Bulletin of Volcanology (2022) 84:64
https://doi.org/10.1007/s00445-022-01571-7

PERSPECTIVES

Phreatic and Hydrothermal Eruptions: From Overlooked to Looking Over

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Received: 15 July 2021 / Accepted: 6 May 2022

Abstract

Over the last decade, field investigations, laboratory experiments, geophysical exploration and petrological, geochemical and numerical modelling have provided insight into the mechanisms of phreatic and hydrothermal eruptions. These eruptions are driven by sudden flashing of ground- or hydrothermal water to steam and are strongly influenced by the interaction of host rock and hydrothermal system. Aquifers hosted in volcanic edifices, calderas and rift environments can be primed for instability by alteration processes affecting rock permeability and/or strength, while magmatic fluid injection(s), earthquakes or other subtle triggers can promote explosive failure. Gas emission, ground deformation and seismicity may provide short- to medium-term forerunner signals of these eruptions, yet a definition of universal precursors remains a key challenge. Looking forward in the next 10 years, improved warning and hazard assessment will require integration of field and experimental data with models combining case studies, as well as development of new monitoring methods integrated by machine learning approaches.

Keywords Phreatic eruptions · Hydrothermal eruptions · Triggers · Dynamics · Forecasting

Introduction

Phreatic and hydrothermal eruptions are explosive phenomena ubiquitous to volcanoes, calderas and tectonic rifts areas (Browne and Lawless 2001). Phreatic eruptions are produced by explosive expansion of groundwater due to the sudden arrival of heat and gas from intruding magma (or magmatic fluids), whereas hydrothermal eruptions result from the flashing and expansion of hydrothermal water without the need for any magmatic input (Mastin 1995; Browne and Lawless 2001; Thiéry and Mercury 2009). Despite their comparatively small size, these eruptions can be deadly as they often lack precursors (Barberi et al. 1992; Hurst et al. 2014; Stix and de Moor 2018). When occurring, precursors are too weak, initiate only shortly before the eruption onset or affect a small localised area that cannot be detected with normal monitoring networks (Jolly et al. 2014; Dempsey et al. 2020). As a result, useful forecasts cannot be made. Absent or ambiguous signals may be related to temporal and spatial scales of priming and precursory processes as in the case, for example, of slow accumulation of magmatic gas within aquifers (Sano et al. 2015; Battaglia et al. 2019), or rapid heating and pressurisation of a small volume of

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This paper constitutes part of a topical collection:

Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

Editorial responsibility: K. V. Cashman

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fluids (Christenson et al. 2010; Kobayashi et al. 2018). This may result in gradual development of pressurised aquifers over long timescales versus fast and dynamic interaction of ascending magmatic fluids with the existing aquifer involving cold and/or hydrothermal water, where short-term precursory signals can be present (Chiodini et al. 1995).

Here we discuss advances in processes, characteristics, triggers and lithological factors influencing fragmentation and eruptive dynamics of phreatic and hydrothermal eruptions on observed or monitored eruptions from the past ten years. Different precursory signals and their meaning are explained in the light of their source mechanisms and geological context. A number of unanswered questions about triggering and forecasting these eruptions, as well as future directions and perspectives, are also presented. A video footage of an unheralded phreatic eruption at Rincón de la Vieja (Costa Rica), and a full library sorted and collated into 17 thematic topics covering the last ten years of research are supplied in the Online Resources.

Key events of the past 10 years

Researchers have long struggled to provide consistent definitions and genetic criteria for phreatic and hydrothermal eruptions (Browne and Lawless 2001; Montanaro et al. 2016c; Stix and de Moor 2018). This problem is further exacerbated by the similarity of their dynamics and deposits with those from phreatomagmatic eruptions involving small amounts of magma, and occurring at "wet" volcanoes where vent-hosted hydrothermal systems are common (Pardo et al. 2014; Alvarado et al. 2016; Christenson et al. 2017). It also must be recognised that one eruption type can transition into another in just a few minutes (Swanson et al. 2014; Battaglia et al. 2019). These eruptions can last from seconds to hours, eject large ballistics, generate highly energetic steam-rich density currents (surges) and expel wet jets of poorly sorted rock debris (Lube et al. 2014; Maeno et al. 2016; Kilgour et al. 2019). Deposits are generally of low volume ($< 10^6$ m^3) and restricted to within hundreds of metres to a few kilometres from crater margins, while resulting craters range from a few metres up to hundreds of metres in diameter, with depths from few to several hundred metres (Kilgour et al. 2010; Breard et al. 2014; Montanaro et al. 2016b; Strehlow et al. 2017; Terada et al. 2021). As summarised in Table 1, more than 30 phreatic and hydrothermal eruptions were observed during 2011–2021. The example of a video obtained during the recent phreatic eruption at Rincón de la Vieja in Costa Rica (Online Resources 1) shows the unpredictable nature of these types of explosive events, and how fast products can be dispersed over wide areas. In addition, hundreds of studies published during the last decade have provided insight that elucidate their triggering mechanisms and eruptive processes (Online Resources 2). Illustrative events during the past 10 years include:

