

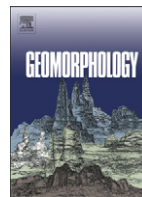


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# Controls on the geomorphic expression and evolution of gryphons, pools, and caldera features at hydrothermal seeps in the Salton Sea Geothermal Field, southern California

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## ARTICLE INFO

### Article history:

Received 23 November 2010

Received in revised form 13 April 2011

Accepted 17 April 2011

Available online 22 April 2011

### Keywords:

Mud volcanoes

Gryphons

Mud Pots

Salton Sea

Seeps

Hydrothermal vent

## 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<sup>3</sup> to 1.59 g/cm<sup>3</sup>), 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.

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## 1. Introduction

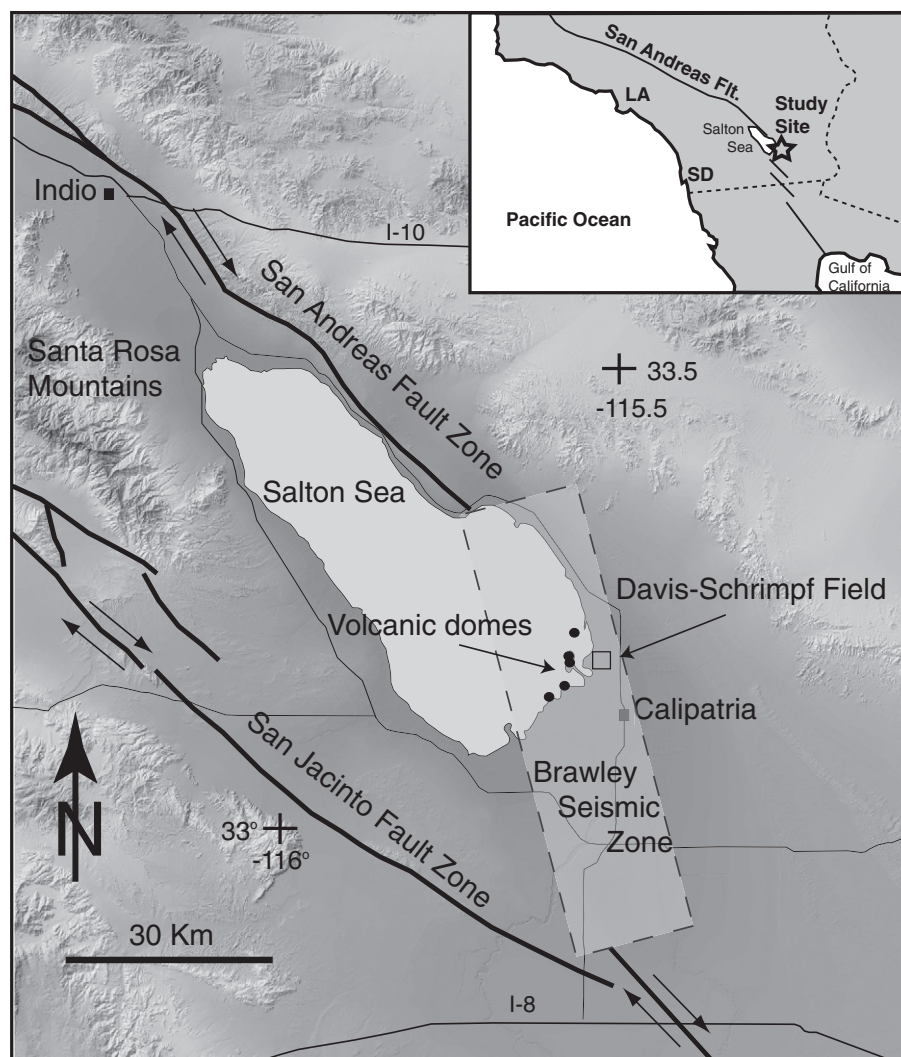
### 1.1. Regional setting

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<sup>2</sup> (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  $\text{CO}_2$  gas that leaks out at the surface and creates hydrothermal seeps in the SSGF (Muffler and White, 1968, 1969). Smaller amounts of  $\text{CH}_4$  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  $10,000 \text{ m}^2$  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  $0.8 \text{ }^\circ\text{C/m}$  at the peak of the anomaly to  $0.1 \text{ }^\circ\text{C/m}$  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



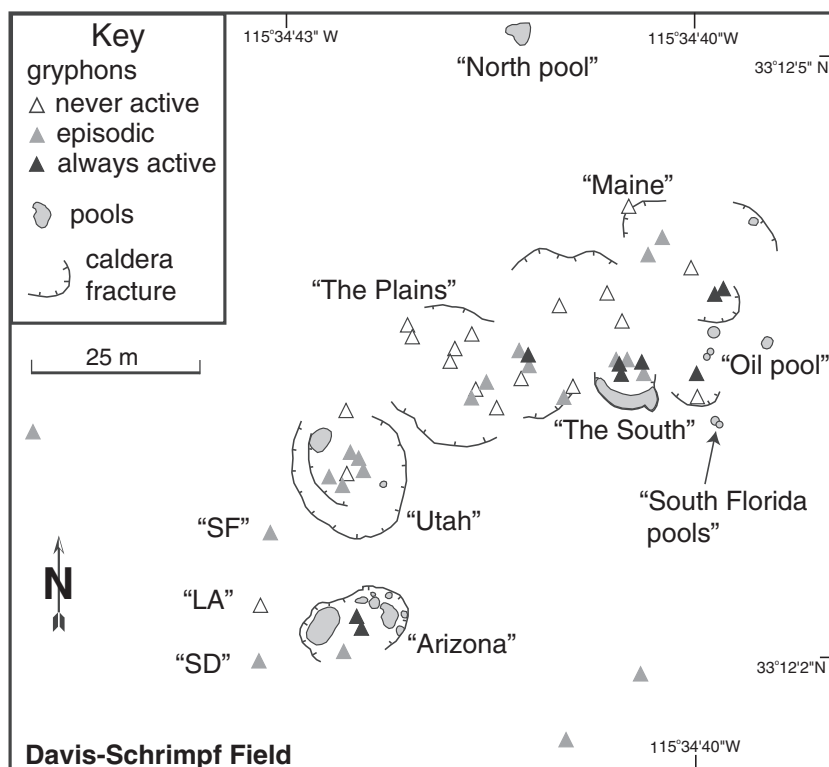
**Fig. 2.** Gryphons and pools within the Salton Sea Geothermal Field. Note gas bubbles in foreground pool. Approximately 2 m-tall person for scale.

southern San Andreas Fault zone (including the Calipatria fault) and/or subsurface stratigraphy in the area that focuses the gas and directs it to the surface (e.g., Rook and Williams, 1942; Lynch and Hudnut, 2008). However, the reason for the anomalously high concentration of vents in a few specific locations along these faults has not been determined.

Most of the gryphons in the Davis–Schrimpf field occur in clusters that are surrounded by caldera-like ring faults (Svensen et al., 2007) that drop the gryphon clusters down (with offsets of 1 to 10 cm) relative to the surrounding field. These calderas also contain pools of muddy water with gas vents bubbling through them. The pools vary in density (Svensen et al., 2007) and size, and have water levels that fluctuate over the year (this study). Smaller isolated gryphons and pools are also found scattered around the area that are not associated

with a caldera depression. The surrounding topography of the field is flat with no regional build-up of material or subsidence.

The gryphons in the Davis–Schrimpf field vary in size, mud expulsion style, and temperature. They currently range from 0.5 m to 2.5 m in height and previous observations indicate that this size distribution has not changed since the 1980s (e.g., Sturz et al., 1992, 1997). Some are actively spewing mud from their vents in periodic Strombolian-type eruptions, some have craters at the top that contain small mud lakes that bubble and sometimes spill over the rim of the craters, and some emit only gas or are not active at all. The bubbling mud often spills out of the top of the active gryphons and flows down the sides. The expelled mud is primarily composed of smectite clay (45–70% smectite, 20–35% illite, and 10–20% kaolinite: Sturz et al., 1992) that has significantly higher concentrations of smectite than the



**Fig. 3.** Map of the Davis–Schrimpf field showing seep features and caldera ring fractures. Features mentioned in the text are labeled. SF = “San Francisco” gryphon, LA = “Los Angeles” gryphon, SD = “San Diego” gryphon.

soil that comprises the surrounding field, which is dominated by mica-like clay (Sturz et al., 1997). There is an associated color difference; with the erupted mud being a darker gray and the surface soil a lighter red. Continuous temperature monitoring of the gryphons (Svensen et al., 2009) showed that the temperature of the mud varies temporally and spatially across the field (from 40 °C to 70 °C).

