Bathymetry of Eruptive Fissures in the Submarine North Arch Volcanic Field

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Abstract

Submarine volcanoes make up 75% of volcanic activity on Earth, but are relatively understudied due to the lack of real-time observations of eruptions and their inaccessibility, often several kilometers below sea level. Underwater volcanoes behave differently than their land counterparts due to the cold sea water surrounding them. Some submarine volcanism is violent as water pours into active vents, rapidly cooling lava and shattering it into fragments. Other eruptions can produce lava flows that extend tens of several kilometers before solidifying. The majority of submarine volcanoes occur in areas of tectonic activity such as mid-ocean ridges and hotspot island chains. One interesting site of submarine volcanic activity is the Submarine North Arch Volcanic Field 100 kilometers north of Oahu, Hawaii, hosting a few of the longest flows on Earth and covering over 25,000 $kilometers^2$. The field is associated with the Hawaii hotspots but the source of such extensive volcanism is poorly understood. Past studies have mapped the volcanic field flow but only at low resolution. The southeast portion of the field comprises of a series of lengthy flows, hypothesized to emanate from a 75 kilometer long fissure in the seafloor. However, the resolution of the maps was too low to test this theory. On the R.V. Thomas G. Thompson, our team used the high-resolution Kongsberg EM302 30-kHz multibeam echosounder to map the eastern boundary of the southeastern lava flow where the fissure would likely be located. Although area covered was limited by bad weather, we were able to map a 6 kilometer wide swath track extending 63 kilometers along the inferred fissure. We identified the presence of three features that were potentially part of fissures. Each extends about 1-2 kilometers and comprise a 5 meter deep and 100-400 meters wide trough with a levee on either sides.

Plain Language Summary

Submarine volcanoes make up most of the world's volcanic activity, but are relatively understudied due to the lack of real-time observations of eruptions and their inaccessibility, often several kilometers below sea level. Underwater volcanoes behave differently than their land counterparts due to the cold sea water surrounding them. Some submarine volcanism is violent as water pours into active vents, rapidly cooling lava and shattering it into fragments. Other eruptions can produce lava flows that extend tens of several kilometers before solidifying. One interesting site of submarine volcanic activity is the North Arch Volcanic Field, north of Oahu, Hawaii, that hosts a few of the world's longest lava flows. However, the source of such extensive volcanism is poorly understood. Past studies have mapped the volcanic field to understand the source of the field's lengthy flows, specifically in the southeastern portion, but due to the low resolution of the maps, the suggested 75 kilometer fissure source could not be confirmed. On the R.V. Thomas G. Thompson our team used a high-resolution multibeam echosounder to map the eastern boundary of the southeastern lava flow where the fissure would likely be located. Although area covered was limited by bad weather, we were able to map 63 kilometers along the inferred fissure. I identified the presence of three fissures features along with evidence of other fissure like activity off track.

Introduction

Underwater volcanic activity accounts for 75% of the earth's volcanic eruptions and has occurred long before human-life began (Crisp, 1984). However, it is relatively understudied due to both limited technology and resources and its inaccessible location of around 4,000 meters below sea level. Only in the last 50 years has mapping technology advanced for comprehensive study on this submarine phenomenon (Clague et al. 1990).

Unlike their land counterparts, submarine volcanoes act differently due to their chemical make-up and cold high pressure water environments. Rapid cooling of lava by surrounding sea water forms a skin on the surface of lava flows, insulating the interior from heat loss and minimizing explosive eruptions. Therefore, physical characteristics of underwater lava flows are largely dictated by factors such as flow rate, cooling rate, and lava viscosity. Different settings of volcanic activity such as divergent plate boundaries (mid-ocean ridges), convergent plate boundaries (island arcs and back-arcs), and intraplate settings (oceanic plateaus and hotspots from island chains) produce distinct types of magma that affect these factors. For instance, magma near arcs is chemically evolved and volatile-rich resulting in primarily explosive eruptions and shorter lava flows. At oceanic plateaus and island hotspots, magma is lower in SiO_2 and thus more mafic and less volatile rich resulting in sluggish effusive eruptions that can travel longer distances (Perfit and Soule, 2015).

There are three primary types of submarine lava flow morphologies, pillows, lobates, and sheets. Pillow flows shown in Figure 1 occur when lava seeps out of the ground like toothpaste, expanding below its protective glassy rind and inflating. When the pressure of following magma overcomes the strength of the rind, the rind ruptures allowing the flow to travel in stacked pillow formations. Lobates depicted in Figure 2 are similar in their formation, but more individual in their flow units. Lobates are larger in width by several meters and are emplaced quickly enough to produce one interconnected flow instead of stacked lobes. Both types of flows are correlated to shorter travel due to their relatively slow rate of lava extrusion or magma supply rate. Sheet flows in Figure 3 are characterized by their uniform height upper surfaces that can change into folded, lineated, jumbled, or hackly morphologies due to a variety of processes occurring under the rind such as flows along channel margins, repeated inflation/deflation episodes, and flow through restrictions. However, these flows tend to allow for the longest travel due to their high flow rates (Perfit and Soule, 2015).

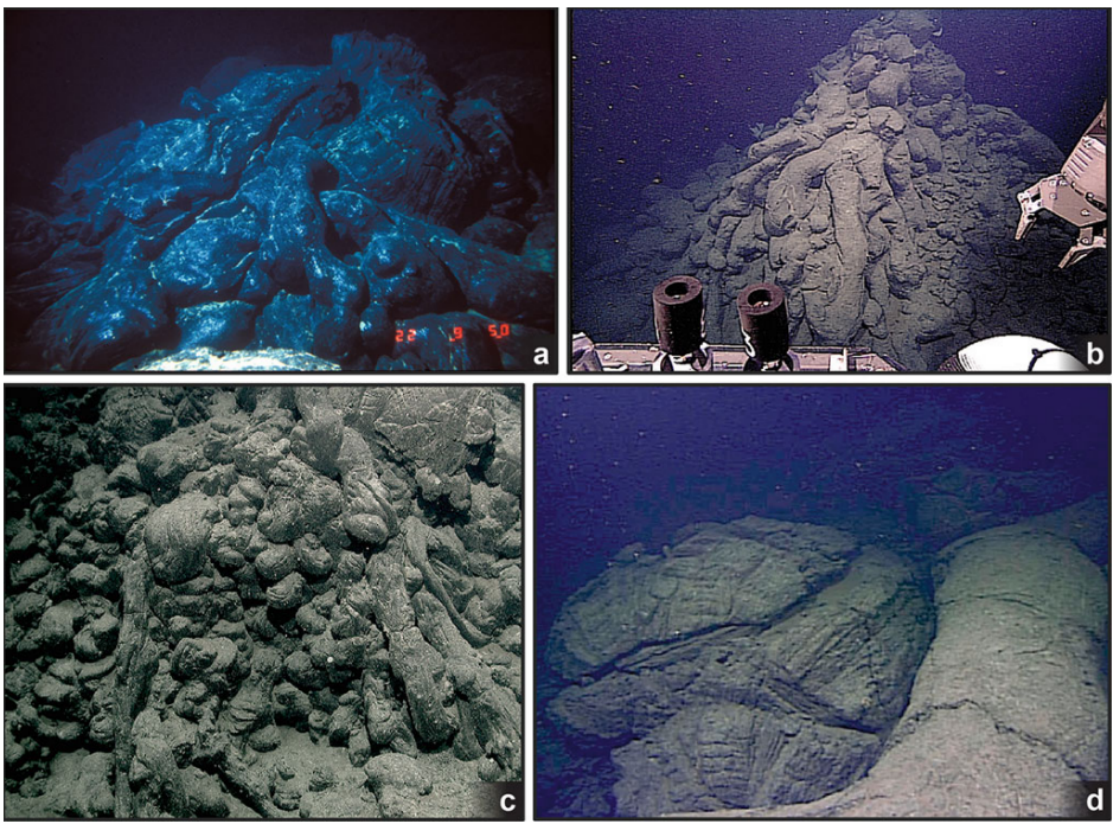

Figure 1. Steep-sided minds, ridges, and haystacks formed by pillow lavas. (a) Upper part of pillow mounds. (b) Haystack showing tubular forms. (c)Pillow mound showing elongated tubes. (d) Large pillows and tubes formed from high-silica lavas (Perfit and Soule, 2015).

