

**Supplementary information**

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**Subaqueous foraging among carnivorous dinosaurs**

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# Subaqueous foraging among carnivorous dinosaurs

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Taxa	
<i>Alca torda</i>	<i>Spinosaurus</i>
<i>Anarosaurus</i>	<i>Strigiops_habroptilus</i>
<i>Anas discors</i>	<i>Sula dactylatra</i>
<i>Anas erythroincha</i>	<i>Tachybaptus ruficollis</i>
<i>Anhinga anhinga</i>	<i>Trybonix ventralis</i>
<i>Anser fabalis</i>	<i>Turdus_olivater</i>
<i>Anseranas semipalmata</i>	<i>Uria</i>
<i>Aptenodytes</i>	<i>Xenicus longipes</i>
<i>Apteryx owenii</i>	<i>Mammuthus sp.</i>
<i>Aramus guarauna</i>	<i>Elephas maximus</i>
<i>Atlantisia rogersi</i>	<i>Felis felis</i>
<i>Baryonyx</i>	<i>Vulpes vulpes</i>
<i>Basilosaurus</i>	<i>Ursus maritimus</i>
<i>Callophoca obscura</i>	<i>Tapirus terrestris</i>
<i>Caloenas nicobarica</i>	<i>Ceratotherium simum</i>
<i>Chauna chavaria</i>	<i>Rhinoceros sondaicus</i>
<i>Cinclus cinclus</i>	<i>Sus scrofa</i>
<i>Crypturellus tataupa</i>	<i>Giraffa camelopardalis</i>
<i>Cygnus olor</i>	<i>Rangifer tarandus</i>
<i>Gavia immer</i>	<i>Capreolus capreolus</i>
<i>Glareola pratincole</i>	<i>Bison bonasus</i>
<i>Goura cristata</i>	<i>Castor fiber</i>
<i>Leptophoca proxima</i>	<i>Choeropsis liberiensis</i>
<i>Maiacetus</i>	<i>Hippopotamus amphibius</i>
<i>Metryorhynchus</i>	<i>Dasyurus maculatus</i>
<i>Nanophoca vitulinoides</i>	<i>Desmana moschata</i>
<i>Nestor notabilis</i>	<i>Diplomesodon pulchellum</i>
<i>Neusticosaurus</i>	<i>Euroscaptor micrura</i>
<i>Nothosaurus</i>	<i>Hemiechinus azurites</i>
<i>Pelagodroma marina</i>	<i>Lutra vulgaris</i>
<i>Pelecanoides urinatrix</i>	<i>Monodelphis domestica</i>
<i>Phaethon aethereus</i>	<i>Mussetla nivalis</i>
<i>Phalacrocorax harrisi</i>	<i>Noemys fodiens</i>
<i>Phoenicopteris ruber</i>	<i>Ornithorhynchus anatinus</i>
<i>Podica senegalensis</i>	<i>Procavia capensis</i>
<i>Porphyrio Poliocephalus</i>	<i>Rhynchocyon petersi</i>
<i>Porzana carolina</i>	<i>Taxidea taxus</i>
<i>Psophia crepitans napensis</i>	<i>Tenrec ecaudatus</i>
<i>Rodhocetus</i>	<i>Rattus rattus</i>
<i>Sarothrura rufa</i>	<i>Microgale thomasi</i>
<i>Serpianosaurus</i>	<i>Hydromys chrysogaster</i>
<i>Spheniscus humboldti</i>	

**Supplementary Table 1. List of taxa (n=83) shared between the femoral and dorsal rib datasets**

<b>Taxon</b>	<b>Catalogue number</b>	<b>Skeletal elements sampled</b>	<b>Side</b>	<b>Technique</b>
<i>Baryonyx</i>	NHM R 9951	Femur and dorsal rib	Right femur and right dorsal rib	Femur: CT scan Dorsal rib: thin section
<i>Suchomimus</i>	G5; G94	Femur	Right	Thin section
<i>Spinosaurus</i>	FSAC KK 11888	Femur and dorsal rib	Right femur and right dorsal rib	Thin sections

**Supplementary Table 2. Specimen number, skeletal elements and techniques applied for collection of ontogenetic data, and bone density among spinosaurid taxa.**

