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Preseismic and Coseismic Magnetic Field Measurements Near the Coyote Lake, California, Earthquake of August 6, 1979

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The epicenter of the Coyote Lake earthquake ($M_L = 5.9 \pm 0.2$) of August 6, 1979, is located within an array of recording magnetometers which has been in operation since 1974. The nearest instrument, COY, was within 5 km of the epicenter. It was installed in October 1978 and is located on sedimentary rock, although volcanic and ultramafic rocks with magnetizations of up to 1 A/m outcrop 2 km to the west. A second recording magnetometer was operated for 18 days, beginning 4 days after the main event, to record the latter stages of the aftershock activity. Although longer-term magnetic field variations were recorded at station COY early in 1979 relative to other sites in the area, no anomalous changes within the two months prior to the earthquake were observed outside the present measurement uncertainty of 0.8 nT for hourly average differences. During the late aftershock stage, no magnetic field change greater than 0.25 nT occurred for more than a day. We conclude that in contrast to the 2-nT change observed before a previous $M = 5.2$ earthquake near Hollister, California, no demonstrable preseismic, coseismic, or postseismic tectonomagnetic effect was detected. A reasonable seismomagnetic model of the earthquake indicates that station COY was poorly located to detect stress-generated magnetic perturbations from this earthquake. Using a magnetization distribution indicated by modeling the aeromagnetic data over the area, we have calculated that homogeneous shear stress changes of about 5 MPa or greater would have been necessary to produce any observable effect at COY. This change in stress is precluded by geodetic data from over the area. However, COY is ideally situated for detection of electrokinetically generated magnetic anomalies. This initial null observation indicates that the assumptions used in the calculation of electrokinetic effects have, in this case, not been satisfied.

INTRODUCTION

A moderate earthquake ($M_L = 5.9 \pm 0.2$) occurred near Coyote Lake, California, on the Calaveras fault on August 6, 1979, at a depth of about 10 km. The earthquake generated minor surface rupture (~5 mm) along about 15 km of the fault trace to the southeast of Coyote Lake [*Herd et al.*, 1979]. Aftershocks occurred at depths of from 4 to 12 km along a 21-km fault segment, also to the southeast of the main shock [*Lee et al.*, 1979]. The radiation pattern of the main shock indicates a predominantly strike-slip focal mechanism with a rupture direction from northwest to southeast [*Lee et al.*, 1979; *Archuleta*, 1979]. The seismic moment, seismic stress drop, and length of the aftershock zone were about 0.5×10^{18} N m, 1 MPa, and 21 km, respectively [*Lee et al.*, 1979].

The earthquake occurred within an array of continuously recording magnetometers installed since 1974 as part of a search for earthquake precursors and indications of active tectonic behavior [*Johnston et al.*, 1976]. For the only previous earthquake of magnitude greater than 5 in this area, *Smith and Johnston* [1976] reported anomalous magnetic field variations of about 2 nT within a 2-month period prior to this earthquake in November 1974. The August 6, 1979, Coyote Lake earthquake provided an opportunity to detect similar magnetic anomalies before or coincident with the earthquake and to test the different models of magnetic field generation near active faults [*Stacey*, 1964; *Talwani and Kovach*, 1974; *Mizutani et al.*, 1976; *Johnston*, 1979; *Fitterman*, 1979].

OBSERVATIONS

The locations of recording magnetometers in the central California area are shown in the inset of Figure 1. Because the instrument separation in the region of the Coyote earthquake is quite large, only one instrument, COY, was recording within 10 km of the epicenter. The area around the earthquake epicenter and the location of the instrument COY is shown in Figure 1. The aftershocks all occurred within the dashed area approximately 21 km long and 4 km wide. All the instruments shown operate at 0.25-nT sensitivity, and the digital data are telemetered to Menlo Park at one sample every 10 min. The instrument COY was installed in September 1978. The portable instrument CIY was installed 4 days after the main shock at a point where we calculated an expected maximum coseismic field perturbation due to changes in stress resulting from failure.

