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Streamflow increase due to rupturing of hydrothermal reservoirs: Evidence from the 2003 San Simeon, California, Earthquake

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[1] Following the $M_w = 6.5$ San Simeon, California, earthquake on December 22, 2003, USGS stream gauges documented two consecutive increases in streamflow in the Salinas River and Lopez Creek in the central Coast Ranges. The first increase occurred within 15 minutes after the earthquake and lasted about an hour; the second one occurred a few hours later and lasted much longer. Evidence and simulation suggest that these increases were caused by earthquake-induced rupturing of pressurized hydrothermal reservoirs. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 1832 Hydrology: Groundwater transport; 7212 Seismology: Earthquake ground motions and engineering; 8135 Tectonophysics: Hydrothermal systems (8424). **Citation:** Wang, C.-Y., M. Manga, D. Dreger, and A. Wong (2004), Streamflow increase due to rupturing of hydrothermal reservoirs: Evidence from the 2003 San Simeon, California, Earthquake, *Geophys. Res. Lett.*, *31*, L10502, doi:10.1029/2004GL020124.

1. Introduction

[2] Increased streamflow is commonly observed following earthquakes [see *Muir-Wood and King*, 1993; and *Montgomery and Manga*, 2003, for overview]. Following the 1974 Izu-Hanto-oki earthquake, Japan, *Wakita* [1975] suggests that the coseismic elastic strain caused changes in groundwater level. Following the 1989 Loma Prieta earthquake in California, increases of streamflow in nearby basins and changes in ionic concentrations in the water led *Rojstaczer and Wolf* [1992; also *Rojstaczer et al.*, 1995] to suggest a model of increased permeability of the shallow crust. Recession analysis of the stream flows at Sespe Creek, California, *Manga* [2001; *Manga et al.*, 2003] shows no detectable changes in the permeability of the groundwater system providing baseflow following several earthquakes, in apparent contradiction to the enhanced permeability model; instead, they propose coseismic liquefaction and consolidation of sediments as the cause of the streamflow increase.

[3] After the San Simeon, California, earthquake we observed a new type of streamflow response in the earthquake-affected area, which cannot be explained by any of the proposed models. Instead, the observation appears to be more consistent with a mechanism proposed by *Brodsky et al.* [2003] that ground shaking during an earthquake clears clogged fractures from a pressurized hydrothermal reservoir. In this paper we report the observation and propose an explanation.

2. Setting

[4] The Paso Robles Basin is located in the central California Coast Ranges (Figure 1a); it borders the Santa Lucia Range on the southwest, the Cholame Hills and the Temblor Range on the northeast, and the La Panza Range in the south. Active tectonics since the late Tertiary has repeatedly faulted and uplifted the crust, producing the Coast Ranges, the Salinas Valley and the Paso Robles Basin [*Page*, 1981]. The epicenter of the San Simeon earthquake occurred 11 km NE of the town of San Simeon, 39 km WNW of Paso Robles, and >100 km NW of Arroyo Grande (Figure 1a). Rupture during the earthquake shows a strong SE directivity [*Hardeback et al.*, 2004].

[5] The climate of the area is semiarid. Most of the annual 250–330 mm precipitation occurs during the winter [*San Luis Obispo County*, 2003]. The Salinas River, with a flood plain ~100 m wide, runs NW through the Paso Robles Basin. Growing population and a proportionate increase in urbanization and agriculture in the past several decades has caused a basin-wide decline of the groundwater level. As a result, the streambed is generally dry except during the rainy season, and it was dry before the San Simeon earthquake.

[6] Lopez Creek near Arroyo Grande (Figure 1a) is located in the Santa Lucia Range south of the Paso Robles Basin. There is no distinct flood plain; instead, colluvium of angular rock fragments rises from the streambed to the hillside. Water runs in the creek throughout the year.

[7] The San Antonio River gauge and the Nacimiento River gauge are both upstream of local dams. These streams, bounded by flood plains of sands and gravel, had substantial discharge before the earthquake.

