A Tectonomagnetic Effect Observed Before A Magnitude 5.2 Earthquake Near Hollister, California

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Simultaneous measurements of geomagnetic field with an array of seven proton precession magnetometers along the San Andreas fault show that the most significant local changes during 1974 were recorded at a site 11 km from a magnitude 5.2 earthquake that occurred on November 28, 1974. A systematic increase in magnetic field of 0.9 γ occurred at this site during the early part of 1974. A more dramatic increase of 1.5 γ occurred about 7 weeks before the earthquake, lasting about 2 weeks. Four weeks prior to the earthquake the magnetic field returned to approximately its initial value and remained at this value through April 1975. These data cannot be explained by ionospheric disturbances or telluric currents. The most probable source is a piezomagnetic effect, which implies that the magnetic field changes represent changes in stress in the rocks nearby the anomalous station.

INTRODUCTION

Current attempts to predict earthquakes are based primarily on the assumptions that crustal stress and strain changes will occur prior to earthquakes and that these changes have some clearly measurable surface manifestation. A prototype network of instruments for simultaneously detecting these changes is currently operating in central California along one of the most active sections of the San Andreas fault (creep array [*Yamashita and Burford*, 1973], strainmeter array [*Jones and Johnston*, 1974], resistivity array [*Mazzella and Morrison*, 1974], tiltmeter array [*Mortensen and Johnston*, 1975], geodetic strain [*Prescott and Savage*, 1974], magnetometer array [*Smith et al.*, 1974], seismic array [*Wesson et al.*, 1974]). This paper reports observations of local magnetic field changes from a magnetometer network prior to an earthquake of magnitude 5.2 that occurred near Hollister, California, on Thanksgiving Day 1974. A companion paper [*Mortensen and Johnston*, 1976] reports tilt observations for the same earthquake.

BACKGROUND

The suggestion that crustal stress changes could be monitored by observing changes in the local magnetic field was first made by *Wilson* [1922]. Laboratory measurements [*Kalashnikov*, 1954; *Kapitsa*, 1955; *Ohnaka and Kinoshita*, 1968] have since verified that for rocks containing magnetic grains a change in stress will produce changes in the magnetic field which are probably due to a piezomagnetic effect. Theoretical studies are in general agreement with the laboratory studies [*Kern*, 1961; *Stacey*, 1962; *Nagata*, 1970; *Stacey and Johnston*, 1972]. Calculations of expected local magnetic field changes for typical earthquake types indicate that surface anomalies of a few gammas can be expected [*Shamsi and Stacey*, 1969].

A number of experiments have been conducted to try to observe tectonomagnetic effects. Until recently, such experiments have not met with much success, primarily because short-term effects can easily be confused with ionospheric and magnetospheric disturbances and the instruments employed did not have sufficient stability to search for long-term changes. With the introduction of the absolute total field proton precession magnetometer (with proper precautions the only possible source of drift in this instrument is an easily monitored crystal oscillator), long-term stability for total field measurements is no longer a problem. Long-term stability problems of vector component magnetometers have not yet been overcome.

Recent tectonomagnetic studies employing proton magnetometers [*Yamazaki and Rikitake*, 1970; *Johnston et al.*, 1973; *Johnston et al.*, 1975] have shown some encouraging results, but so far no systematic or reproducible precursor magnetic event has been observed for an individual earthquake.

INSTRUMENTATION AND RESULTS

The U.S. Geological Survey has been operating a seven-station total field proton precession magnetometer array in central California along an 80-km section of the San Andreas fault since late 1973 (Figure 1). The instruments currently operate at a sensitivity of 0.25 γ and sample simultaneously at 1-min intervals. Although instrumental drift is not expected at this sensitivity, each magnetometer is periodically calibrated as an added precaution. The data are telemetered digitally via telephone or radio link to the U.S. Geological Survey office in Menlo Park, California, where the total field values from all stations have been recorded in digital form on magnetic tape since January 1, 1974. The differences between adjacent stations and selected total field records are generated in analog form for visual monitoring in real time.

To detect magnetic signals below the 1-γ level at these sites, it is necessary to reduce the effects of ionospheric and magnetospheric disturbances by about a factor of 40. In searching for long-period (i.e., >1 day) tectonomagnetic effects the method of simple differencing combined with 1-day averaging makes subgamma discrimination possible at all except the two northernmost site pairs. These pairs (2-1 and 2-3) are noisier because of anomalous low amplitudes of magnetic disturbances at station 2. The noise in the differences between sites depends on station separation and on the electrical and magnetic characteristics of the sites. Work is currently being done in an attempt to understand the noise sources and to determine if the noise can be further reduced.

