Dynamics of hydrothermal seeps from the Salton Sea geothermal system (California, USA) constrained by temperature monitoring and time series analysis

Henrik Svensen,1 Øyvind Hammer,1 Adriano Mazzini,1 Nathan Onderdonk,2 Stephane Polteau,1 Sverre Planke,1,3 and Yuri Y. Podladchikov1

Received 11 December 2008; revised 16 June 2009; accepted 30 June 2009; published 15 September 2009.

[1] Water-, mud-, gas-, and petroleum-bearing seeps are part of the Salton Sea geothermal system (SSGS) in southern California. Carbon dioxide is the main component behind the seeps in the Davis-Schrimpf seep field (~20,000 m²). In order to understand the mechanisms driving the system, we have investigated the seep dynamics of the field by monitoring the temperature of two pools and two gryphons for 2180 h (90.8 days) in the period from December 2006 to March 2007, with a total of 32,700 measurements per station. The time series have been analyzed by statistical methods using cross correlation, autocorrelation and spectral analysis, and autoregressive modeling. The water-rich pools never exceed 34.0°C and are characterized by low-amplitude temperature variations controlled by the diurnal cycles in air temperature. The long-term validity of these results is evident from a second period of temperature monitoring of one of the pools from December 2007 to April 2008 (120 days). In contrast to the pools, the mud-rich gryphons have a strikingly different behavior. The gryphons are hotter (maximum 69.7°C) and have large amplitude variations (standard deviation of 6.4) that overprint any signal from external diurnal forcing. Autoregressive modeling shows the presence of distinct hot and cold pulses in the gryphon temperature time series, with amplitudes up to 3°C. These pulses likely reflect a combination of hydrothermal flux variations from the SSGS and the local temporal changes in bubbling activity within the gryphons. Citation: Svensen, H., Ø. Hammer, A. Mazzini, N. Onderdonk, S. Polteau, S. Planke, and Y. Y. Podladchikov (2009), Dynamics of hydrothermal seeps from the Salton Sea geothermal system (California, USA) constrained by temperature monitoring and time series analysis, J. Geophys. Res., 114, B09201, doi:10.1029/2008JB006247.

1. Introduction

[2] Seeps in sedimentary basins are commonly related to vertical migration pathways such as faults, mud volcanoes, dewatering pipes, pockmarks, and hydrothermal vent complexes [Brown, 1990; Planke et al., 2003; Svensen et al., 2003; Berndt, 2005]. Seep systems often show large spatial and temporal variations in temperature, pH, and solute content of the expelled fluids [e.g., Sturz et al., 1992; Planke et al., 2003; Svensen et al., 2007]. For these reasons, temperature time series analysis of expelled fluids represent a powerful tool for understanding seep dynamics and have successfully been applied in studying tidal-influenced spreading axis hydrothermal systems [e.g., Tivey et al., 2002; Scheirer et al., 2006; Sohn, 2007] and marine gas hydrate systems [e.g., MacDonald et al., 2005]. In this paper, we present the results from two periods of temperature monitoring of an onshore seep field (the Davis-Schrimpf site) in the Salton Sea geothermal system (SSGS). The SSGS is the result of shallow magmatic intrusions in a sedimentary basin [e.g., Elders et al., 1972; Younker et al., 1982] (Figure 1). This makes the area ideal for investigating the consequences of magmatic intrusions in sediments, petroleum generation in a rift basin, and seep dynamics in general [Svensen et al., 2007]. In addition, the constant activity and the rich variety of surface expressions make this an attractive area for studying long-term seep dynamics, and it makes a relevant analog setting for the offshore Guaymas Basin hydrothermal seeps in the Gulf of California [e.g., Simonet, 1985]. The morphological features of the Davis-Schrimpf seep field [Sturz et al., 1992; Svensen et al., 2007] are strikingly similar to seep fields on dormant mud volcanoes [Jakubov et al., 1971; Delisle et al., 2002; Planke et al., 2003]. However, the Davis-Schrimpf seeps are not related to mud volcanism, as mud volcanism normally implies large-scale mud breccia eruptions and a low-temperature seep stage (~30°C) (for mud volcano terminology, see, e.g., Planke et al. [2003]). The aim of this study is to use time series analysis to characterize the hydrology of four seep structures (two pools and two gryphons) with contrasting surface expressions, temperature, and fluid geochemistry.
A key issue is to determine the connection between seep morphology and the external (air) and internal (hydrothermal) temperature forcing.

