Monitoring super-volcanoes: geophysical and geochemical signals at Yellowstone and other large caldera systems

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Earth's largest calderas form as the ground collapses during immense volcanic eruptions, when hundreds to thousands of cubic kilometres of magma are explosively withdrawn from the Earth's crust over a period of days to weeks. Continuing long after such great eruptions, the resulting calderas often exhibit pronounced unrest, with frequent earthquakes, alternating uplift and subsidence of the ground, and considerable heat and mass flux. Because many active and extinct calderas show evidence for repetition of large eruptions, such systems demand detailed scientific study and monitoring. Two calderas in North America, Yellowstone (Wyoming) and Long Valley (California), are in areas of youthful tectonic complexity. Scientists strive to understand the signals generated when tectonic, volcanic and hydrothermal (hot ground water) processes intersect. One obstacle to accurate forecasting of large volcanic events is humanity's lack of familiarity with the signals leading up to the largest class of volcanic eruptions. Accordingly, it may be difficult to recognize the difference between smaller and larger eruptions. To prepare ourselves and society, scientists must scrutinize a spectrum of volcanic signals and assess the many factors contributing to unrest and toward diverse modes of eruption.

Keywords: Yellowstone; super-volcano; super-eruption; caldera;
volcano monitoring; eruption

> Anyone who has spent summers with pack-train in a place like the Yellowstone comes to know the land to be leaping… The mountains are falling all the time and by millions of tons. Something underground is shoving them up…
>
> (T. A. Jaggar 1922, p. 352)

1. Introduction

During periods of volcanic unrest, scientists must intensively measure the signals emanating from the volcano to determine whether an eruption is likely and to provide appropriate warnings. The process of monitoring is complex, involving

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sophisticated equipment and data-reduction techniques, yet it relies ultimately on the subjective judgments of scientists who must weigh likely outcomes resulting from the observed volcanic behaviour. This contrasts with large tectonic earthquakes, which currently have no reliable precursory activity, relegating most human response to the aftermath of the event.

The largest scale of volcanic eruptions, the so-called *super-eruptions*, can destroy all living beings and infrastructure over tens of thousands of square kilometres, can disrupt agriculture over millions of square kilometres and can alter global climate for years or decades. As such, society must endeavour to create reliable volcano-monitoring systems that can detect the sorts of Earth processes leading to large-scale explosive volcanism. Although the volcanological community has had some success in predicting small eruptions, the scarcity of great eruptions over the past 150 years means that we have little experience understanding the prelude to major events. This is particularly true at caldera systems, which are capable of large-scale volcanism and exhibit frequent unrest but have undergone only small eruptions historically (Newhall & Dzurisin 1988).

The USA hosts three caldera systems responsible for super-eruptions in the past 2 million years. Two of them, the Long Valley (California) and Yellowstone (Wyoming) calderas, today show frequent signs of unrest, such as earthquake swarms, ground deformation and considerable heat and gas emissions. The third system, the Valles Caldera of New Mexico, appears quiescent, but nevertheless erupted more recently than Yellowstone (40 000 years ago, compared with 70 000), and could plausibly reawaken. In this article, using Yellowstone as our primary example, we summarize current knowledge of caldera systems and their underlying magma chambers, and we address the methods used to detect unrest that could lead to renewed volcanism.

2. Defining and characterizing a super-volcano

The evocative 'super-eruption' is an informal term referring to volcanic events in which at least $300 \, \text{km}^3$ of magma are explosively evacuated from a subsurface magma chamber (Sparks *et al.* 2005) and deposited on the countryside as pyroclastic (i.e. fire-fragmental) materials—ash, pumice and rock fragments. Rapid withdrawal of large volumes of magma causes the ground overlying the magma chamber to collapse, swallowing up the overlying countryside and creating a volcanic depression (caldera) that may be more than 30 km in diameter. Previously, such mega-eruptions were often referred to simply as large caldera-forming eruptions, but both popular and informal scientific usage have recently highlighted the term 'super-eruption', which has now become widespread. Typically, any volcanic system that has produced a super-eruption is consequently dubbed a super-volcano.

As with hurricanes and earthquakes, scientists categorize explosive volcanic eruptions by their relative size. The most commonly used scale is the volcanic explosivity index (VEI) of Newhall & Self (1982), which ranks eruptions primarily according to the volume of ejecta and the height of the eruptive plume. VEI 7 and 8 eruptions (100 and $1000 \, \text{km}^3$ of ash deposits, respectively) are typically highly explosive. They eject such massive volumes of ash and accompanying acid aerosols into the atmosphere that civilization would be

challenged to adapt to the severe effects on world agricultural production and near-term climate change over the following years to decades (see Self 2006 for an extensive discussion of super-eruptions and their effects). Extremely high magma ejection rates allow hundreds to thousands of cubic kilometres of magma to erupt within a matter of days (Wilson & Hildreth 1997).

Mason *et al.* (2004) compiled a catalogue of large VEI 7 and 8 eruptions (not including some of the smallest super-eruptions). Forty-two such events were identified in the past 36 million years, though they report that the number of eruptions may be greatly under-represented in this catalogue because of the difficulty in estimating magma volumes for older eroded volcanic deposits. For example, the catalogue includes five eruptions within the past one million years, but only 42 over the past 36 million years. In the Snake River Plain (USA) alone, there may be scores of pyroclastic deposits, 5–17 million years old, that are extensive enough in volume to qualify as super-eruption deposits (Perkins & Nash 2002), but the deposits have not been characterized adequately for inclusion in the catalogue. Accordingly, the likelihood of future catastrophic eruptions is certainly greater than would be calculated solely by considering the record of well-studied volcanic deposits.

