ing to a procedure adapted from a method first applied to the modification of ribosomal subunits (8). From a freshly prepared 2-iminothiolane hydrochloride solution (0.5*M* in 0.1*M*, *p*H 8.0, phosphate buffer) 2.4 μl was added to 0.021 μmol of *trp* repressor in 250 μl of phosphate buffer, containing 1% 2-mercaptoethanol and 1 mg of L-tryptophan at 4°C. After overnight incubation at 4°C, the mixture was passed through a G-25 (coarse) spin column [H. S. Penefsky, *Methods Enzymol.* **56**, 527 (1979)] to remove the unreacted 2-iminothiolane. The spin column was equilibrated in 0.1*M* phosphate buffer, *p*H 8.0, prior to use. Then, 1.6 μmol of [^{3}H]5-iodoacetamido-OP (specific activity, 3 mCi/mmol) in *N,N*-dimethylformamide (4 μl) was added to the eluant collected from the spin column. The alkylation reaction proceeded at 4°C overnight. The product was isolated by passing the mixture through a G-25 spin column.

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12. The *aroH* operator region was part of a 257-bp Bam HI–Eco RI fragment, which had been cloned into pBR327 (11). The control region of *trpEDCBA* was contained in a Bam HI–Eco RI restriction fragment which had also been cloned into pBR327. We carried out 5′ and 3′ labeling of these fragments as described [T. Maniatis, E. F. Fritsch, J. Sambrook, *Molecular Cloning* (Cold Spring Harbor Laboratory, Cold Spring Harbor, NY, 1982)]. For the footprinting and cleavage reactions, a solution of labeled *aroH* operator fragment (100 n*M*, 10,000 count/min), *trp* repressor or OP-*trp* repressor (100 n*M* to 200 n*M*), and L-tryptophan (10 m*M*) was incubated at room temperature for 5 minutes in 10 μl of tris-HCl (30 m*M*, *p*H 8.0), KCl (100 m*M*), and $MgCl_2$ (3 m*M*). Footprinting reactions were carried out with 0.04 unit of DNase I for 5 minutes at room temperature. The reactions were quenched by the addition of "stop" solution [transfer RNA (200 μg/ml), 2*M* sodium acetate, and 10 m*M* EDTA]. The DNA was then precipitated with ethanol, redissolved in Maxam-Gilbert loading buffer, and analyzed by the use of a 10% polyacrylamide gel that contained 8.34*M* urea and was cross-linked at a ratio of 19:1. The chemical cleavage reaction was initiated by adding 1 μl of 20 μ*M* cupric sulfate and 1 μl of 58 m*M* mercaptopropionic acid. After 30 minutes at room temperature or at 37°C, the reaction was quenched by adding 2,9-dimethyl-1,10-phenanthroline followed by 1 μl of stop solution. The DNA was then precipitated with ethanol, redissolved in Maxam-Gilbert loading buffer, and analyzed by 10% polyacrylamide 8.34*M* urea, 19:1 cross-linked gel.
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Seismomagnetic Observation During the 8 July 1986 Magnitude 5.9 North Palm Springs Earthquake

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A differentially connected array of 24 proton magnetometers has operated along the San Andreas fault since 1976. Seismomagnetic offsets of 1.2 and 0.3 nanotesla were observed at epicentral distances of 3 and 9 kilometers, respectively, after the 8 July 1986 magnitude 5.9 North Palm Springs earthquake. These seismomagnetic observations are the first obtained of this elusive but long-anticipated effect. The data are consistent with a seismomagnetic model of the earthquake for which right-lateral rupture of 20 centimeters is assumed on a 16-kilometer segment of the Banning fault between the depths of 3 and 10 kilometers in a region with average magnetization of 1 ampere per meter. Alternative explanations in terms of electrokinetic effects and earthquake-generated electrostatic charge redistribution seem unlikely because the changes are permanent and complete within a 20-minute period.