The simplest method of isolating local magnetic field changes and reducing the effects of ionospheric and magnetospheric disturbances, and, most importantly, the general diurnal variation, is to difference the magnetic field observations between adjacent stations no more than a few tens of kilometers apart. In particular, we wish to search for and isolate changes that might have occurred at COY, the magnetometer nearest to the Coyote Lake main shock. Figure 2*a* shows the magnetic field differences in 10-min samples between station COY and the surrounding stations MTH, EUC, and QSB for the period around the time of the earthquake. For comparison, the differences excluding COY are also shown. Clearly, the local magnetic field did not change significantly coincident with or immediately before the earthquake.

We have applied several methods for noise reduction to these data to improve discrimination of signals that may be of tectonic origin. The simplest of these methods is a variation on the weighted-difference technique [*Rikitake*, 1966]. In our application this technique focuses primarily on the short-term noise in the difference data that arises from incomplete cancellation of the diurnal variation. By plotting the data from other sites against those from COY during the daily interval of significant diurnal variation, a mean-response difference or 'weight factor' was obtained by a least squares line fit. Figure 2*b* shows the result of applying this technique to data from COY and MTH.

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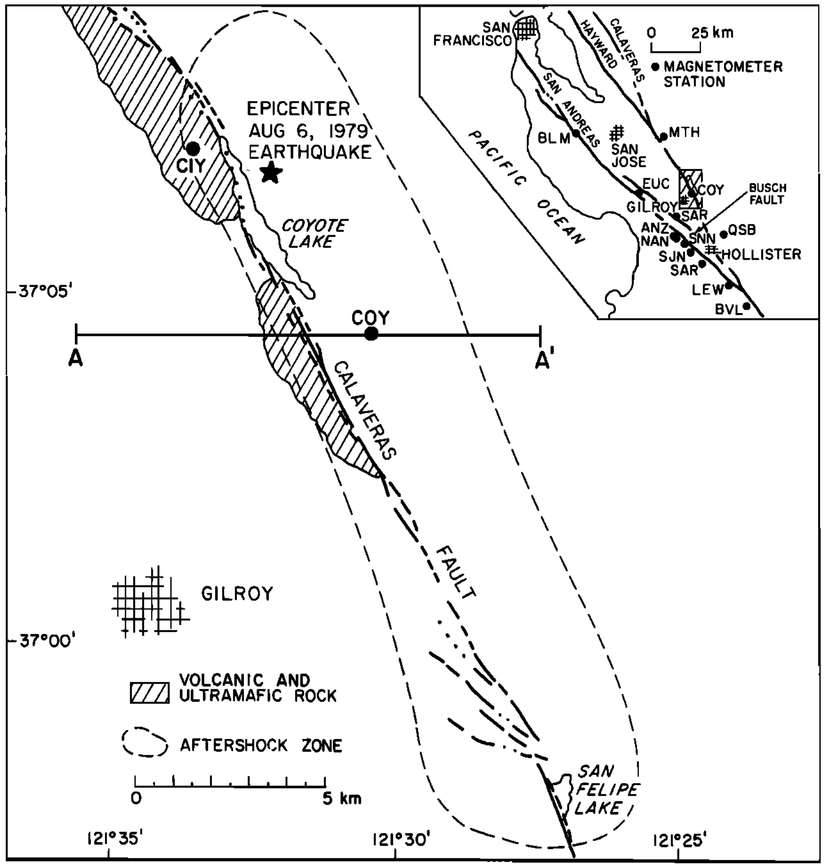

Fig. 1. Map of central California showing locations of continuously recording magnetometers. The location of the August 6 earthquake is shown as an asterisk in the expanded section together with the aftershock zone, generalized geology, and the locations of the permanent station COY and the temporary station CIY. The profile AA′ is used in the text for modeling the magnetic structure.

The upper plot in Figure 2*b* shows, for comparison, the raw magnetic field differences from Figure 2*a*. The standard deviation is 0.8 nT. The middle plot shows the weighted differences according to the expression

$$b(\mathrm{COY}) - (\mathrm{MTH}) + c$$

where b and c, obtained by least squares line fitting on 30 days of data, are 1.038 and −94.4 nT, respectively. The standard deviation for these data is 0.65 nT. This represents a 19% improvement in the standard deviation using weighted differences. The bottom plot shows a six-point (i.e., hourly) average of the weighted-difference data. The standard deviation here is 0.44 nT. We note that the magnetic field variation at the time of the August 6 earthquake is not significant at the 95% confidence level if we use a data segment longer than 4 days (Figure 2*c*).

