Changes in geyser eruption behavior and remotely triggered seismicity in Yellowstone National Park produced by the 2002 M 7.9 Denali fault earthquake, Alaska

S. Husen* Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah 84112, USA
R. Taylor National Park Service, Yellowstone Center for Resources, Yellowstone National Park, Wyoming 82190, USA
R.B. Smith Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah 84112, USA
H. Healser National Park Service, Yellowstone Center for Resources, Yellowstone National Park, Wyoming 82190, USA

ABSTRACT

Following the 2002 M 7.9 Denali fault earthquake, clear changes in geyser activity and a series of local earthquake swarms were observed in the Yellowstone National Park area, despite the large distance of 3100 km from the epicenter. Several geysers altered their eruption frequency within hours after the arrival of large-amplitude surface waves from the Denali fault earthquake. In addition, earthquake swarms occurred close to major geyser basins. These swarms were unusual compared to past seismicity in that they occurred simultaneously at different geyser basins. We interpret these observations as being induced by dynamic stresses associated with the arrival of large-amplitude surface waves. We suggest that in a hydrothermal system dynamic stresses can locally alter permeability by unclogging existing fractures, thereby changing geyser activity. Furthermore, we suggest that earthquakes were triggered by the redistribution of hydrothermal fluids and locally increased pore pressures. Although changes in geyser activity and earthquake triggering have been documented elsewhere, here we present evidence for changes in a hydrothermal system induced by a large-magnitude event at a great distance, and evidence for the important role hydrothermal systems play in remotely triggering seismicity.

Keywords: Yellowstone National Park, geysers, hydrothermal processes, earthquake swarms.

INTRODUCTION

Hydrothermal systems, including geysers and hot springs, are regions in Earth's crust where hot fluids circulate at shallow depths. Numerical simulations indicate that geyser eruption intervals are highly sensitive to the intrinsic permeabilities of the geyser's conduit and the surrounding rock matrix (Ingebritsen and Rojstaczer, 1993, 1996). It has been suggested that geyser eruption intervals respond to small changes in strain induced by atmospheric loading, Earth tides (Rinehart, 1972), and earthquakes (Silver and Valette-Silver, 1992). Hot springs and geysers in the Yellowstone National Park have displayed significant changes in their eruption patterns following large earthquakes at regional distances (<200 km) and following intense local earthquake swarms (Hutchinson, 1985; Marler, 1964; Pitt and Hutchinson, 1982; Watson, 1961). A recent study (Rojstaczer et al., 2003), however, suggested that geysers might be less sensitive to elastic deformation than previously assumed. In addition, variations in geyser eruption intervals may also be controlled by internal dynamic processes of the geysers (Rojstaczer et al., 2003).

Fluids play a critical role in earthquake nucleation, since elevated fluid pressure will alter the strength and the local stress regime on a fault (Hickman et al., 1995). Evidence for elevated fluid pressures was, for example, detected at the nucleation zone of the M 7.2 1995 Kobe earthquake, Japan (Zhao et al., 1996). Migration and redistribution of fluids might also trigger earthquake swarms (Waite and Smith, 2002) and drive aftershocks (Nur and Booker, 1972). Furthermore, remotely triggered earthquakes occur preferentially in geothermal and volcanic areas, suggesting that fluids are important in explaining this phenomenon (Hill et al., 1993).

On 3 November 2002, a M 7.9 earthquake ruptured the Denali fault in central Alaska (Fig. 1). The Denali fault earthquake (hereafter Denali earthquake) was one of the largest strike-slip earthquakes in North America in the past 150 yr (Eberhart-Phillips et al., 2003). Within hours after the Denali earthquake, we observed significant changes in the eruption intervals of several geysers throughout Yellowstone, despite the large distance, 3100 km, from its epicenter. In addition, intense swarms of local earthquakes occurred close to hydrothermal systems that experienced the changes in geyser activity. In this paper we report on these observations and discuss mechanisms that might explain the observations.

*Now at Swiss Seismological Service, ETH Hoenggerberg, CH 8093 Zurich, Switzerland.

