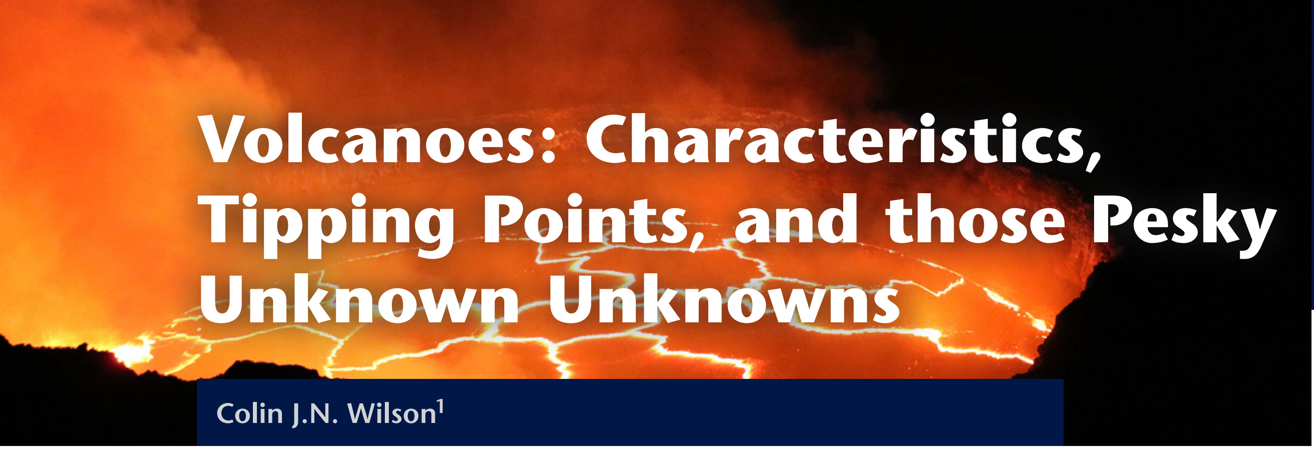

Volcanoes: Characteristics, Tipping Points, and those Pesky Unknown Unknowns

Colin J.N. Wilson[1]

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The geological record of volcanic eruptions suggests that scientists are some way from being able to forecast eruptions at many of the world's volcanoes. There are three reasons for this. First, continuing geological discoveries show that our knowledge is incomplete. Second, knowledge is limited about why, how, and when volcanic unrest turns into eruptions, and over what timescales. Third, there are imbalances between the studies of past eruptions, and the geophysical techniques and observations on modern events, versus the information needed or demanded by society. Scientists do not yet know whether there are other, presently unknown, factors that are important in controlling eruptions, or if there is an inherent unknowability about some volcanic systems.

Keywords: volcano, volcanic eruption, unknown unknowns, eruption records, eruption forecasting, geological record

INTRODUCTION

"Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know." (Rumsfeld 2002)

This quotation from the former US Secretary of Defense Donald Rumsfeld, echoing numerous earlier sources, has served for many as a polarising statement attached to a sequence of controversial political decisions (e.g. Morris 2014). I use this quotation here as a basis for considering selected aspects of volcano behaviour and our present understanding of progress towards forecasting volcanic eruptions. In the last few decades, enormous advances have been made in volcanic monitoring and forecasting techniques and their application for many of the world's volcanoes. This overview, however, considers the case of volcanoes that erupt infrequently (or have been inactive in historic times) and/or that discharge evolved magmas in explosive eruptions, accompanied in the largest examples by caldera collapse. Here, I consider some aspects of what we know about such volcanoes, what we do not know but still are aware of ("known unknowns"), and whether there are likely to be aspects of these volcanoes and their behaviour about which we are unaware (the "unknown unknowns").

Modern studies (over the last ~60 years) have discovered and quantified many aspects of volcanoes and volcano systems within the Earth's crust. By *system* I include the subsurface reservoir (potentially occupying tens of thousands of km^3) in which magma (molten rock) is generated and stored, the melt-dominant bodies that represent the eruptible magma, the plumbing systems that feed magma to the surface, and the physical processes that operate prior to and during eruptions to control the eruption style. There are two main threads involved in volcano studies: first, a dominantly geological thread concerned with the products of past events; and second, a dominantly geophysical thread that, fundamentally, can only be applied to live systems. Of course, geochemical studies are also essential and are common to both approaches. But my aim here is to compare studies on what has happened, as witnessed by eye or evidenced in the rock record, versus studies concerned with the real-time behaviour of volcanic systems.

