2003

High precision earthquake locations reveal seismogenic structure beneath Mammoth Mountain, California

Stephanie Prejean
U.S. Geological Survey

Anna Stork
University of Durham

William Ellsworth
U.S. Geological Survey

David Hill
U.S. Geological Survey

Bruce Julian
U.S. Geological Survey

High precision earthquake locations reveal seismogenic structure beneath Mammoth Mountain, California

Stephanie Prejean,[1] Anna Stork,[2] William Ellsworth,[1] David Hill,[1] and Bruce Julian[1]

Received 4 August 2003; revised 25 October 2003; accepted 6 November 2003; published 18 December 2003.

[1] In 1989, an unusual earthquake swarm occurred beneath Mammoth Mountain that was probably associated with magmatic intrusion. To improve our understanding of this swarm, we relocated Mammoth Mountain earthquakes using a double difference algorithm. Relocated hypocenters reveal that most earthquakes occurred on two structures, a near-vertical plane at 7–9 km depth that has been interpreted as an intruding dike, and a circular ring-like structure at ~5.5 km depth, above the northern end of the inferred dike. Earthquakes on this newly discovered ring structure form a conical section that dips outward away from the aseismic interior. Fault-plane solutions indicate that in 1989 the seismicity ring was slipping as a ring-normal fault as the center of the mountain rose with respect to the surrounding crust. Seismicity migrated around the ring, away from the underlying dike at a rate of ~0.4 km/month, suggesting that fluid movement triggered seismicity on the ring fault. *INDEX TERMS:* 7209 Seismology: Earthquake dynamics and mechanics; 7230 Seismology: Seismicity and seismotectonics; 7280 Seismology: Volcano seismology (8419); 7299 Seismology: General or miscellaneous; 8499 Volcanology: General or miscellaneous. **Citation:** Prejean, S., A. Stork, W. Ellsworth, D. Hill, and B. Julian, High precision earthquake locations reveal seismogenic structure beneath Mammoth Mountain, California, *Geophys. Res. Lett.*, *30*(24), 2247, doi:10.1029/2003GL018334, 2003.

1. Introduction

[2] Mammoth Mountain is a dacitic cumulovolcano located on the southwestern rim of the Long Valley Caldera in eastern California, near the town of Mammoth Lakes (Figure 1) [see *Bailey*, 1989; *Hill et al.*, 2002a; and *Prejean et al.*, 2002; for review of caldera history and recent activity]. In May 1989 an eleven-month-long earthquake swarm began beneath the mountain [*Hill et al.*, 1990]. Deformation data suggest that magma was intruded beneath Mammoth Mountain at the time of the swarm [*Langbein et al.*, 1995]. Like many earthquake swarms associated with magmatic intrusion [*McNutt*, 2002], the 1989 Mammoth Mountain swarm had a high b-value and was characterized by spasmodic bursts of high-frequency brittle-failure earthquakes and mid-crustal long-period (LP) earthquakes [*Hill et al.*, 1990]. No broadband seismometers were operating in the area in 1989, but more recent data show that spasmodic bursts beneath Mammoth Mountain are sometimes associated with very-long-period (VLP) earthquakes that likely reflect the movement of fluids beneath the mountain [*Hill et al.*, 2002a]. The onset of magmatic CO_2 degassing around the flanks of the mountain (Figure 2a) [*Farrar et al.*, 1995] and an increase in magmatic helium in helium isotopic ratios from a fumerole on the north flank of Mammoth Mountain [*Sorey et al.*, 1999] indicate that the 1989 swarm was associated with the release of magmatic volatiles. The continued occurrence of mid-crustal LP and occasional VLP earthquakes together with CO_2 degassing to the present time suggest that magma continues to move at depth in the vicinity of Mammoth Mountain [*Pitt and Hill*, 1994; *Hill et al.*, 2002b].

