Supplementary Material

# Rise of the titans: baleen whales became giants earlier than thought

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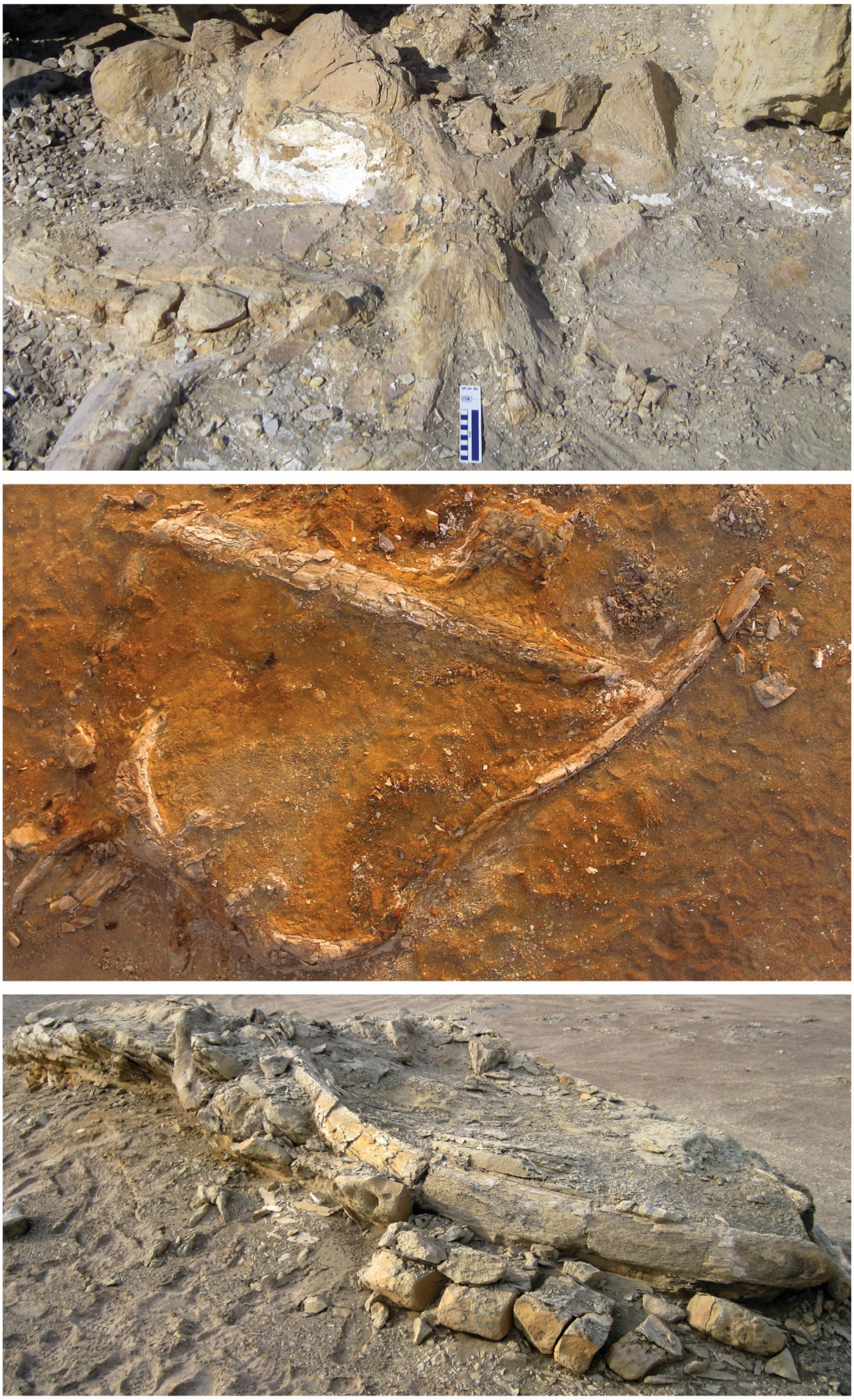

(*a*) (*b*) (*c*)

**Figure S1.** Mysticete fossils from the Miocene Pisco Formation of Peru. (a) *Pelocetus* sp. at Mal Paso; balaenopterids at (*b*) the base and (*c*) the top of Cerro Los Quesos. Photo in (*b*) by Elena Ghezzo.

