REVIEWS

Transformation and diversification in early mammal evolution

Zhe-Xi Luo[1]

Evolution of the earliest mammals shows successive episodes of diversification. Lineage-splitting in Mesozoic mammals is coupled with many independent evolutionary experiments and ecological specializations. Classic scenarios of mammalian morphological evolution tend to posit an orderly acquisition of key evolutionary innovations leading to adaptive diversification, but newly discovered fossils show that evolution of such key characters as the middle ear and the tribosphenic teeth is far more labile among Mesozoic mammals. Successive diversifications of Mesozoic mammal groups multiplied the opportunities for many dead-end lineages to iteratively evolve developmental homoplasies and convergent ecological specializations, parallel to those in modern mammal groups.

Mammals are an important group for understanding life and its evolution. With some 5,400 extant species and 4,000 fossil genera, they developed a spectacular diversity of ecomorphological specializations, ranging from the 1-gram bumblebee bat to the 100-tonne blue whale. Basal diversifications of the three extant mammalian groups, monotremes (egg-laying mammals), marsupials (pouched mammals) and placentals, occurred in the Mesozoic Era[1–4]. Their ancestors are nested in a great evolutionary bush with 25 or so lineages that co-existed with non-avian dinosaurs and other small vertebrates during the Mesozoic. Mammals were not abundant in the Mesozoic, but they were relatively diverse. Compared to the 547 known dinosaur genera[5], over 310 Mesozoic mammaliaform genera are now known to science, two-thirds of which were discovered in the last 25 years (Box 1).

The rise of mammals from premammaliaform cynodonts is an important transition in vertebrate evolution[1,2,6–9]. This already richly documented transition has been rapidly re-written by recent discoveries of very informative fossils (Box 1), by the increasingly comprehensive phylogenies with which to infer the pattern of diversification (Fig. 1), and by a more complex picture of the evolution of key anatomical features. The newly improved fossil record can reciprocally illuminate the molecular evolution of mammals, especially in light of the large discrepancies between the molecular time estimates and the fossil records for the origins of major marsupial and placental super-order lineages. These new fossils and their analyses shed new light on several controversies:

- Temporal evolution: is early mammal evolution best characterized by major long branches reaching deep into the Mesozoic and by the long evolutionary fuse that delayed diversification within long branches? Or is this evolution dominated by many short-lived branches with a short evolutionary fuse before diversification?

- Ecological diversification: is lineage splitting of early mammals decoupled from, or correlated with ecological diversification?

- Morphological transformation: are originations of key mammalian characters singular evolutionary events, or iterative convergences despite their complexity?
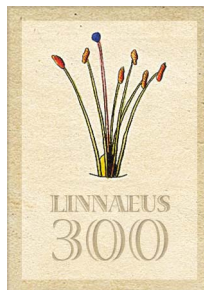
Temporal pattern of early mammal evolution

The evolution of early mammals occurred in successive diversifications or episodes of quick splitting of relatively short-lived clades. Most order- or family-level clades are clustered around the several nodes of their evolutionary tree. Mapped on the geological time scale, successive clusters of emergent clades represent waves of diversification (Fig. 1). Clades in a preceding episode of diversification are mostly dead-end evolutionary experiments; the majority of them have no direct ancestor–descendant relationship to the emergent clades in the succeeding episode of diversification, consistent with significant taxonomic succession and turnover between mammaliaform faunas of different geological epochs. The main episodes of diversification are: diversification of premammalian mammaliaforms—the extinct relatives outside mammals—during the Late Triassic and Early Jurassic (Fig. 1, node 1), the Middle Jurassic diversification of docodonts, theriiform mammals, and the australosphenidan mammals that are basal to monotremes (Fig. 1, node 2), the Late Jurassic diversification within the extinct theriiform groups (Fig. 1, node 3) that are closer to marsupials and placentals than to monotremes (Fig. 1, node 4), and the Early Cretaceous divergence of the marsupial lineage and the placental lineage (Fig. 1, nodes 5 and 6).
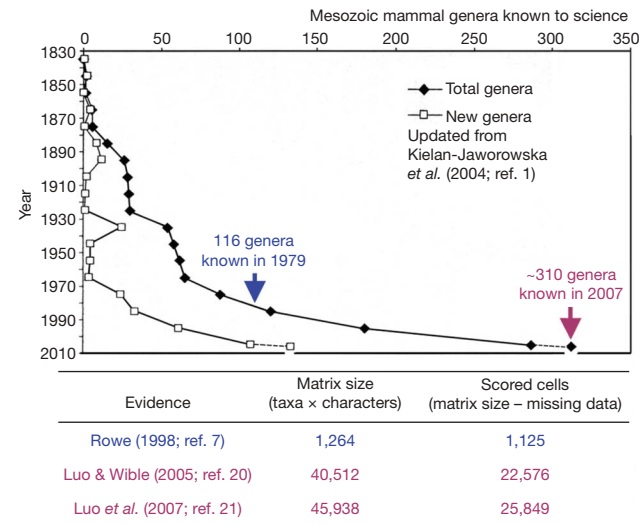
Cenozoic placentals and marsupials represent a new episode of diversification in succession to the Cretaceous stem eutherians and metatherians. Cenozoic marsupials are nested, as a whole, in the Cretaceous metatherians, but the emergent Cenozoic marsupial orders or families cannot be related directly to the known Cretaceous metatherian genera by the best available morphological data sets[10–12]. The latest analyses of all eutherians also strongly favour placement of all known eutherians of the Cretaceous outside the Cenozoic placentals[13,14], in contrast to a previous analysis[15]. The successive clusters of emergent clades and faunal turnover between the Cretaceous and Cenozoic are consistent with the overall pattern of successive diversification of Mesozoic mammaliaforms as a whole (Fig. 1).

These prevailing patterns are significantly different from the historical but now out-of-date views that a few long branches of Cenozoic or extant mammals would extend deep into the Mesozoic, but taxonomic diversification would be confined in a

[1]Carnegie Museum of Natural History, Pittsburgh, Pennsylvania 15213, USA.

Box 1 | Rapid accumulation of new data by recent discoveries of Mesozoic mammals.

In comparison to 116 Mesozoic mammal genera known to science in 1979 (ref. 3), about 200 additional Mesozoic mammals were discovered in the last 25 years, a tenfold increase from all those found in the first 200 years since the first Mesozoic mammal was unearthed in 1764 (ref. 1). Total Mesozoic mammal genera now number over 310, as compared to 540 co-existing dinosaur genera[5]. More important than the great increase in taxonomic abundance is the superb quality of new fossils that reveals a richer and more complex picture of their morphological evolution, and a much better data set for estimating phylogeny. Before 1990, skulls and skeletons were described only for a handful of Mesozoic mammals[3,35,54]. The best data set for estimating the early mammal phylogeny in 1988 scored 1,125 cells in the taxon-character matrix[7]. Today, at least 18 Mesozoic mammals are represented by nearly complete skeletons and twice as many by well-preserved skull fossils. The latest data sets for morphological phylogenetic estimates have scored 22,000 to 25,000 cells in matrices[20,21]—about 200 times that of the best available data set in the 1980s.

Mesozoic mammal genera known to science

Evidence	Matrix size (taxa × characters)	Scored cells (matrix size – missing data)
Rowe (1998; ref. 7)	1,264	1,125
Luo & Wible (2005; ref. 20)	40,512	22,576
Luo et al. (2007; ref. 21)	45,938	25,849

few long-established lineages[16]. A widely accepted view, when only teeth were available for inferring early mammal history in the 1970s, was that two 'prototherian' and 'therian' lines extended to the Late Triassic[3]. These historical ideas are now replaced by more detailed phylogenies, with better sampling of skull and skeletal characters[7,17,18], in addition to dental evidence, in a great many more taxa[19–21] (Box 1). It is uncommon for any Mesozoic group to maintain a long history with little diversity, or a much delayed diversification within a lineage. Instead of a few long lineages, early mammal evolution has many short lineages in successive clusters (Fig. 1)[1,19,22].

Recent molecular dating of early mammal evolution also postulates the extension of long lineages of extant mammal superorders or orders deep into the Cretaceous, although for entirely different reasons. Molecular datings of the origins of major placental and marsupial clades at super-order or order levels are generally older than the earliest fossil records of these groups[23–25]. By one recent molecular estimate[26], all 18 extant placental orders originated in the early Late Cretaceous, as did two marsupial orders. The molecular picture of mammal evolution is a massive case of multiple long branches extending far back into deep history, with long-delayed diversification within each long branch, almost down to every modern placental order (for example, ref. 26).

