

Review

Review of Explosive Hydrovolcanism

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Abstract: Hydrovolcanism is a type of volcanism where magma and water interact either explosively or non-explosively. The less frequently used term, hydromagmatism, includes all the processes responsible for magma and water interaction in a magmatic system. Hydrovolcanism is commonly used as a synonym for phreatomagmatism. However, in recent years phreatomagmatism appears more in association with volcanic eruptions that occur in shallow subaqueous or terrestrial settings and commonly involves molten fuel-coolant interaction (MFCI) driven processes. Here a revised and reviewed classification scheme is suggested on the basis of the geo-environment in which the magma-water interaction takes place and the explosivity plus mode of energy transfer required to generate kinetic energy to produce pyroclasts. Over the past decade researchers have focused on the role hydrovolcanism/phreatomagmatism plays in the formation of maar craters, the evolution of diatremes and the signatures of magma–water interaction in the geological record. In the past five years, lithofacies-characterization is the most common approach to studying hydrovolcanism. By far mafic monogenetic volcanic fields generated the greatest number of research results. Significant knowledge gaps are identified, especially in developing tools to identify the textural signatures hydrovolcanism leave behind on eruptive products and exploring the role of hydrovolcanism in the growth of intermediate and silicic small volume volcanoes.

Keywords: phreatomagmatic; hydromagmatic; hydroclastic; explosive; maar; tuff ring; tuff cone; Surtseyan; peperite; phreatoplinian

1. Introduction: Historic Perspective and Definitions

There is a need to understand the different aspects of explosive volcanic activity associated with the interaction between magma and external water. Understanding explosive hydrovolcanism is imperative because it occurs with any composition of magma in almost any geotectonic environment from the small-volume eruptions of monogenetic volcanoes to polygenetic volcanoes such as composite cones or caldera-forming eruptions. In caldera-forming eruptions there is evidence that even several tens of km³ volume of magma might have been fragmented as consequence of magma and water interaction [1–4].

The first documented observations on magma and water interaction were made by Charles Darwin in the early 1830's along the coastline of Galapagos Islands (Ecuador), where the formation of pyroclastic cones was attributed to the interaction between basaltic magma and sea water typically in a shallow marine environment. About hundred years later some of the volcanic edifices on Snake River Plains in Idaho (USA) were identified as tuff cones, where groundwater and magma were deduced to have interacted explosively [5]. The first observations of nuclear testing (since 1945 onward) provided an understanding of the transport and depositional processes of explosive hydrovolcanism, whereas further key observations were made during the 1958 Capelinhos, 1963 Surtsey, 1965 Taal and 1977 Ukinrek volcanic eruptions [6–11]. During the 1970's the physics of explosive interactions

between magma and water was studied using vapor (steam) explosions as analogues. These, also called molten fuel-coolant interaction (MFCI), have been observed in the nuclear, smelting and chemical industries [12–16].

The nomenclature of processes and products of explosive hydrovolcanism is in part ambiguous due to different authors using different terminologies as knowledge has expanded. Hydrovolcanism was originally defined as explosive volcanism due to the presence of steam from any kind of water (e.g., ground-water, lake, river, sea) [17]. Phreatomagmatic eruptions have also been distinguished as volcanic explosions triggered by the interaction of ascending magma and groundwater [18], whereas in phreatic [19–22] or hydrothermal [23–25] eruptions ground water is vaporized by heat without direct contact with fresh magma [26] and the resultant explosive eruptions do not expel juvenile material. The distinction between phreatic and hydrothermal explosive eruptions is difficult and commonly convoluted with phreatomagmatic eruptions as seen from the 2012 Te Maari eruption at Tongariro, New Zealand [27]. Based on the observations at Capelinhos (Azores, Portugal) and Surtsey (Iceland), the term Surtseyan was proposed for eruptions initiated in shallow seawater [28]. Shallow is generally around or less than 100 m. However, this number varies greatly from author to author. Mostly there is no consistency and authors generalize “phreatomagmatic” or “hydrovolcanic” to include magma with water interactions, explosive or non-explosive, in any environment [29]. However, there may be substantial differences in the eruption physics, magma fragmentation, pyroclast transport processes and mode of deposition between eruptions in different environments [30]. The explosivity of phreatomagmatic eruptions is widely accepted to result from MFCI processes [31–40]. MFCI represents a self-driven violent interaction of magma and vaporizable water, which is sustained by thermal and hydrodynamic interaction between molten fuel (magma) and coolant (water) [41–45]. In contrast, Surtseyan activity is characterized by active magmatic ejection into water or a water-rich environment without self-driven steam expansion. This represents quite a different eruption mechanism from the MFCI-driven phreatomagmatic activity [46,47]. If all the direct explosive hydrovolcanic activity is called phreatomagmatic, we need to find a plausible terminology for eruptions characterized by interaction between magma and groundwater without any involvement of magmatic fragmentation and need to refine what we call MFCI. Here we suggest to call an eruption phreatomagmatic explosive in the *sensu stricto* point of view when MFCI is the main process behind the magma fragmentation [18] as part of the direct magma-water interaction generated direct hydromagmatic explosive eruptions (Figure 1). On the other hand, hydrovolcanic is an informal term commonly criticized because it means a type of volcanism where water is the main source of liquid, e.g., water droplets and ice fragments are the fragmented clasts (that could be defined as hydroclasts). While applying these terminologies on Earth might be straightforward, in extra-terrestrial geology the term could be confusing especially on those planets where water only exists in frozen state. In such cases any type of eruption likely will disrupt ice as “hydroclasts”. This process is clearly different from “real” hydrovolcanism on Earth. At present planetary geology defines this type of volcanism as cryovolcanism [48–51].

We propose a nomenclature system for hydrovolcanism that is practical and defines various sub-terms that retain some of the evolution of the term (Figure 1). In this system hydrovolcanism refers to every process (explosive to non-explosive) where magma and water interact in any geoenvironment. Explosive hydrovolcanism can then be subdivided into “direct” versus “indirect” types to emphasize whether the magma was in direct physical contact with external water or water-saturated sediments. In case of indirect contact, we can define phreatic or hydrothermal explosive eruptions. At present these two terms are commonly used as synonyms. However, we suggest the term hydrothermal apply to an eruption style where the explosions are fueled by the heat of a long-lived and established hydrothermal system and phreatic be reserved for sudden heating event of a normal ground water by deeper magmatic heat sources such as intrusions. Direct explosive hydrovolcanism refers to any explosive eruptions where magma and any external water interact regardless of whether MFCI processes were involved in the explosive fragmentation. This type of eruptions commonly defined as phreatomagmatic in “*sensu lato*” in the literature over past decades. To avoid the usage of the

same words to different processes we suggest using phreatomagmatic explosive eruptions as “sensu stricto” to those eruptions where MFCI processes are the main energy transfer driving the explosive fragmentation (Figure 1). These are most likely to occur when magma and ground water interact explosively. The role and degree of external water in the explosive eruptions show a wide spectrum hence the resulting volcano stratigraphy, textural features reflect this very well (Figure 2a,b). Rarely in the literature such eruption types defined as Taalian (only 3 papers can be located in Web of Sciences topic search since 1900 to present days) referring to the Taal (Philippines) 1965 eruption formed maar craters and generated base surges [6,8]. Taalian as an eruption type appears in few times in volcanology text books such as a sub-category of explosive phreatomagmatic eruption types characterized by closely timed phreatomagmatic explosions generating radially expanding pyroclastic density currents and ash plumes, typical for tuff ring-forming short lived (monogenetic) eruptions [52].

