Monitoring a Supervolcano in Repose: Heat and Volatile Flux at the Yellowstone Caldera

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Although giant calderas ("supervolcanoes") may slumber for tens of thousands of years between eruptions, their abundant earthquakes and crustal deformation reveal the potential for future upheaval. Any eventual supereruption could devastate global human populations, so these systems must be carefully scrutinized. Insight into dormant but restless calderas can be gained by monitoring their output of heat and gas. At Yellowstone, the large thermal and CO_2 fluxes require massive input of basaltic magma, which continues to invade the lower to mid-crust, sustains the overlying high-silica magma reservoir, and may result in volcanic hazard for millennia to come. The high flux of CO_2 may contribute to the measured deformation of the caldera floor and can also modify the pressure, thermal, and chemical signals emitted from the magma. In order to recognize precursors to eruption, we must scrutinize the varied signals emerging from restless calderas with the goal of discriminating magmatic, hydrothermal, and hybrid phenomena.

KEYWORDS: Yellowstone, caldera, volatiles, heat, supervolcano

EVALUATING FUTURE ERUPTIVE POTENTIAL AT LARGE CALDERAS

Over the past 2.1 million years, the Yellowstone Plateau volcanic field has produced two of the largest and most devastating eruptions documented on Earth. When will it erupt again, or might it have reached the end of its volcanic lifetime? With extended breaks between eruptive episodes, the most recent now reaching 70,000 years, large calderas like Yellowstone present special challenges to hazard assessment (Christiansen et al. 2007). In 2006 alone, Yellowstone experienced over 1200 earthquakes, and parts of its caldera rose more than 7 cm (volcanoes.usgs.gov/yvo/monitoring.html). Yet how can we determine the relevance of this dynamism to eruptive potential? How can we know whether the volcano is recharging for future activity or simply cooling and stagnating? Herein we explore the insight afforded by heat and volatile flux. By *volatile*, we refer to chemicals within gases or brines (salty liquids) released during depressurization and crystallization of magma. At the ground surface, some volatiles emerge as gases (CO_2 and H_2S) whereas others are dissolved in groundwater (Cl^-, F^-, SO_4^{2-}, HCO_3^-). We use the Yellowstone Caldera as our primary example and show how a simple analysis of gas and heat flux informs our understanding of one of Earth's most powerful volcanoes.

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HEAT AND MASS DISCHARGE AT THE YELLOWSTONE CALDERA

The Yellowstone Caldera formed 640,000 years ago when >1000 km^3 of rhyolitic magma erupted catastrophically, creating deposits of the Lava Creek Tuff (Christiansen 2001). The elliptical caldera measures about 80×50 km (FIG. 1) and is the site of thousands of annual earthquakes and abundant ground-surface displacements (Smith and Braile 1994; Christiansen et al. 2007). Uplift/subsidence (bradyseismic) cycles focused on the resurgent domes (FIG. 1) can last decades, with tens of centimeters of net change (Dzurisin et al. 1990; Smith and Braile 1994; Wicks et al. 2006). Since the caldera formed, it has partly filled with over 500 km^3 of erupted rhyolitic lava. A much smaller volume of basaltic magma has erupted, but solely outside the margins of the caldera (Christiansen 2001; Christiansen et al. 2007). The lack of intracaldera basaltic volcanism is interpreted to reflect the existence of a significant volume of silicic magma beneath the caldera that prevents the denser, mantle-derived basaltic magma from rising to the surface (Hildreth 1981; Hildreth et al. 1991; Christiansen 2001). The existence of a silicic upper-crustal magma reservoir is consistent with seismic velocity and gravity anomalies as well as with the shallow depth of the seismogenic zone beneath the caldera (Smith and Braile 1994; Husen et al. 2004). The magmas provide the heat that sustains the unparalleled number of hot springs, geysers, and mud pots on the Yellowstone Plateau (FIG. 2).