The first appearance of a lineage in the fossil record represents its minimal age constraint. The actual origin of a lineage should be older than its earliest fossil record, given that the earliest history may not have been documented owing to an imperfect fossil record[27]. The inferred long delay of diversification within a major clade after its origination is aptly characterized as a 'long-fuse' evolution[28].

It is a matter of course that the minimum age constraint of the fossil record differs from the actual origin, but there is a great disagreement

about the magnitude of this difference, or how frequently a long evolutionary fuse would occur in early mammal lineages. The older molecular dates would predict an abundance of long branches, and a long delay of diversification within each long branch after a branch's origin. However, studies using morphological data of both fossil and extant taxa demonstrate that there are few[15] or no such lineages with a long evolutionary lag time[13,14]. This discrepancy is so systemic and widespread that it cannot be explained by the difference between minimum age constraint (represented by actual fossils) and the timing of origin that can be hypothetically estimated by molecules in marsupial and placental evolution. The diversification models that have fully accounted for the incompleteness of the fossil record suggest that these discrepancies cannot be dismissed as a general artefact of an incomplete fossil record[29,30]. The latest morphological studies with nearly exhaustive sampling of Cretaceous fossils[10–14,20] have all shown significant gaps in the 'younger' fossil record compared to the much 'older' molecular dating of the marsupial and placental lineages, a phenomenon with which molecular evolutionists also agree.

To account for these broad discrepancies between the dating by fossils and the estimate by molecules, some have extensively argued that lineages could phylogenetically diverge long before their morphological diversification[31]. The putative long delay in evolution of identifiable features for fossils to demarcate the lineage's first appearance would be due to the decoupling of speciation and ecomorphological adaptation. More generally, it is proposed that splits of early mammal lineages were not accompanied by morphological differences and were 'silent' with regard to their ecological diversification[32].

Ecological diversification in Mesozoic mammals

Whether or to what extent the lineage splitting is correlated with morphological and ecological diversification is a question with broad implications for macroevolution[31–33]. Marsupials and placentals, the two main groups that make up 99% of all extant mammal species, show great ecomorphological diversity, and most of their orders have unique ecological specializations correlated with distinctive morphological traits (Fig. 2). There is no question that this spectacular ecomorphological diversification accelerated in an Early Cenozoic adaptive radiation of mammals into the niches vacated on the extinction of non-avian dinosaurs.

However, in the absence of contrary evidence from the previously poor fossil record, it was extrapolated to a broad generalization that Mesozoic mammals failed to develop any ecomorphological specializations. They were viewed as small animals with a generalized feeding and unspecialized limb structure for terrestrial habits (Fig. 2a), and without the widely divergent ecological specializations of Cenozoic descendants. The postulation that many mammal lineages have extended invisibly into the Mesozoic without morphological difference[27,31,33] is dependent on the extrapolation that Mesozoic mammals as a whole were generalized and lacking ecological diversification, owing to exclusion from diverse terrestrial niches by co-existing dinosaurs and other small vertebrates.

The hypothesis of the decoupling of phyletic divergence from ecological diversifications rests on the assumption that the major Mesozoic mammal groups lacked ecological specializations, other than generalized habits. This assumption is now falsified by discoveries of several new Mesozoic mammals with convergences to highly specialized extant mammals (Fig. 2). Although the majority of mammals in such Mesozoic ecosystems as the Jehol Biotas[34], and some earliest mammaliaforms[35], are certainly generalized (Fig. 2a), there is now strong evidence for ecological specializations in many other clades.

Fossorial behaviour was documented by taphonomic evidence for some premammaliaform cynodonts[36], but only recently did the fossorial skeletal specializations (such as scratch digging) become known for mammaliaform lineages. This is now shown to be

widespread in multituberculates, the most abundant group in Late Jurassic and Cretaceous mammalian faunas[37]. In docodonts, the hypertrophied burrowing limb features represent an exaptation for swimming, as in modern platypus, and invasion of freshwater habitats (Fig. 2b): *Castorocauda* (Middle Jurassic) has a broad, scaly and beaver-like tail for swimming[38]; *Haldanodon* from the Late Jurassic also shows phenotypic convergence to semi-aquatic moles[39,40].

Myrmecophagian ('ant-eating' or 'termite-eating') specialization for feeding on colonial insects, along with limbs built for scratch-digging, are the defining features of several placental groups (aardvark, pangolin and armadillo) and monotremes (echidnas). The hypertrophied digging-limb features and the unique columnar and enamel-less teeth were developed in the Late Jurassic *Fruitafossor*[20] (Fig. 2d) 150 million years (Myr) ago, 100 Myr before a similar character complex evolved convergently in armadillos and aardvarks, among placentals.

Predation and scavenging on vertebrates require a larger body mass than those of generalized insectivorous mammals (20 to
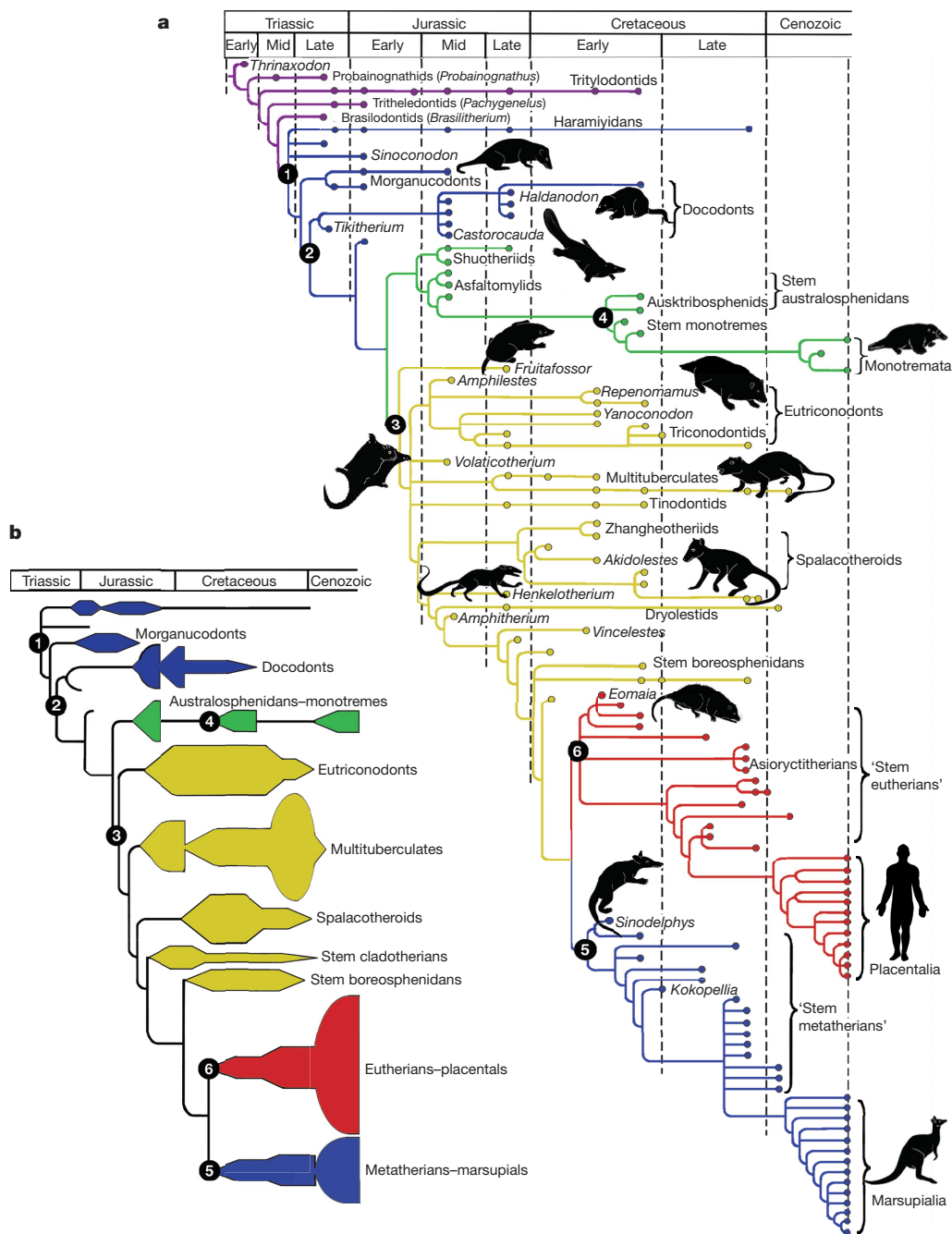