With the geological thread, the processes that generate and accumulate magma at depth can be followed by studying the mineralogy and chemistry of eruption products and/or by performing laboratory experiments on natural or simplified rock compositions and/or by running numerical or analogue models. By 'past events' I mean things that have happened such that there is something to measure or analyse in the form of volcanic products (solids, liquids or gases), although these may have only just been erupted (e.g. Pankhurst et al. 2014). A particularly fruitful area of research is to take eruptions for which there are eyewitness controls and then study them geologically so as to compare eruption products with the observational constraints (e.g. Newhall and Punongbayan 1996; Hildreth and Fierstein 2012). The geophysical thread uses geophysical and geochemical techniques in real-time to follow the movement of magma during volcano unrest, the rise of magma to the surface prior to and during eruptions, and the release of mobile components in advance of the magma itself (e.g. Pallister and McNutt 2015).

A primary aim of both of the above geological and geophysical threads is to understand and forecast the behaviour of volcanoes in a way that is useful to society: to be able to forecast future activity in ways that reduce risk and minimise impacts on people and infrastructure. In frequently (historically) active volcanoes, especially those erupting fluid mafic magmas, such an aim is, in principle,

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[1] School of Geography, Environment and Earth Sciences
Victoria University
PO Box 600
Wellington 6140, New Zealand
E-mail: colin.wilson@vuw.ac.nz

achievable (e.g. Aki 2004). This is because there is knowledge from multiple observed events and because of the scope and range of sizes of the volcanic activity, i.e. such activity has not been large or violent enough to pose a serious hazard, or it can be successfully mitigated against because it falls within clear boundaries of behaviour. However, with volcanoes that erupt more viscous, intermediate to felsic magmas, historic eruptions and those represented in the geological record sometimes display features that are seemingly not forecastable or that are unique to single events (see next section). Yet, these unanticipated features have a strong influence on eruption styles (and associated hazards and risks) and the timescales over which such hazards develop and are prolonged. Observations suggest that we are still not able to accurately forecast or predict the timing and styles of future eruptions at many of the world's volcanoes, particularly those capable of large-scale explosive eruptions.

VOLCANO CHARACTERISTICS

Volcanoes worldwide have distinctive shapes (e.g. shield, cone, caldera), settings (e.g. arc or intraplate; subaerial or submarine) and eruption products and sequences. As such, many volcanoes are instantly recognisable in an image. The past histories of many volcanoes can allow patterns of past behaviour to be deduced. However, as we are constantly reminded is the case with investment funds, past performance is not necessarily a guide to future performance: the past geological history of a volcano is not an infallible guide to what will happen in the next eruption. Consequently, the world's volcano observatories typically utilize probabilistic forecasts that incorporate not only the particular volcano's history but also global databases, conceptual and physical models, and geophysical monitoring to forecast eruptions.

However, to illustrate the issues that I am raising here, consider the natures of three recent eruptions from three New Zealand volcanoes (Fig. 1).

- On 10 June 1886, the latest eruption occurred from Tarawera (a dome complex that is part of the rhyolitic Okataina caldera volcano). This eruption was basaltic, short-lived (4.5 hours), and deadly (Thomas 1888). Although minor volumes of basalt had previously been erupted at the onset of other rhyolite eruptions at Okataina, the 1886 eruption represents the largest basaltic event known in the ~2 Ma history of the Taupo Volcanic Zone. There has, to date, been no associated rhyolite eruption, however.
- Rangitoto is the youngest and largest (0.7 km^3) of 53 eruptive centres in the basaltic Auckland Volcanic Field. This centre alone represents 40%–50% of the magma erupted in the field over its >190 ky lifespan, yet was erupted in two short pulses only ~550–500 years ago (Needham et al. 2011). Both the volume of this centre and its two periods of activity are unprecedented in the geological history of the field.
- The 232 CE eruption of Taupo was the largest event at that volcano for over 23 ky, and culminated in emplacement of a ~30 km^3 ignimbrite (Wilson 1985). The parental pyroclastic flow to this ignimbrite was disgorged as a blast-like event in only ~400 seconds, and travelled radially to 80 ± 10 km from vent at speeds exceeding 200 m/s, devastating ~20,000 km^2 of uninhabited landscape, including pristine forest that had remained undisturbed by volcanism for thousands of years.