[8] Both Paso Robles and Arroyo Grande are well known for their hot springs (~40°C). Drilling at Paso Robles encountered the hydrothermal reservoir at a depth of ~100 m (*Floyd Butterfield*, personal communication, 2004). No hot springs are known in the area near the San Antonio River or the Nacimiento River.

3. Observations

[9] Following the earthquake, four new hot springs appeared (Figure 1b) along a straight line striking WNW subparallel to the earthquake rupture (Figure 1a) and crossing the Salinas River ~1 km upstream of the stream gauge. The elevations of the springs were nearly the same as that of the gauge. The well-head pressure of the hot spring reservoir at Paso Robles was steady at 0.33 MPa before the earthquake (inset in Figure 2a). Pressure dropped to ~0.2 MPa within 2 days after the earthquake, and has since declined slowly with time.

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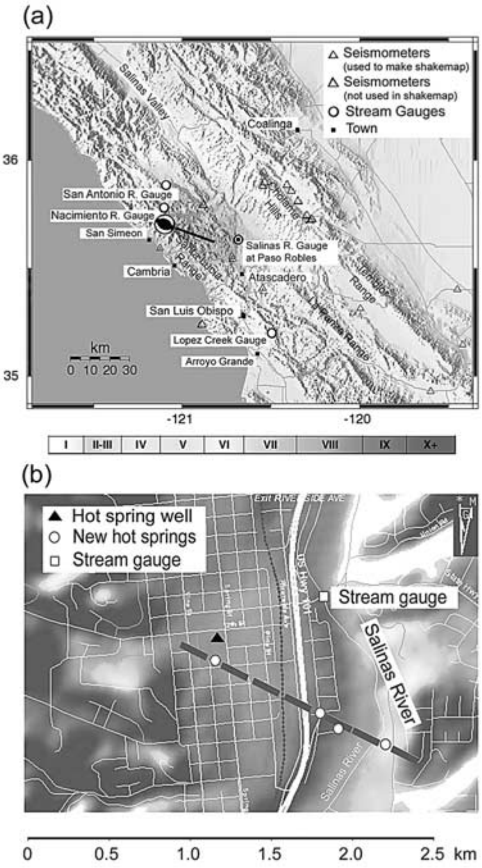

Figure 1. (a) Map showing locations of stream gauges, locations of strong-motion seismic stations and instrumental intensity of ground shaking in San Simeon earthquake [modified from *Hardeback et al.*, 2004]. Focal mechanism taken from Harvard CMT Catalog. Bold line shows rupture extent. Salinas River flows NW through town of Paso Robles and Salinas Valley. (b) Map of Paso Robles showing locations of new hot springs after earthquake and stream gauge. Note the linear distribution of new hot springs nearly parallel to the fault direction shown in (a); line intersects Salinas River ~1 km upstream of stream gauge. See color version of this figure in the HTML.

[10] After the earthquake, USGS stream gauges documented two consecutive increases in streamflow in the Salinas River at Paso Robles and in the Lopez Creek near Arroyo Grande (Figures 2a and 2b). The first increase occurred within 15 minutes of the earthquake and lasted about an hour. The second increase occurred several hours after the earthquake and lasted much longer. In contrast, no streamflow response was detected at the San Antonio or the Nacimiento Rivers. Precipitation started on the third day after the earthquake and overwhelmed the stream-gauge records. The evidence for the first increase degraded in the USGS stored database because the original data was averaged into hourly bins before its storage.

[11] For the first increase in streamflow the relationship between the logarithm of discharge, q, and time, t, is linear (Figures 2a and 2b), i.e.,

$$\ln q = a - bt \qquad (1)$$

where a and b are parameters from a least-square fit of the stream-gauge records (Table 1). Defining a characteristic time $\tau = b^{-1}$, we get $\tau = 2400$ s for Salinas River and 2930 s for Lopez Creek. The similarity in τ at the two streams suggests that these increases were caused by the same mechanism. Integrating the discharge with time we get the total amount of extra discharge in the first increase: $Q \sim 35$ m^3 in Salinas River and ~780 m^3 in Lopez Creek. The large difference in discharge may reflect the fact that the streambed of the Salinas River was dry before the earthquake so that much of the expelled water infiltrated into the dry sediments before reaching the stream gauge. The second increase in streamflow occurred only in the streams showing the first increase. Since the records for the second increase were incomplete and complicated by rainfall, a similar recession analysis cannot be made.

