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Review Article

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A Review of Pumice Raft Formation Environments, Saturation, and Dispersal Mechanisms

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Abstract

Pumice rafting events are a common result of volcanic eruptions occurring near or beneath bodies of water. Such events are frequently associated with hazards such as tsunamis, and drift pumice is known to cause local economic disruptions, damage ships, impede naval traffic, devastate marine populations, and distribute potentially invasive species over long distances. However, our current understanding of the mechanisms that drive the formation and dispersal of drift pumice are extremely limited. This article reviews historical and characteristic pumice raft-forming eruptions, how interactions with water factor into macro- and micro- scale controls on pumice clast formation and dispersal, and current methods for detection and analysis to better track and mitigate hazards associated with explosive volcanic eruptions and pumice rafts.

Introduction

Understanding the formation and dispersal of pumice rafts can provide important insights into the mechanisms of subaqueous eruptions; the risk they pose to coastal environments, marine life, and naval travel and transport; and their dispersal of flora and fauna populations[1]. Pumice rafts can form in a wide array of volcanic settings, but are particularly prevalent in subaqueous volcanism. Despite making up approximately 85% of the world's volcanic eruptions, our understanding of submarine volcanism is extremely limited because eruptions and deposits are hard to observe, detect, and access[2–4]. This review aims to provide an overview of our contemporary understanding of how pumice rafts form and are subsequently deposited by bridging current research in geology, materials science, and remote sensing.

To do so, I will explore characteristic eruptions that formed pumice rafts for each of three volcanic settings, characterized as (1) subaerial volcanism, (2) sublacustral volcanism, and (3) submarine volcanism. To illustrate subaerial volcanism, I selected the 1883 eruption of Krakatau and the more recent 1985 eruption of the Niuafo'ou Island caldera; Krakatau provides an example of a volcanic island producing a pumice raft that is dispersed via the ocean, whereas Niuafo'ou demonstrates a caldera lake dispersal setting. I use the 13300 ± 500 BP Surtseyan eruption of the Black Point basaltic cone in Mono Basin, California to exemplify a sublacustral eruption environment. Finally, I discuss the 2012 eruption of the Havre seamount, north of New Zealand, and the Hunga Tonga-Hunga Ha'apai submarine volcanoes to elucidate the mechanisms of deep and shallow submarine eruptions, respectively.

In order to better understand the part water plays in the formation of pumice, I provide a broad overview of macro- and micro- scale controls on pumice formation. In particular, I will discuss how hydrostatic pressure, eruption depth, and thermochemical interactions with water affect the texture and vesicularity of pumice formed in different volcanic settings with new supporting evidence from field observations made at Mono Lake, California (see Figure 1). These ideas will be extended to pumice raft dispersal to examine the factors controlling how and when a pumice clast will become saturated with water and sink.

Finally, to understand how pumice rafts are currently studied and possibles avenues for further research, I discuss current analytical methods for identifying subaqueous eruptions and pumice rafts. This review focuses on analytical methods for recent or ongoing eruptions and rafting events, rather than identifying historical pumice raft deposits in the geologic record.

Background

Pumice is a relatively common product of explosive volcanic eruptions. Its most impressive characteristic is, arguably, that it has a range of densities lower than $1.0\,\mathrm{g\,cm^{-3}}$, allowing it to float on water[5]. While it is typically felsic to intermediate in composition, samples of basaltic pumices and other variable compositions have also been found. Pumice is a highly microvesicular volcanic glass that forms when magma is rapidly ejected during an eruption. As a result of a rapid decrease in temperature and pressure, volatiles in the magma begin to exsolve; the resulting bubbles are preserved because the rock is cooled quickly[6,7]. Experiments demonstrating vacuum impregnation of resin in pumice indicate that the vesicles form an interconnected network[8]. This has important consequences for the fate of pumices deposited in water.

