A New Mammaliaform from the Early Jurassic and Evolution of Mammalian Characteristics

SUPPLEMENTARY INFORMATION (Hadrocodium wui IVPP8275)

SCIENCE (Manuscript No. 1058476)

Z.-X. Luo, A. W. Crompton & A.-L. Sun

(Correspondence: luoz@carnegiemuseums.org)

Table of Contents

PART I. AGE AND FAUNA

Hadrocodium wui (IVPP 8275) is from the Upper Red Beds of the Lower Lufeng Formation, in Lufeng Basin of Yunnan Province, China. The Lower Lufeng Formation consists of lacustrine and fluvial sediments, which yielded one of the richest vertebrate faunas of the late Triassic and early Jurassic in the world (Sun et al., 1985; Sun and Cui, 1986; Luo and Wu, 1994, 1995). Two primitive mammaliaform genera, representing three species, were known previously from the Lower Lufeng Formation: Sinoconodon rigneyi (Patterson and Olson, 1961; Crompton and Sun, 1985; Crompton and Luo, 1993; Zhang et al., 1998) and Morganucodon oehleri, and Morganucodon ("Eozostrodon") heikoupengensis (Rigney, 1963; Kermack et al., 1973, 1981; Young, 1982; Crompton and Luo, 1993; Luo and Wu, 1994). Hadrocodium wui, as described in this paper, is the fourth mammaliaform taxon from this fauna.

The Lower Lufeng Formation is considered to be the Early Jurassic (Sinemurian age, ~195 myr) by correlation of derived tritylodontids (Bienotherium-Kayentatherium, and Dinnobitodon-Yunnanodon) (Sues, 1985, 1986a, b; Luo and Wu, 1994), and by correlation of the Lufeng Morganucodon species with morganucodontids elsewhere in the world (Luo and Wu, 1994, 1995).

PART II. MORPHOLOGICAL COMPARISON

Hadrocodium wui gen. et sp. nov. (IVPP 8275 [Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Science, Beijing]: Figs. 1 and 2, main text) is distinguishable from all other non-mammalian mammaliaforms and the majority of Jurassic mammals by some unique dental features. Its dental formula: I5.C1.P2.M2/i4.c1.p2.m2. Each of the molars has three main cusps, and two accessory cuspules in alignment on the laterally compressed crown. Primary cusp a of the lower molar occludes in the embrasure between the opposite upper molars. This cusp occlusal pattern differs from those of Morganucodon (Mills, 1971; Crompton, 1974), Erythrotherium (Crompton, 1974), Dinnetherium (Jenkins et al., 1983; Jenkins, 1984; Crompton and Luo, 1993), and the Triconodontidae (Crompton, 1974; Crompton and Jenkins, 1979; Crompton and Luo 1993; Cifelli et al., 1998), in which the primary cusp a of the lower molar occludes in the valley between cusps A and B of the upper. The new taxon also differs from Megazostrodon (Crompton, 1974; Gow, 1986a) and Gobiconodon (Jenkins and Schaff, 1988; Kielan-Jaworowska and Dashzeveg 1998) in lacking prominent labial cingulid cuspules of the upper molars. It differs from Kuehneotherium (Kermack et al., 1968) and kuehneotheriid-like Woutersia (Sigogneau-Russell and Hahn, 1994, 1995) in lacking the triangulation of the molar cusps. The postcanine diastema of Hadrocodium is much larger than those of morganucodontids and kuehneotheriids (Parrington, 1973,1978). In this feature it differs from amphilestids (Simpson, 1928, 1929), gobiconodontids (Jenkins and Schaff, 1988; Kielan-Jaworowska and Deshzeveg, 1998), Jeholodens (Ji et al., 1999) and triconodontids (Simpson, 1928, 1929; Jenkins and Crompton, 1979; Cifelli et al., 1998) that have little or no postcanine diastema. It differs from Sinoconodon (Crompton and Sun, 1985; Crompton and Luo 1993; Zhang et al. 1998) in having the one-to-one precise occlusion of the upper and lower molars. It lacks the muli-row and multi-cuspate teeth of haramiyids (Sigogneau-Russell 1989; Hahn et al., 1989; Jenkins et al., 1997; Butler, 2000), multituberculates (Hahn, 1969, 1993; Clemens and Kielan-Jaworowska, 1979; Kielan-Jaworowska and Hurum, 1997; Wible and Rougier, 2000), and the highly specialized teeth of docodonts (Jenkins, 1969; Gingerich, 1973; Krusat, 1980; Butler, 1988; Lillegraven and Krusat, 1991).

Hadrocodium wui is different from all other non-mammalian mammaliaforms by a long list of derived skull features (Figs. 1 and 2, main text). All other non-mammalian mammaliaform crania have a temporomandibular joint positioned in the same antero-posterior level as the occipital condyles and a small brain vault (Kermack et al., 1981; Gow, 1986a; Crompton and Sun, 1985; Lillegraven and Krusat, 1991; Crompton and Luo, 1993; Lucas and Luo, 1993; Luo 1994). By contrast, Hadrocodium wui has an anteriorly placed temporomandibular joint and a brain vault that is more expanded posteriorly and beyond the temporomandibular joint (Main text, Fig. 2). Hadrocodium is more similar to the mammalian crown group in these features. Hadrocodium retains several primitive characters of Sinoconodon. Its squamosal glenoid faces anteromedially, and is located on the ventromedial side of the zygoma, and there is no constricted neck between the glenoid and the narrow cranial moiety of the squamosal, as in Morganucodon (Main text, Fig. 2), and in Haldanodon (Lillegraven and Krusat, 1991).

Morganucodontids (Kermack et al., 1973, 1981; Parrington, 1973; 1978; Crompton and Luo, 1993), kuehneotheriids (Kermack et al., 1968), and Haramiayvia (Jenkins et al., 1997) from the Late Triassic to Early Jurassic have a very prominent postdentary trough with a shelf-like dorsal medial ridge. All other non-mammalian mammaliaforms (including Sinoconodon) have a medial concavity on the mandibular angle (Kermack et al., 1968, 1973; Lillegraven and Krusat, 1991; Crompton and Luo, 1993). The postdentary trough and the concavity on the mandibular angle accommodate the post-dentary bones of the surangular, the pre-articular and the angular that are the homologues to the mammalian middle ear (Allin, 1975; Kermack and Musset, 1983; Allin and Hopson, 1992; Crompton and Luo, 1993; Luo and Crompton 1994). By contrast, the mandible of Hadrocodium has a smooth periosteal surface on its medial side, with neither postdentary trough nor the medial concavity on the mandibular angle, indicating that the postdentary bones ("middle ear ossicles") must have been separated from the mandible (Text Fig. 3). Hadrocodium differs also from the above-mentioned groups, plus the pre-tribosphenic eupantothere therians in the absence of the Meckel's sulcus on the mandible.

Hadrocodium wui has a slightly inflected angle of the dentary (Fig. 1B). In this feature it differs from all other non-mammalian mammaliaforms and from gobiconodontids (Jenkins and Schaff, 1988), triconodontids (Simpson, 1928, 1929; Jenkins and Crompton, 1979; Ji et al., 1999), multituberculates (Kielan-Jaworowska and Hurum, 1997; Wible and Rougier, 2000) and spalacotheriid symmetrodonts (Hu et al., 1997, 1998; Cifelli and Madsen, 1999).

The majority opinion of most workers is that the angle on the mandible in of non-mammalian mammaliaforms represents a "pseudo-angle," as first proposed by Patterson (1956) and followed by many workers (Sinoconodon, Crompton and Sun, 1985; Crompton and Luo, 1993; Megazostrodon, Gow, 1986a; Dinnetherium, Jenkins et al., 1983; Jenkins, 1984; Hopson 1994). Others have used the term "angular process" for the same structure (Kermack et al., 1973; Gambaryan and Kielan-Jaworowska, 1995; Kielan-Jaworowska, 1997). The angle in Dinnetherium, Megazostrodon and Haramiyavia are reduced in size. The angular region of mandible in Kuehneotherium has a rounded outline. The main differences of the angular features ("pseudo-angle") in these mammaliaforms from those of pretribosphenic eupantotheres, and living therians are two folds. First, the mandibular angle is more posteriorly positioned below the dentary condyle in the latter groups but anteriorly positioned below the anterior border of the coronoid process in the non-mammalian mammaliaforms. Second, the mandibular angle is associated with the reflected lamina of angular bone in the mammaliaforms, whereas not associated with the tympanic (homologue of the reflected lamina) in advanced therians, except for a transient ontogenetic stage of early development in marsupials (Maier, 1989, 1993). In view of the conflicting opinions about the homology of features of the mandibular angle, the most prudent approach is to treat the morphological elements of the mandibular angle (size, anterior vs. posterior positions, presence vs. absence of its association with the reflected lamina of angular bone) as separate characters in matrix-based analysis. The homology (or the homoplasy) of this feature will be decided, a posteriori, on the basis of congruence or discordance of this angular feature with other apomorphies in a parsimony phylogeny supported by independent evidence (Kielan-Jaworowsk et al., 1998; Luo et al. 2001, supplementary information). Because our phylogeny shows discontiguous (and discordant) distributions of of the "mammaliaform mandibular angle" and the "eupantothere-therian mandibular angle," we provisionally consider the angle of mandible in non-mammalian mammaliaforms to be a convergent character state to the mandibular angle ("angular process" of the dentary), following Kielan-Jaworowska et al., 1998. This feature should be further evaluated elsewhere.

PART III. SCOPE PHYLOGENETIC AND ANATOMICAL STUDIES

The character analysis is focused on the skull and the dentition, as represented by the holotype specimen of Hadrocodium wui (IVPP 8275). For this analysis, we prefer to concentrate on the phylogenetic position of Hadrocodium among the major lineages of non-mammalian mammaliaforms and mammals. It is not the intention of the authors to produce an all-encompassing matrix with all possible characters of all major clades of cynodonts and early mammals.

The characters of this study represent only a part of some larger datasets published by several lengthy studies on non-mammaliaform cynodonts and non-mammalian mammaliaforms, and early mammals (Prothero, 1981; Kemp, 1982, 1983; Sues, 1985; Hopson and Barghusen, 1986; Rowe, 1986, 1988, 1993; Wible, 1991; Rougier et al., 1992; Luo, 1994; Hopson, 1994; Rougier et al., 1996a; Kielan-Jaworowska and Gambaryan, 1994; Kielan-Jaworowska, 1996; Luo et al., 2001).

The character list used by this study is modified from several cranio-dental character lists published by Kemp (1983), Hopson and Barghusen (1986), Rowe (1986, 1988), Wible (1991; Wible and Hopson, 1993; Wible et al., 1995), Rougier (1993; Rougier et al., 1996a, b), Luo (1994), Kielan-Jaworowska (1996; Gambaryan and Kielan-Jaworowska, 1997), Hu et al. (1998), Ji et el. (1999), Luo et al (2001). Other characters have also been adopted from Crompton (1971; 1974), Kielan-Jaworowska et al. (1987).

PART IV. SOURCES OF ANATOMICAL DATA

Non-Mammaliaform Cynodonts

Probainognathus (designated as the out-group) (Romer, 1970; Crompton, 1972a; Allin, 1986; Rougier et al., 1992; Luo and Crompton, 1994; Wible and Hopson, 1995).

Tritylodontids (Kühne, 1956; Crompton, 1964, 1972b; Hopson, 1964; Kemp, 1983; Sun, 1984; Sues, 1983,1986; Luo and Crompton, 1994; Luo, 1994, 2000).

Tritheledontids (Crompton, 1958, 1994; Allin and Hopson, 1992; Wible and Hopson, 1993; Hopson and Rougier, 1993).

Non-Mammalian Mammaliaforms

(Traditional concept of the Mammalia)

Adelobasileus (Lucas and Luo, 1993).

Sinoconodon (Patterson and Olson, 1961; Crompton and Sun, 1985; Crompton and Luo, 1993; Luo, 1994; Zhang et al., 1998).

Morganucodon (Kermack et al., 1973, 1981; Parrington, 1973, 1978; Crompton and Luo, 1993; Luo, 1994; Luo and Crompton, 1994).

Haldanodon (Krusat, 1980; Lillegraven and Krusat, 1991).

Hadrocodium (this study).

Mammals

(Crown-group concept: Rowe, 1988; McKenna and Bell, 1997)

Triconodontids (Simpson, 1928; Kermack, 1963; Jenkins and Crompton, 1979; Crompton and Sun, 1985; Crompton and Luo, 1993; Wible and Hopson, 1993; Rougier et al., 1996; Cifelli et al., 1998; Ji et al., 1999). Two earlier studies (Rowe, 1988; Rougier et al., 1996) placed triconodontids within the mammalian crown-group. A more recent study that has incorporated the postcranial data (Ji et al. 1999) has suggested that Jeholodens, a triconodontid-like taxon, may be placed outside the mammalian crown-group. Given the current dataset on dental and cranial features, triconodontids may be placed as the first out-group of the mammalian crown-group (the single tree from the search with all multi-state characters ordered), or on an unresolved polytomy with the basal node of the crown group (on the strict consensus of trees from un-ordered search). Triconodontids are provinsionally considered to be a part of the mammalian crown group in this study for the purpose of using consistent cladistic terminology. Further resolution of the position of triconodontids in unordered search may require addition data on postcranium that is beyond the consideration here for comparative analysis of Hadrocodium. We note that regardless the placement of trioconodontids, the main conclusion about the position of Hadrocodium remain the same.

Ornithorhynchus (Simpson, 1929; Gregory, 1951; Kuhn, 1971; Zeller, 1989, 1993; Wible and Hopson, 1993, 1995). In the description of characters, some references have been made to the fossil ornithorhynchid Obdurodon (Woodburne and Tedford, 1975; Musser and Archer, 1998), and Steropodon (Archer et al., 1985, 1993), which are considered to be related to ornithorhynchids. The implications of Obdurodon were discussed in the main text of the paper (e.g., the postglenoid region is better developed in Obdurodon than in Ornithorhynchus). However, these fossil taxa are not coded in the character list and the matrix, because they are either incomplete (Steropodon), or simply identical to Ornithorhynchus in those features coded for this analysis (Obdurodon). The echidna Tachyglossus is also mentioned in the comparative discussion in main text, but not coded for the matrix-based analysis. Living Tachyglossus and Ornithorhynchus are considered to be a monophyletic group on the basis of diverse lines of molecular evidence (the protamine gene sequence, Retief et al., 1993; the lactalbumin amino-acid sequence, Messer et al., 1998) and by some unique features of the basicranium (Kuhn, 1971; Zeller, 1989; Rougier et al., 1996), plus a plethera of soft-tissue anatomical characters (Gregory, 1910, 1947; Griffiths, 1978) and reproductive features (Zeller, 1999a, b). In this paper, we assume the Tachyglossus and Ornithorhynchys are a monophyletic clade (text figure 3), Ornithorhynchus is selected as the representative living taxon for monotremes as a group for the matrix-based analysis because of its better fossil records than the Tachyglossidae.

Multituberculates (Clemens, 1963; Hahn, 1969, 1977, 1981, 1985, 1988; Clemens and Kielan-Jaworowska, 1979; Kielan-Jaworowska et al., 1986; Miao, 1988; Luo, 1989; Lillegraven and Hahn, 1993; Wible and Hopson, 1995; Kielan-Jaworowska, 1996; Rougier et al., 1996b; Hurum, 1998a, b; Wible and Rougier, 2000).

Zhangheotherium (Hu et al., 1997, 1998).

Vincelestes (Bonaparté and Rougier, 1987; Rougier et al., 1992; Rougier, 1993; Hopson and Rougier, 1993).

Metatherians (including marsupials) (Muizon, 1994, 1998; Szalay and Trofimov, 1996; Muizon et al., 1997; Rougier et al., 1998; McKenna et al., 2000).

Eutherians (including placentals) (Kielan-Jaworowska, 1981, 1984; Novacek, 1986; Wible et al. In press).

PART V. PHYLOGENETIC ANALYSES

Search by PAUP 4.*.

Branch and bound search. Maxtrix has 15 taxa (selection of taxa justified above) and 90 characters (48 binary characters, 42 multi-state characters; selection of the characters explained above). Matrix is available in the PAUP files. No topological constraint is imposed in any searches. All characters have equal weight. All trees are available from PAUP files in supplementary information package (Part IX, see below).

Selection of Outgroup – Non-Mammaliaform Cynodonts

Probainognathus is treated as a default out-group, and used to root the trees. Its cranial and dental features have been well documented by a series of studies (Romer, 1970; Crompton, 1972a; Allin, 1986; Rougier et al., 1992; Luo and Crompton, 1994; Wible and Hopson, 1995). It is considered to be a very advanced non-mammalian cynodont by all recent phylogenetic analyses (Kemp, 1982, 1983; Sues, 1985; Hopson and Barghusen, 1986; Rowe, 1988, 1993; Luo, 1994; Luo and Crompton, 1994; Sidor and Hopson, 1998). It is universally accepted to be more distant than tritheledontids are to mammals (Kemp, 1982, 1983; Hopson and Barghusen, 1986; Rowe, 1988, 1993; Luo, 1994; Luo and Crompton, 1994; Sidor and Hopson, 1998). Some studies considered it to be more distant to mammals than both tritylodontids and tritheledontids (Kemp, 1983, 1988; Rowe, 1988, 1993; Luo, 1994; Luo and Crompton, 1994). Based on these previous large-scale analyses we treat Probainognathus as an outgroup for this study.

Tritylodontids are included because several studies have considered this group to the sister-taxon to mammaliaforms (Kemp, 1983; Rowe, 1988, 1993; Wible 1991). The orbital, palatal and sphenoid features of this group bear more resemblance to mammaliaforms than any other non-mammaliaform cynodonts.

Tritheledontids are included because several studies have considered this group to the sister-taxon to mammaliaforms (Hopson and Barghusen, 1986; Shubin et al., 1991; Crompton and Luo, 1993; Luo, 1994; Luo and Crompton, 1994; Hopson, 1994). Features of the craniomandibular joint of this group bear more resemblance to mammaliaforms than any other non-mammaliaform cynodonts.

In-Groups – Non-mammalian mammaliaforms

Adebolobasileus, Sinoconodon, Morganuodonitdae, Haldanodon, Hadrocodium. The above sixe taxa are coded for matrix-based phylogenetic analysis. Kuehneotherium is also considered to be a non-mammalian mammaliaform by this study, but is only used for general comparison in the text discussion, but not in the matrix-based analysis because it is very incomplete.

In-Groups – Crown group of Mammalia

Multituberculates, Zhangheotherium, Vincelestes, metatherians (including marsupials), eutherians (including placentals). Triconodontidae is also treated as a member of the mammalian crown group (Rougier et al., 1996), although in some recent study, it was placed outside of the mammalian crown group (Ji et al., 1999). Here triconodontids are provisionally considered to be a part of the mammalian crown group because it is on the same node as the living Mammalia (Text Fig. 4A). The position of triconodontids will be further discussed below.

Polymorphic Characters

Multi-state polymorphic characters of the terminal taxa here are run as polymorphisms in PAUP search.

Not-preserved vs. Not-applicable Characters

PAUP and other currently available softwares for phylogenetic analyses treat both missing and inapplicable characters as “missing.” Therefore the “not preserved” characters and the “inapplicable” characters are both coded as “?” in the matrix and are treated the same by the phylogenetic algorithms, although in the empirical anatomical survey, these categories of characters are clearly different. We the authors are aware of the limit of PAUP in this regard, but we have to rely on it for the lack of a better and feasible alternative algorithm. For recent discussion on this general issue of methodology see Strong and Lipscomb (1999), Lee and Bryant (1999).

Ordered vs. Unordered Multi-state Characters

Search #1 -- ALL multi-state characters are unordered.

