Using MODIS Satellite Imagery to Find Pumice Rafts from Submarine Volcanic Eruptions

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ABSTRACT

Large rafts made of pumice can form from submarine volcanic eruptions and float on the surface of the ocean for months. The largest known deep-water silicic submarine eruption came from Havre in the Kermadec arc in July of 2012. Using MODIS satellite images, I tracked this eruption through time in the style of Jutzeler et al. (2014). Then, I combed through more MODIS images searching for more pumice rafts. I found six pumice rafts between the years of 2004 to the present and compared them to seismic data, but I was unable to trace any of them to their origins. This could be due to the size of these eruptions, the lack of many other datasets to compare the MODIS images to, or the uncertainty on whether those pumice rafts were from deep underwater volcanoes at all. Using MODIS data alone to track pumice rafts back to their sources was not an effective method, but it does have the potential to play a useful role in researching future large eruptions.

Key Words: Havre; Kermadec arc; MODIS; pumice rafts; submarine volcanoes.
INTRODUCTION

Submarine volcanic eruptions have the potential to form large floating rafts made entirely of pumice, and if the rafts are large enough, they can be seen in satellite images of Earth (Jutzeler et al., 2014). Previous studies were able to track pumice seen in the Pacific Ocean back to its origin at the submarine Havre caldera volcano (Jutzeler et al., 2014; Carey et al., 2018), which was not known to be an active volcano before this discovery. The original goal of my own study was to see if I could find pumice rafts that proved that dormant seamounts formed by the Louisville hot spot had been reactivated as they were being subducted at the Kermadec arc (Fig. 1). However, I found no evidence to support that reactivation and my study’s purpose became locating pumice rafts and tracing them back to their origins to hopefully find previously unknown submarine volcanoes.

Studying pumice rafts is important for several reasons. One reason is that pumice rafts affect marine life. For instance, they collect many species of marine organisms, and as they travel far distances in the ocean, they connect different previously isolated ecosystems. This affects colonization processes, damages sensitive environments, and introduces invasive species into other habitats (Bryan et al., 2012). Additionally, the more that is known about volcanoes and their locations, then the more people can prepare for volcanic hazards. Finding the locations of pumice rafts and where they have potential to form can help inform boats to minimize the financial effects experienced by shipping and fishing companies (Jutzeler et al., 2014).
Figure 1. Map of the south Pacific showing the location of the Havre seamount. It is part of the Kermadec Arc and is only about 800 km north of Auckland, New Zealand. The red box is where I was looking for pumice rafts and it is the area between 23° S and 31° S latitudes and 180° and 172° W longitudes. The Louisville ridge is being subducted beneath the Kermadec arc in this area. The scale bar is 400 km. Map from Google Earth and modified in Adobe Illustrator.
Background

Pumice Rafts

There was no evidence that pumice rafts could come from deep submarine (>700 mbsl) eruptions until recent years (Jutzeler et al., 2014). Prior to this discovery, all pumice rafts were thought to have come from shallow seamounts, domes, pyroclastic flows and fallout from volcanoes above sea level, shore erosion and fluvial transport, or landslides triggered by volcanic activity (Whitham and Sparks, 1986; Carey et al., 2001; Jutzeler et al., 2014; Larsen et al., 2014). Additionally, the only signs that pumice rafts existed before the use of satellite imagery were reports from passing ships and pumice washing up on the coast and being incorporated into the sedimentary record (Risso et al., 2002; Bryan et al., 2004; Jutzeler et al., 2014).

It is also important to note the appearance of the ocean surrounding eruptions in order to help identify them in satellite images. In the early stages after an eruption there is a plume in the air and discolored water around the pumice raft (Jutzeler et al., 2014; Fig. 2). This discoloration is caused by the precipitation of silicon dioxide, aluminum oxide, and iron oxide particles that come from hydrothermal fluids when the eruption mixes with seawater. The temperature of the surface water is also higher directly following an eruption (Vaughan et al., 2007).