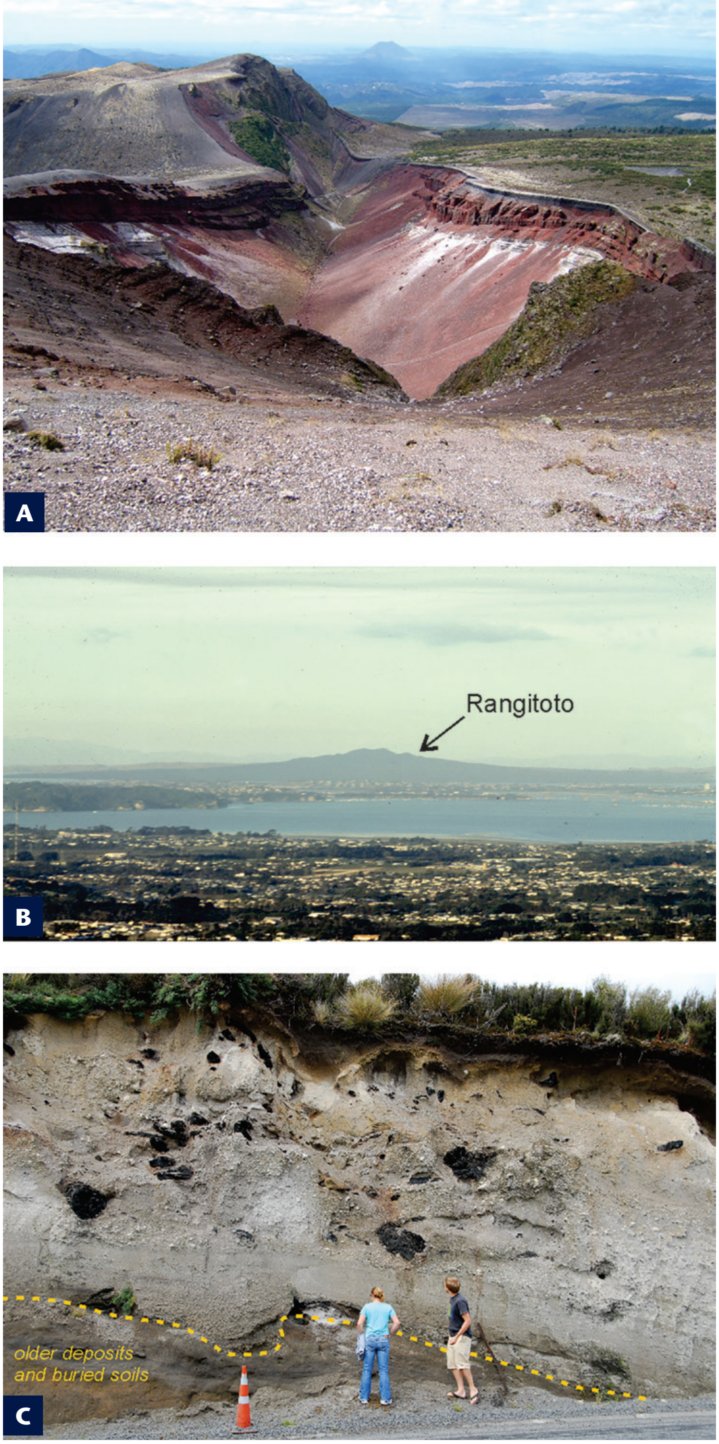

Figure 1 Three illustrative examples from the recent New Zealand volcanological record of unique events. (**A**) View looking northeast along the line of craters that formed in the 10 June 1886 eruption of Tarawera. The red-brown thick scoria beds visible in the crater walls represent 4.5 hours of vigorously explosive activity. (**B**) Distant view of Rangitoto, the youngest of 53 basaltic centres in the Auckland Volcanic Field. (**C**) Pale grey Taupo ignimbrite, formed at the climax of the 232 CE eruption of Taupo volcano, with numerous incorporated black, charred logs and branches. This location is about 50 km from source, the flow having climbed about 700 m to reach this site.

