

Investigation of lava flow morphology using a sub-bottom profiler

in the North Arch Volcanic Field

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3/11/2022

Abstract

Located 100 km north of Oahu and over four kilometers of water, the North Arch Volcanic Field covers an area of 25,000 km² and includes the longest known underwater lava flow. There have been a few previous studies of the area, but overall, the volcanic field is not well understood. Further classification the flow morphology of these lava flows can contribute to the understanding of the history of volcanism within the area, as well as marine effusive lava flows. A transect was mapped within the southernmost part of the field using 30 kHz EM302 multibeam echosounder and 3.5 kHz Knudsen echosounders aboard the R/V Thomas G. Thompson. These surveys yielded a high-resolution bathymetric map and sub-bottom profiles that image shallow structures beneath the ship's track. The seafloor is 300 meters shallower within the northern parts of the study area, as the transect moved onto the Hawaiian Arch. The lava flows here are more extensive and presumably closer to the eruptive source. Through the analysis of the Knudsen data, 29 lava flow crossings were found that vary in width and height. The lava flows have complex flow morphology, including different boundary structure, sediment pockets, and complex flow paths and elevation changes. There are two main areas of flows within the southern part of the study site with differing characteristics that may be related to the lava viscosity. The lava field is more variable than expected, which suggests that even in the small region sampled, it was formed by several effusive events over a period that had lava with different chemical properties.

Plain Language Summary

Volcanic hazards are a threat to humans all over the world, and better understanding of past eruptions can mitigate these risks. A study was done 100 km north of Oahu, Hawaii on the North Arch Volcanic Field, which has the longest lava flows in the world, to further scientific understanding about underwater volcanic eruptions. The southern portion was mapped to further understand the behavior and nature of this underwater eruption and the interactions between the lava and the existing seafloor sediments. On a research vessel, two sensors were used to map the area. These sensors create a sound pulse that travels through the water until it reaches the bottom of the ocean, where the sound is reflected to the sensor, which can hear the return and calculate the distance that the sound traveled. One sensor measures the first reflection to calculate the depth of the water, while the other takes measurements within the seafloor to reveal different features of the seafloor sediments or rocks. These two sensors made a map of the depth and of the different material that makes up the ground right below the ship. This map showed that towards the north the seafloor got shallower and had more lava flows, which most likely shows that the source of the lava is to the north. In comparing the different material, 29 lava flow crossings were found that had different structures and landforms. There are two main areas of flows within the southern part of the study site with differing characteristics that may be related to the lava viscosity, which is how easily a liquid can flow. Some of the variation is seen in differing widths and heights, sediment pockets within the lava flows, and complex flow paths. The lava flows that were found are more variable than expected, which suggests that, even in the small region sampled, it was formed by several eruptions over a period time that had lava with different chemical properties.

Introduction

Volcanism is fundamental in the creation of rocky planets like Earth and plays an integral part in controlling climate (Robock, 2000; Rothery, 2010). Continental and oceanic crust are created through the process of volcanism in different plate boundaries or hot spots, allowing for the hypsographic divide that results in large, deep ocean basins and dry land. Volcanic gases play a key role in climate through the release of greenhouse gases such as carbon dioxide and sulfur dioxide. Over geologic timescales, volcanism and mid-ocean ridge systems act as the major source of CO₂ into the atmosphere (Robock, 2000). Conversely, on short timescales, volcanic gases cause cooling on the planet due to sulfur dioxide converting into sulfuric acid, which acts as an aerosol that reflects significant amounts of solar radiation (Robock, 2000). Volcanoes are also one of the most significant geologic hazards. While underwater eruptions may not pose the same threat as continental volcanoes, three-quarters of volcanic eruptions, both effusive and eruptive, are in the deep sea (Helo, 2016). It has also been proposed that large-scale, underwater volcanic activity could alter ocean circulation due to the release of a significant amount of heat, and in turn create climate anomalies (Shaw and Moore, 1988). Since underwater eruptions are usually under several thousand meters of water, they are not well classified and have rarely been observed. However, it has become clear that the general spectrum of eruptions is similar between oceanic and continental volcanoes. Therefore, researching specific eruptive events, like those at the North Arch Volcanic Field, allows for better understanding of all eruptive events.

The North Arch is part of a complex hot spot system that formed the Hawaiian Island chain. While most volcanic activity in the ocean occurs at mid-ocean ridges (Crisp, 1984), a significant amount is due to hot spot activity, such as Hawaii. The Hawaiian Island chain was formed by hot spot activity under the Pacific plate. The Pacific plate below Hawaii is

approximately 80 Ma with the oldest island rocks being younger than 1 Ma (Holcomb et al., 1988). Each island was created by the formation of shield volcanos due to the hot spot being directly underneath creating volcanism. As the Pacific plate moved northwest, the hot spot and subsequent volcanism moved further south creating the next island in the chain. This creates the pattern of older rocks on the Northern islands, with the youngest island being Hawaii in the south. The weight of the island chain caused significant subsidence of the underlying plate creating the Hawaiian Trough and the Arch (Fig. 1) surrounding the islands (Moore, 1989). On the Arch, there are two volcanic fields, the North and South Arch Volcanic Fields, with significant eruptive lava flows.

