Bi/Ge105: Evolution
Homework 1
Due Date: Wednesday, January 10, 2024

"The real voyage of discovery consists not in seeking new landscapes but in having new eyes." - Marcel Proust

1. A feeling for the numbers in evolution

The processes of evolution take place at many different scales in both space and time. The goal of this first problem is nothing more than to "play" with some of the characteristic scales associated with a broad range of processes in evolution ranging from the very small (e.g. number of mutations per cell in a bacterium after one round of replication) to the very large (e.g. how far do the Galapagos islands travel in a million years). These estimates are intended to be done using simple arithmetic of the "one-few-ten" variety (i.e. few times few is ten) and to give an order-of-magnitude picture of the phenomenon of interest. Take pride in your results and state and justify (with citations) the assumptions you make carefully and give a simple, intuitive description of how you came to your results. Please don't report rough estimates with long lists of "significant" figures.

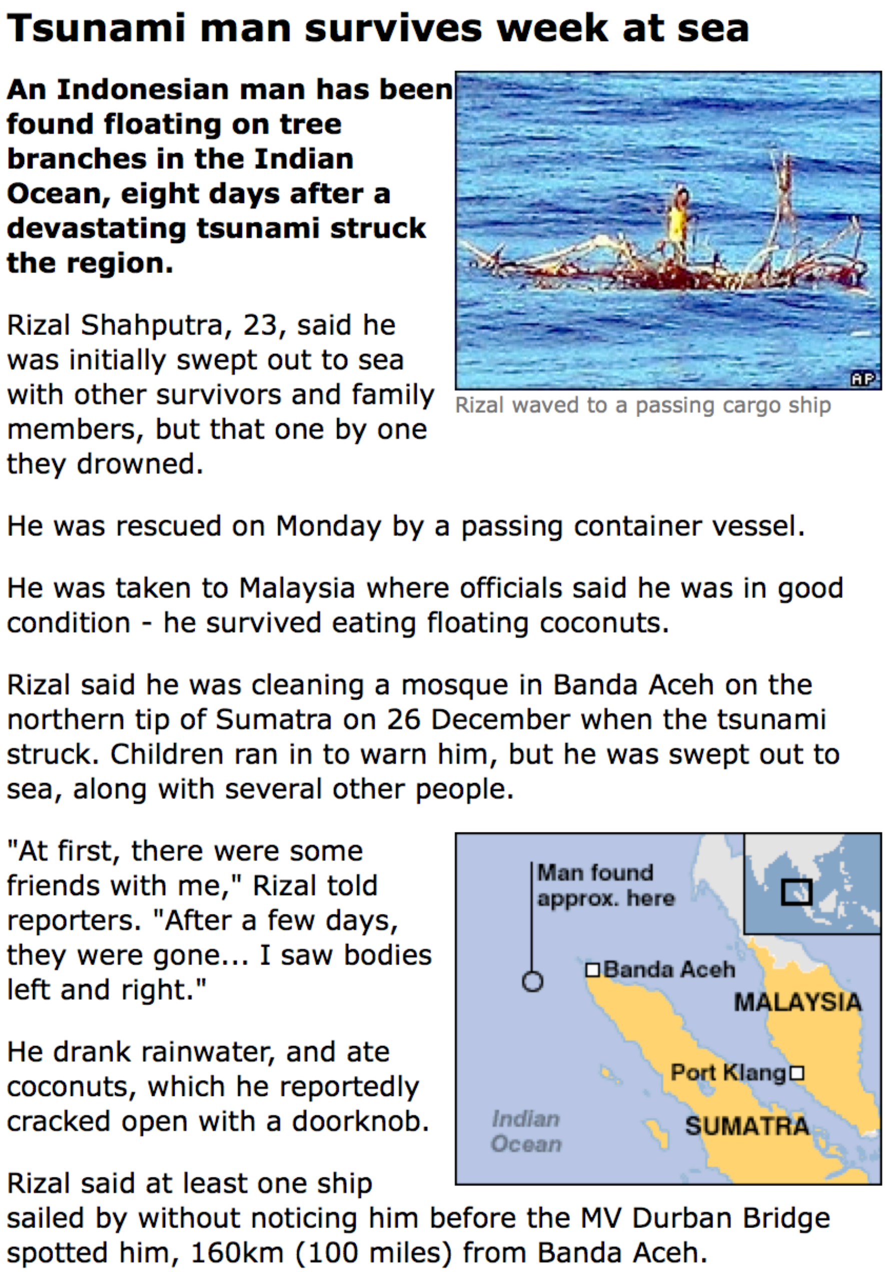
(a) A key debate that has colored the subject of biogeography (and hence evolution) since the time of Wallace and Darwin is that of how oceanic islands have been colonized by the species of flora and fauna that now occupy them. In particular, the great botanist Joseph Hooker quipped "Oceanic islands are in fact, to the naturalist, what comets and meteorites are to the astronomer." A central element of that debate has focused on mechanism with two main alternatives, vicariance and dispersal in play. Vicariance refers to the idea of continental breakup and subsequent speciation. For example, both New Zealand and Madagascar were once attached to larger landmasses and the vicariance hypothesis holds that their current flora and fauna reflect these initial origins. This has led with tongue in cheek to the idea of New Zealand as Moa's Ark. The dispersal idea is completely different, arguing that oceanic islands are colonized through chance events in which some rare event involving an animal or plant is moved about by ocean currents and ends up on the island of interest.