4. Model

[12] The line connecting the new hot springs may mark an earthquake-produced fracture or the reactivation of a preexisting fracture, although the earthquake fault did not pass through Paso Robles. Its location just upstream of the

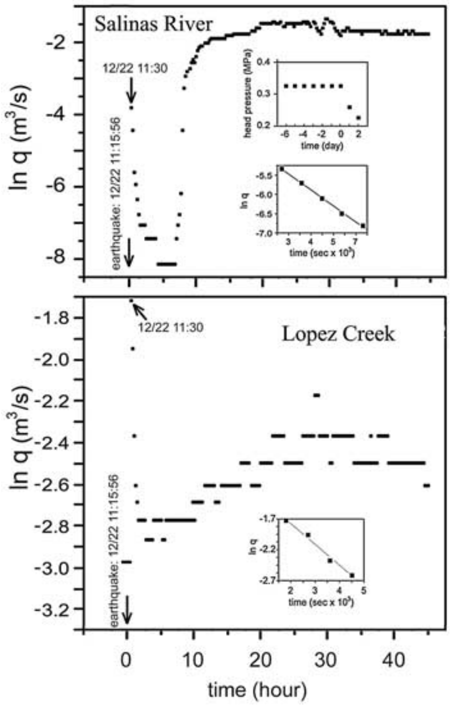

Figure 2. Log(discharge) vs time in (a) Salinas River at Paso Robles (USGS gauge 11147500) and (b) Lopez Creek near Arroyo Grande (USGS gauge 11141280). Since the Salinas River was dry before the earthquake (t = 0), discharge at t < 0 is off the scale on this plot. Time 0 is arbitrary. Arrows indicate earthquake occurrence (11:15:56 local time) and the first data point of increased flow (at 11:30). Records of the second increase were interrupted by precipitation on the third day after the earthquake (off diagram). Insets show well-head pressure of Paso Robles hot spring as function of time and least-square fit to data for the first increases.

Table 1. Parameters for the First Streamflow Increase Following the San Simeon Earthquake[a]

	Salinas River at Paso Robles	Lopez Creek near Arroyo Grande
b (s^{-1})	0.000416	0.000341
r^2	1.0	0.99
τ (s)	2400	2930
Q (m^3)	35	780

b: coefficient in equation (1).
r: correlation coefficient of least square fit.
τ: characteristic time.
Q: intergrated discharge.
[a] Since starting time is arbitrary, coefficient a is not listed.

stream-gauge in the Salinas River (Figure 1b) suggests that the increased discharge at this location could have been the expelled water from a hydrothermal reservoir (Figure 3a). Several perennial sulfur springs occur in the upper reach of Lopez Creek (near Sulfur Pots). Reports on the occurrence of new springs after the earthquake, however, are not available, perhaps reflecting the relatively remote location of the creek.

