Determining the makeup of the highly reflective crust layer on White Island, New Zealand through the uses of ground penetrating radar

Rachel Lupien

Abstract

Ground penetrating radar (GPR) data was collected by Amy Dougherty and her team on White Island (Whakaari), New Zealand in early 2011. This data along with cores and field observations were used to map the subsurface. The goal of this study is to identify the makeup of the “crust”. The layer acts as a crust by keeping gasses from escaping and it appeared in all of the charts at about 1 meter below the surface. It appeared strongly due to its extremely low conductivity of the GPR’s electromagnetic rays. Four theories as to what the crust is have been developed and analyzed. (1) The Phreatomagmatic Theory posits that an entire phreatomagmatic eruptive period (1977-82) on White Island could be the cause of this highly reflective crust. (2) The Hydrothermal Theory puts forward the prediction that the acidic hydrothermal water that exists on White Island altered the rock up to this point in the stratigraphy. It also includes predictions of ore deposition and hydrothermal precipitates. (3) The Glass Theory highlights an eruption that took place in 1987 that produced a rock material made up of blocks that has a quenched glass matrix. (4) The Time Gap Theory states that the crust is present due to a quiet eruptive period. The time gave the surface rock a chance to weather and now it is buried under younger volcanic rocks. Considering what exactly makes a rock have a low conductivity of electromagnetic waves (high porosity and high density), the Time Gap Theory is the most likely. It is a common phenomenon and the theory includes all of the criteria such as the rock has a low conductivity and it is hard (as the core discovered). However, in conclusion, a physical and chemical analysis must be done on this crust rock to determine what exactly makes it up.

Introduction

Amy Dougherty lead a team in 2011 to map the subsurface of White Island (Whakaari), New Zealand using ground penetrating radar (GPR) technology. Graphs and images were produced and they show where gases escape in the form of fumaroles through the layers of rock. GPR imaging shows the differences in rocks based on their respective conductivities. There is one layer that appears in all of the graphs that has an extremely low conductivity (or high reflectivity) and it has been named the “crust”. With coring technology, it was discovered that the crust could not be penetrated because it is very hard. The goal of this study is to present theories on what type of rock comprises this crust. There will also be a commentary on the usefulness of GPR as a method of studying active volcanoes.

The GPR is able to map the subsurface and by doing this we are able to tell which rocks have properties pertaining to density, conductivity, location, and thickness. It does not, though, tell us what the rock is in actuality.

There is no literature available on the uses of GPR on active volcanoes because it has not been done before. However, there are many sources that have been pieced together to make the background of White Island very clear. J. W. Cole has created a very straightforward stratigraphy of the north and south ends of the Central Cone. He also presents drawings of structures, maps, and composition tables. This groundwork has been done to aid other scientists, such as myself, in further studying the workings of White Island.

Background

White Island is New Zealand’s most recently and most frequently active volcano. It is located 48 km off the coast of the Bay of Plenty and is a part of the Taupo Volcano Zone (TVZ). It is the northernmost active volcano in the TVZ, which is formed by the Pacific Plate subducting underneath the Australian Plate. White Island is an andesitic stratovolcano with two overlapping cones. The Central Cone is where the GPR work was done and where the crust layer has been noted (the other is the Ngatoro Cone). The island is the top of a large submarine volcano, which lies in a graben structure. (Bickerton)

There is an acid hydrothermal system that is chemically sealed from the seawater and saturates the ground. (Ingham) It is possible that this hot, acidic ground water alters the volcanic rocks or produces deposits.

