Introduction:

The Hawaiian-Emperor chain is one of the best examples of an age-progressive set of volcanic islands created by hot-spot activity. The Hawaiian part of the chain formed approximately 5 m.y. ago and has been widely studied. Numerous geochemical and geophysical experiments have been conducted in order to determine how the islands were formed and how the geological activity of the islands changes over time, and the results point to the hot-spot theory as the most widely accepted model for the formation of the islands. This theory states that age-progressive volcanism occurred as the Pacific Plate moved over a rising, deep-seated mantle plume (Wilson, 1963). In this paper, I explore the spatial progression of the islands as well as the geochemical changes they have undergone.

Geologic Setting:

The Hawaiian Archipelago (Figure 1) consists of 8 principal islands and 10 minor islands (Macdonald et al., 1983). The island chain starts at the main island of Hawaii, extends northwest to Niihau, and continues to the north and northwest as the Emperor Seamounts.

The Hawaiian Archipelago is in the center of the Pacific Plate, so the formation of the islands could not have been due to to plate boundary processes. Wilson (1963) proposed that such linear, age-progressive chains originated above mantle plumes as basaltic magmas generated by the plume rose and erupted to form large shield volcanoes.

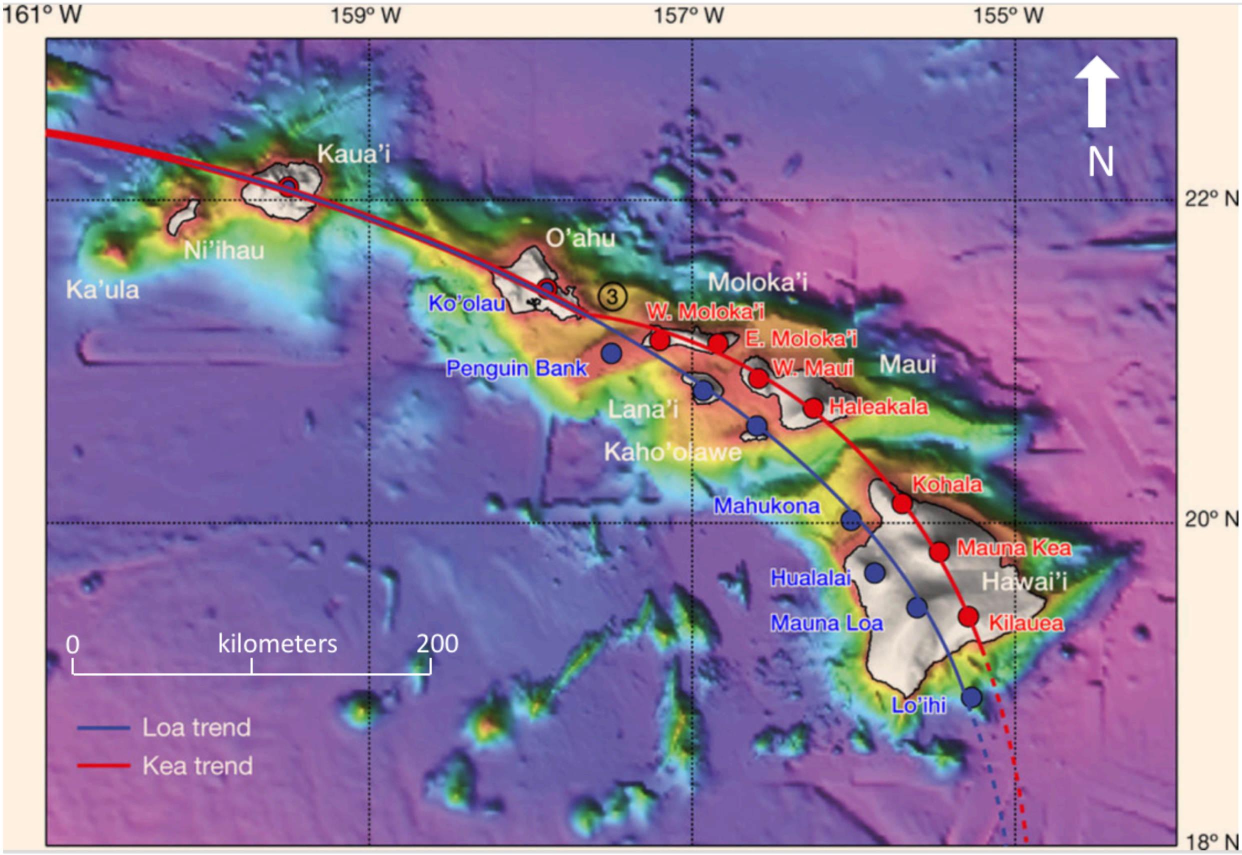

Figure 1. A map of the Hawaiian Islands and their most dominant volcanoes along with the subparallel Loa and Kea trends (blue and red, respectively). The names of the principal islands are written in white, and the names of the volcanoes are written in either blue or red, corresponding to which of the trends it belongs to. The Loa trend starts at the Koolau volcano series and extends to the Lo'ihi Seamount, and the Kea trend starts at West Molokai and extends to Kilauea. (Image Credit: Jones et al, doi: 10.1038/nature22054.)

