Detecting seafloor lava flows with seafloor roughness

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Abstract

Much of the seafloor is currently unexplored. As such, increasing the number of options in the “tool box” is vital for studying the oceans. This study uses the North Arch Volcanic Field, an area of seafloor north of Hawaii partially covered with lava flows and seamounts, as a case study to evaluate the usefulness of an additional tool to explore the seafloor and its features - roughness. This location was previously mapped using GLORIA side-scan sonar, yielding a low-resolution image of the area, revealing abnormally large lava flows. This study surveyed a portion of the North Arch Volcanic Field, creating a high-resolution map of the area with a 30 kHz Kongsberg multibeam echo sounder aboard the R/V Thomas G. Thompson. By creating an algorithm to calculate roughness values based on bathymetric data, a second map of the area was created that was compared with the collected bathymetry data and high resolution sub-bottom seismic profiles to determine if roughness can be used to identify lava flows. To do this, it was hypothesized that there will be an increase in roughness at lava flows and lava boundaries compared to surrounding sediment. Results show that roughness can be a useful tool to identify and emphasize the structure of lava flows and may reveal features of interest that bathymetry alone may miss. It is important to note that the roughness algorithm will enhance error in the bathymetric data, particularly those at the edges of swaths that arise from ship roll. Roughness may be an important parameter in future artificial intelligence algorithms to aid in finding features of interest in large bathymetric data sets.

Plain Language Summary

Much of the seafloor is currently unexplored. So, This study tried to create a new tool to be used to understand the ocean floors better. It focused on the North Arch Volcanic Field, an area of seafloor north of Hawaii partially covered with lava flows and underwater mountains, as an important area to figure out if roughness, the focus of this study, can be useful for exploring the seafloor. This location was previously explored, revealing interesting lava flows to compare to roughness. This study mapped a portion of the North Arch Volcanic Field, creating a more accurate map of the area while on board the R/V Thomas G. Thompson. By creating a way to calculate roughness, a second map of the area was created that was compared with the previously-collected data and collected lava flow information to determine if roughness can be used to identify lava flows. Results show that roughness can be a useful tool to identify and confirm the location of lava flows and may potentially reveal features of interest that the original data alone may miss. The current calculation for roughness will show the errors due to the rocking of the boat more than in the depth map. The calculated roughness may likely be useful to add to computer artificial intelligence to identify seafloor features in larger data sets.

Introduction

The planet Earth is estimated to have formed 4.52 to 4.58 billion years ago. However, the oldest rocks that have been found are *acasta gneisses* in northwestern Canada, dating back around 4.03 billion years ago (Newman 1997). To account for this time difference, there must be places on Earth where "new" rock is being formed, and old rock is being recycled. On Earth, a combination of plate tectonics and volcanism are the mechanisms by which there is a recycling of surface rock. While volcanism is common throughout the other planets in the solar system, plate tectonics is found uniquely on Earth, and contributes heavily to creating the topography of the surface of Earth (Martin 2008).

Subduction zones, locations on Earth where tectonic plates are moving towards one another and one plate is denser than the other, are areas where surface rock is being reintroduced to the interior of the Earth. On average, the volume of terrestrial material that is subducted by these zones is around 1.6 km^3 per year, which is similar to that of the estimated rate at which material is added to Earth's surface. (Roland von Huene 1991). Material is added to Earth's surface through divergent zones, locations on earth where tectonic plates are spreading apart from one another, and other volcanic features such as hot spots and eruptive fissures. Hot spots are locations around Earth where the mantle is hot enough to melt and release magma on the surface, forming island arcs, and eruptive fissures are locations on Earth where there is a tear in the crust, allowing magma to spill out. According to Crisp (1984), mid-ocean ridges (a divergent zone) will resurface ocean basins around every 100 million years. In other words, the topography and bathymetry of Earth is ever changing and is relatively young when compared to the age of the planet itself.

Submarine volcanoes (and the seafloor in general) are difficult to study for a multitude of reasons. The first and foremost reason for this is that they are often thousands of meters underwater, making it difficult for humans to go down and physically observe and sample. This means we must find other methods of learning about volcanoes on the seafloor. Multibeam data utilizes sound waves to measure the bathymetry of the seafloor, illuminating morphological features of the volcano. Magnetometers can be used to collect information about the magnetic field of a lava flow, giving insight on the viscosity of the flow. Coring can be done to physically get stratified samples of the marine sediments that lay on the surface of the seafloor. Finally, to get information about the rock below the sediment, you must use dredging or utilize a ROV that can sample the seafloor. In order to understand the physical makeup of the flows, contributing to our temporal understanding of the lava flow and what may have happened before in the area.

Much of the seafloor itself is not actually mapped. Only a portion of it is mapped by direct measurements, and the rest is filled in by predictions from satellite altimeter data, only providing an approximate estimation of the seafloor (Wolfl et al. 2019). The bathymetry and morphology of the seafloor is important to understand as the ocean plays an important role in navigation as well as many other aspects. Additionally, with climate change, understanding geographical features of the seafloor may help with conservation and sustainability efforts by those who use them. (Wolf et al. 2019). A greater understanding of tectonics and Earth processes in general will make it easier to adapt to changes due to climate change, and may help direct resources to areas that are at greatest risk. There are currently global efforts (such as the Nippon Foundation GEBCO Seabed 2030 Project) that aim to decrease the gap in knowledge of the seafloor. However, most projects are focused on primary measurements of the seafloor, such as directly measuring the bathymetry, which alone doesn't often give a whole picture of the seafloor.

Once those studies are done, secondary measurements can be conducted in the same area to compare with currently-known information to create a more whole picture of the seafloor, which may reveal and/or confirm morphological features in said areas.

Which brings us to the area of focus: Hawaii's North Arch Volcanic Field. The North Arch volcanic field is a relatively large area of flood basalts just north of Oahu, spanning an area of around 25,000 km^2 and up to 5.5 km deep (Figure 1). Much of the area within the flood basalts are relatively flat, with unusually large marine lava flows (~100km) and intermittent seamounts spanning the field. (Holcomb et al. 1988). Some of the lava landslides and debris avalanches from the field are more than 200km long and about 5000km^3 in volume, making them among the largest on Earth (Moore et al. 1989). Previous research in this area was conducted last in the 1970s by the Japanese, with both Gloria SONAR imagery and lower-resolution bathymetric data mapping out the area, while stratigraphy research was done to learn more about the composition of the lavas. It's estimated to be 0.5 - 1.15 million years old for the youngest lava flows (Frey et al. 2000), and older than 2.7 million years old for the oldest of lava flows (Clague et al. 2002). The bathymetry and Gloria data were taken in an era of generally poor navigation, yielding poor results from the study that showed the area with low confidence.