**Table S2.** Parameter estimates and support for each model, with *Balaenoptera musculus* truncated at 1.25 and 1.49 Ma, respectively. BM, time-homogenous single rate Brownian motion; AC/DC, time-dependent rates (accelerating/decelerating); trend, biased random walk; OU, single peak Ornstein–Uhlenbeck; temp-dep. rates, temperature dependent rates; $\sigma^2$; evolutionary rate, Θ, root state; $t_{shift}$, timing of the rate/ mode shift; lnL, log-likelihood; k, number of free parameters; AICc, sample-size corrected Akaike Information Criterion; ΔAICc, difference in the AICc; $w_i$, Akaike weight.

| | **$\sigma^2$** | **Θ** | **parameter** | **$t_{shift}$ (Ma)** | **lnL** | **k** | **AICc** | **ΔAICc** | **$w_i$** |
|---|---|---|---|---|---|---|---|---|---|
| ***Balaenoptera* cf. *musculus* 1.25 Ma, Peruvian specimens excluded** | | | | | | | | | |
| BM | 0.00293 | 2.68 | NA | NA | 44.03 | 2 | -83.89 | 6.55 | 0.03 |
| AC/DC | 0.00190 | 2.67 | 0.018 | NA | 44.32 | 3 | -82.30 | 8.14 | 0.02 |
| trend | 0.00279 | 2.65 | 0.006 | NA | 44.72 | 3 | -83.11 | 7.33 | 0.02 |
| OU | 0.00293 | 2.68 | 0.000 | NA | 44.03 | 3 | -81.73 | 8.72 | 0.01 |
| temp.-dep. rates | 0.00075 | 2.68 | 0.002 | NA | 44.31 | 3 | -82.29 | 8.16 | 0.02 |
| rate shift | 0.00232 | 2.67 | 0.003 | 19.92 | 44.21 | 4 | -79.86 | 10.58 | 0.01 |
| mode shift | 0.00230 | 2.67 | 0.051 | 3.62 | 49.51 | 4 | -90.44 | 0.00 | 0.90 |
| ***Balaenoptera* cf. *musculus* 1.49 Ma, Peruvian specimens excluded** | | | | | | | | | |
| BM | 0.00294 | 2.68 | NA | NA | 43.95 | 2 | -83.73 | 6.01 | 0.04 |
| AC/DC | 0.00190 | 2.67 | 0.019 | NA | 44.24 | 3 | -82.15 | 7.59 | 0.02 |
| trend | 0.00281 | 2.65 | 0.006 | NA | 44.61 | 3 | -82.89 | 6.84 | 0.03 |
| OU | 0.00294 | 2.68 | 0.000 | NA | 43.98 | 3 | -81.63 | 8.11 | 0.02 |
| Temp.-dep. rates | 0.00076 | 2.68 | 0.002 | NA | 44.22 | 3 | -82.11 | 7.62 | 0.02 |
| rate shift | 0.00232 | 2.67 | 0.003 | 19.92 | 44.14 | 4 | -79.71 | 10.02 | 0.01 |
| mode shift | 0.00235 | 2.67 | 0.049 | 3.66 | 49.15 | 4 | -89.73 | 0.00 | 0.87 |
| ***Balaenoptera* cf. *musculus* 1.25 Ma, Peruvian specimens included** | | | | | | | | | |
| BM | 0.00337 | 2.69 | NA | NA | 40.41 | 2 | -76.65 | 3.48 | 0.12 |
| AC/DC | 0.00218 | 2.67 | 0.019 | NA | 40.71 | 3 | -75.09 | 5.04 | 0.05 |
| trend | 0.00329 | 2.66 | 0.005 | NA | 40.77 | 3 | -75.22 | 4.91 | 0.06 |
| OU | 0.00337 | 2.69 | 0.000 | NA | 40.41 | 3 | -74.51 | 5.62 | 0.04 |
| Temp.-dep. rates | 0.00177 | 2.69 | 0.002 | NA | 40.52 | 3 | -74.72 | 5.41 | 0.04 |
| rate shift | 0.00187 | 2.66 | 0.004 | 17.93 | 41.20 | 4 | -73.87 | 6.26 | 0.03 |
| mode shift | 0.00285 | 2.68 | 0.054 | 3.00 | 44.34 | 4 | -80.13 | 0 | 0.66 |
| ***Balaenoptera* cf. *musculus* 1.49 Ma, Peruvian specimens included** | | | | | | | | | |
| BM | 0.00339 | 2.69 | NA | NA | 40.34 | 2 | -76.53 | 3.02 | 0.14 |
| AC/DC | 0.00218 | 2.67 | 0.019 | NA | 40.65 | 3 | -74.98 | 4.57 | 0.06 |
| trend | 0.00330 | 2.66 | 0.00471 | NA | 40.69 | 3 | -75.06 | 4.48 | 0.07 |
| OU | 0.00339 | 2.69 | 0.000 | NA | 40.34 | 3 | -74.36 | 5.18 | 0.05 |
| Temp.-dep. rates | 0.00178 | 2.69 | 0.002 | NA | 40.46 | 3 | -74.59 | 4.95 | 0.05 |
| rate shift | 0.00187 | 2.66 | 0.004 | 17.93 | 41.15 | 4 | -73.76 | 5.78 | 0.03 |
| mode shift | 0.00289 | 2.68 | 0.052 | 3.06 | 44.05 | 4 | -79.54 | 0 | 0.61 |

