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Further Evidence of Localized Geomagnetic Field Changes Before the 1974 Thanksgiving Day Earthquake, Hollister, California

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Abstract. Seven weeks prior to the M=5.1 Hollister, Calif., Thanksgiving Day earthquake of 28 November, 1974, an anomalous magnetic variation was observed at one of the magnetometers of the USGS array. The anomaly lasted for about three weeks. Recently developed methods of reducing noise on magnetic records reveal that anomalous magnetic changes occurred at about the same time at three of the six stations analysed. Such changes have not been seen either previously or subsequently. The largest variation occurred at the two stations closest to the earthquake, but a change also occurred at a station 44 km to the south.

Introduction

In 1974 the USGS installed a proton precession magnetometer array along a section of the San Andreas fault. The purpose was to search for localized secular variation of the earth's magnetic field that might be caused by stress changes in the crust. Seven weeks prior to the M=5.1 Thanksgiving earthquake of 28 Nov 1974 at 2301 UT, a magnetic variation was observed at one of the stations closest to the earthquake. This variation lasted for about three weeks (Smith and Johnston, 1976). During this period the tilt rate of a nearby tiltmeter changed substantially, leading Smith and Johnston to propose that the observed variation was due to stress changes affecting the magnetization of the crust.

It has been well established that stress induced changes of magnetization occur in laboratory samples of crustal rock (e.g., Wilson, 1922; Kalashnikov and Kapitsa, 1952; Kalashnikov, 1954; Ohnaka and Kinoshita, 1968a,b) amounting to 2% per MPa on average. These effects have been explained in terms of perturbation of the magnetostrictive energy component of the magnetocrystalline anisotropy of the magnetic grains in a rock. A recent theoretical treatment of the problem is given by Stacey and Johnston, 1972. Estimates of anticipated magnetic field changes due to stress changes in the crust associated with earthquakes (Stacey, 1963, 1964; Shamsi and Stacey, 1969; Talwani and Kovach, 1972) based on the laboratory observations, agree that effects between 1 and 10 nT should be observed in areas in which tectonic stress changes of order 1 MPa occur.

In view of the importance of measuring stress changes in an earthquake zone, we have reexamined the fields for 1974 from six stations of the USGS array using recently developed predictive cleaning methods (Davis et al., 1979, 1980) to reduce fluctuations of ionospheric and magnetospheric origin. Our aim was to see if anomalous variation prior to and during the earthquake is evident on the cleaned records from stations other than that reported. In particular, attention has been focused on the station ten kilometers north of the anomalous one, since this station was at the same distance from the earthquake but had such a high intrinsic noise level that it was impossible to tell if it had registered tectonomagnetic effects of 1 to 2 nT (Smith and Johnston, 1976).

The Analysis

For the following discussion, the magnetometer station numbering scheme of the paper by Smith and Johnston (1976) is used with stations 1-6 spread, north to south, over 60 km of the San Andreas fault south of San Jose (Fig. 1). The earthquake occurred on the Busch fault, which lies to the east of the array. Its epicenter was approximately equidistant (11 km) from both stations 2 and 3. The previously reported anomaly was observed at station 3.

The total field magnetometers have a sensitivity of 0.25 nT with synchronous readings taken every minute. In order to eliminate first-order variations in the earth's field due to ionospheric and magnetospheric currents, which may amount to many tens of gammas, differences are taken between simultaneous readings of the total field at adjacent sites. This is based on the assumption that if the distance from the current sources is large compared to site separation, the magnetic fluctuations should resemble electromagnetic plane waves, which on differencing should cancel. In practice, differencing reduces the fluctuations by about 95%, depending on the choice of sites. We think that the residual variations are caused by local variations of impedance in the crust, which cause the induced magnetic field to vary from site to site. For example, variable electromagnetic induction in the ground results in a disturbance field that varies