Results: Branch and Bound search yields 9 equally parsimonious trees (EPT’s). The strict consensus is presented as Fig. 5A in the main text.

```
/---------------------------------------------------------- Probainognathus
+---------------------------------------------------------- Tritylodontids
+---------------------------------------------------------- Tritheledontids
|     /---------------------------------------------------- Adelobasileus
|     +---------------------------------------------------- Sinoconodon
\-----+      /--------------------------------------------- Morganucodon
      |      |     /--------------------------------------- Haldanodon
      \------+     |      /-------------------------------- Hadrocodium
             \-----+      |     /-------------------------- Triconodontids
                   \------+     +-------------------------- Ornithorhynchus
                          \-----+-------------------------- Multituberculate
                                |      /------------------- Zhangheotherium
                                \------+     /------------- Vincelestes
                                       \-----+      /------ Metatherians
                                             \------+------ Eutherians
```

(Text Fig. 5A. Strict consensus of 9 EPT’s from search #1 with all multi-state characters run as unordered.).   All 9 EPT’s are presented in PAUP files of search results in supplementary information. Each of the 9 EPT’s has: Tree length=288; CI=0.642; RI=0.675. EPT #8 is presented as Text Fig. 5B.

Search # 2 -- 16 multi-state characters are run as ordered.

The multiple states of 16 characters (characters 6, 8, 10, 11, 15, 37, 38, 40, 44, 49, 53, 54, 67, 70, 77, 82) show morphological intermediacy and they clearly represent series of transformations. So there are strong anatomical rationale and justification for these 16 characters to be ordered for the PAUP search. The remaining 26 multi-state characters are unordered in this search.

Results: Branch and Bound search yields a single most parsimonious tree (Tree length = 293; CI=0.631; RI=0.688). This tree is identical to the EPT #8 (text Fig. 5B) of search #1 with all multi-state characters run as unordered.

```
/----------------------------------------------------------- Probainognathus
+----------------------------------------------------------- Tritylodontids
|    /------------------------------------------------------ Tritheledontids
|    |    /------------------------------------------------- Adelobasileus
\----1    |   /--------------------------------------------- Sinoconodon
     \----2   |    /---------------------------------------- Morganucodon
          \---3    |    /----------------------------------- Haldanodon
              \----4    |    /------------------------------ Hadrocodium
                   \----5    |    /------------------------- Triconodontids
                        \----6    |                   /----- Ornithorhynchus
                             \----7    /-------------+----- Multituberculate
                                  \----8   /--------------- Zhangheotherium
                                       \---9    /---------- Vincelestes
                                           \---10    /----- Metatherians
                                                \---11----- Eutherians
```

(Text Fig. 5B. Single tree from search #2 with 16 multi-state characters run as ordered; this is identical to EPT #8 from search #1 with all multi-state characters as unordered.)

Search #3 – ALL (42) multi-state characters are run as ordered.

Results: Branch and Bound search with all 42 multi-state characters ordered has yielded an identical tree as Search #2 (see Text Fig. 4B). The boostrap and jackknife 50% majority-rule consensus tree with all 42 multi-state characters ordered yielded a tree similar to Text-Fig. 4A, except for tritylodontids.

Discussion

No matter which scheme of ordering vs. unordering multi-state characters, all searches consistently show Hadrocodium to be the sister-taxon to the crown-group of Mammalia, or to the clade of (triconodontids + crown-group Mammalia), in all fundamental trees and consensus trees. No matter which scheme of ordering vs. unordering multi-state characters, all searches have consistently placed Hadrocodium closer to the Mammalia than the successively more distant Haldanodon, Morganucodon, and Sinoconodon. Given the matrix presented here, the position of Hadrocodium is stable, so are the successively more distant positions of Haldanodon, Morganucodon, and Sinoconodon.

Therefore the preferred tree (text Fig. 4A) of this study represents the most conservative estimate of the phylogenetic position of Hadrocodium that can be upheld regardless the scheme of ordering vs. unordering characters.

Positions of triconodontids, Ornithorhynchus, and multituberculates may change according to different schemes of ordering (or unordering) of multi-state characters. In the 9 fundamental trees from the all-unordered search, sister-taxon of triconodontids to the Mammalia (as proposed by Ji et al., 1999) is retained in 3 trees; the sister-taxa of Ornithorhynchus and multituberculates (as proposed by Wible and Hopson, 1993; Meng and Wyss, 1995) are supported by 4 trees; the topology of (Ornithorhynchus(multituberculates (triconodontids(therians))) (as shown by Rougier et al., 1996a) is retained in 3 trees.

If the 16 selected multi-state characters are ordered (based on empirical anatomical justifications), the bootstrap and the Jackknife 50% majority-rule consensus trees recover the topology of (triconodontids (multituberculates, Ornithorhynchus) therians). If all 42 multi-state characters are ordered, the bootstrap and the Jackknife 50% majority rule consensus trees would produce the polytomy of (triconodontids, multituberculates, Ornithorhynchus, therians). While the position of Hadrocodium is consistent and stable, the placement of triconodontids, multituberculates, and Ornithorhynchus may vary with the number or multi-state characters that are ordered for the bootstrap and jackknife searches.

Additional morphological evidence, such as postcranial features (Rowe, 1988; Sereno and McKenna, 1995; Hu et al., 1998; Ji et al., 1999) is necessary to resolve the ambiguous polytomy of triconodontids, Ornithorhynchus, and multituberculates, as presented in the strict consensus of the unordered search (text Fig. 5A). When postcranial characters are included (Rowe, 1988, 1993; Sereno and McKenna, 1995; Hu et al., 1997; Ji et al., 1999), the clade of (multituberculates + therians) is supported.

However, in any scenarios of alternative placement of triconodontids, Ornithorhynchus and multituberculates, Hadrocodium remains to be the most derived mammaliaform and closely related to the living Mammalia. Therefore the main phylogenetic conclusion of this paper is not susceptible to the uncertainty in the placement of triconodontids and multituberculates.

PART VI. LIST OF APOMORPHIES FOR MAJOR CLADOGRAM NODES

Descriptive apomorphy list for major node of the tree (text Fig. 4B):

```
      P A U P *
   Unrooted tree(s) rooted using outgroup method
   Optimality criterion = maximum parsimony
   Character-status summary:
         16 characters are of type 'ord' (Wagner)
       73 characters are of type 'unord'
       All characters have equal weight
       All characters are parsimony-informative
   Gaps are treated as "missing"
   Character-state optimization: Accelerated transformation (ACCTRAN)
   Multistate taxa interpreted as polymorphism ("min" values for CI, RI, and RC are
     minimum-possible character lengths)

The Single Most Parsimonious Tree from search with 16 characters ordered (same as one of the nine equally
parsimonious trees with all characters unordered) (rooted using default outgroup)

Tree length = 292
Consistency index (CI) = 0.6301
Homoplasy index (HI) = 0.5240
Retention index (RI) = 0.6870
Rescaled consistency index (RC) = 0.4329

/------------------------------------------------------------------------- Probainognathus
|
+------------------------------------------------------------------------- Tritylodontids
|
28    /------------------------------------------------------------------- Tritheledontids
|     |
|     |     /------------------------------------------------------------- Adelobasileus
\----27     |
      |     |     /------------------------------------------------------- Sinoconodon
      \----26     |
            |     |     /------------------------------------------------- Morganucodon
            \----25     |
                  |     |     /------------------------------------------- Haldanodon
                  \----24     |
                        |     |     /------------------------------------- Hadrocodium
                        \----23     |
                              |     |     /------------------------------- Triconodontids
                              \----22     |
                                    |     |                       /------ Ornithorhynchus
                                    \----21     /----------------16
                                          |     |                 \------ Multituberculate
                                          |     |
                                          \----20     /------------------ Zhangheotherium
                                                |     |
                                                \----19     /------------ Vincelestes
                                                      |     |
                                                      \----18     /------ Metatherians
                                                            \----17
                                                                  \------ Eutherians
```

Apomorphy lists (below) are based on the optimization of accelerated transformation (ACCTRAN):

Node 26. Apomorphies of the Mammaliaformes (sensu Rowe 1988; McKenna and Bell 1997; = traditional concept of “Mammalia”)

Unambiguous apomorphies:

(1) Pars cochlearis with a promontorium (at least partially exposed ventrally)

(2) Floor of the lateral trough of the squamosal present

(3) Basioccipital is only partially overlapping the petrosal promontorium

(4) Reduction of basisphenoid constricture typical of non-mammaliaform cynodonts.

(5) Separation of the cranial nerve foraen (XII) from the jugular foramen

14 equivocal apomorphies also support this node (listed in the PAUP output file)

Node 25. Synapomorphies of the clade of (Sinoconodon + Living Mammals)

Unambiguous apomorphies:

(1) Petrosal floor below the geniculate ganglion (VII)

(2) Distinctive bony groove for the channel of perilymphatic duct

(3) Complete loss of the basisphenoid wing

(4) Reduced size of ventral opening of cavum epiptericum

4 additional equivocal apomorphies also support this node (listed in the PAUP output file)

Node 24. Synapomorphies of the clade of (Morganucodon + Living Mammals)

Unambiguous apomorphies:

(1) Loss of Quadrate pit in the squamosal

(2) Withdrawal of the squamosal flank of the anterior paroccipial process (including crista parotica)

(3) Complete absence of the bosioccipital overlap of pars cochlearis

(4) Reduction of the size of occipital condyle

(5) Mandibular angle is elevated from the sigmoid ventral curve of the mandibular horizontal ramus

(6) Diphyodont replacement of incisors and canines

(7) Presence of the interlocking mechanism of molars

(8) Presence of precise occlusion of the upper and lower molar cusps

(9) Presence of consistent wear facets on individual molar cusps

9 additional equivocal apomorphies also support this node (listed in the PAUP output file)

Node 23. Synapomorphies of the clade of (Haldanodon + Living Mammals)

Unambiguous apomorphies:

(1) 2nd bony palate extending posteriorly beyond the tooth row

(2) Pterygopalatine ridges are absent (reversed in multituberculates

(3) Pterygoid hamulus vestigial or absent

(4) Absence of basisphenoid constricture

(5) Bony roof of the pharyngeal passage is broad and U-shaped

(6) Absence of the groove of the replacement dental lamina (see Parrington 1978 for definition of character)

8 additional equivocal also support this node (listed in the PAUP output file)

Node 22. Synapomorphies of the clade of (<u>Hadrocodium</u> + Living Mammals)

Unambiguous apomorphies:

(1) Absence of the medial ridge above the postdentary trough

(2) Separation of the postdentary (middle ear) bones from the mandible

(3) Reduction or absence of the Meckel's sulcus

(4) Mandibular angle is positioned at the level with the posterior border of the coronoid process):

(5) Absence of the medial concavity on the mandibular angle

(6) Bulbous and oval-shaped promontorium

(7) Absence of the quadrate ramus of the alisphenoid

(8) Reduction of the jugal

(9) Separation of the posterior opening of mandibular foramen from the Meckel's sulcus

(10) Absence of the splenial

8 additional equivocal also support this node (listed in the PAUP output file)

Node 21. Clade of Triconodontidae + Mammalia (please note that the strict consensus of unordered search would collapse the triconodontids in the same node as crown-group mammals).

Unambiguous apomorphies:

(1) Dentary condyle and peduncle are up-truned

(2) Pterygoid muscle fossa present

(3) Pterygoid ridge present on along the ventral border of the angular region

(4) Masseteric muscle fossa with a ventral crest

(5) Absence of vascular foramina of the lateral flange of petrosal

(6) Stapedial muscle fossa within the tympanic cavity (except monotremes)

7 other equivocal also support this node (listed in the PAUP output file)

PART VII. CHARACTER DESCRIPTION AND DISTRIBUTIONS

Squamosal (8 characters)

1. Size of the cranial moiety of the squamosal (Rowe, 1988; Wible, 1991; Luo, 1994):

(a) narrow: Progainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates;

(b) broad: Adelobasileus, Vincelestes, metatherians, eutherians;

(?) Not preserved: Zhangheotherium.

2. Participation of the cranial moiety of the squamosal in the braincase (Wible, 1991; Luo, 1994):

(a) does not participate in the endocranial wall of the braincase: Progainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates (based on Hurum, 1998a);

(b) participates in the endocranial wall of the braincase: Vincelestes, metatherians, eutherians;

(?) unknown: Adelobasileus; not preserved: Zhangheotherium .

3. Squamosal articulation for the quadrate (modified from Kemp, 1983; character distribution following Luo and Crompton, 1994):

(a) Present: Probainognathus (outgroup), tritylodontids (present as a notch); tritheledontids (present as a pit: following Allin and Hopson, 1992; Luo and Crompton, 1994), Sinoconodon (present as a pit: Luo and Crompton, unpublished data);

(b) Absent: Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus.

4. Constriction between the zygoma and the cranial moiety of the squamosal of the squamosal (or the entoglenoid constriction of the taxa with the dentary - squamosal joint; this character is best seen in the ventral view) (modified from Luo, 1994; Hu et al., 1998):

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Hadrocodium, Ornithorhynchus, Vincelestes;

(b) Present: Morganucodon, Haldanodon, triconodontids, multituberculates, Zhangheotherium, metatherians;

(a/b polymorphic): eutherians (constriction absent in zalambdalestids and leptictids, but present in other eutherians);

(?) Not preserved: Adelobasileus.

5. Postglenoid depression on the squamosal posterolateral to the craniomandibular joint:

(a) Absent: Sinoconodon, Morganucodon, triconodontids, Ornithorhynchus, multituberculates;

(b) Present: Haldanodon, Hadrocodium, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: *Adelobasileus*; not-applicable (because there is no squamosal glenoid for craniomandibular joint): *Probainognathus* (outgroup), tritylodontids, tritheledontids.

6. Glenoid fossa for the craniomandibular joint:

(a) On the inner side of the zygoma and facing ventromedially: *Sinoconodon*, *Hadrocodium*;

(b) On platform of the zygoma and facing ventrally, without a postglenoid ridge: *Ornithorhynchus*, triconodontids, multituberculates;

(c) On the ventral side of the zygoma, with a postglenoid ridge: *Haldanodon*, *Zhangheotherium*, *Vincelestes*, metatherians, eutherians;

(b/c polymorphic): *Morganucodon* (*Morganucodon watsoni*, b; *Morganucodon oelheri*, a);

(?) Not preserved: *Adelobasileus*; not applicable: *Probainognathus* (outgroup), tritylodontids, tritheledontids (tritheledontids have a dentary-squamosal contact on the inner side of the zygoma but lack a distinctive glenoid fossa).

7. Position of craniomandibular joint (Rowe, 1988; Wible, 1991):

(a) Lateral to fenestra vestibuli: *Probainognathus* (outgroup), tritylodontids, tritheledontids, *Sinoconodon*, *Morganucodon*, *Haldanodon*, *Ornithorhynchus*;

(b) Anterior to the level of fenestra vestibuli: *Hadrocodium*, *Zhangheotherium*, *Vincelestes*, metatherians, eutherians;

(a/b polymorphic): the djadochtatherians *Chulsanbaatar* and *Nemegtbaatar* (b); paulchoffatiids, North American ptilodontoids and taeniolabidoids (a);

(?) Not preserved: *Adelobasileus*, triconodontids.

8. Maximum vertical depth of the zygomatic arch relative to the length of the skull (this character is designed to indicate the robust vs. gracile nature of the zygomatic arch):

(a) Between 15-20%: Probainognathus (outgroup), tritylodontids;

(b) Between 8-12%: tritheledontids, Haldanodon, Vincelestes;

(c) Between 5-7%: Sinoconodon, Morganucodon, Hadrocodium (measured in the preserved anterior part of zygoma), triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, metatherians, eutherians;

(?) Not preserved: Adelobasileus.

Petrosal Characters (26 characters)

9. Pars cochlearis of petrosal (Rowe, 1988; Wible, 1991; Luo, 1994; Rougier et al., 1996a):

(a) No external exposure ("absent in the ventral view"): tritylodontids (Gow, 1986; Luo, 2000), tritheledontids (Crompton, 1994);

(b) Ventrally exposed as the promontorium ("present in the ventral view"): Adelobasileus, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not applicable: Probainognathus (outgroup).

10. Promontorium outline (modified from Rougier et al., 1996a):

(a) Triangular, with steep and slightly concave lateral wall: Adelobasileus, Sinoconodon, Haldanodon;

(b) Elongate (almost cylindrical) and with steep lateral wall: Morganucodon, multituberculates;

(c) Finger-like and without a steep lateral wall: triconodontids, Ornithorhynchus, Zhangheotherium;

(d) Bulbous and oval shaped: Hadrocodium, Vincelestes, metatherians, eutherians;

(?) Not applicable (the pars cochlearis not exposed in ventral view, therefore no promontorium): Probainognathus (outgroup), tritylodontids, tritheledontids.

11. Cochlea structures (Rowe, 1988; Wible, 1991; Lillegraven, J. A., and G. Hahn. 1993; Luo, 1994, 2000; Meng and Wyss, 1995; Rougier et al. 1996a; Hurum, 1998b; Hu et al., 1998; literature cited therein):

(a) Cochlear recess (no distinctive canal): Probainognathus (outgroup), tritheledontids (Crompton 1994);

(b) Short canal and uncoiled (although canal can be slightly curved): tritylodontids (Luo, 2000), Sinoconodon, Morganucodon, Haldanodon, triconodontids, multituberculates, Zhangheotherium;

(c) Elongate and partly coiled (180 degress): Ornithorhynchus;

(d) Elongate and coiled at least 270˚: Vincelestes (Rougier, 1993), metatherians, eutherians;

(?) Unknown (in the intact type specimens): Adelobasileus, Hadrocodium.

12. Secondary bony lamina for the basilar membrane within the cochlear canal (Meng and Fox, 1995; Rougier et al., 1996a):

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, triconodontids, Ornithorhynchus, multituberculates;

(b) Present: <u>Vincelestes</u> (Rougier et al., 1996a), metatherians (Meng and Fox, 1995), eutherians (Meng and Fox, 1995);

(?) Unknown (in the intact specimens): <u>Adelobasileus</u>, <u>Hadrocodium</u>,.

13. Fenestra vestibuli:

(a) Facing laterally: <u>Probainognathus</u> (outgroup), tritylodontids, tritheledontids, <u>Adelobasileus</u>, <u>Sinoconodon</u>, <u>Morganucodon</u>, <u>Haldanodon</u>, <u>Hadrocodium</u>, <u>Vincelestes</u>;

(b) Facing ventrolaterally: <u>Ornithorhynchus</u>, multituberculates, <u>Zhangheotherium</u>;

(a/b polymorphic): triconodontids, metatherians, eutherians.

14. Prootic canal (Modified from Crompton and Sun, 1985; Lucas and Luo, 1993; Luo, 1994; Wible and Hopson, 1995; Rougier et al., 1996):

(a) Prootic canal absent: tritylodontids, tritheledontids;

(b) Prootic canal present, and its tympanic aperture is a distinct foramen (and separated from the pterygoparoccipital foramen = foramen for the ramus superior of stapedial artery, if the latter is present): <u>Probainognathus</u> (outgroup), <u>Adelobasileus</u>, <u>Sinoconodon</u>, <u>Morganucodon</u>, <u>Haldanodon</u> (Wible, pers. comm.), <u>Hadrocodium</u>, triconodontids, <u>Zhangheotherium</u>, <u>Vincelestes</u>, metatherians (marsupials lack the ramus superior for the stapedial artery, but have a distinctive prootic canal: Wible and Hopson, 1995).

(c) Prootic canal is present, and its tympanic aperture is confluent with the pterygoparoccipital foramen: <u>Ornithorhynchus</u>;

(a/b polymorphic): eutherians (present and separate in <u>Prokennalestes</u>, Wible et al. In press; prootic canal is absent in other eutherians, such as <u>Daulestes</u>, McKenna et al., 2000; and asioryctitherians; for distribution of this character among extant therians, see Wible, 1987);

(b/c polymorphic): multituberculates (present and partially confluent in ptilodontoid petrosals and some Meniscoessus petrosals, present and separate in other multituberculates, such as Catopsalis).