Figure 1 | Phylogeny and diversification of Mesozoic and major extant mammal groups. Almost all Mesozoic mammaliaform clades are relatively short-lived, clustered in several episodes of accelerated diversification. The short branches arising in each episode of diversification are mostly phylogenetic dead-ends without ancestor–descendant relationship to the similar dead-end branches in the episodes either before or after[1,22].
a, Mesozoic mammalian macroevolution is by waves of diversification of relatively short-lived clades in succession or by replacement: node 1, the Late Triassic–Early Jurassic diversification of mammaliaform stem clades (blue branches and dots); node 2, diversification of docodonts (peak diversity in the Middle Jurassic) and splits of several extinct groups in Mammalia (green and yellow); node 3, the Late Jurassic diversification within euriconodonts, multituberculates and cladotherians; and the Early Cretaceous originations of character-based monotremes (node 4), stem-based metatherians (including marsupials; node 5) and stem-based eutherians (including placentals; node 6). Animal silhouettes are major taxa, either newly discovered or re-interpreted with better fossils after the 1990s, showing previously unsuspected ecological diversification. **b**, Diversity patterns of the order- or family-level Mesozoic mammal groups. Phylogeny is from refs 20 and 21, with additional taxa[49,57].

100 g). Some individuals could reach 500 g in *Sinoconodon*[41], 700 g in *Castorocauda*[38] and even 5–12 kg for several gobiconodontid species that could prey on other small vertebrates[42]. The Jurassic and Cretaceous saw multiple evolutions of predatory carnivores in unrelated groups (Fig. 2c).

The capacity to climb on uneven terrain is inherent in generalized small mammals[35]. Derived scansorial adaptation is widespread among Early Cenozoic marsupials[43–45] and some multituberculates[46]. New skeletal fossils suggest that some (although not all) Mesozoic eutherians and metatherians and their near kin also developed such adaptations, as shown by the elongate intermediate phalanges and convex profiles of manual and pedal distal phalanges, and in the tarsus, among other skeletal features[11,47,48] (Fig. 2e). The adaptation for climbing is a pre-requisite for extant volant (gliding and flying) mammals. The recent discovery of *Volaticotherium* (possibly a eutriconodont) shows the skin membrane (patagium) associated with elongate limbs for gliding, convergent to marsupial sugar gliders, and 'flying' squirrels and dermopterans among placentals[49] (Fig. 2f).

Treated individually, these curious cases of convergent adaptations in extinct Mesozoic mammals represent many separate evolutionary experiments[20,37–39,49]. But taken together (Fig. 2), they unveiled a new picture in which ecological diversification is not unique to the Early Cenozoic mammalian radiation, and that many dead-end Mesozoic mammal clades developed similar ecomorphotypes long before the analogous modern mammals (Fig. 2).

Although far less abundant numerically in the Mesozoic than in the Cenozoic, within the limited snap-shot windows of the Middle Jurassic to the Early Cretaceous—for which we happen to have sufficient fossil data—mammalian ecological specializations attained nearly the same diversification as the early-middle Palaeocene placentals in North America (except for cursorial ungulates) and as marsupials of the Oligocene-Miocene of Australia. The decoupling hypothesis can certainly be rejected as a rationale for the gap between molecular time estimates and the first appearance in fossil data of the major placental and marsupial lineages. Correlation of ecomorphological specializations with phylogenetic splitting is a basic feature of Mesozoic mammal evolution. Cenozoic placental carnivores are an independent case for correlated ecomorphological and phyletic diversifications[33].

Transformation of key evolutionary apomorphies

On the broadest possible scale, evolution from premammalian synapsids to mammaliaforms shows incremental acquisition of mammalian apomorphies[8,9,41,50]. Stepwise assembly of incremental precursor conditions towards complex mammal structure is an evolutionary paradigm of functional adaptation and taxonomic diversification of mammals[50–52]. Some best-documented 'textbook' scenarios are acquisitions of key characters along a transformation series: transformations of the mammalian middle ear and the jaw hinge (Fig. 3), and evolution of the tribosphenic molars (Fig. 4).

Homoplasies in mammal middle-ear evolution. The postdentary bones in the posterior part of the mandible make up the jaw hinge and the mandibular middle ear in premammalian cynodonts. They show a gradual size reduction in the mandible—as the dentary bone shows gradual enlargement—among transitional taxa successively
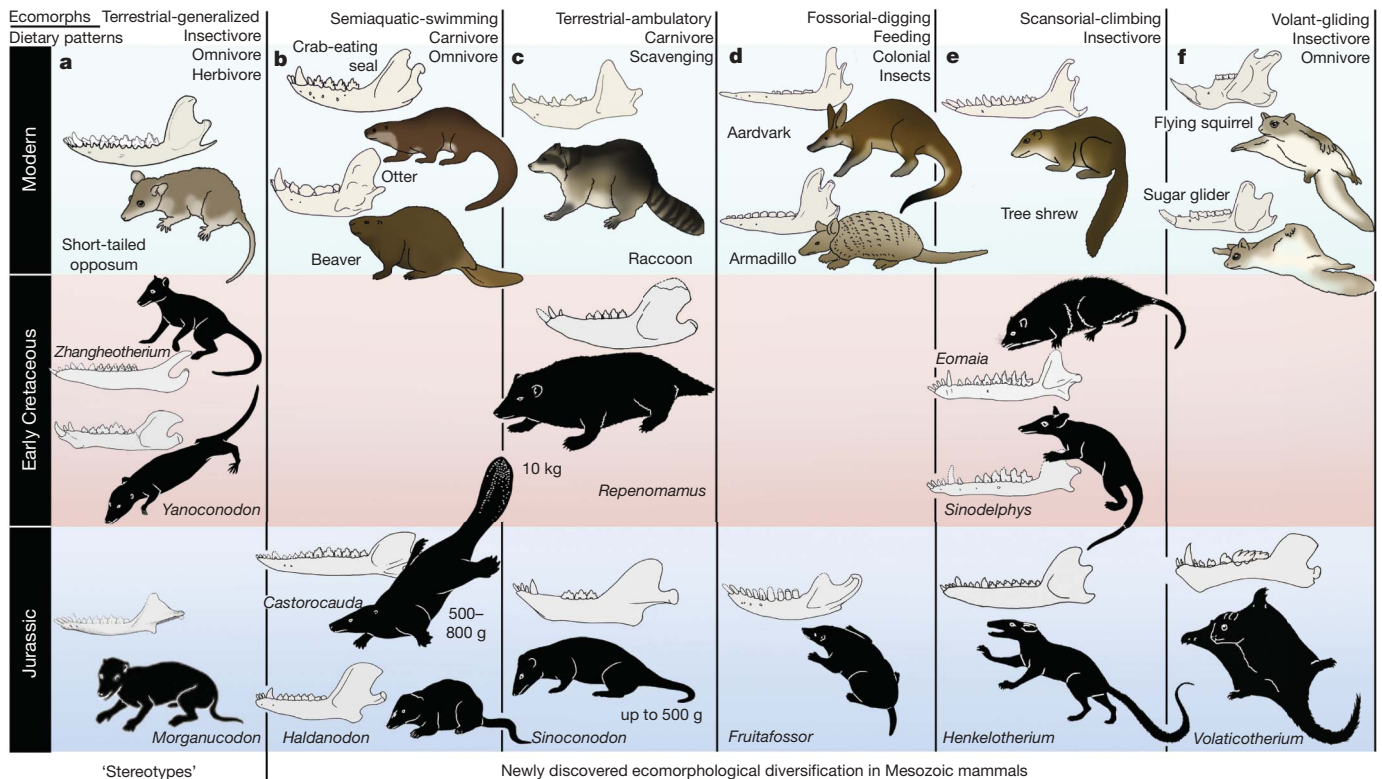