- On September 27, 2014, the rupture of a hydrothermal seal produced a phreatic eruption at Mt. Ontake (Japan), killing 63 people (Kato et al. 2015; Kaneko et al. 2016). Long-period and volcano-tectonic earthquakes were detected September 6–11, resuming 10 min prior to eruption (Zhang and Wen 2015; Kaneko et al. 2016). A slight deviation in the stress field was observed a week before the eruptive event; ground inflation of the volcanic edifice occurred seven minutes before the eruption (Terakawa et al. 2016). The eruption launched ballistics reaching a distance of ~ 1 km, produced a 7 km-high ash plume and generated low-temperature pyroclastic density currents (Kaneko et al. 2016; Oikawa et al. 2016).
- On April 27, 2016, Whakaari/White Island (New Zealand) produced a phreatic eruption generating a small pyroclastic density current following weak tremors and decreasing crater lake levels (Hamling 2017; Walsh et al. 2019; Kilgour et al. 2019; Caudron et al. 2021). On December 9, 2019, seismic activity and SO_2 flux increased ~ 40 min before another eruption that produced a 3–4 km-high ash plume and warm (< 100 °C) pyroclastic density currents that killed 21 people and injured 26 (Dempsey et al. 2020; Burton et al. 2021).
- A hydrothermal eruption at Te Maari/Tongariro (New Zealand) occurred on August 6, 2012, following seismic unrest between July 13 and August 1, which resumed 5 min prior to the eruption (Hurst et al. 2014; Jolly et al. 2014). A landslide unroofed the over-pressured and sealed hydrothermal system producing a 7 km-high plume and warm (~ 80 °C) pyroclastic density currents (Lube et al. 2014; Pardo et al. 2014). A second smaller eruption occurred without precursors on November 21, 2012, and was observed and recorded by tourists (Erfurt-cooper 2014).

Ejected ash from the Te Maari's August eruption included glassy fragments among the mechanically fragmented host rock (lavas and pyroclasts). The difficulty in identifying fresh juvenile pyroclasts in fine ash deposits raised the questions about the capability to discern juvenile products in small phreatomagmatic eruptions and requires rethinking of the long-standing definition of phreatic and hydrothermal as eruptions involving no magmatic material (Pardo et al. 2014).

Some volcanoes experience periods of prolonged activity with alternating or consecutive phreatic and phreatomagmatic events. For instance, between 2014 and 2020 Turrialba (Costa Rica) produced frequent eruptions of these types due to magma injection and/or breaking of

Table 1 List of phreatic, hydrothermal, and phreatomagmatic eruptions from the last 10 years. Settings, processes, triggers, characteristics, products and timing are summarised

Site	Date	Eruption type/geologic/lithologic setting	Juvenile material present	Processes	Triggers	Characteristics	Volume/area/crater size(s)	Unrest to activity timing	References
Ontake (Japan)	September 27, 2014	Phreatic / Volcano flank (lava, pyroclastic deposits)	Yes: < 0.7 wt% glassy particles	Rupture of a hydrothermal seal	Injection magmatic gas	Ballistics shower (up to ~ 1 km); ash plume (7 km); low-T PDC	Ballistic field, ash plume, PDC *Volume (tot)*: 0.7–1.3×10^6 m.^{3} *Area:* 2, ~ 1200, 3 km.^{2} *Crater size(s)*: < 50–150 m	*Mid-term:* Crustal deformation (1 month); LP and VT earthquakes (21 days) *Short-term:* VT earthquakes, seismic tremor, and ground inflation (< 10 min)	[1–5]
Te Maari/ Tongariro (New Zealand)	August 6, 2012	Hydrothermal / Volcano flank (breccias, brecciated-tuffs, lavas)	No	Unroofing of hydrothermal system	Landslide	Ballistics shower (up to ~ 1.4 km); ash plume (7.8–10 km); low-T PDC	Ballistic field, ash plume, PDC *Volume*: > 200, 2.3–2.8×10^5, 3.4×10^5 m.^{3} *Area:* 5.1, > 6000, 6.1 km.^{2} *Crater size*: $> 400 \times 65 \times 15$ m	*Long-term*: change in seismic attenuation (Months) *Mid-term*: Seismic swarms (20 days)	[6–10]
	November 21, 2012	Hydrothermal	No	Unknown	Unknown	Ballistics shower (< 0.2 km); ash plume (3−5 km); low T PDC	Unknown	No precursor	[11]
Whakaari/ White Island (New Zealand)	April 27, 2016	Phreatic / Vent-hosted (unconsolidated pyroclastic deposits)	No	Rupture of a hydrothermal seal	Injection magmatic gas	Ballistics shower (up to ~ 0.3 km); low-T PDC	Ballistic field, PDC *Volume (tot)*:1.3×10^4 m.^{3} *Area:* 0.1, 0.33 km.^{2} *Crater size*: < 50 m	*Long-term:* Ground deformation, change in seismic attenuation (months) *Mid-term:* Lake drainage (2 weeks) *Short-term:* VLP (2 h)	[12–15]
	December 19, 2019	Phreatic/ hydrothermal	Unknown	Rupture of a hydrothermal seal	Injection magmatic gas	Ballistics shower; gas and ash plume (4 km); low-T PDC	Unknown	*Short-term:* Increased SO_2 flux, plume height, and seismic tremor (~ 40 min)	[16,17]

Table 1 (continued)

Site	Date	Eruption type/geologic/lithologic setting	Juvenile material present	Processes	Triggers	Characteristics	Volume/area/crater size(s)	Unrest to activity timing	References
Kverkfjöll / Gengissig (Iceland)	August 15, 2013	Hydrothermal / Caldera (unconsolidated lake sediments)	No	Rupture of low-permeable clay-rich seal	Lake drainage	Ballistics shower; ash plume (< 0.1 km);	Ballistic field, ash plume *Volume (tot)*: 8×10^3 m.^{3} *Area (tot)*: 0.3 km.^{2} *Crater size*: 9–20 m	No precursor	18
Ebinokogen Ioyama (Japan)	April 19, 2018	Hydrothermal / Volcano flank (unconsolidated pyroclastic deposits)	No	Rupture of a hydrothermal seal	Injection hydrothermal fluids	Ballistic launch (< 100 m); gas and ash jet (100–200 m)	Ballistic field, ash plume *Volume (tot)*: 1.5×10^3 m.^{3} *Area (tot)*: 0.04 km.^{2} *Crater size*: 9–37 m	*Long-term*: Ground thermal anomalies, spring T°C increase (2 yrs); fumarole T°C increase (1 yr.); fluid kick at a fumarole (1 yr.)	19,20
Turrialba (Costa Rica)	2011–2021 (9 eruptive phases)	Phreatic-phreatomagmatic / Vent-hosted (lava, pyroclastic deposits)	Yes: < 10% fresh glass	Rupture of a hydrothermal seal	Injection magmatic gas	Repeated ash plumes (0.1–2.5 km), near constant gas emissions	Ballistic field, ash plume *Volume*: variable *Area*: variable *Crater size*: 200 m	*Long-term*: Seismic swarms, increased fumarolic activity (8 years) *Mid-term*: Increased CO_2/SO_2, decreased H_2S/SO_2 (1–3 weeks) *Short-term*: Seismic tremor (hours-days)	21,22
Rincón de la Vieja (Costa Rica)	2011–2021 (9 eruptive phases)	Phreatic-phreatomagmatic / Vent-hosted Crater Lake (lava, pyroclastic deposits)	Yes: 1–44% fresh glass	Rupture of a hydrothermal seal	Injection magmatic gas	Repeated ash plumes (0.1–2 km), repeated lahar (< 10 km)	Ballistic field, ash plume, lahar *Volume*: variable *Area*: variable *Crater size*: 500 m	*Long-term*: Increased fumarolic and seismic activity (6 months)	23