Model	AICc	AIC weights	R2	Lambda	Variable	Coefficient	Std.Error	t value	p value
<b>compactness ~ subaqueous foraging</b>	-283.64/ <b>-278.27</b> /-272.84	0.664/ <b>0.673</b> /0.681	0.166/ <b>0.172</b> /0.176	0.91/ <b>0.919</b> /0.929	<b>Intercept</b>	0.621/ <b>0.63</b> / 0.637	0.104/ <b>0.108</b> / 0.112	5.623/ <b>5.8585</b> /6.067	0.00
					<b>subaqueous foraging</b>	0.161/ <b>0.164</b> / /0.166	0.023/ <b>0.023</b> / /0.024	6.9/ <b>7.0225</b> /7.12	0.00
<b>compactness ~ subaqueous foraging + sustained flight</b>	-280.81/ <b>-275.35</b> -269.83	0.162/ <b>0.156</b> /0.1 51	0.163/ <b>0.168</b> /0 .173	0.905/ <b>0.915</b> /0.925	<b>Intercept</b>	0.623/ <b>0.6315</b> / 0.639	0.102/ <b>0.105</b> /0. 11	5.746/ <b>6.0075</b> /6 .231	0.00
					<b>subaqueous foraging</b>	0.161/ <b>0.163</b> /0 .166	0.023/ <b>0.023</b> /0. 024	6.921/ <b>7.039</b> /7. 162	0.00
					<b>sustained flight</b>	-0.058/ <b>0.056</b> /-0.053	0.025/ <b>0.026</b> /0. 026	-2.227/ <b>-2.151</b> / 2.057	0.0271/ <b>0.0</b> 326/0.041
<b>compactness ~ subaqueous foraging + flight</b>	-280.76/ <b>-275.33</b> -269.82	0.157/ <b>0.154</b> /0.1 5	0.163/ <b>0.168</b> /0 .173	0.901/ <b>0.912</b> /0.923	<b>Intercept</b>	0.624/ <b>0.633</b> /0 .64	0.101/ <b>0.104</b> /0. 0109	5.813/ <b>6.089</b> /6. 321	0.00
					<b>subaqueous foraging</b>	0.159/ <b>0.162</b> /0 .164	0.023/ <b>0.023</b> /0. 024	6.826/ <b>6.945</b> /7. 066	0.00
					<b>flight</b>	-0.06/ <b>-0.057</b> / 0.054	0.026/ <b>0.027</b> /0. 027	-2.234/ <b>-2.14</b> / 2.056	0.0266/0.0 335/0.0411
<b>compactness ~ midshaft diameter + subaqueous foraging</b>	-275.9/ <b>-270.5</b> -264.94	0.0138/ <b>0.0138</b> / 0.0131	0.143/ <b>0.148</b> /0 .153	0.911/ <b>0.921</b> /0.931	<b>Intercept</b>	0.61/ <b>0.621</b> /0. 631	0.107/ <b>0.11</b> /0.1 15	5.387/ <b>5.6235</b> /5 .875	0.00
					<b>midshaft diameter</b>	0.003/ <b>0.009</b> /0 .015	0.02/ <b>0.021</b> /0.0 21	0.14/ <b>0.4305</b> /0. 72	0.4726/ <b>0.6</b> 674/0.8891
					<b>subaqueous foraging</b>	0.161/ <b>0.163</b> /0 .166	0.023/ <b>0.023</b> /0. 024	6.826/ <b>6.949</b> /7. 04	0.00
<b>compactness ~ subaqueous foraging + sustained flight + midshaft diameter</b>	-272.81/ <b>-267.39</b> -261.97	0.00296/ <b>0.029</b> / 0.00296	0.139/ <b>0.144</b> /0 .149	0.904/ <b>0.915</b> /0.926	<b>Intercept</b>	0.621/ <b>0.632</b> /0 .642	0.104/ <b>0.1075</b> / 0.112	5.609/ <b>5.877</b> /6. 151	0.00
					<b>subaqueous foraging</b>	0.161/ <b>0.163</b> /0 .166	0.023/ <b>0.023</b> /0. 024	6.886/ <b>7.116</b> 6.886/7.116	0.00
					<b>sustained flight</b>	-0.059/ <b>0.056</b> /0.053	0.026/ <b>0.027</b> /0. 027	-2.2/ <b>-2.1075</b> / 2.012	0.029/ <b>0.03</b> 63/0.0455 0.7369/ <b>0.9</b> 3065/0.995 1
<b>compactness ~ infrequent subaqueous foraging</b>	-261.62/ <b>-256.98</b> -252.32	0.000011/ <b>0.000</b> 0.000023	0.078/ <b>0.081</b> /0 .085	0.885/ <b>0.896</b> /0.907	<b>Intercept</b>	0.661/ <b>0.669</b> /0 .676	0.102/ <b>0.105</b> /0. 109	6.11/ <b>6.3525</b> /6. 573	0.00
					<b>infrequent subaqueous foraging</b>	0.116/ <b>0.118</b> /0 .12	0.023/ <b>0.024</b> /0. 024	4.889/ <b>4.9795</b> /5 .061	0.00
<b>compactness ~ midshaft diameter + infrequent subaqueous foraging</b>	-253.99/ <b>-249.34</b> -244.53	2.41/ <b>3.508</b> /4.86 4.86	0.053/ <b>0.056</b> /0 .059	0.886/ <b>0.897</b> /5/0.908	<b>Intercept</b>	0.65/ <b>0.659</b> /0. 668	0.105/ <b>0.108</b> /0. 112	5.85/ <b>6.094</b> /6.3 39	0.00
					<b>midshaft diameter</b>	0.005/ <b>0.01</b> /0. 015	0.021/ <b>0.022</b> /0. 022	0.211/ <b>0.462</b> /0. 777	0.4804/ <b>0.6</b> 448/0.833
					<b>infrequent subaqueous foraging</b>	0.114/ <b>0.117</b> /0 .119	0.024/ <b>0.024</b> /0. 024	4.804/ <b>4.8895</b> /4 .99	0.00
<b>compactness ~ flight</b>	- <b>-243.793</b> -239.667/ -235.449	1.477/ <b>2.783</b> /5.1 74	- 0.002/ <b>0</b> /0.003	0.892/ <b>0.902</b> /0.912	<b>Intercept</b>	0.761/ <b>0.77</b> /0. 776	0.107/ <b>0.11</b> /0.1 14	6.708/ <b>6.9905</b> /7 .251	0.00
					<b>Flight</b>	-0.074/ <b>0.07</b> /-0.066	0.029/ <b>0.03</b> /0.0 3	-2.45/ <b>-2.35</b> / 2.235	0.0149/ <b>0.0</b> 197/0.0265
<b>compactness ~ sustained flight</b>	-241.71/ <b>-238.54</b> -234.35	8.59/ <b>1.584</b> /2.98	-0.007/ <b>0.005</b> /-0.003	0.9/ <b>0.909</b> /0. 918	<b>Intercept</b>	0.761/ <b>0.769</b> /0 .776	0.11/ <b>0.113</b> /0.1 17	6.551/ <b>6.816</b> /7. 051	0.00
					<b>Sustained flight</b>	-0.063/ <b>-0.06</b> / 0.057	0.029/ <b>0.029</b> /0. 029	-2.17/ <b>-2.071</b> / 1.98	0.0312/ <b>0.0</b> 396/0.0482
<b>compactness ~ midshaft diameter</b>	-239.12/ <b>-234.78</b> -230.12	1.429/ <b>2.427</b> / 3.608	-0.026/ <b>0.024</b> /-0.021	0.911/ <b>0.919</b> / 0.927	<b>Intercept</b>	0.734/ <b>0.745</b> / 0.756	0.117/ <b>0.12</b> / 0.124	5.98/ <b>6.1985</b> / 6.438	0.00
					<b>midshaft diameter</b>	0.015/ <b>0.021</b> / 0.027	0.023/ <b>0.023</b> / 0.023	0.664/ <b>0.9175</b> / 1.183	0.2381/ <b>0.35975</b> / 0.5074
<b>compactness ~ midshaft diameter + flight</b>	-236.22/ <b>-232.067</b> -227.75	3.35/ <b>6.22</b> /1.10	-0.03/ <b>-0.027</b> / 0.025	0.893/ <b>0.904</b> /0.914	<b>Intercept</b>	0.748/ <b>0.759</b> / 0.77	0.11/ <b>0.114</b> /0.1 18	6.397/ <b>6.6775</b> / 6.967	0.00
					<b>Midshaft diameter</b>	0.003/ <b>0.009</b> / 0.014	0.023/ <b>0.023</b> / 0.024	0.126/ <b>0.3695</b> / 0.614	0.54/ <b>0.7124</b> / 0.8998
					<b>Flight</b>	-0.071/ <b>0.067</b> /-0.061	0.03/ <b>0.031</b> / 0.031	-2.291/ <b>-2.181</b> / 2.041	0.023/ <b>0.0303</b> / 0.0425
<b>compactness ~ midshaft diameter + sustained flight</b>	-235.24/ <b>-231.04</b> -226.69	2.05/ <b>3.73</b> /6.51	-0.034/ <b>0.032</b> /-0.03	0.901/ <b>0.911</b> /0.92	<b>Intercept</b>	0.745/ <b>0.756</b> / 0.767	0.113/ <b>0.117</b> /0. 12	6.246/ <b>6.4995</b> / 6.763	0.00
					<b>midshaft diameter</b>	0.005/ <b>0.011</b> / 0.017	0.023/ <b>0.023</b> /0.024	0.224/ <b>0.4725</b> / 0.725	0.4695/ <b>0.63715</b> / 0.8226
					<b>Sustained flight</b>	-0.06/ <b>-0.057</b> / 0.053	0.029/ <b>0.03</b> /0.0 3	-1.994/ <b>1.9045</b> /-1.794	0.0475/ <b>0.0582</b> / 0.0743

**Supplementary Table 3. Phylogenetic regressions comparing explanations of bone density among femora using size and ecological traits (all values).** Explanatory variables are combined in all possible ways in different linear models. Linear models are ordered from best to worst. Values organized as minimum/**median**/maximum from the 100 phylogenies used for the phylogenetic regressions. Akaike weights are derived from summarized maximum, median, and minimum values of AICc. These analyses are two-sided and no adjustments were applied for multiple comparisons.