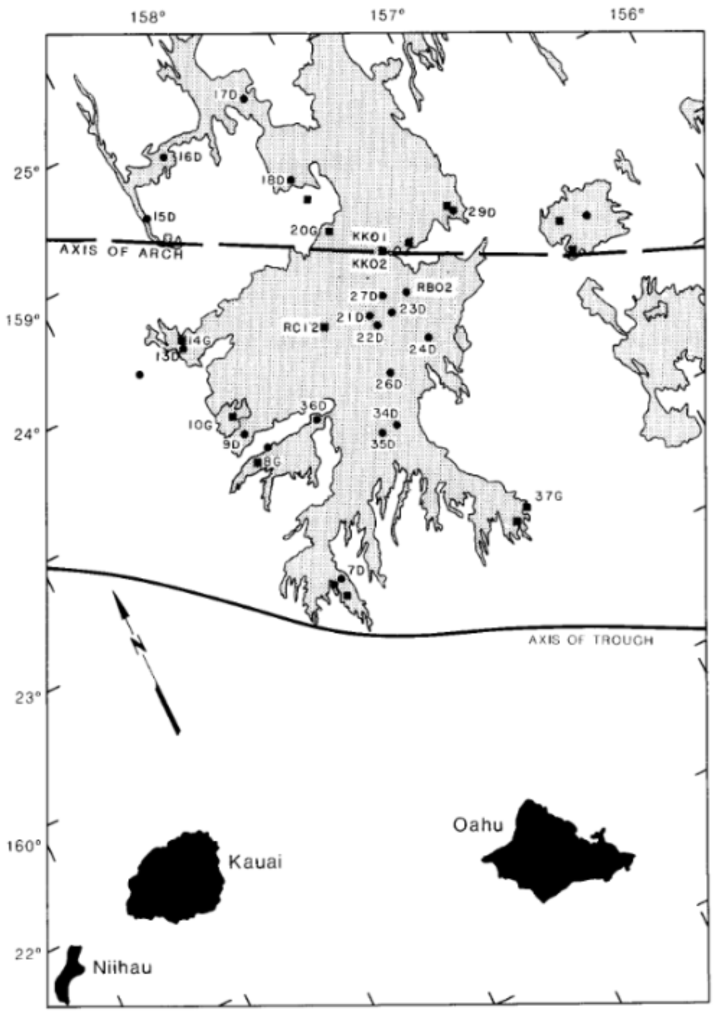


Figure 1. A map of the North Arch Volcanic Field as depicted from Gloria SONAR data from the Clague et al. (1990) paper. It's important to note that Gloria SONAR data only shows backscattering, and not bathymetry itself, so what is being shown in gray are the areas that are assumed to be covered in lava flows.

Within the North Arch Volcanic field, this study aimed to collect bathymetry information about the seafloor through a multibeam system, transform the seafloor information with a roughness algorithm, and display the roughness of the seafloor in the area. With the calculated information, it is hypothesized that the roughness calculations will reveal the transition (or boundary) areas between lava flows in the North Arch Volcanic field and regular marine sediment deposits. I hypothesize I will find a strong decrease in the roughness of the seafloor as you move from a lava flow to marine sediments. As sediments accumulate on the seafloor, they settle according to gravity, making a rather flat area. However, there hasn't been enough time to cover the current lava flows in the area, as they were recently discovered by the Gloria SONAR data by Clague et. al (2002), meaning the roughness of the lava flow should still be relatively high compared to the surrounding area. Because the Gloria data could be inaccurate, we must double check the roughness map (after we determine boundaries of lava flows) with a bathymetry map, to see if the boundaries agree with one another. If roughness is able to confirm the location of lava flows and spot other geological features on the seafloor, it may be used in the future with only gathered bathymetric data to identify areas that should be further researched.

Methods

The bathymetry data of the North Arch Volcanic Field survey was taken from a 30 kHz Kongsberg multibeam echo sounder aboard the R/V Thomas G. Thompson at a 50 meter resolution, and is shown in figure 2. The study was conducted between 22°N 51' and 23°N 40' and 155°W 56' and 157°W 95' with time of study being from 1200 on December 19 until 0830 December 20 UTC. Figure 2 additionally shows the trackline of the survey as a black line, as well as lava flow boundaries highlighted in red as found from a Knudsen echosounder, also aboard the Thompson (Pfluger, 2022). Once the raw multibeam data was collected, it was processed as per the steps outlined in the "CARIS HIPS and SIPS 8.1 User Guide" (2013). Some important steps of the multibeam processing stage include: calculating the Sound Velocity Profile (which in this case was calculated from XBTs and CTD casts), manually "cleaning" the swath data, running the data through a tidal model to correct for changes in sea surface height (we have used the TXPO tidal model for this purpose, Egbert 2002), and finally translating the data into a grid to be analyzed further in programs such as MatLab or Python.