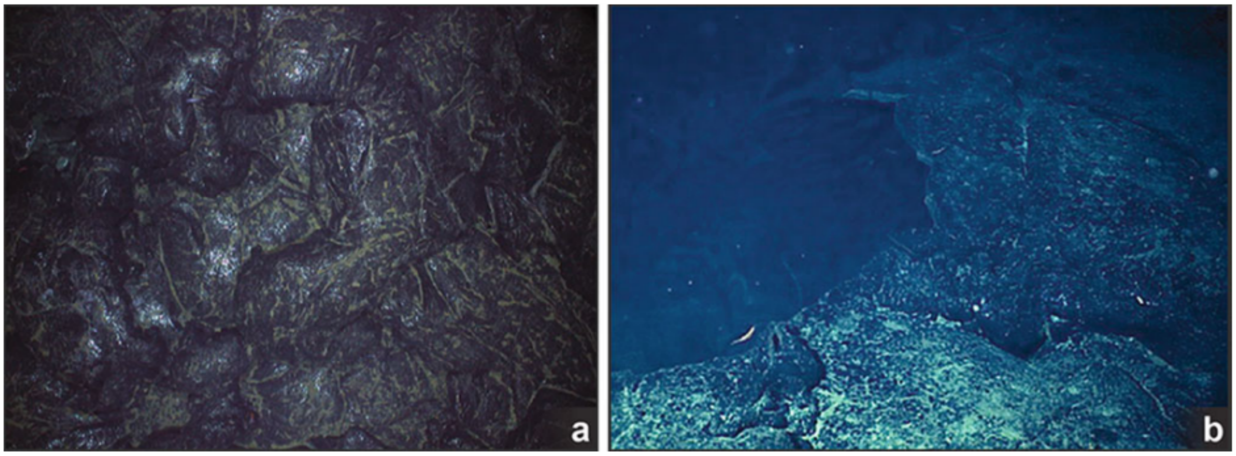

Figure 2. Lobate flows. (a) Directly down perspective of a rapidly emplaced lobate flow resulting in one interconnected flow. (b) Inflated lobate lava with collapsed features (Perfit and Soule, 2015).

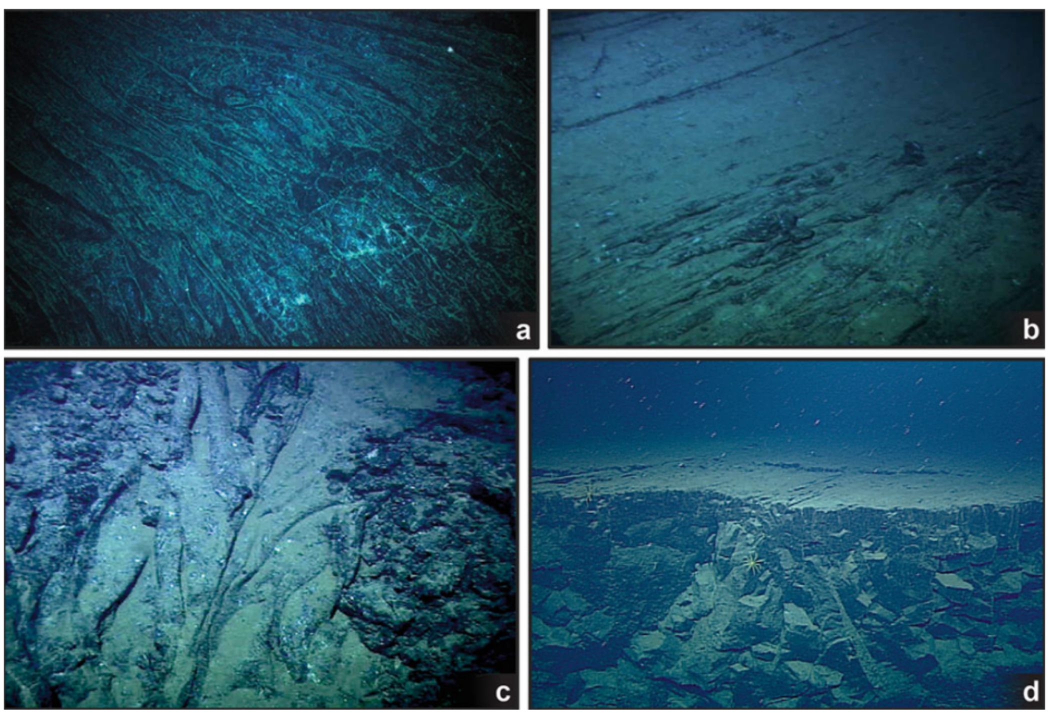

Figure 3. Sheet flows with different morphologies. (a) Lineated sheet flow from above. (b) Lineated sheet flow with folding at edges. (c) Folded sheet flow transitioned into hackly flow. (d) Vertical exposure of sheet flow (Perfit and Soule, 2015).

Over time, all these types of lava flows solidify fully, and become permanent installments on the sea-floor. Research on submarine volcanic activity is thus often conducted through the topographical mapping and physical sampling of these residual lava flow emplacements as they contain evidence of the flow's nature and origin (Perfit and Soule, 2015).

One area of interest for volcanic study is located in the North Arch Volcanic Field. Unlike most lava activity that occurs directly at mid-ocean ridges or on island chain hotspots, this volcanic field is located about 100 to 390 kilometer north of Oahu, Hawaii (Clague et al. 1990), away from any immediate island hotspots, and overlays the flexural arch produced by the spreading of oceanic lithosphere by the Hawaiian Island chain. (Figure 4; Moore 1970, Clague et al. 1990).