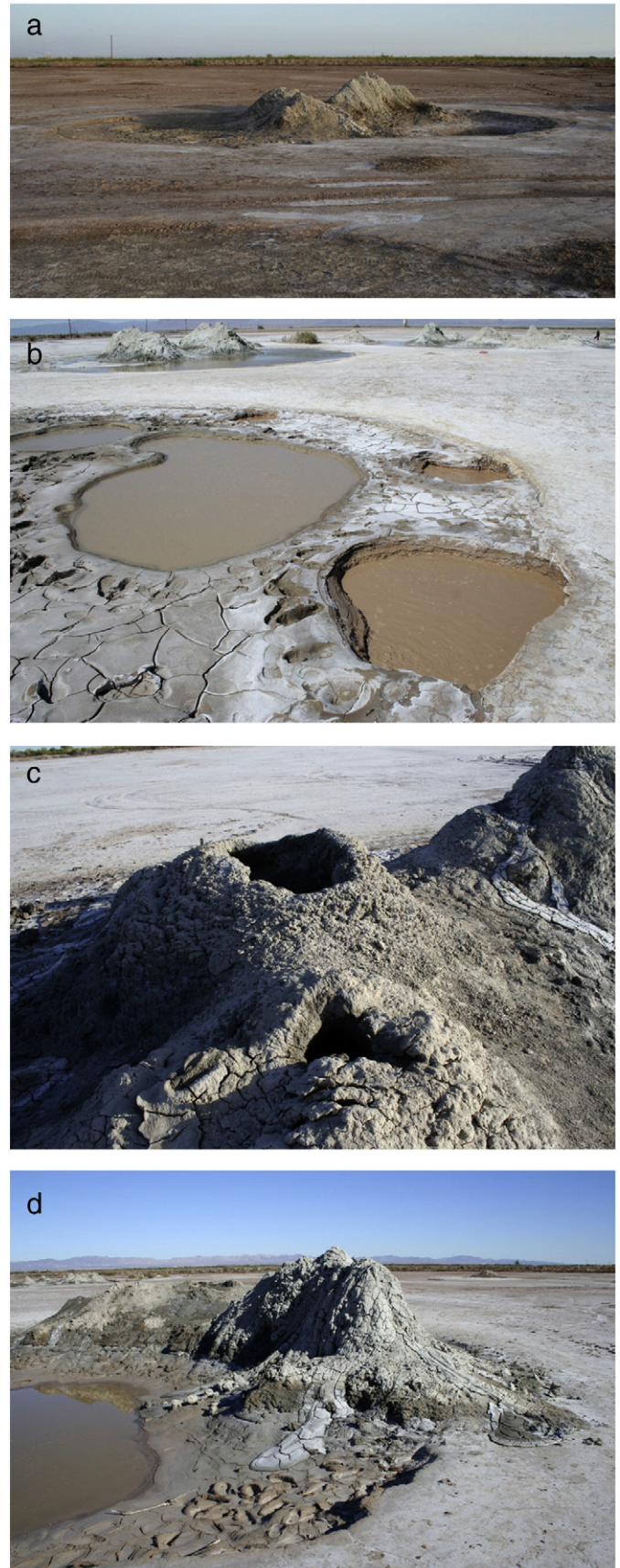
The pools in the Davis–Schrimpf field currently vary from a few 10s of centimeters in diameter to more than 3 m across (Fig. 4). Depths are hard to determine due to the density of the muddy water and the uneven bottoms, but exceed 2 m in many places. Fluid densities range from 1 g/cm<sup>3</sup> to 1.4 g/cm<sup>3</sup> and chemical analysis shows a range of solute concentrations that suggest *in situ* evaporation (Svensen et al., 2007) or possibly mixing between shallow and deeper waters (Sturz et al., 1992). The temperatures of the pools fluctuate with air temperature and are cooler (15 °C to 35 °C) than the gryphon mud (Svensen et al., 2009). Both the gryphons and pools occur where gas is being expelled, and isotopic analyses of these gases indicate a thermogenic origin (Svensen et al., 2007). The expelled gases drive the mud eruptions in the gryphons and create bubbles in the viscous mud that explode and spatter mud or erupt small flows down the sides. The low viscosity of the muddy water in the pools allows the gas bubbles to easily move up through the water where constant bubbling can be seen above the active vents.

These constantly active seeps are some of the most-visited geologic features in southern California and receive attention almost daily from tourists and geology classes from all over the country. In addition to being popular geologic curiosities, they provide an opportunity to study geomorphic features that can develop at hydrothermal seeps. Despite the large amount of data regarding the geothermal aspects of the SSGF the controls on the surface morphology and evolution of these features have not been systematically investigated. In addition, numerous studies have described the morphology of gryphons from both dormant mud volcanoes and other environments (i.e., Hovland et al., 1997; Dimitrov, 2002; Bonini, 2009; Mazzini et al., 2009a), but none of these studies have monitored the temporal evolution and variations in morphology and activity of a group of gryphons. Here we present the results of a 28-month study using repeated differential GPS surveys, observations of seep activity throughout the year, and measurements of the physical characteristics of the expelled material. The goal of this study was to describe and monitor the morphology and activity in order to gain a better understanding of the processes controlling the geomorphic evolution of these features. Specific questions included:

1. What dictates the variable heights of the gryphons; their age; physical properties of the mud; and degree of eruptive activity?
2. What is the average growth/erosion rate of the gryphons collectively? Are they increasing, decreasing, or unchanging in height over time?
3. Why is there no large-scale build-up of material in the area if these gryphons are constantly delivering mud to the surface?
4. What is the cause of the caldera-like depressions that contain most of the pools and gryphons? Are the calderas actively subsiding? And is there a direct relationship between caldera subsidence and gryphon growth?
5. What controls the variable water levels in the pools and how do these change over time?
6. How stable are the positions of the seeps over time and what can this tell us about the subsurface geometry of the system?

## 2. Methods

Differential GPS was used to map the features in the field, monitor gryphon heights, pool levels, outlines of pools and calderas, and cross-sections across some features. The vent features were surveyed 7 times over a 28-month period with a Trimble 5800 system. A reference mark



**Fig. 4.** a. Gryphon cluster with caldera ("Arizona"—viewed from the North), b. pools (East side of "Arizona" caldera), c. two adjacent "always active" gryphons (note large open craters), d. 2 m-high "episodic gryphons" with lower "always active" gryphons in the back left.

was made on a metal power-line anchor along the road adjacent to the field and the base station was established at a set height over this mark. This allowed us to re-occupy the exact base station position for each of the following surveys. The local base reference enabled increased accuracy, which we calculated to be  $\pm 2$  cm vertical and less than 1 cm horizontal, based on repeated surveys of control points established on the flat, undisturbed parts of the field well away from any active erosion or deposition. All the heights, changes in heights, and growth rates presented in this paper are thus accompanied by an error of  $\pm 2$  cm. Each vent feature was named to aid in recognition and mapping, and repeat observations of activity type of each feature were recorded during the surveys (see Supplemental Data). Data from the surveys were then compared to calculate growth or erosion of gryphons during different time periods, document changes in activity throughout the study period, calculate changes in water levels within the pools, identify new features forming during the study period, and detect growth of the pools or caldera features.

Physical characteristics of the actively erupting mud were also measured during some surveys. Temperature was measured *in situ* using a Traceable ISO 17025 calibrated digital probe thermometer inserted into the bubbling mud in the craters. Density of the erupting mud was measured in the field using an electronic scale and volume measurements of samples immediately after the mud was scooped out of the active gryphons. Samples were also collected and used to measure water content (percent weight) by weighing erupted mud samples in the field and then drying them in the lab for several days and re-weighing them. Soil samples were collected from within caldera structures as well as outside and at various depths (ranging from 5 to 50 cm) to make qualitative comparisons of soil type.

### 3. Results

#### 3.1. Gryphons

The size, growth, and activity level of the gryphons vary within the Davis–Schrimpf field. At the beginning of the study period, the gryphons ranged from 0.7 m to 2.19 m in height with a mean of 1.49 m (Table 1). At the end of the study period the data show a range of 0.6 m to 2.4 m with a mean of 1.38 m, indicating that there was little net change in the distribution of gryphon heights over the 28-month period. The volumes of individual gryphons are not as easy to measure since most of the gryphons occur in clusters or ridges where multiple gryphons overlap and share a common base. Some of the larger individual isolated gryphons, such as “San Francisco” and “Los Angeles”, have volumes of roughly 30 m<sup>3</sup> whereas the “Arizona” gryphon cluster (Fig. 3) has a volume of about 65 m<sup>3</sup>.

Repeated differential GPS surveys show that there is no consistent pattern of growth or erosion of the gryphons in the Davis–Schrimpf field. Some of the gryphons grew between surveys, some showed no measurable change in height, and some were eroded (Table 1).