Table 1 (continued)

Site	Date	Eruption type/geologic/lithologic setting	Juvenile material present	Processes	Triggers	Characteristics	Volume/area/crater size(s)	Unrest to activity timing	References
Hakone (Japan)	June 29, 2015	Phreatic / Volcano flank (pyroclastic deposits)	No	Deformation and extensional crack opening	Injection magmatic gas (CO_2)	Ballistic launch (< 30 m); gas and ash jet (unknown), mud- and debris flow (~150 m)	Ballistic field, ash plume *Volume (tot)*: 1×10^2 m.^{3} *Area (tot):* < 0.02 km.^{2} *Crater size*: ≤ 15 m	*Long-term:* Ground deformation, seismic swarm, thermal anomalies (3 months) *Mid-term:* Intense steaming ground, seismic swarms (1–2 weeks) *Short-term:* Seismic tremor (2 h)	24–26
Poás (Costa Rica)	2011−2017 (6 eruptive phases)	Phreatic Vent-hosted Crater Lake (pyroclastic deposits)	No	Rupture of a hydrothermal seal below a crater lake	Injection magmatic gas (CO_2 and SO_2)	Gas bursts to vertical jets of solids and fluids (10–400 m), radial base surge of vapour (< 150 m)	Ballistics, ash plume *Volume*: variable *Area*: < 0.06 km.^{2} *Crater size*: unknown	*Short-term:* fluctuations in lake gas composition (24–36 h)	27,28
Kusatsu-Shirane (Motoshirane) (Japan)	January 23, 2018	Phreatic / Volcano flank (pyroclastic deposits)	No	Breaking of seals or weak levels along a fault	Injection hydrothermal fluids	Ballistic launch (0.5 km); ash plume (3.4 km)	Ballistic field, ash plume *Volume (tot)*:3.4–4.9 × 10^4 m.^{3} *Area:* 0.5, < 100 km.^{2} *Crater size*: 500 m long craters row	*Long-term:* Ground deformation, seismic swarm (4 years) *Short-term:* Volcanic tremor and tilt deformation (~ 2 min)	29,30

1. Kaneko et al. 2016; 2. Oikawa et al. 2016; 3. Miyagi et al. 2020; 4. Terakawa et al., 2016; 5. Zhang and Wen, 2015; 6. Hurst et al. 2014; 7. Jolly et al. 2014b; 8. Pardo et al. 2014; 9. Lube et al. 2014; 10. Caudron et al., 2019; 11. Erfurt-cooper 2014; 12. Jolly et al. 2018; 13. Kilgour et al. 2019; 14. Walsh et al. 2019; 15. Caudron et al., 2021; 16. Burton et al. 2021; 17. Dempsey et al. 2020; 18. Montanaro et al. 2016b; 19. Tajima et al. 2020; 20. Ohba et al. 2021; 21. Mick et al. 2021; 22 Rouwet et al. 2021; 23. Battaglia et al. 2019, 24. Doke et al. 2018; 25. Kobayashi et al. 2018; 26. Narita et al. 2020; 27. de Moor et al. 2016; 28. Salvage et al. 2018; 29. Matsunaga et al. 2020; 30. Yamada et al. 2021

hydrothermal sealing that generated ash plumes up to 4 km high (Alvarado et al. 2016; de Moor et al. 2016; Stix and de Moor 2018; DeVitre et al. 2019).

The complexity in the processes, sources and dynamics of these eruptions is striking. Therefore, we suggest that explosive events with a hydrological component occur on a spectrum between three end-members: phreatic, hydrothermal and phreatomagmatic. Combining a number of observations from different volcanic systems, we propose a conceptual classification for different eruption types (Fig. 1, Table 1). The presence of juvenile material is a key feature to identify phreatomagmatic events, whereas phreatic and hydrothermal origins can be defined by considering: i) energetic source type, ii) hydrologic setting, iii) erupted lithology, iv) triggers and v) timescale between any magmatic perturbation and hydrothermal system response.

