Figure Captions

Figure 1: Proportional Graph

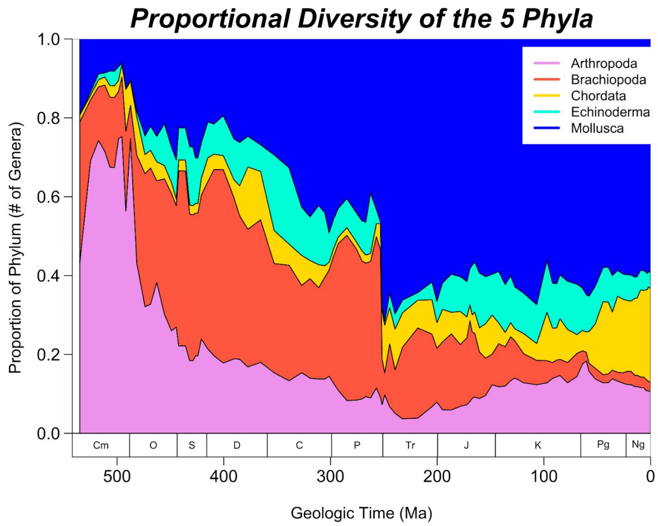


Figure 1. Proportions of the Five Phyla (# of Genera) over Geologic Time (Ma). The proportion of phyla over geologic time. In the pre-Ordovician the phylum Arthropoda dominated. As time went on, the phylum Mollusca shows a growing trend that leads to its domination in the post-Permian. The Brachiopod diversity drops greatly around the Permian mass extinction.

Figure 2: Diversification Rates

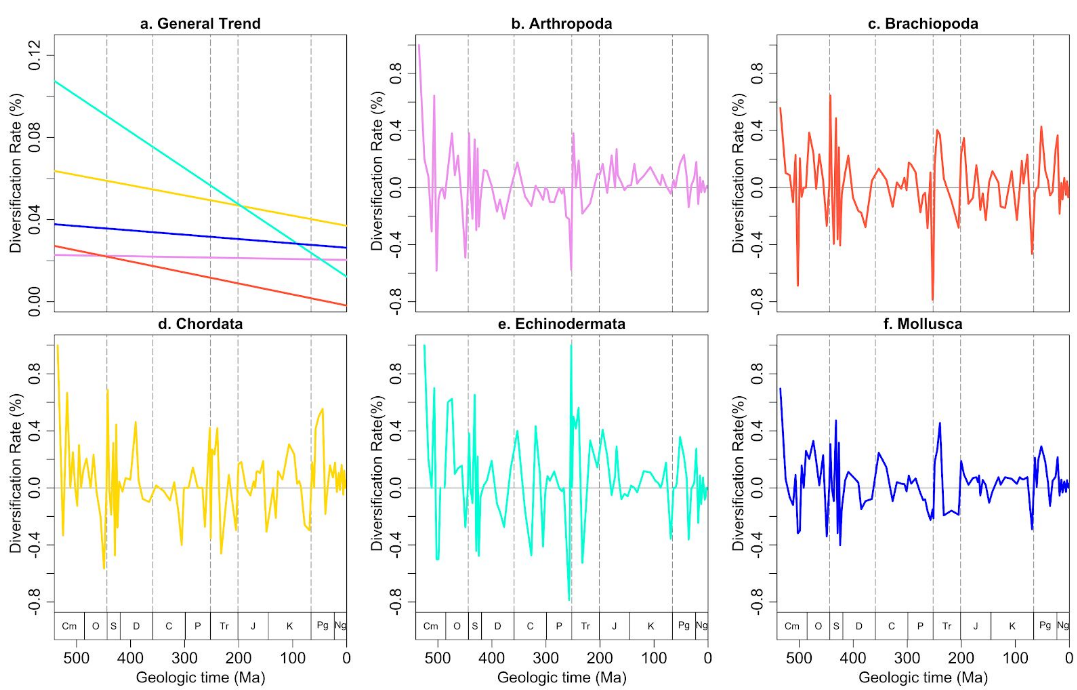


Figure 2. The Diversification Rates for the Five Phyla over Geologic Time. The diversification rates of each phyla (a-e) and the general trend of their rates in comparison to one another (f) are shown. Diversification was calculated by taking the extinction rate of all phyla from the origination rate of the phyla, resulting in a value that displays the new number of species emerging in a time period. All the phyla have similar diversification trends. For all the phyla, the diversification rates were at their highest or one of the highest during the early Cambrian.

