REVIEWS OF GEOPHYSICS, VOL. 25, NO. 5, PAGES 983–988, JUNE 1987
U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1983–1986

Tectonomagnetism and Tectonoelectricity

M. J. S. JOHNSTON

U. S. Geological Survey
Menlo Park, California 94025

The last four years has seen a considerable waning of efforts in the U.S. to use the inherent stress sensitivity of the magnetization of rocks in tectonically active regions as a tool for understanding and, perhaps predicting, earthquake activity and volcanic eruptions. The primary reasons for this decreased interest derive from accumulating evidence that the mean deviatoric stress release during earthquakes (and the ambient shear stress near active faults) is lower than than had been previously assumed and, secondly, the observational limits of magnetometers separated by about 10 km, after application of a variety of noise reduction techniques, appear to be no better than about 0.1 nT. Lower estimates of the average change in deviatoric stress associated with earthquake rupture correspondingly reduce the fields calculated from tectonomagnetic models. At the same time, some unexpected and exciting results have been obtained which indicate many aspects of magnetic field changes near active faults and volcanoes are still not completely understood. The more important of these results are: 1) the observation of correlated magnetic, strain, uplift, and gravity changes during the latter stages of a remarkable deformation episode near the San Andreas fault in southern California, 2) indications of anomalous change in magnetic fields along the San Andreas fault to the southeast of Palm Springs, 3) an unambiguous observation of a volcanomagnetic effect at Mt. St. Helens prior to an extrusive eruption, and 4) the first observations of coseismic seismomagnetic effects on two independent magnetometers during the July 8, 1986, M_L 5.9 North Palm Springs earthquake. A resurgence of interest has occurred during the quadrennium in a related area concerning electrical phenomena and electromagnetic effects related to earthquakes and volcanoes. Mechanisms have been proposed to explain the occurrence of earthquakes lights and the possibility of electromagnetic emission prior to the 1960 Chilean earthquake has been proposed. Self potential anomalies have been observed before and during several eruptions on Kilauea volcano in Hawaii.

BACKGROUND

Tectonomagnetism - the study of magnetic fields that result from earthquake or volcano related crustal deformation - has long shown promise as a simple and inexpensive method for monitoring deviatoric crustal stress and perhaps providing a tool for predicting crustal failure (*Wilson*, 1922; *Kalashnikov*, 1954; *Stacey*, 1964; *Stacey et al.*, 1965), but few unambiguous results have been obtained. Subfields of tectonomagnetism are volcanomagnetism and seismomagnetism which describe the magnetic field perturbations related to the actual volcanic eruption process and the earthquake rupture process, respectively.

The stress dependence of rock magnetization has been demonstrated under laboratory conditions (*Kalashnikov and Kapitsa*, 1952; *Katipsa*, 1955; *Ohnaka and Kinoshita*, 1968; *Kean et al.*, 1976; *Revol et al.*, 1977; *Martin*, 1980; *Pike et al.*, 1981) and theoretical models have been developed in terms of single domain and pseudo-single domain rotation (*Kern*, 1961; *Stacey*, 1963; *Nagata*, 1969; *Stacey and Johnston*, 1972) and multi-domain wall translation (*Kern*, 1961; *Kean et al.*, 1976; *Revol et al.*, 1977).

The stress sensitivity of induced and remanent magnetization from theoretical and experimental studies have been combined with stress estimates from dislocation theory of fault rupture and elastic pressure loading in active volcanoes to calculate field changes expected to accompany earthquakes and volcanoes (*Stacey*, 1964; *Stacey et al.*, 1965; *Johnston*, 1978; *Davis et al.*, 1979; *Sasai*, 1980; *Hao et al.*, 1982; *Davis et al.*, 1984). These models show that moderate scale magnetic anomalies of a few nanoTeslas (nT) should be expected to accompany earthquakes and volcanic eruptions for rock magnetizations and stress sensitivities of 1 Ampere/meter (A/m) and 10^{-4} bar^{-1}, respectively. Unambiguous observation of local magnetic signals of this amplitude require dedicated efforts to understand and reduce noise in magnetic field measurements.

Paper number 7R0126.

TECTONOMAGNETISM

a) Crustal Deformation

Undoubtedly, the most notable development during the past four years has been the identification of temporal magnetic fields that correspond to local gravity, strain, and uplift changes during part of a remarkable episode of crustal deformation in southern California. This deformational episode, known generally as the "Palmdale Uplift", was first identified in leveling data (*Castle et al.*, 1976). During the period between 1974 and 1976 changes in the uplift in the region between Cajon Pass and Palmdale occurred at the same time as offsets in local magnetic field (*Johnston et al.*, 1979). Aseismic strain changes were also identified in geodetic data taken near the San Andreas fault between 1979 and 1982 (*Savage et al.*, 1981a, 1981b; *Savage and Gu*, 1985) and, in an attempt to integrate these and other data, *Jachens et al.*, (1983) reported that, during the 1979 to 1982 period, changes in level lines, changes in strain, and changes in gravity, all occurred in a correlated manner.