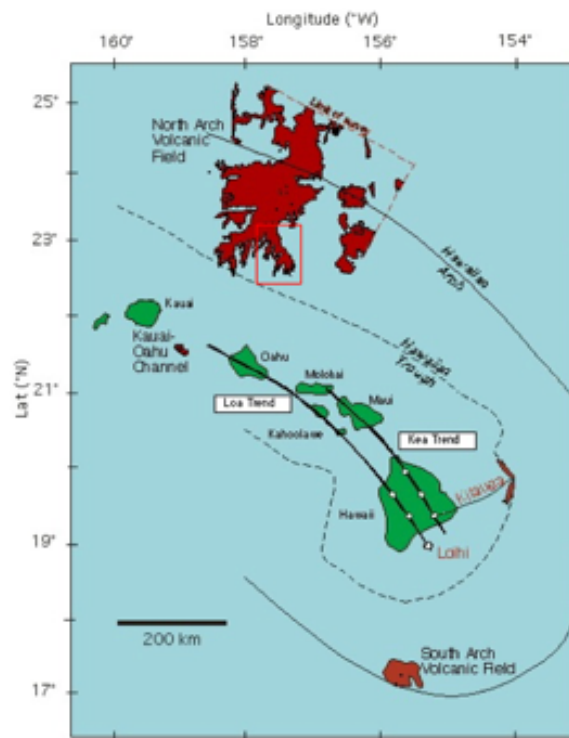


Figure 1. Map of the Hawaiian Island Chain, the Hawaiian Trough, and the North and South Arch Volcanic Fields (Monterey Bay Aquarium Research Institute, 2001). The mapping location is indicated by the red box. Note: This figure is in a different coordinate system than the rest of the maps in this paper.

The age range of the volcanism at the North Arch Volcanic Field has a large span as there is evidence of multiple, distinct volcanic events starting around 2.7 Ma and ending with the most recent events between 0.5 to 1.6 Ma (Wallin, 1982 and Clague et al., 2002). The nature of the volcanic field was proposed by Yamamoto and Phipps Morgan (2009) to be part of the restite-root hypothesis about the origin of the Hawaiian hotspot. This hypothesis for the formation is based on the idea of viscosity of the upwelling hot spot and fracture zones created by spreading and thinning of the lithosphere (Yamamoto and Phipps Morgan, 2009). An alternate hypothesis for the distinct volcanism is the upwelling mantle erodes the base of the lithosphere causing different thicknesses of the lithosphere and making volcanic activity asymmetrical (Ballmer et al., 2011). This allows for small-scale convection of the lithosphere and the potential for decompression melting.

The North Arch Volcanic Field is located 100 km north of Oahu and covers around 25,000 km² of the seafloor on the flexural arch of Hawaii (Fig. 1) making it the longest known underwater lava flow excluding the mid-ocean ridge systems (Clague et al., 1989). Originally it was proposed by Menard (1964) that there could be melt in the Hawaii Arch. It was not until deep-tow surveys were done in the area that young lava flows were discovered in the North Arch Volcanic Field (Normark and Shor, 1968; Spiess et al., 1969). Evidence of the volcanic field was also presented by Wallin (1982) who described widespread volcanic activity on the northern arch. The volcanic activity was seen in shallow seismic reflectors between 5 and 30 meters into the sediment at the transition between the lava flows and the sediment as there is an abrupt edge at the margin of the flows (Wallin, 1982). Following this study, GLORIA (Geologic Long Range Inclined Asdic), a side-scan sonar system, mapped most of the lava field on a survey of the

Hawaiian Exclusive Economic Zone in 1986 (Holcomb et al., 1988). However, the maps created only show the relative roughness of the seafloor, so it is not a clear bathymetric map of the area.

In an unpublished master's thesis, Wallin (1982) used seismic reflection profiles which showed that the North Arch Volcanic Field is a distinct, relatively young volcanic feature. Using seismic reflection profiles and 3.5 kHz echograms to examine shallow crustal structures in the field, it was shown that the Musicians Seamounts, a chain of volcanoes north of the Hawaiian Ridge, is not the cause of the volcanic field due to the small amount of sediment on the features. Earlier work was done with seismic reflection profiles and 3.5-kHz echograms which gave a clear picture of areas with little sediment cover and a rough texture (Normark and Shor, 1968). Interpretation of the seismic profiles show evidence of extruded lava on the sediment surface as well as intruded lava within the sediment column (Spiess et al., 1968). Mapping the area using GLORIA allowed for an understanding of the massive extent of the volcanic field. The highest resolution maps have been created using SeaBeam 2100 mapping and allowed for individual features to be identified (Clague et al., 2002). Volcanic features in the area that have been identified include low shields, small summit craters, effusive lava flows, and more than 100 vent structures (Clague et al., 2002). Due to the large spatial extent of the field, there are no high-resolution multibeam maps of most of the area.

