Supplementary Information

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Supplementary Methods

Sampling rationale

Our sample captures taxonomic, phylogenetic, morphological, ecological, behavioural and locomotor diversity, but was constrained by the availability of material. We focused on densely sampling mammals and birds, which we used as independent models for endotherms; we used the large lepidosaurian sample as a model for ectotherms. The remaining extant specimens covered the range of body temperatures in vertebrates, but they are not the focus of this study. Our fossil sample included several mammaliamorphs, where the transition to endothermy is thought to occur. Although less accurate than the 3D sets, the 2D dataset was only used to extend the analysis to lower body temperatures, which clarified the relationship with the TMI. Predictions for the thermal regime of fossil synapsids are only based on the 3D sets.

Definition of the Thermo-Motility Index

In this study, in the context of a single duct model, we consider the mass and damping terms specific for the common crus, simple crus, anterior utriculus and posterior utriculus as being negligible. We re-express the upper corner frequency of a semicircular duct (Rabbitt et al., 2004, David et al. 2016):

$$\omega_{2,n} \approx \frac{\mu_{(T)}\lambda_{\mu,S,n}}{2\rho\pi \cdot a_{S,n}} \text{ (Equ. SM 1)}$$

in a way that clearly separates endolymph viscosity, as the first term, from information that is provided by bony semicircular canals, as the third term. Information only available from membranous semicircular ducts corresponds to the second term:

$$\omega_{2,n} \approx \mu_{(T)} \cdot \alpha_{\omega_2,n} \cdot \beta_{\omega_2,n} \text{ (Equ. SM 2)}$$

where

$$\alpha_{\omega_2,n} = \frac{\lambda_{\mu,S,n}}{2\rho\pi\delta_{a_S:r_{S,B}+R_{e,B},n}} \text{ (Equ. SM 3)}$$

,

$$a_{S,n} = \delta_{a_S:r_{S,B}+R_{e,B},n} b_{a_S:r_{S,B}+R_{e,B},n} r_{S,B,n}^{m_{a_S:r_{S,B},n}} R_{e,B,n}^{m_{a_S:R_{e,B},n}} \text{ (Equ. SM 4)}$$

,

$$\beta_{\omega_2,n} = \frac{1}{\delta_{r_{S,B}:R_{e,B},n}^{m_{a_S:r_{S,B},n}}} b_{\omega_2:R_{e,B},n} R_{e,B,n}^{m_{\omega_2:R_{e,B},n}} \quad \text{(Equ. SM 5)}$$

,

$$r_{S,B,n} = \frac{d_{S,B,n}}{2} = \delta_{r_{S,B}:R_{e,B},n} b_{r_{S,B}:R_{e,B},n} R_{e,B,n}^{m_{r_{S,B}:R_{e,B},n}} \quad \text{(Equ. SM 6)}$$

,

$$R_{e,B,n} = \frac{2\sqrt{\pi}L_{e,B,n} + 4\pi\sqrt{\Lambda_{e,B,n}}}{8\pi\sqrt{\pi}} \quad \text{(Equ. SM 7)}$$

,

$$b_{\omega_2:R_{e,B},n} = \frac{1}{b_{a_S:r_{S,B}+R_{e,B},n} \cdot b_{r_{S,B}:R_{e,B},n}^{m_{a_S:r_{S,B},n}}} \quad \text{(Equ. SM 8)}$$

and

$$m_{\omega_2:R_{e,B},n} = -m_{a_S:R_{e,B},n} - \left(m_{r_{S,B}:R_{e,B},n} \cdot m_{a_S:r_{S,B},n} \right) \quad \text{(Equ. SM 9)}$$

In these formulae:

$\omega_{2,n}$ stands for the upper corner frequency of the semicircular duct n.

$\mu_{(T)}$ is the viscosity of the endolymph at temperature T, while ρ is its density.

$\lambda_{\mu,S,n}$ and $a_{S,n}$ are respectively the average wall shape drag factor and average cross-sectional area of the slender portion of the semicircular duct n.

$\alpha_{\omega 2,n}$ represents a factor accounting for functional information relevant to the upper corner frequency that is unavailable from the bony semicircular canal n.

$\beta_{\omega 2,n}$ represents a factor accounting for functional information relevant to the upper corner frequency that is available from the bony semicircular canal n.

$R_{e,B,n}$, $L_{e,B,n}$ and $\Lambda_{e,B}$ are respectively the average radius, the perimeter and the area of the ellipse best fitting the projection of the torus of the semicircular canal n on its maximal response plane.

$d_{S,B,n}$ and $r_{S,B,n}$ are respectively the average diameter and average cross-sectional radius of the slender portion of the semicircular canal n.

$\delta_{aS:rS,B+Re,B,n}$ (relative duct thickness) corresponds to the ratio between the cross-sectional area of the slender portion of the semicircular duct n and its value predicted from the the combination of the cross-sectional radius of the slender portion of the corresponding semicircular canal and the corresponding radius of curvature.

$\delta_{rS,B:Re,B,n}$ (relative canal thickness) corresponds to the ratio between the cross-sectional radius of the slender portion of the semicircular canal n and its value predicted from the corresponding radius of curvature.

b_x and m_x are respectively the coefficient and exponent of the corresponding power law x.
For an eccentricity $e_{,B,n} < 0.96$, $R_{e,B,n}$ can be approximated as:

$$R_{e,B,n} \approx \frac{D_{M,B,n} + D_{m,B,n}}{4} \quad \text{(Equ. SM 10)}$$

where $D_{M,B,n}$ and $D_{m,B,n}$ are respectively the major and minor axes of the ellipse best fitting the projection of the torus of the semicircular canal n on its maximal response plane.

Similarly, we re-express the sensitivity of a semicircular duct (David et al., 2016):

$$G_{V,n} \approx \frac{2\rho\Lambda_n E_n a_{S,n}^2}{\mu_{(T)}\lambda_{\mu,S,n} L_{S,n}} \quad \text{(Equ. SM 11)}$$

as

$$G_{V,n} \approx \frac{1}{\mu_{(T)}} \cdot \alpha_{G_V,n} \cdot \beta_{G_V,n} \quad \text{(Equ. SM 12)}$$

where

$$\alpha_{G_V,n} = \frac{\varepsilon_{\Lambda,n}\delta_{a_S:r_{S,B}+R_{e,B},n}\delta_{E:R_{e,B},n}}{\alpha_{\omega_2,n}\pi\varepsilon_{L'_S,n}} \quad \text{(Equ. SM 13)}$$

,

$$\beta_{G_V,n} = \frac{\sigma_{e,B,n}\delta_{r_{S,B}:R_{e,B},n}^{2m_{a_S:r_{S,B},n}} b_{G_V:R_{e,B},n} R_{e,B,n}^{m_{G_V:R_{e,B},n}}}{\delta_{L'_{S,B}:R_{e,B},n}} \quad \text{(Equ. SM 14)}$$

,

$$\varepsilon_{\Lambda,n} = \frac{\Lambda_n}{\Lambda_{e,B,n}} \quad \text{(Equ. SM 15)}$$

,

$$E_n = \delta_{E:R_{e,B},n} b_{E:R_{e,B},n} R_{e,B,n}^{m_{E:R_{e,B},n}} \quad \text{(Equ. SM 16)}$$

,

$$\varepsilon_{L'_{S,n}} = \frac{L_{S,n}}{L'_{S,B,n}} \quad \text{(Equ. SM 17)}$$

,

$$\sigma_{e,B,n} = f(e_{B,n}) = \frac{\Lambda_{e,B,n}}{R_{e,B,n}^2} \quad \text{(Equ. SM 18)}$$

,

$$e_{B,n} = \sqrt{1 - \frac{D^2_{m,B,n}}{D^2_{M,B,n}}} \text{ (Equ. SM 19)}$$

,

$$L'_{S,B,n} = \delta_{L'_{S,B}:R_{e,B},n}\, b_{L'_{S,B}:R_{e,B},n}\, R_e^{m_{L'_{S,B}:R_{e,B},n}} \text{ (Equ. SM 20)}$$

,

$$b_{G_V:R_{e,B},n} = \frac{b_{E:R_{e,B},n}\, b^2_{a_S:r_{S,B}+R_{e,B},n}\, b^{2m_{a_S:r_{S,B},n}}_{r_{S,B}:R_{e,B},n}}{b_{L'_{S,B}:R_{e,B},n}} \text{ (Equ. SM 21)}$$

and

$$m_{G_V:R_{e,B},n} = 2 + m_{E:R_{e,B},n} + 2m_{a_S:R_{e,B},n} + \left(2m_{r_{S,B}:R_{e,B},n} \cdot m_{a_S:r_{S,B},n}\right) - m_{L'_{S,B}:R_{e,B},n} \text{ (Equ. SM 22)}$$

In these formulae:

$G_{V,n}$ stands for the sensitivity, or gain to angular velocity, of the semicircular duct n.

$\Lambda_{,n}$ is the enclosed area of the projection of the torus of the semicircular duct n on its maximal response plane.

$E_{,n}$ (deflection factor) is a transfer factor linking endolymph volume displacement to cilia deflection.

$L_{S,n}$ is the three-dimensional length of the slender portion of the semicircular duct n.

$L'_{S,n}$ is the two-dimensional length of the slender portion of the semicircular canal n.

$\alpha_{GV,n}$ represents a factor accounting for functional information relevant to the sentivity that is unavailable from the bony semicircular canal n.

$\beta_{GV,n}$ represents a factor accounting for functional information relevant to the sensitivity that is available from the bony semicircular canal n.

$\varepsilon_{\Lambda,n}$ (area error factor) corresponds to a ratio between the enclosed area of the torus of the semicircular duct n and the area of the ellipse best fitting the torus of the corresponding semicircular canal, both projected on their respective maximal response planes

$\varepsilon_{LS',n}$ (slender length error factor) corresponds to a ratio between the three-dimensional length of the slender portion of the semicircular duct n and the two-dimensional length of the slender portion of corresponding semicircular canal.

$\delta_{E:Re,B,n}$ (relative deflection factor) corresponds to the ratio between the deflection factor of the semicircular duct n and its value predicted from the radius of curvature of the corresponding semicircular canal.

$\delta_{LS',B:Re,B,n}$ (relative slender length) corresponds to the ratio between the two-dimensional length of the slender portion of the semicircular canal n and its value predicted from the corresponding radius of curvature.

$\sigma_{e,B,n}$ (eccentricity factor) corresponds to a ratio, between the area of an ellipse and its squared average radius, which negatively correlates with the eccentricity $e_{B,n}$ of the semicircular canal torus n.

As we compare specimens of very different body sizes in this study, we need to re-express $\beta_{\omega 2,n}$ and $\beta_{GV,n}$ in relation to Z, a body size variable that alternatively corresponds to body mass, condylo-basal length or condylo-antero-orbital length. Hence:

$$\beta_{\omega_2,n} = \frac{\delta_{R_{e,B}:Z,n}^{m_{\omega_2:R_{e,B},n}}}{\delta_{r_{S,B}:R_{e,B},n}^{m_{a_S:r_{S,B},n}}} b_{\omega_2:Z,n} Z^{m_{\omega_2:Z,n}} \quad \text{(Equ. SM 23)}$$

and

$$\beta_{G_V,n} = \frac{\sigma_{e,B,n} \delta_{r_{S,B}:R_{e,B},n}^{2m_{a_S:r_{S,B},n}} \delta_{R_{e,B}:Z,n}^{m_{G_V:R_{e,B},n}} b_{G_V:Z,n} Z^{m_{G_V:Z},n}}{\delta_{L'_{S,B}:R_{e,B},n}} \quad \text{(Equ. SM 24)}$$

where

$$R_{e,B,n} = \delta_{R_{e,B}:Z,n} b_{R_{e,B}:Z,n} Z^{m_{R_{e,B}:Z,n}} \quad \text{(Equ. SM 25)}$$

,

$$b_{\omega_2:Z,n} = b_{\omega_2:R_{e,B},n} b_{R_{e,B}:Z,n}^{m_{\omega_2:R_{e,B},n}} \quad \text{(Equ. SM 26)}$$

,

$$b_{G_V:Z,n} = b_{G_V:R_{e,B},n} b_{R_{e,B}:Z,n}^{m_{G_V:R_{e,B},n}} \quad \text{(Equ. SM 27)}$$

,

$$m_{\omega_2:Z,n} = m_{\omega_2:R_{e,B},n} \cdot m_{R_{e,B}:Z,n} \quad \text{(Equ. SM 28)}$$

and

$$m_{G_V:Z,n} = m_{G_V:R_{e,B},n} \cdot m_{R_{e,B}:Z,n} \quad \text{(Equ. SM 29)}$$

where $\delta_{Re,B:Z,n}$ (relative radius of curvature) corresponds to the ratio between the radius of curvature of the semicircular canal n and its value predicted from the body size variable.

$m_{\omega 2:Z,n}$ is predicted to be negative, while $m_{GV:Z,n}$ is predicted to be positive (Jones and Spells 1963).

We note that, in a given plane of rotation, the average frequency of head motion f_H is related to the average angular velocity $\dot{\Omega}_H$ and average angular amplitude A_H of head motion, such that:

$$f_H = \frac{\dot{\Omega}_H}{A_H} \text{ (Equ. SM 30)}$$

These three parameters are also expected to be related to body size parameters, following the formulae:

$$f_H = \delta_{f_H:Z} b_{f_H:Z} Z^{m_{f_H:Z}} \text{ (Equ. SM 31)}$$

,

$$\dot{\Omega}_H = \delta_{\dot{\Omega}_H:Z} b_{\dot{\Omega}_H:Z} Z^{m_{\dot{\Omega}_H:Z}} \text{ (Equ. SM 32)}$$

and

$$A_H = \delta_{A_H:Z} b_{A_H:Z} Z^{m_{A_H:Z}} \text{ (Equ. SM 33)}$$

Where $m_{fH:Z}$ and $m_{\Omega H:Z}$ are both predicted to be negative (Jones and Spells 1963), with absolute values expected to be several orders of magnitude higher than $m_{AH:Z}$.

To simplify functional comparisons, we introduce the parameter K_H, which represents an overall measure of head motion, such that:

$$K_H = \sqrt{f_H \dot{\Omega}_H} \text{ (Equ. SM 34)}$$

K_H is expected to be related to body size such that:

$$K_H = \delta_{K_H:Z} b_{K_H:Z} Z^{m_{K_H:Z}} \text{ (Equ. SM 35)}$$

with

$$\delta_{K_H:Z} = \delta_{f_H:Z} \sqrt{\delta_{A_H:Z}} = \frac{\delta_{\dot{\Omega}_H:Z}}{\sqrt{\delta_{A_H:Z}}} \text{ (Equ. SM 36)}$$

,

$$b_{K_H:Z} = b_{f_H:Z} \sqrt{b_{A_H:Z}} = \frac{b_{\dot{\Omega}_H:Z}}{\sqrt{b_{A_H:Z}}} \text{ (Equ. SM 37)}$$

and

$$m_{K_H:Z} = m_{f_H:Z} + \frac{m_{A_H:Z}}{2} = m_{\dot{\Omega}_H:Z} - \frac{m_{A_H:Z}}{2} \text{ (Equ. SM 38)}$$

which likely reduce to

$$m_{K_H:Z} \approx m_{f_H:Z} \approx m_{\dot{\Omega}_H:Z} \text{ (Equ. SM 39)}$$

In this context, both the upper corner frequency $\omega_{2,n}$ and the sensitivity $G_{V,n}$ of the semicircular duct n are expected to be related to the overall measure of head motion K_H, following the formulae:

$$\omega_{2,n} = \delta_{\omega_2:K_H,n} b_{\omega_2:K_H,n} K_H^{m_{\omega_2:K_H,n}} \text{ (Equ. SM 40)}$$

and

$$G_{V,n} = \delta_{G_V:K_H,n} b_{G_V:K_H,n} K_H^{m_{G_V:K_H,n}} \text{ (Equ. SM 41)}$$

where $m_{\omega2:KH,n}$ is predicted to be positive, while $m_{GV:KH,n}$ is predicted to be negative (Jones and Spells 1963).

Accounting for Equ. SM 2 and 12, it follows that:

$$\delta_{\omega_2:K_H,n} b_{\omega_2:K_H,n} K_H^{m_{\omega_2:K_H,n}} \approx \mu_{(T)} \cdot \alpha_{\omega_2,n} \cdot \beta_{\omega_2,n} \text{ (Equ. SM 42)}$$

and

$$\delta_{G_V:K_H,n} b_{G_V:K_H,n} K_H^{m_{G_V:K_H,n}} \approx \frac{1}{\mu_{(T)}} \cdot \alpha_{G_V,n} \cdot \beta_{G_V,n} \text{ (Equ. SM 43)}$$

which develop to

$$\delta_{\omega_2:K_H,n} \delta_{K_H:Z}^{m_{\omega_2:K_H,n}} b_{\omega_2:K_H,n} b_{K_H:Z}^{m_{\omega_2:K_H,n}} Z^{\left(m_{K_H:Z} \cdot m_{\omega_2:K_H,n}\right)} \approx \mu_{(T)} \cdot \alpha_{\omega_2,n} \cdot \frac{\delta_{R_{e,B}:Z,n}^{m_{\omega_2:R_{e,B},n}}}{\delta_{r_{S,B}:R_{e,B},n}^{m_{a_S:r_{S,B},n}}} b_{\omega_2:Z,n} Z^{m_{\omega_2:Z,n}} \text{ (Equ. SM 44)}$$

and

$$\delta_{G_V:K_H,n} \delta_{K_H:Z}^{m_{G_V:K_H,n}} b_{G_V:K_H,n} b_{K_H:Z}^{m_{G_V:K_H,n}} Z^{\left(m_{K_H:Z} \cdot m_{G_V:K_H,n}\right)} \approx \frac{1}{\mu_{(T)}} \cdot \alpha_{G_V,n} \cdot \frac{\sigma_{e,B,n} \delta_{r_{S,B}:R_{e,B},n}^{2m_{a_S:r_{S,B},n}} \delta_{R_{e,B}:Z,n}^{m_{G_V:R_{e,B},n}} b_{G_V:Z,n} Z^{m_{G_V:Z},n}}{\delta_{L'_{S,B}:R_{e,B},n}}$$

(Equ. SM 45)

From these equations, we deduce that:

$$m_{\omega_2:Z,n} = m_{K_H:Z} \cdot m_{\omega_2:K_H,n} \text{ (Equ. SM 46)}$$

,

$$m_{G_V:Z,n} = m_{K_H:Z} \cdot m_{G_V:K_H,n} \quad \text{(Equ. SM 47)}$$

and of particular interest for this study:

$$\mu_{(T)} \cdot \alpha_{\omega_2,n} \cdot \frac{\delta_{R_{e,B}:Z,n}^{m_{\omega_2:R_{e,B},n}}}{\delta_{r_{S,B}:R_{e,B},n}^{m_{a_S:r_{S,B},n}}} b_{\omega_2:Z,n} \approx \delta_{\omega_2:K_H,n} \delta_{K_H:Z}^{m_{\omega_2:K_H,n}} b_{\omega_2:K_H,n} b_{K_H:Z,n}^{m_{\omega_2:K_H,n}} \quad \text{(Equ. SM 48)}$$

and

$$\frac{1}{\mu_{(T)}} \cdot \alpha_{G_V,n} \cdot \frac{\sigma_{e,B,n} \delta_{r_{S,B}:R_{e,B},n}^{2m_{a_S:r_{S,B},n}} \delta_{R_{e,B}:Z,n}^{m_{G_V:R_{e,B},n}} b_{G_V:Z,n}}{\delta_{L'_{S,B}:R_{e,B},n}} \approx \delta_{G_V:K_H,n} \delta_{K_H:Z}^{m_{G_V:K_H,n}} b_{G_V:K_H,n} b_{K_H:Z}^{m_{G_V:K_H,n}} \quad \text{(Equ. SM 49)}$$

Equations SM 48 and 49 can be re-expressed as:

$$\frac{\mu_{(T)}}{\delta_{K_H:Z}^{m_{\omega_2:K_H,n}} \delta_{\omega_2:K_H,n}} c_{\omega_2,n} \approx \frac{1}{\alpha_{\omega_2,n}} \cdot \frac{\delta_{r_{S,B}:R_{e,B},n}^{m_{a_S:r_{S,B},n}}}{\delta_{R_{e,B}:Z,n}^{m_{\omega_2:R_{e,B},n}}} \quad \text{(Equ. SM 50)}$$

and

$$\mu_{(T)} \delta_{K_H:Z}^{m_{G_v:K_H,n}} \delta_{G_V:K_H,n} c_{G_V,n} \approx \alpha_{G_V,n} \cdot \frac{\sigma_{e,B,n} \delta_{r_{S,B}:R_{e,B},n}^{2m_{a_S:r_{S,B},n}} \delta_{R_{e,B}:Z,n}^{m_{G_V:R_{e,B},n}}}{\delta_{L'_{S,B}:R_{e,B},n}} \quad \text{(Equ. SM 51)}$$

where

$$c_{\omega_2,n} = \frac{b_{\omega_2:Z,n}}{b_{K_H:Z}^{m_{\omega_2:K_H,n}} b_{\omega_2:K_H,n}} \quad \text{(Equ. SM 52)}$$

and

$$c_{G_V,n} = \frac{b_{G_V:K_H,n} b_{K_H:Z}^{m_{G_V:K_H,n}}}{b_{G_V:Z,n}} \quad \text{(Equ. SM 53)}$$

are constants.

