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Invited review article

Monitoring gas and heat emissions at Norris Geyser Basin, Yellowstone National Park, USA based on a combined eddy covariance and Multi-GAS approach

J.L. Lewicki [a,*], P.J. Kelly [b], D. Bergfeld [c], R.G. Vaughan [d], J.B. Lowenstern [c]

[a] U.S. Geological Survey, National Research Program, Menlo Park, CA, USA
[b] U.S. Geological Survey, Volcano Science Center, Vancouver, WA, USA
[c] U.S. Geological Survey, Volcano Science Center, Menlo Park, CA, USA
[d] U.S. Geological Survey, Astrogeology Science Center, Flagstaff, AZ, USA

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ABSTRACT

We quantified gas and heat emissions in an acid-sulfate, vapor-dominated area (0.04-km^2) of Norris Geyser Basin, located just north of the 0.63 Ma Yellowstone Caldera and near an area of anomalous uplift. From 14 May to 3 October 2016, an eddy covariance system measured half-hourly CO_2, H_2O and sensible (H) and latent (LE) heat fluxes and a Multi-GAS instrument measured (1 Hz frequency) atmospheric H_2O, CO_2 and H_2S volumetric mixing ratios. We also measured soil CO_2 fluxes using the accumulation chamber method and temperature profiles on a grid and collected fumarole gas samples for geochemical analysis. Eddy covariance CO_2 fluxes ranged from -56 to 885 g m^{-2} d^{-1}. Using wavelet analysis, average daily eddy covariance CO_2 fluxes were locally correlated with average daily environmental parameters on several-day to monthly time scales. Estimates of CO_2 emission rate from the study area ranged from 8.6 t d^{-1} based on eddy covariance measurements to 9.8 t d^{-1} based on accumulation chamber measurements. Eddy covariance water vapor fluxes ranged from 1178 to 24,600 g m^{-2} d^{-1}. Nighttime H and LE were considered representative of hydrothermal heat fluxes and ranged from 4 to 183 and 38 to 504 W m^{-2}, respectively. The total hydrothermal heat emission rate ($H + LE +$ radiant) estimated for the study area was 11.6 MW and LE contributed 69% of the output. The mean $\pm$ standard deviation of H_2O, CO_2 and H_2S mixing ratios measured by the Multi-GAS system were 9.3 $\pm$ 3.1 parts per thousand, 467 $\pm$ 61 ppmv, and 0.5 $\pm$ 0.6 ppmv, respectively, and variations in the gas compositions were strongly correlated with diurnal variations in environmental parameters (wind speed and direction, atmospheric temperature). After removing ambient H_2O and CO_2, the observed variations in the Multi-GAS data could be explained by the mixing of relatively H_2O-CO_2-H_2S-rich fumarole gases with CO_2-rich and H_2O-H_2S-poor soil gases. The fumarole H_2O/CO_2 and CO_2/H_2S end member ratios (101.7 and 27.1, respectively, on average) were invariant during the measurement period and fell within the range of values measured in direct fumarole gas samples. The soil gas H_2O/CO_2 end member ratios (~15–30) were variable and low relative to the fumarole end member, likely resulting from water vapor loss during cooling and condensation in the shallow subsurface, whereas the CO_2/H_2S end member ratio was high (~160), presumably related to transport of CO_2-dominated soil gas emissions mixed with trace fumarolic emissions to the Multi-GAS station. Nighttime eddy covariance ratios of H_2O to CO_2 flux were typically between the soil gas and fumarole end member H_2O/CO_2 ratios defined by Multi-GAS measurements. Overall, the combined eddy covariance and Multi-GAS approach provides a powerful tool for quasi-continuous measurements of gas and heat emissions for improved volcano-hydrothermal monitoring.