Figure 2 | Diverse evolutionary experiments of Mesozoic mammals and their ecological convergence to modern mammal ecomorphotypes.
a, Representation of the traditional assumption that Mesozoic mammals were generalized small animals with generalized feeding and terrestrial habits, and had few of the diverse ecomorphotypes of Cenozoic mammals; the hypothesis on decoupling of lineage splitting from ecological diversification is based on this assumption[27,31,32], which is now contradicted by recent discoveries of a great range of ecological specializations, such as: **b,** swimming and fish-feeding in the docodont *Castorocauda*[38], and semi-aquatic habits of *Haldanodon*[39,40]; **c,** ambulatory carnivory or scavenging (predation or feeding on other vertebrates) in large gobiconodontids[42] and large individuals of *Sinoconodon*[41]; **d,** scratch-digging and feeding on colonial insects in *Fruitafossor*[20]; **e,** scansorial (climbing) limb characteristics in basal eutherians and metatherians, and their near relatives[11,47,48]; and **f,** volant (gliding) adaptation in *Volaticotherium*[49]. The Jurassic and Cretaceous mammals developed, iteratively, similar niche specializations to modern Australasian monotremes and marsupials, and are no less diverse, ecologically, than the early-to-middle Palaeocene mammals of similar body-size range. Splits of Mesozoic mammal groups were accompanied by ecological diversification.

closer to mammals (Fig. 3a–e)[8,52–56]. In more derived premammalian mammaliaforms, the dentary is so enlarged as to have a condyle articulating with the squamosal glenoid, forming the true mammalian jaw hinge, known as the temporomandibular joint (Fig. 3d, e). Further along the evolution of living mammals, the middle ear became detached from the mandible to form the 'cranial middle ear', or the definitive mammalian middle ear (Fig. 3f, h). The detachment

of the middle ear from the mandible in adults and the mobile suspension of the middle ear via the incus to the cranium are crucial for sensitivity of the mammal middle ear[55,56]. Sound transition from the tympanic membrane through the middle ear also requires the malleus manubrium, as an in-lever, and the incus stapedial process, as an out-lever, for the impedance-match and amplification of airborne sound (Fig. 3)[51,55].
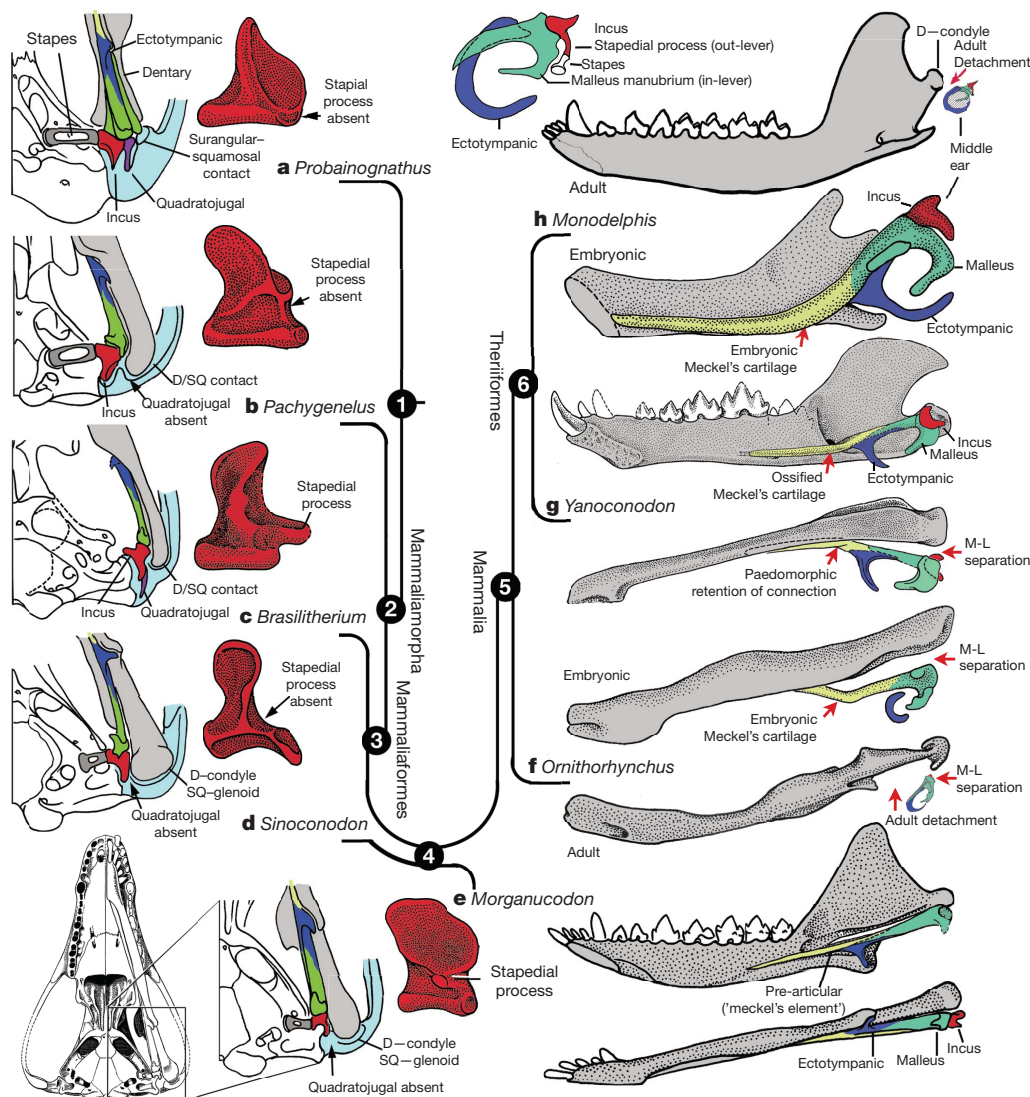

Figure 3 | Evolution of the mammalian cranio-mandibular joint and the definitive mammalian middle ear through the cynodont–mammal transition. Homoplasies occurred for the simplification of the incus articulation, the stapedial process of the incus and the detachment of the ectotympanic from mandible. **a**, The cynodont *Probainognathus*[51,55]; ventral view of left basicranium and posterior view of the incus (quadrate). **b**, The mammaliamorph *Pachygenelus*[51,55]. **c**, The mammaliamorph *Brasilitherium* (modified from ref. 57 by personal observation). **d**, The mammaliaform *Sinoconodon*. **e**, *Morganucodon* (redrawn from refs 53 and 54): left panel, left basicranium, ventral view; middle panel, left incus, posteromedial view; and right panel, the mandible and 'mandibular' middle ear in ventral (below) and medial (above) views. **a–e**, Homoplastic loss of the quadratojugal for a more mobile incus occurs in *Pachygenelus* (**b**) and mammaliaforms (**d**, **e**), but not in *Probainognathus* (**a**), tritylodontids (not shown) and *Brasilitherium* (**c**). The stapedial process of the incus, the out-lever for the middle ear, is present in tritylodontids (not shown), *Brasilitherium* (**c**) and *Morganucodon* (**e**), but not in other taxa (**a**, **b**, **d**). **f**, The monotreme *Ornithorhynchus* lower jaw (ventral view): the middle ear attached anteriorly to the mandible by Meckel's cartilage in the embryonic stage[59], but detached from the mandible after re-absorption of Meckel's cartilage in the adult. **g**, The euticonodont *Yanoconodon* lower jaw (lower panel, ventral view; upper panel, medial

view): the middle ear is medio-laterally (M-L) separated from, but anteriorly connected to, the mandible by the prematurely ossified Meckel's cartilage, similar to the embryonic condition of monotremes of medio-lateral (M-L) separation of the ear from the mandible, and to the monotreme configuration of the ectotympanic and malleus. **h**, The medial view of the mandible and middle ear of the marsupial *Monodelphis*: the middle ear is attached to the mandible by Meckel's cartilage in the embryonic stage[60,61], but detached from the mandible after the re-absorption of Meckel's cartilage in the adult. Because *Yanoconodon* (**g**) is nested between extant monotremes (**f**) and therians (**h**), both of which have have separation of the middle ear from the mandible, the Meckel's connection of the ectotympanic to the mandible in *Yanoconodon* shows that some Mesozoic mammals had homoplastic evolution of the definitive mammalian middle ear, defined by full detachment of the ectotympanic from the dentary. The ossified Meckel's cartilage of *Yanoconodon* is very similar to the embryonic Meckel's cartilage of extant monotremes, and has paedomorphic resemblance to the embryonic condition of extant mammals. The homoplastic attachment of the mandible and the middle ear in *Yanoconodon* is correlated with changes in the timing and rate of development. D, dentary; SQ, squamosal; D/SQ, the dentary–squamosal contact or joint.