Yellowstone's Hydrothermal System

As described below, scientists can quantify heat and volatile fluxes by monitoring the volume and composition of emitted hydrothermal fluids (i.e. hot waters and gases). At Yellowstone, soluble magmatic volatiles emerge at the ground surface dissolved in hot spring waters. Neutral to alkaline, Cl^--rich waters generally issue at lower elevations, where they create terraces of amorphous silica (sinter) along the outflow of geysers and springs (Fournier 1989). These waters originate from subsurface, high-temperature (>200°C) hydrothermal reservoirs, and cool and boil as they rise. Isotopic data show the water to be dominantly meteoric in origin, having traveled decades (or more) prior to discharge (Rye and Truesdell 1993). Far different are the low-Cl^-, acid waters of Yellowstone, emitted principally at higher elevations (FIG. 1), often in the eastern part of the caldera. These waters form when gases (mainly steam, CO_2,

and (H_2S) are released by the boiling Cl^--rich waters of the deep hydrothermal system and condense just below the ground surface (Fournier 1989). Subsequent oxidation of H_2S creates sulfuric acid, which reacts with the rhyolitic surface rocks to form clays and muds, and these materials dominate the resulting steam-heated (also called acid-sulfate) thermal areas. Very little thermal water flows away from these steam-heated terrains (Fournier 1989).

Estimated Heat Flow

The water expelled from Yellowstone's hydrothermal system carries considerable heat, which in turn reflects the presence of magma below. Fournier et al. (1976) first estimated heat flow at Yellowstone by tallying the total Cl^- flux through its rivers using stream gages combined with periodic chemical analyses. They assumed that the Cl^- was almost entirely derived from a deep parent water of known composition and heat content. Geochemical characteristics of Yellowstone hot springs provided corroborating evidence for the single parent fluid and its initial temperature of 340°C (Fournier 1989 and references therein). The total Cl^- flux could then be tied to a mass of parent water. The calculations account for the heat content of the released Cl^--rich waters as well as the boiling they undergo during ascent and lateral transport. The method can thereby account for heat flow at distal steam-heated areas as well as at the geyser basins where the boiling waters actually emerge. By quantifying the total Cl^- flux through the rivers of Yellowstone, a heat flow or power output was calculated to range from 4.5 to 6.0 GW (Fournier 1989; Friedman and Norton 2007), corresponding to a heat flux density of 1550 to 2100 mW m^{-2} over the entire 2900 km^2 caldera, about 30–40 times that of the neighboring Rocky Mountains. If this high surface heat flux were transferred by conduction alone, it would imply a temperature gradient of 700 to 1000°C per kilometer (Fournier 1989), suggesting the presence of very shallow magma; however, research drilling in the 1960s (White et al. 1971) revealed temperature–depth relations inconsistent with temperatures exceeding ~310°C at 1000 m. Clearly, the enormous hydrothermal system is able to act as a wick, transferring heat advectively from a deep but very large magma source.
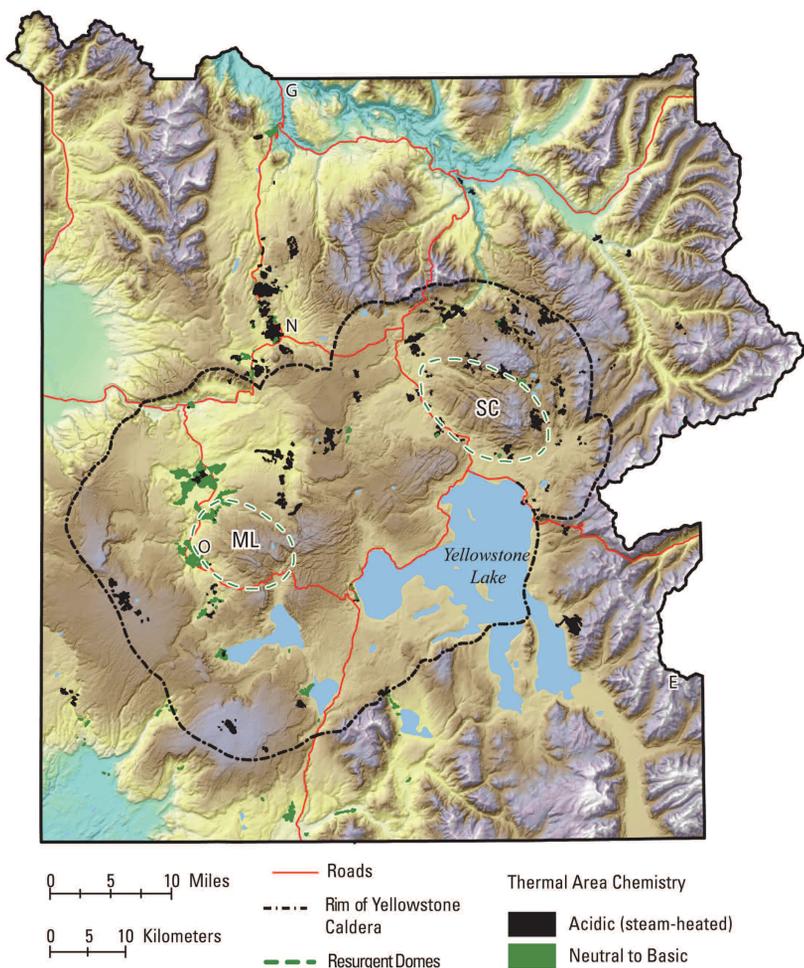
Dissolved Volatile Flux

