Supplementary Information for:

Lunge feeding in early marine reptiles and fast evolution of marine tetrapod feeding guilds

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Supplementary Note

A. Permian marine reptile

Mesosaurs are the only group of marine reptiles before the Triassic but their limited geographical and temporal spans prevented them to affect the open marine trophic structure before the end-Permian extinction. These reptiles lived in restricted seas[1], only for a short time span within the Artinskian (Early Permian)[2].

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B. Triassic marine reptiles before mid-Spathian.

There is no Triassic marine reptiles that is known to be definitively older than the mid-Spathian. Almost all Early Triassic marine reptile records are from the Subcolumbites Zone, which is the fourth from the bottom of the five ammonite zones of the Spathian[1], when known. This is true for Anhui[2], South Kitakami[3], and Spitsbergen[4]. Specimens from British Columbia[5, 6, 7, 8] and Idaho[9, 10] are from screes, while *Thaisaurus* from Thailand has unknown age within the Triassic[11]. *Corosaurus* from Wyoming has a controversial stratigraphic position that could be anywhere in the Anisian (Middle Triassic) and Olenekian (Lower Triassic) because of disconformity and lack of index fossils.

Some of thalattosaurs[6] and ichthyosaurs[8] from British Columbia were once considered to be from the Smithian but this idea was later overturned by the original authors[7], who considered them to be younger. The only record definitively older than the Subcolumbites Zone is a *Chaohusaurus* from the Procolumbites Zone (mid-Spathian)[2].

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C. Effect of metabolic rate on the relative skull size of lunge feeders.

The difference in metabolic rates between mammals and reptiles may lead to different size of lunge feeding apparatuses, especially the mandible. We accounted for this bias by using an approximate model below. The weak positive allometry observed in mandibular length is expected based on a simple dimensional argument. It is generally known that the basal metabolic rates (Mb) are approximately proportional to the body mass (W) raised to 0.75, although controversies exist. Assuming that the body mass is roughly proportional to the cube of body length (Lb) in similarly shaped animals:

$$Mb = c_1W^{0.75} = c_1c_2Lb^{2.25} \quad (1)$$

where c_1 and c_2 are constants. The amount of food that passes through the gape per time is proportional to the cross sectional area of the gape, which is roughly proportional to the square of mandibular length (Lm), assuming a limited variation in jaw design, including gape angle. Then, if food consumption rate is roughly proportional to the basal metabolic rate and foraging duration does not differ drastically among individuals:

$$Mb = c_3Lm^2 \quad (2)$$

where c_3 is a constant. Then, from (1) and (2):

$$Lm = (c_1c_2)^{0.5}c_3^{-1}Lb^{1.125} \quad (3).$$

This model involves many approximations and therefore is admittedly simplistic. Yet, the expected slope of 1.125 is similar to 1.07 reported in this paper, and 1.11 previously[1]. In equation (3), the difference in metabolic rates is represented by a constant c_1. Then, the difference in mandibular length is expected to be roughly proportional to the square root of the difference in metabolic rates.

The model described above suggests that reptiles should have smaller mandibles for lunge feeding than mammals because of their lower metabolic rates that would mandate less food consumption, everything else being the same. At 37°C, average mammals would use about 7 times more oxygen than the average reptiles of the same size, based on the data compiled by[2] and the equations of[3]. Then, from equation (3) in Methods, average reptiles would have about 38% the mandibular length of average mammals for lunge feeding, where mandibular size is expected to determine the amount of water captured per time for a given relative speed. If so, an average lunge-feeding reptile at the size of *Hupehsuchus* would have a mandibular length of about 6.19 cm. The observed length of 13.34 cm is much longer than this expected value. A combination of many factors can explain the difference between the two values, such as lower prey density, less foraging time, and higher-than-average metabolic rate for *Hupehsuchus*. None of these factors, however, can be estimated reasonably. In conclusion, the skull of *Hupehsuchus* is not smaller than what is expected for a lunge-feeding reptile of its size.

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D. R packages used.

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E. References used for Figure 2.

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Supplementary Table S1. Feeding type diversity of marine reptiles in the Triassic. Brackets suggest that a feeding style was necessarily present because the following clades persisted through the interval despite the lack of direct record: Pelagic-ram-pointed, Ichthyoptrygia; Pelagic-ram-rounded, Omphalosauridae; Demersal-ram-pointed, Eosauropterygia; and Demesal-ram-rounded, Placodontia.