We note that endolymph viscosity is related to body temperature such that (David et al. 2016):

$$\mu_{(T)} = A_W \cdot \mu_{e/w} \cdot 10^{\left(\frac{C_{T_1}}{T - C_{T_2}}\right)} \quad \text{(Equ. SM 54)}$$

Where A_w corresponds the viscosity coefficient of water and equals 0.0241 mPa.s, $\mu_{e/w}$ corresponds to a ratio between the viscosity coefficients of endolymph and water, T corresponds to body temperature in Kelvin and C_{T1} and C_{T2} equal 247.8 K and 140 K respectively.

Taking this into account, we re-express equations SM 50 and 51 as:

$$\frac{10^{\left(\frac{C_{T_1}}{T-C_{T_2}}\right)}}{\delta_{K_H:Z}^{m_{\omega_2:K_H,n}}\delta_{\omega_2:K_H,n}}c_{\omega_2,n}\approx\frac{1}{A_W.\mu_{e/w}}\cdot\frac{1}{\alpha_{\omega_2,n}}\cdot\frac{\delta_{r_{S,B}:R_{e,B},n}^{m_{a_S:r_{S,B},n}}}{\delta_{R_{e,B}:Z,n}^{m_{\omega_2:R_{e,B},n}}}\quad\text{(Equ. SM 55)}$$

and

$$10^{\left(\frac{C_{T_1}}{T-C_{T_2}}\right)}\delta_{K_H:Z}^{m_{G_v:K_H,n}}\delta_{G_V:K_H,n}c_{G_V,n}\approx\frac{1}{A_W.\mu_{e/w}}\cdot\alpha_{G_V,n}\cdot\frac{\sigma_{e,B,n}\delta_{r_{S,B}:R_{e,B},n}^{2m_{a_S:r_{S,B},n}}\delta_{R_{e,B}:Z,n}^{m_{G_V:R_{e,B},n}}}{\delta_{L'_{S,B}:R_{e,B},n}}\quad\text{(Equ. SM 56)}$$

Taking the decimal logarithm of both terms of these equations, we get:

$$\begin{gathered}\left(\frac{C_{T_1}}{T-C_{T_2}}\right)-m_{\omega_2:K_H,n}\log_{10}\left(\delta_{K_H:Z}\right)-\log_{10}\left(\delta_{\omega_2:K_H,n}\right)+\log_{10}\left(c_{\omega_2,n}\right)\\\approx-\log_{10}\left(A_W.\mu_{e/w}\right)-\log_{10}\left(\alpha_{\omega_2,n}\right)+\log_{10}\left(\frac{\delta_{r_{S,B}:R_{e,B},n}^{m_{a_S:r_{S,B},n}}}{\delta_{R_{e,B}:Z,n}^{m_{\omega_2:R_{e,B},n}}}\right)\end{gathered}\quad\text{(Equ. SM 57)}$$

and

$$\begin{gathered}\left(\frac{C_{T_1}}{T-C_{T_2}}\right)+m_{G_v:K_H,n}\log_{10}\left(\delta_{K_H:Z}\right)+\log_{10}\left(\delta_{G_V:K_H,n}\right)+\log_{10}\left(c_{G_V,n}\right)\\\approx-\log_{10}\left(A_W.\mu_{e/w}\right)+\log_{10}\left(\alpha_{G_V,n}\right)+\log_{10}\left(\frac{\sigma_{e,B,n}\delta_{r_{S,B}:R_{e,B},n}^{2m_{a_S:r_{S,B},n}}\delta_{R_{e,B}:Z,n}^{m_{G_V:R_{e,B},n}}}{\delta_{L'_{S,B}:R_{e,B},n}}\right)\end{gathered}\quad\text{(Equ. SM 58)}$$

From equations SM 57 and 58 we define the Thermo-Motility Index $TMI_{P,n,Z}$ of the semicircular duct n as:

$$\mathrm{TMI}_{P,n,Z} \approx I_{B,P,n,Z} + I_{M,P,n} + I_E \approx \left(f\left(K_{H:Z}\right) + \varepsilon_{P:K_H,n,Z}\right) - \left(\frac{C_{T_1}}{T + C_{T_2}}\right) + C_{P,n,Z} \text{ (Equ. SM 59)}$$

where

$$f\left(K_{H:Z}\right) = m_{\omega_2:K_H,n} \log_{10}\left(\delta_{K_H:Z}\right) \approx -\left(m_{G_V:K_H,n} \log_{10}\left(\delta_{K_H:Z}\right)\right) \text{ (Equ. SM 60)}$$

,

$$\varepsilon_{\omega_2:K_H,n,Z} = \log_{10}\left(\delta_{\omega_2:K_H,n}\right) \text{ (Equ. SM 61)}$$

,

$$\varepsilon_{G_V:K_H,n,Z} = -\log_{10}\left(\delta_{G_V:K_H,n}\right) \text{ (Equ. SM 62)}$$

and

$$C_{P,n,Z} = -\log_{10}\left(c_{P,n}\right) \text{ (Equ. SM 63)}$$

In these formula $I_{B,P,n,Z}$, $I_{M,P,n}$ and I_E respectively stand for the bony, membranous-only and endolymph parts of the TMI; P corresponds to either the upper corner frequency or sensitivity of the semicircular duct n and Z corresponds to the body size variable (body mass, condylobasal length or condyle-anteroorbital length); $f(K_{H:Z})$ is a function that positively correlates to overall head motion K_H relative to body size, and reflects behavioural activity; $C_{p,n,Z}$, C_{T1} and C_{T2} are constants and $\varepsilon_{P:KH,n,Z}$ is an error term reflecting the difference between semicircular duct function and head motion metrics.

As endotherms show increased body temperatures and are behaviourally more active than ectotherms, which is likely reflected by increased overall head motion, they are clearly expected, from equation SM 59, to show higher TMI. In this context, it should be noted that the error term $\varepsilon_{P:KH,n,Z}$, whose statistical distribution should be similar between endotherms and ectotherms, is expected to differ between species, affecting their TMI. However, the effect of the error term should be averaged out when comparing groups, provided enough species have been sampled.

The endolymph part of the TMI is expressed as:

$$I_E = \log_{10}\left(A_W . \mu_{e/w}\right) \text{ (Equ. SM 64)}$$

where A_w corresponds the viscosity coefficient of water and equals 0.0241 mPa.s and $\mu_{e/w}$ corresponds to a ratio between the viscosity coefficients of endolymph and water.

Bony parts of the TMI are expressed as:

$$I_{B,\omega_2,n,Z} = \log_{10}\left(\frac{\delta_{R_{e,B}:Z,n}^{m_{\omega_2:R_{e,B},n}}}{\delta_{r_{S,B}:R_{e,B},n}^{m_{a_S:r_{S,B},n}}}\right) \text{ (Equ. SM 65)}$$

and

$$I_{B,G_V,n,Z} = \log_{10}\left(\frac{\delta_{L'_{S,B}:R_{e,B},n}}{\sigma_{e,B,n}\,\delta_{r_{S,B}:R_{e,B},n}^{2m_{a_S:r_{S,B},n}}\,\delta_{R_{e,B}:Z,n}^{m_{G_V:R_{e,B},n}}}\right) \text{ (Equ. SM 66)}$$

where:

$\delta_{Re,B:Z,n}$ (relative radius of curvature) corresponds to the ratio between the radius of curvature of the semicircular canal n and its value predicted from the body size variable.

$\delta_{rS,B:Re,B,n}$ (relative canal thickness) corresponds to the ratio between the cross-sectional radius of the slender portion of the semicircular canal n and its value predicted from the corresponding radius of curvature.

$\delta_{LS',B:Re,B,n}$ (relative slender length) corresponds to the ratio between the two-dimensional length of the slender portion of the semicircular canal n and its value predicted from the corresponding radius of curvature.

$\sigma_{e,B,n}$ (eccentricity factor) corresponds to a ratio, between the area of an ellipse and its squared average radius, which negatively correlates with the eccentricity $e_{B,n}$ of the semicircular canal torus n.

Membranous-only parts of the TMI are expressed as:

$$I_{M,\omega_2,n} = \log_{10}\left(\frac{\lambda_{\mu,S,n}}{2\rho\pi\delta_{a_S:r_{S,B}+R_{e,B},n}}\right) \text{ (Equ. SM 67)}$$

and

$$I_{M,G_V,n} = I_{M,\omega_2,n} + \log_{10}\left(\frac{\pi\varepsilon_{L'_S,n}}{\varepsilon_{\Lambda,n}\,\delta_{a_S:r_{S,B}+R_{e,B},n}\,\delta_{E:R_{e,B},n}}\right) \text{ (Equ. SM 68)}$$

where:

ρ is the density of the endolymph.

$\lambda_{\mu,S,n}$ is the average wall shape drag factor of the slender portion of the semicircular duct n.

$\delta_{aS:rS,B+Re,B,n}$ (relative duct thickness) corresponds to the ratio between the cross-sectional area of the slender portion of the semicircular duct n and its value predicted from the the combination of the cross-sectional radius of the slender portion of the corresponding semicircular canal and the corresponding radius of curvature.

$\delta_{E:Re,B,n}$ (relative deflection factor) corresponds to the ratio between the deflection factor of the semicircular duct n and its value predicted from the radius of curvature of the corresponding semicircular canal.

$\varepsilon_{\Lambda,n}$ (area error factor) corresponds to a ratio between the enclosed area of the torus of the semicircular duct n and the area of the ellipse best fitting the torus of the corresponding semicircular canal, both projected on their respective maximal response planes

$\varepsilon_{LS',n}$ (slender length error factor) corresponds to a ratio between the three-dimensional length of the slender portion of the semicircular duct n and the two-dimensional length of the slender portion of corresponding semicircular canal.

Exponents $m_{\omega 2:Re,B,n}$, $m_{aS:rS,B,n}$ and $m_{GV:Re,B,n}$ were computed in R, using measured morphological parameters and applying phylogenetic least square regressions on relevant datasets, following equations SM 4, 6, 9, 20, 16 and 22 (Supplementary Note 2). Their value is provided in the following table:

	Anterior	Posterior	Lateral
$m_{aS:rS,B}$	1.140	0.876	0.824
$m_{\omega 2:Re,B}$	-1.083	-1.149	-0.992
$m_{GV:Re,B}$	0.890	1.062	0.811

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Jones, G. M. & Spells, K. E. A theoretical and comparative study of the functional dependence of the semicircular canal upon its physical dimensions. *Proc. R. Soc. Lond. Ser. B. Biol. Sci.* **157**, 403-419 (1963).

Rabbitt, R. D., Damiano, E. R. & Grant J. W. in *The vestibular system* (eds Highstein, S. M., Fay R. R. & Popper A. N.) 153–201 (Springer, 2004).

Discussion on the endolymph viscosity of diapsids

The phylogenetic distribution of the endolymph part in available species indicates that a low-viscosity endolymph was the basal condition for Euarchontoglires and Euteleostei, thus parsimoniously the basal condition for Osteichtyes too. Conversely, feral rock pigeons, which possess a high-viscosity endolymph, do not show any peculiarities in terms of locomotor behaviours, body temperature or labyrinth morphology when compared to other birds. We thus assume that a high-viscosity endolymph is typical for Aves. This raises the question as to when a high-viscosity endolymph originated in diapsids. Data from audition in various lizard species suggest that an endolymph with water-like viscosity would better fit empirical results in these species (Manley 2006, 2014). These results indicate that a high-viscosity endolymph would be unlikely for lepidosaurs, and the acquisition of a high-viscosity endolymph would have occurred between the origin of birds and the divergence of Lepidosauria and Archelosauria. In this context it should be noted that Crocodilia and Testudines are in line with the theoretical and empirical relationships between the TMI and body temperature (Fig. 2), which suggests, *a posteriori*, the retention of a low-viscosity endolymph part in these taxa.

Manley, G. A. Spontaneous otoacoustic emissions from free-standing stereovillar bundles of ten species of lizard with small papillae. *Hearing Res*. **212**, 33-47 (2006).

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Supplementary Note 1. *Dimetrodon* inner ear reconstruction from a serial sectioned model

The *Dimetrodon* specimen used in this study (FMNH PR 4976) is a wax endocast model that was reconstructed from a serially-sectioned skull. The inclusion of the specimen was paramount because, despite our efforts to scan multiple non-therapsid synapsids (Supplementary Data 3), only one retrieved usable data. The FMNH collections records do not include information on the original specimen that was sectioned to make the endocast model. However, comments in Olson (1938; also see Romer and Price, 1940) and notes from A. S. Romer preserved in the Museum of Comparative Zoology archives suggest that the endocast was reconstructed from serial sections of MCZ 9560. For measurement purposes, a photogrammetric model of FMNH PR 4976 was created based on 50 individual photographs of the specimen. The model was reconstructed using Colmap 3.5 (https://colmap.github.io/index.html). The endocast is comprised of about 30 slices with an average thickness of 2.147 mm, resulting in a total length of 64.42 mm. We estimate that the condylobasal length of MCZ 9560 was about 260 mm, so the model clearly has been scaled up from the original size of the bony labyrinth. In his description of his serial sectioning technique, Olson (1944; p.9) states: "In cases of skulls under 40mm in length, it has proved very difficult to obtain evenly spaced sections since they should not be over .15mm apart. Intervals of .3 mm to .5 mm are satisfactory for skulls between 50 and 65 mm, and intervals of .75 mm for those between 65 and 100 mm. The best results have been obtained with skulls of over 100 mm by using intervals of .6 to .8mm in the otic region of the brain cases and intervals of 1.0 to 1.5mm for the more anterior parts of the skulls." He also lists slice thickness ranging from 0.37 mm to 1.1 mm (average 0.744 mm) for the specimens he describes in that work. Based on those values, we estimate that the endocast has been scaled up by a factor of between 2.68x (0.8mm slice thickness) to 3.58x (0.6 mm slice thickness), as suggested by the original publications (Olson 1938, 1944, Romer et al. 1940) and notes of A. S. Romer. Hence, measurements taken on the wax model were corrected by the average scaling factor. Using either factor instead of the average does not affect the conclusions of the study.

Olson, E. C. The occipital, otic, basicranial and pterygoid regions of the Gorgonopsia. *J. Morphol.* **62**,141–175 (1938).

Olson, E. C. Origin of mammals based upon cranial morphology of the therapsid suborders. *Geol. Soc. Am.*, **55** (1944).

Romer, A. S., Price, L. W. & Price, L. I. Review of the Pelycosauria. *Geol. Soc. Am.* **28**(1940).

Supplementary Note 2. Summary of the statistics.

Abbreviations

Body mass: **BM**

Condylobasal length: **CBL**
Condylo-anteroorbital length: **CAOL**
3D Bony dataset: **3DB**
3D Membranous dataset: **3DM**
2D Membranous dataset: **2DM**
Anterior canal/duct: **_a**
Posterior canal/duct: **_p**
Lateral canal/duct: **_l**
Bony semicircular canals: **_B**

Radius of curvature: **R**
Cross-sectional area of the middle section of the cupula: **aC_ _Md**
Average thickness of the crista ampullaris: **tCr**
Cross-section radius of the slender portion: **rS**
Length of the slender portion: **LS**
Cross-sectional area of the slender portion of the membranous semicircular duct: **aS**
Height of the cilia area: **hc**
Average thickness of the cupula: **tC**
Transverse diameter of the slender part (including the walls): **dS_ _Out**
Deflection factor of the cupula: **E**
Temperature ratio: **RT**
Upper corner frequency: **ω_2**
Sensitivity: **Gv**
Thermo-Motility Index: **TMI**
Thermic regime: **TR**
Phylogenetic generalized least square regression: **PGLS-R**

PGLS-R of height of cilia areas of cristae ampullares of semicircular ducts against corresponding average cristae thicknesses and cross-sectional areas of middle sections of cupulae

	Intercept	Log$_{10}$(tCr_a)		Pagel's λ	adj. R^2	p-value	AICc	N
Log$_{10}$(hc_a)	1.797	0.387		0.88	0.71	**8.93 10^{-13}**	-97.9	43 (3DM)
	Intercept	Log$_{10}$(tCr_p)		Pagel's λ	adj. R^2	p-value	AICc	N
Log$_{10}$(hc_p)	1.798	0.368		1.00	0.67	**1.55 10^{-11}**	-98.2	43 (3DM)
	Intercept	Log$_{10}$(tCr_l)	Log$_{10}$(aC_l_Md)	Pagel's λ	adj. R^2	p-value	AICc	N
Log$_{10}$(hc_l)	1.904	0.369	0.140	0.90	0.66	**1.39 10^{-10}**	-100.4	43 (3DM)

Only specimens with measurements of height of cilia areas were included.

PGLS-R of deflection factors of cupulae against corresponding average thicknesses of cupulae models and cross-sectional areas of middle sections of cupulae

	Intercept	Log$_{10}$(tC_a)	Log$_{10}$(aC_a_Md)	Pagel's λ	adj. R^2	p-value	AICc	N
Log$_{10}$(E_a)	-0.431	0.422	-1.718	0.98	0.99	**< 2.2 10^{-16}**	-154.2	43 (3DM)
	Intercept	Log$_{10}$(tC_p)	Log$_{10}$(aC_p_Md)	Pagel's λ	adj. R^2	p-value	AICc	N
Log$_{10}$(E_p)	-0.408	0.479	-1.739	0.95	0.99	**< 2.2 10^{-16}**	-153.3	43 (3DM)
	Intercept	Log$_{10}$(tC_l)	Log$_{10}$(aC_l_Md)	Pagel's λ	adj. R^2	p-value	AICc	N
Log$_{10}$(E_l)	-0.417	0.364	-1.655	0.82	1.00	**< 2.2 10^{-16}**	-184.0	43 (3DM)

Only specimens with measurements of deflection factors were included.

PGLS-R of transverse diameters with wall included against corresponding cross-sectional areas of slender portions of membranous semicircular ducts

	Intercept	Log$_{10}$(aS_a)	Log$_{10}$(aS_p)	Log$_{10}$(aS_l)	Pagel's λ	adj. R^2	p-value	N
Log$_{10}$(dS_a_Out)	0.205	0.544			0.39	0.85	**< 2.2 10^{-16}**	47 (3DM+2DM)
Log$_{10}$(dS_p_Out)	0.209		0.532		0.52	0.82	**< 2.2 10^{-16}**	47 (3DM+2DM)
Log$_{10}$(dS_l_Out)	0.227			0.544	0.72	0.85	**< 2.2 10^{-16}**	47 (3DM+2DM)

Only specimens with measurements of cross-sectional areas and transverse diameter (with walls) were included.

PGLS-R of cross-section radii of slender portions against corresponding transverse diameters with wall included

	Intercept	Log$_{10}$(dS_a_Out)	Pagel's λ	adj. R^2	p-value	AICc	N
Log$_{10}$(rS_a_B)	-0.023	1.291	0.66	0.97	**< 2.2 10^{-16}**	-66.2	22 (3DM)
	Intercept	Log$_{10}$(dS_p_Out)	Pagel's λ	adj. R^2	p-value	AICc	N
Log$_{10}$(rS_p_B)	0.017	1.315	0.00	0.93	**1.56 10^{-13}**	-50.9	22 (3DM)
	Intercept	Log$_{10}$(dS_l_Out)	Pagel's λ	adj. R^2	p-value	AICc	N
Log$_{10}$(rS_l_B)	0.021	1.286	0.35	0.88	**7.92 10^{-11}**	-38.6	22 (3DM)

Only specimens with measurements of cross-section radii and transverse diameter (with walls) were included.

PGLS-R of body mass against condylobasal and condylo-anteroorbital lengths

	Intercept	Log$_{10}$(CBL)	Log$_{10}$(CAOL)	Pagel's λ	adj. R^2	p-value	N
Log$_{10}$(BM)	-2.441	1.181	2.162	0.86	0.89	**< 2.2 10^{-16}**	233 (3DB)

Only specimens with measurements of body mass were included.

PGLS-R of cross-section radii and lengths of slender portions of bony semicircular canals against corresponding radii of curvature

	Intercept	Log$_{10}$(R_a_B)	Log$_{10}$(R_p_B)	Log$_{10}$(R_l_B)	Pagel's λ	adj. R^2	p-value	N
Log$_{10}$(rS_a_B)	-0.766	0.799			0.74	0.71	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(rS_p_B)	-0.735		0.811		0.68	0.71	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(rS_l_B)	-0.785			0.829	0.56	0.74	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(LS_a_B)	0.570	1.010			0.67	0.94	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(LS_p_B)	0.596		0.994		0.58	0.95	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(LS_l_B)	0.654			0.969	0.67	0.94	**< 2.2 10^{-16}**	298 (3DB)

PGLS-R of deflection factors of cupulae against corresponding radii of curvature

	Intercept	Log$_{10}$(R_a_B)	Log$_{10}$(R_p_B)	Log$_{10}$(R_l_B)	Pagel's λ	adj. R^2	p-value	N
Log$_{10}$(E_a)	2.059	-2.266			0.00	0.87	**< 2.2 10^{-16}**	43 (3DM)
Log$_{10}$(E_p)	1.947		-2.241		0.48	0.90	**< 2.2 10^{-16}**	43 (3DM)
Log$_{10}$(E_l)	1.971			-2.204	0.00	0.90	**< 2.2 10^{-16}**	43 (3DM)

Only specimens with measurements of deflection factors were included.