None of these events could realistically have been forecast or foreseen from the preceding historical or geological records for the volcanoes concerned. How can one forecast the unique?

In addition, there are three points about volcano behaviour that arise from consideration of historic events. First, the largest eruption, globally, in the past 2,000 years is of the Indonesian volcano of Tambora (1815). Yet, despite its size and impact on contemporary society, the Tambora eruption is accepted to be roughly two orders of magnitude smaller than the largest Quaternary eruption, that of the Indonesian volcano of Toba, which occurred at ~74 ka (Petraglia et al. 2012). Historic activity at volcanoes worldwide thus covers only a fraction of the potential scale of volcanic activity under 'normal' circumstances (i.e. excluding flood basalt events). Second, perceptions of what a volcano will produce in its next eruption are often skewed by the rarest, largest events. The classic case of this is the Yellowstone volcano (USA), around which the term 'supervolcano' is so intertwined, where its activity is generally linked to its largest eruptions, not the most frequent eruptive size or style, nor the most probable next event. Indeed, for some people, a major supereruption at Yellowstone is seemingly imminent (see Klemetti 2016). Third, there is for many volcanoes an inescapable obstacle to the forecasting of future behaviour. If you take a long enough time period in the eruptive history of a volcano to get a sound statistical approach to forecasting (e.g. through magnitude–frequency relationships), the analysis is quite likely to be misleading (e.g. Aki 2004). This is because during that time period the parental magma system feeding and controlling the eruptive behaviour of the volcano may have changed in its characteristics, or become wholly changed into a new system, or become moribund (e.g. Hildreth 2004). Although viable from a purely statistical perspective, a probabilistic approach to the timing and size of the next eruption at a volcano cannot utilise data from a defunct magma system. Furthermore, there is no possibility of an eruption from a volcano with no live magma system, regardless of its past behaviour. Ngauruhoe volcano in New Zealand (Hobden et al. 2002) may be an example of the latter situation: frequent eruptive activity (recorded from 1840 onwards) ceased in 1975, and any future activity will be from a system that may be wholly new in its characteristics.

Even if the parental magma system is assumed to have stayed active and relatively uniform in its characteristics, a given sequence of eruptions does not necessarily provide a clear means of forecasting the timing or size of the next event. At Taupo volcano (New Zealand), for example, eruption sizes and their repose periods considered separately are not normally distributed, and plots of the eruption sizes versus repose periods show no clear relationships (Wilson 1993) (Fig. 2). Forecasts of future eruption size at that volcano have to resort to a probabilistic approach. This approach, however, then has to consider a recent (post-25.4 ka) geological history which encompasses eruptions that have varied by three orders of magnitude in size and includes repose periods lasting anything from a decade to several thousand years (Fig. 2).

ERUPTION CHARACTERISTICS

Within single eruptions, wide differences in their nature and timings present great challenges. Some historic eruptions started vigorously [e.g. Rabaul volcano (Papua New Guinea) 1994: Global Volcanism Program 1994] and prehistoric examples like the Bishop Tuff (~767 ka, California, USA) show an abrupt onset and no geological evidence for significant time breaks (Wilson and Hildreth 1997). In contrast, other eruptions have started and stopped multiple times: Montserrat is a notable recent example (Global Volcanism Program 2013), and the ~25.4 ka Oruanui eruption (New Zealand) a prehistoric example (Allan et al. 2012). There is a huge gap in our knowledge of the deposits of prehistoric eruptions that would allow us to infer the presence of short time breaks (hours to decades). These time breaks are not always geologically significant or obvious and present challenges to quantify with better than order-of-magnitude outline. Although such time breaks are of human interest, they may be unpredictable for volcanologists charged with forecasting or predicting the course of an imminent or ongoing eruption. Breaks between activity of hours to years are difficult to document in the geological record but may cover time periods during which eruption styles or conditions (e.g. ash plume dispersal directions) have changed drastically. I would argue that the recognition of periods of inactivity is of equal significance to that of recognising the processes and products of activity in the study of past eruptions. Civil authorities need sound advice on the future progress of an ongoing eruption, and such advice may be problematic to supply.