15. Lateral trough floor anterior to the tympanic aperture of the prootic canal and/or the primary facial foramen (modified from Lucas and Luo, 1993; Luo, 1994):

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids (tritylodontids and tritheledontids both lack the prootic canal; in these two groups the primary facial foramen is used as a landmark for assessment of the lateral trough floor);

(b) Present: Adelobasileus, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes;

(c) Vestigial: metatherians, eutherians.

16. Enclosure of the geniculate ganglion by bony floor of petrosal (modified from Crompton and Sun, 1985; Wible and Hopson, 1993; Luo, 1994; Rougier et al., 1996a):

(a) Absent: Probainognathus (outgroup), tritylodontids (with possible exception of Oligokyphus), tritheledontids, Adelobasileus;

(b) Present: Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Vincelestes, metatherians, eutherians;

(?) Not preserved: Zhangheotherium.

17. Site for the attachment of the tensor tympani muscle on the petrosal (modified from Rougier et al., 1996a):

(a) Indistinct: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Ornithorhynchus;

(b) Present on a shallow anterior embayment anterior to the hiatus fallopi in the lateral trough: Morganucodon, Hadrocodium;

(c) Present as a distinctive recess (or a groove) anterior to the hiatus fallopi in the lateral trough (differs from state b in which the embayment in lateral trough would be anteriorly open): Haldanodon, triconodontids, Vincelestes;

(d) Present on an oval shape fossa (although the position of the fossa may be variable): multituberculates;

(a/d polymorphic): metatherians, eutherians (absent in some Cretaceous to earliest Tertiary taxa: Wible, 1990; Wible et al., in press; McKenna et al., 2000; present in many others, e.g. Cifelli, 1982; Novacek, 1996; Geisler and Luo, 1998; Luo and Gingerich, 1999);

(?) Not preserved: Zhangheotherium.

18. Crista interfenestralis (Rougier et al., 1996a):

(a) Horizontal and extending to base of paroccipital process: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus;

(b) Vertical, limited to the back of the promontorium: Zhangheotherium, Vincelestes, metatherians, eutherians;

(a/b polymorphic): multituberculates.

19. Post-tympanic recess (Wible, 1990; Rougier et al., 1996a):

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates;

(b) Present: Zhangheotherium, Vincelestes, metatherians, eutherians.

20. Caudal tympanic process of petrosal (Wible, 1990; Rougier et al., 1996a):

(a) Absent (indistinguishable from surrounding structures): Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus;

(b) Present (forming a protuberance or a crest continuous with the paroccipital process): Zhangheotherium, Vincelestes, metatherians, eutherians.

(a/b polymorphic): multituberculates (Rougier et al., 1996a).

21. Morphology of anterior paroccipital region:

(a) Indistinct from surrounding structures: Probainognathus (outgroup), tritheledontids, Adelobasileus;

(b) Anterior paroccipital is bulbous and distinctive from the surrounding structures: tritylodontids, Sinoconodon;

(c) Anterior paroccipital region has a distinct crista parotica: Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians.

22. Relationship of the squamosal to the anterior part of paroccipital process (Modified from Luo, 1989; Rougier et al., 1996a: ch 23):

(a) Squamosal covers the lateral aspect of the anterior paroccipital process: Probainognathus (out-group), tritheledontids, Adelobasileus, Sinoconodon, Zhangheotherium, Vincelestes, metatherians, eutherians;

(b) Squamosal is dorsally withdrawn from the paroccipital region so the anterior part of paroccipital is exposed: tritylodontids, Morganucodon, Haldanodon, Hadrocodium, triconodontines, Ornithorhynchus, multituberculates.

23. Epitympanic recess:

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Morganucodon, Haldanodon, triconodontids (with a fossa incudis, but not an epitympanic fossa), Ornithorhynchus (with a fossa incudis, but not an epitympanic fossa);

(b) Present: Hadrocodium, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians.

24. Lateral flange orientation -- (Modified from Luo, 1994; Rougier et al., 1996a):

(a) Horizontal shelf: tritylodontids, tritheledontids, Sinoconodon;

(b) Ventrally directed crest: Probainognathus (outgroup), Adelobasileus, Morganucodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates (ventrally directed in the posterior part, but anterior the lateral flange bent medially to contact the promontorium), Vincelestes;

(c) Vestigial or absent: metatherians, eutherians;

(?) Not preserved: Haldanodon (damaged on the specimens described by Lillegraven and Krusat, 1991), Zhangheotherium (damaged on the type specimen).

25. Vertical component of lateral flange ("L-shaped" and forming a vertical wall to pterygoparoccipital foramen) (Modified from Luo, 1994):

(a) Present: tritylodontids, Sinoconodon;

(b) Absent: Probainognathus (outgroup), tritheledontids, Adelobasileus, Morganucodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Vincelestes;

(?) Not preserved: Haldanodon (damaged on the illustrated specimen by Lillegraven and Krusat, 1991), Zhangheotherium (damaged on the type specimen); not applicable: metatherians, eutherians.

26. Relationship of lateral flange to the crista parotica (or the anterior paroccipital process that bears the crista) (modified from Rougier et al., 1996a; ch. 30)

(a) Widely separated: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon;

(b) Narrowly separated: Morganucodon, triconodontids;

(c) Continuous: Adelobasileus, Hadrocodium, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes;

(?) Haldanodon (not preserved on the specimens illustrated by Lillegraven and Krusat, 1991); not applicable: metatherians, eutherians.

27. Pterygoparoccipital foramen (or foramen for the ramus superior of the stapedial artery):

(a) Laterally open notch (laterally open pterygoparoccipital foramen): tritylodontids, tritheledontids, Sinoconodon, Morganucodon, triconodontids;

(b) Foramen enclosed exclusively by the petrosal: Hadrocodium, Ornithorhynchus, multituberculates, Vincelestes ("ascending canal" of Rougier et al., 1992);

(c) Other bones (e.g. squamosal, or the quadrate ramus of epipterygoid) also contribute (in addition to the petrosal) to the enclosure of the foramen: Probainognathus (outgroup) (Luo and Crompton, 1994; Wible and Hopson, 1995), Adelobasileus, Zhangheotherium;

(d) Absent: metatherians;

(b/c polymorphic): eutherians (b for Prokennalestes, Wible et al., in press; Erinaceus; c- for other eutherians);

(?) Not preserved: Haldanodon.

28. The position of pterygoparoccipital foramen relative to the fenestra vestibuli (adopted from Wible et al., 1995):

(a) The pterygoparoccipital foramen is posterior or lateral to the level of the fenestra vestibuli: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, Ornithorhynchus, Zhangheotherium;

(b) The foramen is anterior to the level of the fenestra vestibuli: triconodontids, multituberculates, Vincelestes, eutherians;

(?) Not applicable: metatherians.

29. Vascular foramen in the posterior part of the lateral flange (and anterior to the "pterygoparoccipital or the ramus superior foramen"):

(a) Present: tritylodontids, Adelobasileus, Sinoconodon, Morganucodon, Hadrocodium;

(b) Absent: Probainognathus (outgroup), tritheledontids, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, metatherians, eutherians;

(a/b polymorphic): Vincelestes;

(?) Haldanodon (not preserved in the relevant area in the specimen studied by Lillegraven and Krusat, 1991).

30. "Bifurcation of paroccipital process" (anterior paroccipital part separated from the posterior part by the stapedial muscle fossa and related groove) -- presence vs. absence (this is modified from the character of several previous studies):

(a) Bifurcation absent: Probainognathus (outgroup), tritheledontids, Adelobasileus, Hadrocodium, Zhangheotherium, Vincelestes, metatherians, eutherians;

(b) Bifurcation present: tritylodontids, Sinoconodon, Morganucodon, Haldanodon, triconodontids, Ornithorhynchus;

(a/b polymorphic): multituberculates.

31. Ventral projection of the posterior paroccipital process:

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Haldanodon (= posteromedial condyle of crista parotica's main body, as described by Lillegraven and Krusat, 1991), Hadrocodium, Zhangheotherium, metatherians, eutherians;

(b) Present (projecting below the surrounding structures): Morganucodon, triconodontids, Ornithorhynchus, Vincelestes;

(a/b polymorphic): multituberculates.

32. Stapedial muscle fossa (modified from Rowe, 1988; Wible, 1991; Luo, 1994; Rougier et al., 1996a):

(a) Absent: Probainognathus (outgroup), tritheledontids, Adelobasileus, Ornithorhynchus;

(b) Present and in alignment to the crista interfenestralis: tritylodontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium;

(c) Present and lateral to the crista interfenestralis: triconodontids, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians.

33. Separation of the fenestra cochleae from jugular foramen:

(a) Absent: Probainognathus (outgroup), tritylodontids;

(b) Present: tritheledontids, Adelobasileus, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, Zhangheotherium, Vincelestes, metatherians, eutherians;

(a/b polymorphic): multituberculates.

34. Bony channel for the perilymphatic duct (distribution modified from Rougier et al., 1996a):

(a) Indistinct: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus;

(b) Distinctive, an open sulcus in the trough between perilymphatic foramen and the jugular foramen: Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus;

(c) Completely enclosed by bone (to form the cochlear aqueduct): Vincelestes, metatherians, eutherians;

(a/b polymorphic): multituberculates;

(?) Not preserved: Zhangheotherium .

Other Basicranial Characters (5 characters)

35. The ventral opening of the cavum epiptericum anterior to the lateral trough:

(a) Present and large: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus;

(b) Present with reduced size (due the anterior expansion of the lateral trough floor): Sinoconodon, Morganucodon, Hadrocodium, Ornithorhynchus;

(c) Partially enclosed by the lateral flange of the petrosal: Haldanodon, triconodontids, multituberculates, Vincelestes;

(d) Enclosed by both the alisphenoid in addition to the petrosal: metatherians, eutherians;

(?) Not preserved: Zhangheotherium.

36. "Quadrate ramus" of alisphenoid

(a) Forming a rod overlapping with the anterior part of the lateral flange: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Morganucodon, Haldanodon;

(b) Quadrate ramus absent: Hadrocodium, triconodontids, Ornithorhynchus, multituberculates (from Hurum, 1998), Vincelestes, metatherians, eutherians;

(?) Not preserved: Zhangheotherium.

37. The basisphenoid wing ("the parasphenoid ala"):

(a) Present, overlapping the entire prootic cochlear housing (a part of the petrosal) to the rim of the fenestra vestibuli: Probainognathus (outgroup);

(b) Present, overlapping a part of the pars cochlearis (cochlear housing): tritylodontids, tritheledontids, Adelobasileus;

(c) Basisphenoid does not overlap the petrosal pars cochlearis: Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians.

38. Overalp of the basioccipital to the pars cochlearis:

(a) Overlapping the entire cochlear housing: Probainognathus (outgroup), tritylodontids (Gow, 1986; Luo, 2000), tritheledontids (Crompton, 1994);

(b) Overlapping the medial side of the promontorium: Adelobasileus (reinterpreted from Lucas and Luo, 1993), Sinoconodon;

(c) No overlapping: Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians.

39. The hypoglossal foramen (Lucas and Luo, 1993, as modified by Rougier et al., 1996a):

(a) Indistinct, either confluent with the jugular foramen or sharing a depression with the jugular foramen: Probainognathus (outgroup), tritylodontids (confluent), tritheledontids (sharing the same depression), Ornithorhynchus (confluent);

(b) Separated from the jugular foramen: Adelobasileus, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians.

Palatal and Jugal Characters (7 characters)

40. Bony secondary palate:

(a) Ending anterior to the tooth row: Probainognathus (outgroup), tritylodontids, multituberculates;

(b) Level with the tooth row: tritheledontids, Sinoconodon, Morganucodon, Vincelestes;

(c) Extending posterior to the tooth row: Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, metatherians;

(b/c polymorphic): eutherians;

(?) Not preserved: Adelobasileus, Zhangheotherium.

41. Relationship of the maxilla to the subtemporal margin or the orbit:

(a) Excluded from the orbit in the ventral view: Probainognathus (outgroup);

(b) Participating in the rounded subtemporal margin of the orbit: tritylodontids, tritheledontids;

(c) Forming a well defined edge along the subtemporal margin: Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus.

42. Pterygopalatine ridges:

(a) Present: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Morganucodon, multituberculates, Vincelestes;

(b) Absent: Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, metatherians, eutherians;

(?) Not preserved: Zhangheotherium.

43. Transverse process (hamulus) of the pterygoid:

(a) Present and massive (extensive contact to the coronoid on mandible): Probainognathus (outgroup), tritheledontids;

(b) Present but reduced (to the extent that it has reduced its contact to the mandibular coronoid process): Sinoconodon, Morganucodon, Vincelestes, metatherians; eutherians;

(c) Greatly reduced (a vestigial protuberance) or absent: Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus;

(a/b polymorphic): tritylodontids (enlarged for some tritylodontids, see Sues, 1985, but not in others see Kemp, 1983);

(b/c polymorphic): multituberculates (present but small in Kryptobaatar and Kamptobaatar, absent in others, Wible and Rougier, 2000);

(?) Not preserved: Adelobasileus, Zhangheotherium.

44. Basisphenoid constricture (= nasopharyngeal roof width anterior to the basisphenoid):

(a) Very narrow anterior to the basisphenoid: Probainognathus (outgroup), tritylodontids, tritheledontids;

(b) Intermediate (wide anterior to the basisphenoid): Adelobasileus, Sinoconodon, Morganucodon, Vincelestes;

(c) No constricture (nasopharyngeal roof width is as broad as the internal choane): Haldanodon, Hadrocodium, Ornithorhynchus, multituberculates;

(b/c polymorphic): triconodontids (intermediate: Kermack, 1963; broad: the Cloverly triconodontid), metatherians, eutherians;

(?) Not preserved: Zhangheotherium .

45. Shape (curvature) of the bony nasal pharyngeal roof at the level of the hamulus or lateral flange of the pterygoid:

(a) Bony roof of the pharynx has the inverted V-shape in transverse section, narrowing toward the basisphenoid: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon;

(b) Bony roof of the pharynx is U-shaped roof in transverse section: Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Vincelestes;

(a/b polymorphic): metatherians, eutherians;

(?) Not preserved: Adelobasileus, Zhangheotherium.

46. Jugal:

(a) Present: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Zhangheotherium, Vincelestes, metatherians, eutherians;

(b) Reduced or absent: Hadrocodium (inferred from its anterior part), triconodontids, Ornithorhynchus, multituberculates.

Occipital and Skull Roof characters (6 characters)

47. The posterior opening of the post-temporal canal:

(a) At the junction of the petrosal, squamosal and the tabular: Probainognathus (outgroup), tritylodontids, tritheledontids (following Crompton, 1958), Sinoconodon (Luo and Crompton, unpublished data);

(b) Between the petrosal and the squamosal, or within the petrosal: Adeblobasileus, Morganucodon, Haldanodon (identified as feature #65 in Fig. 6, Lillegraven and Krusat, 1991), Hadrocodium, triconodontids, Ornithorhynchus, multituberculates (withing the petrosal, following Kielan-Jaworowska et al., 1986; Hurum 1998), Vincelestes, metatherians, eutherians;

(?) Not preserved: Zhangheotherium.

Note: this character has the same distribution as the presence vs. absence of the tabular bone among the taxa listed in this matrix. So the character on the "tabular bone" was omitted from this analysis to avoid redundance.

48. The anterior ascending vascular channel for the arteria diploetica magna in the temporal region (immediately anterior to the post-temporal canal):

(a) Open groove: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Ornithorhynchus;

(b) Partially enclosed in a canal: Adelobasileus, Hadrocodium, triconodontids;

(c) Completely enclosed in a canal or endocranial: multituberculates, Vincelestes, eutherians;

(?) Not preserved: Zhangheotherium; condition uncertain: Haldanodon; not-applicable: metatherians .

49. Morphology of supraoccipital region and the lambdoidal crest:

(a) Supraoccipital is concave below an overhaning lambdoidal crest: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Vincelestes, metatherians, eutherians;

(b) Supraoccipital is flat below the lambdoial crest: Adelobasileus, Haldanodon, triconodontids;

(c) Suproaccipital convex in the lambdoidal region, and the crest is is weak or absent: Hadrocodium, Ornithorhynchus;

(b/c polymorphic): multituberculates (several djadochtatherian multituberculates have state c; the majority of other multituberculates have state b);

(?) Not preserved: Zhangheotherium.

50. The sagittal crest:

(a) Prominently developed: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Vincelestes, metatherians, eutherians;

(b) Weakly developed: Adelobasileus, Morganucodon, Haldanodon, triconodontids;

(c) Absent, the area near the median suture of parietals is uniformly convex: Hadrocodium, Ornithorhynchus, multituberculates;

(?) Not preserved: Zhangheotherium.

51. Shape of the occipital condyles (in lateral view):

(a) Bulbous: Probainognathus (outgroup), tritylodontids, Adelobasileus, Sinoconodon;

(b) Ovoid to cylindrical: tritheledontids, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Vincelestes, metatherians, eutherians;

(?) Not preserved: Zhangheotherium.

52. Expansion of the braincase in the parietal region:

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Adelobasileus, Sinoconodon, Morganucodon, Haldanodon;

(b) Expanded (the parietal part of the cranial vault is wider than the frontal part, but expansion does not extend to lambdoidal region): triconodontids, Vincelestes;

(c) Greatly expanded (expansion of cranial vault extends to lambdoidal region): Hadrocodium, Ornithorhynchus;

(b/c polymorphic): multituberculates, metatherians, eutherians;

(?) Not preserved: Zhangheotherium.

Mandible (20 characters)

53. Medial ridge overhanging the post-dentary trough on the dentary:

(a) Prominent ridge over a broad groove: Probainognathus (outgroup), tritylodontids, tritheledontids, Morganucodon;

(b) Weak ridge over a shallow or vestigial groove: Sinoconodon, Haldanodon;

(c) Both groove and ridge are absent: Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus.

54. Meckelian groove in adults (Rowe, 1988; Wible, 1991; Luo, 1994):

(a) Distinctive and well developed groove: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon;

(b) Weakly developed sulcus: triconodontids, Zhangheotherium, Vincelestes (faint trace of sulcus, condition variable; see figs. 44, 45 of Rougier, 1993),

(c) Absent: Hadrocodium, Ornithorhynchus, multituberculates, metatherians;

(b/c polymorphic): eutherians (present in Prokennalestes, Kielan-Jaworowska and Deshzeveg, 1989; Montanalestes, Cifelli, 1999; absent in other eutherian mammals);

(?) Not preserved: Adelobasileus.

55. Curvature of the middle segment of the Meckelian groove:

(a) Parallel to (and separated from) the ventral margin of the mandible: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Haldanodon, triconodontids, Zhangheotherium, Vincelestes;

(b) Convergent toward or intersecting with the ventral border of the mandible: Morganucodon (convergent and intersect); eutherians (Prokennalestes and Montanalestes can be coded for state b, Kielan-Jaworowska and Dashzeveg, 1989; Cifelli, 1999; this character is not applicable to other eutherians that have lost the Meckelian sulcus);

(?) Not preserved: Adelobasileus; not applicable: Hadrocodium, Ornithorhynchus, multituberculates, metatherians.

56. Mandibular symphysis:

(a) Fused: Probainognathus (outgroup), tritylodontids;

(b) Unfused symphysis extending below (or beyond) the first postcanine: tritheledontids, Sinoconodon, Morganucodon, Haldanodon, triconodontids, multituberculates, Vincelestes, metatherians, eutherians;

(c) Unfused and reduced symphysis: Hadrocodium (terminating below the canine), Ornithorhynchus, Zhangheotherium (terminating below the canine);

(?) Not preserved: Adelobasileus.

57. Groove for the replacement dental lamina (Crompton and Luo, 1993; Luo, 1994):

(a) Present: Probainognathus (outgroup), tritheledontids, Sinoconodon, Morganucodon (based on Parrington, 1973, 1978);

(b) Absent: tritylodontids, Haldanodon, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus; unknown (preserved but not exposed): Hadrocodium.