PGLS-R of cross-sectional areas of slender portions of membranous semicircular ducts against corresponding radii of curvature

	Intercept	Log$_{10}$(rS_a_B)	Log$_{10}$(R_a_B)	Pagel's λ	adj. R^2	p-value	N
Log$_{10}$(aS_a)	-0.497	1.174	0.164	0.70	0.87	**< 2.2 10^{-16}**	47 (3DM)
	Intercept	Log$_{10}$(rS_p_B)	Log$_{10}$(R_p_B)	Pagel's λ	adj. R^2	p-value	N
Log$_{10}$(aS_p)	-0.710	0.927	0.420	0.83	0.86	**< 2.2 10^{-16}**	47 (3DM)
	Intercept	Log$_{10}$(rS_l_B)	Log$_{10}$(R_l_B)	Pagel's λ	adj. R^2	p-value	N
Log$_{10}$(aS_l)	-0.845	0.829	0.372	0.59	0.80	**< 2.2 10^{-16}**	47 (3DM)

Only specimens with measurements of cross-section radii of bony canals were included.

PGLS-R of radii of curvature against the square root of body mass and condylobasal and condylo-anteroorbital lengths

	Intercept	Log$_{10}$(√BM)	Log$_{10}$(CBL)	Log$_{10}$(CAOL)	Pagel's λ	adj. R^2	p-value	N
Log$_{10}$(R_a_B)	-0.232	0.483			0.93	0.75	**< 2.2 10^{-16}**	233 (3DB)
Log$_{10}$(R_p_B)	-0.285	0.485			0.89	0.74	**< 2.2 10^{-16}**	233 (3DB)
Log$_{10}$(R_l_B)	-0.197	0.475			0.93	0.71	**< 2.2 10^{-16}**	233 (3DB)
Log$_{10}$(R_a_B)	-0.632		0.544		0.79	0.70	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(R_p_B)	-0.673		0.536		0.84	0.68	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(R_l_B)	-0.580		0.536		0.80	0.68	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(R_a_B)	-0.623			0.610	0.76	0.73	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(R_p_B)	-0.687			0.616	0.76	0.75	**< 2.2 10^{-16}**	298 (3DB)
Log$_{10}$(R_l_B)	-0.584			0.610	0.71	0.73	**< 2.2 10^{-16}**	298 (3DB)

Only extant specimens with measurements of body mass were included in relevant regressions.

PGLS-R of the temperature ratio against 18 models for the TMI, resulting from all possible combinations between 3 semicircular ducts, 2 functional parameters and 3 body size parameters

	Intercept	TMI_ω_2_a_√BM	TMI_ω_2_p_√BM	TMI_ω_2_l_√BM	Pagel's λ	adj. R^2	p-value	N
RT	1.277	-0.305			0.00	0.83	**$8.62\ 10^{-12}$**	28 (3DB+3DM+2DM)
RT	1.270		-0.309		0.00	0.79	**$2.05\ 10^{-10}$**	28 (3DB+3DM+2DM)
RT	1.356			-0.256	1.00	0.41	**$1.55\ 10^{-4}$**	28 (3DB+3DM+2DM)
	Intercept	TMI_Gv_a_√BM	TMI_Gv_p_√BM	TMI_Gv_l_√BM	Pagel's λ	adj. R^2	p-value	N
RT	1.420	-0.173			1.00	0.59	**$1.16\ 10^{-6}$**	28 (3DB+3DM+2DM)
RT	1.443		-0.175		1.00	0.45	**$6.06\ 10^{-5}$**	28 (3DB+3DM+2DM)
RT	1.468			-0.166	1.00	0.30	**$1.59\ 10^{-3}$**	28 (3DB+3DM+2DM)
	Intercept	TMI_ω_2_a_CBL	TMI_ω_2_p_CBL	TMI_ω_2_l_CBL	Pagel's λ	adj. R^2	p-value	N
RT	1.307	-0.296			0.43	0.74	**$2.90\ 10^{-9}$**	28 (3DB+3DM+2DM)
RT	1.371		-0.246		1.00	0.46	**$3.97\ 10^{-5}$**	28 (3DB+3DM+2DM)
RT	1.386			-0.242	1.00	0.40	**$1.65\ 10^{-4}$**	28 (3DB+3DM+2DM)
	Intercept	TMI_Gv_a_CBL	TMI_Gv_p_CBL	TMI_Gv_l_CBL	Pagel's λ	adj. R^2	p-value	N
RT	1.433	-0.170			1.00	0.59	**$1.04\ 10^{-6}$**	28 (3DB+3DM+2DM)
RT	1.467		-0.163		1.00	0.43	**$9.62\ 10^{-5}$**	28 (3DB+3DM+2DM)
RT	1.491			-0.151	1.00	0.28	**$2.37\ 10^{-3}$**	28 (3DB+3DM+2DM)
	Intercept	TMI_ω_2_a_CAOL	TMI_ω_2_p_CAOL	TMI_ω_2_l_CAOL	Pagel's λ	adj. R^2	p-value	N
RT	1.294	-0.302			0.32	0.72	**$6.36\ 10^{-9}$**	28 (3DB+3DM+2DM)
RT	1.375		-0.238		1.00	0.40	**$2.04\ 10^{-4}$**	28 (3DB+3DM+2DM)
RT	1.363			-0.261	1.00	0.39	**$2.31\ 10^{-4}$**	28 (3DB+3DM+2DM)
	Intercept	TMI_Gv_a_CAOL	TMI_Gv_p_CAOL	TMI_Gv_l_CAOL	Pagel's λ	adj. R^2	p-value	N
RT	1.437	-0.165			1.00	0.54	**$4.68\ 10^{-6}$**	28 (3DB+3DM+2DM)
RT	1.475		-0.152		1.00	0.37	**$3.86\ 10^{-4}$**	28 (3DB+3DM+2DM)
RT	1.490			-0.150	1.00	0.25	**$3.78\ 10^{-3}$**	28 (3DB+3DM+2DM)

In these regressions we used average values for the clades Acanthopterygii, Anguimorpha, Anura, Atlantogenata, Batoidea, Caudata, Crocodylia, Elopomorpha, Euarchontoglires, Galloanserae, Gekkota, Gymnophiona, Holocephali, Iguania, Lacertoidea, Laurasiatheria, Marsupialia, Monotremata, Neoaves, Otocephala, Palaeognathae, Paracanthopterygii, Protacanthopterygii, Rhynchocephalia, Scincomorpha, Selachii, Serpentes and Testudines. Only specimens with measurements of body temperature were included. These groups were chosen to best balance taxonomic sampling with robust averaging of TMI.

Akaike information criterion of 18 models for the TMI, and resulting weights used in model averaging

Model	AICc	Akaike Weights
TMI_ω_2_a_√BM	-93.4	0.135
TMI_ω_2_p_√BM	-86.6	0.005
TMI_ω_2_l_√BM	-84.1	0.001
TMI_Gv_a_√BM	-94.4	0.224
TMI_Gv_p_√BM	-86.1	0.004
TMI_Gv_l_√BM	-79.4	0.000
TMI_ω_2_a_CBL	-94.9	0.288
TMI_ω_2_p_CBL	-86.9	0.005
TMI_ω_2_l_CBL	-84.0	0.001
TMI_Gv_a_CBL	-94.6	0.249
TMI_Gv_p_CBL	-85.1	0.002
TMI_Gv_l_CBL	-78.6	0.000
TMI_ω_2_a_CAOL	-90.5	0.032
TMI_ω_2_p_CAOL	-83.5	0.001
TMI_ω_2_l_CAOL	-83.3	0.001
TMI_Gv_a_CAOL	-91.4	0.051
TMI_Gv_p_CAOL	-82.2	0.001
TMI_Gv_l_CAOL	-77.6	0.000

PGLS-R of the temperature ratio against the weighted TMI, using species values or group averages

	Intercept	TMI	Pagel's λ	adj. R^2	p-value	N
RT	1.618	-0.018	0.99	0.01	0.11	230 (3DB+3DM+2DM)
RT	1.347	-0.248	0.27	0.80	**$9.45\ 10^{-11}$**	28 (3DB+3DM+2DM)

Only specimens with measurements of body temperature were included. The first regression is based on all relevant specimens, while the second regression is based on average values for the clades Acanthopterygii, Anguimorpha, Anura, Atlantogenata, Batoidea, Caudata, Crocodylia, Elopomorpha, Euarchontoglires, Galloanserae, Gekkota, Gymnophiona, Holocephali, Iguania, Lacertoidea, Laurasiatheria, Marsupialia, Monotremata, Neoaves, Otocephala, Palaeognathae, Paracanthopterygii, Protacanthopterygii, Rhynchocephalia, Scincomorpha, Selachii, Serpentes and Testudines.

Logistic regression of the thermic regime against the weighted TMI

	Intercept	p-value	TMI	p-value	AIC	N
TR	7.09	$7.32\ 10^{-13}$	10.080	$1.26\ 10^{-12}$	118.04	180 (3DB)

Only amniote specimens with measurements of body temperature were included.

Phylogenetic logistic regression of the thermic regime against the weighted TMI

	Intercept	p-value	TMI	p-value	N
TR	4.942	0.083	6.928	0.041	180 (3DB)

Only amniote specimens with measurements of body temperature were included.

Supplementary Note 3. Divergence times and Last Occurrence Datum

Divergence Times

Common ancestor of *Diadectes* and Amniota: The relationships of diadectomorphs are controversial. They have often been recovered as the sister group of Amniota (e.g., Gauthier et al. 1988; Laurin & Reisz 1995, 1997; Lee & Spencer 1997; Kissel & Reisz 2004a; Reisz 2007; Kissel 2010; Liu & Bever 2015; Laurin & Piñeiro 2017; Ford and Benson 2019), but other analyses have recovered them nested within Amniota, either as the sister taxon of Sauropsida (Ruta et al. 2003; Ruta & Coates 2007; Marjanović & Laurin 2019) or Synapsida (Sumida et al. 1992; Berman et al. 1992; Berman 2000; Berman 2013). Here, we used the "traditional" hypothesis that diadectomorphs are the sister group of amniotes, although we acknowledge that this is an area of continuing research. Despite this stemward position, the known fossil record of diadectomorphs begins after the first appearances of Synapsida and Sauropsida. The oldest records of diadectomorphs are occurrences of *Desmatodon* in the Kasimovian (Late Pennsylvanian) Sangre de Cristo Formation of Colorado and the Red Knob Formation of Pennsylvania (Reisz 2007; Kissel 2010). The nested position of *Desmatodon* within Diadectomorpha and the stratigraphic ranges of other taxa in the clade imply that much of the earliest history of the clade is not recorded (Reisz 2007; Kissel 2010). Therefore, it is necessary to turn to other taxa to calibrate the time of origin of Amniota.

Benton et al. (2015) used the Visean (Middle Mississippian) aïstopod *Lethiscus stocki* to calibrate the divergence of crown Tetrapoda, reflecting the hypothesis that aïstopods are members of Lepospondyli and thus part of total group Amniota (e.g., Ruta et al. 2003; Ruta and Coates 2007). However, reconsideration of the phylogenetic relationships of aïstopods has raised the possibility that they are stem tetrapods, not members of the crown group (Pardo et al. 2017). If that hypothesis is correct, the stem lissamphibian *Balanerpeton* and the stem amniote *Westlothiana* from the upper Visean East Kirkton locality of Scotland (Pardo et al. 2017), which has been dated to 332.9–330.9 Mya (Benton et al. 2015), are the next relevant calibration points. Therefore, the divergence between diadectomorphs and crown amniotes must have occurred between the upper Visean and the Bashkirian given the first occurrences of synapsids and sauropsids in the Joggins Formation of Nova Scotia, which has been calibrated at 318 Mya (Benton et al. 2015; also see below). We use the midpoint of this age range (324.5 Mya) to calibrate the divergence of Diadectomorpha and Amniota.

Synapsida + Sauropsida: The divergence between synapsids and sauropsids occurred by the Bashkirian Stage of the Early Pennsylvanian (late Carboniferous Period). This divergence is calibrated by the presence of the sauropsid *Hylonomus lyelli* and the putative synapsids *Protoclepsydrops haplous* and *Asaphestera platyris*, which occur in the same stratigraphic horizon in the Joggins Formation of Nova Scotia (Carroll 1964; Mann et al. 2020). *Protoclepsydrops* is known from limited, fragmentary material, and its identity as a synapsid has been questioned (Reisz 1972, 1986; Mann & Paterson 2019). *Asaphestera* was long considered a ‘microsaur’, but had recently been re-identified as a synapsid, possibly a caseasaur (Mann et al. 2020). The sauropsid identity of *Hylonomus* is better supported (Müller and Reisz 2006), so its presence in the fossil record implies that synapsids and sauropsids must have diverged by this time, even if *Protoclepsydrops* and/or *Asaphestera* are not synapsids. Age estimates for the Joggins Formation range from about 319–310 million years ago (Reisz and Müller 2004, van Tuinen and Hadly 2004), and Benton et al. (2015) recommended of 318 million years ago as a minimum age for this divergence. We use a slightly older date of 320 Mya to accommodate the earliest divergences among sauropsids (see divergence between Captorhinidae and Diapsida below).

Caseasauria + Eupelycosauria: *Eocasea martinsi* and *Datheosaurus macrourus* are the oldest known relatively certain caseasaurs, and both are likely Gzhelian in age (Reisz and Fröbisch 2014; Spindler et al., 2016). However, the oldest taxa relevant for calibrating this node are the ophiacodontids *Archaeothyris florensis* and *Echinerpeton intermedium*, and the varanopid *Dendromaia unamakiensis* (assuming varnopids are synapsids; see discussion in Ford and Benson 2019) from the slightly older Morien Group of Nova Scotia (Reisz 1972; Maddin et al. 2019; Mann & Paterson 2019), which is likely Moscovian–Kasimovian in age (see discussion in van Tuinen and Hadley 2004). The presence of ophiacodontids at this time implies the caseasaurs had also diverged by this point, regardless of the recent debate on the phylogenetic relationships of early synapsids (e.g., compare the results of Benson 2012 and Brocklehurst et al. 2016). If *Asaphestera* is indeed a caseasaur (Mann et al. 2020), it would provide direct confirmation of this hypothesis. The numerical age of the divergence should be between 309.2 Mya (the older end of the range given for the age of *Archaeothyris* in van Tuinen and Hadley 2004) and 318 Mya (Benton et al.'s 2015 hard minimum for the divergence of Synapsida). 313.6 Mya is the midpoint of this range.

Sphenacodontidae + Therapsida: Sphenacodontidae is the sister taxon of Therapsida and first appears in the Kasimovian Sangre de Cristo Formation in Colorado (Sumida & Berman 1993). Potentially older sphenacodontid material has been reported from Nova Scotia (Reisz 1972), but given the uncertainty in its identification we use the Sangre de Cristo record as the oldest sphenacodontid. The oldest known therapsid material is substantially younger: the early Permian *Tetraceratops insignis* and the middle Permian *Raranimus dashankouensis* (Liu et al. 2009; Amson & Laurin 2011; although see Spindler 2014, 2020). The Kasimovian ranges in age from 307.0–303.7 Mya, and we use the midpoint of this range (305.35 Mya) as the calibration point for this divergence.

Biarmosuchia + Eutherapsida: Biarmosuchians are generally considered to be the most stemward major therapsid clade (e.g., Sidor & Hopson 1998; Liu et al. 2009, 2010), although *Raranimus dashankouensis* and *Tetraceratops insignis* likely fall even further down the therapsid stem (Liu et al. 2009; Amson & Laurin 2011; Brink et al. 2015) (and *Tetraceratops* may not be a therapsida at all; see

Conrad and Sidor 2001; Spindler 2020). Sphenacodontidae, the sister taxon of Therapsida, first appears in the Late Pennsylvanian (Sumida and Berman, 1993), but there are no known Pennsylvanian therapsids (although see Spindler 2014). Therefore, while divergences between therapsid lineages could date back to the Pennsylvanian, there is no direct evidence for this. The putative early Permian therapsid *Tetraceratops insignis* (Amson & Laurin 2011; although see Spindler 2020) does not help to resolve this issue because it does not appear to fall within any of the major therapsid clades. The divergence between biarmosuchians and other therapsids is calibrated by the oldest record of Dinocephalia. Specifically, anteosaurid dinocephalians are present in the Golyusherma Assemblage of Russia, which is considered to be early Roadian (early middle Permian) in age (Golubev 2015), making these fossils the oldest known unequivocal therapsid occurrence. The Roadian is 272.3 to 268.8 Mya, and we calibrate this divergence at 271 Mya, in part to accommodate other divergences whose timing is based on the first appearance of dinocephalians (see below).

***Hipposaurus* + Burnetiamorpha:** The biarmosuchians *Luecocephalus*, *Herpetoskylax*, and *Lemurosaurus* occur in the Wuchiapingian *Tropidostoma-Gorgonops* subzone (*Endothiodon* Assemblage Zone) and *Cistecephalus* Assemblage Zone of the Karoo Basin, South Africa (e.g., Sidor & Welman 2003; Sidor & Rubidge 2006; Day et al. 2016, 2018a; Day and Smith 2020; Smith 2020), but *Hipposaurus* is older, occurring in the Capitanian upper Abrahamskraal Formation (*Diictodon-Styracocephalus* subzone, *Tapinocephalus* Assemblage Zone) (e.g., Day et al. 2018; Day and Rubidge 2020). The divergence time of *Hipposaurus* is bracketed by the presence of the more stemward biarmosuchian *Biarmosuchus* in the likely Wordian Ocher Subassemblage of European Russia (e.g., Sennikov & Golubev 2017) and the presence of the more derived bullacephalids *Pachydectes* and *Bullacephalus* in the lunderlying *Eosimops-Glanosuchus* subzone of the *Tapinocephalus* Assemblage Zone (Day and Rubidge 2020). Lanci et al. (2013) provided an age range of 268.5–264.6 Mya for the lower Abrahamskraal Formation, and we use the lower end of this range (268.5 Mya) as the calibration point for this node.

***Herpetoskylax* + Burnetiamorpha:** The biarmosuchian *Leucocephalus* occurs in the Wuchiapingian *Tropidostoma-Gorgonops* subzone of the *Endothiodon* Assemblage Zone of the Karoo Basin, whereas *Herpetoskylax* and *Lemurosaurus* both occur in the slightly younger *Cistecephalus* Assemblage Zone of the Karoo Basin, South Africa (e.g., Sidor & Welman 2003; Sidor & Rubidge 2006; Day et al. 2016, 2018a; Day and Smith 2020; Smith 2020), but they are members of two distinct lineages of biarmosuchians that diverged earlier in the Permian. The age of this divergence depends strongly on whether the lower *Tapinocephalus* Assemblage Zone taxa *Pachydectes* and *Bullacephalus* (i.e., the Bullacephalidae) are members of the nested clade Burnetiamorpha or if they fall near the base of the biarmosuchian phylogeny (Day et al. 2016). Phylogenetic hypotheses supporting bullacephalids as burnetiamorphs are more common in the biarmosuchian literature despite their poorer overall fit to stratigraphy (e.g., Sidor & Smith 2007; Kruger et al. 2015; Day et al. 2016, 2018a; Kammerer 2016a), and we use this topology here. Lanci et al. (2013) provide dates ranging from 268.5–264.6 Mya for the lower Abrahamskraal Formation (i.e., the lower *Tapinocephalus* Assemblage Zone) so we use 265 Mya (approximate age of the Wordian-Capitanian boundary) for this calibration point.

***Lemurosaurus + Leucocephalus*:** As noted in the previous entry, *Leucocephalus* occurs in strata assigned to the *Tropidostoma-Gorgonops* Subzone (*Endothiodon* Assemblage Zone) of the Karoo Basin, whereas *Lemurosaurus* occurs in strata assigned to the *Cistecephalus* Assemblage Zone (Sidor & Welman 2003; Day et al. 2018a; Day and Smith 2020; Smith 2020). *Lemurosaurus* is typically reconstructed as the most stemward burnetiamorph (e.g., Sidor & Welman 2003; Smith et al. 2006; Kruger et al. 2015; Day et al. 2016; Kammerer 2016a), so the minimum age of this divergence is calibrated by the oldest burnetiamorph records. In addition to *Lemurosaurus*, the oldest burnetiamorphs are *Proburnetia* and *Niuksenitia*, both of which occur in the Ilinskoe faunal assemblage of Russia (e.g., Sennikov & Golubev 2017) whose early Wuchiapingian age likely falls within the *Endothiodon* Assemblage Zone of South Africa, potentially within the *Tropidostoma-Gorgonops* Subzone (Sennikov & Golubev 2017; Schneider et al. 2019; Day and Smith 2020). The *Endothiodon* Assemblage Zone is between 260.26–256.8 Mya, with the *Tropidostoma-Gorgonops* Subzone being about 258 – 256.8 Mya (Rubidge et al. 2013; Day et al. 2015; Day and Smith 2020), and we calibrate this divergence at 260 Mya to allow time for the multiple burnetiamorph lineages to diverge before their first appearances in Russia and South Africa.