2. Seep System

[3] The SSGS is situated in the Salton Trough in southern California, an area with abundant surface manifestations of hydrothermal activity. The hydrothermal system in the Salton Trough occurs in a pull-apart setting where rifting and associated magmatic intrusions are responsible for a heat flow up to 600 mW m$^{-2}$ [e.g., Helgeson, 1968; Robinson et al., 1976; Lachenbruch et al., 1985; Williams, 1997]. The intrusions cause contact metamorphism and fluid flow within predominantly Pleistocene fluvial and lacustrine sediments, giving rise to temperatures exceeding 350$^\circ$C at a depth of 1400 m [e.g., Helgeson, 1968; Muffler and White, 1969; Elders and Sass, 1988], and a considerable focused and diffuse CO$_2$ degassing [Kerrick et al., 1995]. Both the salinity and temperature distribution of hydrothermal fluids from boreholes from the area suggest the presence of a fluid density interface between deep saline brines and less saline shallow waters [Williams and McKibben, 1989; Williams, 1997]. The high salinity of the deep hydrothermal reservoir fluids (up to 150,000 ppm total dissolved solids) is attributed to dissolution of evaporites modified by high-temperature fluid-rock interactions [Helgeson, 1968].

[4] Most of the seeps in the SSGS are located along the southeastern edge of the Salton Sea, with seeps occurring both offshore and onshore (Figure 1). Onshore seeps include bubbling mud pools, gryphons, and gas vents and have been found in the whole Salton Trough area [Ives, 1951]. In the Salton Sea, seep activity has been observed as gas eruptions that usually occur in shallow water along a lineament extending north from the eastern shoreline [Muffler and White, 1968; Lynch and Hudnut, 2008; V. Signorotti, personal communication, 2007].

[5] One of the most concentrated and well-expressed onshore seep fields is the Davis-Schrimpf field, where more than 50 individual seeps are located in a 120 m × 120 m area. At this location, gas, mud, and water are expelled from gryphons, pools, and gas vents (Figure 1) [Ives, 1951; Muffler and White, 1968; Sturz et al., 1992; Svensen et al., 2007]. Gas venting from gryphons and pools is vigorous with a continuous bubbling activity. Water and mud mixtures are continuously expelled down the flanks of the gryphons, whereas the pools generally keep the water confined. On the basis of isotope evidence, it has been suggested that carbon dioxide produced from devolatilization reactions involving sedimentary carbonate is the main driver for the seep activity [Muffler and White, 1968; Svensen et al., 2007]. Minor CH$_4$ (<1 vol %) and liquid petroleum is produced from hydrothermal alteration of organic matter [Svensen et al., 2007]. The individual seeps typically have different water tables, gas fluxes, and fluid exit temperatures. Gryphons are mud-rich and normally hot (22–69$^\circ$C), whereas the water-rich seeps are generally colder (<32$^\circ$C) and form pools. The seep water may have a shallow meteoric origin with an overprint of surface evaporation [Svensen et al., 2007], but a deep saline component has also been suggested [Sturz et al., 1992].

3. Data

[6] Temperature monitoring of the Davis-Schrimpf seep field was carried out in the period 18 December 2006 to 19 March 2007. Two gryphons and two pools were selected for monitoring, representing the two main seepage modes. For the gryphons, we used HOBO U12 stainless steel temperature data loggers, valid in the −40–125$^\circ$C range, with a reported accuracy of 0.22$^\circ$C, a resolution of...
0.025°C (both at 20°C), and a response time of less than 3.5 min. For monitoring the pools, we used StowAway TidbiT loggers valid in the 20–70°C range, with a reported accuracy of 0.20°C, a resolution of 0.16°C (both at 20°C), and a response time of about 5 min. All loggers were programmed for temperature measurements every fourth minute and were placed 1–2 m below the local seep surface. The total number of individual measurements per station is 32,700, spanning a period of 2180 h (90.8 days). One additional HOBO U12 logger was deployed in a petroleum-bearing pool (the “oil pool”) east in the field (see Svensen et al. [2007] for location) but was destroyed by corrosion.

We monitored one of the pools (the North pool) and the air temperature the following winter and spring, from 4 December 2007 to 2 April 2008. The aim was to check the consistency and long-term stability of the pool temperature trend, and to test for correlations between seep temperature anomalies and the regional seismicity. The time series are shown in Figure 4. Furthermore, we monitored the oil pool using two HOBO U12 loggers placed at two different depths (30 cm and 150 cm) for 48 h in December 2007. The aim was to measure the vertical temperature distribution and hence the degree of heat convection within the pool. We can use these results as indicative of the degree of convection in the other pools as all studied pools have the same typical vigorous gas bubbling.