There was a period between 1977 and 1982 of phreatomagmatism. (Bickerton) This process combines eruptive magma and hot water to form a fine-grained, well-sorted rock with few vesicles. (Heiken) During 1987 there was still magma being erupted that had phreatomagmatic characteristics. There was one eruption in particular that produced a blocky rock in a quenched glass matrix. These phreatomagmatic eruptions were viscous and, unlike strombolian eruptions, the lava was not spewed so high. Rather, they may have caused a plug in the vent of the Central Cone. (Wood)

The GPR data was collected by Amy Dougherty and her team. They took a total of six transects including a circular path around a mud pool and over a mound where gas is hypothesized to be building up. The crust appears in every transect and is generally continuous throughout. It is typically at a depth of one meter but gets as low as two meters below the surface and as high as ¾ of a meter below the surface. It is parallel with topography. Fig. 1 is a GPR image collected and produced by Dougherty showing where the highly reflective crust layer is.

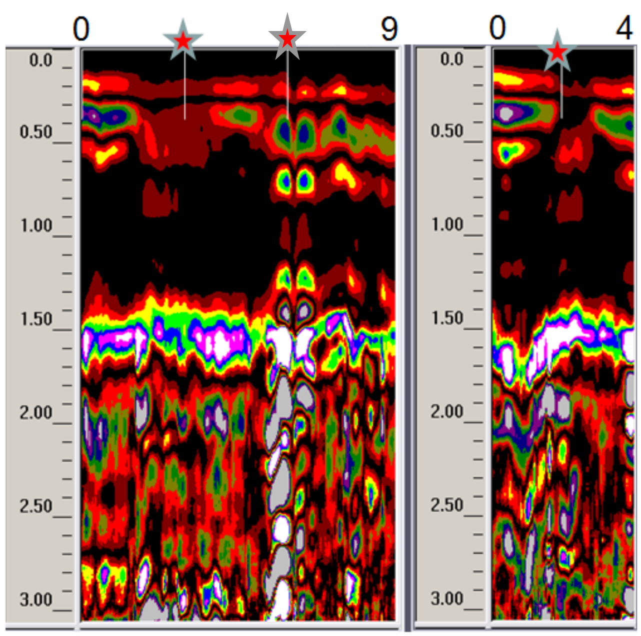

Figure 1. The crust layer is shown with the white highly reflective coloring at about 1.5 meters depth. Where the crust is not continuous is marked with red stars.

The crust has a low conductivity, which is why it appears to be white on the GPR images. A low conductivity means that the electromagnetic waves emitted by the GPR are not absorbed by the rock but instead bounce off. Density and porosity are the main factors that determine a rock's conductivity. The higher the porosity and the denser the material, the lower the conductivity.

Methods

A literary and interview study was conducted while using the GPR data that was already collected. The parameters for the GPR are such that the antenna was 200 megahertz and the range varied from 100-300 nanoseconds. The transects were done twice: once for a low quality deep picture (at 300 nanoseconds) and once for a higher quality image of the more shallow subsurface (at 100 nanoseconds). (Dougherty)

The general GPR data collecting methods are as follows. While dragging along a box in a transect line, the data collector clicks a button to shoot a radar beam of electromagnetic waves down into the ground at the specified depth. These clicks are a specified distance apart (which is later corrected because the GPR software reads in terms of time) along a transect line that includes the desired study area, such as a fumarole or a mud pool. Another member of the team holds a laptop computer that is live streaming the information that is being received by the GPR. Once the transect is collected, topography surveyed, and lengths calculated, all of this information is put into the computer program, RADAN. The program runs the information and produces a figure that can be read to determine the make-up of the sub surface. On a volcano, however, this may be more difficult, because the GPR is typically used on sediments.

Results

After looking at the data and literature that were presented, a few theories regarding the nature of the crust were developed. It is known that the crust is very hard because the cores that were taken were unable to penetrate it. The active eruptive history of White

Island is very recent, which makes the 1 meter deep crust harder to determine because there was a lot of material produced in a short amount of time. The surface of the island contains vents, mud pools, craters, and other formations that make the topography variable and interesting. Detailed accounts of past eruptions help to narrow down the possibilities. Four theories will be laid out and then discussed later on.

