GEOPHYSICAL RESEARCH LETTERS, VOL. 18, NO. 4, PAGES 601–604, APRIL 1991

POSSIBLE TECTONOMAGNETIC EFFECT OBSERVED FROM MID-1989, TO MID-1990, IN LONG VALLEY CALDERA, CALIFORNIA.

R. J. Mueller, M. J. S. Johnston, and J. O. Langbein

U.S. Geological Survey, Menlo Park, CA 94025

Abstract. Precise measurements of local magnetic fields have been obtained with a differentially connected array of three proton magnetometers in the Long Valley caldera region since 1984. Two magnetometers are located inside the caldera with a third reference magnetometer located 26 km southeast of the caldera. After correction for secular variation, it is apparent that an anomalous 2 nT decrease in the magnetic field occurred from mid-1989 to mid-1990 at the magnetometer located closest to the center of the resurgent dome inside the caldera. During this period a significant increase in geodetic strain rate of 8.5 ppm/a was observed on the two-color geodimeter network within the caldera from October, 1989, to mid-1990 and a dramatic increase in seismic activity occurred from December, 1989 to July, 1990. A simple dilatational point-source model with pressure increasing by 52 Mpa from October 1989 to August 1990 at a depth of about 7 km beneath the center of the resurgent dome can be fit to the strain data. If this same model is used to calculate piezomagnetic fields in the caldera, the results obtained agree with the observed local magnetic field data provided the Curie point isotherm is at a depth of ≤5 km. Taken together, these magnetic, seismic and geodetic data suggest that an episode of active magmatic intrusion occurred from late 1989 to mid-1990 at a depth of about 7-8 km beneath the resurgent dome within the Long Valley caldera. Other indications of this intrusion should be evident in measurements of leveling, local gravity, and seismic imaging data.

Introduction

The Long Valley caldera is located between the Sierra Nevada and the Owens Valley in east-central California (Figure 1). Continuing episodes of seismic and deformational activity indicate the hazardous nature of this region, even though the dominant features of the collapsed caldera were formed following a major eruption of Bishop tuff about 0.7 Mys ago, and the most recent eruptions have occurred just to the north of this region some 500 to 600 years ago (*Bailey et al.*, 1976).

The last major episode began with the M=5.7 Bishop earthquake on October 4, 1978, and four M6 earthquakes on the southern margin of the caldera on May 25-27, 1980, (*Cramer and Toppazada*, 1980), and was followed by a M=5.7 earthquake on September 30, 1981, an earthquake swarm in January 1983, a M=5.8 earthquake on November 23, 1984, and thousands of smaller earthquake swarms with possible spasmodic tremor (*Ryall and Ryall*, 1981; *Savage and Cockerham*, 1984). Following the 1980 earthquakes, level line measurements indicated 50 cm of accumulative uplift occurred in the vicinity of the resurgent dome in the west central part of the caldera between 1975 and 1985 (*Hill et al.*, 1985). Observations were also made of increased fumerole activity (*Miller, et al.*, 1982). This deformational and seismological activity has been generally attributed to intrusion of magmatic material at a depth of approximately 10 km beneath the resurgent dome together with secondary slip on faults in the south moat (*Savage and Clark*, 1982; *Hill et al.*, 1985).

The most recent of these episodes appears to have occurred from late-1989 to mid-1990. Against a background of high, but decreasing, extensional strain (≈ 10^{-6}/a) (*Langbein*, 1989) and decreasing minor seismicity from 1984 to 1989, the strain rate over the resurgent dome increased almost tenfold in late-1989. Subsequently, in early 1990, local seismicity also increased abruptly. A steady (≈ 2 nT/a) decrease in local magnetic field on the resurgent dome started in 1989 and has continued to the present.