[3] In order to better understand the internal structure and plumbing system of Mammoth Mountain, we relocated ~2700 high-frequency brittle-failure earthquakes, all with magnitude less than or equal to M 3.4 (detection threshold M ~ 0.0, completeness threshold M 1.2), that occurred between 1980 and 2002 under Mammoth Mountain by applying the double-difference earthquake location algorithm, *HypoDD*, of *Waldhauser and Ellsworth* [2000] to routinely determined P-phase arrival time readings from the Northern California Seismic Network (NCSN) (Figure 1). The double-difference algorithm has been used to resolve sharp images of fault structure in the south moat of the Long Valley Caldera and the Sierra Nevada batholith to its south with roughly 100 m accuracy [*Prejean et al.*, 2002]. The hypocenters described in this paper were relocated using the same velocity model and input parameters used by *Prejean et al.* [2002] with comparable success. The 1989 Mammoth Mountain swarm contained 52% of the 2700 earthquakes relocated in this study in the 1980 to 2002 time period, and we focus on the geometry of structures that were seismically active during this swarm.

2. High-Precision Earthquake Locations

[4] During the 1989 Mammoth Mountain swarm earthquakes in the 7–9 km depth range occurred on a NNE trending slab-like structure with dimensions of roughly 2 km in length and 0.5 km in width (Figures 2b, 2f, and 3). This structure has been interpreted as an intruding dike [*Hill et al.*, 1990]. Fault-plane solutions support this interpretation, as T-axes are oriented perpendicular to the slab (Figure 4c).

[5] With the exception of seismicity along the inferred dike and deep LP earthquakes southeast of Mammoth Mountain [*Pitt and Hill*, 1994; *Hill et al.*, 2002b], the crust directly beneath Mammoth Mountain at depths greater than 6 km has been aseismic since 1980. Thus, the crust below 6 km depth may be unable to undergo brittle failure unless strained very rapidly, as when a dike is intruded. It is interesting to note that the brittle-ductile transition is shal-

[1]U.S. Geological Survey, Menlo Park, California, USA.
[2]Department of Geological Sciences, University of Durham, Durham, UK.

0094-8276/03/2003GL018334$05.00

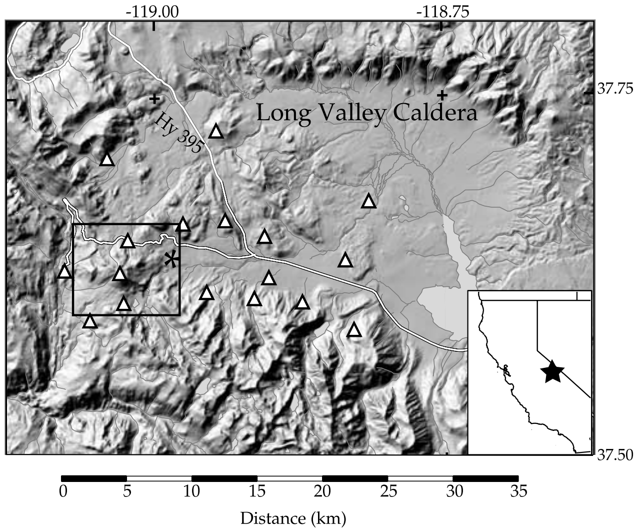

Figure 1. Shaded relief map of Long Valley Caldera showing location of Mammoth Mt. (black box), the town of Mammoth Lakes, CA (black star) and NCSN seismometers (white triangles). Inset shows location of Long Valley Caldera in Eastern California.

lower beneath Mammoth Mountain than beneath the crust south and east of Mammoth Mountain [*Hill*, 1992], possibly due to the presence of magma.