The aftershock activity of the Coyote Lake earthquake decreased rapidly after the main event [*Lee et al.*, 1979]. By the time the instrument CIY was installed 4 days after the main event, this activity was less than 25% of the original rate of about 150 earthquakes per day, and no earthquakes occurred subsequently with magnitudes greater than 3.6. Figure 3 shows 19 days of magnetic field differences between CIY and COY, together with the aftershock activity. The standard deviation of these differences is 0.50 nT.

Because these stations are much closer together, the measurement resolution is much higher. However, we are still unable to determine any significant changes in these data greater than 0.25 nT over periods longer than 1 day, either of systematic form or coseismic with any aftershocks during the latter stage of the aftershock activity.

DISCUSSION

It has been argued that magnetic field changes might be expected preseismically, coseismically, or postseismically on the basis of two primary physical mechanisms. These are the seismomagnetic effect [*Stacey*, 1964; *Shamsi and Stacey*, 1969; *Stacey and Johnston*, 1972; *Talwani and Kovach*, 1972; *Johnston*, 1978] and the electrokinetic effect [*Mizutani et al.*, 1976; *Dmowska*, 1977; *Fitterman*, 1979]. The seismomagnetic effect is derived from the stress dependence of the magnetic properties of rocks and the electrokinetic effect from streaming potentials set up by pore pressure variations near active faults.

Regarding seismomagnetic effects, we can calculate the form and amplitude of magnetic changes expected at COY as a result of finite slip on the Calaveras fault using models similar to those of *Stacey* [1964], *Talwani and Kovach* [1972], and *Johnston* [1978]. The surface anomaly at a point on the earth's surface is a function primarily of the fault geometry, the distribution of magnetization, and the change in stress state in the region. Following *Johnston* [1978], we calculated an upper estimate of the seismomagnetic effect at COY using a model of a finite slip patch from 1 to 11 km deep and 21 km in extent. The fault slip was estimated as 10 cm from the seismic moment of from 0.5 to 0.6 × 10^{18} N m reported for this earthquake by *Lee et al.* [1979]. We assumed that the magnet-

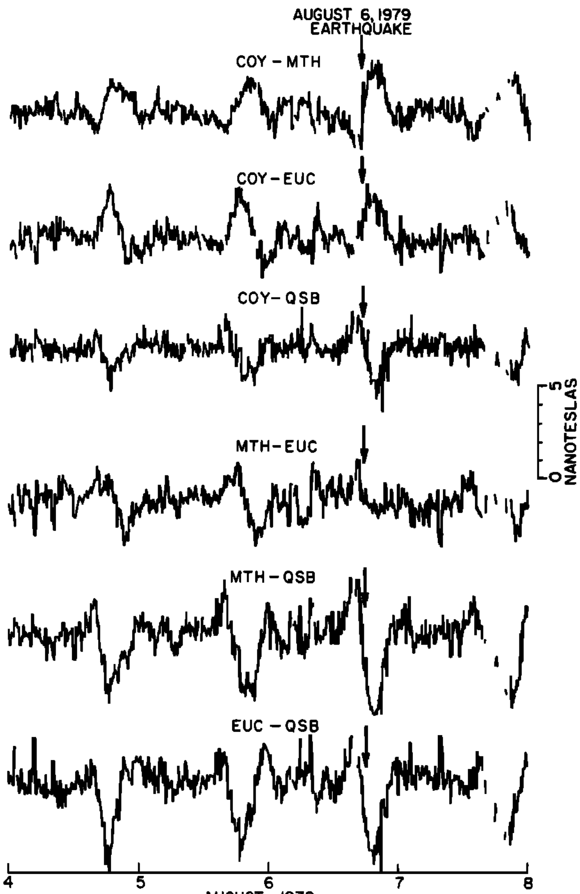

Fig. 2*a*. Magnetic field differences between data recorded at COY and various other stations within a 25-km radius of the epicenter for 2 days before and 1 day after the 1979 earthquake. Standard deviations of the plots are 0.8, 0.8, 0.7, 0.8, 1.3, and 1.25 nT, respectively.