Dinocephalia + Neotherapsida: As with the divergence between biarmosuchians and Eutherapsida, this divergence is calibrated by the first appearance of dinocephalians in the Roadian Golyusherma Assemblage of Russia (Golubev 2015). We calibrate this divergence at 270 Mya, placing it in the Roadian, but slightly after the divergence of Biarmosuchians and eutherapsids.

Anomodontia + Theriodontia: The exact time of divergence between Anomodontia and Theriodontia (i.e., Gorgonopsia + Therocephalia + Cynodontia) is somewhat uncertain. In South Africa, anomodonts, therocephalians, and very fragmentary gorgonopsian remains are known from the *Eodicynodon* Assemblage zone in the Abrahamskraal Formation (e.g., Abdala et al. 2008; Day et al. 2018; Rubidge and Day 2020). Dates from near the base of this formation range from 268.5–264.6 Mya (Lanci et al. 2013). The portion of the formation corresponding to the overlying *Tapinocephalus* Assemblage Zone are in the range of 262–261 Mya (Day et al. 2015), and the underlying Ecca Group has been dated to approximately 290–265 Mya (e.g., Tohver et al. 2015; Rubidge et al. 2016; Belica et al. 2017), but the latter strata are well below any therapsid occurrences. Together, this implies that the oldest South African therapsids (including early anomodonts) are in the Wordian to early Capitanian range. The non-dicynodont anomodont *Otsheria* is known from the Ocher Assemblage of Russia, which also probably falls in the Wordian (Golubev 2015). The most stemward anomodont, *Biseridens* is known from the

Dashankou locality in China, where it co-occurs with dinocephalians but not theriodonts (Liu et al. 2010). This locality is often portrayed as older than either the *Eodicynodon* zone or the Ocher Assemblage (e.g., Liu et al. 2009, 2010) based on the primitive gestalt of *Biseridens* and the primitive therapsid *Raranimus*, but its age is poorly constrained and Rubidge and Day (2020) suggested a broad correlation between it and the *Eodicynodon* zone (also see Olroyd and Sidor 2017). Based on this information, the divergence of anomodonts and theriodonts is likely older than 262 Mya and probably older than 264–265 Mya, but younger than 272 Mya. We use 268.5 Mya as the date for this divergence (upper end of the Lanci et al. 2013 range of ages for the lower Abrahamskraal Formation).

***Patranomodon* + Dicynodontia**: *Eodicynodon oosthuizeni*, the most stemward dicynodont, occurs in the eponymous *Eodicynodon* Assemblage Zone (lower Abrahamskraal Formation, Karoo Basin, South Africa), where it co-occurs with the non-dicynodont anomodont *Patranomodon nyaphulii* (e.g., Day et al. 2018; Rubidge and Day 2020). Radiometric dates and biostratigraphic correlations do not exist with sufficient precision to differentiate the first appearance of *Eodicynodon* from the divergence of Anomodontia, so we place the origin of Dicynodontia one million years after the origin of Anomodontia, 267.5 Mya.

Common ancestor of *Eodicynodon* and *Lystrosaurus*: As noted above, the currently-available fossil record lacks sufficient resolution to provide clear ages for divergences at the base of Dicynodontia. Therefore, we calibrate this divergence point one million years after the origin of Dicynodontia, 266.5 Mya.

Common ancestor of *Diictodon* and *Lystrosaurus*: *Diictodon feliceps* is a member of the dicynodont clade Pylaecephalidae. *Eosimops newtoni* and *Robertia broomiana* are the oldest members of this clade, with stratigraphic ranges extending down into the Koornplaats Member of the Abrahamskraal Formation (*Eosimops*-*Glanosuchus* Subzone of the *Tapinocephalus* Assemblage Zone; Day 2013; Day et al., 2018b; Day and Rubidge 2020). However, its sister lineage (including *Lystrosaurus*) has a potentially older first appearance in *Brachyprosopus broomi*. The latter species also is present in the Abrahamskraal Formation at least as far down as the Leeuvlei Member. A first appearance in the Leeuvlei member would put the first appearance of *Brachyprosopus* the lowermost *Tapinocephalus* Assemblage Zone, near the boundary with the *Eodicynodon* Assemblage Zone (Angielczyk et al. 2016; Day et al. 2020). Together, these data indicate that this divergence falls between the 261–262 Mya radiometric dates in the upper *Tapinocephalus* zone (Day et al. 2015) and the 268–264 Mya range for the dates from the base of the Abrahamskraal Formation (Lanci et al. 2013). We place this divergence at 264 Mya.

Common ancestor of *Pristerodon* and *Lystrosaurus*: As with the previous calibration, *Brachyprosopus broomi* is likely the oldest relevant taxon whose age is relatively well-constrained. We calibrate this node at 263 Mya, subtracting one million years from the previous calibration.

Endothiodontia + Therochelonia: The oldest members of these lineages, *Abajudon, Rastodon*, and *Emydops* co-occur with dinocephalian therapsids in the Karoo (South Africa), Ruhuhu (Tanzania), Mid-Zambezi (Zambia), and Paraná (Brazil) basins (Boos et al. 2016; Day et al. 2018; Olroyd et al. 2018; Day and Rubidge 2020). *Abajudon* and *Rastodon* are assumed to be Capitanian in age because of their co-occurrence with dinocephalians, but their ages are otherwise poorly constrained. The records of *Emydops* in the uppermost Abrahamskraal Formation (upper *Tapinocephalus* Assemblage Zone) in the Karoo Basin are close to the dates of 261.24–260.26 Mya for the upper *Diictodon*-*Styracocephalus* Subzone of the *Tapinocephalus* Assemblage Zone (Rubidge et al. 2013; Day et al. 2015; Day and Rubidge 2020). We calibrate this node at 262.5 Mya to reflect that the divergence must have occurred after the divergence in the previous calibration but before the ca. 261 Mya first appearance of *Emydops* in the fossil record.

Endothiodontia: *Abajudon kaayai*, which co-occurs with tapinocephalid dinocephalians in the Ruhuhu Formation of Tanzania and the lower Madumabisa Mudstone Formation of the Mid-Zambezi Basin of Zambia is likely the oldest known endothiodont, although radiometric dates are not available for either formation (Angielczyk et al. 2014a; Olroyd et al. 2018). However, the widespread genus *Endothiodon* is not known to co-occur definitively with dinocephalians (it is uncertain whether the *Endothiodon* specimen from the Brazilian Rio do Rasto Formation comes from the same stratigraphic level as the dinocephalians reported from that formation; Boos et al. 2013. 2015; Day and Smith 2020), nor does the recently described genus *Niassodon* (e.g., Ray 2000; Boos et al. 2013; Castanhinha et al. 2013; Cox & Angielczyk 2018; Day et al. 2018; Macungo et al. 2020) implying they are at least slightly younger. We calibrate the base of Endothiodontia at 262 Mya to reflect that divergences within the clade must have post-dated the divergence between Endothiodontia and Therochelonia (see previous entry) and must pre-date the first appearance of *Endothiodon bathystoma* in the lower Poortjie Member of the Teekloof Formation, which is between approximately 261–259 Mya (Rubidge et al. 2013; Day et al. 2015; Day and Smith 2020), and the likely similarly-aged first appearance of *E. tolani* in the Ruhuhu Formation of Tanzania (Angielczyk et al. 2014; Cox & Angielczyk 2015) and the K5 Formation of Mozambique (Macungo et al. 2020).

***Abajudon* +*Endothiodon*:** The presumably Capitanian first appearance of *Abajudon* discussed in the previous entry is the oldest relevant calibration point for this divergence as well. We calibrate this node at 261.5 Mya to reflect the fact that it must post-date the emergence of Endothiodontia and pre-date the first appearance of *E. bathystoma* in the lower Poortjie Member of the Teekloof Formation (Day et al. 2018).

Endothiodon tolani + _Endothiodon bathystoma_: *Endothiodon tolani* was described recently from the middle fossiliferous horizon of the Ruhuhu Formation (R2 of Olroyd & Sidor 2017), Ruhuhu Basin, Tanzania (Cox & Angielczyk 2015). The age of this horizon is not well constrained, but it has been hypothesized to fall near the Guadalupian-Lopingian boundary based on biostratigraphic comparisons (Angielczyk et al. 2014a; Cox & Angielczyk 2015; Olroyd & Sidor 2017). Recently, Macungo et al. (2020) reported *E. tolani* specimens from the K5 Formation of the Metangula Graben of Mozambique, and unerupted tusks visible in CT-scans of the maxillae of NHCC LB648 allow us to recognize that specimen as the first occurrence of *E. tolani* in the Madumabisa Mudstone Formation of the Mid-Zambezi Basin, Zambia. The ages of these units are not well constrained, but there are reasons to believe that fall within the Lopingian (Castanhinha et al. 2013; Barbolini et al. 2016). *Endothiodon bathystoma* has a cosmopolitan distribution in Gondwana (e.g., Boos et al. 2013; Cox & Angielczyk 2015), but its best-dated records are in the Karoo Basin of South Africa. There, *E. bathystoma* first appears in in the lower Poortjie Member of the Teekloof Formation (Day et al. 2018), which is between approximately 261–259 Mya (Rubidge et al. 2013; Day et al. 2015; Day and Smith 2020). Together, these observations suggest that *E. tolani* and *E. bathystoma* diverged no later than the latest Capitanian, and we calibrate this divergence at 261 Mya.

Emydopoidea + Bidentalia: The records of *Emydops* and *Rastodon* noted in the entry for Endothiodontia + Therochelonia are the oldest relevant calibration points for this node. We calibrated the divergence at 262 Mya based on the fact that it must post-date the divergence of Endothiodontia and Therochelonia, but pre-date the first appearance of *Dicynodontoides* in the Capitanian-Wuchiapingian *Lycosuchus*-*Eunotosaurus* subzone of the *Endothiodon* Assemblage Zone of the Karoo Basin (Angielczyk et al. 2009; Day and Smith 2020).

Dicynodontoides + Cistecephalidae: The first appearance of *Dicynodontoides* is in the upper Poortjie Member of the Teekloof Formation (*Lycosuchus*-*Eunotosaurus* subzone of the *Endothiodon* Assemblage Zone) of the Karoo Basin (Angielczyk et al. 2009; Day et al. 2018; Day and Smith 2020), which is between 260.26–259.26 Mya (Rubidge et al. 2013; Day et al. 2015; Day and Smith 2020). The oldest well-documented cistecephalid is likely *Cistecephalus microrhinus*, which first appears in the upper *Tropidostoma*-*Gorgonops* Subzone of the *Endothiodon* Assemblage Zone of the Karoo Basin (Smith & Keyser 1995; Day and Smith 2020). This assemblage zone is bracketed by radiometric dates of 259.26 Mya and 256.25 Mya (Day et al. 2015). The undescribed Mid-Zambezi Basin cistecephalid (see Angielczyk et al. 2019) may be older, but its age is very poorly constrained. We calibrate this node at 259 Mya based on the age of the *Lycosuchus*-*Eunotosaurus* Subzone.

Kawingasaurus + _Kembawacela_: Our dataset includes two cistecephalid species, *Kawingasaurus fossilis* from the Usili Formation (Ruhuhu Basin, Tanzania; Cox 1972) and *Kembawacela kitchingi* from the upper Madumabisa Mudstone Formation (Luangwa Basin, Zambia; Angielczyk et al. 2019).

Angielczyk et al. (2014b) correlated the Usili and upper Madumabisa Mudstone formations with the Wuchiapingian *Cistecephalus* Assemblage Zone of the Karoo Basin, but more recent work suggests that they may encompass parts of the upper *Cistecephalus* Assemblage Zone and the lower *Daptocephalus* Assemblage Zone (Angielczyk & Kammerer 2017; Angielczyk 2019; Smith 2020; Viglietti 2020; also see Sidor et al. 2010; Kammerer 2019). Therefore, the divergence between *Kawingasaurus* and *Kembawacela* must have occurred sometime between the divergence of Cistecephalidae (presumably near the Capitanian-Wuchiapingian boundary; see previous entry) and Wuchiapingian-Changhsingian boundary (i.e., near the *Cistecephalus*-*Daptocephalus* Assemblage one boundary; see dates in Rubidge et al. 2013; Day et al. 2015). We calibrate this node at 256 Mya, based on Rubidge et al.'s (2013) date of 256.25 Mya near the base of the Oudeberg Member of the Balfour Formation, which corresponds in part to the *Cistecephalus* Assemblage Zone.

Common ancestor of *Oudenodon* and *Lystrosaurus*: The common ancestor of *Oudenodon* and *Lystrosaurus* must have existed after the divergence of the stemward, presumably Capitanian bidentalian *Rastodon* and early cryptodonts and geikiids such as *Tropidostoma, Australobarbarus*, and *Bulbasaurus*, all of which are early Wuchiapingian in age (approximately the *Endothiodon* Assemblage Zone of the Karoo Basin or its likely equivalents; e.g., Kurkin, 2011; Benton et al., 2012; Kammerer & Smith 2017; Sennikov & Golubev, 2017; Kammerer & Masyutin, 2018a; Day et al. 2018; Day and Smith 2020). Radiometric dates of 259.26 Mya and 256.25 Mya bracket the *Endothiodon* Assemblage Zone in the Karoo Basin (Rubidge et al. 2013; Day et al. 2015), and we calibrate this node at 258 Mya, reflecting the presence of *Tropidostoma* and *Bulbasaurus* in the *Tropidostoma*-*Gorgonops* Subzone of the *Endothiodon* Assemblage Zone (Day et al. 2018).

Common ancestor of *Aulacephalodon* and *Lystrosaurus*: The early Wuchiapingian (*Tropidostoma_Gorgonops* Subzone of the *Endothiodon* Assemblage Zone) geikiid *Bulbasaurus* is the oldest taxon that is relevant to this calibration (Kammerer & Smith 2017). We calibrate this node at 257.5 Mya to reflect the fact that *Bulbasaurus* is present in the *Tropidostoma*-*Gorgonops* Subzone (Day et al. 2018; Day and Smith 2020) but must have diverged after the common ancestor of *Oudenodon* and *Lystrosaurus* (see previous entry).

Common ancestor of *Lystrosaurus* and *Sangusaurus*: The fossils that are most relevant for calibrating this divergence depend strongly on which taxa are most closely related to *Lystrosaurus* and where Lystrosauridae falls relative to other dicynodontoids in dicynodont phylogeny (*Sangusaurus* dates from the Anisian–Carnian interval and is well nested within Triassic kannemeyeriiform dicynodonts; Angielczyk et al. 2018; Peecook et al. 2018a). Unfortunately, these are both areas where recent phylogenetic analyses of the group have differed (e.g., compare Angielczyk & Kammerer 2017; Kammerer 2018, 2019; Olroyd et al. 2018; Kammerer et al. 2019; Olivier et al. 2019; Liu 2020). For this analysis, we assumed that the topology of Kammerer (2019) is correct, but our results would not vary dramatically if other recent phylogenies were used as a reference instead. In this context, *Dicynodon lacerticeps*, *Dicynodon angielczyki*, *Daptocephalus huenei*, *Dinanomodon gilli*, and *Peramodon amalitzkii* all are known from faunal assemblages that are thought to span the Changhsignian-Wuchiapingian boundary (i.e., the *Cistecephalus* and *Daptocephalus* Assemblage zones of South Africa, the Usili Formation of Tanzania, the upper Madumabisa Mudstone Formation of Zambia, and the Sokolki Subassemblage of Russia; see e.g. Viglietti et al. 2016; Sennikov & Golubev 2017; Angielczyk & Kammerer 2017; Angielczyk 2019; Smith 2020; Viglietti 2020; dates from Rubidge et al. 2013). Permian occurrences of *Lystrosaurus* in China and South Africa seem to be restricted to the Changhsingian (i.e., the Guodikeng Formation and the *Lystrosaurus maccaigi-Moschorhinus* Subzone of the *Daptocephalus* Assemblage Zone; dates from Yang et al. 2010; Rubidge et. al. 2013; Gastaldo et al. 2015; also see Liu 2018; Viglietti 2020) and thus are slightly younger. Based on the radiometric dates for the Karoo Basin in Rubidge et al. (2013) and Gastaldo et al. (2015), the age of this node likely falls in the 256–253 Mya range and we calibrate it at 255 Mya.

<u>*Lystrosaurus declivis* + *Lystrosauruus murrayi*:</u> *Lystrosaurus declivis* and *L. murrayi* are best known from the Karoo Basin of South Africa, where they occur in strata assigned to the earliest Triassic *Lystrosaurus declivis* Assemblage Zone (e.g., Botha & Smith 2006, 2007; Smith & Botha-Brink 2014; Botha and Smith 2020; although see Gastaldo et al. 2020 for an alternative age assessment). Phylogenetic relationships within the genus *Lystrosaurus* have been unstable in recent phylogenetic analyses (e.g., compare Angielczyk & Kammerer 2017; Kammerer 2018, 2019; Olroyd et al. 2018; Kammerer et al. 2019; Olivier et al. 2019; Liu et al. 2020). In some cases, they are reconstructed as sister taxa, meaning their divergence could be as young as earliest Triassic, whereas in other cases species with first occurrences in the late Permian fall between them, implying a late Permian divergence. Here, we place this divergence in the late Permian (equivalent to *Lystrosaurus maccaigi-Moschorhinus* subzone of the *Daptocephalus* Assemblage Zone) and calibrate it at 253 Mya based on the radiometric date of Gastaldo et al. (2015).

<u>Gorgonopsia + Eutheriodontia:</u> The oldest well-characterized gorgonopsian is *Eriphostoma microdon*, which first appears in the Capitanian *Diictodon-Styracocephalus* Subzone of the *Tapinocephalus* Assemblage Zone of the Karoo Basin, South Africa (Kammerer 2014; Kammerer et al. 2015; Day et al. 2018; Day and Rubidge 2020), although fragmentary material has also been reported from the Wordian *Eodicynodon* Assemblage Zone (Abdala & Rubidge 2008; Rubidge and Day 2020). More reliable Wordian to Wordian-Capitanian records exist for Eutheriodontia, in the form of therocephalians in Russia and South Africa (e.g., Abdala & Rubidge 2008; Huttenlocker & Smith 2017), with *Glanosuchus macrops* and *Ictidosaurus angusticeps* from the lower Abrahamskraal Formation (*Eodicynodon* Assemblage Zone) comprising the oldest occurrences of the clade (Huttenlocker & Smith 2017; Day et al. 2018; Rubidge and Day 2020). Dates from near the base of the Abrahamskraal

Formation range from 268.5–264.6 Mya (Lanci et al. 2013). We calibrate this node at 265.5 Mya, one million years after our calibration for the divergence of Theriodontia from Anomodontia.

'*Aloposaurus*' + *Scylacocephalus* + *Lycaenops* + *Dixeya* + BP/1/155: Our dataset includes five African gorgonopsians, but only one (*Lycaenops;* Wuchiapingian–Changhsingian) has been formally included in recent phylogenetic analyses of the clade. An important result of this work is the new hypothesis that African gorgonopsians form a single clade that is distinct from Russian members of the group (Kammerer & Masyutin 2018a; Bendel et al. 2018). *Eriphostoma microdon* is the oldest and most stemward well-characterized African gorgonopsian, occurring in the upper Abrahamskraal and lower Teekloof formations in the Karoo Basin (*Tapinocephalus–Endothiodon* assemblage zones; Kammerer 2014; Kammerer et al. 2015; Kammerer & Masyutin 2018a; Bendel et al. 2018; Day and Rubidge 2020; Day and Smith 2020). As such it provides a useful estimate of the maximum time of divergence for the African specimens in our dataset. The upper *Tapinocephalus* Assemblage Zone has been dated to the late Capitanian (ca. 261 Mya; Rubidge et al. 2013; Day et al. 2015; Day and Rubidge 2020), and the first appearance of *Eriphostoma* is likely slightly older than the dated strata. We calibrate this node at 262 Mya to reflect its position between the divergence of Gorgonopsia and Eutheriodontia (see previous entry) and the 261.24 Mya date for the upper *Tapinocephalus* Zone (Rubidge et al. 2013).

