Exploring KT Extinction Patterns: Teacher Background

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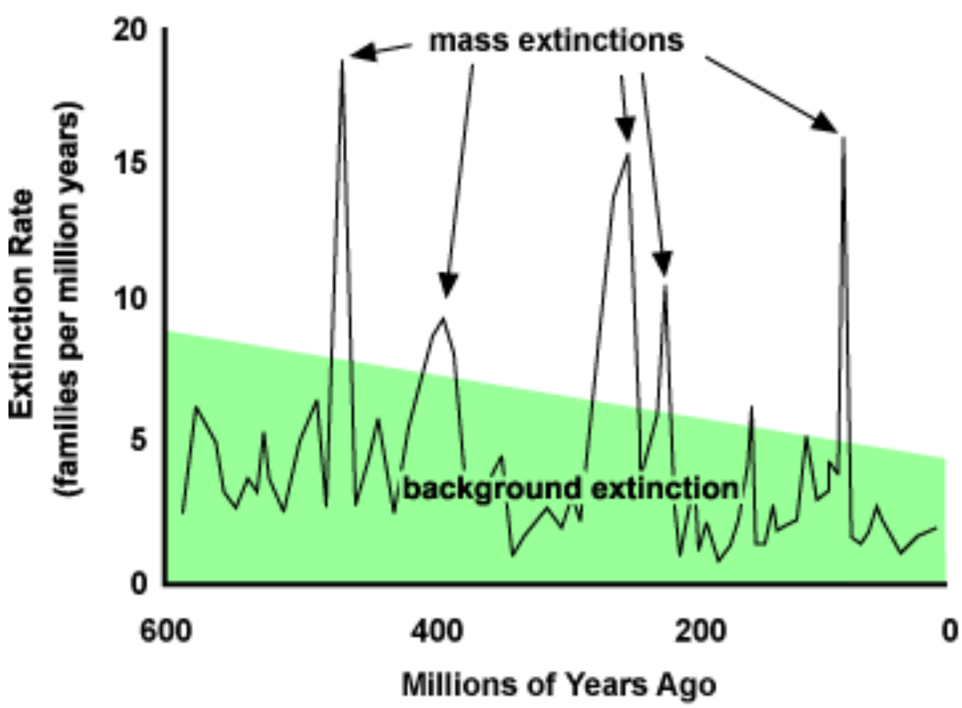
Background extinction and mass extinction

Extinctions of species have occurred steadily throughout the history of life, creating a turnover of species through time. This is often called background extinction. However, during particular, short time intervals in Earth's history, a very large number of species have gone extinct on a global scale, resulting in a mass extinction. The five biggest events of the geologic past are called the "Big Five" mass extinctions, with the most recent event occurring approximately 65 million years ago at the K-T boundary when the non-avian dinosaurs went extinct. K-T is short for Cretaceous-Tertiary (with the K representing the German translation of "Creta", meaning chalk, the characteristic rock deposited at this time in northern Europe, including the White Cliffs of Dover), but more recently scientists have been referring to this transition as the K-Pg boundary, which is short for Cretaceous-Paleogene (with the Paleogene being the first half of the now-obsolete Tertiary Period). This activity will focus on the causes and patterns of the K-T mass extinction—which didn't just affect the dinosaurs, but life in all Earth's ecosystems, including the oceans.



The K-T mass extinction happened around the same time that a massive meteor, generally estimated at about 10 km in diameter, hit the Yucatan peninsula. Geological and chemical evidence suggests that the meteor at least helped trigger the extinction, but scientists are unsure exactly how. Among the hypotheses proposed are that the impact produced:

- A giant dust cloud that blocked out the sun for years, halting photosynthesis and causing the collapse of food webs—and hence, a mass extinction.
- Wildfires that polluted the atmosphere with soot, halting photosynthesis and causing the collapse of food webs—and hence, a mass extinction.
- Dust, aerosols, and soot from wildfires, which, when deposited in the Earth's atmosphere, caused short-term global cooling—and hence, a mass extinction.
- Water and carbon dioxide injected into Earth's atmosphere, which caused a sharp spike in global temperatures due to the greenhouse effect—and hence, a mass extinction.
- Sulfates and nitrogen compounds, which, when deposited in the Earth's atmosphere, caused sulfuric and nitric acid rain—and hence, a mass extinction.
- Sulfates, which, when deposited in the Earth's atmosphere, caused ocean acidification—and hence, a mass extinction.
- Compounds and heat that thinned the ozone layer, exposing organisms to fatal levels of UV radiation—and hence, causing a mass extinction.