3. Geological and geographical settings for super-volcanoes

Certain requirements are essential to produce a rapid, highly explosive and large-volume volcanic eruption. First, a large volume of magma must be stored close enough to the Earth's surface that it can be withdrawn rapidly. The magma usually consists of a high-silica (SiO_2) or 'rhyolitic' melt (liquid) plus up to 40% suspended crystals. Second, the magma must contain sufficient dissolved gas, so that any initial eruption and consequent 'uncorking' of the magma will result in continued forceful ejection of magma. Third, the magma must be relatively viscous (resistant to flow) and have a high surface tension, so that bubbles cannot form easily. Such is the case with rhyolitic melt, which has viscosities tens of thousands of times greater than basaltic melts. As a result, rapid degassing results in catastrophic fragmentation of the magma into incandescent clouds of ash particles (actually chilled bits of magmatic glass) that expand upwards into the stratosphere and partially collapse laterally into masses of ash that flow radially away from the eruptive centre.

Most large silicic magma chambers in the Earth's crust (generally, the upper 40 km) form due to repeated and sustained intrusion by hot, silica-poor basaltic melts created in the underlying mantle. Melting crust then mixes with liquids formed as the basalt is cooled and crystallized, creating more 'evolved' (silica-rich) melts that rise towards the surface. Resulting magma chambers grow over thousands of years by secular addition of new melts, and if the magma fails to leak through to the surface as frequent small (pressure-reducing) eruptions, the system may eventually develop into one capable of a super-eruption.

Only certain places on Earth have geological conditions appropriate for development of super-volcanoes, where silicic magma can be generated rapidly. Indeed, other than Yellowstone, all but one of the 18 super-eruptions within the past two million years occurred around the Pacific Rim, including New Zealand, Indonesia, the Philippines, Japan, Kamchatka, the United States, Central

America and the Andes of South America (Sparks *et al.* 2005). Candidates for new super-eruption sites would logically include the Pacific Rim subduction zone and, in particular, any volcanic systems that have previously served as the source for such an eruption. Many caldera systems eventually produce more than one large eruption, so that conditions leading to a super-eruption can occur repeatedly at a single site. Nevertheless, volcanic centres wax and wane with time, and new ones are created. Any volcanic region with relatively high magma input rate from the mantle, and the tendency to create silicic magma compositions, can be considered a potential site for a super-eruption. Regions with relatively low rates of volcanism, or areas such as ocean islands that erupt only basalt, will tend not to create immense pyroclastic eruptions.

4. Yellowstone: regional setting

One of the better-known super-volcanoes is the Yellowstone volcanic field and its three youthful calderas, less than 2.1 million years old, which are the most recent manifestations of a mantle hotspot that has produced a string of large calderas stretching 700 km along the Snake River Plain from northern Nevada to Yellowstone (Smith & Braile 1994; Smith & Siegel 2000). Magmatism began *ca* 16.5 million years ago and has moved progressively northeastwards as the overriding North American tectonic plate moves steadily southwest relative to a seemingly 'fixed' mantle hotspot. Though the rate of plate movement appears to have stayed roughly constant, the rate of volcanism has decreased within the past 10 million years, presumably due to the increasingly cold and thick nature of the more easterly continental crust upon which the hotspot progressively impinges (Pierce & Morgan 1992).

The presence of a low-density mantle hotspot creates an anomaly in the geoid, the equipotential surface of the gravity field, which at Yellowstone sits 10 m above that of the geometric ellipsoid. The magnitude of this geoid anomaly is similar to that of oceanic hotspots, such as the Hawaiian Islands, the Azores and the Galápagos. The geoid anomaly is accompanied by a topographic anomaly wherein the Yellowstone highland or plateau sits about 600 m above the surrounding terrain in Wyoming, Montana and Idaho.

Yellowstone acts as a focal point for geological activity in the northern Rocky Mountains. It sits at the tectonically complex intersection of the hotspot with the actively spreading Basin and Range province to the west. In addition, old fold and thrust structures of the Rocky Mountains tend to accommodate some of the ongoing regional strain. The trends of faults and earthquake epicentres change markedly as they pass through the Yellowstone area, switching from a north–south azimuth south of Yellowstone and bending around to the northwest further north. The result is a 'tectonic parabola' pivoting around Yellowstone and clearly demonstrating the considerable influence of the hotspot on the regional stress field (Smith & Braile 1994).

The Yellowstone highland itself has subdued topography as a result of the three caldera-forming eruptions and infilling by long-continued lava extrusions. Since the formation of the Yellowstone caldera, 640 000 years ago, the caldera itself has been buried by lavas, such that only a few clear remnants of the original caldera wall remain (Christiansen 2001). Maps of earthquake epicentres within

the caldera show linear trends, implying that regional faults still control much of the earthquake generation beneath the caldera (figure 1). Moreover, vents for post-caldera lava flows follow clear linear trends through the central caldera and along its western margin, parallel to the structural grain of the mountains south of the caldera.

Like many volcanoes, Yellowstone has an active hydrothermal (hot water and steam) system that resides between the Earth's surface and the underlying magma. Because the Yellowstone Plateau is a high mountainous region, it receives abundant winter precipitation, much of which recharges the aquifers within the volcanic rocks. The aquifer intercepts rising heat and gases, forming reactive waters that interact with subsurface rocks to form solute-rich hydrothermal fluids. These fluids convect beneath the ground surface, precipitating mineral deposits as they flow. The constant earthquakes and ground movements within the caldera create new fractures and regions of permeability, which are continually filled by the migrating fluids. The importance of the hydrothermal system cannot be understated, as many of the geochemical and geophysical signals measured at the surface have hydrothermal origins or magmatic origins modulated by the intervening hydrothermal aquifer.