STUDY AREA

The Yellowstone volcanic field, Wyoming, centered in Yellowstone National Park (hereafter called "Yellowstone"), is one of the largest silicic volcanic systems in the world (Christiansen, 2001; Smith and Siegel, 2000). Three major caldera-forming eruptions occurred within the past 2 m.y., the most recent 0.6 m.y. ago. The current Yellowstone caldera spans 75 km by 45 km (Fig. 1). Yellowstone includes >10,000 geysers, hot springs, and fumaroles, which are considered the result of hot water circulating along fracture systems in the upper crust and heated by crystallizing magma at a depth of 10–15 km (Fournier, 1989). Most of Yellowstone's hydrothermal features are located inside the Yellowstone caldera close to two resurgent domes and along a fault zone extending north from Norris Geyser Basin (Fig. 1).

HYDROTHERMAL OBSERVATIONS

Coincident with the arrival of Denali earthquake surface waves, hydrothermal changes were observed at 100 Spring Plain, a hot-spring system at Norris Geyser Basin (S. Sturtevant, 2003, written commun.). Several small hot springs, not known to have geysered before, suddenly surged into a heavy boil with eruptions as high as ~1 m. The temperature at one of these springs increased rapidly from ~42 to 93 °C and the pH value increased from 2.44 to 5.30 before returning to 3.72 ~18 min later. In the same area, another hot spring that was usually clear showed muddy, turbid water.

We monitored eruption intervals of 22 geysers during the winter of 2002–2003 by placing temperature sensors in the runoff channels.[1] Of these 22 instrumented geysers, 8 displayed notable changes in their eruption intervals, i.e., the changes were larger than the

[1]GSA Data Repository item 2004087, table and graphs of changes in eruption intervals at monitored geysers, and cumulative number of earthquakes close to major geyser basins prior to and after the 2002 Denali fault earthquake, is available at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Document Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