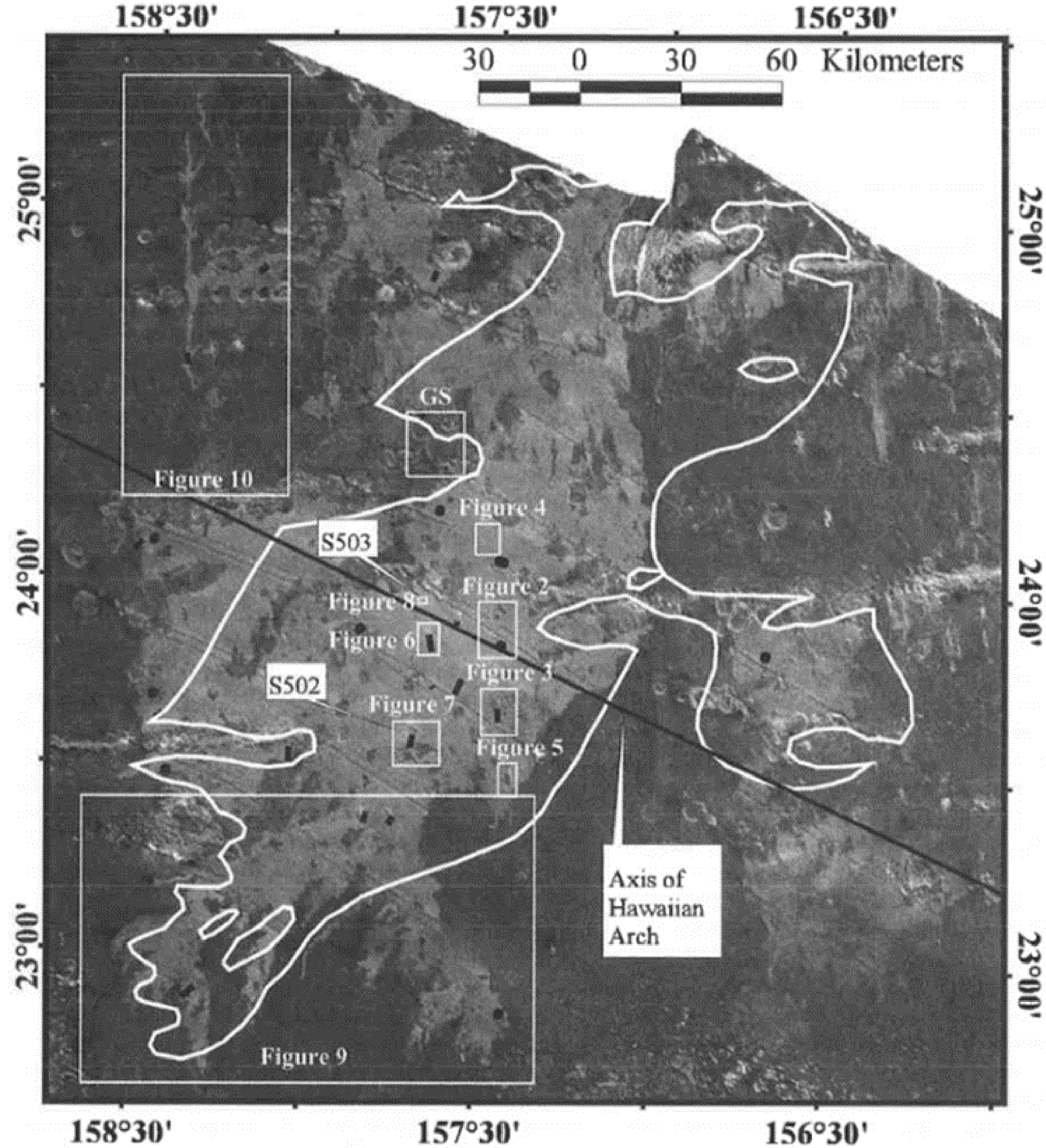

Figure 4. Gloria side-scan image of the North Arch Volcanic Field. Light regions indicate high backscatter where lava emplacement occurs. Dark areas are sediment covered Cretaceous seafloor. The Axis of Hawaiian Arch is labeled as the black line across the grid. (Clague et al. 2002)

Sonar mapping surveys uncovered geophysical data pertaining to the field's lava boundaries and general flow characteristics (Holcomb et al. 1988). Covering nearly 25,000 kilometers^2 and housing one of the longest subaerial lava flows that exceeds the 100 kilometer length criteria (Cashman et al. 1998), lava flows in the field are estimated to have a volume of 1,000 to 1,250 kilometers^3 and are over 4,000 meters deep in the ocean. Previous bathymetry mapping of this field was conducted by the Japan Marine Science and Technology Center (JAMSTEC) in 1999, which mapped near 12,000 kilometers^2 of the southern half of the field (Figure 5; Clague et al. 2002).

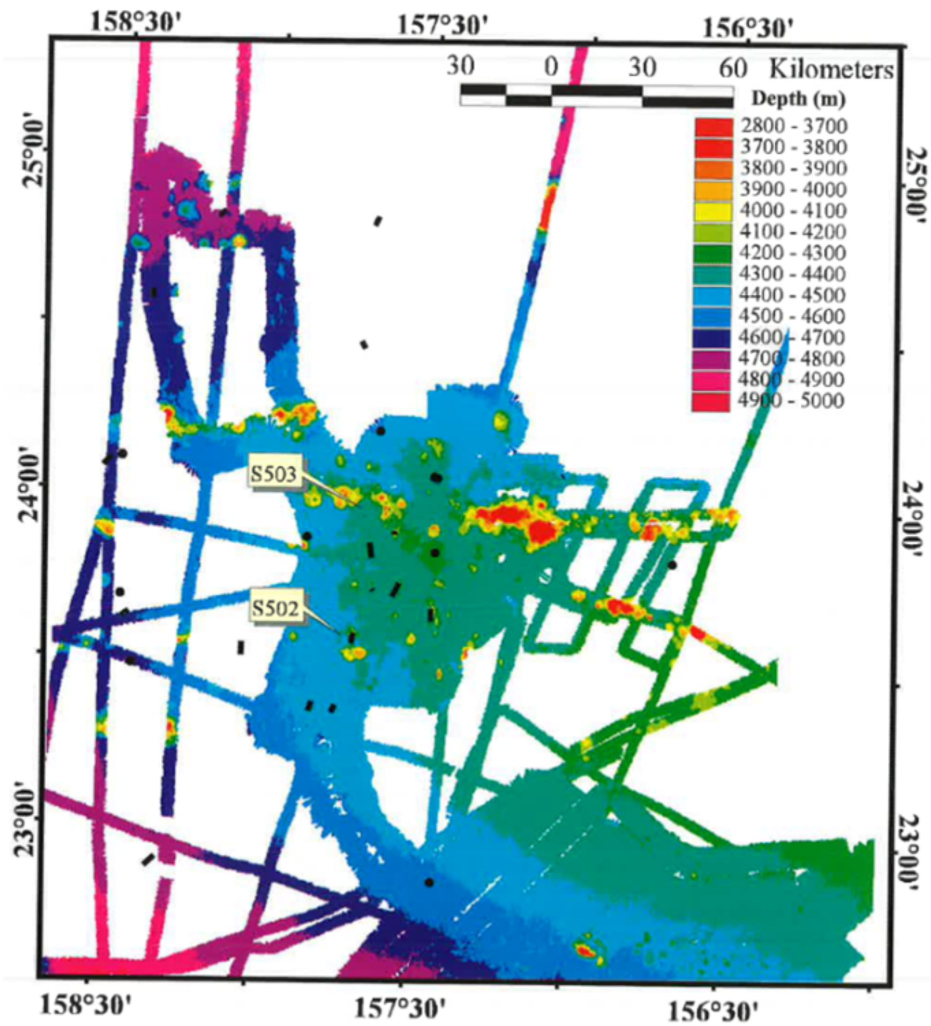

Figure 5. SeaBeam bathymetric coverage of the North Arch Volcanic Field. (Clague et al. 2002)

Through the usage of a SeaBeam 2100 multibeam system, they discovered about 100 volcanic structures from steep cones to low shields (Clague et al. 2002). With a combination of the SeaBeam bathymetry, GLORIA imagery, and samples of outcrops, researchers suggested one reason for the area's lengthy lava flows was due to a fountain like behavior that began with an aggressive eruption of highly vesicular lava creating the observed steep cones of pillow basalt and hyaloclastite (Clague et al. 2002). A more passive but higher effusion rate eruption of dense, low viscosity lava followed, forming the low-relief lava shields made of massive sheet flows (Clague et al. 2002). However, these sheet flows were unlikely to have traveled so far downhill. Yet, in the southern portion of the field there continues to be various lengthy lava flows, implicating the chance of fissures extending south that continued to supply magma for continuous lava flows. Focusing on the southern longest lava flow, it was proposed that there was a 75 kilometer fissure that attributed to its over 100 kilometer length shown in Figure 6 (Clague et al. 2002).

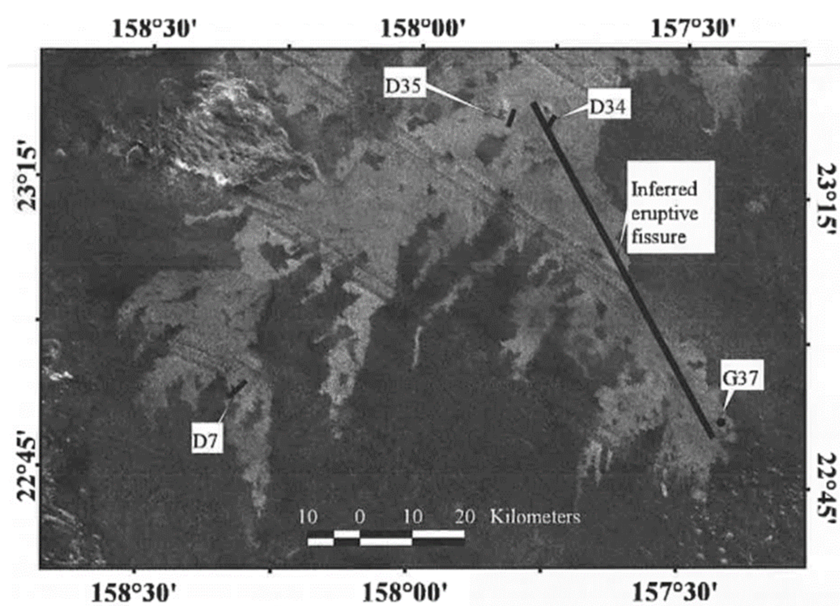

Figure 6. GLORIA image of the southern region of the North Arch Volcanic Field and the approximate location of the inferred eruptive fissure that fed lava flows. (Clague et al. 2002)

Fissures are elongated fractures or cracks in the earth's lithosphere that allow magma and gasses to escape into the ocean. They proceed submarine volcanism in locations away from mid-ocean ridges and hotspots such as the southern region of the field. The fissure's location was deduced by looking at the widest part of the flow field running parallel to the contours in that region and the highest elevation portions (Figure 5; Clague et al. 2002). However, because the vertical resolution of the SeaBeam 2100 was only capable of detecting structures greater than 10 meters high, researchers were unable to produce a detailed bathymetric map to confirm the inferred fissure (Clague et al. 2002) that would likely be only 5 meters in height similar to fissures found in the East Pacific Rise shown in Figure 7. The only imaging explored for this potential fissure location was a rough GLORIA image that lacked sufficient sea floor coverage due to a limited ship pathway and an inconclusive bathymetric map that was unable to capture significant gradients (Figure 5; Clague et al. 2002).