Therocephalia + Cynodontia: The oldest cynodont species are *Charassognathus gracilis* and *Abdalodon diastematicus*, both of which are known from the Hoedemaker Member of the Teekloof Formation in the Karoo Basin (lower Wuchiapingian *Tropidostoma-Gorgonops* Subzone of the *Endothiodon* Assemblage Zone; Botha et al. 2007; Kammerer 2016b; age from Rubidge et al. 2013; Day et al. 2015; Day and Smith 2020). Therocephalia has a deeper fossil record, with *Glanosuchus macrops* and *Ictidosaurus angusticeps* from the lower Abrahamskraal Formation (*Eodicynodon* Assemblage Zone) comprising the oldest occurrences of the clade (Huttenlocker & Smith 2017; Day et al. 2018; Rubidge and Day 2020). Lanci et al. (2013) dated the lower Abrahamskraal Formation to 268.5–264.6 Mya, and we calibrate this node at 265 Mya to reflect these ages and also the fact that this divergence must post-date the divergence of Gorgonopsia from Eutheriodontia (see above). Our calibration is notably younger than statistical estimates of the root age for Cynodontia presented by Lukic-Walther et al. (2019), which clustered near the Cisuralian-Guadalupian boundary. However, our calibration is consistent with the known therapsid fossil record.

Akidnognathidae + Baurioidea: The therocephalians in our dataset comprise members of two major clades, Akidnognathidae (*Euchambersia*, *Olivierosuchus*) and Baurioidea (*Ictidosuchoides, Mupashi, Choerosaurus, Microgomphodon*) (e.g., Huttenlocker & Smith 2017; Liu & Abdala 2017; Kammerer and Masyutin 2018b). Of these two clades, baurioids appear earlier in the fossil record, near the Capitanian-Wuchiapingian boundary (e.g., cf. *Ictidosuchoides* in the South African *Lycosuchus-Eunotosaurus* Subzone of the *Endothiodon* Assemblage Zone, *Karenites* in the Russian Kotelnich

Subassemblage; Huttenlocker and Smith 2017; Day and Smith 2020). The base of the *Lycosuchus-Eunotosaurus* Subzone is constrained by a radiometric date of 260.26 Mya at the base of the Poortjie Member of the Teekloof Formation (Day and Smith 2020), and we calibrate this node at 260.26 Mya.

***Olivierosuchus + Euchambersia*:** Although it is relatively well-nested within Akidnognathidae, *Euchambersia mirabilis* is one of the first members of the clade to appear in the fossil record (Wuchiapingian *Cistecephalus* Assemblage Zone, Karoo Basin; Benoit et al. 2017a; Huttenlocker & Smith 2017; age from Rubidge et al. 2013). Radiometric dates and revisions to Karoo litho- and biostratigraphy suggest that the base of the *Cisteephlaus* Assemblage zone is older the 256 Mya and that the boundary between the *Cistecephalus* and *Daptocephalus* assemblage zones is slightly older than 255 Mya (Rubidge et al. 2013; Viglietti et al. 2016, 2017, 2018a; Smith 2020; Viglietti 2020). Therefore, we calibrate this node at 257 Mya.

Common ancestor of *Ictidosuchoides* and *Microgomphodon*: *Ictidosuchoides longiceps* is one of the oldest baurioids, with well characterized records extending back to the Wuchiapingian *Tropidostoma-Gorgonops* Subzone of the *Endothiodon* Assemblage Zone of South Africa and a potential occurrence in the Capitanian-Wuchiapingian *Lycosuchus-Eunotosaurus* Subzone of the *Endothiodon* Assemblage Zone (Huttenlocker & Smith 2017; Day et al. 2018; Day and Smith 2020). *Karenites ornamentatus* from the Kotelnich Subassemblage in Russia is likely of similar age (Huttenlocker & Smith 2017; Sennikov & Golubev 2017; Kammerer & Masyutin 2018b). The *Lycosuchus-Eunotosaurus* Subzone is bracketed by radiometric dates of 260.26 Mya and 259.25 Mya (Rubidge et al. 2013; Day et al. 2015; Day and Smith 2020), and we calibrate this node at 259.5 Mya.

Common ancestor of *Mupashi* and *Microgomphodon*: *Mupashi migrator*, from the upper Madumabisa Mudstone Formation of Zambia, is commonly reconstructed as the sister taxon of *Karenites ornamentatus* from Russia (Huttenlocker & Sidor 2016; Huttenlocker & Smith 2017; Liu & Abdala 2017; Kammerer & Masyutin 2018b). *Karenites* occurs in the Kotelnich Subassemblage, which is generally considered to be close to the Capitanian-Wuchiapingian boundary in age (e.g., Kurkin 2011; Benton et al. 2012; Kammerer & Masyutin 2018; Sennikov & Golubev 2018), although radiometric dates do not yet exist for the assemblage. We calibrate the age of this node as 259 Mya, making it slightly younger than the age of the common ancestor of *Ictidosuchoides* and *Microgomphodon*.

Common ancestor of *Choerosaurus* and *Microgomphodon*: *Choerosaurus dejageri* occurs in the Wuchiapingian *Tropidostoma-Gorgonops* Subzone of the *Endothiodon* Assemblage Zone of the Karoo Basin (Benoit et al. 2016a; Huttenlocker & Smith 2017; Smith and Day 2020), making it one of the oldest baurioids. By contrast *Microgomphodon oligocynus* dates to the Middle-?Late Triassic *Langbergia-Garjainia* Subzone of the *Cynognathus* Assemblage Zone (Abdala et al. 2014; Huttenlocker & Smith 2017; Hancox et al. 2020). The *Tropidostoma-Gorgonops* Subzone is thought to be between 258 Mya and 256.8 Mya in age (Rubidge et al. 2013; Day et al. 2015; Day and Smith 2020). We calibrate this node at 258 Mya, one million years after the age of the common ancestor of *Mupashi* and *Microgomphodon*.

Common ancestor of *Procynosuchus* and mammals: There is uncertainty about the exact phylogenetic placement of *Procynosuchus* (e.g., compare Botha et al. 2007; Kammerer 2016b; Van den Brandt & Abdala 2018; Abdala et al. 2019; Huttenlocker and Sidor 2020; supertree results of Lukic-Walther et al. 2019), which impacts on which taxa are most useful for calibrating this node. If *Procynosuchus* (or a clade comprised of *Procynosuchus* and *Dvinia*) is the most stemward known cynodont lineage, then the presence of *Charassognathus* and *Abdalodon* in the early Wuchiapingian *Tropidostoma*-*Gorgonops* Subzone of the *Endothiodon* Assemblage Zone of South Africa (Day and Smith 2020) implies that *Procynosuchus* must have diverged by that time. Alternatively, if *Procynosuchus* is in a more nested position than *Charassognathus* and/or *Abdalodon* (or Charassognathidae *sensu* Huttenlocker and Sidor 2020), then its divergence time might be closer to its actual first appearance near the boundary of the *Cistecephalus* and *Daptocephalus* assemblage zones (e.g., Huttenlocker et al. 2011; Kammerer 2016b, Viglietti et al. 2016; Smith 2020; Viglietti 2020). For the purposes of this analysis, we assumed that *Procynosuchus* falls stemward of *Charassognathus* and *Abdalodon*, and we calibrate this node at 259 Mya (i.e., near the boundary between the boundary between the *Lycosuchus*-*Eunotosaurus* and *Tropidostoma*-*Gorgonops* subzones of the *Endothiodon* Assemblage Zone in the Karoo Basin; dates from Rubidge et al. 2013; Day et al. 2015; Day and Smith 2020).

Epicynodontia: *Cynosaurus suppostus* occurs in the upper Wuchiapingian-Changhsingian *Cistecephalus* and *Daptocephalus* assemblage zones of South Africa (Van den Brandt & Abdala 2018; Smith 2020; Viglietti 2020) and provides a calibration point for this node. The base of the *Cistecephalus* Assmeblgae zone dates to 256.6 Mya (Rubidge et al. 2013; Viglietti et al. 2016, 2017, 2018a; Smith 2020), so we calibrate this node at 258 Mya, in part to accommodate additional divergences that must have occurred in the latest Permian (see next two entries)

Common ancestor of *Galesaurus* and mammals: *Galesaurus planiceps* is a well characterized cynodont known from the Early Triassic *Lystrosaurus declivis* Assemblage Zone of South Africa (e.g., Jasinoski & Abdala 2017a, 2017b; Butler et al. 2018; Pusch et al. 2019; Botha and Smith 2020). However, the presence of the phylogenetically more deeply-nested cynodonts *Nanictosaurus* and *Vetusodon* in the Changhsingian *Daptocephalus* Assemblage Zone of the Karoo Basin (e.g., Abdala et al. 2019; Viglietti 2020) implies that the lineage including *Galesaurus* must have diverged in the Permian as well. The base of the *Daptocephalus* Assemblage Zone is approximately 255 Mya (Rubidge et al.; Viglietti 2020), and we use 257 Mya as a calibration point for this node to accommodate additional divergences that must have occurred in the latest Permian (see next entry).

<u>Common ancestor of *Thrinaxodon* and mammals:</u> *Thrinaxodon liorhinus* is unquestionably the most thoroughly studied non-mammalian cynodont, and it has a well-documented stratigraphic range in the Early Triassic Palingkloof Member of the Balfour Formation and the Katberg Formation in the Karoo Basin (e.g., Botha & Smith 2006; 2020) as well as the lower Fremouw Formation in Antarctica (e.g., Kitching et al. 1972; Colbert and Kitching 1977; Hammer 1990; Peecook et al. 2018b). As in the case of *Galesaurus* (see previous entry), the occurrence of the phylogenetically more-nested cynodonts *Nanictosaurus* and *Vetusodon* in the *Daptocephalus* Assemblage Zone (e.g., Abdala et al. 2019; Viglietti 2020) implies that the lineage including *Thrinaxodon* must have diverged in the Permian as well. We calibrate this node at 256 Mya, reflecting the fact that the base of the *Daptocephalus* Assemblage Zone is slightly younger than this age (Rubidge et al. 2013; Viglietti et al. 2016, 2017, 2018a; Viglietti 2020).

<u>Eucynodontia:</u> A consistent feature of analyses of cynodont phylogeny is the division of "higher" cynodonts into two major clades, the extinct Cynognathia and Probainognathia, whose extant representatives are mammals (e.g., see supertree in Lukic-Walther et al. 2019), which are united within Eucynodontia. The strata hosting the oldest occurrences of eucynodonts, such as the lower Burgersdorp Formation of the Karoo Basin (*Laingbergia-Garjainia* Subzone of the *Cynognathus* Assemblage Zone), have typically been thought to be Olenekian in age (e.g., Rubidge 2005; Lucas 2010; Schneider et al. 2019; Hancox et al. 2020 although see further discussion in the following entry). However, depending on the identity of its sister taxon, the eucynodont lineage must have diverged by the Early Triassic (e.g., if *Playtcraniellus* is the sister taxon; Abdala 2007) or the latest Permian (e.g., if *Vetusodon* is the sister taxon; Abdala et al. 2019). For this analysis, we assumed the latter hypothesis is correct, and used Gastaldo et al.'s (2015) radiometric date of 253.48 Mya for the *Lystrosaurus maccaigi-Moschorhinus* subzone of the *Daptocephalus* Assemblage Zone to calibrate this node.

<u>Common ancestor of Trirachodontidae and *Massetognathus*:</u> The most stemward cynognathian lineage in our dataset is Trirachodontidae. In addition to *Trirachodon* itself, Trirachodontidae also includes the genera *Langbergia* and *Cricodon* (Sidor & Hopson 2018), and possibly *Beishanodon* and *Sinognathus* from China (Liu & Abdala 2014). We treat Trirachodontidae as a clade in our phylogeny, but recently Hendrickx et al. (2020) proposed that the trirachodontids may instead be a paraphyletic assemblage on the stem leading to Traversodontidae. *Langbergia,* from the lower Burgersdorp Formation (*Langbergia-Garjainia* Subzone of the *Cynognathus* Assemblage Zone; Hancox et al. 2020) of the Karoo Basin is the stratigraphically lowest-occurring trirachodontid. Traditionally. one record of *Trirachodon berryi* was suggested to have originated in this subzone (Abdala et al. 2006), but Hancox et al.'s (2020) redfined *Cynognathus* zone biostratigraphy would place this specimen in the overlying *Trirachodon-Kannemeyeria* Subzone. *Langbergia* also occurs stratigraphically below other stemward cynognathians such as *Cynognathus* and *Diademodon* (Neveling 2004), making it the most relevant record for calibrating this divergence. As noted in the previous entry, the *Laingbergia-Garjainia*

Subzone has generally been regarded as Olenekian in age, although it has not been radiometrically dated directly. Recent radiometric dates of strata that are biostratigraphically-correlated with the *Cynognathus* Assemblage Zone have raised the possibility that it parts of it might be substantially younger than previously thought (e.g., Ottone et al. 2014; Marsicano et al. 2016; also see discussion in Martinelli et al. 2017a; Peecook et al. 2018a; Schneider et al. 2019). Detrital zircon crystals from the lower part of the underlying Katberg Formation with a minimum age of 250 ± 5 Mya (Viglietti et al. 2018b) also are consistent with a younger age for the *Cynognathus* Assemblage Zone. However, the wide error range on the latter date and the existence of dates for other biostratigraphically-correlated strata more in accordance with the traditional hypothesis (Liu et al. 2018) suggest that further work on the problem is needed. For the purposes of this paper, we have maintained the assumption that subzone A of the *Cynognathus* Assemblage Zone is Olenekian (Hancox et al. 2020). We calibrate this node at 248 Mya, in the late Olenekian, to accommodate the possibility of an Olenekian age for at least part of the underlying Katberg Formation. This is slightly younger than the statistically estimated root age of 249.34 Mya for Cynognathia presented by Lukic-Walther et al. (2019).

Common ancestor of *Trirachodon* and *Cricodon*: *Trirachodon berryi* is an index fossil for the *Trirachodon-Kannemeyeria* Subzone of the of the *Cynognathus* Assemblage Zone of the South Africa Karoo Basin (Hancox et al. 2020). The two species of *Cricodon* recognized by Hopson and Sidor (2018) include occurrences in the *Trirachodon-Kannemeyeria* subzone of the *Cynognathus* Assemblage Zone (*C. kannemeyeri*) as well as the overlying *Cricodon-Ufudocyclops* Subzone, the Ntawere Formation of Zambia, and the Lifua Member of the Manda Beds of Tanzania (all *C. metabolus*; Hopson & Sidor 2018; Peecook et al. 2018a; Hancox et al. 2020). As noted in the previous entry, the age of the *Cynognathus* Assemblage Zone and many biostratigraphically-correlated assemblages has been the subject of recent debate. We calibrate this divergence at 247.5 Mya (latest Olenekian), slightly older than the traditionally-assumed early Anisian age for the *Trirachodon-Kannemeyeria* Subzone (e.g., Hancox et al. 2020, although see discussion above).

Common ancestor of *Scalenodon* and *Massetognathus*: Traditionally, the Lifua Member of the Manda Beds, which hosts the cynodont *Scalenodon angustifrons* (e.g., Liu & Abdala 2014), has been considered to be Anisian–early Ladinian in age (e.g., Lucas 1998, 2010; Rubidge 2005), although no radiometric dates are available for the Lifua Member or nearby biostratigraphically-correlated strata in southern Africa (e.g., Ntawere Formation of Zambia, Burgersdorp Formation of South Africa). Recently published radiometric dates from South American strata (Philipp et al. 2013, 2018; Ottone et al. 2014; Marsicano et al. 2016; Langer et al. 2018) and the increasing number of cynodonts (including *Scalenodon* itself) and other taxa shared between basins in South America and southern Africa (e.g., Abdala et al. 2013; Martinelli et al. 2017a; Melo et al. 2017; Peecook et al. 2018a) have raised the strong possibility that *Scalenodon* is no older than late Ladinian and could be early Carnian in age. A Ladinian–

early Carnian age for *Massetognathus* is relatively certain (e.g., Marsicano et al. 2016; Schmitt et al. 2019). We calibrate this node at 239 Mya, reflecting the fact that the *Dinodontosaurus* Assemblage Zone of Brazil (Santa Maria Supersequence) is likely older than 236–237 Mya and may fall within the late Ladinian (e.g., Martinelli et al. 2017a; Melo et al. 2017; Philipp et al. 2018; Schmitt et al. 2019), as well as the need to accommodate the divergence between *Massetognathus* and *Luangwa*, both of which also are present in the *Dinodontosaurus* Assemblage Zone of Brazil (see next entry).

Common ancestor of *Luangwa* and *Massetognathus*: As its name suggests, *Luangwa* was first discovered in the upper portion of the Triassic Ntawere Formation of the Luangwa Basin, Zambia (Brink 1963), but it was subsequently found in Brazil, Namibia, and Tanzania (Abdala & Sa-Teixeira 2004; Abdala & Smith 2009; Martinelli et al. 2017a; Peecook et al. 2018a). The upper Ntawere Formation was traditionally considered to be Anisian in age (Rubidge 2005), but the presence of *Luangwa* in Brazilian strata radiometrically dated to near the Ladinian–Carnian boundary strongly suggest that the Ntawere Formation is younger than previously appreciated (Peecook et al. 2018a; also see previous entry). We calibrate this divergence at 238 Mya, reflecting the fact that the *Dinodontosaurus* Assemblage zone of Brazil (Santa Maria Supersequence) is likely older than 236–237 Mya (e.g., Martinelli et al. 2017a; Melo et al. 2017; Philipp et al. 2018; Schmitt et al. 2019).

Common ancestor of *Lumkuia* and mammals: There has been uncertainty over the last two decades as to the identity of the most stemward member of Probainognathia, the cynodont clade that includes mammals as its extant representatives (e.g., compare Hopson & Kitching 2001; Liu & Olsen 2010; Martínez et al. 2013a; Ruta et al. 2013; Martinelli et al. 2017a, 2017b, 2017c; Stefanello et al. 2018; Lukic-Walther et al. 2019; Wallace et al. 2019). Here, we follow the hypothesis that *Lumkuia fuzzi* is the most stemward probainognathian, which appears to be an emerging consensus among recent analyses (also see Benoit et al. 2019). The only known specimen of *Lumkuia* was collected from the *Trirachodon-Kannemeyeria* Subzone of the *Cynognathus* Assemblage Zone (Burgersdorp Formation, Karoo Basin) (Hopson and Kitching 2001; Hancox et al. 2020). As noted in several entries above, the *Cynognathus* Assemblage zone was traditionally regarded as Anisian (Middle Triassic) in age based on biostratigraphical correlations, but new radiometric dates from South America have raised the possibility of an age as young as Ladinian–Carnian (Middle–Late Triassic). Therefore, the divergence between *Lumkuia* and the lineage including other probainognathians could be as early as Olenekian (based on the presence of cynognathians in the record at this time and assuming a “traditional” age for the *Cynognathus* zone; see entry for the common ancestor of Trirachodontidae and *Massetognathus* above), or as late as Ladinian (assuming an age no older than Ladinian for most of the “classic” African and South American cynodont-bearing basins) (e.g., see discussion in Martinelli et al. 2017a). We calibrate this node at 244 Mya (i.e., the midpoint of the Olenekian-Ladinian age range). The difference between this calibration and that for the divergence between *Trirachodon* and *Massetognathus* implies the existence of a probainognathian ghost lineage following the divergence of Cynognathia and Probainognathia. Our calibration is also notably younger than the statistically estimated root age of 251.9 Mya for Probainognathia presented by Lukic-Walther et al. (2019).

Common ancestor of *Chiniquodon* and mammals: Following the taxonomic revision of Abdala & Giannini (2002), *Chiniquodon* is one of the stratigraphically and geographically widest-ranging early probainognathians (see review in Abdala & Gaetano 2018; Martinelli et al. 2017a). The oldest records of the genus are from the *Dinodontosaurus* Assemblage Zone (Santa Maria Supersequence) of Brazil and the Chañares Formation of Argentina (e.g., Abdala & Giannini 2002; Abdala & Gaetano 2018; Schmitt et al. 2019), which are late Ladian–early Carnian in age (Marsicano et al. 2016; Philipp et al. 2018). We calibrate this node at 238 Mya, reflecting the stratigraphic position of the *Dinodontosaurus* Assemblage Zone (Pinherios-Chiniquá sequence) below Philipp et al.'s (2018) radiometric date of 237 Mya for the base of the overlying *Santacruzodon* Assemblage Zone (Santa Cruz sequence).

Common ancestor of *Riograndia* and mammals: The ictidosaur (sensu Martinelli and Rougier 2007) *Riograndia guaibensis* is known from the *Riograndia* Assemblage Zone (Candelária Sequence, Santa Maria Supersequence) of the Paraná Basin, Brazil (e.g., Soares et al. 2011). Rocks from this assemblage zone were recently dated at 225.42 Mya (Norian) by Langer et al. (2018). This is almost certainly an underestimate of the age of this divergence, and a more likely estimate of the age is calibrated by the presence of the more stemward prozostrodonts *Prozostrodon*, *Therioherpeton*, and *Alemoatherium* in the underlying *Hyperodapedon* Assemblage Zone (e.g., Martinelli et al. 2016, 2017b; Pacheco et al. 2017), which is thought to be as old as 231.4 Mya (Carnian) based on biostratigraphical correlation with the radiometrically-dated Ischigualasto Formation of Argentina (Martínez et al. 2013b). We calibrate this divergence at 234 Mya, in part to accommodate the presumably Carnian divergence of tritylodontids, brasilodontids, and mammaliaforms (see next entry).