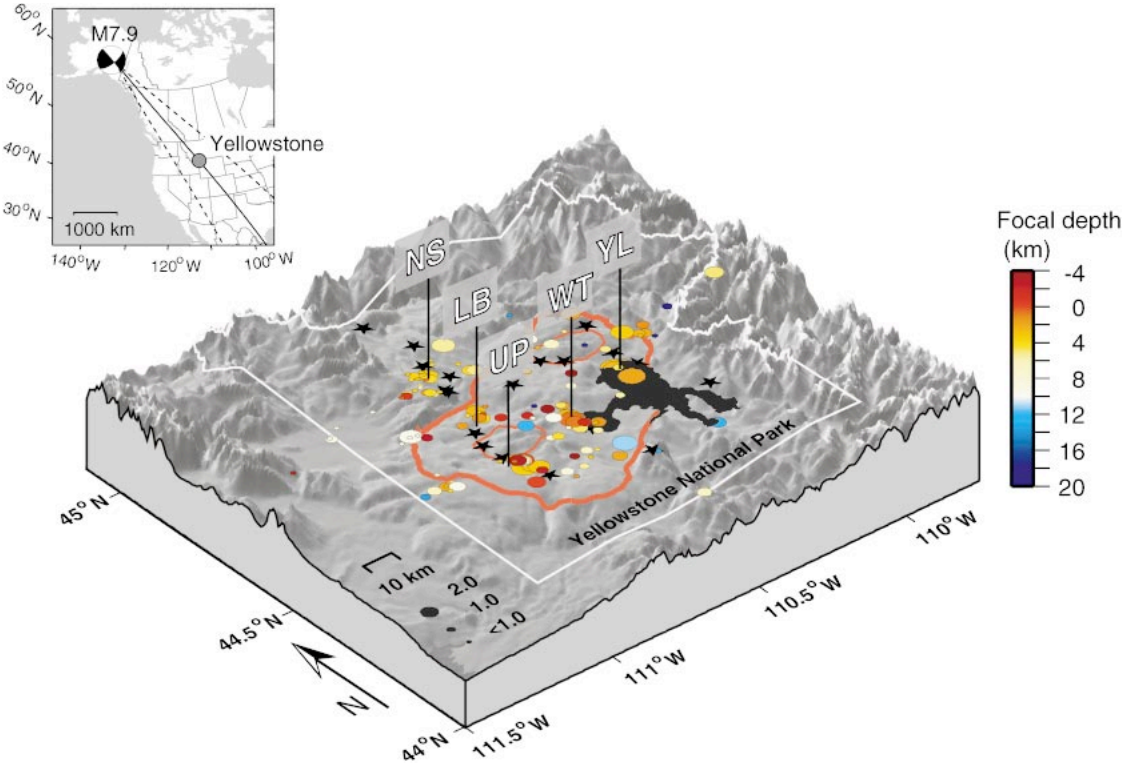

Figure 1. Location of remotely triggered earthquakes (colored circles) within first 6 h following passage of M 7.9 2002 Denali earthquake surface waves. Color of circles is scaled by focal depth and size of circles is scaled with magnitude. Bold red line marks outline of 0.60 Ma Yellowstone caldera. Resurgent domes are shown by thin red lines. White line marks outline of Yellowstone National Park. Major hydrothermal systems are shown by black stars. Major geyser basins are labeled: YL—Yellowstone Lake; WT—West Thumb Geyser Basin; UP—Upper Geyser Basin; LB—Lower Geyser Basin; NS—Norris Geyser Basin. Inset map shows locations of Denali earthquake relative to Yellowstone volcanic field. Solid and dashed lines mark great circle path ±10° traversed by surface waves directed along strike of Denali fault earthquake.

standard error of the intervals prior to the Denali earthquake. Four geysers were too erratic to show any effects, and 10 geysers showed no significant changes. There was no common pattern in geyser response to the Denali earthquake. The most obvious example, Daisy Geyser (Fig. 2) in Upper Geyser Basin, showed a rapid decrease in the eruption interval following the Denali earthquake, recovering close to pre-Denali eruption intervals over subsequent weeks. Other geysers such as Castle, Plate, and Plume Geysers in Upper Geyser Basin, and Pink Geyser in Lower Geyser Basin, displayed short-term irregularities in their eruption behavior lasting for a few days. Lone Pine Geyser in West Thumb Geyser Basin, on the other hand, showed a gradual increase in eruption intervals that peaked three weeks after the Denali earthquake. It is noteworthy that geysers affected by previous nearby earthquakes (Hutchinson, 1985; Marler, 1964)—including the 1959 M 7.5 Hebgen Lake, Montana, and the M 7.3 1983 Borah Peak, Idaho—were not affected by the Denali earthquake, for example, Old Faithful and Grand Geysers in Upper Geyser Basin.

SEISMOLOGICAL OBSERVATIONS

The increase in local earthquake activity in Yellowstone following the Denali earthquake started with the onset of the large-amplitude surface waves. Within the first 6 h following the passage of the surface waves, most of the earthquakes clustered close to major hydrothermal systems (Fig. 1). The triggered earthquakes showed swarm-like behavior, clustering in time and space (Figs. 1 and 3). Many of the triggered events had magnitudes of Mc > 2.0 (Mc denotes a duration magnitude scaled to the local Richter magnitude scale), and some were felt by National Park Service employees. Seismicity in the geyser basins had returned to pre-Denali earthquake background levels 24 h following the passage of the surface waves (Fig. 3). Most of the triggered earthquakes close to the hydrothermal areas were relatively shallow; their focal depths were <5 km (Fig. 1).

Although earthquake swarms are common in Yellowstone, the seismicity following the Denali earthquake is unusual for two reasons. First, 80% of the triggered earthquakes had Mc > 2.0 compared to $<3\%$ of the annual seismicity. Second, earthquakes occurred simultaneously throughout the Yellowstone caldera (Fig. 1). Prior to the Denali earthquake, earthquake swarms of similar intensity—i.e., number of earthquakes with Mc > 1.0—had occurred close to particular hydrothermal systems; however, they never occurred simultaneously throughout Yellowstone.

DISCUSSION

The Denali earthquake was associated with two distinct phenomena in Yellowstone: (1) changes in hydrothermal activity and (2) triggering of local earthquakes. The latter is not an unusual phenomenon; remote triggering of local earthquakes was observed following the 1992 M 7.4 Landers (Hill et al., 1993) and the 1999 M 7.1 Hector mine (Gomberg et al., 2001) earthquakes. Also, the 1988 M 7.6 Gulf of Alaska earthquake triggered swarms of local earthquakes in the Geysers, California, geothermal field at a distance similar to that from the Denali earthquake to Yellowstone (Stark and Davis, 1996).