The Hawaiian Islands are wholly volcanic, and Hawaii, the largest island, exhibits the most voluminous current volcanic activity. The islands' hot-spot track comprises two parallel curvilinear chains: the Loa trend and the Kea trend (Fig. 1; Moore and Clague, 1992). The Loa trend starts at the island of Kauai and extends to the island of Hawaii. The Kea trend starts at the island of Molokai and also extends to Hawaii. These two trends produced lavas with near-identical major-element compositions, but there were also geochemical differences in the amount of major and rare earth elements. Bianco et al. (2008) proposed that the geochemical differences between the Loa trend and the Kea trend were caused by the spatial variability of their relative location to the hotspot and the composition of the mantle.

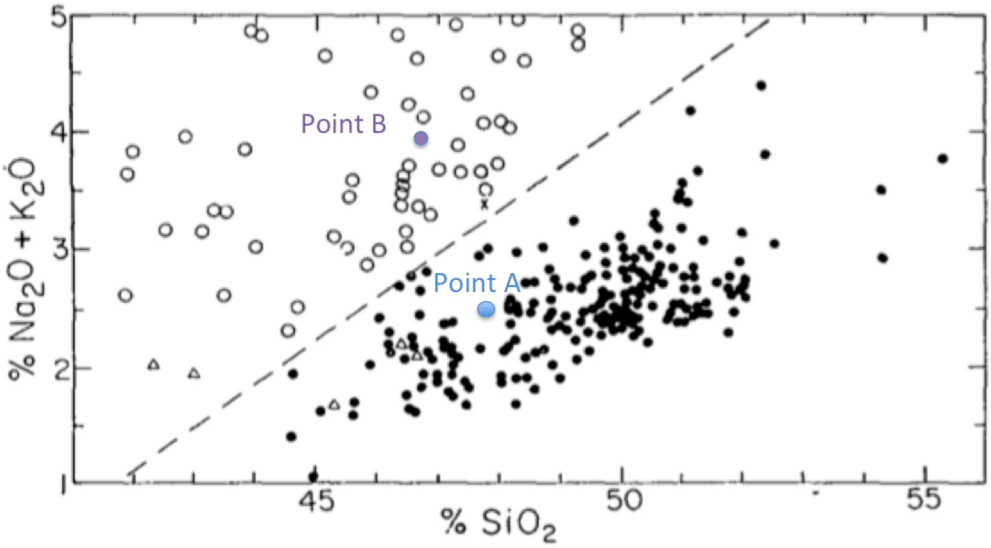

Figure 2. An alkali-silica diagram of Hawaiian basalts (Macdonald and Katsura, 1965). The boundary between tholeiitic and alkalic compositions is shown as a dotted line. White circles represent rocks with an alkalic composition, triangles represent ankaramites, and black circles represent rocks with a tholeiitic composition. The 'x' near the middle of the dotted line represents the liquid that rose into the hole that was drilled through the crust of the Kilauea Iki lava lake. Point B is an alkalic sample, and its color is purple on both animation and plot. Point A is a tholeiitic sample and appears in blue in both the animation and in the plot in Figure 5. Alkalinity is determined by the distance above or below the line.