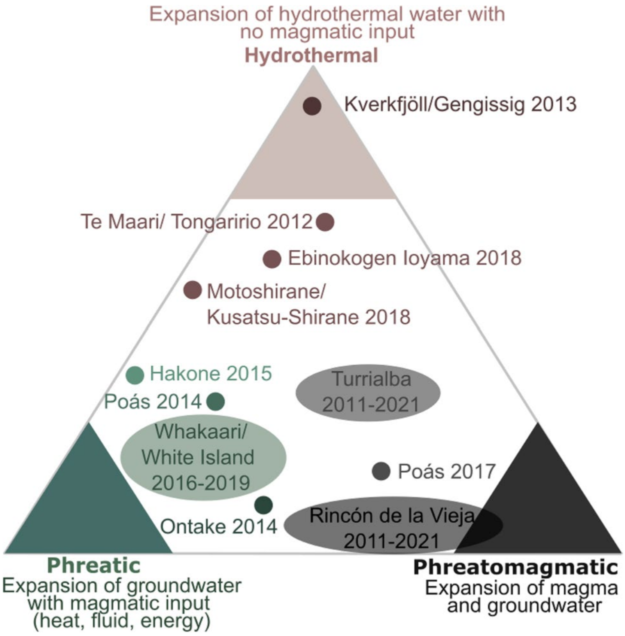

Fig. 1 Ternary diagram illustrating the conceptual classification of volcanic eruptions resulting from the explosive expansion of water with phreatic, hydrothermal and phreatomagmatic end-members. Significant eruptions over the last 10 years are plotted qualitatively: Te Maari/Tongariro August 6, 2012, Ontake September 27, 2014, Poás February–October 2014, Ebinokogen Ioyama April 19, 2018, Hakone June 29, 2015, Kverkfjöll/Gengissig August 16, 2013, Whakaari/White Island 2016–2019, Poás April 14, 2017, Turrialba 2011–2021, Rincón de la Vieja 2011–2021 (see also Table 1). Differentiation between end-members is based on qualitative assessment of the: i) presence and proportion of juvenile material indicative for phreatomagmatic contributions, ii) identification of injected fluids—when present—and their abundance to discriminate magmatic input, iii) hydrologic setting indicative of the balance between hydrothermal and groundwater, iv) presence of an active hydrothermal aquifer and its relative size indicative of the proportion of hydrothermal contributions, v) erupted lithologies, vi) triggering mechanism and vii) timescale between any external perturbations and aquifer response

Processes, triggers and characteristics

Priming and eruption controlling parameters

Phreatic and hydrothermal eruptions are powered by the sudden conversion of thermal energy stored in fluids into mechanical work (rock fragmentation and particle ejection). The main factors controlling the preparatory state (priming) of both fluids and host reservoir, as well as the fragmentation and ejection mechanisms, include:

1. The pressure/temperature differential from source region to ambient surface conditions and the rate of pressure release (Thiéry and Mercury 2009; Montanaro et al. 2016a);
2. The state of the fluid (gas, liquid, gas + liquid) and its volume (Mastin 1995; Ohba et al. 2007; Thiéry and Mercury 2009; Toramaru and Maeda 2013; Montanaro et al. 2016c, a; Fullard and Lynch 2012);
3. The geometry and properties (connected porosity, permeability and strength) of the aquifer host rock (Haug et al. 2013; Galland et al. 2014; Mayer et al. 2016; Kennedy et al. 2020; Montanaro et al. 2021a, b; Fullard and Lynch 2012).

The first two factors define the overpressure conditions and the bulk mechanical energy available during an eruption, which could also be augmented by additional dissolved gases (e.g. CO_2) that lower the liquid stability limit (Thiéry and Mercury 2009; Thiéry et al. 2010; Hurwitz et al. 2016). The third factor influences the style of an eruption, as well as its intensity via the relative partitioning of energy between work of rock fragmentation versus conversion into kinetic energy (Raue 2004; Montanaro et al. 2016b, 2021a; Rosi et al. 2018; Kilgour et al. 2019).

Geological settings

Phreatic and hydrothermal eruptions can occur in volcanic and vent-hosted hydrothermal systems, as well as in active geothermal fields within calderas or volcano-tectonic rifts (Fig. 2, Table 1). Aquifers can be "primed" for eruption by sealing via hydrothermal alteration and mineralisation, including build-up of pore/fracture-filling sulphates, clays, sulphur minerals and silica (Gurioli et al. 2012; Sutawidjaja et al. 2013; Heap et al. 2019; Gaete et al. 2020; Mick et al. 2021). However, sealing can be localised or affect extensive areas in these diverse geological environments and occur progressively or suddenly, as well as can be contrasted by rapid permeability increase (e.g. fracturing). Therefore, changes in aquifer conditions can occur over

