Dynamics and rapid migration of the energetic 2008–2009 Yellowstone Lake earthquake swarm

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[1] Yellowstone National Park experienced an unusual earthquake swarm in December–January, 2008–2009 that included rapid northward migration of the activity at 1 km per day and shallowing of the maximum focal depths from 12 to 2 km beneath northern Yellowstone Lake. The swarm consisted of 811 earthquakes, $0.5 < M_W < 4.1$, aligned on a N–S 12-km-long vertical plane of hypocenters. The largest earthquake of the swarm had a 50% tensile crack-opening source determined by a full waveform inversion that we interpret as a magmatic expansion component. In addition, GPS data revealed E–W crustal extension coincident with the swarm. Modeling of GPS and seismic data is consistent with E–W opening of ~10 cm on a N–S striking vertical dike. Our interpretation is that the swarm was induced by magmatic fluid migration or propagation of a poroelastic stress pulse along a pre-existing fracture zone. **Citation:** Farrell, J., R. B. Smith, T. Taira, W.-L. Chang, and C. M. Puskas (2010), Dynamics and rapid migration of the energetic 2008–2009 Yellowstone Lake earthquake swarm, *Geophys. Res. Lett.*, *37*, L19305, doi:10.1029/2010GL044605.

1. Introduction

[2] The Late Quaternary Yellowstone silicic volcanic system is characterized by three caldera-forming eruptions in the last 2.1 million years, the youngest occurring 640,000 years ago producing the Yellowstone caldera [*Christiansen*, 2001]. Moreover, the extraordinarily high heat flow values averaging 2,000 mWm^{-2} over the caldera and exceeding 30,000 mWm^{-2} in northern Yellowstone Lake, [*Blackwell and Smith*, 2000; *David Blackwell personal communication*, 2005] more than 10,000 hydrothermal features, intense seismicity, and decadal-scale crustal uplift and subsidence reflects the active tectonic-magmatic nature of Yellowstone [*Smith et al.*, 2009]. Important to our study is a tomographically imaged crustal magma reservoir [*Husen et al.*, 2004] that extends from ~8 km to ~16 km beneath the Yellowstone caldera and beneath the 2008–2009 Yellowstone Lake earthquake swarm.

[3] GPS studies of the Yellowstone caldera have recorded multiple uplift and subsidence episodes at decadal scales [*Puskas et al.*, 2007]. Most recently, GPS and InSAR data revealed accelerated caldera uplift at rates up to ~7 cm/yr beginning in mid-2004 and continuing into 2009 at a lower value of ~2.0 cm/yr. The source of this remarkable uplift episode was modeled as an inflating sill at ~10 km depth beneath the caldera and coincident with the top of the imaged magma reservoir [*Chang et al.*, 2007; W. L. Chang et al., Magmatic source modeling of temporal variations of high uplift rates in the Yellowstone caldera, 2004–2009, manuscript in preparation, 2010].

[4] We present an analysis of earthquake and GPS data associated with the 2008–2009 Yellowstone Lake earthquake swarm and evaluate the possibility of a hydrothermal-volcanic source. The results are key to understanding the interaction of earthquakes and volcanic sources of Yellowstone as well as plausible volcano models for assessing its geologic hazards.

2. Earthquake Setting

[5] The seismic data used in this study are from the Yellowstone seismograph network that includes 26 seismographs and from 5 Plate Boundary Observatory (PBO) borehole short-period seismometers. More than 36,500 earthquakes were located in the Yellowstone area from 1973 to 2010. Since 1995, the Yellowstone area has averaged ~1,600 earthquakes per year with magnitudes from $-1.4 \leq M_C \leq 4.5$ (Figure S1 of the auxiliary material).[1] The majority of earthquakes in the Yellowstone caldera are less than 5 km deep. The shallow nature of the maximum focal depths is attributed to the shallow depth of the brittle-ductile transition at ~400°C associated with the caldera magma reservoir [*Smith et al.*, 2009]. Maximum depths of hypocenters deepen to >15 km south and north of the caldera.

[6] Earthquake swarms are the common mode of earthquake occurrence in Yellowstone with more than 80 distinctly identified swarms from 1995 to 2010 containing 12,504 earthquakes and representing 42% of all earthquakes [*Farrell et al.*, 2009]. The majority of the swarms were located in the zone of high seismicity northwest of the caldera, but 24 independent swarms were located within or on the rim of the Yellowstone caldera.

