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Supplementary Materials: Decoding the dynamics of dental distributions: insights from shark demography and dispersal

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1. Supplementary Materials

(a) Geologic Settings

(i) Banks Island, NWT Canada

On northern Banks Island, Northwest Territories, Canada, there is an abundance of coarsening-upward cycles within the Eureka Sound Formation that consist of shale, interbedded shale and silt, sand, then lignitic coal within the Cyclic Member [1]. An abundance of shark teeth, bivalves, and the trace fossil *Ophiomorpha* were recovered by Eberle and team from the Cyclic Member [1]. The shark teeth were collected by Eberle and field teams (in 2004, 2010, and 2012) as float on unconsolidated sands in the Cyclic Member. Marine microfossils (foraminiferans and radiolarians) also are documented (though rare) from the Cyclic Member [2]. Miall [2] concluded that the depositional environment was a proximal delta-front to delta-plain environment with various channels and coal swamps based on the lithology of the upward cycles of coal, shale, and sand in the Cyclic Member of the Eureka Formation. The presenence of *Ophiomorpha* [2,3] are inferred to be shrimp burrows suggesting a shallow-water, high-energy marine environment [4]. The unconsolidated sand is interpreted as a channel or mouth bar deposit in the delta front [1]. A crocodyliform fossil recovered from the Cyclic Member, as well as a tooth of the ray Myliobatis (a genus restricted today to tropical and warm temperate seas [1]) suggests a mild temperature on Banks Island in the early - middle Eocene. Eocene paleotemperature estimates from Ellesmere Island, Nunavut, in Canada's eastern Arctic, based on oxygen isotope analysis of fossil vertebrates [5] and paleofloral analysis [6,7] suggest a MAT of $8 - 11°$C, and a warm month mean (WMM) of $19 - 21°$C, with winters above freezing. The paleo-precipitation has been estimated using isotopic analysis of fossil wood samples collected from the deltaic deposits in the Margaret Formation on Ellesmere Island and the Cyclic Member on northern Banks Island. High resolution δ^{13}C values from tree ring samples indicate a summer precipitation that was two to four times higher than in the winter [8]. An ocean paleotemperature of 12-13 C was estimated for the early-middle Eocene Arctic based on the TEX86 method [9]. A riverine temperature on Ellesmere Island was estimated to be around 9 C based on δ^{18}O from terrestrial vertebrate bioapatite (Eberle et al., 2010). A mean paleosalinity of 12.7 PSU was estimated using a paleosalinity model modified by Kim et al. [10]; this is much lower than today's Arctic surface waters, which have a salinity of 25-33 PSU and therefore implies a brackish water environment for the early Eocene Arctic Ocean [10,11].

(ii) Seymour Island, Antarctica

Seymour Island, Antartica Seymour island is an andesitic, shallow gradient succession of sandstone, siltstone, and shell marine beds and is stratified into 7 numbered units referred to as Tertiary Eocene La Meseta stratigraphic units (TELMs). The La Meseta Fm. unconformably rests on top of the less-felsic upper Cretaceous- lower Paleocene Marambio Unit [12–14], and has undergone minimal burial and diagenetic alteration [15]. TELMs are fault-bounded by an angular unconformity at the bottom of the formation, and biostratigraphically categorized [12,16,17]. La Meseta TELMs preserve fossil flora and fauna similar to temperate latitude species today and species living in temperate latitudes during the Eocene [13,17]. For example, sand tiger teeth (*Striatolamia macrota*) and sparnotheriodontid mammalian teeth (Victorlemoinea) are vertebrates also found in Brazil and Argentina [13]. Extant driftwood fossils suggest regular temperate rainfall in the region [18,19]. Although the depositional setting could have potentially been influenced by freshwater influx, La Meseta faunal composition and geochemical analyses suggest normal marine conditions [15,19,20].