The largest growth observed at any one gryphon was 0.78 m between surveys and 0.55 m over the entire study period. The maximum amount of erosion was  $-0.59$  m between successive surveys and  $-0.98$  m over the study period. Most of the gryphons experienced growth during some intervals and erosion during others. Some of the inactive gryphons showed consistent erosion between each survey, but none of the gryphons showed consistent growth between surveys. There was also no consistent pattern of growth or erosion among the population as a whole and no detectable correlation of changes with the seasons or rainfall amounts (Table 1). The average amount of change observed over the full 28-month study period was 24 cm and the change in mean elevation of the gryphons was a decrease of 11 cm. This shows that the net change in gryphon heights in the field is not dramatic and the gryphons as a group are not growing over time.

Observations of activity type at each survey show a range of mud expulsion styles that varied between gryphons. After the first few surveys, it was clear that not all the gryphons behave the same and they were divided into three groups based on their activity observed at the survey times throughout the year. Some gryphons are “always active”, some are “episodically active”, and others are “never active”. Although it is impossible to determine if the gryphons we assigned to the various designations are truly “always active” or “never active” without monitoring them daily, certain aspects of their morphology, eruption style, and evidence of recent eruptions recorded by dried mudflows support these divisions. Mud is brought to the surface by the upward force of rising gas bubbles and mud expulsion does not occur without gas expulsion. The “always active” gryphons are characterized by wider vents that have a greater gas flux, which can be seen as constant bubbling (often from multiple points) in small open craters (typically 0.4 m to 1 m in diameter) filled with mud at the top of the gryphon (Fig. 4c). Gas flux was not measured quantitatively and is only inferred qualitatively based on the frequency and size of gas bubbles exploding at the surface of the mud lakes in the open craters. The “episodically active” gryphons, when active, typically expel mud and gas as discrete bursts or pulses of mud separated by a few seconds or minutes from smaller diameter (approximately 5 cm to 15 cm) vents that do not contain craters at the top (Fig. 4d). The timing between eruptive bursts is determined by the frequency of discrete gas bubbles moving up through a single conduit in the gryphon, which can be observed by looking down into the vent between eruptions. The conduits are roughly the same size as the vent in the upper meter that can be observed. However, we were unable to directly measure the diameter of the conduits and have no data regarding the deeper plumbing of the gryphons. Eruptive episodes at the “episodically active” gryphons typically last minutes to hours. These Strombolian-type eruptions result in deposition of mud at the top of the gryphon where it is splattered, or spilled over the side by the bursting bubble.

An examination of the morphology of flows that have erupted over the side of the gryphons can give a qualitative indication of the activity over the past few weeks or months. The mudflows that are deposited on the flanks of the gryphons quickly dry and crack in the desert environment. The mud then becomes hard and relatively resistant to light rain and/or wind until the hardened flows gradually break up, lose their preserved flow structures, and degrade into more uniform silt and clay. The process by which these flows gradually break down was not investigated, nor was any attempt made to quantify the rate at which recent flows degrade. However, we infer that this process takes at least several months based on the observation that actively erupting flows observed during one survey period could easily be identified and still largely intact months later. Fig. 5 shows an example of previously expelled, solidified flows observed approximately one month apart with minimal changes. Only the flanks of gryphons that have not been active for at least a year begin to lose their flow structures as the mud weathers into more uniform topography and structure.

Growth of the gryphons is solely the result of mud expulsion, which adds material to the top and sides of the structures. The erosional processes active in the field are not as clear. None of the gryphons exhibited any morphology indicative of erosion by rain or water flow down the sides (such as rills or small gulleys) at the times of the surveys. However none of our survey dates occurred immediately after large storm events. It is reasonable to assume that heavy rainfall would contribute to gryphon erosion, although heavy or prolonged rainfall is rare in this desert environment where the maximum monthly rainfall average is about 1.3 cm. Comparison of changes in gryphon heights with the measured rainfall between survey periods (Table 1, Fig. 6) shows no indication that the gryphons were eroded more after wet periods than dry. Some of the highest average erosion rates between surveys among the inactive gryphons





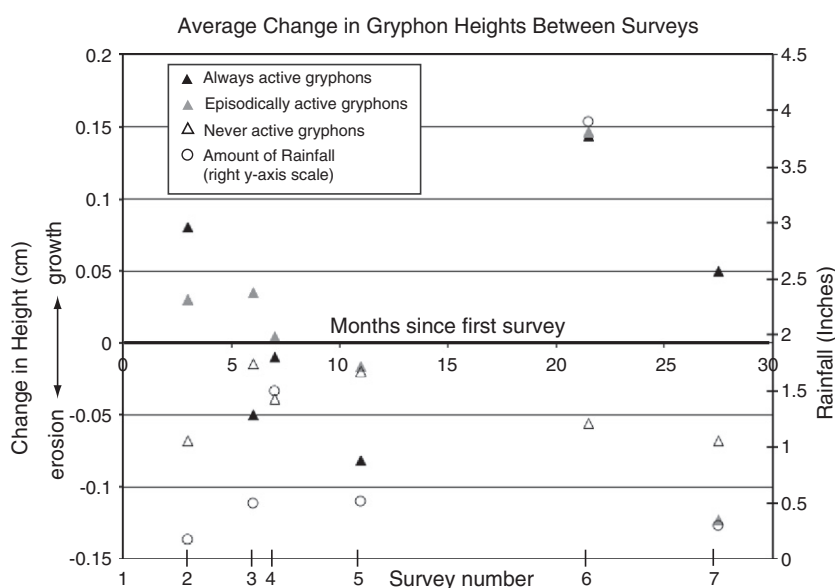
**Fig. 5.** Pictures of previously erupted flows on “The Plains East Ridge North Gryphon” approximately one month apart. Note that the morphology has not changed and there are no observable signs of erosion or degradation.

were during the driest periods (Table 1), suggesting that the small amount rainfall is not the main factor in gryphon erosion over a time scale of a year or two. However, gryphons that are eroded at their bases when the pools fill to a level where the water begins to soak and mobilize mud from the sides of the gryphons. This often results in very steep (vertical in some places) gryphon sides and can cause some gryphons to split apart as the sides begin to calve off. Wind most likely contributes to the erosion, since the mud can be blown away after it degrades into dry, loose particles, although this would only affect gryphons that have been inactive long enough for older flows to degrade into loose material. Visitors to the field also contribute to eroding the gryphons as they climb and walk on some of the more easily accessible features. The amount of erosion due to human interference is impossible to estimate without continuous observations. As a result, all the growth observed in the field must be regarded as a minimum and the degradation assumed to be a maximum erosion amount.

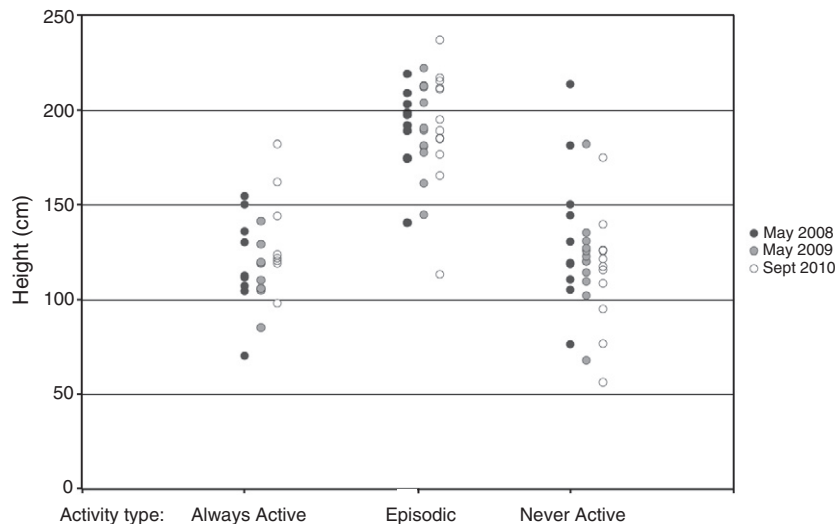
Comparison of dGPS data with observations of activity indicates that the heights and growth or erosion of the individual gryphons are

related to their activity type. Fig. 7 shows that the “episodically active” gryphons are about 75 cm taller on average than the “always active” gryphons. In addition, the average growth and maximum growth of the “episodically active” gryphons exceed that of the “always active” gryphons (Table 1). The “never active” gryphons span a range of heights, but show a consistent decrease in average height over the study period. These gryphons may have been active previously and have shut off, or are episodically active on a longer time scale than two years and were eroding during the study period. None of the inactive gryphons grew during the survey period and the erosion rates were highest in this group (Fig. 7, Table 1).

