Living with Geology:
How Galapagos Rocks Change the Course of Evolution

The base of life is geology because it provides foundations on which organisms live and adapt. In such an unusual place as the Galapagos islands, with cool, temperate climates and isolation that spurs speciation, geology must be the base off which organisms first begin to change and adapt. Evolution is usually tied with biotic factors such as the presence of other species, and vegetation communities; however, abiotic features such as geology affect evolution on a base level and this research urges to consider demanding geological conditions as opposed to demanding ecological conditions. Island archipelagos “have repeatedly been referred to as “theaters of evolution”” (Hutchinson, 1957) and consequently, the differing geology on each island provides different ‘stages’ on which organisms must adapt, leading to speciation. The Galapagos islands are volcanically formed, so how does the unique geology of the Galapagos influence the constraints and opportunities for island biota speciation? Geology effects evolution on the Galapagos islands through edaphic (soil) features, which provide constraints and opportunities for vegetation communities; geomorphology and edaphic features, which impact the hydrological cycle which then affects vegetation and animal speciation; and properties of volcanic islands, specifically submergence, which change the physical environment and affect speciation.
Contrary to Darwin’s first assumption that the Galapagos islands had rifted from South America and drifted west, the islands have never had contact with the continent, which heightens the islands’ isolation from mainland species of animals and plants. The Galapagos islands are volcanically formed from a volcanic hotspot (fig. 1)- a stationary magmatic chamber underneath the oceanic crust that occasionally becomes active, spewing magma up through the oceanic crust and forming new islands over millions of years.

The Galapagos islands are on the Nazca tectonic plate, which is moving slowly eastward towards South America as the Nazca plate subducts under the South American Plate. Because of this crustal movement, the islands are formed and carried eastward, creating a chain of islands from one stationary magmatic source (Geist, unpublished).

As islands form, different amounts of magma are produced for the different lengths of time that the hot spot is active; therefore each island has a different shape, elevation and size. Because “each island has a unique history and unique set of constraints” (Geist, unpublished) each island provides a unique stage on which species must adapt and evolve.

This study analyzes the effects of geology on four organism’s speciation: opuntia cacti, giant tortoises, lava lizards and Darwin’s finches. Outside studies will also be used to support the hypothesis that geology affects evolution in three main ways on Galapagos, and will look at similar archipelagos as well as speciation on the Galapagos islands.
Edaphic Features

Evolution on the Galapagos is affected by edaphic, or soil, features. Edaphic features include depth of soil, water retention and type of soil (clay or crumbled volcanic soil). Soil is an integral component of geology affecting evolution because of the sharp differentiation between soil types on the islands. The unique dry equatorial climate of the islands “slows the weathering of rock into soil” (Simkin, 2008) and therefore soil remains very shallow on most islands. Water is required for the weathering of rock, as “variation of rainfall according to elevation [is] the main factor controlling the soil development” (Aldinet, 2007). The presence of water leading to soil development is especially important for such rough volcanic rock of the Galapagos to be able to weather into soil. However, if an island has low elevation, it will receive very little to no rainfall or garua, the low cloud cover that saturates high elevations on the Galapagos. There are two main soil regions on the Galapagos: low elevation soils and high elevation soils. These two groups exist because “hydraulic conductivity of soils is controlled by altitude,” which can be related to “the variation of rainfall with altitude” (Aldinet, 2007). Soils at low elevations- below 300 meters- have “high porosity,” (Aldinet, 2007) which means any rainfall will not be retained for plant growth. These lowland soils are also very shallow and made of coarse materials- which relates to slow weathering of rough volcanic rocks (Aldinet, 2007). Highland soils have the opposite characteristics: these soils, located above 350
meters, have “low hydraulic conductivity,” meaning they have high water retention, are very thick, “several meters,” and are “homogeneous without coarse components” (Aldinet, 2007) combinations crucial to the development of complex vegetation communities.

Characteristics of each type of soil respectively affect the evolution of plant and animal communities because they provide different constraints and opportunities for growth and food sources. The characteristics of lowland soils directly affect the evolution of plant life on the Galapagos because shallow, porous and coarse materials allow little hold for roots and very little water for extensive growth or fruit production. A test case for edaphic features affecting evolution is Darwin’s finches, all 14 species. Finch speciation can be seen by “adaptation to local food resources in geographically separate regions,” (Grant, 2002). Food resources, or vegetation communities, are dependent on edaphic features because the depth and water retention provide constraints and opportunities for vegetation communities to evolve.