Since 1983, scientists have continued to track Cl^- flux from the Yellowstone hydrothermal system by monitoring the discharge and composition of the park's rivers (Friedman and Norton 2007). Recently, the protocol was expanded to include SO_4^{2-}, HCO_3^-, F^-, and Br^- (Hurwitz et al. 2007a). TABLE 1 lists the average annual dissolved fluxes for Cl, F, S, and CO_2 between 2002 and 2004. Significant proportions of these volatiles are transported to the hydrothermal system by the degassing of deeper magmas. However, Cl^- and F^- may also be leached from previously erupted rhyolitic rocks that now host the shallow hydrothermal system. Some of the HCO_3^- and SO_4^{2-} can be derived from pre-Tertiary metasedimentary basement rocks. Also, S will be fixed within the hydrothermal system during water–rock interaction. One important goal for scientists is to estimate the proportion of these volatile constituents that is directly derived from active magma degassing beneath Yellowstone.

Gas Flux

Additional volatiles emerge at the ground surface in gaseous form, both by diffuse degassing through soils and directly from bubbling pools and fumaroles. Werner and Brantley (2003) mapped the distribution of diffuse soil emissions of CO_2 at a variety of thermal areas at Yellowstone. They found low CO_2 fluxes through soils near terrains in which silica sinter and travertine ($CaCO_3$) were forming compared to those in the acid, steam-heated regions of the park. We infer that the neutral, high-Cl waters discharged from sinter-forming terrains are comparatively degassed after migrating laterally through and beneath the lava flows that surround the low-elevation geyser basins. When such waters boil, they also provide abundant gas (mainly CO_2, H_2, and H_2S) to the overlying steam-heated areas. The mean diffuse CO_2 flux through soils in steam-heated thermal areas is 1250 g m^{-2} d^{-1}, about 40 to 60 times greater than typical biogenic yields in non-thermal regions (Werner and Brantley 2003).

Werner and Brantley (2003) extrapolated the CO_2 flux rates measured in a few selected areas to all active thermal areas in the park, and thereby estimated emissions of 45,000 ± 16000 t d^{-1} (likely a minimum value because gases from fumaroles and bubbling pools were not included). The apparent CO_2 flux from Yellowstone is among the highest known for individual volcanic centers and is approximately 5% of the estimated global volcanogenic CO_2 flux (Werner and Brantley

FIGURE 1 Shaded-relief image showing topography and pertinent features of Yellowstone National Park. Thermal area database courtesy of A. Rodman, Yellowstone National Park. The maximum elevation is 3640 m at Eagle Peak (**E**) along the east boundary, and the lowest elevation (1608 m) is at the North Entrance near Gardiner, Montana (**G**). Other features include Old Faithful (**O**), the Norris Geyser Basin (**N**), and the Mallard Lake (**ML**) and Sour Creek (**SC**) resurgent domes.

Legend:
- Roads
- Rim of Yellowstone Caldera
- Resurgent Domes

Thermal Area Chemistry
- Acidic (steam-heated)
- Neutral to Basic

2003). Based mainly on carbon and helium isotopes, Werner and Brantley (2003) estimated that 30–50% of the CO_2 output at Yellowstone was derived from pre-Tertiary basement rocks, with the remainder degassed from magma.