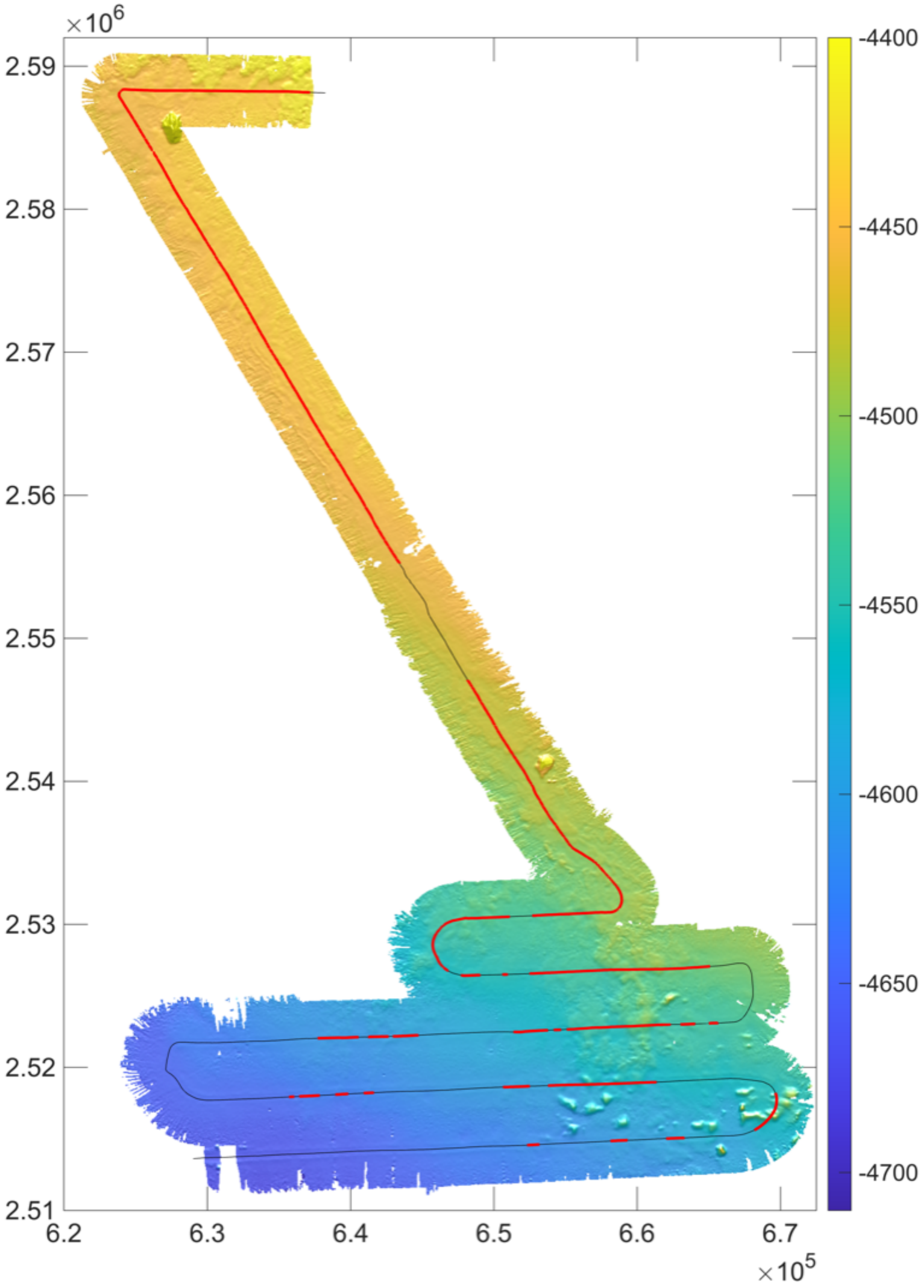


Figure 2. A map of the survey area within the Hawaii North Arch Volcanic Field. The thin black line depicts the track line, while the red marking over the track lines are volcanic lava flows that were identified from Knudsen data (Pfluger 2022).

It is important to note that the conditions during the survey were unfavorable, leading to increased swath error on the outer edges of the beams, and a large emphasis was placed on the manual editing of the multibeam data. The "ping editing" phase thus required much more time and resources than other parts of the initial data collection. Ping editing consists of sifting through each swath and manually removing errors that were visible. The scientists participating in ping editing were briefed on what type of data should be classified as an "error," however it is worth mentioning that each analyst may have different standards when classifying errors.

After ping editing, the data was gridded in multiple formats, and the analysis part of the project occurred in both Matlab and Python. I made a Python program that would calculate the roughness of any given point in the grid and plot it. As mentioned previously, roughness is a unitless, quantitative calculation of how "smooth" or how "rough" a surface is. While there are other, more accurate quantitative calculations for roughness (Fox and Hayes, 1985), a simpler approach was taken for this project, and is depicted in equation 1.

$$(4 * z_{(i,j)}) - z_{(i,j+1)} - z_{(i,j-1)} - z_{(i-1,j)} - z_{(i+1,j)}$$

Equation 1. A 2-dimensional calculation of roughness. The main point, (i, j) is surrounded by multiple points, with the *z* being the depth at that point.

With any given point in 2D, the formula will take 4 times the depth of the given point and subtract it by the four closest points in the four cardinal directions next to the point. The resulting value corresponds to roughness, values closest to 0 corresponding to a not rough, or “smooth” surface. Figure 3 depicts multiple examples and calculations for roughness in one dimension, and highlights importantly the aspect of resolution. The first panel of figure 3 depicts a smooth surface as per the roughness calculation at a resolution of 50 meters (50m between each point). Despite this surface being calculated as “smooth,” there is a bump between the first and second point. Because the depth values at the bump are not being considered for the roughness calculation, it is ignored, and thus the surface is smooth. The third panel of figure 3 depicts a rough surface, as the resulting value from the roughness calculation is a non-zero number.

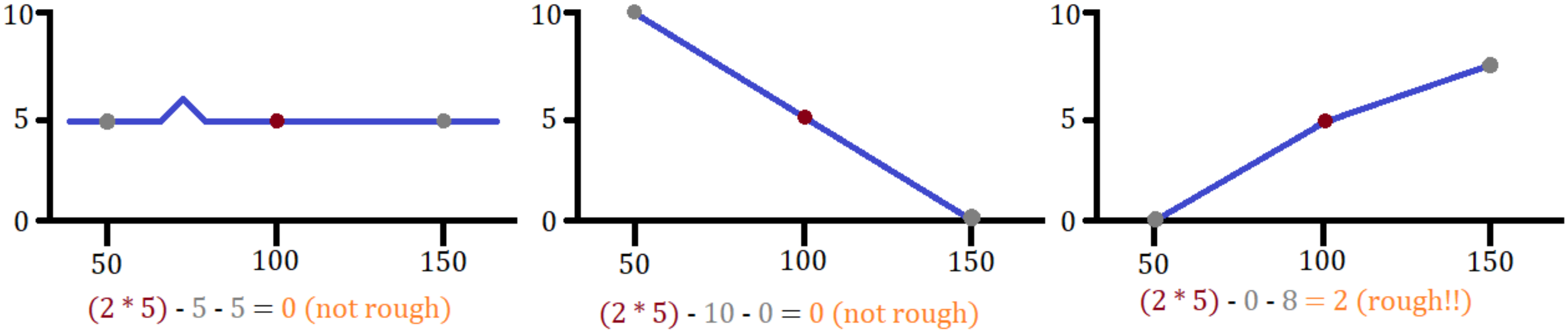


Figure 3. A visual depiction of roughness in one dimension. The x-axis depicts distance, the y-axis depicts depth (units aren’t relevant for roughness). The first and second pictures show a surface that is smooth, and the third picture depicts a rough surface.

Initially, The roughness values of the survey area given by Equation 1 proved difficult to display because positive and negative values of the same magnitude both indicate similar levels of roughness. Therefore, the absolute value can be taken instead, creating a smaller spread of data. Additionally, while the mean of the entire lava flow was close to 0 (meaning the overall area is relatively smooth), there were large outliers, potentially due to mistakes during the ping editing phase, that drowned out much of the roughness patterns on the maps. As such, I removed data from the set that was over three standard deviations away from the original dataset. I also normalized the data to be from a 0 to 1 scale, 0 being the most smooth, and 1 being the most rough. With the data finally analyzed, I created maps of roughness at various scales to compare with bathymetry maps (with lava flow data) of the same areas.

Results

The roughness data calculated over the whole survey area can be seen below in figure 4. The data was taken at a 50 meter resolution, so a roughness value (from 0-1) was calculated for a “point” every 50 meters. There are a couple things that immediately jump out after looking at the roughness chart. The edges of the swaths appear to be almost uniformly rougher than the middle of the swath. This is mainly due to the fact that the roughness calculation is derived simply from bathymetry data, and error from the bathymetry data will be amplified in the roughness calculation. The outer beams are affected the most due to the lever effect, and even in favorable conditions the outer beams will still be noisier than the inner beams. Not only is the error amplified in the outer swaths, but evidence of the trackline can be seen in the roughness chart despite not plotting it directly. This is also due to natural error in bathymetry data around directly under the boat, which is a known error in the multibeam system itself. Despite this, the overall figure still displays areas and features of importance. The existence of seamounts can be seen, such as the large group in the southeastern portion of the survey area, as well as the larger seamounts at around 6.5×10^5 UTM x, 2.54×10^6 UTM y and 6.3 UTM$\times 10^5$ x, 2.585×10^6 UTM y. You can also see evidence of features revealed through roughness; boundaries of a layered surface in the very top of the survey area (from 6.22×10^5 UTM x to 6.4×10^5 UTM x and 2.59×10^6 UTM y) bands of roughness sprinkled about the diagonal stretch of the survey area. There also is a rather rough patch of seafloor in the bottom right (southeast) area of the track, which is an area of focus due to the existence of a large lava flow. The bottom left (southwest) area of the trackline seems to be relatively smooth, with the occasional band of roughness streaking through.