[13] We suggest the following scenario for the streamflow increases after the San Simeon earthquake: Coseismic shaking cleared some clogged cracks [*Brodsky et al.*, 2003] in the seal of a subsurface hydrothermal reservoir (Figure 3b) and significantly increased the effective crack length (Figure 3c). Injection of fluid from the reservoir pressurized the lengthened cracks. Since the stress-intensification factor K equals $P\sqrt{c}$ [*Lawn and Wilshaw*, 1975], where P is the pressure in the crack and c the crack length, an increase in crack length may increase the stress-intensification factor enough to significantly exceed the fracture toughness of the rock, causing a spontaneous rupture. Laboratory measurements show fracture toughness of rocks from 0.01 to 1 MPa $m^{1/2}$ [*Atkinson and Meredith*, 1987]. For $P \sim 0.3$ MPa, $P\sqrt{c}$ may exceed the fracture toughness if c exceeds a few meters. The expulsion of water from the reservoir to the fracture zone caused pressure to drop below the shut-in pressure [*Middleton and Wilcock*, 1994, p.267], resulting in an instant closure of the ruptured fracture in the seal. Subsequent draining of water from the pressurized fracture zone above the seal led to a short-lived increase in streamflow (i.e., the first increase recorded in the Salinas River and the Lopez Creek). Ruptured fractures retain an enhanced connectivity even after they close [*Wang and Xie*, 1998]. Thus a longer-lasting, though delayed, discharge of hydrothermal water through the fracture zone to the surface may have produced the second increase in the Salinas River and the Lopez Creek and a continued decrease in the hot spring pressure in Paso Robles (inset in Figure 2a).

[14] To test this hypothesis we simulate the first streamflow increase by treating the fracture zone as an effective (anisotropic) 1D porous media and using the diffusion equation [e.g., *Ingebritsen and Sanford*, 1998]:

$$S_s \frac{\partial h}{\partial t} = K \frac{\partial^2 h}{\partial x^2} \tag{2}$$

where h is the hydraulic head, S_s and K the specific storage and the hydraulic conductivity of the fracture zone, respectively, and x is measured from the reservoir along the fracture zone. The velocity for turbulent flow of water into the fracture is estimated to be $\sim$1 m/s [using equations 6–39 and 6–42 in *Turcotte and Schubert*, 2002] for an effective fracture width of 10^{-3} m, along-fracture *excess* pressure gradient of 10^4 Pa/m and water viscosity of 10^{-3} Pa s. This corresponds to a time duration of $\sim$1 min for pressurizing the fracture zone, which is much shorter than the decay time of the streamflow. Thus we may assume that the fracture zone was instantly pressurized to a uniform head h_o. For $t > 0$, the closure of the cracks in the seal effectively stopped further injection of water from the reservoir to the fracture, i.e., no flow at $x = 0$; the head h at the streambed ($x = L$) is zero. With these initial and boundary conditions, the *excess* discharge from the fracture zone to the streamflow bed, $q = -KA\ (\partial h/\partial x)$ where A is the cross-sectional area of the fracture zone intersecting the streambed, is given by [*Carslaw and Jaeger*, 1959, p. 104]:

$$q = \frac{8Q'}{\pi^2 \tau} \sum_{n=0}^{\infty} \exp\left[-(2n+1)^2 \frac{t}{\tau}\right] \tag{3}$$

where $Q' = S_s A L h_o$ and is equal to the integrated discharge Q during the first streamflow increase, $\tau = 4L^2/\pi^2 D$, and $D = K/S_s$. Using the values of Q and τ listed in Table 1 we simulated the excess discharge in the two streams

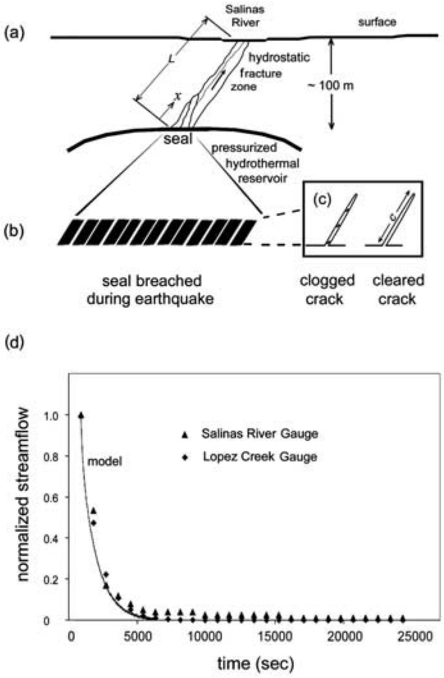

Figure 3. (a) Cartoon of proposed model. Rupturing of the seal of hydrothermal reservoir leads to expulsion of fluid into fracture zone. (b) Enlarged diagram of seal with cracks. (c) Clogged crack and cleared crack; clearing of a clogged crack significantly increases its effective length. (d) Model prediction (curve) compared with normalized stream-gauge data (triangles and diamonds) for the first streamflow increases.