Density measurements of mud from selected gryphons ranged from 1.44 g/cm<sup>3</sup> to 1.59 g/cm<sup>3</sup> and water content varied from 36% to 44% (percent weight). Both these values changed slightly throughout the year with water content higher and density lower during wetter periods (Table 2). Temperatures of the mud were previously monitored continuously for a 2-year period and shown to fluctuate by as much as 30 °C with no detectable patterns (Svensen et al., 2009). Discrete measurements of temperature during this study show



**Fig. 6.** Plot of average change in gryphon heights between surveys. The left vertical axis is the average growth or erosion since the previous survey (plotted as triangles), while the right vertical axis provides a scale for the amount of rainfall since the previous survey (plotted as circles). Horizontal axis is the time since the first survey in months. Note that the growth or erosion of gryphons does not correlate with the amount of rainfall.



**Fig. 7.** Gryphon heights at three different times (start of study, after one year, end of study) vs. activity type observed during the study period.

fluctuations of more than 10 °C over the year in some gryphons, as well as differences of more than 20 °C between vents across the field (Table 2). Although the water content, temperature, and density of the mud vary across the field, comparison of these characteristics with gryphon heights showed no correlation (Fig. 8).

### 3.2. Pools

Differential GPS surveying of pool levels within the field shows that not all the pools behave the same. The pools that are present within the caldera depressions fill up in the winter months after rain events, and have low water levels in the dryer summer and fall months as they dry out in the desert environment (Table 3, Fig. 9). In the wetter months, it is not uncommon for these pools to overtop their edges and combine to fill the entire caldera depression. About half of the pools within the Davis–Schimpf field fall into this category. Fig. 9 shows that during the wetter months, all these pools (left side of graph) fill to approximately the same elevation, but during the dryer months, their water levels differ due to the differences in depth of the pools. The limited amount of rain that falls in the desert environment is not sufficient to fill the pools to the observed levels if the rain is collected solely from the area of the pools. This suggests that some of the water in the pools is derived from the surrounding area either as overland flow or shallow subsurface flow through the soil. The other

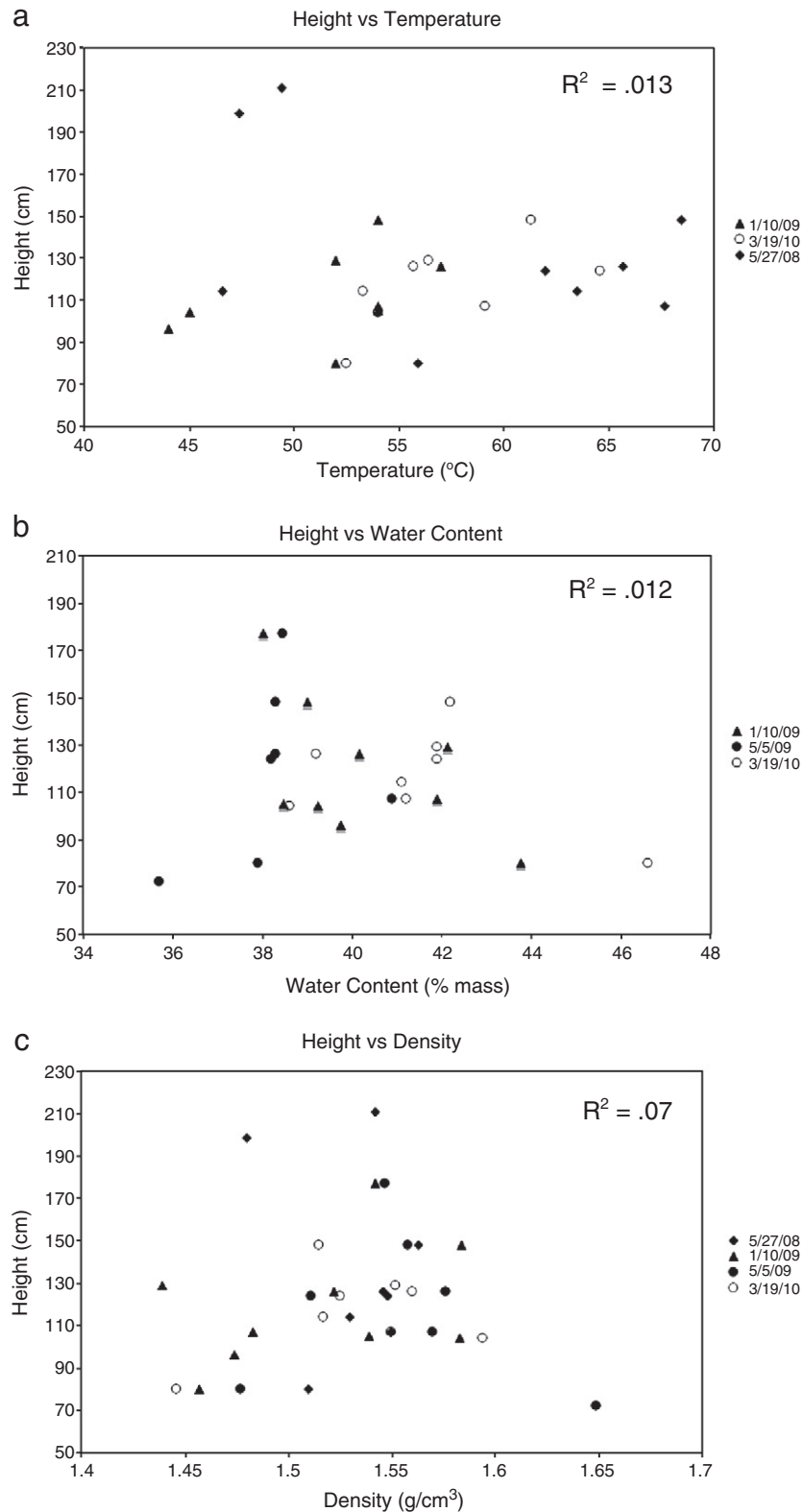
pools present in the field are isolated (not associated with a gryphon cluster) and do not show systematic variations with the seasons. These are plotted on the right half of Fig. 9 and can sometimes have higher water levels in dry months than in the wet months. The “North Pool” in particular shows an average drying trend over the 28-month study period (Table 3), roughly following the decreasing elevation of the nearby Salton Sea (less than 0.5 km away) recorded by the Imperial Irrigation District (M. Kidwell, Personal Communication, August 2010).

The pool levels across the field vary and it is common to see large differences in elevation between pools that are very close together, or in the same gryphon cluster. For example, the South Florida pools are never at the same level and differ by as much as 30 cm (Table 2, Fig. 9) despite the fact that these two pools are only a meter apart. The same relationship is true for the North Florida pools, which are less than 50 cm away from each other. Pools that are present within the calderas exhibit the same behavior. This observation indicates that there is little or no connectivity between the individual seeps at shallow depths.

Repeated observations and surveys of pool outlines show that some of the pools grew outward over time, and a few new pools developed during the study period (Fig. 10). Most of the new pools that developed were situated at the edge of a caldera ring fracture, and all the new pools observed were located within the caldera

**Table 2**  
Physical properties of gryphon mud measured during each survey.

Feature name	Temperature (°C)			Density (g/cm <sup>3</sup> )				Water content (% weight)		
	5/27/08	1/10/09	3/19/10	5/27/08	1/10/09	5/5/09	3/19/10	1/10/09	5/5/09	3/19/10
San Diego	49.4			1.542						
AZ East Ridge North Cone		52	56.4		1.439		1.552	42.13		41.9
AZ east Ridge South Cone	65.7	57	55.7	1.546	1.522	1.576	1.56	40.17	38.3	39.2
Utah North gryphon	46.6									
Utah NE ridge North Cone	47.4			1.48						
Utah NE ridge new far south gryphon						1.649			35.7	
Utah SW Ridge S Middle Peak		30			1.542	1.547		38.02	38.45	
Plains E ridge 2nd N peak	67.7	54	59.1	1.55	1.483	1.57	1.55	41.9	40.9	41.2
Plains E ridge 2nd S peak	63.5		53.3	1.53			1.517			41.1
The south W ridge S chamber	62		64.6	1.548		1.511	1.525		38.2	41.9
The south E ridge	68.5	54	61.3	1.563	1.584	1.558	1.515	39	38.3	42.2
NYC west			45	54	1.583		1.594	39.24		38.6
NYC east		54			1.539			38.47		
Florida main chamber	55.9	52	52.5	1.51	1.457	1.477	1.446	43.76	37.9	46.6
Key West		44			1.474			39.74		



**Fig. 8.** Graphs showing no correlation between gryphon heights and (a) temperature, (b) water content, or (c) density of the actively erupting mud. Note that the inactive gryphons were not included due to the lack of erupting mud.

depressions. These pools start as small bubbling gas vents and expand during wet periods as the mud around the edges becomes saturated, disturbed by gas bubbles and compacts. The muddy water that fills the pools within the calderas varies in color depending on the location and reflects the distribution of erupted mud within the calderas. The

pools closer to the central gryphon cluster in the “Arizona” caldera tend to be darker in color as the water is mixed with the gryphon mud brought up from deeper levels, whereas the pools located at the outer edge of the caldera depression are red in color due to dissolved surface mud present on the outside of the caldera ring fracture (see Fig. 4b).