(1) The Phreatomagmatic Theory. The period from 1977-82 was filled with phreatomagmatism for White Island. This material, as described previously, is fine grained and has few vesicles, making it hard. This rock type is strongly welded as hot fluids were involved. The rock cooled very quickly once it was erupted. These properties may lead the GPR to read it as having a low conductivity because of its high porosity. These characteristics may be enough to determine this as the crust layer.

(2) The Hydrothermal Theory. Ingham describes the hydrothermal system of White Island as being acidic; therefore it must alter the rock it comes in contact with to some extent. This process may have altered the rock from underneath. Because the rocks are saturated with precipitation ground water, the water table may rise fairly high. Perhaps the edge of this acidic water infiltration has chemically changed the rock to make it harder and more reflective of the radar. This process may form a crust. Another way that this hard crust could have been produced is by ores precipitating out. There is hot water flowing through the rock underneath the ground. This circulating hot water could allow hard metal ores to form, making a crust layer. The hydrothermal system could also have formed a precipitate such as silica or acid sulfate. (Cowlyn) This material would have different properties than the volcanic rock making up the rest of the ground. (Wetzel)

(3) The Glass Theory. In 1987 there was an eruption of phreatomagmatic character. Wood describes this eruptive mixture as having a different composition than most White Island eruptions. It was highly peralkaline and perhaps altered. The bombs in the magma contained a glass matrix. Perhaps this quenched material is

the crust. The radar beams may react strongly to a glassy product because it has a high porosity. Because it was only one eruptive event, the layer would be very thin, like the crust layer. Also, glass does not have a very strong hardness on the Mohs scale, but if the glass was mixed in with volcanic rock, perhaps it gave it some strength. After all, the layer was impenetrable, not just the individual minerals.

(4) The Time Gap Theory. After the phreatomagmatic eruptivity ended in 1982 there was a quiet period until 2000. Conceivably, this gap in eruptions would give the chemical weathering time to work on the surface of the rock. This chemical weathering would make the rock have a higher porosity. (Karpuz) With a higher porosity comes a higher reflectivity of the electromagnetic waves. The rocks that were weathered at the surface during this gap in eruptions may have been reworked into streams and other systems, making them harder perhaps because of a change in mineralogy. (Cowlyn) Once the surface had time to weather and be reworked, it was then buried again by new eruptions (probably by the ones that took place in 2000). It is possible for the surface layer that was weathered to appear about a meter below the ground as a hard rock material with a low conductivity. With this time gap, too, would come a small gap in space. The rock deposited on top of the weathered surface would not form a perfect seal.

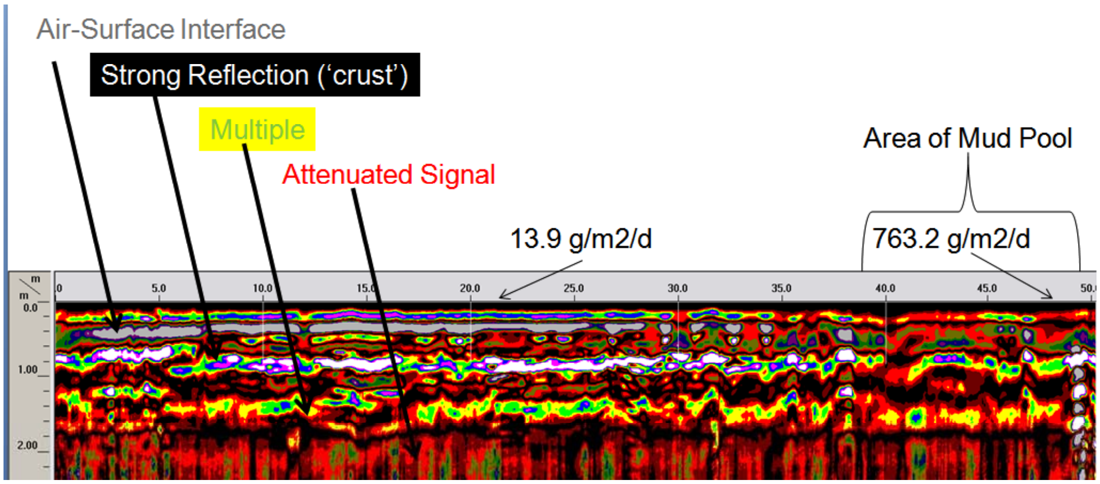

Figure 2. One of Dougherty's GPR images pointing out how the different reflective layers are interpreted.