Common ancestor of Tritylodontidae + *Pseudotherium* and mammals:

Triylodontids are known primarily from the Jurassic and Cretaceous (e.g., Abdala & Gaetano 2018), but *Oligokyphus* has been reported from the Late Triassic (Rhaetian) of Nova Scotia and Germany (Fedak et al. 2015). However, there are older Triassic fossils that are relevant to calibrating this divergence, but the question of which specific taxa are most important depends strongly on the phylogenetic relationships assumed for tritylodontids. Two main phylogenetic positions have been proposed for tritylodontids. One posits that they are derived cynognathians (e.g., Hopson & Kitching 2001; Sues & Jenkins 2006; Bonaparte & Crompton 2017; Sidor & Hopson 2018), whereas the other places them within Probainognathia, close to the base of Mammaliaformes (e.g., Abdala 2007; Liu & Olsen 2010; Ruta et al. 2013; Martinelli et al. 2016; Lukic-Walther et al. 2019; Wallace et al. 2019). Among phylogenies that place tritylodontids within Probainognathia, there also is debate concerning the branching order of tritylodontids, trithelodontids, and brasilodontids relative to Mammaliaformes (e.g., compare Abdala 2007; Liu & Olsen 2010; Ruta et al. 2013; Martinelli et al. 2016, 2017b; Wallace et al. 2019; also see summary supertree of Lukic-Walther et al. 2019). Resolving these questions is beyond the scope of this analysis. Here, we assumed the branching order: (Trithelodontidae (Tritylodontidae (Brasilodontidae, Mammaliaformes))), consistent with the analyses of Liu & Olsen (2010), Martinelli et al. (2016), and Wallace et al. (2019).

Brasilodon and other taxa of potential relevance to the age of this correlation (e.g., *Botucaratherium*) co-occur with *Riograndia* in the Norian *Riograndia* Assemblage Zone of Brazil (e.g., Martinelli et al. 2016; 2017b). *Adelobasileus* from the Tecovas Formation of Texas (Lucas and Luo 1993), which is likely more closely related to mammals than *Brasilodon*, was shown as having an older occurrence by Martinelli et al. (2017b; also see e.g., Abdala and Gaetano 2018) that potentially implied a Carnian age for this divergence. However, recent work suggests a younger Norian age for *Adelobasileus* (Sarigül 2017). *Tikitherium* and *Gondwanadon* from the Tiki Formation of India (Datta & Das 1996; Datta 2005) have been suggested to be members of Mammaliaformes (e.g., Luo & Martin 2007; Debuysschere et al. 2015; see reviews in Abdala & Gaetano 2018; Martin 2018), and the Tiki Formation typically is biostratigraphically correlated with the Carnian *Hyperodapedon* Assemblage Zone and the Ischigualasto Formation (e.g., Ray et al. 2016; Bhat et al. 2018). If this correlation is correct, it would indicate that divergences between trithelodontids, tritylodontids, and mammaliforms all occurred no later than the late Carnian. The recent discovery of *Pseudotherium* in the Ischigualasto Formation (radiometrically dated to 231.4– 225.9 Mya; Martínez et al. 2013b), which may be the sister taxon of Tritylodontidae (Wallace et al. 2019; although see below), provides additional support for a Carnian divergence among these lineages. Therefore, we calibrate this divergence at 233 Mya, in part to accommodate the divergences between *Brasilodon* and mammals and between *Pseudotherium* and tritylodontids (see below).

Common ancestor of *Pseudotherium* and Tritylodontidae: Tritylodontids are primarily a post-Triassic radiation of mammaliamorphs, although their oldest records extend into the Late Triassic (see previous and following entries). The recently described species *Pseudotherium argentinus* from the Carnian Ischigualasto Formation of Argentina may be the sister taxon of Tritylodontidae, although branch support for this hypothesis is somewhat weak (Wallace et al. 2019) and ongoing research suggests an alternative phylogenetic placement (A.G. Martinelli, unpublished data). For simplicity, we assumed that *Pseudotherium* is a stem tritylodont because this is the primary hypothesis that has been presented in the literature at this time. The Ischigualasto Formation has been dated radiometrically to 231.4–225.9 Mya (Martínez et al. 2013b), so we calibrate this divergence at 232 Mya.

Common ancestor of *Tritylodon* and *Oligokyphus*: *Oligokyphus* is generally considered to be the most stemward tritylodontid (see review in Velazco et al. 2017) and is the only member of the clade that is well documented from the Late Triassic (Fedak et al. 2015). Putative tritylodontid postcrania reported from the Los Colorados Formation of Argentina, which is Nornian in age (Kent et al. 2014), would constitute an even older record for the group, but a recent re-assessment found that they could only be identified as an indeterminate non-mammaliaform cynodont (Martinelli and Soares 2016; Gaetano et al. 2017). If the possible stem-tritylodontid status of *Pseudotherium* is assumed to be correct (see discussion in Wallace et al. 2019 and above) it provides an even older, potentially Carnian upper bound for divergences among tritylodontids. The locality of the McCoy Brook Formation record of *Oligokyphus* is approximately 201.45 Mya (Fedak et al. 2015), providing a minimum age for this divergence; other material of *Oligokyphus* is of likely Jurassic age or has less precise age constraints (e.g. Clemens & Martins 2014; Whiteside et al. 2016). We calibrate this divergence at 204.9 Mya, the midpoint of the Rhaetian Stage.

Common ancestor of *Brasilodon* and mammals: *Brasilodon quadrangularis* occurs in strata assigned to the *Riograndia* Assemblage Zone of the Candelária Sequence (Santa Maria Supersequence) in the Paraná Basin, Brazil (e.g., Bonaparte et al. 2003; Martinelli et al. 2016; 2017b; Guignard et al. 2019). Rocks from this assemblage zone were recently dated at 225.42 Mya (Norian) by Langer et al. (2018). As discussed above (see entry for divergence between Tritylodontidae + *Pseudotherium* and mammals), however, divergences between trithelodontids, tritylodontids, and mammaliforms all occurred no later than the late Carnian. Therefore, we calibrate this divergence at 232 Mya, slightly older than the radiometric date for the lower Ischigualasto Formation (Martínez et al. 2013b).

Common ancestor of Morganucodonta and mammals: Morganucodonts are best known from the latest Triassic and Early Jurassic, but Norian records of the clade also exist (Debuysschere et al. 2015). If *Gondwanadon* is a morganucodont (Datta & Das 1996; Kielan Jaworowska et al. 2004; Debuysschere et al. 2015) it would push the first appearance of the clade into the Carnian, based on the biostratigraphical correlation of the Tiki Formation with the Carnian *Hyperodapedon* Assemblage Zone and the Ischigualasto Formation (e.g., Ray et al. 2016; Bhat et al. 2018). The presence of the putative docodont or docodont relative *Tikitherium* in the Tiki Formation (Datta 2005; Luo & Martin 2007; Luo et al. 2015; Panciroli et al. 2019) also implies that morganucodonts must have diverged by the Carnian because Docodonta is consistently recovered crownward of Morganucodonta in mammaliaform phylogenetic analyses (e.g., see reviews in Abdala & Gaetano 2018; Martin 2018). We calibrate this divergence at 230.5 Mya, slightly younger than the radiometric date of 231.4 Mya for the Ischigualasto Formation, but still within the Carnian.

Common ancestor of *Morganucodon watsoni and Morganucodon oehleri:* Despite early occurrences of morganucodontans as early as the late Early Rhaetian from the Howell quarry in Wales (Whiteside et al. 2016), material that can be confidently attributed to *Morganucodon watsoni* is only present at the Triassic-Jurassic transition in the St. Brides community (Whitside et al. 2016). *Morganucodon oehleri* is known from the Zhangjia'ao Member (sensu Fang et al. 2000) of the Lufeng Formation of China (Luo and Wu 1994), which is considered to be Sinemurian in age based on biostratigraphical comparisons (e.g., Luo and Wu 1994; Sullivan et al. 2013). However, as noted above, there is considerable uncertainty about phylogenetic relationships within Morganucodonta, which complicates identifying the correct calibration point for this divergence. Therefore, we use the age of the oldest species of *Morganucodon*, *Morganucodon peyeri* from the Hallau locality in Switzerland, which is dated as late Norian to early Rhaetian (Whiteside et al. 2017). We calibrate this divergence at 207 Mya, the latest possible occurrence of *M. peyeri*.

Common ancestor of *Haldanodon* and mammals: *Haldanodon exspectatus* is a well-studied docodont known from the Alcobaça Formation of the Guimarota coal mine of Portugal (e.g., Lillegraven and Krusat 1991; Martin 2005; 2018; Ruf et al. 2013), which is considered Kimmeridgian in age (Schudack 2000a, 2000b). *Haldanodon* is well-nested within Docodonta (Meng et al. 2015; Panciroli et al. (2019), and the oldest members of the clade date back to the Bathonian (Panciroli et al. 2019). However, the presence of the putative docodont or docodont relative *Tikitherium* in the Carnian Tiki Formation (Datta 2005; Luo & Martin 2007; Luo et al. 2015; Panciroli et al. 2019) implies a long ghost lineage for Docodonta. Therefore, we calibrate this node at 230 Mya (Carnian), slightly younger than the divergence of Morganucodonta (see above).

Common ancestor of *Morganucodon* and *Megazostrodon*: Species of *Morganucodon* and *Megazostrodon* span the Triassic–Jurassic boundary, but the oldest records of both genera are in the Rhaetian (Debuysschere et al. 2015), providing a minimum age for their divergence. Potential records of *Hallutherium* and *Brachyzostrodon* in the Norian of Greenland and Poland (Jenkins et al. 1994; Świło et al. 2014; Debuysschere et al. 2015), and the presence of *Gondwanadon* in the Carnian of India (Datta & Das 1996), could imply an even older divergence time for *Morganucodon* and *Megazostrodon*, depending on the pattern of phylogenetic relationships within Morganucodonta. However, most mammaliaform phylogenetic analyses include few morganucodonts, leaving relationships within the clade (and even the monophyly of the clade) in question (e.g., Rougier et al. 2007; Gaetano & Rougier 2012; Zhou et al. 2013; Close et al. 2015; Luo et al. 2015; Meng et al. 2015; Huttenlocker et al. 2018; Panciroli et al. 2019; also see Abdala & Gaetano 2018). Given this uncertainty, we calibrate this node at the base of the Rhaetian Stage, 208.5 Mya.

Common ancestor of *Hadrocodium* and mammals: *Hadrocodium wui* is known from the Early Jurassic (Sinemurian) Lufeng Formation of China (Luo et al. 2001). The maximum age of this divergence is calibrated by the Carnian occurrence of the potential docodont *Tikitherium*, given that docodonts fall stemward of *Hadrocodium* in most recent mammaliaform phylogenies (e.g., Zhou et al. 2013; Close et al. 2015; Luo et al., 2015; Meng et al. 2015; Huttenlocker et al. 2018). The minimum age of this divergence depends strongly on whether the clade Haramiyida falls crownward or stemward of *Hadrocodium* (e.g., compare results of Zhou et al. 2013; Close et al. 2015; Luo et al., 2015; Meng et al. 2015; Huttenlocker et al. 2018). If the former option is correct, Norian–Rhaetian occurrences of haramiyidans such as *Haramiyavia* and *Thomasia* (Hahn 1973; Jenkins et al. 1997; Clemmensen et al. 2016) would imply that the lineage including *Hadrocodium* must have diverged by the Norian, whereas the latter would suggest a minimum divergence time closer to the Early Jurassic (although note that the analysis of Close et al. 2015 still implies a Triassic age for this node even when *Hadrocodium* is in a more crownward position). Resolving this phylogenetic problem is beyond the scope of this analysis. We calibrate this node at 214 Mya (late Norian), which is consistent with the case where haramiyidans are crownward of *Hadrocodium* and close to the divergence time estimate of Close et al.'s (2015) for a topology in which *Hadrocodium* occupied a more crownward position.

Common ancestor of *Dryolestes* and Theria: *Dryolestes* and its closest relatives (Dryolestidae) are cladotherian mammals known from the Jurassic and Cretaceous periods. *Dryolestes* itself is best known from the Late Jurassic (Kimmeridgian–Tithonian) of Europe and North America, but other records of Dryolestidae extend back into the Middle Jurassic (see reviews in Kielan-Jaworowska et al. 2004; Martin 2018), with the Bathonian *Anthracolestes sergeii* representing the oldest well-characterized member of the clade (Averianov et al. 2014). Additional evidence for a divergence of dryolestids by the Bathonian comes from *Amphitherium*, a member of Zatheria (the clade including therian mammals) (e.g., Averianov et al. 2013; Close et al. 2015; Luo et al. 2015; Huttenlocker et al. 2018), which is known from the lower Bathonian Tayton Limestone Formation of England (Butler & Clemens 2001). We calibrate this node at the base of the Bathonian (168.3 Mya).

Common ancestor of Captorhinidae and Diapsida: Captorhinidae is a clade of important Permian eureptiles, but only one species is known from the Carboniferous, the Gzhelian *Euconcordia cunninghami* from the Hamilton Quarry of Kansas (Müller & Reisz 2005; Reisz et al. 2016). However, several older (Bashkirian to Moscovian) taxa, including *Hylonomus*, *Brouffia*, and *Paleothyris* likely either fall on the captorhinid stem or diapsid stem, but have been difficult to place phylogenetically (Müller & Reisz 2006). *Hylonomus* is the oldest of these taxa and occurs in the Joggins Formation of Nova Scotia, whose estimated age range is about 319–310 Mya (Reisz and Müller 2004, van Tuinen and Hadly 2004; Benton et al. 2015). We calibrate this node at 319 Mya, which is slightly older than Benton et al.'s (2015) recommendation of 318 Mya for the age of the synapsid-sauropsid divergence.

***Captorhinus* and *Labidosaurus*:** *Labidosaurus* is a derived captorhinid that occurs in the Kungurian Arroyo Formation of Texas (*sensu* Lucas 2006; equivalent to the lower Clear Fork Group of Hentz 1988) (Dodick & Modesto (1995), whereas the first occurrence of the genus *Captorhinus* is represented by records of *Captorhinus laticeps* from the Artinskian Petrolia Formation of Texas (Heaton 1979; taxonomy following Dodick & Modesto 1995; stratigraphy based on Hentz 1988; Lucas 2006; Schneider et al. 2019). Therefore, we calibrate this divergence at 286 Mya, in the mid-Artinskian.

Common ancestor of *Youngina* and Sauria: *Youngina capensis* is a well-studied stemward diapsid, but recent phylogenetic analyses have differed on whether it represents a distinct lineage or a member of a larger subclade (Younginiformes), as well as the membership of that subclade when present (e.g., Bickelmann et al. 2009; Reisz et al. 2011; Ezcurra et al. 2014; Turner et al. 2017; Simões et al. 2018). For simplicity, we treated *Youngina* as an individual lineage although the inclusion of other putative younginiforms would not result in a dramatic age increase. The earliest occurrence of *Youngina* is in strata of the Hoedemaker Member (Teekloof Formation; Karoo Basin) that are assigned to the *Tropidostoma-Gorgonops* Subzone of the *Endothiodon* Assemblage Zone (Smith & Evans 1996; Day and Smith 2020). This assemblage zone is bracketed by radiometric dates of 259.26 Mya and 256.25 Mya (Day et al. 2015; Day and Smith 2020). However, this occurrence postdates the more crownward divergence of Testudines and Archosauromorpha, which occurred no later than the late Capitanian. Therefore, we calibrate this node at 263 Mya to accommodate the divergence of Testudines and Archosauromorpha.

Common ancestor of Testudines and Archosauromorpha: Although our sample does not include any fossil turtles, the age of this node has implications for other calibrations in the diapsid portion of the tree that require some discussion. The phylogenetic position of turtles within Sauropsida has been controversial (see review in Schoch & Sues 2019). A consensus is emerging that turtles are members of Diapsida, but there is still debate over where they fall relative to lepidosauromorphs, archosaurs, and extinct lineages such as sauropterygians (e.g., Lyson et al. 2010; Field et al. 2014; Bever et al. 2015; Crawford et al. 2015; Irisarri et al. 2017; Schoch & Sues 2015; 2018; Li et al. 2018; Simões et al. 2018). Here, we follow the hypothesis that turtles are more closely related to archosaurs than lepidosaurs.

The Permian archosauromorph fossil record is extremely sparse and of limited utility for calibrating this node (e.g., Ezcurra 2016; also next entry). Very little is known of the Permian portion of the turtle lineage but an increasing amount of data suggests that *Eunotosaurus africanus* from the Karoo Basin of South Africa is the oldest known stem turtle (e.g., Lyson et al. 2010; 2013; 2014, 2016; Bever et al. 2015, 2016). Day (2013) and Day et al. (2013) reported that *Eunotosaurus* occurs in the upper portion of the Abhrahamskraal Formation and the Poortjie Member of the Teekloof Formation in that Karoo Basin of South Africa (equivalent to the *Eosimops-Glanosuchus* and *Diictodon-Styracocephalus* subzones of the *Tapinocepahlus* Assemblage Zone and the *Lycosuchus-Eunotosaurus* Subzone of the *Endothiodon A*ssemblage Zones; Day and Rubidge 2020; Day and Smith 2020). Occurrences of *Eunotosaurus* in the upper Abrahamskraal formation are close to the dates of 261.24–260.26 Mya (Capitanian) for the upper *Tapinocephalus* Assemblage Zone (Rubidge et al. 2013; Day et al. 2015). We calibrate this node at 262 Mya (but see discussion in Marjanović 2019).

Common ancestor of *Prolacerta* and Archosauriformes: *Prolacerta broomi* and its sister taxon *Kadimakara australiensis* fall near the base of Archosauriformes within Archosauromorpha, and they occur in Induan (Early Triassic) strata in Antarctica, Australia, and South Africa (e.g., Ezcurra 2016; Spiekman 2018). However, the minimum age of this node is calibrated by the presence of the archosauriform *Archosaurus rossicus* in the upper Changhsingian Vyazniki Assemblage of Russia (e.g., Sennikov & Golubev 2006; 2017). The Russian taxon *Eorasaurus olsoni* could push this divergence farther back into the Permian (Sennikov 1997; Ezcurra et al. 2014; Bernardi et al. 2015; Ezcurra 2016), but its status as an archosauriform (and even a sauropsid) has been challenged (Peecook et al. 2018c). Sennikov & Golubev (2006) considered the Vyazniki Assemblage to be transitional between more typical late Permian tetrapod assemblages and those of the Early Triassic, implying an age close to the Permo–Triasssic boundary. We calibrate this node at 254 Mya, near the base of the Changhsingian Stage, although the very limited Permian archosauromorph fossil record raises the possibility that this is an underestimate.

Last Appearance Datum

Eothyris: *Eothyris parkeyi* is known from a single specimen that was collected in the Petrolia Formation of Texas (Reisz et al. 2009). The Petrolia Formation has produced a tetrapod assemblage assigned to the Seymouran Land Vertebrate Faunachron (e.g., Lucas 2006; 2018), which is considered to be middle–late Artinskian in age (Schneider et al. 2019), so we calibrate this last occurrence at 287 Mya.

Dimetrodon**:** *Dimetrodon* is a very abundant and stratigraphically long-ranging genus known from North America and Western Europe (e.g., Romer & Price 1940; Reisz 1986; Berman et al. 2001). *Dimetrodon angelensis* from the San Angelo Formation of Texas (Olson 1962) is the youngest species of *Dimetrodon*, although it is known from limited, fragmentary material. The San Angelo Formation tetrapod assemblage is assigned to the Littlecrotonian Land Vertebrate Faunauchron (Lucas 2006; 2018), and the San Angelo formation is considered to be late Kungurian in age based on fusilinids that occur in the formation (Schneider et al. 2019). Therefore, we calibrate the last occurrence of *Dimetrodon* at 275 Mya.

Hipposaurus**:** *Hipposaurus boonstrai* primarily occurs in the *Diictodon-Styracocephalus* Subzone of the *Tapinocephalus* Assemblage Zone (Abrahamskraal Formation, Karoo Basin, South Africa; Day and Rubidge 2020). The stratigraphically highest specimens of the species range at least as high as the Karelskraal Member of the Abrahamskraal Formation, and one specimen may reach the lower Poortjie Member of the overlying Teekloof Formation, although its exact stratigraphic position is uncertain (Day 2013). The uppermost occurrences of *Hipposaurus* are close to the dates of 261.24–260.26 Mya for the upper *Tapinocephalus* Assemblage Zone (Rubidge et al. 2013; Day et al. 2015). Therefore, we calibrate this last occurrence at 261 Mya.

***Herpetoskylax*:** *Herpetoskylax hopsoni* occurs in strata of the Teekloof Formation that are assigned to the *Cistecephalus* Assemblage Zone (Karoo Basin, South Africa) (Sidor & Rubidge 2006). *Cistecephalus* Assemblage Zone strata are approximately bracketed by radiometric dates of 256.25 Mya and 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith 2020). We calibrate this last occurrence at 255 Mya, near the end of *Cistecephalus* zone times.