Figure 3: Box Plot Mean Size

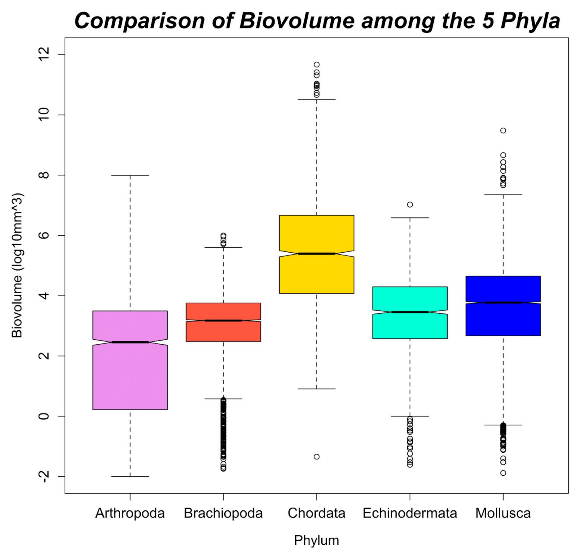


Figure 3. Box Plot of Biovolume and mean size intervals of the five phyla. The distribution of body size for each phylum. The open circles represent outliers. The notches represent the 95% confidence intervals on the medians. Chordata is the largest phylum out of the five phyla, with a median biovolume of about five $\log_{10} mm^3$ while Arthropoda remains the smallest with a median biovolume closer to two $\log_{10} mm^3$.