Hawaiian basalts comprise two major groups: alkalic and tholeiitic. Tholeiitic lavas have low Na_2O+K_2O in comparison to alkalic lavas (Fig. 1). Tholeiitic lavas largely form during the shield-building stage of shield volcanoes when the magma has a high degree of partial melting, whereas alkalic lavas are usually more depleted and formed before and after the shield-building stage of a volcano (MacDonald et al..,1960). Alkalic lavas also have high Na_2O and K_2O concentration, as shown in Figure 2. The major difference between tholeiitic and alkalic lavas is their alkalic elements. Thus, the term 'alkalinity' is defined as %(Na_2O and K_2O) over % SiO_2 concentration in a rock as a measurement of the alkalic elements' concentration in the lava (Macdonald et.al ,1964). High alkalinity indicates high concentration of alkalic elements.

The Hawaiian volcanic series is known to have a general trend changing from tholeiitic to alkalic, with less alkalic intensity and a larger intensity of tholeiitic eruptions. Clague and Cousens (2005) stated that the islands in this volcanic series typically go through three stages of development: the pre-shield stage (alkalic), the shield-building stage (tholeiitic), and the rejuvenation stage (alkalic). Of all these stages, tholeiites from the shield-building stage contributed the most to the ultimate volume of the volcanoes.

Sample and Method:

This project is based on datasets gathered from Earthchem (earthchem.org)

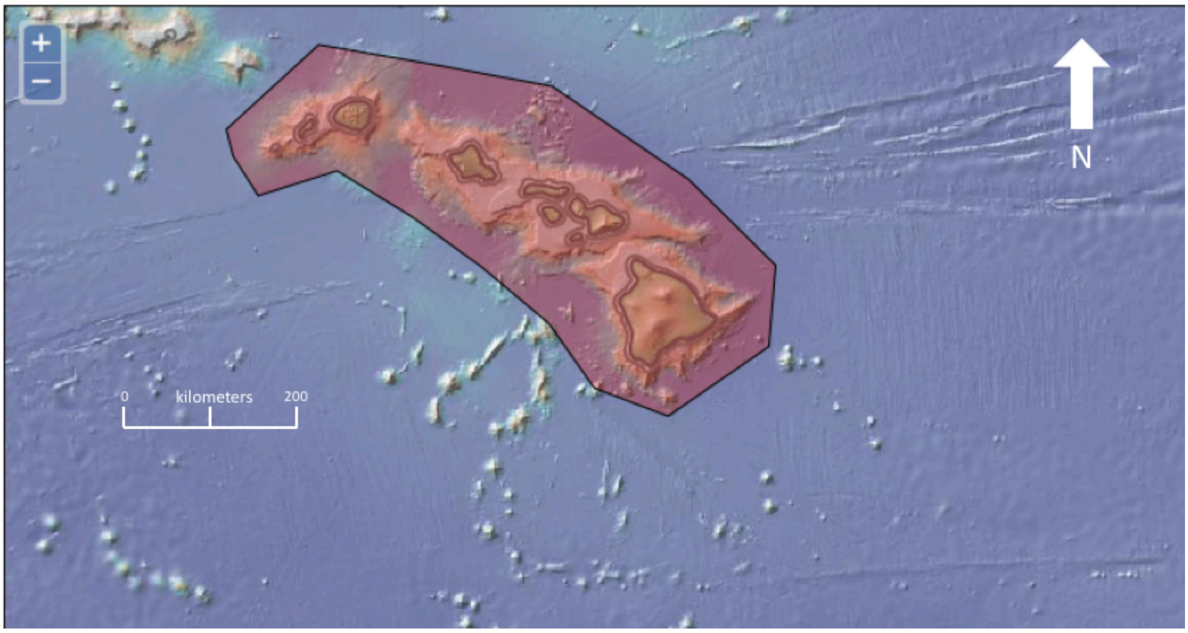

Figure 3. A map of the selected polygon (red) from Earthchem's data selection. The polygon covers the eight principle islands of the Hawaiian island chain. (Earthchem, 2018)

Samples within the polygon in Figure 3 were selected. The additional search queries were sample type, age, and material. The sample type was "igneous," the age was selected as "age exists," and the material was "whole-rock analysis."

The resulting dataset was insufficient for analysis due to lack of information, however, so some corrections were made. First, most samples in the original version had incorrect ages and locations. Some of the ages were negative, and a lot of the samples appeared to be from the same location. The negative ages were converted to positive ages because they were recorded as positive ages in the pages these data came from.

Besides having the wrong ages and locations, most of the samples did not have any age data at all. This could be due to an error in the Earthchem website, since people could have forgotten to enter this information. The missing information for the samples was filled in after consulting the corresponding papers, and data were eliminated if the necessary information could not be found.

