character 36; Cloutier and Arratia (2004), Character 129; Zhu *et al*. (2006), Character 38; Friedman (2007), Character 34.

112 Contact between otic and supraorbital canals: not in contact (0); in contact (1).

Cloutier and Ahlberg (1996), Character 102; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 67; Schultze and Cumbaa (2001), Character 65; Zhu and Schultze (2001), Character 49; Zhu *et al*. (2001), Zhu and Yu (2002), Character 37; Cloutier and Arratia (2004), Character 130; Zhu *et al*. (2006), Character 39; Friedman (2007), Character 35.

113 Contact of supraorbital and infraorbital canals: in contact rostrally (0); not in contact rostrally (1).
Zhu *et al*. (2001), Zhu and Yu (2002), Character 34; Friedman (2007), Character 32.

114 Otic canal: runs through skull roof (0); follows edge of skull roof (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 66.

115 Infraorbital canal follows premaxillary suture: no (0); yes (1).
Cloutier and Ahlberg (1996), Character 100; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 69; Zhu and Schultze (2001), Character 46; Zhu *et al*. (2001), Zhu and Yu (2002), Character 35; Zhu *et al*. (2006), Character 37; Friedman (2007), Character 33.

116 Sensory canal or pit-line associated with maxilla: absent (0); present (1).
Friedman (2007), Character 152.

117 Jugal canal: present (0); absent (1).
Maisey (1986), Character N4; Gardiner and Schaeffer (1989), Character A12; Lund *et al*. (1995), Character 46; Cloutier and Ahlberg (1996), Character 106; Schultze and Cumbaa (2001), Character 55; Zhu and Schultze (2001), Character 75; Zhu *et al*. (2001), Zhu and Yu (2002), Character 56; Cloutier and Arratia (2004), Character 136; Zhu *et al*. (2006), Character 52; Friedman (2007), Character 49.

118 Anterior portion of preopercular canal: present (0); absent (1).
Cloutier and Ahlberg (1996), Character 105; Lund (2000), Character 41; Schultze and Cumbaa (2001), Character 81; Zhu and Schultze (2001), Character 72; Zhu *et al*. (2001), Zhu and Yu (2002), Character 55; Cloutier and Arratia (2004), Character 140; Zhu *et al*. (2006), Character 51.

119 Course of mandibular canal: not passing through most posterior infradentary (0); passing through most posterior infradentary (1).
Cloutier and Ahlberg (1996), Character 111; Zhu *et al*. (2001), Zhu and Yu (2002), Character 80; Zhu and Schultze (2001), Character 102; Schultze and Cumbaa (2001), Character 44; Cloutier and Arratia (2004), Character 142; Zhu *et al*. (2006), Character 64; Friedman (2007), Character 68.

120 Course of mandibular canal: passing through dentary (0); not passing through dentary (1).
Patterson (1982), Character 7; Cloutier and Ahlberg (1996), Character 110; Coates (1998), Character A14; Schultze and Cumbaa (2001), Character 43; Zhu and Schultze (2001), Character 101; Zhu *et al*. (2001), Zhu and Yu (2002), Character 79; Cloutier and Arratia (2004), Character 141; Zhu *et al*. (2006), Character 63; Friedman (2007), Character 67.

121 Presupracleithrum: absent (0); present (1).
Patterson (1982), Character13; Gardiner and Schaeffer (1989), Character A13; Lund (2000), Character 54; Zhu and Schultze (2001), Character 160; Schultze and Cumbaa (2001), Character 96; Zhu *et al*. (2001), Zhu and Yu (2002), Character 119; Lund and Poplin (2002), Character 51; Cloutier and Arratia (2004), Character 145; Zhu *et al*. (2006), Character 93; Friedman (2007), Character 105.

122 Anocleithrum: element developed as postcleithrum (0); element developed as anocleithrum *sensu stricto* (1).
Gardiner and Schaeffer (1989), Character B2; Lund *et al*. (1995), Character 69; Cloutier and Ahlberg (1996), Character 112; Dietze (2000), Character 46; Poplin and Lund (2000), Character 28; Schultze and Cumbaa (2001), Characters 92-93; Zhu and Schultze (2001), Character 158; Zhu *et al*. (2001), Zhu and Yu (2002), Character 118; Cloutier and Arratia (2004), Character 146; Zhu *et al*. (2006), Character 92; Friedman (2007), Character 104.

123 Dorsal cleithrum (AL of the Placodermi), ventral cleithrum (AVL of the Placodermi) and pectoral spine (SP of the Placodermi): not fused (0); fused (1).
Forey (1980), Character 15; Gardiner (1984), Character 15; Zhu and Schultze (2001), Character 161; Zhu *et al*. (2001), Zhu and Yu (2002), Character 120; Zhu *et al*. (2006), Character 94; Friedman (2007), Character 106.