The data presented in this paper are from station differences 3-4 and 5-4. These data have been carefully checked for contamination by ionospheric or magnetospheric disturbances, and we have found no correlation between these disturbances and the magnetic signals that will be discussed. Changes in 5-day means greater than 0.25 γ for the difference 3-4 and 0.5 γ for the difference 5-4 are statistically significant at the 95% confidence limit. The data from station difference 2-3 are not included in this paper because noise from the northern end of

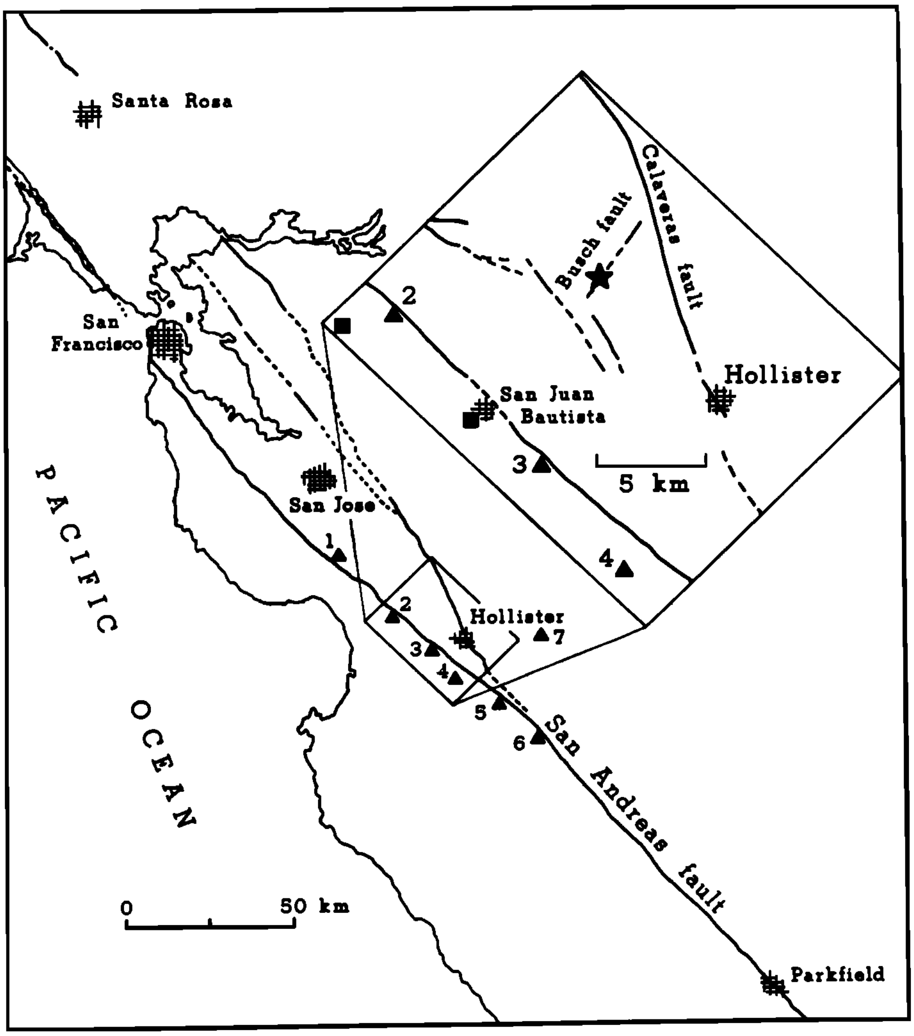

Fig. 1. Simplified fault map of central California near the San Andreas fault. The locations of all seven stations which constitute the U.S. Geological Survey magnetometer net are shown on the larger map (triangles). The detail map shows the location of three magnetometer stations (triangles), two U.S.G.S. tiltmeter stations (squares), and the epicenter of the Thanksgiving Day 1974 magnitude 5.2 earthquake (star).

the net generated a 95% confidence level in the 2-3 difference, for 5-day mean values, of about 2 γ. The noise levels can be reduced to about 0.75 γ by taking a 30-day running mean.

The data from all stations for 1974 have been compared with local earthquakes. With the exception of the magnitude 5.2 Thanksgiving Day earthquakes, earthquakes that occurred within 15 km of an operating magnetometer station had magnitudes to 3.6. We could find no clear relation between these earthquakes and local magnetic field changes.