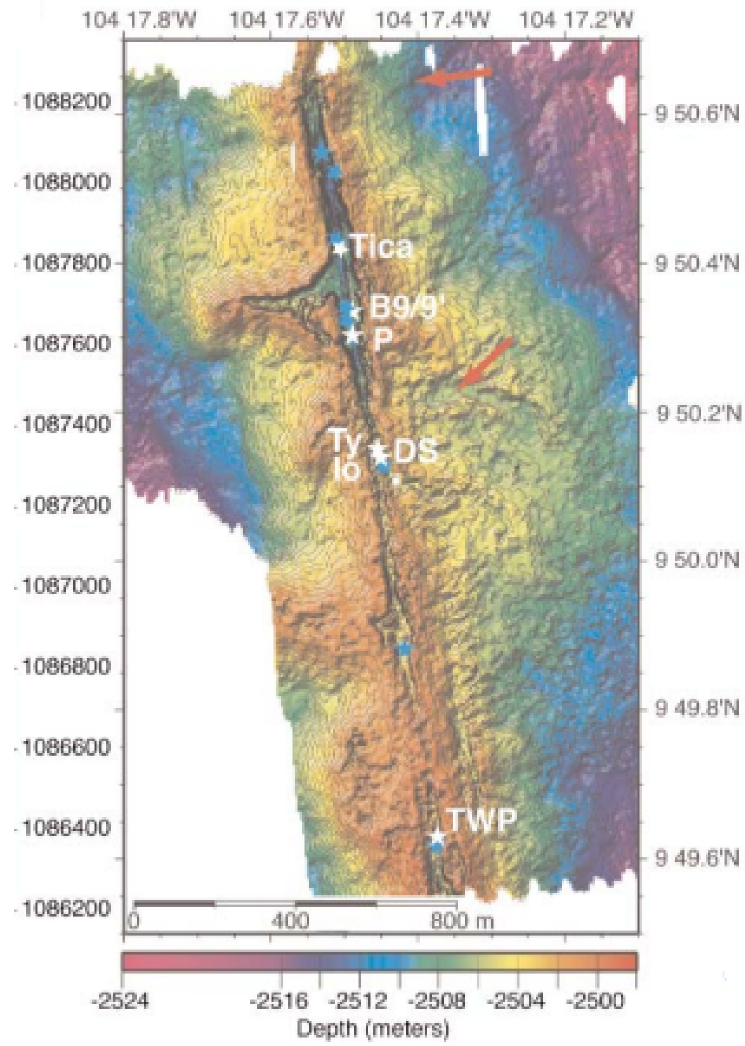

Figure 7. Detailed micro-bathymetry of a fissure in the East Pacific Rise (Fornari et. al. 2004)

I hypothesized that evidence of a fissure would be found on our expedition, and that there was a potential of several smaller fissures that combined, contributed to the flow's length. Locating a fissure or fissures in that area would propose the possibility of other fissures in the larger area of the field that could be contributing factors to the observed uncharacteristically lengthy lava flows.

Methods

On the R.V. Thomas G. Thompson, our team used a high-resolution Kongsberg EM 302 30-kHz multibeam echosounder to map the eastern boundary of the southeastern lava flow where the fissure was likely located. The Kongsberg EM 302 has a maximum of 432 soundings per swath with pointing angles automatically adjusted according to achievable coverage.

Initially, plans were to collect data at 8 knots but due to bad weather, we modified our speed to 4 to 6 knots and mapped a 8 kilometer wide swath track allowing for a 2 kilometer overlap and resulting in a reliable 6 kilometer track. Time allotted for data collection was limited to 24 hours, so we mapped 3 approximately 50,000 meter horizontal segments heading east at 4 knots and then turning back west at 6 knots shown in Figure 8. After completing the horizontal segments that mapped the southern part of the lava flow boundaries, we mapped at 5 knots up along the location of the inferred fissure for 63 kilometer, turning off the lava flow at 4N 625000m E 2588000m N.

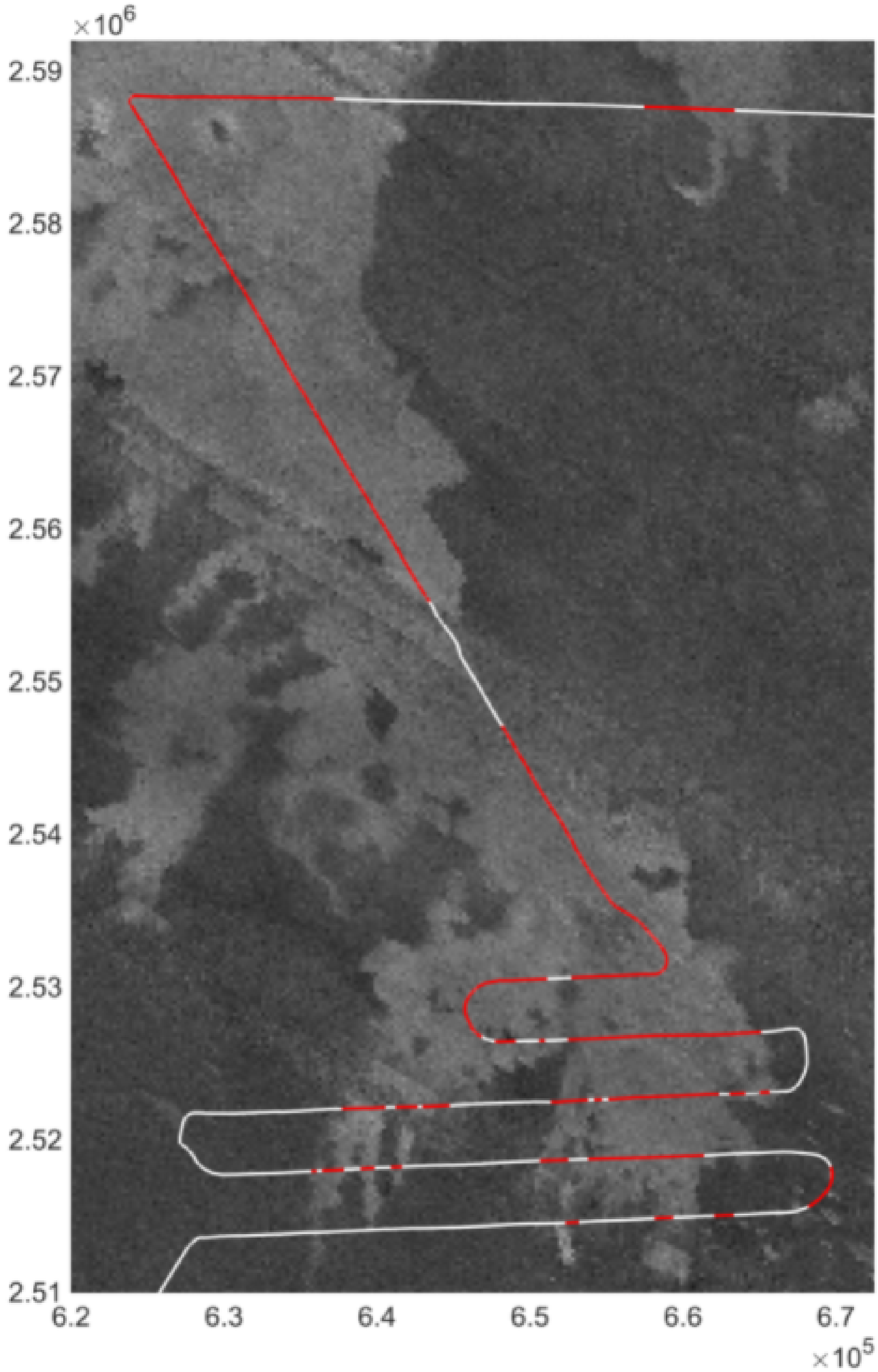

Figure 8. Ship track of area mapped over previous GLORIA imagery of the southeastern portion of the lava flow. Red sections representing echosounder pick up of lava flow with white representing an absence of lava (Pfluger, 2022).