[6] Above the northern end of the seismicity slab described above, relocated hypocenters from the 1989 swarm define a circular ring-like structure centered beneath the summit of Mammoth Mountain at 5–6 km depth (Figures 2e and 3). The earthquakes defining this ring lie on a conical surface ~2 km in diameter, which dips outward away from its aseismic center (Figure 2e, inset). Earthquake hypocenters suggest that at shallow depths there is at least one additional ring-like structure at ~3 km depth similar to

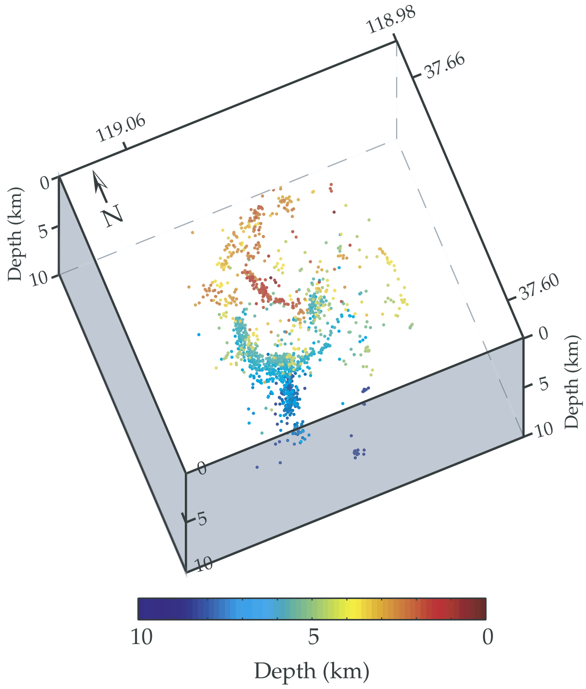

Figure 3. Relocated seismicity for the 1989 Mammoth Mt. earthquake swarm shown in perspective view. Azimuth of view is 23° east of north. Elevation of view is 76° from horizontal. Hypocenters are color-coded with depth.