Habitat	Pelagic			Demersal						
Capture	ram with biting							suction	lunge	
Teeth	p	r	n	p	r	n	f'	n	n/f	Total
Rhaetian	X				X					2
Sevatian	(X)				(X)					2
Alaunian	X				X	X				3
Lancian	X				(X)					2
Tuvalian	X				X					2
Julian	X		X	X	X					4
Longobardian	X			X	X					3
Fassanian	X	X		X	X					4
Illyrian	X	X		X	X					4
Pelsonian	X	X		X	X		X			5
Bithynian	X	(X)		(X)	X					4
Aegean	(X)	(X)		X	X					4
Spathian	X	X		X	X			X	X	6

Supplementary Table S2. Data used to make Supplementary Table S1. Stratigraphic range was derived from a Kelley et al. (2014)[1] for most species; references are given for species that we added. In a trial to maximize the number of feeding types per substage, age assignments that were found to be questionable by Kelley et al. (2014) were all considered valid. For the same reason, taxa that span two substages were counted for both substages.

Binomial	CLADE	Habitat	Approach	Teeth	FirstSubstage	LastSubstage
Ichthyosaurus communis	Ichthyopterygia	pelagic	ram	point	Rhaetian	Early Sinemurian
Macroplacus raeticus	Sauropterygia	demersal	ram	round	Rhaetian	Rhaetian
Psephoderma anglicum	Sauropterygia	demersal	ram	round	Rhaetian	Rhaetian
Callawayia neoscapularis	Ichthyopterygia	pelagic	ram	point	Lacian	Lacian
Hudsonelpidia brevirostris	Ichthyopterygia	pelagic	ram	point	Lacian	Lacian
Sikannisuchus huskyi	Archosauria	pelagic	ram	point	Lacian	Lacian
Himalayasaurus tibetensis	Ichthyopterygia	pelagic	ram	point	Lacian/Alaunian	Lacian/Alaunian
Endennasaurus acutirostris	Thalattosauriformes	demersal	ram	none	Alaunian	Alaunian
Macgowania janiceps	Ichthyopterygia	pelagic	ram	point	Alaunian	Alaunian
Psephoderma alpinum	Sauropterygia	demersal	ram	round	Alaunian	Rhaetian
Shonisaurus sikanniensis	Ichthyopterygia	pelagic	ram	point	Alaunian	Alaunian
Californosaurus perrini	Ichthyopterygia	pelagic	ram	—	Tuvalian	Tuvalian
Nectosaurus halinus	Thalattosauriformes	demersal	ram	round	Tuvalian	Tuvalian
Shastasaurus pacificus	Ichthyopterygia	pelagic	ram	point	Tuvalian	Tuvalian
Shonisaurus popularis	Ichthyopterygia	pelagic	ram	point	Tuvalian	Tuvalian
Thalattosaurus alexandrae	Thalattosauriformes	demersal	ram	round	Tuvalian	Tuvalian
Toretocnemus californicus	Ichthyopterygia	pelagic	ram	point	Tuvalian	Tuvalian
Toretocnemus zitteli	Ichthyopterygia	pelagic	ram	point	Tuvalian	Tuvalian
Placochelys placodonta	Sauropterygia	demersal	ram	round	Julian/Tuvalian	Julian/Tuvalian
Anshunsaurus huangguoshuensis	Thalattosauriformes	pelagic	ram	point	Julian	Julian
Bobosaurus forojuliensis	Sauropterygia	pelagic	ram	—	Julian	Julian
Concavispina biseridens[2]	Thalattosauriformes	demersal	ram	round	Julian	Julian