Pumice rafts form from the accumulation of pumice clasts coming from volcanic eruptions and these rafts can be hundreds of km² in area (Fig. 2). They float due to the low density of the pumice (Jutzeler et al., 2014) and the absence of more dense constituents such as lithics and crystals (Carey et al., 2001). These underwater eruptions lead immediately to floating tephra (Larsen et al., 2014), and then vesiculation occurs rapidly (Jutzeler et al.,
Figure 2. Havre caldera eruption on July 18, 2012. The pumice raft is the gray/tan object. The yellow arrow is pointing to the location of the vent and the plume is the white trail of clouds extending to the northwest. The water around the pumice raft is discolored, making it a lighter blue. The red scale bar is 20 km. Image from MODIS and modified in Adobe Illustrator.
Vesicles usually come in three different sizes and they have narrow openings on the outside, but they tend to be larger inside and interconnected. These internal links and large surface areas allow the pumice to degas very quickly (Whitham and Sparks, 1986).

Pumice rafts from pyroclastic flows are generally rhyolitic in composition (Shane et al., 1998), but identifying the specific characteristics of the pumice such as its geochemistry, mineralogy, and refractive index can help identify the rafts’ origins (Bryan, 1971; Shane et al., 1998; Risso et al., 2002). Most recorded submarine eruptions are more mafic in composition (Carey et al., 2018). Sometimes pumice rafts can contain clasts from several different eruptions, so differentiating the origins of the clasts is important to know how many eruptions are represented in a single raft (Bryan, 1971; Shane et al., 1998).

Pumice rafts can remain floating in the ocean for years (Whitham and Sparks, 1986; Jutzeler et al., 2014) before they either become too heavy and full of water and sink or wash up onto shore and become part of the sedimentary record (Jutzeler et al., 2014). Characteristics affecting how long pumice will float include size, shape, initial density, vesicularity, and its temperature when it is introduced into the ocean (Whitham and Sparks, 1986; Jutzeler et al., 2014). Hot pumice will usually sink immediately because it absorbs more water as it cools and water condenses in the vesicles. On the other hand, cold pumice will slowly absorb water and can float for a long time before eventually sinking. Each pumice clast has a unique critical temperature based on its density and the pumice must remain below that temperature in order to stay afloat (Whitham and Sparks, 1986). As pumice rafts continue floating, their shape evolves, becoming stringier and more spread out over time. The pumice is also rounded due to erosion from interactions between clasts (Carey et al., 2001).
While pumice rafts remain floating they can travel far, in some cases even following complicated courses for more than 20,000 km (Risso et al., 2002). The routes of pumice rafts are dependent upon other factors besides just how long they stay buoyant. Their course of travel is affected by the source of the clasts, the initial raft dimensions, oceanic currents, wind direction, and proximity to shore (Vaughan et al., 2007; Jutzeler et al., 2014).

**2012 Havre Eruption**

The pumice raft created by the 2012 eruption of Havre caldera volcano proved that deep submarine silicic eruptions (>700 mbsl) can produce pumice rafts (Jutzeler et al., 2014). The geologic record does not preserve much information on the size or magma production of submarine volcanoes, so not much is known about them (Carey et al., 2018). Prior to studies of this submarine eruption, there was a significant amount of information known about mafic end-member underwater eruptions that take place in the Tonga and Marianas volcanic arcs, but the Havre caldera volcano is part of the Kermadec arc, located about 800 km north of Auckland, New Zealand (Fig. 1), and it is rhyolitic in composition with 72 weight percent SiO$_2$ (Carey et al., 2018). This eruption started on July 18 and likely only lasted a day. It erupted from 14 different vents with depths ranging from 900 to 1220 mbsl. The estimated total volume erupted during this event was about 1.5 km$^3$, a magnitude of five on the volcanic explosivity index. That makes this eruption 1.5 times as big as the 1980 Mount St. Helens eruption and more than ten times as big as the 2010 Eyjafjallajökull eruption in Iceland (Carey et al., 2014). This eruption was the largest and deepest silicic submarine eruption ever recorded (Carey et al., 2014; Carey et al., 2018), a once in a century sized event (Carey et al., 2014).
More than 75% of the volume erupted during this event was accumulated into a pumice raft and transported far away from the source (Carey et al., 2018). The initial size of the pumice raft was over 400 km² (Carey et al., 2014; Carey et al., 2018), and it was spread over an area of about 20,000 km² in just a few days (Carey et al., 2014). The maximum thickness of the pumice raft that was recorded was 60 cm on August 10, 2012 (Jutzeler et al., 2014). Giant pumice clasts up to 9 m in diameter were observed (Carey et al., 2018).

