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Controls on the geomorphic expression and evolution of gryphons, pools, and caldera features at hydrothermal seeps in the Salton Sea Geothermal Field, southern California

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ABSTRACT

In the Salton Sea Geothermal Field in southern California, expulsion of gas, sediment and water creates unique geomorphic features similar to those seen on the surface of dormant mud volcanoes. These include pools of water or highly fluid mud named "mud pots" and 0.5 to 2.5 m-tall gryphons. The features vary in size, shape, and type of eruptive activity and change form over time. To evaluate controls on the surface morphology and evolution of these features we used repeated differential GPS surveys, observations of eruptive activity, and measurements of erupted mud properties to document the physical characteristics and changes in the system over a 28-month period.

We find that the morphology of the gryphons is primarily a function of the mud expulsion style. Taller (1.5 m to 2.4 m) gryphons form where narrower vents (5 cm to 15 cm diameter) expel mud to the surface in discrete Strombolian-type eruptions caused by individual gas bubbles pushing mud up through the gryphon conduit and exploding at the surface. Smaller (0.6 m to 1.5 m) gryphons form where wider vents allow a greater amount of gas to pass through, which creates 0.25 to 1 m diameter mud craters that bubble continuously, often from multiple points within the crater. Although viscous mud is required to create these positive topographic features, variations in erupted mud temperature (30 °C to 68.5 °C), density (1.44 g/cm^3 to 1.59 g/cm^3), and water content (36% to 44%) between different gryphons did not correlate with gryphon size. All the active gryphons experienced periods of growth and erosion over the study period due to changes in the degree of activity or small variations in the vent locations within the gryphons, but the net change in height distributions over time was negligible.

Pools directly adjacent to gryphon clusters are surficial features whose water level depends on seasonal rainfall and temperature. Isolated pools are also present and do not show similar response to seasonal changes, suggesting that these pools are connected to the local groundwater system. Although changes in vent morphology and activity do occur, the new data demonstrate that the system is steady-state in terms of the height distribution of the gryphons, and the location of the main seeps. Most of the gryphons occur in clusters that are surrounded by caldera-like depressions that range from 10 to 25 m in diameter. Mud expelled from the gryphons is largely contained within the caldera depressions, and we infer that subsidence of the calderas accounts for the lack of large-scale build-up of material in the surrounding area. This study provides the first examination of the processes controlling the morphology of these features and the results may help to understand the dynamics and temporal evolution of gryphons, which are found in both hydrothermal systems and on dormant mud volcanoes.

1. Introduction

1.1. Regional setting

The Salton Sea Geothermal Field (SSGF) is an area of high heat flow located in a transtensional sedimentary basin between the southern extent of the San Andreas Fault and the northern end of the Gulf of California rift (Fig. 1). The basin is filled with clastic sediments derived from the Colorado River, lacustrine sediments, and minor amounts of evaporites (Muffler and White, 1969). Magmatic intrusions at depth produce anomalous heat with average heat flow values of more than 100 mW/m^2 (Lachenbruch et al., 1985) and temperatures of 350 °C at depths below 1500 m (Helgeson, 1968). The magmatic intrusions are inferred to be rhyolite and basalt based on pieces recovered in deep wells and the occurrence of five Quaternary rhyolite domes at the surface that contain basaltic xenoliths (Robinson et al., 1976 and