Sand tiger teeth are limited to TELMs 2-5 (early Middle – late Middle Eocene), and absent from TELMs 6 and 7 [16,21], which suggests a gradual cooling trend through the Late Eocene away from temperate conditions that would inhibit ability of sharks to survive at high latitudes [22]. Oxygen isotope ratio analysis of biogenic carbonate from bivalve fossils in La Meseta Fm.

corroborate this cooling trend over the course of the Middle Eocene, estimating a temperature change from 15°C (TELM 2) to 10°C (TELM 5; [19,23]. Oxygen isotope ratio analysis of biogenic phosphate from sand tiger shark fossils in La Meseta Fm. suggest temperatures ranging from $12 - 1°C$ during the same time range, but do not see a similarly conclusive cooling trend [22]. Differences in temperature estimates may relate to biological differences between taxa [22].

(iii) Red Hot Truck Stop, Meridian, Mississippi

The Tuscahoma Fm. includes about 110 meters of interbedded clay, silt, sand, and lignite, but only the upper ten feet is exposed at the locality [24,25] . The sand and silt beds are laminar and cross-bedded, and range from 0.1 foot to 1.5 feet thick. At the base of the sand beds, fossiliferous channel lag deposits appear containing bioturbation, burrow casts, and concretions. Lignite is present throughout the Tuscahoma, and overlying formations include several angiosperm pollen species, such as ferns and mosses that indicate a swamp and marsh environment [24]. Palynofloras at the Red Hot Truck Stop locality contained 113 taxonomic groups that allowed an assessment of a paratropical vegetation habitat in the Gulf Coast [26]. The late Paleocene to early Eocene age is supported by mammalian fossil assemblage correlation [27] and pollen samples [26,28]) and represents an early Eocene (early Wasatchian) age. The lithology of the Tuscahoma Formation and T4 Sand is consistent with that of a large-scale, fluvial-dominated deltaic system [27]. The large-scale cross bedding and cross-cutting represents the cut-and-fill depositional characteristics associated with estuarine channel facies [25].

Paleotemperature estimates indicate the early Eocene to have had the warmest climatic conditions in the Cenozoic Era (i.e., the last 66 Ma; [29]). The shells of bivalve mollusks were analyzed for stable carbon and oxygen isotope ratios in the Bashi Formation on the Gulf Coast (ca. 54-52 Ma) at a paleolatitude of around 30°N [29]. Ten shells were analyzed and resulted in a MAT (Mean Annual Temperature) of $26.5 \pm 1.0°C$; $2 - 3°C$ warmer than modern sea-surface MAT in the northern Gulf of Mexico [**?**]. Analysis of mollusk shells from the Gulf Coast by Kobashi et al. [30] found that the climate of the Mississippi Embayment (paleolatitude of 30°N) changed from a tropical environment of $26 - 27°C$ in the Eocene, to paratropical, $22 - 23°C$ in the Oligocene Epoch. Using modern regional salinity of 33 ppt, and the equation sought out by Grossman and Ku [31], the estimated MAT of the Eocene Gulf Coast ocean water was approximately $23.3 \pm 5°C$, slightly cooler than the continental temperature [30].