The seep geochemistry (Table 1) was measured in situ the same day as the loggers were emplaced. Air temperature was measured simultaneously at one location in the immediate vicinity of the seeps (Figure 1). The HOBO Pro RH/Temperature logger was mounted on a fence post covered by bushes about 1 m above the ground to minimize the effects of direct sunlight on the logger. Seep water salinity was

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude N</th>
<th>Longitude W</th>
<th>Salinity (g L⁻¹)</th>
<th>Density (g cm⁻³)</th>
<th>pH</th>
<th>T (deg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>West gryphon²</td>
<td>33°12.049’</td>
<td>115°34.675’</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>62.9</td>
</tr>
<tr>
<td>East gryphon²</td>
<td>33°12.047’</td>
<td>115°34.664’</td>
<td>3.1</td>
<td>1.7</td>
<td>6.27</td>
<td>64.3</td>
</tr>
<tr>
<td>North pool²</td>
<td>33°12.084’</td>
<td>115°34.690’</td>
<td>17.6</td>
<td>1.2</td>
<td>6.16</td>
<td>19.1</td>
</tr>
<tr>
<td>West pool²</td>
<td>33°12.040’</td>
<td>115°34.714’</td>
<td>50.3</td>
<td>1.6</td>
<td>5.78</td>
<td>23.1</td>
</tr>
<tr>
<td>Air road²</td>
<td>33°11.983’</td>
<td>115°34.793’</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Oil pool²</td>
<td>33°12.050’</td>
<td>115°34.655’</td>
<td>36.4</td>
<td>1.7</td>
<td>5.89</td>
<td>34.6</td>
</tr>
<tr>
<td>North pool²</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>19.4</td>
</tr>
</tbody>
</table>

²Measured in situ 18 December 2006.
³Measured in situ 4 December 2007.

Figure 2. Seep morphology at the monitoring stations. (a) West gryphon. The person is included to show the scale. The arrow shows the logging station. (b) West pool, where the arrow shows the position of the thermometer. The person is included to show the scale. (c) North pool, with a hammer to show the scale and an arrow showing the position of the thermometer. (d) East gryphon with a diameter of ~1 m. The logger was placed in the center.
measured in situ with a VWR EC300 conductivity instrument. The weight of expelled mud and water mixtures of a known volume was measured by a commercial electronic scale, with accuracy better than about 2%.

The seep field is characterized by two main seepage modes: gryphons and pools (Figure 2). The pools are water dominated and the gryphons have a higher proportion of mud (Table 1). The gryphons contain lower-salinity water than the pools. Table 1 gives the density, pH, and salinity characteristics of the monitoring stations, and Table 2 gives the key temperature data from the 90.8 days of monitoring. The 2006–2007 temperature time series are shown in Figure 3, and the series from 2007–2008 are shown in Figure 4. The maximum measured temperature in the seeps is 69.7°C (west gryphon), and the gryphons have higher standard deviations than the pools (4.0°C and 6.4°C for the west and east gryphon, respectively). The north pool is the coldest of the stations, with a minimum of 14.7°C and an average of 19.7°C. Note the consistency of temperatures in the north pool between the two different monitoring periods.
The west pool has the lowest variability of the stations, with a standard deviation of 1.6°C.

4. Methods

[10] Statistical analyses of the temperature time series were performed using the PAST software [Hammer et al., 2001] and MATLAB 7.5.0 (The Mathworks, Inc.), applying several different methods. In order to quantify smoothness, we used autocorrelation analysis [Davis, 1986] measuring similarity of the time series to itself over a range of time displacements (lags). For an equal-spaced time series $X_i$ of length $n$, we used the following estimate $\hat{R}$ for the autocorrelation sequence, where $\mu$ is the sample mean and $\sigma^2$ the variance:

$$\hat{R}(k) = \frac{1}{(n-k)\sigma^2} \sum_{i=1}^{n-k} (X_i - \mu)(X_{i+k} - \mu).$$

[11] A random, uncorrelated (i.e., white noise) signal is expected to have near-zero autocorrelation values except for $k = 0$. A smoother curve will give slower decrease in autocorrelation as a function of lag time $k$. For a single value of $k$, statistical significance with respect to, e.g., a white noise model, can be assessed by standard methods working on the correlation coefficient [e.g., Davis, 1986]. However, two issues arise. First, we are mainly interested in studying the autocorrelation over a range of lags, bringing up the problem of multiple testing. Second, and more fundamentally, for very long time series such as the ones reported here, statistical significance is nearly always achieved even for extremely small values of $R$ because of the high power of the test. Zero autocorrelation can be rejected at high significance for all autocorrelations reported in section 5.1, at all lag times. We therefore choose to report only the strength $\hat{R}$ of the autocorrelation itself.