Figure 4: Mean Size of the Five Phyla Over Time

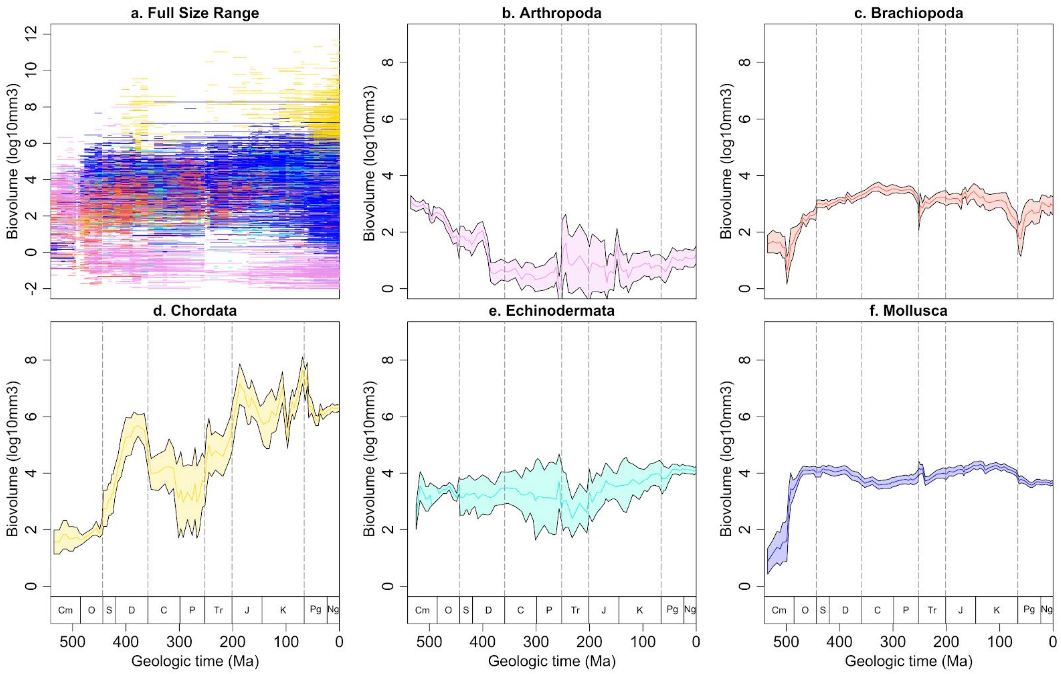


Figure 4. The Biovolume Size (Log 10) of the Five Phyla over Geologic Time. The mean size trends over geologic time for each of the five phyla (a-e). The light-colored polygon regions are 95% confidence intervals. The full size range displays the biovolume recorded for all genera in the dataset (f). The horizontal lines indicate genus durations. Each dashed line indicates one of the five major mass extinctions in the following order from left to right: Ordovician, Devonian, Permian, Triassic, and Cretaceous. Cm, Cambrian; O, Ordovician; S, Silurian; D, Devonian; C, Carboniferous; P, Permian; Tr, Triassic; J, Jurassic; K, Cretaceous; Pg, Paleogene; N, Neogene.

Table 1: Akaike Weights

	Arthropoda	Brachiopoda	Chordata	Echinodermata	Mollusca	All
General Random Walk (GRW)	**0.518**	0.377	**0.52**	**0.562**	0.424	**0.646**
Unbiased Random Walk (URW)	0.482	**0.623**	0.48	0.438	**0.576**	0.354
Stasis (S)	0.000	0.000	0.00	0.000	0.000	0.000

Table 1. Three Models for trends in Body Size Evolution and an evaluation of their fit for each of the Five Phyla. The three models describe a proposed model of phyletic evolution. Unbiased Random Walk is a model based on the idea that evolution occured without a bias for size. General Random Walk is the opposite. Stasis is a model where there is no change without bias. The Akaike Information Criterion (AIC) is used to select a model from a group of models. A higher weight means more support for a model. The grey boxes highlight which model was the best fit for each phylum. There is no support for the stasis model amongst all phyla. The only phylum that has strong support for a singular model is Brachiopoda, which favors the unbiased random walk. The other phyla have similar values of support for the GRW and URW models, making it difficult to indicate which model is this best fit.

Methods

The five phyla that were analyzed were: Arthropoda, which consists of animals like lobsters and crabs; brachiopoda are made of clam-like organisms;chordata examples include fish and otters; echinodermata include sea stars and sea urchins; Mollusca include marine organisms like clams and squid.

<u>Data</u>

The total number of genera in this dataset is 17,915 genera. It is subdivided into five phyla; there are 2692 Arthropoda (15%), 4074 Brachiopoda(22.7%), 1570 Chordata (8.7%), 1547 Echinodermata (8.6%), and 8032 Mollusca (44.8%). These body size and stratigraphic range data were taken from Heim et al. *(2015)*. Refer to this paper for additional information. The ICS International Chronostratigraphic Chart was used to delineate the age boundaries of geologic intervals.Biovolume is our measure of body size and has units of cubic millimeters.For the mean size graphs, biovolume was calculated by taking the $\log_{10}$ of the maximum volume data.

Diversification Rates

Diversification rates were calculated by subtracting extinction rates from origination rates. The usage of the linear regression allows as to see the general trend of each separate phylum; it allows us to see which phyla diversified faster or slower over the whole time interval.