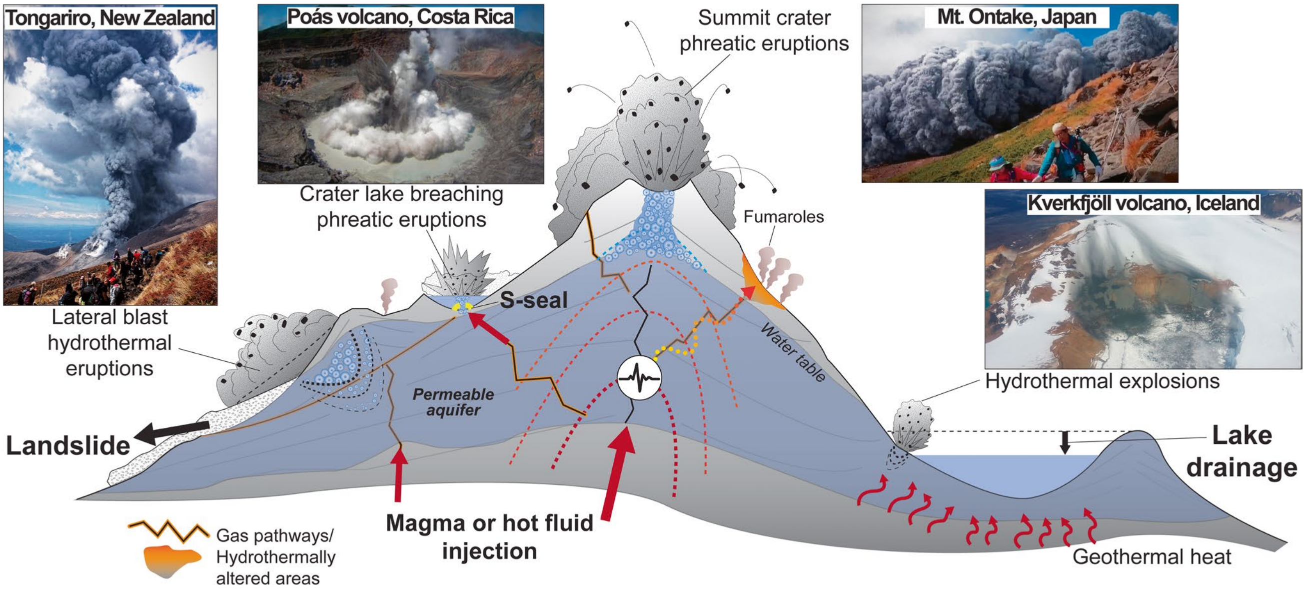

Fig. 2 Conceptual sketch of typical phreatic and hydrothermal eruption types in volcanic and geothermal settings, showing potential trigger mechanisms (e.g., magma/fluid injection; landslide; sulphur sealing; lake drainage). Examples of respective eruption types from Te Maari/Tongariro 2012, Poás 2014, Mt. Ontake 2014, and Kverkfjöll/Gengissig 2013, are shown. *Note*: the Te Maari eruption shown in the picture is the one from November, while the event of August occurred overnight. It can be noted how pyroclastic flow move within the scar left by the landslide triggering the August eruption

varying space and time scales (Harris et al. 2012; Heap and Kennedy 2016; Kanakiya et al. 2017; Roulleau et al. 2017; Kennedy et al. 2020; Cid et al. 2021).

At stratovolcanoes, systems with near-surface magma or lava domes (e.g. Merapi, Lascar, Turrialba, Sinabung, Vulcano), fluids are hosted within primary and reworked pyroclastic deposits, as well as in fractured lavas. The dynamic interaction of ascending magmatic gases with the existing aquifer (cold or hydrothermal water) yields acid-sulphate alteration that can reduce conduit or cap rock permeability by orders of magnitude over timescales of weeks to years (Gurioli et al. 2012; Sutawidjaja et al. 2013; Heap et al. 2019; Gaete et al. 2020; Mick et al. 2021). If lakes occupy active craters (e.g. Poás, Kawah Ijen, Ruapehu, Kusatsu-Shirane), they can act as traps for high temperature gases, allowing the formation of molten elemental sulphur (> 114 °C) within the aquifer (Christenson et al. 2017; Yamamoto et al. 2017). Because sulphur viscosity drastically increases above ~ 160 °C, pore sealing and consequent permeability loss can occur when temperature rises above this threshold value (Christenson et al. 2010; Sutawidjaja et al. 2013; Manville et al. 2015; Scolamacchia and Cronin 2016; Rouwet et al. 2021).

Large calderas and volcano-tectonic rift environments are situated within broad basins containing flat-lying ignimbrites, fractured lavas and volcaniclastic sediments (Morgan et al. 2009; Rowland and Simmons 2012; Kennedy et al. 2018). In these cases, pressurised hydrothermal reservoirs develop below clay caps formed by alteration of feldspar-rich tuffs, breccias and lavas during circulation of alkali chloride-rich fluids as at, for example, Yellowstone, Waiotapu, Ebinokogen Ioyama, Domuyo, Valley of Desolation, Krafla (Mayer et al. 2017; Fowler et al. 2019; D’Elia et al. 2020; Eggertsson et al. 2020; Tajima et al. 2020). The presence of clay-rich and impermeable structures has been confirmed at such systems via geophysical exploration (e.g. magnetotelluric methods; Tajima et al. 2020; Tseng et al. 2020). In such data, hydrothermal seals appear as low resistivity layers overlying a relatively conductive domain corresponding to pressure sources and low-frequency earthquake swarms associated with the dynamics of the hydrothermal reservoir (Seki et al. 2015; Yoshimura et al. 2018; Mannen et al. 2019; Taussi et al. 2019). Clay, silica and zeolite precipitation within surficial fluvial and lacustrine sediments may also form localised to large-scale shallow impermeable layers (Morgan et al. 2009; Montanaro et al. 2016b; Fowler et al. 2019; D’Elia et al. 2020).

Triggers

In all geological settings, sealing locally elevates pressure and increases explosive potential. Addition of gas volume/heat into aquifers from deeper magmatic or tectonic sources can rapidly accelerate local overpressurisation and enhance explosive potential (Fig. 2). Injection of magmatic fluids prior to phreatic and hydrothermal eruptions has been detected by geophysical, geochemical and petrological investigations (Table 1). Cyclical pressurisation and fracturing enhance circulation of hot fluids within shallow portions of the hydrothermal systems and may indicate a greater instability and risk of eruptions (Christenson et al. 2010; Rouwet et al. 2014, 2021; Jolly et al. 2018; Heap et al. 2019; Kennedy et al. 2020; Moretti et al. 2020). Such cyclical unrest periods are observed at Whakaari/White Island where short explosive paroxysms alternate with periods of pressure-induced fracturing resulting in “failed eruptions” (Dempsey et al. 2020). Similar periods of pressure-induced fracturing, and associated seismic and deformation trends, have also been observed and defined at Vulcano where they have been termed “apparent heating” phases (Harris et al. 2012). Characteristic tremor and degassing signals indicate that such behaviour reflects the presence of imperfect seals that readily leak and accommodate deformation pulses following magmatic fluid injections as at, for example, Solfatara in Campi Flegrei (Chiodini et al. 2017; Moretti et al. 2018; Lima et al. 2021).

Another possible trigger of phreatic and hydrothermal eruptions could be large regional tectonic earthquakes disturbing the local stress regime, provided that the “appropriate” priming conditions are present (Lupi and Miller 2014; Seropian et al. 2021). It has been observed that modest, proximal earthquakes can cause an increase in near-vent permeability and trigger mild bursts of hydrothermal fluids (Hurwitz et al. 2014; Reed et al. 2021). Large events may cause rock fracturing to break aquifer seals or produce seismic waves that can perturb hydrothermal systems over different timescales and distances (Rouwet et al. 2019; González et al. 2021). For instance, the M7.6 Nicoya earthquake in Costa Rica in 2012 enhanced seismic and thermal activity at Irazú-Turrialba and Poás volcanoes (Lupi et al. 2014) and affected the eruptive activity in the following 2 to 5 years (de Moor et al. 2017; Salvage et al. 2018). Teleseismic waves from the M6.7 earthquake in Chile in 2014 triggered seismicity and a small phreatic eruption in the Tatun volcano group of Taiwan ~ 200 s afterwards (Lin 2017). A M5.9 earthquake located ~ 10 km NE of Whakaari/White Island occurred on November 24, 2019, about three weeks prior to the deadly eruption on December 19 (Ardid et al. 2022).