[12] Spectral analysis was applied using the Lomb periodogram method [Press et al., 1992] after detrending by linear regression. Spectral analysis involves the estimation of signal power of sinusoids at all frequencies. Significance levels relative to a white noise null hypothesis were estimated according to Press et al. [1992], even

**Table 2. Monitoring Station Data**

<table>
<thead>
<tr>
<th>Station</th>
<th>Maximum $T$ (deg C)</th>
<th>Minimum $T$ (deg C)</th>
<th>Mean $T$ (deg C)</th>
<th>Standard Deviation</th>
<th>Maximum $dT$ (C min$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>West gryphon</td>
<td>69.7</td>
<td>48.9</td>
<td>59.9</td>
<td>4.0</td>
<td>0.089</td>
</tr>
<tr>
<td>East gryphon</td>
<td>68.9</td>
<td>37.3</td>
<td>56.4</td>
<td>6.4</td>
<td>-0.956</td>
</tr>
<tr>
<td>North pool</td>
<td>25.4</td>
<td>14.7</td>
<td>19.7</td>
<td>2.1</td>
<td>-0.003</td>
</tr>
<tr>
<td>West pool</td>
<td>34.0</td>
<td>24.1</td>
<td>30.2</td>
<td>1.6</td>
<td>-0.035</td>
</tr>
<tr>
<td>Air road</td>
<td>40.6</td>
<td>-4.8</td>
<td>14.2</td>
<td>8.0</td>
<td>0.824</td>
</tr>
<tr>
<td>North pool</td>
<td>24.5</td>
<td>-7.7</td>
<td>19.8</td>
<td>1.7</td>
<td>0.012</td>
</tr>
<tr>
<td>Air road</td>
<td>36.6</td>
<td>-1.5</td>
<td>17.9</td>
<td>6.7</td>
<td>0.535</td>
</tr>
</tbody>
</table>

**Figure 4.** Temperature time series of the north pool and air in the period 4 December 2007 to 2 April 2008. Note that the apparent trends of increasing and decreasing north pool temperatures (over ~2 week periods) and that the same trends are seen in the air temperature.
though the relevance of such tests on long time series can be debated.

For sinusoidal fitting to the diurnal component of temperature variation we used the algorithm of least squares and singular value decomposition [Press et al., 1992]. A period of 1 day was imposed, and the amplitude and phase of the sinusoid was fitted by computer. This is a linear fitting problem, as amplitude and phase can be computed from the amplitudes of a fitted sine and cosine. We thus obtained the following model for diurnal variation in air:

\[ T(0) = A \cos(\omega t - \varepsilon), \]

with \( \omega = 7.27 \times 10^{-5} \text{ s}^{-1} \), i.e., one period per day, and \( A \) and \( \varepsilon \) the fitted parameters. Assuming a null hypothesis (to be tested) of heat transport purely by diffusive conduction down into the water column of the seep structures, we have the following analytical solution for the steady state periodic temperature at depth \( x \) in a semi-infinite domain [Carslaw and Jaeger, 1959]:

\[ T(x) = Ae^{-kx} \cos(\omega t - kx - \varepsilon), \]

where \( k = \sqrt{\omega/2D} \). We used \( D = 1.44 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1} \) for the thermal diffusivity of water. Using an observed time delay of \( d \) s, we can therefore compute the corresponding probe depth \( x = \omega d/k \) under the null hypothesis. Unlike the amplitude, the delay of the temperature at depth is independent from possible effects of a constant heat input from below, making this procedure robust to violations of the assumed boundary conditions.