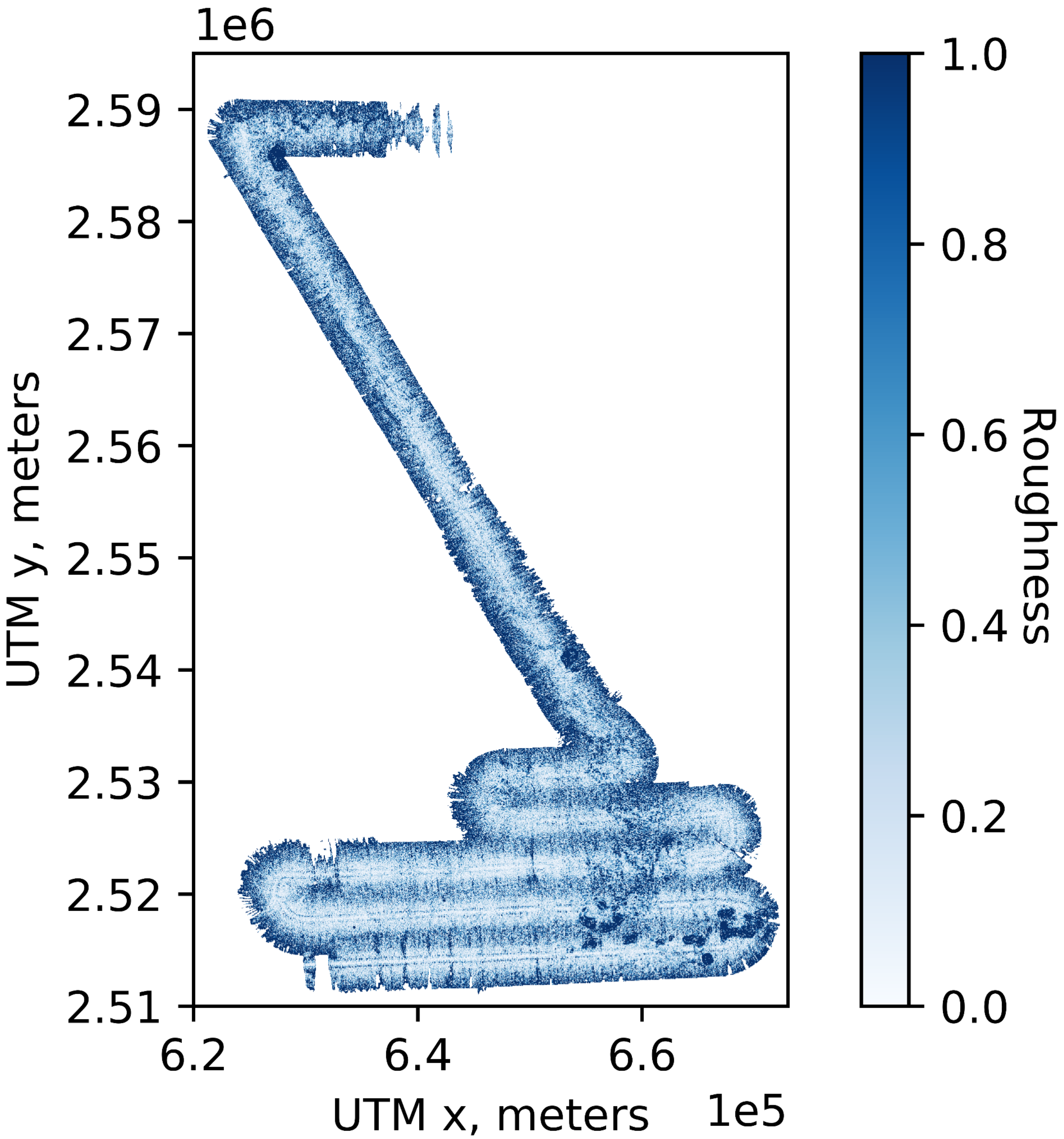


Figure 4. Roughness map of the overall survey area. The lighter colors correspond to a roughness of 0 (very smooth) with the darker colors showing more rough surfaces (with a maximum roughness of 1).

To recap, figure 2 shown above in the methods section is the main chart of the survey field but with the trackline plotted as well as found lava flows plotted (Pfluger, 2022). The lava flows here were found through collected Knudsen data at the same time that bathymetry data was collected. Because information on lava flow boundaries was gathered, I could enlarge the scope on specific areas to see whether or not areas of high roughness corresponded to lava flows or lava flow boundaries. Figure 2 most notably shows a “flat” lava flow on the western part of the survey track, a rather large and continuous lava flow in the southeastern quadrant of the survey area, and a large lava flow spanning the top portion of the area. The aforementioned areas of the map have been zoomed in on in both bathymetry and roughness to compare the location of the lava flows and the location of high roughness areas.

Figure 5 contains bathymetry and roughness charts of the “western lava flow.” This lava flow is perhaps the most intriguing lava flow of the survey area due to this flatness. There is only about a 100m change in depth over the whole area, and this general flatness is backed by the roughness data. At first glance, the roughness data seems to show its usual noisy outer swaths and smoother centers. However, at a second glance, there appear to be bands of higher roughness throughout the area on the lower trackline. Most of these bands of higher roughness on the lower track correspond with the location of known lava flows, as is seen in the bands at 6.39×10^5 UTM x and 6.41×10^5 UTM x. However, there are also bands of higher roughness that don’t appear in the location of known lava flows as seen in the bands at 6.36×10^5 UTM x and 6.43×10^5 UTM x. The band at 6.36×10^5 UTM x may line up with a known lava flow, but it is difficult to tell as the Knudsen data is limited to a single beam directly under the ship. The lava flows on the upper track are longer, and easier to spot the darkening of blue that lines up with them.