BASALT, CO_2, AND THE YELLOWSTONE CALDERA

The preceding discussion summarized current estimates for the flux of volatile constituents and heat from the Yellowstone Caldera. Because there are few sinks for significant volumes of CO_2 and Cl within the magma–hydrothermal system, these fluxes provide powerful constraints on the deep magmatic system. One seemingly clear implication is that CO_2 (and heat) are derived from degassing basaltic magma that underlies the upper- to mid-crustal rhyolitic magma reservoir (White et al. 1988; Christiansen 2001). Aside from the isotopic evidence for magmatic CO_2 and He, the existing CO_2 flux is high enough to rapidly exhaust any plausible non-magmatic source such as limestone (Werner and Brantley 2003). Even some kinds of magma sources are difficult to reconcile with this phenomenal gas flux. The volume of the silicic magma reservoir beneath Yellowstone is estimated at $\sim 1.5 \times 10^4$ km^3 (Lowenstern et al. 2006), and based on the compositions of silicate melt inclusions (now glasses) enclosed within crystals in erupted rhyolites (TABLE 1), Yellowstone silicic magmas contain less than 500 ppm dissolved CO_2. At the current diffuse degassing rate, such a magma body would be entirely purged of dissolved CO_2 in about 1000 years. Similarly, sulfur would be completely degassed in less than 40,000 years. Assigning the annual CO_2 flux to a plausible amount of annually degassed and crystallized rhyolitic magma (0.1 km^3; Fournier 1989) requires 5.5 wt% CO_2, about 20 times that which can be dissolved at 400 MPa (~16 km depth) in rhyolitic liquid (Lowenstern 2001).

The relative proportions of emitted volatiles are also inconsistent with the degassing of silicic magma (FIG. 3). Like silicate melt inclusions from other rhyolitic lavas and tuffs (Wallace 2005), those from Yellowstone contain abundant dissolved Cl and F, but scarce CO_2 and S (A. Abedini, S. Hurwitz, and J. Lowenstern, unpublished data shown in TABLE 1). Yet orders of magnitude more CO_2 is emitted

through the Yellowstone hydrothermal system than Cl, F, or S (TABLE 1). In contrast, basaltic magmas generally contain lower concentrations of dissolved Cl and F, and their composition and origin at mantle pressures permit them to contain 10 to 30 times more dissolved CO_2 (and S) than a mid-crustal rhyolite (Lowenstern 2001 and references therein). Also, thermal considerations dictate that the volume of basaltic magma parental to the rhyolite (or those basaltic intrusions inducing crustal melting) will be at least three to five times greater than that of any derivative silicic magma (White et al. 2006). Thus, basaltic intrusions could contain 50 to 100 times more available CO_2 than the silicic magmas themselves. The basaltic input means that magma continues to accumulate and sustains the overlying silicic magma reservoir (FIG. 3).

If basaltic magmas provide half the CO_2 degassed at Yellowstone (the rest coming from carbonate rocks), associated intrusion, cooling, crystallization, and/or large-scale convection could provide much of the observed heat flow. Parental basalts from Kilauea (Hawai'i) are estimated to have 0.7 wt% CO_2 (Gerlach et al. 2002); more-fertile mantle, as would be expected beneath Yellowstone, would be more CO_2 rich (Thordarson and Self 1996; Dixon et al. 1997; Lowenstern 2001). Assuming 1 wt% CO_2 in mantle-derived basalt, an intrusion rate of 0.3 km^3 y^{-1} would be required to produce the observed gas flux. An intrusion rate of 0.3 km^3 y^{-1} is comparable to, though slightly higher than, those estimated for Kilauea and the Columbia River Basalt (Gerlach et al. 2002; Lange 2002). This intrusion rate would create a power output of 22 GW (assuming full crystallization and further cooling of 300°C), about 3 times the minimum observed heat flow (Fournier 1989). Less heat might be expected if the intruding basalt loses heat laterally, or if it degasses during ascent with minimal cooling and crystallization.

