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# Dynamics within geyser conduits, and sensitivity to environmental perturbations: Insights from a periodic geyser in the El Tatio geyser field, Atacama Desert, Chile

Carolina Munoz-Saez [a,*], Michael Manga [a], Shaul Hurwitz [b], Maxwell L. Rudolph [c], Atsuko Namiki [d], Chi-Yuen Wang [a]

[a] University of California, Berkeley, CA, USA
[b] US Geological Survey, Menlo Park, CA, USA
[c] Portland State University, Portland, OR, USA
[d] Hiroshima University, Hiroshima, Japan

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ABSTRACT

Despite more than 200 years of scientific study, the internal dynamics of geyser systems remain poorly characterized. As a consequence, there remain fundamental questions about what processes initiate and terminate eruptions, and where eruptions begin. Over a one-week period in October 2012, we collected down-hole measurements of pressure and temperature in the conduit of an exceptionally regular geyser (132 s/cycle) located in the Chilean desert. We identified four stages in the geyser cycle: (1) recharge of water into the conduit after an eruption, driven by the pressure difference between water in the conduit and in a deeper reservoir; (2) a pre-eruptive stage that follows the recharge and is dominated by addition of steam from below; (3) the eruption, which occurs by rapid boiling of a large mass of water at the top of the water column, and decompression that propagates boiling conditions downward; and (4) a relaxation stage during which pressure and temperature decrease until conditions preceding the recharge stage are restored. Eruptions are triggered by the episodic addition of steam coming from depth, suggesting that the dynamics of the eruptions are dominated by geometrical and thermodynamic complexities in the conduit and reservoir. Further evidence favoring the dominance of internal processes in controlling periodicity is also provided by the absence of responses of the geyser to environmental perturbations (air pressure, temperature and probably also Earth tides).



## 1. Introduction

Geysers are springs that produce discrete eruptions of steam, liquid water, and non-condensable gases. Their eruptions are smaller and typically more frequent than volcanoes and hydrothermal eruptions, providing a natural laboratory to study eruptive processes (Kieffer, 1984). Geysers are uncommon; less than 1000 have been described worldwide, and this number is decreasing due to geothermal energy development (Bryan, 1995). Special conditions are needed for their formation: a supply of water, a source of heat, and a particular system of fractures and/or porous rocks to permit episodic discharge (e.g., White, 1967; Fournier, 1969; Kieffer, 1989; Ingebritsen and Rojstaczer, 1993, 1996; Kedar et al., 1998; Kiryukhin et al., 2012; Belousov et al., 2013; Karlstrom et al., 2013; Shteinberg et al., 2013; Vandemeulebrouck et al., 2013; Namiki et al., 2014; Vandemeulebrouck et al., 2014).

There are several open questions about processes and conditions before, during and after the eruption: how is heat transported to and within the geyser system? Do eruptions begin in a conduit as observed in some laboratory experiments (Adelstein et al., 2014)?, or in a deeper reservoir as proposed from limited observations in natural systems (Belousov et al., 2013; Vandemeulebrouck et al., 2013) and experiments (Steinberg et al., 1982)? What is the geometry of subsurface fractures and how do they affect the eruption process? Previous studies of natural geysers provide at least partial answers to these questions. Some observations indicate that prior to an eruption, temperature in the water column is below boiling, and the boiling is caused by ascent-driven decompression (e.g., Bunsen, 1847, Fukutomi, 1942a,b; Kieffer, 1984). Conversely, some studies in Yellowstone National Park (USA) suggested that intermittent injection of superheated water leads to eruption (Rinehart, 1972, 1980), assuming hydrostatic conditions and that the depth of the measurements (23 m) was accurate. White (1967) proposed that eruptions begin with the discharge of water below the boiling temperature ($T_{boil}$), progress to a liquid-dominated fountain that becomes steam-rich, and end with a quiescent phase. Seismic observations suggest that steam bubbles are crucial in transferring heat to water in the conduit and in driving the eruption (Kieffer, 1984, 1989). Underground cavities at some geysers may create a “bubble trap” that allows

* Corresponding author.
*E-mail address:* carolimunoz@berkeley.edu (C. Munoz-Saez).

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for the accumulation of a two-phase fluid (liquid + steam) in the system and the episodic release of this fluid (Mackenzie, 1811; Belousov et al., 2013; Vandemeulebrouck et al., 2013, 2014; Adelstein et al., 2014).

The response of geyser eruptions to external influences provides additional insight into how they work. Some geysers in Yellowstone respond to local and remote earthquakes (Marler, 1964; Rinehart and Murphy, 1969; Marler and White, 1975; Hutchinson, 1985; Husen et al., 2004a,b; Manga and Brodsky, 2006; Hurwitz et al., 2014). The responses of geysers to non-seismic strain (Earth tides, barometric pressure), and weather (atmospheric temperature, rainfall and wind) vary between geysers (e.g., Rinehart, 1972; White and Marler, 1972; Rojstaczer et al., 2003; Hurwitz et al., 2008, 2012, 2014).

Most data used to study geysers comes from observations made at the surface. Data on processes in the ground subsurface of geysers are limited due to the complexity of taking measurements in situ. Active and passive field experiments inside conduits have been performed at Yellowstone National Park (Birch and Kennedy, 1972; Rinehart, 1972; Hutchinson et al., 1997; Kedar et al., 1998), and Kamchatka (Belousov et al., 2013; Shteinberg et al., 2013). Data from these experiments provided a better understanding of conduit geometry (Hutchinson et al., 1997; Belousov et al., 2013), thermodynamic conditions (Hutchinson et al., 1997; Kedar et al., 1998), and recharge processes (Shteinberg et al., 2013).