3. Yellowstone Lake Swarm Seismic and GPS Observations

[7] The focus of this paper is the 2008–2009 Yellowstone Lake earthquake swarm that began on December 27, 2008

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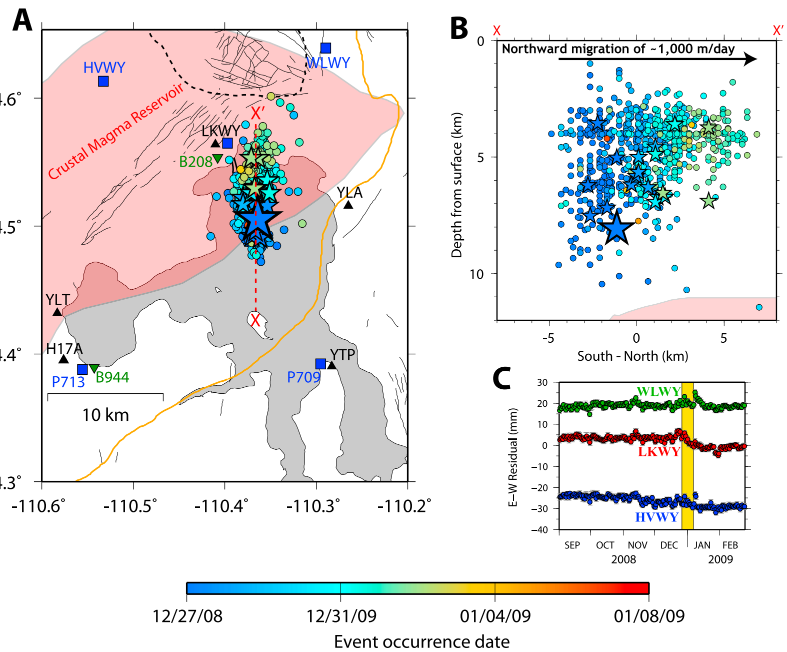

Figure 1. Earthquake epicenters of the 2008-2009 Yellowstone Lake earthquake swarm. (a) Circles represent swarm earthquakes with $M_C < 3.0$ and stars represent events with $M_C \geq 3.0$. The large star is the largest event, M_W4.1, of the swarm. Earthquakes are temporally color-coded showing the northern migration of seismicity. Small black lines are faults and the orange line is the outline of the 0.64-Ma Yellowstone caldera from *Christiansen* [2001]. Black triangles are seismic stations, blue squares are GPS stations, and inverted green triangles are borehole strainmeters and seismometers. The opaque red body is the outline of the tomographically imaged Yellowstone magma reservoir [*Husen et al.*, 2004]. (b) Cross-section showing the shallowing and northward migration of swarm hypocenters and their position relative to the top of the Yellowstone magma reservoir. (c) East-west component of GPS derived ground motion of the Yellowstone Lake area stations: WLWY (green), LKWY (red), and HVWY (blue) show the related deformation. The yellow band shows the time extent of the swarm seismicity.

and lasted until January 07, 2009. Swarm hypocenters were located in the central Yellowstone Lake area where the earthquake sequence began and rapidly migrated north at a rate of ~1 km/day (Figure 1). Maximum focal depths shallowed markedly from ~10 km to ~2 km from south to north. Notably, the swarm initiated at ~10 km, near the top of the magma reservoir (Figure 1), which suggests that magmatic fluids may have been involved.

[8] The Yellowstone Lake swarm consisted of 811 well-located earthquakes, determined employing a three-dimensional V_P velocity model [*Husen et al.*, 2004] with RMS residual values of 0.01 to 0.3 s and with the largest magnitude, a M_W4.1, occurring at the initiation of the swarm. The swarm contained 21 events of $M_C \geq 3.0$ with over 20 events felt in Yellowstone National Park. In contrast, for the previous year there were only two earthquakes of $M_C \geq 3.0$ in Yellowstone. The cumulative seismic moment release for all of the 2008–2009 Yellowstone Lake swarm earthquakes was 6×10^{22} dyne-cm, which is equivalent to a single M_W4.4 event, and accounted for 35% of the total moment release in the Yellowstone area for the previous year.