(iv) Whiskey Bridge, Burleston County, TX USA

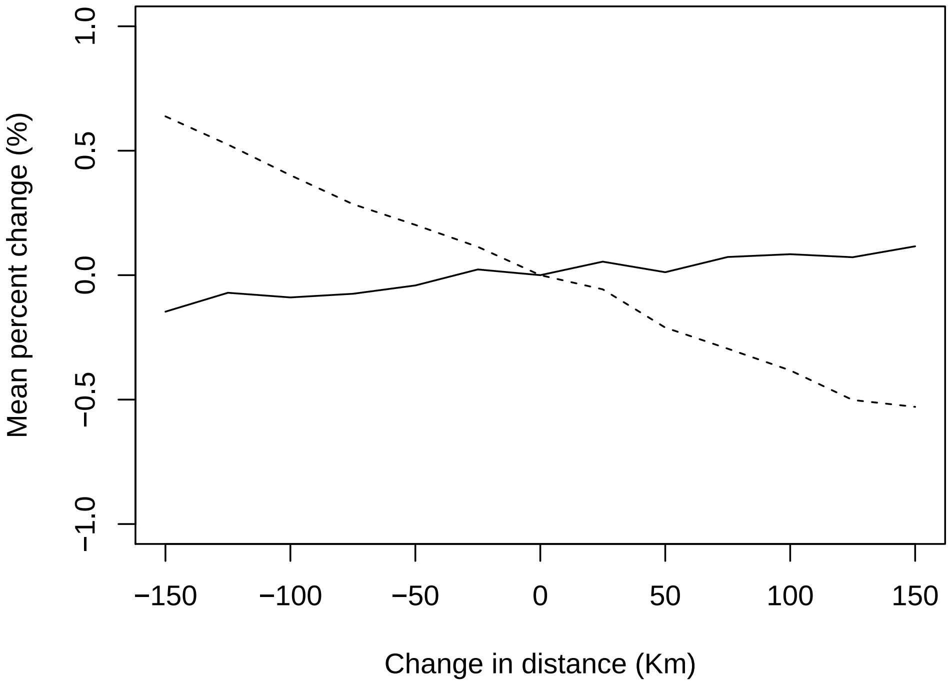
The Whiskey Bridge locality lies within the Stone City Member in the late middle Eocene Crockett Formation, on top of the Sparta Sand Formation and is part of the late Middle Eocene Claiborne Group [32–35]. It is often referred to as the “Main Glauconite Bed,” even though it is largely composed of fossiliferous, odinitic olive-green siliciclastic mudstone and sandstone and there is very little glauconite within the section [32–34] . The Stone City Member has undergone minimal taphonomic alteration, and preserves one of the most diverse Middle Eocene vertebrate fauna within the Gulf Coastal Plain [36]. These diverse taxa include shallow neritic dwellers (i.e., gastropods, bivalves, ootolith-based taxa, rays, teleost fish, reptiles and sharks) and low to moderate diversity of foraminifera [32,36]. The extant fauna is comparable to modern Gulf Coastal Plain fauna living in shallow inner shelf marine waters, and suggests that Stone City Fm. preserves a record of a tropical to sub-tropical climate with normal marine salinity [32,34,35]. Specifically, Stone City Member preserves three species of sand tigers (*Carcharias cuspidata*, *C. hopei*, Striatolamia macrota [32]). X-ray Diffraction and Mossbauer spectral analyses of clay pellets from the Stone City Member further support normal marine conditions and basic pH (7.5-8.5), based on the abundance of oodonite and paucity of glauconite [34], and suggest deposition in a shallower, tropical environment.