58. Angular process of dentary: presence vs. absence (Rowe, 1988; Wible, 1991; Luo, 1994; Rougier et al. 1996a):

(a) Present and strongly developed: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, Vincelestes, metatherians, eutherians.

(b) Absent: triconodontids, Ornithorhynchus (here we are coding only the extant platypus. Although the fossil ornithorhynchid Obdurodon has a weakly developed angle [Archer et al., 1993; Musser and Archer, 1998], this taxon is not considered here), multituberculates, Zhangheotherium;

(?) Not preserved: Adelobasileus.

59. Relative vertical position of the angular process in the dentary (modified from Lillegraven and Krusat, 1991):

(a) Angular process is levelled with a relative straight ventral border of the mandible: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Vincelestes;

(b) Angular process is elevated because of the bowed ventral border of the mandible, elevated towards the level of the alveolar line of the mandible: Morganucodon, Haldanodon, Hadrocodium;

(a/b polymorphic): metatherians, eutherians;

(?) Not preserved: Adelobasileus; not applicable: triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium.

60. Relative anteroposterior position of the angular process of dentary (modified from Luo et al., 2001):

(a) Anteriorly placed (below the coronoid process): Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon;

(b) Intermediate condition (leveled with the posterior border of the coronoid process): Hadrocodium, Vincelestes;

(c) Posteriorly placed (posterior to the coronoid process or just below the dentary condyle): metatherians, eutherians.

(?) Not preserved: Adelobasileus; not applicable for the taxa without the angular process: triconodontids, Ornithorhynchus (here we are coding only the extant platypus. Although the fossil ornithorhynchid Obdurodon has a weakly developed angle, Archer et al., 1993, this taxon is not considered here), multituberculates, Zhangheotherium.

61. Medial concavity (fossa) on the mandibular angle for the reflected lamina of the angular bone (Kermack et al., 1973; Crompton and Luo, 1993):

(a) Present: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon;

(b) Absent: Hadrocodium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus; not applicable (no mandibular angle): triconodontids, Ornithorhynchus (here we are coding only the extant platypus. Although the fossil ornithorhynchid Obdurodon has a weakly developed angle, Archer et al., 1993, we are not considering this fossil taxon), multituberculates, Zhangheotherium.

62. Relationship of the postdentary rod (the complex of the surangular-articular-prearticular and their homologs) to the mandible:

(a) Attached to the mandible: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon;

(b) Detached from the mandible: Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus.

63. Mandibular foramen for the inferior alveolar nerve and vessels:

(a) Located within the mandibular trough or associate with either the meckelian groove: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon;

(b) Not associated with any meckelian structure(s): Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus.

64. Coronoid fossa in adult mandible (Rowe, 1988; Wible, 1991; Luo, 1994):

(a) Present: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Zhangheotherium, Vincelestes;

(b) Absent: triconodontids, Ornithorhynchus, metatherians;

(a/b polymorphic): multituberculates (present in paulchoffatiids, Hahn, 1977; but absent in other multituberculates), eutherians (present in Prokennalestes, Montanalestes, possibly also in Asioryctes, absent in others);

(?) Not preserved: Adelobasileus; Hadrocodium (not exposed);

65. The splenial as a separate element in adult:

(a) Present: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Zhangheotherium;

(b) Absent: Hadrocodium, triconodontids, Ornithorhynchus, multituberculates, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus.

66. The pterygoid muscle fossa on the medial side of the mandible:

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium;

(b) Present: triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus.

67. The pterygoid ridge along the ventral border of the coronoid part of the mandible:

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium;

(b) Present (as a distinct low crest): triconodontids, Zhangheotherium, Vincelestes;

(c) Present, strongly developed and shelf-like: Ornithorhynchus, multituberculates, metatherians;

(a/b polymorphic): eutherians;

(?) Not preserved: Adelobasileus.

68. The ventral crest (border) of masseteric fossa:

(a) Indistinct: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, Zhangheotherium;

(b) Distinct and well-defined: triconodontids, Ornithorhynchus, multituberculates, Vincelestes;

(a/b polymorphic): metatherians, eutherians;

(?) Not preserved: Adelobasileus.

69. The prearticular:

(a) Present (as a separate bone, ankylosed to the articular) in adult: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon;

(b) Absent as a separate element in adult (incorporated into the malleus as the "Os goniale" sensu Zeller, 1989; 1993): Ornithorhynchus, multituberculates, metatherians, eutherians;

(?) Not preserved: Adelobasileus, Hadrocodium, triconodontids, Zhangheotherium, Vincelestes.

70. Dentary condyle and its peduncle:

(a) Condyle absent, homologous part of the peduncle is only represented by the lateral ridge (sensu Crompton, 1972b; Crompton and Luo, 1993): Probainognathus (outgroup), tritylodontids, tritheledontids (dentary contacting the squamosal but lacking a distinctive condyle);

(b) Dentary condyle present, peduncle is posteriorly directed: Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, metatherians, eutherians;

(c) Dentary condyle present, peduncle is up-turned: triconodontids, Ornithorhynchus, multituberculates, Zhangheotherium, Vincelestes;

(?) Not preserved: Adelobasileus.

71. Size and morphology of the dentary condyle:

(a) Small and dorso-ventrally compressed: Hadrocodium;

(b) Massive and bulbous: Sinoconodon, Haldanodon, Ornithorhynchus, Vincelestes, metatherians, eutherians;

(c) Condyle ovoid and mediolaterally compressed: triconodontids, multituberculates, Zhangheotherium;

(a/b polymorphic): Morganucodon;

(?) Not applicable: Probainognathus (outgroup), tritylodontids, tritheledontids; not preserved: Adelobasileus.

72. Position of the craniomandibular joint relative to the level of the lower postcanine alveoli:

(a) Below the alveolar level: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon;

(b) About the same level: Morganucodon, multituberculates;

(c) Above the alveolar level: Haldanodon, Hadrocodium, Ornithorhynchus, Zhangheotherium, Vincelestes, metatherians, eutherians;

(b/c polymorphic): triconodontids;

(?) Not preserved: Adelobasileus.

Dentition (18 characters)

73. Bilateral symmetry in movement of lower jaws (Crompton and Hylander, 1986; Crompton and Luo, 1993):

(a) Unilateral (one side at a time): Probainognathus (outgroup), tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, Ornithorhynchus, Zhangheotherium, Vincelestes, metatherians, eutherians;

(b) Bilateral: tritylodontids (following Crompton, 1972a; Sues, 1985), multituberculates (following Wall and Krause, 1992).

(?) Not preserved: Adelobasileus (mandible is not available for assessment of this feature).

74. Mode of the mandibular movement during power stroke (Kemp, 1983; Kielan-Jaworowska, 1996):

(a) Orthal movement during power stroke: Probainognathus (outgroup), tritheledontids;

(b) Posteriorly directed power stroke: tritylodontids (following Crompton, 1974; Sues, 1985), multituberculates (following Krause, 1982; Wall and Krause, 1992; Kielan-Jaworowska, 1996);

(c) Moderate rotation along the longitudinal axis in power stroke: Sinoconodon, Morganucodon (following Crompton and Luo, 1993), Haldanodon (Lillegraven and Krusat, 1993), Hadrocodium, triconodontids;

(d) Strong rotation along the longitudinal axis: Zhangheotheriun, Vincelestes, metatherians, eutherians;

(a/b polymorphic): Ornithorhynchus (Hopson and Crompton, 1969 inferred from the wear patterns on the cusps of the juvenile teeth and the shape of the craniomandibular joint that the mandible of the platypus could have both dorsoposteriorly directed and the dorsomedially directed movement);

(?) Not preserved: Adelobasileus.

75. Replacement of incisors and canines:

(a) Alternating and multiple replacement: Probainognathus (outgroup), tritheledontids, Sinoconodon;

(b) Diphyodont replacement: tritylodontids (replacing incisors), Morganucodon, Haldanodon, triconodontids, multituberculates, Zhangheotherium, metatherians, eutherians;

(?) Not preserved: Adelobasileus, Hadrocodium; Ornithorhynchus (uncertain); Vincelestes (unknown).

76. Canine:

(a) Present and enlarged: Probainognathus (outgroup), tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, Vincelestes, metatherians, eutherians;

(b) Present and small: Zhangheotherium;

(c) Absent: tritylodontids, Ornithorhynchus;

(a/b polymorphic): triconodontids;

(b/c polymorphic): multituberculates (present in paucholffatiids; absent in others);

(?) Not preserved: Adelobasileus.

77. Number of postcanine roots (Rowe, 1988; Wible, 1991; Luo 1994):

(a) Single (division incomplete, may be shaped in figure 8 in cross-section): Probainognathus (outgroup), tritheledontids (figure 8), Adelobasileus (figure 8, Lucas, pers. comm.);

(b) Completely divided roots (no more than three): Morganucodon, Haldanodon, Hadrocodium, triconodontids, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(c) Multiple roots (more than three): tritylodontids, Ornithorhynchus (after Woodburne and Tedford, 1975);

(a/b polymorphic): Sinoconodon (modified from Luo, 1994; after Zhang et al., 1998).

78. Alignment of main cusps of upper postcanines:

(a) Single longitudinal row: Probainognathus (outgroup), tritheledontids, Adelobasileus (Lucas, pers. comm.), Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids;

(b) Multiple cusps in multiple rows: tritylodontids, multituberculates;

(c) In reversed triangle: Ornithorhynchus (juvenile teeth stage 1 of Simpson, 1929), Zhangheotherium, Vincelestes, metatherians, eutherians.

79. Interlocking of the adjacent lower postcanines:

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Ornithorhynchus (based on the juvenile teeth), multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(b) Cusp d of anterior molar fits into the embayment between cusp b and cusp e of the posterior molar: Morganucodon, Haldanodon (after Krusat, 1980), Hadrocodium, triconodontids (cusp d applied to the mesial groove of cusp b, we consider this to be a more specialized version of interlocking of other triconodonts);

(?) Not preserved: Adelobasileus.

80. Cingulid on the lower postcanines:

(a) Present on the lingual side: Probainognathus (outgroup), tritheledontids, Morganucodon, triconodontids, Zhangheotherium;

(b) Present on both lingual and labial cingula: Haldanodon, Ornithorhynchus (based on juvenile teeth);

(c) Vestigial or absent: tritylodontids, Adelobasileus, Sinoconodon, multituberculates, Vincelestes, metatherians, eutherians;

(?) Not preserved: Hadrocodium.

81. Occlusion of the principal cusps of the upper and lower molariform postcanines:

(a) Principal cusps of the upper and the lower molariforms lack consistent contact relationship: Probainognathus (outgroup), tritheledontids, Sinoconodon;

(b) Principal cusp a of lower molar is positioned anterior to cusp A but posterior to cusp B of the opposite upper molar: Morganucodon, Haldanodon, triconodontids;

(c) Embrasure occlusion -- principal cusp a (protoconid) anterior to cusp B (stylar cusp) but posterior to cusp C (metacone) of the preceding tooth: Hadrocodium, Zhangheotherium, Vincelestes, metatherians, eutherians;

(d) Interdigital occlusion between multiple rows of cusps: tritylodontids, multituberculates;

(?) Not preserved: Adelobasileus; uncertain: Ornithorhynchus (occlusal relationship of upper and lower cusps are uncertain according to Simpson, 1929).

82. Functional development of occlusal wear facets on molar cusps:

(a) Absent for lifetime: Probainognathus (outgroup), tritheledontids, Sinoconodon;

(b) Absent at eruption but developed later by wearing of the crown: Morganucodon, Haldanodon, Hadrocodium, triconodontids;

(c) Upper and lower wear facets present and match upon eruption: tritylodontids, multituberculates, Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus, Ornithorhynchus (uncertain for juvenile teeth, not applicable to adult teeth).

83. Relationships of wear facets to the main cusps:

(a) Principal cusp bears two longitudinal wear facets (a of the lower bears two facets, which either occlude with the facets of cusp B of the opposite tooth and the cusp C of the preceding tooth, or occlude with the facets of cusps A and B of the opposite tooth): Morganucodon, Haldanodon, Hadrocodium (lower cusp a supporting two wear facets occluding with C of the preceding upper molar and B of the opposite upper molar), triconodontids;

(b) Single facet supported by two cusps (a and c of the lower occlude with the facet supported by cusps A and B of the opposite tooth; single facet supported by cusps a and b occludes with the facet supported by A and C of the preceding tooth: Zhangheotherium, Vincelestes, metatherians, eutherians;

(c) Multiple cusps, with each cusp bearing one or two transverse and crescentic facets: tritylodontids, multituberculates;

(?) Not applicable: Probainognathus (outgroup), tritheledontids (wear facet absent or a simple longitudinal facet that extends the entire length of the crown), Sinoconodon; not preserved: Adelobasileus, Ornithorhynchus (uncertain for juvenile teeth, not applicable to adult teeth).

84. Upper molar labial stylar shelf (the area labial to the paracone/metacone):

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, multituberculates;

(b) Present: Ornithorhynchus (juvenile teeth), Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus.

85. Orientation of protocristid relative to the length of the molar (from Hu et al., 1998):

(a) Longitudinal orientation: Probainognathus (outgroup), tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids;

(b) More transverse: Zhangheotherium, Vincelestes, metatherians, eutherians;

(?) Not applicable: tritylodontids, Ornithorhynchus, multituberculates; not-preserved: Adelobasileus.

86. Upper molar protocone:

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, multituberculates, Zhangheotherium, Vincelestes;

(b) Present: metatherians, eutherians;

(?) Not preserved: Adelobasileus; uncertain: Ornithorhynchus.

87. Lower molar talonid:

(a) Absent: Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, triconodontids, multituberculates, Zhangheotherium;

(b) Present: Vincelestes, metatherians, eutherians;

(?) Not preserved: Adelobasileus; uncertain (questionable homology): Ornithorhynchus.

88. Wear facet on talonid (or on posterior cingulid on the lower molar) (applicable to taxa with reversed triangulation plus a distal cusp d):

(a) Talonid heel present but no basin with functional wear facet: Zhangheotherium, Vincelestes;

(b) Talonid present with wear facet development within the basin: metatherians, eutherians;

(?) Not applicable (no talonid): Probainognathus (outgroup), tritylodontids, tritheledontids, Sinoconodon, Morganucodon, Haldanodon, Hadrocodium, multituberculates; not preserved: Adelobasileus, Ornithorhynchus (interpretation uncertain, but see Luo et al., 2001).

89. Replacement pattern of the postcanines:

(a) Alternating replacement of all postcanines: Probainognathus (outgroup), tritheledontids;

(b) Single replacement of premolariform, partial replacement of molariform: Sinoconodon;

(c) Single replacement of premolariform, no replacement of molariform: Morganucodon, Haldanodon, triconodontids, multituberculates, Zhangheotherium, metatherians (only ultimate premolariform is replaced), eutherians;

(d) Sequential addition of postcanines, no replacement: tritylodontids;

(?) Not preserved or unknown: Adelobasileus, Hadrocodium, Vincelestes; not-applicable: Ornithorhynchus.

90. Enlarged diastema in the anterior dentition:

(a) Absent: Probainognathus (outgroup), tritheledontids, Haldanodon, triconodontids, Zhangheotherium, Vincelestes, metatherians, eutherians;

(b) Present and behind the canine: Sinoconodon, Morganucodon (in older individuals), Hadrocodium;

(c) Present and behind the posterior incisor: tritylodontids;

(b/c polymorphic): multituberculates (paulchoffatiids b; other multituberculates, c);

(?) Not preserved: Adelobasileus; not applicable: Ornithorhynchus.

PART VIII. References

Allin, E. F. 1975. Evolution of the mammalian middle ear. Journal of Morphology 147:403-436.

Allin, E. F. 1986. Auditory apparatus of advanced mammal-like reptiles and early mammals. Pp. 283-294. In N. Hotton, P. D. MacLean, J. J. Roth & E. C. Roth (Eds.) The ecology and biology of mammal-like reptiles. Washington and London: Smithsonian Institution Press.

Allin, E. F. and Hopson, J. A. 1992. Evolution of the auditory system in Synapsida ("mammal-like reptiles" and primitive mammals) as seen in the fossil record. Pp. 587-614. In D. B. Webster, R. R. Fay, and A. N. Popper (Eds.), The evolutionary biology of hearing. New York: Springer-Verlag.

Archer, M., Flannery, T. F., Richtie, A., and Molnar, R. E. 1985. First Mesozoic mammal from Australia -- an early Cretaceous monotreme. Nature 318:363-366.

Archer, M, Murray, P., Hand, S. J., and Godthelp, H. 1993. Reconsideration of monotreme relationships based on the skull and dentition of the Miocene Obdurodon dicksoni (Ornithorhynchidae). Pp. 75-94. In, F. S. Szalay, M. J. Novacek, and M. C. McKenna (Eds.), Mammal Phylogeny. Volume 1. Springer-Verlag: New York.

Bonaparté, J. F. and Rougier, G. W. 1987. Mamíferos del Cretácico Inferior de Patagonia. Actas IV Congreso Latinoamericano de Paleontologia, Bolivia 1:343-359.

Butler, P. M. 1988. Docodont molars as tribosphenic analogues (Mammalia, Jurassic). *In*: D. E. Russell, J. P. Santoro, & D. Sigogneau-Russell (eds.). Teeth revisited: Proceedings of the VIIth International Symposium on Dental Morphology. 329-340. Mémoirs du Muséum national d'Histoire naturelle, Paris *C* **53**.

Butler, P. M. 2000. Review of the early allotherian mammals. Acta Palaeontologica Polonica 45:317-342.

Cifelli, R. L. 1982. The petrosal structure of Hyopsodus with respect to that of some other ungulates and its phylogenetic implications. Journal of Paleontology 56:795-805.

Cifelli, R. L. 1999. Tribosphenic mammal from the North American Early Cretaceous. Nature 401:363-366.

Cifelli, R. L. & S. K. Madsen. 1999. Spalacotheriid symmetrodons (Mammalia from the medial Cretaceous (upper Albian or lower Cenomanian) Mussentuchit local fauna, Cedar Mountain Formation, Utah, USA. Geodiversitas 21:167-214.

Cifelli, R. L., Wible, J. R. and Jenkins, F. A., Jr. 1998. Triconodont mammals from the Cloverly Formation (Lower Cretaceous), Montana and Wyoming. Journal of Vertebrate Paleontology 16:237-241.

Clemens, W. A. 1963. Fossil mammals of the Type Lance Formation, Wyoming. Part I. Introduction and Multituberculata. University of California Publications in Geological Sciences 48:1-105.

Clemens, W. A. and Kielan-Jaworowska, Z. 1979. Multituberculata. Pp. 99-149. In, J. A. Lillegraven, Z. Kielan-Jaworowska, and W. A. Clemens (Eds.), Mesozoic Mammals: the First Two-thirds of Mammalian History. Berkeley: University of California Press,.

Crompton, A. W. 1958. The cranial morphology of a new genus and species of ictidosaurian. Proceedings of the Zoological Society of London 140:697-750.

Crompton, A. W. 1964. On the skull of Oligokyphus. Bulletin of British Museum of Natural History, Geology 9: 70-82.

Crompton, A. W. 1971. The origin of the tribosphenic molar. Pp. 65-87. In. D. M. Kermack and K. A. Kermack (Eds.), Early Mammals. New York, New York: Academic Press.

Crompton, A. W. 1972a. Evolution of the jaw articulation in cynodonts. Pp. 231-253. In K.A. Joyce and T.S. Kemp (Eds.), Studies in Vertebrate Evolution. Edinburgh: Oliver and Boyd.

Crompton, A. W. 1972b. Postcanine occlusion in cynodonts and tritylodonts. Bulletin of British Museum (Natural History) 21:27-71.

Crompton, A. W. 1974. The dentitions and relationships of the southern African Triassic mammals Erythrotherium parringtoni and Megazostrodon rudnerae. Bulletin of British Museum (Natural History), Geology 24:399-437.

Crompton, A. W. 1994. Masticatory function in non-mammalian cynodonts and early mammals. Pp. 55-75. In J. J. Thomason (ed.), Functional Morphology in Vertebrate Paleontology. Cambridge: Cambridge University Press.