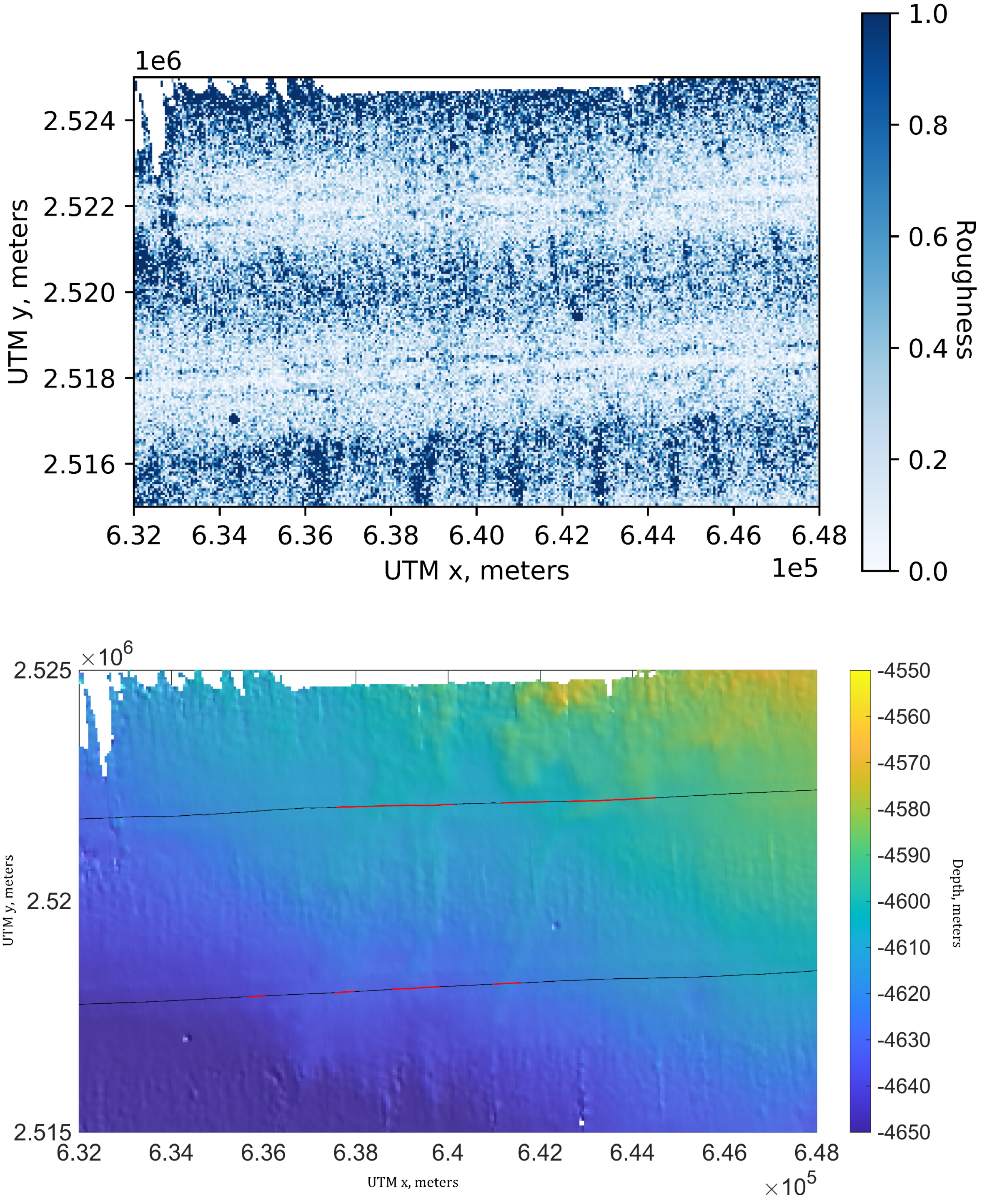


Figure 5. The top portion of the figure is the roughness chart for the "western" lava flow. The darker blue the point, the more rough the point is. The bottom portion shows the bathymetry and lava flow data, with the trackline highlighted in black and known lava flows highlighted in red.

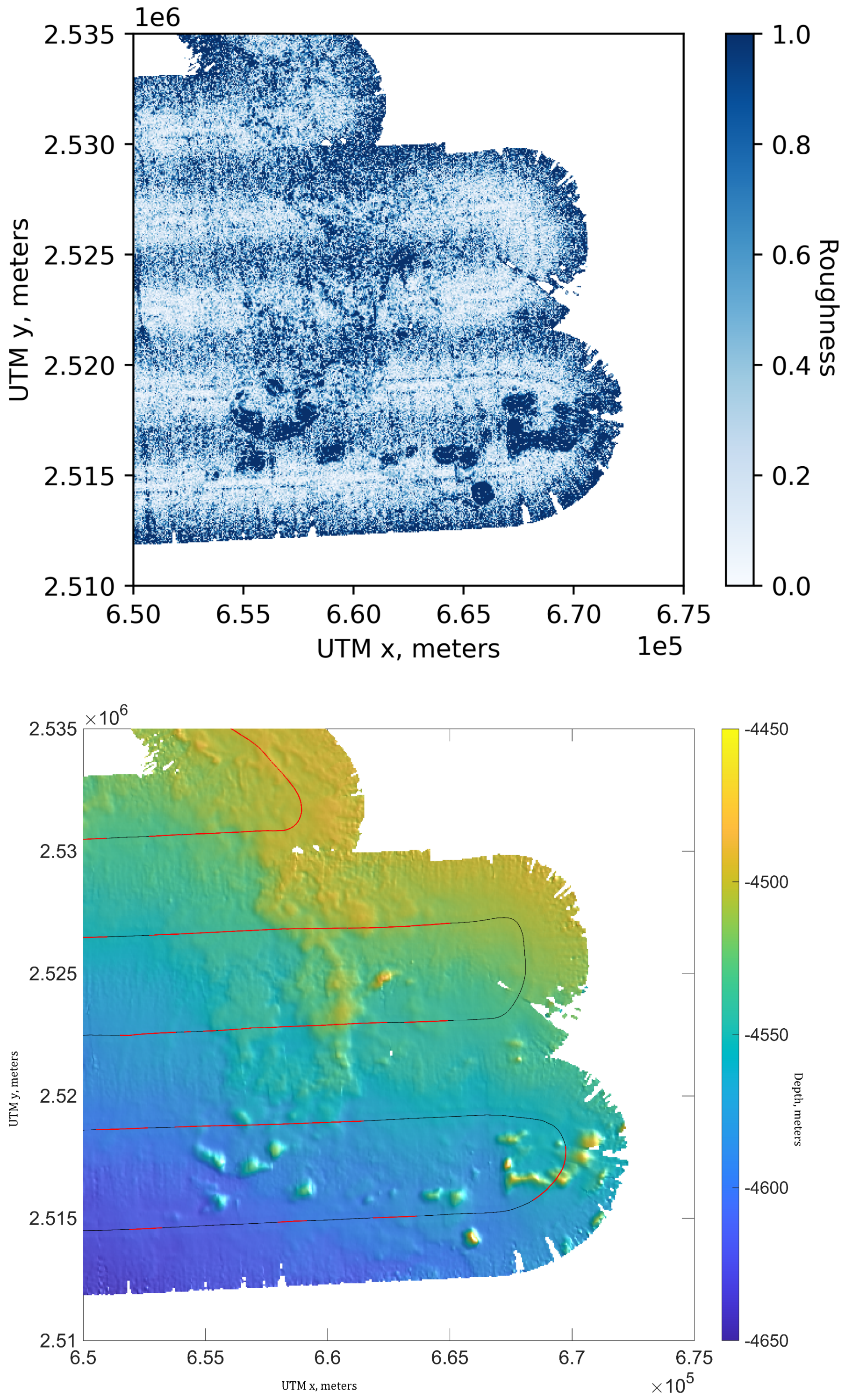
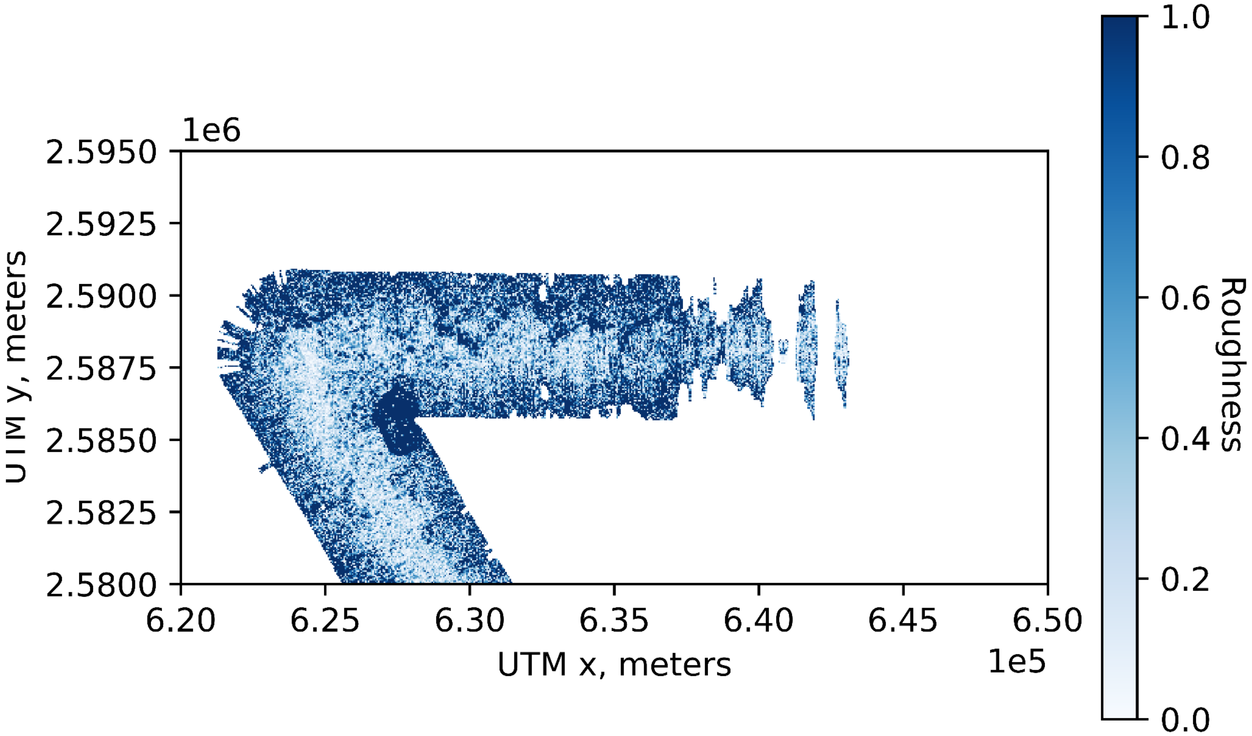


