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LOCAL MAGNETIC FIELD MEASUREMENTS AND FAULT CREEP OBSERVATIONS ON THE SAN ANDREAS FAULT

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ABSTRACT

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Simultaneous creep and magnetic field records have been obtained for more than 60 episodic creep events since early 1974, no clear magnetic transients or offsets, as suggested by Breiner and Kovach (1968), are observed at or up to several days before the occurrence times of these events. Although some patterns of creep onset times at adjacent stations over periods of weeks to months appear to correspond to some periods of longer term change in local magnetic field, these changes do not always occur and other groups of creep events have no corresponding changes in local magnetic field. Changes in stress related to the surface expression of episodic fault creep on the San Andreas fault can be estimated from dislocation models fit to observations of simultaneous strains and tilts at points near the fault. These stress values are generally less than 1 bar. For these stress levels and with the apparent limited extent of surface failure, tectonomagnetic models of creep events indicate that simultaneous observations of related magnetic field variations at detectable levels of a gamma or so are unlikely. Slip at greater depth may occur more smoothly and would load the near-surface material to failure. These data also argue against large-scale dilatant cracking occurring along the region of the fault presently monitored.

INTRODUCTION

Episodes of fault creep with amplitudes of up to 10 mm and durations of a few minutes to a few days have been observed at many locations on active faults within the San Andreas fault system (Tocher, 1960; King et al., 1973; Burford et al., 1973; Yamashita and Burford, 1973; Nason et al., 1974; Schulz et al., 1976). Breiner and Kovach (1968) have reported that possible changes in local magnetic field, measured with differential magnetometers near Hollister, California, preceded observations of fault creep at the Almaden winery creepmeter (*CWC*) by several tens of hours.

A more comprehensive array of magnetometers and creepmeters has been installed in this area, and it is now possible to undertake a more complete search for results similar to those of Breiner and Kovach (1968). More important, for many of the creep events observed recently along the fault, simultaneous tilt and strain observations have been made. From these data it is possible to place some crude constraints on the physical dimensions of the slip zone involved (Johnston et al., 1976, McHugh and Johnston, 1976; Mortensen et al., 1977; Johnston et al., 1977; Goulty and Gilman, 1979) and to estimate the changes in stress resulting from the fault slip. It is the purpose of this paper: (1) to report the comparison of creep observations along the fault with the actual measurements of local magnetic field; and (2) to estimate the local changes in magnetic field expected to result from the perturbations in stress and other consequences of fault creep. We note that on the basis of the creep-magnetic model proposed by Talwani and Kovach (1972) magnetic field changes should be expected out to distances of at least 5 km from the fault.

OBSERVATIONS

More than 90 creep events have occurred since early 1974 at several creepmeter sites within an array of recording differential magnetometers. Figure 1 shows the location of recording magnetometers and creepmeters along the section of the fault where creep events occur. Table I lists the detailed occurrence time, creep amplitude, and the distance to the nearest magnetometer for all the events considered at each creepmeter. Further details of creep events at these meters are listed in Schulz et al. (1976). The magnetizations of rocks in this area are typically in the range 10^{-4}—10^{-3} e.m.u. In a few places they exceed 10^{-2} e.m.u.

For more than 60 of these creep events, concurrent magnetic field data have been obtained. Figure 2a shows three days of one-minute samples of magnetic difference field and total-field data bracketing the times of the three largest creep events for which simultaneous data exists at the creepmeters *XMR1*, *XFL1*, *XPR1* and *CWC* and at magnetometers around these creepmeters. The total-field record chosen in each case is the one closest to the creepmeter. The magnetic data are differenced to isolate changes of local origin and to reduce effects of ionospheric and magnetospheric origin. Standard deviations of the one-minute samples of the magnetic field differences are typically less than one gamma.