Direct samples of the volcanic rocks and sediments have been taken using cores and drilling. In Clague et al. (1989), piston and gravity cores and dredges were used to get samples of the seafloor. The samples showed a variety of ages of the lava flows, making it clear that distinct events of volcanism occurred (Clague et al., 1989). The igneous rocks tend to be alkalic basalts to nephelinite that are chemically like lavas on Kauai and Oahu (Clague et al., 1989). Using these samples' age ranges have been estimated for the different eruptive events, with volcanism

beginning during the late Pliocene and continuing into the Pleistocene (Clague et al., 1989). The rock samples' petrology was further investigated in Frey et al. (2000). The lavas most likely originate from an olivine-rich source due to the abundance of scandium, chromium, cobalt, nickel, and zinc, while they may be somewhat derived from unaltered oceanic lithosphere, it is not the only source (Frey et al., 2000). The origin of the lavas is likely a combination of the Hawaiian plume and oceanic lithosphere, both altered and unaltered (Frey et al., 2000). While there have been previous studies on the North Arch Volcanic Field, many basic and important questions about the site are still unanswered or debated, such as the location of eruptive vents and the eruptive and emplacement mechanism of the lava flows (Clague et al., 2002).

I propose to test the hypothesis that the Knudsen sub-bottom profiles will reveal characteristics of the lava flows and their boundaries. These differences could be due to different chemical properties that affect viscosity, the slope of the seafloor, or obstacles that limit flow. Additionally, the margins between erupted lava flow and sediment will be visible in the sub-bottom profiles. The lava flows will show up as areas with faster sound velocities, meaning a greater reflection in the sub-bottom profile. Since basaltic eruptions would be denser than the overlying submarine sediments, it would make sense that there are a significant number of igneous rocks below the sediment surface in the form of sills as seen in Wallin (1982). Using multibeam bathymetry and sub-bottom profile data, I will investigate the extent of an effusive lava flow in the North Arch Volcanic Field to find lava flows and proposed sills of lava under the sediment surface. There is the potential for other areas where the lava did not reach the sediment surface. The sills would show up in the sub-bottom profiler as denser, as well as create shallower areas due to the lava pushing sediments up. The presence and volume of these features will further the understanding of the behavior and nature of underwater eruptions and their

interactions with seafloor sediments. Since underwater volcanic eruptions are often hidden from the scientific world, the behavior of underwater eruptive fissures is relatively unknown.

Understanding the deposits of past lava flows will help understand the nature of underwater lava flows, and how they interact both with the seawater and the sediments.

Methods

Mapping for this study took place on the R/V Thomas G. Thompson from 1200 on December 19 until 0830 December 20 UTC. The area mapped was in the southernmost part of the North Arch Volcanic Field between 22°N 51' and 23°N 40' and -155°W 56' and -157°W 95' in UTM 4N. The survey plan (Fig. 2) followed a hypothesized fissure from Clague et al. (2002). The transect was designed to optimize the number of flow boundaries crossed based on the proposed lava flow (Clague et al. 2002), as this would allow for many boundaries between sediment and lava to be seen. Due to the less than favorable weather conditions, the ship had to maintain a lower speed than initially planned, from four to six knots, therefore reducing the mapped area by almost half. The Kongsberg EM302 Multibeam Echo Sounder mapping at 30 kHz and the Knudsen 3.5 kHz sub-bottom profiler were used to generate the multibeam and sub-bottom profiles, respectively.

The processing of the raw multibeam data was done using Seafloor Information System (SIS) and Caris with adjustments made for tides using TXPO tide model and sound velocity measured using Expendable Bathythermographs (XBTs). Analysis of the sub-bottom profile and multibeam data was done using code written in MATLAB. The code plotted individual profiles for visual examination of the surfaces and boundaries between the lava and sediment (Fig. 3). Lava flow location was determined by examining the sub-bottom profile and comparison with

bathymetry. Each lava crossing was classified by height, roughness, and boundaries type, including the lava intrusion into the sediment and the angle between the lava and sediment surface. These lava flows were then plotted onto the track line on the bathymetry map, and individual sections on this map were analyzed at different depth ranges, and the slope over the proposed lava flow area was calculated.

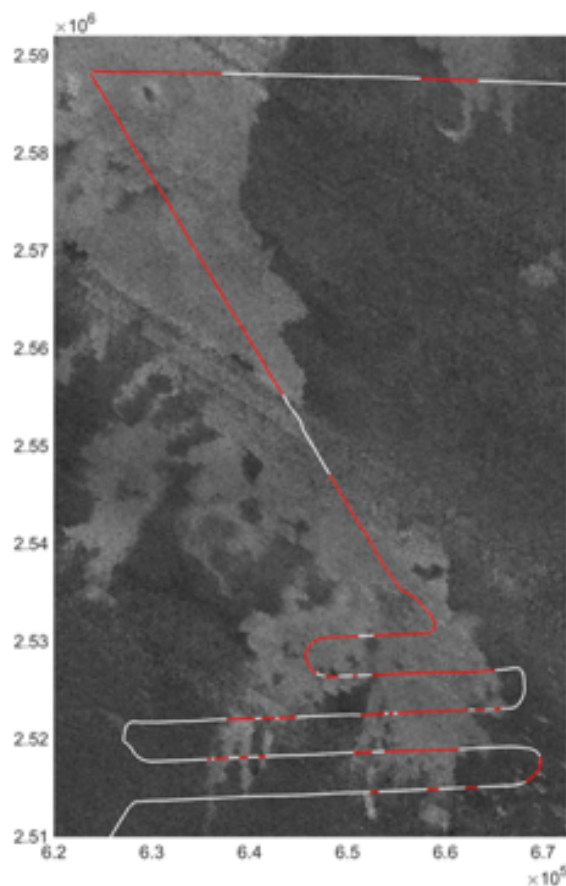


Figure 2. Survey lines on GLORIA image of an inferred eruptive fissure from Clague et al. (2002). Darker grey indicates areas of that are flat, while lighter grey shows areas with greater roughness. Axes are in UTM x/y, meters. Lava flows found in study are in red, while areas with sediment are shown in white.