The most significant changes in the local magnetic field during 1974 and early 1975 were observed at station 3. The general pattern of these changes can best be seen from a plot of 5-day running means of the differences 3-4 (Figure 2). This plot also includes the record from the difference 5-4, which is relatively flat during the period shown, the indication being that the major changes seen on the 3-4 record did in fact occur at station 3. The local magnetic field at station 3 increased systematically by 0.9 γ during the period mid-February to late July. The field dropped slightly during August and the first half of September and then started to rise again. The field increased during October by 1.5 γ. Because of lost data due to telemetry problems, it is not known whether this increase occurred gradually or in several discrete steps. The field remained very constant for about 2 weeks and then decreased by 1.8 γ on about November 1.

A plot of 1-day means shows a small decrease of about 0.3 γ for the October 31 mean value and a larger decrease of about 1.3 γ for the November 1 mean value (Figure 2), suggesting that the full 1.8-γ decrease took place over several days starting on October 31. One-min difference values from stations 3-4, 3-5, and 3-6 have been plotted to try to determine the short-term character of the 1.8-γ decrease (Figures 3 and 4). The noise on these plots is primarily of two types. One appears as random noise to 2 γ with a period of less than a few minutes. The second type is incomplete cancellation of the diurnal variations and can be seen to track these variations closely. Note that when the total field at station 3 decreases, the difference 3-4 increases, and the differences 3-5 and 3-6 decrease (Figure 3). Because of these noise levels it is apparent that the exact form and duration of the 1.8-γ decrease cannot be precisely determined. However, since all three differences show a decrease of about 1.25 γ occurring at about 0040 UT on November 1, this decrease is probably the 1.3-γ decrease shown in the 1-day mean values. The duration of the decrease appears to be between 2 and 6 min (Figure 4). The remainder of the 1.8-γ decrease cannot be identified on the 1-min plots.

The field at station 3 appears to have increased by about 0.25 γ during November and early December and then to have remained constant through April 1975.

The noise in differences 2-1 and 2-3 with the present processing is too high to distinguish long-term changes at station 2 similar to those seen at station 3 during the first half of the year. Neither the 5-day nor 30-day running mean records show any indication of an anomaly outside the noise levels at station 2 during the months of October and November.

DISCUSSION AND CONSIDERATION OF THE SOURCE

Since the magnetic field changes observed at station 3 were unrelated to geomagnetic variations of magnetospheric origin, the source of these changes is almost certainly due to a local process. The changes are not likely to be due to cultural effects because the station is relatively remote and a particular and very unusual sequence of events is necessary to cause these changes. It is also difficult to argue for changes in the Curie point isotherm for reasons of low thermal diffusivity and lack of observed heat flow anomalies [*Lachenbruch and Sass,* 1973]. A telluric current source would require a local geoelectric field change within a few kilometers of station 3, since the magnetic field change was not observed at other stations. Assuming a conductivity for this region of 5×10^{-2} mho/m [*Mazzella and Morrison,* 1974], a 1-γ magnetic field change could result from a localized long-term geoelectric field change of approximately 30 mV/km if current is assumed to flow to a depth of 5 km. This type of source appears improbable, since long-term changes greater than a few millivolts per kilometer have not been observed in this region or other regions.

Other than an unknown instrumental effect, the most likely source process is a piezomagnetic effect. If this is the case, then an exciting implication is that the form of the change in the data would relate through the rock magnetization to a change in stress in the vicinity of station 3. With observations from only one station and incomplete knowledge of the rock magnetization, it is not possible to determine the exact spatial extent and source location of the magnetic changes, although some limitations can be placed on the approximate extent and location. The long-term changes recorded from mid-February through July were not observed at stations 4–7, and because of the high noise levels it is not known whether these changes occurred near stations 1 or 2. Therefore for the long-term changes it appears that the source does not extend southeast along the fault as far as station 4 and is probably within about

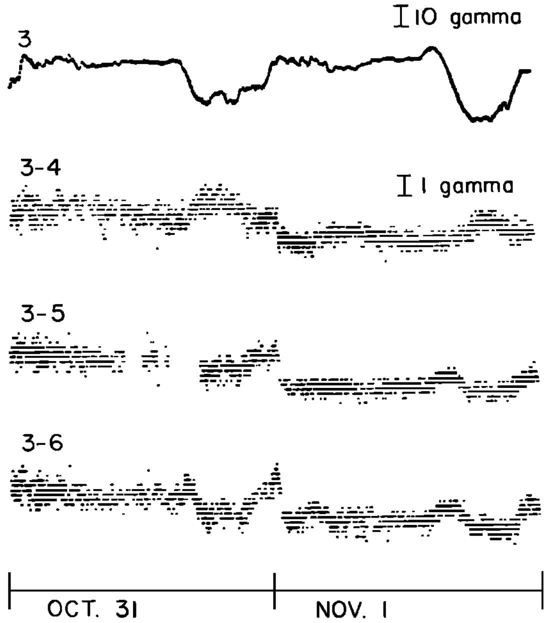

Fig. 3. Plots for 2 days of total field and differenced magnetic field data sampled at 1-min intervals. The upper record, labeled 3, represents total magnetic field values recorded at station 3. The lower records, labeled 3-4, 3-5, and 3-6, represent total magnetic field difference values for these stations. The even spacing of the difference values in the vertical axis reflects the 0.25-γ digital steps of the instruments. A 1.25-γ decrease can be observed in the difference records shortly after the beginning of November 1.