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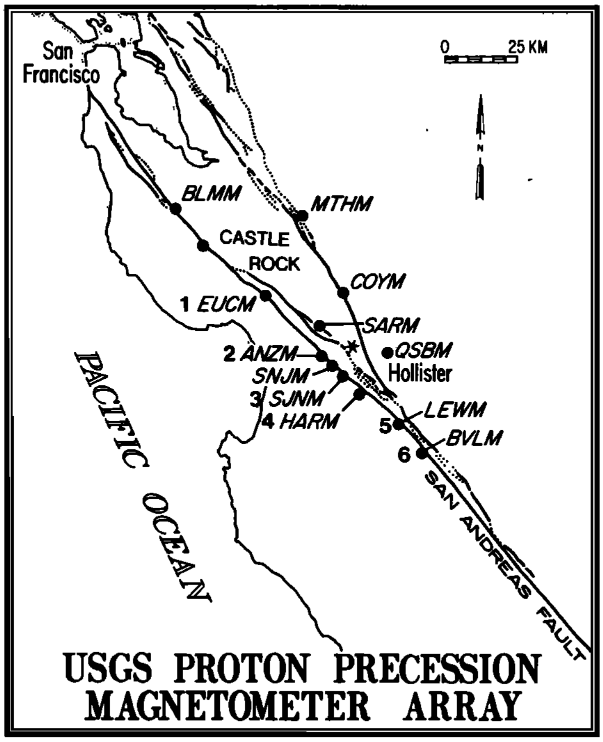

Fig. 1. Map of USGS permanently recording proton magnetometer stations numbered according to Smith and Johnston (1976). The epicenter of the 1974 Busch fault earthquake, M=5.1 (star), lies closest to stations 2 and 3 which recorded the largest anomalous variation prior to its occurrence.

in amplitude and phase across an array depending on its frequency content and polarization. Other possibilities include variable induced magnetization due to large susceptibility contrasts and total field differences arising from the vector addition of uniform disturbance fields and non-parallel local total fields. Non-parallel local fields occur in regions of heterogeneous remanence. Magnetic induction and remanence effects are independent of the frequencies of the disturbing field, but will depend on its orientation. Because the simple differences between total field observations do not make use of directional information, improvement is possible when 3-component magnetic-field data are used to eliminate residual variations.

The effects of electromagnetic induction depend both on frequency and site. These effects are reduced by taking daily or longer-term averages of the difference field readings because at sufficiently long periods a conducting body becomes transparent to an oscillatory magnetic field. This means that at these periods a frequency-independent cleaning scheme suffices to remove residual difference field variation. However, at shorter periods frequency-dependent methods must be used. For this reason we have analysed daily and hourly averages separately.

The frequency-independent method (Davis et al., 1979) consists of computing the raw daily averages of the difference fields which are then detrended and high pass filtered by convolution with a Butterworth filter having a corner frequency of 0.02 days^{-1}. A linear combination of the component fields from the Castle Rock magnetic observatory is then found that best predicts the differences in a least squares sense. Finally the predicted field is subtracted from the raw differences to produce a cleaned difference field.

Raw and cleaned differences from the USGS array are shown in Figure 2. The cleaning process has been most effective for differences 1-2, 2-3, and considerably less effective for differences 3-4, 4-5, 5-6. The anomalous variation of dif-