Pumice rafts, also referred to as drift pumice, are mobile accumulations of pumice floating on the water's surface[7,8]. They have been known to span tens of thousands of square kilometres of the ocean surface and are capable of travelling thousands of kilometres[2,9]. Pumice rafts have the potential to form from explosive volcanic eruptions in a number of volcanic settings; however, they are most commonly associated with shallow subaqueous eruptions[8,10]. These eruptions are often referred to as Surtseyan eruptions, named for the shallow submarine eruption off the coast of Iceland in 1963 that resulted in the emergence of a new island, Surtsey[11].

Figure 1. Silicic Rafted Pumice. A partially buried silicic pumice clast on the modern western shore of Mono Lake in California. At this time, it is unclear which Mono dome or island produced the clast pictured; the Negit Island domes or the Paoha Island dome are both likely candidates given that Black Point is basaltic[12]. Mono Basin has been a site of frequent volcanism for the past 60,000 years, and the lavas erupted between 500 and 150 years ago from the northwestern quadrant of Paoha Island are the youngest in the region[12]. Photo by author, taken at 37.97818N, 119.13274W in October 2022.

As a result, pumice rafts can have significant effects on coastal and marine environments and human activities. Additionally, they can be used to map drift trajectories and better understand ocean currents and wind fields. The vesicular nature of pumice and the extensive rafts formed facilitate floral and faunal dispersion. For example, beached pumice on Fiji was populated with organisms such as algae, goose barnacles, serpulid worms, calcareous algae, bryozoans, coral, oysters, and more. The size of some corals on the rafted pumice indicated it had been carried by the raft for at least 12 months, indicating that the pumice is a significant dispersal mechanism[1,13,14]. Consequently, pumice rafts deposited on coastlines may be sources of marine pests and invasive species that pose both short- and long-term threats to coastal ecosystems[15,16]. Similarly, pumice rafts may have played an important part in global speciation and biodiversity; recent research suggests that pumice rafts are a favourable environment for the initial origins of life on Earth[1,17]. Pumice rafting can also have important consequences for marine populations, for instance, Akiyama et al. observed a mass mortality of cultured fish after they ingested pumice stones from a rafting event[18]. Pumice rafts also block sunlight and inhibit the air-water heat and gas exchange in the upper ocean, damaging ecosystems beneath the raft[19].

The impressive extent of pumice rafts can also impose major disruptions to human activities such as fishing, shipping, and tourism. Rafts can block harbours for many months at a time, as well as make beaches inaccessible or unattractive for tourism. Pumice rafts can rapidly alter local ecosystems for weeks to months, forcing fish populations to move or causing (local) population extinctions which can have devastating effects on fishing. Additionally, the rough nature of pumice often results in damage to boat hulls. The effects on fishing, shipping, and tourism can significantly disrupt local economies[19].

Volcanic Settings

Subaerial Volcanism

Subaerial volcanic events in near-shore and crater lake environments have been known to produce pumice rafts. In a subaerial eruption, pumice is produced when the magma is ejected from the vent and rapidly cools in the atmosphere. The pumice is then deposited into a lake or ocean, where it floats on the surface and accumulates as a raft. Crater lakes commonly form after an explosive eruption; the emptying of the magma chamber induces a caldera collapse[20,21]. Groundwater, precipitation, and snow melt fill the resulting crater to form a lake[21].

Krakatau (1883)

In 1883, the volcanic island of Krakatau erupted in the Sunda Strait between the Indonesian islands of Sumatra and Java[22]. Preceding the 1883 eruption, the Krakatau Group consisted only of the Danan, Perbuatan, and Rakata islands which were parts of an ancient caldera[23,24]. Krakatau is aligned with the Sunda trench, a subduction zone where the Indo-Australian plate is subducting beneath the Eurasian plate[24]. The unrest spanned August 26^{th} and 27^{th}, 1883, starting with small eruptions that transitioned into Plinian-style activity, followed by ignimbrite-forming activity on the 27th[24]. This activity is expected along subduction zones, in which water and other volatiles that are subducted result in explosive eruptions. The eruption produced abundant pumiceous material that was deposited in the Sunda Strait, accumulating as rafts. The tsunami waves, thought to have been generated by the displacement of water by pyroclastic flows, stranded floating pumice fragments in low-lying shoreline regions after receding[22,23].

