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Journal of Volcanology and Geothermal Research 154 (2006) 169 – 180

Journal of volcanology and geothermal research

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Geochemistry of low-temperature springs northwest of Yellowstone caldera: Seeking the link between seismicity, deformation, and fluid flow

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Received 6 June 2005; received in revised form 22 December 2005; accepted 4 January 2006
Available online 10 March 2006

Abstract

A comprehensive geochemical survey of springs outside the northwest margin of the Yellowstone caldera was undertaken in 2003 and 2004. This survey was designed to detect: (1) active leakage from a huge reservoir of CO_2 gas recently postulated to extend from beneath the caldera into this area; and (2) lingering evidence for subsurface flow of magmatic fluids into this area during the 1985 seismic swarm and concomitant caldera subsidence. Spring temperatures are low ($<15\,°C$), but two large-discharge springs contain ^{14}C-dead carbon that can be identified as magmatic from calculated end-member values for $\delta^{13}C_{(dead)}$ and $^{3}He/C_{(dead)}$ of $-4‰$ and 1×10^{-10}, respectively, similar to values for intra-caldera fumarolic and hot-spring gases. However, the combined discharge of magmatic C is only 5.4 tonnes/day, $<0.1\%$ of the total output from Yellowstone. The two springs have slightly elevated $^{3}He/^{4}He$ ratios near $1\,R_A$ and anomalous concentrations of Cl, Li, and B, and appear to represent minor leakage of gas-depleted, thermal waters out of the caldera. The small CO_2 signal detected in the springs is difficult to reconcile with a large underlying reservoir of gas in faulted and seismically active terrain. When considered with analyses from previous decades, the results provide no evidence to associate the ten-year period of caldera deflation that began in 1985 with expulsion of magmatic fluids through the caldera rim in this area.
Published by Elsevier B.V.

Keywords: Yellowstone National Park; magmatic gas; geochemistry; carbon dioxide; helium

1. Introduction

Interest in volcanic hazards at Yellowstone increased in 1975 when geodetic surveys showed that the central part of the caldera floor had risen ~1 m during the previous 5 decades (Pelton and Smith, 1982). Uplift continued for several years, but subsidence was detected in 1985 (Dzurisin et al., 1994), and 0.25 m of subsidence occurred over the next 10 years (Wicks et al., 1998; Waite and Smith, 2002). In late 1985, a major seismic swarm began at the northwest caldera boundary. This swarm was unique among recorded events in that the epicenters gradually migrated away from the caldera for

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0377-0273/$ - see front matter. Published by Elsevier B.V.
doi:10.1016/j.jvolgeores.2006.01.001

several km to the northwest. The propagating seismicity coupled with caldera deflation pointed to subsurface fluid flow out of the caldera as the cause for both events (Waite and Smith, 2002; Fournier, 2004), but questions about the fluid and its role in the events remain. Magmatic brines, gases, and magma itself have all been invoked to account for Yellowstone's cycles of deformation and seismicity (Fournier, 1989; Dzurisin et al., 1994; Wicks et al., 1998; Waite and Smith, 2002; Wicks et al., 2002).

Negative anomalies in Vp and Vp/Vs recently detected in seismic tomographic imaging led Husen et al. (2004) to propose that a large reservoir of gas at depths as shallow as ~4 km below land surface extends from beneath the caldera to the northwest, in the same general area as the 1985 seismic swarm. They hypothesize that the gas is most likely CO_2 released from crystallizing magma beneath the caldera, and imply that migration of CO_2-rich fluid might explain the propagating seismicity. Husen et al. (2004) note that CO_2 from such a shallow reservoir would likely leak to the surface and escape diffusely through soil, as occurred at Mammoth Mountain, California (Farrar et al., 1995).

A search for anomalous CO_2 emissions northwest of the caldera was warranted, but detecting anomalous efflux over large regions of wilderness and in the absence of clear vegetation kills is logistically daunting. We chose instead to search for dissolved magmatic C in springs and streams, because CO_2 is fairly soluble in cold water. High-pressure CO_2 has been implicated in propagating seismic swarms at Mammoth Mountain USA (Hill and Prejean, 2005), Colfiorito Italy (Miller et al., 2004; Chiodini et al., 2004), and the Eger rift in central Europe (Bräuer et al., 2003). Springs with highly anomalous concentrations of magmatic C are long-lived and conspicuous features in these areas (Sorey et al., 1998; Chiodini et al., 1999; Bräuer et al., 2003). An advantage to collecting waters is that the samples can be analyzed for other magmatic or hydrothermal species of interest (e.g., He, Cl); and because the study area was included in previous regional geochemical studies, we can evaluate whether any chemical anomalies could be related to the 1985 seismic swarm and ensuing subsidence.

2. Study area, sampling logistics, and methods

The study area (Fig. 1) extends to the north and west from Terrace Spring, a sub-boiling hot spring located near the caldera rim 14 km southwest of Norris, and covers the location of the 1985 seismic swarm, the general region of elevated seismicity trending through the Madison Valley, and a substantial part of the hypothesized gas reservoir of Husen et al. (2004). The study area includes numerous normal faults (Christiansen, 2001) and encompasses the discharge area for groundwaters draining from the northwest caldera rim to provide the best chances of detecting any Yellowstone fluids forced out beneath this part of the rim that then rise toward the surface.

Paleozoic and Mesozoic marine sedimentary rocks (shaded green in Fig. 1) are exposed in the northern part and to the west of the study area. Cenozoic volcanic rocks, Precambrian gneisses and schists and alluvium occupy the rest of the study area (Christiansen, 2001; O'Neill and Christiansen, 2004). The contrasting geology is clearly reflected in calcium and magnesium concentrations of spring waters. The products of Yellowstone volcanism are predominantly rhyolites that are exceptionally low in both elements, whereas limestone and dolomite are common in the sedimentary rocks to the north (Christiansen, 2001; Hildreth et al., 1991).

Annual precipitation in the study area averages about 1 m/year with up to 30% recharge (Kharaka et al., 2002), feeding a voluminous groundwater flow that could easily dilute magmatic or hydrothermal inputs to trace concentrations. The strategy adopted to search for anomalies was to measure the specific conductance of streams at low elevations in their drainages, and if conductance was abnormally high, to move upstream to the source springs and sample those with the highest conductance. Increased conductance can potentially reflect chloride input from thermal waters or HCO_3^- generated from magmatic CO_2. Many of the springs in the study area actually consist of clusters of distinct vents. The field conductance measurements indicated whether all of the vents discharged similar fluids. At two of the springs, Black Sand and Big Springs, vents showed a significant range in temperature and conductance, and two vents that spanned the range were sampled at each of these vent clusters.

Many springs and streams were visited but not sampled if conductivity, temperature, or pH measurements indicated no anomalies. Flow rate, determined from visual estimates or direct gaging, and areal distribution were also used to select sample sites. Large-discharge springs were especially targeted because their recharge zones cover more of the study area, and they represent a greater total flux for a given concentration anomaly than do low-discharge springs. Known spring areas around the alluvium-filled Madison Valley were visited as were most streams flowing into the valley from the north and east (Fig. 1) to provide