Model	AICc	AIC weights	R2	Lambda	Variable	Coefficient	Std.Error	t-value	p value
compactness ~ subaqueous foraging	-168.805/ <b>-164.167</b> /-157.891	0.671/ <b>0.638</b> /0.641	0.102/ <b>0.108</b> /0.113	0.963/ <b>0.969</b> /0.975	Intercept	0.612/ <b>0.648</b> /0.668	0.059/ <b>0.061</b> /0.063	9.812/ <b>10.652</b> /11.113	<b>0</b>
					subaqueous foraging	0.149/ <b>0.154</b> /0.159	0.032/ <b>0.033</b> /0.033	4.597/ <b>4.7195</b> /4.818	<b>0</b>
compactness ~ subaqueous foraging + sustained flight	-165.848/ <b>-161.538</b> /-155.209	0.153/ <b>0.171</b> /0.167	0.096/ <b>0.104</b> /0.111	0.964/ <b>0.97</b> /0.976	Intercept	0.614/ <b>0.651</b> /0.67	0.059/ <b>0.06</b> /0.062	9.961/ <b>10.8315</b> /11.299	<b>0</b>
					subaqueous foraging	0.146/ <b>0.152</b> /0.157	0.031/ <b>0.032</b> /0.033	4.598/ <b>4.735</b> /4.837	<b>0</b>
					sustained flight	-0.058/ <b>-0.055</b> /-0.051	0.024/ <b>0.024</b> /0.025	-2.369/ <b>-2.2595</b> /-2.139	0.0193/ <b>0.02545</b> /0.0343
compactness ~ subaqueous foraging + flight	-165.77/ <b>-161.421</b> /-155.063	0.147/ <b>0.161</b> /0.155	0.096/ <b>0.104</b> /0.111	0.962/ <b>0.968</b> /0.974	Intercept	0.618/ <b>0.655</b> /0.673	0.058/ <b>0.06</b> /0.062	10.049/ <b>10.9355</b> /11.406	<b>0</b>
					subaqueous foraging	0.143/ <b>0.148</b> /0.153	0.032/ <b>0.032</b> /0.033	4.443/ <b>4.575</b> /4.671	<b>0</b>
					Flight	-0.059/ <b>-0.056</b> /-0.052	0.025/ <b>0.025</b> /0.025	-2.353/ <b>-2.234</b> /-2.106	0.0201/ <b>0.0271</b> /0.037
compactness ~ midshaft diameter + subaqueous foraging	-161.771/ <b>-157.201</b> /-151.343	0.019/ <b>0.019</b> /0.024	0.071/ <b>0.076</b> /0.083	0.962/ <b>0.967</b> /0.974	Intercept	0.636/ <b>0.6705</b> /0.697	0.067/ <b>0.069</b> /0.071	9.007/ <b>9.7115</b> /10.257	<b>0</b>
					midshaft diameter	-0.031/ <b>-0.019</b> /-0.008	0.028/ <b>0.029</b> /0.03	-1.048/ <b>-0.672</b> /-0.286	0.2964/ <b>0.5027</b> /0.7754
					subaqueous foraging	0.15/ <b>0.155</b> /0.16	0.032/ <b>0.033</b> /0.034	4.606/ <b>4.7135</b> /4.817	<b>0</b>
compactness ~ subaqueous foraging + sustained flight + midshaft diameter	-159.617/ <b>-155.457</b> /-149.508	0.0067/ <b>0.0081</b> /0.0096	0.069/ <b>0.078</b> /0.088	0.962/ <b>0.967</b> /0.974	Intercept	0.654/ <b>0.689</b> /0.714	0.067/ <b>0.068</b> /0.07	9.367/ <b>10.0835</b> /10.653	<b>0</b>
					subaqueous foraging	0.147/ <b>0.154</b> /0.158	0.032/ <b>0.032</b> /0.033	4.589/ <b>4.7385</b> /4.843	<b>0</b>
					sustained flight	-0.064/ <b>-0.061</b> /-0.057	0.024/ <b>0.025</b> /0.025	-2.564/ <b>-2.424</b> /-2.304	0.0115/ <b>0.0167</b> /0.0228
				midshaft diameter	-0.045/ <b>-0.033</b> /-0.021	0.028/ <b>0.029</b> /0.03	-1.542/ <b>-1.1415</b> /-0.743	0.1255/ <b>0.25575</b> /0.4589	
compactness ~ flight	-153.683/ <b>-149.212</b> /-143.267	0.00035/ <b>0.00036</b> /0.00042	0.001/ <b>0.006</b> /0.01	0.951/ <b>0.9585</b> /0.967	Intercept	0.762/ <b>0.802</b> /0.823	0.05/ <b>0.052</b> /0.054	14.177/ <b>15.546</b> /16.277	<b>0</b>
					Flight	-0.074/ <b>-0.07</b> /-0.066	0.027/ <b>0.028</b> /0.028	-2.639/ <b>-2.514</b> /-2.391	0.0093/ <b>0.0131</b> /0.0182
compactness ~ sustained flight	-152.502/ <b>-148.011</b> /-142.191	0.00019/ <b>0.00019</b> /0.00025	-0.007/ <b>-0.003</b> /0	0.954/ <b>0.961</b> /0.969	Intercept	0.762/ <b>0.802</b> /0.823	0.051/ <b>0.052</b> /0.055	13.961/ <b>15.2815</b> /16.001	<b>0</b>
					sustained flight	-0.064/ <b>-0.061</b> /-0.057	0.027/ <b>0.027</b> /0.028	-2.352/ <b>-2.2335</b> /-2.128	0.0201/ <b>0.02715</b> /0.0352
compactness ~ infrequent subaqueous foraging	-152.235/ <b>-147.676</b> /-141.739	0.00017/ <b>0.000168</b> /0.00019	-0.011/ <b>-0.006</b> /-0.003	0.95/ <b>0.957</b> /0.966	Intercept	0.701/ <b>0.735</b> /0.756	0.059/ <b>0.061</b> /0.062	11.29/ <b>12.166</b> /12.621	<b>0</b>
					infrequent subaqueous foraging	0.061/ <b>0.067</b> /0.07	0.031/ <b>0.032</b> /0.032	1.948/ <b>2.103</b> /2.198	0.0297/ <b>0.03735</b> /0.0535
compactness ~ midshaft diameter	-148.352/ <b>-143.656</b> /-138.36	2.43E-05/ <b>2.24E-05</b> /3.68E-05	-0.038/ <b>-0.036</b> /-0.032	0.957/ <b>0.963</b> /0.97	Intercept	0.784/ <b>0.8215</b> /0.85	0.063/ <b>0.065</b> /0.067	11.748/ <b>12.616</b> /13.358	<b>0</b>
					midshaft diameter	-0.029/ <b>-0.017</b> /-0.005	0.03/ <b>0.031</b> /0.032	-0.909/ <b>-0.5345</b> /-0.153	0.365/ <b>0.5941</b> /0.8787
compactness ~ midshaft diameter + flight	-147.695/ <b>-143.5885</b> /-138.059	1.75E-05/ <b>2.17E-05</b> /3.17E-05	-0.026/ <b>-0.02</b> /-0.01	0.947/ <b>0.954</b> /0.964	Intercept	0.811/ <b>0.8495</b> /0.876	0.06/ <b>0.062</b> /0.065	12.605/ <b>13.6175</b> /14.451	<b>0</b>
					midshaft diameter	-0.053/ <b>-0.0405</b> /-0.027	0.03/ <b>0.031</b> /0.033	-1.668/ <b>-1.282</b> /-0.877	0.0977/ <b>0.20195</b> /0.3818
					Flight	-0.086/ <b>-0.081</b> /-0.075	0.028/ <b>0.029</b> /0.029	-2.981/ <b>-2.778</b> /-2.656	0.0034/ <b>0.0063</b> /0.0089