In the early 2000s, there was a massive earthquake in Indonesia leading to a huge loss of life. Many people were swept out to sea in the resulting tsunami. Several lucky souls were later found way offshore. Use Figure 1 to estimate the speed of the ocean currents experienced by Rizal Shahputra.

(b) As we will discuss in the course, the study of dispersal has become a subject of observation and measurement with many interesting independent threads of evidence coming together to show that plants and animals are moving around in ocean currents all the time. One compelling example from more than a decade ago was the arrival of an Aldabra tortoise from the Indian Ocean on the shores of Africa. Using your estimate from the first part of the problem, give an estimate of the time spent in the ocean by the tortoise shown in Figure 2 in its journey drifting from Aldabra (see Figure 3) to Tanzania!

(c) One of the reasons that evolution is hard to think about is because of the vast times involved in evolutionary processes. One of the more interesting things we have to remember is the interplay between the dynamics of the earth and the dynamics of the living organisms on earth. For example, we will later learn about the consequences of the closing off of the Isthmus of Panama for evolution. Similarly, the collision of India with the Asian continent brought an end to the Tethys Sea. In this part of the problem, we will think about such geological processes as they bear on some of our favorite topics from the course.

We begin by thinking about how fast the Galapagos Islands are moving. Note that these islands, like the Hawaiian Islands, are being produced by a "hotspot" that is near the current islands of Isabella and Fernandina. The islands then move in a southeasterly direction towards the coast of South America. Given that the island of Espanola is roughly 3.5×10^6 years old, make an estimate for the mean rate at which these islands are moving to the southeast per year. Give your answer in cm/year. Also, notice that as the islands age, their height is reduced with the new islands of Fernandina and Isabella with volcanoes over 1500 m in height while Espanola has a height of only roughly 200 m. Assuming that the speed you found for the Galapagos is typical for island chains, make an estimate of the age of the island Kauai using the same kind of logic. What factors might complicate this comparison, and how would they change this estimate (qualitatively)?



Tsunami man survives week at sea

An Indonesian man has been found floating on tree branches in the Indian Ocean, eight days after a devastating tsunami struck the region.

Rizal waved to a passing cargo ship

Rizal Shahputra, 23, said he was initially swept out to sea with other survivors and family members, but that one by one they drowned.

He was rescued on Monday by a passing container vessel.

He was taken to Malaysia where officials said he was in good condition - he survived eating floating coconuts.

Rizal said he was cleaning a mosque in Banda Aceh on the northern tip of Sumatra on 26 December when the tsunami struck. Children ran in to warn him, but he was swept out to sea, along with several other people.

"At first, there were some friends with me," Rizal told reporters. "After a few days, they were gone... I saw bodies left and right."

He drank rainwater, and ate coconuts, which he reportedly cracked open with a doorknob.

Rizal said at least one ship sailed by without noticing him before the MV Durban Bridge spotted him, 160km (100 miles) from Banda Aceh.

Figure 1: Article about tsunami survivor after Boxer Day earthquake in Indonesia in 2004.

Figure 1. The Aldabra tortoise at Kimbiji, shortly after its discovery in December 2004. Photograph: C. Muir.

Figure 2: Tortoise found in Tanzania after traveling across the ocean. Notice the barnacles that have attached to the tortoise.

2. Deep time and earth history

One of the most interesting topics in science is how we have learned to probe deep time. In this course, the subject of deep time will appear repeatedly and we will spend a lot of time examining how DNA sequence has permitted us to explore deep time in the biological setting. Of course, biology and the dynamics of the Earth are not independent phenomena and the point of this problem is to better understand the details of how scientists figure out how old the Earth is as well as how old various fossil-bearing strata are. To that end, we will first consider a simple model of the radioactive decay process for potassium-argon dating methods, recognizing that there are many other dating methods that complement the one considered here.

Potassium-Argon dating

Potassium-argon dating is based upon the decay of ^{40}K into ^{40}Ar. To a first approximation, this method can be thought of as a simple stopwatch in which at t = 0 (i.e. when the rocks crystallize), the amount of ^{40}Ar is zero, since it is presumed that all of the inert argon has escaped. We can write an

Figure 3: Map showing the position of the Aldabra Atoll in the Indian Ocean.

equation for the number of potassium nuclei at time $t + \Delta t$ as

$$N_{\mathrm{K}}(t + \Delta t) = N_{\mathrm{K}}(t) - (\lambda \Delta t) N_{\mathrm{K}}(t). \tag{1}$$