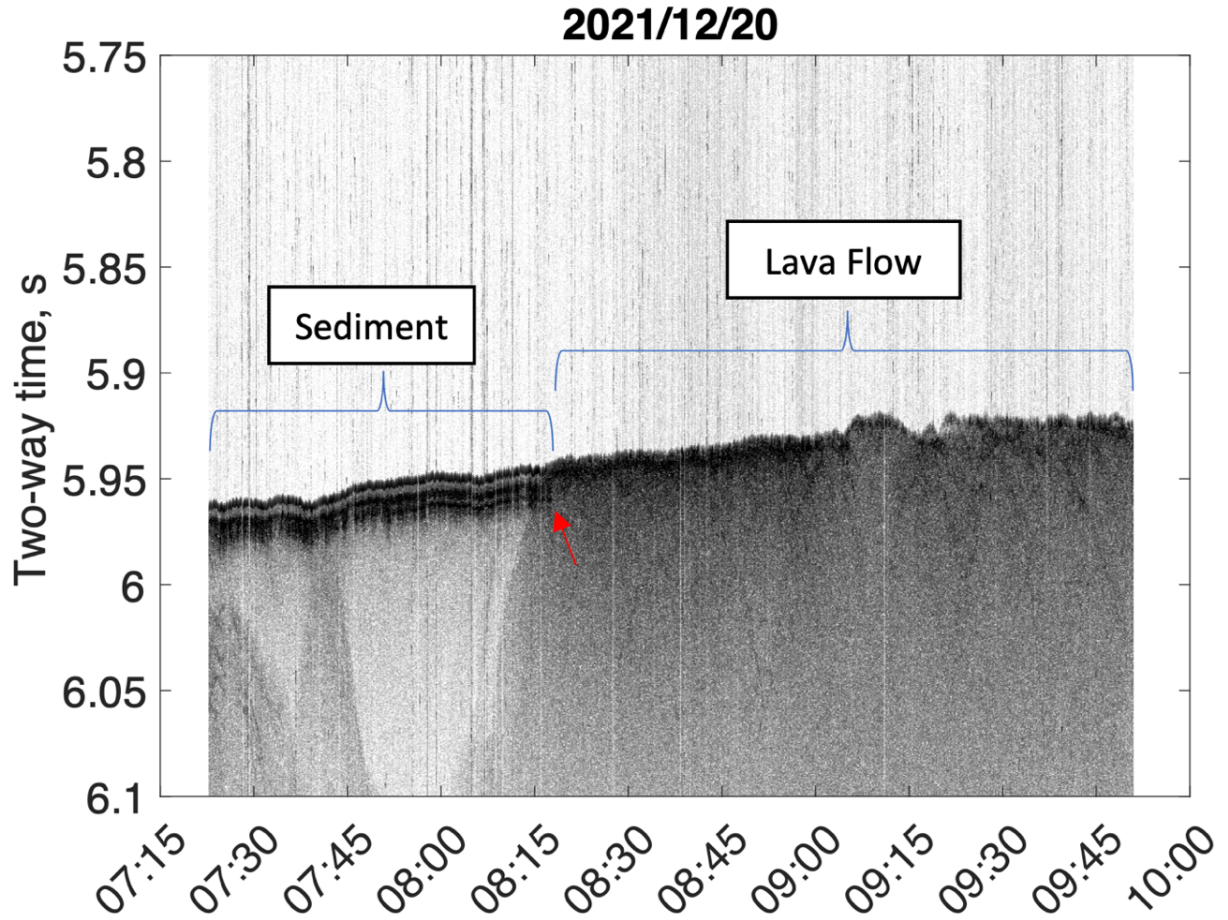


Figure 3. Image from Knudsen 3.5 kHz and 12 kHz sub-bottom profiler that shows both sediment and lava flow due to a difference in reflection. Sediment layers make up the left side of the map with lava flows on the right. The red arrow points to the margin between lava flow and sediment. Two-way time in seconds denotes depth as sound must travel up and down the water column.

Results

Bathymetry decreased northward, with a change of 300 meters, as sampling moved closer to the crest of the arch with depths ranging from 4300 to 4700 meters (Fig. 4). There were distinct seamount features seen in the bathymetry, mainly concentrated in the southeastern part of the survey, that are possibly related to the Musician Seamounts. The lava flows determined using the sub-bottom profiles, are from the path directly underneath the track line of the vessel. However, the flows were not clearly visible on the bathymetry map, which limits the understanding of the flow path. Comparing the flows to the GLORIA map (Clague et al., 2002) the lava flows clearly line with the areas of high backscatter (Fig. 2).