Mean Body Size

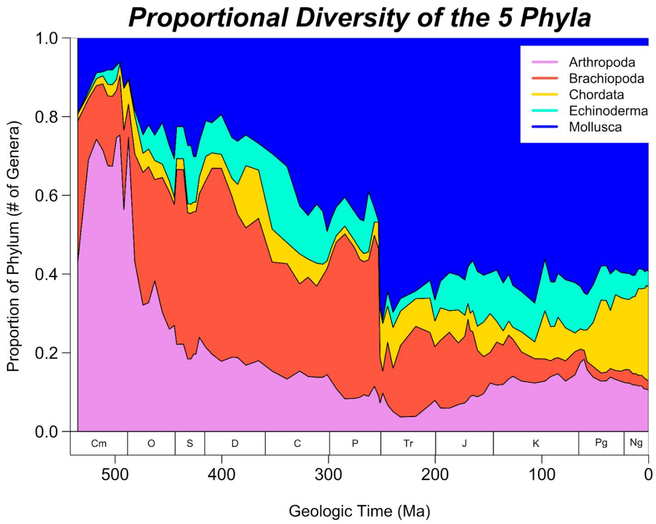
To analyze body size, the data was displayed in the form of two graphs. The first displays the mean body size of all the phyla throughout geologic time along with segments which display the actual size for individual genera and the time interval for which they lived (i.e., stratigraphic range). The second is a box plot which was used to compare the median size for each phylum.

Proportional Diversity

The proportion of taxa for each phylum during each geologic time interval was used in conjunction with the extinction, origination and diversification rate graphs to visualize the change in diversity for all marine phyla.

Statistical/Other Data Analysis

The Akaike Information Criterion (AIC) function in the paleoTS package (Hunt 2015) was used to determine which model for phyletic evolution (General Random Walk, Unbiased Random Walk, or Stasis) fit the body size trend over time for each phylum. The goodness of fit was determined by AIC weights. We interpret weights greater than 0.7 as strong support that a phylum follows a particular evolutionary model.The paleoTS package (Hunt 2015) for R was used to assess the AICc weights.



Results

Figure 1. Proportions of the Five Phyla (# of Genera) over Geologic Time (Ma).

The phylum Arthropoda had the largest proportion of genera in the early-Cambrian; at its peak, it composes nearly 75% of early-Cambrian genera (Fig. 1). A drastic decrease in the proportion of Arthropoda occurs in the early Ordovician as well as a drastic increase in the proportion of Brachiopoda. In the early Ordovician, the Chordata genera proportion begins growing until present day. Also noticeable is Brachiopoda and Chordata in this time period are about equivalent proportion wise up until the End-Permian mass extinction. Following the End-Permian extinction , Echinodermata practically disappear until near mid-Triassic. Brachiopoda also experience a large drop in proportion. Chordata are the only phylum that increase post End-Permian, essentially taking over all the other phyla in terms of number until present day, comprising about 50% of all the marine genera dataset (Fig 1). During the Cretaceous-Paleogene mass extinction, we see a drastic decrease in number of genera of the Brachiopoda phylum; this decreasing trend is kept consistent up until present day. After the Permian-Triassic extinction, Echinodermata genera disappear until early Triassic. Of the five phyla, Mollusca, Echinodermata, and Brachiopoda proportions get smaller following the end-Cretaceous mass extinction; although, mollusca still remains as the biggest proportion. On the other hand, arthropoda and chordata proportions increase after the extinction; they take different directions after, where Arthropoda genera proportion begin to decrease until modern day and chordata vice versa. Slowly over geologic time, the phylum Mollusca increased in proportion, with a peak of around 70% subsequent to the Permian Mass Extinction. In the Holocene, the phylum Mollusca has the highest proportions while Brachiopoda Have the lowest. This geologic time interval is also the peak for Chordata.

Figure 2. The Diversification Rates for the Five Phyla over Geologic Time.