Crompton, A. W., and Hylander, W. L. 1986. Changes in mandibular function following the acquisition of a dentary-squamosal jaw articulation. Pp. 263-282. In N. Hotton, P. D. MacLean, J. J. Roth & E. C. Roth (Eds.) The ecology and biology of mammal-like reptiles. Washington and London: Smithsonian Institution Press.

Crompton, A. W. and Luo, Z. 1993. Relationships of the Liassic mammals, Sinoconodon, Morganucodon oehleri, and Dinnetherium. Pp. 30-44. In, F. S. Szalay, M. J. Novacek, and M. C. McKenna (Eds.), Mammal Phylogeny. Volume 1. New York: Springer Verlag.

Crompton, A. W., and Sun, A. L. 1985. Cranial Structure and relationships of the Liassic mammal Sinoconodon. Zoological Journal of the Linnean Society 85: 99-119.

Gambaryan P. P. and Kielan-Jaworowska, Z. 1997. Sprawling versus parasagittal stance in multituberculate mammals. Acta Palaeontologica Polonica 42:13-44.

Geisler, J. H. and Luo, Z.-X. 1998. Cranial vascular evolution in mesonychids and cetaceans and the phylogenetic position of cete. Pp. 161-212. In, J. G. M. Thewissen (ed.), Evolutionary Emergence of Whales. New York: Plenum Press.

Gingerich, P. D. 1973. Molar occlusion and function in the Jurassic mammal Docodon. Journal of Mammalogy 54:1008-1013.

Gow, C. E. 1986a. A new skull of *Megazostrodon* (Mammalia, Triconodonta) from the Elliot Formation (Lower Jurassic) of Southern Africa. Palaeontologia Africana 26**:**13-26.

Gow, C. E. 1986b. The sidewall of the braincase in cynodont therapsids and a note on the homology of the mammalian promontorium. South African Journal of Zoology 21:136-148.

Gregory, W. K. 1910. The orders of mammals. Bulletin of the American Museum of Natural History 27:1-524.

Gregory W. K. 1947. The monotremes and the palimpset theory. Bulletin of the American Museum of Natural History 88:1-52.

Gregory, W. K. 1951. Evolution Emerging: A Survey of Changing Patterns from Primeval Life to Man. 730 Pp. New York: The MacMillan Company.

Griffiths, M. 1978. The Biology of the Monotremes. Academic Press, New York, viii + 352 pp.

Hahn, G. 1969. Beiträge zur Fauna der Grube Guimarota Nr. 3. Die Multituberculata. Palaeontographica 133:1-100.

Hahn, G. 1977. Das Coronoid der Paulchoffatiidae (Multituberculata, Ober-Jura). Paläontologische Zeitschrift 51:246-253.

Hahn, G. 1981. Zum Bau der Schädel-Basis bei den Paulchoffattiidae (Multituberculata; Ober-Jura). Sencknbergiana Lethaea 61:227-245.

Hahn, G. 1985. Zum Bau des Infraorbital-Foramens bei den Paulchoffattiidae (Multituberculata, Ober Jura). Berl. Geowiss. Abh. 60:5-27.

Hahn, G. 1988. Die Ohr-region der Paulcholffattiidae (Multituberculata, Ober-Jura) Palaeovertebrata (Montpellier) 17:155-196.

Hahn, G. 1993. The systematic arrangement of the Paulchoffatiidae (Multituberculata) revisited. Geologica et Palaeontologica 27:201-214.

Hahn, G., Sigogneau-Russell, D. &Wouters, G. 1989. New data on Theroteinidae - their relations with Paulchoffatiidae and Haramiyidae. Geologica et Palaeontologica 23:205-215.

Hopson, J. A. 1964. The braincase of the advanced mammal-like reptile Bienotherium. Postilla 87:1-30.

Hopson, J. A. 1994. Synapsid evolution and the radiation of non-eutherian mammals. Pp. 190-219. In, Prothero, D. R. and R. M. Schoch (Eds.), Major features of Vertebrate Evolution. Short Courses in Paleontology 7. Nashivlle, Tennessee: Paleontological Society.

Hopson, J. A. and Barghusen, H. R. 1986. An analysis of therapsid relationships. Pp. 83-106. In, N. Hotton, III, P. D. MacLean, J. J. Roth, and E. C. Roth (Eds.), The Ecology and Biology of Mammal-like Reptiles. Smithsonian Institution Press: Washington, D. C.

Hopson, J. A. and A. W. Crompton. 1969. Origin of mammals. Evolutionary Biology 3:15-72.

Hopson, J. A. and Rougier. G. W. 1993. Braincase structure in the oldest known skull of a therian mammal: implications for mammalian systematics and cranial evolution. American Journal of Science 293A:268-299.

Hu, Y.-M., Y.-Q. Wang, Z.-X. Luo and C.-K. Li. 1997. A new symmetrodont mammal from China and its implications for mammalian evolution. Nature 390:137-142.

Hu, Y.-M., Y.-Q. Wang, C.-K. Li, and Z.-Z. Luo. 1998. Morphology of dentition and forelimb of Zhangheotherium. Vertebrata PalAsiatica 36: 102-125.

Hurum, J. H. 1998a. The braincase of two Late Cretaceous Asian multituberculates studied by serial sections. Acta Paleontologica Polonica 43:21-52.

Hurum, J. H. 1998b. The inner ear of two Late Cretaceous multituberculate mammals, and its implications for multituberculate hearing. Journal of Mammalian Evolution 5:65-93.

Jenkins, F. A. Jr. 1969. Occlusion in *Docodon* (Mammalia, Docodonta). Postilla 139: 1-24.

Jenkins, F.A. Jr., 1984. A survey of mammalian origins. In P.D. Gingerich and C.E. Badgley (Eds.) Mammals: Notes for a Short Course, University of Tennessee Department of Geological Sciences, Studies in Geology 8:32-47.

Jenkins, F. A. Jr. and Crompton, A. W. 1979. Triconodonta. Pp. 74-90. In, Lillegraven, J. A., Kielan-Jaworowska, Z. and Clemens, W. A. (Eds.), Mesozoic Mammals: The First Two-thirds of Mammalian History. Berkeley: University of California Press.

Jenkins, F. A. Jr., A. W. Crompton, and W. R. Downs, 1983. Mesozoic mammals from Arizona: new evidence on mammalian evolution. Science, 222: 1233-1235.

Jenkins, F. A. Jr. & Schaff, C. R. 1988. The Early Cretaceous mammal *Gobiconodon* (Mammalian, Triconodonta) from the Cloverly Formation in Montana. Journal of Vertebrate Paleontology 6:1-24.

Jenkins, F. A. Jr., Gatesy, S. M., Shubin, N. H. & Amaral, W. W. 1997. Haramiyids and Triassic mammalian evolution. Nature 385:715-718.

Ji, Q., Luo, Z.-X. and Ji, S.-A. 1999. A Chinese triconodont mammal and mosaic evolution of mammalian skeleton. Nature 398:326-330.

Kemp, T. S. 1982. Mammal-like reptiles and origin of mammals. Pp. 1-363. London: Academic Press.

Kemp, T. S. 1983. The interrelationships of mammals. Zoological Journal of the Linnean Society (London) 77:353-384.

Kemp, T. S. 1988. Interrelationships of the Synapsida. Pp. 1-22. In, Benton, M. J. (Ed.), The Phylogeny and Classification of the Tetrapods. Volume 2: Mammals. Systematics Association Special Volumes No. 35B. Oxford, Clarendon Press.

Kermack, D. M., Kermack, K. A. & Mussett, F. 1968. The Welsh pantothere *Kuehneotherium praecursoris*. Journal of the Linnean Society (Zoology) 47:407-423.

Kermack, K. A. 1963. The cranial structure of the triconodontids. Philosophical Transactions of the Royal Society of London 246(B): 83-103.

Kermack, K. A. & Mussett, F. 1983. The ear in mammal-like reptiles and early mammals. Acta Palaeontologica Polonica 28, 147-158.

Kermack, K. A., Mussett, F., and Rigney, H. W. 1973. The lower jaw of Morganucodon. Zoological Journal of Linnean Society (London) 53:87-175.

Kermack, K. A., Mussett, F., and Rigney, H. W. 1981. The skull of Morganucodon. Zoological Journal of Linnean Society (London) 71:1-158.

Kielan-Jaworowska, Z. 1981. Evolution of the therian mammals in the Late Cretaceous of Asia. Part IV. Skull structure in Kennalestes and Asioryctes. Palaeontologia Polonica 42:25-78.

Kielan-Jaworowska, Z. 1984. Evolution of the therian mammals in the Late Cretaceous of Asia. Part VI. Endocranial casts of eutherian mammals. Palaeontologia Polonica 46:157-171.

Kielan-Jaworowska, Z. 1996. Characters of multituberculates neglected in phylogenetic analyses of early mammals. Lethaia 29:249-266.

Kielan-Jaworowska, Z., Cifelli, R. L. and Luo, Z. 1998. Alleged Cretaceous placental mammal from down under. Lethaia 31: 267-268.

Kielan-Jaworowska, Z., Crompton, A. W., and Jenkins, F. A., Jr. 1987. The origin of egg-laying mammals. Nature 326:871-873.

Kielan-Jaworowska, Z. and Dashzeveg, D. 1989. Eutherian mammals from the Early Cretaceous of Mongolia. Zoologica Scripta 18:347-355.

Kielan-Jaworowska, Z. and Dashzeveg, D. 1998.

Kielan-Jaworowska, Z. and Gambaryan, P. P. 1994. Postcranial anatomy and habits of Asian multituberculate mammals. Fossils and Strata 36:1-92.

Kielan-Jaworowska, Z. and Hurum, J. H. 1997. Djadochtatheria - a new suborder of multituberculate mammals. Acta Palaeontologica Polonica 42:201-242.

Kielan-Jaworowska, Z., Presley, R., and Poplin, C. 1986. The cranial vascular system in taeniolabidoid multituberculate mammals. Philosophical Transactions of the Royal Society of London 313B:525-602.

Krause, D. W. 1982. Jaw movement, dental function, and diet in the Paleocene multituberculate Ptilodus. Paleobiology 8:265-281.

Krusat, G. 1980. Contribuição para o conhecimento da Fauna do Kimeridgiano da Mina de Lignito Guimarota (Leira, Portugal). IV. Parte -- Haldanodon exspectatus Kühne & Krusat 1972 (Mammalia, Docodonta). Memórias dos Serviços Geolócos de Portugal 27:1-79.

Kuhn, H.-J. 1971. Die Entwicklung und Morphologie des Schädels von Tachyglossus aculeatus. Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft, Frankfurt am Main 528:1-224.

Kühne, W, G. 1956. The Liassic therapsid Oligokyphus. Pp. 149. London: British Museum (Natural History).

Lee, D-C. and Bryant, H. N. 1999. A reconsideration of the coding of inapplicable characters: assumptions and problems. Cladistics 15: 373-378.

Lillegraven, J. A., and Hahn, G. 1993. Evolutionary analysis of the middle and inner ear of Late Jurassic multituberculates. Journal of Mammalian Evolution **1**: 47-74.

Lillegraven, J. A. and Krusat, G. 1991. Cranio-mandibular anatomy of Haldanodon exspectatus (Docodonta; Mammalia) from the Late Jurassic of Portugal and its implications to the evolution of mammalian characters. Contributions to Geology, University of Wyoming 28:39-138.

Lucas, S. G. and Luo, Z.-X. 1993. Adelobasileus from the Upper Triassic of West Texas: The Oldest Mammal. Journal of Vertebrate Paleontology 13: 309-334.

Luo, Z.-X. 1989. The petrosal structures of Multituberculata (Mammalia) and the molar morphology of the early arctocyonids (Condylarthra: Mammalia). Ph.D. Dissertation, Department of Paleontology, University of California at Berkeley 422 Pp.

Luo, Z.-X. 1994. Sister taxon relationships of mammals and the transformations of the diagnostic mammalian characters. Pp. 98-128. In, Fraser, N. C. and H.-D. Sues (Eds.), In the Shadow of Dinosaurs--Early Mesozoic Tetrapods. Cambridge: Cambridge University Press.

Luo, Z.-X. 2000. Inner ear and its bony housing in tritylodonts and implications for evolution of mammalian ear. Pp. 621-637. In: F. A. Jenkins et al. (eds.), Symposium Proceedings in Honor of Professor A. W. Crompton. Bulletin of Museum of Comparative Zoology, Harvard University 155:621-637.

Luo, Z.-X., Cifelli, R. L., and Kielan-Jaworowska, Z. 2001. Dural origin of tribosphenic mammals. Nature 409:53-57.

Luo, Z.-X. and Crompton, A. W. 1994. Transformations of the quadrate (incus) through the transition from non-mammalian cynodonts to mammals. Journal of Vertebrate Paleontology 14:341-374.

Luo, Z.-X., Crompton, A. W., and Lucas, S. G. 1995. Evolutionary origins of the mammalian promontorium and cochlea. Journal of Vertebrate Paleontology 15:113-121.

Luo, Z.-X. and Gingerich, P. D. 1999. Transition from terrestrial ungulates to aquatic whales: transformation of the basicranium and evolution of hearing. Papers on Paleontology 31: 1-98. Monographic Series of Museum of Paleontology, University of Michigan, Ann Arbor, Michigan.

Luo, Z.-X. and X.-C. Wu. 1994. The small vertebrate fauna of the Lower Lufeng Formation, Yunnan; pp.251-270 in N. C. Fraser & H.-D. Sues (eds.), In the Shadow of Dinosaurs--Early Mesozoic Tetrapods. Cambridge University Press, Cambridge and New York.

Luo, Z.-X. and X.-C. Wu. 1995. Correlation of Vertebrate Assemblage of the Lower Lufeng Formation, Yunnan, China; pp. 83-88 in A. Sun & Y. Wang (eds.), Sixth Symposium on Mesozoic Terrestrial Ecosystems and Biotas, Short Papers. China Ocean Press, Beijing, China.

McKenna, M. C., Kielan-Jaworowska, Z. and Meng, J. 2000. Earliest eutherian mammal skull, from the Late Cretaceous (Coniacian) of Uzbekistan. Acta Palaeontologica Polonica 45:1-54.

Meng, J. and Wyss, A. 1995. Monotreme affinities and low-frequency hearing suggested by multituberculate ear. Nature 377:141-144.

Meng, J. and Fox, R.C. 1995. Osseous inner ear structures and hearing in early marsupials and placentals. Zoological Journal of Linnen Society (London) 115:47-71.

Messer, M., A. S. Weiss, D. C. Shaw, and M. Westerman. 1998. Evolution of the monotremes: phylogenetic relationship to marsupials and eutherians, and estimation of divergence dates based on ∂-lactalbumin amino acid sequences. Journal of Mammalian Evolution 5:95-105.

Miao, D. 1988, Skull morphology of Lambdopsalis bulla (Mammalia. Multituberculata) and its phylogenetic implications to mammalian evolution. Contributions of Geology, University of Wyoming, Special Paper 4:1-104.

Mills, J. R. E. 1971. The dentition of *Morganucodon*. *In*: Kermack, D. M. & Kermack, K. A. (eds.), Early Mammals. Zoological Journal of the Linnean Society, Supplement 1 to volume 50:29-63.

Muizon, C. de. 1994. A new carnivorous marsupial from the Paleocene of Bolivia and the problem of marsupial monophyly. Nature 370:208-211.

Muizon, C. de., 1998. Mayulestes ferox, a borhyaenoid (Metatheria, Mammalia) from the early Palaeocene of Bolivia. Phylogenetic and palaeobiological implications. Geodiversitas 20:19-142.

Muizon, C. de., Cifelli, R. L., and Céspedes Paz, R. 1997. The origin of the dog-like borhyaenoid marsupials of South America. Nature 389:486-489.

Musser, A. M. and Archer, M. 1998. New information about the skull and dentary of the Miocene platypus Obdurodon dicksoni, and a discussion of ornithorhynchid relationships. Philosophical Transactions of the Royal Society of London, Biological Sciences 353(B): 1063-1079.

Novacek, M. J. 1986. The skull of leptictid insectivorans and the higher-level classification of eutherian mammals. Bulletin, American Museum of Natural History 183:1-112.

Patterson, B. 1956. Early Cretaceous mammals and evolution of mammalian molar teeth. Fieldiana (Geology) 13:1-105.

Parrington, F. R. 1973. The dentition of the earliest mammals. Zoological Journal of the Linnean Society (London) 52: 85-95.

Parrington, F. R. 1978. A further account of the Triassic mammals. Philosophical Transactions of the Royal Society of London. 282(B):177-204.

Patterson, B. and Olson, E. C. 1961. A triconodontid mammal from the Triassic of Yunnan. International Colloquium in the evolution of lower and non-specialized mammals. 129-191. Brussels: Koninklijke Vlaamse Academiie voor Wetenschapen, Letteren en Schone Kunsten van Belgie.

Prothero, D. R. 1981. New Jurassic mammals from Como Bluff, Wyoming, and the interrelationships of non-tribosphenic Theria. Bulletin of American Museum of Natural History 167:277-326.

Retief, J. D., Winkfein, R. J., & Dixon, G. H. 1993. Evolution of the monotremes: the sequences of the protamine P1 genes of platypus and echidna. European Journal of Biochemistry 218:457-461.

Rigney, H.W. 1963. A specimen of Morganucodon from Yunnan. Nature 197:1122-1123.

Romer, A.S. 1970. The Chanares (Argentina) Triassic reptile fauna. VI. A chiniquodontid cynodont with an incipient squamosal-dentary jaw articulation. Breviora. 344: 1-18.

Rougier, G. W. 1993. Vincelestes neuquenianus Bonaparte (Mammalia, Theria), un primitivo mammifero del Cretacico Inferior de la Cuenca Neuqina. Pp. 720. Ph.D. Thesis, Buenos Aires: Universidad Nacional de Buenos Aires. Facultad de Ciencias Exactas y Naturales.

Rougier, G. W., Wible, J. R., and Hopson, J. A. 1992. Reconstruction of the cranial vessels in the Early Cretaceous mammal Vincelestes neuquenianus: implications for the evolution of the mammalian cranial vascular system. Journal of Vertebrate Paleontology 12:188-216.

Rougier, G. W., Wible, J. R., and Hopson, J. A. 1996a. Basicranial anatomy of Priacodon fruitaensis (Triconodontidae, Mammalia) from the Late Jurassic of Colorado, and a reappraisal of mammaliaform interrelationships. American Museum Novitates 3183:1-28.

Rougier, G. W., Wible, J. R., and Novacek, M. J. 1996b. Middle-ear ossicles of the multituberculate Kryptobaatar from the Mongolian Late Cretaceous: Implications for mammaliamorph relationships and the evolution of the auditory apparatus. American Museum Novitates 2187:1-43.

Rougier, G. W., Wible, J. R., and Novacek , M. J. 1998. Implications of Deltatheridium specimens for early marsupial history. Nature 396:459-463.

Rowe, T. 1986. Osteological diagnosis of Mammalia. L. 1758, and its relationship to extinct Synapsida. Pp. 446. Ph.D. Dissertation, University of California at Berkeley..

Rowe, T. 1988. Definition, diagnosis, and origin of Mammalia. Journal of Vertebrate Paleontology 8:241-264.

Rowe, T. 1993. Phylogenetic systematics and the early history of mammals. Pp. 129-145. In, F. S. Szalay, M. J. Novacek, and M. C. McKenna (Eds.), Mammal Phylogeny. Volume 1. New York: Springer-Verlag.

Sereno, P. and McKenna, M. C. 1995. Cretaceous multituberculate skeleton and the early evolution of the mammalian shoulder girdle. Nature 377:144-147.

Sidor, C. A. and J. A. Hopson. 1998. Ghost lineages and "mammalness": assessing the temporal pattern of character acquisition in the Synapsida. Paleobiology 24:254-273.