We obtained continuous time series of pressure and temperature inside the conduit of a geyser located in El Tatio, northern Chile (Fig. 1a). This geyser does not have an official name, so we nicknamed it "El Jefe" (Fig. 1b,c) and use this name throughout the manuscript. This geyser corresponds to feature T35 described in Glennon and Pfaff (2003) as one of the more significant and periodic geysers in the basin. One unusual aspect of the El Tatio geysers is that they are located in the middle of a very dry area, the Atacama Desert, in contrast to other geyser fields in the world (Yellowstone National Park, Kamchatka, Iceland, and New Zealand). The marked daily variation in air pressure and temperature, very high evaporation rates, and the limited meteoric water recharge, make El Tatio's geysers ideal for examining the sensitivity of multiphase systems to external perturbations. A better understanding of "cause and effect" relationship between external conditions and geyser cycle may help to constrain and quantify the processes governing the eruptions.

Down-hole measurements of pressure and temperature from 3531 eruptions of El Jefe geyser during one week in October 2012 provide an extensive record of thermodynamic conditions during the entire geyser cycle. We combined these data with measurements at the surface to: 1) examine the geyser's response to environmental forcing, and; 2) better understand the thermodynamics within the geyser conduit.

We begin with a description of the study area. Then, we describe the field measurements and instruments, followed by a compilation of observations and results. We end with an interpretation of the measurements and evaluate proposed hypotheses for the mechanisms leading to geyser eruptions.

## 2. El Tatio geyser field

The El Tatio geyser field contains more than 80 active geysers (Glennon and Pfaff, 2003). It is located in northern Chile at an elevation of 4200 to 4300 m. The field is situated among Holocene andesitic stratovolcanoes, which provide the heat for the geothermal system, but no historical eruptions were documented (Lahsen, 1976a,b). Thermal manifestations develop in the hanging wall of a NS trending half-graben (Fig. 1a), that is filled with ~1000 m of sub-horizontal ignimbrites, tuffs and lavas, and covered by Holocene alluvial and glacial deposits (Healy, 1974; Lahsen and Trujillo, 1975). According to the distribution of the geothermal features, the field is divided into a Lower, Middle and Upper Basin (Glennon and Pfaff, 2003) (Fig. 1a). Data from geothermal wells suggest that the permeability is dominated by open fractures in the ignimbrite layers (Cusicanqui et al., 1975, 1976). The maximum temperature measured at the bottom of a 600 m deep geothermal well was 253 °C (Lahsen and Trujillo, 1976).

At El Tatio in October 2012, we measured the average daily air temperature and pressure, which vary between approximately −5 °C to 20 °C and $6.07 \times 10^4$ to $6.10 \times 10^4$ Pa, respectively. The boiling temperature ($T_{boil}$) of pure water at these air pressures ranges between 86.2 and 86.4

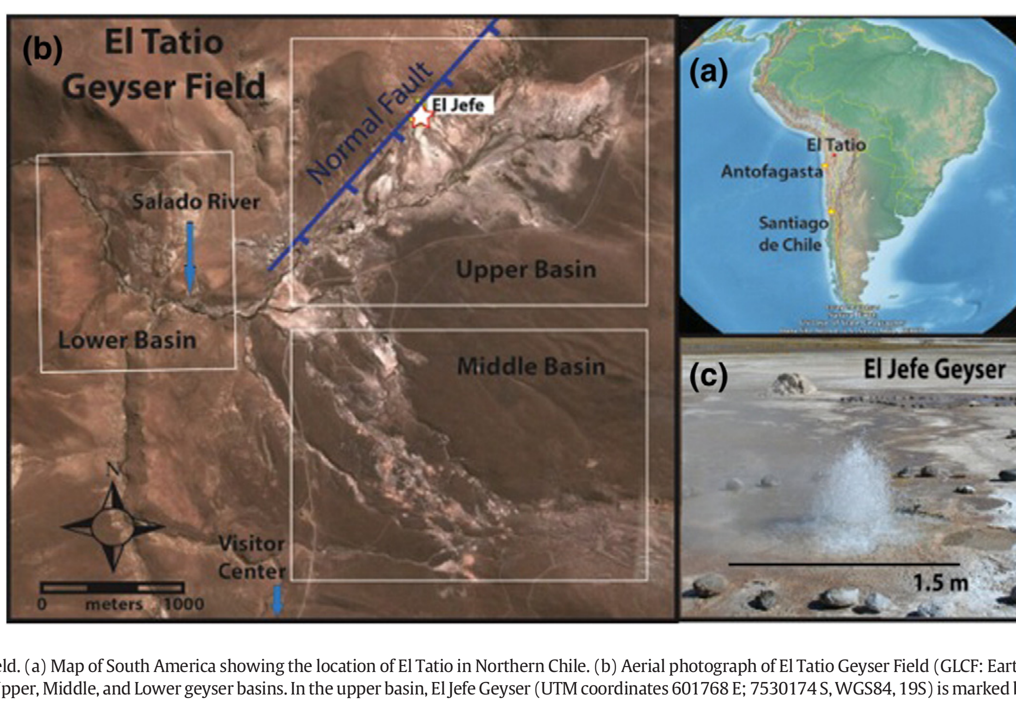


**Fig. 1.** El Tatio geyser field. (a) Map of South America showing the location of El Tatio in Northern Chile. (b) Aerial photograph of El Tatio Geyser Field (GLCF: Earth Science Data Interface); white boxes show the Upper, Middle, and Lower geyser basins. In the upper basin, El Jefe Geyser (UTM coordinates 601768 E; 7530174 S, WGS84, 19S) is marked by the white star. The blue line indicates the normal fault that bounds the El Tatio half-graben. El Jefe geyser is located in the hanging wall of that fault. (c) El Jefe geyser erupting.