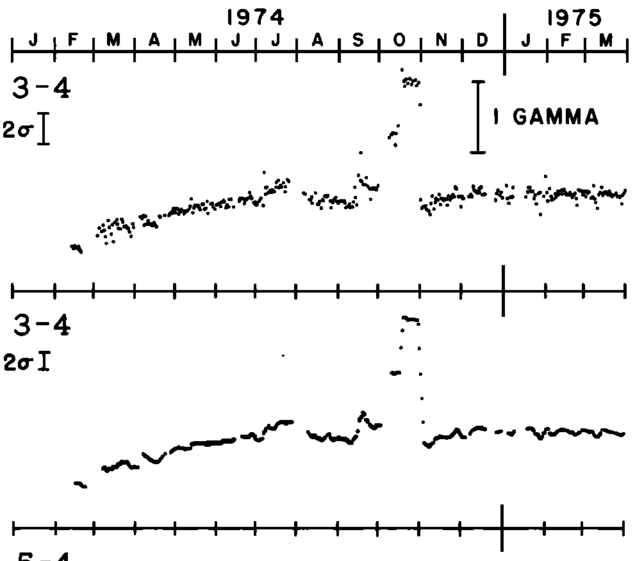

Fig. 2. Plots of 1-day means (top record) and 5-day running means (bottom two records) of the total magnetic field differences for station pairs 3-4 and 5-4. The error bars represent two standard deviations calculated by using the 1-day or 5-day mean values from March through July 1974 after removing the long-term trend. This period of time includes the largest ionospheric disturbances observed during 1974.

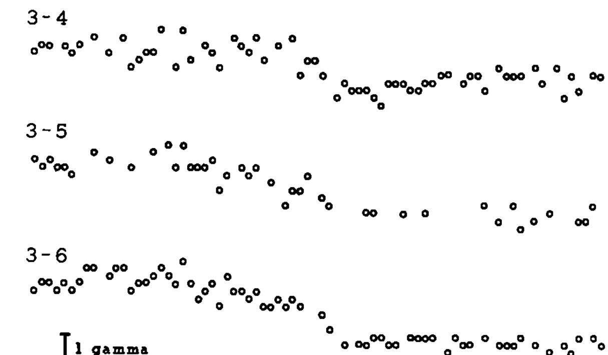

Fig. 4. Plots of 1-min difference values for stations 3-4, 3-5, and 3-6, a time-expanded rendition of the difference data shown in Figure 3 near the time of the 1.25-γ decrease.

10 km of station 3. During the time of the larger anomaly during October, no similar signal appears to have been recorded at any of the other stations, implying a source location within a few kilometers of station 3. The size of the magnetic field changes (up to 1.8 γ) is consistent with calculations that predict magnetic anomalies along the San Andreas fault, caused by a shear stress change of 10 bars, using a finite dislocation model of a locked fault with a rock magnetization of 10^{-3} emu [*Talwani and Kovach,* 1972]. Since surface measurements indicate a more realistic magnetization in this area of 10^{-4} emu, the stress change could approach 100 bars. Any realistic attempt at stress field inversion would require observations of the same magnetic event from at least three three-component magnetometers.

Of particular interest in questioning the relation of the magnetic field changes to the Thanksgiving Day earthquake are the time scales of the anomalies and comparison of these anomalies with other observations. The long-term changes observed from February to August 1974, if stress related, should have detectable, though as yet unobserved, consequences in seismicity, tilt, and strain in the region. As details of the long-term character of these parameters become available, along with more records from station 3, it will be easier to determine the significance of these magnetic field changes.

The more rapid changes in local magnetic field observation during October and on November 1 have a form and time scale similar to the 'bays' which have been reported as earthquake precursors from seismic velocity data and which may be related to crustal stress changes [e.g., *Aggarwal et al.,* 1975; *Sadovsky et al.,* 1972; *Semenov,* 1969; *Robinson et al.,* 1974]. A possible velocity anomaly with a similar form has been observed during the same period of time [*Lee and Healy,* 1975]. However, this velocity anomaly is not clearly outside the noise, and its validity is currently questioned. Since the magnetic anomaly can be explained by three discrete events, its apparent bay shape may be only a coincidence.