If mapped on a limited number of exemplary fossils on a broad phylogenetic scale, evolution of the definitive mammalian middle ear and mammalian jaw hinge is orderly both in qualitative[51,55] and quantitative terms[8,56]. However, a series of newly discovered fossils have shown more complex transformations of the main components of the mammalian middle ear[21,57]. This can be demonstrated for how the middle ear became connected to the cranium but disconnected from the mandible.

Mobile suspension of the middle ear and its impedance-match system. A highly agile and mobile suspension of the incus in the cranium contributes to sensitive hearing function. The incus is ancestrally associated with the quadratojugal bone (Fig. 3a, c, purple). The quadratojugal–incus articulation to the cranium reinforces
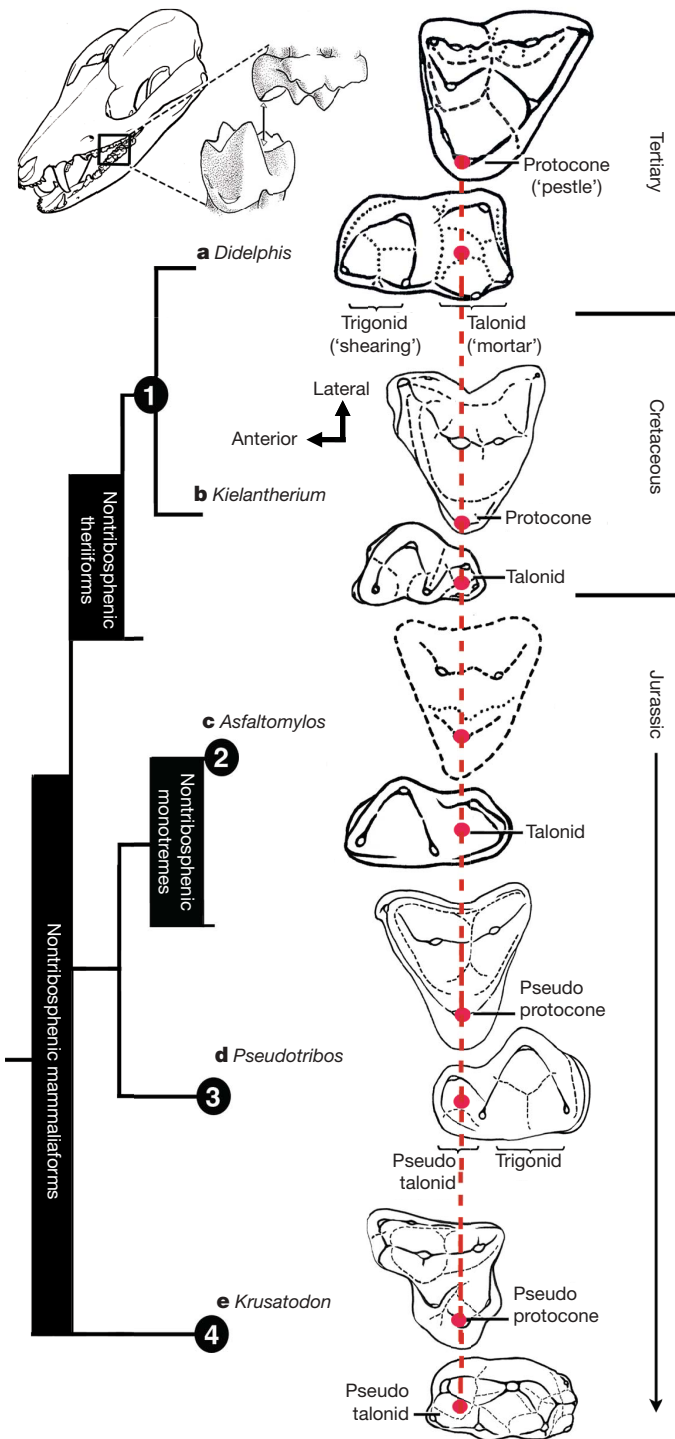
the incus for the load-bearing function of the jaw hinge, but also reduces the hearing sensitivity (Fig. 3a, c). The stapedial process is present in most mammaliaforms, fulfilling the crucial function of the out-lever of the middle-ear lever system for the impedance-match and amplification, but is absent in the incus of most premammaliaform cynodonts (Fig. 3a, b). These functionally important apomorphies (and their respective precursory conditions) have incongruent distributions in the transitional taxa from premammalian cynodonts to mammaliaforms. The stapedial process has a discontinuous distribution: it is present in tritylodontids (not illustrated), *Brasilitherium*[57] and *Morganucodon*[17,51,54], but absent in the tritheledontid *Pachygenelus*[51]—which is phylogenetically between tritylodontids and *Brasilitherium*—and in *Sinoconodon*, which is between *Brasilitherium* and *Morganucodon*. The quadratojugal is lost in *Pachygenelus*, *Sinoconodon* and *Morganucodon*, thereby allowing more mobility in the middle ear, but is present in *Brasilitherium*, a taxon more derived than *Pachygenelus* in cynodont–mammal evolution[57].

Regardless of the alternative tree topology of such transitional forms as *Pachygenelus*, *Brasilitherium* and *Sinoconodon*, the loss of the quadratojugal and the development of the stapedial process are not only homoplastic in their overall distributions, but are also in conflict with each other. It is abundantly evident that separate evolutionary experiments occurred repetitively during the transformation of the incus structure for better impedance-match and hearing sensitivity.

Mandible–ear detachment and formation of the definitive mammalian middle ear. In premammalian outgroups, the middle ear is attached to the dentary, by the pre-articular (an ossified Meckel's element) and the ectotympanic (Fig. 3e). In extant mammals, such as the monotreme *Ornithorhynchus* (Fig. 3f) and the marsupial *Monodelphis* (Fig. 3h), the connection between the dentary and Meckel's element is conserved in embryonic and fetal stages, but lost in the adult owing to the re-absorption of embryonic Meckel's cartilage, the homologue to part of the prearticular[56,58–62].

Opinions waxed and waned as to whether detachment of the definitive mammalian middle ear occurred a single time[7,17,56,63,64] or more than once in mammal evolution[21,53,65,66]. It can be argued that disconnection by the adult re-absorption of the embryonic Meckel's cartilage happened only once, and that the definitive mammalian middle ear had a monophyletic origin, if these extant mammals are directly compared to the premammalian mammaliaforms without considering several fossil groups nested within the crown Mammalia. Adult monotremes have complete separation of the middle ear from the mandible (Fig. 3f), but in extinct taxa in the monotreme

Figure 4 | Convergent and iterative evolution of protocones and pseudo-protocones in Mesozoic mammals. The tribosphenic and pseudotribosphenic molars achieved analogous pulping, crushing and grinding functions by opposite arrangements of main structures: in tribosphenic molars the protocone of the upper molar is aligned to the talonid basin posterior to the primitive trigonid of the lower; in pseudotribosphenic molars the analogous pseudoprotocone is aligned to a pseudotalonid basin anterior to the same trigonid on the lower molar. The protocone or its analogous cusp is developed independently from the immediate ancestors without such a structure (black bands) four times: boreosphenidan mammals (node 1, *Kielantherium* + the common ancestor of marsupials and placentals), australosphenidans (node 2, Gondwanan tribosphenic mammals as the immediate outgroups to non-tribosphenic monotremes), pseudotribosphenidans (node 3, *Pseudotribos* and kin) and docodont mammals (node 4, *Krusatodon*). Three lineages had experimented with the protocone or a similar structure in the Middle Jurassic without success, and gone extinct, long before the common ancestor of marsupials and placentals re-evolved the protocone, which may be correlated to their early diversification. **a**, The marsupial *Didelphis* had typical tribosphenic molars. **b**, The Early Cretaceous northern tribosphenic (boreosphenid) *Kielantherium*[74]. **c**, The Middle Jurassic southern tribosphenic (australosphenid) *Asfaltomylos* (hypothetical upper molar)[82,83]. **d**, The Middle Jurassic pseudo-tribosphenic (shuotheriid) *Pseudotribos*[78]. **e**, The Middle Jurassic 'pseudo-tribosphenic' docodont *Krusatodon*[90].

lineage, the receiving structure on the mandible for connecting the middle ear is still present[19,65], although the middle-ear bones themselves are not preserved, causing some uncertainties in interpretation[63,64]. For groups that are nested among modern mammals, the most conclusive evidence for attachment of the middle ear to the mandible is from several eutriconodonts. Several gobiconodontids have preserved an ossified Meckel's cartilage[67–69]. In the newly discovered *Yanoconodon*[21], this ossified Meckel's cartilage connects the mandible to the ectotympanic and the malleus, the two bones supporting the tympanic membrane in extant mammals. Regardless of whether the middle ear's connection to the mandible is considered to be an atavistic reversal or a convergent acquisition, it is beyond doubt that the last step in the transformation of the definitive mammalian middle ear occurred homoplastically in some Mesozoic lineages (Fig. 3).