**Table 3**  
Pool levels measured during each survey.

Feature name	5/27/08		9/5/08		12/10/08		1/10/09		5/5/09		3/19/10		9/13/10		Labels
	Elevation	Change	Elevation	Change	Elevation	Change	Elevation	Change	Elevation	Change	Elevation	Change	Elevation	Change	
Arizona big west pool	–69.62	–0.078	–69.698	–69.14	–68.847	0.558	–68.847	0.293	–69.312	–0.465	–68.774	0.538	–69.99	–1.216	AZ1
Arizona biggest east pool	–69.358	–0.207	–69.565	–69.273	–68.884	0.292	–68.884	0.389	–69.434	–0.55	–68.813	0.621	–69.649	–0.836	AZ2
Utah pool	–69.66	–0.052	–69.712	–69.576	–68.811	0.136	–68.811	0.765	–69.382	–0.571	–68.782	0.6	–69.925	–1.143	U
Plains middle depression/pool	–69.053	–0.026	–69.079	–68.901	–68.783	0.178	–68.783	0.118	–69.112	–0.329	–68.783	0.361	–69.132	–0.5	P
The South big pool on S side	–69.06	–0.28	–69.34	–69.034	–68.795	0.306	–68.795	0.239	–69.144	–0.349	–68.783	0.361	–69.283	–0.612	S1
The South pool on SE side	–69.08	–0.221	–69.301	–69.078	–68.791	0.223	–68.791	0.287	–69.225	–0.434	–68.783	1.361	–69.395	–0.612	S2
Oil pool	–69.169	–0.123	–69.292	–69.22	–69.064	0.072	–69.064	0.156	–69.386	–0.322	–69.099	0.287	Dry		O
North pool	–69.506	0.14	–69.366	–69.712	–69.851	–0.346	–69.851	–0.139	–69.65	0.201	–69.765	–0.115	–69.83	–0.065	Nrth
S NYC pool south			–68.765	–69.076	–68.937	0.139	–68.937	0.139			–68.88	0.536	–69.383	–0.503	NYC
Nantucket Pool			–68.751	–69.319	–69.154	–0.554	–69.154	0.165			–68.971				Nan
N Florida pools N pool		–0.471	–69.222	–69.145	–69.032	0.077	–69.032	0.113			–68.863		Dry		NF1
N Florida pools S pool		–0.096	–68.993		–69.115		–69.115				–68.947	0.362	Dry		NF2
S Florida pools E pool	–69.427	0.135	–69.292	–69.246	–69.354	0.046	–69.354	–0.108			–69.429		Dry		SF1
S Florida pools W pool	–69.231	–0.199	–69.43	–69.038	–69.199	0.392	–69.199	–0.161			–69.17		Dry		SF2
Salton Sea lake levels	–69.46	–0.22	–69.68	–69.85	–69.79	–0.17	–69.79	0.06			–69.881	–0.234	Dry		
Rainfall since last measurement		.17 in.			1.5 in.				.51 in.		3.9 in. (prev. 4 mo.)			0.3 all in late March	

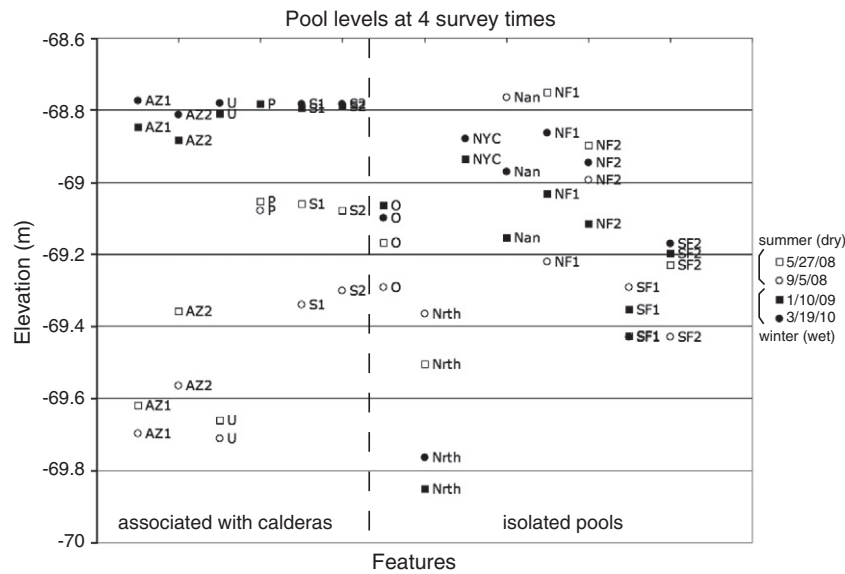
### 3.3. Caldera depressions

The caldera depressions within the Davis–Schrimpf field occur only around gryphon clusters and are not found surrounding the few isolated gryphons or pools (Fig. 3). Repeated differential GPS transects across two of the larger caldera structures and dense surveying of the “Arizona” caldera were done to characterize the morphology of these features and to look for evidence of active subsidence. Comparison of transects done one year apart shows subsidence of 3 cm to 7 cm within the “Utah” caldera, while no observable change was seen at the “Arizona” caldera (Fig. 11). However, the amount of subsidence documented by the transect data may be underestimated if additional material has been deposited within the caldera depressions between surveys. Shallow soil pits excavated within and outside the caldera structures show that some of the material erupted from the gryphons is eventually distributed throughout the caldera depressions, most likely by saturation of the gryphon sides by water in the wet months. The red oxidized silty clay soil that is found at the surface throughout the study area is markedly different in color than the darker mud erupted from the gryphons. It is therefore possible to see where the expelled mud has been deposited. Shallow soil pits (0.5 m deep) within the “Utah” and “Arizona” caldera depressions showed that the darker gray mud is more than 0.5 m thick close to the gryphons, whereas only a thin layer (2 cm to 10 cm) of darker mud is present overlying red soil towards the outer edges of the depressions. The darker mud was not present in shallow pits outside the calderas. When the caldera depressions are filled with water during the wetter months, the darker mud erupted from the gryphons is most likely spread out within the depressions. In order to accurately measure the amount of subsidence between surveys, the volume and distribution of new material added would need to be measured, and hence, we regard the subsidence documented by our data to be a minimum amount.

To document the morphology of the caldera structures, a dense dGPS survey consisting of approximately 850 points was undertaken at the “Arizona” caldera and used to construct a Digital Elevation Model (Fig. 10). This data was also analyzed using GIS software (ESRI ArcMap) to evaluate the degree to which the positive volume of the gryphon cluster is compensated by subsidence through comparison of the volume of the gryphon cluster to the negative volume of the caldera depression. A reference plane was first established by fitting a plane to the surface elevations outside the caldera ring fault. This plane was extrapolated through the caldera and gryphon cluster complex and used to calculate positive volume (gryphons) above the plane, and negative volume (caldera depression) below the plane. The negative and positive volumes are roughly equal *only* when the negative volume of the pools within the caldera depression is not included. This omission of the pools is appropriate if they are assumed to develop due to compaction of the surface soil and not due to evacuation of material from beneath. This assumption was not fully evaluated, but the observation that the pools present within the field, and elsewhere in the SSGF, are negative topographic features with no corresponding positive mass, suggests that their formation involves the reduction of mass by compaction, dissolution, or a combination of both. We thus infer that the mud delivered to the surface from the gryphons is most likely not derived from the negative volume of the pools. The match between positive gryphon volume and negative depression volume suggests that subsidence is continuous and roughly compensates for the volume of mud delivered to the surface.