These mechanisms are not all mutually exclusive, and much work attempts to determine which, if any, had the most important effects

Some evidence also suggests that extinction rates were on the rise even before the meteor hit, so other ongoing processes may have also contributed to the magnitude of this event. For example, large volcanic eruptions were occurring at the same time and could have released gases that caused sudden global warming, causing additional extinctions.

One reason that scientists are interested in past mass extinctions is that they are relevant to life today. Although estimates vary on the precise numbers of current extinctions, most scientists agree that we are close to entering a sixth mass extinction event due to human actions such as habitat destruction, pollution, and overexploitation. For example, the IUCN (an international union of scientists and conservation organizations) estimates that 20% of the world's 5,494 living mammal species are now threatened with extinction. Given their current rates of decline, it is estimated that all threatened mammals may go extinct within 1000 years, which exceeds the rates of background extinction estimated from the fossil record.

Further reading

- http://undsci.berkeley.edu/article/alvarez_01
- Barnosky, A. D., Matzke, N., Tomiya, S, Wogan, G. O. U., Swartz, B., Quental T. B., ... Ferrer, E. A. (2011). Has the Earth's sixth mass extinction already arrived? *Nature*. 471: 51-57.
- Kring, D. A. (2007). The Chicxulub impact event and its environmental consequences at the Cretaceous-Tertiary boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology.* 255: 4-21.
- Schulte, P., Alegret, L., Arenillas, I., Arz, J. A., Barton, P. J., Bown, P. R., ... Willumsen, S. (2010). The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. *Science.* 327: 1214-1218.

Non-random extinctions

It has long been recognized that extinctions appear to be non-random with respect to which species survive and which go extinct. This is known as extinction bias or selectivity. For example, large carnivores that specialize on large vertebrate prey (known as hypercarnivores) evolve repeatedly but go extinct much more quickly than other mammalian species. Many other traits have been proposed to broadly predispose species to extinction as well (see table below). Extinction selectivity during mass extinctions can reshape Earth's biota. The species that survive a mass extinction form the roots for the radiation of new lineages that will repopulate Earth's habitats. If the surviving species are different in some way from those that perish, the new lineages that evolve after mass extinctions are likely to inherit those differences.

Trait	Hypothesized modes of action
Small populations	Experience chance population fluctuations and inbreeding, and so may be wiped out by a local catastrophe.
Slow reproductive rate	Less able to rebound from increased mortality.
Poor dispersal abilities	Less able to move away from unfavorable conditions, to maintain gene flow among fragmented habitats, or to maintain broad geographic ranges (see below).
Ecological specialization	If availability of the specialist resource changes, may be unable to switch to other more common resources. Also, specialization is often linked to other traits such as low population density because specialized resources often are scarce or have a patchy distribution.
Higher position on food chain	Are more vulnerable to disturbance of species lower down the food chain. Also, carnivory is often linked to other traits that may increase threat, such as low population densities and small population sizes.

However, only one trait has been *consistently* shown to be related to the probability of going extinct: narrow geographic range. If a species or evolutionary lineage is widespread, it may persist in areas less affected by the threatening processes. In addition, because closely related organisms tend to inherit similar traits from their common ancestor, extinction selectivity can lead to extinction risk being clustered within families or orders. For example, over the last 200 million years, extinctions in mollusks have been clustered within certain families (see https://evolution.berkeley.edu/evo-news/a-species-unwelcome-inheritance-extinction-risk/). Using the data set, your students will be able to explore both of these established hypotheses, as well as new ones that they develop.

Further reading

- https://evolution.berkeley.edu/how-to-survive-a-mass-extinction/
- https://evolution.berkeley.edu/evo-news/a-species-unwelcome-inheritance-extinction-risk/
- Van Valkenburgh, B. et al. (2004) Cope's rule, hypercarnivory, and extinction in North American canids. Science 306(5693), 101-104. \
- Jablonski, D. 2001. Lessons from the past: Evolutionary impacts of mass extinctions. Proceedings of the National Academy of Sciences USA 98: 5393-5398. (https://web.archive.org/web/20120216071220/http://geosci.uchicago.edu/pdfs/jablonski/PNAS01.pdf)

Bivalve biology

The data set that students will work with contains information on bivalves—a class of mollusks that have two shells, like mussels, oysters, and scallops. Bivalves live in fresh or marine waters, but the marine fossil record is much richer, and we will focus on that part of their environmental range. They have soft bodies within their shells and absorb oxygen from the water through their gills. Many species also use their gills to filter particles and plankton out of the water for food. Bivalves may be infaunal and burrow into the sediment (i.e., in mud), or may be epifaunal and live above it (e.g., by attaching themselves to a rock). Most cannot move far as adults, but some species have larvae that can disperse across large distances, often floating for weeks or even months, before settling down.