Sensor configurations had been completed prior to our mapping so we began by inputting the parameters for navigation, such as our sonar model and number of transducers, and the point from where swath sonar beams radiated from to calculate the Total Propagated Uncertainty for each individual sounding. Additionally, we defined parameters for sound velocity corrections using data collected from the synchronous XBT deployments during our periodic CTD casts.

After calibrations were completed, data collected was revised for sound velocity corrections, loaded tide data from OSU TPXO Tide Models for tide variance (Egbert and Svetlana, 2002), and Total Propagated Uncertainty using an automated process. We merged vertical and horizontal information, producing geo-referenced datasets that we organized into practical sections with defined locations and map projections. Bad weather caused multiple erroneous pings and artifacts appeared in the data which were manually removed during the later days of the cruise. A large portion of the pings displayed a false parabolic bathymetry and were outliers to the seafloor line. After we removed these off target pings, we developed a code in MATLAB that plotted the bathymetry collected in a 50 meter UTM grid.

Additionally, using data collected synchronously from an echosounder, Pfluger (2022) identified points where lava flow was present and absent, represented in the track lines as red and black respectively shown in Figure 9. The plot illustrated was a gradient map of -4700 to -4400 meters depth. The code allowed for modifications that could change the x and y limits of focus and the gradient scale in meters. I focused on roughly 10 by 10 kilometers^2 sections of the map, reducing the gradient scale to increments of 10 meters, to identify bathymetric features.

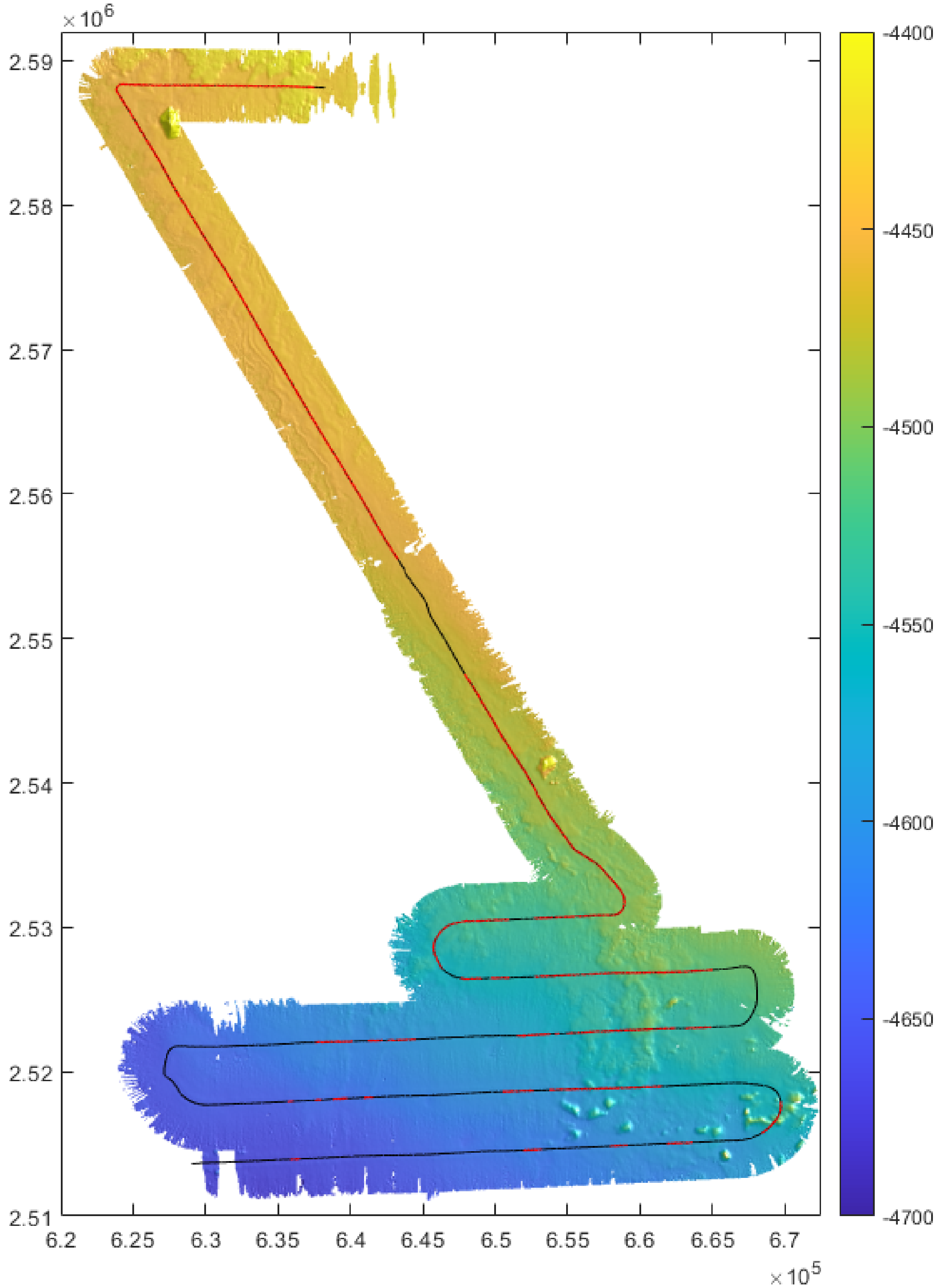

Figure 9. Plot produced in MATLAB of the mapped lava field between -4700 meter and -4400 meter depths. Red sections on track lines represent correlating lava flow detection from the echosounder with black lines representing the lack of lava flow.

Results

Evident from the bathymetric map in Figure 9, the field's southeastern region declines from -4400 meters to -4700 meters southward. Several seamounts can be seen spotted in the north section or the map and just off the southern borders of the lava flow.

At a closer look in Figure 10, the bathymetry from the northern section of the map is illustrated at a reduced gradient scale of -4500 to -4400 meters and there is a visible gradient of 20 to 25 meters declination towards the west where off the map, the lava flow ends. On the very top portion, there is an overlying sheet flow of uniform height of -4400 to -4410 meters that covers another sheet flow of -4430 to -4450 meters. This indicates the possibility that volcanic activity in the region was not a singular eruption, but rather two occurrences of low viscosity high flow rate eruptions. A seamount is also evident at 4N 628000m E and 2585000m N. Following down the track, the lava flow descends westward about 10-15 meters displaying subtle ripple like features of 5-10 meters height roughly parallel to the track lines.