Sigogneau-Russell, D. 1989. Haramiyidae (Mammalia, Allotheria) en provenance du Trias superieur de Lorraine (France). *Palaeontographica A*, **206**, 137-198.

Sigogneau-Russell, D. & Hahn, G. 1994. Late Triassic microvertebrates from central Europe. *In*: N. C. Fraser & Sues, H.-D. (eds.), *In the Shadow of the Dinosaurs*, 197-213. Cambridge University Press, Cambridge.

Sigogneau-Russell, D. & Hahn, R. 1995. Reassement of the lat Triassic symmetrodont mammal Woutersia. Acta Palaeontological Polonica. 40:245-260.

Simpson, G. G. 1928. A catalogue of the Mesozoic Mammalia in the Geological Department of the British Museum. Pp. 1-215. London, Oxford University Press.

Simpson, G. G. 1929. The dentition of Ornithorhynchus as evidence of its affinities. American Museum Novitates 390:1-15.

Strong, E. E. and D. Lipscomb. 1999. Character coding and inapplicable data. Cladistics 15: 363-371.

Sues, H.-D. 1983. Advanced mammal-like reptiles from the Early Jurassic of Arizona. Ph. D. Dissertation, Harvard University. 1-247, pp.

Sues, H.-D. 1985. The relationships of the Tritylodontidae (Synapsida). Zoological Journal of the Linnean Society (London) 85: 205-217.

Sues, H.-D. 1986a. Relationships and biostratigraphic significance of the Tritylodontidae (Synapsida) from the Kayenta Formation of northeastern Arizona; pp.279-284 in K. Padian (ed.), The Beginning of the Age of Dinosaurs. Cambridge University Press, New York.

Sues, H.-D. 1986b. Dinnebitodon amarali, a new tritylodontid (Synapsida) from the lower Jurassic of Western North America. Journal of Paleontology 60:758-762.

Sues, H.-D. 1986c. The skull and dentition of two tritylodontid synapsids from the Lower Jurassic of Western North America. Bulletin of the Museum of Comparative Zoology, Harvard University 151: 217-268.

Sun, A. L., 1984. Skull morphology of the tritylodont genus Bienotheroides of Sichuan. Scientia Sinica (Series B), 27: 270-284.

Sun, A.-L., G.-H. Cui, Y.-H. Li, and X.-C. Wu. 1985. A verified list of Lufeng Saurischian Fauna. Vert. PalAs 22:1-12.

Sun, A. L. and G. Cui. 1986. A brief introduction to the Lower Lufeng saurischian fauna (Lower Jurassic: Lufeng, Yunnan, People's Republic of China); pp. 275-278 in. K. Padian, (ed.), The Beginning of the Age of Dinosaurs--Faunal Change across the Triassic-Jurassic Boundary.

Cambridge University Press, London and New York.

Szalay, F. S. and Trofimov, B. A. 1996. The Mongolian Late Cretaceous Asiatherium, and the early phylogeny and paleobiogeography of Metatheria. Journal of Vertebrate Paleontology 16:474-509.

Wall, C. E. and Krause, D. W. 1992. A biomechanical analysis of the masticatory apparatus of Ptilodus (Multituberculata). Journal of Vertebrate Paleontology 12:172-187.

Wible, J. R. 1987. The eutherian stapedial artery: character analysis and implications for superordinal relationships. Zoological Journal of Linnean Society (London) 91:107-135.

Wible, J. R. 1990. Petrosals of late Cretaceous marsupials from North America and a cladistic analysis of the petrosal in therian mammals. Journal of Vertebrate Paleontology 10:183-205.

Wible, J. R. 1991. Origin of Mammalia: the craniodental evidence reexamined. Journal of Vertebrate Paleontology 11:1-28.

Wible, J. R. and Hopson, J. A. 1993. Basicranial evidence for early mammal phylogeny. Pp. 45-62. In, F. S. Szalay, M. J. Novacek, and M. C. McKenna (Eds.), Mammal Phylogeny. Volume 1. New York: Springer Verlag.

Wible, J. R. and Hopson, J. A. 1995. Homologies of the prootic canal in mammals and non-mammalian cynodonts. Journal of Vertebrate Paleontology 15:331-356.

Wible, J. R. and Rougier, G. W. 2000. Cranial anatomy of Kryptobaatar dashzevegi (Mammalia, Multituberculata), and its bearing on the evolution of mammalian characters. Bulletin of American Museum of Natural History 247:1-124.

Wible, J.R., Rougier, G.W., Novacek, M.J., and McKenna, M.C. in press. Earliest eutherian ear region: a petrosal of Prokennalestes from the Early Cretaceous of Mongolia. American Museum Novitates.

Wible, J. R., Rougier, G. W., Novacek, M. J., McKenna, M. C., and Dashzeveg, D. 1995. A mammalian petrosal from the Early Cretaceous of Mongolia: implications for the evolution of the ear region and mammalimorph interrelationships. American Museum Novitates 3149:1-19.

Woodburne, M. O. and Tedford, R. H. 1975. The first Tertiary monotreme from Australia. American Museum Novitates 2588:1-11.

Young, C. C. 1982. Selected Works of Yang Zhongjian (Young Chung-Chien). Science Press, Beijing, China.

Zeller, U. 1989. Die Entwicklung und Morphologie des Schädels von Ornithorhynchus anatinus (Mammalia: Prototheria: Monotremata), Abhandlungen der Senchenbergischen Naturforschenden Gesellschaft, Frankfurt am Main 545:1-188.

Zeller, U. 1993. Ontogenetic evidence for cranial homologies in monotremes and therians, with special reference to Ornithorhynchus. Pp. 95-107. In, F. S. Szalay, M. J. Novacek, and M. C. McKenna (Eds.), Mammal Phylogeny, Volume 1. New York: Springer-Verlag.

Zeller, U. 1999a. Mammalian reproduction: origin and evolutionary transformations. Zoologischer Anzeiger 238:117-130.

Zeller, U. 1999b. Phylogeny and systematic relations of the Monotremata: why we need an integrative approach. Courier Forschungsinstitut Senckenberg 215:227-232.

Zhang, F-K, Crompton, A. W., Luo, Z.-X., and Schaff, C. R. 1998. Pattern of dental replacement of Sinoconodon and its implications for evolution of mammals. Vertebrata PalAsiatica 36: 197-217.

Part IX. PAUP(4*) Search Results

```
Search #1 P A U P *
Version 4.0b5 for Macintosh
Friday, February 23, 2001  1:32 PM

This copy registered to: Zhe-Xi Luo
                         Carnegie Museum of Natural History

Processing of file "Luomatrix2.doc" begins...

Data matrix has 15 taxa, 90 characters
Valid character-state symbols: abcdefghij
Missing data identified by '?'
Gaps identified by '-'

1 tree read from TREES block
   Time used = 0.00 sec

1 tree converted from rooted to unrooted.

*** Skipping "MACCLADE" block

Processing of file "Luomatrix2.doc" completed.

Input data matrix:

                           111111111122222222223333333333444444444455555555556666666666777
Taxon/Node        123456789012345678901234567890123456789012345678901234567890123456789012
------------------------------------------------------------------------------------------
Probainognathus   aaaa??aa??aaabaaaaaaaaaabbacabaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa?a
Tritylodontids    aaaa??aaa?baaaaaaaaabbaaaaaaababaaaabaaabaaaaaaaaaaaaaaaabaaaaaaaaaaaa?a
                                                            b
Tritheledontids   aaaa??aba?aaaaaaaaaaaaaabaaabaaabaaabaabbaaaaaaaaabaaaabaaaaaaaaaaaaaa?a
Adelobasileus     b???????ba??abbaaaaaaaabbccaaaaabaaabbb??a?b??bbbbaa????????????????????
Sinoconodon       aaaaaaacbabaabbbaaaabaaaaaaaababbbbacbbbcabbaaaaaaaabaabaaaaaaaaaaaaabba
Morganucodon      aabbabacbbbaabbbbaaacbabbbaaabbbbbbaccbbcabbaabaabbaaabbaabaaaaaaaaaabab
                       c                                                                b
Haldanodon        aabbbcabbabaabbbcaaacba????a?babbbcaccbccbccbab?bbbabaabbabaaaaaaaaaabbc
Hadrocodium       aabababcbd??abbbbaaacbbbbcbaaaabbbbbccbccbccbbbbccbccc?c?abbbbb?baaa?bac
Triconodontids    aabbab?cbcbaabbbcaaacbabbbabbbbcbbcbccbccbcbbbbbbbbbcbabbb???bbbbbbb?ccb
                              b                              c                           c
Ornithorhynchus   aabaabacbccabcbbaaaacbabbcbabbbabbbbccaccbccbbbaccbccc?cbb???bbbbbcbbcbc
Multituberculate  aabbabacbbbabbbbdaaacbbbbcbbbaacaacbccbacabcbbbcbcbbcc?bbb???bbabbcbbccb
                        b      c   b b         bb bb        c     c  c           b
Zhangheotherium   ??bbbcbcbcb?bbb??bbbcab??ccabaacb???ccb?c????a??????cbacbb???bbaabba?ccc
Vinceleстes       bbbabcbbbddbabbbcbbbcabbbcbbaabcbccbccbbcabbbabcaabbcbabbaabbbbabbbb?cbc
                                              b
Metatherians      bbbbbcbcbddbabcbabbbcabc??d?baacbcdbccbccbbbaab?aabbcc?bbaacbbbbbbcabbbc
                              b   d                          cb      c      b        b
Eutherians        bbbabcbcbddbaacbabbbcabc??bbbaacbcdbccbbcbbbaabcaabbcbbbbaacbbbabbaabbbc
                     b        bb  d         c            c   cb      c c    b    b  bb

Input data matrix (continued):

                  777777788888888889
Taxon/Node        345678901234567890
------------------------------------
Probainognathus   aaaaaaaaaa?aaaa?aa
Tritylodontids    bbbccbacdcca?aa?dc
Tritheledontids   aaaaaaaaaa?aaaa?aa
Adelobasileus     ????aa?c??????????
Sinoconodon       acaaaaacaa?aaaa?bb
                      b
Morganucodon      acbababab baaaaa?cb
Haldanodon        acbababbbbaaaaa?ca
Hadrocodium       ac?abab?cbaaaaa??b
Triconodontids    acbabababbaaaaa?ca
                     b
Ornithorhynchus   aa?cccab???b?????c
                   b
Multituberculate  bbbbbbacdcca?aa?cb
                     c             c
```

```
Zhangheotherium   adbbbcaaccbbbaaaca
Vincelestes       ad?abcacccbbbaba?a
Metatherians      adbabcacccbbbbbbca
Eutherians        adbabcacccbbbbbbca

Branch-and-bound search settings:
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        All characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Initial upper bound: unknown (compute heuristically)
  Addition sequence: furthest
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
  Trees are unrooted

Branch-and-bound search completed:
   Score of best tree found = 288
   Number of trees retained = 9
   Time used = 6.70 sec

Strict consensus of 9 trees:

/------------------------------------------------------------------------- Probainognathus
+------------------------------------------------------------------------- Tritylodontids
+------------------------------------------------------------------------- Tritheledontids
|       /----------------------------------------------------------------- Adelobasileus
|       +----------------------------------------------------------------- Sinoconodon
\-------+       /--------------------------------------------------------- Morganucodon
        |       |       /------------------------------------------------- Haldanodon
        \-------+       |       /----------------------------------------- Hadrocodium
                \-------+       |       /--------------------------------- Triconodontids
                        \-------+       +--------------------------------- Ornithorhynchus
                                \-------+--------------------------------- Multituberculate
                                        |       /------------------------- Zhangheotherium
                                        \-------+       /----------------- Vincelestes
                                                \-------+       /--------- Metatherians
                                                        \-------+--------- Eutherians

Lengths and fit measures of trees in memory:
  Character-status summary:
    Of 90 total characters:
      All characters are of type 'unord'
      All characters have equal weight
      All characters are parsimony-informative
  Gaps are treated as "missing"
  Multistate taxa interpreted as polymorphism ("min" values for CI, RI, and RC are
    minimum-possible character lengths)

   Sum of min. possible lengths = 185
   Sum of max. possible lengths = 502

Tree #      1     2     3     4     5     6     7     8     9
Length    288   288   288   288   288   288   288   288   288
CI      0.642 0.642 0.642 0.642 0.642 0.642 0.642 0.642 0.642
RI      0.675 0.675 0.675 0.675 0.675 0.675 0.675 0.675 0.675
RC      0.434 0.434 0.434 0.434 0.434 0.434 0.434 0.434 0.434


Tree number 1 (rooted using default outgroup)

/------------------------------------------------------------------------- Probainognathus
+------------------------------------------------------------------------- Tritheledontids
|     /------------------------------------------------------------------- Tritylodontids
\-----+    /-------------------------------------------------------------- Adelobasileus
      \----+     /-------------------------------------------------------- Sinoconodon
```

```
           \-----+    /-------------------------------------------------- Morganucodon
                 \----+     /-------------------------------------------- Haldanodon
                      \-----+    /--------------------------------------- Hadrocodium
                            \----+     /--------------------------------- Ornithorhynchus
                                 \-----+    /---------------------------- Multituberculate
                                       \----+     /---------------------- Triconodontids
                                            \-----+    /----------------- Zhangheotherium
                                                  \----+     /----------- Vincelestes
                                                       \-----+    /------ Metatherians
                                                             \----+------ Eutherians
```

Tree number 2 (rooted using default outgroup)

```
/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritylodontids
|     /------------------------------------------------------------------ Tritheledontids
\-----+    /------------------------------------------------------------- Adelobasileus
      \----+     /------------------------------------------------------- Sinoconodon
           \-----+    /-------------------------------------------------- Morganucodon
                 \----+     /-------------------------------------------- Haldanodon
                      \-----+    /--------------------------------------- Hadrocodium
                            \----+     /--------------------------------- Ornithorhynchus
                                 \-----+    /---------------------------- Multituberculate
                                       \----+     /---------------------- Triconodontids
                                            \-----+    /----------------- Zhangheotherium
                                                  \----+     /----------- Vincelestes
                                                       \-----+    /------ Metatherians
                                                             \----+------ Eutherians
```

Tree number 3 (rooted using default outgroup)

```
/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritheledontids
|     /------------------------------------------------------------------ Tritylodontids
\-----+    /------------------------------------------------------------- Sinoconodon
      \----+     /------------------------------------------------------- Adelobasileus
           \-----+    /-------------------------------------------------- Morganucodon
                 \----+     /-------------------------------------------- Haldanodon
                      \-----+    /--------------------------------------- Hadrocodium
                            \----+     /--------------------------------- Ornithorhynchus
                                 \-----+    /---------------------------- Multituberculate
                                       \----+     /---------------------- Triconodontids
                                            \-----+    /----------------- Zhangheotherium
                                                  \----+     /----------- Vincelestes
                                                       \-----+    /------ Metatherians
                                                             \----+------ Eutherians
```

Tree number 4 (rooted using default outgroup)

```
/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritheledontids
|      /----------------------------------------------------------------- Tritylodontids
|      |     /----------------------------------------------------------- Adelobasileus
\------+     |      /---------------------------------------------------- Sinoconodon
       \-----+      |     /---------------------------------------------- Morganucodon
             \------+     |      /--------------------------------------- Haldanodon
                    \-----+      |     /--------------------------------- Hadrocodium
                          \------+     |                   /------------- Triconodontids
                                 \-----+      /------------+     /------- Ornithorhynchus
                                       |      |            \-----+------- Multituberculate
                                       \------+     /-------------------- Zhangheotherium
                                              \-----+      /------------- Vincelestes
                                                    \------+     /------- Metatherians
                                                           \-----+------- Eutherians
```

Tree number 5 (rooted using default outgroup)

```
/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritylodontids
|      /----------------------------------------------------------------- Tritheledontids
|      |     /----------------------------------------------------------- Adelobasileus
\------+     |      /---------------------------------------------------- Sinoconodon
```

```
       \-----+      |     /---------------------------------------------- Morganucodon
             \------+     |      /--------------------------------------- Haldanodon
                    \-----+      |     /--------------------------------- Hadrocodium
                          \------+     |                   /------------- Triconodontids
                                 \-----+      /------------+     /------- Ornithorhynchus
                                       |      |            \-----+------- Multituberculate
                                       \------+     /-------------------- Zhangheotherium
                                              \-----+      /------------- Vincelestes
                                                    \------+     /------- Metatherians
                                                           \-----+------- Eutherians
```

Tree number 6 (rooted using default outgroup)

```
/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritheledontids
|      /----------------------------------------------------------------- Tritylodontids
|      |     /----------------------------------------------------------- Sinoconodon
\------+     |      /---------------------------------------------------- Adelobasileus
       \-----+      |     /---------------------------------------------- Morganucodon
             \------+     |      /--------------------------------------- Haldanodon
                    \-----+      |     /--------------------------------- Hadrocodium
                          \------+     |                   /------------- Triconodontids
                                 \-----+      /------------+     /------- Ornithorhynchus
                                       |      |            \-----+------- Multituberculate
                                       \------+     /-------------------- Zhangheotherium
                                              \-----+      /------------- Vincelestes
                                                    \------+     /------- Metatherians
                                                           \-----+------- Eutherians
```

Tree number 7 (rooted using default outgroup)

```
/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritheledontids
|     /------------------------------------------------------------------ Tritylodontids
|     |     /------------------------------------------------------------ Adelobasileus
\-----+     |     /------------------------------------------------------ Sinoconodon
      \-----+     |     /------------------------------------------------ Morganucodon
            \-----+     |     /------------------------------------------ Haldanodon
                  \-----+     |     /------------------------------------ Hadrocodium
                        \-----+     |     /------------------------------ Triconodontids
                              \-----+     |                       /------ Ornithorhynchus
                                    \-----+     /-----------------+------ Multituberculate
                                          \-----+     /------------------ Zhangheotherium
                                                \-----+     /------------ Vincelestes
                                                      \-----+     /------ Metatherians
                                                            \-----+------ Eutherians
```

Tree number 8 (rooted using default outgroup)

```
/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritylodontids
|     /------------------------------------------------------------------ Tritheledontids
|     |     /------------------------------------------------------------ Adelobasileus
\-----+     |     /------------------------------------------------------ Sinoconodon
      \-----+     |     /------------------------------------------------ Morganucodon
            \-----+     |     /------------------------------------------ Haldanodon
                  \-----+     |     /------------------------------------ Hadrocodium
                        \-----+     |     /------------------------------ Triconodontids
                              \-----+     |                       /------ Ornithorhynchus
                                    \-----+     /-----------------+------ Multituberculate
                                          \-----+     /------------------ Zhangheotherium
                                                \-----+     /------------ Vincelestes
                                                      \-----+     /------ Metatherians
                                                            \-----+------ Eutherians
```