1. Introduction

The Yellowstone magmatic system has been responsible for three cataclysmic volcanic eruptions during the past 2.1 million years, the most recent of which formed the 0.63 Ma Yellowstone Caldera (Fig. 1; Christiansen, 2001; Matthews et al., 2015). The Yellowstone magmatic system then underwent two cycles of intracaldera eruptions, which ended ~70 ka. Today, Yellowstone Caldera's unrest is manifested by abundant seismicity, episodes of uplift and subsidence, and variations in activity of one of the world's largest hydrothermal systems (see Hurwitz and Lowenstern, 2014 for review). In particular, Norris Geyser Basin, located 7.5 km north of the 0.63 Ma Yellowstone Caldera (Fig. 1) has displayed large variations in hydrothermal activity on diurnal to

* Corresponding author.
E-mail address: jlewicki@usgs.gov (J.L. Lewicki).

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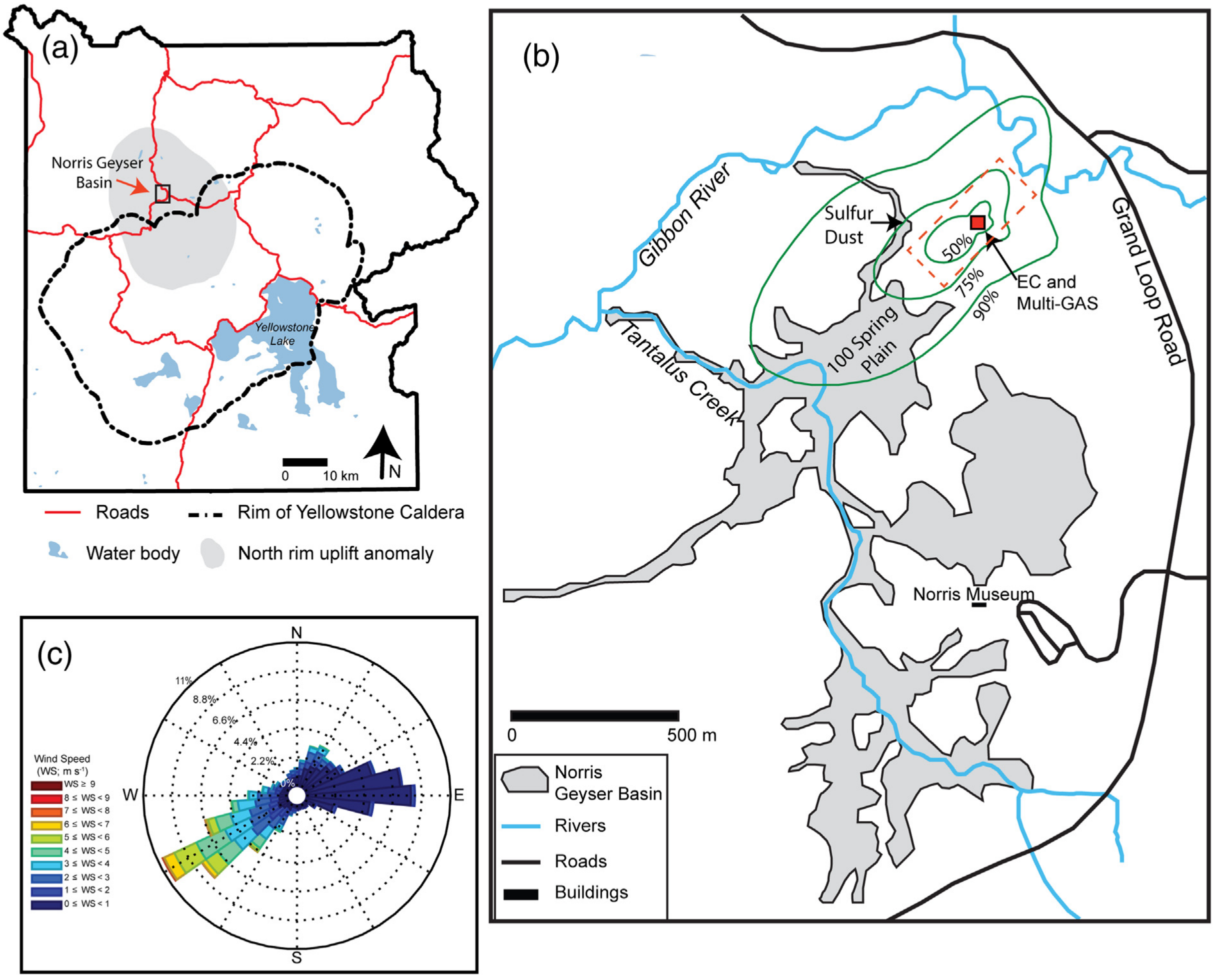