It is apparent that no clear magnetic transients greater than about a gamma have been observed simultaneous with, or preceding these creep events by up to a day or so, other than might be expected by pure chance. There are also no systematic offsets. For a number of the larger creep events ten-minute and one-hour averages of the magnetic field differences have been calculated in order to reduce the noise. These data exhibit standard deviations less than 0.7 and 0.4 gammas respectively, and transients or offsets of consistent form related to creep events are still not evident. With signal stacking and other filtering techniques it may be possible to reduce the noise

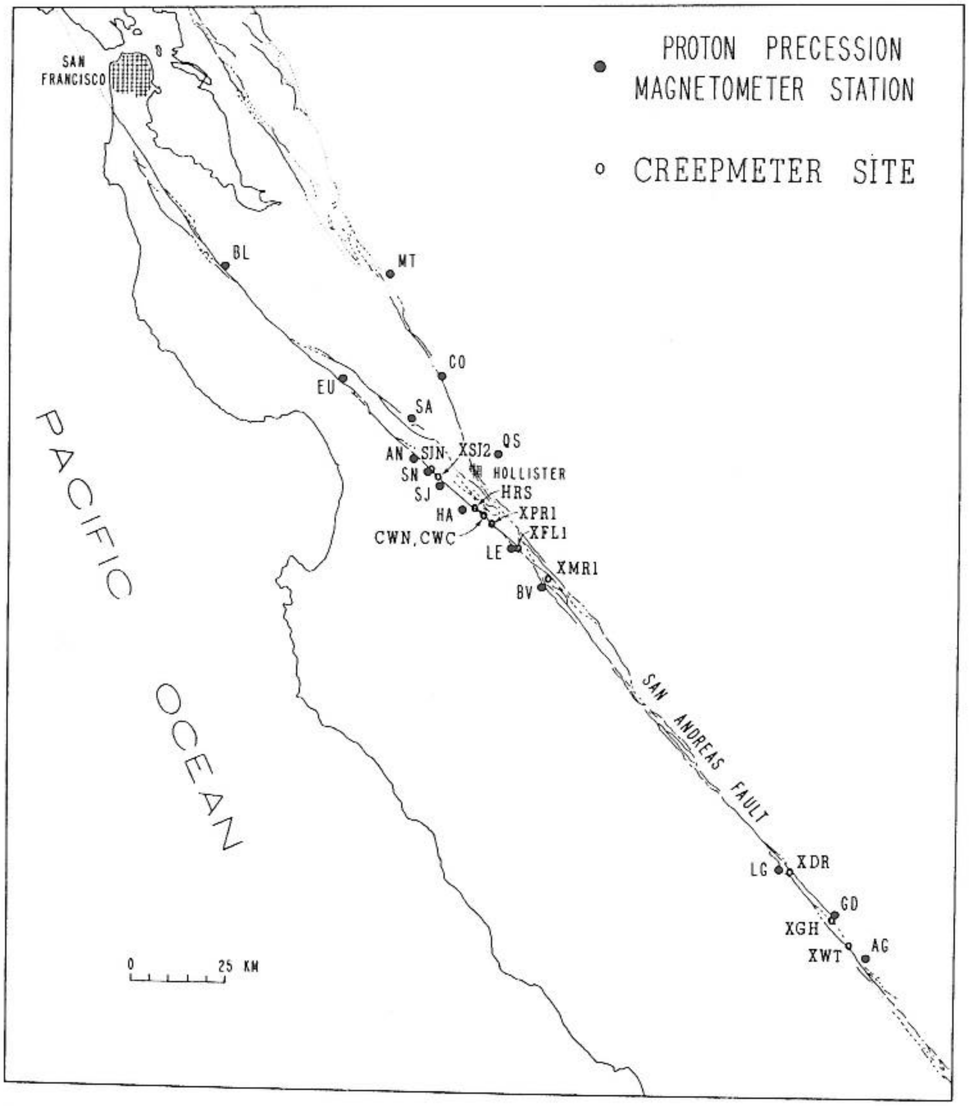

Fig. 1. Locations of recording proton precession magnetometers and creepmeters along the San Andreas fault.

in the data further. These techniques have not yet been applied comprehensively to the magnetic field data.

Of particular interest in Fig. 2a are the data obtained at creepmeter *XFL1* and the magnetometer *LE*, since the magnetometer is less than 300 m from the creepmeter. It might be expected that any correspondence between creep events and magnetic transients would be seen most clearly in these data. It is apparent also that this is not the case for these data or for longer

TABLE I

Creepmeter identification codes, locations, and distances from the nearest recording magnetometer with occurrence times dates and amplitudes of recorded creep events.