**Locality and age of the studied material**

**Italy.** *Balaenoptera* cf. *musculus* was recovered from the Argille Subappennine Formation exposed along the shore of Lago di San Giuliano (Matera, southern Italy, N 40°36'33.62", E 16°31'43.72"), and is now housed at the Museo Archeologico Nazionale Domenico Ridola, Matera (specimen number 2016-MT-GIU). In the vicinity of the fossil locality, the Argille Subappennine Formation is thought to date to the Lower Pleistocene (Gelasian + Calabrian), but its age is poorly constrained [1]. To obtain a more precise estimate, we collected six sediment samples (SG1–SG6) along a 3 m section, spanning from the lake level to the fossil whale horizon.

We searched each sample for foraminiferans after washing it through a 63-µm sieve, and drying the residue overnight at 50°C. The planktic assemblage consists mainly of *Orbulina universa*, *Globigerina bulloides* and *Globigerinoides ruber*. *Neogloboquadrina pachyderma* occurs sporadically, mainly in the lower part of the section. *Turborotalita quinqueloba,* and *Globigerinita glutinata* occur in small numbers throughout the succession. In the lower samples, the benthic assemblage is diverse, and comprises both epifaunal (*Planulina ariminesis, Cibicidoides kullenbergy, Hyalinea balthica*) and infaunal species (e.g. *Cassidulinoides bradyi, Melonis barleanus)*. By contrast, the assemblage from the upper samples is less diverse and indicative of dysoxic and eutrophic conditions at the sea floor. The presence of *Hyalinea balthica* indicates an age younger than 1.492 Ma [2, 3].

All samples were furthermore searched for calcareous nannofossils after preparing smear slides, based on an optical adhesive (Norland #61) cured under ultraviolet light. Each slide was qualitatively analysed under a Zeiss Axioscope microscope at magnifications of 1000X and 1250X. Two samples (SG1 and SG2) yielded well-preserved and abundant nannofossils, characterised by the presence of large *Gephyrocapsa*. The latter defines zone MNN19d [4] and ranges from 1.59 to 1.25 Ma [5], thus indicating an Emilian (Calabrian) age [6]. Sample SG4 only contains scarce and badly preserved nannofossils. The remaining samples are barren.

Taken together, the microfossil assemblage thus indicates an age of 1.49–1.25 Ma for samples SG1 and SG2. The latter are located 2.5 m below the fossil horizon, which could therefore be somewhat younger; however, given a sedimentation rate of 0.25–0.5 m/ka for the Argille Subappennine Formation [1], this 2.5-m distance likely only accounts for ≤ 10 ka. Our estimate of 1.49–1.25 Ma can thus reasonably be applied to the entire section.