As we see in Dougherty's GPR image, there is the air-surface interface that the GPR always picks up. This layer is right below the surface and appears to be extremely reflective of the rays. Perhaps there a slight air gap due to the quiet period and it is now reflecting back the electromagnetic rays of the GPR in the same manner as this.

These theories will be examined further. Because GPR is a way of mapping the subfurface, it is useful for many things. It has led to the creation of these theories because it found a strange crust-like layer. However, GPR can only go so far, as it cannot actually tell us what the type of rock is. Only with exact dating and chemical analysis will the crust be identified.

Discussion

Extensive literature review was done in order to evaluate each theory on what the crust material is. Here, each theory will be discussed and an explanation will follow on why it is or is not plausible. Even though a theory is plausible, however, the actual answer will not be known without a chemical and physical analysis of a sample of the crust.

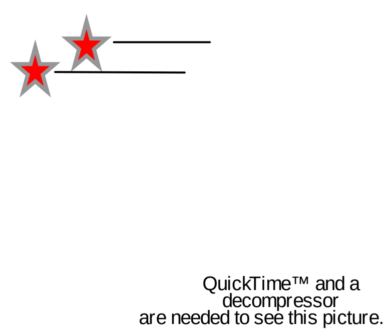

Figure 3. The stratigraphic columns for the north and south sides of the Central Cone of White Island are here. The northern stratigraphy is on the left and the southern is on the right. Although the southern stratigraphic column is cut off here, the northern one is shown in its entirety.

(1) The Phreatomagmatic Theory. Cole's stratigraphies in the Central Cone show two phreatomagmatic layers. One is at the very top and one is the third unit of the northern stratigraphic column (represented as white with black dots). The northern stratigraphy (on the left) has more prominent layers of this rock than the southern stratigraphy (on the right). The transects that were looked at with GPR were located in the western central part of the Central Cone. Therefore, these phreatomagmatic layers certainly may exist there but may be thinner than they are presented in the northern stratigraphy. The scale on these stratigraphic columns is so that the northern column is a total of approximately 200 meters thick, meaning that the second starred layer would be about 10 meters in the field. The composition of a phreatomagmatic rock would make it appear as highly reflective in the GPR graph. However, the stratigraphic columns may show the layer as being too thick. The time period that the phreatomagmatic eruptions took place in (1977-82) may simply be too much time to produce only half meter thick crust layer. (Houghton) The stars in Fig. 3 show the two phreatomagmatic layers that could be the crust. The first one, however, is too shallow: in reality, the crust is buried one meter below the surface. The second one, as just discussed, is too thick to represent the one half meter thick crust. The rock makeup fits the mold to be the crust, but this is not represented on the stratigraphic columns.

(2) The Hydrothermal Theory. It is probable that the crust layer is somewhat altered hydrothermally. There is a large amount of very hot acidic water flowing underneath the surface. In addition, the area where the transects were taken were over vents and crater walls. These crater walls are a series of faults creating a graben-like structure. The faults enable the transfer of water from close to the heat source (the magma) upwards towards the surface. (Dougherty) As we look at the graphs that the GPR team produced, it is obvious that the crust layer is parallel with the surface of the ground, because topography is corrected for in the charts. If the topography was not corrected for and there was an internal heat source altering the rocks to form the crust layer, then it would be a simple horizontal line. However, it is parallel to the surface and not parallel to the heat source (and we know this because it is horizontal when the topography *is* corrected for), which