2. Supplemental Tables

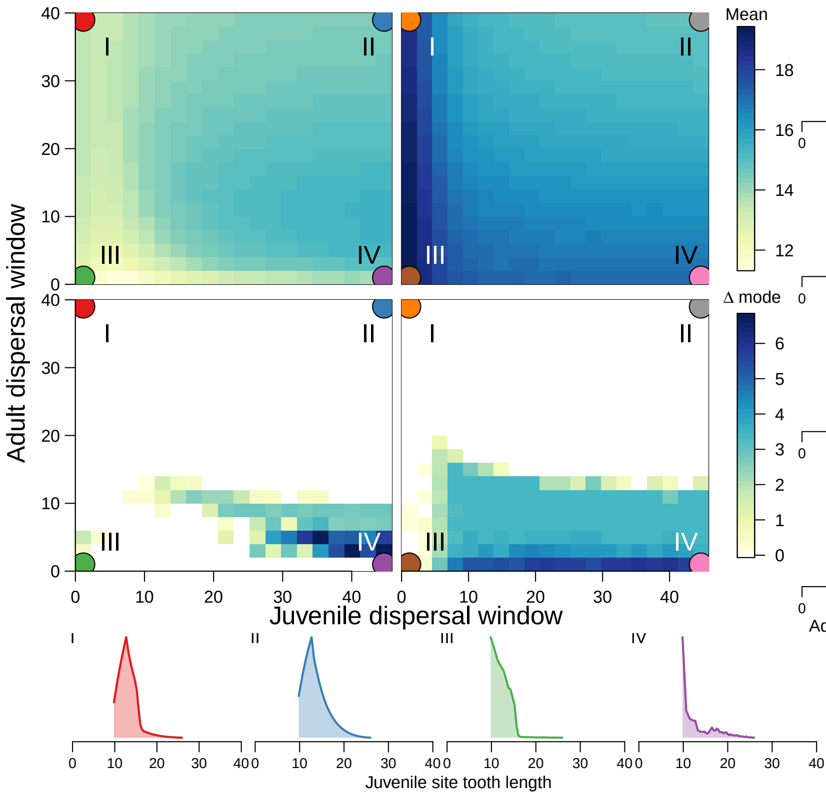
Site	Banks Island	Seymour Island	Red Hot Truck Stop	Whiskey Bridge	Delaware Bay
Formation	Eureka Sound	La Meseta	Bashi/Tuscahoma	Crockett	modern
Latitude	73°43′N	64°17′S	32°38′N	30°63′N	38°52′N
Longitude	120°46-51′W	56°45′W	88°65′W	96°54′W	75°2′W
Habitat	Brackish	Marine	Brackish	Marine	mix
N ATCH	397	126	372	158	137
D’Angostino Test					
skew	-0.1084	0.8009	0.4725	0.1368	0.5231
z	-0.8953	6.3373	3.1796	0.7289	2.480
p-value	0.37	« 0.0001	0.0015	0.47	0.013
Kurtosis - Bonett Test					
tau	2.9512	5.2225	3.0971	3.8681	2.0870
z	-6.2215	0.7680	-1.1280	-2.7321	2.6309
p-value	«0.0001	0.44	0.26	0.0063	0.0085
skew	-0.1084025	0.8009457	0.4724565	0.1367579	0.5230945
kurtosis	1.927971	3.328463	2.845512	2.168379	3.273326
moment	13.70411	19.21683	12.62215	22.50671	18.91735