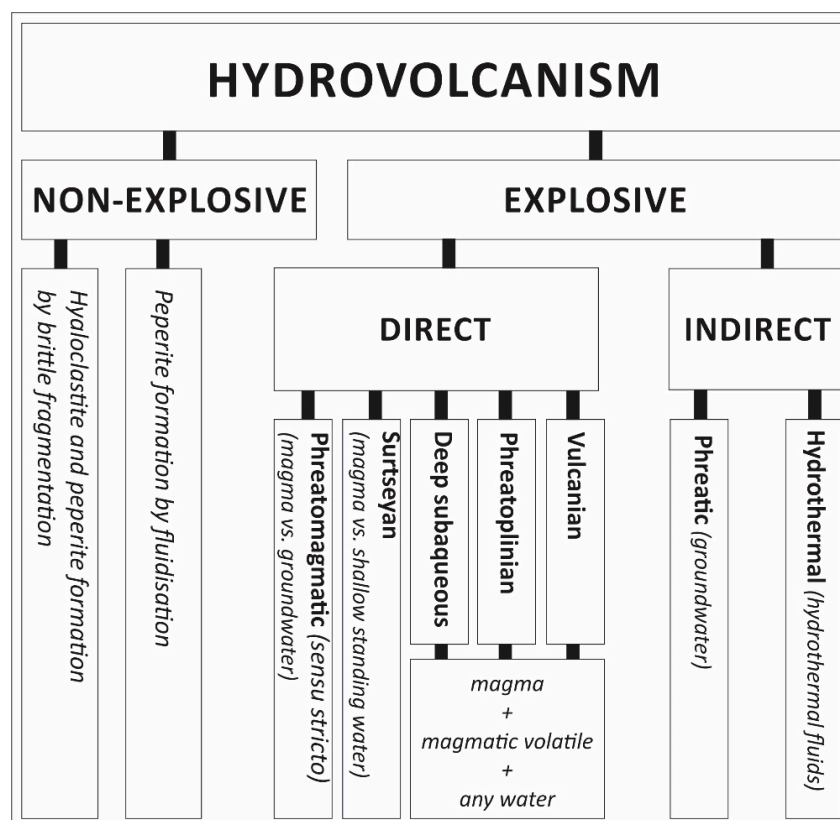


Figure 1. Proposed classification of hydrovolcanism using a process and products perspective. “Deep subaqueous” category contains a typical Surtla-type volcano, while the “Phreatomagmatic” category would be similar but broader to those defined by Taalian-type volcanism.

Surtseyan volcanic eruption style refers to magma interacting with any standing water body (lakes, rivers, marine) [53]. The water depth in a Surtseyan eruption should be shallower than the water mass required to suppress the explosive expansion of fragmented pyroclasts to the shallow range where the explosive energy completely displaces the overlying water by generating a near-vent environment essentially the same as in subaerial conditions [47,54–61]. It is estimated that this would be somewhere between around 100 to 10 m water depth [62]. In regard of Surtseyan eruption style it is important to point out whether the generated eruption column pierced the water surface or not [60]. During edifice growth the standing water body will become shallower and shallower with each successive eruption thereby enabling pyroclasts to expel through the water column to the surface [60]. Such type of volcanism commonly cited as emergent type subaqueous volcanism. There needs to be a distinction between when majority of the explosive outbursts expel pyroclasts that accumulate above the water

table and in the adjacent shallow water region and those that kept the edifice under the water mass throughout most of its growth. To retain this distinction the term Surtla applies to fully subaqueous events versus Surtseyan style which refers to a satellite vent opened next to the main volcano, such as occurred at Surtsey [46,47,63,64]. Naturally, if water depth is great, both Surtseyan and Surtla type volcanoes start their eruption fully under water, without piercing the water table by explosion jets or eruption column. If the volcano never grows to have only shallow water coverage over its vent and the ability of its eruptions pierce the water level, Surtla type eruption is commonly defined. When the volcano reaches the fully emergent stage, the resulting volcano is defined as Surtseyan type of volcano. From the explosive eruption process perspective, we distinguish here Surtseyan type direct explosive hydrovolcanism when it is possible to establish by direct (e.g., pyroclast texture, clast population) or indirect (e.g., geological context, stratigraphy) evidences that the explosions pierced the water level at least in the late stage of the volcanic edifice growth. Any other cases we suggest using deep water direct explosive hydrovolcanism to all those cases where the explosive eruptions remained fully subaqueous through the entire time of the edifice growth. This category contains the Surtla-type eruptions and also the explosive eruptions occurred in the deepest water depth where explosions can take place. This is typically a much wider water depth range than a typical Surtla-type eruption those Authors use this term.

In recent years, several researchers exploring the style of explosive magma-water interaction driven eruptions recognize the role of magmatic volatiles to enhance the explosive eruption efficiency. In particular, when volatile-rich magma is trapped in volcanic conduits for a short while, the volatiles beneath a conduit-filling plug accumulate so when the hot magma interacts with the groundwater an explosive eruption capable of producing pyroclastic deposits with textural and depositional similarities with those formed by pure Vulcanian explosive eruptions can occur [65–70]. External water commonly plays a pivotal role in this type of explosive eruptions, so we suggest including Vulcanian type eruptions in this category when suspected external water triggered the explosions. Similarly, phreatoplinian eruptions could be grouped under the same category to express the role of external water to facilitate fragmentation of magma. Many of the eruptive products of phreatoplinian eruptions show textural evidence (Figure 2c) that magma fragmentation was driven by MFCI processes [71–73].

There are two major groups of non-explosive hydrovolcanism that we suggest be distinguished; one where the magma and water or water-saturated sediment interaction failed to produce fully developed MFCI processes and the other, explosive expansion, where frozen MFCI produces mixed rocks called peperite [44,74–86]. Another major non-explosive hydrovolcanism type is hyaloclastite formation. This occurs where the water depth is too deep and/or the magma volatile content too low and/or the magma invades glaciers and there is autoclastic fragmentation of the chilled margin of the lava flow [87–93].

2. Explosive Hydrovolcanism in Large Magmatic (Polygenetic) Systems

Large magmatic systems are where the erupted volumes of a single (e.g., silicic calderas) or consecutive eruptions of polygenetic volcanoes (e.g., stratovolcanoes and shield volcanoes) are significantly larger than at small-volume/monogenetic volcanoes often associated with monogenetic volcanic fields [94,95]. Based on the typical volcanic activity of these systems, we distinguished stratovolcanic systems, silicic caldera systems and shield volcanoes as a generally accepted framework of volcano types [96]. In addition, we also include the hydrovolcanism in subglacial [93,97,98] and subaqueous settings [61].

2.1. Stratovolcanic Systems

Stratovolcanoes are referred to as composite volcanoes where consecutive eruptions take place over a long time scale (normally in the range of several million to several ky) establishing a stable, main vent [96]. In contrast, compound (or complex) volcanic systems refer to volcanic massifs that are the result of eruptions from closely spaced-vents, such as the Tongariro volcano, New Zealand [99–101].

Stratovolcanoes either grow vertically or have a compound form, commonly as overlapping volcanic massifs where rising magma can be affected by external water in various ways. If volcanoes are above the snow line, glaciation can cover their summit regions hence glacio-volcanism interaction is likely to affect any volcanic eruptions during their evolution [102–109]. Lateral vent migration can produce various local hydrogeological features that can be encountered by the rising magma providing opportunities for various types of hydrovolcanism. In the case of complex volcano architecture, the volcanic cone can enhance groundwater infiltration into the volcanic system and enhance interaction between the magma and water [110,111] producing pyroclastic successions recording textural features characteristic for wet fragmentation conditions (Figure 2d). Crater lakes [112] on active, long-lived stratovolcanic systems provide a significant geoenvironment where hydrovolcanism can take place. This includes anything from small magma batch-fed eruptions producing localized intra-crater Surtseyan explosive eruptions to eruptions into a standing body of water that initiate lahars. The latter occurred on Ruapehu, New Zealand when the crater lake water emptied through an ongoing eruption producing multiple lahars [113–118]. Similar eruptive episodes are also recorded from Costa Rica [119,120], Mt. Redoubt, Alaska [121].