The ossified Meckel's cartilage of eutriconodonts is morphologically similar to the embryonic Meckel's cartilage of extant monotremes in having a bend in the Meckel's cartilage and in the medio-lateral (M-L) separation of the ectotympanic and malleus from the mandible, and can be regarded to be paedomorphic by comparison to the embryonic condition of extant monotreme and placental mammals[59–61] (Fig. 3). The middle ear's attachment to the mandible in *Yanoconodon* (and possibly in eutriconodonts as a whole) is attributable to differences in developmental timing and rate between *Yanoconodon* and extant mammals. Because reabsorption of Meckel's cartilage is crucial for extant mammals to complete the ontogeny of their middle ear, an early ossification of Meckel's cartilage influenced the retention of the ectotympanic–dentary connection in some major Mesozoic mammal groups. This provides a common ontogenetic heterochrony as a main mechanism for the homoplastic evolution of a critical component of the mammalian middle ear.

Evolution of tribosphenic and pseudotribosphenic molars. Tribosphenic molars of basal marsupials and placentals have the protocone (pestle) of the upper molar crushing and grinding in the talonid basin (mortar) on the lower molar[70–74]. Because this new function by the derived protocone and talonid is added to the basic shearing function of the primitive structure of the trigonid (Fig. 4), this complex structure with more versatile functions is considered to be a key dental innovation for more effective faunivory and omnivory, leading to the basal diversification of marsupials and placentals. It was widely assumed that the upper-molar protocone, the lower-molar talonid, and their occlusal correspondence evolved together in a single origin in the group Tribosphenida, defined by the common ancestor of marsupials, placentals and their proximal kin[72,73].

However, the discovery of the pseudotribosphenic mammals *Shuotherium* and *Pseudotribos* changed the assumption that the derived function of the protocone- and the talonid-like structure was a singular evolutionary event[75–78]. Pseudotribosphenic molars have a design that is geometrically reversed from that of the tribosphenic molars: a pseudo-talonid is anterior to the trigonid, and receives the pseudo-protocone of the upper molar (Fig. 4d). This functionally analogous pseudo-talonid is anteriorly placed in pseudotribosphenic mammals and opposite to the posterior talonid basin of the true tribosphenic mammals (Fig. 4a, b). Therefore, a protocone-like structure of the upper molar can occlude either a talonid in the posterior part of the lower molar, or a pseudo-talonid in the anterior part of the lower molar, in different clades; the protocone-like structure of the upper molar evolved homoplastically in mammalian history.

Discoveries of southern tribosphenic mammals, or australosphenidans, from the Mesozoic of Gondwana[79–84] falsified the traditional notion that tribosphenic mammals had a single origin on the northern continents[72,73]. The earliest tribosphenic mammals of Gondwana are fairly diverse, with a wide distribution. They are more derived than the northern tribosphenic mammals with respect to unique premolar features and in having distinctive wear patterns concentrated apically on the peripheral crests of the molar talonid; this is

similar to toothed monotremes, but not boreosphenidans[83–85]. One school of thought argues that these australosphenidans are placentals[79,80,87]. Because australosphenidans have the postdentary trough accommodating the mandibular middle ear[83,84], this implies that the ancestral mandibular ear would have re-evolved independently within placentals after the marsupial–placental split. This hypothesis also postulates that placentals would originate earlier than 170 Myr ago[87], much earlier than even the current earliest molecular dating (~147 Myr ago) for the placental–marsupial split[26]. A contrasting view, based on analyses of all major Mesozoic and extant mammal clades (Fig. 1), is that the lower-molar talonid basin in australosphenidans represents convergent evolution. These southern mammals are extinct relatives to monotremes, which are relictual taxa from an ancient mammal diversification within the Gondwanan continents[1,19,85]. Several recent and independent analyses supported the hypothesis of dual evolution of tribosphenic molars and the australosphenidan clade[83,84,88], some with modified outgroup relationships of australosphenidans[84,89].

Some docodont mammaliaforms also achieved a pseudo-protocone structure not unlike those of tribosphenic or pseudotribosphenic molars[90]. Three Middle Jurassic lineages developed a protocone, or a similar structure, without much evolutionary success, and became extinct long before the common ancestor of marsupials and placentals re-evolved the protocone during their Cretaceous and early Cenozoic diversification. Dental evolution was far more labile in Mesozoic mammals than can be inferred from Cenozoic mammals (Fig. 4)[19,83–85], and is consistent with the functional analysis that there was more than one pathway to combine slicing and crushing functions, as exemplified by tribosphenic and pseudotribosphenic molars for more effective faunivory and omnivory, in early mammalian history[91].

Concluding remarks

The traditional paradigm of early mammal evolution portrayed the origin of key innovations as an incremental assembly of complex features with great functional adaptation in the time of diversification of a major group. Two classic examples of this paradigm are the sensitive hearing by the sophisticated middle ear in the earliest mammaliaforms, leading to exploitation of the nocturnal niches, and the versatile functions of the tribosphenic molar in northern tribosphenic mammals, leading to the great diversification of marsupials and placentals. Because there used to be no evidence to the contrary, it was granted that processes of evolutionary innovation leading to ecological diversification were singular events—these evolutionary innovations of mammals are so intricate and unique that it would be unlikely for these sophisticated structures to be homoplastic[33,66].

Character conflicts are inevitable when more characters become available from better 'transitional' fossils. For the several key mammaliaform structures known to have evolved by incremental or stepwise assembly, their precursor conditions have shown character conflicts in the recently found fossils (Fig. 3). This suggests labile evolutionary experiments before the accomplishment of the complex structure. Character transformation and the attendant homoplasies can now be attributable to functional adaptation, evolutionary development, or both. Homoplasies in the definitive mammalian middle ear by the ossified Meckel's cartilage in eutriconodonts are a case of developmental heterochrony. Models on developmental mechanism[92,93] and functional analysis[91] of dental characters are consistent with iterative evolution of the protocone-like structure among docodont, pseudotribosphenic and tribosphenic mammals, as postulated by parsimonious phylogeny of fossils (Fig. 4). Other similar examples include thoraco-lumbar vertebral homoplasies among Mesozoic mammals that are dead-ringers for loss and gain of *hox* gene patterning[21,94–98]. Perhaps most interestingly, successive waves of Mesozoic mammal diversification multiplied the chances for many short-lived lineages to iteratively experiment with developmental patterning and ecological diversification that were previously

known only for Cenozoic mammals, but that are now shown to be widespread among Mesozoic mammals. This shows that lineage splits are accompanied by significant ecological diversification and by more labile developmental patterning in early mammal evolution.

An emergent new paradigm is that successive diversifications of Mesozoic mammals made it possible for many extinct lineages to exploit diverse niches—as during Cenozoic mammalian diversification (albeit less successfully)—in independent evolutionary experiments facilitated by extensive developmental homoplasies and convergent functional and ecological adaptation.