### 3.4. Spatial distribution of features

Over the course of this study, no changes in the position of established gryphons or pools were observed. However, comparison of our mapping with the only other mapping of the Davis–Schrimpf field, done in 2002 by Svensen et al. (2007), suggests that some minor

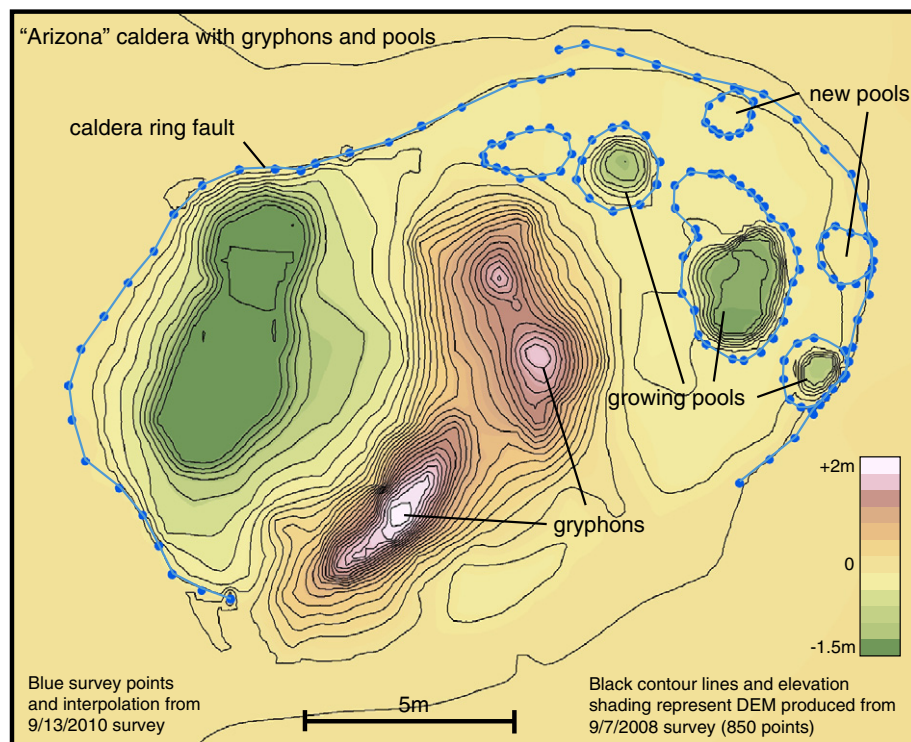


**Fig. 9.** Graph showing pool elevations at different survey times. Refer to Table 3 for feature labels. Pools associated with calderas show elevated water levels in the wetter months, while the isolated pool levels do not correspond to rainfall.

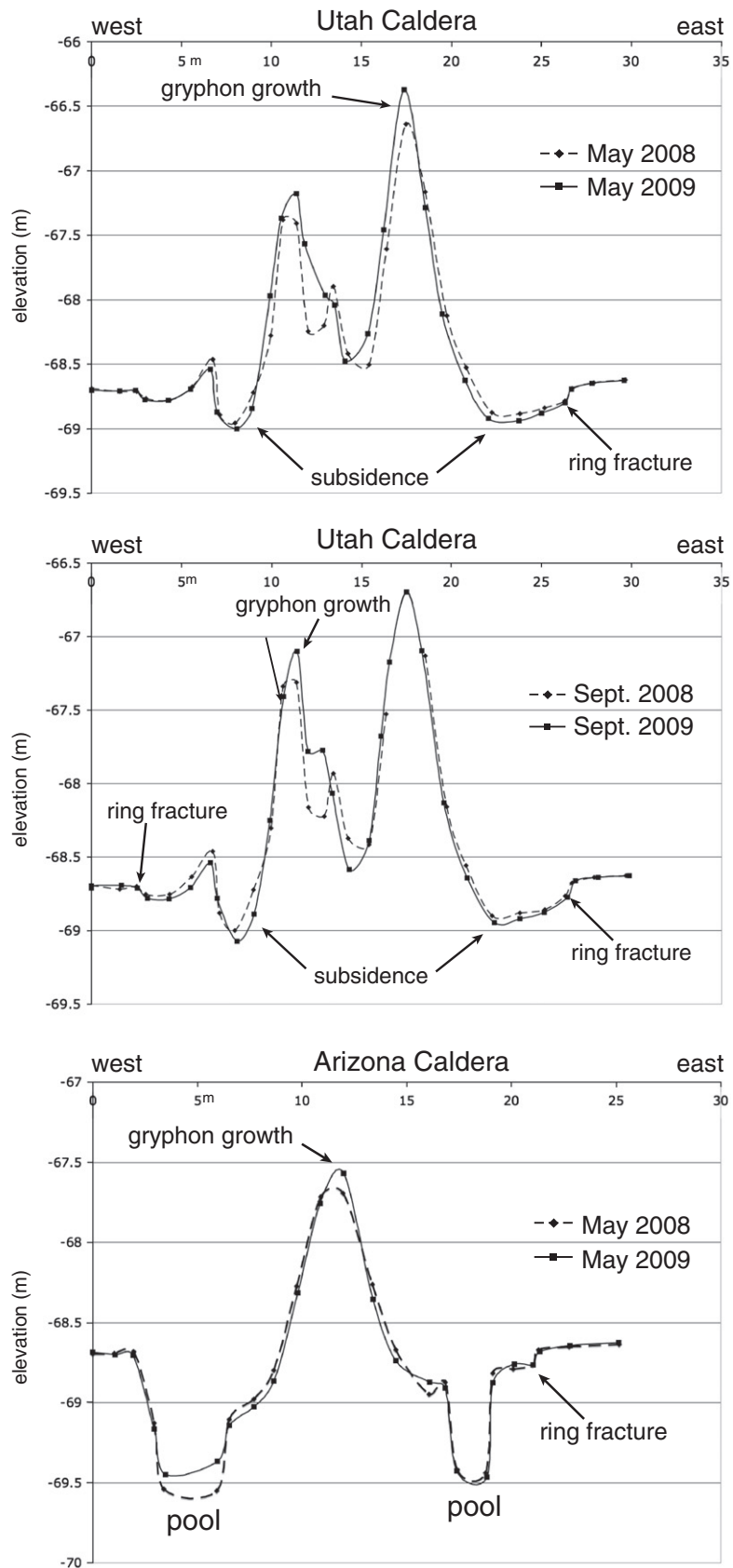
changes in the position of smaller features in the field may have occurred and several new features (both gryphons and pools) might have formed in the last 5 to 6 years. The differences between our mapping and that of *Svensen et al. (2007)* are present in the western section of the field around the “Utah” and “Arizona” gryphon clusters, where the positions of some gryphons have changed slightly, at least 4 new pools have formed, and the caldera ring faults have expanded outward (Fig. 12). However, these changes in position of the individual gryphons and caldera faults cannot be quantified and

may be negligible because of the difference in spatial accuracy between this study (horizontal error of  $\pm 2$  cm) and *Svensen et al. (2007)*: horizontal error estimated to be  $\pm 4$  m).

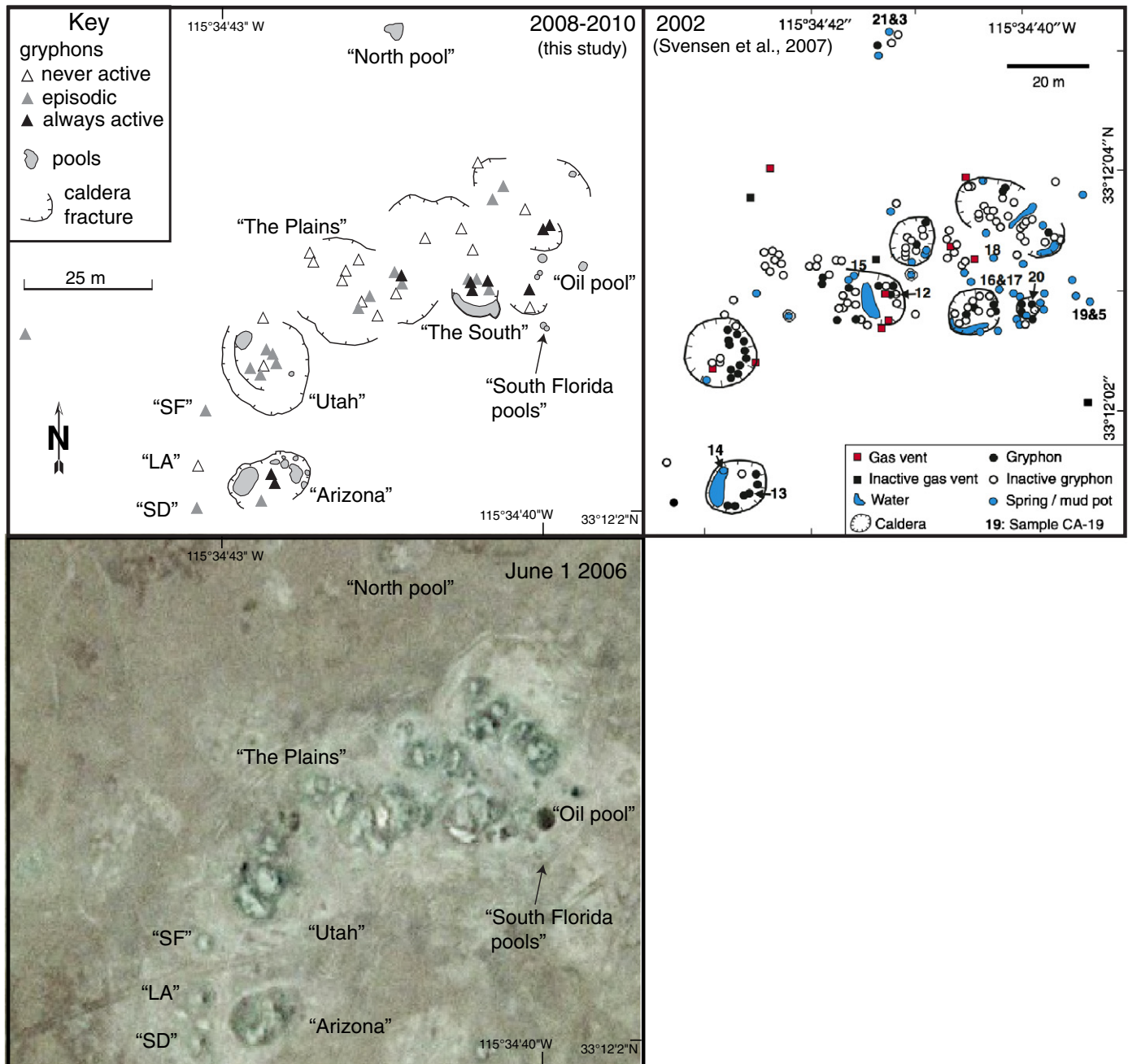
Analysis of historical air photos that are at sufficient resolution to resolve the individual gryphons and pools in the Davis–Schimpf field shows that there have been no recognizable changes in the position of features in the field since June of 2005. Available aerial photography prior to this time is not detailed enough to resolve individual features, but the larger gryphon clusters can be seen in even the oldest air