leads to the thought that the crust is in fact a stratigraphic layer. Although it is most likely a stratigraphic layer, its highly reflective property may be caused by hydrothermal alteration. The crust rock would need to be analyzed and checked for typically hydrothermal alteration minerals, such as quartz and chlorite. (Wetzel) However, if the rocks were hydrothermally altered, there would not be just one layer. Everything below the crust layer would also be highly reflective. This theory is not plausible, but may be combined with another idea to pinpoint just what the crust material, which will be discussed later. The idea that the hydrothermal system may have caused ores to be produced is also not plausible. The layer is only one meter deep, meaning that it is fairly young. Ores take a long time to be produced and the crust would need a lot of this hard metal material to appear so strongly on the GPR. A precipitated layer such as silica or acid sulfate may by hard, but it would not appear as such a continuous and even layer as the crust does. The crust was found in all of the transects that Dougherty's team examined. Because it is constant over a large area, it is probably not just a simple precipitation event. White Island's hydrothermal system probably has something to do with the crust layer, however it is not the sole cause.

(3) The Glass Theory. The eruption that Wood describes as cooling in a glass matrix is a more plausible cause. As described above, this eruption in 1987 was phreatomagmatic and the rock cooled as blocks within a glass matrix. Glass forms due to immediate quenching before grains have time to form. This process makes for a hard material that would be highly reflective under GPR rays. Because this type of eruption occurred only one time, it would make sense that it was just a thin layer. Also, it happened fairly recently, so it is reasonable that the stratigraphic crust layer is only about one meter underground. The reason that the glassy layer does not show up in the stratigraphic columns produced by Wood is because it is simply another type of phreatomagmatic rock so it is classified as such. Most of the criteria for the identification of the crust are met with this theory: it is a layer of stratigraphy, it is thin, it has a high porosity, and it is close to the surface. However, glass is not dense. This aspect probably is involved in the makeup of the crust because to have an extremely low conductivity (which the

crust has) it must have a high porosity *and* be dense. Once a physical and chemical analysis have been done on the rock, we will be able to know for sure if the high reflectivity of the crust is due to the matrix being glass.

(4) The Time Gap Theory. This theory is the most plausible because this process occurs often. Discontinuities are common because material is not deposited at a constant rate. Exposure to air and earth processes altars rock and it is then buried. It is not difficult to see the variation in rock that has been weathered in a rock face or road cut with a naked eye. The time gap would affect the entire surface equally, which would account for the fact that the crust layer is continuous. It also must be hard but have a high porosity. Chemical weathering would cause both of these properties to occur, as discussed above. The gap in space that would occur due to a lag in the eruptions of White Island could be accounted for by the lowly conductive layer. The hard aspect of the rock may come from the actual surface and the low conductivity may come from the air-surface space. This theory includes all possible plausible explanations for the production of the mysterious crust-like layer.

Conclusion

The Time Gap Theory answers the ambiguity of the crust layer at White Island in New Zealand. It is possible, however, that the explanation lies in a combination of theories. Because there is such an active sealed hydrothermal system on White Island, alteration and precipitation are likely. Perhaps within the space gap that is present due to the lack of a perfect fit between old weathered rocks and newly erupted rocks there is a hydrothermal precipitate. Although it was said that this space might be what caused the GPR to pick up a highly reflective layer, perhaps it was not. It is possible that the hot fluids traveled into this space gap and precipitated out some sort of hydrothermal material. This would explain the precipitate being a continuous thickness and having different properties than the surrounding rock. Although, it would be difficult for this rock to have such a low conductivity of the GPR's emissions. Hydrothermal activity could also have altered a certain type of rock to change its properties so that it has a low conductivity, high porosity, and strong behavior. Because this hydrothermal water would alter all of the rock below this point, as well, the crust must have been a different composition, such as a rock with a glass matrix. It is possible that this small glassy eruption formed a thin layer of rock containing different properties than the surrounding rock. It was then buried and hydrothermally altered to have a high porosity and a strong structure. There are more ways that these theories could be combined to explain the existence of the crust. However, GPR is a way of mapping the subsurface and cannot tell us exactly what the rock is made up of. To determine the material, it is necessary to retrieve a sample and do a chemical and physical analysis.