Stress changes that accompany seismic failure are expected to cause piezomagnetic effects and consequent time-dependent local magnetic anomalies (1). Local magnetic field changes accompanying, and perhaps preceding, moderate to large earthquakes have therefore been actively sought in countries subject to earthquake hazards (2). Observations of local magnetic field transients apparently related to aseismic crustal activity (tectonomagnetic effects) have been well recorded (3, 4), but the most easily identifiable tectonomagnetic effect—the coseismic change or seismomagnetic effect expected to accompany rupture—has not yet been unambiguously detected near any moderate to large earthquake. Stable data in this search have been obtained only since about 1960 when modern drift-free and vibration-insensitive absolute magnetometers were first introduced (5).

A moderate earthquake (M_L 5.9, where M_L is the local Richter magnitude) occurred at a depth of 11.3 km on the Banning fault, approximately 12 km northwest of North Palm Springs, California, at 0921 UT on 8 July 1986. Preliminary determination of the focal mechanism indicates strike-slip motion in a direction N60°W on the Banning fault with a dip of 45° down to the north (6). This earthquake provided a rare opportunity to verify the reality of the elusive seismomagnetic effect; two proton magnetometers had been installed in 1979 at distances of 3 km and 9 km from the subsequent epicenter and have been sampling and transmitting data every 10 minutes since then through a 16-bit digital telemetry system to Menlo Park, California (7). Unambiguous observations of a seismomagnetic effect were obtained on these instruments and are reported here.

Figure 1 (left) shows locations of magnetometer sites in southern California at the time of the North Palm Springs earthquake. Because of discontinued maintenance, only ABLM, CHUM, and the two magnetometers LSBM and OCHM in the epicentral area (all shown as closed circles) were operating. The location of the earthquake (star) in relation to the two nearby magnetometers, the aftershock zone, and the primary faults is shown in the upper right section of Fig. 1.

Magnetic field differences between OCHM and LSBM for the 38 days before, and a few days after, the earthquake are shown in Fig. 2A. Close inspection of the data near the time of the earthquake indicates that the offsets were possibly complete within one sample interval, and certainly complete within two (< 20 minutes). The net field offset generated by the earthquake between these two sites is 1.0 ± 0.2 nT. To isolate the relative offsets at each site, simultaneously recorded data from the nearest operating magnetometer, CHUM, about 260-km distant, were subtracted from each time series. Figure 2, B and C, shows the plots of these differences during the same time as the OCHM-LSBM difference. The local magnetic field at OCHM and LSBM apparently decreased by 1.3 ± 0.2 and 0.3 ± 0.2 nT, respectively, at the time of the earthquake. Although these changes are quite small, they are still quite evident in 13-month (Fig. 2D) and 7.5-year plots (Fig. 2E) of OCHM-LSBM difference data, and have remained since the earthquake.

It might be argued that the offsets result from earthquake-induced physical displacement of both of the sensors. Each sensor holder is 2 m above ground and its 15 cm by 15 cm wooden support is set vertically in 1 m of concrete in a borehole. Even though both LSBM and OCHM are within a substantial regional magnetic anomaly derived from metamorphic rocks with measured surface magnetizations between 0.1 and 1 A/m, both sites were chosen in areas with low local gradients (< 2 nT/m). Sensor displacements of between 15 and 65 cm, which are