Changing magnetic fields are often observed associated with eruptions from active volcanoes (*Davis et al.*, 1979; *Davis et al.*, 1984; *Sasai et al.*, 1991) and, if very rapid, appear to result from magnetohydrodynamic (*Mueller and Johnston*, 1989) and electrokinetic effects (*Fitterman*, 1979), if, moderately rapid (hours to months), from piezomagnetic effects, and, if very slow (years), from thermal demagnetization caused by migration of the Curie point isotherm (*Sasai*, 1979). In this paper, we compare the seismic, deformation, and magnetic data and propose that

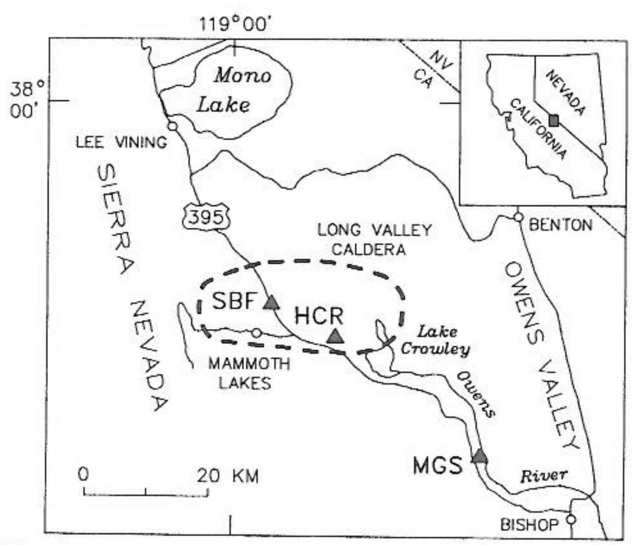

Fig. 1. Map showing the locations of magnetometers (solid triangles) in the Long Valley region, California.

Paper number 91GL00814

a very simple physical model can explain all three data sets.

Data

Three automated magnetometer sites have operated in the Long Valley caldera region since 1984 (Figure 1). Each site has identical proton precession type magnetometers (E.G.& G. Geometrics model G-826) operated at 0.25 nT resolution. The magnetometers syncronously sample every 10 minutes and telemeter the total magnetic field data to Menlo Park, California. Simple differencing of data from adjacent magnetometers enables observation of any temporal changes in local magnetic field. Data from the two magnetometers located within the boundary of the Long Valley caldera are referenced to the third station located 26 km to the southeast (Figure 1).

After smoothing (3 day running mean) and removal of secular variation (*Johnston et al.*, 1985), these differential magnetic field data are shown in Figure 2. The most interesting feature of these data (shown in the top trace of

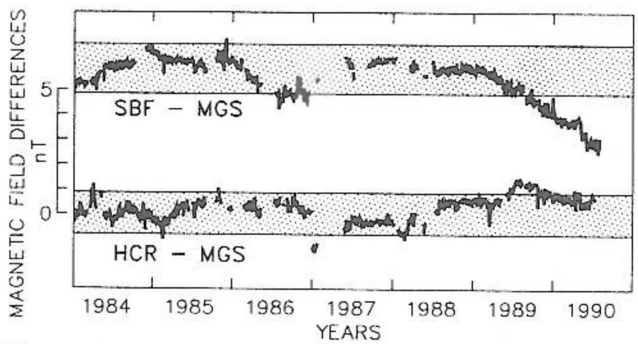

Fig. 2. Local magnetic field data from the two magnetometers located in the Long Valley caldera referenced to magnetometer MGS. All data are displayed with identical vertical scales (nanoteslas) and the stipled area represents the 95% confidence limits about the mean computed between 1984 and 1989.

Figure 2 (SBF-MGS)) is a 2 nT decrease in local magnetic field at SBF between mid-1989 to mid-1990. While both differential data sets exceed the 95% confidence limits for short durations at various times, the decrease in magnetic field indicated on the SBF-MGS trace beginning in mid-1989, is the most significant signal observed in these data during more than 6 years of recording in the Long Valley caldera. A less significant longer term variation with a duration of more than three years is also apparent in these data. Determination of the exact onset time of the observed magnetic field decrease at SBF is difficult. The initial change in rate occurs in early 1989, but the net change does not exceed the 95% confidence limits until August or September in 1989. In contrast, no significant change is observed at HCR (Figure 2; bottom).