Cross correlation [Davis, 1986] was used to quantify the similarity of two time series \( X \) and \( Y \) as a function of relative time displacement \( k \):

\[ \hat{r}(k) = \frac{1}{(n-k)\sqrt{\sigma_X^2 \sigma_Y^2}} \sum_{t=1}^{n-k} (X_t - \mu_X)(Y_{t+k} - \mu_Y). \]

To account for possible drift over time in the statistical properties of the data, cross correlation was computed within sliding windows of length \( n \). For each window position, the maximum correlation value \( \max(\hat{r}) \) and the corresponding lag time \( k_{\text{max}} \) were extracted, giving an estimate of the strength of the correlation and of the delay between the two series. Traditional significance tests against a white noise null hypothesis for cross correlation at single lags are invalid in this case because of multiple testing across lag times and the considerable autocorrelation [Pyper and Peterman, 1998]. We therefore used a computer-intensive Monte Carlo method described by Simpson et al. [2001]. For each window, we generated 1000 random replicate pairs of the two time series, each with the same amplitude spectra as the original data but with random phases. The maximal cross-correlation value across lags in each replicate was compared with the original maximum in order to estimate the probability of the observed maximum. However, multiple testing across moving windows may still be an issue.

Figure 5. Autocorrelogram of the 2006–2007 time series. One day represents 360 samples. The diagram shows that within the region of autocorrelation, the temperature dynamics of pools are slower than those of gryphons.
The magnitude-squared coherence spectrum was calculated for the air-north pool pair, in order to emphasize the cross correlation of the diurnal component in the frequency domain. The Welch averaged, modified periodogram method "mscohere" in Matlab was used with a window size of 2048.

As shown by direct inspection and autocorrelation analysis, the time series are fairly autocorrelated (smooth). In order to emphasize possible transients, we used autoregressive modeling. In such a model, the time series $Y_i$ is regarded as resulting from an uncorrelated, stochastic component $X_i$ being filtered (e.g., smoothed) by a simple recursion relation:

$$Y_i = b_1 Y_{i-1} + b_2 Y_{i-2} + X_i.$$ 

In this case, the model is of order 2 and is referred to as AR(2). The parameters of the AR(2) model were estimated by maximum likelihood according to Melard [1984]. The order of the model was established using the Akaike information criterion, indicating that AR(1) produces insufficient fit, while AR(3) and higher lead to overfitting. We plot the residual (error) time series $X_i$ simply as a visualization aid to bring out transients, and no statistical assumptions or inferences are made.

5. Results

5.1. Curve Smoothness

Autocorrelation among the 2006–2007 seep time series shows that at time scales shorter than about 2 days (720 samples), the temperature curves for the two pools are considerably smoother (more autocorrelated) than the two gryphons (Figure 5). The smoothness is also evident visually in the temperature time series (Figure 3). At time scales exceeding 2–3 days, the positive autocorrelation breaks down in all of the time series. The negative autocorrelations in Figure 5 arise from the weak, large-scale ~1 week quasiperiodic oscillations. The oscillations...
are best developed in the time series shown in Figure 4, where they appear to be in phase with comparable air temperature oscillations.

5.2. Influence of Air Temperature

[18] Heat interchange between the air and the seeps can be assessed using the response to the daily temperature cycle. This was done by fitting the phase and amplitude of a sinusoid with a period of 1 day.

[19] For the pools, the identification of a corresponding peak in the spectrum confirmed the presence of diurnal periodicity with a frequency of 1 day (Figures 6 and 7). A peak is also observed for periods on the order of 1 week, possibly associated with weekly air temperature oscillations, as remarked in the previous chapter. The amplitude and wavelength of these larger-scale oscillations seem to vary over time, showing that the time series is not statistically stationary, and this low-frequency peak may simply reflect the autocorrelation present in the data. In addition, air temperature shows an increasing trend, especially from mid-January and onward. The procedure was therefore carried out over three time spans in the 2006–2007 series in order to study changes over time and in different air temperature

Table 3. Results of Temperature-Sinusoid Fitting From 2006–2007

<table>
<thead>
<tr>
<th></th>
<th>Days 1–33</th>
<th>Days 33–66</th>
<th>Days 66–90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak-Peak Amplitude (deg C)</td>
<td>Delay (min)</td>
<td>Peak-Peak Amplitude (deg C)</td>
<td>Delay (min)</td>
</tr>
<tr>
<td>Air</td>
<td>13.88</td>
<td>15.92</td>
<td>20.00</td>
</tr>
<tr>
<td>Western pool</td>
<td>0.11</td>
<td>0.34</td>
<td>0.35</td>
</tr>
<tr>
<td>Northern pool</td>
<td>0.56</td>
<td>0.83</td>
<td>1.24</td>
</tr>
</tbody>
</table>