We know about extinct bivalve species from their fossilized shells. Their soft bodies rarely fossilize, but the shells can be extremely abundant in the fossil record; for example fossil oysters from the Cretaceous Period are used to pave country roads in some parts of Texas. Many mollusk shells are made of several layers, and different species build these layers out of two different materials:

aragonite and calcite. Both aragonite and calcite are forms of calcium carbonate ($CaCO_3$), but calcite is chemically more durable Some mollusks have shells made almost entirely out of calcite, some have shells made with outer layers of calcite and an inner layer of aragonite, and some have shells made of just aragonite. To further complicate matters, the aragonite that makes up these shells may be rich in organic material or it may have very little. As discussed below, all of these factors potentially affect how resistant the shell is to acidic conditions in its environment.

Cretaceous seas contained an extraordinary group of bivalves that went extinct at the K-T boundary, the rudists (members of the order Hippuritoida). Rudists lived on the surface of the seafloor and formed enormous, dense aggregations that could extend for miles in shallow tropical seas. Many had a conical lower shell that may have harbored symbiotic algae like the ones that promote coral reef growth today. On the other hand, they may have been suspension feeders like most other bivalves. Scientists need more evidence to figure it out. This data set classifies the rudists as suspension feeders, but because the rudists' extinction is still not fully understood and specialists continue to debate the issue, below we recommend exploring the data with and without this group when searching for extinction selectivity. To facilitate this, we've provided two versions of the data set: one that includes rudists and one that excludes them. You can decide if you want to use just one or both with your classes.

<u>Further reading</u>

- http://www.ucmp.berkeley.edu/taxa/inverts/mollusca/rudists.php
- Jablonski, D. 1996. The rudists re-examined. Nature 383: 669-670 (https://web.archive.org/web/20120227090849/http://geosci.uchicago.edu/pdfs/jablonski/Jabonski1996RudistsRe-Examined.pdf)

Introduction to the data set

The dataset contains information on bivalve genera that lived on Earth at the time of the K-T extinction event. Some of the genera survived the mass extinction and some did not. Because it is difficult to distinguish species from one another based on fossils, the dataset includes genus-level data, but not species-level data. Here is a summary of the different variables:

Evolutionary relationships – Linnaean ranks are an imperfect stand-in for an actual tree showing how these genera are related. However, in general, genera that are in the same family are more closely related to each other than any is to a genus in a different family, and they almost always have similar modes of life. Similarly, families in the same order are more closely related to each other than any is to family in a different order

- Order – The order of the mollusk genus
- Family – The family of the mollusk genus

- Genus – The mollusk genus

Victim/survivor – Whether the genus went extinct during the K-T mass extinction or survived it

Geographic distribution – These variables document where on Earth this genus lived at the time of the K-T mass extinction. Scientists have reconstructed how the continents were positioned at this time and divided this K-T Earth into different geographic provinces. To see how the continents were positioned and where these provinces are, take a look at the map that accompanies this lesson. Remember that bivalves live in the ocean, and most of the fossil record is from sediments that were deposited somewhere between the beach and the edge of the continental shelf, and not in the deep sea, so the provinces that interest us mainly involve shorelines and the nearby seafloor. In the dataset, the number 1 indicates that the genus was present in that province. For a few genera, this information is unknown and, hence, they are not associated with any of the provinces. We know those genera survived, because they're found in deposits older and younger than the K-T boundary, but they haven't yet been recognized in the last ~6 million years of the Cretaceous Period that provides the basis for the spatial distributions shown here.

Geographic range – These variables indicate how large a range the genus occupied.

- Number of provinces occupied - This variable indicates how many provinces the genus was present in. Larger numbers indicate a more widespread distribution. The number 0 indicates that this information is unknown.
- Polar/temperate/tropical/widespread – Indicates where longitudinally the genus was present—in polar, temperate, or tropical zones. Widespread species occupied more than one zone.

Shell type – These variables indicate the chemical composition of the genus' shell.