Previous studies of remote earthquake triggering in volcanic areas favor models where magmatic or hydrothermal fluids interact with dynamic stress transients produced by large-amplitude surface waves (Hill et al., 1995, 1993; Johnston et al., 1995; Linde et al., 1994; Sturtevant et al., 1996). At distances of several fault lengths, static stress changes can be ruled out as an earthquake-triggering mechanism, because they decrease rapidly with distance, falling below stress changes typical of Earth's tidal forces at large distances (Hill et al., 1993). Static stress changes in Yellowstone due to the 2002 Denali earthquake were <10 Pa (G. Anderson, 2003, personal commun.), which is well below static stress changes of ~0.1 MPa that have been proposed to trigger earthquakes (King et al., 1994). Peak dynamic stress associated with the passage of large-amplitude surface waves of the 2002 Denali earthquake was 0.16–0.22 MPa, measured at

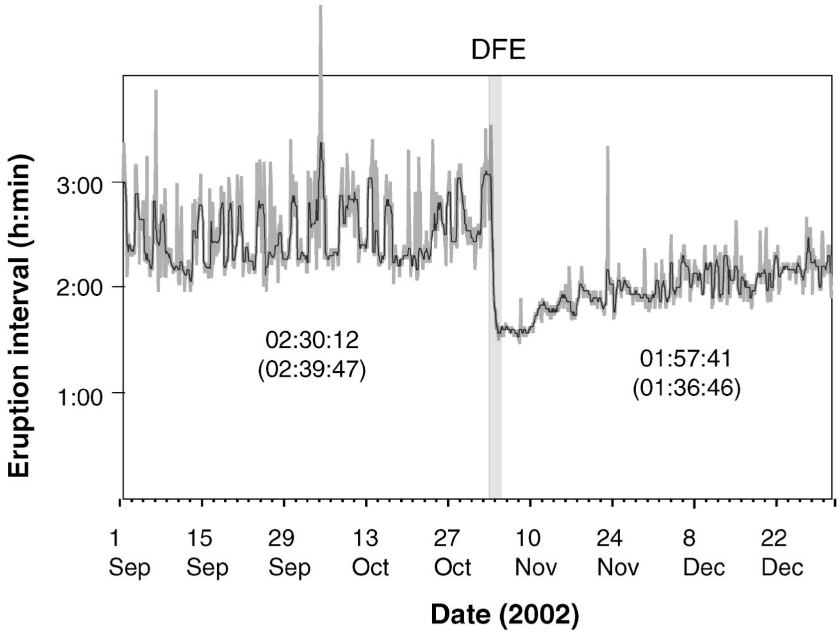

Figure 2. Geyser eruption intervals of Daisy Geyser in Upper Geyser Basin between 1 September and 31 December 2003 affected by Denali fault earthquake (DFE). Gray lines are raw data (individual eruption intervals); black lines are smoothed data (moving median over several data points). Median eruption intervals prior to and after DFE are shown in hour:minute:second (h:min:s). Median eruption intervals prior and after DFE are computed over several weeks and over few days (in brackets), respectively. Time of DFE is marked by bold gray line.

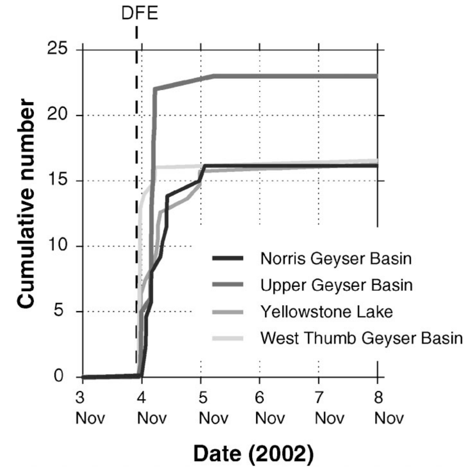

Figure 3. Cumulative number of triggered earthquakes at geyser basins described in this study, following Denali earthquake. Time of Denali fault earthquake (DFE) is indicated by dashed line.

broadband seismometers in Yellowstone (Farrell et al., 2002).

One type of model proposed to transfer dynamic stress transients into sustained stress changes involves the interaction of large-amplitude surface waves with a partially crystallized magma body, such as advective overpressurization (Linde et al., 1994) or relaxation of a crustal magma body (Hill et al., 1995). Although a body of partially crystallized magma might exist beneath Yellowstone (Husen et al., 2004; Miller and Smith, 1999), these models have time constants of several days. They cannot explain the rapid decay of seismicity within 24 h observed at Yellowstone.