The sub-bottom profile data shows 29 individual lava flows within the mapped area. The lava flows are indicated where sediment meets lava as the lava flows have a greater reflection with a dark color that is consistent with depth. The sediments show clear layering, while the flows appear as a single unit of reflectance (Fig. 3). Within the sub-bottom profiles there was no evidence of sub-surface lava flows or sills, although the deepest profiles were able to only image approximately 25 meters into the seafloor. The lava flows have complex flow morphology with many distinct features that are not easily categorized. The flows vary in width, height, and overall roughness. There are various boundaries when they meet the sediment, however there are no distinct types of boundaries. The boundaries are mainly sloped or angled with some being curved. Mapping the flows on the bathymetry map show the flows fit into two distinct areas with a flow in the east and the western side of the study site (Fig. 5). Grouping the lava flows into these categories, the eastern lava flows (Fig. 6) are characterized by more roughness and bigger depth variations, while the western flows (Fig. 7), have a smaller change in depth and are less rough. The regional gradient of slope over the east lava flow is 0.5° , with the west being 0.6° .

These slopes are negligibly different and are caused by transition from the Hawaiian Trough to the Hawaiian Arch.

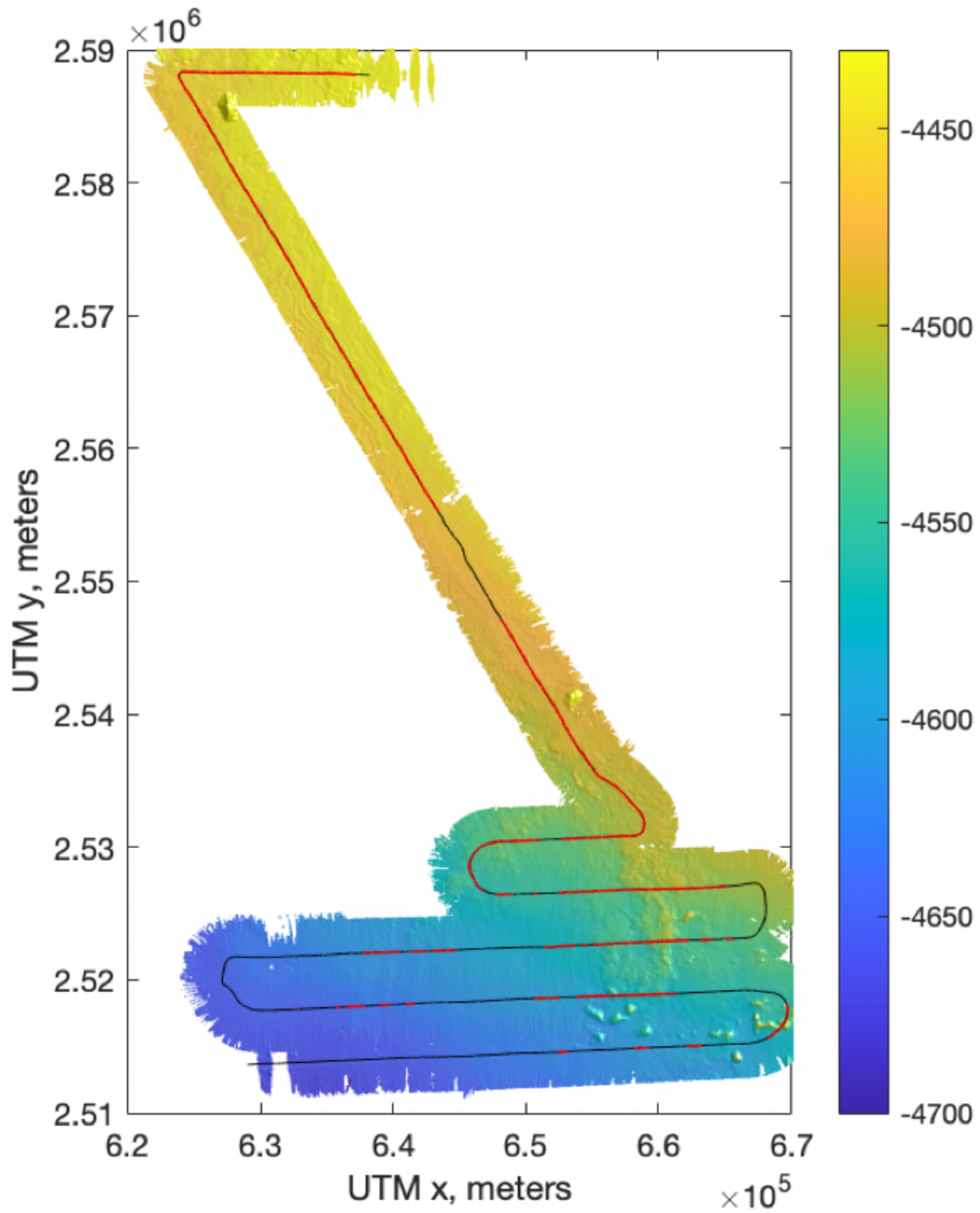


Figure 4. Bathymetric map of the study site in UTM 4N. The track line of the ship with the red line representing lava flows and the black being areas over sediment. Color bar represents the depth of the water in meters.