- Aragonite only – Aragonite is the form of calcium carbonate ($CaCO_3$) that is less chemically stable than other shell types and could be a liability in an acidified ocean.
- Calcite - Calcite is the most durable, chemically stable form of calcium carbonate ($CaCO_3$). Shells made with calcite are expected to make it easier for animals to survive in an acidified ocean.
- High-organic matter aragonite - High-organic matter aragonite is a form of aragonite that incorporates an especially larqe amount of organic material into the shell structure. The organic matter helps to protect the mineral aragonite from chemical damage. Shells made with high-organic matter

aragonite are expected to make it easier for animals to survive in an acidified ocean, although not as well as those with a calcite shell.

- Low-organic matter aragonite – Low-organic matter aragonite is a form of aragonite that has little organic material in the shell structure. Shells made with low-organic matter aragonite are expected to make it harder for animals to survive in an acidified ocean.
- Resistance to ocean acidification – Ranges from 1 to 5. Genera with a low rating have a shell structure that is likely to be more vulnerable to ocean acidification, and genera with a high rating are more likely to be resistant to ocean acidification.

Lifestyle – These variables describe, in broad terms, how the genus makes its living.

- Infaunal/epifaunal – Infaunal organisms live buried in the mud or sediment, and epifaunal organisms live on the surface of the ocean bottom.
- Feeding type:
    - Suspension feeders take in water and strain plankton out through their gills.
    - Deposit feeders swallow mud and absorb the organic matter (excreting the indigestible substances). Some do this from within the mud itself, and others slurp sediments from the surface of the ocean bottom.
    - Chemosynthetic feeders have symbiotic bacteria in their gills that convert inorganic compounds in the sediment into organic compounds that the mollusk can use for energy.
    - Carnivorous feeders catch and eat other animals. Carnivorous bivalves spread sticky threads on the seafloor to trap prey or use suction to pull prey into their shells for digestion.

Age of genus– These variables delineate the span of time over which the genus lived.

- Oldest – This is the age of the first occurrence of the genus in the fossil record, in millions of years. So, for example, the oldest known fossils of the genus *Acar* is are 96.2 million years old.
- Youngest – This is the most recent occurrence of fossils (or live organisms) of the genus in millions of years. When a zero appears in this column, it indicates that the genus is alive today. When numbers between 66 and 70.2 appear in this column (a time span that encompasses the final time interval within the Cretaceous Period), it indicates that the genus went extinct during the K-T extinction event, allowing for the uncertainty around the last known specimen. Some genera survived the mass extinction but have since gone extinct; their date of extinction is between 0 and 66 million years ago.

Further reading

- Data set source: Krug, A. Z., Jablonski, D. (2012). Long-term origination rates are reset only at mass extinctions. *Geology.* 40:731-734.
- http://www.bivatol.org/index.php/bivalvia-1011

What sorts of hypotheses can students explore with the data?

These data are potentially relevant to many different hypotheses. Here are a few of those hypotheses and expectations relevant to the data that they generate. We have listed many, but students will likely explore only a few:

- Hypothesis: At the K-T, the sun was blocked out, halting photosynthesis. Expectation: Suspension feeders, which rely directly on photosynthetic plankton, may have been more vulnerable to extinction than other types of feeders.
- Hypothesis: At the K-T, food webs collapsed. Expectation: Suspension feeders and carnivores, which rely on other live organisms, may have been more vulnerable to extinction than other types of feeders. Chemosynthetic feeders may have been least vulnerable to extinction because they get their energy from inorganic compounds in the sediment, not from other organisms.
- Hypothesis: At the K-T, rapid global climate change occurred, which disrupted ecosystems all over the world. Expectation: Genera with widespread geographic ranges were more likely to occupy a safe harbor than genera with narrow ranges—and so widespread genera were less vulnerable to extinction.
- Hypothesis: At the K-T, rapid, short-term temperature fluctuations stressed vulnerable animals. Expectation: Infaunal genera, which were protected by the sediment from these temperature swings, were less vulnerable to extinction than epifaunal genera.
- Hypothesis: At the K-T, long term global warming pressed organisms to their physiological limits. Expectation: Tropical genera may have been more vulnerable to extinction because they were already close to physiological limits for heat tolerance, and polar genera may have been more vulnerable to extinction because they already lived in the coolest places on Earth and could not change their range to a cooler area. Temperate genera may have been most likely to survive.
- Hypothesis: At the K-T, both oceans and rain became more acidic. Expectation: Genera with shell types more resistant to acidic conditions may have been less vulnerable to extinction.
- Hypothesis: At the K-T, the ozone layer thinned, exposing organisms at the surface of the ocean to dangerous levels of UV radiation. Expectation: Since phytoplankton live at the surface of the ocean, suspension feeders, which rely directly on plankton to survive, may have been more vulnerable to extinction than other types of feeders.