5. Yellowstone: recognizing the presence of a magma chamber

Owing to Yellowstone's relatively subdued Rocky Mountain topography and the widely forested volcanic structures within the park, Yellowstone was thought to be extinct and was historically overlooked as a volcanic system with eruptive potential. Though volcanologist Jaggar (1922) recognized Yellowstone's dynamism (see epigraph above), his 'mountain' observatory was not actually envisioned to be a volcano observatory. It was not until the 1960s that the geological mapping of Robert Christiansen (Christiansen & Blank 1972) revealed that the Yellowstone country had experienced three, large, explosive eruptions over the past two million years, accompanied by many other smaller eruptions. In the 1970s, geodetic surveys demonstrated that the central part of the Yellowstone caldera had risen 80 cm since the 1920s (Pelton & Smith 1979), primarily around areas that Christiansen & Blank (1972) identified as 'resurgent domes' within the central part of the caldera. Other scientific studies documented the formation of post-glacial hydrothermal-explosion craters, young faults and abundant seismicity. It became clear that Yellowstone was still active and posed an unknown risk of future catastrophic eruptions. To quantify that risk, Earth scientists needed to characterize the size, depth and physical status of any magma reservoirs still present beneath the surface.

Probably the most convincing evidence for a relatively shallow magma body is the immense heat flow issuing from Yellowstone on a continual basis. Even though fumaroles at Yellowstone have far lower temperatures than at many volcanoes, thousands of boiling thermal features dot the landscape and cover about 70 km^2 (out of 9000 km^2 in the park). The estimated convective heat flow (more than 75% of the total) is 5–6 GW, averaging *ca* 2 W m^{-2} within the caldera, or roughly 30 times greater than the average continental value (Smith & Braile 1994). Gas flux at Yellowstone is also highly anomalous. Extrapolations of soil–gas flux data imply that Yellowstone is one of Earth's most prolific sources
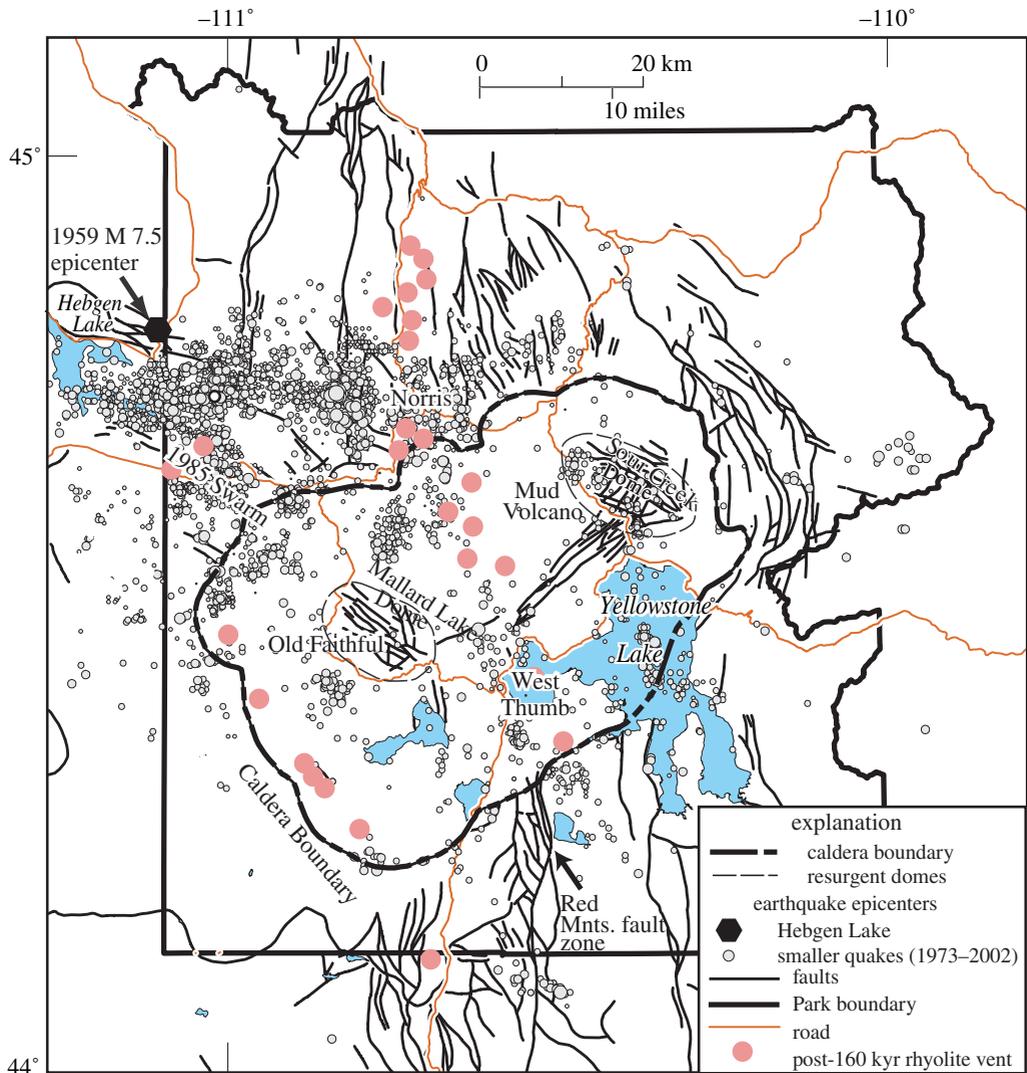
Figure 1. Map of Yellowstone National Park, including volcanic features, the Yellowstone caldera and high-quality earthquake epicentres from the period 1973 to 2002. Map features are from Christiansen (2001) and Husen & Smith (2004).

of CO_2 (Werner & Brantley 2003), releasing over 45 000 tons per day. At this point, we cannot be certain whether the heat and gas output are consistent with cooling of a large but static rhyolitic magma chamber or whether continual addition of hot, mantle-derived basalt is required to sustain the current output. Obviously, the topic is of more than academic concern, as it reflects whether Yellowstone is currently cooling down or heating up.