When continuous measurements of magnetic field in each

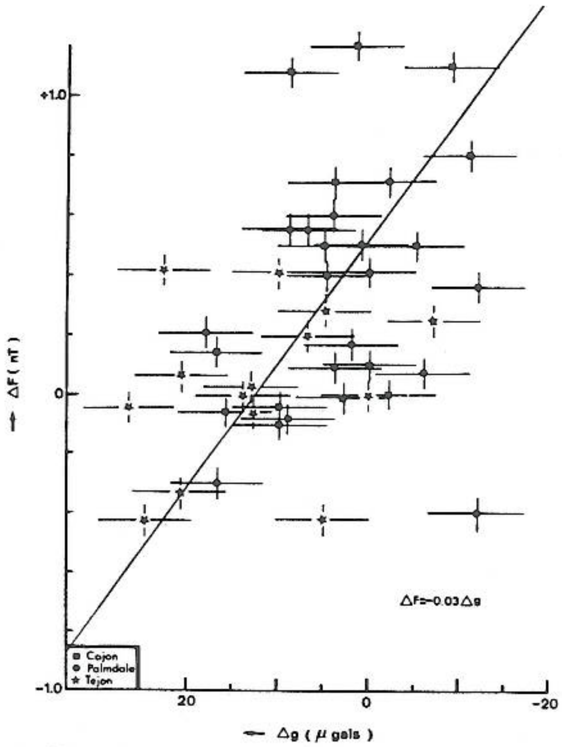

Fig. 1. Plot of magnetic field against gravity fluctuations from the Tejon, Palmdale, and Cajon regions in southern California. Shown also is the least-squares fit to the data (from *Johnston et al.*, 1986).

of the regions investigated by Jachens were sampled at the same time as the gravity strain, and level data, and then tested for correlation, the results showed correlation significant at the 95% level or better (*Johnston*, 1986). Figure 1 shows the regression plot between gravity data and magnetic data from the Tejon, Palmdale and Cajon regions. When the data are plotted all together in this way (i.e. with no allowance for different response in different regions) the correlation coefficient is 0.93 and is significant at the 1% level. Figure 2 is a composite plot showing superimposed time-histories of magnetic field (stars), gravity (dots), areal strain (triangles), and elevation (squares) data, together with their error bars, from the three regions in southern California.

Least-square fits between the magnetic data and each of the various parameters give transfer functions of the form;

$$\Delta F = -0.03 \Delta g \tag{1}$$

where ΔF is in nanoTeslas and Δg is in microGals,

$$\Delta F = -0.98 \Delta strain \tag{2}$$

where $\Delta strain$ is areal strain in ppm (compression negative), and

$$\Delta F = 9.1 \Delta h \tag{3}$$

where Δh is in meters.

Two possible explanations for these relationships exist. Either a short term deformational episode has been independently recorded in each data set or all data sets have been contaminated by a common source of meteorologically generated crustal or instrumental noise. Because the inferred relationships between these parameters is in approximate agreement with those expected from simple deformational models (*Jachens et al.*, 1983) and tectonomagnetic models (*Johnston*, 1986), and since no relation was found between the continuous magnetic field data and either rainfall, pressure, or temperature, the deformational explanation is preferred (*Johnston*, 1986). Correspondence between leveling data and magnetic field changes have been also observed in Japan associated with an episode of uplift on the Izu Peninsula (*Ohshiman et al.*, 1983; *Honkura and Taira*, 1983).

b) Instrument Development and Measurement Precision

Determination of the precision of local magnetic field measurements with arrays of magnetometers as a function of instrument, spatial scale, sampling frequency, and site location has attracted continued attention since 1982. Simple differences from 5 km to 10 km station separations are quite effective at reducing disturbance fields from external geomagnetic field variations common to all sites. However, the ability to resolve temporal magnetic fields of crustal origin becomes progressively worse with increasing site separation, increasing time duration, and with differences in magnetization between sites. The decreased resolution with increasing site separation measured on the 27 recording magnetometers installed along 800 km of the San Andreas fault has the form;

$$\sigma(nT) = 0.01(\pm 0.003) D\,(km) + 0.07(\pm 0.08) \tag{4}$$

over the spatial scale of most interest for tectonic processes of 0 to 50 km. σ is the standard deviation of hour averages of magnetic field differences (*Johnston et al.*, 1984).

Power spectra obtained from pairs of typical magnetometers with site separations between 8 and 15 km show noise power decreases with increasing frequency by about 8 dB per decade of frequency, as shown in Figure 3. It is only at high frequencies (more than 10 cpd in this case) that the noise power approaches the least count noise limit of the magnetometers (0.25 nT). At lower frequencies these spectra have dominant noise peaks that result from diurnal variations and tidal effects from ocean tide induction (*Johnston et al.*, 1983).