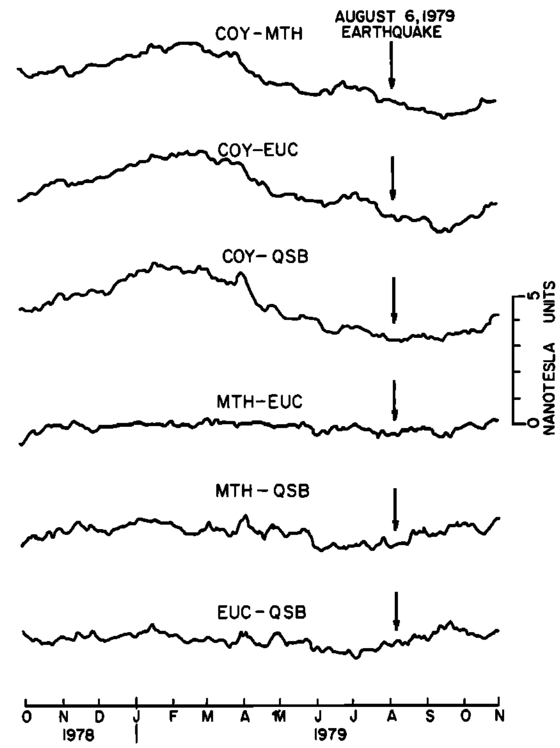

Fig. 2*c*. Five-point running average on daily average values of differential magnetic data for the stations around the Coyote earthquake.

ization was 1 A/m and that the remanent and induced components were in the same direction. This solution is illustrated in Figure 4. Clearly, if this solution is correct, the location of station COY for this earthquake was unfortunate. On the other hand, if further stress release occurred over the same area, then CIY would be ideally situated to detect it if the assumptions of uniform magnetization and geometry are correct. Taking the geometry of the slip patch to be from only 4 to 11 km deep, as indicated by the aftershock distribution [*Lee et al.*, 1979], the calculated anomaly in Figure 4 is attenuated slightly and the contour pattern is extended. Increasing the

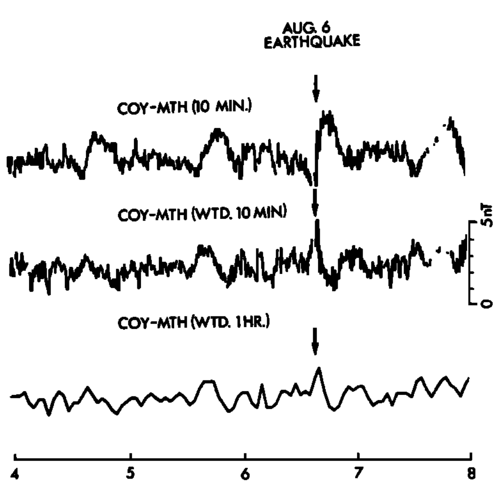

Fig. 2*b*. Noise reduction in weighted differences between 10-min records obtained between COY and MTH. The weights were calculated from a least squares fit of COY data to MTH data. The lower plot shows hourly averages of weighted differences.

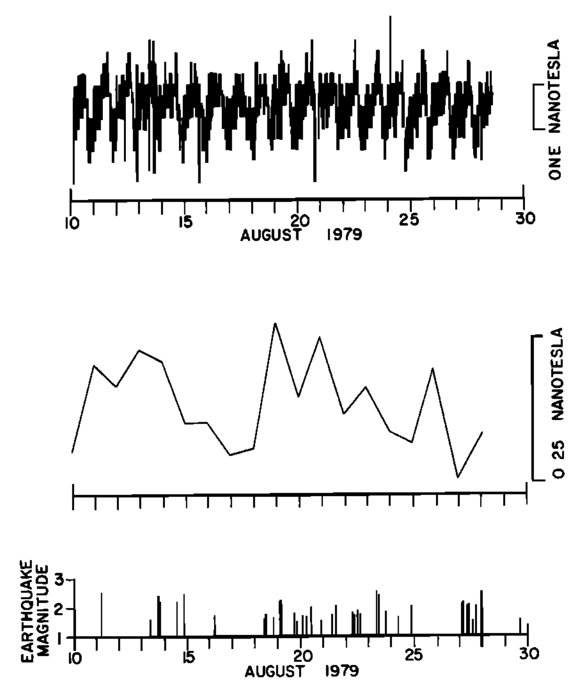

Fig. 3. Ten-minute (top) and daily-average (middle) magnetic field differences between CIY and COY for the period August 10 to August 28, 1979. The magnitudes and occurrence times of aftershocks during this period whose hypocenters were within 10 km of COY are plotted at the bottom of the figure.