Ongoing eruptions, ranging from mildly explosive to large explosive events, that have been influenced by external water, often from the local hydrothermal system (e.g., heated), can produce highly unpredictable volcanic eruptions. These include numerous currently or recently active volcanic craters such as lakes of Rincón de la Vieja, Poas (both in Costa Rica) [20], White Island, Ruapehu (both in New Zealand) [25,109], Aso, Kuchinoerabujima, (both in Japan) [122,123], Santa Ana (in El Salvador) [124], and Samalas volcano, Lombok [125]. In the geological record, the presence of a crater lake is commonly marked by eruptive products that show evidence of magma-water interaction such as the Tufa Trig Formation in the Ruapehu ring plain in New Zealand [118] (Figure 2e). Phreatomagmatism is also common in settings where basement geology is characterized by a groundwater network and water has access to the conduit systems, such as the situation at Vesuvius, Italy [126–130].

Frequent explosive hydrovolcanic activity at composite volcanoes is often associated with lakes in summit craters [131,132], active hydrothermal systems [133] or glaciation [134,135]. In some cases during high intensity eruptions phreatoplinian activity is common (e.g., Mt. Redoubt, Alaska [121]). Eruptions that occur through satellite vents may be affected by groundwater reservoirs established in the ring plains around central volcanoes [136].

2.2. Silicic Caldera Systems

Silicic caldera systems here refer to large calderas (with common super-eruptions) that are not developed on stratovolcanoes [96]. Volcanic activity of silicic caldera systems is characterized by either large-volume caldera forming eruptions [137] or more frequent smaller volume volcanic events, similar in size and eruptive style to the eruptions of dispersed volcanic fields (e.g., in basaltic monogenetic volcanic fields) such as the 1965 phreatomagmatic eruption of Taal volcano, Philippines [6]. Moreover, some of these calderas are characterized by post-caldera composite cones, such as Sakurajima volcano in the Aira caldera, Japan [138,139]. We are only focusing on the caldera-forming eruptions that produce eruptive products in the range of few tens to few thousand cubic kilometers [140]. It is likely that some degree of interaction between magma and groundwater exists for the majority of caldera-forming events. However, it is not always easy to recognize textural features of the eruptive products to establish the magma-water interaction due to the low water ratios relative to the erupted magma. Caldera-forming eruptions usually consist of numerous phases characterized by different eruption styles from which initial vent-opening phases are often phreatomagmatic (in the narrow sense), such as the ~110 ka Toya and 120 ka Kutcharo caldera-forming eruptions in Japan [141,142] or the ~285 ka Rotorua and 232 AD Taupo caldera-forming eruptions in New Zealand [73,143]. If the eruptions occurred beneath shallow marine or lacustrine environments then hydrovolcanism may dominate multiple phases, such as the formation of the Kos Plateau Ignimbrite, Greece [144] and Hatepe and Rotongaio Ash of Taupo Pumice Formation, New Zealand [73,145] (Figure 2g) or the entire activity

such as, e.g., 25.4 ka Oruanui eruption in New Zealand [3,146]. The role of phreatomagmatism in large caldera forming silicic eruptions is evident in the geological record of regionally significant eruption sites such as those in the Miocene rhyolitic ignimbrite-forming eruptions across the Pannonian Basin that was a shallow marine, well-drained low-land basin at the time of the volcanism [147]. In contrast with the initial phreatomagmatic phases, phreatoplinian, high eruption flux phases associated with magmatic and hydrovolcanic fragmentation produce large volumes and widespread dispersal of tephra that is characterized by much finer grain sizes than typical Plinian deposits [148]. Despite the numerous lines of evidence from the depositional record of large volume silicic eruptions, it is still not fully understood what role the water plays in magma fragmentation. The question is still commonly posed whether water is the key in the magma fragmentation through MFCI processes or if it is just an environmental parameter that alters the course of the eruption by providing an aqueous environment.

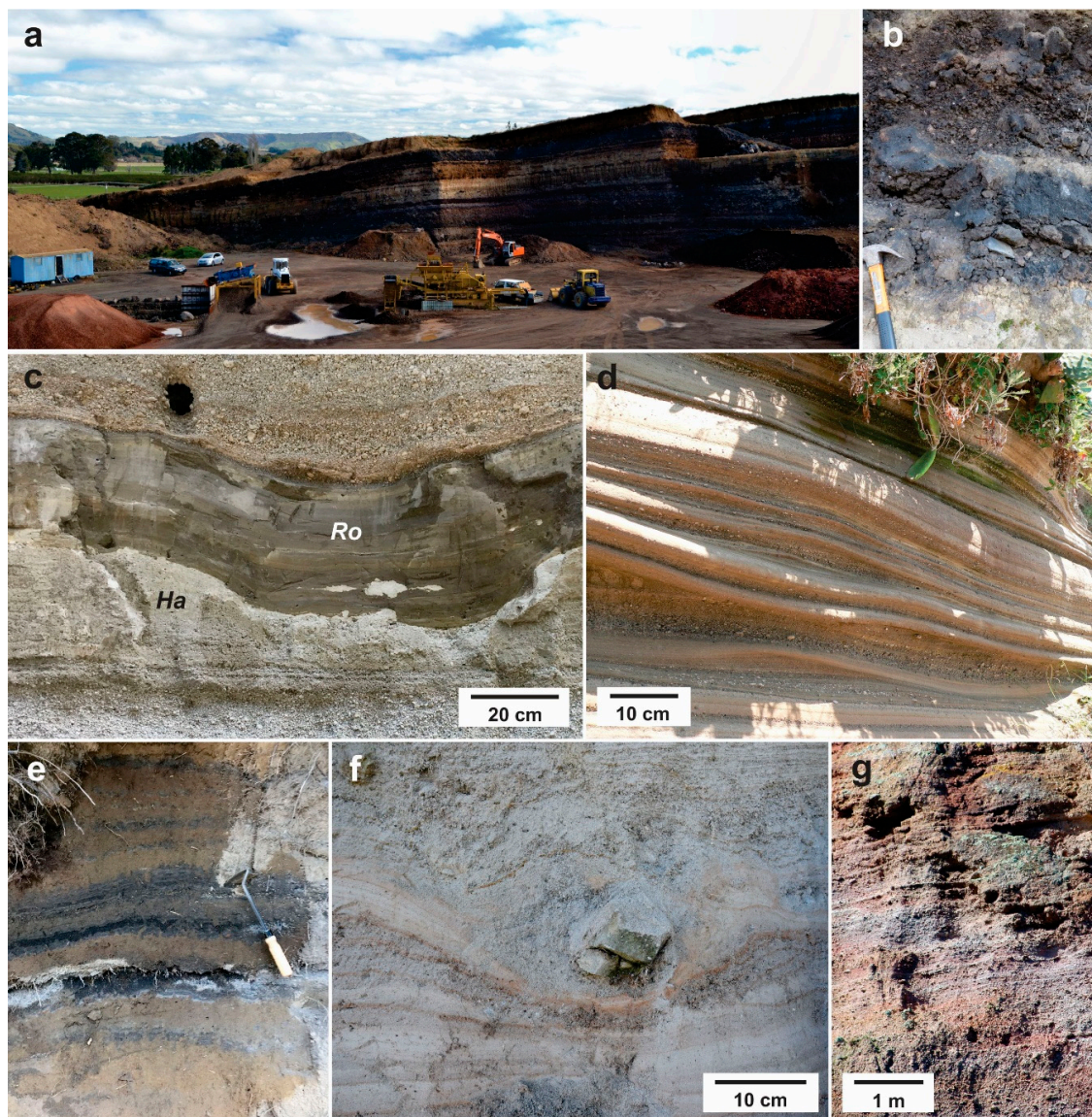


Figure 2. Deposits relating to different hydrovolcanic eruption styles in monogenetic and polygenetic volcanic systems: (a)—Deposits formed by alternating water-influenced Strombolian and phreatomagmatic eruptions at a satellite vent (Ohakune Volcanic Complex) of Ruapehu volcano, New Zealand; (b)—Cauliflower-shaped bombs in Strombolian beds suggest some influence of magma-water interaction at the Ohakune Volcanic Complex, New Zealand; (c)—Phreatoplinian Hatepe (Ha) and