The very rapid decrease in magnetic field on about November 1 did not appear to be associated with any observable seismicity. A possible explanation for this decrease is that it represents stress changes due to local aseismic slip on the San Andreas fault. Unfortunately, there were no creepmeters in operation in this area near the time of the magnetic event that might have detected a surface expression of this slip.

Tiltmeters in the area (Figure 1) produced records that show a significant increase in the tilt rate beginning during the period of anomalous magnetic field change in October [*Mortensen and Johnston,* 1976], although the forms of these changes were not the same. Whereas the magnetic field at station 3 returned approximately to its original value in November, the tiltmeters did not. None of the tiltmeters in the network recorded a fast change at the time of the rapid magnetic field decrease on October 31–November 1, further evidence that this event occurred very close to station 3. Direct correspondence between the two types of instruments is not expected, since the instruments are not located at the same place and the tiltmeters cannot distinguish between tilts of elastic and anelastic origin and also an anelastic tilt is not necessarily accompanied by significant stress changes.

Since the source location for the long-term changes during the first half of the year is not clear and since supporting observations have not been obtained, it is not possible to relate these changes unambiguously to the Thanksgiving Day earthquake. On the other hand, the shorter term changes during October and early November were approximately coincident in time and space with the occurrence of anomalous tilting and a possible velocity anomaly. This correspondence, together with the fact that both the earthquake and the observed magnetic anomaly were the largest within the network since it was established, strongly suggests that some relation between the magnetic anomaly and the Thanksgiving Day earthquake exists. Although the magnetic anomaly apparently did not occur within the focal region of the Thanksgiving Day earthquake, a relation may occur through an interaction of the various faults in this region. This interaction has been studied by *Burford and Savage* [1972], who suggest that the southeast tip of a 'crustal wedge' is formed where the Calaveras fault branches off of the San Andreas fault near Hollister (Figure 1) and that when right-lateral movement occurs along the San Andreas or Calaveras fault in the vicinity of this wedge tip, a shear load is applied such that the likely load of left lateral slip on any transverse fault trends within the wedge tip is significantly increased. It is, of course, possible that this interaction can work in the opposite sense (i.e., left lateral movement within the wedge tip on a transverse fault causes a right lateral shear stress increase along the San Andreas and Calaveras faults). The Thanksgiving Day earthquake occurred on the Busch fault (Figure 1), which is within the crustal wedge tip referred to above. The most probable focal plane solution indicates left lateral strike-slip motion with the same strike as the Busch fault [*Lee and Healy,* 1975]. With these ideas in mind, it is suggested that the October–early November magnetic anomaly may have had the following relationships to the Thanksgiving Day earthquake:

1. Right lateral slip on the San Andreas fault added some left lateral shear stress in the region of the Thanksgiving Day earthquake, perhaps leading to the earthquake.

2. Preearthquake slip occurred on the Busch fault in the region of the Thanksgiving Day earthquake, resulting in a change in shear stress and subsequent aseismic slip on the San Andreas fault near San Juan Bautista.

If aseismic slip did produce some of the observed magnetic signals, then it is possible that future magnetic signals will occur that are not followed, within a reasonable period of time, by earthquakes. It is hoped that future occurrences of significant aseismic slip within the magnetometer network can be identified with the help of creep, tilt, and strain measurements.

CONCLUSIONS

The most significant changes in local magnetic field observed in central California during 1974 occurred in the 2 months preceding, though at a site 11 km away from, the largest earthquake in this region. Although no definite relation has been established between the magnetic changes and this earthquake, the most probable source of these changes is a tectonomagnetic effect in the complex fault system around the earthquake epicenter. If this is the case, these results indicate that magnetic observations can be used to monitor crustal stress changes in areas of sufficient magnetization. It is apparent that additional observations of magnetic signals near the time of earthquakes are needed in order to establish the usefulness of magnetic observations for predicting earthquakes. To make such observations in central California within a reasonable period of time, it appears necessary that a magnetometer network be able to detect signals from earthquakes in the magnitude range of 4–5. Since few changes exceeding 1 γ were observed during 1974, it appears that total field instruments utilized in such a study should have a sensitivity and long-term stability of at least 0.25 γ and must be able to discriminate tectonomagnetic effects of about 0.5 γ. Since it appears that tectonomagnetic effects can be observed on the San Andreas fault, a larger array is being considered with a view to obtaining better details of the source of future magnetic events.

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