[9] Nearby GPS stations (Figure 1a) recorded a notable episode of E–W crustal extension coincident with the swarm. The closest GPS station (LKWY), only ~1 km west of the swarm, experienced ~7 mm a total of westward motion associated with the swarm (Figure 1). Station HVWY, located ~7 km northwest of the swarm epicenters, had ~3 mm of westward motion.

4. Seismic Source Determinations

[10] A seismic moment tensor solution [*Taira et al.*, 2010] for the largest event, a M_W4.1, revealed an unexpected result of a 50% tensile crack source and 50% shear double-couple source corresponding to an opening dislocation of 9.6 cm and a shear dislocation of 9.6 cm (Figure S2). The tensile crack was oriented with a strike of 185°, a dip of 90°, and a rake of 100°, which agrees with the dominantly N–S fault planes and E–W extension from the focal mechanism solutions (Figure S2). Details of the moment tensor solution are given in Text S1 as well as in Tables S1 and S2.

[11] The stress field was determined from focal mechanisms of 43 of the swarm earthquakes that had at least six clear first-motion arrivals. The majority of the focal mechanisms revealed dominantly normal, dip-slip fault motions with N–S fault planes interpreted to be associated with an E–W tensional stress regime (Figure S2) revealing a vertical principal-stress axis, σ_1, and an ENE–WSW minimum compressional stress σ_3 (Figure S2). This stress regime is similar to the caldera-wide tensional stress-field deduced by *Waite and Smith* [2004] and *Smith et al.* [2009] from focal mechanisms of background seismicity, GPS, and