**Fig. 10.** Colored Digital Elevation Model with contour lines of “Arizona” caldera structure. Constructed from 850 survey points taken in September of 2008. Note the growth of some pools and formation of new ones when the pool outlines were resurveyed in September of 2010 (blue points and interpolation lines).



**Fig. 11.** Transects of the “Arizona” and “Utah” caldera structures. Subsidence can be seen at the “Utah” caldera ring faults, but no significant changes were seen across the “Arizona” caldera faults.



**Fig. 12.** Comparison of mapping from this study (left) with that of [Svensen et al. \(2007\)](#) done in 2002 (reproduction of their Fig. 1), and an air photo from 2006. Note that the recent mapping does not include every vent within the seep field, but only shows vents monitored during the course of the study. The apparent decrease in the number of vents is a result of our selective mapping of monitored features, but locations of the main gryphon clusters and pools are the same in both maps, as well as the air photo.

photos (May 4, 1953) and indicate that no significant changes have occurred in the spatial distribution of the main vents. No determination of the height of the features can be made from the older air photos, but we note that in the 1953 photos the surrounding fields have been plowed but the area covered by the Davis–Schimpf vent features is not. This may indicate that the features were tall enough at this time to prevent plowing across them.

#### 4. Discussion

##### 4.1. Evidence of steady-state conditions

Repeated dGPS surveys and observations of activity indicate that the Davis–Schimpf vent field is largely steady state. Individual

features turn off and on, grow and erode, but no increase in mean height of the gryphons was observed over the 28-month study period, despite constant activity. Periodic observations by [Sturz et al. \(1992, 1997\)](#) between 1985 and 1995 also show no consistent increases in height over time. Based on these observations, we interpret the height and morphology of the gryphons to be primarily a function of their activity type and not directly related to the age of the feature. The data also show that the height of the gryphons is largely independent of the variations in mud temperature, water content, or density measured across the field. We propose that the activity type (“always active” vs. “episodically active”) is determined by the diameter of the vent and the amount of gas being expelled. Wider vents and a larger gas flux characterize the “always active” gryphons. These gryphons can increase in height by the accumulation of splattered material on

the rim of the crater, and can sometimes start to form a “roof” of mud over the crater. However, the constant vigorous bubbling tends to erode the edges of the crater, which collapses the crater walls or opens holes through which mud can leak out and spill down the side of the gryphon. Consequently, the constant bubbling prevents these gryphons from building up much higher than 30 cm to 40 cm above the mud level in the crater. The “episodically active” gryphons, when active, typically erupt as discrete bursts or pulses of mud separated by a few seconds or minutes from smaller diameter (5 cm to 15 cm) vents that do not contain craters at the top. The lack of constant activity at these gryphons allows the mud that has been erupted to harden and provide a stronger structure on which subsequent flows and splattered mud can be deposited. This allows the episodic gryphons to increase in height when active, although there appears to be an upper height limit as none of the gryphons were observed to be higher than about 2.5 m in this study or previous studies.

Although the distribution of gryphon heights within the field is largely steady-state, mass is constantly being delivered to the surface via mud expulsion, such that the mass of the gryphons should be increasing over time. However, there is no large-scale build-up of material in the surrounding field and the gryphon clusters remain relatively distinct and abrupt geomorphic features despite being constantly active at this location for at least 60 years (Ives, 1951; air photo analysis). This suggests that the field may also be steady-state with respect to mass distribution at the surface. Although wind may contribute to some removal of material from the area, it is inferred to be relatively minor as no geomorphic evidence of wind erosion of the gryphons or surrounding area was observed during any of the surveys. The lack of relief, significant slope, or fluvial morphology of the surrounding field indicate that very little, if any, mass is leaving the area via fluvial processes. We propose that the subsidence of the calderas compensates for the additional mass brought to the surface and that the caldera depressions develop due to the collapse of subterranean voids created by the transfer of mud from depth to the surface. The spatial correlation between the larger gryphon clusters and calderas supports this model and the lack of calderas at the larger isolated gryphons (e.g., SF, LA, SD; Fig. 3) suggests that there is a critical amount of material that must be evacuated from depth and added to the surface before collapse occurs (greater than about 30 m<sup>3</sup>—the volume of the larger isolated gryphons). Progressive subsidence was documented at one of two calderas that were monitored over the study period (“Utah” caldera), and the mass balance between the “Arizona” gryphon cluster and associated caldera depression supports this hypothesis and suggests that subsidence keeps pace with the addition of new mud to the surface through gryphon eruption and growth. Mud expelled from the gryphons is largely contained within the caldera depressions that continue to subside, and this prevents a larger-scale buildup of expelled mud in the area that would be expected after years of constant activity. The color variation in the pools and soil pits within the caldera depressions shows that the darker gray mud is present at deeper depths closest to the gryphons, which is most likely related to the distance of mud transport within the depressions, but may also be a result of the outward growth of the caldera ring faults over time.

The Davis–Schrimpf field appears to be largely static in terms of the location of seeps. Although mud expulsion points in some gryphon clusters can sometimes shift position slightly (5 to 30 cm), the location of the main vents did not change over the study period and the present day positions do not differ significantly with previous mapping (Svensen et al., 2007) or positions observed in available historic air photos. The occasional small changes in position of mud expulsion from the gryphon clusters are most likely the result of very shallow (upper 1 to 2 m) re-routing of conduits within the gryphon cluster mass itself and not related to subsurface changes. Some new pools did develop during the study period, and a few grew, but none of the pre-existing pools shifted their positions. The pools appear to form

from compaction and/or partial dissolution of surface soil where gas vents pass through the water table near the surface, although this hypothesis was not tested during the course of this study. When the muddy surface soil is saturated near a gas vent, the soil is disturbed and may partially compact or dissolve, resulting in a depression that fills with water.

#### 4.2. Implications for subsurface processes

The morphology of the seep features in the SSGF is primarily the result of subsurface processes. Consequently, the surface morphology, spatial distribution of features, and processes observed at the surface can lend some insight into the subsurface architecture and dynamics of the seeps. The largely static nature of the seep positions indicates that the conduits that deliver mud and gas to the surface are fixed and are most likely controlled by subsurface structure, such as fractures or faults. Mapping of seeps within the surrounding region by Lynch and Hudnut (2008) led them to conclude that the seep locations in the SSGF are dictated by fractures and/or faults in the subsurface associated with the southern San Andreas Fault system which passes directly through the SSGF. This may also be the controlling the distribution of features on a smaller scale within the Davis–Schrimpf field. Most of the gryphon clusters are ridges comprised of several gryphons. These ridges typically trend within 20° of N40°W, which is parallel to the San Andreas Fault zone, or N30°E, subparallel to conjugate oblique slip faults within the Salton Sea pull-apart basin (Brothers et al., 2009). These linear orientations suggest that the vents may be forming above smaller secondary faults related to the San Andreas system. Mazzini et al. (2009a) found a similar relationship at the Dashgil mud volcano in Azerbaijan where the locations of gryphons and pools on the dormant mud volcano are controlled by faults. The new pools that formed in the Davis–Schrimpf field during this study were located along the ring faults of the calderas and some of the gryphons within the field are also situated on the ring faults of caldera features (ex: the Northern edge of the “Utah” caldera, the eastern edge of the “Plains” caldera, “Maine” gryphon; Fig. 3). These spatial relationships suggest that progressive subsidence and outward growth of the caldera structure over time can result in the development of additional features by providing new fractures through the subsurface. Deep-seated and fixed pathways are also suggested by the observation that water levels in the pools and mud levels and temperatures in the “always active” gryphon craters often differ dramatically over very short distances. These differences imply little connectivity in the shallow subsurface and may be due to differences in conduit width.