Notwithstanding the uncertainties in absolute gas and heat fluxes, both variables clearly point towards high intrusion rates of basaltic magma, comparable to those of the Hawaiian hotspot and up to 100 times the long-term eruption rate of rhyolite in Yellowstone (0.003 km^3 y^{-1}; Christiansen 2001). Evidence points to a dense, high-velocity mid-crust beneath the Snake River plain, consistent with emplacement and crystallization of basaltic magma throughout the 16-million-year history of the Yellowstone hotspot (Smith and Braile 1994; Shervais et al. 2006). Models for the generation of Yellowstone rhyolites involve

TABLE 1 VOLATILE ABUNDANCES IN YELLOWSTONE RIVERS, SOIL GASES, AND LAVAS

	River solute flux 2002–2004 (t d^{-1})*	Diffuse soil flux (t d^{-1})**	Average MI post-caldera rhyolite (ppm)***	Average MI Columbia River Basalt (ppm)****
Cl	137	-	1100	295
F	17	-	2000	1310
S	56	164	<100	1965
CO_2	553	45,000	0 to 400	1 wt%

* From Hurwitz et al. (2007a). River flux for S and CO_2 recalculated from SO_4^{2-} and HCO_3^-.

** CO_2 value from Werner and Brantley (2003). Soil flux of S assumes a molar ratio for CO_2/H_2S of 200.

*** Quartz-hosted silicate melt inclusions (MI) from postcaldera rhyolites at Yellowstone analyzed by electron microprobe and Fourier transform infrared spectroscopy (n = 50). Unpublished data from A. Abedini, J. Lowenstern, and S. Hurwitz

**** Melt inclusions in olivine reported by Thordarson and Self (1996) for Cl, F, and S. The CO_2 estimate is based on values for initial mantle melts inferred for similar trace-element-enriched tholeiite sources (Lowenstern 2001).

crystallization and/or melting of abundant mafic (basaltic composition) sources in the lower crust combined with 10 to 30% melting of radiogenic crust (Hildreth et al. 1991). Gas released during ascent and crystallization of the basaltic magma would be too abundant to dissolve within the overlying silicic magma and hydrothermal system, effectively saturating the crust with CO_2-rich gas.
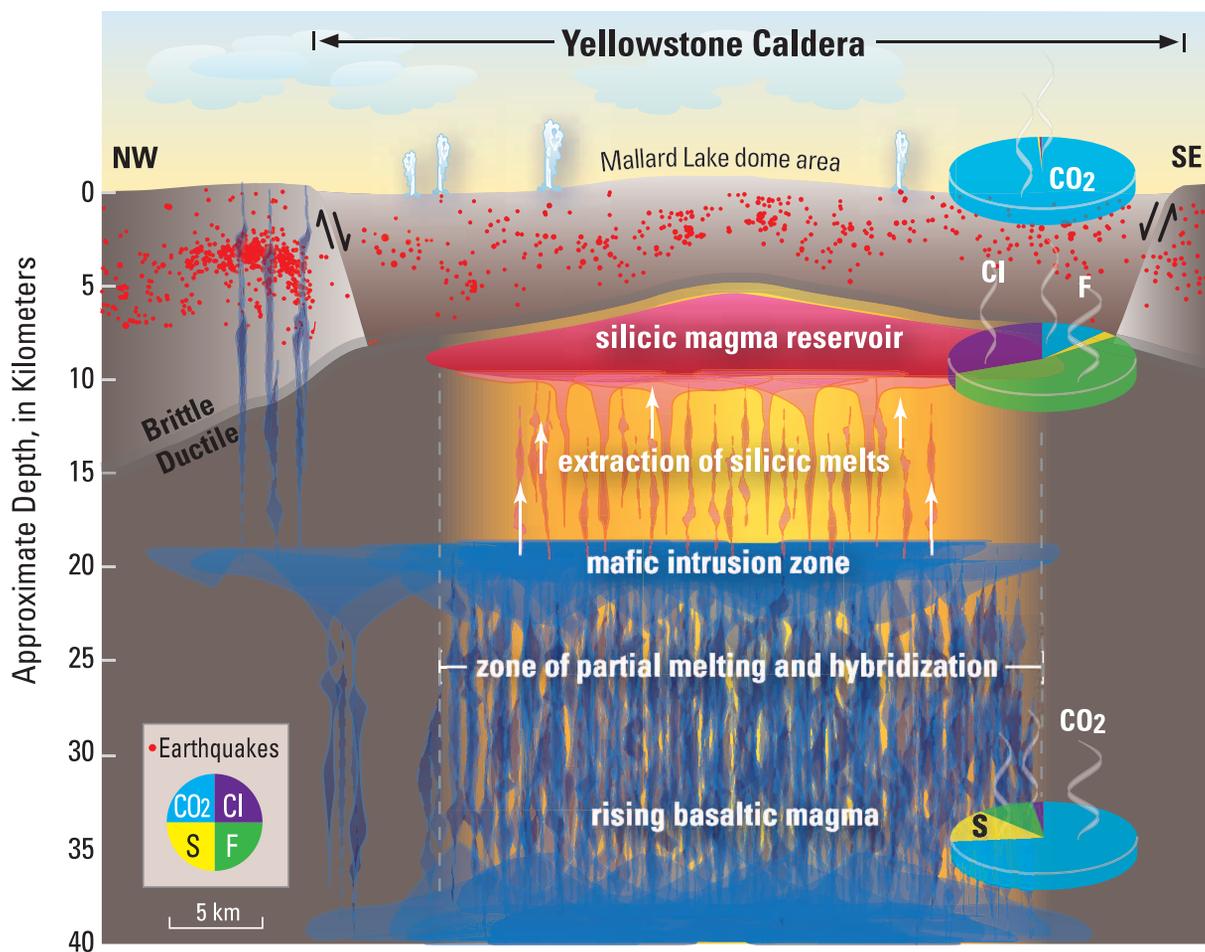
GAS SATURATION IN THE YELLOWSTONE SUBSURFACE