Stated simply, this means that in every small time increment Δt, every nucleus has a probability $\lambda \Delta t$ of decaying, where λ is the decay rate of $^{40}\mathrm{K}$ into $^{40}\mathrm{Ar}$. We also employ the important constraint that the number of total nuclei in the system must remain constant, so that

$$N_{\mathrm{K}}(0) = N_{\mathrm{K}}(t) + N_{\mathrm{Ar}}(t), \tag{2}$$

where $N_{\mathrm{K}}(0)$ is the number of $^{40}\mathrm{K}$ nuclei present when the rock is formed, $N_{\mathrm{K}}(t)$ is the number of $^{40}\mathrm{K}$ nuclei present in the rock at time t, and $N_{\mathrm{Ar}}(t)$ is likewise the number of $^{40}\mathrm{Ar}$ nuclei present in the rock at time t. In this part of the problem you will use equations 1 and 2 to construct differential equations to find the relationship between $N_{\mathrm{K}}(t)$, $N_{\mathrm{Ar}}(t)$, and t.

(a) Using equations 1 and 2 as a guide, write differential equations for $N_{\mathrm{K}}(t)$ and $N_{\mathrm{Ar}}(t)$. How do these two expressions relate to one another?

(b) Next, we note that the solution for a linear differential equation of the form $\frac{dx}{dt} = kx$ is given by $x(t) = x(0)e^{kt}$. Use this result to solve for $N_{\mathrm{K}}(t)$.

(c) Use the constraint encapsulated by equation 2 to write an equation for the lifetime of the rock, t, in terms of the ratio $\frac{N_{\mathrm{Ar}}}{N_{\mathrm{K}}}$.

Age of the Galapagos Islands

The potassium-argon dating method described above has been used in several contexts central to the themes of this course. When we are in the Galapagos, our guides will tell us about the ages of islands such as Santa Cruz and Isabella. But how are these numbers known and what evidence substantiates these claims when naturalist guides make them? In a beautiful article from Science Magazine in 1976 (Science, New Series, Vol. 192, No. 4238 (Apr. 30, 1976), pp. 465-467), Kimberly Bailey tells us of her efforts to determine the ages of the islands of Santa Cruz, San Cristobal and Espanola. We will now use her data to find out the K-Ar ages of several of these islands ourselves.

(d) Read Bailey's paper and give a brief synopsis (1 paragraph) of her approach and findings.

(e) Use the results from Sample H70-130 and JD1088 of Table 1 to determine ages for Santa Cruz Island and Santa Fe Island. To do this, you will need to navigate a few subtleties. First, note that the amount of Argon is presented in moles, and so you can use those numbers directly. To determine the number of moles of ^{40}K, you will need to use the weight percentage that is K_2O and use that in combination with the mass of the sample to figure out how much K is present. Note that not all of the potassium in the sample will be the isotope ^{40}K, so you will need to use the ratio of ^{40}K to total potassium, $\frac{^{40}\mathrm{K}}{\mathrm{K}_{\mathrm{total}}} \approx 1.2 \times 10^{-4}$. Additionally, use the decay constant $\lambda \approx 5.8 \times 10^{-11}$ yr^{-1}.

Determining Lucy's age

In 1974, a fossil of *Australopithecus afarensis* (shown in Figure 4) was discovered in Ethiopia. This specimen, which was dubbed "Lucy," marks an important step in understanding human evolution because at the time of its discovery, it was the earliest known species to show evidence of bipedal locomotion. Because Lucy was found in an area that was rich in volcanic rock, potassium-argon dating was an ideal method for determining Lucy's age (Aronsen 1977).

Unfortunately for us, real-world K-Ar dating data are generally not neatly presented in the form of N_{Ar} and N_{K}. Instead, geologists will measure a concentration of ^{40}Ar in mol/g and a weight percent of $\mathrm{K_2O}$. These data must be used to identify the number of ^{40}Ar and ^{40}K nuclei in the sample. In this part of the problem, we will look at such measurements from an actual paleontological specimen as reported in Aronsen (1977) in order to determine its age.

(f) Using the table of ^{40}Ar and $\mathrm{K_2O}$ measurements below (Aronsen 1977), obtain an estimate for Lucy's age. Be sure to explain the steps you take to obtain your answer. Since each sample is taken from the area in which Lucy was found, we expect each sample to give you roughly the same answer; you will need to take the mean of the ages of each sample to obtain an estimate for Lucy's age.

Figure 4: The remains of Lucy, a specimen of *Australopithecus afarensis*.

Assume that each sample has a total mass of 1 g. Also, note that not all of the potassium in the sample will be the isotope ^{40}K, so you will need to use the ratio of ^{40}K to total potassium, $\frac{^{40}\text{K}}{\text{K}_{\text{total}}} \approx 1.2 \times 10^{-4}$. Additionally, use the decay constant $\lambda \approx 5.8 \times 10^{-11}$ yr^{-1}.

Sample Number	**^{40}Ar $\times 10^{-12}$ mol/g**	**wt. % K_2O**
1	2.91	0.657
2	3.18	0.755
3	3.08	0.680