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Local Variations in Magnetic Field, Long-Term Changes in Creep Rate, and Local Earthquakes along the San Andreas Fault in Central California

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Comparison between local variations in magnetic field, long-term changes in creep rate, and local earthquakes have been made for the seismically active and creeping section of the San Andreas fault between the most southern extent of the 1906 earthquake fault break and the most northern extent of the 1857 break, for the period early 1974 through mid-1977. The data utilized are from stations located near the two ends of this section of the San Andreas fault where strain accumulation is expected. The proton precession magnetometer stations included in this study have recorded local magnetic field variations up to 1.8γ with durations of a few minutes to several months. The creep data indicated changes in creep rate of up to 10 mm/year lasting for 6 months or more and a close similarity between the changes in creep rate on two adjacent creepmeters about 7 km apart. Earthquakes with magnitudes less than 4.0 do not appear to correspond in time to local changes in magnetic field greater than 0.75γ or variations in the creep rate. There is no general correspondence between creep events and magnetic field variations. There is, however, an approximate correspondence, in both space and time, between the long-term changes in creep rate and the variations in magnetic field. In order to explain the observations presented in this study, it appears necessary to allow for a substantial amount of deep aseismic slip without any obvious attendant changes in the time distribution or size of the local earthquakes.

1. Introduction

Since early 1974 the U.S. Geological Survey has been measuring total magnetic field in central California with an array of proton precession magnetometers (Fig. 1). The purpose of these measurements is to identify local changes in the magnetic field that might be associated with the active faults in the region. The theory and laboratory studies which indicate that tectonomagnetic signals should occur as the result of stress induced changes in rock magnetization (piezomagnetic effect) have been reviewed a number of times previously (e.g., JOHNSTON *et al.*, 1976a; RIKITAKE, 1976; SMITH and JOHNSTON, 1976; STACEY and BANERJEE, 1974).

Most of the magnetometer stations are located in two areas within the San Andreas fault system: around the south end of the 1906 earthquake fault break, near station SN; and around the north end of the 1857 break, believed to be between

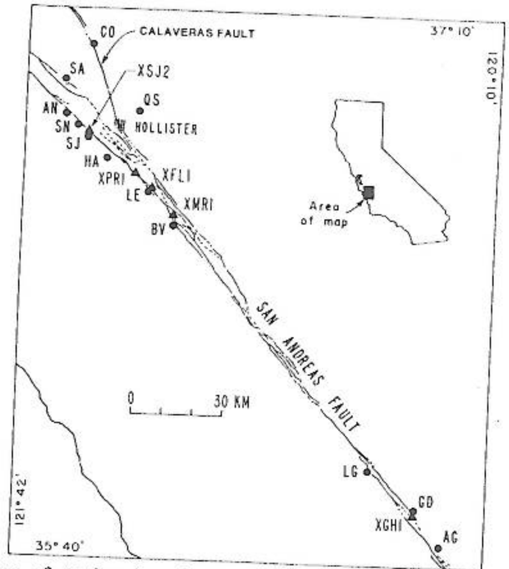

Fig. 1. Map of station locations and faults along the seismically active secton of the San Andreas fault in central California. Dots are magnetometer stations; triangles, creepmeter stations. Three magnetometer stations (not included in this study) are located northwest of the map area.

stations GD and AG (Fig. 1). The larger earthquakes in this region tend to occur near the ends of these fault breaks. Between these two areas the fault is presently creeping and the recorded earthquakes have magnitudes up to about 5.5. Near the center of the creeping section the rate of recorded creep is relatively high, about 30 mm/year, but it decays to zero near the two ends where strain accumulation might be expected (Savage and Burford, 1971).

The magnetometer stations included in this study have detected local changes in the magnetic field with amplitudes as high as $1.8\,\gamma$ (Johnston *et al.*, 1976a; Smith and Johnston, 1976). Although it is likely that these changes are produced by the piezomagnetic effect, they have not yet been observed to occur simultaneously with stress changes from local earthquakes with $M_L < 4.0$ or from surface creep events. An unanswered question concerns whether episodes of subsurface aseismic slip are the cause of these magnetic field changes.