compactness ~ midshaft diameter + sustained flight	-146.096/ <b>-141.875</b> /-136.412	7.87E-06/ <b>9.21E-06</b> /1.39E-05	-0.038/ <b>-0.033</b> /-0.025	0.951/ <b>0.958</b> /0.967	<b>Intercept</b>	0.803/ <b>0.841</b> /0.868	0.061/ <b>0.063</b> /0.066	12.318/ <b>13.29</b> /14.085	<b>0</b>
					<b>midshaft diameter</b>	-0.045/ <b>-0.033</b> /-0.02	0.03/ <b>0.031</b> /0.032	-1.427/ <b>-1.05</b> /-0.658	0.1558/ <b>0.2956</b> /0.5114
					<b>sustained flight</b>	-0.072/ <b>-0.068</b> /-0.063	0.027/ <b>0.028</b> /0.029	-2.579/ <b>-2.4025</b> /-2.307	0.011/ <b>0.01765</b> /0.0226
compactness ~ midshaft diameter + infrequent subaqueous foraging	-145.299/ <b>-140.9405</b> /-135.251	5.29E-06/ <b>5.77E-06</b> /7.78E-06	-0.045/ <b>-0.041</b> /-0.036	0.949/ <b>0.955</b> /0.964	<b>Intercept</b>	0.727/ <b>0.758</b> /0.786	0.068/ <b>0.069</b> /0.071	10.225/ <b>10.9115</b> /11.521	<b>0</b>
					<b>midshaft diameter</b>	-0.033/ <b>-0.021</b> /-0.009	0.03/ <b>0.031</b> /0.032	-1.063/ <b>-0.688</b> /-0.296	0.2898/ <b>0.49245</b> /0.7674
					<b>infrequent subaqueous foraging</b>	0.063/ <b>0.069</b> /0.072	0.031/ <b>0.032</b> /0.033	1.991/ <b>2.144</b> /2.241	0.0267/ <b>0.0338</b> /0.0485

**Supplementary Table 4. Phylogenetic regressions comparing explanations of bone density in dorsal ribs using size and ecological traits (all values).** Explanatory variables are combined in all possible ways in different linear models. Linear models are ordered from best to worst. Values organized as minimum/**median**/maximum from the 100 phylogenies used for the phylogenetic regressions. Akaike weights are derived from summarized maximum, median, and minimum values of AICc. These analyses are two-sided and no adjustments were applied for multiple comparisons.

Taxon	Ecology
<i>Antetonitrus</i>	Graviportal
<i>Callophoca obscura</i>	Deep diver
<i>Ichthyosaur sp.</i>	Deep diver
<i>Ichthyosaurus</i>	Deep diver
<i>Leptophoca proxima</i>	Deep diver
<i>Alamosaurus</i>	Graviportal
<i>Stegosaurus sp.</i>	Graviportal
<i>Mammuthus sp.</i>	Graviportal
<i>Elephas maximus</i>	Graviportal
<i>Loxodonta africana</i>	Graviportal
<i>Ceratotherium simum</i>	Graviportal
<i>Dicerorhinus sumatrensis</i>	Graviportal
<i>Rhinoceros sondaicus</i>	Graviportal
<i>Rhinoceros unicornis</i>	Graviportal
<i>Brachyodus onoideum</i>	Deep diver
<i>Hexaprotodon garyam</i>	Graviportal
<i>Metryorhynchus</i>	Deep diver

Supplementary Table 5. List of deep diving and graviportal taxa included in the dataset of femoral bone density.

Taxon	Ecology
<i>Dallasaurus turneri</i>	Deep diver
<i>Clidastes sp.</i>	Deep diver
<i>Tylosaurus sp.</i>	Deep diver
<i>Platecarpus sp.</i>	Deep diver
<i>Metriorhynchid indet.</i>	Deep diver



<i>Phoca vitulina</i>	Deep diver
<i>Balaenoptera brydei</i>	Deep diver
<i>Elephas maximus</i>	Graviportal
<i>Rhinoceros sondaicus</i>	Graviportal
<i>Ceratotherium simum</i>	Graviportal
<i>Orcinus orca</i>	Deep diver
<i>Lissodelphis borealis</i>	Deep diver
<i>Monodon monoceros</i>	Deep diver
<i>Delphinapterus leucas</i>	Deep diver
<i>Behemotops katsuiei</i>	Deep diver
<i>Desmostylus hesperus</i>	Deep diver
<i>Mollesaurus</i>	Graviportal
<i>Alamosaurus</i>	Graviportal
<i>Callophoca obscura</i>	Deep diver
<i>Spinophorosaurus nigerensis</i>	Graviportal
<i>Apatosaurus sp.</i>	Graviportal
<i>Diplodocus sp.</i>	Graviportal
<i>Brachiosaurus sp.</i>	Graviportal
<i>Miragaia longicollum</i>	Graviportal
<i>Mammuthus primigenius</i>	Graviportal
<i>Rhinoceros unicornis</i>	Graviportal

**Supplementary Table 6. List of deep diving and graviportal taxa included in the dataset of dorsal rib bone density.**

**Phylogenetic character coding of the *Spinosaurus* neotype** for the two analyses (neotype as a separate OTU [in the phylogenetic dataset published by Malafaia et al.<sup>1</sup>] or included in the *Spinosaurus* OTU [in the dataset published by Rauhut and Pol<sup>2</sup>]).