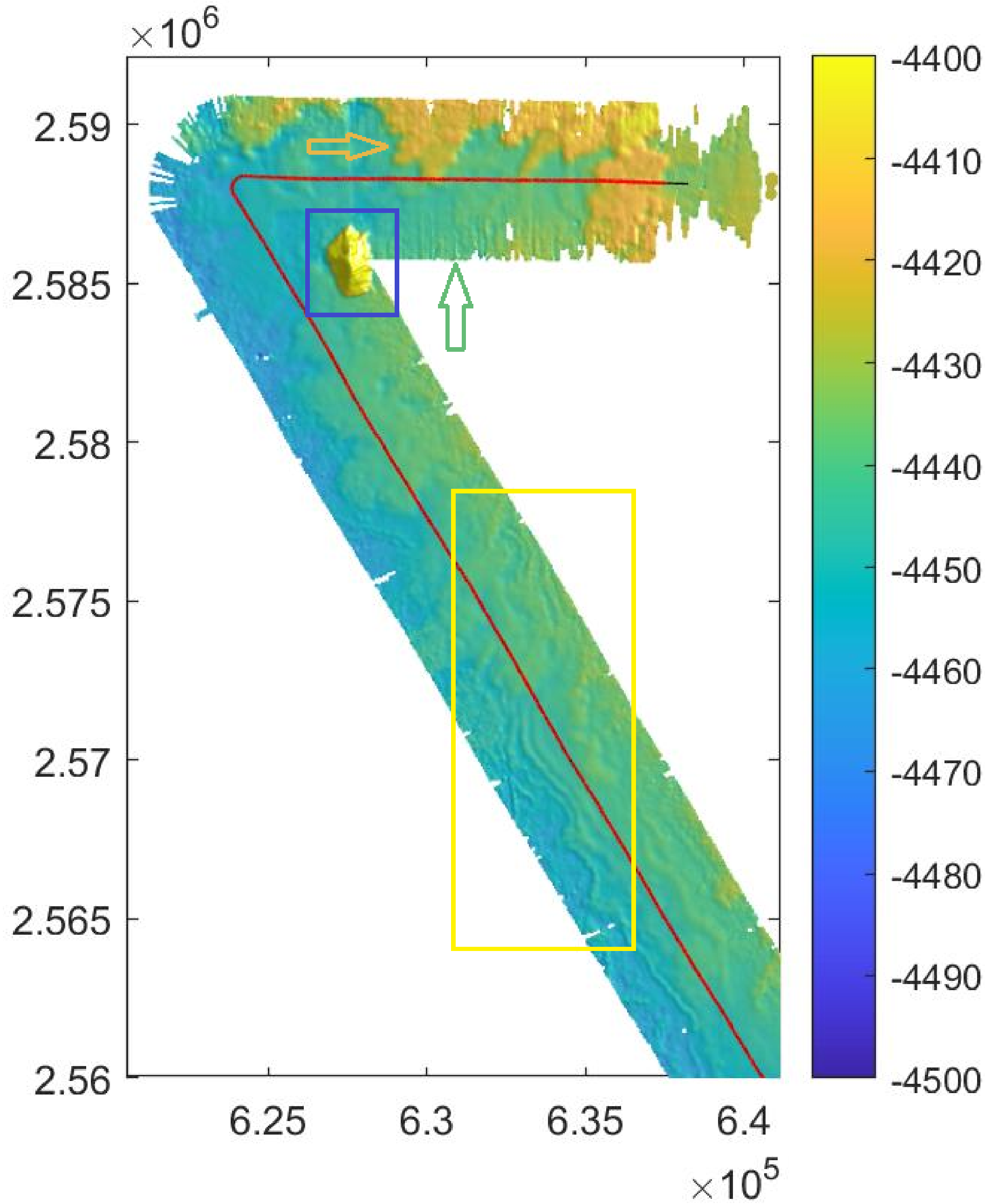

Figure 10. Northern region of the track showing two overlaying lava sheet flows, the sheet flow of depth height -4400 to -4410 meters and -4430 to -4450 meters indicated by a orange and green arrow respectively. A seamount emplacement boxed in dark purple that was unrelated to this instance of volcanic activity. Parallel ripples identified along the track southward boxed in yellow, mirroring the downhill flow.

In Figure 11 with the gradient scale edited to -4430 to -4470 meters, the rippling feature in Figure 10 have a clear chanel that parallels between the undulating ridges. This feature is 1-2 kilometer length, 100-300 meters width, and approximately 5 meters depth. The direction of these rippling effects suggests some sort of activity propagating from the east or right side off the mapped track. In its upper portion, this rippling effect crosses the track lines from right to left annotated by the purple arrow. However, after crossing it, it remains to the left and somewhat consistently parallel to the track lines, resembling a linear levee outlined in a purple box. This feature extends about 14,000 meters with a 5 meter height and 100-300 meter width. Although it is not clear what this lengthy rippling topography is, we can assume there is significant volcanic activity to the east that cause topographical changes that extend to the edge of the lava flow towards the west side of the track.

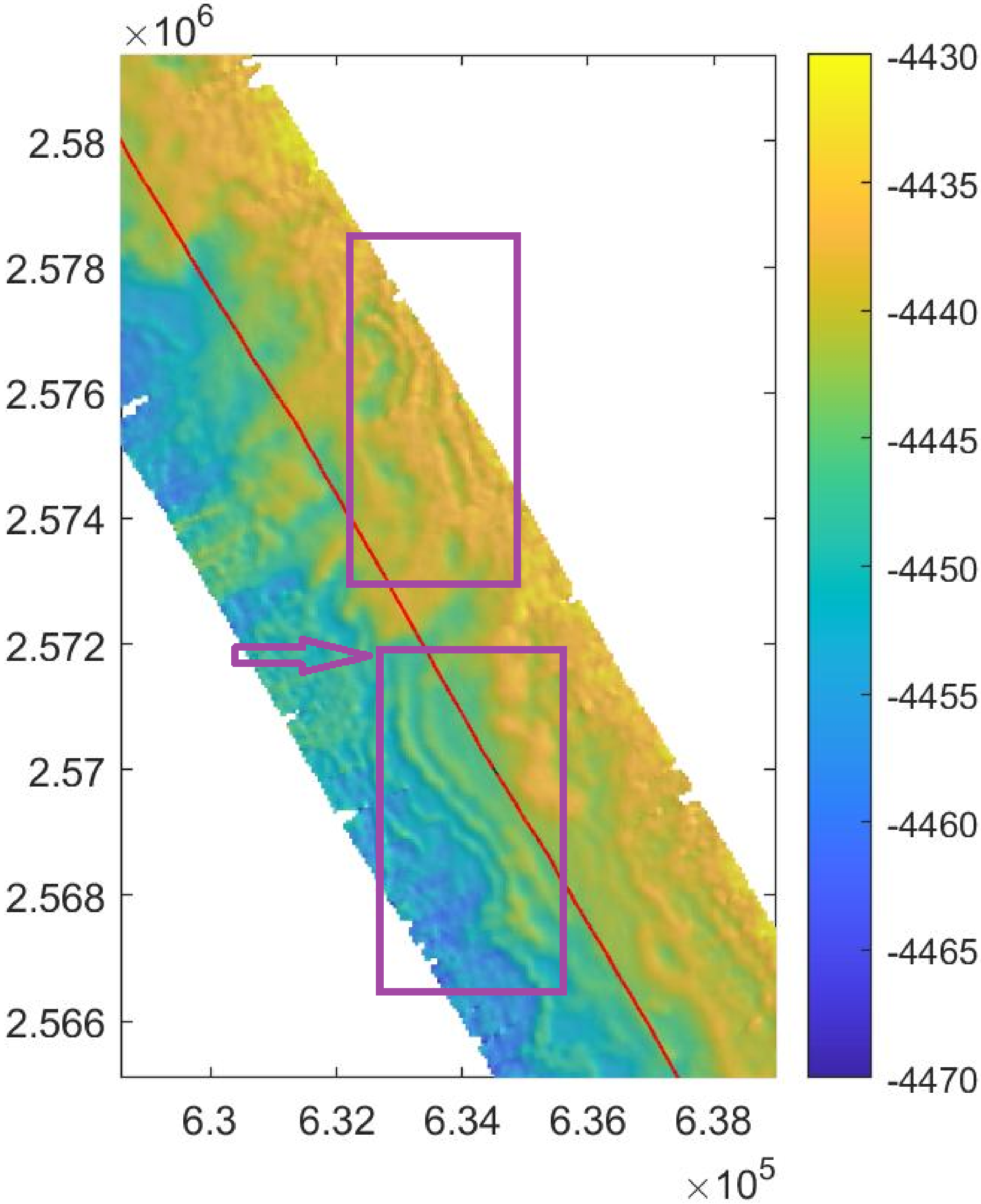

Figure 11. Rippling effects boxed in purple at a scale of -4430 to -4470 meters suggest volcanic activity propagating fro east to west. The ripping feature crosses the track lines at the purple arrow.