124 Dorsal end of cleithrum or dorsal cleithrum: pointed (0); broad and rounded (1).
Cloutier and Ahlberg (1996), Character 115; Schultze and Cumbaa (2001), Character 94; Zhu and Schultze (2001), Character 164; Zhu *et al*. (2001), Zhu and Yu (2002), Character 122; Cloutier and Arratia (2004), Character 148; Zhu *et al*. (2006), Character 96.

125 Posterior process of cleithrum or pectoral spine: present (0); absent (1).
Schultze and Cumbaa (2001), Character 95; Zhu and Schultze (2001), Character 165; Cloutier and Arratia (2004), Character 149; Zhu *et al*. (2006), Character 98.

126 Relationship of clavicle to cleithrum: ascending process of clavicle overlapping cleithrum laterally (0); ascending process of clavicle wrapping round anterior edge of cleithrum, overlapping it both laterally and mesially (1).
Cloutier and Ahlberg (1996), Character 116; Schultze and Cumbaa (2001), Character 97; Zhu and Schultze (2001), Character 168; Zhu *et al*. (2001), Zhu and Yu (2002), Character 125; Zhu *et al*. (2006), Character 100; Friedman (2007), Character 109.

127 Interclavicle: absent (0); present (1).
Cloutier and Ahlberg (1996), Character 118; Dietze (2000), Character 47; Schultze and Cumbaa (2001), Character 91; Zhu and Schultze (2001), Character 170; Zhu *et al*. (2001), Zhu and Yu (2002), Character 126; Cloutier and Arratia (2004), Character 153*;* Zhu *et al*. (2006), Character 101; Friedman (2007), Character 110.

128 Triradiate scapulocoracoid: absent (0); present (1).

Zhu and Schultze (2001), Character 171; Zhu *et al*. (2001), Zhu and Yu (2002), Character 127; Zhu *et al*. (2006), Character 102; Friedman (2007), Character 111.

129 Subscapular foramen/fossa: absent (0); present (1).
Zhu and Schultze (2001), Character 173; Zhu *et al*. (2001), Zhu and Yu (2002), Character 128; Daeschler *et al*. (2006), Character 109; Long *et al*. (2006), Character 78; Zhu *et al*. (2006), Character 103; Friedman (2007), Character 112.

130 Endoskeletal supports in pectoral fin: multiple elements articulating with girdle (0); single element ("humerus") articulating with girdle (1).
Zhu and Schultze (2001), Character 175; Zhu *et al*. (2001), Zhu and Yu (2002), Character 129; Zhu *et al*. (2006), Character 104; Friedman (2007), Character 113.

131 Pectoral propterygium: absent (0); present (1).
Zhu and Schultze (2001), Character 176; Zhu *et al*. (2001), Zhu and Yu (2002), Character 130; Zhu *et al*. (2006), Character 105.

132 Dorsal fin: double (0); single (1).
Gardiner and Schaeffer (1989), Character A17; Schultze and Cumbaa (2001), Character 98; Zhu and Schultze (2001), Character 184; Zhu *et al*. (2001), Zhu and Yu (2002), Character 135; Cloutier and Arratia (2004), Character 164; Zhu *et al*. (2006), Character 106; Friedman (2007), Character 118.

133 Median fin spines: absent (0); present (1).
Zhu *et al*. (2001), Zhu and Yu (2002), Character 139; Friedman (2007), Character 122.

134 Pelvic fin: long (0); short insertion (1).
Gardiner and Schaeffer (1989), Character A16; Coates (1998), Character A16; Coates (1999), Character 64; Lund (2000), Character 62; Schultze and Cumbaa (2001), Character 99; Cloutier and Arratia (2004), Character 166; Zhu *et al*. (2006), Character 107.

135 Caudal fin: heterocercal (0); triphycercal (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 95; Lund (2000), Characters 63-64; Schultze and Cumbaa (2001), Character 100; Cloutier and Arratia (2004), Character 172 ; Zhu *et al*. (2006), Character 108; Daeschler *et al*. (2006), Character 59; Long *et al*. (2006), Character 96;

136 Size of scale: micromeric (0), macromeric (1).
Cloutier and Arratia (2004), Character 175.

137 Scale: rhomboid (0); round (1).
Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 98; Zhu and Schultze (2001), Character 198; Zhu *et al*. (2001), Zhu and Yu (2002), Character 144; Daeschler *et al*. (2006),

Character 61; Long *et al*. (2006), Character 97; Zhu *et al*. (2006), Character 111; Friedman (2007), Character 127.