The creepmeters record short-term creep events which typically last from a few minutes to a few days and have measured displacements of up to 5 mm. It is important to question whether these surface creep events reflect aseismic slip that extends down through the whole seismic zone ($\sim$15 km deep). Recent studies, using arrays of tiltmeters and strainmeters that have recorded near-simultaneous strain events associated with creep events (Johnston *et al.*, 1976b; McHugh and Johnston, 1976; Mortensen *et al.*, 1977), indicate that the creep seen at the surface probably occurs in the top 2 km of the crust. The short-term creep events, therefore, probably do not play a significant role in the release of accumulated strain in the seismic zone

(2 to 15 km deep). More likely they are just a surface response to deeper slip. Additional support for this possibility comes from continuous geodetic strain measurements, obtained near Hollister, over baselines 3 to 9 km long. These data indicate that accelerated slip episodes, lasting for several weeks and extending to a depth of about 10 km, precede surface creep events by several weeks (SLATER and BURFORD, 1978).

This paper will try to determine if deep aseismic slip can explain the observed local magnetic field changes by comparing magnetic, creep and earthquake data from the section of the San Andreas fault between the south end of the 1906 fault break and the north end of the 1857 break.

2. Data

The proton precession magnetometers used in this study have a sensitivity and precision of $0.25\,\gamma$. All the magnetometer stations sample the total magnetic field simultaneously, within ± 0.2 sec, once a minute. The electronics are housed in an insulated fiberglass pit, 1.8 m deep, buried in the ground so that only the top few centimeters is exposed. The sensor is housed on top of a wooden post about 2 m above the ground. Each site is selected on the basis of low magnetic field gradient ($<3\,\gamma$/m), remoteness from any cultural objects that could significantly contaminate the magnetic field, and proximity to known or suspected magnetic rocks adjacent to active faults. Each station automatically samples the total magnetic field, converts the data to a serial digital code, and telemeters the data to Menlo Park, California, via radio links and/or telephone lines. Each total field value is recorded on magnetic tape, which is later transferred to a computer where all data processing is done.

The diurnal variation of the total magnetic field, due to ionospheric and magnetospheric effects, is typically 40 to $60\,\gamma$. Since tectonomagnetic signals are probably not more than a few gammas (STACEY and BANERJEE, 1974), it is necessary to reduce the diurnal variations by a factor of 50 or more. To accomplish this reduction, we first calculate the difference between two stations that are separated by less than a few tens of kilometers (usually adjacent stations). Simple differences reduce the diurnal variations by about a factor of 10. A 5-day average further reduces the diurnal variations to an amplitude of about 0.50 to $0.25\,\gamma$. The magnetic data presented in this paper are 5-day running averages of differences between adjacent stations. These data show many variations with amplitudes of about $0.50\,\gamma$. It is not clear what fraction of these variations are due to a tectonomagnetic source, ionospheric or magnetospheric effects, or some other physical process. For brevity we will discuss only those variations with amplitudes greater than $0.75\,\gamma$.

The creep data used in this study are from the wire creepmeter network established by the U.S. Geological Survey (YAMASHITA and BURFORD, 1973). Five of these creepmeters were chosen for this study on the basis of nearness to magnetometer stations and completeness of data (Fig. 1). These data show that right-lateral fault creep occurs at an approximately constant rate for the time frame of this study. In