Other eruption triggers include (Fig. 2 and Table 1): i) mass movements causing unroofing of hydrothermal aquifers or burying of gas emission vents (Lube et al. 2014; Procter et al. 2014; Mayer et al. 2017; Isaia et al. 2021); ii) extensional fracturing (Ort et al. 2016); iii) groundwater-lake level changes (Montanaro et al. 2016b; Rott et al. 2019); iv) sudden precipitation events (Gaete et al. 2020); and v) rapid fracture/vein filling by calcite precipitation (Simpson et al. 2014).

Lithological factors

The eruptive mechanisms and processes of phreatic and hydrothermal events are strongly influenced by the properties of fragmented lithologies (Fig. 3; Breard et al. 2014; Graettinger et al. 2015; Valentine et al. 2015b; Pittari et al. 2016; Geshi and Itoh 2018; Montanaro et al. 2020, 2021b; Graettinger and Bearden 2021). In particular, rock permeability determines whether expanding fluids may fragment the host rocks or escape via efficient outgassing, while rock strength can modulate fragmentation initiation, craterisation processes, and eruptive dynamics (Haug et al. 2013; Mayer et al. 2015; Montanaro et al. 2016a, c, 2021a). Both parameters can be influenced by alteration, fracturing and compaction processes (Fig. 3a). Mineral dissolution can increase permeability and reduce rock strength, whereas mineral precipitation has the opposite effect, favouring brittle behaviour (Pola et al. 2012; Mayer et al. 2016; Mordensky et al. 2019). Fractures tend to enhance permeability, favouring fluid circulation and eventual dissolution/precipitation, but might weaken host rocks, whereas compaction tends to close pores and fractures reducing permeability and increasing strength (Heap et al. 2015; Heap and Violay 2021).

Experiments, field studies and modelling (Taddeucci et al. 2013; Graettinger et al. 2015; Valentine et al. 2015a; Macorps et al. 2016; Montanaro et al. 2016a, 2021a; Tsunematsu et al. 2016; Strehlow et al. 2017; Rosi et al. 2018; Gallagher et al. 2020) reveal that fragmentation of fresh or altered “strong” lithologies requires significant mechanical energy to create intergranular fractures, thus reducing the efficiency of size-reduction processes and ash generation (Fig. 3b, c). Consequently, disruption of aquifers dominated by lithologies of high rock strength can result in relatively smaller deposit footprints, abundant blocks and low particle ejection velocities as inferred from eruption deposits at King's Bowl and Vulcano (Fig. 3d; Hughes et al. 2018; Rosi et al. 2018). In contrast, fragmentation and/or disaggregation of weathered and degraded rocks, or poorly consolidated to unconsolidated “weak” lithologies requires little energy, and produces a significant amount of ash (Fig. 3b, c). Thus, eruptions that disrupt aquifers within lithologies of low rock strength result in more efficient craterisation and debris dispersion. That is, they are associated with relatively higher ejecta volumes, greater particle ejection velocities and larger ejecta footprints as at, for example, Turrialba, Whakaari/White Island, Kusatsu-Shirane, and Kverkfjöll/Gengissig (Fig. 3d, Table 1). Aquifers composed of a mixture of strong and weak lithologies are expected to produce a mixed spectrum of eruption types and hazards (Fig. 3c), as at, for example, Te Maari/Tongariro and Mt. Ontake (Table 1), or as inferred from eruption deposits at Lake Okaro and El Humazo (D’Elia et al. 2020; Montanaro et al. 2020). Lithological effects on eruption dynamics are masked by eruptions through lakes, which can produce vapour-debris mixtures such as cockscomb jets, base surges and eventual lake breaching as at, for instance, Poás and Ruapehu (Fig. 2; Kilgour et al. 2010; Manville et al. 2015).