Guanlingsaurus liangae	Ichthyopterygia	pelagic	ram	none	Julian	Julian
Guizhouichthyosaurus tangae	Ichthyopterygia	pelagic	ram	point	Julian	Julian
Henodus chelyops	Sauropterygia	demersal	ram	round	Julian	Julian
Miodentosaurus brevis	Thalattosauriformes	pelagic	ram	point	Julian	Julian
Protenodontosaurus italicus	Sauropterygia	demersal	ram	round	Julian	Julian
Psephochelys polyosteoderma	Sauropterygia	demersal	ram	round	Julian	Julian
Qianichthyosaurus zhoui	Ichthyopterygia	pelagic	ram	point	Julian	Julian
Sinocyamodus xinpuensis	Sauropterygia	demersal	ram	round	Julian	Julian
Xinpusaurus bamaolinensis	Thalattosauriformes	demersal	ram	round	Julian	Julian
Xinpusaurus suni	Thalattosauriformes	demersal	ram	round	Julian	Julian
Anshunsaurus huangnihensis[3]	Thalattosauriformes	pelagic	ram	point	Longobardian	Longobardian
Anshunsaurus wushaensis	Thalattosauriformes	pelagic	ram	point	Longobardian	Longobardian
Fuyuansaurus acutirostris[4]	Protorosauria	pelagic	ram	point	Longobardian	Longobardian
Glyphoderma kangi	Sauropterygia	demersal	ram	round	Longobardian	Longobardian
Keichousaurus hui	Sauropterygia	demersal	ram	point	Longobardian	Longobardian
Lariosaurus balsami	Sauropterygia	demersal	ram	point	Longobardian	Longobardian
Lariosaurus valceresii	Sauropterygia	demersal	ram	point	Longobardian	Longobardian
Lariosaurus xingyiensis	Sauropterygia	demersal	ram	point	Longobardian	Longobardian
Macrocnemus fuyuanensis	Protorosauria	pelagic	ram	point	Longobardian	Longobardian
Neusticosaurus staubi	Sauropterygia	demersal	ram	point	Longobardian	Longobardian
Neusticosaurus toeplitschi	Sauropterygia	demersal	ram	point	Longobardian	Longobardian
Nothosaurus cymatosauroides	Sauropterygia	demersal	ram	point	Longobardian	Longobardian
Nothosaurus edingerae	Sauropterygia	demersal	ram	point	Longobardian/Julian	Longobardian/Julian
Nothosaurus youngi	Sauropterygia	demersal	ram	point	Longobardian	Longobardian
Psephosaurus suevicus	Sauropterygia	demersal	ram	round	Longobardian	Longobardian

Qianichthyosaurus xingyiensis[5]	Ichthyopterygia	pelagic	ram	point	Longobardian	Longobardian
Qianxisaurus chajiangensis[6]	Sauropterygia	demersal	ram	point	Longobardian	Longobardian
Yunguisaurus liae	Sauropterygia	pelagic	ram	point	Longobardian	Longobardian
Lariosaurus curionii	Sauropterygia	demersal	ram	point	Fassanian/Longobardian	Fassanian/Longobardian
Askeptosaurus italicus	Thalattosauriformes	pelagic	ram	point	Fassanian	Fassanian
Blezingeria ichthyospondylus	Thalattosauriformes		ram	–	Fassanian	Fassanian
Ceresiosaurus calcagnii	Sauropterygia	demersal	ram	point	Longobardian	Fassanian
Ceresiosaurus lanzi	Sauropterygia	demersal	ram	point	Longobardian	Fassanian
Cyamodus hildegardensis	Sauropterygia	demersal	ram	round	Fassanian	Fassanian
Cymbospondylus piscosus	Ichthyopterygia	pelagic	ram	point	Fassanian	Fassanian
Lariosaurus buzzii	Sauropterygia	demersal	ram	point	Fassanian	Fassanian
Neusticosaurus edwardsi	Sauropterygia	demersal	ram	point	Fassanian	Fassanian
Neusticosaurus peyeri	Sauropterygia	demersal	ram	point	Fassanian	Fassanian
Neusticosaurus pusillus	Sauropterygia	demersal	ram	point	Fassanian	Fassanian
Nothosaurus jagisteus	Sauropterygia	demersal	ram	point	Fassanian	Fassanian
Omphalosaurus wolfi	Omphalosauria	pelagic	ram	round	Fassanian	Fassanian
Paraplacodus broilii	Sauropterygia	demersal	ram	round	Fassanian	Fassanian
Serpianosaurus mirigiolensis	Sauropterygia	demersal	ram	point	Fassanian	Fassanian
Simosaurus gaillardoti	Sauropterygia	demersal	ram	point	Fassanian	Julian
"Psephosaurus" sinaiticus	Sauropterygia	demersal	ram	round	Illyrian/Fassanian	Illyrian/Fassanian
Clarazia schinzi	Thalattosauriformes	demersal	ram	round	Illyrian/Fassanian	Illyrian/Fassanian
Eusaurosphargis dalsassoi	Helveticosauridae	demersal	ram	point	Illyrian/Fassanian	Illyrian/Fassanian
Helveticosaurus zollingeri	Helveticosauridae	demersal	ram	point	Illyrian/Fassanian	Illyrian/Fassanian
Hescheleria ruebeli	Thalattosauriformes	demersal	ram	round	Illyrian/Fassanian	Illyrian/Fassanian
Lariosaurus stensioei	Sauropterygia	demersal	ram	point	Illyrian/Fassanian	Illyrian/Fassanian
Macrocnemus bassanii	Protorosauria	pelagic	ram	point	Illyrian/Fassanian	Illyrian/Fassanian