Creepmeter and location	Creep event occurrence time (GMT)	Date	Amplitude (mm)	Nearest magne-tometer	Distance to nearest magne-tometer (km)
XMR1					
(36°35.7′N,	1508	Jan. 10, 1974	2.5	*BV*	1.54
121°11.2′W)	0057	Jan. 29, 1974	1.9		
	0015	Apr. 14, 1974	2.9		
	1808	Jul. 11, 1974	3.0		
	0837	Oct. 03, 1974	2.3		
	1221	Feb. 02, 1975	2.9		
	1617	Mar. 07, 1975	1.1		
	0826	Apr. 14, 1975	2.0		
	2134	Jun. 29, 1975	2.5		
	1830	Oct. 27, 1975	2.4		
	1256	Jan. 25, 1975	1.7		
	1114	Apr. 16, 1976	2.5		
	1902	Jul. 29, 1976	2.3		
	0522	Nov. 11, 1976	2.8		
XFL1					
(36°39.9′N,	1850	Jan. 13, 1974	0.8	*LE*	0.27
121°16.3′W)	2323	Feb. 01, 1974	1.7		
	1355	Jun. 16, 1974	3.1		
	1828	Nov. 24, 1974	1.5		
	2153	May 14, 1975	2.4		
	0354	Sep. 29, 1975	1.9		
XPR1					
(36°43.4′N,	0058	Feb. 25, 1974	2.0	*LE*	9.3
121°20.9′W)	1102	Mar. 16, 1974	1.3		
	0119	Jun. 07, 1974	0.7		
	0751	Jun. 21, 1974	1.0		
	0243	Jul. 27, 1974	1.3		
	0329	Aug. 04, 1974	0.6		
	2200	Oct. 21, 1974	0.7		
	1836	Oct. 30, 1974	1.3		
	1611	Feb. 15, 1974	2.4		
	0755	May 19, 1975	1.0		
	1137	May 21, 1974	1.3		
	0809	Jun. 10, 1975	1.0		
	1815	Oct. 04, 1975	2.3		
	2154	Nov. 02, 1975	0.9		
	0745	Feb. 09, 1975	0.2		
	1818	Mar. 30, 1975	1.9		
	2048	Apr. 20, 1975	2.2		
	1005	Aug. 08, 1975	0.8		
	1925	Aug. 30, 1975	1.6		
	1608	Sep. 10, 1975	1.9		

TABLE I (continued)

Creepmeter and location	Creep event occurrence time (GMT)	Date	Amplitude (mm)	Nearest magne-tometer	Distance to nearest magne-tometer (km)
CWC (36°45.0′N, 121°23′W)	1042	Apr. 16, 1974	1.2	*HA*	5.9
	0648	Jul. 16, 1974	1.8		
	1902	Feb. 16, 1975	2.9		
	0413	Feb. 21, 1975	1.1		
	1458	Apr. 10, 1975	4.1		
	1713	Sep. 09, 1975	3.0		
	1519	Sep. 28, 1975	1.9		
CWN (36°45.0′N, 121°23.1′W)	0330	Apr. 10, 1974	0.4	*HA*	5.9
	0000	Aug. 31, 1974	2.5		
	1902	Feb. 16, 1975	2.9		
	0413	Feb. 21, 1975	1.8		
	0413	Jun. 20, 1975	3.1		
	2152	Sep. 17, 1975	1.4		
	1940	Sep. 28, 1975	2.5		
	1445	Apr. 10, 1975	4.2		
	1521	Sep. 28, 1975	2.0		
	1601	Dec. 01, 1975	0.2		
HRS (36°45.3′N, 121°25.3′W)	1315	Jan. 07, 1975	2.2	*HA*	2.4
	0451	Mar. 27, 1974	2.2		
	1200	Jul. 22, 1974	2.3		
	0804	Aug. 03, 1974	1.1		
	1922	Sep. 14, 1974	0.9		
	1520	Sep. 17, 1975	2.4		
	1339	May 10, 1976	2.4		
	0314	Sep. 21, 1976	−0.6		
	1913	Sep. 28, 1976	1.5		
	0413	Sep. 29, 1976	1.0		
XSJ2 (36°50.2′N, 121°31.2′W)	2301	Nov. 28, 1974	0.3	*SJ*	2.63
	0516	May 27, 1975	4.0		
	1034	Oct. 01, 1975	2.6		
	0243	May 15, 1976	4.9		
SJN (36°51.3′N, 121°32.7′W)	2339	Nov. 28, 1975	0.9	*AN*	5.47
	1113	Feb. 03, 1975			
	0813	Feb. 15, 1975	−0.1		
	1138	Mar. 03, 1975	0.6		