The third problem in the data from Earthchem was that it sometimes included the wrong type of data. Some of the glass samples were entered into the database along with the whole rock in which they were found and therefore were eliminated from the data. About a hundred papers were consulted, and about 5000 data points were corrected in this process. In total, approximately 3000 negative ages were converted to positive and about 800 data points were eliminated.

About fifty percent of the data in this dataset was obtained indirectly from the USGS online dataset, so it was harder to obtain the age and location information than it would be to obtain from regular papers. The ages and accurate locations for the data had to be determined by looking at the names and locations listed in the additional information section of the relevant paper. For example, sample ID D102531 came from the Kiekie volcanic series, and its location was (21.96667, -160.11667). It can therefore be concluded that the sample came from the Kiekie vent, and, based on other papers, has an approximate age of 2.32 to 0.35 Ma (Cousens and Clague, 2015).

Data Analysis:

Two methods were used in analyzing the samples. In the first method, an animation was made to display the alkalinity of the samples. The second analytical method was the creation of a scatter plot of time vs. distance of the samples' alkalinity. Matlab was the numerical analytical tool for both methods.

An animation was made using Matlab in order to display the sample. It has four parameters: latitude, longitude, alkalinity and age. Latitude and longitude has a precision to 0.0001, and age and alkalinity each have a precision to 0.001. The age in the animation ranged from 5000 k.a. to present, with an increment of 20 k.a.. The animation was then split into 4 parts for a more detailed analysis.

The method provided by MacDonald et. al was used to analyze the alkalinity (1964). The rock's alkalinity was defined as the ratio of %(Na_2O +K_2O) versus the %SiO_2. In the MacDonald et. al diagram of alkalinity (1964), the alkalinity of the rocks was divided into two parts along the Hawaii trend line, with the alkalic rocks at the top and tholeiitic rocks at the bottom. From MacDonald's diagram, I calculated the trend line's equation by linear interpolation. The equation of the trend line was $y = 0.35x-13.5$, the alkalinity of each sample was calculated based on the trend line. Samples with an alkalinity higher than 13 were eliminated because the information for %SiO2 was not included.

The scatter plot was generated in Matlab as a time vs. distance graph. The time was the age of each sample, and the distance was computed by linear projection on Figure 4 as indicated below.