Such questions can also be addressed by geophysical studies, which provide a broad array of constraints on the nature of the Yellowstone magma chamber. Seismic tomography based on local earthquakes indicates an anomaly in the velocity of compressional (P) waves starting at depths of *ca* 8 km (figure 2). The anomaly can be interpreted as a partly molten zone shaped like an inverted
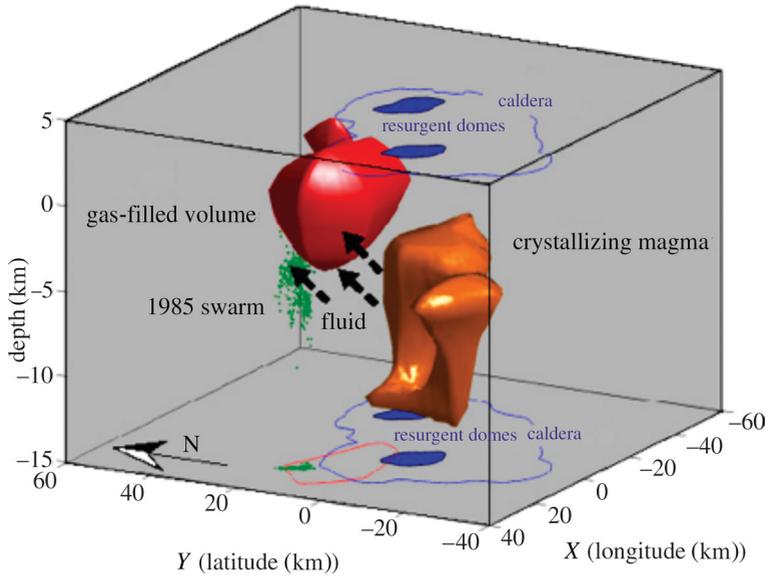
Figure 2. Diagram illustrating seismic-wave-velocity anomalies in the shallow crust beneath Yellowstone as viewed from the southwest (adapted from Husen *et al.* 2004*a*). The orange volume outlines the anomaly attributed to partially molten rock extending above the main magma chamber (and beneath the surface expressions of the Sour Creek and Mallard Lake resurgent domes). The red volume is an anomaly with properties suggesting gas-filled fractured rock. The green dots are hypocentres from the 1985 earthquake swarm. The arrows are postulated trends of hydrothermal fluid flow from the magma body to the inferred gas-filled body as discussed by Waite & Smith (2002) and Husen *et al.* (2004*a*). Though the tomographic imaging of Husen *et al.* (2004*a*) did not extend beneath 12 km depths, other workers have inferred partially molten crustal magma chambers extending to *ca* 20 km beneath the caldera (Iyer *et al.* 1981; Lehman *et al.* 1982).

banana, with the ends located beneath the two resurgent domes (Husen *et al.* 2004*a*). Severe attenuation of shear (S) waves at some seismic stations is consistent with volumes of partly molten rock. In fact, earlier tomographic studies had concluded that the caldera was underlain by zones with up to 15% melt (Iyer *et al.* 1981; Lehman *et al.* 1982), extending down to 20 km or more. Further information can be gleaned by analysis of the maximum depths to earthquake hypocentres within the caldera, which implies that ductile rock with temperatures above 350 °C exists at *ca* 5 km depths (Fournier & Pitt 1985). Outside the caldera, such temperatures are not achieved shallower than *ca* 15 km. Yellowstone's gravity field is dominated by a −60 mGal residual low centred over the caldera, and extending to the northeast. Models of these data suggest that the caldera is underlain by low-density volcanic deposits sitting on top of a mostly crystallized body of rhyolitic (granitic) magma. To the northeast, beneath one of Yellowstone's largest thermal areas, Hot Springs Basin, the gravity anomaly is more pronounced and consistent with perhaps as much as 15% melt by volume (Krukoski 2002).

Overall, geophysical and geochemical evidence points strongly towards the presence of a large thermal anomaly in the shallow- to mid-crust. Given the size of the caldera and the implied depths, it is reasonable to infer that at least 15 000 km^3 of crystal-melt mush are located beneath the Yellowstone caldera, at depths from

ca 8 to 18 km. If melt fractions are 0.1–0.15, then sufficient melt exists to form the mass for a super-eruption—if it can be extracted and accumulated into an eruptible volume. Most geophysical images have insufficient resolution to define volumes less than *ca* 10 km on a side. It is fully plausible that volumes with high melt fractions (more than 0.6) exist within dikes and sills within the greater magma chamber, and could erupt as moderate-volume (less than 100 km^3) lavas or pyroclastic flows. Current evidence suggests, however, that the gravity and seismic anomalies are not sufficiently large to allow for a larger, highly molten (and thereby eruptible) volume of magma beneath Yellowstone at this time.