In Yellowstone, seismicity was mainly triggered close to major geyser basins, indicating that hydrothermal fluids play a critical role. There are a number of triggering mechanisms involving the interaction of hydrothermal fluids with large-amplitude surface waves. These mechanisms include rupturing of isolated compartments in which superhydrostatic fluid pressure prevailed (Brodsky et al., 2003; Johnston et al., 1995), the release of gas bubbles within hydrothermal fluids producing advective gas overpressure (Linde et al., 1994), and oscillation of gas bubbles within a saturated hydrothermal fluid, thereby increasing local pore pressure through rectified diffusion (Sturtevant et al., 1996). We note that theoretical problems have been suggested for the mechanisms of advective gas overpressure (Bagdassarov, 1994) and rectified diffusion (Ichihara et al., 2003), which might reduce the efficiency of these mechanisms. Hydrothermal systems in Yellowstone satisfy all the conditions required by triggering mechanisms, i.e., the existence of a highly fractured medium filled with a highly pressurized two-phase fluid consisting of steam and liquid. Hence, all mechanisms are possible and capable of triggering local earthquakes in Yellowstone.

Numerical modeling of geyser periodicity (Ingebritsen and Rojstaczer, 1993, 1996) indicates that permeability is a key control on eruption intervals. An increase in the permeability of the geyser's conduit or the surrounding rock matrix can decrease eruption intervals. Coseismic changes in local permeability have been inferred in response to the M 7.1 Loma Prieta earthquake (Rojstaczer and Wolf, 1992), but they were restricted to distances of a few fault lengths. For distances larger than a few fault lengths, it has been suggested that dynamic stress transients associated with large-amplitude surface waves can alter local permeability through loosening and entraining of particles that were deposited by weathering (Brodsky et al., 2003). In hydrothermal areas, fractures are clogged by rapid precipitation of silica (Lowell and Germanovich, 1993). Loosening of these deposits can reopen existing fractures and alter permeability, thus changing geyser eruption intervals. Ongoing precipitation after the Denali earthquake can reseal these fractures, thus decreasing permeability and increasing geyser eruption intervals through time, as observed at Daisy Geyser (Fig. 2). Static stress changes, which in Yellowstone were well below stresses associated with Earth tidal forces, can be ruled out as a cause of the observed changes in geyser activity because geysers in Upper Geyser Basin did not respond to Earth tides (Rojstaczer et al., 2003).

Seismicity remotely triggered by the Denali earthquake might also have produced stress transients that could, if close enough, have altered geyser permeability. But within our error limits, these earthquakes were not triggered close to the geysers, but appear to be associated with the deeper parts of the hydrothermal reservoirs (Fournier, 1989). It is unlikely that those earthquakes changed permeability a few kilometers away, because their magnitudes were relatively small. However, local seismicity could have changed fluid flow within the hydrothermal reservoirs, and consequently affected the recharge rates of individual geysers. Although geyser eruption intervals are largely independent of recharge rates (Ingebritsen and Rojstaczer, 1996), mass discharge per eruption cycle is quite sensitive to mass recharge into the geyser. Unfortunately, we are not able to estimate mass discharges, because only information on water temperatures in the runoff channels is available. The lack of mass-discharge data prevents us from resolving any possible influence of local seismicity on geyser eruption behavior.

In Yellowstone, geysers in Upper Geyser Basin have been shown to be insensitive to small strains produced by Earth tides and atmospheric loading of ~20–100 nanostrain

(Rojstaczer et al., 2003). Peak dynamic strains associated with the surface waves of the Denali earthquake were ~470 nanostrain, based on a measured peak ground velocity of 1.6 cm/s at a broadband seismic station close to Upper Geyser Basin. Thus, strain dynamically induced by the Denali earthquake is several times larger than strain induced by diurnal or semidiurnal processes, suggesting that large-amplitude surface waves can induce strain transients that are large enough to change geyser eruption behavior.