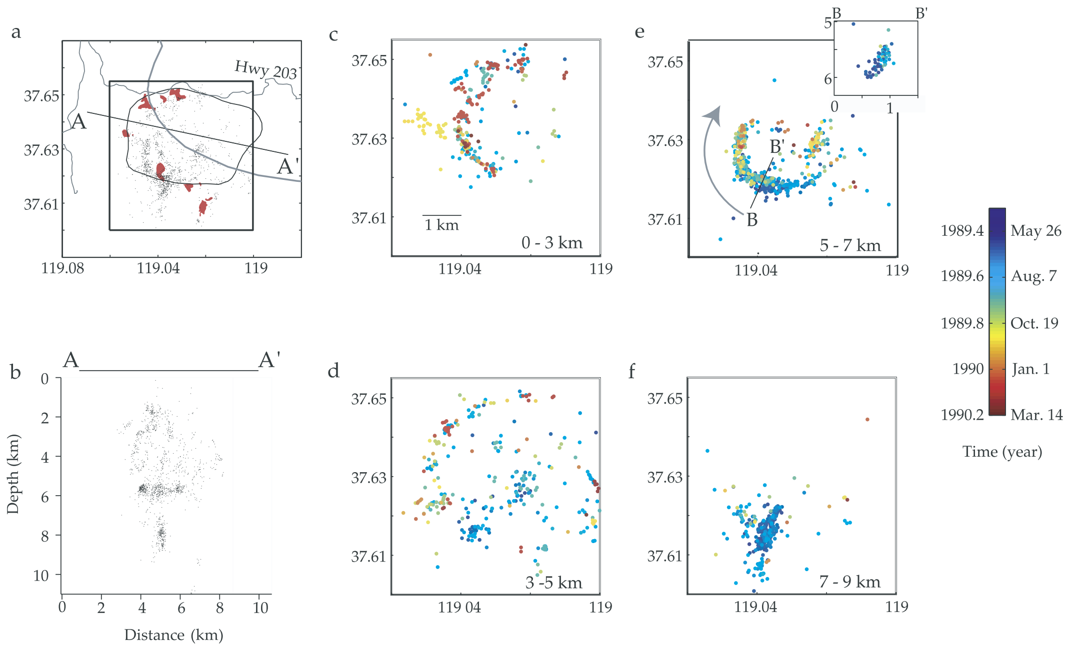

Figure 2. Relocated seismicity for the 1989 earthquake swarm beneath Mammoth Mt. (a) Map view of entire swarm showing the outline of Mammoth Mt. High CO_2 flux areas are shown in red. (b) Cross section of hypocenters shown in a. (c)–(f) Map views of 1989 relocated seismicity, color-coded with time for specific depth intervals. The black square in (2a) indicates the area shown in (2c–2f). Panel (2e) also shows a cross section of the ring structure in the 5–7 km depth range. Axes of this inset are labeled in km. Arrow in panel (2e) shows direction seismicity migrated around ring structure from May 1989 to January 1990.

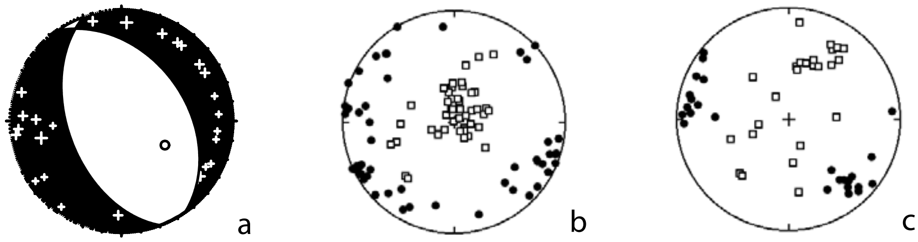

Figure 4. (a) Typical-first motion fault-plane solution of an earthquake on the primary ring fault at 5–6 km depth. Crosses denote compressional first motions. Circle denotes dilatational first motion. Sterographic plots of P- and T-axes of earthquakes on primary ring fault at (b) 5–7 km depth. (c) 7–9 km depth. Squares are P-axes. Filled circles are T-axes.

the primary ring at 5–6 km depth (Figures 2c, 2d, and 3). However, because there are few earthquakes in this shallow depth range of 1–5 km, it is difficult to determine whether the shallow ring is an extension of the primary ring, which would suggest that either the earthquakes occurred on a SSW plunging cylinder, or the ring structures are noncontiguous, concentric ring faults.

[7] The 1989 swarm began in late May at ~6 km depth beneath the south flank of Mammoth Mountain near the intersection of the slab-like structure (inferred dike) and the primary ring structure (Figures 2e and 2f). The slab was seismically active only through July 1989, whereas the ring was active through January 1990. Following the onset of seismicity along the southern side of the ring in late May, earthquake hypocenters migrated circumferentially around the ring toward the north away from the probable dike, covering a distance of roughly 2.5 km in 7 months. Seismicity also shallowed with time so that by January seismicity was primarily confined to depths above 4 km.

3. Physical Processes Driving the 1989 Mammoth Mountain Swarm

[8] Outward dipping rings of seismicity have been observed bounding Rabaul caldera [*Mori and McKee*, 1987] and have been suggested to bound Mount Pinatubo caldera [*Mori et al.*, 1996]. *Ekstrom* [1994] and *Nettles and Ekstrom* [1998] have also suggested similar structures at Bardarbunga volcano in Iceland. Such outwardly dipping ring faults located above spherical or cylindrical magmatic bodies are surfaces optimally oriented for failure [*Anderson*, 1936; *Chadwick and Dieterich*, 1995] and could accommodate deformation above intruding magma, which may be the case at Mammoth Mountain.

[9] We determined first motion fault-plane solutions for 49 earthquakes that occurred in 1989 along the primary ring structure at 5–6 km depth. If we assume these earthquakes are shear failure double-couple events, The P- and T- axes distribution indicates that the ring structure was acting as a ring normal fault (Figure 4b). This suggests that the ring fault was acting like the walls of a piston as the center of the mountain rose slightly with respect to the surrounding crust as magma was emplaced beneath it. The total brittle-failure normal slip on the ring fault was ~1 cm based on cumulative earthquake moment, assuming a stress drop of 2 MPa.