A comparison of proton and self-calibrating rubidium magnetometers with 0.01 nT sensitivity and proton magnetometers with 0.12 nT sensitivity over a range of baselines in seismically inactive and seismically active regions has been made to determine whether and under what conditions improved sensitivity might be useful in tectonomagnetic measurements (*Ware et al.*, 1985). The most relevant experiment using a 13 km baseline in a seismically active and geologically complex region of the San Andreas fault showed that external noise which decreases at about 10 dB per decade of frequency, dominates the observations at periods longer than about 10 minutes and both systems make equivalent measurements. This is shown in the comparative plots of power spectral density in Figure 4. For periods less than 3.5 minutes (420 cycles/day), the proton magnetometers become limited by least-count noise (0.12 nT) and the improved sensitivity of the rubidium magnetometer becomes apparent. If noise power continues to decrease with frequency magnetic field measurements at about the 0.001 nT level should be possible at frequencies greater than 1 Hz. This raises the intriguing possibility that magnetic variation corresponding to the propagation of

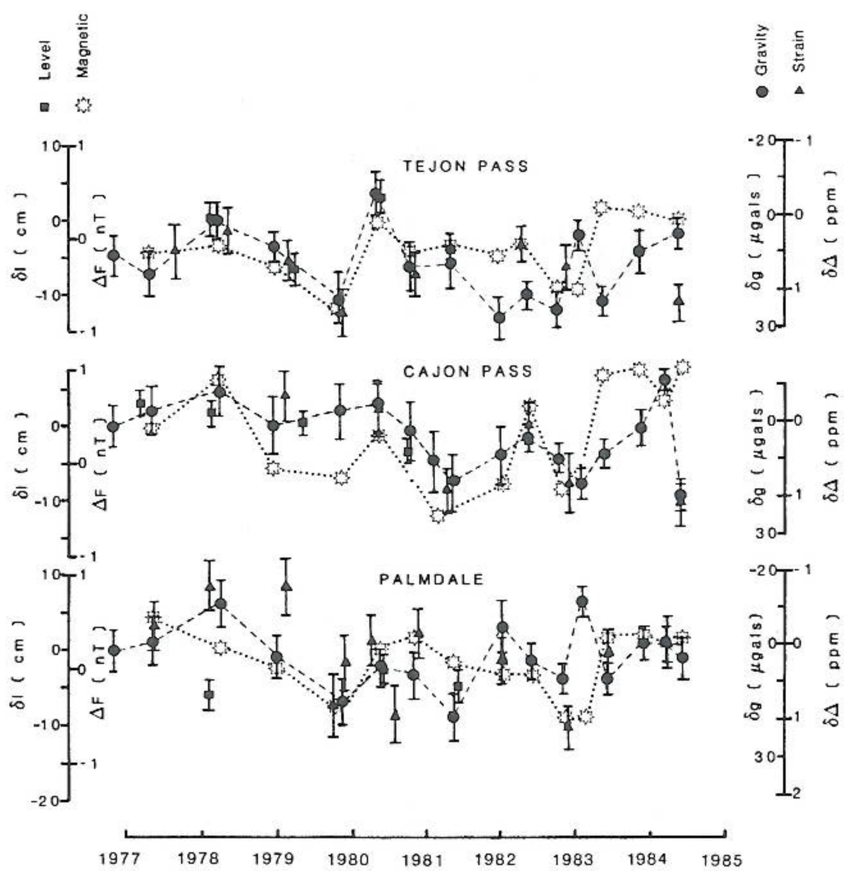

Fig. 2. Superimposed time-histories of magnetic field (stars), gravity (dots), areal strain (triangles), and elevation (squares) data, together with their error bars, from Tejon, Palmdale, and Cajon. Shown also is the least-square linear fit to the data (from *Johnston*, 1986).

dynamic seismic waves might be detectable on ultrasensitive magnetometers.

With regard to the detection threshold for tectonomagentic effects, the most important development concerned the realization that most of the noise (long period and short period) can be removed if corrections are made for local site response to external field variations. Since different sites will respond differently because disturbance fields are in different directions and since disturbance fields in the same direction may generate different responses at different sites because the site magnetization vectors are different, these response effects limit the detection threshold. These effects can be identified and removed by defining multichannel Wiener filters which predict the total magnetic field at a site from component magnetic data during periods of disturbed geomagnetic field (*Davis et al*, 1979; *Davis et al*, 1980; *Davis et al.*, 1981; *Davis and Johnston*, 1983). This technique reduced the noise in hour averages from 0.7 nT to 0.3 nT for baselines from 8 km to 100 km (*Davis and Johnston*, 1983).

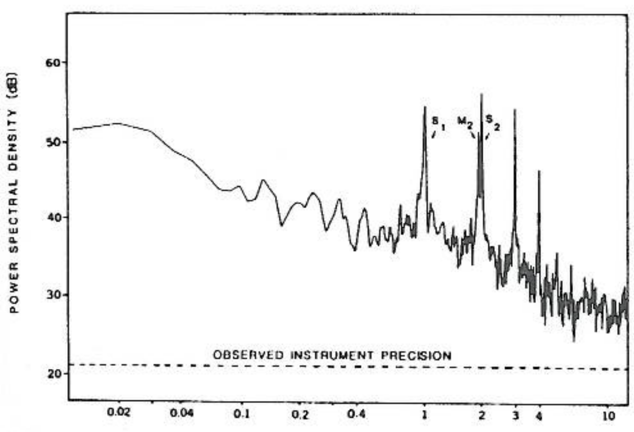

Fig. 3. Geomagnetic difference-field noise spectra obtained from multiple magnetometer pairs with site separations between 10 and 15 km. Shown also is the observed instrument precision limit obtained from magnetometers with a 0.25 nT sensitivity (from *Johnston et al.*, 1984).