Figure 7. Analysis of diurnal variation in the detrended temperature curve for the north pool, now for the north pool 2007–2008 monitoring. (a) The 1 day periodicity and its first harmonic event. (b) The sinusoid fitted data. Again, it is demonstrated that the pools are strongly influenced by the diurnal air temperature.
domains (Table 3). The difference in fitted phase between air and pool series was used to estimate the delay time. The temperature of the west pool responded to air temperature with a lag of 314–443 min, whereas the north pool responded with a lag of 197–263 min. Note that delays may be 1 or more whole days longer than indicated, as this is indeterminate using this method alone. With these observed delays, the probe depth expected under a regime of purely diffusive conduction would be 8.6–12.2 cm in the west pool, and 5.4–7.2 cm in the north pool. This estimate is based upon solving the heat diffusion equation, and the calculated temperature probe depth would be much less than the actual depth of 1–2 m. Alternatively, delay of an additional whole day would be unlikely under this model considering that the corresponding amplitude attenuation would be much larger than observed, whereas attenuation estimated from the delay being smaller than observed could be explained by heat flux from below.

[20] The lack of clear cross correlations between air and gryphon temperatures (Figure 8a) and the lack of 1-day periodicity (Figure 8b) discard a diurnal periodicity for the gryphons. Thus, there is no evidence for a thermal coupling between air and gryphon probes. The cross correlation between air and pool temperatures is, however, significant, and particularly clear for a period of 1 day and its harmonics (Figure 9). The cross correlogram between air and north pool temperatures is similar for the three time windows, but only the results from the first 33 days are shown in Figure 9. On short time scales, the first peak is found for a delay of 3.3 h (50 samples), in reasonable accordance with the result from sinusoidal fitting, reflecting heat transport from air to water driven by daily temperature variations. Given a peak correlation value around 0.4, the proportion of temperature variation in the north pool explained by variation in air temperature is $R^2 = 0.16$.

5.3. Correlations and Delays Between Seeps

[21] Possible thermal couplings and delays between seeps were evaluated by cross correlation. After day 24, the west pool seems to follow the west gryphon with a delay of...
1–5 days, with high correlation coefficients up to 0.6, significant or nearly significant at the p < 0.05 level (Figure 10). In the same time period, the two gryphons are correlated with much shorter delays (Figure 11). No persistent cross correlations were found for other pairs of probes.

5.4. Heat Flux Pulses in the Gryphons

[22] The individual temperature curves were fitted to an AR(2) model, assuming a stochastic signal input (“residual”) driving a smoothing filter. In this case, the stochastic input can be interpreted as sudden heat flux pulses, being smoothed by the thermal reaction time of the system (e.g., slow heating of water reservoirs). In the gryphons, and especially the eastern gryphon, discrete peaks are present in the residual (Figure 12) representing both positive (hot) and negative (cold) perturbations. The AR(2) modeling was less successful for the pools because of the probe sensitivity in combination with small amplitudes producing a spike in the residual for every change of value.

5.5. Vertical Temperature Variations Within a Pool

[23] To measure the vertical temperature distribution in the pools, and to determine the dominant mode of heat transport (i.e., advective versus conductive), we monitored the oil pool for 48 h. The results are applicable to the other pools based on their general similarities in bubbling activity. Figure 13 shows the results of cross-correlation analysis of the temperature data from 30 and 150 cm depth. After a period of low temperature difference between the two depths, short delay times and high correlation coefficients, there is an abrupt change at about 22 h. Here we have a transition to a regime characterized by a larger temperature difference between the probes, longer delay times, and slightly lower correlations. Rapid pulses are present in the delay time and correlation curves.

6. Discussion

[24] The geochemistry of the seep water is consistent with data from 2003, for both pH and the relationship between density, salinity, and temperature (Table 1) [Svensen et al., 2007]. Thus, the seep system is apparently stationary on a multiyear time scale with respect to the distribution of temperature on the scale of the seep field and the positions of the various gryphons and pools. Furthermore, the seep activity and morphology of the field has remained virtually the same since the early 1990s [Sturz et al., 1992], and the seeps have been active on this site for decades [Ives, 1951]. However, the temperature time series demonstrates that the seep system is more dynamic than previously recognized. In sections 6.1–6.3, we address the varying controlling mechanisms on seep temperature, why there is a considerable temperature difference between gryphons and pools, and the implications for seep dynamics.

6.1. Hot Gryphons and Cold Pools

[25] If water is the main heat carrier in the seep system, then the water-dominated seeps (i.e., the pools) should also be the hottest. This is not the case. The fact that gryphons are hotter than the water-rich pools suggests that water cannot be the main heat carrier. There are two end-member hypotheses that can explain the presence of hot gryphons and cold pools within the same seep field. (1) Hot gas is the main heat carrier, or (2) mobilized mud from deeper levels is the heat carrier. The maximum measured seep temperature (69.7°C) corresponds to the temperature reached at about 120 m depth in the nearby State 2–14 well [Sass et al., 1988]. This suggests that the source region for the high temperature, regardless of the heat transport mechanism, is located close to the 120 m level assuming a similar geothermal gradient below the seep field.