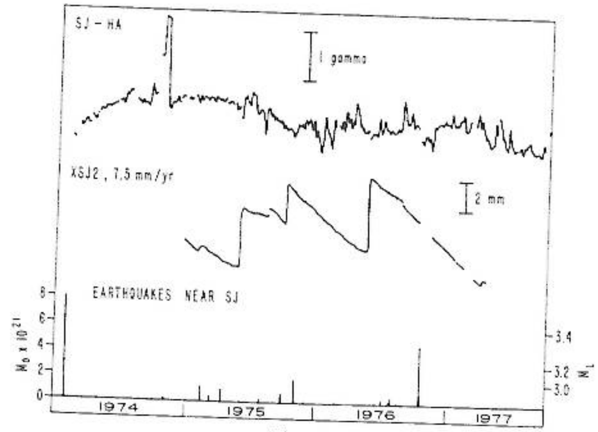

Fig. 2

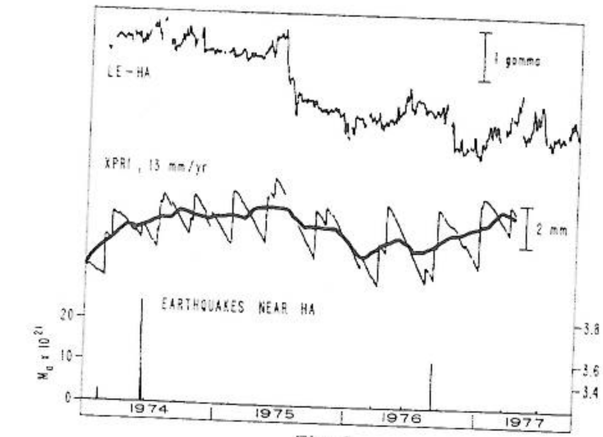

Fig. 3

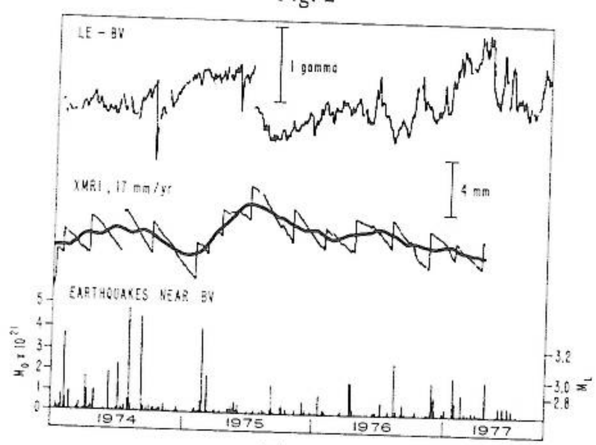

Fig. 4

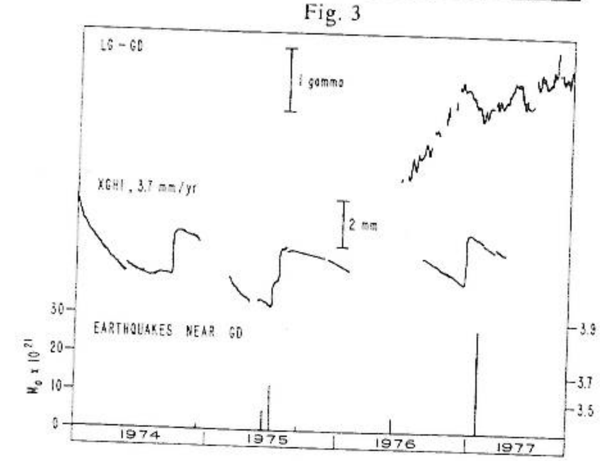

Fig. 5

Figs. 2–5. Plots of magnetometer differences (top), detrended creep (center) and earthquake moments (bottom). Labels on detrended creep data indicate station code name and average creep rate that was removed from original data. Gaps in both magnetic and creep data represent periods of no data, but absolute reference is believed to have been maintained so that changes that span these gaps can be considered real. The plots of creep data on Figs. 3 and 4 also include 120-day running averages (heavy lines). The label for earthquake data indicates nearest magnetometer station (see text). Moments are in dyne cm, and a magnitude scale is included.

order to determine whether changes in creep rate correspond to changes in magnetic field, the average rate from these records has been removed by determining the best linear fit to the data and subtracting this line from the original values; a technique similar to that employed in a previous investigation of the relationship between creep rate and moderate earthquakes (BURFORD, 1976). The detrended creep data show the small variations of creep rate much more clearly than do the untreated data.

The earthquake data used in this study are from the unpublished earthquake catalog compiled by the U.S. Geological Survey. A lower magnitude cutoff of 1.3 was chosen because it is the lowest magnitude that is likely to provide a complete data set in the regions studied. The earthquakes were then chosen to include only those that appeared to have occurred on the San Andreas fault and within 8 km of a magnetometer station. When adjacent magnetometers were located closer than 16 km apart, the set of earthquakes was further divided to include only the earthquakes closest to each magnetometer station. The earthquake sets are denoted by 'earthquakes near (station code name)'. The largest earthquake included in this study has a magnitude of 3.9, and the rate of occurrence of earthquakes below magnitude 3.0 is fairly steady. The earthquakes show little variation in magnitude with time. Therefore, in order to show more clearly what may be the more relevant earthquakes in terms of association with tectonomagnetic signals, we have chosen to plot earthquake moments. Moments were calculated using a magnitude-moment relation derived from central California earthquakes (BAKUN *et al.*, 1976):

$$M_0 = 10^{(1.4M_L + 17)} \text{ dyne cm}$$

where M_0 is the moment and M_L is local magnitude.

The comparison of magnetic data, creep data, and earthquakes was made by plotting all three of these parameters on the same time scale. For the time period and regions included in this study, local changes in the magnetic field greater than 0.75γ occur only on the following difference records: SJ-HA, LE-HA, LE-BV, and LG-GD. All four of these difference records are shown in Figs. 2, 3, 4, and 5, along with the most relevant plots of detrended creep data and earthquake moments. Gaps in the magnetic and creep data indicate periods where data were lost owing to a variety of reasons. In all cases we believe that the absolute reference has been maintained so that changes that span these gaps can be considered real.