*Spinosaurus* (neotype only; Malafaia et al.<sup>1</sup>)

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????????????????????????????????????????00130??1????????????????0??????0??????01[12]??00000[01
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*Spinosaurus* (OTU; Rauhut and Pol<sup>2</sup>)

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10121201-114101??0?00?00-0??10?1000130??1????????????????0-
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## Phylogenetic analyses

The dataset published by Malafaia et al.<sup>1</sup> was chosen because it includes the majority of all known spinosaurid taxa scored on the basis of individual specimens rather than amalgamated into genera or species. This dataset is the latest iteration of that which was originally presented by Evers et al.<sup>3</sup>. The neotype skeleton of *Spinosaurus* (FSAC-KK 11888) was coded and included as a separate OTU in this dataset. The analysis found 1,150 most parsimonious trees (MPTs) with a length of 1,101 steps. The strict consensus is largely unresolved. The majority rule consensus shows the clade Spinosauridae as the sister taxon of other megalosaurs. The ‘traditional’ dichotomy between Baryonychinae and Spinosaurinae is recovered. Baryonychinae is composed of *Suchomimus*, *Baryonyx*, and *Sigilmassasaurus*, whereas all other spinosaurids, including the holotype and neotype of *Spinosaurus*, are recovered within Spinosaurinae. These results, in combination with the multiple anatomical apomorphies shared between the holotype and neotype, support the previous attribution of FSAC-KK 11888 to *Spinosaurus aegyptiacus*<sup>4,5,6,7</sup>. Although these results might superficially appear to support the validity of the taxon *Sigilmassasaurus*, we suggest that taphonomic bias and minimal overlapping remains with the *Spinosaurus* neotype coincidentally relates *Sigilmassasaurus*—the holotype of which is a cervical vertebra—with the only other spinosaurids that preserve relatively complete cervical series (*Baryonyx* and *Suchomimus*).

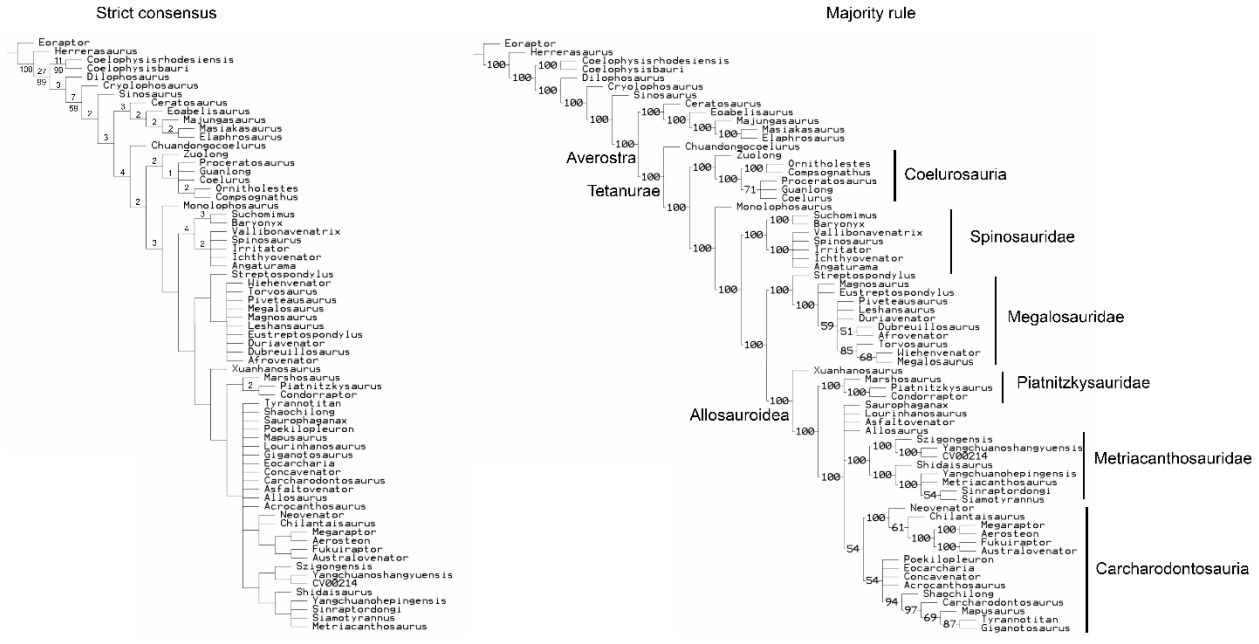
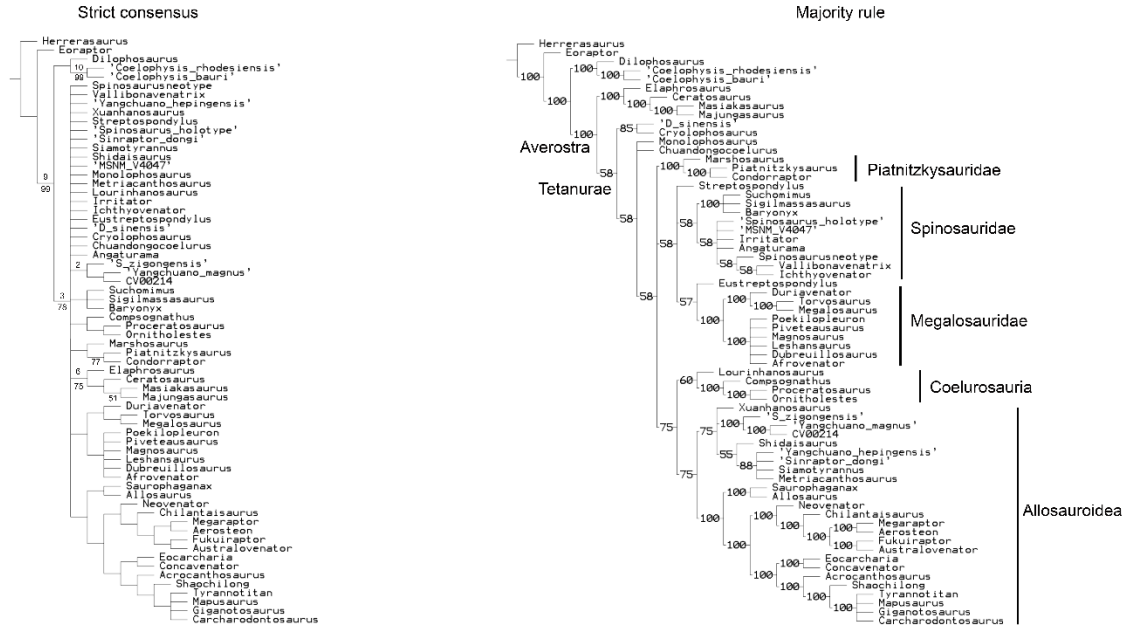
Based on these results and observations, we used the dataset recently published by Rauhut and Pol<sup>2</sup> to revisit the phylogenetic relationships of Spinosauridae within Tetanurae.

*Vallibonavenatrix*<sup>1</sup>, a spinosaurine from Eurasia, was added to the data matrix, and the neotype of *Spinosaurus aegyptiacus* was incorporated into the *Spinosaurus* OTU. The analyses resulted in 3,210 MPTs with a length of 1,371 steps. Our phylogenetic results found a major rearrangement of tetanuran relationships, as recently recovered by other studies<sup>2</sup>. Averostra, Ceratosauria, and Tetanurae are recovered as monophyletic. Within Tetanurae, a monophyletic Carnosauria is found to be the sister group of Coelurosauria. Megalosauroidea is divided into subclades that are found as subsequent outgroups of a monophyletic Allosauroidea.