Rontongaio (Ro) ash of the 232 AD Taupo eruption, New Zealand (d)—Accretionary lapilli bearing surge deposits in Lipari, Italy; (e)—Distal ash layers of dominantly phreatomagmatic layers of Tufa Trig Formation, Ruapehu volcano, New Zealand; (f)—Silicic phreatomagmatic beds with impacted rhyolite lava bomb at Puketerata Volcanic Complex, Taupo Volcanic Zone, New Zealand; (g)—Deposits of fall-dominated silicic Surtseyan-like emergent eruptions of the Motuoapa Peninsula, Taupo Volcanic Zone, New Zealand [149].

2.3. Shield Volcanoes and Oceanic Island Volcanoes

Explosive hydrovolcanic activity of shield volcanoes building island volcanoes most often occurs along their shorelines as a result of satellite eruptions that follows rift zones, such as at Kilauea, Hawaii [150] and Ambae Island, Vanuatu [151]. These eruptions usually create pyroclastic cones by predominantly Surtseyan activity offshore, while onshore a set of maars and tuff rings can form; for example the rift edge of Ambae, Ambrym Islands in Vanuatu [151,152] or in Upolu in Samoa [153]. Another type of littoral explosive activity is associated with tube-fed pahoehoe lava flows that reach the shorelines and produce rootless/littoral cones [154–156]. Rootless cones may also form as a result of lava contact with underlying water-saturated sediments, as is suggested on the basis of investigating the eruptive products of the 1783–1784 Laki fissure eruption's lava flows in Iceland [157].

The other type of hydrovolcanic explosive activity of shield volcanoes is associated with their summit regions. Hydrovolcanic activity of summit craters or calderas of volcanic shields occupied by lakes is mostly characterized by Surtseyan activity [158]. More powerful, phreatomagmatic activity, associated with large tephra dispersal and pyroclastic density current generation, is believed to relate to large-scale magma withdrawal from the summit region by flank eruptions along the rift zones or large-scale submarine effusive episodes [159]. The drop of magma levels can allow the crater/conduit to develop below the groundwater table. When magma pressure drops in low magma flux time groundwater can get access to the hot magma. This occurred during the 2018 eruption of Kilauea volcano at the Halema'uma'u crater, where such conditions have triggered strongly explosive phreatomagmatic eruptions in the past [159–161].

2.4. Subglacial Volcanism

Subglacial volcanic activity is volcanism beneath glaciers or ice sheets [93,135,162]. The eruption style of subglacial eruptions is principally controlled by the confining pressure generated by the ice thickness, along with the magma composition, efficiency of magma-ice heat transfer and local glacier hydrology [135,163]. Subglacial explosive activity is most frequently mild due to the thick overlying ice and/or water in the vault resulting in the formation of hyaloclastite breccias. Subglacial volcanic edifices such as tuyas and tindars composed of glassy fragmented volcanic rocks commonly defined as hyaloclastite to catch-all for any fragmented glassy clastic rock generated explosively. Hyaloclastite is preferred here to be used in the restricted sense proposed by White and Houghton [82]. The hyaloclastites of tuyas are tuff breccias mainly formed in lava-fed deltas by fundamentally non-explosive fashion. Glassy fragmented volcanic rocks (lapilli tuffs) of tindars formed in a very different fashion through explosive fragmentation [93]. The effective drainage of meltwater may cause decrease of lithostatic load allowing more powerful subglacial explosive activity that may produce pyroclastic piles/cones constructed from tens to a few hundreds of metre thick, fine, pyroclastic deposits [164]. Explosive activity that penetrates right through an ice sheet usually Surtseyan [93], but it can be phreatomagmatic if any meltwater that was confined in the englacial vault becomes drained, thus causing a transition to phreatomagmatic behaviour. Eruption reached phreatomagmatic stage, such as the Eyjafjallajökull in 2010 and Katla in 1755 [165,166], or phreatoplinian, such as the 1362 AD Öraefajökull eruption [167]. Subglacial volcanism also common among small-volume monogenetic volcanic system and they share similar geological characteristics outlined here.

2.5. Subaqueous Volcanism

Subaqueous volcanism is usually classified as either shallow, where water depth is less than 100 meters, or deep subaqueous, where water depth exceeds 100 meters [62]. Hydrovolcanic explosions can be violent in shallow water but increasing water depth significantly decreases the explosive energy of the eruptions as the expansion of steam becomes limited [30,168]. In the shallow water environment hydrovolcanic eruption styles are diverse and range from mild Surtseyan to phreatomagmatic and phreatoplinian activity during the transition from a subaqueous to a subaerial edifice [169–171]. In deep subaqueous/submarine settings the high hydrostatic pressure prevents the completion of MFCI processes [38], which rules out phreatomagmatic eruptions *sensu stricto*. Instead, explosive fragmentation is induced by bulk mixing of magma with water, similar to the physics of Surtseyan activity [46]. Most deep submarine eruptions generate hyaloclastites [82,172], believed to form non-explosively below the critical depth [173]. Water-free conditions associated with steam cupolas usually develop at high magma supply stages and may produce fine-grained pyroclasts, ballistically-transported fragments and rarely armoured or accretionary lapilli, similar to their subaerial setting counterparts [57]. An interesting example of a deep explosive subaqueous eruption that broke the surface and produced a subaerial eruption cloud is the 2010 South Sarigan eruption, which produced an eruption cloud to 12 km highlighting the hazard potentials of such hidden volcanoes [174]. Large and complex volcanic edifices that are almost completely evolved under water displays volcanic eruptive history associated with the development of long-lived and established hydrothermal systems, complex crater history, common migration of vents and mineralization such as the case in the White Island (Whakaari), New Zealand [19,25]. Recent eruption (2016–2017) on Bogoslof Island (Alaska) [175] also displays the variety of eruption styles such volcanoes can display as a reflection of the sudden and commonly unpredictable changes due to the wet eruptive environment conditions. The active vent of Bogoslof was submerged in shallow seawater through most of the eruptions lasted between December 2016 and April 2017 [176]. During several of the longer events a low subaerial edifice grew developing a vent above the sea level and providing more dry magmatic fragmentation conditions with substantial ash falls [176]. While Bogoslof clearly resembling a Surtseyan volcanic setting [46] its eruptive products, geophysical signals, and eruptive style are all inferred to be more consistent with vulcanian activity—where slow magma ascent leads to repetitive dome or plug formation, overpressurization in the upper conduit, and sudden release during short-lived explosions [176]. The role of seawater to provide the wet eruptive environment certainly influenced the eruption dynamics but in this case were discredited as a major driving force for the eruption [176–178]. It is, however need to be stated that the eruption was not observed continuously and true Surtseyan style eruption phases may have been unnoticed. The Bogoslof's case also highlights the problem to define the eruption style of a complex, polygenetic volcanic system due to the unpredictable and complex wet environment that interact with the magmatic system. Such complexity also can be seen in a smaller geometrical scale in association with small-volume monogenetic subaqueous volcanism.

3. Explosive Hydrovolcanism in Small Magmatic (Monogenetic) Systems

There are specific volcanic landforms and associated eruptive products that are believed to form as a result of explosive hydrovolcanic activity within monogenetic volcanic fields.