6. Yellowstone: current activity

Despite Yellowstone's long period of volcanic dormancy, now over 70 000 years, the caldera continues to be an active and dynamic environment, with thousands of earthquakes, active ground deformation and considerable heat and mass flux. The monitoring system of the Yellowstone Volcano Observatory (volcanoes.usgs. gov/yvo) is designed to listen to these signals, to see how they relate to each other, and to provide adequate characterization of background activity. Only by cataloguing the range of normal activity can we start to decipher the signals emanating from caldera systems headed towards eruption. Here, we now address the kinds of Earth signals documented over the past 50 years.

(*a*) *Earthquakes*

Anywhere from 1000 to 3000 detectable earthquakes occur in the Yellowstone region during any given year. Almost two-thirds take place in an east–west trending linear zone connecting Hebgen Lake with the northern rim of the Yellowstone caldera (figure 1). The earthquakes appear to be concentrated along the trend of the buried ring-fracture system formed during caldera collapse during the 2.1 million year eruption, and they may be the result of stress transferred to the area by the magnitude 7.5 Hebgen Lake earthquake in 1959, the largest historical earthquake in the western US interior. Because no seismic network existed in the area prior to the 1970s, it is impossible to confirm if this area was comparably seismogenic prior to 1959. Regardless of the reasons for its activity, this small zone, outside the Yellowstone caldera, is one of the most seismogenic areas within the US outside California and Alaska. Other Yellowstone earthquakes occur along linear trends within the caldera, along faults south of the caldera and beneath obvious hydrothermal zones, such as geyser basins. Over one-third of the earthquakes at Yellowstone are related to discrete swarms of small earthquakes occurring over a localized area over a short period of time (usually 1–2 days). Many of these swarms occur along the east–west seismogenic zone described above, though many others have occurred within the caldera as well as to its south and east. One notable swarm during the autumn of 1985 (figure 1) consisted of over 3000 recordable events (up to magnitude 4.9) over a three-month period in the region extending northwest from the west margin of the caldera toward Hebgen Lake (Waite & Smith 2002). In the past 20 years, several swarms have been recorded within the northern part of Yellowstone Lake, and others near West Thumb, in a north-trending line colinear with the Red Mountain Fault, which intersects the southern boundary

of the caldera. Earthquake swarms are a common mode of seismic energy release at Yellowstone and other caldera systems. At stratovolcanoes, swarms are usually interpreted as a sign of unrest, plausibly leading towards eruption, or at least indicating a subsurface episode of magma intrusion. Nonetheless, swarms are also recorded along faults in areas far removed from active volcanism. In view of the profound regional tectonism and extension, the lingering effects from the magnitude 7.5 Hebgen Lake earthquake, and the considerable intra-caldera deformation, swarms at Yellowstone may well reflect a variety of causative mechanisms.

At the Long Valley caldera, which formed during a super-eruption 760 000 years ago, scientists have recorded long-period and very-long-period volcanic earthquakes that apparently reflect the movements of slugs of magmatic or hydrothermal fluids at depths ranging from 3 to more than 30 km (Hill *et al.* 2002*a,b*). Deep, long-period earthquakes have been documented at a variety of volcanic settings, usually during periods of inferred magma recharge at mid- to lower-crustal levels. At Yellowstone, however, such events have never been identified. It is unclear whether they are completely absent or whether they are too subtle to be detected by the existing seismic network.

(*b*) *Deformation*

Since recognizing that the Yellowstone region actively rises and subsides with time, scientists have used a variety of techniques such as levelling, the global positioning system (GPS) and most recently interferometric synthetic aperture radar (InSAR) to map out spatial-temporal deformation patterns. Subsequent to the *ca* 80 cm of uplift measured prior to 1985, workers noted the onset of subsidence within the caldera that persisted through the mid-1990s. In the late 1990s, deformation data showed that the two resurgent domes could operate independently, with one subsiding while the other rose or did nothing (Wicks *et al.* 1998). Today, we know that uplift can occur at other locations in and around the caldera, as both GPS and InSAR data reveal that between 1997 and 2003, the north-central caldera underwent a maximum of *ca* 12 cm of uplift, while the resurgent domes subsided (Wicks *et al.* 2006). Deformation then shifted to the resurgent domes, which began to rise again, with more than 8 cm of upward movement recorded by continuous GPS stations between late 2004 and the present time (early 2006). Geological studies of lake terraces strongly suggest that uplift/subsidence cycles of deformation at Yellowstone have taken place throughout the Holocene (less than *ca* 11 000 years) with localities near the outlet of Yellowstone Lake (between the resurgent domes) changing elevation by more than 3 m (Pierce *et al.* 2002). The principal mechanism of the deformation is speculated to be either magma intrusion, or migration of hydrothermal fluids, such as brines or gas. Without time-series monitoring of geochemical proxies that might track with uplift/subsidence, however, it remains difficult to corroborate any particular mechanism.

(*c*) *Hydrothermal*

At present, we have adequate estimates of the enormous long-term discharge of heat and gas at Yellowstone, but we have no system for monitoring temporal changes in heat and mass output other than on an annual basis. Long-term

geochemical changes (annual to decadal) for heat and some volatiles (Cl^-, F^-, SO_4^{2-}, HCO_3^-) are currently assessed by monthly sampling of river discharge and composition. With this sampling, heat discharge can be estimated by tying the Cl^- flux from Yellowstone's rivers to the enthalpy of an inferred high-temperature, high-Cl parent water in the hydrothermal system (Fournier 1989). This yields an estimate of the heat emitted by water discharge and steam condensation each year (5–6 GW). Similar estimates for gases are not feasible because of the immense area of discharge and myriad sources within the Yellowstone area. At present, estimates of gas flux are constrained by extrapolations from local (and time-consuming) soil flux surveys (Werner & Brantley 2003) and periodic aircraft flights over discrete geyser basins. Potentially, scientists can develop continuous geochemical monitoring stations that provide proxies for system-wide phenomena.