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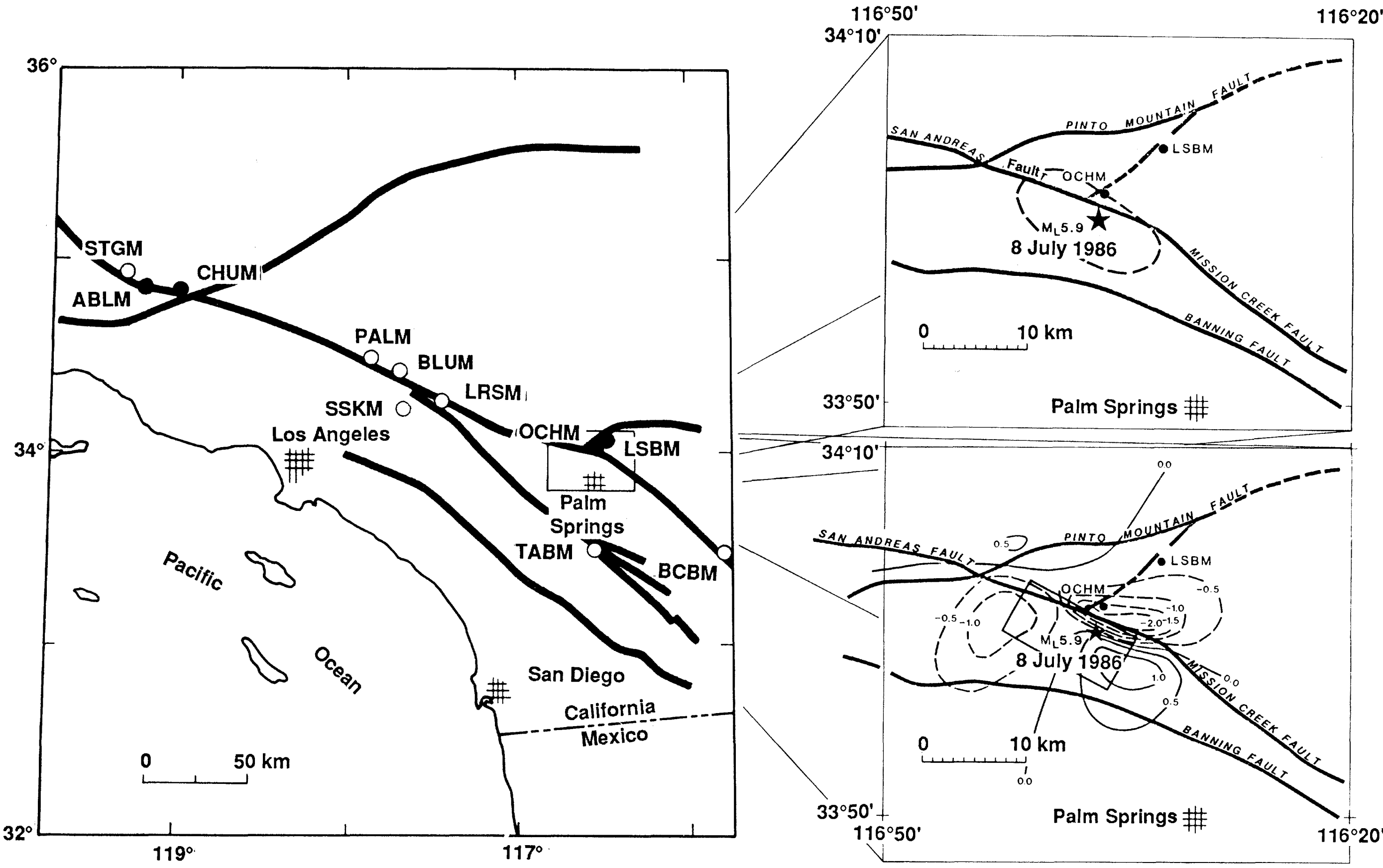

Fig. 1. (**Left**) Recording magnetometer network along the San Andreas fault system in southern California. Filled dots show locations of instruments operating at the time of the 8 July 1986, North Palm Springs earthquake. (**Upper right**) Expanded section shows the location of the two nearest recording magnetometers, OCHM and LSBM, relative to the epicenter (star) and the aftershock zone (dashed line) of the earthquake. (**Lower right**) Expanded section shows contours of magnetic field change expected from the earthquake using the model described in the text. The surface projection of the fault model is shown as a solid rectangle.

necessary to explain these data, could be readily detected. Site inspection at both LSBM and OCHM indicates no disturbance of the sensors.