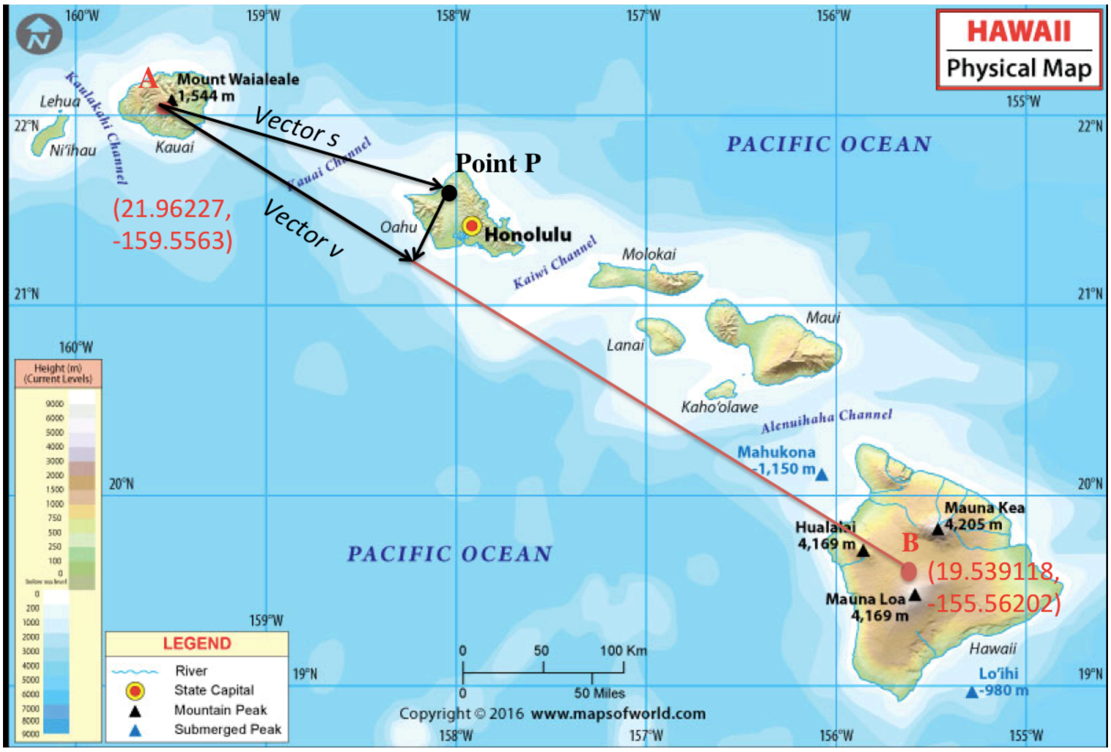

Figure 4: The reference line for linear projection (red). The red filled circles indicate the two reference points, point A and point B. The reference line AB for linear projection was plotted by connecting the two reference points, and then all samples were projected onto this reference line. For instance, point P is on the island of Kauai, and its vector with point A (vector s) was projected vertically onto line AB as vector v. The magnitude of vector v is the projected distance of point P. (Map: N.A. Afputra(Maps of USA), 2018)

In the projection, the two points on the reference line were point A (21.96277, -159.5563) and point B (19.539118, -155.56202) on the bottom right corner. The vector projected for each sample was computed by subtracting a reference point from their locations. The reference point was point A, in the top left corner. After the projection was calculated, the distance was obtained by calculating the magnitude of the projected vector. For instance, as shown on Figure 4, point P was projected vertically onto line AB. The vector *s* was projected onto line AB as vector *v*. The magnitude of vector *v* was then calculated as the 'distance' from point P to point A.

A scatter plot based on the age, distance and alkalinity of the samples was plotted after the age and distance data were obtained. The scatter plot is attached as Figure 5 below.