In the early Cambrian, all of the phyla had experienced their highest diversification rates. The phylum Echinodermata seemed to experience this peak during a time when the other phylum, notably Chordata, experienced a decline in diversification rate. Echinodermata also had a similar rate during the End-Permian Mass Extinction. The five phyla experienced a trough near the end of the Cambrian. For the Arthropoda, Brachiopoda, and Echinodermata phyla, it was severe. The trend for all phyla had a slight increase during the beginning of the Ordovician. As time progressed toward the End-Ordovician Mass Extinction, diversification for the five phyla dropped dramatically. Chordata had their lowest levels during this time. Ensuing the mass extinction, the phyla had a period of high diversification with all exhibiting a similar trend of three peaks followed by three troughs during the whole of the Silurian. Trends remain near zero during the first half of the Devonian. In this interval, Chordates have a trend dissimilar to other phyla, with rates that remained near zero until the mid-Devonian when a peak occurred followed by a slight decrease. In the other phyla, a slight increase took place during the early Devonian followed by a decline during the latter half. For most phyla, trends stagnated at zero in the Carboniferous and Permian. Echinoderms had a massive increase in diversification at the beginning of the Carboniferous followed by a massive decrease in the middle which was followed by another peak and trough. Chordates had a trough during the end of the period as well. Towards the end-Permian Mass Extinction, diversification rates dropped for the phyla. Echinoderms and brachiopods were affected the most severely with both experiencing their lowest diversification rates. However, the trough for Brachiopods occurred during an extreme peak for Echinoderms. Chordates also had a smaller peak at the same time. Mimicking the trend present in other Mass Extinctions, diversification rates increase in the early Triassic for all phyla followed by a decrease. For Echinoderms and Chordates, there was a major trough followed by a slight increase and another trough prior to the End-Triassic Mass Extinction. Arthropods had a slight increase in rate through the end-Triassic. Brachiopods had a sharp decline just prior to the end-Triassic. In the early Jurassic, a small rise in diversification occurs in all phyla following the End-Triassic extinction. The trends stay around zero for all phyla until a sudden drop preceding the end-Cretaceous Mass Extinction. During the Paleogene, all phyla also experienced a sharp increase in diversification until mid-Paleocene; following, all rates plummeted to around zero.

The regressions of all phyla experienced downward slopes over time. The Echinodermata phylum saw the most drastic drop in all. The chordata and brachiopoda phylum, although having different values, shared a almost parallel slope. The second to last steepest phylum is the mollusca while arthropoda seemed to have a almost flat slope across geologic time

Figure 3. Box Plot of Biovolume and mean size intervals of the five phyla.

Figure 3 displays an overall size comparison between the different phyla. The median size for the phylum Chordata is significantly larger than the median for the other phyla, by nearly 4 orders of magnitudes (Arthropoda versus Chordata). Arthropoda median sizes are the smallest of all the phyla. In the phylum of Brachiopoda and Mollusca, it can be observed to see that both have a plethora of small outliers.

Figure 4. The Biovolume Size (Log 10) of the Five Phyla over Geologic Time.

As seen in Figure 4, the phylum Arthropoda started off as being the biggest marine phylum during the early Cambrian. Over time, the mean body size for Arthropoda experienced a drastic decrease. By present day, the Arthropoda became the smallest marine phylum in terms of mean biovolume. In the pre-Ordovician, the phylum Chordata and Brachiopoda started off as the phyla with the smallest genera. Although over time, the Chordata began to grow in size at a steady rate to eventually become the biggest genera amongst the five in the Holocene. The phylum Mollusca had a dramatic increase in mean size during the Cambrian. From the Ordovician and onward, the mean body size for Mollusca plateaued. The mean size increased until mid-Ordovician; after this, a plateau like line was maintained up until present day.

Table 1. Three Models for trends in Body Size Evolution and an evaluation of their fit for each of the Five Phyla.

Using the Akaike Information Criterion (AIC) it was determined that general random walk (directional change) is the best supported model for body size evolution when considering all of the genera in our data set. For each individual phylum except Brachiopods, generalized random walk (GRW) and unbiased random walk (URW) were almost equally supported which makes it difficult to determine which model best supports their body size evolution. In Brachiopods, there was strong support for the URW model. The model of Stasis was not supported for any phylum.

Discussion

Throughout geologic time the five phyla display similar trends in diversification rates, the rate at which new species originate and living species go extinct. They all exhibit noticeably high rates during the Cambrian Explosion and fluctations thereafter. Peaks in diversification generally occur after one of the five major mass extinctions. This trend likely occurred because the loss of species after these mass extinctions left vacant spots for various ecological niches.

During the Triassic-Jurassic mass extinction, all phyla experienced an increasing trend in mean body size. This is an indication that marine genre were generally not affected by this mass extinction. Although it was unlike the next mass extinction, Cretaceous-Paleogene, where all the phyla decreased in size overall. Through the other mass extinctions, there is no general correlation or similarities in the phyla.