[26] In the case of hypothesis one, hot gas from a deep gas reservoir would migrate through the overlying sediments...
and heat the near-surface mud in the gryphons. When the gas interacts with shallow water reservoirs, as in the pools, the gas is efficiently cooled via a “water pipe” effect because of the high heat capacity of water. However, the main challenge with this hypothesis is that the hot gas has a low mass, hence a limited capability for heating the dense mud.

As our hypothesis two, we can explore the possibility of the seeps being hot because of bulk movement of hot mud from below 120 m depth. The mud could get mobilized by the gas, and the high flux causes fluidization and transport toward the surface. This results in gryphon build-ups and caldera structures forming because of a downward sagging as material is remobilized at depth. If correct, this hypothesis implies that the gryphon formation and the caldera subsidence are in a steady state, and that a pipe-like structure connects the gas and mud source region and the caldera (Figure 14). Eventually, convection within the pipe would lead to remobilization of mud erupted at an earlier stage. The pools and gas vents, normally found outside the calderas, would have their own dynamics related to gas flow through the sediments and interaction with meteoric water. This model is consistent with data from seeping mud volcanoes in Azerbaijan, where water in gryphons have a deep origin and a temperature independent of seasonal air temperature variations, and pools and salsa lakes are filled with cold shallow meteoric water [Mazzini et al., 2008].

6.2. External Forcing of Pool Temperature

[28] The smoothness of the temperature time series in the pools relative to the gryphons can be explained by the high water content. The smoothening reflects a fundamental mechanism controlling the temperature in the seep system. Accordingly, the pools will react slower to any imposed temperature forcing from the hydrothermal system compared to the gryphons because of the low gas to mud mass ratio. In addition, the stronger diurnal temperature signals in the pools (Figures 6 and 7) and the weak ~1 week periodicity shows that the air temperature is relatively more important than the hydrothermal flux in controlling seep temperature. The end result is cold pools and warm gryphons, where the local variations in the temperature time series reflect the local hydrological regimes (Figure 14). One example is the north pool, which reacts faster to air temperature than the west pool. Since the probe depth was similar in the two pools, the shorter reaction time must be a result of stronger advection in the north pool due to higher water content and/or more vigorous gas flow. Also, the consistent increase in response amplitude and reaction speed in the north pool over time possibly indicates that the pool is evaporating. The

---

**Figure 10.** Moving window cross-correlation analysis of temperature logs for west gryphon and pool. The window size is 12,000 samples, or 33 days. After day 24 the delay is 2–5 days, and the correlation coefficients are high, showing that the time series follow each other closely. The bottom plot shows probability of the maximal correlation value under the null hypothesis, with a $p < 0.05$ significance line.
stochastic modeling suggests that the two pool temperature series can be understood as mainly controlled by slow external forcing from the air on a near-surface water reservoir, with weak residual peaks in the model. This further means that perturbations in the temperature are effectively buffered by the surface water. Still, some perturbations in the pools (Figure 3, Table 2) cannot be explained simply by air forcing. This is likely controlled by the local permeability and fluid flow pathways. As evident from Figure 4, the apparent periodic rise and fall in water temperature is controlled by the air temperature, also showing that the major perturbations in the pool temperature are weather induced.

The mismatch between actual probe depth (1–2 m) in one of the pools and depth predicted from observed time delays using a diffusive model (5–12 cm) shows that heat transport is not purely diffusive but is enhanced by convection within the pools. This is consistent with the observation of vigorous gas bubbling in the pools. Also, the data from the loggers deployed at two different depths in the oil pool in December 2007 (Figure 13) confirm that convection rather than diffusion is the main mechanism for heat transport. The temperature difference between the probes during the first 12 h is negligible. Purely diffusive heat transport through a water column of 1.2 m would involve delay times of hours rather than a few seconds as observed especially in the initial region of Figure 13. Still, the rapid changes in temperature difference, delay, and correlation between 22 and 45 h show that convection rates vary considerably. This is likely related to short-term flux variations, as reflected by the temperature variations in the mud-rich west pool (Figure 3).