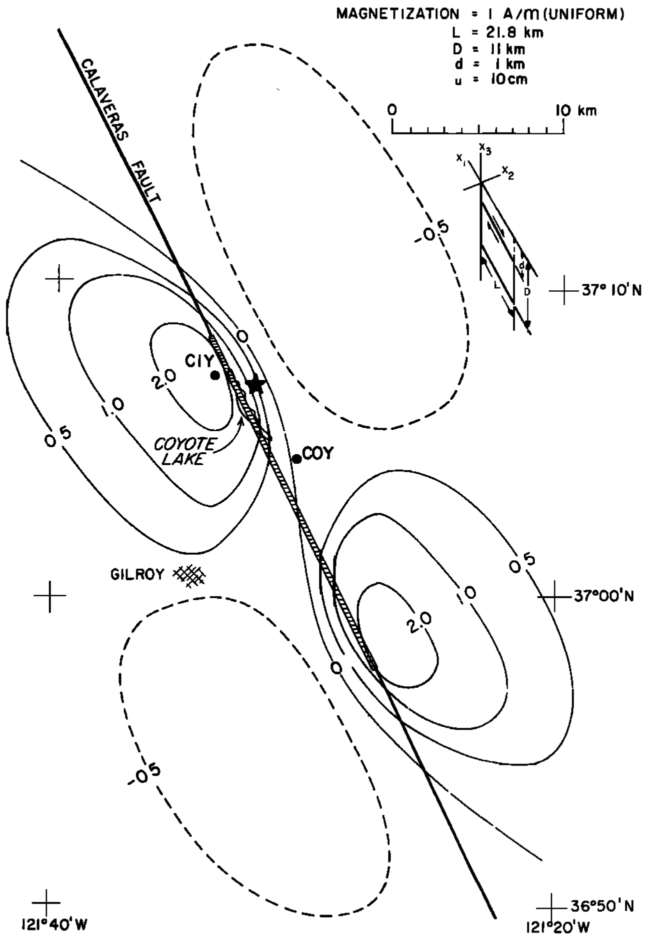

Fig. 4. Magnetic anomaly contours (in nanoteslas) for 10 cm of slip on a fault between 1 and 11 km deep by 21 km long in a homogeneous material with a normal magnetization of 1 A/m. The August 6 earthquake epicenter is marked with an asterisk.

fault slip from 10 cm to 33 cm, as indicated by the geodetic data to be the total amount of slip on the fault from May to September 1979 [*King et al.*, 1979], correspondingly amplifies the calculated anomaly at COY by about 5 to 0.3 nT. We conclude, therefore, that reasonable variations in geometry and fault slip still appear insufficient to generate a measurable coseismic signal at station COY.

As regards the location of COY for the present fault geometry, other parameters that might control whether a piezomagnetic anomaly could be generated are the distribution of magnetization or a more complex and heterogeneous stress state than has been assumed. The surface anomaly field could be greatly perturbed if the distribution of magnetization were nonuniform. Some indication of this actual distribution in this area, albeit an underestimate, can be obtained by surface sampling. Observed values ranged from 0.1 to 0.001 A/m on the east side of the fault near COY, from 0.5 to 2 A/m on the west side of the fault across the volcanic and ultramafic rocks (Figure 1), and from 0.1 to 0.001 A/m further to the west. Aeromagnetic surveys at a height of 914 m [*U.S. Geological Survey*, 1974] indicate regional magnetic anomalies above the volcanic and ultramafic rocks of about 100 nT. A better indication of the regional magnetic structure can be obtained by determining the simplest distribution of magnetization that generates an anomaly which best fits the observed regional anomaly. The observed east-west profile through station COY (A-A′, Figure 1) is plotted in Figure 5 together with a calculated profile at the same elevation obtained by assuming the magnetization distribution of the model magnetic structure illustrated in the lower part of the figure. Although other similar distributions could be chosen, the necessary feature of these distributions is that the dominant near-surface magnetic material occurs on the west side of the fault, as indicated by the surface geology.

The simplest approximation to this distribution for a seismomagnetic calculation is a magnetization of 1 A/m on the west side of the fault and 0.1 A/m on the east side. The solution for this case, with all other parameters the same as in the previous case (Figure 4), is illustrated in Figure 6. The coseismic change now expected at COY is still too small to be detected unambiguously. A further difficulty, that CIY is also poorly located with respect to the anomaly, is now apparent.