It is possible that the increasing local magnetic field during the 4-month period prior to the earthquake (Fig. 2D) reflects precursory stress localization that was released when the earthquake occurred. However, inspection of the data of previous years (Fig. 2E) indicates that changes of similar amplitude occurred without associated seismic activity. Some of the field perturbations during 1979–1980 have been shown to relate to episodes of aseismic uplift, gravity, and areal dilation in this region (*4*). Other long-term changes, such as occurred in 1983, are not clearly related to tectonic activity, though deformation monitoring in this area is sparse and infrequent. Some short-term changes result from incomplete cancellation of ionospheric and magnetospheric disturbances that can be predicted and removed with more complete noise reduction techniques (*8*), but the primary features of the record cannot be explained in this manner.

Since the static magnetic offsets occurred at the time of the earthquake and have remained since, electrical charge redistribution mechanisms that may occur with rock fracture (*9*) and with the dynamic rupturing process (*10*) cannot be invoked to explain the observations. For the same reasons, magnetic fields resulting from pore fluid flow when the earthquake irreversibly changes the static strain field (*11*) are also likely to be transient in nature, as indicated, for example, by the well level records near the 1964 Alaskan earthquake (*12*). Even when massive changes in the hydrologic system occur, such as during the 1983 Borah Peak earthquake (*13*), these changes were not accompanied by corresponding changes in local magnetic field (*14*). This earthquake occurred in a region where the rock magnetization is low and tectonomagnetic effects would not be expected.

The coseismic offsets could result from piezomagnetic effects generated by the earthquake-related decrease in the local stress field. The stress dependence of rock magnetization has been demonstrated under laboratory conditions (*15, 16*) and theoretical models have been developed for single-domain and pseudo–single-domain rotation (*17*) and multi-domain wall translation (*18*). The stress sensitivity of induced and remanent magnetization from theoretical and experimental studies is approximately 3×10^{-3}/MPa. This value has been combined with estimates of stress change from dislocation theory of fault rupture in seismomagnetic models that calculate field changes expected to accompany earthquakes (*18, 19*). These models show that magnetic anomalies of a few nanoteslas should be expected to accompany earthquakes in regions with a mean rock magnetization of 1 A/m.

Such a seismomagnetic dislocation model was constructed for the North Palm Springs event in which the strike, dip, depth, fault length, fault width, and style of faulting were chosen to be consistent with the seismically determined parameters indicated above (*6*). To obtain the required earthquake moment, the hypothetical fault was assumed to have 20 cm of right lateral displacement. The 16-km segment of the Banning fault indicated by the aftershock distribution lies at a depth between 3 and 10 km. On the basis of observations of surface magnetization at the two sites, a value of 1.0