c) Short Wavelength Secular Variation

Further application of this technique was made to correct for site response and identify the secular variation in data from the array of 34 total field magnetometers throughout central and southern California during the period 1976 to 1984 (*Johnston et al.*, 1985). The secular variation obtained has the form;

$$\dot{F} = k_1 * \theta + k_2 * \phi + K \quad (5)$$

where $\dot{F}$ is in nT/a, θ and ϕ are the geographic latitude and longitude, and k_1, k_2 and K are 1.50±0.08 nT/a.degree, -0.23±0.06 nT/a.degree, and -129.2±0.1 nT/a, respectively.

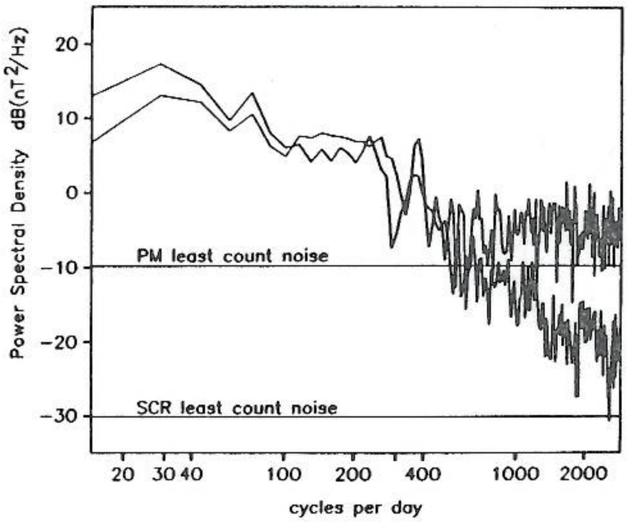

Fig. 4. Comparative power spectral density of simultaneous differences from proton magnetometers with a 0.12 nT sensitivity and self-calibrating rubidium magnetometers with a 0.014 nT sensitivity. Both sets of magnetometers were installed in a tectonically active region near the San Andreas fault with a site separation of 13 km (from *Ware et al.*, 1985).

Surprisingly, the observed secular variation obtained did not agree with that predicted from global secular variation models. The secular variation was removed from the data to attempt to identify crustal fields of tectonic origin. The residual fields obtained are shown in Figure 5 and are most apparent on the San Andreas fault in southern California where subsequently a M_L 5.9 occurred (see below).

SEISMOMAGNETISM

a) North Palm Springs Earthquake

The single most important result in the field of seismomagnetism was the first recording of co-seismic seismomagnetic effects during the July 8, 1986, North Palm Springs earthquake. This earthquake had a moment of $2*10^{25}$ dyne-cm and a magnitude of 5.9. Two total field proton magnetometers were installed at distances of 3 km and 8 km from the subsequent earthquake and had been sampling once every 10 minutes since early 1979. The data are transmitted with digital telemetry to Menlo Park, California (*Mueller et al*, 1981).

The local magnetic field at the magnetometer closest to the earthquake decreased by 1.2 nT while that at the second, eight kilometers from the epicenter, increased by 0.33 nT. Both instruments were on the same side of the fault. Figure 6 shows the records from the two sites OCHM and LSBM referenced to another site in the area CHUM during the period June 1 to July 12, 1986, and also the difference between the two local sites OCHM and LSBM.

A tectonomagnetic model of the earthquake has been constructed using seismically determined parameters for the rupture length, width, and the depth. To satisfy the moment a slip of 20 cm was assumed and the magnetization in the region was estimated from surface samples and regional magnetic anomalies to be 2 A/m. Within the uncertainties this model predicts the changes observed (*Johnston and Mueller*, 1986).

VOLCANOMAGNETISM

Volcanomagnetic monitoring has been confined to the Long Valley caldera in eastern California and Mt. St. Helens in Washington. No significant eruptive activity has occurred in either of these regions during the last four years. Activity in the Long Valley caldera has been restricted to a number of moderate tectonic earthquakes. Higher rates of change of magnetic field have been observed in the region (*Mueller et al.*, 1984) but no clear episodic events have been observed simultaneously on several instruments.

The most significant recent volcanomagnetic event on Mt. St. Helens occurred before an extrusive dome building eruption on October 30, 1981 (*Davis et al.*, 1984). During this period, five magnetometers were being operated at sites on the mountain and electric fields were measured on the east flank of the volcano. Two magnetometers on the crater floor recorded reversible changes in magnetic field at the time of accelerated tilting of the crater floor but before surface extrusion of material became obvious as shown in Figure 7. No correlated activity was apparent in the electric field measurements.