A better fit to the observed aeromagnetic anomaly requires the inclusion of more complexity in the magnetization pattern to the west of the fault. This does not seem warranted at this point, since it is unlikely to change significantly the expected anomaly at COY. We note that the changes in mean shear stress on the fault necessary to generate an observable coseismic anomaly greater than 1.5 nT at COY for the two cases considered are about 21 and 5.2 MPa, respectively. Following *Chinnery* [1963], these changes could be produced by uniform slip in the two cases of 150 and 37 cm, respectively. The first value is certainly precluded by geodetic observations over the area [*King et al.*, 1979]. The second case is possible if comparable preseismic or coseismic slip occurred and may be indicated perhaps by the longer-term change earlier in the year.

Mizutani et al. [1976] suggested that electrokinetic effects may be associated with active faulting. *Fitterman* [1979] recently presented the most complete formulation and modeling of this effect. According to *Fitterman*'s [1979] model, the maximum magnetic field perturbation should be recorded around the center of the rupture zone with an amplitude of up to 10 nT depending on the electrical conductivities, streaming potential coefficients, and pore pressure changes chosen. Thus if electrokinetic effects occur, site COY should be ideally located to detect them. However, since no change was apparently observed in these data, the assumptions used by *Fitterman* [1979]

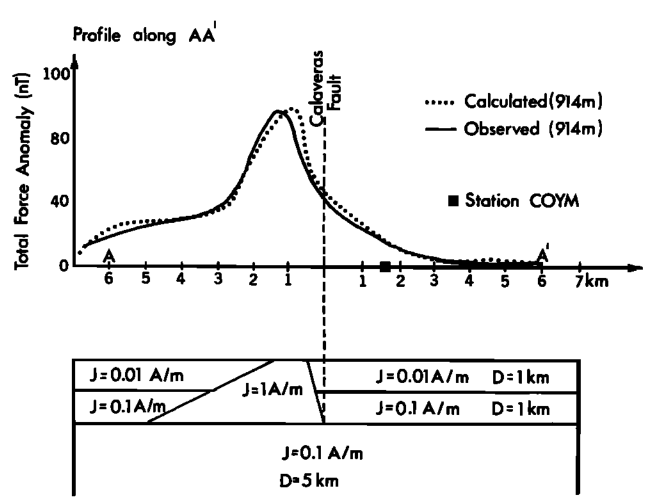

Fig. 5. Observed aeromagnetic anomaly (solid curve) at 914 m along the profile A-A′ (Figure 1). The calculated anomaly (dotted curve) is for the model magnetic structure shown in the lower diagram.