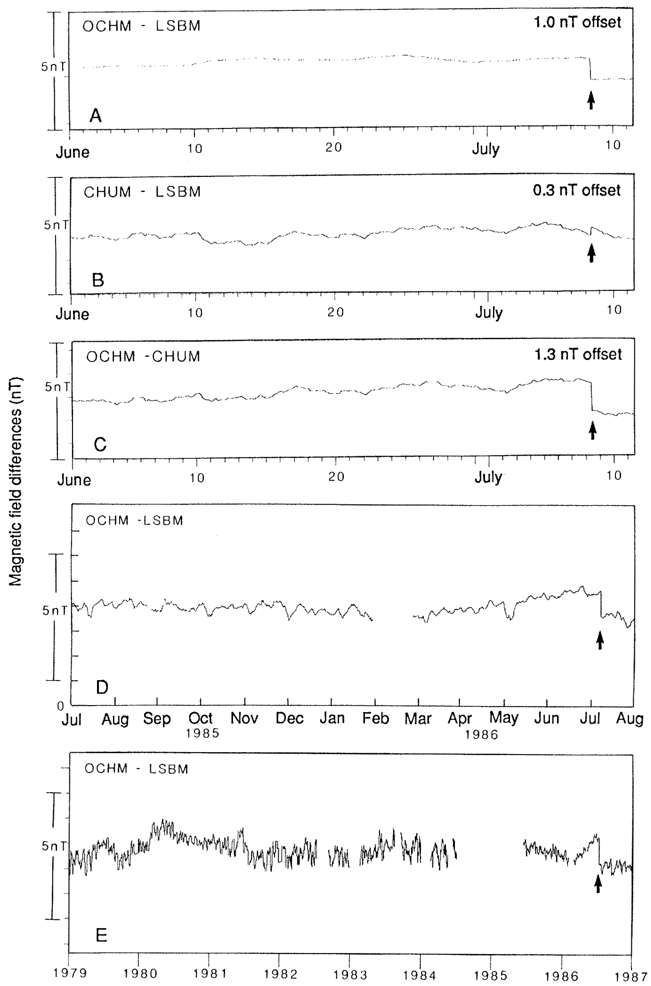

Fig. 2. (**A**) Magnetic field differences between the two local sites, OCHM and LSBM, for more than a month before and a few days after the North Palm Springs earthquake (occurrence time indicated by an arrow). (**B**) Magnetic field differences between the sites LSBM and site CHUM about 260 km to the northwest for the same time period. (**C**) Magnetic field differences between sites OCHM and CHUM also for the same time period. (**D**) Magnetic field differences between sites OCHM and LSBM for the 12-month period before the earthquake. (**E**) Magnetic field differences between sites OCHM and LSBM for the 7.5-year period before the earthquake.

A/m was chosen to represent the average regional magnetization. The stress field components were spatially averaged on a 1-km scale.

The contours of calculated magnetic field change in nanoteslas for this model are shown in Fig. 1 (lower right). The surface projection of the fault rupture is shown as a solid rectangle. Both the sense and approximate amplitude of the observed field offsets are consistent with this simple model. Reasonable variations of the model parameters, consistent with the uncertainties in the fault parameters, are, of course, possible. However, models in which the stress components are averaged on large spatial scales ($\sim$0.3 of the fault length) (*19*) would both underestimate the magnetic field offsets reported here and imply offsets in simultaneously recorded strain and displacement data that are inconsistent with the earthquake moment and the actual observations.

Two physical mechanisms could explain the seismomagnetic effects recorded during the 8 July 1986, North Palm Springs, M_L 5.9 earthquake: (i) Either there are substantial electric currents generated rapidly by either rupture-driven charge-generation mechanisms or by earthquake-driven fluid flow (electrokinetic effects), or (ii) the seismic stress drop causes piezomagnetic effects and consequent local magnetic field changes. The irreversibility of the changes, the rapidity of occurrence, and the highly conductive nature of the earth's crust appear to preclude both electrostatic and electrokinetic effects as primary physical mechanisms driving these changes. The observations are consistent in amplitude and sense with a reasonable tectonomagnetic model of the event.

Since coseismic magnetic field changes occur, questions naturally arise concerning the likely amplitude of preseismic magnetic field changes and whether these could be used for earthquake prediction purposes. Longer term preseismic transients, with amplitudes similar to these preseismic and coseismic changes, have been detected several weeks and longer before other moderate earthquakes (*3, 4*). Since recent records from highly sensitive strainmeters obtained near to, and immediately before, many recent large earthquakes (*20*) indicate precursory strain (and stress) changes in the source region are less than 1% of the coseismic changes, hopes that short-term prediction might similarly be derived from preseismic changes in the last hours to seconds before moderate to large earthquakes appear to be fading. With regard to earthquake prediction research we conclude that (i) intermediate term precursory phenomena with amplitudes similar to these observed coseismic phenomena should be, and apparently are, detectable with magnetic monitoring techniques, but that (ii) detection of short-term precursory changes by magnetic, or other techniques with similar stress sensitivity, will be difficult at the present resolution level of near-fault stress changes ($\sim$100 kPa).

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