Even local geochemical monitoring would be useful because Yellowstone's active hydrothermal system exerts its own eruptive activity, including not merely geysering of steam and hot water, but more explosive 'hydrothermal explosions' that eject rock fragments. Over the past 30 years, most of these events have been small, forming craters only a few metres across, although geologists find evidence for 10–20 geologically recent (less than 15 000 years) hydrothermal-explosion craters with diameters ranging from 100 to 3000 m (Muffler *et al.* 1971). Triggers for these events might include earthquakes, increased gas emissions from below, or reduced hydrostatic pressure resulting from drought or deglaciation. Monitoring for precursors to hydrothermal explosions may be feasible but has not been implemented.

7. Correlations of geophysical and geochemical signals

As discussed above, Yellowstone's vital signs are monitored through observations of seismicity and ground deformation, augmented with geochemical surveys. Over the years, one clear lesson is that measurable parameters are tied together in complex ways, and that understanding will grow only by integrating disparate data streams. Below, we relate several examples.

Derivative effects of earthquakes were clearly recognized prior to implementation of current monitoring networks at Yellowstone. Besides causing landslides and destruction to buildings, the 1959 Hebgen Lake earthquake (M 7.5) was notable in effecting many changes to Yellowstone's hydrothermal system. According to Marler & White (1975), within a few days of the earthquake, 289 springs had erupted as geysers; 160 of them were springs with no previous record of geysering. Changes in the plumbing of many hot springs caused increases in turbidity as well as temperature. One count showed 590 turbid springs within the first few days after the earthquake, most clearing within a few days but some remaining cloudy for years. Temperature data for springs of the Firehole River drainage showed an average increase of 3 °C relative to their pre-earthquake values. Changes in subsurface permeability also caused formerly cold ground to convert to thermal ground over the weeks, months and years following this energetic earthquake. Other smaller earthquakes at Yellowstone also caused considerable changes to the hydrothermal system. Pitt & Hutchinson (1982) described widespread changes in thermal features at the Mud Volcano area

following a series of earthquake swarms in 1978. Even distant earthquakes can trigger both local earthquakes and hydrothermal changes at Yellowstone. On 3 November 2002, the magnitude 7.9 Denali, Alaska, earthquake generated large surface waves that travelled dominantly southeast, causing dynamic microstrain amplitudes of *ca* 0.5 at Yellowstone, a distance *ca* 3100 km from the epicentre. The surface waves triggered several hundred small earthquakes at Yellowstone within the first day (Husen *et al.* 2004*b*), and anomalous seismicity continued for several days. A number of geysers at Yellowstone also exhibited changes in their eruption periodicity immediately after the Denali earthquake, presumably because the dynamic strain associated with the surface waves caused temporary changes in the permeability of the subsurface underlying some of Yellowstone's geyser basins (Husen *et al.* 2004*b*).

Recently, localized uplift in the north-central caldera also appears to be linked to temporary hydrothermal phenomena. During the period 1997–2003, uplift in this area produced dilatation greater than 6 microstrain (Wicks *et al.* 2006). Such dilatation could be responsible for some of the unusual thermal phenomena noted at the nearby Norris geyser basin during 2003, wherein the normally dormant Steamboat geyser erupted three times, a 75 m long rift opened up 3 km to the north of Norris, creating a new fumarole field, and a 'disturbance' in the geyser basin created new mudpots, fumaroles and acres of vegetation killed by heat.

It thus appears that both earthquakes and ground deformation can result in significant hydrological changes in active caldera environments. Many workers also believe that upward migration of fluids from depth may trigger earthquakes and caldera deformation. In the autumn of 1985, the largest earthquake swarm yet recorded at Yellowstone coincided with the change from long-term uplift to a period of subsidence. Quite possibly, the earthquakes resulted from release of accumulated stress on the caldera walls and allowed pressure, in the form of hydrothermal fluid, to be released from the uplifted region. Waite & Smith (2002) interpreted the swarm to reflect migration of fluids along a near-vertical crack (dike) from the caldera. Later, using seismic tomography, Husen *et al.* (2004*a*) found areas of anomalous seismic velocities, which they interpreted as evidence for accumulation of gas (CO_2) in the same region as the 1985 swarms (figure 2).

Such correlations of fluid or gas discharge with seismic swarms, long-period earthquakes and deformation have been documented at other calderas around the world. At Mammoth Mountain, just outside the western edge of the Long Valley caldera, a swarm of earthquakes in 1989 was followed by a plume of cold CO_2 that later killed *ca* 70 ha of forest and continues to pose a health hazard to visitors to the area (Farrar *et al.* 1995). At Campi Flegrei, near Naples, Italy, a long-term record of fumarole output shows that uplift/subsidence cycles are closely followed by changes in the CO_2/steam ratio of gas discharges, a phenomenon interpreted as periods of increased release of magmatic gas (Todesco *et al.* 2004). Yet at Yellowstone, volcanologists have yet to firmly document the causative links between hydrothermal fluids and either swarms or uplift cycles. Ingebritsen *et al.* (2001) found no increase in the flux of chloride (a proxy for hydrothermal fluid discharge) in the waters draining the areas of the 1985 swarm. Nor was there a Park-wide increase in hydrothermal fluid flux during that time. Recently, Evans *et al.* (in press) failed to detect significant discharge of CO_2 in the same region, even though there is abundant CO_2 discharge only 10 km away within the caldera (Werner & Brantley 2003). Thus far, at Yellowstone, the evidence for fluid-driven

'unrest' is inferred from geophysics rather than geochemistry, though this partly reflects the minimal geochemical network that currently exists. It is clear, though, that before we can reliably forecast impending activity at Yellowstone and the world's other large caldera systems, we need to monitor a diverse collection of volcanic signals at high temporal resolution.