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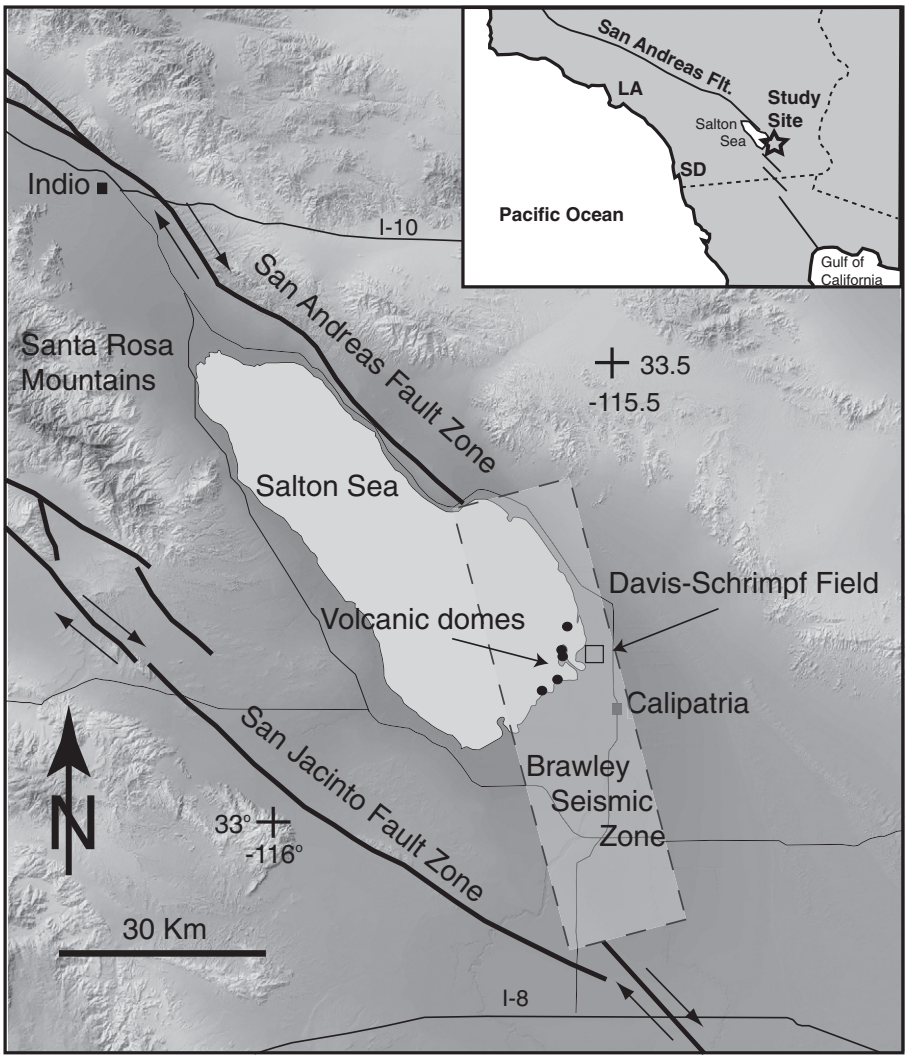

Fig. 1. Map of the Salton Sea area showing the location of major faults, the Salton Sea, and the Davis–Schrimpf field plotted on a 30 m DEM. Inset map shows location of the study area within southern California.

references therein). Contact metamorphism of the clastic sediments around these intrusions produces CO_2 gas that leaks out at the surface and creates hydrothermal seeps in the SSGF (Muffler and White, 1968, 1969). Smaller amounts of CH_4 are also present and some of the seeps contain minor amounts of hydrocarbons, most likely due to interaction with organic sediments at depth (Svensen et al., 2007). Most of the hydrothermal seeps occur at the southeastern edge of the Salton Sea both onshore and offshore. Offshore seeps have been mainly identified by gas eruptions in shallow water (Muffler and White, 1968; Lynch and Hudnut, 2008). Onshore seeps often interact with shallow water and sediments that become remobilized and create a geomorphic expression at the surface. Two types of geomorphic features form at these onshore seeps; small (0.5 m to 10 m diameter) circular pools filled with muddy water that are informally called "mud pots" and (0.5 m to 2.5 m tall) conical volcano-like structures (gryphons) formed by eruption of highly viscous mud from the top of the structure (Fig. 2: Ives, 1951; Sturz et al., 1992). The later are almost identical to the small structures that commonly form in the craters of larger mud volcanoes during dormant periods (e.g., Hovland et al., 1997; Planke et al., 2003; Mazzini et al., 2009a). The earliest records of seep activity in the SSGF are historical accounts from the 1850s and 1860s (Le Conte, 1855; Veatch, 1860) that describe large gryphons (up to 5 m high), salses, and eruptions of steam and mud. Present day activity is not as violent as described in these accounts, but does not differ significantly in terms of type of activity and morphological structures. These early accounts show that the seep activity has been occurring for at least 150 years.

1.2. Seep features in the Davis–Schrimpf field

The highest concentration of onshore seeps in the SSGF occurs at the intersection of Davis Road and Schrimpf Road near the southeast shore of the Salton Sea (Fig. 1), where more than 100 pools, gryphons, and gas vents are present in a 10,000 m^2 area (Fig. 3). This seep field exhibits consistent activity throughout the year (Muffler and White, 1968; Sturz et al., 1992) and is where the majority of the gryphons within the SSGF field are found. The Davis–Schrimpf field lies at the northeast edge of a large temperature anomaly in the shallow subsurface within the SSGF where thermal gradients drop from 0.8 °C/m at the peak of the anomaly to 0.1 °C/m over a distance of less than 4 km (Newark et al., 1988). This linear gradient also corresponds with the position of the Calipatria fault and a lineament of scattered vent features that extends to the northwest into the Salton Sea (Lynch and Hudnut, 2008). Recent lowering of the Salton Sea water level has exposed several new clusters of vent features and these all line up along the inferred surface trace of the Calipatria fault (David Lynch, personal communication, 2010). It has been postulated that the spatial distribution of vents in the SSGF, is controlled by strands of the