In mafic (e.g., basaltic) intracontinental volcanic fields [179] hydrovolcanism is a common phenomenon and it indicates the relative role of external water in shaping the style of eruptions of small volume high temperature and low viscosity mafic magmas [94]. Typical landforms include tuff cones [180] (Figure 3a,b), tuff rings [181] (Figure 3h) and maar-diatreme [182,183] (Figure 3c–g) volcanoes. These landforms depend on the efficiency of the magma and external water interaction. While experimentally established energy configurations work roughly in the natural environment, various aspects of the external water such as its temperature, the ground water recharge rate, the country rock permeability, or the physical properties of the fine sediment particles within clastic sediment-dominated aquifers play a role in the final eruptive style.



Figure 3. Geomorphology of typical volcanoes formed under the dominance of explosive hydrovolcanic activity: (a)—Eruption cloud with a small emergent pyroclastic cone captured during the December 2005 Surtseyan-style intra-caldera eruption in the caldera lake on top of Ambae, Vanuatu; (b)—Gully erosion on the steep upper edifice of Koko Crater tuff cone with coastal section of pyroclastic surge deposits, Ohau, Hawaii, USA; (c)—A typical tuff ring showing low angle tephra ring around a crater that has a crater floor (photo is taken from the crater floor) above the syn-eruptive surface (Songaksan tuff ring in Jeju Island, South Korea); (d)—A maar cut into the syn-eruptive surface deeply at the Blue Lake at Mount Gambier in South Australia. Note the bright, white rocks exposed just above the water level marking the exposed country rocks below the tephra rim and above the crater floor and lake level; (e)—Shallow maar with a flooded maar basin (Lake Gnotuk, Victoria, Australia), which has its crater floor slightly below the syn-eruptive surface. The maar is surrounded by thin tephra ring; (f)—Nearly 300 meters deep maar crater of the Joya Honda Maar, San Luis Potosi, Mexico; Coalesced maar craters relating to the initial fissural phase of a rhyolitic dome forming eruption (g) and a lava dome that surrounded by an atypical tuff ring comprising block-and-ash flow deposits among more typical fall and surge beds (h), Puketerata Volcanic Complex, Taupo Volcanic Zone, New Zealand.

The spectrum of volcano types forming in intracontinental mafic volcanic fields ranges from simple lava spatter cones, through scoria cones, tuff rings and tuff cones, to large hole-in-the ground landforms or maar volcanoes and some glaciovolcanic landforms such as tindars. It is important to highlight that these terms refer to volcanic landforms and each of these landforms can grow through multiple styles of eruptions including various types of hydrovolcanic activity. Even in lava spatter cone growth dominated by magmatic fragmentation, intermittent explosive magma-water interactions can take place when magma flux drops or the ongoing eruption facilitates new fracture development that drives groundwater toward the active conduit [184,185]. As the general wisdom is that phreatomagmatism is associated with the initial phase of the small-volume edifice growth [186] and its eruptive products also commonly preserved in the basal successions of scoria cones [187]. This scenario is commonly interpreted as the result of the gradual overrun of the magmatic system by environmental aspects such as in eruptions where the magma flux gradually increases over the course of the eruption or where the conduit gradually becomes isolated from the surrounding groundwater, with chilled magma plating the conduit walls [136,188]. With an increasing role of external water in the course of an eruption, phreatomagmatic explosive eruptions can be more prominent and develop a tuff ring or tuff cone around the vent that will be composed of tephra abundant in chilled juvenile pyroclasts. In the case of magma and groundwater explosive interaction excavation can also incorporate abundant country rock fragments derived from the conduit. While the type of country rock and their relative abundance in the forming pyroclastic deposits are commonly used as a proxy to determine the explosion depth [186,189], recent large scale experiments on cratering suggest that the appearance of different lithologies in the eruptive products do not directly relate to explosion depth as multiple explosive bursts can gradually push deep-seated rock fragments closer to the surface where a successful explosive event may propel them out to be deposited with the pyroclastic succession [190–198]. It is also important to highlight that maar volcanoes generally refer to a morphological feature (depression, commonly lake-filled) (Figure 3c–g). The most common process responsible for the formation of maars, however, is magma-water explosive interaction, i.e., phreatomagmatism (*sensu stricto*). However, there are maars which are thought to have formed by magmatic volatile expansion without clear evidence for explosive interaction with water [199,200]. To establish the phreatomagmatic origin of maar craters requires good exposures where pyroclast textures can be documented from associated pyroclastic deposits. Direct evidence can be ambiguous and numerous indirect aspects need to be considered to establish phreatomagmatism is the most appropriate process to create the crater.

Among small-volume, monogenetic volcanoes (Figure 4a–h), silicic examples are common but have received only limited attention. These volcanoes are associated with various geotectonic environment including calderas and polygenetic volcanoes of convergent plate margins [201]. Economically significant ore deposits are associated with small-volume silicic volcanoes. However, such deposits tend to be linked with clusters of such volcanoes [201–206]. The problem with understanding the role of phreatomagmatism in silicic systems is that the magma interacting with water is viscous, its exit temperature is significantly lower than for mafic magmas and they tend to have a higher volatile content. Hence the eruptive products of such volcanism normally share more similarities to those pyroclasts formed purely by magmatic volatile expansion. Lava dome fields for instance are common among rift-related, caldera-dominated volcanism such as the Taupo Volcanic Zone, New Zealand [207,208] or in convergent plate margin volcanism such as along the Andean volcanic arc [209].

Phreatomagmatism is also a major volcanic landform producing process in intra-caldera volcanism in the Campanian region, such as Solfatara volcano, recently defined as a silicic maar-diatreme volcano [210]. In the small-volume silicic volcanism commonly associated with the formation of extensive lava dome fields [207] external water can influence or even dominate the course of volcanism before, during or after lava dome growth [207].

Explosive phreatomagmatic silicic eruptions can produce similar volcanic landforms to those in mafic systems with the difference being that lava dome landforms can dominate the volcanic edifice architecture [211,212].