138 Scale with interlocking peg and socket: absent (0); present (1).
Friedman (2007), Character 193.

139 Peg on rhomboid scale: narrow (0); broad (1).
Patterson (1982), Character 5*;* Cloutier and Ahlberg (1996), Character 4; Dietze (2000), Character 57; Schultze and Cumbaa (2001), Character 88; Zhu and Schultze (2001), Character 199; Zhu *et al*. (2001), Zhu and Yu (2002), Character 145; Cloutier and Arratia (2004), Character 178; Zhu *et al*. (2006), Character 112; Friedman (2007), Character 128.

140 Anterodorsal process on scale: absent (0); present (1).
Patterson (1982), Character 4; Gardiner, (1984) Character 1; Gardiner and Schaeffer (1989), Character A20; Schultze and Cumbaa (2001), Character 89; Zhu and Schultze (2001), Character 201; Zhu *et al*. (2001), Zhu and Yu (2002), Character 146; Cloutier and Arratia (2004), Character 179; Zhu *et al*. (2006), Character 113; Friedman (2007), Character 129.

141 Lepidotrichia: absent (0); present (1).
Friedman (2007), Character 186.

142 Epichordal lepidotrichia in caudal fin: absent (0); present (1).
Cloutier and Ahlberg (1996), Character 134; Schultze and Cumbaa (2001), Character 101; Zhu and Schultze (2001), Character 191; Zhu *et al*. (2001), Zhu and Yu (2002), Character 140; Cloutier and Arratia (2004), Character 173; Zhu *et al*. (2006), Character 110; Friedman (2007), Character 123.

143 Fringing fulcra: absent (0); present as modified distal tips of lepidotrichia (1); present as 'true' fringing fulcra (2).
Friedman (2007), Character 188.

144 Basal fulcra: absent (0); present (1).
Zhu *et al*. (2001), Zhu and Yu (2002), Character 138; Friedman (2007), Character 121.

145 Pore-canal network: present (0); absent (1).
Cloutier and Ahlberg (1996), Character 1; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 34; Schultze and Cumbaa (2001), Character 105; Zhu and Schultze (2001), Character 203; Zhu *et al*. (2001), Zhu and Yu (2002), Character 148; Daeschler *et al*. (2006), Character 26; Long *et al*. (2006), Character 1; Zhu *et al*. (2006), Character 115; Friedman (2007), Character 131.

146 Dermal bone surface with large openings of pore canals: absent (0); present (1).
Zhu *et al*. (2001), Zhu and Yu (2002), Character 149 ; Zhu *et al*. (2006), Character 116; Friedman (2007), Character 132.

147 Enamel lining of pore canals: absent (0); present (1).
Zhu and Schultze (2001), Character 204; Zhu *et al*. (2001), Zhu and Yu (2002), Character 150; Zhu *et al*. (2006), Character 117; Friedman (2007), Character 133.

148 Resorption and redeposition of odontodes + enamel: lacking (0); partially developed (1); developed (2).
Zhu *et al*. (2006), Character 122; Friedman (2007), Character 195.

149 Ganoine (*sensu stricto*, defined as single or multilayered enamel covering with fine tubercles or very smooth surface, with no pores or very fine pores of vascular cavities): absent (0), present (1).
Zhu *et al*. (2001), Zhu and Yu (2002), Character 155 ; Zhu *et al*. (2006), Character 121.

150 Rostral tubuli: absent (0); present (1).
Cloutier and Ahlberg (1996), Character 77; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 82; Schultze and Cumbaa (2001), Character 19; Zhu and Schultze (2001), Character 208; Zhu *et al*. (2001), Zhu and Yu (2002), Character 153; Zhu *et al*. (2006), Character 119; Friedman (2007), Character 136.

151 Acrodin: absent (0); present (1).
Patterson (1982), Character 12; Maisey (1986), Character N6; Gardiner and Schaeffer (1989), Character B1; Cloutier and Ahlberg (1996), Character 7; Taverne (1997), Character 7; Coates (1999), Character 1; Poplin and Lund (2000), Character 21; Schultze and Cumbaa (2001), Character 35; Zhu and Schultze (2001), Character 210; Zhu *et al*. (2001), Zhu and Yu (2002), Character 154; Cloutier and Arratia (2004), Character 32; Zhu *et al*. (2006), Character 120; Friedman (2007), Character 137.