1. Kielan-Jaworowska, Z. *et al. Mammals from the Age of Dinosaurs—Origins, Evolution, and Structure* (Columbia Univ. Press, New York, 2004).
2. Kemp, T. S. *The Origin And Evolution of Mammals* (Oxford Univ. Press, Oxford, 2005).
3. Lillegraven, J. A., Kielan-Jaworowska, Z. & Clemens, W. A. (eds) *Mesozoic Mammals: The First Two-thirds of Mammalian History* (Univ. Calif. Press, Berkeley, 1979).
4. McKenna, M. C. & Bell, S. K. *Classification of Mammals Above the Species Level* (Columbia Univ. Press, New York, 1997).
5. Wang, C. S. & Dodson, P. Estimating the diversity of dinosaurs. *Proc. Natl Acad. Sci. USA* **103**, 13601–13605 (2006).
6. Hopson, J. A. & Kitching, J. W. A probainognathian cynodont from South Africa and the phylogeny of nonmammalian cynodonts. *Bull. Mus. Comp. Zool. (Harvard)* **156**, 5–35 (2001).
7. Rowe, T. B. Definition, diagnosis, and origin of Mammalia. *J. Vertebr. Paleontol.* **8**, 241–264 (1988).
8. Sidor, C. A. Simplification as a trend in synapsid cranial evolution. *Evolution Int. J. Org. Evolution* **55**, 1419–1442 (2001).
9. Sidor, C. A. & Hopson, J. A. Ghost lineages and ''mammalness'': assessing the temporal pattern of character acquisition in the Synapsida. *Paleobiology* **24**, 254–273 (1998).
10. Rougier, G. W. *et al.* Implications of *Deltatheridium* specimens for early marsupial history. *Nature* **396**, 459–463 (1998).
11. Luo, Z.-X. *et al.* An Early Cretaceous tribosphenic mammal and metatherian evolution. *Science* **302**, 1934–1940 (2003).
12. Asher, R. J. *et al.* First combined cladistic analysis of marsupial mammal interrelationships. *Mol. Phylogenet. Evol.* **33**, 240–250 (2004).
13. Asher, R. J. *et al.* Stem Lagomorpha and the antiquity of Glires. *Science* **307**, 1091–1094 (2005).
14. Wible, J. R. *et al.* Cretaceous eutherians and Laurasian origin for placental mammals near the K-T boundary. *Nature* **442**, 1003–1006 (2007).
15. Archibald, J. D. *et al.* Late Cretaceous relatives of rabbits, rodents, and other extant eutherian mammals. *Nature* **414**, 62–65 (2001).
16. Simpson, G. G. *A Catalogue of the Mesozoic Mammalia in the Geological Department of the British Museum* (British Museum, London, 1928).
17. Kemp, T. S. The relationships of mammals. *Zool. J. Linn. Soc.* **77**, 353–384 (1983).
18. Wible, J. R. & Hopson, J. A. in *Mammal Phylogeny* Vol. 1 (eds F. S. Szalay *et al.*) 45–62 (Springer-Verlag, New York, 1993).
19. Luo, Z.-X. *et al.* In quest for a phylogeny of Mesozoic mammals. *Acta Palaeontol. Polonica* **47**, 1–78 (2002).
20. Luo, Z.-X. & Wible, J. R. A new Late Jurassic digging mammal and early mammalian diversification. *Science* **308**, 103–107 (2005).
21. Luo, Z.-X. *et al.* A new euticonodont mammal and evolutionary development of early mammals. *Nature* **446**, 288–293 (2007).
22. Cifelli, R. L. Early mammalian radiations. *J. Paleontol.* **75**, 1214–1226 (2001).
23. Murphy, W. J. *et al.* Resolution of the early placental mammal radiation using Bayesian phylogenetics. *Science* **294**, 2348–2351 (2001).
24. Springer, M. S. *et al.* Placental mammal diversification and the Cretaceous-Tertiary boundary. *Proc. Natl Acad. Sci. USA* **100**, 1056–1061 (2003).
25. Nilsson, M. A. *et al.* Marsupial relationships and a timeline for marsupial radiation in South Gondwana. *Gene* **340**, 189–196 (2004).
26. Bininda-Emonds, O. R. P. *et al.* The delayed rise of present-day mammals. *Nature* **446**, 507–512 (2007).
27. Benton, M. J. & Donoghue, P. C. J. Paleontological evidence to date the tree of life. *Mol. Biol. Evol.* **24**, 26–53 (2007).
28. Archibald, J. D. & Deutschman, D. H. Quantitative analysis of the timing of the origin and diversification of extant placental orders. *J. Mamm. Evol.* **8**, 107–124 (2001).
29. Foote, M. *et al.* Evolutionary and preservational constraints on origins of biologic groups: divergence times of eutherian mammals. *Science* **283**, 1310–1314 (1999).
30. Hunter, J. P. & Janis, C. M. Spiny Norman in the Garden of Eden? Dispersal and early biogeography of Placentalia. *J. Mamm. Evol.* **13**, 89–123 (2006).
31. Easteal, S. Molecular evidence for the early divergence of placental mammals. *BioEssays* **21**, 1052–1058 (1999).
32. Bromham, L. *et al.* Growing up with dinosaurs: molecular dates and the mammalian radiation. *Trends Ecol. Evol.* **14**, 113–118 (1999).
33. Wesley-Hunt, G. D. The morphological diversification of carnivores in North America. *Paleobiology* **31**, 35–55 (2005).
34. Zhou, Z.-H. *et al.* An exceptionally preserved Lower Cretaceous ecosystem. *Nature* **421**, 807–814 (2003).
35. Jenkins, F. A. Jr & Parrington, F. R. The postcranial skeletons of the Triassic mammals *Eozostrodon, Megazostrodon* and *Erythrotherium. Phil. Trans. R. Soc. Lond. B* **273**, 387–431 (1976).
36. Damiani, R. *et al.* Earliest evidence of cynodont burrowing. *Proc. R. Soc. Lond. B* **270**, 1747–1751 (2003).
37. Kielan-Jaworowska, Z. & Gambaryan, P. P. Postcranial anatomy and habits of Asian multituberculate mammals. *Fossils Strata* **36**, 1–92 (1994).
38. Ji, Q. *et al.* A swimming mammaliaform from the Middle Jurassic and ecomorphological diversification of early mammals. *Science* **311**, 1123–1127 (2006).
39. Martin, T. Postcranial anatomy of *Haldanodon exspectatus* (Mammalia, Docodonta) from the Late Jurasssic (Kimmeridgian) of Portugal and its bearing for mammalian evolution. *Zool. J. Linn. Soc.* **145**, 219–248 (2005).
40. Martin, T. Paleontology: early mammalian evolutionary experiments. *Science* **311**, 1109–1110 (2006).
41. Luo, Z.-X. *et al.* A new mammaliaform from the Early Jurassic of China and evolution of mammalian characteristics. *Science* **292**, 1535–1540 (2001).
42. Hu, Y.-M. *et al.* Large Mesozoic mammals fed on young dinosaurs. *Nature* **433**, 149–153 (2005).
43. Szalay, F. S. & Sargis, E. J. Model-based analysis of postcranial osteology of marsupials from the Palaeocene of Itaboraí (Brazil) and the phylogenetics and biogeography of Metatheria. *Geodiversitas* **23**, 139–302 (2001).
44. Muizon, C. de. *Mayulestes ferox*, a borhyaenoid (Metatheria, Mammalia) from the early Palaeocene of Bolivia. Phylogenetic and palaeobiologic implications. *Geodiversitas* **20**, 19–142 (1998).
45. Argot, C. Functional–adaptive anatomy of the forelimb in the Didelphidae, and the paleobiology of the Paleocene marsupials *Mayulestes ferox* and *Pucadelphys andinus. J. Morphol.* **247**, 51–79 (2001).
46. Krause, D. W. & Jenkins, F. A. Jr. The postcranial skeleton of North American multituberculates. *Bull. Mus. Comp. Zool. Harv.* **150**, 199–246 (1983).
47. Krebs, B. Das Skelett von *Henkelotherium guimarotae* gen. et sp. nov. (Eupantotheria, Mammalia) aus dem Oberen Jura von Portugal. *Berliner Geowissensch. Abh.* **A133**, 1–110 (1991).
48. Ji, Q. *et al.* The earliest-known eutherian mammal. *Nature* **416**, 816–822 (2002).
49. Meng, J. *et al.* A Mesozoic gliding mammal from northeastern China. *Nature* **444**, 889–893 (2006).
50. Luo, Z.-X. in *In the Shadow of the Dinosaurs—Early Mesozoic Tetrapods* (eds N. C. Fraser & H.-D. Sues) 98–128 (Cambridge Univ. Press, Cambridge, 1994).
51. Luo, Z.-X. & Crompton, A. W. Transformation of the quadrate (incus) through the transition from non-mammalian cynodonts to mammals. *J. Vertebr. Paleontol.* **14**, 341–374 (1994).
52. Crompton, A. W. in *Studies in Vertebrate Evolution* (eds K. A. Joysey & T. S. Kemp) 231–253 (Oliver & Boyd, Edinburgh, 1972).
53. Kermack, K. A. *et al.* The lower jaw of *Morganucodon. Zool. J. Linn. Soc.* **53**, 87–175 (1973).
54. Kermack, K. A. *et al.* The skull of *Morganucodon. Zool. J. Linn. Soc.* **71**, 1–158 (1981).
55. Allin, E. F. & Hopson, J. A. in *The Evolutionary Biology of Hearing* (eds Webster, D. B. *et al.*) 587–614 (Springer, New York, 1992).
56. Rowe, T. B. Coevolution of the mammalian middle ear and neocortex. *Science* **273**, 651–654 (1996).
57. Bonaparte, J. F. *et al.* New information on *Brasilodon* and *Brasilitherium* (Cynodontia, Probainognathia) from the Late Triassic, southern Brazil. *Revist. Brasil. Paleontol.* **8**, 25–56 (2005).
58. Gaupp, E. Die Reichertsche Theorie (Hammer-, Amboss- und Kieferfrage). *Archiv. Anatomie Entwick.* **1912**, 1–426 (1913).
59. Zeller, U. Die Entwicklung und Morphologie des Schädels von *Ornithorhynchus anatinus* (Mammalia: Prototheria: Monotremata). *Abh. Senckenberg. Naturforsch. Ges.* **545**, 1–188 (1989).
60. Maier, W. Phylogeny and ontogeny of mammalian middle ear structures. *Nether. J. Zool.* **40**, 55–75 (1990).
61. Maier, W. in *Mammal Phylogeny* Vol. 1 (eds Szalay, F. S. *et al.*) 165–181 (Springer, New York, 1993).
62. Sánchez-Villagra, M. R. *et al.* Ontogenetic and phylogenetic transformations of the ear ossicles in marsupial mammals. *J. Morphol.* **251**, 219–238 (2002).
63. Bever, G. *et al.* Comment on ''Independent origins of middle ear bones in monotremes and therians.''. *Science* **309**, 1492a (2005).
64. Rougier G. W., Forasiepi, A. M. & Martinelli, A. G. Comment on ''Independent origins of middle ear bones in monotremes and therians.''. *Science* **309**, 1492b (2005).
65. Rich, T. H. *et al.* Independent origins of middle ear bones in monotremes and therians. *Science* **307**, 910–914 (2005).
66. Martin, T. & Luo, Z.-X. Paleontology: homoplasy in the mammalian ear. *Science* **307**, 861–862 (2005).
67. Wang, Y.-Q. *et al.* An ossified Meckel's cartilage in two Cretaceous mammals and origin of the mammalian middle ear. *Science* **294**, 357–361 (2001).
68. Li, C.-K. *et al.* A new species of *Gobiconodon* (Triconodonta, Mammalia) and its implication for the age of Jehol Biota. *Chin. Sci. Bull.* [English] **48**, 1129–1134 (2003).
69. Meng, J. *et al.* The ossified Meckel's cartilage and internal groove in Mesozoic mammaliaforms: implications to origin of the definitive mammalian middle ear. *Zool. J. Linn. Soc.* **138**, 431–448 (2003).