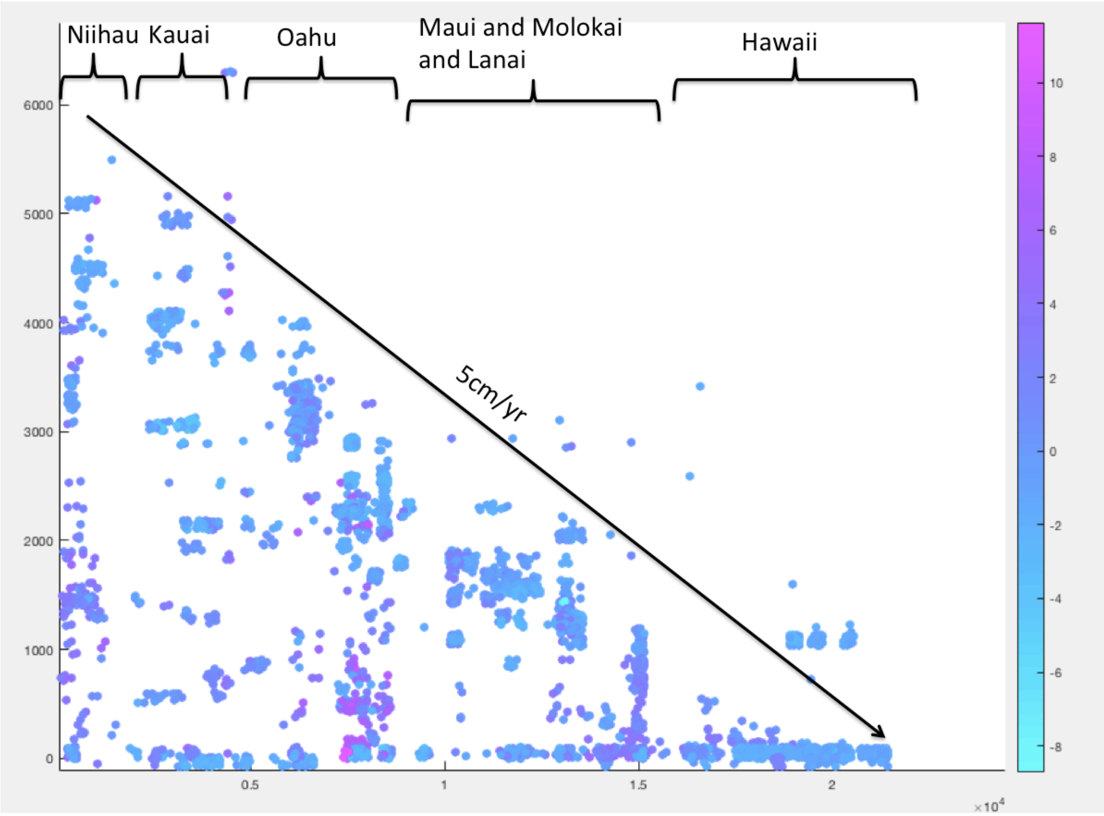

Figure 5. A space-time diagram of the alkalinity of Hawaiian basalt, showing the moving rate (the black line) of 5cm/year. The relative positions of the principle islands are labeled on top of the plot. The color scale is on the right. Samples with high alkalic composition are shown as purple dots, and high tholeiitic composition are shown as blue dots.

Data:

The animation shows a trend of alkalinity changing from tholeiitic to alkalinic as time goes on. Tholeiitic lavas started forming on the islands of Niihau and Kauai from 5000 k.a. to 4000 k.a. Alkalic lavas erupted from Mt. Wai'ale'ale and other smaller volcanoes on Kauai around 4700 k.a., when there was a low eruption intensity. There were more tholeiitic eruptions along the adjacent flanks between Oahu and Kauai after 4200 k.a., and the rate of lava accumulation started to increase rapidly.

From 4000 k.a. to 2000 k.a., volcanic activity stared to expand to the islands of Oahu, Maui and Molokai. Oahu had the most volcanic activity and erupted mostly tholeiitic lavas. Older islands, such as Kauai and Niihau, began to erupt alkalic and depleted lavas, whereas the Mt. Wai’ale’ale and Koloa volcanic series were some of the most active volcano series on Kauai.

From 2000 k.a. to 1000 k.a., the center of volcanic activity had shifted to the islands of Molokai and Maui, with the volcanic series from Molokai erupting a large amount of tholeiitic lavas. Alkalic lavas began to erupt from volcanoes on Oahu, and older islands like Kauai began to produce more depleted lavas. This is especially true of the Kola volcanic series on the flank of Kauai’s southeast coast.

More alkalic lavas have erupted from the islands of Oahu, Molokai and Maui from 1000 k.a. to the present, and the alkalinity has also increased. The main island of Hawaii started to have volcanic activity around 500 k.a. The lavas that erupted on the island were mainly tholeiitic, but there were also some alkalic lavas with a low alkalinity on the northwest side of the island. Around 560 k.a., older islands like Niihau and Kauai once again erupted lavas with an alkalic composition. Highly alkalic lavas also erupted from the Southeast side of Oahu and between the islands of Oahu and Kauai.

The scatter plot shows a general trend in the data from tholeiitic to alkalic and also shows that the data form a triangular shape. The ‘cool’ color map was used for the scatter plot, so a bluer color indicates a more tholeiitic concentration and a pinker color indicates a more alkalic concentration. The slope of the curve matches the Hawaii hot-spot rate of 5-10 cm/year. The data represented in this diagram were mainly tholeiitic. Islands like Niihau and Koolau had particularly young, alkalic lavas from around 70 to 80 k.a., and the main island Hawaii has young alkalic lavas that erupted around 400 k.a. to 300 k.a. and erupted some highly transitional tholeiites or basanites with a large amount of uniformly alkalic basalt.

Discussion

The model was consistent with the general theory about Hawaii that Hawaiian volcanoes eruption changes to more tholeiitic. Clague and Dalrymple stated that the length of mean shield building stage for most of the volcanoes in Hawaii is 1-2 million years (1987), and both Figure 5 and the animation agree with this statement by having a majority of tholeiites in eruption.

The animation shows that Kahoolawe, a volcano on one of the older islands, went from producing tholeiitic lavas to producing alkalic lavas. This transformation confirms what Leeman and others discovered in 1992: Leeman et al. (1992) stated that the Kahoolawe shield volcano produced both pre-caldera and caldera-filling tholeiites in its shield building stage and then produced alkalic post-shield lavas.

Not all volcanoes showed the general trend of transitioning from tholeiitic to alkalic lavas. The first such anomaly is that young alkalic lava erupted from older islands such as Niihau and Kauai around 300 k.a. to 500 k.a. It is unusual that these alkalic lavas erupted so recently. The second anomaly is the large amount of alkalic lava that erupted from volcanoes on Hawaii when they were still relatively young.