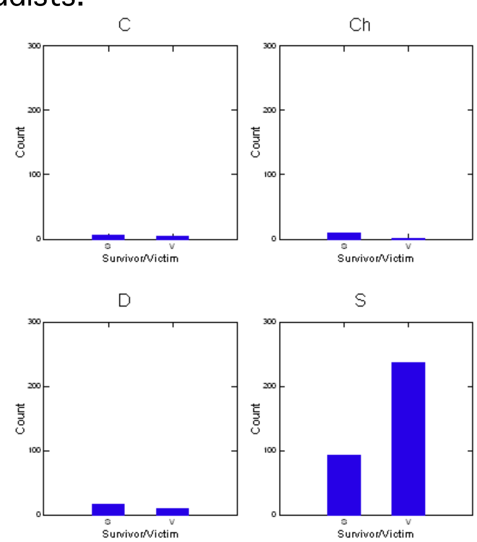
- Hypothesis: The K-T meteor impact caused local effects that increased extinction rates near the impact. Expectation: Genera living only near the Yucatan peninsula may have been more vulnerable to extinction than genera with ranges outside that region.
- Hypothesis: A variety of inherited life history traits affect a genus' likelihood of going extinct during mass extinctions. Expectation: Genera within different families and orders should have significantly different chances of going extinct at the K-T.
- Hypothesis: Over time, genera acquire adaptations that protect them during times of mass extinctions. Expectation: Older genera should be less likely to go extinct during the K-T mass extinction than younger genera.

What patterns exist in the data?

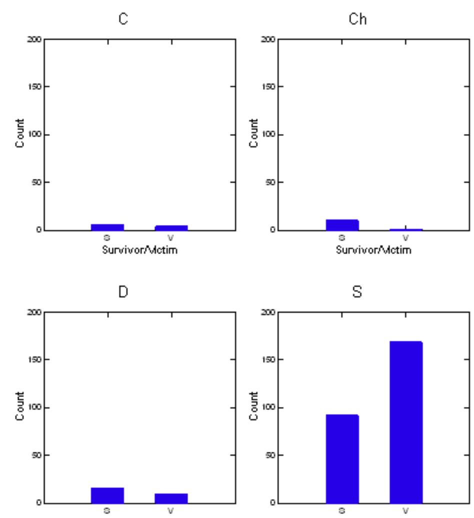
Here we've summarized some broad patterns in the data. We show results including and excluding the rudists separately. These suggest just a few ways that students might analyze the data. Many other analyses are possible.

- Suspension feeders are more likely to be victims of the mass extinction than are other feeding types—but because of the low numbers of other types of feeders, we cannot feel confident about this pattern. Results like these should be used to illustrate the importance of sample size in determining how much we are able to conclude from an analysis. Also note that this pattern is somewhat sensitive to how we classify rudists (excluding rudists makes the pattern less strong) – are rudists their own category, perhaps relying on symbiotic algae for nutrition, or are they suspension-feeders, like most other bivalves?

With rudists:

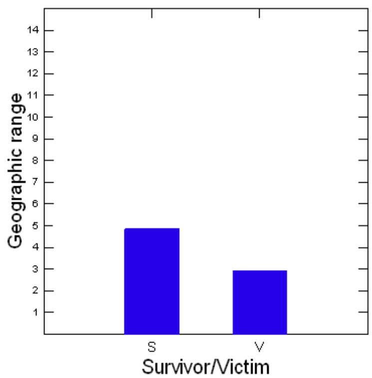


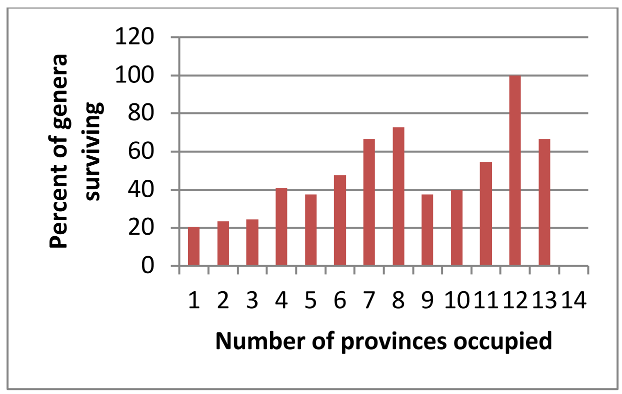
Without rudists:



- Survivors have wider geographic ranges than victims. These results hold up whether or not the rudists are included. This finding is consistent with the results of many other studies showing that narrow geographic range increases a species' risk of extinction and is the broadest, most important pattern in the data. It is also consistent with the hypothesis that a broad, global change (such as climate change) contributed to the K-T mass extinction. In that situation, we might expect genera with widespread geographic ranges to be more likely to occupy a safe harbor than genera with narrow ranges.