Spinosauridae is recovered as the basal-most clade within Tetanurae.

Bremer and bootstrap support values are generally found to be weak, leading multiple nodes to collapse and providing only minimal support for others. In order to identify the reasons behind the instability of multiple nodes within the phylogeny, we applied tree pruning to identify unstable taxa in the dataset. We identified 16 unstable taxa, as follows: *Irritator*, *Angaturama*, *Coelurus*, *Piveteausaurus*, *Megalosaurus*, *Magnosaurus*, *Leshansaurus*, *Duriavenator*, *Saurophaganax*, *Poekilopleuron*, *Lourinhanosaurus*, *Concavenator*, *Carcharodontosaurus*, *Acrocanthosaurus*, *Neovenator*, and *Metriacanthosaurus*. Low support for the phylogenetic results therefore arises from a combination of fragmentary taxa, the high degree of homoplasy among early tetanurans, and the rapid divergence of the major clades composing Tetanurae, as previously quantified in other studies<sup>5</sup>. On the other hand, Spinosauridae and the dichotomy between Baryonychinae and Spinosaurinae are relatively well supported. Synapomorphies of Spinosauridae include the following: (26) promaxillary foramen present (0->1); (35) nasal participation in antorbital fossa (0->1); (41) morphology of lateral lamina of ventral process of

lacrima invaginated dorsally and convex ventrally (0->1); (49) anterior end of jugal excluded from internal antorbital fenestra (0->1); (66) frontal comprises one third or more of dorsal margin of orbit (0->1); (125) morphology of posterior margin of dentary posteroventrally sloping with incision for mandibular fenestra (0->1); (155) anterior articular facet of cervical vertebrae flat (0->1); (194) centrum length relative to height in dorsal vertebrae less than 2 (0->1); (201) anterior morphology of ventral surface of caudal vertebrae grooved (0->1); (229) longitudinal torsion of humerus present (0->1); (256) proximal end of metacarpal III triangular (0->1); and (302) ischia distally fused in adults (0->1). Baryonychinae is supported by a single synapomorphy: (227) prominent fossa on ventral surface of coracoid posteroventral to glenoid (0->1). Members of Spinosaurinae share the following characters: (30) posterior end of maxillary tooth row positioned anterior to orbit (0->1); (81) quadrate anteroventrally inclined in lateral view (0->1); (84) ventral rim of base of paraoccipital process situated at mid-height of occipital condyle or more ventrally (0->1); (86) dorsoventral depth of median ridge of supraoccipital greater than occipital condyle length (0->1); (208) anterior process of cervical ribs short (1->0); (239) radius shaft straight (0->1); (301) distal end of ischium expanded (0->1); (312) development of medial epicondylar ridge of femur (0->1); (332) orientation of distal condyle of astragalus 30–45 degrees anterior (0->1). The phylogenetic relationships found in these analyses were used to build the informal consensus tree.



**Supplementary Figure 1. Phylogenetic relationships of Spinosauridae.** Strict and majority rule (50% cutoff) consensus trees representing the phylogenetic relationships of Spinosauridae based on the modified datasets of Malafaia et al.<sup>1</sup> and Rauhut and Pol<sup>2</sup>, respectively. Bremer (>1) and bootstrap (>50%) support values are reported in the strict consensus trees.

## **Osteohistological description of *Condorraptor*, *Suchomimus*, *Baryonyx* and *Spinosaurus*.**

### *Condorraptor*

The femur shows an open medullary cavity, a plesiomorphic condition among predatory dinosaurs. Woven-fibrolamellar bone composes the cortical tissue. The primary vascularization is radial in its arrangement. Rare secondary osteons are present in the innermost cortex. At least six lines of arrested growth (LAGs) are present and decrease in spacing towards the outer surface of the bone. An external fundamental system (EFS) is not present. We suggest that this individual of *Condorraptor* is somatically immature.

### *Baryonyx*

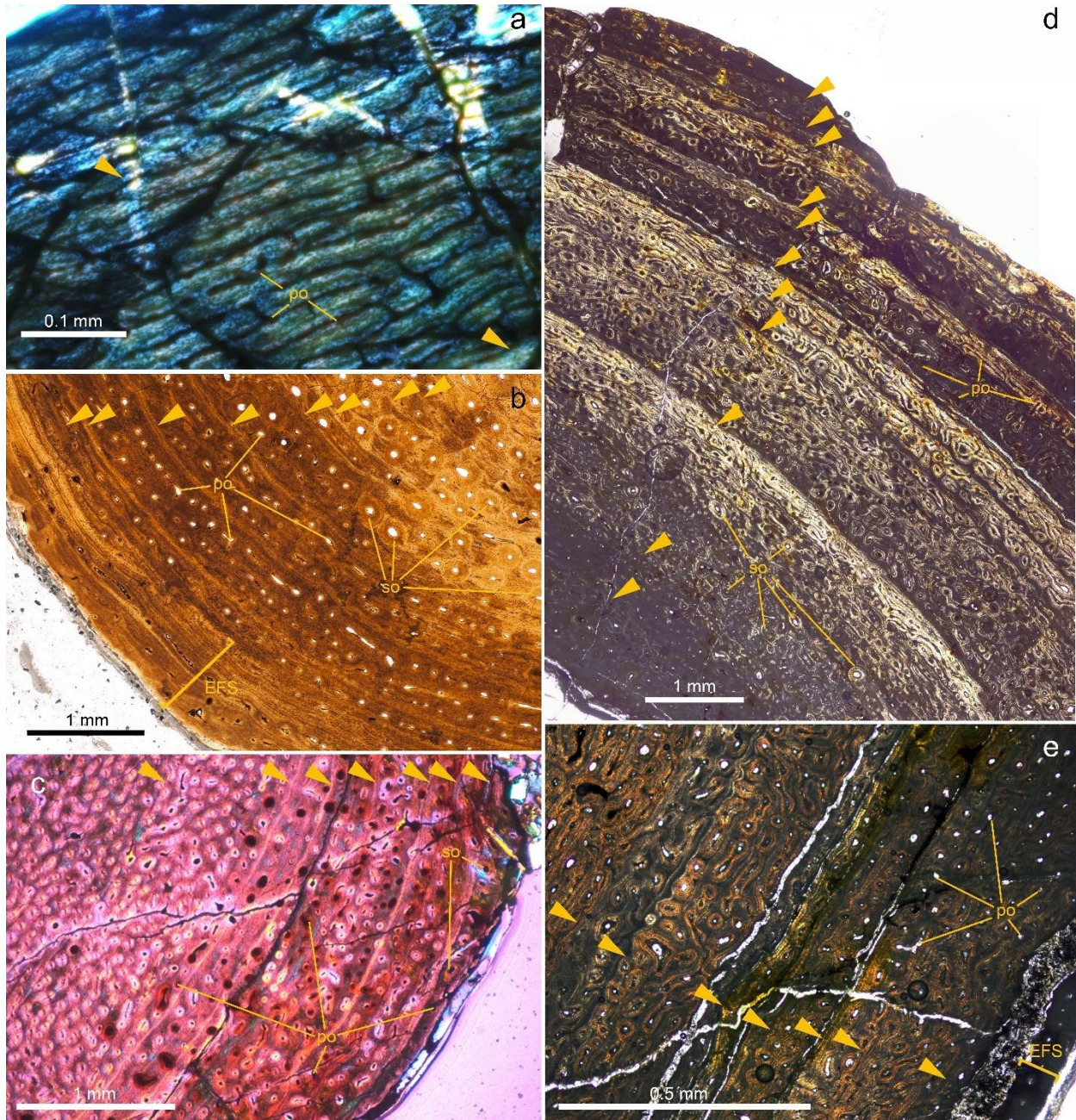
The dorsal rib of *Baryonyx* shows a remarkably rounded outline. Dinosaur ribs are usually ellipsoidal or triangular in section. Rounded outlines are generally found in osteosclerotic animals, such as marine mammals and reptiles. A clear medullary cavity is absent, being filled with trabecular bone. The transition from the inner spongiosa to the compact cortex is gradual. The cortex microstructure is composed of woven-fibrolamellar bone. Vascularization is longitudinally oriented and decreases in density towards the outer cortex. Remodeling and secondary osteons are present in the innermost cortex and decrease towards the outer surface of the rib. LAGs rapidly decrease in spacing towards the surface of the bone, culminating in an EFS. The holotype of *Baryonyx* was somatically mature at the moment of death.