Despite the large size of this eruption, no one knew it had occurred until a passenger on a commercial flight noticed large rafts of pumice floating in the Pacific Ocean below (Carey et al., 2014). That is when researchers used satellite imagery to trace back the pumice raft to the location of the Havre caldera volcano (Carey et al., 2014; Carey et al., 2018). These observations were corroborated by data showing there was an earthquake swarm of 18 events that occurred at the Havre caldera on July 17 and MODIS images from July 18 and 19 show an atmospheric plume (probably consisting of steam only) and a thermal hot spot also at Havre (Carey et al., 2014; Jutzeler et al., 2014; Fig. 2). Using satellite imagery, this eruption could be tracked from July 18 to November 17 (Fig. 3) and small rafts could still be seen in images until December 22, 2012 (Jutzeler et al., 2014).

METHODS

I used satellite images from the Moderate Resolution Imaging Spectroradiometer (MODIS) to locate and track pumice rafts in the Pacific Ocean. The NASA MODIS website (https://modis.gsfc.nasa.gov/about/) provides information about the MODIS instrument. It is aboard both the Terra and Aqua satellites. The Terra moves from north to south and passes over the equator in the morning hours while the Aqua moves from south to north and passes
Figure 3. Havre caldera eruption spreading out over time. The entire extent of the pumice raft on each of these days is not always shown, but the largest and most visible parts are shown in order to demonstrate that the raft is becoming thinner and more spread out over time. The pumice raft is still visible until later in the year, but it becomes so spread out, that it is hard to show in a figure. A, B, C, and D all have the same scale (red scale bar is 50 km). Images from MODIS and modified in Adobe Illustrator. (A) Pumice raft on July 21, 2012. (B) Pumice raft on July 24, 2012. (C) Pumice raft on August 12, 2012. (D) Pumice raft on September 3, 2012. The pumice raft appears to cover less area on this day than in C because some pumice is sinking and it is so spread out that it is less visible. (E) Map showing how the pumice raft has moved over time. The different colors are outlines of the extent of the pumice raft on different days. Green is the raft in part A, pink is the raft in part B, yellow is the raft in part C, and orange is the raft in part D. The red scale bar is 200 km. The base map is from Google Earth and modified in Adobe Illustrator.
the equator in the afternoon. These two satellites have differently timed orbits in order to cover every part of Earth. Depending on where and what time of day Earth is being observed, the images from one satellite will be higher quality than the images from the other because of their different locations relative to Earth. The Terra MODIS and Aqua MODIS are able to examine the complete surface area of Earth every one to two days. MODIS contains 36 spectral bands of different wavelengths that are divided into four Focal Plane Assemblies (FPAs). These FPAs include Visible (VIS), Near Infrared (NIR), Short-Wave and Mid-Wave Infrared (SWIR/MWIR), and Long-Wave Infrared (LWIR). The different FPAs are what enable the large assortment of data and three different resolution levels. Bands 1-2 have 250 m/pixel resolution, bands 3-7 have 500 m/pixel resolution, and bands 8-36 have 1000 m/pixel resolution.

Images from the MODIS satellites are available through the Earth Observing System Data and Information System (EOSDIS) Worldview interface, courtesy of NASA. I learned to use the MODIS data and to calibrate my eye to the appearance of pumice rafts by tracking the 2012 Havre eruption. I compared my results to Jutzeler et al. (2014) in order to check my findings and confirm that I could sufficiently trace the course of pumice rafts as they float through the ocean.

MODIS was the method that worked best for my study because, between the Terra and Aqua satellites, I was able to access images from every day. This allowed me to trace pumice rafts through time and see how their locations and appearances changed. There are other satellites that also take images of Earth, but they either do not cover the entire globe or do not have data from every day, making them less useful to me. I originally picked the area covered by latitudes ranging from 23° S to 31° S and longitudes ranging from 180° to 172°
W because that is where there Louisville ridge and Kermadec arc intersect (Fig. 1), but I used this same area as my study’s purpose evolved. Then, I scrolled through that section every day from 2004 to the present looking for pumice. Once I found pumice, I would try to trace it back in time to find out where the eruption originated, and forward in time to see how long it remained visible. I also used the U.S. Geological Survey’s earthquake catalog to search for earthquake swarms around the times that I found pumice rafts to try to get more accurate information on the exact dates and locations of their origins.