Niuafo'ou Island Caldera (1985)

The 1985 eruption of the Niuafo'ou Island caldera, Tonga also reportedly produced pumice rafts. The island is approximately 8 km wide with an impressively spherical caldera lake that spans 4.6 km in diameter[21]. It is located at the northern end of the Lau-Basin, an actively spreading back-arc basin west of the Tonga subduction trench[21,25]. A study published by Regelous et al. in indicates that Niuafo'ou likely formed via intraplate magmatism resulting from decompression melting beneath a microplate[26]. The Niuafo'ou caldera is known to erupt both effusively and explosively, but the characteristics of the 1985 eruption are not well documented[25]. Unlike the 1883 Krakatau event, pumice accumulated in the lake formed by the steep-sided caldera rather than the surrounding ocean[22,25].

Sublacustral Volcanism

Similar to the pumice rafting event on Niuafo'ou's crater lake, pumice rafts have been observed in sublacustrine environments. The major difference between a sublacustral and subaerial eruption at a volcanic lake is that pumice formed during a sublacustral event is quenched by water rather than air. Sublacustral eruptions occur when magma erupts under the surface of a lake.

Black Point (13300$\pm$500)

The 13300 $\pm$ 500 BP Surtseyan eruption of the Black Point basaltic cone in Mono Basin, California is a prime example of a sublacustral event that produced a pumice raft. The cone formed alongside what is now Mono Lake, a volcanogenic lake in the Mono Basin-Long Valley region of California[27,28]. The eruption initially occurred approximately 105 m below the surface of the water before transitioning to an emergent Surtseyan eruption as the deposits built up the volcanic cone[29,30]. Motion along the San Andreas and Walker Lane fault complexes on either side of the Sierra Nevada mountains account for the transtension deformation in the Mono Basin-Long Valley area. Volcanism is induced by the range front faulting allowed by regional transtension[28,31]. Subaerial volcanic islands in Mono Lake have also been known to produce silicic rafted pumice, such as the white cone illustrated to the southeast of Black Point in Figure 2.

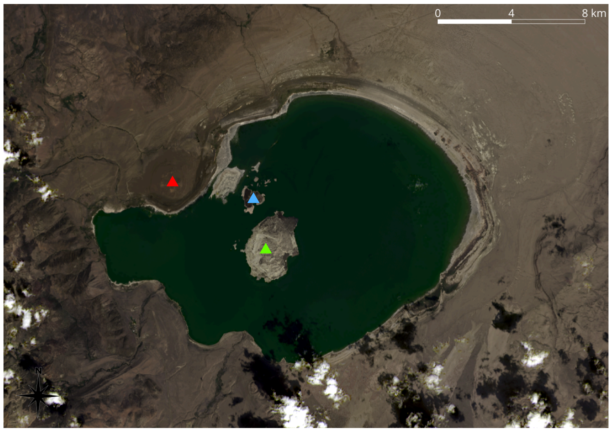

Figure 2. Paoha Island and Black Point. Satellite image of Mono Lake on Sept. 2nd, 2022, sourced from NASA/USGS Landsat-8 and centered at approximately 38.02192N,-119.02042E. Black Point is marked by a red triangle, the Negit Islands are marked by a blue triangle, and Paoha Island is marked by a green triangle. Black Point is a basaltic Surtseyan emergent volcano that formed at approximately 13300 ± 500 BP in Lake Russell, the Pleistocene predecessor of Mono Lake (present). Image courtesy of the U.S. Geological Survey.

Pyroclast textures from the eruption are consistent with water modification, indicating that the eruption occurred beneath the lake's surface[29]. The modern shore of Mono Lake is primarily composed of white to grey drift pumice which is visible via satellite (see Figure 2), rafted there by the waves and currents of the lake[32].

Submarine Volcanism

Submarine volcanoes are found in intraplate settings as well as along all types of plate boundaries, but predominantly at spreading centers, the Pacific Ring of Fire, and over mantle hotspots[2]. As with sublacustral volcanism, products of submarine eruptions are quenched by water rather than air. Submarine eruptions differ from sublacustrine activity primarily in the depth at which they occur[2].