Tree number 9 (rooted using default outgroup)

```
/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritheledontids
|     /------------------------------------------------------------------ Tritylodontids
|     |     /------------------------------------------------------------ Sinoconodon
\-----+     |     /------------------------------------------------------ Adelobasileus
```

```
      \-----+     |     /------------------------------------------------ Morganucodon
            \-----+     |     /------------------------------------------ Haldanodon
                  \-----+     |     /------------------------------------ Hadrocodium
                        \-----+     |     /------------------------------ Triconodontids
                              \-----+     |                       /------ Ornithorhynchus
                                    \-----+     /-----------------+------ Multituberculate
                                          \-----+     /------------------ Zhangheotherium
                                                \-----+     /------------ Vincelestes
                                                      \-----+     /------ Metatherians
                                                            \-----+------ Eutherians

Bootstrap method with heuristic search:
  Number of bootstrap replicates = 100
  Starting seed = 788115465
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        All characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Starting tree(s) obtained via stepwise addition
  Addition sequence: simple (reference taxon = Probainognathus)
  Number of trees held at each step during stepwise addition = 1
  Branch-swapping algorithm: tree-bisection-reconnection (TBR)
  Steepest descent option not in effect
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
  Trees are unrooted

   100 bootstrap replicates completed
   Time used = 1.50 sec

Bootstrap 50% majority-rule consensus tree

/-------------------------------------------------------------------- Probainognathus(1)
+-------------------------------------------------------------------- Tritylodontids(2)
+-------------------------------------------------------------------- Tritheledontids(3)
|      /------------------------------------------------------------- Adelobasileus(4)
|      |      /------------------------------------------------------ Sinoconodon(5)
\--81--+      |     /------------------------------------------------ Morganucodon(6)
       \--58--+     |      /----------------------------------------- Haldanodon(7)
              \-88--+      |      /---------------------------------- Hadrocodium(8)
                    \--87--+      |      /--------------------------- Triconodontids(9)
                           \--85--+      |                   /------- Ornithorhynchus(10)
                                  \--55--+--------57---------+------- Multituberculate(11)
                                         |      /-------------------- Zhangheotherium(12)
                                         \--90--+     /-------------- Vincelestes(13)
                                                \-79--+      /------- Metatherians(14)
                                                      \-100--+------- Eutherians(15)

Bipartitions found in one or more trees and frequency of occurrence (bootstrap support
values):

         1    1
123456789012345      Freq
-------------------------
.............**    100.00
...........****     89.75
.....**********     88.08
......*********     87.06
.......********     85.07
...************     81.25
............***     78.79
....***********     57.94
.........**....     57.50
........*******     54.55
.*.************     49.83
...*.**********     39.81
```

```
........***....     34.25
..*************     31.67
.........******     29.98
.......*.******     23.78
.......*...****     18.88
...........**..     18.87
........*.*****     18.28
.*..***********     17.33
........*..****     12.98
...*..*********     11.92
.**.***********     10.33
......*.*******      9.62
..........*****      9.04
.**............      8.17
........*.*....      7.50
.........*.****      6.41
.......*.*.....      5.56
........****...      5.50
.....**........      5.00

30 groups at (relative) frequency less than 5% not shown

Jackknife method with heuristic search:
  Number of jackknife replicates = 100
  Nominal percentage of characters deleted in each replicate = 50
  Starting seed = 1188326570
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        All characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Starting tree(s) obtained via stepwise addition
  Addition sequence: simple (reference taxon = Probainognathus)
  Number of trees held at each step during stepwise addition = 1
  Branch-swapping algorithm: tree-bisection-reconnection (TBR)
  Steepest descent option not in effect
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
  Trees are unrooted

   Note: 45 characters are deleted in each replicate; actual deletion percentage = 50.000

   100 jackknife replicates completed
   Time used = 2.68 sec

Jackknife 50% majority-rule consensus tree

/-------------------------------------------------------------------- Probainognathus(1)
+-------------------------------------------------------------------- Tritylodontids(2)
+-------------------------------------------------------------------- Tritheledontids(3)
|      /------------------------------------------------------------- Adelobasileus(4)
|      |      /------------------------------------------------------ Sinoconodon(5)
\--75--+      |     /------------------------------------------------ Morganucodon(6)
       \--69--+     |      /----------------------------------------- Haldanodon(7)
              \-91--+      |      /---------------------------------- Hadrocodium(8)
                    \--92--+      |      /--------------------------- Triconodontids(9)
                           \--86--+      |                   /------- Ornithorhynchus(10)
                                  \--57--+-------54----------+------- Multituberculate(11)
                                         |      /-------------------- Zhangheotherium(12)
                                         \--91--+     /-------------- Vincelestes(13)
                                                \-78--+      /------- Metatherians(14)
                                                      \--99--+------- Eutherians(15)

Bipartitions found in one or more trees and frequency of occurrence (jackknife support
values):

         1    1
```

```
123456789012345      Freq
-------------------------
.............**     98.83
......*********     91.94
.....**********     91.44
...........****     90.80
.......********     85.92
............***     78.40
...************     74.54
....***********     69.29
........*******     56.82
.........**....     54.25
.*.************     45.35
........***....     39.16
...*.**********     30.54
..*************     29.00
.........******     25.21
.*..***********     23.63
...........**..     19.15
........*.*****     19.01
.**.***********     17.23
.......*...****     16.65
.......*.******     15.69
........*..****     12.58
..........*****     12.18
........*.*....     11.40
.**............      9.08
.......****....      8.86
...*..*********      7.36
.......*.*.....      6.42
......*.*******      5.70

43 groups at (relative) frequency less than 5% not shown
```

Search #2
P A U P *
Version 4.0b5 for Macintosh
Friday, February 23, 2001 9:17 PM

This copy registered to: Zhe-Xi Luo
                         Carnegie Museum of Natural History

Processing of file "Luomatrix2.doc" begins...

Data matrix has 15 taxa, 90 characters
Valid character-state symbols: abcdefghij
Missing data identified by '?'
Gaps identified by '-'

1 tree read from TREES block
   Time used = 0.00 sec

1 tree converted from rooted to unrooted.

*** Skipping "MACCLADE" block

Processing of file "Luomatrix2.doc" completed.

Character-status summary:
  Current optimality criterion = maximum parsimony
  No characters are excluded
  Of 90 total characters:
    16 characters are of type 'ord' (Wagner)
    74 characters are of type 'unord'
    All characters have equal weight
    All characters are parsimony-informative

Current status of all characters:

Character	Type	Status	Weight	States
1 (SQ cranial)	Unord	-	1	ab
2 (SQ cranial)	Unord	-	1	ab
3 (Q-pit_in_S)	Unord	-	1	ab
4 (Zygo const)	Unord	-	1	ab
5 (Postglenoi)	Unord	-	1	ab
6 (Glenoid fo)	Ord	-	1	abc
7 (TMJ positi)	Unord	-	1	ab
8 (Zygoma dep)	Ord	-	1	abc
9 (Prom expos)	Unord	-	1	ab
10 (Prom outli)	Ord	-	1	abcd
11 (Cochlea)	Ord	-	1	abcd
12 (2nd bony l)	Unord	-	1	ab
13 (FV orienta)	Unord	-	1	ab
14 (Prootic ca)	Unord	-	1	abc
15 (lt trough)	Ord	-	1	abc
16 (VII-floor)	Unord	-	1	ab
17 (Tensor tym)	Unord	-	1	abcd
18 (Crista int)	Unord	-	1	ab
19 (Post-tym_r)	Unord	-	1	ab
20 (Caud tym p)	Unord	-	1	ab
21 (Crista par)	Unord	-	1	abc
22 (SQ flank t)	Unord	-	1	ab
23 (Epitympani)	Unord	-	1	ab
24 (lt_flange_)	Unord	-	1	abc
25 (lt_flange_)	Unord	-	1	ab
26 (lt fl to c)	Unord	-	1	abc
27 (pt-par_for)	Unord	-	1	abcd
28 (ppf to fv)	Unord	-	1	ab
29 (lt fl fora)	Unord	-	1	ab
30 (paroc bifu)	Unord	-	1	ab
31 (post paroc)	Unord	-	1	ab
32 (stapedial)	Unord	-	1	abc
33 (fc-jf_sepa)	Unord	-	1	ab
34 (peril duct)	Unord	-	1	abc
35 (ca ep open)	Unord	-	1	abcd

```
36 (Q-ramus_of)  Unord          -              1   ab
37 (Bs wing)     Ord            -              1   abc
38 (Bo overlap)  Ord            -              1   abc
39 (XII forame)  Unord          -              1   ab
40 (2nd palate)  Ord            -              1   abc
41 (Mx orbit m)  Unord          -              1   abc
42 (Pterygopal)  Unord          -              1   ab
43 (trn flge h)  Unord          -              1   abc
44 (Bs constri)  Ord            -              1   abc
45 (NOP roof)    Unord          -              1   ab
46 (Jugal)       Unord          -              1   ab
47 (PTC post o)  Unord          -              1   ab
48 (Ascending )  Unord          -              1   abc
49 (Lambdoidal)  Ord            -              1   abc
50 (Sagittal c)  Unord          -              1   abc
51 (Occipital )  Unord          -              1   ab
52 (Parietal e)  Unord          -              1   abc
53 (Postdentar)  Ord            -              1   abc
54 (Meckelian )  Ord            -              1   abc
55 (Meckelian )  Unord          -              1   ab
56 (Mandible s)  Unord          -              1   abc
57 (Dental lam)  Unord          -              1   ab
58 (Angular_pr)  Unord          -              1   ab
59 (Angular pr)  Unord          -              1   ab
60 (position o)  Unord          -              1   abc
61 (Med fossa )  Unord          -              1   ab
62 (Attach pos)  Unord          -              1   ab
63 (Mand. fora)  Unord          -              1   ab
64 (Coronoid)    Unord          -              1   ab
65 (Splenial)    Unord          -              1   ab
66 (Pterygoid )  Unord          -              1   ab
67 (Pterygoid )  Ord            -              1   abc
68 (Masseteric)  Unord          -              1   ab
69 (Prearticul)  Unord          -              1   ab
70 (Den.cond.p)  Ord            -              1   abc
71 (Size_D-con)  Unord          -              1   abc
72 (TMJ to alv)  Unord          -              1   abc
73 (Uni vs. bi)  Unord          -              1   ab
74 (Rotation o)  Unord          -              1   abcd
75 (I/C_Replac)  Unord          -              1   ab
76 (Canine)      Unord          -              1   abc
77 (PC roots)    Ord            -              1   abc
78 (cusp align)  Unord          -              1   abc
79 (PC interlo)  Unord          -              1   ab
80 (Lower PC c)  Unord          -              1   abc
81 (Cusp occlu)  Unord          -              1   abcd
82 (Wear devel)  Ord            -              1   abc
83 (Facets-to-)  Unord          -              1   abc
84 (Stylar she)  Unord          -              1   ab
85 (Protocrist)  Unord          -              1   ab
86 (Upper prot)  Unord          -              1   ab
87 (Lower talo)  Unord          -              1   ab
88 (Talonid we)  Unord          -              1   ab
89 (PC replace)  Unord          -              1   abcd
90 (Anterior d)  Unord          -              1   abc

Branch-and-bound search settings:
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        16 characters are of type 'ord' (Wagner)
        74 characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Initial upper bound: unknown (compute heuristically)
  Addition sequence: furthest
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
```

```
  Trees are unrooted

Branch-and-bound search completed:
   Score of best tree found = 293
   Number of trees retained = 1
   Time used = 2.18 sec

Lengths and fit measures of trees in memory:
  Character-status summary:
    Of 90 total characters:
      16 characters are of type 'ord' (Wagner)
      74 characters are of type 'unord'
      All characters have equal weight
      All characters are parsimony-informative
  Gaps are treated as "missing"
  Multistate taxa interpreted as polymorphism ("min" values for CI, RI, and RC are
    minimum-possible character lengths)

   Sum of min. possible lengths = 185
   Sum of max. possible lengths = 531

Tree #      1
Length    293
CI      0.631
RI      0.688
RC      0.434

Tree description:

  Unrooted tree(s) rooted using outgroup method
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        16 characters are of type 'ord' (Wagner)
        74 characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism ("min" values for CI, RI, and RC are
      minimum-possible character lengths)

    Character-state optimization: Accelerated transformation (ACCTRAN)

Tree number 1 (rooted using default outgroup)

Tree length = 293
Consistency index (CI) = 0.6314
Homoplasy index (HI) = 0.5222
Retention index (RI) = 0.6879
Rescaled consistency index (RC) = 0.4343

/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritylodontids
28    /------------------------------------------------------------------ Tritheledontids
|     |     /------------------------------------------------------------ Adelobasileus
\----27     |     /------------------------------------------------------ Sinoconodon
      \----26     |     /------------------------------------------------ Morganucodon
            \----25     |     /------------------------------------------ Haldanodon
                  \----24     |     /------------------------------------ Hadrocodium
                        \----23     |     /------------------------------ Triconodontids
                              \----22     |                       /------ Ornithorhynchus
                                    \----21     /----------------16------ Multituberculate
                                          \----20     /------------------ Zhangheotherium
                                                \----19     /------------ Vincelestes
                                                      \----18     /------ Metatherians
                                                            \----17------ Eutherians

Apomorphy lists:

               Branch                 Character                     Steps     CI   Change
------------------------------------------------------------------------------------------
         node_28 --> Probainognathus  14 (Prootic canal)                1  0.800  a --> b
```

	24 (lt_flange_(anterior))	1	0.500	a --> b
	27 (pt-par_foramen)	1	0.571	a ==> c
	29 (lt fl foramina)	1	0.500	a --> b
	37 (Bs wing)	1	1.000	b ==> a
	41 (Mx orbit margin)	1	1.000	b ==> a
node_28 --> Tritylodontids	11 (Cochlea)	1	0.600	a --> b
	21 (Crista parotica)	1	0.667	a ==> b
	22 (SQ flank to paro)	1	0.333	a ==> b
	25 (lt_flange_(posterior))	1	0.500	b ==> a
	30 (paroc bifurcation)	1	0.400	a ==> b
	32 (stapedial fossa)	1	0.500	a ==> b
	57 (Dental lamina grv)	1	0.500	a ==> b
	73 (Uni vs. bilat occlus)	1	0.500	a ==> b
	74 (Rotation of mand)	1	0.800	a ==> b
	75 (I/C_Replacement)	1	0.500	a ==> b
	76 (Canine)	1	0.800	a ==> c
	77 (PC roots)	2	0.600	a ==> c
	78 (cusp alignment)	1	0.667	a ==> b
	80 (Lower PC cingulum)	1	0.286	a --> c
	81 (Cusp occlusion)	1	0.600	a ==> d
	82 (Wear development)	2	0.500	a ==> c
	83 (Facets-to-cusps)	1	0.667	a --> c
	89 (PC replacement)	1	1.000	a ==> d
	90 (Anterior diastema)	1	0.500	a ==> c
node_28 --> node_27	8 (Zygoma depth)	1	0.500	a ==> b
	33 (fc-jf_separation)	1	1.000	a ==> b
	40 (2nd palate)	1	0.500	a ==> b
	56 (Mandible symphysis)	1	0.500	a ==> b
node_27 --> Tritheledontids	29 (lt fl foramina)	1	0.500	a --> b
	51 (Occipital condyle)	1	0.500	a ==> b
node_27 --> node_26	8 (Zygoma depth)	1	0.500	b --> c
	9 (Prom exposure)	1	1.000	a ==> b
	11 (Cochlea)	1	0.600	a --> b
	14 (Prootic canal)	1	0.800	a --> b
	15 (lt trough flr)	1	1.000	a ==> b
	24 (lt_flange_(anterior))	1	0.500	a --> b
	26 (lt fl to crista parot)	1	0.500	a --> c
	38 (Bo overlap)	1	1.000	a ==> b
	39 (XII foramen)	1	0.500	a ==> b
	41 (Mx orbit margin)	1	1.000	b --> c
	43 (trn flge hamulus)	1	0.800	a --> b
	44 (Bs constricture)	1	0.833	a ==> b
	47 (PTC post opening)	1	0.500	a --> b
	50 (Sagittal crest)	1	0.400	a --> b
	53 (Postdentary ridge)	1	0.667	a --> b
	70 (Den.cond.peduncle)	1	0.667	a --> b
	74 (Rotation of mand)	1	0.800	a --> c
	80 (Lower PC cingulum)	1	0.286	a --> c
	89 (PC replacement)	1	1.000	a --> b
	90 (Anterior diastema)	1	0.500	a --> b
node_26 --> Adelobasileus	1 (SQ cranial moiety)	1	0.500	a ==> b
	27 (pt-par_foramen)	1	0.571	a ==> c
	48 (Ascending channel)	1	0.500	a ==> b
	49 (Lambdoidal crest)	1	0.500	a ==> b
node_26 --> node_25	16 (VII-floor)	1	1.000	a ==> b
	21 (Crista parotica)	1	0.667	a --> b
	30 (paroc bifurcation)	1	0.400	a ==> b
	32 (stapedial fossa)	1	0.500	a ==> b
	34 (peril duct channel)	1	1.000	a ==> b
	35 (ca ep opening)	1	0.600	a ==> b
	37 (Bs wing)	1	1.000	b ==> c
	77 (PC roots)	1	0.600	a --> b
node_25 --> Sinoconodon	24 (lt_flange_(anterior))	1	0.500	b --> a
	25 (lt_flange_(posterior))	1	0.500	b ==> a
	26 (lt fl to crista parot)	1	0.500	c --> a
	47 (PTC post opening)	1	0.500	b --> a
	50 (Sagittal crest)	1	0.400	b --> a
node_25 --> node_24	3 (Q-pit_in_SQ)	1	1.000	a ==> b
	4 (Zygo constriction)	1	0.400	a ==> b
	6 (Glenoid fossa)	1	0.600	a --> b
	10 (Prom outline)	1	0.500	a --> b
	17 (Tensor tympani)	1	0.625	a --> b

	21 (Crista parotica)	1	0.667	b --> c
	22 (SQ flank to paro)	1	0.333	a ==> b
	38 (Bo overlap)	1	1.000	b ==> c
	51 (Occipital condyle)	1	0.500	a ==> b
	59 (Angular proc. level)	1	0.750	a ==> b
	72 (TMJ to alveolar level)	1	0.750	a --> b
	75 (I/C_Replacement)	1	0.500	a ==> b
	79 (PC interlocking)	1	0.500	a ==> b
	80 (Lower PC cingulum)	1	0.286	c --> a
	81 (Cusp occlusion)	1	0.600	a ==> b
	82 (Wear development)	1	0.500	a ==> b
	89 (PC replacement)	1	1.000	b --> c
node_24 --> Morganucodon	26 (lt fl to crista parot)	1	0.500	c --> b
	31 (post paroc project)	1	0.400	a ==> b
	53 (Postdentary ridge)	1	0.667	b --> a
	55 (Meckelian curve)	1	0.500	a ==> b
node_24 --> node_23	5 (Postglenoid depres)	1	0.333	a --> b
	17 (Tensor tympani)	1	0.625	b --> c
	27 (pt-par_foramen)	1	0.571	a --> b
	35 (ca ep opening)	1	0.600	b --> c
	40 (2nd palate)	1	0.500	b ==> c
	42 (Pterygopal ridges)	1	0.333	a ==> b
	43 (trn flge hamulus)	1	0.800	b ==> c
	44 (Bs constricture)	1	0.833	b ==> c
	45 (NOP roof)	1	1.000	a ==> b
	48 (Ascending channel)	1	0.500	a --> b
	49 (Lambdoidal crest)	1	0.500	a ==> b
	57 (Dental lamina grv)	1	0.500	a ==> b
	72 (TMJ to alveolar level)	1	0.750	b --> c
	90 (Anterior diastema)	1	0.500	b --> a
node_23 --> Haldanodon	6 (Glenoid fossa)	1	0.600	b ==> c
	8 (Zygoma depth)	1	0.500	c ==> b
	10 (Prom outline)	1	0.500	b --> a
	80 (Lower PC cingulum)	1	0.286	a ==> b
node_23 --> node_22	7 (TMJ position)	1	0.667	a --> b
	10 (Prom outline)	1	0.500	b ==> c
	23 (Epitympanic recess)	1	0.333	a --> b
	36 (Q-ramus_of_alisph)	1	1.000	a ==> b
	46 (Jugal)	1	0.500	a ==> b
	50 (Sagittal crest)	1	0.400	b --> c
	52 (Parietal expansion)	1	0.833	a --> b
	53 (Postdentary ridge)	1	0.667	b ==> c
	54 (Meckelian sulcus)	1	0.600	a ==> b
	60 (position of angle)	1	1.000	a ==> b
	61 (Med fossa on angle)	1	1.000	a ==> b
	62 (Attach postdentaries)	1	1.000	a ==> b
	63 (Mand. foramen)	1	1.000	a ==> b
	64 (Coronoid)	1	0.600	a --> b
	65 (Splenial)	1	0.500	a ==> b
	69 (Prearticular)	1	1.000	a --> b
	71 (Size_D-condyle)	1	0.600	b --> a
	81 (Cusp occlusion)	1	0.600	b --> c
node_22 --> Hadrocodium	4 (Zygo constriction)	1	0.400	b ==> a
	6 (Glenoid fossa)	1	0.600	b ==> a
	10 (Prom outline)	1	0.500	c ==> d
	17 (Tensor tympani)	1	0.625	c --> b
	30 (paroc bifurcation)	1	0.400	b ==> a
	35 (ca ep opening)	1	0.600	c --> b
	49 (Lambdoidal crest)	1	0.500	b ==> c
	52 (Parietal expansion)	1	0.833	b --> c
	54 (Meckelian sulcus)	1	0.600	b ==> c
	56 (Mandible symphysis)	1	0.500	b ==> c
	90 (Anterior diastema)	1	0.500	a --> b
node_22 --> node_21	5 (Postglenoid depres)	1	0.333	b --> a
	13 (FV orientation)	1	0.800	a --> b
	28 (ppf to fv)	1	0.333	a --> b
	29 (lt fl foramina)	1	0.500	a ==> b
	31 (post paroc project)	1	0.400	a --> b
	32 (stapedial fossa)	1	0.500	b ==> c
	58 (Angular_proc_(p/a))	1	0.500	a ==> b
	59 (Angular proc. level)	1	0.750	b --> a
	66 (Pterygoid fossa)	1	1.000	a ==> b