RESULTS

I was able to duplicate the results of Jutzeler et al. (2014) and track the pumice raft from the 2012 Havre eruption through time using MODIS (Fig. 3). When the volcano first erupted on July 18, 2012, the raft was more compact. Over time, the pumice raft spread out into long, thin strands. As the raft continued to spread out, it eventually reached the point where it was no longer visible. The last sighting of the pumice raft using satellite imagery was in December of 2012.

In my search of the area covered by latitudes ranging from 23° S to 31° S and longitudes ranging from 180° to 172° W from 2004 to the present I found six different pumice rafts. I tried to compare all six of them to seismic data, but only the pumice raft that I initially spotted on December 17, 2005 appeared to have an earthquake swarm associated with it (U.S. Geological Survey, 2018).

The pumice raft that I first spotted on December 14, 2004 was spread out into very thin strands and seen between 19°24’S-22°48’S and 177°30’W-174°W. As I tracked it
through time, I was able to also see it on the 15, 16, 17, and 19 of December, but I did not
spot the raft on any other days prior to the 14.

I spotted another pumice raft on December 17, 2005 (Fig. 4). This raft was spread out
and covered a very large area. It was seen between latitudes of 24°S and 17°25′S and
between longitudes of 180° and 173°12′W. This pumice raft was one of easiest to track of
the six I found. I was able to spot it the four days leading up to December 17 and for four
days after before I lost its trace. Seismic data reveals that there was an earthquake swarm of
10 events in 13 hours from December 7-8. All of these earthquakes were located around 30°
S and 177° W, but I still did not find any evidence of a pumice raft earlier than December 13.

I found another pumice raft on February 14, 2007. It was in very thin strands that
were located throughout the area covered by 23°36′S to 21°24′S and 175°12′W to 174°W on
the 14, but I could not find any more pumice on any of the surrounding days.

There was a pumice raft visible between 23°18′S and 24°S latitudes and 173°48′W
and 172°36′W longitudes on January 4, 2011. This pumice raft was just two strings,
appearing to be a smaller volume than some of the other pumice rafts spotted. It could not be
tracked into the future at all, but it was spotted on January 2 and 3, 2011 and December 31,
2010.

On February 16, 2013, I found a small pumice raft located at 24°10′S and 178°09′W.
This pumice raft also looked like it had a very small volume. However, there were lots of
clouds on this day, and the surrounding days, making it especially hard to track. It was
spotted again through the clouds on the 18 and the 20.

The last pumice raft that I found as part of my search was one of the easier ones to
track. I first saw the stringy raft on January 26, 2016 between 24°12′S and 22°48′S latitude
Figure 4. Pumice raft moving through time. This is the pumice raft that I first saw in MODIS on December 17, 2005. The parts pictured here were the most visible parts on these days. Again, the raft moves over time. A, B, and C, all have the same scale (red scale bar is 50 km). Images from MODIS and modified in Adobe Illustrator. (A) Pumice raft on December 16, 2005. (B) Pumice raft on December 17, 2005. (C) Pumice raft on December 19, 2005. (D) Map showing how the pumice raft moves even on a short timescale. The different colors are outlines of the extent of the pumice raft on different days for as much as I was capable of seeing. Green is the raft in part A, pink is the raft in part B, and yellow is the raft in part C. The red scale bar is 250 km. The base map is from Google Earth and modified in Adobe Illustrator.
and 180° and 177°48’W longitude. It was also visible on a couple days prior to this discovery on the 23 and 24 of January and on several days following the day of my initial sighting of it on January 30 and 31 and February 1, 3, 4, and 8.

DISCUSSION

Of the six pumice rafts I was able to find by searching through MODIS, none of them were traceable beyond a few days in either direction. This could be due to a number of reasons, but it does demonstrate that using MODIS to trace pumice rafts is not always an effective method.

One reason that pumice rafts were difficult to trace through time was that many clouds are usually present in MODIS images. They often block the view of the ocean completely in some places and they can look fairly similar to the pumice rafts floating in the ocean. The presence of these clouds makes finding pumice rafts using MODIS significantly more difficult. For this reason, it is probably not a coincidence that all six of the eruptions I found were in the summer months: December, January, and February. It is possible that there were less clouds that time of year, making it easier to spot pumice rafts.