[10] In order to investigate the hypothesis that a 1989 dike intrusion, itself, formed the ring faults we calculated the stress field resulting from a dike intrusion beneath the south flank of Mammoth Mountain using the computer program *Coulomb* [*Toda et al.*, 1998]. In our model, the spatial extent of the intrusion is defined by the seismicity slab observed at 7–9 km depth (Figures 2f and 3). Although this analysis predicts normal slip across the observed ring fault at 5–6 km depth in response to the dike intrusion, the differential stress caused by the dike intrusion is much higher south of the ring faults than on the ring faults themselves. Thus, if rock properties are homogenous throughout the Mammoth Mountain area, the observed ring faults are not likely surfaces to fail in response to dike intrusion along the seismicity slab. This suggests that the ring faults may be pre-existing zones of weakness that formed above previous magmatic intrusions and were simply reactivated during the 1989 swarm. Earthquake locations beneath Mammoth Mountain for the time period 1980–1988 support this interpretation, as they show a concentration of seismicity on the ring faults before 1989, suggesting that they are in fact pre-existing structures.

[11] Likely physical processes that may have reactivated the ring structure beneath Mammoth Mountain during the 1989 intrusion involve magmatic fluids exsolving from an intruding dike (possibly including H_2O and/or CO_2) and migrating around the perimeter of the preexisting ring fault away from the underlying dike, triggering earthquakes along this zone of weakness. The seismicity migration rate is consistent with observed rates for the diffusion of water through rocks with permeabilities of 10^{-2} to 10^{-1} mdarcy [e.g., *Zoback and Hickman*, 1982] based on a one-dimensional fluid flow model following *Carslaw and Jaeger* [1959]. Thus the spatial and temporal development of the swarm supports the conclusion that earthquakes that occurred on the ring fault at 5–6 km depth were triggered by fluids.

[12] The tomography study of *Foulger et al.* [2003] suggests that following the 1989 swarm CO_2 and/or water were added to the crust beneath Mammoth Mountain in the 0–5 km depth range, where we observe at least one shallow ring structure (Figures 2c and 2d). Figure 2a shows that areas of high CO_2 flux at the surface form a partial ring about the summit of Mammoth Mountain that is quasi-coincident with the underlying rings of seismicity. This suggests that the ring structure provides a pathway for magmatic volatiles to reach the surface.

[13] *Dreger et al.* [2000] and *Julian et al.* [1999] obtained earthquake moment tensor focal mechanisms in the Long Valley Caldera area in 1997 that have positive volumetric components. They conclude that these moment tensor

solutions reflect the movement of magmatically derived fluids. Thus we might expect moment tensors of earthquakes that occurred on the seismicity ring in 1989 to have a volumetric component as well. Unfortunately, because the focal mechanisms of the earthquakes on the ring fault are poorly constrained by first motion data alone (Figure 4) and there were no three-component seismometers in the area, we cannot determine if the earthquakes' moment tensors have volumetric components.

[14] It is interesting to note that the crustal volume encircled by the rings was largely aseismic during the 1989 swarm. This observation raises the question: Was magma present within the volume outlines by ring faults? Because the volume inside the ring faults experienced some high frequency enriched earthquakes in the 1980s and 1990s, we conclude that at 0–6 km depth, the crust beneath Mammoth Mountain is primarily cold and therefore brittle. A thin dike intrusion at these depths however, as suggested by deformation data [*Langbein et al.*, 1995; *Langbein*, 2003], remains a possibility. However, we infer that the seismicity migration around the ring fault itself does not reflect the tip of a propagating dike. A dike with a thickness consistent with deformation data (<20 cm) [*Langbein et al.*, 1995] would freeze at the relatively slow propagation rate we observe in the seismicity [following *Rubin*, 1995].