Havre Seamount (2012)

On July 7th, 2012, the Havre seamount along the Kermadec arc erupted 800 km north of Auckland, New Zealand[33]. The caldera is 4 km long and 3 km wide (elongate northwest-southeast). Havre erupted effusively at around 900 m depth[34]. This eruption was the largest recorded submarine eruption since A.D. 1650—likely twice the size of the 1980 subaerial eruption of Mount St. Helens—the bulk volume of erupted rhyolitic pumice reached $1.2\,km^{3}$[33,35]. Significantly, the Havre eruption was the first to unambiguously establish that deep silicic submarine eruptions can generate pumice rafts, where "deep" is defined as greater than 700 m below sea level (MBSL)[7]. An approximately $22\,000\,km^3$ raft of floating pumice and a $0.1\,km^3$ field of giant (>1 m) pumice clasts up to 10 m in diameter were observed down-current from the vent[34,36].

Hunga Tonga-Hunga Ha'apai (2009, 2014–2015, 2021–2022)

West of the main inhabited islands of the Kingdom of Tonga lies the Hunga Tonga-Hunga Ha'apai volcano, a submarine volcano that includes small islands, islets, and shallow submarine reefs along the caldera rim of a much larger submarine structure. It exists at approximately 150 m depth along the Tofua arc, a segment of the Tonga-Kermadec volcanic arc that formed as a result of subduction of the Pacific Plate beneath the Indo-Australian Plate[37]. On March 17th, 2009 material erupted effusively from two vents, located northwest and south of Hunga Ha'apai, a pre-existing, uninhabited volcanic island near Tonga[38]. The Hunga Tonga-Hunga Ha'apai volcanic group erupted again from September 2014 through January 2015, during which a tephra cone coalesced the two existing islands[39]. It erupted yet again from December 2021–January 2022, obliterating the tephra cone from the 2014–2015 eruption and triggering a giant atmospheric shock wave and a tsunami[40].

In 2009, satellite imagery was used to measure the distribution of pumice rafts and determine the volume of erupted material. A minimum bound on the volume of pumice raft in 2009 was estimated to be approximately $0.0158\,km^3$, with a total erupted volume of at least $0.0176\,km^{3}$[38]. Large pumice rafts, each spanning up to 4 km in its widest dimension, were visible in satellite imagery in early January 2022 and found drifting nearly 100 km away from the volcano[41]

Interactions with Water

The relative temperature difference between a magma and water is greater than that between a magma and air[39]. The rapid heat transfer from the magma to the water leads to rapid volume expansion of vaporized seawater which is likely related to the explosive eruptive style of Surtseyan and deep submarine eruptions[2,42].

Surtseyan eruptions that transition to sustained emergence above the water's surface are typically observed to shift their eruptive style to weak fire-fountaining or effusive lava flow activity. For this reason, Surtseyan eruptions are generally considered to be Strombolian or Hawaiian eruptions that have been modified by water[29]. This transition exemplifies the importance of the effects water has on eruption dynamics and the quenching of eruptive products. Furthermore, water drives the dispersal patterns of pumice rafts.

Microtextural Controls on Pumice Formation

Eruptions that occur in water are subjected to a higher confining pressure from the overlying water column than subaerial eruptions. Hydrostatic pressure suppresses volatile exsolution, expansion of erupting magma, bubble coalescence, and permeability development[42,43]. Prefragmentation vesiculation may be hindered by hydrostatic pressure at depth and postfragmentation vesiculation of erupted products may be interrupted by rapid quenching[39]. Specifically in deep submarine pumice, [43] noted that samples had homogeneous textures with low-vesicularity clasts and contained sub-round or ellipsoidal bubbles with thick vesicle walls. Deep submarine pumices have been shown to have similar colour, density, and macrotexture to subaerial and Surtseyan pumices[43]. However, the deep submarine pumices present with fewer small vesicles and have narrower vesicle size distributions when compared to subaerially erupted pumices[43]. A recent study of pumice from the 2012 Havre eruption by Mitchell et al. in also concurs that interactions with water have microtextural controls on pumice formation[44]. Their analysis of microtextural characteristics revealed that rafted pumice clasts have lower pore space connectivity and higher vesicle density than sunken clasts[44]. Field observations of rafted pumices at Mono Lake, California display centimeter-scale surface jointing that is similar to the columnar jointing that is commonly observed in rapidly cooled basaltic flows, as seen in Figure 3.