The primary geodetic monitoring network in the Long Valley caldera is centered on Casa Diablo at the southern side of the resurgent dome (Figure 3) where most of the deformation since 1980 has occurred. The data are collected using a two-color geodimeter (*Langbein*, 1989). The Casa-Krakatau line, which crosses near the center of the resurgent dome, provides a good example of a line

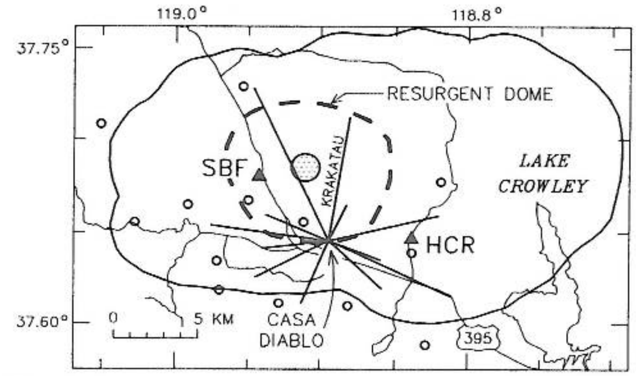

Fig. 3. Map showing the location of part of the two-color geodetic network (radial lines), seismic stations (circles), and magnetometers (triangles) in the Long Valley caldera. The stipled circle indicates the center of deformation determined from the geodetic data.

sensitive to inflation. From 1984 to 1988, the mean strain rate on this line was about 1.2 ppm/a (Figure 4). However, starting in late 1989, the strain rate on this and other adjacent lines increased dramatically to a rate of almost 8.5 ppm/a. Langbein *et al.*, 1990) has shown that these data are best fit by a Mogi point source with increasing pressure of 52 Mpa at a depth of about 7 km.

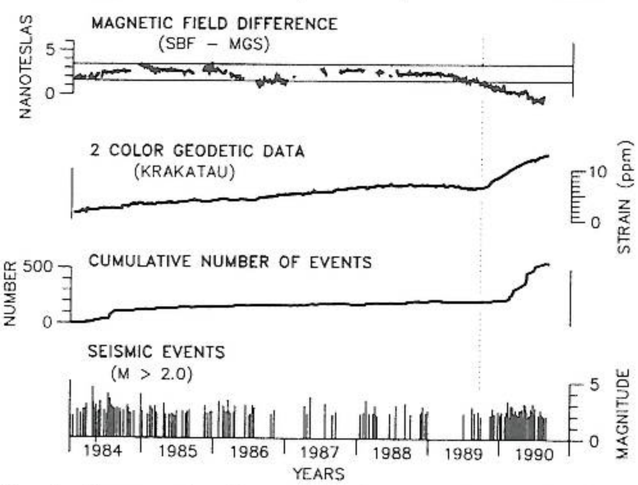

Fig. 4. Comparative time-series plots of differential magnetic field (top), geodetic (next), and seismic data (two bottom) from 1984 to mid-1990. The vertical dashed line is for temporal reference only.

Seismicity within the Long Valley caldera is recorded on a telemetered array of seismometers for which the locations are shown on Figure 3. The catalog is complete for $M \geq 2.0$ (*Hill et al.*, 1990). Subsequent to the increase in strain rate and change in local magnetic field, seismicity in this region increased markedly from December 1989 to July 1990 as shown in the seismicity time history and the cumulative number of seismic events in the lower two plots in Figure 4.