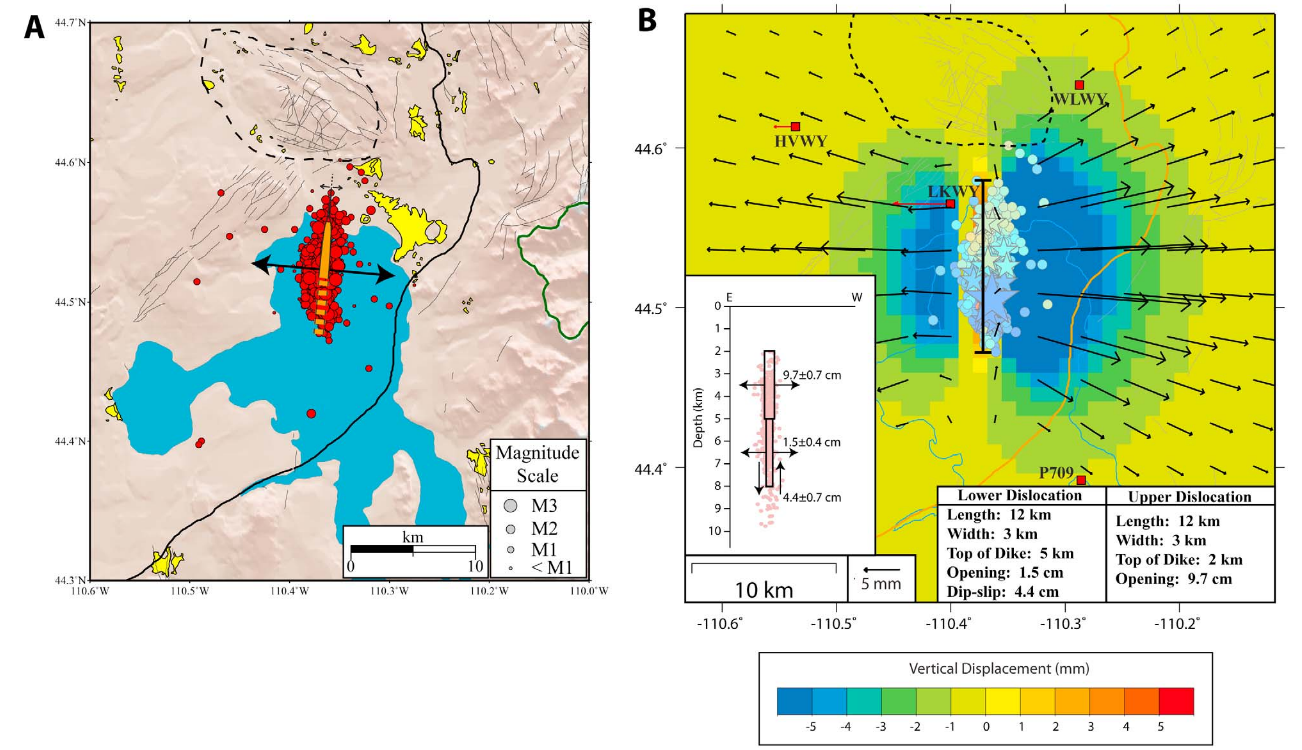

Figure 2. Schematic model for a hypothetical fluid-dike intrusion for the 2008–2009 Yellowstone Lake earthquake swarm. (a) The north-south oriented dike (orange) with modeled east-west crustal extension. Hydrothermal areas are shown in yellow. (b) Forward model of the surface deformation from a N–S oriented dike. The color background is the modeled vertical displacement in mm and the black vectors show the modeled horizontal displacement. The red vectors show the observed horizontal displacements at stations LKWY and HVWY in mm/yr. GPS stations are shown as red squares.

L. Quaternary fault-orientations of the entire Yellowstone region.

5. Dike-Fracture Source Modeling

[12] We employed an elastic half-space vertical dislocation model with a shear modulus (μ) of 3×10^{10} Pa and a Poisson's ratio (υ) of 0.35 [*Simpson and Reasenberg*, 1994] to model the stress field, hypocenter geometry, and GPS-derived deformation. We defined the lateral and depth extent of the fracture model from the geometry of the swarm hypocenters, with two vertical dislocations, both 12 km long and 3 km wide (Figure 2). The two dislocations were adjacent to each other, with the top of the upper dislocation at 2 km depth and the top of the lower dislocation at 5 km depth (Figure 2).

[13] To match the observed 7 mm westward deformation at the GPS station LKWY, the model required an E–W extensional opening of 9.7 ± 0.7 cm for the top dislocation together with an opening of 1.5 ± 0.4 cm with a dip-slip shear motion of 4.4 ± 0.7 cm on the bottom dislocation (Figure 2). This model also provided a westward surface deformation of ~3 mm at station HVWY, consistent with that measured by GPS, as well as eastward surface deformation at station WLWY of ~2 mm. Although there was no noticeable deformation at WLWY, at 11 km to the northeast, given the uncertainties in the GPS-determined daily position, it would be difficult to resolve the 2 mm displacement inferred by the modeling.

[14] We then evaluated fluid properties of a modeled dike intrusion by determining the viscosity of a migrating fluid using the time-duration of the swarm. Using a numerical heat production model [*Carslaw and Jaeger*, 1959; *Rubin*, 1995] we determined the width of a magmatic dike intruded into a host rock during the 10 days of swarm migration:

$$w = 2\lambda\sqrt{\kappa t} \tag{1}$$

where w is the half-width of the frozen margin, t is time (10 days), and κ is the thermal diffusivity of the host rock (1.5×10^{-6} m^2/s). The dimensionless parameter λ depends on the magma and host rock temperatures, the latent heat of crystallization (L = 500 kJ kg^{-1}), and the heat capacity (1 kJ kg^{-1} °C^{-1}) [*Carslaw and Jaeger*, 1959]. For rocks of rhyolitic composition, we used a temperature range of 750°C to 950°C, and for basalts we used a temperature range of 1000°C to 1300°C. This gave λ values of 0.2 to 0.4 for rhyolites and 0.4 to 0.6 for basalts. The dike needs to be at least 1 to 2 meters wide to avoid freezing for rhyolite and at least 2 to 3 meters wide for basalt. It should be noted that equation (1) assumes that advection of heat by magma is unimportant which could be a valid assumption given a 1 km/day migration rate. Using the equations [*Carslaw and Jaeger*, 1959; *Rubin*, 1995]:

$$\Delta P = \frac{w\mu}{l(1-\upsilon)}, \tag{2}$$

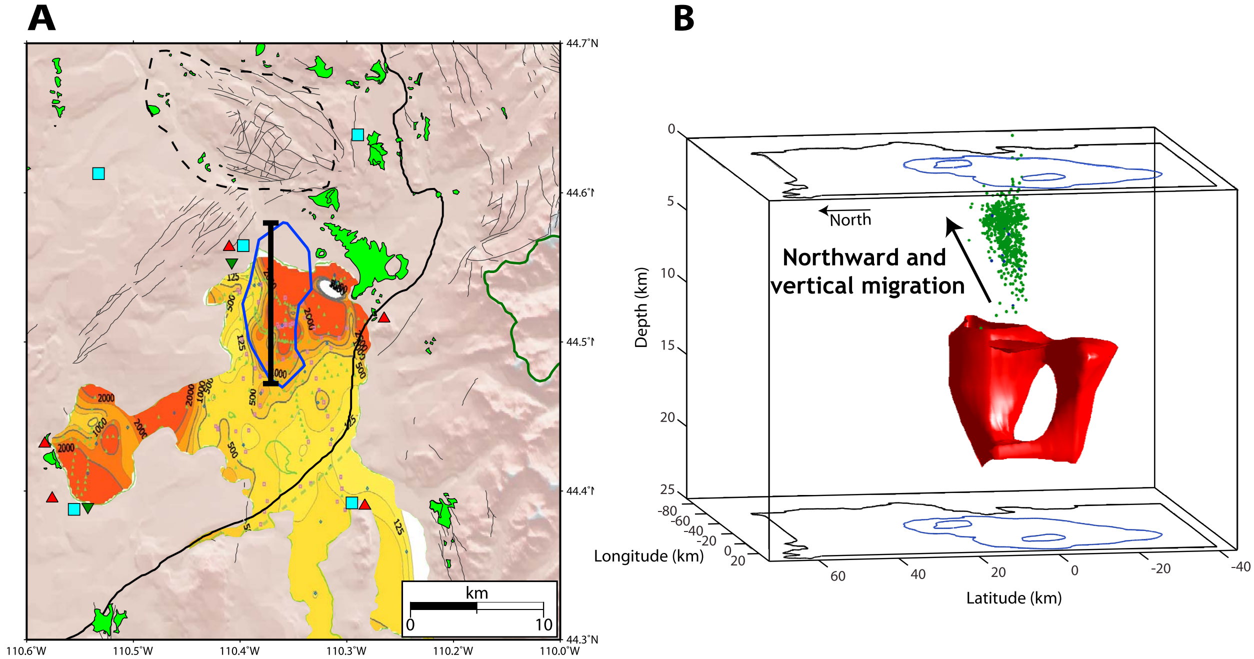

Figure 3. Outline of the 2008–2009 Yellowstone Lake earthquake swarm with heat flow. (a) Heat flow of Yellowstone Lake showing the north-south band of high heat flow (>2,000 mWm^{-2}) [*Blackwell and Smith*, 2000; data from *David Blackwell*, 2005] and the outline of the swarm seismicity (blue polygon). Hydrothermal areas are shown in green. The N–S black line inside the seismicity is the modeled dike location. Seismic stations are shown as red triangles, GPS stations as blue squares. (b) Three-dimensional tomographic image showing the relation of the swarm hypocenters (green circles) and the Yellowstone crustal magma reservoir (red body).

where ΔP is equal to the magma pressure minus the compressive stress, l is the half length of the dike and:

$$\eta = \frac{w^2}{3\dot{u}_x}\frac{d\Delta P}{dx}, \qquad (3)$$

where $\dot{u}_x$ is the horizontal velocity of 1000 m/d determined from the earthquake pattern migration rate, we calculated fluid pressures of 4–7 MPa necessary to produce the dike width for a rhyolite and 1–7 MPa for a basalt. We determined a fluid viscosity on the order of 10^3 to 10^4 Pa s for rhyolites that agrees with lower published rhyolite melt viscosities of 10^4 to 10^8 Pa s [*Rubin*, 1995]. In contrast, if we assume basaltic material, we calculate a viscosity on the order of 10^4 Pa s, which is two to four orders of magnitude larger than published basaltic melt viscosities ranging from 10 to 10^2 Pa s [*Rubin*, 1995].

[15] Similar observations of migrating earthquake swarm activity and associated surface deformation have been noted at other active volcanic areas and have been attributed to dike intrusions. These include Lake Tahoe, CA [*Smith et al.*, 2004], Iliamna volcano, AK [*Roman et al.*, 2004], the Izu Islands, Japan [*Ukawa and Tsukahara*, 1996; *Toda et al.*, 2002], Kilauea Volcano, HI [*Rubin et al.*, 1998], and the Long Valley Caldera, CA [*Hill et al.*, 1990].