The impressive gas discharge hints that the shallow subsurface beneath Yellowstone should be gas saturated over a wide depth–temperature range. An initial understanding is gained by comparing the CO_2 flux to that of the Cl^- released through rivers. If the two volatiles are currently emerging from the hydrothermal system at their long-term rates, then the CO_2/Cl^- mass ratio in the subsurface can be estimated at ~300 (TABLE 1). Fournier (1989 and references therein) inferred the existence of a parent thermal water with 400 ppm Cl^-. If the gas could be dissolved back into that water, the CO_2 concentration would be 400 ppm multiplied by 300, equaling 12 wt% (or 5 mol%). However, under most pressure and temperature conditions, the CO_2 is too abundant to dissolve completely, as demonstrated in FIGURE 4, which displays the phase boundaries in the system 95% H_2O–5% CO_2, assuming a hydrostatic pressure gradient. Model calculations suggest that the upper 4 km of the

Yellowstone subsurface should host a two-phase hydrothermal system containing liquid water and bubbles of a mixed steam–CO_2 vapor phase. The relative abundance of the two phases can be estimated for a common pressure–temperature regime at Yellowstone: 1 km depth and 250°C (red square in FIGURE 4). Under those conditions, a 95% H_2O–5% CO_2 fluid cannot exist as a single phase, but would unmix into a vapor phase (50% CO_2) and liquid water with minor dissolved gas. The vapor phase would have a volume approximately equal to that of the liquid. In reality, the two phases are unlikely to remain together and would separate, so that vapor-dominated hydrothermal reservoirs could form above areas of deep boiling and degassing (White et al. 1971; Fournier 1989). The key point is that the considerable flux of CO_2 almost certainly requires that large portions of the hydrothermal system beneath Yellowstone are gas saturated, plausibly down to depths of 4 km or more.

IMPLICATIONS OF A GAS-RICH SUBSURFACE

Gas-rich conditions in the shallow subsurface may relate to the origin and style of long-timescale deformation (bradyseisms), the dominant form of unrest at calderas around the world. At the Phlegrean Fields in Italy, the correlation of caldera uplift with the CO_2/H_2O ratios of fumarolic gases was ascribed to magmatic gas input and pressurization of the shallow hydrothermal system (Chiodini et al. 2003). Recent numerical models (Todesco et al. 2004; Hurwitz et

FIGURE 3 Schematic cross-section of the crust beneath the Yellowstone Caldera based on Hildreth (1981) and Husen et al. (2004). Red dots represent earthquake epicenters. The silicic magma reservoir is responsible for most of the volcanism over the past 2.1 million years and overlies a middle and lower crust invaded by mantle-derived basalt. The silicic magma is a hybrid of crustal melts and residual liquid formed as mafic magma cools and crystallizes. Magma rises closest to the surface (5–7 km depth) beneath the resurgent domes. Pie diagrams compare the relative abundances of volatiles emitted from the Yellowstone hydrothermal system (top) with the abundances of volatiles dissolved in Yellowstone rhyolites (middle) and hotspot basalts (bottom). The CO_2-rich hydrothermal system appears to reflect the basalt-dominated crust below. The diagrams are constructed with data from TABLE 1.