Discussion

If magma injection has occurred beneath the resurgent dome, uplifted the surface material, and generated associated seismic swarms within the caldera, as proposed by Langbein *et al.*, (1990), then indications of this should be apparent in other types of data, such as gravity, magnetic, seismic velocity, etc, that are sensitive to stress, strain, and changes in material properties beneath the caldera. Stress changes within the earths crust are expected to cause piezomagnetic effects in volcanic regions. These effects are usually termed volcanomagnetic effects and can be calculated in a straightforward manner for elastic deformation models (*Davis*, 1976; *Oshiman*, 1990; *Sasai*, 1991). The pressure source obtained by inversion of the two-color geodetic data was used to calculate the expected volcanomagnetic effect at the magnetometer sites in the Long Valley caldera in order to see whether the two data sets are internally consistent.

The volcanomagnetic model used consists of a sphere, with a 1 km radius, embedded in a half space 8 km beneath the resurgent dome, with a hydrostatic pressure of 50 MPa applied from within, similar to those indicated by inversion of the two-color geodetic data (*Langbein et al.*, 1990). Assuming a stress sensitivity of $2*10^{-3}$ MPa^{-1}, rock magnetization of 1 A/m, elastic constants λ=μ=10^4 MPa, and the Curie point isotherm (≈600° C) is at a depth of 5 km, in a simple volcanomagnetic model such as described by Sasai (1991), the total magnetic field perturbation at the caldera surface is shown in Figure 5. The calculated surface magnetic field anomaly at the SBF and HCR sites are -1 nT and 0.0 nT, respectively. The observed changes at these sites are about -2 nT and 0.0 nT and agree within the uncertainties in the model parameters.

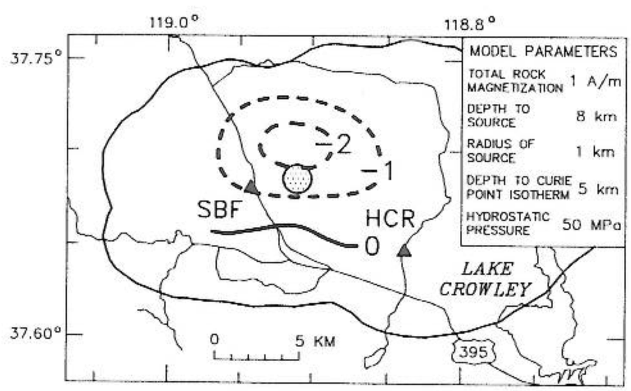

Fig. 5. Surface magnetic field contours (nanoteslas) calculated for a pressure source (stipled circle) at 8 km beneath the resurgent dome. Model parameters used are in the upper righthand table. The model assumes a magnetic inclination of 60° and a magnetic declination of 0°.

We note an important feature of this model, as pointed out by *Oshiman*, (1990), that if the Curie point isotherm is deeper then 8 km (the source depth), then the sign of the surface anomaly is opposite to that observed. So, it would appear that we have indirect constraint, albeit weak, on the depth of the 600° C isotherm. Similar depths of the 600° C isotherm are indicated in seismic studies of the Long Valley caldera (*Sanders*, 1984 ; *Dawson et al.*, 1990) which suggest that the top of the magma body (≈800° C) is at a depth of between 4.5 to 8 km beneath the resurgent dome area. Temperature gradients determined from well logs (*Sorey*, 1985; *Sorey et al.*, 1990) are not consistent with magmatic temperatures at these depths, but temperature measurements in this area are complicated by hydrologic flow and have only been made to depths less than 2 km. A more complex heterogenous model would be required to satisfy the observed data for which a Curie point isotherm is deeper than 8 km.