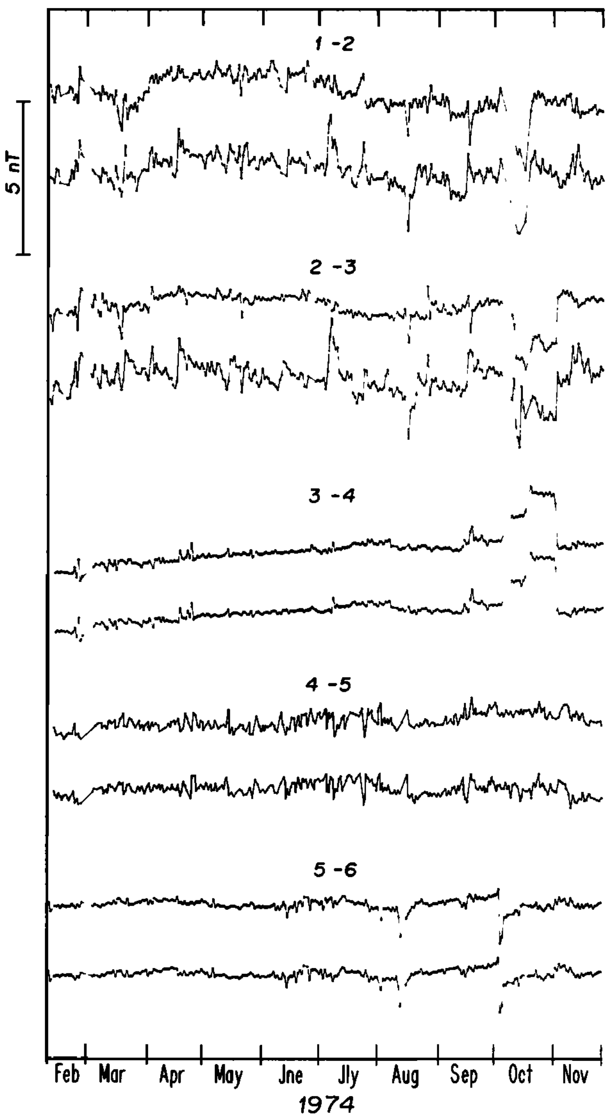

Fig. 2. Comparison of the daily averages of the difference fields before (lower trace) and after (upper trace) frequency-independent cleaning. Cleaning is most successful for differences 1-2 and 2-3. Differences 4-5 remain constant during the period of anomalous variation of 2-3 and 3-4 prior to the Busch fault earthquake. Thus 4 and 5 are taken to be stable reference stations. Differences taken with respect to 4 and 5 show that anomalous variation occurs at stations 2, 3 and 6 during October 1974. Data gaps exist at station 1 and station 3 in October 1974. Corresponding difference fields for these and other gaps have been filled by linear interpolation.

ferences 3-4 is unaffected by the cleaning, confirming Smith and Johnston's (1976) view that it could not be explained by magnetospheric or ionospheric effects. The fact that differences 4-5 show no anomalous variation leads us to believe that the fields at both stations remained at a constant level over this period. Thus, the variation seen in the differences 3-4 most probably occurred at 3. Two further observations can be made. Although the anomaly at 3 shows up in the differences 2-3, it has a different time signature, so that if instead we form differences 2-4 (by adding differences 2-3 to 3-4), an anomalous change appears that is most likely to have occurred at 2. A more detailed investigation of the field at that station follows. The other observation concerns the 2-nT excursion and 1-nT offset in the differences 5-6 which begins on 1 October 1974 about the time of onset of the anomaly at the northern magnetometer pair. Since this signal is absent from the differences 4-5, we attribute it to station 6.

In order to examine the magnetic variations at station 2, hourly averages of station differences between 2 and 4 and 3 and 4 were compared, since 4 had been established as a relatively stable reference station. A frequency-dependent cleaning scheme was used (Davis et al., 1980) which involved predicting the difference field from Castle Rock Observatory component fields convolved with multichannel Wiener filters. Cleaned differences are found by subtracting the raw and predicted differences. These are shown in Figure 3.

As was seen in the cleaned daily averages of 3-4, the cleaning has had little effect on the hourly averages 3-4. Nonetheless, the anomaly is clearly visible in the hourly averaged data. However, for differences 2-4 the cleaning has considerably reduced the fluctuations in the record and reveals a hitherto obscured anomalous variation that commences on October 10, reverses sign on October 16, and may even persist until October 30. This period of anomalous behavior

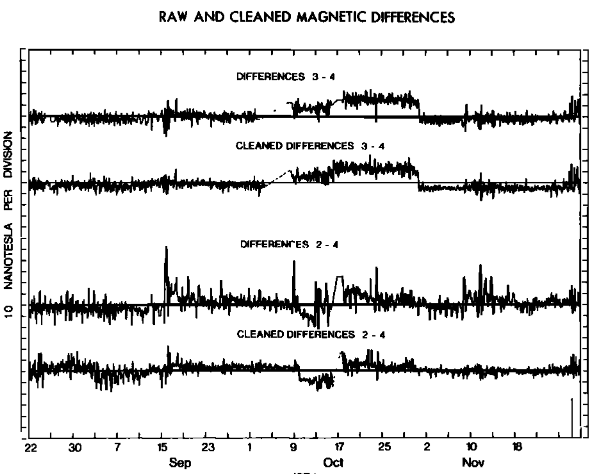

Fig. 3. Raw and cleaned hourly averages of differences 2-4 and 3-4, showing that anomalous magnetic variation occurred at station 2 as well as that previously reported at station 3. The time of occurrence of the M=5.1 Thanksgiving day earthquake on the 28th November 1974 is marked with an arrow.