Additionally in Figure 12a, located just above and to the left of a section of the elongated rippling ridges in Figure 11, there is a feature just east of the track lines that appears fissure like but with a wider depressions of 10 meters depth and 300-500 meters width. Although wider than an expected fissure, the feature shows both sides of the indentations at similar heights of -4435 meters, and the south and downhill portion has evidence of drainage as it resolves to around -4435 meters as well. This wider but somewhat fissure levee pattern is found again further down the rippling ridges with a 6-10 meter depth as shown in Figure 12b, however it lacks the evidence of lava drainage downhill shown in Figure 12a.

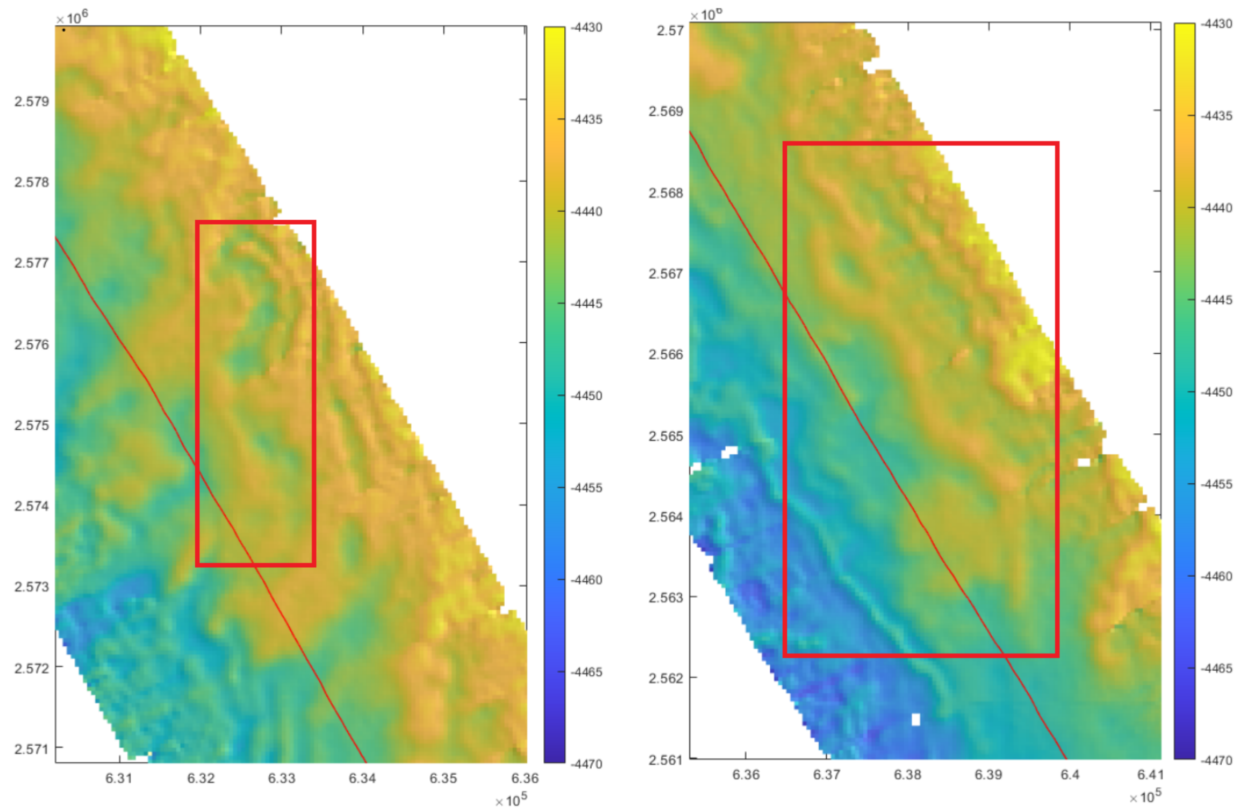

Figure 12a and 12b. Two similar fissure like bathymetric features with wider indentations at around 300-500 meters widths.

Figure 13 with a scale of -4445 to -4455 meters shows the most apparent fissure feature with a lengthy levee to the east of a parallel indented channel, then it resolves to a similar height of the levee of around -4448 meters. The downhill portion of the fissure in the southern side also shows a gradual increase from -4455 to -4449 meters where the lava likely accumulated while draining. This feature is 1 to 2 kilometers in length with a depth of 5 meters and width of 200-400 meters.

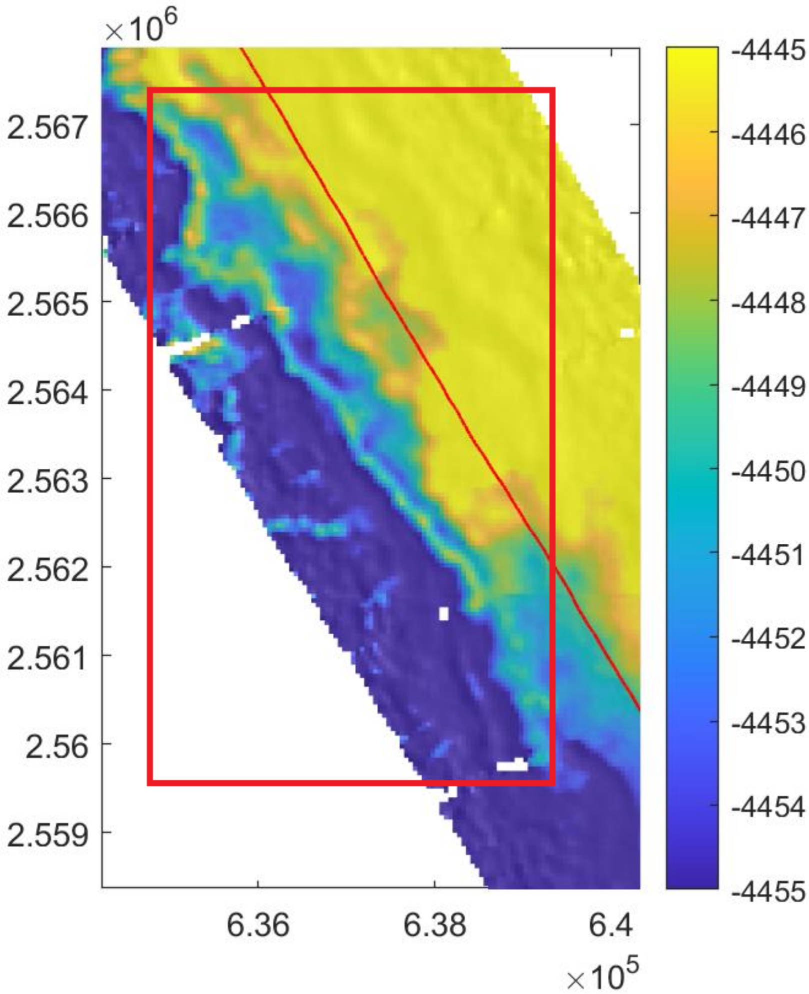

Figure 13. A fissure of 1-2 kilometers, 5 meters depth, and 200-400 meters width stretching parallel to the track lines.

Shown in Figure 14, there is another seamount at the far left corner of the section of the map. At the southern boundaries of the lava, a scatter of seamounts are also evident as the lava flow drops off to around -4600 meters. The group of seamounts located at the southern border of the flow are likely part of the Musicians Seamounts of Hawaii.