Other possible contributions to local magnetic field perturbations within active volcanic regions are thermal demagnetization (*Sasai*, 1979) and electrokinetic effects due to pressure generated fluid flow (*Fitterman*, 1979). Thermal demagnetization effects are caused by migration of the Curie point isotherm and have a long time constant (years) due to the low thermal diffusivity of rock (1 km^2/10^4 years). Electrokinetic effects are more difficult to quantify. Some anomalous changes in water wells have been observed in this region over this time period (*Sorey*, pers. comm., 1990), however, except for a long-term decline in water level, these changes are not systematic and systematic changes are required to generate the sustained magnetic anomaly. Furthermore, material and structural parameters needed to estimate the amplitudes of electrokinetic effects are poorly known and the hydrologic system in the Long Valley caldera is complex (*Sorey et al.*, 1990). Since the magnetic field observations can be explained with a relatively simple and straightforward volcanomagnetic model, appeal to a more complex and poorly understood physical process appears unnecessary.

Conclusion

Anomalous geodetic strain at a rate approaching 8.5 ppm/a and local magnetic field changes of -2 nT/a were observed between mid-1989 and mid-1990 near the resurgent dome in the Long Valley caldera. These changes were followed by increased seismicity within the caldera in early 1990. The geodetic observations have been fit to a spherical inflation model at a depth of 7 km beneath the resurgent dome in which the pressure increases systematically with time (*Langbein et al.*, 1990). The modelled chamber is located beneath, and just 3 km to the ENE of the magnetometer (SBF). Using similar source parameters, as indicated by the geodetic inversion, in a volcanomagnetic model, the surface anomaly at the magnetometer has approximately the same amplitude and sense as that observed provided that the Curie point isotherm (≈600° C) is at a depth of about 5 km. This isotherm depth is consistent with that indicated by seismic imaging.

The relatively rapid decrease in magnetic field would appear to preclude explanations in terms of a thermal demagnetization. Explanations in terms of electrokinetic effects are poorly understood and require systematic changes in the complex hydrologic system in the caldera. However, these mechanisms, and perhaps others, cannot be completely ruled out. Since the observed magnetic field change occurred at only one of the two magnetometers located in the Long Valley caldera, addition of other magnetometers near the resurgent dome would clearly help to differentiate between the different physical models and to identify the form and amplitude of future local magnetic anomalies in this region.

Taken together, these magnetic, seismic and geodetic data suggest that an episode of active magmatic intrusion occurred from late 1989 to mid-1990 at a depth of about 7-8 km beneath the resurgent dome within the Long Valley caldera. Other indications of this intrusion should be evident in direct leveling measurements, changes in local gravity measurements, and perhaps in seismic imaging data.

Acknowledgements. We are grateful to A. M. Pitt for seismic data, V. Keller and G.D. Myren for installation and maintenance of the magnetometers, and M. L. Sorey and C. D. Farrar for useful hydrologic comments.

References

Bailey, R. A., G.B. Dalrymple, and M.A. Lanphere, Volcanism, structure, and geochronology of Long Valley caldera, Mono County California, *J. Geophys. Res.*, **81**, 725-744, 1976.

Cramer, C. H., and T. R. Toppozada, A seismological study of the May 1980 and earlier earthquake activity near Mammoth Lakes, California, 141 pp.,*Spec. Rep. Calif. Div. Mines Geol.*, **150**, 1980.

Dawson, P. B., J. R. Evans, and H. M. Iyer, Teleseismic tomograghy of the compressional wave velocity structure beneath the Long Valley region, California, *J. Geophys. Res.*, **95**, 11021-11102, 1990.

Davis, P. M., The computed piezomagnetic anomaly field for Kilauea volcano, Hawaii, *J. Geomag. Geoelectr.*, **28**, 113-122, 1976.

Davis, P. M., F. D. Stacey, C. J. Zablotki, and J. V. Ioben, Improved signal discrimination in tectonomagnetism - Discovery of a volcano-magnetic effect at Kilauea, Hawaii, *Phys. Earth Planet.*, **19**, 331-336, 1979.

Davis, P. M., R. L. McPherron, D. Dzurisin, T. Murray, M. J. S. Johnston, anf R. Mueller, A volcanomagnetic observation on mount ST. Helens, Washington, *Geophys. Res. Let.*, **11**, 233-236, 1984.