GPR is a new technology that is beneficial, especially compared to its alternatives. It maps a planar transect, which only trenching, before, could do. However, trenching is highly intrusive. Property owners do not want their land cut up. GPR allows a transect to be computer analyzed and the results appear as the research is being carried out. As the box is dragged over the desired area, the computer program RADAN is producing graphs. If there is an issue, the process can be stopped right away. There is no cost to run multiple transects and it takes very little extra time. Coring is an easy option, but it only looks at a point. It is expensive to go far down into the earth, while GPR is simply a push of a button. With multiple cores, one would be able to put together a transect or even a three dimensional map, but that would take time and may not be accurate. Coring could miss faults, as well, which is a main reason to do subsurface mapping in the first place. GPR is very useful, non-intrusive, cheap (once the technology is acquired), and quick. Although it is extremely successful, it must be noted that the goal of GPR is to map subsurfaces. This mapping technique is not able to determine what type of rock is being looked at. Scientists are able to infer the type of rock based off of these maps, but cannot be fully certain. However, it is not useless, because it alerts scientists to the existence of certain materials, such as the crust.

Amy Dougherty’s study was the first instance of mapping the subsurface of an active volcano using GPR. Prediction of the eruptions of volcanoes is a desirable ability and GPR may give us a way to do this sooner and more accurately than other techniques. Heather Bickerton did a study on the carbon dioxide levels on White Island. She concluded that this was a good way of predicting volcanic eruptions because CO_2 level change is a very early indication of when an eruption will occur. CO_2 is released from vents and other geological features in the ground. GPR is able to map these openings. If these CO_2 emitting gaps are located, we will know where to put a remote sensing apparatus. (Bickerton) White Island, however, does not endanger anyone (except for scientists at work and tourists) because it is in the middle of the ocean. Nevertheless, these practices can be applied to other active volcanoes to create an early warning system for evacuation. GPR research is useful in many ways and it is safe to have subsurficial maps of dangerous areas such as active volcanoes.

References

Bickerton, Heather. "CO_2 Survey of White Island Volcano, New Zealand." Thesis. University of Canterbury, 2011. Print.

Cole, J. W., T. Thordarson, and R. M. Burt. "Magma Origin and Evolution of White Island (Whakaari) Volcano, Bay of Plenty, New Zealand." *Journal of Petrology* 41 (2000): 867-95.

Cowlyn, James. "Frontiers Abroad Project." Message to the author. 23 May 2011. E-mail.

Dougherty, Amy J., 2011, Field Report: Ground Penetrating Radar and Infrared Thermography on an active volcano, White Island, New Zealand. Institute of Earth Science and Engineering Internal Report

Dougherty, Amy J. Message to the author. 21 May 2011. E-mail.

Heiken, G., and K. H. Wohletz. 1985, *Volcanic Ash*. University of California Press, Berkeley, California, 245 pp.

Houghton, B. F., and I. A. Nairn. "The 1976–1982 Strombolian and Phreatomagmatic Eruptions of White Island, New Zealand: Eruptive and Depositional Mechanisms at a ‘wet’ Volcano." *Bulletin of Volcanology* 54.1 (1991): 25-49.

Karpuz, C., and A. Paamehmetoglu. "Field Characterisation of Weathered Ankara Andesites." *Engineering Geology* 46.1 (1997): 1-17. Print.

Wetzel, Laura Reiser, Jeff P. Raffensperger, and Everett L. Shock. "Predictions of Hydrothermal Alteration within Near-ridge Oceanic Crust from Coordinated Geochemical and Fluid Flow Models." *Journal of Volcanology and Geothermal Research* 110.3-4 (2001): 319-41. *Science Direct*. Web. 21 May 2011.

Wood, C., and P. Browne. "Chlorine-rich Pyrometamorphic Magma at White Island Volcano, New Zealand." *Journal of Volcanology and Geothermal Research* 72.1-2 (1996): 21-35.