Supplementary Table 1: stuff

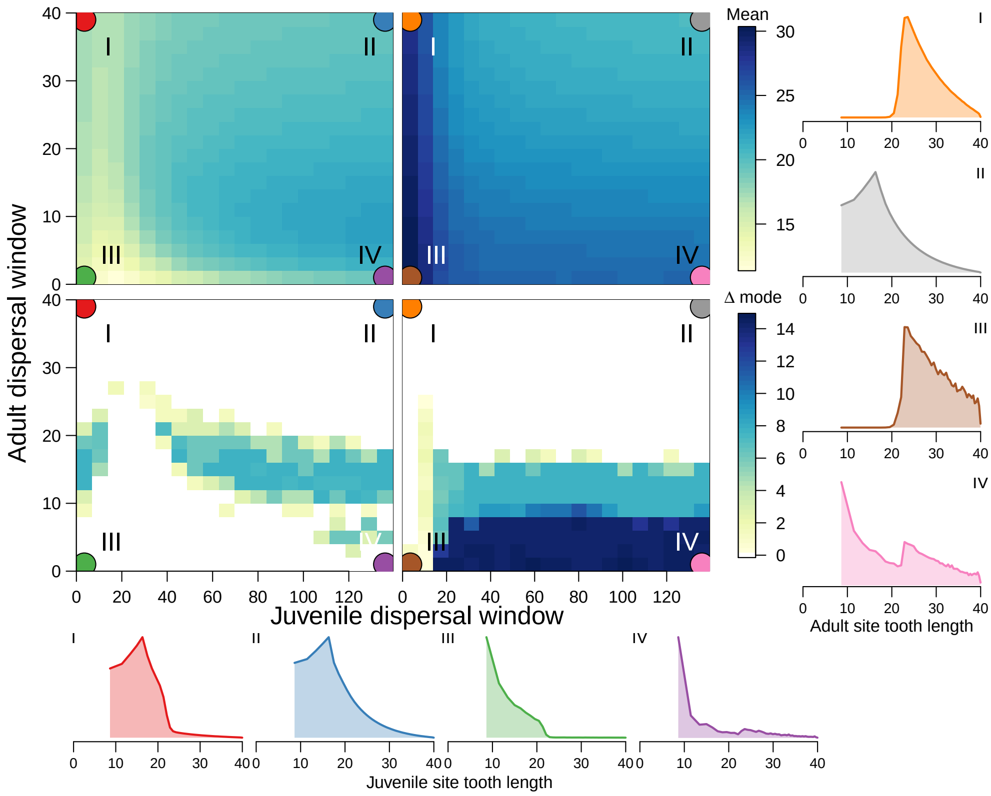
3. Supplemental Figures



Supplementary Figure 1: The effect of decreasing and increasing distance on simulated dental distribution means, averaged across ξ_j and ξ_a, for contemporary sand tiger populations. Changes in the juvenile site distributions are denoted by the dashed line; changes in the adult site distributions are denoted by the solid line. In all cases, decreasing or increasing distance $\pm 150 Km$ results in a mean percent difference in distributional means of $< 1\%$.



Supplementary Figure 2: Simulation results for the dynamic population model as a function of juvenile and adult dispersal windows (ξ_j and ξ_a, respectively) given conditions experienced by the contemporary Delaware Bay population. Changes in dental distribution shape are captured by site-specific means (top two panels) and the distance between modes (Δ mode; bottom two panels). A Δ mode value of zero means there is only one mode. Representative distributions of anterior tooth crown height are shown for juvenile site and adult sites for regions I-IV (horizontal along bottom and vertical along right edge, respectively), where color denotes both region and site identity. Regions I-IV depict various combinations of small and large dispersal windows. Region I (high ξ_a, low ξ_j); II (high ξ_a, high ξ_j); III (low ξ_a, low ξ_j); IV (low ξ_a, high ξ_j).



Supplementary Figure 3: Simulation results for the dynamic population model as a function of juvenile and adult dispersal windows (ξ_j and ξ_a, respectively) given low latitude Eocene conditions. Changes in dental distribution shape are captured by site-specific means (top two panels) and the distance between modes (Δ mode; bottom two panels). A Δ mode value of zero means there is only one mode. Representative distributions of anterior tooth crown height are shown for juvenile site and adult sites for regions I-IV (horizontal along bottom and vertical along right edge, respectively), where color denotes both region and site identity. Regions I-IV depict various combinations of small and large dispersal windows. Region I (high ξ_a, low ξ_j); II (high ξ_a, high ξ_j); III (low ξ_a, low ξ_j); IV (low ξ_a, high ξ_j).