Fitterman, D. V., Theory of electrokinetic-magnetic anomalies in a faulted half-space, *J. Geophys. Res.*, **84**, 6031-6041, 1979.

Hill, D. P., R. A. Bailey, and A. S. Ryall, Active tectonics and magmatic processes beneath Long Valley caldera, eastern California: an overview, *J. Geophys. Res.*, **90**, 11111-11120, 1985.

Hill, D. P., W. L. Ellsworth, M. J. S. Johnston, J. O. Langbein, D. H. Oppenheimer, A. M. Pitt, P. A. Reasonberg, 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. Seism. Soc. Am.*, **80**, 325-339, 1990.

Johnston, M. J.S., S. A. Silverman, R. J. Mueller, and K. S. Breckenridge, Secular variation, crustal sources, and tectonic activity in California, 1976-1984, *J. Geophys. Res.*, **90**, 8707-8717, 1985.

Langbein, J., The deformation of the Long Valley caldera, eastern California, from mid-1983 to mid-1988; Measurements using two-color geodimeter, *J. Geophys. Res.*, **94**, 3833-3849, 1989.

Langbein, J., D. P. Hill, T. N. Parker, S. K. Wilkinson, and A. M. Pitt, Renewed inflation of the resurgent dome in Long Valley caldera, California, from mid-1989 to mid-1990, (abstract) *Eos Trans. AGU*, **71**, 1466, 1990.

Miller, C. D., D. R. Mullineaux, D. R. Crandell, and R. A. Bailey, Potential hazards from future volcanic eruptions in the Long Valley- Mono Lake area, east-central California and southwestern Nevada- A preliminary assessment, *U.S. Geol. Surv. Circ.*, **77**, 1-10, 1982.

Mueller, R. J. and M. J. S. Johnston, Large-scale magnetic field perturbation arising from the 18 may 1980 eruption of mount St. Helens, Washington, *Phys. Earth Planet. Inter.*, **57**, 23-31, 1989.

Oshiman, N., Enhancement of tectomagnetic change due to non-uniform magnetization in the earth's crust-Two dimensional case studies, *J. Geomag. Geoelectr.*, **42**, 607-619, 1990.

Ryall, A., and F. Ryall, Spatial-temporal variations in seismicity preceding the May 1980 Mammoth Lakes earthquakes, California, *Bull. Seismol. Soc. Am.*, **71**, 747-760, 1981.

Sanders, C. O., Location and configuration of magma bodies beneath Long Valley, California, determined from anomalous earthquake signals, *J. Geophys. Res.*, **89**, 8287-8302, 1984.

Sasai, Y., The piezomagnetic field associated with the mogi model, *Bull. Earthq. Res. Inst.*, **54**, 1-29, 1979.

Sasai, Y., The piezomagnetic field associated with the mogi model revisited: Analytic solution for finite spherical source, *J. Geomag. Geoelectr.*, **43**, 21-64, 1991.

Savage, J. C., and M. M. Clark, Magmatic resurgence in Long Valley caldera, California: Possible cause of the 1980 Mammoth Lakes earthquakes, *Science*, **217**, 531-533, 1982.

Savage, J. C., and R. S. Cockerham, Earthquake swarm in Long Valley caldera, California, January 1983: Evidence for dike injection, *J. Geophys. Res.*, **89**, 8315-8324, 1984.

Sorey, M. L., Evolution and present state of the hydrothermal system in Long Valley caldera, *J. Geophys. Res.*, **90**, 11219-11228, 1985.

Sorey, M. L., G. A. Suemnicht, N. C. Sturchio, and G. A. Norquist, New evidence on the hydrothermal system in Long Valley caldera, California from wells, fluid sampling, electrical geophysics, and age determinations of hot-spring deposits, *J. Volc. Geoth. Res.*, in press, 1990.

R. J. Mueller and M. J. S. Johnston, U.S. Geological Survey, Menlo Park, CA 94025.

(Received December 27, 1990;
Accepted January 22, 1991.)