(Figure 3d). Comparison of simulated result with the stream-gauge data (Figure 3d) shows excellent agreement.

5. Discussion

[15] Peak ground velocity at the four stream gauges was computed using a finite-source model that incorporates 9 three-component records from regional seismic stations (Figure 1a), two near-fault GPS observations of deformation, and site-corrected Green's functions [e.g., *Dreger et al.*, 2004]. The predicted ground shaking is strongest at the Nacimiento River gauge, with a peak ground velocity of 0.137 m/s representing the geometric mean of the maximum velocity of the two horizontal components, followed by 0.123 m/s at the Salinas River gauge at Paso Robles, 0.073 m/s at the San Antonio River gauge, and 0.038 m/s at the Lopez Creek gauge near Arroyo Grande. The presence of a post-seismic streamflow increase at Lopez Creek, where ground shaking is weakest, and the absence of a post-seismic streamflow increase at Nacimiento River, where ground shaking is the strongest, contradict the prediction of the coseismic consolidation model. In addition, the Salinas River streambed was dry before the earthquake; thus no water was available even if coseismic consolidation did occur here.

[16] The short timescale of the first increase in streamflow implies a nearby water source. Because the groundwater table in the Paso Robles Basin has been extensively lowered, near-surface water was available only in the distant mountains, too far away to have supplied the first streamflow increase. Thus the source for the increased discharge in the Salinas River was most likely a subsurface hydrothermal reservoir.

[17] The delayed appearance of the second increase implies a relatively long characteristic time ($\sim 10^6$ s) and a low post-seismic fracture permeability (closed fractures). Assuming that the hydrothermal reservoir is also the source for this increase and given a depth of 100 m for the hydrothermal reservoir beneath Paso Robles, we estimate a fracture permeability of $\sim 10^{-15}$ m^2, which is within the range of permeability of fractured rocks [10^{-9}–10^{-17} m^2, *Freeze and Cherry*, 1979] and consistent with a conduction-dominated heat flow regime for the Coast Ranges [*Lachenbruch and Sass*, 1977].

[18] Hydrological changes in geothermal areas have been reported previously. Many geysers at Yellowstone changed their eruptive behaviors after the 1959 Hebgen Lake, Montana, earthquake [*Marler and White*, 1977] and the 1983 Borah Peak, Idaho, earthquake [*Hutchinson*, 1985]. Some hot spring pools, once clear and placid before the earthquakes, became turbulent and clouded with suspended particulates. Hot springs in Long Valley Caldera also increased discharge during a nearby earthquake swarm in 1980 [*Sorey and Clark*, 1981]. A 1997 aftershock sequence in Northern Apennines, Italy, was interpreted as being driven by trapped high-pressure gas [*Miller et al.*, 2004]. These results are consistent with the assumed model here that seismic shaking cleared clogged conduits [*Brodsky et al.*, 2003]. The two consecutive streamflow increases, one with a short characteristic time and the other with a much longer characteristic time, however, have not been reported or anticipated before.

[19] Several large aftershocks in the San Simeon sequence, though not in the immediate vicinity of the stream gauges, exhibited strong non-double-couple components. Such behavior has been previously reported in other hydrothermal seismicity. In some cases volume changes have been identified in the source processes and inferred to be due to the injection of pressurized hydrothermal water into a fracture [e.g., *Dreger et al.*, 2000].

[20] An obvious and direct test of the proposed model would be temperature measurement and geochemical and isotopic analysis of the water in the increased streamflow. However, since the first increase in the streamflow after the San Simeon earthquake lasted only about an hour, the sampling of this water would be a challenging task.

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