References

1. Padilla A, Eberle JJ, Gottfried MD, Sweet AR, Hutchison JH. 2014 A sand tiger shark-dominated fauna from the Eocene Arctic greenhouse. *Journal of Vertebrate Paleontology* **34**, 1307–1316.
2. Miall AD. 1979 Mesozoic and Tertiary geology of Banks Island, Arctic Canada: the history of an unstable craton margin. *Geological Survey of Canada Memoir* **387**, 1–235.
3. Eberle JJ, Greenwood DR. 2012 Life at the top of the greenhouse Eocene world- A review of the Eocene flora and vertebrate fauna from Canada's High Arctic. *Bulletin of the Geological Society of America* **124**, 3–23.
4. Frey RW, Howard JD, Pryor WA. 1978 Ophiomorpha: its morphologic, taxonomic, and environmental significance. *Palaeogeography, Palaeoclimatology, Palaeoecology* **23**, 199–229.
5. Eberle JJ, Fricke HC, Humphrey JD, Hackett L, Newbrey MG, Hutchison JH. 2010 Seasonal variability in Arctic temperatures during early Eocene time. *Earth and Planetary Science Letters* **296**, 481–486.
6. West CK, Greenwood DR, Basinger JF. 2015 Was the Arctic Eocene 'rainforest'monsoonal? Estimates of seasonal precipitation from early Eocene megafloras from Ellesmere Island, Nunavut. *Earth and Planetary Science Letters* **427**, 18–30.
7. West CK, Greenwood DR, Reichgelt T, Lowe AJ, Vachon JM, Basinger JF. 2020 Paleobotanical proxies for early Eocene climates and ecosystems in northern North America from middle to high latitudes. *Climate of the Past* **16**, 1387–1410.
8. Schubert BA, Jahren AH, Eberle JJ, Sternberg LS, Eberth DA. 2012 A summertime rainy season in the Arctic forests of the Eocene. *Geology* **40**, 523–526.
9. Sluijs A, Röhl U, Schouten S, Brumsack HJ, Sangiorgi F, Damsté JSS, Brinkhuis H. 2008 Arctic late Paleocene–early Eocene paleoenvironments with special emphasis on the Paleocene-Eocene thermal maximum (Lomonosov Ridge, Integrated Ocean Drilling Program Expedition 302). *Paleoceanography* **23**.
10. Kim SSL, Eberle JJJ, Bell DDM, Fox DDA, Padilla A. 2014 Evidence from shark teeth for a brackish Arctic Ocean in the Eocene greenhouse. *Geology* **42**, 695–698.
11. Waddell LM, Moore TC. 2008 Salinity of the Eocene Arctic Ocean from oxygen isotope analysis of fish bone carbonate. *Paleoceanography* **23**, 1–14.
12. Sadler PM. 1988 Paleogene units on Seymour Island , northern Antarctic Peninsula. .
13. Marenssi SA, Reguero MA, Santillana SN, Vizcaino SF. 1994 Review Eocene land mammals from Seymour Island, Antarctica: palaeobiogeographical implications. .
14. Ivany LC, Wilkinson BH, Lohmann KC, Johnson ER, McElroy BJ, Cohen GJ. 2004 Intra-annual isotopic variation in Venericardia bivalves: implications for early Eocene temperature, seasonality, and salinity on the US Gulf Coast. *Journal of Sedimentary Research* **74**, 7–19.
15. Marenssi SA, Net LI, Santillana SN. 2002 Provenance, environmental and paleogeographic controls on sandstone composition in an incised-valley system: the Eocene La Meseta Formation, Seymour Island, Antarctica. *Sedimentary Geology* **150**, 301–321.
16. Long DJ. 1992 Sharks from the La Meseta Formation (Eocene), Seymour Island, Antarctic Peninsula. *Journal of Vertebrate Paleontology* **12**, 11–32.
17. Reguero MA, Marenssi SA, Santillana SN. 2012 Weddellian marine/coastal vertebrates diversity from a basal horizon (Ypresian, Eocene) of the Cucullaea I Allomember, La Meseta formation, Seymour (Marambio) Island, Antarctica. *Rev. peru. biol.* **19**, 275–284.
18. Case GR. 1994 Fossil fish remains from the late Paleocene Tuscahoma and early Eocene Bashi formations of Meridian, Lauderdale County, Mississippi. Part II. Teleosteans. *Palaeontographica Abteilung A* pp. 139–153.
19. Ivany LC, Lohmann KC, Hasiuk F, Blake DB, Glass A, Aronson RB, Moody RM. 2008 Eocene climate record of a high southern latitude continental shelf: Seymour Island, Antarctica. *Bulletin of the Geological Society of America* **120**, 659–678.
20. Stilwell JD, Zinsmeister WJ. 1992 *Molluscan systematics and biostratigraphy: Lower Tertiary La Meseta Formation, Seymour Island, Antarctic Peninsula*. Washington: American Geophysical Union antarctic edition.