### *Suchomimus*

The femora of specimens G51 and G94 were investigated. Both show an open medullary cavity. Whereas G94 exhibits a sudden transition between the medullary cavity and the bony cortex, G51 is characterized by a gradual transition due to heavy remodeling and erosional cavities in the inner cortex. The bone tissue is composed of woven-fibrolamellar bone. Primary vascularization shows a mix of laminar and reticular orientation, with increasing and decreasing organization and density, respectively, towards the outer surface. Remodeling, including secondary osteons, is present in both femora, but is much more accentuated and widespread in G51. The distance between LAGs tends to decrease towards the surface of both femora. An early EFS, potentially represented by a single non-vascularized zone in the outermost part of the cortex, is present in G51 but absent in G94. Our data suggest that G51 and G94 were somatically mature and immature, respectively.

### *Spinosaurus*

The ontogenetic analysis performed for FSAC-KK 11888 has been published as supplementary information by Ibrahim et al.<sup>4,7</sup>. Here, we report a general description of the osteohistology characterizing the neotype specimen. Osteohistological analyses were performed on a dorsal vertebral neural spine, dorsal rib, femur, and fibula. In general, none of these skeletal elements shows an open medullary cavity. A dense network of trabeculae is present in the dorsal rib and neural spine. Woven-fibrolamellar bone characterizes all investigated skeletal elements. Vascularization varies from reticular to longitudinal and decreases in density towards the surface of the bone in all investigated samples. Remodeling and haversian systems are common in the inner bone cortex and reach the bone surface in the fibula. Spacing between LAGs tends to decrease towards the outer cortex. An EFS is not found in any of the investigated skeletal elements. The ontogenetic stage of the *Spinosaurus* neotype is somatically immature.



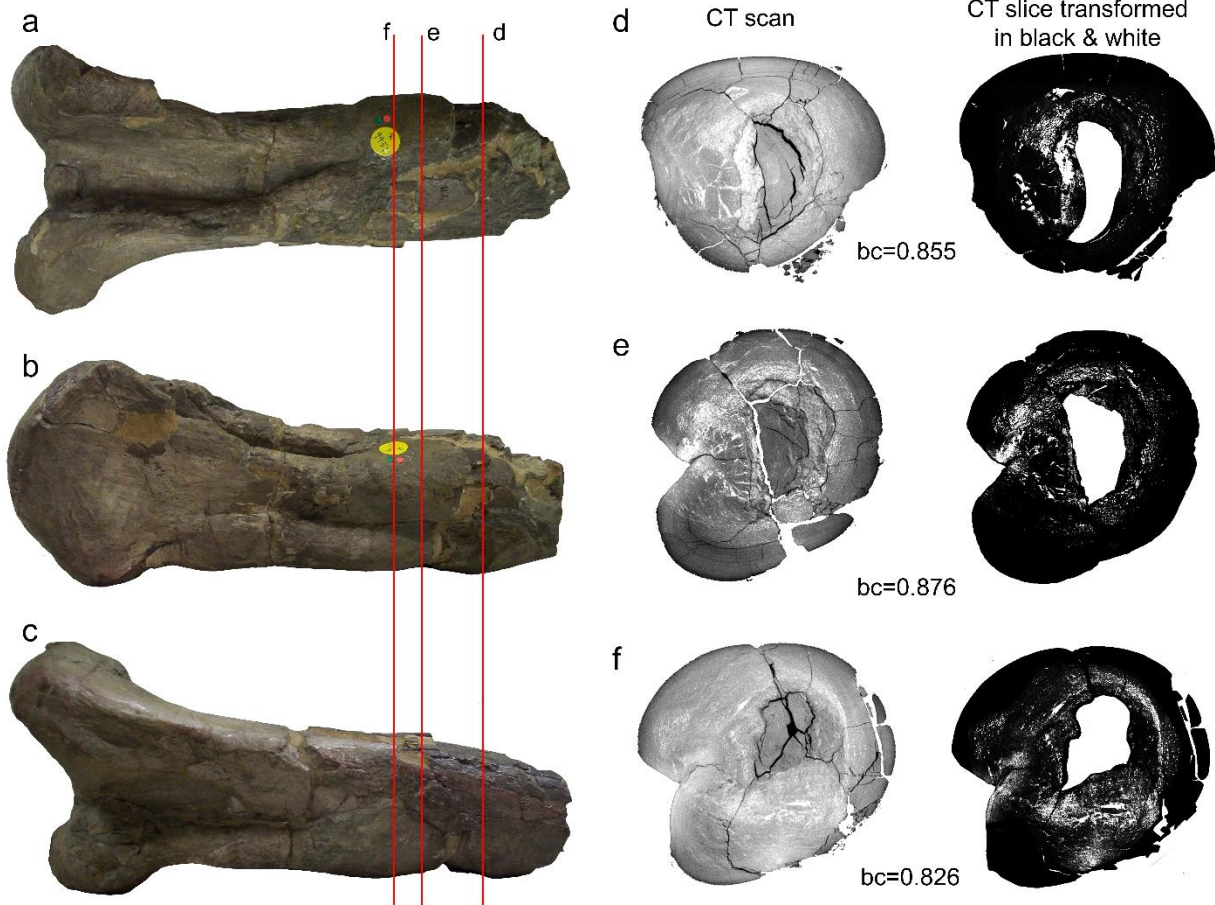
**Supplementary Figure 2. Ontogenetic assessment of carnosaur bones sampled in this study.** (a) Thin section of outer cortex of femur of *Condorraptor* (MPEF-PV 1691)<sup>8</sup>; (b) Thin section of outer bone tissue in dorsal rib of holotype of *Baryonyx* (NHM R 9951)<sup>9</sup>; (c) Thin section of fibula of *Spinosaurus* neotype (FSAC-KK 11888)<sup>4,7</sup>; (d) Thin section of femur of somatically immature individual of *Suchomimus* (G94)<sup>10</sup>; (e) Thin section of femur of somatically mature *Suchomimus* (G51)<sup>10</sup>. Abbreviations: EFS, external fundamental system; LAGs, lines of arrested growth; po, primary osteons; so, secondary osteons. Arrows indicate LAGs.