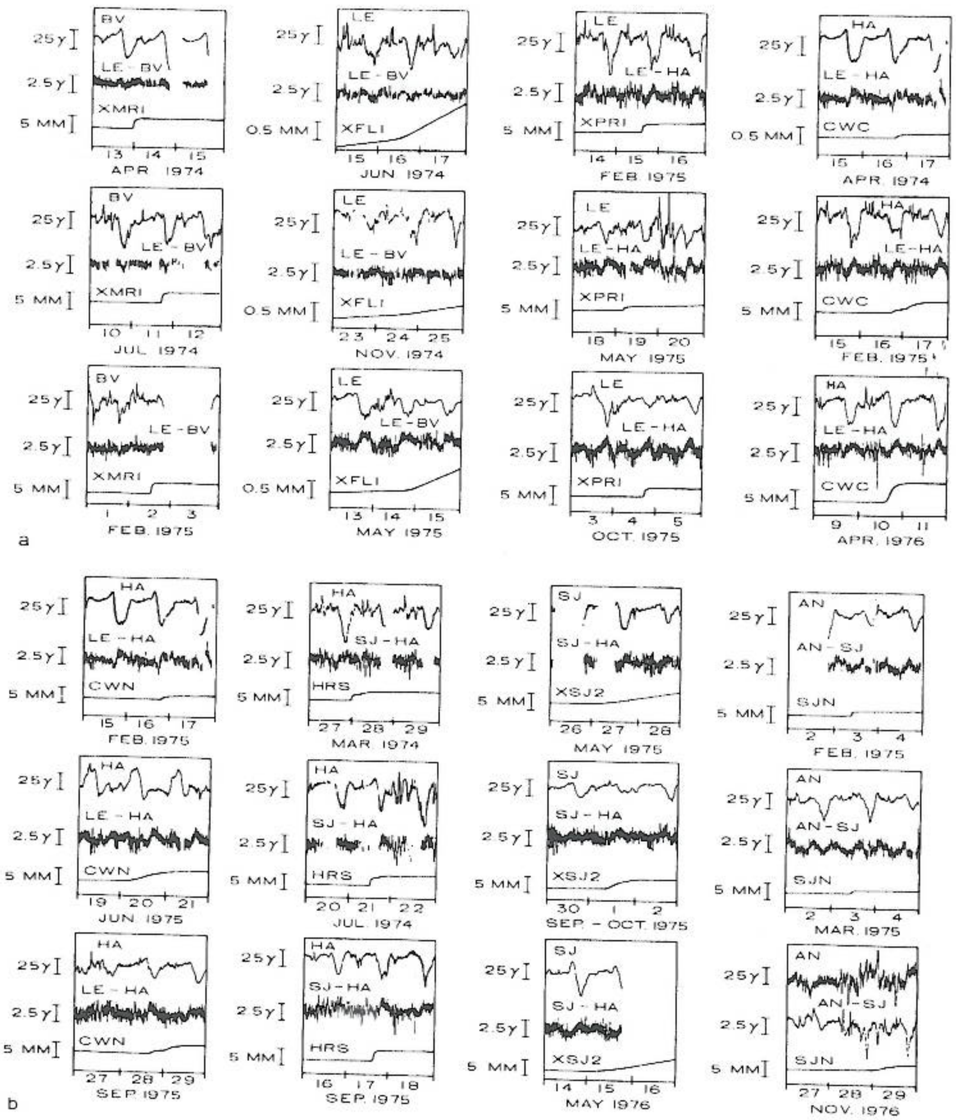

Fig. 2. a. Plots of total field, differenced magnetic field, and fault creep for three days spanning the three largest events at *XMR1*, *XFL1*, *XPR1*, and *CWC*, for which simultaneous records exist. b. Plots of total field differenced magnetic field and fault creep for three days spanning the three largest events at *CWC*, *HRS*, *XSJ1* and *SJN*.

term averages where the resolution is greater. Figure 2b shows similar plots of data during the three largest creep events for which simultaneous data was obtained on the four creepmeters and magnetometers in the northern part of the array.

The broader questions, whether deeper slip on the fault might trigger episodes of local surface failure or change the long term creep rate, are still unanswered by the data considered so far. In any case the magnetic changes associated with deeper slip would be difficult to interpret. If triggered surface failure occurs, as appears to be the case in Hollister Valley (Slater and Burford, 1978), a general correspondence in time of clusters of creep events and magnetic field transients or offsets might be expected. To probe this possibility and to search for more complex relationships between the magnetic and creep data, three years of magnetic-difference data are shown in a general space—time plot (Fig. 3) together with the occurrence point, occurrence time and amplitude of creep events.