8. Recognition of unrest at large calderas

Yellowstone is an active magmatic system emitting a variety of signals related to tectonic, magmatic and hydrothermal processes. The challenge to volcanologists remains to identify those unrest patterns that are potential indicators of impending eruption. Below, we briefly discuss some examples of unrest at large calderas during the past 30–40 years of volcano monitoring, and the challenges that volcanologists face in recognizing calderas headed toward eruption.

At Long Valley caldera, unrest in 1980 began with four M 6.0 earthquakes south of the caldera, three of which occurred on the same day. Scientists quickly measured the area for deformation and found evidence for over 20 cm of uplift within the caldera since the previous summer (Hill 1984). By 2006, the caldera has experienced nearly 80 cm of intermittent uplift (table 1), as well as over 1100 earthquakes over M 3.0 (about twice as many as Yellowstone). Subsequent unrest episodes of note included (i) an intense earthquake swarm in January 1983 with two M 5.2 earthquakes accompanied by a 7 cm uplift of the resurgent dome, (ii) an 11-month-long swarm that began in April 1989 beneath Mammoth Mountain, a 50 kyr volcano on the southwest caldera rim, accompanied by the onset of CO_2 emissions that persist today and (iii) a six-month-long swarm during the last half of 1997 that included nine M>4 earthquakes and an additional 10 cm uplift of the resurgent dome. Intervening activity from 1981 to 1999 was characterized by recurring moderate earthquake swarms, gradual inflation of the resurgent dome at varying rates, as well as both mid-crustal long-period earthquakes and shallow very-long-period earthquakes beneath and west of Mammoth Mountain. Only minor unrest has occurred in Long Valley caldera since 2000 with the resurgent dome maintaining its *ca* 80 cm elevation increase accumulated during the 1980–1999 unrest (Hill in press).

The crustal movements of Campi Flegrei, located just northwest of Naples, Italy, are better documented than any other post-caldera system. Since Roman times, the region has famously swelled and subsided with relatively little earthquake activity. After the most recent eruption at Campi Flegrei in 1538, the city of Pozzuoli, within the caldera, subsided continuously until 1968, when it commenced 2.5 m of uplift in two episodes over the next 17 years. Pozzuoli rose *ca* 1.8 m between 1982 and 1984 and was rocked by numerous swarms of small earthquakes, causing considerable consternation of the local populace. Officials evacuated 40 000 people, but considered evacuating *ca* 200 000 more, though eventually the caldera ceased swelling and once again began to subside (Barberi & Carapezza 1996).

The most extreme example of post-caldera deformation occurs on the island of Iwo Jima, in the Volcano Islands 1200 km south of Tokyo. The island represents the resurgent dome of a caldera apparently formed 3000 years ago during a large pyroclastic eruption. A series of wavecut terraces preserves a record of the island's

Table 1. Examples of caldera-deformation episodes and their rates. ($+/-$, uplift or subsidence; t, duration of event; d, amount of uplift; rate, rate of uplift; eruption, did the deformation culminate in an eruption (yet)?)

caldera	$+/-$	time (common era)	t (years)	d (m)	rate (m yr^{-1})	eruption?	reference
Iwo Jima	+	1600–2000	400	120.0	0.30	no	Yokoyama & Nazzarro (2002)
Iwo Jima	+	1911–1978	67	10.0	0.15	no	Yokoyama & Nazzarro (2002)
Campi Flegrei	−	−200–1000	1200	12.0	0.01	no	Yokoyama & Nazzarro (2002)
Campi Flegrei	+	~1538	~20	6.0	0.30	yes	Yokoyama & Nazzarro (2002)
Campi Flegrei	+	1983–1985	2	1.5	0.75	no	Yokoyama & Nazzarro (2002)
Long Valley	+	1980–2000	20	0.8	0.04	no	Hill (in press)
Rabaul	+	1974–1984	10	1.5	0.15	yes[a]	McKee et al. (1984)
Yellowstone	+	1925–1985	60	0.8	0.013	no	Dzurisin et al. (1990)
Yellowstone	−	1985–1995	10	0.14	0.014	no	Waite & Smith (2002)
Yellowstone	+	2005	1	0.1	0.1	no	http://volcanoes.usgs.gov/yvo

[a] Rabaul eruption in 1994.

migration upward with time, *ca* 120 m in the past 420 years (Ukawa *et al.* 2003). Even during the past 25 years of volcano monitoring, parts of the island have risen 3.5 m. This geodetic unrest is accompanied by occasional hydrothermal explosions, as well as swarms of small earthquakes, and considerable heat and gas flux. Without knowing anything about Iwo Jima, volcanologists might expect that such deformation would inevitably lead to an eruption, but at Iwo Jima, no volcanic eruption has occurred during the past 400 years of geologically rapid uplift.