The first anomaly took place on older islands such as Kauai, Oahu, Niihau and Molokai. The Matlab animation shows that volcanoes from these islands were a lot more active than regular volcanoes. Figure 5 shows a small amount of alkalic samples (pink spots) underneath tholeiitic samples (blue spots) from between 300 k.a. and 400 k.a. This apparent anomaly was actually the rejuvenation stage. According to Cousens and Clague (2015), the Honolulu Group from Oahu, the Kiekie Volcanics on Niihau, the Koloa Volcanics on Kauai, the Lahaina Volcanics, and Hana Groups on Maui all underwent rejuvenation stages. Molokai, for example, is shown in the animation as having a high intensity of data points during its rejuvenation stage. The eruptive products of the post-erosional stage in Molokai came from two main vents: a northern vent on the Kalaupapa Peninsula and a tuff cone off the east coast of Molokai (Cousens and Clague, 2015). Chen and his team proved that the samples from these two vents have an age of around 344 k.a. with an uncertainty around 28 k.a. and stated that Molokai underwent a rejuvenation stage. This project therefore confirms the findings of others who studied the island of Molokai.

According to the animation and the scatter plot in Figure 5, Niihau also underwent a rejuvenation stage. The volcanic series on Niihau appear to have been active at around 0.52 Ma to 0.3 Ma. The Kiekie Volcanic series on Niihau is one of the volcanoes series that had a post-erosional volcanic stage. Cousens and Clague (2015) stated that the Kiekie volcanic series was active between

2300 k.a. and 300 k.a. and erupted a large amount of uniformly alkalic basalt. The Matlab model matches these claims and therefore confirms others' findings about Niihau as well.

The second anomaly in the dataset is the large amount of alkalic lava that erupted in Hawaii from 400 k.a to the present. The animation shows that these young, alkalic magmas were spread out on the northwest side of the main island. Although these lavas might appear to be an anomaly, they are actually not a mistake in the dataset: most volcanoes on the island of Hawaii are currently in their pre-shield stage. The lavas from the preshield-stage were alkalic because the magma-transport system was still nascent and because of the low degree of melting at the edge of the mantle plume (Clague and Sherrod, 2014). Among all of the island's volcanoes, Loihi typifies the pre-shield stage of Hawaiian volcanism because it is closer to the Hawaiian hotspot. Loihi shows a transition from alkalic to tholeiitic volcanism that is nearly complete (Gracia et al. 1995). Besides Loihi, the scatter plot shows that the volcano Kilauea also had a pre-shield stage. Kilauea also erupted alkalic lavas because it shared the same parental magmas with Loihi (Gracia et.al., 1998) and had a composition identical to that of Loihi. Samples from Hawaii Scientific Drilling Project shows that Mauna Kea also had a pre-shield stage (Gracia et al., 1998). Thus, alkalic lavas that erupted Mauna Kea, Kilauea, and Loihi together emplace around 95% to 98% of the total mass and volume of Hawaii (Gracia et al., 1998).

Besides the stages of volcanic development, the animation also shows the difference between the Loa trend and the Kea trend's volcanic activities. The Kea trend appears to have more volcanoes rejuvenation stage, and the Loa trend' volcanoes appears to be less active. Volcanoes, such as

Haleakala in the Kea trend, are shown by the animation to be in the rejuvenation stage because they are erupting depleted lavas at young age. On the other hand, the Loa trend appears to be more stable and tholeiitic. The alkalic lavas from Loa trend also show a lower alkalinity than the alkalinity of the alkalic lavas from the Kea trend, indicating that the lavas from the Loa trend are less depleted than the lavas from the Kea trend. This finding agrees with other papers that focus on the Loa and Kea trends. Xu et al. (2005) discovered that the volcanoes in the Kea trend had more rejuvenation stages. By having more volcanoes with rejuvenation stages, the Kea trend had more frequent transitions between tholeiitic lavas and alkalic lavas. The animation and scatter plot in this paper therefore support the general conclusion about the two trends that the Kea trend has more rejuvenation stage.

The animation and scatter plot both show that the Hawaiian volcanic series is more alkalic than it is tholeiitic. The animation also indicates that several of the volcanoes underwent a pre-shield stage and a rejuvenation stage and is therefore in accordance with other studies that have been conducted on the volcanoes The animation also shows that Kea trend volcanoes have been more active than Loa trend volcanoes in recent times. These successes ultimately prove that animation is an effective tool that can be used for future studies in geology.

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