Although some patterns are perhaps apparent, there is no significant correlation between groups of creep events and magnetic changes. We do note that on this time scale a few events such as the October 3, 1974 and June 29, 1975 events at *XMR1* and the May 14, 1975 event on *XFL1* do appear to correspond to times of changing local field. However, other creep events of greater creep amplitude occur at these same meters without similar magnetic signals. Magnetic signals, such as occurred at the end of June, 1975 primarily

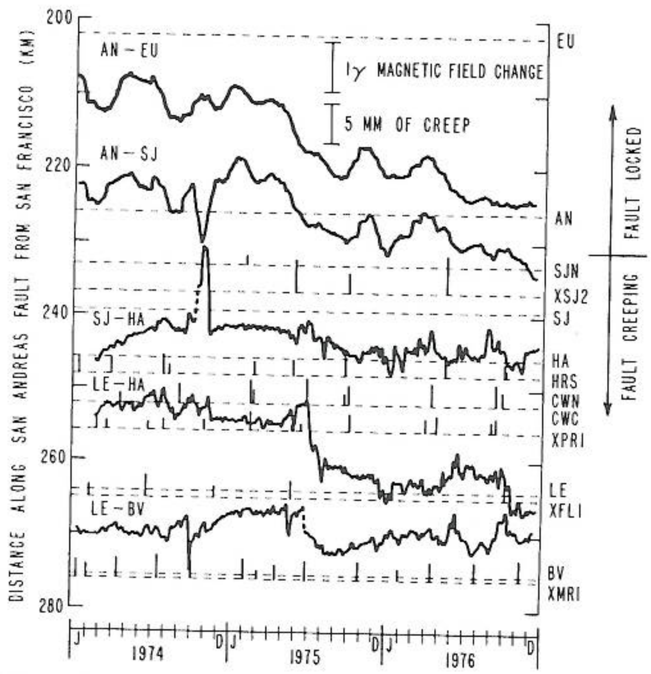

Fig. 3. Space time plots of creep occurrence and magnetic field differences between adjacent sites for the years 1974—1976. Occurrence times and amplitudes are plotted as vertical bars for creep events with amplitudes greater than 1 mm. These events occurred on creepmeters within a few kilometers of the each recording magnetometers.

at the *LE* magnetometer (since it is common to the *LE—HA* and *LE—BV* difference), have also occurred without a creep event at the *XFL1* creepmeter only 270 m away. The question whether changes in long term creep rate are related to local magnetic field is the subject of a different study (Smith et al., 1978).

DISCUSSION

Changes in magnetic field might be expected to occur with creep events either from demagnetization by repeated shear failure, distortion and local cracking in the fault face or from stress induced changes of the magnetic properties of surrounding rocks (Breiner and Kovach, 1968). Telluric currents due to perturbed streaming potentials (Mizutani and Ishido, 1976) might also be suggested.

In the first case, laboratory measurements of changes in magnetization after repeated cycling at high stress (>1 kilobar) can be used to estimate the largest field perturbations likely to be generated in this way. In these experiments magnetization changes of 100% have been observed (Martin and Wyss, 1975; Revol et al., 1978). Even greater changes (~500%) result if intact rock is uniaxially compressed to failure without prior stress cycling (Nagata and Carleton, 1968; Revol et al., 1978). Recent records of tilt and strain at points around the regions of observed surface creep allow crude estimates of the dimensions of the fault slip involved (Johnston et al., 1976; Mortensen et al., 1977; McHugh and Johnson, 1976; Johnston et al., 1977; Goulty and Gilman, 1979). These data indicate that the horizontal dimensions are typically from 0.5 to 3 km and the depths are typically less than 2 km.

Assuming that 10% of the fault gauge experiences transient kilobar stresses and 100% demagnetization while the mean change in stress is 10 bars, the surface anomaly in total field can be calculated with techniques described in Henderson and Zietz (1957), Jakowsky (1961) and others. Taking the dimensions to be 1 km long, 1 km deep and 100 cm thick the distance at which this change is detectable at the 1 gamma level is within about 26 m from the fault for a magnetization of 10^{-3} e.m.u. This would, of course, appear as an irreversible change or offset in local magnetic field. If the slab is 10 m thick this distance becomes 115 m and if new cracks are occurring everywhere, detectable magnetic changes would also occur. We note also that magnetic changes generated in this way would be a detectable consequence of large scale dilatancy models that have been recently proposed (Whitcomb, 1976; Wys, 1977). If these effects do occur with creep events then the present data would constrain their source to be in a zone that must be quite narrow.