With rudists:





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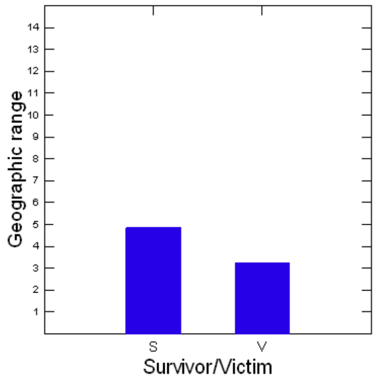
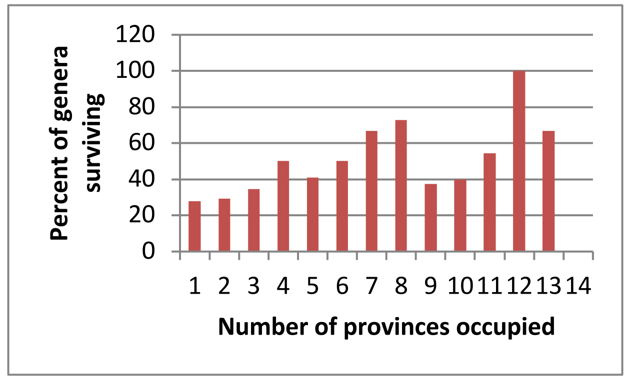
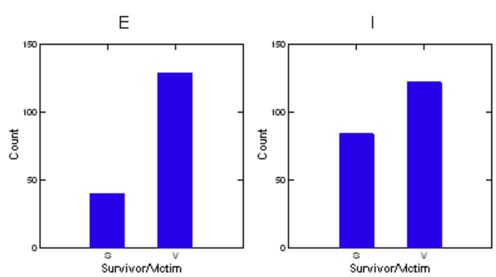


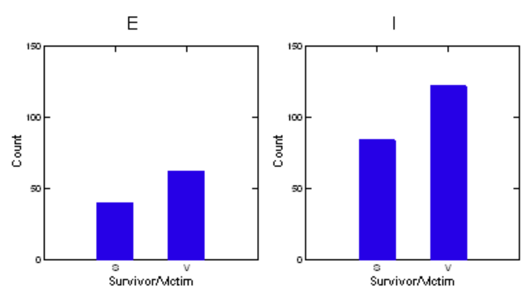


- Epifaunal genera are more likely to be victims during the mass extinction than are infaunal genera. This is consistent with the hypothesis that rapid, short-term temperature fluctuations stressed vulnerable animals during the K-T extinction. In that situation, we might expect infaunal genera to be protected by the sediment from such temperature swings. Here the result depends on whether we consider the rudists to be "typical" bivalves or a special category: leaving them out of this test removes the apparent trend. Perhaps the rudists *are* a special case.

With rudists:

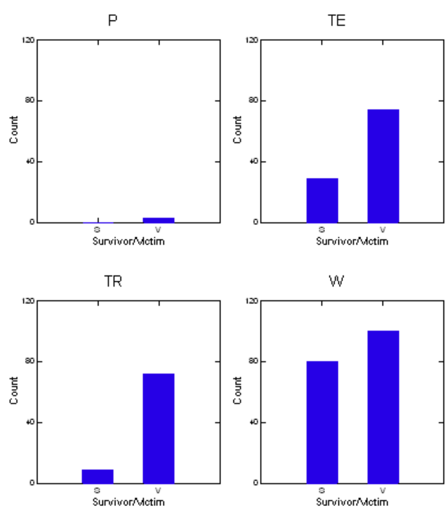


Without rudists:

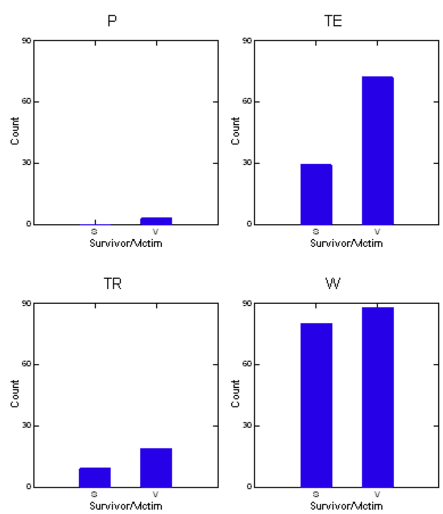


- Strictly temperate genera survived at higher rates than polar or tropical genera—but widespread genera outsurvived them all (and in fact, it is likely that temperate genera survive better than polar or tropical general because there are more temperate zones than tropical or polar zones and these genera are *also* more widespread). The apparently greater extinction in the tropics is driven by those highly unusual tropical bivalves, the rudists. When we leave them out of the analysis, the other tropical bivalves fare neither better nor worse than those of the temperate zones. Perhaps being specialized for very shallow, tropical waters, made rudists especially vulnerable to extinction. Again, the most important factor in determining survival seems to be breadth of geographic range, not the location of a genus' home range. The main pattern here is: widespread genera are much more likely to survive than restricted genera.

With rudists:



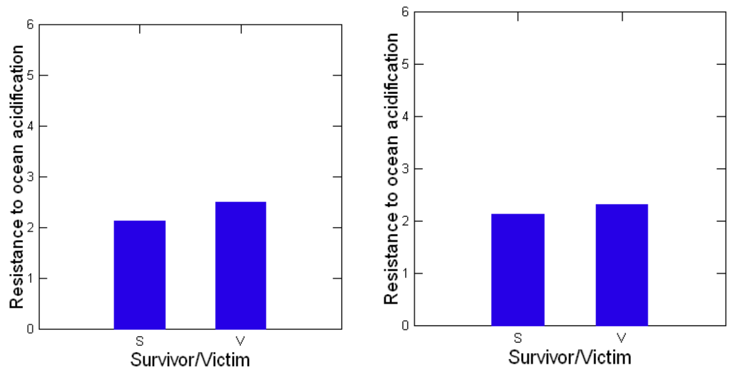
Without rudists:



- Resistance to acidic conditions doesn't seem to make much difference in whether a genus survived the mass extinction. These results hold up whether or not the rudists are included. This result does not particularly support the hypothesis that ocean acidification or acid rain played an important role in marine extinctions during the K-T.

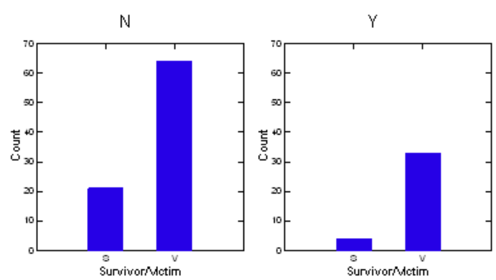
With rudists:

Without rudists:

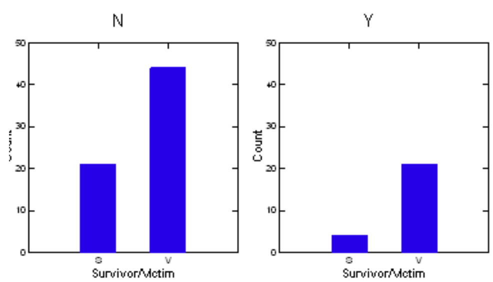


- For genera living in a single geographic province, having that province be one of the three nearest the impact site (Western Central America, Antilles, and Gulf/Atlantic; shown on the graphs at right below) might increase the likelihood of extinction slightly compared to other genera in single provinces elsewhere in the world (at left on the graphs below); however, this trend is largely driven by the rudists and mostly disappears when they are excluded. This supports the idea that global, and not merely local, disturbances caused the K-T extinction.

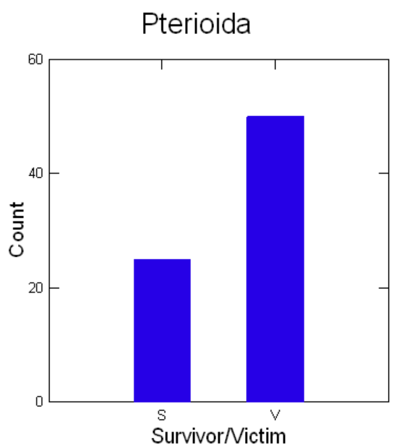
With rudists:



Without rudists:



- Some families have very high rates of extinction and some were much more likely to survive the mass extinction. Extinction can run in families. For example, members of Pterioida were much more likely to survive than rudists (Hippuritoida), even though both were epifaunal. Is this difference support for the idea that rudists depended on vulnerable symbiotic algae for their nutrition? Or is it simply a matter of rudists' small geographic range size putting them at high risk? These data cannot distinguish between these two hypotheses.