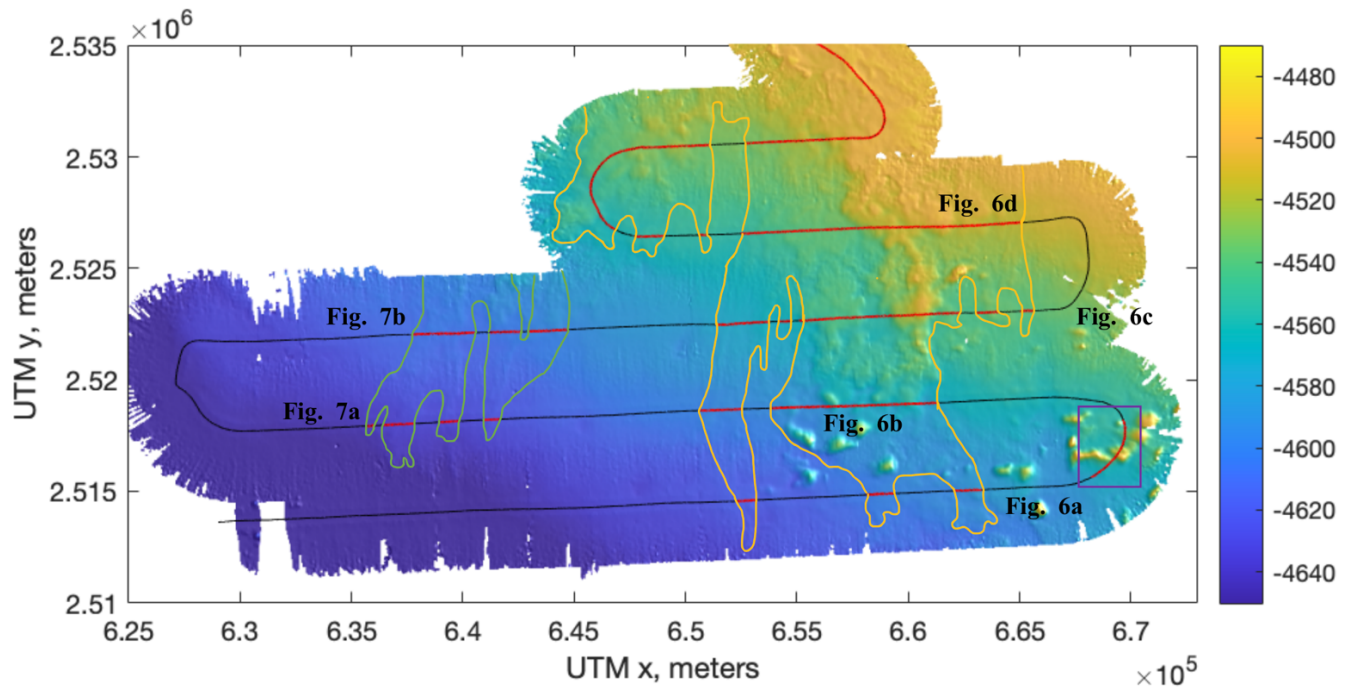


Figure 5. *Interpreted lava flow paths based on Knudsen and Multibeam data. The eastern lava flow is drawn in yellow and the western in green. The purple box represents the seamount that is most likely part of an older flow events, possibly part of the Musician Seamount Chain.*

The eastern lava flows are characterized by more roughness and greater depth variations, even the sediment is not as flat in the eastern portion of the map (Fig. 6). The flows extend over a longer area under the track line, especially further north (Fig. 6a, b, c). Diffraction hyperbolas are present within the surveys, which present near the lava flows themselves (Fig. 6b and c). The most distinct boundaries are small sediment pockets (Fig. 6d) that appear to have lava underneath based on the greater reflection below the sediment. Generally, sediment layers absorb the reflection leading to a lighter grey underneath within the profile, but these sediment pockets

have the darker color under them like lava flows. Additionally, the flow denoted by the purple box, along the first eastern curve, falls outside the proposed flow morphology (Fig. 7). This feature has distinct characteristics in the sub-bottom profile as seen with a pile of sediment near the edges of the flow and a significant amount of diffraction hyperbolas (Fig. 6a).