4. Conclusions

[15] By relocating earthquakes beneath Mammoth Mountain, CA using *HypoDD*, we have gained a better understanding of the internal seismogenic structures of the mountain and the pathways through which magmatic volatiles escape to the surface. Relocated catalog seismicity beneath Mammoth Mountain, shows an outward dipping ring of seismicity beneath the center of the mountain at roughly 5.5 km depth that was seismically active during a probable dike intrusion in 1989. The ring structure appears to have been reactivated in 1989 as a ring normal fault, possibly accommodating deformation above a deeper inflating dike. Seismicity migrated around the ring structure at a rate of ~0.4 km per month. We infer that these earthquakes were triggered by the movement of over-pressured magmatically-derived fluids away from their source. We suggest that the ring structure provides a pathway for the continuing degassing of magmatic CO_2 that has been observed around the flanks of Mammoth Mountain since 1989.

[16] **Acknowledgments.** Discussions with Mark Zoback, Mitch Pitt, Gillian Foulger, Emily Brodsky, and Allan Rubin contributed to the ideas presented in this paper. We thank Phillip Dawson, Margaret Mangan, Jim Mori and one anonymous reviewer for their helpful reviews.

References

Anderson, E. M., The dynamics of the formation of cone sheets, ring-dikes and cauldron subsidences, *R. Soc. Edinburgh Proc.*, *56*, 128–163, 1936.

Bailey, R., Geologic map of the Long Valley caldera, Mono-Inyo craters volcanic chain, and vicinity, eastern California, *U.S. Geol. Surv. Misc. Inv. Ser.*, 160–753, 1989.

Carslaw, H. S., and J. C. Jaeger, *Conduction of Heat in Solids*, 2nd ed., 510 pp., Oxford Univ. Press, New York, 1959.

Chadwick, W. W., and J. H. Dieterich, Mechanical modeling of circumferential and radial dike intrusion on Galapagos volcanoes, *J. Vol. and Geotherm. Res.*, *66*, 37–52, 1995.

Dreger, D. S., H. Tkalcic, and M. Johnston, Dilatational processes accompanying earthquakes in the Long Valley caldera, *Science*, *288*, 122–125, 2000.

Ekstrom, G., Anomalous earthquakes on volcano ring-fault structures, *Earth Planet. Sci. Lett.*, *128*, 707–712, 1994.

Farrar, C. D., M. L. Sorey, W. C. Evans, J. F. Howle, B. D. Kerr, B. M. Kennedy, C.-Y. King, and J. R. Southon, Forest-killing diffuse CO_2 emission at Mammoth Mountain as a sign of magmatic unrest, *Nature*, *376*, 675–678, 1995.

Foulger, G. R., B. R. Julian, A. M. Pitt, D. P. Hill, P. E. Malin, and E. Shalev, Three-dimensional crustal structure of Long Valley caldera, California, and evidence for the migration of CO_2 under Mammoth Mountain, *J. Geophys. Res.*, *108*(B3), 2147, doi:10.1029/2000JB000041, 2003.

Hill, D. P., Temperatures at the base of the seismogenic crust beneath Long Valley caldera, California, and the Phlegrean Fields caldera, Italy, *IAVCEI Proceedings in Volcanology, Volume 3*, edited by P. Gasparini, R. Scarpa, and K. Aki, 432–461, 1992.

Hill, D. P., W. L. Ellsworth, M. J. S. Johnston, J. O. Langbein, D. H. Oppenheimer, A. M. Pitt, P. A. Reasenberg, M. L. Sorey, and S. R. McNutt, The 1989 earthquake swarm beneath Mammoth Mountain, California: An initial look at the 4 May through 30 September activity, *Bull. Seismol. Soc. Am.*, *80*, 325–339, 1990.

Hill, D. P., D. Dzurisin, W. L. Ellsworth, E. T. Endo, D. L. Galloway, T. M. Gerlach, M. S. J. Johnston, K. A. McGee, C. D. Miller, D. Oppenheimer, and M. L. Sorey, Response plans for volcanic hazards in the Long Valley caldera and Mono craters area, California, *U.S. Geol. Surv. 2185*, 2002a.