***Leucocephalus*:** *Leucocephalus wewersi* is known from a single specimen collected in the Hoedemaker Member of the Middleton Formation (Karoo Basin South Africa), which is assigned to the *Tropidostoma-Gorgonops* Subzone of the *Endothiodon* Assemblage Zone (Day et al. 2018a; Day and Smith 2020). The *Tropidostoma-Gorgonops* Subzone is bracketed by radiometric dates of 259.26 Mya and 256.25 Mya (Rubidge et al. 2013; Day et al. 2015) and Day and Smith (2020) considered it to begin about 258 Mya, so we calibrate its last occurrence at 258 Mya.

***Lemurosaurus*:** *Lemurosaurus pricei* is known from rocks of the Balfour and Middleton formations (Karoo Basin, South Africa) that are assigned to the *Cistecephalus* Assemblage Zone (Sidor & Welman 2003; Sidor & Rubidge 2006; Smith 2020). *Cistecephalus* Assemblage Zone strata are approximately bracketed by radiometric dates of 256.25 Mya and 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith 2020). We calibrate this last occurrence at 255 Mya, near the end of *Cistecephalus* zone times.

***Moschops*:** The genus *Moschops* is one of the more abundant tapinocephalid taxa known from the Karoo Basin of South Africa, and its stratigraphic range extends into the Karelskraal Member of the Abrahamskraal Formation (*Diictodon-Styracocephalus* Subzone of the *Tapinocephalus* Assemblage Zone) (Day 2013; Day and Rubidge 2020). Radiometric dates of 261.24 Mya to 260.26 Mya have been reported from the upper *Tapinocephalus* Assemblage Zone (Rubidge et al. 2013; Day et al. 2015), and we calibrate this last occurrence at 261 Mya.

***Patranomodon*:** *Patranomodon nyaphulii* is known from a single specimen collected in rocks of the Abrahamskraal Formation (Karoo Basin, South Africa) assigned to the *Eodicynodon* Assemblage Zone (Rubidge & Hopson 1996; Rubidge and Day 2020). Dates from near the base of this formation range from 268.5–264.6 Mya (Lanci et al. 2013), and the upper portion of the *Tapinocephalus* Assemblage Zone has been dated to about 262–261 Mya (Day et al. 2015). We calibrate this last occurrence at 265 Mya.

***Eodicynodon*:** *Eodicynodon oosthuizeni* occurs in the *Eodicynodon* Assemblage Zone of the Abrahamskraal Formation (Karoo Basin, South Africa), with its highest occurrence falling in the Koornplaats Member (e.g., Day 2013; Day et al. 2018). The last occurrence of *E. oosthuizeni* is stratigraphically higher than the occurrence of *Patranomodon* (Day 2013; Day et al. 2018), so we calibrate this last occurrence at 264 Mya.

***Diictodon*:** Although *Diictodon feliceps* is also known from China and Zambia (Angielczyk & Sullivan 2008), its full temporal range is best documented in the Karoo Basin of South Africa. There, *D. feliceps* ranges through most of the *Daptocephalus* Assemblage Zone (Viglietti et al. 2016; Viglietti 2020). This places it close to the level of Gastaldo et al.'s (2015) radiometric date of 253.48 Mya for the *Lystrosaurus maccaigi-Moschorhinus* Subzone, and we calibrate this last occurrence at 253 Mya.

***Pristerodon*:** Like *Diictodon*, the temporal range of *Pristerodon mackayi* is best documented in the Karoo Basin, where its last occurrence is in the upper portion of the *Dicynodon-Theriognathus* Subzone of the Daptocephalus Assemblage Zone (Viglietti 2020). Therefore, we calibrate this last occurrence at 253.5 Mya, slightly older than Gastaldo et al.'s radiometric date of 253.48 Mya.

***Niassodon*:** The single known specimen of *Niassodon mfumukasi* was collected in the K5 Formation of the Metangula Graben (Mozambique), which was with the *Cistecephalus* Assemblage Zone of the Karoo Basin by Castanhinha et al. 2013. However, a detrital zircon-based maximum depositional age of 258.85 Mya for the K5c horizon reported by Araújo et al. (2020) implies an age close to the boundary of the South African *Lycosuchus-Eunotosaurus* and *Tropidostoma-Gorgonops* subzones of the *Endothiodon* Assemblage Zone (Day and Smith 2020). We use an age of 258 Mya to calibrate this last occurrence.

Abajudon: *Abajudon kaayai* has been reported from the Ruhuhu Formation (Ruhuhu Basin, Tanzania) and the Lower Madumabisa Mudstone Formation (Mid-Zambezi Basin, Zambia) (Angielczyk et al. 2014a). In each area, it co-occurs with tapinocephalid dinocephalians (Simon et al. 2010; Sidor et al. 2014), leading to a broad correlation with the *Tapinocephalus* Assemblage Zone of the South African Karoo Basin (Olroyd & Sidor 2017; Day and Rubidge 2020). Radiometric dates of 261.24–260.26 Mya have been reported from the upper *Tapinocephalus* Assemblage Zone (Rubidge et al. 2013; Day et al. 2015; Day and Rubidge 2020) and we calibrate this last occurrence at 260 Mya, in part to accommodate our calibrations for divergence times within Endothiodontia (see above).

***Endothiodon tolani*:** *Endothiodon tolani* was first described from the Ruhuhu Formation of Tanzania, where its range appears to be limited to an interval near the Guadalupian-Lopingian boundary (Angielczyk et al. 2014a; Cox & Angielczyk 2015; Olroyd & Sidor 2017). New records from the Metangula Graben of Mozambique (Macungo et al. 2020) and the mid-Zambezi Basin of Zambia (this paper) do not have precisely-constrained ages but could be as young as late Wuchiapingian (~*Cistecephalus* Assemblage Zone of the South African Karoo Basin; Castanhinha et al. 2013; Barbolini et al. 2016; Araújo et al. 2020). Here, we calibrate the last occurrence of *E. tolani* at 258 Mya, reflecting its co-occurrence with *Niassodon* in the K5 Formation (see above), although we acknowledge that it may eventually be shown to have a younger last occurrence as the ages of the Mozambican and Zambian records become more certain.

***Endothiodon bathystoma*:** *Endothiodon bathystoma* is stratigraphically and geographically wide-ranging (e.g., Cox 1964; Ray 2000; Boos et al. 2013; Angielczyk et al. 2014b; Cox & Angielczyk 2015; Macungo et al. 2020), but its temporal range is best constrained in the Karoo Basin of South Africa. In the Karoo, *E. bathystoma* ranges into the *Cistecephalus* Assemblage Zone (Smith et al. 2012; Smith 2020), which is approximately bracketed by radiometric dates of 256.25 and 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith et alk. 2020). We calibrate this last occurrence at 256 Mya, reflecting the fact that *Endothiodon* does not appear to reach the upper *Cistecephalus* Zone in the Karoo (Viglietti et al. 2016; Smith 2020). Occurrences of *Endothiodon* in the upper Madumabisa Mudstone Formation (Zambia) and the Usili Formation (Tanzania) may imply a slightly later last occurrence because these formations may sample a time interval near the *Cistecephalus*/*Daptocephalus* assemblage zone boundary (Angielczyk & Kammerer 2017; Angielczyk 2019; Viglietti 2020), but the ages of those formations have not been corroborated with radiometric dates.

***Dicynodontoides*:** The genus *Dicynodontoides* is known from India, South Africa, Tanzania, and Zambia (e.g., Ray & Bandyopadhyay 2003; Angielczyk et al. 2009, 2014b), but its temporal range is best constrained in the South African Karoo Basin. There, its last occurrence is very close to the traditionally-recognized Permo–Triassic boundary (Angielczyk et al. 2009; Smith & Botha-Brink 2014; Viglietti et al. 2016; Viglietti 2020). Therefore, we calibrate this last occurrence at 252 Mya.

***Kawingasaurus*:** *Kawingasaurus fossilis* is known only from the Usili Formation of the Ruhuhu Basin, Tanzania (Cox 1972). Angielczyk et al. (2014b) correlated the Usili Formation with the Wuchiapingian *Cistecephalus* Assemblage Zone of the Karoo Basin, but more recent work suggests that it may encompass parts of the upper *Cistecephalus* Assemblage Zone and the lower *Daptocephalus* Assemblage Zone (Angielczyk & Kammerer 2017; Angielczyk 2019; also see Sidor et al. 2010; Kammerer 2019; Viglietti 2020). Radiometric dates from the South African Karoo Basin suggest the *Cistecephalus-Daptocephalus* zone boundary is approximately 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith 2020; Viglietti 2020), and Gastaldo et al. (2015) reported a date of 253.48 Mya for the *Lystrosaurus maccaigi-Moschorhinus* Subzone of the *Daptocephalus* Assemblage Zone. We calibrate this last occurrence at 254 Mya, placing it in the *Dicynodon-Theriognathus* Subzone of the *Daptocephalus* Assemblage Zone.

***Kembawacela*:** *Kembawacela kitchingi* is a newly-described cistecephalid dicynodont known only from the upper Madumabisa Mudstone Formation of the Luangwa Basin (Zambia) (Angielczyk et al. 2019). Angielczyk et al. (2014b) correlated the upper Madumabisa Mudstone Formation with the Wuchiapingian *Cistecephalus* Assemblage Zone of the Karoo Basin, but more recent work suggests that it may encompass parts of the upper *Cistecephalus* Assemblage Zone and the lower *Daptocephalus* Assemblage Zone (Angielczyk & Kammerer 2017; Angielczyk 2019; also see Sidor et al. 2010; Smith 2020; Viglietti 2020). Radiometric dates from the South African Karoo Basin suggest the *Cistecephalus*-

Daptocephalus zone boundary is approximately 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith 2020; Viglietti 2020), and Gastaldo et al. (2015) reported a date of 253.48 Mya for the *Lystrosaurus maccaigi-Moschorhinus* Subzone of the *Daptocephalus* Assemblage Zone. We calibrate this last occurrence at 254 Mya, placing it in *Dicynodon-Theriognathus* Subzone of the *Daptocephalus* Assemblage Zone.

***Oudenodon*:** *Oudenodon bainii* is a widespread dicynodont in southern Africa (e.g., Botha & Angielczyk 2007; Sidor et al. 2010; Castanhinha et al. 2013; Angielczyk et al. 2014b), and like many such taxa its temporal range is best known in the South African Karoo Basin. In the Karoo, *Oudenodon* ranges into the *Lystrosaurus maccaigi-Moschorhinus* Subzone of the *Daptocephalus* Assemblage Zone, but disappears some distance below the Permo–Triassic boundary (Smith & Botha-Brink 2014; Viglietti et al. 2016; Viglietti 2020). We calibrate this last occurrence at 253 Mya, taking into account the radiometric date of Gastaldo et al. (2015) for the *Lystrosaurus maccaigi-Moschorhinus* Subzone and the fact that the last occurrence of *Oudenodon* is stratigraphically close to that of *Diictodon* (Viglietti 2020).

***Aulacephalodon*:** The specimen of *Aulacephalodon* used in this analysis is an undescribed specimen that originated in the upper Madumabisa Mudstone Formation of the Luangwa Basin, Zambia. Angielczyk et al. (2014b) correlated the upper Madumabisa Mudstone Formation with the Wuchiapingian *Cistecephalus* Assemblage Zone of the Karoo Basin, but more recent work suggests that it may encompass parts of the upper *Cistecephalus* Assemblage Zone and the lower *Daptocephalus* Assemblage Zone (Angielczyk & Kammerer 2017; Angielczyk 2019; also see Sidor et al. 2010; Smith 2020; Viglietti 2020). The stratigraphic range of *Aulacephalodon* is better constrained in the Karoo Basin itself, where it disappears in the lower portion of the *Lystrosaurus maccaigi-Moschorhinus* Subzone of the *Daptocephalus* Assemblage Zone. Radiometric dates from the Karoo Basin suggest the *Cistecephalus-Daptocephalus* zone boundary is approximately 255.2 Mya (Rubidge et al. 2013; Day et al. 2015), and Gastaldo et al. (2015) reported a date of 253.48 Mya for the *Lystrosaurus maccaigi-Moschorhinus* Subzone. We calibrate this last occurrence at 254 Mya, placing it in lower *Daptocephalus* Assemblage Zone times (i.e., the *Dicynodon-Theriognathus* Subzone), reflecting its potentially slightly greater age than the youngest specimens known from the Karoo.

***Lystrosaurus murrayi*:** The genus *Lystrosaurus* is famous for its Pangaean geographic range (e.g., Fröbisch 2009). These occurrences have long been thought to fall in the Early Triassic, but the exact temporal range encompassed by *Lystrosaurus*-bearing strata is somewhat uncertain, particularly in regard to whether any of the strata were deposited in the Olenekian (e.g., Rubidge 2005; Lucas 2010; Schneider et al. 2019). In the South African Karoo Basin, the last occurrence of *L. murrayi* is in the Swartberg Member of the Katberg Formation, slightly below that last occurrence of *L. declivis* in the upper Katberg Formation (both *Lystrosaurus declivis* Assemblage Zone; Botha & Smith 2006, 2007, 2020). We calibrate the last occurrence of *L. murrayi* at 251.2 Mya, the boundary between the Induan and the Olenekian.

<u>Lystrosaurus declivis</u>**<u>:</u>** *Lystrosaurus declivis* has a slightly longer stratigraphic range in the South African Karoo Basin than *L. murrayi* (Botha and Smith 2006, 2007; 2020). Therefore, we calibrate its last occurrence at 251 Mya, in the early Olenekian.

<u>Sangusaurus:</u> The genus *Sangusaurus* occurs in the Lifua Member of the Manda Beds (Ruhuhu Basin, Tanzania) and the upper Ntawere Formation (Luangwa Basin, Zambia) (Angielczyk et al. 2018). Traditionally, these strata have been considered to be Anisian–early Ladinian in age (e.g., Lucas 1998, 2010; Rubidge 2005; Hancox et al. 2020), but recent dating of biostratigraphically-correlated strata in South America suggests a younger, Ladinian–Carnian age may be more likely (e.g., Peecook et al. 2018a). We calibrate this last occurrence at 237 Mya (latest Ladinian), although we acknowledge the uncertainty that accompanies this estimate (e.g., Schneider et al. 2019).

<u>"Aloposaurus":</u> This specimen (GPIT/RE/7124) has been variously assigned to the genera *Aloposaurus*, *Aelurosaurus*, and Gorgonopsia *incertae sedis* (see review in Araújo et al. 2017). It was collected in *Cistecephalus* Assemblage Zone strata in the South African Karoo Basin (Araújo et al. 2017), establishing a maximum age for the specimen regardless of its taxonomic assignment. However, based on their compositions in the revisions of Sigogneau-Russell (1989) and Gebauer (2007), the genera *Aloposaurus* and *Aelurosaurus* both have stratigraphic ranges that extend into the *Daptocephalus* Assemblage Zone. We calibrate this last occurrence at 254 Mya, in the *Dicynodon-Theriognathus* Subzone of the *Daptocephalus* Assemblage Zone, although we acknowledge that it is somewhat uncertain until a firm taxonomic assignment exists for this specimen.

<u>Lycaenops</u>**<u>:</u>** The taxonomy of the genus *Lycaenops* was most recently reviewed by Gebauer (2007), who recognized five named species and a possible unnamed sixth species. Some more recent works (e.g., Kammerer 2016c) considered certain species historically referred to the genus but did not focus on formally revising the genus. Specimens of *Lycaenops* range into the *Lystrosaurus maccaigi-Moschorhinus* Subzone of the *Daptocephalus* Assemblage Zone (e.g., supplementary data of Viglietti et al. 2016; Viglietti 2020). We calibrate this last occurrence at 253 Mya, reflecting Gastaldo et al.'s (2015) date of 253.48 Mya for the *Lystrosaurus maccaigi-Moschorhinus* Subzone.

<u>Scylacocephalus</u>**<u>:</u>** The specimen in question (BP/1/216) was identified as *Scylacocephalus watermeyri* in Benoit et al. (2017b). However, the genus *Scylacocephalus* was considered a synonym of *Aelurosaurus* or *Aloposaurus* in the revisions of Sigogneau-Russell (1989) and Gebauer (2007), respectively. Based on their compositions in the revisions of Sigogneau-Russell (1989) and Gebauer (2007), the genera *Aloposaurus* and *Aelurosaurus* both have stratigraphic ranges that extend into the

Daptocephalus Assemblage Zone. We calibrate this last occurrence at 254 Mya, in the *Dicynodon-Theriognathus* Subzone of the *Daptocephalus* Assemblage Zone, although we acknowledge that it is somewhat uncertain pending a revision of *Scylacocephalus* in the taxonomic framework for Gorgonopsia that is currently emerging (e.g., Kammerer 2016c, 2017; Kammerer& Masyutin 2018a).

***Dixeya*:** GPIT/RE/7119 was originally described as *Dixeya nasuta* by von Huene (1950). Sigogneau-Russell (1989) and Gebauer (2007) suggested that it may instead represent *Arctognathus*, but Kammerer (2015) noted that the specimen differed from more certain *Arctognathus* material and preferred to treat *Dixeya* as a valid taxon. Araújo et al. (2017) recently described the endocranial anatomy of this specimen but noted that its systematic placement was uncertain. GPIT/RE/7119 was collected in the Usili Formation of the Ruhuhu Basin, Tanzania. Based on biostratigraphy, the fossil assemblage of the Usili Formation has been considered to correlate with the *Cistecephalus* Assemblage Zone of the South African Karoo Basin (Sidor et al. 2010; Angielczyk et al. 2014a, 2014b), although recent discoveries in the correlative upper Madumabisa Mudstone Formation of the Zambian Luangwa Basin (Angielczyk & Kammerer 2017; Angielczyk 2019; also see Kammerer 2019; Smith 2020; Viglietti 2020) raise the possibility that the Usili Formation may span the *Cistecephalus–Daptocephalus* assemblage zone boundary. No radiometric dates exist for the Usili Formation, but radiometric dates from the Karoo Basin suggest the *Cistecephalus-Daptocephalus* zone boundary is approximately 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith 2020; Viglietti 2020), and Gastaldo et al. (2015) reported a date of 253.48 Mya for the *Lystrosaurus maccaigi-Moschorhinus* Subzone of the *Daptocephalus* Assemblage Zone. We calibrate this last occurrence at 254 Mya, which would make it equivalent to the *Dicynodon-Theriognathus* Subzone of the *Daptocephalus* Assemblage Zone.

BP/1/155: BP/1/155 is a gorgonopsian in the collections of the Evolutionary Studies Institute (University of the Witwatersrand). Benoit et al. (2016b, 2017c, 2017d) included it in their studies of therapsid endocranial anatomy and identified it as Gorgonopsia indet. The specimen was collected in strata assigned to the *Cistecephalus* Assemblage Zone in the Karoo Basin of South Africa (Benoit et al. 2017c). *Cistecephalus* Assemblage Zone strata are approximately bracketed by radiometric dates of 256.25 Mya and 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith 2020). We calibrate this last occurrence at 255 Mya, near the end of *Cistecephalus* zone times.

Euchambersia: *Euchambersia mirabilis* is known from only two specimens that were collected in strata assigned to the *Cistecephalus* Assemblage Zone in the South African Karoo Basin (e.g., Benoit 2016). The *Cistecephalus* zone is approximately bracketed by radiometric dates of 256.25 and 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith 2020), and we calibrate this last occurrence at 255 Mya.

***Olivierosuchus*:** *Olivierosuchus parringtoni* is known from strata assigned to the Early Triassic *Lystrosaurus declivis* Assemblage Zone in the Karoo Basin, South Africa (e.g., Botha & Smith 2006;

2020; Huttenlocker & Smith 2017). The *Lystrosaurus declivis* Assemblage Zone is generally considered to be Induan to potentially early Olenekian in age (e.g., Rubidge 2005; Lucas 2010; Schneider et al. 2019; Botha and Smith 2020). We calibrate the last occurrence of *Olivierosuchus* at 251 Mya, in the earliest Olenekian, to accommodate this uncertainty.

Ictidosuchoides**:** *Ictidosuchoides longiceps* has a long stratigraphic range in the Karoo Basin of South Africa, with its latest occurrences falling in the lower *Daptocephalus* Assemblage Zone (Viglietti et al. 2016; Huttenlocker & Smith 2017). Radiometric dates from the South African Karoo Basin suggest the *Cistecephalus-Daptocephalus* zone boundary is approximately 255.2 Mya (Rubidge et al. 2013; Day et al. 2015), and Gastaldo et al. (2015) reported a date of 253.48 Mya for the upper *Daptocephalus* Assemblage Zone. We calibrate this last occurrence at 254 Mya, placing it in lower *Daptocephalus* Assemblage Zone times.