CONCLUSIONS

The M 7.9 Denali earthquake provided the first observations on changes in geyser activity and seismicity in Yellowstone following a large earthquake at a distance of several fault lengths. Prior to the Denali earthquake, only the 1992 Landers earthquake was known to remotely trigger earthquakes in Yellowstone (Hill et al., 1993), but observations on hydrothermal changes were not available. The observed changes in geyser activity and seismicity were induced by large-amplitude surface waves associated with the Denali fault earthquake. Induced dynamic stresses or strains were well above those associated with Earth tides. Our observations suggest that fluids play an important role to transfer dynamic stress transients into sustained stress changes capable of triggering earthquakes, as suggested previously (Hill et al., 1993; Sturtevant et al., 1996; Brodsky et al., 2003). Furthermore, our observations demonstrate that geyser activity can be altered by large-magnitude earthquakes at distances of several fault lengths.

ACKNOWLEDGMENTS

Smokey Sturtevant kindly provided us with his personal observations in Norris Geyser Basin. We thank S. Nava and F. Terra of the University of Utah Seismograph Stations for picking earthquake arrival times. S. Miller, K. Pankow, G. Waite, Jamie Farrell, and S. Wiemer provided helpful discussions and information. Thoughtful reviews by Mark H. Anders, Steve E. Ingebritsen, and Michael Manga significantly improved this manuscript. This research was supported by a cooperative University of Utah–Swiss Science Foundation (grant 8220-061284) project, the U.S. Geological Survey Volcano Hazard Program, the Yellowstone Volcano Observatory, the National Science Foundation Continental Dynamics Program, and the National Park Service, Yellowstone National Park.

REFERENCES CITED

Bagdassarov, N., 1994, Pressure and volume changes in magmatic systems due to the vertical displacement of compressible materials: Journal of Volcanology and Geothermal Research, v. 63, p. 95–100.

Brodsky, E.E., Roeloffs, E., Woodcock, D., Gall, I., and Manga, M., 2003, A mechanism for sustained groundwater pressure changes induced by distant earthquakes: Journal of Geophysical Research, v. 108, no. B8, 2390, doi: 10.1029/2002JB002321.

Christiansen, R.L., 2001, The Quaternary and Pliocene Yellowstone plateau volcanic field of Wyoming, Idaho, and Montana: U.S. Geological Survey Professional Paper 729-G, 145 p.

Eberhart-Phillips, D., and 28 others, 2003, The 2002 Denali fault earthquake, Alaska: A large magnitude, slip-partitioned event: Science, v. 300, p. 1113–1118.

Farrell, J., Smith, R.B., Benz, H.M., Pankow, K.L., and Husen, S., 2002, Amplified ground response across the western U.S. interior from the M7.9 Denali earthquake: Eos (Transactions, American Geophysical Union), v. 83, abs. S72F-1358.

Fournier, R.O., 1989, Geochemistry and dynamics of the Yellowstone National Park hydrothermal system: Annual Review of Earth and Planetary Sciences, v. 17, p. 13–53.

Gomberg, J., Reasenberg, P.A., Bodin, P., and Harris, R.A., 2001, Earthquake triggering by seismic waves following the Landers and Hector Mine earthquake: Nature, v. 411, p. 462–466.

Hickman, S., Sibson, R., and Bruhn, R., 1995, Introduction to special section: Mechanical involvement of fluids in faulting: Journal of Geophysical Research, v. 100, p. 12,831–12,840.

Hill, D.P., Reasenberg, and 30 others, 1993, Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake: Science, v. 260, p. 1617–1623.

Hill, D.P., Johnston, M.J.S., and Langbein, J.O., 1995, Response of Long Valley caldera to the Mw = 7.3 Landers, California, earthquake: Journal of Geophysical Research, v. 100, p. 12,985–13,005.

Husen, S., Smith, R.B., and Waite, G.P., 2004, Evidence for gas and magmatic sources beneath the Yellowstone volcanic field from seismic tomographic imaging: Journal of Volcanology and Geothermal Research (in press).

Hutchinson, R.A., 1985, Hydrothermal changes in the upper Geyser Basin, Yellowstone National Park, after the 1983 Borah Peak, Idaho, earthquake, *in* Stein, R.S., and Bucknnam, R.C., eds., Proceedings of Workshop XXVIII on the Borah Peak, Idaho, earthquake: U.S. Geological Survey Open-File Report 85-0290-A, p. 612–624.

Ichihara, M., Brodsky, E.E., and Kanamori, H., 2003, Reconsideration of the effect of rectified diffusion in volcanic-seismic systems: Sapporo, Japan, General Assembly, International Union of Geodesy and Geophysics, Abstract volume, p. JSV04/01P/D-001.