Figure 5. The top portion of the figure is the roughness chart for the "eastern" lava flow. The bottom chart shows bathymetry data, with trackline outlined in black and the lava flows highlighted in red.

Figure 5 shows a large portion of the "eastern" lava flow. This lava flow covers a large area and has intermittent seamounts as can be seen in both the bathymetry and the roughness map. The seamounts are characterized by steep decreases in seafloor depth while they are shown in the roughness graph by the extremely dark splotches of roughness that reach the maximum roughness the chart allows. What is most important about this roughness chart is that it shows that areas of increased roughness agree relatively well with what's known about lava flows. The large center area (from 6.55x10^5 UTM x to 6.65x10^5 UTMx and 2.512x10^6 UTM y to 2.535x10^6 UTM y) is covered in a lava flow, and the whole area is covered by high roughness values. Additionally, the eastern parts of this graph show a relatively flat area (despite the noise from bathymetry errors) which is expected as an area without lava flows.



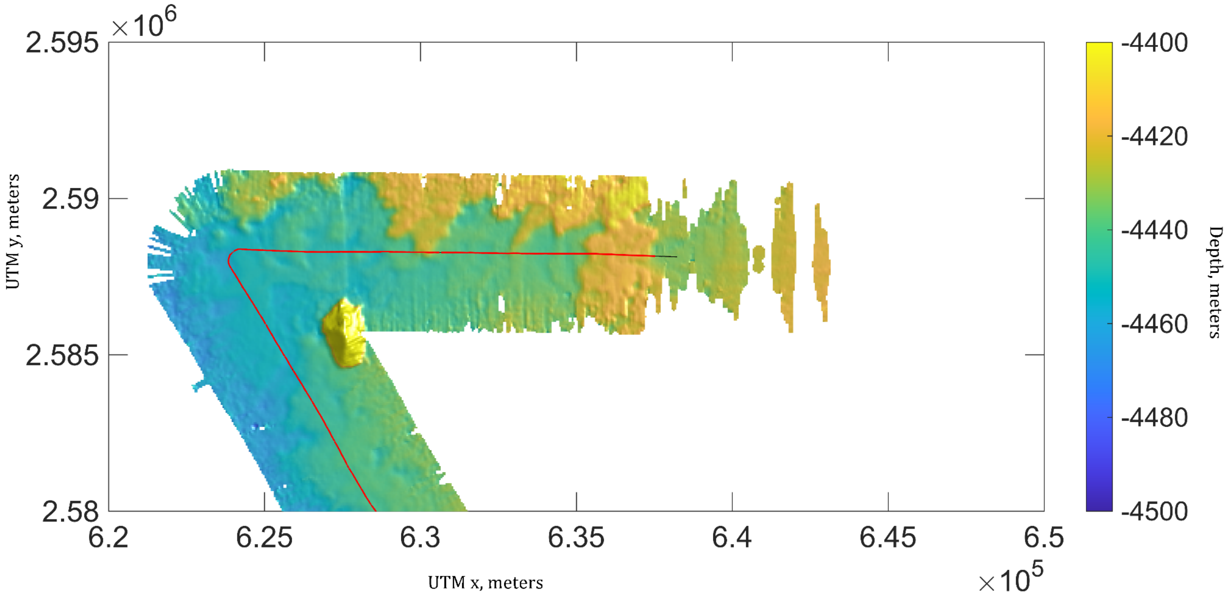


Figure 6. The top portion of the figure is the roughness chart for the "northern" lava flow. The bottom chart shows bathymetry data, with trackline outlined in black and the lava flows highlighted in red.

Figure 6 shows the "northern" lava flow. The lava flow in this area of the survey is entirely encompassed by a lava flow, so looking at lava flow boundaries compared to sediments won't be possible. What is interesting however, is that there appears to be a layer of something on top of the lava flow in the northern part of the area, as evidenced by the steep change in depth at this area. This is hypothesized to be a lava flow on top of another lava flow. This boundary of the change in layers is actually reflected in the roughness chart; along the northern part of the survey area there is a sharp increase in roughness which shows the edge of the boundary, and then it decreases again. The entire chart contains a lava flow, but the sharp increase in roughness along the boundary matches the expected pattern of a lava flow boundary, as seen on the upper parts of the track.