TECTONOMAGNETIC MODELS

No new work has been reported on tectonomagnetic models but results from related fields may have a serious impact on interpretation of these calculations. New work of the state of stress in seismically active areas (*McGarr et al.*, 1982) and observations of measured stress drops for earthquakes (*Hanks*, 1980) suggests the average deviatoric stress change during earthquakes may be about 10 or 20 bars rather than 100 bars as had been previously assumed (*Stacey*, 1964; *Sasai*, 1980; *Hao et al.*, 1982). If stress changes

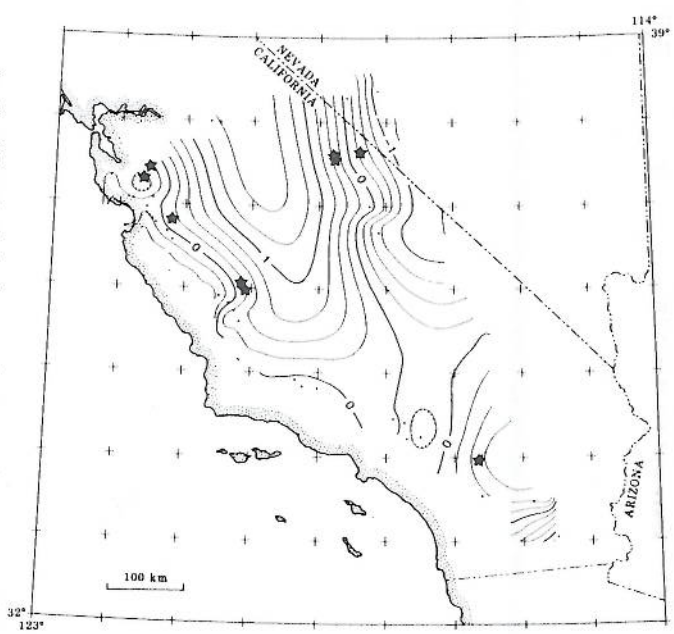

Fig. 5. Residual total secular magnetic field changes along the San Andreas fault in central and southern California not apparently related to sources in the core or the ionosphere/magnetosphere (from *Johnston et al.*, 1985). The locations of earthquakes with $M_L > 5.5$ during the last five years are shown with stars.

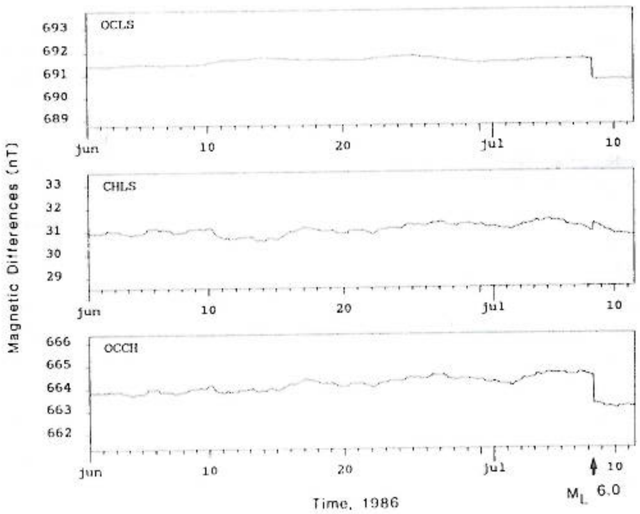

Fig. 6. Magnetic field at sites LSBM and OCHM with respect to a common site CHUM (OCCH - bottom, and CHLS - middle) as a function of time from June 1 to July, 12, 1986, and also the difference between the two local sites (OCLS, top). The M_L 5.9 North Palm Springs earthquake (occurrence time shown with arrow) occurred on July 8, 1986, at an epicentral distance of 3 km from OCHM and 8 km from LSBM (from *Johnston and Mueller*, 1986).

are at this level, then the fields expected from them as a consequence of the piezomagnetic properties of rocks are correspondingly reduced. This, plus the fact that the present tectonomagnetic models already underestimate observations of tectonomagnetic effects generated by dam loading (*Davis and Stacey*, 1972) and uplift (*Ohshiman et al.*, 1983; *Johnston*, 1986) by at least a factor of five, indicates possible inadequacies in the current theory and modeling techniques.

TECTONOELECTRIC EFFECTS

Electrical phenomena and electromagnetic effects related to earthquakes experienced a resurgence of interest during the quadrennium. While these subjects do not fall under the perview of tectonomagnetism as discussed above, they are of sufficient importance and are sufficiently related that they are included here. Mechanisms have been proposed to explain the occurrence of earthquakes lights (*Lockner et al.*, 1983) and the possibility of electromagnetic emission before the 1960 Chilean earthquake has been proposed (*Warwick et al.*, 1982).

a) Earthquake Lights

The age-old problem of earthquake lights seems not to be such a paradox anymore. While the very existence of these lights had long been questioned because of the paucity of unambiguous data, the anecdotal nature of many of the reports, and the absence of satisfactory theory explaining how large charge concentration can be generated and maintained in a highly conducting earth, recent documentation of lights during the Tangshan earthquake in China (*Huang and Hanzen*, 1979) and the Matushiro earthquakes in Japan (*Derr*, 1973) have indicated that they are physically real. A mechanism for charge generation and charge concentration near earthquake rupture zones has been proposed (*Lockner et al.*, 1983) that could explain many of the luminous, electric and electromagnetic phenomena that are reported to accompany earthquakes.