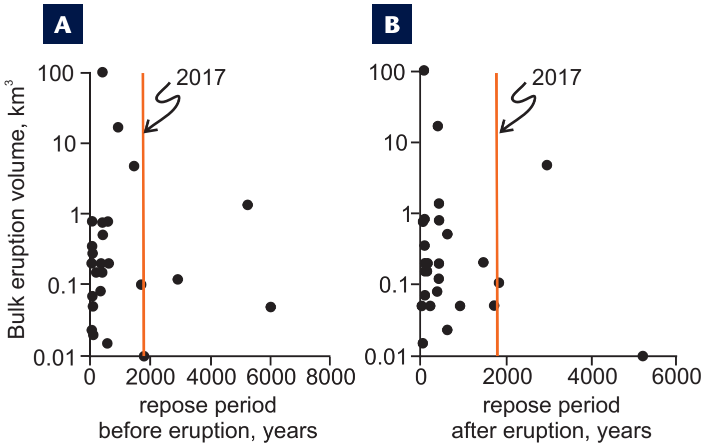

Figure 2 Two plots of the eruption volumes (bulk volume of pumice and ash) versus repose period for eruptions at Taupo volcano (New Zealand) since the 25.4 ka Oruanui eruption. (**A**) If the magma chamber is considered to be a strong container being filled at uniform rate and that produces an eruption once the container bursts, then the size of a given eruption should be proportional to the time period prior to that eruption. (**B**) If, on the other hand, the magma chamber is considered to be a weak container (e.g. the Taupo area is heavily traversed by normal faults associated with rifting), then the repose period after the eruption should be proportional to the size of the eruption. In that case, the recovery time is related to the degree to which the magma system was drained, so the volcano should show longer repose periods after larger eruptions. Data plotted for both cases (A and B) reveal no simple relationships: large eruptions arrive after short repose periods, and long repose periods may be broken by small eruptions. The line marked '2017' represents the current position of the volcano along these timelines, when this issue of *Elements* was erupted. Modified from Wilson (1993).

Coupled with this (possible) spectrum of eruptive timings is the fundamental issue of deciding when an eruption has actually finished so that recovery operations (whether social, infrastructural, ecological, or magmatic) can begin. What time period after significant activity has to pass before an eruption can be considered to have finished? This is often challenging to determine because of the contrast between the timescales of geological processes and human activity (political and fiscal). For example, should the 2004–2008 activity at Mount St. Helens (Washington, USA) be considered as a natural extension of the 1980–1986 events, or as a separate eruption? And how would the products be judged as part of the prehistoric geological record some thousands of years from now?

TIPPING POINTS

As mentioned above, with the present state of volcano studies, there are two major sources of information that can be applied. First, there is the geological study of past events, supplemented in the historical record with eyewitness information (e.g. Hildreth and Fierstein 2012), but mostly undertaken in the prehistoric record through studies of eruption products. Our knowledge is, thus, limited to processes and events that leave a tangible marker in the geological record. For example, an earthquake that leaves no surface evidence in the form of, for example, a datable surface fault rupture or landslides over a large area cannot be discerned in the prehistoric record. The influence of earthquakes on the behaviour of volcanoes is, therefore, largely unknown: cause and effect cannot be demonstrated for virtually all eruptions in the geological record. Second, there is presently an ever-increasing array of geophysical and geochemical techniques that can directly detect signals of sub-surface activity, but these signals cannot necessarily be translated, with confidence, to specific volcanic processes, let alone used to predict what eruptive activity will follow.

In an active eruption, the two approaches (the past record and the real-time observations) converge, in some cases with great success (e.g. Mount Pinatubo (Philippines): Newhall and Punongbayan 1996). But there are inevitable gaps. One gap is that we can only assess the composition and state of the magma involved once it has reached the surface, although there are possibilities arising of gaining information on the properties of newly erupted materials rapidly enough to make forecasts within the lifetime of an eruption (e.g. Pankhurst et al. 2014). A second gap is that whereas we can reconstruct magmatic processes from historic eruption products and plausibly link these processes to geophysical signals recorded at the time (e.g. Kilgour et al. 2014), the reverse cannot yet be done with confidence in many cases. For example, signals of uplift at caldera volcanoes are often linked to magmatic inflation; but, other causes (such as changes in the state of a hydrothermal system) may contribute to the surface signals and so lead to ambiguity (Acocella et al. 2015). Signals of unrest may, in turn, be no guide to the likelihood or imminence of eruptive activity. At Long Valley Caldera (California, USA), magma is proposed to underlie the resurgent dome complex and be contributing to present-day unrest (Seccia et al. 2011). Yet geological evidence implies that the magmatic system in that particular area is moribund and that no eruption has occurred for ~100 ka (Hildreth 2004).