In the early Cambrian, Arthropoda began by having the biggest means size of the five phyla(Fig 3). Similarly, it also dominated the proportion of genera in this time period, consisting of about half of the genera. This suggests that being the largest gave Arthropoda an advantage amongst the phyla. Arthropoda comprised almost half of the Cambriangerna. Bigger body sizes are advantageous in survival because it not only makes it harder for one to become prey, but it also makes it easier for them to be a predator. The Arthropoda class also consists of animals like crabs and lobsters, which are carnivorous animals; this larger size allowed them to eat many of the other phyla without having trouble in competition for food or resources.

In exception to the Cambrian, the Brachiopoda Also follows the same trend of bigger mean sizes leading to a bigger proportion over time. Brachiopoda, unlike Arthropoda, are not carnivores but are filter feeders; the rules of competition still apply. Being bigger, although requiring more food to compensate for size, also allows it to gather more food to survive. All the other phyla also share the same trend of being bigger contributes to larger proportions of genera.

The End-Permian and Cr mass extinction, diversification rate of all phyla experienced a significant increase (Fig 4). This may have occurred because the End-Permian extinction caused a loss of 48.6% marine families Benton et al. (2003). With the loss of many marine families, despite having a large negative impact on pre-Permian marine life, there was now less competition in the ocean for resources like shelter and food. Due to this lowered competition, it allowed room for many new species to emerge to take advantage of these resources; this is why the diversification rates rise so high so quickly following the End-Permian extinction.

Citations

1. Benton, Michael J. "How to Kill (Almost) All Life: the End-Permian Extinction Event." Trends in Ecology and Evolution, Elsevier, 6 May 2003
2. Cohen, K.M., S. C. Finney, P. L. Gibbard, and J.-X. Fan. 2013. The ICS International Chronostratigraphic Chart. Episodes 36:199-204.
3. Heim, N. A., Knope, M. L., Schaal, E. K., Wang, S. C., & Payne, J. L. 2015. Cope's rule in the evolution of marine animals. Science, 347:867–870. doi: 10.1126/science.1260065.
4. Hunt, G. 2015. paleoTS: Analyze Paleontological Time-Series. R package version 0.5-1.
5. R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Extra

Arthropoda = lobster, crab

    - exoskeleton composed of chitin
    - body often segmented
    - jointed appendages

- Brachiopoda= lamp shells (lingula anatina)

    - shells consisting of 2 parts called valves
    - bilateral symmetry
    - lophophore, structure used for feeding and respiration
    - most have pedicle which anchors them to a substrate
- Chordata = otters, humans
    - some features only present in embryo
    - pharyngeal slits - connect inside of throat to outside of neck
    - dorsal nerve cord - bundle of nerve fibers that connects brain with muscles and organs
    - notochord - supporting the nerve cord
    - post-anal tail - extension of body past anal opening
- Echinodermata = sea stars, sea urchins
    - hard, spiny covering/skin
    - many extant species have pentamerous radial symmetry
    - endoskeleton made of interlocking calcium carbonate plates and spines
    - water-vascular system derived from the coelom
        - set of water filled canals which lead to podia (tube feet)
    - coelom - fluid filled body cavity
- Mollusca = squids, clams
    - soft bodies with head, visceral mass, and foot
    - internal or external shell
    - toothed tongue called radula
    - dorsal epidermis called mantle which excretes shell
    - mantle cavity

http://www.pnas.org/content/104/47/18404

- permian-triassic
    - Echinodermata had huge diversification
    - Mollusca also in comparison to previous times
    - Arthropoda kind of
    - Brachiopoda bit
    - Chordata kind of
    - all the phyla were either increasing or had an increase in mass during this mass extinction except Brachiopoda Which decreased in size and Echinodermata which were decreasing
    - Mollusca increased in proportion, Brachiopoda Decreased, Arthropoda slight increased, Chordata and Echinodermata seemed to stay the same