However, despite the difficulties, I was still able to track the 2012 Havre eruption. One reason that particular pumice raft could be traced in this way, despite the inefficiency of using this method for other eruptions, could be because of the size of the eruption. The Havre eruption in July of 2012 was the largest known submarine volcanic eruption in recorded history (Carey et al., 2014; Carey et al., 2018). So, even though that eruption could be observed using MODIS, that does not necessarily mean that other smaller eruptions are visible at this scale. The best possible resolution of MODIS images according to the NASA
The MODIS website (https://modis.gsfc.nasa.gov/about/) is 250 m/pixel, so seeing any objects smaller than that would not be feasible.

The origin of the 2012 Havre eruption was also confirmed with other data sets besides just tracing the pumice raft back to where it was no longer seen. The MODIS images were corroborated by bathymetric maps showing the presence of a deep seamount located there, seismic data showing a swarm of activity at Havre leading up to the eruption, and the presence of a thermal hot spot (Carey et al., 2014; Jutzeler et al., 2014). Therefore, making educated guesses on the initial sources of the six eruptions I found, is difficult using MODIS images alone because if the rafts stop being visible, it is unclear whether that is their origin or they are less visible for another reason. Looking through seismic data, I only found an earthquake swarm that could be related to one of the six pumice rafts I found (U.S. Geological Survey, 2018), and that was based on time and location of the swarm alone. There is no proof that those events were definitively related to the eruption that caused the pumice raft and I was not able to detect the pumice raft any earlier than December 13, almost a week after the earthquake swarm occurred.

Another factor that might change the appearances of the pumice rafts that I found from the appearance of the pumice raft from Havre in 2012 is that their sources might not be from deep submarine volcanoes. It is possible for pumice rafts to form from shallow seamounts, pyroclastic flows and fallout from subaerial eruptions, shore erosion and fluvial transport, or volcanically generated landslides (Whitham and Sparks, 1986; Carey et al., 2001; Jutzeler et al., 2014; Larsen et al., 2014). Prior to my search for unknown pumice rafts, I had only tracked a pumice raft that came from a deep silicic submarine volcano. If pumice rafts that come from other sources have different appearances, it is possible that I would not
have recognized their origins. For example, the 2012 Havre eruption’s pumice raft started out very condensed, so when I was attempting to trace the new eruptions’ origins, I was looking for condensed rafts with discolored water around them. I did not find that which led me to conclude that I could not find where the pumice rafts were generated. However, it is possible that pumice rafts not originating from underwater volcanoes, do not start out as condensed, but rather are already spread out strands of pumice by the time they reach the ocean.

CONCLUSION

Despite being able to track the pumice raft from the 2012 Havre eruption, MODIS was not an effective method on its own for tracing pumice rafts back to their origins. I found six pumice rafts and tried to track all of them back to where they were generated, but I was not successful at finding any of their initial sources. Reasons that I was able to track the pumice raft from Havre and not the six others that I found could be related to the sizes of the eruptions, the lack of other datasets I had to compare them to, and uncertainty on whether they came from submarine volcanoes or some other source.

There are still plenty of unanswered questions about pumice rafts that future research could help answer. First, comparing my findings to other data sets could help narrow down where these eruptions originated. Continuing to study these pumice rafts and potentially finding more could also help lead to a better understanding of submarine volcanoes. This could help future researchers to learn about the frequency of eruptions in the Kermadec arc and the average volume of materials erupted in each event. Also, if a pumice raft in this area can be traced back to the Louisville ridge as its origin, then that would mean that the subduction activity from the Pacific Plate moving beneath the Indo-Australian Plate could
have reactivated an old, previously dormant seamount initially created by the Louisville hot spot. Also, it would be valuable to expand this same process beyond just this small portion of the Pacific Ocean to cover more of the Earth’s oceans in order to learn more about the behaviors of submarine volcanoes in other parts of the world. Lastly, I did all of this searching through MODIS images manually and had to rely on my own eyes to detect pumice. This is both difficult and time consuming. Further research could develop a computer program to find pumice rafts, using the pumice images I have already compiled as a catalog.

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