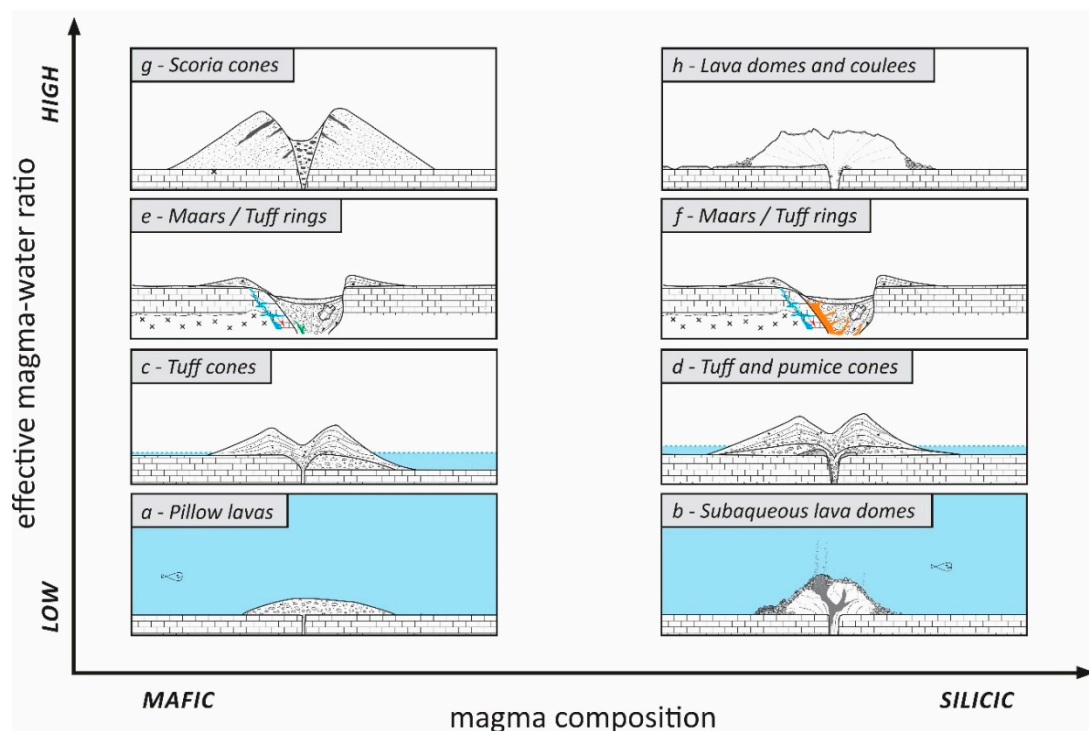


Figure 4. Typical architecture of mafic and silicic small-volume volcanic edifices formed within deep subaqueous to subaerial environments and resulting different effective magma-water ratios (after Wohletz and Sheridan, 1983 [213]). At deep subaqueous environment volcanic activity mostly controlled by the hydrostatic pressure allowing mostly effusive activity (e.g., pillow lavas or hyaloclastites) (a,b). In shallow subaqueous environment explosive eruptions can take place and form tuff/pumice cones (c,d). Silicic tuff cones usually composed of angular lithic fragments (e.g., obsidian). In subaerial settings small-volume eruptions may dominated by phreatomagmatic eruptions and form maar-diatreme volcanoes (e,f). Silicic systems often characterized by long-lived hydrothermal system and ore mineralization (f). Eruptions that are influenced by minor or ad hoc interaction with external water usually insignificant to be expressed in the large-scale architecture of volcanic edifices. However, some phases of the eruptions may differ significantly from typical mafic Strombolian eruptions or effusive emplacement of lava domes of silicic systems (g,h).

4. Features Relating to Phreatomagmatism

Determining whether fragmentation was influenced by magma-water interaction is challenging and there are limited studies that explicitly describe and attribute features to specific processes. Moreover, recent studies of diatremes from Arizona (when compared to other similar diatreme fields) recognized the “practical” aspects that can be applied to envision magma and water explosive interaction even if no real positive evidence can be provided. “Absence of evidence is not evidence of absence” as it has been summed up in a recent paper [65].

Deep, broad craters surrounded by typical ejecta deposits are the most common vent structures cited as evidence of explosive phreatomagmatic eruptions. It is considered that magma-water explosive interaction is able to provide enough energy at fast enough rate to excavate country rock and form such craters (Figure 3c–g). Identification of deep diatremes, i.e., a volcanic debris filled, deep conduit beneath maar crater is one of the strongest lines of evidence for explosive magma-water interaction. Any processes that are energetic enough to remove overburden and open large, deep craters are likely to be the product of phreatomagmatism. Typical volcanic structures, volcanic edifices and deposits of maar-diatreme, tuff ring, tuff/pumice cone volcanoes are volcanic landforms that can form from explosive magma and water interaction. However, their identification alone does not warrant supporting a phreatomagmatic origin [190].

The textural characteristics of fine-grained, dune- and cross-bedded pyroclastic deposits with horizontal transportation indicators commonly defined as base surge deposits and also used as strong evidence for supporting an origin involving phreatomagmatic explosive eruptions. The rationale for this is that the sudden explosive event commonly generates blasts that travel radially away from the eruption point accumulating typical pyroclastic density current (PDC) deposits [214–217].

On a micro scale, juvenile pyroclast textures are the best means of establishing phreatomagmatic explosive origin of a deposit. The juvenile pyroclast vesicularity, vesicle shapes and bubble density being the strongest supporting evidence [35] (Figure 5i). In addition, particles, which were derived from the interaction zone between the magma and water typically range in size from a few tens of microns across and carry characteristic textural features [27,36,218]. Typical particle morphology of equidimensional, angular and low vesicular glassy pyroclasts are commonly used as the main criteria for establishing that a phreatomagmatic explosive eruption took place [219–221].

Various ash aggregates, such as accretionary lapilli (Figure 5c,d), also form during phreatomagmatic explosive eruptions [222]. They provide compelling evidence of water droplets in the eruption column or pyroclastic density currents, but do not indicate directly the nature of fragmentation. Such ash aggregates can also be produced by the eruption column when it encounters a moist air body such as a meteoric cloud. The presence of accretionary lapilli is also used to determine the distance from an eruption source as steam has to condense to free water in the pyroclast mixture hence the PDC or the eruption cloud should be below 100 °C degrees. This is normally the case a few hundred meters from the eruption point laterally. Vertical eruption column can also cool sufficiently to cause condensation, with fallout around the vent. Hence lateral transport is not necessary to achieve such condensation.

More direct evidence is the presence of abundant cauliflower shaped lapilli and bomb in the pyroclastic deposits supporting the presence of water during magma rise. Cauliflower-shaped bombs or chilled rim pyroclasts are a common feature when a cooling agent such as water is present during the eruption (Figures 2b and 5e,f).

Adhering dust (fine ash) (Figure 5h) and/or some specific salt minerals on the surface of fine ash particles are used as strong evidence of magma and water interaction. This has been observed for recent eruptions in Iceland such as Eyjafjallajökull 2010 [165]. The presence of fine ash particles on pyroclasts with surface cracks, pitting and step-like surface roughness (Figure 5g,h) are among the supporting evidence for MFCI-driven explosive fragmentation [36].

The presence (and abundance) of accidental non-volcanic lithic fragments in the pyroclastic deposits (Figure 5a,b) that usually correspond to excavating country rock is commonly attributed to sub-surface phreatomagmatic explosive eruptions [183,186]. While these features are used as a strong argument for phreatomagmatism, caldera-forming eruptions and vent-wall erosion may also produce lithic-rich deposits [3]. However, they are normally distinguishable on the basis of the geological context, which requires geological mapping of the distribution of deposits.

The large proportion of fine particles is considered evidence for powerful magma fragmentation and envisioned as a strong criterion for phreatomagmatic explosive fragmentation [39,223–227]. However, laboratory experiments indicate that only about one third of the melt mass interacts with water during strong phreatomagmatic activity and fragments produced are dominantly fine ash [37,38]. The majority of the fragments originating from near the site of explosions by hydrodynamic fragmentation do not always bear clear signatures of magma and water interaction. On the basis of this, interactive and passive pyroclast populations are commonly distinguished as a characteristics of the vent/conduit dynamics during the fragmentation driven by MFCI processes [65].