A key concept that arises from the points made above is that of a tipping point in volcano behaviour, marking the point when unrest [which may run for decades to centuries, such as at Campi Flegrei (Italy) (Acocella et al. 2015)] irrevocably leads to an eruption. However, the time gaps between (i) the tipping point and the onset of eruption, (ii) the eruption onset and when hazardous conditions begin, and (iii) the onset and eruption climax have been exceedingly variable in observed eruptions and have ranged from a day or so in the case of Chaitén volcano (Chile) (Major and Lara 2013) to decades in the case of Rabaul volcano (Robertson and Kilburn 2016). If a volcano is escalating rapidly towards eruptive activity, such as happened for Pinatubo in 1991 (Newhall and Punongbayan 1996), the symptoms can be identified and made use of in valuable forecasting and mitigation efforts on societally useful timescales (e.g. Voight 1988). However, such methods still cannot always identify the tipping point. A key example of the problem is Rabaul, where a major seismic crisis occurred in 1983–1985 yet the eruption occurred in 1994 with only about 27 hours warning, following a regional earthquake (Global Volcanism Program 1994). The tipping point for a particular eruption may, thus, be an external agent, invisible in the geological record and unanticipated in real time. The precise timing of the 18 May 1980 cone collapse at Mount St. Helens, for example, was controlled by a separate earthquake, which in and of itself will have left absolutely no trace in the geological record.

Thus, at one end of the spectrum, in the monitoring of long-dormant, large caldera volcanoes, and especially those with geological records of large explosive eruptions and reputations to uphold [e.g. Taupo, Yellowstone, Toba, Long Valley, Laguna del Maule (Chile/Argentina), Campi Flegrei], how could one recognise the tipping point? The amounts of deformation involved at caldera centres are often large, occurring on geologically rapid timescales and often leading to perceptions of imminent eruption (e.g. Singer et al. 2014; Acocella et al. 2015). Yet, comparisons of the timescales of unrest (years to decades or centuries) versus studies of the geological record of eruption frequencies (at intervals typically of centuries to tens of thousands of years) show that unrest events at such volcanoes are one to three orders of magnitude more frequent than eruptions. The current states of unrest at large caldera volcanoes (e.g. Acocella et al. 2015) are, thus, no guide to which of them will erupt first or what will turn unrest into activity. If the specific timing of any particular eruption is controlled by external factors, such as the regional stress state (Allan et al. 2012) or a linked or independent seismic event (Manga and Brodsky 2006), then there may be insoluble challenges in eruptive forecasting because of the possibility of random events that are wholly independent of the volcanic system but that force the volcano past its tipping point at short notice.

VOLCANO 'KNOWN UNKNOWNS' AND 'UNKNOWN UNKNOWNS'

Observations and conceptual models of volcanic products have built a remarkably detailed picture of the subsurface magmatic systems, but all have the inescapable limitation that they are built on what is known. For models, boundary conditions have to be set, and these are based on what we know or on what we know that we don't know, such as the temperature structure in the crust. Therefore, models tend to be self-limiting. Models are also problematic because they need to be ground-truthed and hence are not necessarily predictive. For example, at the Taupo and Yellowstone caldera volcanoes (Fig. 3), studies of past eruptions (e.g. Barker et al. 2015; Stelten et al. 2015) imply that there are currently large volumes (hundreds to thousands of cubic kilometres) of partially molten rock (geophysically imaged at Yellowstone) that are fuelling the modern geothermal heat fluxes. Yet, however sophisticated the models are made for these and other volcanoes, the amount of magma released in the next eruption, and the timing of that release are not forecastable except in probabilistic terms (Fig. 2). But probabilities are in themselves problematic. In the event of volcano unrest that might lead to an eruption, does one, for example, advise civil authorities to prepare for the smallest, the median, or the potentially largest event? What if, for sake of argument, the next eruption turns out to be unprecedented in the history of the volcano (Fig. 1)?