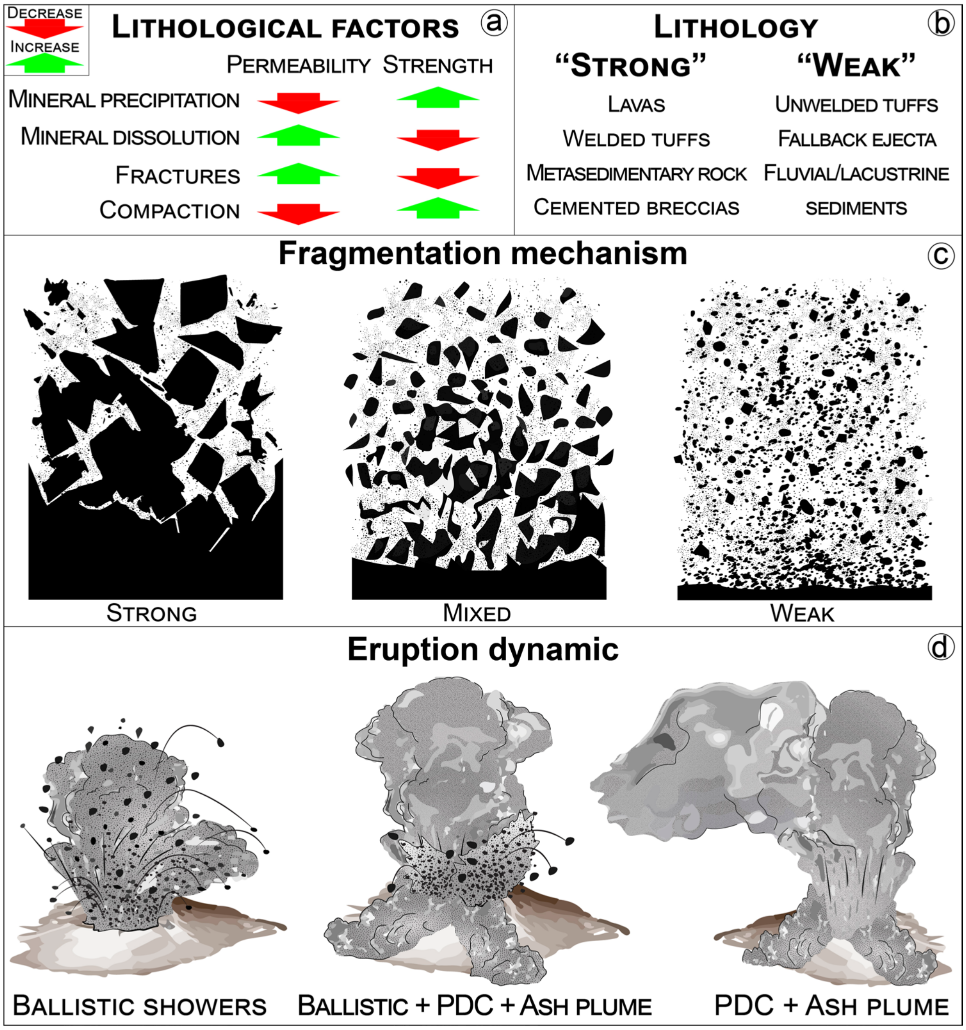

Fig. 3 Lithological factors and their implication for fragmentation and eruption dynamics. **a** Effect of mineral dissolution/precipitation, fractures and compaction over bulk permeability and strength of aquifer host rocks. **b** Example of essential strong and weak lithologies is also given. **c** Conceptual sketch of host rock fragmentation showing how strong lithologies are difficult to fragment, producing mainly coarse fragments. Conversely, fragmentation/disaggregation of weak/unconsolidated lithologies is more efficient and produces larger proportions of fine ejecta. **d** Conceptual model of eruptive dynamics in relation to dominant lithologies within exploded aquifers. Eruptions involving dominantly strong lithologies produce ballistic showers and ash blasts, weak lithologies produce mainly surges and ash plumes, while mixed lithologies can produce both

Forecasting

To date no phreatic or hydrothermal eruption has been successfully forecasted. This presents a significant challenge to volcano observatories and monitoring systems. Here we outline four recent notable advances that may aid in increasing our forecasting capabilities:

- Seismicity and/or tremor commonly occurs just prior to (e.g. Kawakatsu et al. 2000; Park et al. 2020) or associated with phreatic and hydrothermal eruptions (Maeda et al. 2015; Tajima et al. 2020). Such signals may reflect periods of pressurisation. At Whakaari/White Island, some of the phreatic and hydrothermal eruptions were preceded by tremor episodes during which seismic amplitude increased from 2 to 5 Hz (Chardot et al. 2015; Dempsey et al. 2020; Ardid et al. 2022). Seismic velocities and attenuation can also change preceding the eruptions (Mordret et al. 2010; Saade et al. 2019; Yates et al. 2019). Month to year-long changes in seismic amplitude ratios prior to several eruptive events have indicated enhanced attenuation at shallow levels (Caudron et al. 2019). These seismic "signatures" may be sensitive monitors of both sudden gas influx and volatile accumulation due to sealing.
- On timescales of years, increases in radiant heat fluxes were observed prior to phreatic eruptions at Mt. Ontake and Ruapehu, possibly related to magmatic fluid-enhanced hydrothermal activity (Girona et al. 2021). Deformation signals can also occur, such as at Hakone, where InSAR and GNSS data revealed ground inflation starting in mid-2014 prior to a small hydrothermal eruption in June 2015 (Doke et al. 2018; Kobayashi et al. 2018; Mannen et al. 2019). Such anomalies require spatial resolutions of ~ 100 m if they are to be detected within the limits of our current remote sensing capability (Narita et al. 2020). A similar but subtle signal was detected in hindsight by stacking GNSS data prior to the 2014 Mt. Ontake eruption (Miyaoka and Takagi 2016).

Conversely, more widespread deformation was observed prior to the 2017 Poás eruption, which involved magma (de Moor et al. 2019).

- Continuous gas monitoring provides significant insight into eruption "priming" processes at various timescales. Examples include: i) Poás, where SO_2 fluxes and MultiGAS SO_2/CO_2 and H_2S/SO_2 ratios distinguish periods of hydrothermal sealing (closed-system, SO_2 flux < 20 T/day, $SO_2/CO_2 < 0.1$, H_2S/SO_2 1–5) from magmatic inputs (open-system, SO_2 fluxes > 50 T/day, $SO_2/CO_2 > 1$, H_2S/SO_2 near zero) on timescales of weeks to months (de Moor et al. 2019); ii) Rincón de la Vieja, where low concentrations of SO_2 and H_2S are observed minutes prior to phreatic eruptions—likely due to a forming sulphur seal—while eruptive gases are characterised by large increases in SO_2 relative to H_2S and CO_2 (Battaglia et al. 2019); and iii) Turrialba with peaks in CO_2/SO_2 prior to eruptive phases in 2014 and 2015 signal magma injection that disrupted the overlying hydrothermal system, whereas the disappearance of H_2S in emissions marked the transition from phreatic to phreatomagmatic activity (de Moor et al. 2016). The distinct degassing behaviour of these volcanoes highlights the challenge of identifying universal precursors to phreatic and hydrothermal eruptions.
- Several studies have utilised Bayesian tools to combine catalogued phreatic and hydrothermal eruptions (e.g. ballistics and pyroclastic deposit distributions) with monitoring data (seismic, gas emissions, deformation) to model multiple variables for probabilistic forecasting and hazard assessment (Garcia-Aristizabal et al. 2013; Rouwet et al. 2014; Tonini et al. 2016; Strehlow et al. 2017; Christophersen et al. 2018). New monitoring data will enable better uncertainty assessment and statistical analyses to support more accurate risk analysis. A method of tremor analysis that uses machine learning has been used to scrutinise continuous seismic energy data to forecast eruptions at Whakaari/White Island (Dempsey et al. 2020). Patterns of events preceding past eruptions were used to classify 48-h-long windows of the seismic record. Patterns that could indicate pre-eruptive "boiling" instabilities in the aquifer were identified, and threshold values of seismic energy indicating higher probabilities of eruption were constructed for automatic recognition. Both these novel approaches hold significant promise.