Hill, D. P., P. Dawson, M. J. S. Johnston, and A. M. Pitt, Very-long period volcanic earthquakes beneath Mammoth mountain, California, *Geophys. Res. Lett.*, *29*(10), doi:10.1029/2002GLO14833, 2002b.

Julian, B. R., G. R. Foulger, D. P. Hill, A. M. Pitt, P. E. Malin, and E. Shalev, Moment tensors of volcanic microearthquakes at Long Valley caldera, Eastern California, *Eos Trans. AGU*, *80*, F665, 1999.

Langbein, J. O., Deformation of the Long Valley caldera, California; Inferences from measurements from 1988 to 2001, *J. Volcanol. Geotherm. Res.*, in press, 2003.

Langbein, J., D. Dzurisin, G. Marshall, R. Stein, and J. Rundle, Shallow and peripheral volcanic sources of inflation revealed by modeling two-color geodimeter and leveling data from Long Valley caldera, California, 1988–1992, *J. Geophys. Res.*, *100*, 12,487–12,495, 1995.

McNutt, S., Volcano seismology and monitoring for eruptions, *International Handbook of Earthquake and Engineering Seismology*, edited by W. Lee, H. Kanamori, P. C. Jennings, and C. Kissinger, 383–402, 2002.

Mori, J., and C. McKee, Outward-dipping ring-fault structure at Rabaul caldera as shown by earthquake locations, *Science*, *235*, 193–194, 1987.

Mori, J., R. White, D. Harlow, P. Okubo, J. Power, R. Hoblitt, E. Laguerta, L. Lanuza, and B. Bautista, Volcanic earthquakes following the 1991 climactic eruption of Mount Pinatubo, Philippines: Strong seismicity during a waning eruption, in *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines*, edited by C. G. Newhall and R. S. Punongbayan, Univ. of Washington Press, 339–350, 1996.

Nettles, M., and G. Ekstrom, Faulting mechanism of anomalous earthquakes near Bardarbunga volcano, Iceland, *J. Geophys. Res.*, *103*, 17,973–17,983, 1998.

Pitt, A. M., and D. P. Hill, Long-period earthquakes in the Long Valley caldera region, eastern California, *Geophys. Res. Lett.*, *21*, 1679–1682, 1994.

Prejean, S., W. L. Ellsworth, M. Zoback, and F. Waldhauser, Fault structure and kinematics of the Long Valley caldera region, California, revealed by high-accuracy earthquake hypocenters and focal mechanism stress inversions, *J. Geophys. Res.*, *107*, doi:10.1029/2001JB001168, 2002.

Rubin, A. M., Propagation of magma-filled cracks, *Ann. Rev. Earth Plan. Sci.*, *23*, 287–336, 1995.

Sorey, M. L., W. C. Evans, B. M. Kennedy, J. D. Rogie, and A. C. Cook, Magmatic gas emissions from Mammoth Mountain, Mono County, California, *Calif. Geol.*, *52*, 4–16, 1999.

Toda, S., R. S. Stein, P. A. Reasenberg, and J. H. Dieterich, Stress transferred by the Mw = 6.5 Kobe, Japan, shock: Effect on aftershocks and future earthquake probabilities, *J. Geophys. Res.*, *103*, 24,543–24,565, 1998.

Waldhauser, F., and W. L. Ellsworth, A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California, *Bull. Seismol. Soc. Am.*, *90*, 1353–1368, 2000.

Zoback, M. D., and S. Hickman, In situ study of the physical mechanisms controlling induced seismicity at Monticello Reservoir, South Carolina, *J. Geophys. Res.*, *87*, 6959–6974, 1982.

W. Ellsworth, D. Hill, B. Julian, and S. Prejean, U.S. Geological Survey, Menlo Park, CA 94035, USA. (sprejean@usgs.gov)

A. Stork, Department of Geological Sciences, University of Durham, Durham, UK.