6.3. Gryphon Dynamics

The time series analyses shows that external forcing from the air on the temperature evolution of the gryphons can be discarded (Figure 8). On the basis of the time series and the stochastic model (Figure 12), we suggest three hypothetical mechanisms that can explain the gryphon temperature and dynamics: (1) flux variations of mud and gas, giving rise to positive temperature peaks; (2) cold water pulses from a shallow meteoric reservoir, giving rise to negative temperature anomalies; and (3) spatial variations in the bubbling activity within each gryphon, resulting in both negative and positive temperature changes when the mud is either heated or cooled.

The maximum positive temperature fluctuation is recorded in the west gryphon (7.4°C over 83 min, or 0.089°C min⁻¹; Table 2), whereas the other stations have maximum responses as negative perturbations. Hot pulses occurring during short time periods are best explained by flux variations or rapid changes in the bubbling activity and position. Hot pulses in the seeps could thus reflect deep processes in the hydrothermal system, either in fluid.
production rates or in changes in the permeability structure. Hot fluid pulses are known from mud volcanoes in the Gulf of Mexico, where exit temperatures correspond to the ambient temperature at several kilometers depth \cite{MacDonald2000}. However, unlike the SSGS seeps, mud volcanoes are larger systems involving bulk mobilization of mud from great depth, and the temperature anomalies may last for months.

The cold pulses can best be explained by meteoric water influx if the temperature change is rapid. The nearby shallow lakes and streams had temperatures of about 10°C during field work in December 2006. Gryphon cooling over longer time scales would in contrast be the result of conductive cooling following a shift in the position of the gas bubbling or in significantly reduced activity. Even submarine hydrothermal systems may stop discharging entirely and reverse into the seafloor \cite{Sohn2007}. Note that the SSGS seeps differ strongly from marine cold seeps and hydrothermal seep systems which are commonly affected by tidal forcing \cite[e.g.,][]{Tivey2002, Sohn2007}.

The cross correlation shows that the west pool temperature lags behind the west gryphon by 3 days in the 66–90 days time frame. No cross correlation exists between the other temperature probes. This suggests the presence of local heat pulses with lateral communication between nearby seeps, where the time delay is due to diffusion and/or advection, again controlled by the water content and permeability of the host sediments and the seep plumbing system. Thus, in the Davis-Schrimpf seep system, the gryphons are more dynamic than the pools and react faster to the forcing from the Salton Sea geothermal system.

7. Conclusions

Temperature monitoring of seeps in the Salton Sea geothermal system shows surprisingly large variations on time scales ranging from minutes to days. The two main seepage structures in the Davis-Schrimpf seep field are gryphons and pools, representing common seep morphologies in many continental seep fields. The gryphons are hot and have temperature time series characterized by rapid changes and high amplitudes. The temperature time series from the pools are smoother with less amplitude variations. Furthermore, there are no detectable daily cycles in the gryphons, whereas the pools are characterized by diurnal temperature forcing from the air. There is no tidal influence on the seep dynamics, in contrast to seeps and high-temperature discharge in submarine hydrothermal systems. These observations are consistent with a model where fast and partly discontinuous variations in heat influx in the gryphons are controlled by bulk fluidization of hot mud from deep reservoirs. Pools, on the other hand, have lower temperatures because of efficient cooling of hot gas by shallow water. Thus, in the pools, the gas is cooled by the water pipe effect. Heat transport in the pools is not purely diffusive, and the advective or convective component is a
Figure 13. Moving window cross-correlation analysis of temperature logs at 30 and 150 cm depth through a 48 h period in the oil pool, sampled in December 2007. The window size corresponds to 1200 samples, or 2 h. (a) Temperature at 150 cm depth. (b) Temperature at 30 cm depth. (c) Temperature difference between the loggers at 150 and 30 cm depth. The deepest station is always hotter. (d and e) Delay time and correlation coefficient corresponding to the cross-correlation peak. A small temperature difference, short delay, and high correlation are all interpreted to signify strong advection.
combined effect of the gas bubbling and possibly of shallow fluid flow and water replenishing cycles.

Acknowledgments. We gratefully acknowledge support from the Norwegian Research Council via a SFF grant to PGP and a PetroMaks grant (169457/S30) to H. Svensen. We would like to thank A. Sturz for fruitful discussions about the Salton Sea seeps. The paper was improved by thorough and constructive comments by two anonymous reviewers, a JGR Associate Editor, Robert Sohn, and Jean Van de Meulebrouck.

References


Melard, G. (1984), Algorithm AS 197: A fast algorithm for the exact

Robinson, P. T., W. A. Elders, and L. J. P. Muffler (1976), Quaternary