Ingebritsen, S.E., and Rojstaczer, S.A., 1993, Controls on geyser periodicity: Science, v. 262, p. 889–892.

Ingebritsen, S.E., and Rojstaczer, S.A., 1996, Geyser periodicity and the response of geysers to deformation: Journal of Geophysical Research, v. 101, p. 21,891–21,905.

Johnston, M.J.S., Hill, D.P., Linde, A.T., Langbein, J.O., and Bilham, R.G., 1995, Transient deformation during triggered seismicity from the 28 June 1992 M_w = 7.3 Landers earthquake at Long Valley volcanic caldera, California: Seismological Society of America Bulletin, v. 85, p. 787–795.

King, G.C.P., Stein, R.S., and Lin, J., 1994, Static stress changes and the triggering of earthquakes: Seismological Society of America Bulletin, v. 84, p. 935–953.

Linde, A.T., Selwyn Sacks, I., Johnston, M.J.S., Hill, D.P., and Bilham, R.G., 1994, Increased pressure from rising bubbles as a mechanism for remotely triggered seismicity: Nature, v. 371, p. 408–410.

Lowell, R., and Germanovich, L., 1993, Silica precipitation in fractures and the evolution of permeability in hydrothermal upflow zones: Science, v. 260, p. 192–194.

Marler, G.D., 1964, Effects of the Hebgen Lake Earthquake of August 17, 1959, on the hot springs of the Firehole Geyser Basins, Yellowstone National Park: U.S. Geological Survey Professional Paper 435-Q, p. 185–197.

Miller, D.S., and Smith, R.B., 1999, P and S velocity structure of the Yellowstone volcanic field from local earthquake and controlled-source tomography: Journal of Geophysical Research, v. 104, p. 15,105–15,121.

Nur, A., and Booker, J.R., 1972, Aftershocks caused by pore fluid flow?: Science, v. 175, p. 885–887.

Pitt, A.M., and Hutchinson, R.A., 1982, Hydrothermal changes related to earthquake activity at Mud Volcano, Yellowstone National Park, Wyoming: Journal of Geophysical Research, v. 87, p. 2762–2766.

Rinehart, J.S., 1972, Fluctuations in geyser activity caused by variations in Earth tidal forces, barometric pressure, and tectonic stresses: Journal of Geophysical Research, v. 77, p. 342–350.

Rojstaczer, S.A., and Wolf, S., 1992, Permeability changes associated with large earthquakes: An example from Loma Prieta, California: Geology, v. 20, p. 211–214.

Rojstaczer, S.A., Galloway, D.L., Ingebritsen, S.E., and Rubin, D.M., 2003, Variability in geyser eruptive timing and its causes: Yellowstone National Park: Geophysical Research Letters, v. 30, no. 18, 1953, doi: 10.1029/2003GL017853.

Silver, P.G., and Valette-Silver, N.J., 1992, Detection of hydrothermal precursors to large northern California earthquakes: Science, v. 257, p. 1363–1368.

Smith, R.B., and Siegel, L., 2000, Windows into the Earth: The geology of Yellowstone and Grand Teton parks: London, Oxford University Press, 247 p.

Stark, M.A., and Davis, S.D., 1996, Remotely triggered microearthquakes at The Geysers geothermal field, California: Geophysical Research Letters, v. 23, p. 945–948.

Sturtevant, B., Kanamori, H., and Brodsky, E.E., 1996, Seismic triggering by rectified diffusion in geothermal systems: Journal of Geophysical Research, v. 101, p. 25,269–25,282.

Waite, G.P., and Smith, R.B., 2002, Seismic evidence for fluid migration accompanying subsidence of the Yellowstone caldera: Journal of Geophysical Research, v. 107, no. B9, 2177, doi: 10.1029/2001JB000586.

Watson, B.N., 1961, Effects of the August 17, 1959 earthquake and subsequent quaking upon thermal features of Yellowstone National Park [M.S. thesis]: Tucson, University of Arizona, 83 p.

Zhao, D., Kanamori, D., Negishi, H., and Wiens, D., 1996, Tomography of the source area of the 1995 Kobe earthquake: Evidence for fluids at the hypocenter?: Science, v. 274, p. 1891–1894.

Manuscript received 3 December 2003
Revised manuscript received 5 February 2004
Manuscript accepted 17 February 2004

Printed in USA