6. Discussion

[16] The intense 2008–2009 Yellowstone Lake earthquake swarm was characterized by a swarm-front that migrated north at ~1 km/day with maximum hypocenter depths shallowing toward the north at the margin of the mapped Yellowstone caldera (Figure 1). In addition, GPS data revealed a westward surface extension pulse coincident with the swarm (Figure 1). These observations are consistent with an interpretation of magmatic fluid transport (hydrothermal, gaseous, magma, etc.) through an expanding vertical fracture that was modeled as a vertical dislocation 12 km long at a depth range of 2–8 km and is a plausible source for the observed seismic and geodetic observations (Figure 2).

[17] The Yellowstone Lake earthquake swarm occurred in an area of very high heat flow in northern Yellowstone Lake (Figure 3) with averaged values exceeding 2,000 mWm^{-2} [*Blackwell and Smith*, 2000; *Blackwell et al.*, 2006; *Smith et al.*, 2009]. It has been hypothesized that the extraordinarily high heat flux is due to fluid migration on a pre-existing fracture zone of high porosity allowing the rapid percolation of fluids [*Blackwell and Smith*, 2000]. The dike could be a pre-existing, longterm feature that was re-activated with an influx of new material during the swarm with 10 cm of additional opening. The N–S lobe of high heat flow (Figure 3) and the N–S pattern of background seismicity (Figure S1) could be evidence of the pre-existing fracture which allowed magmatic fluids to flow upward from the top of the Yellowstone crustal magma reservoir introducing hydrothermal fluids at shallower depths inducing the seismicity and ground deformation that was observed during the swarm (Figure 3).

[18] *Waite and Smith* [2002] attributed a similar source to the largest Yellowstone earthquake swarm in 1985, during which earthquake activity migrated away from the caldera rim to the northwest, although their observed rate of

migration was an order of magnitude lower, ~150 m/day, than that of the 2008–2009 swarm. Their preferred scenario for the 1985 swarm involves the rupture of a self-sealed hydrothermal layer and subsequent migration of hydrothermal fluids through a preexisting fracture zone out of the caldera [*Waite and Smith*, 2002]. Importantly, the 1985 swarm was followed by a caldera-wide reversal in the deformation from uplift to subsidence suggestive of lateral magmatic fluid transport out of the shallow hydrothermal system. While there was no observed deformation reversal following the 2008–2009 Yellowstone Lake swarm, the accelerated uplift rate determined from GPS for the period 2004-present (Chang et al., manuscript in preparation, 2010) has decreased from as high as 7 cm/yr of uplift to a rate of ~2.0 cm/yr of uplift in 2009.

[19] Moreover, the notable shallowing of maximum focal depth swarm hypocenters is consistent with the rapid shallowing of the depth of the brittle-ductile transition, as modeled as the ~400°C–500°C isotherm [*Smith et al.*, 2009], from ~10 km to ~6 km in the Yellowstone caldera (Figure S3). As the swarm front migrated north, the earthquakes would have encountered higher crustal temperatures that restricted earthquake nucleation.

[20] We note another plausible cause of the migratory nature of the Yellowstone Lake earthquake swarm is a poroelastic stress pulse migrating through a series of pressurized fluid-filled fractures. Such a mechanism could have originated from expansion of the magma reservoir and nucleated earthquakes as it propagated through the preexisting fault system. This could explain the discrepancy between the geodetically modeled opening (10 cm) and the numerically calculated dike width (1–2 m).

[21] We prefer an interpretation of the 2008–2009 Yellowstone Lake swarm as the result of an upper-crustal dike-intrusion of magma or magmatically-derived aqueous fluids from the shallow Yellowstone magma reservoir, although we cannot specify the type and depths of specific fluids (magma vs. hydrothermal). The fluid could have followed the pre-existing fracture zone that extends northward toward the largest part of the magma reservoir (Figure 3b). We also note that this unusual earthquake swarm may represent the first geophysical observations of a failed surficial hydrothermal-volcanic event in Yellowstone. Moreover, the observed temporal-spatial seismic and deformation pattern reflects the style of volcano-tectonic activity that can be expected in the Yellowstone volcanic field and that could lead to triggering of larger earthquakes or volcanic eruptions in the future.

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