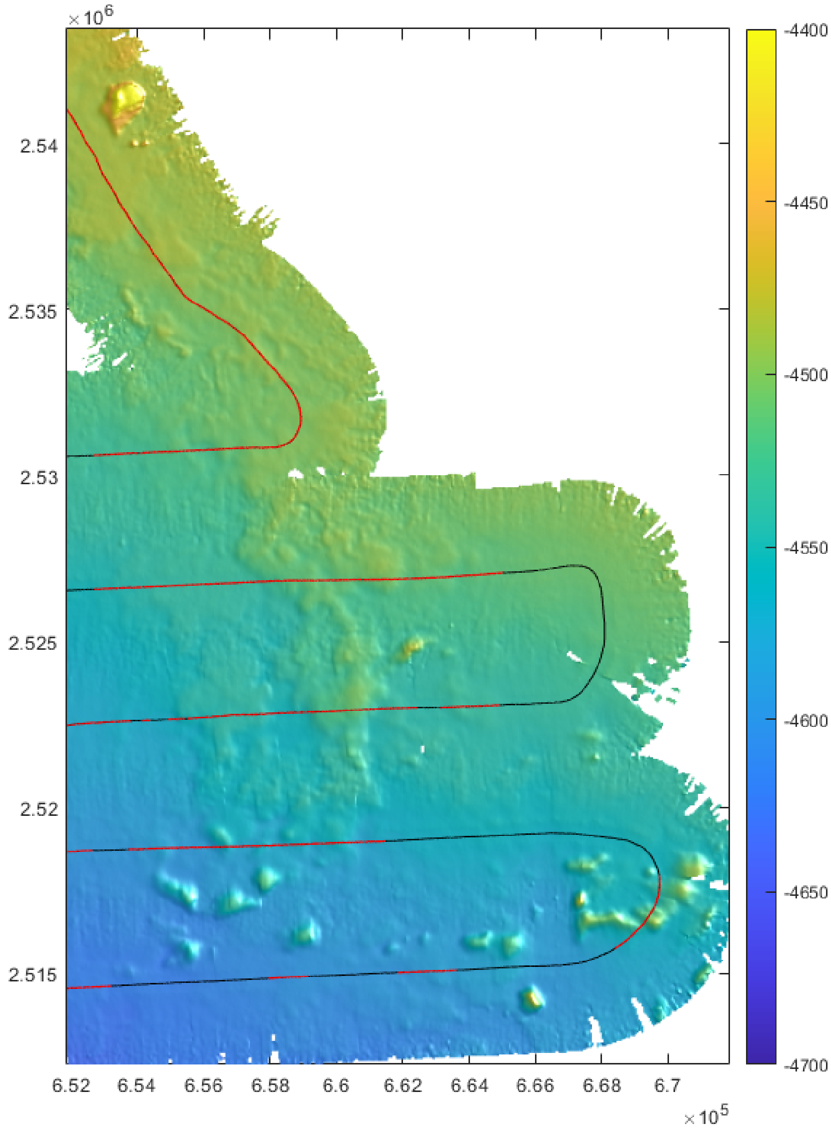

Figure 14. Seamounts scattered on the southern borders of the lava flow and further below the end of the flow, related to the Musicians Seamounts of Hawaii.

Discussion

From the bathymetric map, I found evidence of fissures along the track lines covered by hardened lava flow, supporting my hypothesis that we would be able to capture bathymetric evidence of fissures in the flow. To identify fissures, I looked for linear indentations in the bathymetry. In the quick cooling environment of sea water, magma that rises out of fissures flows downhill and cools rapidly creating lava levees at the lowest elevation edge of the fissure. As magma supply replenishes, new magma fills the crack and spreads uphill until even with the height of the lower levees, and then back down hill and over the levee. When maga supply runs out and it cools, the magma drains back into the fissure creating a feature identified by a linear protruding edge followed by a parallel lower indentation channel and then resolving to a similar height of the initial edge (Wright, 1998). Typically, the downhill portion of the fissure also resolves to a similar height as its surroundings due to the draining lava accumulating in areas of lower elevation. Fissures imprinted with overlying lava flow are typically only 5-10 meters in depth. Thus, looking through the map, I reduced the gradients to 10-30 meter scales for clarity.

This type of fissure characteristic in bathymetry is evident primarily in Figure 13 with the obvious levee, indented channel, and resolve in height to the east of the channel with drainage downhill. Furthermore, this feature has a 5 meters depth similar to that of the fissure found in the East Pacific Rise. In Figure 12a and 12b, we see similar fissure like features but with an indentation channel slightly greater at 6-10 meter depths and a width much greater at 300 to 500 meters. Due to these outlying characteristics, there is speculation if these are actual fissures or some other volcanic flow mechanism.

In Figure 11 evidence of the ripple effects in the bathymetry suggest possible volcanic activity to the right of our track. The connected behavior of propagation from the east even as it crosses the track lines indicates a need to map to the right of our track to provide a better understanding of what those topographical features mean and if they are fissure related.

The mapped seamounts were determined to be unrelated to the flow of focus. The seamount in the north and on the bottom of the fissure track line appear to have occurred after the emplacement of the large lava flow due to its isolated bathymetry, and the seamount cluster at southern borders of the flow are part of the Musicians Seamounts of Hawaii.

Looking at all the features together, my hypothesize was confirmed as I identified 3 individual fissures that contributed to the lengthy southeastern lava flow. However, because I would expect multiple fissures to be in echelon to each other and the fissures I identified were generally along the same parallel length of the track, there is a possibility that what I found were just visible sections of a fissure that extends the theorized 75 kilometers. Unfortunately, due to the narrow scope of our inferred fissure location mapping, I lack comprehensive data that could give me perspective on my features relative to any other features nearby to the east of the track.

Conclusion

My hypothesis was that with a high resolution multibeam echosounder, we would find proof of a 75 kilometer fissure or smaller fissures in the inferred region. This was confirmed as I found 3 fissures in the southeastern region of the lava flow, one elongated fissure and two wider fissure features. Because we would expect fissures to form in echelon patterns, the features we see may not be all fissures as they seem to travel streamline with each other and the track lines. However, there is also the possibility we are seeing evidence of a lengthy fissure that extends across all three fissure features with sections of the fissure hidden under thick solidified lava flow. However, because the general direction and distance covered by the features are all seemingly related to the lava flow, I conclude that they are all evidence of fissures.

The multibeam system we used had a high enough resolution to map features like the fissures I discovered, but I was limited by both time and weather. Favorable weather and additional time would have permitted more swaths that could give us a better image of the fissure locations in relation to each other and the flow. Likely, there were clearer fissures east of the track we created.

I suggest a thorough mapping of the right side of our north to south track. Looking at the rippling effect propagating to the west, I would expect some sort of volcanic activity to the right just off our track could change the context on our mapped bathymetry. Furthermore, a wider coverage of that area could allow us to see a clearer echelon pattern of fissures to verify that the features seen in this study were individual fissures or if they are sections of an isolated lengthy fissure.

Acknowledgements

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References

Cashman, K., Pinkerton and J. Stephenson. 1998. Introduction to special section: long lava flows. J. Geophys. Res: 103, 27, 281-27, 289.

Clague, D. A., R. T. Holcomb, J. M. Sinton, R.S. Detrick, and M. E. Torresan. 1990. Pliocene and Pleistocene alkalic flood basalts on the seafloor north of the Hawaiian islands. Earth Plant Sci. Lett.: 98, 175-191.

Clague, D. A., K. Uto, K. Satake, and A. S. Davis. 2002. Eruption style and flow emplacement in the submarine North Arch Volcanic Field, Hawaii, in Hawaiian Volcanoes, Deep Underwater Perspectives. AGU Geophysical Monograph: 128.

Crisp, Joy A. 1984. Rates of Magma Emplacement and Volcanic Output. Journal of Volcanology and Geothermal Research, vol. 20, no. 3-4: 177-211.

Egbert, Gary D., and Svetlana Y. Erofeeva. 2002. Efficient inverse modeling of barotropic ocean tides. Journal of Atmospheric and Oceanic Technology 19.2: 183-204.

Fornari, Daniel & Tivey, Maurice & Schouten, Hans & Perfit, Michael & Yoerger, Dana & Bradley, Al & Edwards, Margo & Haymon, Rachel & Scheirer, Daniel & Damm, Karen & Shank, Timothy & Soule, Adam. 2004. Submarine Lava Flow Emplacement at the East Pacific Rise 9°50´N: Implications for Uppermost Ocean Crust Stratigraphy and Hydrothermal Fluid Circulation. Geophysical Monograph Series. 10.1029/148GM08.

Holcomb, R. T., M. Holmes, R. P. Denlinger, R. C. Searle, and W. R. Normark. 1998. Submarine Hawaiian North Arch volcanic field. EOS, Trans. Am. Geophys. Union: 69, 1445.

Moore, J. G., Relationship between subsidence and volcanic load, Hawaii. 1970. Bull. Volcano: 34.

Perfit, Michael & Soule, Adam. 2015. Submarine Lava Types.
10.1007/SpringerReference_350467.

Wright, Dawn. 2018. Formation and Development of Fissures. Orst.edu.