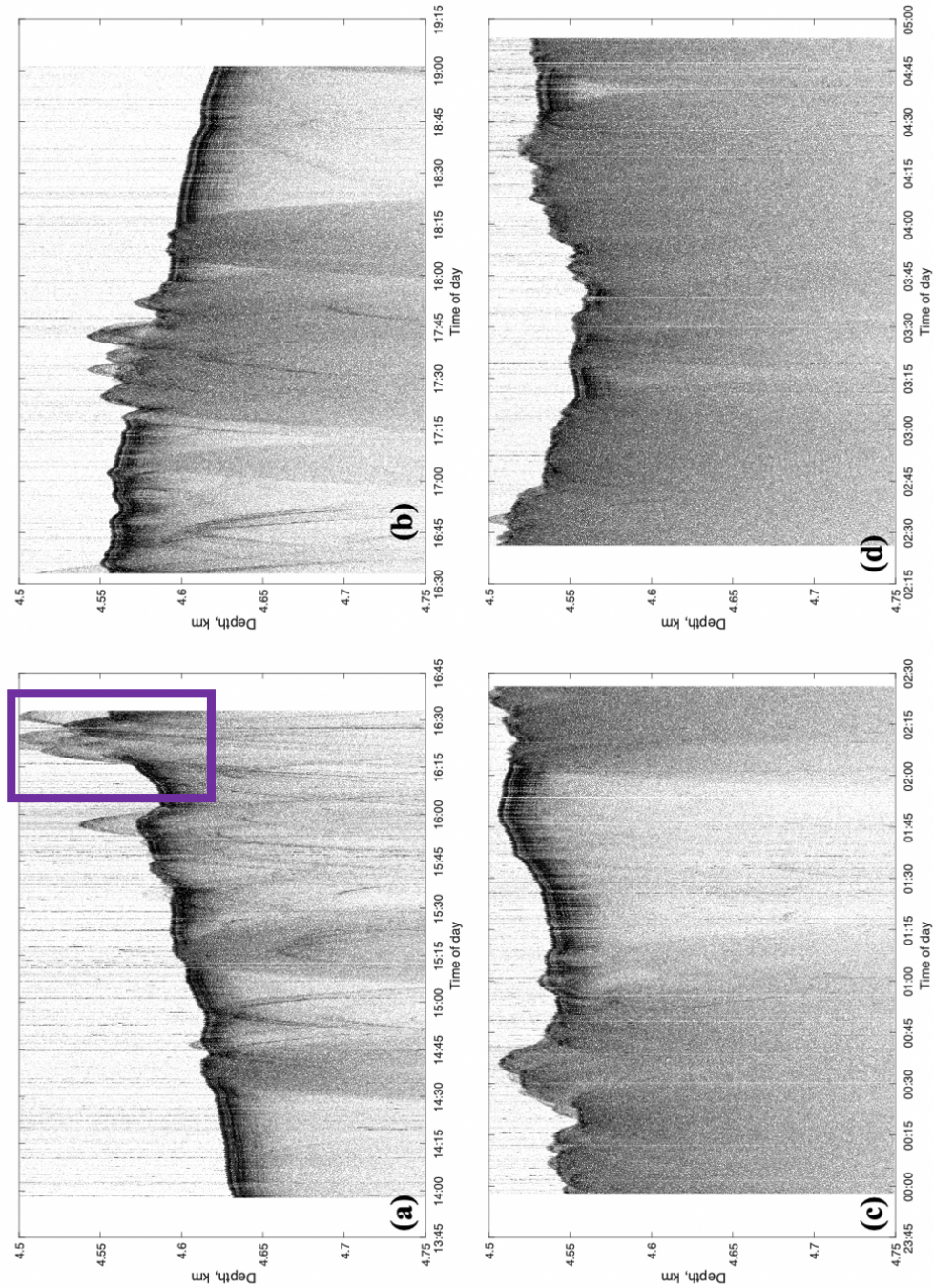


Figure 6. Sub-bottom profiles from the western lava flows with x-axis representing the time of the survey and y-axis showing depth in kilometers. (a) The lava flows in southern track line of the western flow and (b) the northern track line of the western flow with the final lava flow being the start of an eastern lava flow.

On the western side of the survey area, the lava flows tend to be smoother with less overall change in depth (Fig. 7). There is a greater number of shorter flows within a smaller area present in the south flows in the west compared to the east (Fig. 7a). These flows are fairly interspersed with sediment separating them and each with an arch of lava that extends higher than the sediment (Fig. 7a). The northern part of this flow has slightly rougher lava flows that extend longer as well (Fig. 7b). There are no large features or seamounts within the western part of the map (Fig. 5).

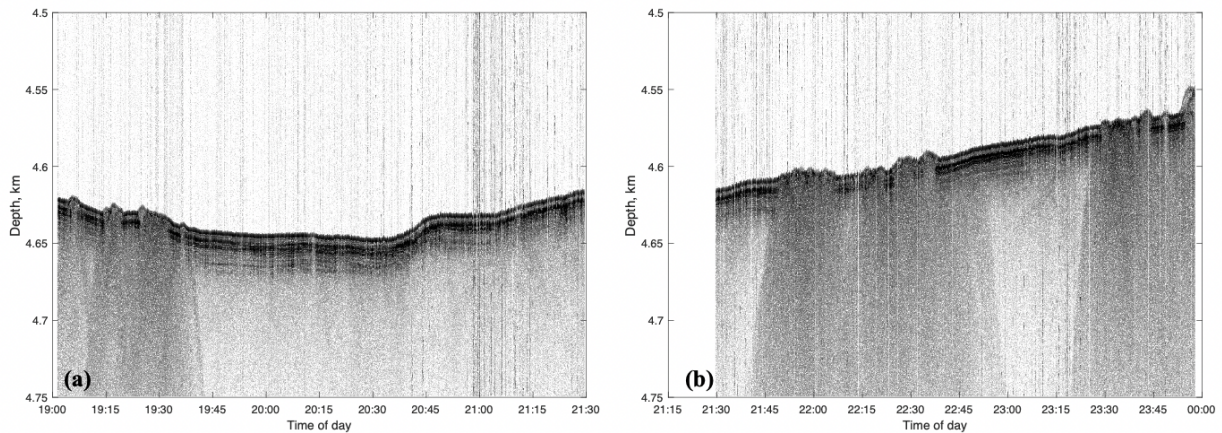


Figure 7. Sub-bottom profiles from the western lava flows with x-axis representing the time of the survey and y-axis showing depth in kilometers. (a) The lava flows in southern track line of the western flow and (b) the northern track line of the western flow with the final lava flow being the start of an eastern lava flow.