Geomorphological Features

Geomorphological features affect evolution and speciation of Galapagos flora and fauna by providing considerable constraints and opportunities for speciation. Geomorphological features include island shape, size and elevation. As Geist states, an important issue for the study of speciation associated with geological formations “is the dynamic nature of the geography in the Galapagos […] owing to the geologic processes of plate tectonics, [and] volcanism,” (Geist, unpublished). Because the islands were formed volcanically from a periodically active hotspot, or “a melting anomaly in the earth’s upper mantle,” (Geist, unpublished) the islands form in different sizes because the hotspot is active for different length of time. The variation in
activity results in islands of higher or lower elevations or land areas, both prominent geomorphological features that affect speciation on each island. “Each island has a unique history and a unique set of constraints,” (Geist, unpublished) which leads to unique constraints and opportunities for speciation.

Elevation, land area and soil type and availability are the three geomorphological features researched the most extensively. Elevation determines the climatic zones of each island in the Galapagos, which invariably affects the weathering of rock into soil, as described in the above section. Climatic zones in the Galapagos vary every few hundred meters, with islands above 300 meters receiving rainfall and garua. Speciation of flora and fauna depend on elevation because the amount of vegetation increases as elevation goes up due to increased moisture. The upper zones of elevation- Scalesia, the Brown Zone, Miconia Zone and the Pama or Fern-sedge Zone- all receive increased moisture respectively (Fig. 2).

Because rainfall and garua only reach islands of higher elevation, islands of lower elevation are much drier and therefore have different constraints and
opportunities for species such as finches, Opuntia cacti and lava lizards. Opuntia exhibit this especially on low islands, on which they thrive with shallow soils and little moisture.

All three geomorphological features—elevation, land area and soil type and availability—vary from island to island, which leads to the hypothesis that speciation is distinct on each island due to geomorphological feature combinations. There would be approximately 13 species of each organism according to this hypothesis, one on each of the 13 major islands in the archipelago (Helsen, 2011). This is supported by studies done on finches, lava lizards and opuntia cacti on all islands, showing that each island has its own taxon of the three organisms. This is characterized as “one island, one taxon,” or one community of species per island (Helsen, 2011). Opuntia exhibit this trait because “species distribution [not every species is on every island] on Galapagos are reported to be limited. With each large island possessing its own taxon,” (Helsen, 2011).

More specifically, the opuntia cacti are divided into six main species, which are then further divided into “14 subspecific categories,” (Helsen, 2011). The low elevation around the coasts of Santa Cruz island makes an “arid zone ecosystem, which is the most important habitat for Opuntia species […] and] forms a “vegetation” ring around higher altitude regions,” (Helsen, 2011). The current “jagged and steep shoreline [of Daphne Major island] makes it difficult for opuntia pads to recolonize the island,” which has led to a separate species than those on Santa Cruz because of the more difficult geomorphological features of Daphne Major (Helsen, 2011).
Similarly to opuntia, lava lizard speciation is a function of new geomorphological constraints and opportunities as new islands with differing geology were formed. “As each new volcano became available for colonization [after volcanic activity had subsided] a dispersal event associated with speciation occurred from the older to younger volcano,” resulting in “a single species per island,” (Benevides, 2008). Giant tortoise speciation across the archipelago is also consistent with one species per island based on differing geomorphological features. A study by Beheregaray et al. concluded that “patterns of colonization and lineage sorting [in giant tortoises] appear highly consistent with the chronological formation of the archipelago,” (Beheregaray, 2004). Specifically, tortoise speciation can be analyzed looking at populations “in younger islands, which have higher elevations and more ecological complexity,” (Beheregaray, 2004) a statement consistent with more complex vegetation communities on islands of higher elevation.

Darwin’s Finches are the last case study analyzed in speciation related to geomorphological features. Speciation occurs like that of the opuntia, lava lizards and tortoises. New populations of finches on an island “evolve by natural selection, becoming better adapted to the prevailing conditions, [then dispersers] colonize a second island and adapt to the new conditions,” (Grant, 2002). Further research determined that “as the number of islands increased, so did the number of finch species,” (Grant,
2002). Grant also included that a “changing environment- differing numbers of islands, climate and vegetation- acts as a force driving the radiation [speciation],” (Grant, 2002). Darwin’s finches are a complex model, however, because currently, the 14 species have reached a point at which they can survive on different islands from which they speciated, coexisting with species supposedly specific to one island. The finches initially speciated across the archipelago much like lava lizards, tortoises and opuntia, with the number of species increasing with number of islands (Grant, 2002). Today, however, multiple species can be found on one island because, “given enough time, populations are expected to diverge sufficiently to permit coexistence, and coexistence will be achieved as a result of dispersal among islands,” (Grant, 2002). Species associated with new islands are therefore estimated by “simply back-calculating from the estimated ages of contemporary species,” (Grant, 2002) therefore finches are another example of how different geomorphological features affect speciation on each island.