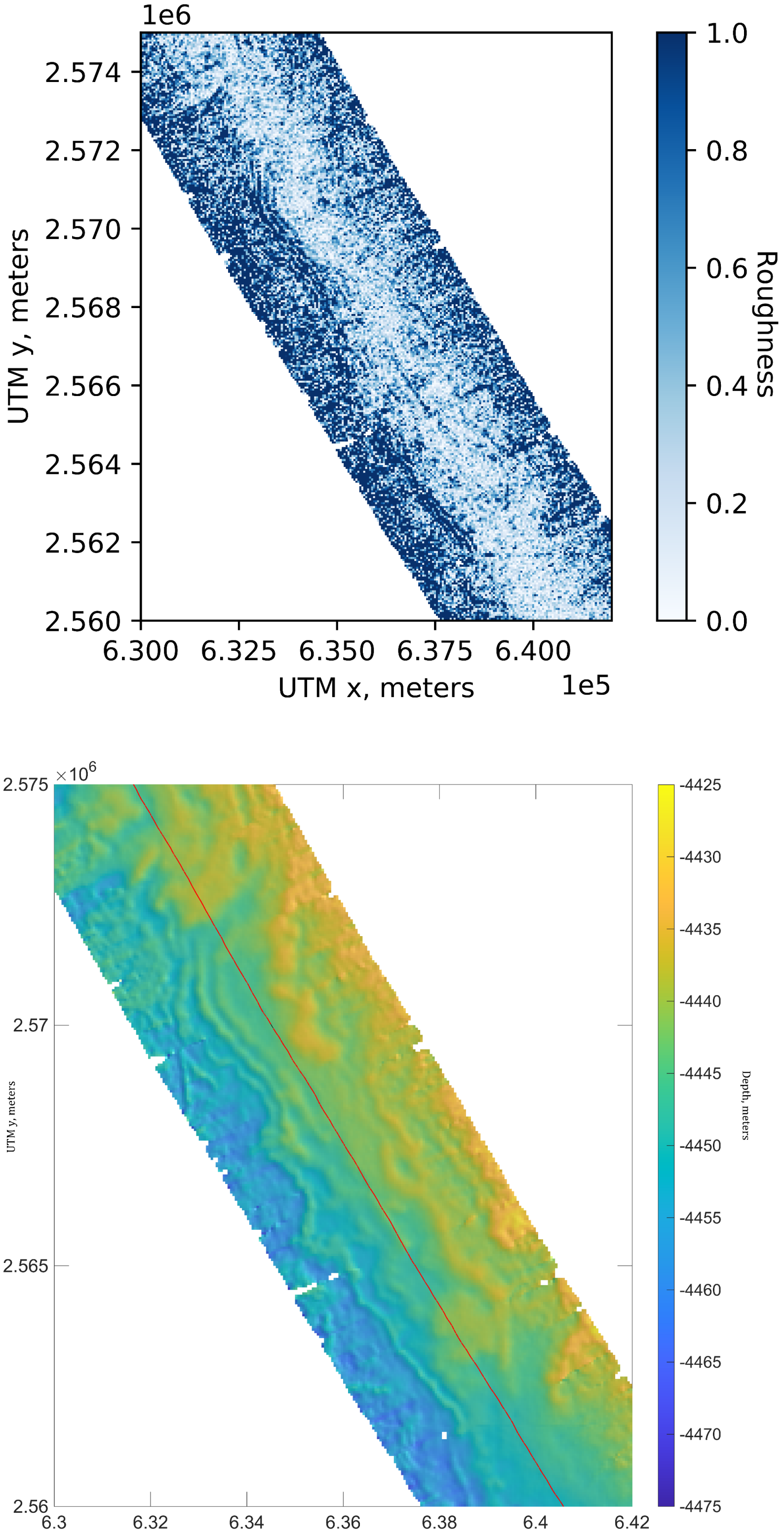


Figure 7. The top portion of the figure is the roughness chart for a feature in the survey area. The bottom chart shows bathymetry data, with trackline outlined in black and the lava flows highlighted in red.

Figure 7 shows an area of the survey fully covered with a lava flow. As such, confirming the existence of lava flows and their boundaries isn't exactly possible. What is possible however, is looking at the shape of the roughness graph, to see if there's anything of interest to point out. There is a strong band pattern on the western part of the roughness graph, despite seeing this wavy pattern all over the bathymetry data. This may potentially belong to a channel from an eruptive fissure, the presumed source of the lava flows.