Discussion

The two distinct lava flows are characterized by different flow morphologies, with the east being rougher, with greater elevation changes, and sediment pockets. While the western flows tend towards the opposite, with less roughness and changes in elevation, which break up

into several narrow flows that are not due to obvious obstructions. The areas in the east show more diffraction hyperbolas (Fig. 6b), which are evidence of a rough and irregular surface (Wallin, 1982). These factors contribute to the idea that the eastern flow has some different properties than the western flow. Slope angle and viscosity both contribute and impact the length and morphology of a lava flow (Miyamoto and Sasaki, 1998). The difference in slope between the two areas is 0.1° , so it may have very slight impacts in creating different morphologies, but it is not the major cause. Another possible explanation for this is the larger number of features and seamounts in the eastern part of the site. The flows may have behaved in this fashion due to ponding behind obstructions, like these older seamounts. However, the flows make it beyond these points and still behave differently from the western flows (Fig. 7), so this is also not likely the main factor.

The factor that likely causes the different flow morphologies is chemical properties that could cause variations in viscosity. A lower viscosity would allow for the western lava flows to be smoother and spread out, while the eastern flow could have had a higher viscosity which would allow it to be rougher and more irregular. Additionally, this could account for the greater amounts of diffraction hyperbolas seen in the eastern flows, as the surrounding area would be rougher as well. Due to the limited area of the study site, the origins of the two flows are unknown and so are their travel distances. There are many factors that could impact the morphology of the two distinct flows, but viscosity is likely one of the major controls. This contradicts the idea in Clague et al. (2002), as this feature was one eruptive fissure. However, it matches the idea of the field being formed over a broad range with many flow events.

The flow paths of the eastern and western flows are based on the lava flow locations and bathymetry (Fig. 5). Based on the known location of the flows, the lava breaks up into smaller,

less rough flows as it moves farther away from the eruptive source. The bathymetry can show some patterns of the lava flows between the track lines, however having a closer spacing between track lines would allow for a better image of the flow path. Due to the lack of information in drawing the flow paths, it is possible that these two determined flows could be composed of overlapping flows as well.

The decreasing depth to the north is due to slope of the Hawaiian Arch, which caused these two lava flows to move downslope. As well as these lava flows, there are many seamount features seen in the bathymetry. Only one of the features was captured by the sub-bottom profile (Fig. 6a). The sediment near the edges seemed to have been built up over a longer period than the almost non-existent sediment on the other flows. These layers onlap and slope up on the sides of topographic highs. Due to the slope of the feature and remobilization due to currents, the sediment was deposited but slid down into a sediment pile near the edge of seamount feature. The greater amount of diffraction hyperbolas shows that the area right around the lava is much rougher. The feature seen on the farthest east of the study site (Fig. 5 and Fig. 6a) in the purple box, and it is most likely an older seamount, maybe related to the Musician Seamount Chain (Smith et al., 2018; Wallin, 1982) from the late Craterous.

While the high-resolution multibeam map gave a clearer image of the seafloor than there has ever been, it was not able to show much information about the flow locations or morphologies. The sub-bottom profile data was necessary to determine the precise location of lava flows, as it was difficult to see using the bathymetry alone. This could be due to less-than-ideal weather conditions during mapping that caused more movement of the vessel and required a slower mapping speed, however due to the clear difference in lava and sediment the sub-bottom profile data is far superior. Initially, the sub-bottom profiles were going to be used to find

sub-surface flows but, there were none present along the track lines. The hypothesized sub-surface flows could have been deeper than expected, or the flows that were seen could have a source further away and there was no lava below the surface in this area. Based on the appearance of sediment pockets with greater reflection beneath them (Fig. 6d), the sub-bottom profiler was able to detect lava beneath sediments. It would be useful to have a higher powered sub-bottom profiler for deeper sills. Lava sills would most likely be present near the source of these lava flows or other flows within the field.

Conclusion

The two distinct regions found within the mapping area of the North Arch Volcanic Field show a difference in morphology, most likely due to different chemical properties that changed the viscosity of the flows. While there were no sub-surface features seen within the area, they could possibly exist within the volcanic field, as these features were seen by Wallin (1982). Using the Knudsen sub-bottom profiles and the high-resolution multibeam map, submarine effusive lava flows have complex morphologies that are based on a couple of aspects, including the slope and viscosity of the lava. Going forward it would be useful to have additional surveys done with the multibeam and Knudsen further north within the volcanic field to determine if there is a greater density of lava flows there. While sills were not found within this survey, it would be likely they are closer in proximity to the source of the flows. To further investigate these, surveys done closer to the middle of the field would be useful and using a higher resolution seismic profiling to look for these deeper features. It would also be useful to take samples of the two lava flows that were found and determine if are of the same age and chemical properties. While these lava flows may be buried by four kilometers of water, their patterns and

morphologies would help further the understanding of terrestrial and submarine lava flows, as well as hot spot volcanism.

Acknowledgments

I would like to thank the teaching team for the senior thesis class, especially Professor William Wilcock, and my peers. I am grateful to the marine technicians and the crew of the R/V Thomas G. Thompson as they made this work possible.

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