The second possible source for magnetic changes with creep events arises from the stress sensitivity of the magnetic properties of rocks, as proposed by Breiner and Kovach (1968). Stress sensitivities of both induced and remanent magnetization of rocks are typically about 0.01% bar^{-1} (Stacey and

Johnston, 1972). The critical question determining whether observations are likely concerns the magnitude, extent, and form of the stress field. Talwani and Kovach (1972) have proposed a semi-infinite model that extends to a 10 km depth corresponding to the bottom of seismogenic zone.

The tilt and strain records obtained near the fault at the times of creep events indicate, as previously discussed, a much more limited zone of failure. Worse still, following Chinnery (1964) the shear stress release τ_{12} for a section of near surface fault of length 1 km, depth 1 km is 0.04 bars mm^{-1} of fault slip. For a typical 5 mm event the mean stress change, which is typically on the order of or less than τ_{12}, is about 0.2 bar. This contrasts sharply with the 10 bar stress change assumed by Talwani and Kovach (1972).

Other estimates of the stress changes with creep events give similar values. Nason and Weertman (1973) were able to estimate the peak stresses associated with creep events by analyzing displacement time histories. They conclude that the maximum stresses are typically less than 1 bar. In the calculation by King et al. (1970), typical events of about 5 mm over distances of about 500 m given maximum stresses of up to 1 bar.

Preliminary tectonomagnetic models have been generated using the quasi-static dislocation solutions of McHugh and Johnston (1976) together with the equations outlined by Stacey et al., (1965), Shamsi and Stacey (1969) and Talwani and Kovach (1972) in order to calculate the magnetic effects expected with creep events. It is obvious from these models that, for these stress levels, the expected magnetic effects are of limited extent and are almost an order of magnitude below the present resolution, at periods of an hour or so, of the magnetometer array on the San Andreas fault (Smith and Johnston, 1976). Typical surface anomalys are about 0.02 gammas.

It would appear from these and other tectonomagnetic models of creep events that it is extremely unlikely, for such low stresses and limited slip dimensions, that an observable local magnetic field perturbation would occur simultaneous with the surface observations of fault creep. Exceptions might result, perhaps, with particular geometries or situations in which some related localized stress concentration or inhomogeneity is near a field observation point.

It is more likely that the near-surface failure is a consequence of, and perhaps triggered by, deeper slip of longer duration and larger spatial scale (Johnston et al., 1977; Slater and Burford, 1979). Periods of changing local magnetic field might then be expected to occur at the same time as either clusters of creep events in the same region or long-term changes in the creep rate. In either case a larger scale tectonomagnetic model is required, perhaps similar to that of Talwani and Kovach (1972), in which a surface anomaly of about 1 gamma was generated by semi-infinite slip to a depth of 10 km in material with a magnetization of 10^{-3} e.m.u.

CONCLUSION

In contrast to the measurements reported by Breiner and Kovach (1968), magnetic field changes apparently do not occur clearly prior to episodic fault creep events at a measurement resolution of 0.5 gammas for hour averages and 2 gammas for minute samples. This is consistent with expectations that stress induced magnetic changes should not be observable for the small localized stress changes inferred from simultaneous observations of fault creep and tilt and strain around the creep occurrence point.

Large changes in magnetization have been reported in laboratory samples where deviatoric stresses are in the kilobar range (Nagata and Carleton, 1968; Martin and Wyss, 1975). If these experiments model fault zone behavior, then similar linear and non-linear demagnetization behavior might be expected in the material near and on the fault face during failure (i.e., during non-linear strain associated with earthquakes, fault slip, creep events, dilatancy, etc.). The resulting magnetic field changes should be easily detected on nearby sensitive magnetometers. It is evident from the data reported here that these effects are not observed at sites as close as 270 m from sections of the fault where creep events occur. The zone where failure is occurring, where grains of magnetic material are being reoriented and where the domain structure is changing, must therefore be quite narrow, typically less than a few tens of meters.

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