Microgomphodon**:** *Microgomphodon oligocynus* is known from the Burgersdorp Formation of the South African Karoo Basin and the upper Omingonde Formation of the Namibian Otjiwarongo Basin, with the latter record representing its youngest occurrence (Abdala et al. 2014; Hancox et al. 2020). The upper Omingonde Formation is biostratigraphically correlated with the *Dinodontosaurus* Assemblage Zone of the Santa Maria Supersequence, Brazil (e.g., Abdala et al. 2013; Martinelli et al. 2017a; Melo et al. 2017; Peecook et al. 2018a). The *Dinodontosaurus* Assemblage Zone is likely older than 236–237 Mya (e.g., Martinelli et al. 2017a; Melo et al. 2017; Philipp et al. 2018; Schmitt et al. 2019), so we calibrate the last occurrence of *Microgomphodon* at 237 Mya.

Choerosaurus**:** *Choerosaurus dejageri* occurs in the Wuchiapingian *Tropidostoma-Gorgonops* Subzone of the *Endothiodon* Assemblage Zone of the Karoo Basin (Benoit et al. 2016a; Huttenlocker & Smith 2017). The *Tropidostoma-Gorgonops* Subzone is thought to be between 258 Mya and 256.8 Mya in age (Rubidge et al. 2013; Day et al. 2015; Day and Smith 2020). We calibrate this last occurrence at 256.5 Mya, near what is presumably the end of *Tropidostoma-Gorgonops* Subzone time.

Mupashi**:** *Mupashi migrator* is known from a single specimen collected in the upper Madumabisa Mudstone Formation of the Luangwa Basin, Zambia (Huttenlocker & Sidor 2016). Angielczyk et al. (2014b) correlated the upper Madumabisa Mudstone Formation with the Wuchiapingian *Cistecephalus* Assemblage Zone of the Karoo Basin, but more recent work suggests that it may encompass parts of the upper *Cistecephalus* Assemblage Zone and the lower *Daptocephalus* Assemblage Zone (Angielczyk & Kammerer 2017; Angielczyk 2019; also see Sidor et al. 2010; Smith 2020; Viglietti 2020). Radiometric dates from the South African Karoo Basin suggest the *Cistecephalus-Daptocephalus* zone boundary is approximately 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith 2020, Viglietti 2020), and Gastaldo et al. (2015) reported a date of 253.48 Mya for the *Lystrosaurus maccaigi*-

Moschorhinus subzone of the *Daptocephalus* Assemblage Zone. We calibrate this last occurrence at 254 Mya, placing it in the *Dicynodon-Theriognathus* Subzone of the *Daptocephalus* Assemblage Zone.

***Procynosuchus*:** *Procynosuchus delaharpeae* is a geographically wide-ranging Permian cynodont (e.g., see review in Kammerer 2016b), but its temporal range is best constrained in the Karoo Basin of South Africa. There, it ranges into the *Dicynodon-Theriognathus* Subzone of the *Daptocephalus* Assemblage Zone (Viglietti 2020). Gastaldo et al. (2015) reported a date of 253.48 Mya for the overlying *Lystrosaurus maccaigi-Moschorhinus* Subzone, so we calibrate the last occurrence of *Procynosuchus* at 253.5 Mya.

***Cynosaurus*:** *Cynosaurus suppostus* occurs in the upper Wuchiapingian-Changhsingian *Cistecephalus* and *Daptocephalus* assemblage zones of South Africa (Van den Brandt & Abdala 2018; Smith 2020; Viglietti 2020), and Viglietti (2020) recorded its stratigraphic range as nearly reaching the Permo–Triassic boundary. Therefore, we calibrate its last occurrence at 252 Mya.

***Galesaurus*:** *Galesaurus planiceps* has a short stratigraphic range in the *Lystrosaurus declivis* Assemblage Zone of the Karoo Basin (South Africa) (Botha & Smith 2006, 2020). The *Lystrosaurus declivis* Assemblage Zone is generally considered to be Induan to potentially early Olenekian in age (e.g., Rubidge 2005; Lucas 2010; Schneider et al. 2019; Botha and Smith 2020). We calibrate its last occurrence at 251.2 Mya, at the top of the Induan Stage.

***Thrinaxodon*:** *Thrinaxodon liorhinus* has a well-documented stratigraphic range that extends through the *Lystrosaurus* Assemblage Zone in the South African Karoo Basin (e.g., Botha & Smith 2006, 2020; Smith and Botha-Brink 2014), and it is also found in the biostratigraphically-correlated lower Fremouw Formation of Antarctica (e.g., Kitching et al. 1972; Colbert and Kitching 1977; Hammer 1990; Peecook et al. 2018b). The exact temporal range encompassed by *Lystrosaurus*-bearing strata is somewhat uncertain, particularly in regard to whether any of the strata were deposited in the Olenekian (e.g., Rubidge 2005; Lucas 2010; Schneider et al. 2019). We calibrate the last occurrence of *Thrinaxodon* at 251 Mya, in the earliest Olenekian, to accommodate this uncertainty.

***Trirachodon*:** In their recent taxonomic revision, Hopson and Sidor (2018) recognized one valid species of *Trirachodon*, *T. berryi*. *Trirachodon berryi* is best known from the *Trirachodon-Kannemeyeria* Subzone of the *Cynognathus* Assemblage Zone (Karoo Basin, South Africa; Abdala et al. 2006; Hopson & Sidor 2018; Hancox et al. 2020). Additional material from the upper Omingonde Formation of Namibia has been referred to *Trirachodon* (Keyser 1973; Smith & Swart 2002), but much of this material has been referred to other non-trirachodontid cynodonts subsequently (Abdala et al. 2006; Abdala & Smith 2009). A remaining Namibian specimen may represent *T. berryi*, but this identification is not completely certain (Abdala et al. 2006). Here, we treat the Namibian record as a valid occurrence of *Trirachodon*. The upper Omingonde Formation is biostratigraphically correlated with the *Dinodontosaurus* Assemblage Zone of the Santa Maria Supersequence of Brazil (e.g., Abdala et al. 2013; Martinelli et al. 2017a; Melo et al. 2017; Peecook et al. 2018a). The *Dinodontosaurus* Assemblage zone of Brazil (Santa Maria Supersequence) is likely older than 236–237 Mya (e.g., Martinelli et al. 2017a; Melo et al. 2017; Philipp et al. 2018; Schmitt et al. 2019), so we calibrate the last occurrence of *Trirachodon* at 237 Mya.

***Cricodon*:** Species of *Cricodon* have been reported from the *Trirachodon-Kannemeyeria* and *Cricodon-Ufudocyclops* subzones of the *Cynoganthus* Assemblage Zone (Karoo Basin, South Africa), the Lifua Member of the Manda Beds (Ruhuhu Basin, Tanzania), and the upper Ntawere Formation (Luangwa Basin, Zambia) (e.g., Abdala et al. 2005; Hopson & Sidor 2018; Peecook et al. 2018a; Hancox et al. 2020). Traditionally, these strata have been considered to be Anisian–early Ladinian in age (e.g., Lucas 1998, 2010; Rubidge 2005; Hancox et al. 2020), but recent dating of biostratigraphically-correlated strata in South America suggests a younger, Ladinian–Carnian age may be more likely (e.g., Peecook et al. 2018a). We calibrate this last occurrence at 237 Mya (latest Ladinian), although we acknowledge the uncertainty that accompanies this estimate.

***Scalenodon*:** The genus *Scalenodon* is represented by two species, *S. angustifrons* from the Tanzanian Lifua Member of the Manda Beds and *S. ribeiroae* from the *Dinodontosaurus* Assemblage Zone of the Santa Maria Supersequence, Brazil (e.g., Liu & Abdala 2014; Melo et al. 2017). The *Dinodontosaurus* Assemblage zone of Brazil (Santa Maria Supersequence) is likely older than 236–237 Mya (e.g., Martinelli et al. 2017a; Melo et al. 2017; Philipp et al. 2018; Schmitt et al. 2019), so we calibrate the last occurrence of *Scalenodon* at 237 Mya.

***Luangwa*:** The genus *Luangwa* is known from the upper Ntawere Formation of Zambia, the upper Omingonde Formation of Namibia, the Lifua Member of the Manda Beds of Tanzania, and the *Dinodontosaurus* Assemblage Zone of the Santa Maria Supersequence, Brazil (Brink 1963; Abdala & Sa-Teixeira 2004; Abdala & Smith 2009; Peecook et al. 2018a). All of these units have been biostratigraphically correlated with each other (e.g., Martinelli et al. 2017a; Peecook et al. 2018a) and are likely in the range of 236–237 Mya based on the estimated age of the *Dinodontosaurus* Assemblage Zone (e.g., Martinelli et al. 2017a; Melo et al. 2017; Philipp et al. 2018; Schmitt et al. 2019). We calibrate the last occurrence of *Luangwa* at 237 Mya.

***Massetognathus*:** The genus *Massetognathus* is known from the *Massetognathus-Chanaresuchus* Assemblage Zone of the Chañares Formation (Argentina) and the *Dinodontosaurus* and *Santacruzodon* assemblage zones of the Santa Maria Supersequence (Brazil) (e.g., Schmitt et al. 2019). The maximum depositional age of the *Santacruzodon* Assemblage Zone is approximately 237 Mya (Philipp et al. 2018); radiometric dates for the Chañares Formation range from approximately 236–233 Mya

(Marsicano et al. 2016; Ezcurra et al. 2017). Based on the date for the upper Chañares Formation, we calibrate the last occurrence of *Massetognathus* at 233 Mya.

***Lumkuia*:** *Lumkuia fuzzi* is known from a single specimen collected in the *Trirachodon-Kannemeyeria* Subzone of the *Cynognathus* Assemblage Zone (Karoo Basin, South Africa) (Hopson & Kitching 2001; Hancox et al. 2020). The *Trirachodon-Kannemeyeria* Subzone has generally been regarded as Anisian in age (e.g., Lucas 1998, 2010; Rubidge 2005; Hancox et al. 2020), although it has not been radiometrically dated directly. Recent radiometric dates of strata that are biostratigraphically-correlated with the *Cynognathus* Assemblage Zone have raised the possibility that it parts of it might be substantially younger than previously thought (e.g., Ottone et al. 2014; Marsicano et al. 2016; also see discussion in Peecook et al. 2018a). Detrital zircon crystals from the lower part of the underlying Katberg Formation with a minimum age of 250 ± 5 Mya (Viglietti et al. 2018b) also are consistent with a younger age for the *Cynognathus* Assemblage zone. However, the wide error range on the latter date and the existence of dates for other biostratigraphically-correlated strata more in accordance with the traditional hypothesis (Liu et al. 2018) suggest that further work on the problem is needed (also see Schneider et al. 2019; Hancox et al. 2020). We calibrate the last occurrence of *Lumkuia* at 242 Mya (Anisian–Ladinian boundary), although we acknowledge that that its exact age will remain uncertain until the questions surrounding the ages of many Middle–Late Triassic faunal assemblages are more firmly resolved.

***Chiniquodon*:** The genus *Chiniquodon* is a geographically-widespread and temporally long-ranging probainognathian cynodont (e.g., Abdala & Gaetano 2018). The latest occurrence of *Chiniquodon* is in the Carnian–Norian Ischigualasto Formation of Argentina (e.g., Martínez & Forster 1996; Abdala & Giannini 2002; Martínez et al. 2013b). Radiometric dates of 231.4 and 225.9 Mya are available for the basal and upper Ischigualasto Formation, respectively (see review in Martínez et al. 2013b). Specimens of *Chiniquodon* are found in the lower Ischigualasto Formation (*Scaphonyx-Exaeretodon-Herrerasaurus* biozone; Martínez et al. 2013b), suggesting they are closer to 231 Mya in age than to 225 Mya. Based on these data, we calibrate the last occurrence of *Chiniquodon* at 230 Mya (late Carnian).

***Riograndia*:** *Riograndia guaibensis* is known from the *Riograndia* Assemblage Zone (Candelária Sequence, Santa Maria Supersequence) of the Paraná Basin, Brazil (e.g., Soares et al. 2011). Rocks from this assemblage zone were recently dated at 225.42 Mya (Norian) by Langer et al. (2018). We calibrate the last occurrence of *Riograndia* at 225 Mya.

***Brasilodon*:** *Brasilodon quadrangularis* occurs in strata assigned to the *Riograndia* Assemblage Zone of the Candelária Sequence (Santa Maria Supersequence) in the Paraná Basin, Brazil (e.g., Bonaparte et al. 2003; Martinelli et al. 2016; 2017b; Guignard et al. 2019). Rocks from this assemblage zone were recently dated at 225.42 Mya (Norian) by Langer et al. (2018). We calibrate the last occurrence of *Brasilodon* at 225 Mya.

***Pseudotherium*:** The only known specimen of *Pseudotherium argentinus* was collected in the upper La Peña Member of the Ischigualasto Formation (Ischigualasto-Villa Unión Basin, Argentina), which corresponds to the lower *Scaphonyx-Exaeretodon-Herrerasaurus* biozone (Wallace et al. 2019). This is close to a radiometrically-dated horizon that has produced an age of 231.4 Mya (Carnian; Martínez et al. 2013b). Therefore, we calibrate the last occurrence of *Pseudotherium* at 231 Mya.

***Tritylodon*:** *Tritylodon longaevus* is best known from the upper Elliot Formation of South Africa and Lesotho, but its range may extend into the lower portion of the overlying Clarens Formation if *Tritylodontoideus maximus* is a junior synonym of *Tritylodon longaevus* (e.g., for the possible synonymy see Hopson and Kitching 1972; Gaetano et al. 2017; for stratigraphic range information see Kitching & Raath 1984; Knoll 2005; Sciscio et al. 2017; Bordy et al. 2020; Viglietti et al. 2020). For the purposes of this analysis, we assumed that the proposed synonymy is correct. Recent radiometric dates suggest that the Clarens Formation ranges in age from 190.5–186.7 Mya, with a preferred maximum depositional age of 187.5 Mya (Pliensbachian; Rademan 2018; Bordy et al. 2020; Viglietti et al. 2020). We calibrate the last occurrence of *Tritylodon* at 190 Mya, near the older end of this range, reflecting the occurrence of the '*Tritylodontoideus maximus*' specimen low in the Clarens Formation (Kitching and Raath 1984; Bordy et al. 2020; Viglietti et al. 2020). A minor increase in age would be needed if the range of *Tritylodon* is restricted to occurrences in the Elliot Formation: preferred maximum depositional ages for rock samples from the upper Eliliot Formation Range from 191.1 to 202.33 Mya (Bordy et al. 2020).

***Oligokyphus*:** The genus *Oligokyphus* is known from North America (Sues 1985; Fedak et al. 2015), Europe (Hennig 1922; Kühne 1956), and China (Luo & Sun 1993). The youngest occurrences of the genus are from the Pliensbachian Kayenta Formation (Sues 1985; Marsh 2014) and Pliensbachian fissure-fill deposits in the United Kingdom (Kühne 1956; Whiteside et al. 2016). Marsh (2014) reported a date of 183.7 Mya (late Pliensbachian) for the Kayenta Formation, and we calibrate the last occurrence of *Oligokyphus* at 183 Mya.

***Morganucodon watsoni*:** The stratigraphic range of *Morganucodon watsoni* extends at least until the early Sinemurian from the St. Brides palaeo-island tetrapod community preserved in fissure fills in the United Kingdom, but it could reach the Pleinsbachian based on the associated marine invertebrate fauna (Whiteside et al. 2016). We conservatively calibrate this last occurrence at 198 Mya (early Sinemurian).

***Morganucodon oehleri*:** *Morganucodon oehleri* is known from the Zhangjia'ao Member (*sensu* Fang et al. 2000) of the Lufeng Formation of China (Luo and Wu 1994), which is considered to be Sinemurian in age based on biostratigraphical comparisons (e.g., Luo and Wu 1994; Sullivan et al. 2013). We calibrate the last occurrence of *M. oehleri* at 191 Mya (latest Sinemurian).

***Megazostrodon*:** Although also known from the Rhaetian of Europe (Debuysschere et al. 2015), the youngest records of the genus *Megazostrodon* are known from the Early Jurassic of South Africa and Lesotho. *Megazostrodon rudnerae* occurs in the upper Elliot Formation (e.g., Kitching & Raath 1984; Scisio et al. 2017; Bordy et al. 2020; Viglietti et al. 2020), with some records coming from just below the contact with the overlying Clarens Formation (Gow 1986; Bordy et al. 2020). Recent radiometric dates suggest that the upper Elliot Formation spans the latest Rhaetian or Hettangian to the Sinemurian and that the Clarens Formation is Pliensbachian in age (Scisio et al. 2017; Rademan 2018; Bordy et al. 2020). Therefore, we calibrate the last occurrence of *Megazostrodon* at 191 Mya (latest Sinemurian).

Haldanodon: *Haldanodon exspectatus* is known from the Alcobaça Formation of the Guimarota coal mine of Portugal (e.g., Lillegraven and Krusat 1991; Martin 2005; 2018; Ruf et al. 2013), which is considered Kimmeridgian in age (Schudack 2000a, 2000b). We calibrate the last occurrence of *Haldanodon* at 152 Mya, at the end of the Kimmeridgian.

***Hadrocodium*:** *Hadrocodium wui* is known from the Zhangjia'ao Member (*sensu* Fang et al. 2000) of the Lufeng Formation of China (Luo et al. 2001), which is considered to be Sinemurian in age based on biostratigraphical comparisons (e.g., Luo and Wu 1994; Sullivan et al. 2013). We calibrate the last occurrence of *Hadrocodium* at 191 Mya (latest Sinemurian).

***Dryolestes*:** The genus *Dryolestes* is known from the Late Jurassic (Kimmeridgian–Tithonian) of Europe and North America (e.g., Martin 2018). The youngest records of *Dryolestes* are from high in the Brushy Basin Member of the Morrison Formation of western North America (e.g., Turner & Peterson 1999; Foster 2003). Radiometric dates suggest that these occurrences are early Tithonian in age (e.g., Trujillo et al. 2014; Trujillo & Kowallis 2015). Based on these dates, we calibrate the last occurrence of *Dryolestes* at 151 Mya (earliest Tithonian).

***Diadectes*:** The stratigraphically highest occurrences of the genus *Diadectes* are in the Vale Formation (*sensu* Lucas 2006; equivalent to the middle Clear Fork Group of Hentz 1988) of Texas (Kissel 2010). The Vale Formation is assigned to the Redtankian Land Vertebrate Faunachron (e.g., Lucas 2006; 2018), which is considered to be mid-Kungurian (mid-upper Leonardian) in age (Schneider et al. 2019). We calibrate the last occurrence of *Diadectes* at 276 Mya, in the early part of the late Kungurian.

***Captorhinus*:** The genus *Captorhinus* has a comparably long stratigraphic range in the early Permian of North America, but its latest reliable occurrences are in the Vale Formation (*sensu* Lucas 2006; equivalent to the middle Clear Fork Group of Hentz 1988) of Texas (e.g., LeBlanc et al. 2015). The Vale Formation is assigned to the Redtankian Land Vertebrate Faunachron (e.g., Lucas 2006; 2018), which is considered to be mid-Kungurian (mid-upper Leonardian) in age (Schneider et al. 2019). We calibrate the last occurrence of *Captorhinus* at 276 Mya, in the early part of the late Kungurian.

***Labidosaurus*:** *Labidosaurus hamatus* occurs in the Arroyo Formation (*sensu* Lucas 2006; equivalent to the lower Clear Fork Group of Hentz 1988) of Texas (Modesto et al. 2007). The Arroyo Formation is assigned to the Redtankian Land Vertebrate Faunachron (e.g., Lucas 2006; 2018), which is considered to be mid-Kungurian (mid-upper Leonardian) in age (Schneider et al. 2019). We calibrate the last occurrence of *Labidosaurus* at 277 Mya, in the early part of the late Kungurian.

***Youngina*:** The stratigraphic range of *Youngina capensis* extends into strata assigned to the *Dicynodon-Theriognathus* Subzone of the *Daptocephalus* Assemblage Zone in the South African Karoo Basin (Viglietti et al. 2016; Viglietti 2020). We calibrate its last occurrence at 254 Mya, taking into account that the *Cistecephalus-Daptocephalus* zone boundary is approximately 255.2 Mya (Rubidge et al. 2013; Day et al. 2015; Smith 2020; Viglietti 2020), and Gastaldo et al.'s (2015) date of 253.48 Mya for the *Lystrosaurus maccaigi-Moschorhinus* Subzone of the *Daptocephalus* Assemblage Zone.

***Prolacerta*:** In the Karoo Basin, *Prolacerta broomi* occurs primarily in strata of the Katberg Formation that are assigned to the *Lystrosaurus declivis* Assemblage Zone (e.g., Botha and Smith 2006; 2020). It is also found in the biostratigraphically-correlated lower Fremouw Formation of Antarctica (e.g., Spiekman 2018). The exact temporal range encompassed by *Lystrosaurus*-bearing strata is somewhat uncertain, particularly in regard to whether any of the strata were deposited in the Olenekian (e.g., Rubidge 2005; Lucas 2010; Schneider et al. 2019). We calibrate the last occurrence of *Prolacerta* at 251 Mya, in earliest Olenekian, to accommodate this uncertainty.

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