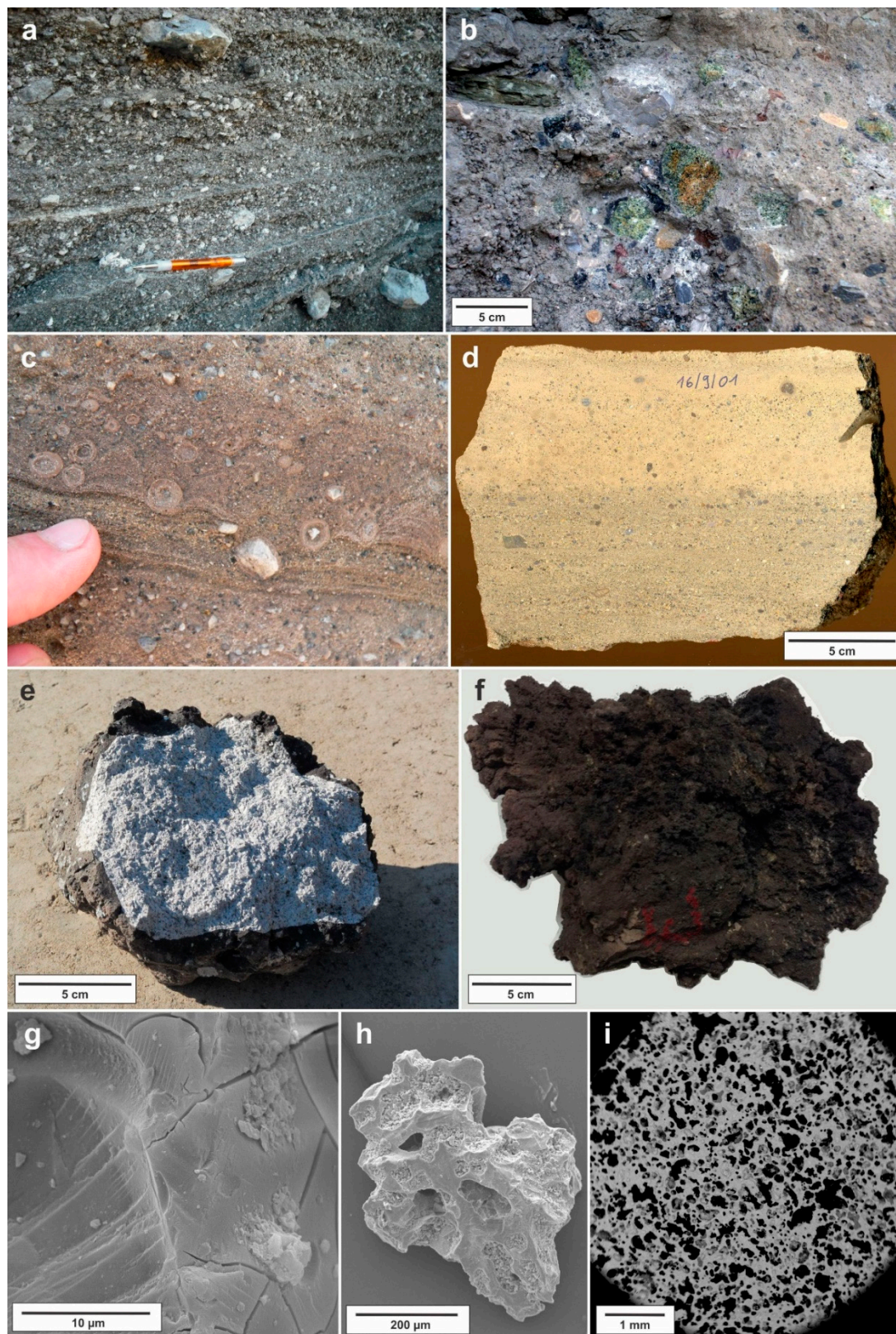


Figure 5. (a)—Lithic-rich proximal deposits around the Joya Honda maar in San Luis Potosi, Mexico; (b)—Lithic-rich pyroclastic flow deposit sourced from the Füzes maar in Szentbékáll (Bakony-Balaton Highland Volcanic Field, Hungary); (c)—Accretionary lapilli in pyroclastic surge deposits, Spiaggia Valle Muria, Lipari, Eolian Islands, Italy; (d)—Typical phreatomagmatic lapilli tuff and tuff section (from the Bakony-Balaton Highland volcanic Field, Hungary) in hand-specimen with abundant accretionary lapilli; (e)—Cauliflower-shaped loaded bomb from the Tongxin volcano, Arxan-Chaihe Volcanic Field,

NE China; (f)—Cauliflower-shaped bomb from the water-influenced Strombolian deposits of the Ohakune Volcanic Complex, New Zealand; (g)—Surface cracks and steps on the surface of a volcanic glass shard from the basal succession of the Songaksan tuff ring (Jeju, South Korea) phreatomagmatic deposits; (h)—Dust-adhered juvenile fragment from phreatomagmatic tuff (Ohakune Volcanic Complex, New Zealand); (i)—Vesicle textures of water-influenced Strombolian cauliflower-shaped bombs (Ohakune Volcanic Complex, New Zealand).

5. Discussion on New Advances

To establish the general research trends regarding hydromagmatism we conducted a basic search and critical analysis of between 2014 and 2019 accessible via the Thomson Reuters Web of Sciences all databases (Figure 6). The survey was conducted in 29 October 2019. As publication record always changing the analysis should be treated as a snapshot of the trends in research in volcanology. We selected research areas such as “physical sciences other topics”, “geology”, “geochemistry geophysics”, “environmental sciences ecology”, “geography”, “paleontology”, “physical geography”, “mineralogy” and “remote sensing” as the main pool of data searched.

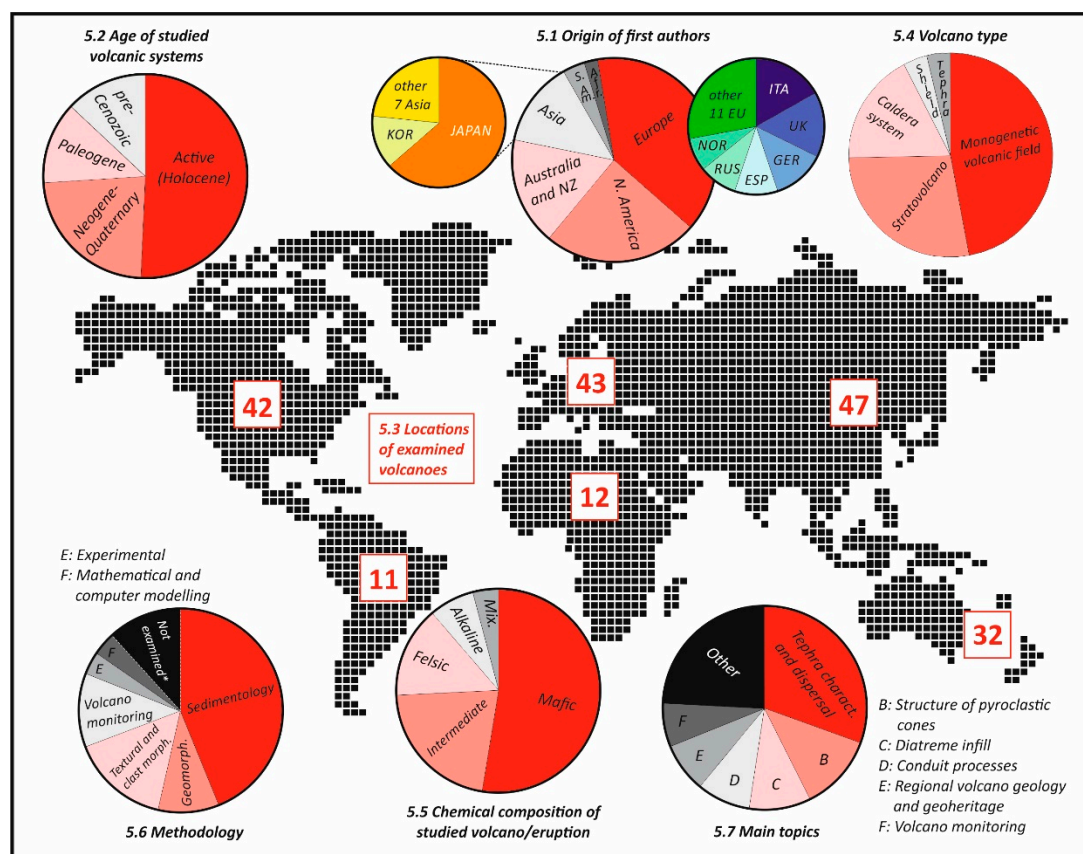


Figure 6. Graphical summary of the statistical analysis performed on articles published between 2014 and 2019 about phreatomagmatism, maars, and hydrovolcanism.