This proposed mechanism depends on the facts that 1) significant frictional heating occurs in an earthquake shear zone during rupture, 2) the heating will vaporize water and pore fluids in and near the shear zone and dramatically decrease the conductivity of the shear zone except on the fault face, and 3) intense shearing and vaporization generates massive charge separation and concentration. Continued frictional heating on the fault face results in a situation where a central conductor a few centimeters wide on the fault face is surrounded by a low conductivity region of sheared rock containing vaporized water. The fault face conductor will collect and concentrate charge on its edges. Charge collected at the surface expression of the fault will produce an intense electric field. Depending on atmospheric electric field conditions, the earthquake generated field may produce corona discharge (St. Elmo's lights), electromagnetic emission, or lightning.

The decay-time of accumulated charge in the earth's crust is an important issue receiving considerable attention. Taken at face value, the charge relaxation time in typical crustal materials with conductivities between 0.0001 and 0.01 Sm^{-1} is less than a microsecond. This would seem to preclude retention of charge in regions other than in transient low-conductivity zones such as discussed above and would imply great difficulty in generating and propagating electromagnetic emission in the crust. Measurements of the frequency dependence of conductivity of crustal rocks and fault zone materials indicate that significant polarization effects occur and that localized charge might remain in the

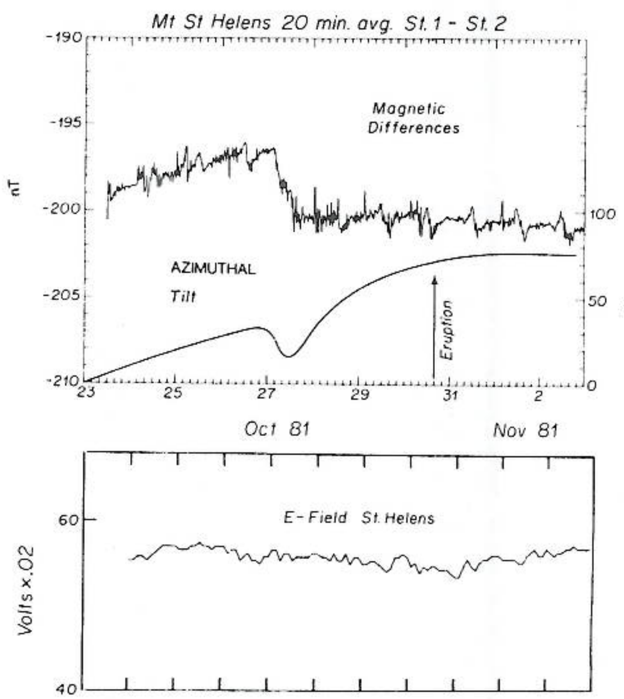

Fig. 7. Electric, magnetic and tilt time histories prior to and following the surface expression of an extrusive eruption (vertical dashed line) on October 29, 1981, on Mt. St. Helens (from *Davis et al.*, 1984).

wet conducting crustal materials for periods as long as a few seconds (*Lockner and Byerlee*, 1985).

b) Electromagnetic Emission

Another, perhaps related, enigma concerns the generation of high frequency electromagnetic emissions during earthquakes. This area of research has received considerable attention following reports of changes in the level of 81-kHz electromagnetic radiation around the time of a magnitude 6.1 earthquake at a depth of 81 km beneath the receiver (*Gokhberg et al.*, 1982). Radio emissions at 18 MHz were recorded at widely separated receivers in the northern hemisphere for about 15 minutes on May 16, 1960. These records have been claimed to be related to the great 1960 Chilean earthquake which occurred 6 days later (*Warwick et al.*, 1982).

While generation of high frequency electromagnetic radiation can be easily demonstrated in controlled laboratory experiments involving rock fracture (*Warwick et al.*, 1982; *Brady and Rowell*, 1986), the physical mechanism of the source and the method of propagation of very high frequency (VHF) electromagnetic waves through many tens to hundreds of kilometers of conducting crust is not at all clear. In all events, there is a need for more systematic observations and experiments in this field.

In a related area, self-potential (SP) anomalies do show apparent correlation to episodes of extrusive activity and eruptions on Kilauea volcano in Hawaii (*Jackson*, 1986). The pertinent physical mechanisms in this case are electrokinetic effects, generated by thermally driven or strain driven fluid flow within the volcano, or thermoelectric effects, generated by injection of hot material into and through the volcano.

REFERENCES

Brady, B. T., and G. A. Rowell, Laboratory Investigations of the Electrodynamics of Rock Fracture, *Nature*, **321**, 488-490, 1986.

Castle, R. O., J. P. Church, and M. R. Elliot, Asiesmic Uplift in Southern California, *Science*, **192**, 251-253, 1976.

Davis, P. M., and F. D. Stacey, Geomagnetic anomalies caused by a man-made lake, *Nature*, **240**, 348-349, 1972.