corresponds to that observed at station 3, that is, early October to November 1. It suggests that the Earth's field at 2 initially decreased by about 1.0 nT whereas at 3 it increased by 0.75 nT. After about 7 days the field at 2 increased by 1.4 nT compared to an increase at 3 of 0.75 nT. Missing data from station 1 preclude extending this analysis to that station. However, from the records we have, we see no large variation in the field at 1 over the second half of the anomalous time interval.

Although no significantly large coseismic anomaly is seen at the time of the earthquake on November 28, it does appear to have occurred at a period of large transient positive fluctuations.

Discussion

The foregoing analysis of the 1974 USGS proton magnetometer data shows that three of the six stations analysed recorded magnetic changes between 1 October and 1 November, the likes of which have not been seen either previously or subsequently (Johnston, 1978). The onset of the change at the most southerly station 6, occurred 9 days before the onset of the change at the northern station 2. Owing to missing data, the onset at 3 could not be determined. The changes at stations 2 and 3 are the most marked. They occur in two steps, the first on October 10, the second on October 16, followed by a return to the baseline level. It has been argued previously (Smith & Johnston, 1976) that the variation at 3 was a precursor to the M=5.1 earthquake on the Busch fault which occurred 27 days later. The alternative hypothesis that the three or possibly four stations had instrumental problems over this period must also be taken into consideration. Arguments that favor this view include: (a) the timing of the failure of station 1, which coincides with the first step of the anomalous variation at 3; (b) the fact that the onset of the anomaly at 3 on 1 October and the changes at stations 2 and 3 on 16 October occur at times of failure of those stations; (c) the quantized step-like nature of the anomalies at 2 and 3 and the distant anomalous variation at 6 are also puzzling. Arguments against the "instrumental error" hypothesis are as follows: (a) on return to normal operation, station 1 shows normal differences with 2 during the second half of the anomalous period; (b) although some of the anomaly onsets occur at times of equipment failure, not all do, such as the onset at 2 on October 10 and the return to the baseline of the field at 3 on November 1; (c) if an equipment failure has given rise to the anomalous changes affecting stations 1, 2, 3 and 6, one would expect to observe the effect on all stations simultaneously, but the variation at 6 occurs 9 days before that at 2. The step-like nature of the anomalies and anomalous variation at 6, the remote station, could in principle be generated by piezomagnetic effects in the crust. Arguments in favor of the observed anomalies being precursive to the Busch fault earthquake include: (a) the fact that each instrument operates as an independent internally powered unit, (b) the observations that a tilt anomaly developed between stations 2 and 3 within the period of anomalous variation, and (c) unexplained apparent anomalies occurred in geodetic measurements over the area (Savage *et al*., 1979). Furthermore, stations 2 and 3 lie closest to the epicenter of the earthquake and see larger anomalous variation than is seen on any other station.

Conclusion

Much of the high frequency noise present in magnetic recordings of the USGS is coherent between stations and is thus removable by prediction filtering. This noise apparently results from the effect of local impedance variations or induced currents, so that a frequency-dependent multichannel prediction filter employing vector magnetic data substantially decreases the residuals. After using this technique to clean data taken at the time of the 1974 Hollister earthquake, it is apparent that the anomalous effects occurred at no less than three sites within a short time interval several weeks before the earthquake. Although there are brief periods of instrumental failure during this time interval, it would require an extraordinary coincidence to explain the observations by instrumental malfunction. The near simultaneity of the observed anomalies and their proximity in space and time to the earthquake, argue in favor of a tectonomagnetic effect. No coseismic magnetic effect above 0.25 nT is apparent from the data.

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