Perspectives

On the basis of our assessment, we identify five priority areas for research over the coming decade. These are:

1. *Unravelling the critical rates of fluid-rock interaction and related aquifer processes that prime hydrothermal systems for explosive failure*: The kinetics of mineral dissolution and precipitation determine *if* and *when* unstable conditions are reached within hydrothermal aquifers. New experimental, geochemical, mineralogical and numerical techniques capable of unravelling the spatial and temporal variability of aquifer sealing are needed. Models built on such knowledge will be pivotal in understanding the relative stability or instability degree of any given aquifer. The extensive recent research related to carbon storage could serve as a cornerstone in advancing experimental, analytical and model-based research (Kaszuba et al. 2013; Tonini et al. 2016; Vialle et al. 2018; Wu and Li 2020; Payton et al. 2022).
2. *Identification of areas with potential for future phreatic and hydrothermal eruptions*: Building extensive and new geological knowledge for areas with long-term hydrothermal activity, crater lake floors, histories of previous/ongoing eruptions and geothermal-system crises are pivotal to delineate cases in which eruptive events are likely to occur without obvious precursory signals. A challenging, but necessary, step will include the identification of potential sites at risk of disruption at relatively long-dormant (decades to centuries) volcanoes, where evidence of past eruptions is absent or not recognisable. New geophysical and remote sensing exploration methods for mapping of altered ground and delimiting covert hydrothermal aquifers might help in tackling this problem (Kruse 2012; Hübert et al. 2016; Gresse et al. 2017, 2021; Vaughan et al. 2020; Mishra et al. 2021; Rodriguez-gomez et al. 2021; Wang et al. 2021).
3. *Building new eruption forecasting tools and indicators over a range of timescales*: Currently, forecasting systems rely on data collected at different sampling frequencies and under different technical and field constraints. For instance the time resolution of continuous acquisition of seismic or deformation data, in contrast to sporadic or punctual gas and geochemical sampling. Real-time seismic amplitude monitoring (RSAM), displacement seismic amplitude ratio (DSAR), radiant heat flux and Multi-GAS datasets can provide remote and quasi-continuous, key information capable of indicating when a system becomes unstable (Caudron et al. 2021). Integrating these tools using a machine-learning approach can provide means to combine high frequency with sporadically collected data, and thus enable the weight of these parameters to objectively forecast an eruption likelihood. Such an approach requires numerical advances in order to transfer knowledge between systems and move from isolated case studies to globally applicable techniques.
4. *Development of broad, global approaches to statistical hazard estimation*: Current understanding of lithological influences on explosive energy partitioning allows us to estimate eruptive scenarios and hazards for a range of volcanic, geothermal and other lithological settings. Integrating large datasets involving a number of differ-

ent sites and using numerical and statistical modelling is needed to generalise and extend an approach based on probabilistic or event-tree type methods.

5. *Developing new hazard mitigation and communication strategies:* The sudden and unexpected nature of phreatic and hydrothermal eruptions demands that we develop rapid and automated warning tools. However, it will be challenging to understand the limits of such tools, and consider how best to transfer the alert information of an imminent eruption as quickly as possible, using plain language that the public can understand, and also remaining true to the inherent uncertainties in forecasting events (Fearnley et al. 2017; Fitzgerald et al. 2017; Yamada 2022). Ongoing strategies used, for example in Japan, foresee precise and dense monitoring of geothermal and fumarolic areas, where anomalies and crises are assessed in terms of seismicity, geodesy and geochemistry. Such dense monitoring allowed, for instance, to detect the unrest at Hakone, and to rapidly implement hazard mitigation measures (e.g., pre-established evacuation manual) that reduced the risk of having people exposed to the volcanic hazard (Mannen et al. 2018).

The last decade has shown great progress in our understanding of priming and triggering conditions of phreatic and hydrothermal eruptions, as well as on the characterisation and modelling of their eruptive processes. Such progress also enabled a better monitoring and analysis of seismic, geochemical and deformational “changes” in the volcanic and geothermal settings eventually preceding eruptive failures. However, inherent uncertainties in interpreting diverse and potentially contradictory signals may still lead to high rates of false "crises" and, thus potentially, "false alarms". In the next decade comprehensive models of aquifer priming and explosive failure will build up on continuous progress through novel approaches and new technologies. Future advancement will enable for more accurate, quantitative forecasts that better communicate uncertainty and mitigate risks from such eruptions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00445-022-01571-7.

Acknowledgements C.M. and B.S. acknowledge the Deutsche Forschungsgemeinschaft grants MO3508/1-1 and SCHE 1634/1-1. C.M., S.J.C. and B.S. also thank the NZ Ministry for Business, Innovation and Employment for funding support through the Transitioning Taranaki to a Volcanic Future Research Programme, UOAX1913. J.S. acknowledges support from an NSERC Discovery grant. J.M.dM. acknowledges support from the Costa Rican Ley Transitorio 8933 for volcanic hazard assessment. OVSICORI is gratefully acknowledged for providing the video footage of Rincón de la Vieja eruption. We thank Dr. Alison Graettinger, an anonymous reviewer, and the Editors Katharine V. Cashman and Andrew Harris for the useful comments that improved the paper.

Author contributions All authors contributed to the writing of the manuscript and the preparation of the figures.

Funding Open Access funding enabled and organized by Projekt DEAL.

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