Davis, P. M., F. D. Stacey, C. J. Zablocki and J. V. Olsen, Improved Signal Discrimination in Tectonomagnetism: Discovery of a Volcanomagnetic Effect at Kilauea, Hawaii, *Phys. Earth Plan. Int.*, **19**, 331-336, 1979.

Davis, P. M., Jackson, D. D., and M. J. S. Johnston, Further evidence of localized Geomagnetic Field Changes Before the 1974 Thanksgiving Day Earthquake, Hollister, California, *Geophys. Res. Lett.*, **7**, 513-516, 1980.

Davis, P. M., Jackson, D. D., Searls, C. A., and R. L. McPherron, Detection of Tectonomagnetic Events Using Multichannel Predictive Filtering, *J. Geophys. Res.*, **86**, 1731-1737, 1981.

Davis, P. M. and M. J. S. Johnston, Localized geomagnetic field changes near active faults in California 1974-1980, *J. Geophys. Res.*, **88**, 9452-9460, 1983.

Davis, P. M., D. R. Pierce, R. L. McPherron, D. Dzurisin, T. Murray, M. J. S. Johnston, and R. Mueller, A Volcanomagnetic Observation on Mount St. Helens, Washington, Geophys. Res. Lett., **11**, 225-228, 1984.

Derr, J., Earthquake Lights, *Bull. Seis. Soc. Am.*, **63**, 2177-2187, 1973.

Gokhberg, M. B., V. A., Morgounov, T. Yoshino, and I. Tomizawa, Experimental Measurements of Electromagnetic Emissions Possibly Related to Earthquakes in Japan, *J. Geophys. Res.*, **87**, 7824-7828, 1982.

Hanks, T. C., Crustal Earthquake Stress Drops, *U.S. Geological Survey Open File Rep. 80-625*, 490-518, 1980.

Hao, J., L. M. Hastie, and F. D. Stacey, Theory of the Seismomagnetic Effect: a Reassessment, *Phys. Earth. Plan. Int.*, **28**, 129-140, 1982.

Honkura, Y., and S. Taira, Changes in the Amplitudes of Short-Period Geomagnetic Variations as Observed in Association with Crustal Uplift in the Izu Peninsula, Japan. *Earthquake Pred. Res.*, **2**, 115-125, 1983.

Huang, L., and D. Hanzen, *Earthquake Light*, 1-140, Earthquake Press, Beijing, China, 1979.

Jachens, R. C., W. Thatcher, C. W. Roberts, and R. S. Stein, Correlation of Changes in Gravity, Elevation, and Strain in Southern California, *Science*, **219**, 1215-1216, 1983.

Jackson, D. B., Geoelectric Observations: September 1982 Summit Eruption and the First Year of the Pu'u 'O'o Eruption, Kilauea Volcano, Hawaii, U.S.G.S. Professional Paper (in Press), 1986.

Johnston, M. J. S., Local Magnetic Field Variations and Stress Change Near a Slip Discontinuity on the San Andreas Fault, *J. Geomag. Geoelec.*, **30**, 511-522, 1978.

Johnston, M. J. S., F. J. Williams, J. McWhirter, and B. E. Williams, Tectonomagnetic Anomaly During the Southern California Downwarp, *J. Geophys. Res.*, **84**, 6026-6030, 1979.

Johnston, M. J. S., Ware, R. H., and R. Mueller, Tidal-current channeling in the San Andreas fault, California, *Geophys. Res Letts.*, **10**, 51-54, 1983.

Johnston, M. J. S., R. J. Mueller, R. H. Ware, and P. M. Davis, Precision of Geomagnetic Measurements in a Tectonically Active Region, *J. Geomag. Geoelec.*, **36**, 83-95, 1984.

Johnston, M. J. S., S. A. Silverman, R. J. Mueller, and K. S. Breckenridge, Secular Variation, Crustal Contributions, and Tectonic Activity in California, 1976-1984, *J. Geophys. Res.*, **90**, 8707-8717, 1985.

Johnston, M. J. S., Local Magnetic Fields, Uplift, Gravity, and Dilational Strain Changes in Southern California, *J. Geomag. Geoelec.*, (in press), 1986.

Johnston, M. J. S. and R. J. Mueller, Seismomagnetic Observation with the July 8, 1986, M_L 5.9 North Palm Springs Earthquake, *Science*, (in press), 1986.

Kalashnikov, A. C., The Possible Application of Magnetometric Methods to the Question of Earthquake Indications, *Tr. Geofiz. Inst. Akad. Nauk. S.S.S.R., Sb. Statei*, **25**, 162-180, 1954.

Kalashnikov, A. C. and S. P. Kapitsa, Magnetic Susceptibility of Elastically Stressed Rocks, *Proc. (Doclady) Acad. Sci. U.S.S.R.*, **86**, 521-523, 1952.

Kapitsa, S. P., Magnetic Properties of Eruptive Rocks Exposed to Mechanical Stresses, *Izv. Akad. Nauk. S.S.S.R., Ser. Geofiz.*, **6**, 489-504, 1955.