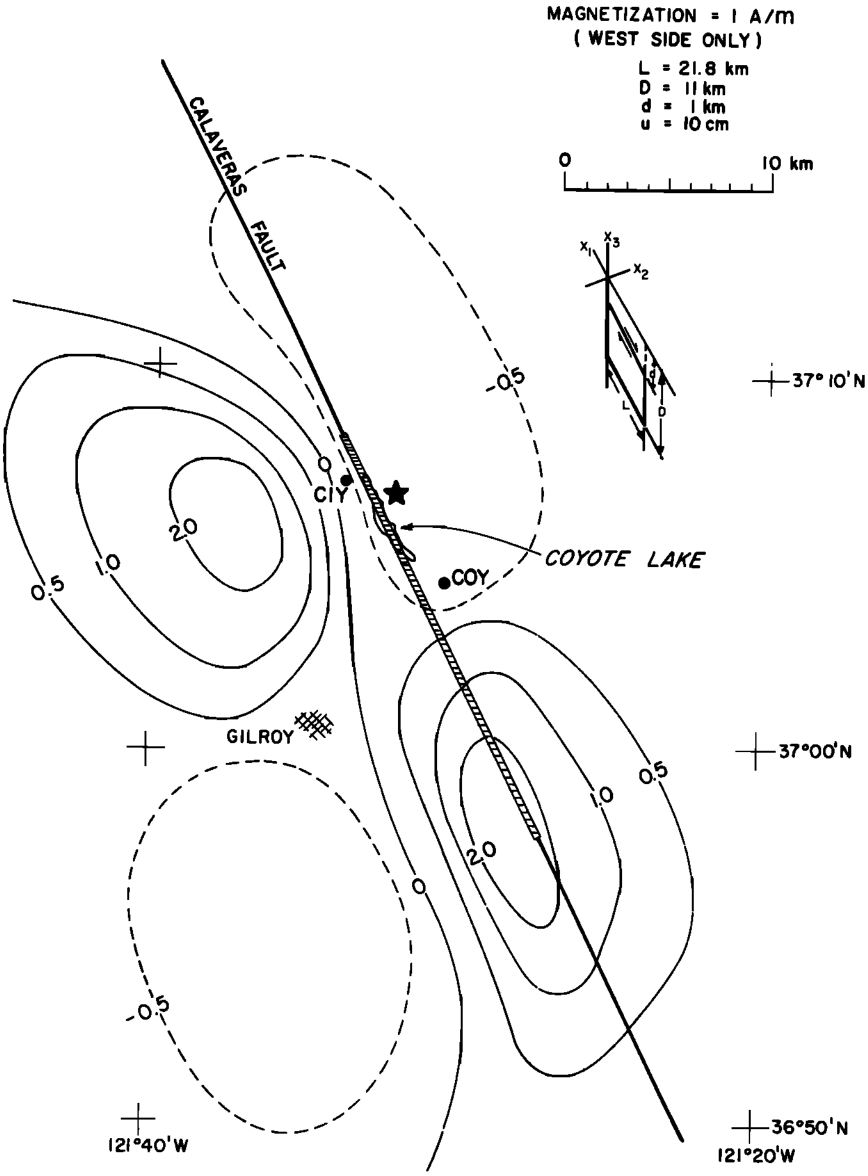

Fig. 6. Magnetic anomaly contours (in nanoteslas) for the model in Figure 4 but for which the magnetization on the east side of the fault is 0.01 A/m.

have, in some way, not been satisfied for this earthquake. The least well known parameters are the source geometry, the streaming potential coefficients, and the changes in pore pressure. This argument can be pursued in a different way if we question whether the longer-term magnetic field changes recorded earlier in 1979 were generated by electrokinetic effects. If so, the electrokinetic models would indicate that electric fields exceeding 100 mV/km should have accompanied these magnetic field changes. Unfortunately, electric field measurements are not made in the area. However, about 25 km to the south, changes in electric field greater than a few millivolts per kilometer apparently did not occur (T. Madden, personal communication, 1980).

It is not easy to quantify the relation, if any, between the longer-term magnetic field variations recorded at COY earlier in 1979 (Figure 2*c*) and those around the time of the August 6 earthquake. By referring all data to a single distant station, it is easy to show that these longer-term variations occur only at COY. However, the variations do appear to reflect part of the annual cycle, and until several more years of data are obtained, a conservative approach to their interpretation seems appropriate.

Conclusions

After examining the data from the single recording magnetometer situated near the August 6, 1979, Coyote Lake earthquake in some detail, we conclude that, in contrast to the November 1974 Hollister, California, earthquake, no anomaly preceding this earthquake can be identified with any significance as a precursor. Although some longer-term magnetic field changes did occur earlier in 1979, it is unclear whether or how these changes relate to longer-term fault activity. We note the following implications regarding either piezomagnetic or electrokinetic mechanisms for tectonomagnetic effects:

1. In terms of a piezomagnetic explanation, the absence of any clear observation of magnetic field change could be due to poor location of COY with respect to the subsequent earth-

quake slip plane, insufficient magnetic material, or a marginal change in mean stress state. For the present geometry and likely distribution of magnetization, a mean shear stress change in excess of 5 MPa probably would be required to obtain a significant observation. The absence also of any postseismic changes on a second recording magnetometer installed 4 days after the main event at the point of maximum expected signal indicates that postseismic stress variation, if reflected in these data, was minimal after that time. We note that the frequency and magnitudes of aftershocks decayed more rapidly than expected for an earthquake of this magnitude [*Lee et al.*, 1979]. During the operating period, no aftershocks with $M_L > 2.6$ occurred within 10 km of the station, and the daily number of aftershocks was less than 25% of the original rate.

2. It appears that the station COY was ideally situated for the detection of electrokinetic effects. The absence of any clear observation in these data indicates that the assumptions used in the calculations of these effects have not been satisfied for this earthquake.

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