152 Plicidentine: absent (0); simple or generalized polyplacodont (1).
Cloutier and Ahlberg (1996), Character 14; Ahlberg and Johanson (1998), Zhu and Ahlberg (2004), Character 14; Schultze and Cumbaa (2001), Characters 102-103; Zhu and Schultze (2001), Characters 213-215; Zhu *et al*. (2001), Zhu and Yu (2002), Character 157; Daeschler *et al*. (2006), Character 10; Long *et al*. (2006), Character 21; Zhu *et al*. (2006), Character 124-125; Friedman (2007), Character 140.

153 True enamel on teeth: absent (0); present (1).
Schultze and Cumbaa (2001), Character 104; Zhu and Schultze (2001), Character 212; Zhu *et al*. (2001), Zhu and Yu (2002), Character 156; Zhu *et al*. (2006), Character 123; Friedman (2007), Character 139.

Table 7. Data matrix with 153 morphological characters and 23 taxa. ? = unavailable character; − = logical impossibility; p = 0/1; q = 1/2.

Character number:	000000000111111111122222222233333333334444444444555555 123456789012345678901234567890123456789012345678901234
Akmonistion	0−−−−−−−−−−−−−−−−−−−−−−−−−−−000??0??????0−?10?00110??
Acanthodes	0−−−−−−−−−−−−−−−−−−−−−−−−−−−01??0???02?00−010??00?0??
Dicksonosteus	1??????????????p?0?0−??01???01030110??000−00100010?0
Lophosteus	1??
Andreolepis	1??
Guiyu	12010001110100010−10110001110100201?10?1010???????????
Ligulalepis	1????????0????00???10−000100?1003??1000?00−0100?00???1
Dialipina	12010????p??010010?10−p11100?????????????0−???????????
Cheirolepis	1q01000111011p00p0?10−00100011??0????????0−0?????11???
Osorioichthys	10111000001−1?0010?10−00010011???????????0−???????????
Howqualepis	10111000001−10000−000−11100011?1?0?????0?0−0???1?110??
Mimia	10111000001−10000−000−111000110130000020000−00011011000
Moythomasia	10111000001−10000−000−111000110130000020000−00011011?0
Meemannia	12????????0??0??00−?10−110000?1???????????0−???????????1
Psarolepis	1????1011???0??10−10100101???100201110110100011?00?001
Achoania	1????1011????????0−1?10????????100201110111?0???????????
Onychodus	12001001110001101O?111020111010020100011011001?110????
Miguashaia	1100?????100−1?010?111000110O1??????????1??????????????
Styloichthys	1????0??????0??00−0?110101??100110111111111101?0110??
Youngolepis	1?0011110??10??111010−010111010011000111?0−10111110011
Diabolepis	1?0011110101O0?211010−01011?0100010001??00−?011?1???0?
Powichthys	11001101010100110−110−010111010021000111110101111?1011?
Kenichthys	120?111101000?1?0−011001011101000100011101??????????

Character number:	00000000000000000000000000000000000000000000011111111 55556666666666777777777788888888889999999990000000 56789012345678901234567890123456789012345678901234567
Akmonistion	?–?–––––––––––––?–––––––––???––––––?––––––––0–––––?
Acanthodes	?–0–––––––––––––00––––––––0??––––––?––––––––0–––––?
Dicksonosteus	000??????0100000 1?0–?––––––???––––––?1–––?0––0??????
Lophosteus	??????????????????10??????????????????0??????????????
Andreolepis	??????????????????10???????????0??????????????????
Guiyu	?0?01000?01000000?11000000010020010 1?0011101 0?1?100?
Ligulalepis	1??????????????????11??????????????????????????????
Dialipina	?0??????????????????110???10?0??20?101???????????211 0??
Cheirolepis	?0001001 0?000101?11100p000000020001020000000?000002?
Osorioichthys	?0001??1???????????110?1100?00?2??0112000??????00000?
Howqualepis	?0001001?00111111?111?110001002 0?0112000000?0000000
Mimia	10001001000101101111001101000020001020000000 11000000
Moythomasia	10001001000111111111p011010000200011200000001 1000000
Meemannia	1??????????????????11??????????0???????0??????????????
Psarolepis	11?010???01000000?111111000110001101000111010??01?01
Achoania	???0?????010?0010?111100???1100011010 00??1010???????
Onychodus	001–0110??1000p00?110100000100201101000011010021 1101
Miguashaia	?01?0110????0????0110?0?–––0112101102000011 1??2110??
Styloichthys	?1??0010?0000101 1?110??0101001001101001??1110?????11
Youngolepis	01?100101101010p1?11000010101100010100110101 0?101111
Diabolepis	???1????0101010 11?110000???00021010121–––100??????11
Powichthys	???10??0101101001011000010101010110100110101 0?101111
Kenichthys	?1?10010?00002001?11000010101020010110110101 0??01111