Kean, W. F., R. Day, M. Fuller, and V. A. Schmidt, The Effect of Uniaxial Compression on the Initial Susceptibility of Rocks as a Function of Grain Size and Composition of their Constituent Titanomagnetites, *J. Geophys. Res.*, **85**, 861-872, 1976.

Kern, J. W., Effect of Moderate Stresses on Directions of Thermoremanent Magnetization, *J. Geophys. Res.*, **66**, 3801-3805, 1961.

Lockner, D. A., M. J. S. Johnston, and J. D. Byerlee, A Mechanism to Explain the Generation of Earthquake Lights, *Nature*, **302**, 28-33, 1983.

Lockner, D. A., and J. D. Byerlee, Complex Resistivity of Fault Gouge and its Significance for Earthquake Lights and Induced Polarization, *Geophys. Res. Lett.*, **12**, 211-214, 1985.

Martin III, R. J., Is Piezomagnetism Influenced by Microcracks During Cyclic Loading, *J. Geomag. Geoelec.*, **32**, 741-755, 1980.

McGarr, A., M. D. Zoback, and T. C. Hanks, Implications of an Elastic Analysis of In Situ Stress Measurements Near the San Andreas Fault, *J. Geophys. Res.*, **87**, 7797-7806, 1982.

Mueller, R. J., M. J. S. Johnston, B. E. Smith, and V. G. Keller, U. S. Geological Survey Magnetometer Network and Measurement Techniques in Western U. S. A., U. S. G. S. Open-file Report 81-1346, Menlo Park, CA, 1981.

Mueller, R. J., M. J. S. Johnston, V. G. Keller, and S. Silverman, Magnetic Field Observations in the Long Valley Caldera of East-Central California, 1976-1984, *Trans A. G. U.*, **65**, 1117, 1984.

Nagata, T., Basic Magnetic Properties of Rocks under the Effect of Mechanical Stresses, *Tectonophysics*, **21**, 427-445, 1969.

Ohnaka, M., and H. Kinoshita, Effects of Uniaxial Compression on Remanent Magnetization, *J. Geomag. Geoelec.*, **20**, 93-99, 1968.

Ohshiman, N., Y. Sasai, Y. Ishikawa, Y. Honkura, and H. Tanaka, Local Changes in the Geomagnetic Total Intensity Associated with Crustal Uplift in the Izu Peninsula, Japan, *Earthq. Pred. Res.*, **2**, 209-219, 1983.

Pike, S. J., T. L. Henyey, J. Revol, and M. D. Fuller, High-pressure Apparatus for Use with a Cryogenic Magnetometer, *J. Geophys. Res.*, **33**, 449-466, 1981.

Revol, J., R. Day, and M. Fuller, Magnetic Behavior of Magnetite and Rocks Stressed to Failure - Relation to Earthquake Prediction, *Earth and Planet. Sci. Lett.*, **37**, 296-306, 1977.

Savage, J. C., and G. Gu, The 1979 Palmdale, California, Strain Event in Retrospect, *J. Geophys. Res.*, **90**, 10301-10309, 1985.

Savage, J. C., W. H. Prescott, M. Lisowski, and N. E. King, Strain on the San Andreas Fault near Palmdale, California: Rapid Aseismic Change, *Science*, **211**, 56-58, 1981a.

Savage, J. C., W. H. Prescott, M. Lisowski, and N. E. King, Strain Accumulation in Southern California, *J. Geophys. Res.*, **86**, 6991-7002, 1981b.

Stacey, F. D., Theory of Magnetic Susceptibility of Stressed Rocks, *Phil. Mag.*, **7**, 551-556, 1962.

Stacey, F. D., The Seismomagnetic Effect, *Pure Appl. Geophys.*, **58**, 5-22, 1964.

Stacey, F. D., K. G. Barr, and G. R. Robson, The Volcanomagnetic Effect, *Pure Appl. Geophys.*, **62**, 96-104, 1965.

Stacey, F. D., and M. J. S. Johnston, Theory of the piezomagnetic effect in titanomagnetite-bearing rocks, *Pure Appl. Geophys.*, **97**, 146-155, 1972.

Sasai, Y., Application of the Elastic Dislocation Theory of Dislocations to Tectonomagnetic Modeling, *Bull. Earthq. Res. Inst.*, **55**, 387-447, 1980.

Ware, R. H., M. J. S. Johnston, A comparison of Proton and Self-Calibrating Rubidium Magnetometers for Tectonomagnetic Studies, *J. Geomag. Geoelec.*, **37**, 1051-1061, 1985.

Warwick, J. W., C. Stoker, and T. R. Meyer, Radio Emission Associated with Rock Fracture: Possible Application to the Great Chilean Earthquake of May 22, 1960. *J. Geophys. Res.*, **87**, 2851-2859, 1982.

Wilson, E., On the Susceptibility of Feebly Magnetic Bodies as Affected by Compression, *Proc. Roy. Soc. A.*, **101**, 445-452, 1922.

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

(Received September 18, 1986; accepted February 2, 1987.)