3. Results

A significant change in magnetic field on the SJ-HA record occurred during October 1974, lasted for the whole month, and had a maximum amplitude of 1.8γ (Fig. 2). By comparison with other difference records, we know that this change was recorded at station SJ. Because the change was recorded only at station SJ, its source is probably within a few kilometers of this station. Unfortunately, the nearest creepmeter, XSJ2, was not operational until early November 1974. There are no obvious correlations between the XSJ2 creep data, the earthquakes near SJ, and the magnetic field record SJ-HA.

The local changes in magnetic field in October 1974 did occur one month prior to a magnitude 5.1 earthquake (SMITH and JOHNSTON, 1976). This earthquake is not shown in the plotted earthquake data because it occurred to the east of the San Andreas fault and about 11 km from station SJ. Because of the distance between the earthquake and the probable source of the magnetic field changes, and the lack of a magnetic signal at the time of the earthquake, there is probably no direct relation between them. However, the magnetic field change could be explained by aseismic slip on the San Andreas fault that may be related to the magnitude 5.1 earthquake by an interaction of the faults in the area, as discussed in detail by SMITH and JOHNSTON (1976).

The difference record LE-HA (Fig. 3) shows a magnetic signal with a maximum amplitude of 1.7 γ occurring during the period June to August, 1975. Comparison with other difference records indicates that signals were recorded at both LE and HA, but in the opposite sense so that the difference LE-HA has the effect of adding the changes from these two stations. The character of the changes recorded at HA and LE can be seen to be dissimilar by comparing the SJ-HA (Fig. 2) and LE-BV (Fig. 4) records. The change at HA is positive and mostly smooth while the change at LE is negative, starts with a sudden event, and then is smoother. The correspondence in time of these magnetic field changes suggests that they may have the same or a related source.

The creep data plotted with the LE-HA record are from station XPR1. The creep events at this station occur fairly regularly. With a 120-day running average (heavy line), it is possible to smooth these events and emphasize the long-term character of the creep data (Fig. 3). The average creep data show that only during the second half of 1975 was the creep rate significantly less than the average rate for the period of time included in this study. The start of the decrease in creep rate occurs during the change in magnetic field at stations LE and HA discussed above. The long-term trends of the averaged creep data from station XFL1 appear to be almost identical to XPR1, except that almost a year of data is missing starting from mid-1975. Both the XFL1 and the XPR1 data show that the creep rate at these stations was below average between mid-1975 and mid-1976, although the exact character of the change at XFL1 cannot be determined because of the missing data.

The plot of earthquakes near HA (Fig. 3) does not show any apparent correspondence to the LE-HA record. It is interesting to note that the larger earthquakes occur during times of higher than average creep rate. The plot of earthquakes near LE shows a fairly even rate of earthquakes up to magnitude 3.2 with no apparent correspondence to either the creep data or the LE-HA magnetic record.

There do appear to be some interesting correspondences between the LE-BV and XMR1 records. The difference record LE-BV (Fig. 4) shows three significant magnetic field changes. One change of short duration and 1 γ amplitude in September 1974 was recorded at station BV. The second change, occurring in mid-1975, was recorded at station LE and is the same signal discussed above in the section covering the LE-HA record. The third change, in late 1976 and early 1977, was one of complex character that appears to be recorded primarily at station LE. The detrended creep data from XMR1 have been smoothed with a 120-day running average, and both the original and smoothed data (heavy line) are plotted together in Fig. 4. The average rate of creep decreased slightly at the end of 1974 and then sharply increased by 10 mm/year during the first half of 1975. The long-term trends on both records are approximately mirror images of each other. The two short-term changes in October 1974 and June 1975 approximately bracket in time the high rate of creep during the first half of 1975 and also occur within one day of creep events. (Because of telemetry failures, the exact time and duration of these changes in magnetic field cannot be determined.) However, all but the October 1974 signal on the LE-BV record were recorded at station LE, 11 km northwest of creepmeter XMR1. There does not appear to be any significant correspondence between the earthquakes near BV and the LE-BV record or the XMR1 record.

The LG-GD record shows a 1.5 γ change in magnetic field during the second half of 1976 (Fig. 5). This change was recorded at station GD. The first data from stations LG and GD were obtained in June 1976, so that the time when this change began is not known. A creep event at XGH1 and a magnitude 3.9 earthquake, the largest to occur within 8 km of station GD during the recording period, occurred just after the end of the change in magnetic field (Fig. 5).