**Peru.** The Peruvian specimens (figure S1) were found in the coastal desert south of the village of Ocucaje, and occupy three separate levels in the Middle-Late Pisco Formation. *Pelocetus* sp. is from the P0 allomember, exposed near Mal Paso [7], whereas the two balaenopterids were found at the well-studied locality of Cerro Los Quesos, and come from the P2 allomember (Members C and F, respectively) [8]. Precise coordinates for each specimen are available on request.

$^{40}$Ar/$^{39}$Ar dating suggests an age of approximately 7.55 ± 0.05 Ma for the balaenopterid from Member C, and an age between 6.93 ± 0.09 Ma and 6.71 ± 0.02 Ma (Messinian) for the rorqual from Member F [8]. The age of the P0 remains problematic, but is constrained by the age of the underlying Chilcatay Formation ($^{40}$Ar/$^{39}$Ar: 17.99 ± 0.10 Ma [7, 9]) and the base of the overlying P1 sequence (9.10 Ma). Diatoms suggest a Middle Miocene age for the lower portion of the Pisco Formation [10], which is consistent with the relatively archaic aspect of the cetacean assemblage from this level [11].

**Sensitivity analysis**

Body length estimates are potentially subject to notable biases, especially when they are based on just a single predictor variable [12]. To guard against this problem, we performed a sensitivity analysis which replaced each of the balaenopterids from Cerro Los Quesos with a previously described, completely articulated skeleton (IC-1) from the same locality [13]. The latter measures 12.6 m in length, which equates to a TL of 13.7 m [14: suppl. fig. 8]. Similarly-sized specimens (12–14 m) have also been reported from coeval (Messinian) strata at Cerro Blanco, another locality to the northeast of Cerro Los Quesos [15]. We do not suggest that IC-1 is necessarily similar to our fossils, or that its TL is a more accurate reflection of their true length. Rather, we use IC-1 to establish a robust, directly measured minimum degree of gigantism rorquals had attained by the Late Miocene.

While it may seem problematic to substitute IC-1 for two independent records from different stratigraphic horizons, this approach is justified by (i) the TL of IC-1 being smaller, and thus more conservative, than our estimates for either of the balaenopterids from Cerro Los Quesos; and (ii) the two balaenopterids from Cerro Los Quesos being close in size and age (< 1 Ma). As in our main analysis, support for the mode shift model is weak ($w_i$ = 0.72), with Brownian motion ($w_i$ = 0.11) being the best-supported alternative (Table S3).

**Table S3.** Parameter estimates and support for each model resulting from equating the size of the Miocene balaenopterids from Cerro Los Quesos with that of specimen IC-1 [13]. BM, time-homogenous single rate Brownian motion; AC/DC, time-dependent rates (accelerating/decelerating); trend, biased random walk; OU, single peak Ornstein–Uhlenbeck; temp-dep. rates, temperature dependent rates; σ2; evolutionary rate, Θ, root state; tshift, timing of the rate/ mode shift; lnL, log-likelihood; k, number of free parameters; AICc, sample-size corrected Akaike Information Criterion; ΔAICc, difference in the AICc; wi, Akaike weight.

| | $\sigma^2$ | Θ | Parameter | $t_{shift}$ (Ma) | lnL | k | AICc | ΔAICc | $w_i$ |
|---|---|---|---|---|---|---|---|---|---|
| BM | 0.00324 | 2.69 | NA | NA | 42.20 | 2 | -80.24 | 3.82 | 0.11 |
| AC/DC | 0.00219 | 2.67 | 0.017 | NA | 42.45 | 3 | -78.58 | 5.49 | 0.05 |
| trend | 0.00315 | 2.66 | 0.005 | NA | 42.61 | 3 | -78.91 | 5.16 | 0.05 |
| OU | 0.00324 | 2.69 | 0.000 | NA | 42.61 | 3 | -78.90 | 5.17 | 0.05 |
| Temp.-dep. rates | 1.13874 | 2.74 | 0.861 | NA | -86.10 | 3 | 178.52 | 262.58 | 0.00 |
| rate shift | 0.00188 | 2.66 | 0.004 | 17.93 | 42.89 | 4 | -77.23 | 6.84 | 0.02 |
| mode shift | 0.00273 | 2.68 | 0.054 | 3.02 | 46.31 | 4 | -84.07 | 0.00 | 0.72 |

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