al. 2007b) and geophysical studies (Gottsmann et al. 2007) highlight the role of gas and aqueous fluid dynamics in caldera deformation. At Yellowstone, bradyseismic events typically are linked to magma intrusion (Wicks et al. 2006) or to upward migration of brines from hot, low-permeability regions (Dzurisin et al. 1990). Without continuous monitoring of volatile flux and comparison with geophysical time series, it remains difficult to verify any particular mechanism of deformation.

Even if the gas is immobile, just the existence of vapor-saturated conditions in the shallow crust should affect the manner in which any hydrothermal region transmits pressure pulses between magma and the ground surface (Norton 1984). Surface displacements are commonly interpreted by assuming a volume change in a discrete magmatic source embedded in a deforming, elastic, isotropic crust; such assumptions would likely lead to underestimating the size and depth of any magma source beneath a gas-rich, compressible hydrothermal system (Dzurisin 2007; Hurwitz et al. 2007b). Clearly, any added insight on the abundance of volatiles and their dynamics in the shallow crust will help us to assess which signals of caldera unrest are most likely to foretell an impending eruption (Newhall and Dzurisin 1988).
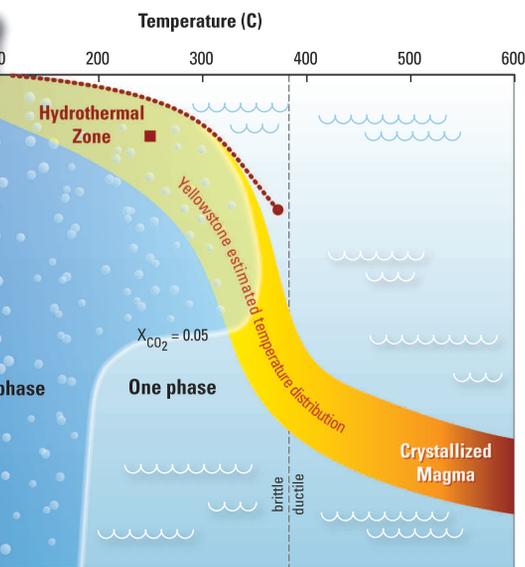
LINGERING QUESTIONS ON VOLATILES, VOLCANOES, AND THE FUTURE OF YELLOWSTONE

It now seems quite certain that abundant basaltic magma intrudes the crust beneath the Yellowstone Caldera, stoking the fires beneath the silicic magma and flooding the overlying hydrothermal system with gas. Yet important and fascinating questions remain. How variable is the surface gas flux at timescales ranging from daily to millennial? Is it possible that current emissions result from a temporary (postglacial?), increased rate of hydrothermal discharge that reflects shallow hydrothermal processes more than the deep intrusions discussed above? If so, increased hydrothermal flow might be cooling the underlying magma and decreasing the long-term volcanic hazard. It is also possible that Yellowstone has remained dormant for so long because its magmas and hydrothermal system are very efficient at releasing their heat and volatiles, thus preventing buildup of magmatic pressure. Ultimately, we cannot assess these issues without greater understanding of the origin, variability, and significance of measured geochemical fluxes and their relationship to the geophysical data that have been collected for decades. Monitoring of heat and volatile flux is only beginning, but it holds great promise to aid us in deciphering the signals emitted by Earth's giant calderas: someday, that ability may save our lives.

FIGURE 4 Temperature versus depth diagram, assuming a hydrostatic pressure gradient. The darker blue field represents conditions at which a 5% CO_2–95% H_2O (molar) fluid will unmix to form a water-dominated liquid and a CO_2-rich gas phase (Duan et al. 1992). The estimated temperature distribution reflects suprasolidus (i.e. $>\sim700°C$) conditions at depths around 8 km (Husen et al. 2004) and temperatures close to the pure H_2O liquid–vapor curve (dotted red line) near the surface. Much of the upper few kilometers is predicted to be vapor saturated. Quartz-bearing rocks undergo a transition from brittle to ductile behavior at temperatures near 400°C. Phase relations at 250°C and 1000 m depth (the red square) are discussed in the text.

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