Figure 3. Micro-jointing on the Surface of Rafted Pumice. This image is a closer look at the drift pumice pictured in Figure 1. Micro-jointing on the surface of a rafted pumice clast on the contemporary western shore of Mono Lake, California. The joints can been seen at a variety of different length scales. Photo by author, taken at 37.97818N, 119.13274W in October 2022.

Buoyancy and Saturation

The initial buoyancy of pumice is determined by its size, shape, vesicularity, permeability and temperature when it comes into contact with water[7,34,45]. Its buoyancy changes over time as the clast becomes saturated with water, ultimately reaching a critical buoyancy at which point the clast will sink, given that it is not washed ashore first. Once a clast is sufficiently saturated, it will drop out and sink in a fashion that is hydrodynamically-similar to normal clastic material. Saturation of a pumice clast is intrinsically related to pore space connectivity and overall vesicularity[5].

Observations of reverse-graded bedding (saturation bedding) composed of sunken pumice clasts in subaqueous environments indicates that the flotation residence time of pumice is inversely proportional to its size[46]. Using an analogue behavioural model based on Darcy's law for the flow of fluids in porous material, Manville et al. modelled pumice saturation to determine residence times for pumice saturation[5]. Their work shows that there is a first-order proportional relationship between time and the square radius of a clast[5]. Experimental observations confirm that smaller clasts tend to saturate faster, however, their experiments were only conducted with clast sizes up to 16 mm in diameter. Pumice vesicularity varies depending on where and how it was formed, which I elaborated on in the previous section on "Microtextural Controls on Pumice Formation." In regards to buoyancy, studies suggest that rafted pumices typically have a higher vesicle density than their sunken counterparts[44]. In general, pumice has a high pore connectivity which would suggest a rapid sinking rate[47]. However, laboratory experiments by Whitham & Sparks show that some pumice clasts can remain afloat in a laboratory environment for over a year and a half[8]. To reconcile observations of long-floating pumice and the expectation of rapid sinking, Fauria et al. propose that the diffusion of trapped gas ultimately determines pumice flotation residence time[45]. Their proposal is supported by experimental measurements on pumice flotation, finding a flotation residence time (τ) that can be described by equation 0.1, where L is the characteristic length of pumice, D is the gas–water diffusion coefficient, and θ is pumice water saturation[45].

$$\tau \propto \frac{L^2}{D\theta^2} \tag{0.1}$$

The temperature of pumice at the time it comes into contact with water is largely determined by the environment in which it formed; pumices that formed in subaerial eruptions and become rafted due to fallout, shore erosion, and fluvial transport[7] may have cooled before rafting began. Experiments by Whitham & Sparks suggest that a critical temperature of pumice exists at which point a clast will sink, regardless of its other physical properties[8]. Rapid saturation of pumices during subaqueous eruptions occurs as a result of quenching when the water phase change from steam to liquid creates strong negative pore pressure within pumice vesicles and hydrodynamic instabilities due to steam generation[46,48,49].

Dispersal and Deposition Mechanisms

Pumice rafts have been known to travel thousands of kilometers from their source, capable of drifting several kilometers a day[38,50]. The dispersal of pumice rafts is largely controlled by prevailing ocean currents, waves, and wind[38,50]. Some subaqueous eruptions cause tsunamis, which also contribute to the dispersal patterns of pumice rafts[22,51]. Jutzeler et al. observed a pumice raft produced by an unnamed submarine volcano in the Tonga Islands in the Pacific Ocean in August 2019 that progressively split into several hundred smaller rafts. Areal dispersion, pumice abrasion, saturation, overloading of clast by biota, and stranding decreased the volume of the rafts[50]. They also noted the formation of patchy, elongate raft "ribbons" forming alongside or behind the main raft. Fauria & Manga provide useful equations (17,18 in their work) for estimating average saturation and cooling rates for drift pumice based on clast porosity, size, and initial temperature that can inform models of raft dispersal[52].