Character number:	1111111111111111111111111111111111111111111111111111 0011111111112222222222333333333344444444445555 5 7890123456789012345678901234567890123456789012345678 9 0123
Akmonistion	???????---????-------??0101000?0-00--00-????0??
Acanthodes	??????0---00??0---0-0?00111?00?0-00--00-000????
Dicksonosteus	???0?00?--1???0?0?00?000?????????????10-0000???
Lophosteus	??????????????????????????1??000-0????0--00????
Andreolepis	??????????????????????????????000-0????0--01????
Guiyu	001000?0 ?1101?110000?????11??101011??10--01000?
Ligulalepis	00?000?0??????????????????????10101????0--01????
Dialipina	?0101010????1???0010?????00011010111p10--01?000
Cheirolepis	??000010011000p0100001?011000000-010110--010000
Osorioichthys	??0000?00?10001010001????1???1?101???10--01?100
Howqualepis	?00000?00?10001010000??0?10001010110110--01?100
Mimia	0100001001100010100011001100010101102 10--010100
Moythomasia	0100001001100010100011001100010101102 10--010100
Meemannia	?0?010??????????????????????????????????10000????
Psarolepis	0110000?011011??p00010001?1?????????????11010?001
Achoania	??101????1?????????????0???????????????11????0?1
Onychodus	1110??000101110110100001000111 10-011000-??0?001
Miguashaia	11?021??0?011001?0100????0010110-011000-??0?001
Styloichthys	0111200?100111??1111?1110????10111????1101000?1
Youngolepis	011110011001 11??1111?1110????10111????101201011
Diabolepis	011110?11???11?????????????????????????101201001
Powichthys	011110001 00?1101111?11??????10110????101201011
Kenichthys	011121001001110?111???????????10110????10020?011

5. Characters and character states defining major clades shown in SI Figure 1. Asterisks indicate ambiguous character states resolved using DELTRAN. Character state is (1), unless marked otherwise.

Node 1: 1(0); 45.

Node 2 (Osteichthyes): 73.

Node 3 (Osteichthyes above *Lophosteus*): 149.

Node 4 (Crown-group Osteichthyes): 30*; 48*; 55*; 74; 136; 138; 140; 141*.

Node 5 (Actinopterygii): 25; 113; 133(0)*; 143*; 144*.

Node 6 (Actinopterygii above *Dialipina*): 13; 29*; 51*; 62*; 65(0)*; 68*; 70*; 72*; 88(0); 89; 91(2)*; 103(0); 109(0); 119(0); 123; 128*; 132*; 142(0).

Node 7: 2(0); 3; 5; 8(0); 9(0); 11; 77*; 78; 121*; 151.

Node 8: 20(0); 23; 24*; 26(0)*; 32*; 66*; 69*.

Node 9: 36(0)*; 47*; 80; 99*; 100; 108; 127*; 143(2).

Node 10 (Sarcopterygii): 50(0); 54.

Node 11 (Sarcopterygii above *Ligulalepis*): 149(0).

Node 12 (Sarcopterygii above *Meemannia*): 10; 21; 27; 28; 33(2)*; 39*; 40*; 42; 46*; 47*; 96*; 98*; 101*; 106*; 120*; 122*; 153*.

Node 13: 16; 19; 20(0); 35*; 37; 71(0)*; 82; 94*; 95.

Node 14 (*Psarolepis*+*Achoania*): 6; 22(0); 75; 76; 83; 85(0); 87; 145*; 146*.

Node 15 (Crown-group Sarcopterygii): 4(0); 5; 15; 43*; 49; 55(0); 59(0); 61; 108*; 111(2); 117(0); 118; 123; 125; 130; 131(0).

Node 16: 12(0)*; 14; 17; 57*; 60; 101(2)*; 102; 107; 133(0)*; 134*; 137; 138(0); 140(0)*.

Node 17 (Rhipidistia, = *Styloichthys* (Dipnomorpha+Tetrapodomorpha)): 24*; 34; 38; 44; 50; 56; 65(0); 68; 79; 81; 93; 105; 110; 115; 116(0); 124; 126; 128; 129; 139*; 145*.

Node 18 (Crown-group Rhipidistia, = Dipnomorpha+Tetrapodomorpha): 6; 9(0)*; 36(0)*; 58*; 83; 94*; 104*; 148(2)*; 152*.

Node 19 (Dipnomorpha): 16*; 21(0); 66; 111; 147; 150*.

Node 20: 7*; 17; 18*; 42(0); 64; 114; 152(0).

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