**Submergence**

Submergence of Galapagos islands affects speciation and evolution because it redefines land area and elevation, therefore redefining geomorphological features. Submergence, or subsidence, is caused when “the Earth’s lithospheric plates cool and contract as they move away from the
hot melting anomaly [hotspot],” (Geist, unpublished). For example, “5 Ma [million years ago], [Geist] estimate[s] that there were seven islands, none of which exist anymore because they have subsided beneath sea level,” (Geist, unpublished). After island formation from the hotspot, the Nazca plate carries the island volcanos east and as islands get farther from the hotspot, they cool and contract, sinking slowly back into the ocean. Oceanic crust is also denser than continental crust, which contributes to islands sinking (Geist, unpublished). As islands sink, there land area becomes smaller, and they lose elevation, taking them out of the upper elevation moisture zones, which leads to a loss of complex vegetation communities. Partial submergence of islands “suggests that vicariance [when the geographical range of a species, or even a whole biota, is split into distinct sections because of a physical barrier] may be a more important mechanism for island biogeography than previously thought,” (Geist, unpublished). The loss of land area and elevation leads to the hypothesis that submergence will affect speciation by either forcing species to devolve or hybridize into fewer species, or natural selection will cause the loss of species previously adapted to higher elevations, leaving the species previously adapted to lower elevations.

While research done on submergence affecting speciation in the Galapagos is insufficient, research on other submerging islands has been done that conclude similarly. In a study done on Cuban green anoles, “geographical processes play the dominant role in intra-island anole speciation,” (Glor, 2004) and partial submergence leads to differentiation. By these standards, it would make sense to conclude that submergence, differing from partial submergence because the entire island slowly sinks instead of parts of the island simply becoming disconnected, causes a loss of speciation. This is because instead of creating new, separated land areas for speciation, full-island submergence decreases both land area and
elevation. Because the islands’ “eventual fate is to slip back into the sea,” (Whittaker, 2007) due to submergence, “the shorelines that we see today are transient features in a geologic (and evolutionary) time frame,” (Geist, 1996) which leads to the determination that submergence affects evolution.

Submergence affecting speciation can be determined as well by carrying capacity, or the room and resources an island has for certain sizes of populations. “As islands decline [submerge] in their old age, opportunities for speciation diminish, in tandem with a reduced carrying capacity,” (Whittaker, 2007). This is because “the carrying capacity of oceanic islands is, to a first approximation, a function of the area and elevational range,” (Whittaker, 2007). As carrying capacity goes down because submergence causes a decrease in area and elevation, species will be pushed to hybridize or will die off due to reverting changing constraints and opportunities. This is because the “carrying capacity of a volcanic island over the course of its existence can be predicted to increase from zero to a maximum with the island is at greatest extent and elevational range, declining thereafter until [complete] submersion,” (Whittaker, 2007).
One example of species, lava lizards, on Galapagos being affected by submergence is a hypothesis by Benevides et al. that “island submergence may lead to lineage extinction,” (Benevides, 2008). Again, the effects of islands submergence are not fully conclusive because of the extremely long time frame associated with submergence, however, studies in Cuba and hypotheses about possible effects of submergence support the hypothesis that submergence will affect speciation due to changing geomorphological conditions.

**Conclusion**

This research attempts to prove that an abiotic feature has substantial effects on speciation in the Galapagos. Most often, speciation is attributed to biotic factors such as vegetation and the presence of predators and other neighboring species; however, this research proposes that geology is the base factor that determines vegetation communities and provides constraints and opportunities for biota speciation. Geology affects evolution through edaphic features, geomorphological features, and submergence of islands over time. Through case studies looking at Darwin’s finches, opuntia cacti, lava lizards and giant tortoises, the effects of geology on speciation and eventual evolution is demonstrated. Edaphic features affect speciation because of their direct effect on
vegetation communities, which become food sources for animal species. Geomorphological features affect speciation by providing constraints and opportunities for flora and fauna such as land area, elevation and soil type and availability. Submergence is hypothesized to affect speciation by slowly decreasing land area and elevation.

Ultimately, more research is needed to substantiate the claim that submergence causes changes in speciation, either to decrease speciation or increase speciation, as most research is speculative at this point. Long periods of time will be sufficient to show effects of submergence on island biota speciation.
References

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