The continuing arrival of new technologies – drones for 'cheap' observations in hazardous conditions, satellite sensoring systems for monitoring and surveillance, rapid

FIGURE 3 Two of the world's largest and most active supervolcanoes in repose. Both volcanoes represent great challenges to forecast. (**A**) Yellowstone volcano (Wyoming, USA), looking northwest from the north side of the Red Mountains. Lewis (nearer) and Shoshone (farther) lakes are surrounded by the large flat-topped rhyolite lavas of the Central Plateau Member (erupted from ~170-70 ka; see Stelten et al. 2015). The Red Mountains are an uplifted block of ~1 km thick Huckleberry Ridge Tuff, eroded by glacial activity. The mountains in the far distance are the Madison, Gallatin and Absaroka ranges, north of the Yellowstone caldera. (**B**) Taupo volcano (New Zealand), looking north-northeast from the summit of Pihanga volcano, an extinct stratovolcano rising ~1 km above its surroundings. Lake Taupo infills a collapse caldera mostly created in a major eruption at 25.4 ka. It has seen 28 eruptions since 25.4 ka, most of them from vents down the eastern (right-hand in this view) side of the lake and now concealed beneath its waters (see Barker et al. 2015).

analytical capabilities for newly erupted magma samples – offers new perspectives in understanding the present state of volcanoes in close to real time (Pankhurst et al. 2014; Pallister and McNutt 2015). However, such tools can also only represent the current, or immediately past, state of the volcano, and are not necessarily a guide to the future (How much? When? What eruption style?). At Yellowstone, there is now extensive knowledge of its patterns of historical unrest, but still no means to forecast when its next eruption will be, what form it will take, or what its size will be. As a result, there is a flourishing web-based cult built around the perception that doomsday from this particular supervolcano is imminent (Klemetti 2016).

CONCLUSIONS

There are several questions that can be applied to any volcano that is not currently in eruption, but are especially applicable to caldera volcanoes that have geological records of large eruptions of felsic magma.

1. When will it next erupt?
2. How big will the eruption be?
3. What eruption products will result and what are their consequent hazards and impacts?
4. What will be the timescale of the total eruption, and will there be breaks in activity?
5. What determines the timing of markers, such as the tipping point at which an eruption is inevitable (although not necessarily imminent), the onset of an eruption when material reaches the surface, and the climactic event or events during an eruption?
6. How does one determine the end of the eruption so that recovery can begin?

Although some of these questions can be answered in outline or as probabilistic assessments based on knowledge of past activity, the major issue is whether confident answers can be given to all of these questions for future events. Any probabilistic assessment of the range of options at a volcano like Taupo, with its greatly diverse range of eruption sizes and styles (Wilson 1993), still means that forecasts or predictions of future events are problematic – even in today's data-rich environment. Does one plan for the most likely event or the worst event, if the change from one to the other scenario may occur rapidly? How then does one plan for events that have no precedents (Fig. 1)? At long dormant volcanoes, does the possible presence of magma and symptoms of unrest necessarily indicate that any eruption is likely or even possible (e.g. Seccia et al. 2011)? In any case, the biggest impacts associated with volcanic eruptions not only include the loss of human life and direct destruction of property and infrastructure but also significant downstream economic effects due to the interconnected nature of modern society (e.g. Budd et al. 2011). The more we uncover and document the timing and dynamics of prehistoric eruptions, the greater diversity we see. In returning to the opening quotation from Rumsfeld (2002), modern volcanology has made enormous progress in characterising volcanic systems (admitting that much remains to be done, especially in arc environments). We now know a lot, and have a good grasp on the 'known unknowns' that may be made accessible through improved technology and be applied to volcanoes erupting in today's world. The success of volcanic monitoring and the societal responses to many eruptions over the past few decades is strong evidence that the behaviour of many historically active or reawakening volcanoes can be dealt with (e.g. Newhall and Punongbayan 1996). What remains are the 'unknown unknowns'. These natural factors seem best (and most worryingly) to apply to volcanoes that erupt felsic magmas and that have or will have the potential to generate eruptions large enough to form calderas. The proportion of such volcanoes that will ever be forecastable or predictable in useful ways remains the greatest challenge to modern volcanology simply because we do not know what we do not know.

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