The correlation of seep locations with active fault traces brings up the hypothesis that there may be a connection between fault activity and variations in seep activity over time. Temperature monitoring at this location showed no correlation with local seismic activity (Svensen et al., 2009) and no significant changes in gryphon morphology or activity were observed after larger local seismic events that occurred during the study period such as the Bombay Beach earthquake swarm in March of 2009 (multiple magnitude 5.0 or above events centered 17 km away) or the El Mayor–Cucapah Earthquake on April 4 of 2010 (Magnitude 7.2 event and associated aftershocks centered 96 km away). Rudolph and Manga (2010) also noted no changes in temperature following the El Mayor–Cucapah Earthquake, but reported changes in gas flux, a larger number of new mud flows (8 fresh flows, versus 4 new flows seen a month before the earthquake), and the development of a new vent after the earthquake. During our 2 years of surveying and monitoring, and multiple visits per year since 2003 we found that new mud flows and changes in the number of active flows are a normal occurrence since activity at individual gryphons continuously changes through time. Consequently, we believe that the observation of eight new flows by Rudolph and Manga (2010) is not unusual and cannot be confidently attributed to

earthquake activity. In addition, our survey data revealed no new vents after the earthquake other than normal small-scale variations in mud expulsion points on existing gryphons. We note that with almost 100 individual features in the Davis–Schrimpf field, identification and monitoring of individual features is difficult through casual observation, which is why we performed long-term detailed surveying of the field and descriptions of activity at each feature to be able to document changes during this study. Based on the continual variations in temperatures, activity level, water levels, and other aspects of Davis–Schrimpf field that we have observed over the past 5 years (Svensen et al., 2009, this study), we suspect that gas flux may also vary at individual vents over time. Consequently, we feel that long-term monitoring would be needed to document the normal variations in gas flux in order to compare to differences seen before and after earthquakes. We also note that since the gas appears to be the heat-carrier in the system (discussed below), we would expect to see an overall increase in temperatures along with any increase in gas flux.

However, changes in seepage activity have been tied to large seismic events at the Cerro Prieto geothermal field about 75 km south of the Salton Sea (e.g., Balderman et al., 1972) as well as in other parts of the world (e.g., Mellors et al., 2007; Bonini, 2009; Manga et al., 2009; Mazzini et al., 2009b). Therefore, monitoring mud volcanoes in tectonically active areas may provide information regarding the local stress field along faults where stress changes affect the permeability of the subsurface or development of new pathways. The fact that the seep features in the SSGF lie directly over a diffuse seismic zone between the southern end of the San Andreas Fault and the northern Imperial fault makes them an ideal candidate for future studies on the interaction between seep activity and fault activity, which could potentially benefit fault hazard predictions. Our new data set may serve as a baseline for future comparisons in changes to morphology, temperature, and activity after significant seismic events in the area. Continuation of temperature monitoring at the Davis–Schrimpf field will also provide a basis for comparison before and after future seismic activity.

Differential GPS monitoring of the pool levels shows that the pools fill and dry according to the season and amount of rainfall. This suggests that the water has a shallow, meteoric source, as shown by previous studies based on chemical analysis and temperature monitoring (Sturz et al., 1992; Svensen et al., 2007, 2009). We also note that there is no net transport of water from depth to the surface as water is not being expelled onto the surface, but is held within the pools. The source of the gas in the system has been shown to be deep (Muffler and White, 1968; Williams and McKibben, 1989; Svensen et al., 2007), but the source of the mud is unclear. Svensen et al. (2009) proposed two models for the source of the mud that also pertain to the development of the caldera structures. In their first model, mud is derived from depths of greater than 120 m based on the temperatures of the erupted mud and the local geothermal gradient. Their second model assumes a shallow source (<50 m depth) of the erupted mud, which is heated by gas from deeper depths. They note that model two is problematic due to the difficulty in heating shallow mud by hot gas, as gas carries far less thermal energy than mud or water. However, the mass flux of gas is considerably greater than the mass flux of the mud in the Davis–Schrimpf field. Although the mass flux of the gas and mud was not directly measured during this study, gas is constantly being emitted from gryphons, pools, and the soil (with a larger total flux from the soil than the vents themselves: Mazzini et al., unpublished data), while mud expulsion from the gryphons is episodic. This is especially apparent in the “always active” gryphons where gas bubbling is continuous while most of the mud remains within the mud crater at the top of the gryphon and is only occasionally expelled down the sides of the gryphons.

The development of the caldera ring faults favors a shallow source for the erupted mud. For the caldera ring faults to develop and cause

subsidence, displacement must occur along the fault plane to the depth of the voids created by mud transported to the surface. Since confining pressure increases with depth, deeper portions of the ring faults would be stronger with depth and less likely to slip. However, almost nothing is known about the shallow stratigraphy in the Davis–Schrimpf field and no samples were collected to calculate the strength of the subsurface material, so no quantitative analysis of the forces needed to form these ring faults could be made at this time.

Although mud volcanoes and geothermal fields differ in many aspects (e.g. triggering mechanisms at depth, type of gas expelled, temperature and fluids involved in the reactions), the manifestations of mud and fluids expulsion at the surface can be strikingly similar. The pools and gryphons present in the Davis–Schrimpf field are morphologically similar to those that sometimes form on dormant mud volcanoes (Jakubov et al., 1971; Hovland et al., 1997; Delisle et al., 2002; Etiope et al., 2004; Bonini, 2008; Mazzini et al., 2009a). Most mud volcanoes are located in compressional tectonic regimes and are associated with methane gas most likely derived from hydrocarbon-bearing sediments at depth (Kopf, 2002). The overall shape and activity style of the gryphons studied here do not vary greatly from those at the dormant Dashgil mud volcano in Azerbaijan in several aspects (Mazzini et al., 2009a; Hovland et al., 1997). In both locations, small conical mounds expel gas and mud of various densities and amounts. Here the size distributions are similar (1 m to 3 m) and satellite seeps in the form of bubbling pools are often found surrounding the gryphons. The formation of these pools has also been attributed to fluid and gas migration up through fractures or faults that develop as the area surrounding the gryphons subsides, however distinct caldera ring faults were not observed. Even in the case of Dashgil the overall spatial distribution of seepage sites is controlled by major regional faults and fractures. The data presented here and by Lynch and Hudnut (2008) show that the seeps in the Salton Sea Geothermal Field are stationary over time and also controlled by the location of faults and/or fractures and support the idea that subsurface structure is the main influence on the spatial distribution of gryphons. These similarities suggest that the general processes controlling the morphology and evolution of gryphons are largely independent of gas type or tectonic environment and are determined by the amount and style of gas release and the viscosity of the material being expelled.

## 5. Conclusions

Repeated dGPS surveys, measurements of mud properties, and field observations over a 28-month period provide data with which to evaluate the controls on geomorphic development and evolution of seep features within the Davis Schrimpf field. Our data show that:

1. Variations in gryphon height and morphology are controlled by the style of mud expulsion and gas release at the individual vent and not directly due to the age of the structure or measured variations in temperature, density, and water content of the erupted mud. Constantly active gryphons with wider vents are shorter than episodically active gryphons with narrower vents.
2. Seep features in the Davis–Schrimpf field are largely steady-state. Although changes in size, shape, and activity of the gryphons did occur over a 28-month period, these changes averaged out and no net growth of the gryphons as a group occurs over time.
3. Despite constant eruption of mud at the surface, no large-scale build-up of material is present in the field due. We attribute this to subsidence of the calderas that provide local depressions where the expelled mud is contained.
4. The development of the caldera structures is due to removal of mud at depth below the gryphon clusters as it is transported to the surface. Repeated surveys and a correlation between the positive volume of the gryphons and the negative volume suggest that this

subsidence is a continuous process and keeps pace with mud expulsion. The caldera ring faults are easier to explain if the source of the expelled mud is shallow.

5. Pools within the study area fall into two categories; those that are associated with gryphon clusters that fill and drain with the seasons, and those that are isolated, do not fluctuate with the seasons, and are most likely connected to a shallow water-table.
6. The stationary nature of the seep locations suggests that their positions are determined by faults and/or fractures in the subsurface. New features do form over time, but these appear to be dictated by the location of the caldera ring faults. Large differences in pool levels from adjacent pools, and mud properties from adjacent gryphons suggest that there is little connectivity of the shallow plumbing system.

## Acknowledgments

We would like to thank M. Bonini and an anonymous reviewer for excellent reviews that improved this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:[10.1016/j.geomorph.2011.04.014](https://doi.org/10.1016/j.geomorph.2011.04.014).

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