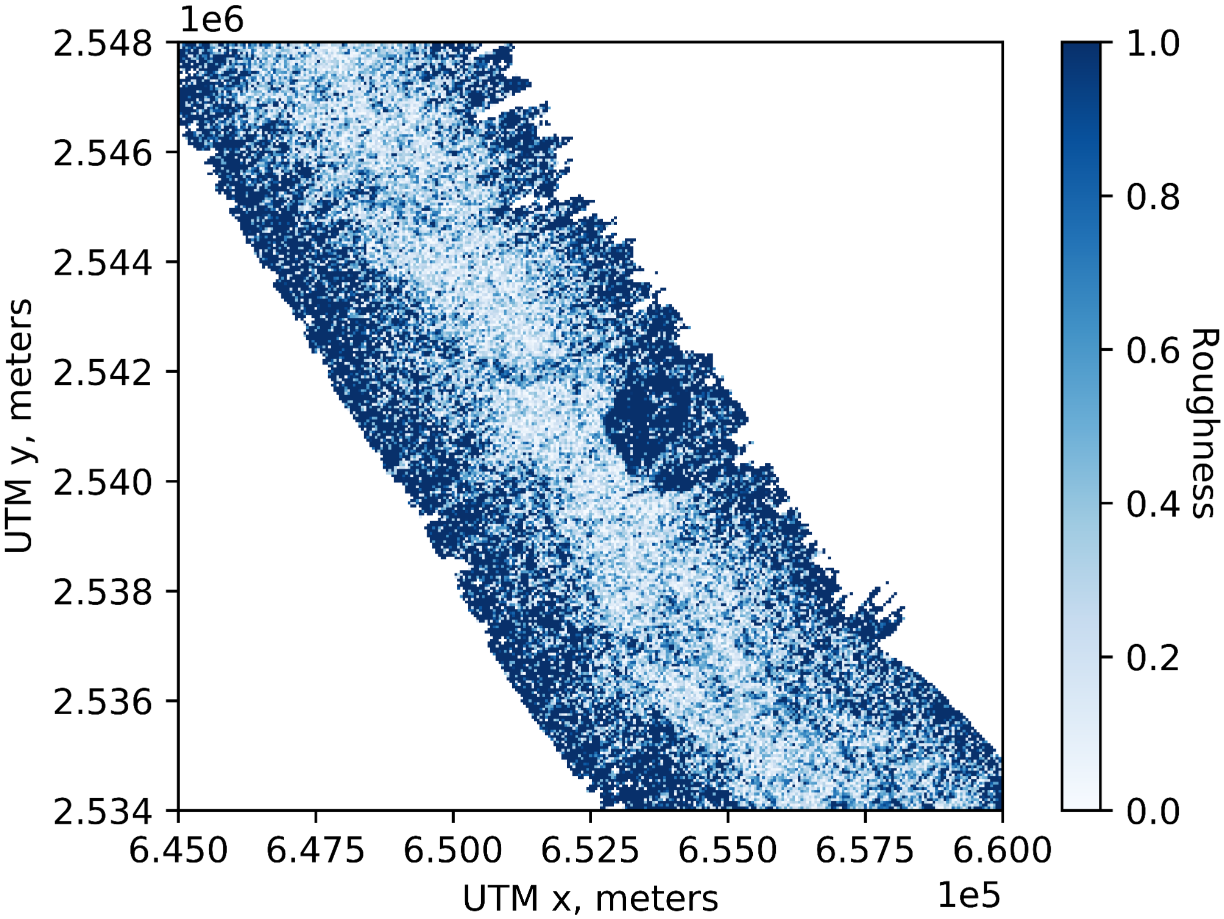


Figure 8. A single panel chart, showing only roughness data on an enhanced area of the overall survey.

Figure 8 is unique in that there is not a bathymetric map created to compare to. This can give a better picture as to what roughness is able to accomplish on its own. Around $6.525\text{x}10^5$

UTM x to 6.55x10^5 UTM x and 2.540x10^6 UTM y there is a large area with a concentration of high levels of roughness. This feature is similar to previous examples of the location of a seamount. Other features that are visible are small band-like increases in roughness, one located from 6.5x10^5 UTM x to 6.55x10^5 UTM x and 2.542x10^6 UTM y, and another easily located from 6.475x10^5 UTM x to 6.525x10^5 UTM x and 6.545x10^6 UTM y. The whole area is covered in a lava flow (which is not pictured, but known to be true), so these areas don't correspond to boundaries, but perhaps to other features that should be studied. There may be other bands in this area, especially closer to the southern part of the trackline, but it is difficult to make out due to high amounts of noise.

Discussion

Because of the need for the methods that can be used to explore and uncover scientifically interesting geological features on the seafloor, the roughness calculation used in this study was created in an attempt to contribute to the available tools for seafloor exploration. he roughness calculation outlined in this paper has its merits in that it is intuitive and simple for humans to understand, cheap for computers to calculate, and the only prior information required is bathymetry data. A single multibeam echosounder system is able to calculate bathymetry from a survey area. However, it is nearly impossible to point out most scientifically interesting features on the seafloor from bathymetry data alone, and in the case of the North Arch Volcanic Field, it is unable to locate every lava flow. An additional tool is required to do so, and in this survey, the Knudsen single-beam system was used for that purpose. The location of the lava flows could be then compared to bathymetry-derived roughness in the attempt to confirm the location of lava flows. The calculation for roughness was used in conjunction with Knudsen echo sounder (lava flow) data and bathymetry data to see if roughness was able to find the lava flows and lava flow boundaries.

It can reasonably be concluded that the roughness calculation can be used at the very least to point out features and locations in a previously surveyed area that should be further studied. From comparing the lava flow data and the roughness calculations, much of the areas of high roughness corresponded with areas of lava flows (this is easier to see in the eastern lava flow, but evidence still aligns in the western lava flow). At the same time, there are also locations of higher roughness that do not correspond with the lava flow data. Geological features like seamounts, fissure channels, ridges, and boundaries may also be reflected in the roughness data. Regardless of if the lava flow data is incorrect, or the roughness calculations are incorrect, or perhaps both are accurate, it signifies an area that should be further investigated with different tools. With just simply bathymetry data, roughness can be calculated from it, and it can highlight regions of interest for further studies. The North Arch Volcanic field was used as a case study to aid in finding this out, due to the fact that there was both bathymetry data (which is required for the roughness calculation) and lava flow data (which is not a given in any specific area and was used to confirm if roughness highlighted regions of interest). Not only was roughness useful for confirming the existence of lava flows, it also may have pointed out regions to be explored further in future research. Such as the regions shown in figure 6, 7, and 8. Despite the whole region already being covered with a lava flow, they still found patterns of roughness that are unique and should be researched further.

Despite the calculation for roughness being quantitative, the results are being discussed in a qualitative manner. There are many important caveats to keep in mind. The current roughness calculation is extraordinarily simple, and thus may be less accurate than desired. Many approaches detailed within Fox and Hayes are more difficult to understand and compute, but may highlight regions of interest with better accuracy. Additionally, the original bathymetric data set from the North Arch Volcanic Field used to calculate roughness is full of noise and error, partially due to unfavorable conditions during sampling and natural errors of the sampling system. Finally, the North Arch Volcanic field is a perfect location for a case study in the effectiveness of roughness due to the fact that the lava flows are relatively young. The effectiveness of roughness in identifying lava flows and lava flow boundaries decreases with age. The main hypothesis is that lava flows are rougher than surrounding sediment because of the buildup of settling sediment due to gravity. Through time, the lava flows could eventually be covered in sediment, and thus become flat again. If roughness were to be calculated both with a more accurate algorithm and with cleaner bathymetry data, a more concrete conclusion may have been able to be reached.T

Conclusion

The combination of lava flow data and roughness data was able to loosely confirm the location of lava flows, as evident in the western lava flow and the eastern lava flows (figures 5 and 6, respectively). Roughness was increased generally in areas where lava flows were located, as predicted by the main hypothesis of the project. The northern feature depicted in figure 6 clearly showed a layer of some sort on top of another layer, with the whole area covered in a lava flow. Roughness at this location was increased on borders of the boundaries between the two layers, following the pattern for what was expected to happen at boundaries as described by the main hypothesis. There are other features such as shown in 7 and 8, that do not directly relate to the existence of lava flows, but follow an unexpected pattern, prompting further research in the area.

The method used to create the roughness maps as well as the steps taken to analyze the roughness maps in conjunction with the bathymetry maps can prove useful to reveal information about the seafloor at any location. This can be applied to any area that has griddable data and information about other things of note on the seafloor (like lava flows) to confirm the location of lava flows, or applied to areas with only bathymetry data to inform future studies on the area. Bathymetry studies in locations with good conditions would be even more useful in finding seafloor features as the roughness maps would be clearer and full of less artifacts. The roughness calculation can confirm the location of lava flows and can be expanded to find other seafloor features with a relatively simple calculation from bathymetry data.

Because of these attractive features of the roughness calculation, it may be used in future locations that have high-quality bathymetric data. With enough changes to the roughness calculation to increase accuracy, it could even be applied to artificial intelligence algorithms or machine learning on large bathymetric data sets to automatically identify or confirm geological seafloor features, without the need for an expert to sift through all of the data, effectively becoming a tool used to paint a more complete picture of the seafloor.

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