Fig. 1. (a) Map of Yellowstone National Park with Norris Geyser Basin outlined by rectangle. Grey area shows location of north rim uplift anomaly approximated from 40 mm uplift contour on stacked interferogram (1996–2002) (Wicks et al., 2006). (b) Map of Norris Geyser Basin (modified from Jaworowski et al., 2006). Dashed red box outlines general Bison Flat study area. Red square indicates location of eddy covariance (EC) and Multi-GAS stations and fumarole gas samples. Green lines show eddy covariance average 50, 75, and 90% CO_2 flux source area isopleths. (c) Wind rose showing joint frequency distribution of mean horizontal wind speed and direction (half-hourly averages) measured by eddy covariance station from 14 May to 3 October 2016.

annual timescales (e.g., White et al., 1988; Fournier et al., 2002; Lowenstern et al., 2003; Clor et al., 2007). A notable period of enhanced activity occurred in 2003, characterized by the formation of new hot springs and fumaroles, renewed activity of dormant geysers, elevated ground temperatures and increased tree mortality (Lowenstern et al., 2003).

Extensive work carried out since the 1980's characterized the chemical and isotopic compositions of gases and waters and quantified fluxes of volatiles and heat emitted from the Yellowstone hydrothermal system (see Hurwitz and Lowenstern, 2014 and Lowenstern et al., 2015 for reviews). These data suggest that the Yellowstone CO_2 emission rate (~45,000 t d^{-1}) is one of the highest from a single volcanic center in the world (Werner and Brantley, 2003). Combined with petrologic constraints, these data also indicate high rates of basaltic magma intrusion (up to 0.3 km^3 y^{-1}; Lowenstern and Hurwitz, 2008), comparable to those estimated for Kilauea, Hawai'i (Gerlach et al., 2002). While basaltic magma intrusion and resulting gas-rich conditions in the subsurface likely drive cycles of uplift and subsidence in Yellowstone, various mechanisms by which this occurs have been proposed (e.g., Dzurisin and Yamashita, 1987; Dzurisin et al., 1990; Wicks et al., 2006; Vasco et al., 2007; Chang et al., 2007).

To improve understanding of caldera unrest, quantification of temporal variations in gas and heat fluxes and gas geochemistry and their relationships to deformation and seismicity are required (Lowenstern and Hurwitz, 2013; Lowenstern et al., 2015). However, while numerous studies have characterized spatial variations in gas and heat fluxes and gas geochemistry across Yellowstone (see Hurwitz and Lowenstern, 2014 and Lowenstern et al., 2015 for reviews), relatively few have focused on temporal variations in these parameters. A number of studies used the chemistry and discharge of major rivers in the Yellowstone Plateau Volcanic Field to monitor hydrothermal mass and heat output from the system (see Hurwitz and Lowenstern, 2014 for review). However, the ability of this method to detect change associated with caldera unrest is limited due to its long response time to magmatic fluid injection into the hydrothermal system and sensitivity to background hydrologic variations (Hurwitz et al., 2007). Werner et al. (2000) tested the ability of the eddy covariance method to measure half-hourly CO_2 fluxes at the Mud Volcano area in Yellowstone during a short-term study in 1999. Based on radiocarbon measurements of annual growth rings of a tree in the Mud Volcano area, Evans et al. (2010) recorded an increase in magmatic CO_2 uptake related to a 1978 seismic swarm. Finally, time variations in gas geochemistry at individual thermal basins in Yellowstone were discerned on coarse (inter-annual) scales based on data sets published by Bergfeld et al. (2011, updated 2014).

We present measurements of temporal variations in CO_2, water vapor and heat fluxes and gas compositions measured using the eddy covariance and Multi-GAS techniques between May and October 2016 in a 0.04-km^2 vapor-dominated hydrothermal area of Norris Geyser Basin. Continuous monitoring of gas and heat emissions was augmented by measurements of ancillary environmental parameters, ground-based

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