Nothosaurus haasi	Sauropterygia	demersal	ram	point	Illyrian/Fassanian	Illyrian/Fassanian
Nothosaurus tchernovi	Sauropterygia	demersal	ram	point	Illyrian/Fassanian	Illyrian/Fassanian
Tanystropheus langobardicus	Protorosauria	pelagic	ram	point	Illyrian/Fassanian	Illyrian/Fassanian
Anarosaurus heterodontus	Sauropterygia	demersal	ram	point	Illyrian	Illyrian
Anarosaurus pumilio	Sauropterygia	demersal	ram	point	Illyrian	Illyrian
Augustasaurus hagdorni	Sauropterygia	pelagic	ram	point	Illyrian	Illyrian
Besanosaurus leptorhynchus	Ichthyopterygia	pelagic	ram	point	Illyrian	Illyrian
Cyamodus kuhnschnyderi	Sauropterygia	demersal	ram	round	Illyrian	Fassanian
Cyamodus muensteri	Sauropterygia	demersal	ram	round	Illyrian	Illyrian
Cyamodus rostratus	Sauropterygia	demersal	ram	round	Illyrian	Illyrian
Cymbospondylus buchseri	Ichthyopterygia	pelagic	ram	point	Illyrian	Illyrian
Cymbospondylus nichollsi	Ichthyopterygia	pelagic	ram	point	Illyrian	Illyrian
Dactylosaurus gracilis	Sauropterygia	demersal	ram	point	Illyrian	Illyrian
Mixosaurus cornalianus	Ichthyopterygia	pelagic	ram	round	Illyrian	Illyrian
Mixosaurus kuhnschnyderi	Ichthyopterygia	pelagic	ram	round	Illyrian	Illyrian
Nothosaurus giganteus	Sauropterygia	demersal	ram	point	Illyrian	Julian
Nothosaurus juvenilis	Sauropterygia	demersal	ram	point	Illyrian	Illyrian
Nothosaurus marchicus	Sauropterygia	demersal	ram	point	Illyrian	Illyrian
Nothosaurus mirabilis	Sauropterygia	demersal	ram	point	Illyrian	Fassanian
Omphalosaurus nevadanus	Omphalosauria	pelagic	ram	round	Illyrian	Illyrian
Phalarodon callawayi	Ichthyopterygia	pelagic	ram	round	Illyrian	Illyrian
Phantomasaurus neubigi	Ichthyopterygia	pelagic	ram	point	Illyrian	Illyrian
Pistosaurus longaevus	Sauropterygia	pelagic	ram	—	Illyrian	Illyrian
Atopodentatus unicus	Sauropterygia	demersal	ram	filter	Pelsonian	Pelsonian
Diandongosaurus acutidentatus[7]	Sauropterygia	demersal	ram	point	Pelsonian	Pelsonian
Dianopachysaurus dingi[8]	Sauropterygia	demersal	ram	point	Pelsonian	Pelsonian

Dinocephalosaurus orientalis	Protorosauria	demersal	ram	point	Pelsonian	Pelsonian
Largocephalosaurus plycarpon[9]	Saurosphargidae	demersal	ram	point	Pelsonian	Pelsonian
Largocephalosaurus qianensis[10]	Saurosphargidae	demersal	ram	point	Pelsonian	Pelsonian
Lariosaurus hongguoensis	Sauropterygia	demersal	ram	point	Pelsonian	Pelsonian
Mixosaurus panxianensis	Ichthyopterygia	pelagic	ram	round	Pelsonian	Pelsonian
Mixosaurus xindianensis[11]	Ichthyopterygia	pelagic	ram	round	Pelsonian	Pelsonian
Nothosaurus rostellatus[12]	Sauropterygia	demersal	ram	point	Pelsonian	Pelsonian
Nothosaurus yangjuanensis	Sauropterygia	demersal	ram	point	Pelsonian	Pelsonian
Phalarodon fraasi	Ichthyopterygia	pelagic	ram	round	Pelsonian	Longobardian
Placodus inexpectatus	Sauropterygia	demersal	ram	round	Pelsonian	Pelsonian
Qianosuchus mixtus	Archosauria	pelagic	ram	point	Pelsonian	Pelsonian
Sinosaurosphargis yunguiensis[13]	Saurosphargidae	demersal	ram	point	Pelsonian	Pelsonian
Tanystropheus haasi	Protorosauria	pelagic	ram	point	Pelsonian	Pelsonian
Tholodus schmidi	Ichthyopterygia	demersal	ram	round	Pelsonian	Pelsonian
Wumengosaurus delicatomandibularis	Sauropterygia	pelagic	ram	point	Pelsonian	Pelsonian
Xinminosaurus catactes	Ichthyopterygia	pelagic	ram	round	Pelsonian	Pelsonian
"Psephosaurus" mosis	Sauropterygia	demersal	ram	round	Bithynian	Bithynian
Phalarodon atavus	Ichthyopterygia	pelagic	ram	point	Bithynian	Illyrian
Placodus gigas	Sauropterygia	demersal	ram	round	Bithynian	Fassanian
Chinchenia sungi	Sauropterygia	demersal	ram	point	Aegean_question	Aegean_question
Cymatosaurus fridericianus	Sauropterygia	demersal	ram	point	Aegean	Aegean
Cymatosaurus latifrons	Sauropterygia	demersal	ram	point	Aegean	Aegean
Cymatosaurus minor	Sauropterygia	demersal	ram	point	Aegean	Aegean
Cymatosaurus multidentatus	Sauropterygia	demersal	ram	point	Aegean	Aegean