70. Patterson, B. Early Cretaceous mammals and the evolution of mammalian molar teeth. *Fieldiana. Geology* **13**, 1–105 (1956).

71. Crompton, A. W. in *Early Mammals* (eds Kermack, D. M. & Kermack, K. A.) 65–87 (Zool. J. Linn. Soc., London, 1971).

72. McKenna, M. C. in *Phylogeny of the Primates* (eds Luckett, W. P. & Szalay, F. S.) 21–46 (Plenum Publ. Corp., New York, 1975).

73. Prothero, D. R. New Jurassic mammals from Como Bluff, Wyoming, and the interrelationships of non-tribosphenic Theria. *Bull. Am. Mus. Nat. Hist.* **167**, 277–326 (1981).

74. Lopatin, A. V. & Averianov, A. O. An aegialodontid upper molar and the evolution of mammal dentition. *Science* **313**, 1092 (2006).

75. Chow, M. & Rich, T. H. *Shuotherium dongi*, n. gen. and sp., a therian with pseudo-tribosphenic molars from the Jurassic of Sichuan, China. *Austral. Mamm.* **5**, 127–142 (1982).

76. Sigogneau-Russell, D. Discovery of a Late Jurassic Chinese mammal in the upper Bathonian of England. *C. R. Acad. Sci. II* **327**, 571–576 (1998).

77. Wang, Y.-Q. *et al.* A probable pseudo-tribosphenic upper molar from the Late Jurassic of China and the early radiation of the Holotheria. *J. Vertebr. Paleontol.* **18**, 777–787 (1998).

78. Luo, Z. X. *et al.* Convergent dental evolution in pseudotribosphenic and tribosphenic mammals. *Nature* **450**, 93–97 (2007).

79. Rich, T. H. *et al.* A tribosphenic mammal from the Mesozoic of Australia. *Science* **278**, 1438–1442 (1997).

80. Rich, T. H. *et al.* An advanced ausktribosphenid from the Early Cretaceous of Australia. *Rec. Queen Victoria Mus.* **110**, 1–9 (2001).

81. Flynn, J. J. *et al.* A Middle Jurassic mammal from Madagascar. *Nature* **401**, 57–60 (1999).

82. Rauhut, O. W. M. *et al.* A Jurassic mammal from South America. *Nature* **416**, 165–168 (2002).

83. Martin, T. & Rauhut, O. W. M. Mandible and dentition of *Asfaltomylos patagonicus* (Australosphenida, Mammalia) and the evolution of tribosphenic teeth. *J. Vertebr. Paleontol.* **25**, 414–425 (2005).

84. Rougier, G. W. *et al.* New Jurassic mammals from Patagonia, Argentina: a reappraisal of australosphenidan morphology and interrelationship. *Am. Mus. Novitates* **3566**, 1–54 (2007).

85. Luo, Z.-X. *et al.* Dual origin of tribosphenic mammals. *Nature* **409**, 53–57 (2001).

86. Rich, T. H. *et al.* Evidence that monotremes and ausktribosphenids are not sistergroups. *J. Vertebr. Paleontol.* **22**, 466–469 (2002).

87. Woodburne, M. O. Monotremes as pretribosphenic mammals. *J. Mamm. Evol.* **10**, 195–248 (2003).

88. Musser, A. M. *Investigations into the Evolution of Australian Mammals with a Focus on Monotremata* PhD thesis, Univ. of New South Wales (2006).

89. Sigogneau-Russell, D. *et al.* The oldest tribosphenic mammal from Laurasia (Purbeck Limestone Group, Berriasian, Cretaceous, UK) and its bearing on the ''dual origin'' of Tribosphenida. *Comptes. Rend. Acad. Sci.* **333**, 141–147 (2001).

90. Sigogneau-Russell, D. Docodonts from the British Mesozoic. *Acta Palaeontol. Polonica* **48**, 357–374 (2003).

91. Evans, A. R. & Sanson, G. D. The tooth of perfection: functional and spatial constraints on mammalian tooth shape. *Biol. J. Linn. Soc.* **78**, 173–191 (2003).

92. Kangas, A. T. *et al.* Nonindependence of mammalian dental characters. *Nature* **432**, 211–214 (2004).

93. Kassai, Y. *et al.* Regulation of mammalian tooth cusp patterning by ectodin. *Science* **309**, 2067–2070 (2005).

94. Jenkins, F. A. Jr. The postcranial skeleton of African cynodonts. *Peabody Mus. Nat. Hist. Bull.* **36**, 1–216 (1971).

95. Filler, A. G. *Axial Character Seriation in Mammals: an Historical and Morphological Exploration of the Origin, Development, Use and Current Collapse of the Homology Paradigm* PhD thesis, Harvard Univ. (1986).

96. Narita, Y. & Kuratani, S. Evolution of vertebral formulae in mammals: a perspective on developmental constraints. *J. Exp. Zool.* **304B**, 91–106 (2005).

97. Wellik, D. M. & Capecchi, M. R. *Hox10* and *Hox11* genes are required to globally pattern the mammalian skeleton. *Science* **301**, 363–367 (2003).

98. Li, G. & Luo, Z.-X. A Cretaceous symmetrodont therian with some monotreme-like postcranial features. *Nature* **439**, 195–200 (2006).