After pumice rafting events, mass swaths of pumice clasts are often observed to wash up on shorelines. However, not all pumice clasts are floated during a raft-forming event; a large volume of pumice clasts are also deposited on the subaqueous flanks of the vent[6,42]. These observations suggest float pumice is typically deposited in three ways: stranding, critical saturation, and saturated-clast redeposition in which clasts are re-entrained and deposited by standard sedimentary processes[46].

Current Analytical Methods

Studying pumice rafts is difficult due to the large scale of dispersal, the unpredictability of volcanism, and the inaccessibility of the subaqueous source vents and historical deposits. Traditional methods for understanding the distribution of pumice rafts primarily focus on clasts deposited on shores, which presents an issue with survivorship bias regarding the size and vesicularity of pumice clasts. Other studies also look at uplifted subaqueous volcanic successions, but this presents problems when determining the source of the pumice rafts and erosion reduces our ability to constrain the initial erupted volume of a pumice raft[8,42,51,53]. Recent advances in remote sensing and modelling have allowed for the study of pumice rafts in a variety of ways. It should be noted that new pumice rafts are often reported first by ocean traffic, which poses issues in terms of studying the initiation and full evolution of pumice rafting events since they may not be discovered immediately, especially in the case of deep submarine raft-forming eruptions.

Remote sensing is a powerful tool for studying pumice rafts. Satellite imagery can be used to track the dispersal of pumice rafts over large areas of the ocean surface[38]. For example, high-temporal resolution Moderate Resolution Imaging Spectroradiometer (MODIS) was used to estimate the magnitude, location, start time, and eruption duration of the 2009 Hunga Ha'apai eruption. More recently, MODIS, Visible Infrared Imaging Radiometer Suite (VIIRS), Sentinel-3 Ocean and Land Color Instrument (OCLI), and Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) satellite images were used for automatic detection and monitoring pumice raft dispersion from a submarine eruption near the Vava'u island group of Tonga[54]. Jutzeler et al. was able to track the evolution and dispersal of the August 7^{th}, 2019 pumice raft that originated from the Tonga Arc in real-time using satellite imagery. They coupled remote sensing observations with oceanographic Langrangian simulations to conduct near-real time forecasting of the event[50].

Remote sensing methods can only be used to study pumice clasts once they reach the surface. To address this issue, Mittal & Delbridge propose the use of existing Argo floats in concert with hydrophone and seismic arrays for the detection of subaqueous volcanism which could be paired with remote sensing techniques to better constrain eruption time and distinguish pumice rafting events. Their model indicates that the spatial sampling resolution of Argo floats is sufficient to detect anomalies generated by submarine eruptions[55].

Murch et al. used a remotely operated vehicle (ROV) to analyze submarine deposits of ash with lapilli that drapes the Havre caldera[42]. ROVs have also been used to directly observe two small submarine eruptions at the NW Rota-1 volcano located on the Marianas arc and the West Mata volcano located in the Lau Basin[2,3]. Numerical modelling and simulations have also been shown to accurately forecast the dispersal of pumice rafts[19,56].

Conclusion

Pumice rafts have important impacts on the environment, the economy, and can provide important insights about subaqueous eruptions. Understanding which regions are susceptible to pumice raft-forming subaerial, sublacustral, and submarine eruptions will help improve how we detect and mitigate the effects of rafting events and other risks associated with explosive eruptions, such as tsunamis. Existing technologies, such as satellite sensors, remotely operated vehicles, hydrophones, and submarine seismic arrays can be co-opted to improve the way we detect and track rafting events, without requiring costly installations of new equipment. When combined with our understanding of historical pumice drift events such as Krakatau (1883) or the Havre seamount eruption (2012), we can better understand the mechanisms of submarine eruptions and the extent of hazards posed by such eruptions.

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