## **Taxonomic implications of ontogenetic assessment of *Baryonyx* and *Suchomimus***

Osteohistological examination of the holotypes of *Baryonyx* (dorsal ribs)<sup>9</sup> and *Suchomimus* (femur)<sup>10</sup> and the neotype of *Spinosaurus* (dorsal rib, dorsal neural spine, femur, fibula)<sup>4,7</sup> was undertaken to infer their ontogenetic stages (Supplementary Figure 5). It has been previously argued that *Baryonyx* and *Suchomimus* represent different ontogenetic stages of the same taxon<sup>e.g.14</sup> and that anatomical differences observed between them are the result of ontogeny; other studies have maintained the two forms as distinct taxa<sup>e.g.10,11</sup>. Our results show that the holotype of *Baryonyx* and at least one individual referred to *Suchomimus* (G51) are somatically mature, strengthening – in line with recent publications<sup>5</sup> - their taxonomic and systematic validity. The neotype of *Spinosaurus* is immature close to somatic maturity (see above for discussion and ontogenetic inference of these and other tetanuran specimens). These results also confirm the smaller body sizes of stratigraphically older spinosaurids, such as *Baryonyx*, with a progressive increase towards gigantism having its highest expression in the most derived taxon, *Spinosaurus*.

## **Skeletal reconstructions**

The skeletal reconstruction of *Spinosaurus* is based on the neotypic and holotypic skeletons, whereas that of *Baryonyx* is based only on the holotype. The reconstruction of *Suchomimus* is based on three previously published individuals (G51, G94, and G70)<sup>4,7,10</sup>. As in *Baryonyx*, the caudal series of *Suchomimus* is highly fragmentary; therefore, the reconstruction of this region is speculative and inspired by Ibrahim et al.<sup>7</sup> and Barker et al.<sup>12</sup>.



**Supplementary Figure 3: Femur of *Baryonyx* in different views (a-c) and corrected translation in binary image for density analyses of three different cross sections (d-f).** Because the femoral diaphysis is eroded and partially crushed, the selected cross section for the analyses performed in this study (e) was taken closer to the epiphyses of the femur. Overall, our quantification remains conservative for this taxon: regions closer to the epiphyses generally show a lower degree of bone density among amniotes<sup>13,14,15</sup>. Additionally, all bone densities quantified throughout the femur never decreased below 0.8, a value that distinguishes modern osteosclerotic archosaurs, such as penguins and crocodylians, from other terrestrial and volant taxa.



Predicted class	LAMBDA-> 0.06	
Taxa	Median probability - subaqueous forager	N predicted as subaqueous forager (100 trees)
<i>Iberosuchus</i>	0.95	100
<i>Tenontosaurus</i>	0.47	0
Unnamed noasaurid from Kem Kem group	0	0
Unnamed averostran from Kem Kem group	0.57	100
<i>Spinosaurus</i>	1	100
<i>Suchomimus</i>	0.31	0
<i>Baryonyx</i>	0.98	100
<i>Eustreptospondylus</i>	0	0
<i>Megalosaurus</i>	0.35	0
<i>Gallimimus_sp</i>	0.23	0
<i>Rativates</i>	0.09	0
<i>Halszkararaptor</i>	0.03	0
<i>Mirusavis</i>	0.05	0
<i>Iteravis</i>	0.04	0
<i>Vegavis</i>	0.67	100

**Supplementary Table 7. Results of the phylogenetically flexible discriminant analysis based on femoral data for selected extinct taxa.** *Baryonyx* and *Spinosaurus* are the only taxa consistently found to be subaqueous foragers. Correct classification rate varies between 84 and 85% (87% and 80% accuracy rate for subaqueous foraging and non-subaqueous foraging, respectively).

Predicted class	LAMBDA-> 0.07	
Taxa	Median probability - subaqueous forager	N predicted as subaqueous forager (100 trees)
<i>Iberosuchus</i>	0.99	100
<i>Tenontosaurus</i>	0.46	0
Unnamed noasaurid from Kem Kem group	0	0
Unnamed averostran from Kem Kem group	0.58	100
<i>Spinosaurus</i>	1	100
<i>Suchomimus</i>	0.25	0
<i>Baryonyx</i>	1	100
<i>Eustreptospondylus</i>	0	0
<i>Megalosaurus</i>	0.32	0
<i>Gallimimus_sp</i>	0.1	0
<i>Rativates</i>	0.01	0
<i>Halszkararaptor</i>	0	0
<i>Mirusavis</i>	0	0
<i>Iteravis</i>	0	0
<i>Vegavis</i>	0.63	100

**Supplementary Table 8. Results of the phylogenetically flexible discriminant analysis based on femoral data for selected extinct taxa excluding pelagic and graviportal taxa from the dataset.**

*Baryonyx* and *Spinosaurus* are the only taxa consistently found to be subaqueous foragers. Correct classification rate equal to 90% (88% and 91% accuracy rate for subaqueous foraging and non-subaqueous foraging, respectively).

Predicted class	LAMBDA-> 0.07	
Taxa	Median probability - subaqueous forager	N predicted as subaqueous forager (100 trees)
<i>Baryonyx</i>	0.96	100
<i>Spinosaurus</i>	0.95	100

**Supplementary Table 9. Results of the phylogenetically flexible discriminant analysis based on dorsal rib data for selected extinct taxa.** *Baryonyx* and *Spinosaurus* are the only taxa consistently found to be subaqueous foragers. Correct classification rate varies between 83% and 84% (69% and 88% for subaqueous foraging and non-subaqueous foraging, respectively).

Predicted class	LAMBDA-> 0.02	
Taxa	Median probability - subaqueous forager	N predicted as subaqueous forager (100 trees)
<i>Baryonyx</i>	1	100
<i>Spinosaurus</i>	1	100

**Supplementary Table 10. Results of the phylogenetically flexible discriminant analysis based on dorsal rib data for selected extinct taxa excluding pelagic and graviportal taxa from the dataset.**

*Baryonyx* and *Spinosaurus* are the only taxa consistently found to be subaqueous foragers. Correct classification rate equal to 90% (74% and 94% for subaqueous foraging and non-subaqueous foraging, respectively).

**Supplementary references**

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