21. Kriwet J, Engelbrecht A, Mörs T, Reguero M, Pfaff C. 2016 Ultimate Eocene (Priabonian) chondrichthyans (Holocephali, Elasmobranchii) of Antarctica. *Journal of Vertebrate Paleontology* **36**.
22. Kim SL, Zeichner SS, Colman AS, Scher HD, Kriwet J, Mörs T, Huber M. 2020 Probing the ecology and climate of the Eocene Southern Ocean with sand tiger sharks Striatolamia macrota . *Paleoceanography and Paleoclimatology* pp. 1–21.
23. Dutton AL, Lohmann KC, Zinsmeister WJ. 2002 Stable isotope and minor element proxies for Eocene climate of Seymour Island, Antarctica. *Paleoceanography* **17**, 6–1.
24. Mancini EA, Tew BH. 1995 Geochronology, Biostratigraphy and Sequence Stratigraphy of a Marginal Marine to Marine Shelf Stratigraphic Succession: Upper Paleocene and Lower Eocene, Wilcox Group, Easter Gulf Coastal Plane, USA. .
25. Ingram S. 1991 The Tuscahoma-Bashi section at Meridian, Mississippi: First notice of lowstand deposits above the Paleocene–Eocene TP2/TE1 sequence boundary. *Mississippi Geology* **11**, 9–14.
26. Harrington GJ. 2003 Wasatchian (Early Eocene) pollen floras from the Red Hot Truck Stop, Mississippi, USA. *Palaeontology* **46**, 725–738.
27. Beard KC, Dawson MR. 2009 Early Wasatchian mammals of the red hot local fauna, uppermost Tuscahoma formation, Lauderdale County, Mississippi. *Annals of Carnegie Museum* **78**, 193–243.
28. Frederiksen NO. 1998 Upper Paleocene and lowermost Eocene angiosperm pollen biostratigraphy of the eastern Gulf Coast and Virginia. *Micropaleontology* **44**, 45–68.
29. Keating-Bitonti CR, Ivany LC, Affek HP, Douglas P, Samson SD. 2011 Warm, not super-hot, temperatures in the early Eocene subtropics. *Geology* **39**, 771–774.
30. Kobashi T, Grossman EL. 2003 The oxygen isotopic record of seasonality in Conus shells and its application to understanding late middle Eocene (38 Ma) climate. *Paleontological Research* **7**, 343–355.
31. Grossman EL, Ku TL. 1986 Oxygen and carbon isotope fractionation in biogenic aragonite: temperature effects. *Chemical Geology: Isotope Geoscience Section* **59**, 59–74.
32. Breard SQ, Stringer GL. 1999 Abstract: Integrated Paleoecology and Marine Vertebrate Fauna of the Stone City Formation (Middle Eocene), Brazos River Section, Texas . *AAPG Bulletin* **83**.
33. Westgate JW. 2001 Paleoecology and biostratigraphy of marginal marine Gulf Coast Eocene vertebrate localities. In *Eocene biodiversity* , pp. 263–297. Springer.
34. Harding SC, Nash BP, Petersen EU, Ekdale A, Bradbury CD, Dyar MD. 2014 Mineralogy and geochemistry of the Main Glauconite Bed in the Middle Eocene of Texas: Paleoenvironmental implications for the Verdine Facies. *PloS one* **9**, e87656.
35. Flis JE, Yancey TE, Flis CJ. 2017 Middle Eocene Storm Deposition in the Northwestern Gulf of Mexico, Burleson County, Texas, U.S.A. *Gulf Coast Association of Geological Societies* **6**, 201–225.
36. Stanton Jr RJ, Nelson PC. 1980 Reconstruction of the trophic web in paleontology: community structure in the Stone City Formation (Middle Eocene, Texas). *Journal of Paleontology* pp. 118–135.