The range and magnitude of unrest unrelated to eruption highlights the difficulties scientists face in providing accurate forecasts of eruptions at large calderas (Newhall & Dzurisin 1988). Many metres of uplift and impressive swarm activity can occur without subsequent eruption. Hydrothermal or phreatic explosions are a common precursor to volcanism at many stratocones, but at calderas, these hydrothermal events may occur without subsequent volcanism. One potentially robust indicator of impending eruption might be tremor, a continuous, low-frequency seismic waveform that often occurs immediately prior to and during most explosive eruptions (McNutt 2005). Caldera systems such as Yellowstone would probably likewise display tremor prior to eruption, though it is not clear whether the activity would last days or only hours prior to the onset of eruption. In most cases, experience suggests that other precursors would highlight an impending eruption long before the commencement of tremor.

Ultimately, an impediment to mitigation of the risk from super-eruptions is the simple reality that humans have not experienced a super-eruption in written history. The most recent one occurred in the Taupo Volcanic Zone (New Zealand) 26 000 years ago. Even smaller caldera-forming eruptions are relatively rare. The most recent volcanic eruption with VEI 7 (and just barely) occurred in 1815 at Tambora, Indonesia, long prior to modern volcanology. Only a single VEI 6 eruption has occurred on a volcano with a monitoring infrastructure. In that case, Philippine and US scientists rapidly installed a temporary seismic network at Mount Pinatubo, just weeks prior to the caldera-forming eruption that wreaked havoc on central Luzon in 1991. The volcanic unrest there was caught only in mid-stream, long after any of the early precursory activity. Scientists are thus challenged to provide adequate warnings of volcanic super-eruptions, given their lack of experience at witnessing and scrutinizing the signals that precede VEI 7 and 8 eruptions. It would be difficult to predict the magnitude of an impending eruption from a volcanic system capable of a wide spectrum of eruption types and sizes.

Yellowstone provides one example of such a system, with as many as 80 individual volcanic eruptions since the time of the last super-eruption. About 40 of these were small to very large eruptions of rhyolite, but consisting largely of slowly extruded lava with minimal explosivity (and thus not rated on the VEI scale). Another 40 were effusive basaltic lava flows outside the Yellowstone caldera. If such eruptions were to happen again today, they would cause considerable impact within Yellowstone National Park, including closed roads, damaged infrastructure, forest fires and general mayhem. Most such eruptions, however, would have minimal impact on surrounding states or the national economy. Only two post-640 kyr eruptions appear to have had a significant explosive component, with the larger eruption (the tuff of Bluff Point) forming an 8 km diameter caldera at the West Thumb of Yellowstone Lake. Given the range of possible eruption magnitudes, scientists would be challenged to recognize the

precursors to a VEI 8, as opposed to a smaller explosive eruption or a large-volume lava extrusion. Possible scenarios might include: (i) intense unrest followed by a super-eruption, (ii) intense unrest followed by a smaller caldera-forming eruption, (iii) intense unrest followed by a lava flow, ranging from small in volume to immense (some at Yellowstone have volumes greater than 60 km^3), (iv) an eruption that commences as a lava flow but accelerates in intensity to a Plinian eruption or (v) intense unrest accompanying a shallow intrusion that fails to reach the surface and does not culminate in an eruption.

All of these scenarios assume that unrest would be profound and well beyond the norm for historically observed eruptive precursors. The assumption seems warranted, but is not absolutely certain. Moreover, the time between initial unrest and subsequent eruption is difficult to constrain and could potentially range anywhere from days to years (Newhall & Dzurisin 1988). Quite possibly, the effect of a large local earthquake could awaken a large caldera into a rapid period of protracted unrest over a period of days to weeks, as has been noted at a substantial number of volcanoes (Hill *et al.* 2002*a,b*). Though scores if not hundreds of large-magnitude earthquakes (greater than 7.0) have likely occurred near Yellowstone since its most recent eruption, 70 000 years ago, none have resulted in volcanic eruption, though the triggering effects of future earthquakes cannot be ruled out.

9. Concluding thoughts

Sometime within the next hundred thousand years, the Earth will almost certainly experience another super-eruption. With a growing global population, and growing dependence on a computerized, electrified infrastructure, society as a whole is increasingly vulnerable to natural catastrophes (Huppert & Sparks 2006). If humans still inhabit the planet, and if they fail to recognize the precursory signals, they will be challenged to survive the eruption's aftermath.

Although volcanologists can point to a number of accomplishments in eruption prediction over the past 30 years, the margin between success and calamity is often very slim (Newhall & Punongbayan 1996). Even when scientists correctly forecast an eruption, a variety of economic and political factors can still lead to disaster (e.g. Nevado del Ruiz, Colombia; Voight 1996). It will take the combined and concerted efforts of scientists, emergency-management officials, politicians and an informed public to prepare for the effects of a giant eruption, and even then, there inevitably may be large loss of life and infrastructure.

Scientists must do their part to deploy comprehensive, yet cost-effective, monitoring systems to track a wide variety of geophysical and geochemical signals produced by volcanic unrest at large calderas and other areas of abundant volcanism. Though traditional networks have proven effective at detecting volcanic unrest, new methods can and should be developed to track a wider spectrum of subsurface magmatic processes. Scientists also need to communicate their knowledge (and their degree of certainty) to the public and responsible officials, to allow an enlightened dialogue on potential avenues for mitigation. With limited experience monitoring and responding to large-scale volcanic crises, society cannot expect a 100% success rate at avoiding future volcanic catastrophes. We can, however, make sure that we learn from the next VEI 6 or

7 eruption, by recording a full spectrum of signals emitted prior to eruption. At present, only a small fraction of Earth's high-threat volcanoes is monitored in a manner that would provide a useful history of the run-up to a volcanic disaster. If we are to decrease the risk from future large eruptions, we will need to do better.

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