Pterioida
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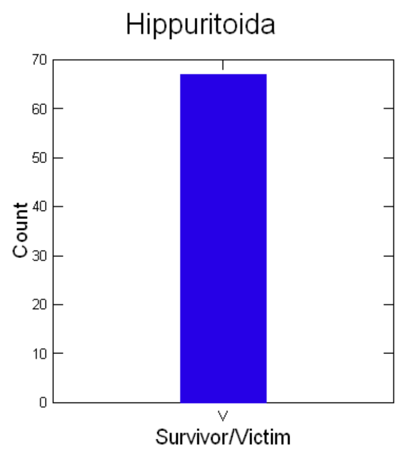
Hippuritoida
70
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Count
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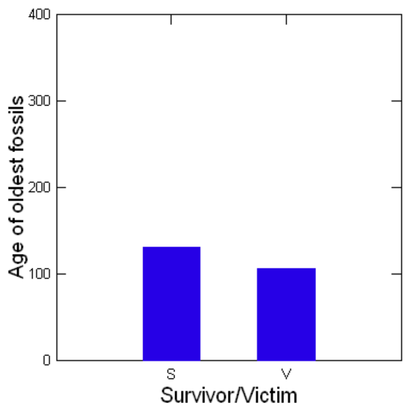
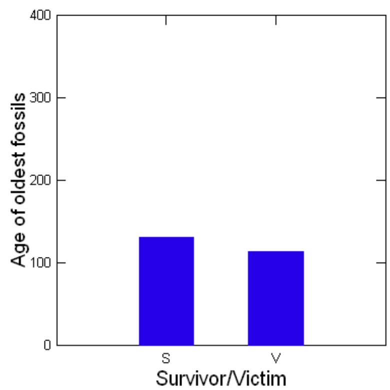
Survivor/Victim

- Older genera are not much more likely to survive the mass extinction than younger genera. These results hold up whether or not the rudists are included. This result does not particularly support the idea that, over time, genera acquire adaptations that protect them during times of mass extinctions. Perhaps the conditions at the K-T boundary were so unusual that evolution during background times did not push lineages towards adaptions that could help during the mass extincton.

With rudists:



Without rudists:



Chi-square tests

Of course, the graphs above just show patterns in the data but do not tell us if the patterns are statistically significant – that is, if they actually represent a real trend that requires an explanation or if they are likely to be caused by chance alone. For many of the graphs shown above (but not the analyses of the effect of geographic range, the effect of resistance to acidic conditions, and the effect of genus age), the appropriate test of statistical significance is a chi-square test. Chi-square tests can be used in the cases where we are examining counts of survivors and victims and want to know if they are randomly distributed with respect to another variable. Chi-square tests are based on the assumption that the variable of interest is independent of (or unrelated to) the distribution of counts. Rejecting this null hypothesis ($p<0.05$, meaning that the observed result is just due to chance is less than 5%) indicates that survivors and victims are non-randomly distributed with respect to the variable and that there is a significant pattern to be investigated.

For example, we might hypothesize that rapid, short-term temperature fluctuations stressed vulnerable animals during the K-T extinction, and thus we might expect infaunal genera to be protected by the sediment from such temperature swings and be less likely to go extinct than epifaunal genera. Our null hypothesis is then that infaunal and epifaunal genera are equally likely to go to extinct. When we do the counts (excluding rudists) and calculate percentages, we find that around ~61% of epifaunal genera went extinct while ~59% of infaunal genera did:

Counts

Victim/Survivor(rows) by Infaunal/epifaunal(columns)

	E	I	Total
S	40	84	124
V	62	122	184
Total	**102**	**206**	**308**

Column Percents

Victim/Survivor(rows) by Infaunal/epifaunal(columns)

	E	I	Total	N
S	39.216	40.777	40.260	124.000
V	60.784	59.223	59.740	184.000
Total	**100.000**	**100.000**	**100.000**	
N	**102.000**	**206.000**		**308.000**

So the trend is in the direction we predicted (i.e., infaunal genera go extinct less often), but it is small. Is it statistically significant? The chi-square test says it is not - that this distribution could have easily occurred by chance alone, since p = 0.793, which is greater than 0.05:

Chi-Square Tests of Association for Victim/Survivor and Infaunal/epifaunal

Test Statistic	Value	df	p-value
Pearson Chi-square	0.069	1.000	0.793

Number of Valid Cases: 308

Students can use statistical software to calculate these statistics or an online calculator such as this one:
http://www.socscistatistics.com/tests/chisquare2/Default2.aspx