We found 240 published articles from the studied time period using the key words; phreatomagmatism, maar, and hydrovolcanism (Figure 6). We used the “or” logical operator to find relevant articles. Alternative keywords such as phreatic, hydrovolcanic, magma-water or Surtseyan were also considered, but in the end were not used in our study. Keyword of “phreatic” were problematic as it picked up too many papers dealing with hydrogeology without volcanic context making the analysis difficult without subjectivity. Similar issue was identified with the keyword

of “magma-water” hence both search terms were abandoned. Hydrovolcanic or Surtseyan has not provided significantly different array of papers than the three keyword we finally used.

To make our research globally representative we focused only on papers visible on the Web of Science. About 93% of the examined publications were written in English, along with 4 articles in Spanish, 3 in Japanese and Russian, 2 in Korean and 1 in Chinese, French, Icelandic and Turkish. We reviewed all these articles “manually” and we have classified them by the following attributes; (1) what is the country of the first author’s institution, (2) age of examined volcanism, (3) the examined volcano located in which regions of the world, (4) what type of volcano (e.g., caldera, volcanic field) was examined, (5) what was the composition of the examined volcanism, (6) what methods were utilized during the research, and (7) what is the main topic of the article. Our Web of Science search picked up 25 articles that are totally irrelevant to hydrovolcanism (e.g., ecosystem of maar lakes). There were a further 31 research studies where none of the aspects of hydrovolcanism were examined, but the topic was in strong relation of hydrovolcanic activity (e.g., water runoff in a lahar triggered by a phreatomagmatic eruption or review articles). The irrelevant papers were rejected from further analysis thus our statistics include 215 published papers.

5.1. Origin of First Authors

From a regional perspective, European researchers contributed most to the science of hydrovolcanism (41.6%), followed by researchers from North America (26.2%), Oceania (Australia and New Zealand; 18.2%), Asia (14%), South America (3.7%) and Africa (2.3%). The contribution of Europe is shared by 16 countries, from which by the number of publications Italy (15), United Kingdom (14), Germany (11), Spain (9), Russia (8), Norway (7) and France (5) can be designated. From North and Central America, numerically United States has contributed the most (34 articles), followed by Costa Rica, Canada (7) and Mexico (6). Asia’s contribution is dominated by Japan with 18 articles, whereas Argentina outnumbered the contribution from South America with 6 manuscripts. We also checked the number of published articles using a population-weighted contribution, which indicates the highest scientific contribution for research relating to hydrovolcanism by New Zealand, Costa Rica and Norway having orders of magnitude higher index than the USA (Figure 6).

5.2. Age of Studied Volcanic Systems

We were interested in the age of volcanic activity in the research. We classified the papers into active or Holocene, Neogene, and older volcanism, and there were a number of articles, which are not related to specific volcanoes, such as review, modelling and experimental papers (13% of the total articles). About 50 % of the manuscripts examined active or very young volcanism, 24% of the volcanoes studied were Neogene, whereas 13% of the examined volcanic activity occurred prior to the Neogene.

5.3. Locations of Examined Volcanoes

For the locations of examined volcanoes, we followed the continents boundaries, thus the research completed in Trans-Ural territories of Russia was included to Asia. The results show that volcanic activity of Asia, Europe and North America almost had the same interest with 47, 44 and 43 papers, respectively. Oceania—dominated by research executed within New Zealand—contributed 32 articles, whereas African (12 articles) and South American (11 articles) volcanism were least.

5.4. Type of Examined Volcanoes

We classified the articles by their subject volcanism as follows; caldera systems (not including calderas formed in stratovolcanoes, e.g., Pinatubo or Crater Lake), strato/composite volcanoes, shield/oceanic island volcanoes, monogenetic volcanic fields (including large mafic igneous provinces, such as Siberian traps), subaqueous or glaciated volcanoes, and tephra blankets around unspecified volcanoes. In articles attributed to tephra, the source of the tephra was unknown or unclear.

Subaqueous/glaciated volcanoes were sometimes classified to one of the other classes, too. About 40% of the research was executed on volcanoes relating to monogenetic volcanic fields, 23% relating to composite volcanoes and 15% relating to caldera systems. About 9% of the examined volcanism was subaqueous or subglacial.

5.5. Composition of Examined Volcanoes

We distinguished calc-alkaline mafic, intermediary and silicic volcanism, along with alkaline and mixed chemical compositions and classified the reviewed articles. About 47% of the articles examined volcanism with calc-alkaline mafic compositions. Over 19% of the subject volcanism was characterized with intermediary compositions, whereas only 13% was silicic. Volcanism with alkaline compositions contributed 6.5% and about 4% of the examined volcanism was characterized by mixed compositions (usually calc-alkaline on the range from mafic to silicic).

5.6. Methodology Used for the Examination of Hydrovolcanism

For the classification of methodology, we tried to keep the number of classes low. We distinguished six classes; sedimentology (e.g., lithofacies analysis), geomorphology-geophysics, clast and vesicle morphological and textural studies, volcano monitoring (including geochemistry and remote sensing), mathematical or computer modelling, and experimental studies. Some of the articles were classified to more than one class, whereas in 32 articles there was no methodology relating to the understanding of hydrovolcanism. The most frequently used method to examine hydrovolcanism is sedimentology (e.g., lithofacies analysis) (56%), followed by clast and vesicle morphology and textural studies (20%), volcano monitoring (14.5%) and geomorphology-geophysics (12.6%). Mathematical or computer modelling, and experimental studies are represented by about 5% of the research.

5.7. Main Topics

The topics of the relevant research were very broad, and we managed to classify them into 14 groups. Some of the articles were classified to more than one class. Most frequently the research focused on the dispersal and characteristics of tephra (43%), followed by the structures of pyroclastic cones (17.3%) and the characteristics of diatreme infills (14%). The understanding of conduit processes (12.1%), regional geology and geoheritage (11.2%), volcano monitoring (9.8%) and volcanic hazards and risks (7.5%) were also common topics. Cratering experiments represent a new avenue of research that has recently provided many new insights of diatreme formation and its relation to the observed morphology. Another recent topic is the explosive activity of mafic large igneous provinces, such as the Siberian Traps, which may have contributed to sudden climate changes.

6. Conclusions

On the basis of our review, we conclude that hydromagmatism (and its common synonym hydrovolcanism) plays a pivotal role in understanding explosive volcanism, shallow magma emplacement and is widespread and plays various pyroclast transportation and deposition processes. While hydromagmatism (or hydrovolcanism) and phreatomagmatism are commonly used as synonyms, in recent years, phreatomagmatism has become the keyword used to define magma and water interaction in both non-explosive and explosive eruption styles. Here we suggest a framework reserving phreatomagmatic as a descriptor for eruptions styles, deposit types and volcanic processes that occur at the contact between magma and sub-surface water (e.g., ground-water aquifers). A general literature review of the past 2 decades indicates that there is an increased interest in understanding the role of magma-water interaction styles, explosive energy generation and volcanic landform formation. Linking the processes responsible for the formation of debris-filled conduits, such as diatremes, and surface expression of small-volume (monogenetic) volcanic landforms' pyroclastic deposits are also among key research areas.

Reviewing publications, the last 5 years indicates that research on hydrovolcanism focused mainly on small-volume basaltic intraplate volcanic fields as the effect of external water over the small magma volume involved in the eruptions can be significant. Hence, this type of volcanism provides a good avenue to understand the relative role of the internal and external factors governing the magma fragmentation. It is also an interesting conclusion that in spite of the emergence of large-scale experimental studies on crater formation and some new approaches to laboratory studies on magma and water interaction, most research is still dominated by sedimentology-based (e.g., lithofacies-based) approaches to link pyroclastic deposits to styles of eruptions. In spite of the great advances in the past three decades, the fundamental questions still remaining relate to understanding hydrovolcanism in silicic systems (small or large), magma and ice interactions, aspects of subaqueous volcanism, linking diatreme rock textures to fragmentation and excavation processes, and volcanic field evolution in the light of the long-term hydrogeological evolution of a volcanic region.

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