Germanosaurus latissimus	Sauropterygia	demersal	ram	point	Aegean	Aegean
Germanosaurus schafferi	Sauropterygia	demersal	ram	point	Aegean	Aegean
Nothosaurus winkelhorsti	Sauropterygia	demersal	ram	point	Aegean	Aegean
Nothosaurus winterswjikensis	Sauropterygia	demersal	ram	point	Aegean	Aegean
Sanchiaosaurus dengi	Sauropterygia	demersal	ram	point	Aegean_question	Aegean_question
Thalattosaurus borealis	Thalattosauriformes	demersal	ram	round	Aegean_question	Aegean_question
Agkistrognathus campbelli	Thalattosauriformes	demersal	ram	round	Spathian_question	Spathian_question
Cartorhynchus lenticarpus[14]	Ichthyosauriformes	demersal	suction	none	Spathian	Spathian
Chaohusaurus chaoxianensis	Ichthyopterygia	pelagic	ram	round	Spathian	Spathian
Chaohusaurus geishanensis	Ichthyopterygia	pelagic	ram	round	Spathian	Spathian
Chaohusaurus zhangjiawanensis[15]	Ichthyopterygia	pelagic	ram	round	Spathian	Spathian
Corosaurus alcovensis	Sauropterygia	demersal	ram	point	Spathian	Spathian
Eohupehsuchus brevicollis[16]	Hupehsuchia	demersal	lunge	none	Spathian	Spathian
Grippia longirostris	Ichthyopterygia	pelagic	ram	round	Spathian	Spathian
Gulosaurus helmi[17]	Ichthyopterygia	pelagic	ram	round	Spathian_question	Spathian_question
Hanosaurus hupehensis	Sauropterygia	demersal	ram	point	Spathian	Spathian
Hupehsuchus nanchangensis	Hupehsuchia	demersal	lunge	none	Spathian	Spathian
Isfjordosaurus minor	Ichthyopterygia	pelagic	ram	point	Spathian	Spathian
Keichousaurus yuananensis	Sauropterygia	demersal	ram	point	Spathian	Spathian
Kwangsisaurus orientalis	Sauropterygia	demersal	ram	point	Spathian	Spathian
Majiashanosaurus discocoracoidis[18]	Sauropterygia	demersal	ram	unknown	Spathian	Spathian
Nanchangosaurus suni	Hupehsuchia	demersal	lunge	none	Spathian	Spathian

Omphalosaurus nettarhynchus	Omphalosauria	pelagic	ram	round	Spathian	Spathian
Omphalosaurus nisseri	Omphalosauria	pelagic	ram	round	Spathian	Spathian
Parahupehsuchus longus[19]	Hupehsuchia	demersal	lunge	none	Spathian	Spathian
Paralonectes merriami	Thalattosauriformes	demersal	ram	round	Spathian_question	Spathian_question
Parvinatator wapitiensis	Ichthyopterygia	pelagic	ram	point	Spathian_question	Spathian_question
Thaisaurus chonglakmanii	Ichthyopterygia	pelagic	ram	point	Spathian	Spathian
Utatsusaurus hataii	Ichthyopterygia	pelagic	ram	point	Spathian	Spathian

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