4. Discussion

The data presented in this study indicate that small-magnitude earthquakes do not correspond in time with the changes in either the magnetic field or the creep rate. This fact is not too surprising since earthquakes in California of the size included in this study ($1.3 < M_L < 3.9$) appear to have slip dimensions of less than 1 km (BAKUN *et al.*, 1976), stress drops of less than 20 bars, and depths of between 5 and 10 km (THATCHER and HANKS, 1973; WESSON *et al.*, 1973). Assuming a magnetic susceptibility of 10^{-3} emu, tectonomagnetic models (JOHNSTON, 1978) using the above parameters show that these earthquakes would not, by themselves, generate a surface anomaly greater than 0.1 γ. Of course, if the earthquake is accompanied or triggered by larger scale readjustments of regional stress, then these could be reflected in the magnetic data. These stress changes could result, for example, from related aseismic slip on the fault (STUART and JOHNSTON, 1974) or be a consequence of the initial stress conditions near the fault. These conditions might be modified by earthquakes or other fault behavior such as pore pressure changes, comminution, and chemical changes. In either case, the changes in magnetic field would not necessarily be expected to occur at the same time as earthquakes.

Another general conclusion evident in these data and discussed in more detail by JOHNSTON *et al.* (1978) is that the large majority of short-term creep events do not correspond to changes in magnetic field. Two possible exceptions, where creep events occur within one day of short-term changes in magnetic field, are evident on the LE-BV record (Fig. 4) in October 1974 and July 1975. Although the changes in magnetic field are not likely to result from the surface creep events, it is possible that deep aseismic slip occurred at about the same time and that this deep slip is the source of both the changes in magnetic field and the creep events. It is interesting that these two creep events occur near the beginning and end of the accelerated creep rate during the first half of 1975. Since only two out of several dozen creep events correspond in time to changes in magnetic field, it is certainly possible that the correspondence is a coincidence.

The most exciting result is the approximate correspondence, in both space and time, of changes in local magnetic field and long-term creep rate. However, the data are too sparse and the time span too short to determine the significance of these correspondences. If the magnetic changes do reflect crustal stress changes in the region and are related to changes in long-term creep rate, than substantial energy transference is apparently occurring aseismically at depths below 2 km.

Models of spatially varying aseismic slip at depths between 2 and 10 km can be fit to the creep data and used to generate tectonomagnetic models that satisfy the magnetic data. These models will not be proposed in detail here since, without additional deformation measurements, it is not possible to demonstrate independently the existence of these failure patches or to constrain the parameters of these models. The correspondence in time between the long-term creep rate at XMR1 and the changes in magnetic field recorded at LE, 11 km to the northwest, is perhaps a good example of how these models might work. If a patch of the fault were slipping, stress concentration would be expected at the edges of this patch. If the patch is centered at XMR1 and extends northwest to a point near LE, then it would not be unreasonable to expect a change in creep rate at XMR1 to be related to a magnetic field change at LE. As more data become available, it will be possible to test and extend these models and their implications further. The occurrence of a moderate magnitude earthquake that breaks a substantial part of the seismic zone will also provide critical data on the amplitudes and interrelationship of the magnetic, creep, seismic and other data.

It is important to question whether any of the general fault models are precluded by these observations. Regardless of the details, the simplest general models of the fault in which the slip is assumed to be uniform or where slip occurs only during earthquakes, are certainly not consistent with these data. The intriguing patterns of behavior at, for example, GD, when a creep event and a magnitude 3.9 earthquake occurred shortly after the end of a change in magnetic field (Fig. 5), and at LE and HA in 1975 during periods of retarded creep on nearby XPR1 and XFL1 creepmeters and of accelerated creep on XMR1 (Figs. 3 and 4), argue for more complex and heterogeneous fault mechanics.

5. Conclusions

1) Local variations in magnetic field with amplitudes as high as 1.8γ occur within the seismically active segment of the San Andreas fault between the south end of the 1906 earthquake fault break and the north end of the 1857 break.

2) Long-term detrended creepmeter records along this section of the San Andreas fault show significant changes in creep rate (up to 10mm/year) lasting for several months.

3) Earthquakes with magnitude less than 4.0 do not appear to correspond in time to local changes in magnetic field greater than 0.75γ or long-term variations in creep rate.

4) In general, the short-term creep events do not correspond with local changes in magnetic field greater than 0.75γ or the local earthquakes.

5) The long-term changes in creep rate show an approximate correspondence in time and space to some long-term changes in magnetic field. The data are too sparse to determine the significance of these apparent correspondences.

6) For fault models to explain the observations presented in this study, it appears necessary to allow for a substantial amount of deep aseismic slip without any obvious attendant changes in the time distribution or size of the local earthquakes.

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