	67 (Pterygoid ridge)	1	0.750	a ==> b
	68 (Masseteric ridge)	1	0.750	a ==> b
	70 (Den.cond.peduncle)	1	0.667	b ==> c
	71 (Size_D-condyle)	1	0.600	a --> c
node_21 --> Triconodontids	23 (Epitympanic recess)	1	0.333	b --> a
	26 (lt fl to crista parot)	1	0.500	c --> b
	27 (pt-par_foramen)	1	0.571	b --> a
	50 (Sagittal crest)	1	0.400	c --> b
	81 (Cusp occlusion)	1	0.600	c --> b
node_21 --> node_20	17 (Tensor tympani)	1	0.625	c --> a
	48 (Ascending channel)	1	0.500	b ==> c
	74 (Rotation of mand)	1	0.800	c --> b
	78 (cusp alignment)	1	0.667	a ==> c
	79 (PC interlocking)	1	0.500	b ==> a
	80 (Lower PC cingulum)	1	0.286	a --> c
	82 (Wear development)	1	0.500	b ==> c
	83 (Facets-to-cusps)	1	0.667	a --> b
	84 (Stylar shelf)	1	0.500	a --> b
	85 (Protocristid orientation)	1	1.000	a --> b
node_20 --> node_16	7 (TMJ position)	1	0.667	b --> a
	14 (Prootic canal)	1	0.800	b --> c
	49 (Lambdoidal crest)	1	0.500	b --> c
	52 (Parietal expansion)	1	0.833	b --> c
	54 (Meckelian sulcus)	1	0.600	b ==> c
	67 (Pterygoid ridge)	1	0.750	b ==> c
	76 (Canine)	1	0.800	a ==> c
	81 (Cusp occlusion)	1	0.600	c --> d
	83 (Facets-to-cusps)	1	0.667	b --> c
	90 (Anterior diastema)	1	0.500	a ==> c
node_16 --> Ornithorhynchus	4 (Zygo constriction)	1	0.400	b ==> a
	11 (Cochlea)	1	0.600	b ==> c
	23 (Epitympanic recess)	1	0.333	b --> a
	28 (ppf to fv)	1	0.333	b --> a
	32 (stapedial fossa)	1	0.500	c ==> a
	35 (ca ep opening)	1	0.600	c ==> b
	39 (XII foramen)	1	0.500	b ==> a
	48 (Ascending channel)	1	0.500	c ==> a
	56 (Mandible symphysis)	1	0.500	b ==> c
	71 (Size_D-condyle)	1	0.600	c --> b
	77 (PC roots)	1	0.600	b ==> c
	80 (Lower PC cingulum)	1	0.286	c --> b
node_16 --> Multituberculate	10 (Prom outline)	1	0.500	c ==> b
	17 (Tensor tympani)	1	0.625	a --> d
	40 (2nd palate)	2	0.500	c ==> a
	42 (Pterygopal ridges)	1	0.333	b ==> a
	72 (TMJ to alveolar level)	1	0.750	c ==> b
	73 (Uni vs. bilat occlus)	1	0.500	a ==> b
	78 (cusp alignment)	1	0.667	c ==> b
	84 (Stylar shelf)	1	0.500	b --> a
node_20 --> node_19	1 (SQ cranial moiety)	1	0.500	a --> b
	2 (SQ cranial wall)	1	1.000	a --> b
	5 (Postglenoid depres)	1	0.333	a --> b
	6 (Glenoid fossa)	1	0.600	b ==> c
	12 (2nd bony lamina)	1	1.000	a --> b
	18 (Crista interfen)	1	1.000	a ==> b
	19 (Post-tym_recess)	1	1.000	a ==> b
	20 (Caud tym proc)	1	1.000	a ==> b
	22 (SQ flank to paro)	1	0.333	b ==> a
	30 (paroc bifurcation)	1	0.400	b ==> a
	31 (post paroc project)	1	0.400	b --> a
	34 (peril duct channel)	1	1.000	b --> c
	43 (trn flge hamulus)	1	0.800	c --> b
	44 (Bs constricture)	1	0.833	c --> b
	46 (Jugal)	1	0.500	b ==> a
	49 (Lambdoidal crest)	1	0.500	b --> a
	50 (Sagittal crest)	1	0.400	c --> a
	64 (Coronoid)	1	0.600	b --> a
	74 (Rotation of mand)	1	0.800	b --> d
node_19 --> Zhangheotherium	27 (pt-par_foramen)	1	0.571	b ==> c
	28 (ppf to fv)	1	0.333	b --> a
	56 (Mandible symphysis)	1	0.500	b ==> c
	65 (Splenial)	1	0.500	b ==> a

```
                             68 (Masseteric ridge)              1  0.750  b ==> a
                             76 (Canine)                        1  0.800  a ==> b
                             80 (Lower PC cingulum)             1  0.286  c --> a
         node_19 --> node_18 10 (Prom outline)                  1  0.500  c ==> d
                             11 (Cochlea)                       2  0.600  b ==> d
                             13 (FV orientation)                1  0.800  b --> a
                             58 (Angular_proc_(p/a))            1  0.500  b ==> a
                             71 (Size_D-condyle)                1  0.600  c --> b
                             87 (Lower talonid)                 1  1.000  a ==> b
         node_18 --> Vincelestes 4 (Zygo constriction)          1  0.400  b ==> a
                             8 (Zygoma depth)                   1  0.500  c ==> b
                             17 (Tensor tympani)                1  0.625  a --> c
                             31 (post paroc project)            1  0.400  a --> b
                             40 (2nd palate)                    1  0.500  c ==> b
                             42 (Pterygopal ridges)             1  0.333  b ==> a
         node_18 --> node_17 15 (lt trough flr)                 1  1.000  b ==> c
                             24 (lt_flange_(anterior))          1  0.500  b ==> c
                             35 (ca ep opening)                 1  0.600  c ==> d
                             54 (Meckelian sulcus)              1  0.600  b --> c
                             55 (Meckelian curve)               1  0.500  a --> b
                             60 (position of angle)             1  1.000  b ==> c
                             64 (Coronoid)                      1  0.600  a --> b
                             70 (Den.cond.peduncle)             1  0.667  c ==> b
                             86 (Upper protocone)               1  1.000  a ==> b
                             88 (Talonid wear)                  1  1.000  a ==> b
         node_17 --> Metatherians 27 (pt-par_foramen)           1  0.571  b ==> d
                             67 (Pterygoid ridge)               1  0.750  b ==> c

Bootstrap method with heuristic search:
  Number of bootstrap replicates = 100
  Starting seed = 911206280
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        16 characters are of type 'ord' (Wagner)
        74 characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Starting tree(s) obtained via stepwise addition
  Addition sequence: simple (reference taxon = Probainognathus)
  Number of trees held at each step during stepwise addition = 1
  Branch-swapping algorithm: tree-bisection-reconnection (TBR)
  Steepest descent option not in effect
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
  Trees are unrooted

   100 bootstrap replicates completed
   Time used = 1.33 sec

Bootstrap 50% majority-rule consensus tree

/---------------------------------------------------------------------- Probainognathus(1)
+---------------------------------------------------------------------- Tritylodontids(2)
+---------------------------------------------------------------------- Tritheledontids(3)
|      /--------------------------------------------------------------- Adelobasileus(4)
|      |      /-------------------------------------------------------- Sinoconodon(5)
\--79--+      |     /-------------------------------------------------- Morganucodon(6)
       \--65--+     |      /------------------------------------------- Haldanodon(7)
              \-91--+      |      /------------------------------------ Hadrocodium(8)
                    \--97--+      |      /----------------------------- Triconodontids(9)
                           \--94--+      |                   /------- Ornithorhynchus(10)
                                  \--60--+--------71---------+------- Multituberculate(11)
                                         |      /-------------------- Zhangheotherium(12)
                                         \--93--+     /-------------- Vincelestes(13)
                                                \-89--+      /------- Metatherians(14)
                                                      \-100--+------- Eutherians(15)
```

```
Bipartitions found in one or more trees and frequency of occurrence (bootstrap support
values):

         1    1
123456789012345      Freq
-------------------------
.............**     99.60
......*********     97.08
.......********     93.75
...........****     93.14
.....**********     91.47
............***     88.57
...************     79.00
.........**....     70.83
....***********     65.28
........*******     59.73
.*.************     43.23
..*************     38.93
.........******     34.95
........***....     32.04
...*.**********     31.22
.......*.******     26.13
.*..***********     18.67
.......*...****     16.29
........*.*****     13.45
.**.***********     12.83
..........*****     12.43
.......*.*.....      9.46
...........**..      8.27
...*..*********      7.87
.......*.**....      7.76
........*..****      7.50
.**............      5.00
31 groups at (relative) frequency less than 5% not shown

Jackknife method with heuristic search:
  Number of jackknife replicates = 100
  Nominal percentage of characters deleted in each replicate = 50
  Starting seed = 375082359
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        16 characters are of type 'ord' (Wagner)
        74 characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Starting tree(s) obtained via stepwise addition
  Addition sequence: simple (reference taxon = Probainognathus)
  Number of trees held at each step during stepwise addition = 1
  Branch-swapping algorithm: tree-bisection-reconnection (TBR)
  Steepest descent option not in effect
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
  Trees are unrooted

   Note: 45 characters are deleted in each replicate; actual deletion percentage = 50.000
   100 jackknife replicates completed
   Time used = 2.23 sec

Jackknife 50% majority-rule consensus tree

/-------------------------------------------------------------------- Probainognathus(1)
+-------------------------------------------------------------------- Tritylodontids(2)
+-------------------------------------------------------------------- Tritheledontids(3)
|      /------------------------------------------------------------- Adelobasileus(4)
|      |      /------------------------------------------------------ Sinoconodon(5)
\--72--+      |     /------------------------------------------------ Morganucodon(6)
       \--67--+     |      /----------------------------------------- Haldanodon(7)
```

```
              \-87--+      |      /---------------------------------- Hadrocodium(8)
                    \--91--+      |      /--------------------------- Triconodontids(9)
                           \--94--+      |                   /------- Ornithorhynchus(10)
                                  \--53--+--------59---------+------- Multituberculate(11)
                                         |      /-------------------- Zhangheotherium(12)
                                         \--85--+     /-------------- Vincelestes(13)
                                                \-89--+      /------- Metatherians(14)
                                                      \-100--+------- Eutherians(15)
```

Bipartitions found in one or more trees and frequency of occurrence (jackknife support values):

```
         1    1
123456789012345      Freq
-------------------------
.............**    100.00
.......********     93.98
......*********     91.10
............***     88.87
.....**********     87.22
...........****     85.12
...************     72.34
....***********     67.21
.........**....     58.89
........*******     53.35
.*.************     45.87
.........******     34.19
..*************     32.76
.......*.******     30.50
...*.**********     29.66
........***....     27.10
.*..***********     23.61
..........*****     21.59
.**.***********     14.84
.......*...****     12.93
........*.*****     12.50
...*..*********     11.87
.......*.*.....     10.80
...........**..      8.24
.......*.**....      7.24
.**............      6.78
..........*.***      5.79
.........*.****      5.74
........*.*....      5.19
41 groups at (relative) frequency less than 5% not shown
```

```
Search #3

P A U P *
Version 4.0b5 for Macintosh
Friday, February 23, 2001  3:33 PM

This copy registered to: Zhe-Xi Luo
                         Carnegie Museum of Natural History

Processing of file "Luomatrix2.doc" begins...

Data matrix has 15 taxa, 90 characters
Valid character-state symbols: abcdefghij
Missing data identified by '?'
Gaps identified by '-'

1 tree read from TREES block
   Time used = 0.00 sec

1 tree converted from rooted to unrooted.

*** Skipping "MACCLADE" block

Processing of file "Luomatrix2.doc" completed.

Branch-and-bound search settings:
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        42 characters are of type 'ord' (Wagner)
        48 characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Initial upper bound: unknown (compute heuristically)
  Addition sequence: furthest
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
  Trees are unrooted

Branch-and-bound search completed:
   Score of best tree found = 313
   Number of trees retained = 0
   Time used = 1.42 sec

Outgroup status changed:
  1 taxon transferred to outgroup
  Total number of taxa now in outgroup = 1
  Number of ingroup taxa = 14

Branch-and-bound search settings:
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        42 characters are of type 'ord' (Wagner)
        48 characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Initial upper bound: unknown (compute heuristically)
  Addition sequence: furthest
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
  Trees are unrooted

Branch-and-bound search completed:
```

```
   Score of best tree found = 313
   Number of trees retained = 0
   Time used = 1.45 sec

Processing TREES block from file "Luomatrix2.doc":
   Keeping: trees from file (replacing trees in memory)
   1 tree read from file
   Time used = 0.00 sec

1 tree converted from rooted to unrooted.

Tree number 1 (rooted using user-specified outgroup)

/------------------------------------------------------------------------ Probainognathus
+------------------------------------------------------------------------ Tritylodontids
|     /------------------------------------------------------------------ Tritheledontids
|     |     /------------------------------------------------------------ Adelobasileus
\-----+     |     /------------------------------------------------------ Sinoconodon
      \-----+     |     /------------------------------------------------ Morganucodon
            \-----+     |     /------------------------------------------ Haldanodon
                  \-----+     |     /------------------------------------ Hadrocodium
                        \-----+     |     /------------------------------ Triconodontids
                              \-----+     |                       /------ Ornithorhynchus
                                    \-----+     /-----------------+------ Multituberculate
                                          \-----+     /------------------ Zhangheotherium
                                                \-----+     /------------ Vincelestes
                                                      \-----+     /------ Metatherians
                                                            \-----+------ Eutherians

Bootstrap method with heuristic search:
  Number of bootstrap replicates = 100
  Starting seed = 266523217
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        42 characters are of type 'ord' (Wagner)
        48 characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Starting tree(s) obtained via stepwise addition
  Addition sequence: simple (reference taxon = Probainognathus)
  Number of trees held at each step during stepwise addition = 1
  Branch-swapping algorithm: tree-bisection-reconnection (TBR)
  Steepest descent option not in effect
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
  Trees are unrooted

   100 bootstrap replicates completed
   Time used = 1.07 sec

Bootstrap 50% majority-rule consensus tree

/-------------------------------------------------------------------- Probainognathus(1)
+-------------------------------------------------------------------- Tritheledontids(3)
|     /-------------------------------------------------------------- Tritylodontids(2)
|     |     /-------------------------------------------------------- Adelobasileus(4)
\-70--+     |      /------------------------------------------------- Sinoconodon(5)
      \-61--+      |     /------------------------------------------- Morganucodon(6)
            \--58--+     |     /------------------------------------- Haldanodon(7)
                   \-92--+     |     /------------------------------- Hadrocodium(8)
                         \-97--+     |     /------------------------- Triconodontids(9)
                               \-98--+     +------------------------- Ornithorhynchus(10)
                                     \-62--+------------------------- Multituberculate(11)
                                           |     /------------------- Zhangheotherium(12)
                                           \-94--+      /------------ Vincelestes(13)
                                                 \--93--+     /------ Metatherians(14)
                                                        \-100-+------ Eutherians(15)
```

```
Bipartitions found in one or more trees and frequency of occurrence (bootstrap support
values):

         1    1
123456789012345      Freq
-------------------------
.............**    100.00
.......********     98.00
......*********     96.58
...........****     94.17
............***     93.03
.....**********     91.94
.*.************     69.67
........*******     61.74
...************     60.80
....***********     58.50
........*.*****     43.89
..........*****     43.09
.*..***********     36.83
...*.**********     34.67
.......*.*.....     23.99
.........**....     23.79
.......*.******     23.15
.**.***********     22.50
.........******     20.75
........***....     12.89
.......*.**....     12.47
........*..****     12.17
.........*.****      8.17
...*..*********      8.06
..*************      7.50
.*...**********      6.83

22 groups at (relative) frequency less than 5% not shown

Jackknife method with heuristic search:
  Number of jackknife replicates = 100
  Nominal percentage of characters deleted in each replicate = 50
  Starting seed = 1322032661
  Optimality criterion = maximum parsimony
    Character-status summary:
      Of 90 total characters:
        42 characters are of type 'ord' (Wagner)
        48 characters are of type 'unord'
        All characters have equal weight
        All characters are parsimony-informative
    Gaps are treated as "missing"
    Multistate taxa interpreted as polymorphism
  Starting tree(s) obtained via stepwise addition
  Addition sequence: simple (reference taxon = Probainognathus)
  Number of trees held at each step during stepwise addition = 1
  Branch-swapping algorithm: tree-bisection-reconnection (TBR)
  Steepest descent option not in effect
  Initial 'MaxTrees' setting = 100
  Branches collapsed (creating polytomies) if maximum branch length is zero
  'MulTrees' option in effect
  Topological constraints not enforced
  Trees are unrooted

   Note: 45 characters are deleted in each replicate; actual deletion percentage = 50.000

   100 jackknife replicates completed
   Time used = 1.23 sec

Jackknife 50% majority-rule consensus tree

/-------------------------------------------------------------------- Probainognathus(1)
+-------------------------------------------------------------------- Tritheledontids(3)
|     /-------------------------------------------------------------- Tritylodontids(2)
|     |     /-------------------------------------------------------- Adelobasileus(4)
\-65--+     |      /------------------------------------------------- Sinoconodon(5)
```

```
      \-58--+      |     /------------------------------------------- Morganucodon(6)
            \--54--+     |     /------------------------------------- Haldanodon(7)
                   \-88--+     |     /------------------------------- Hadrocodium(8)
                         \-96--+     |     /------------------------- Triconodontids(9)
                               \-99--+     +------------------------- Ornithorhynchus(10)
                                     \-61--+------------------------- Multituberculate(11)
                                           |     /------------------- Zhangheotherium(12)
                                           \-96--+      /------------ Vincelestes(13)
                                                 \--90--+     /------ Metatherians(14)
                                                        \-100-+------ Eutherians(15)
```

Bipartitions found in one or more trees and frequency of occurrence (jackknife support values):

```
         1    1
123456789012345      Freq
-------------------------
.............**    100.00
.......********     98.64
...........****     96.13
......*********     96.07
............***     90.45
.....**********     87.93
.*.************     64.66
........*******     61.22
...************     58.50
....***********     54.04
.*..***********     39.03
...*.**********     38.45
........*.*****     37.50
..........*****     34.98
.........**....     32.45
.........******     26.43
.**.***********     23.76
.......*.******     21.65
.......*.*.....     20.47
........***....     13.92
.......*.**....     12.43
...*..*********     12.07
..*************     11.00
........*..****     10.70
.........*.****      9.53
.*...**********      7.51
.......*...****      6.40
...........*.**      6.05
```

23 groups at (relative) frequency less than 5% not shown