

ULF MAGNETIC SIGNATURES AT THE EARTH SURFACE DUE TO  
GROUND WATER FLOW: A POSSIBLE PRECURSOR TO EARTHQUAKES

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*Abstract.* Magnetic field fluctuations at the earth's surface of  $\frac{\Delta B}{B} \sim 10^{-5}$  at  $< 1$  Hz are shown to result from motion with a peak velocity of  $\sim 4$  cm/s of ground water ( $\sim 4$  S/m) at  $\sim 5$  km depth. Surface field changes can occur due to either divergence free fluid motion with transverse spatial wavelengths of a few tens of km, and/or homogeneous flow which displaces local inhomogeneities in the earth magnetic field.

1. Introduction

Slight ( $\frac{\Delta B}{B} \sim 10^{-5}$ - $10^{-4}$ ) variations of the earth's magnetic field at ULF (0.01-0.5 Hz) frequencies observed prior to the Loma Prieta earthquake were recently reported as a possible precursor signature [Fraser-Smith *et al.*, 1990]. Hydromagnetic waves at  $\sim 1$  Hz and quasistatic electric field fluctuations were also observed on a low altitude (800 km) satellite over an earthquake center in the southern Pacific [Chmyrev *et al.*, 1989]. In this paper we suggest a mechanism by which such ULF variations may result from motion of ground water within the earth's crust in the absence of any motion near the surface.

The coupling of horizontal water motion with the earth's field and its penetration upward is efficient when the electrical conductivity of water is relatively high while that of the overlying layer is moderate. Similar physical mechanisms have been considered in the investigation of electromagnetic fluctuations over the sea induced by water motion [Sanford, 1971; Cox, 1980; Chave, 1983].

2. Theoretical Formulation

For parameter values considered in this paper the Magnetohydrodynamic (MHD) approximation is valid ( $\sigma \gg \omega \epsilon_0$ , where  $\sigma$  is the conductivity,  $\omega$  is the angular frequency, and  $\epsilon_0$  is the permittivity of free space) and thus the magnetic field response to fluid motion is governed by:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \vec{v} \times \vec{B} + \frac{1}{\mu_0 \sigma} \nabla^2 \vec{B} + \frac{1}{\mu_0 \sigma^2} \nabla \sigma \times \nabla \times \vec{B} \quad (1)$$

where  $\vec{v}$  is the fluid velocity,  $c$  is the speed of light, the coordinate system is such that  $z$  is positive into the earth,  $\vec{B}$  has components  $B_x, B_z \neq 0, B_y = 0$ , and  $\vec{v}$  has component  $v_x \neq 0$ . We assume that  $\sigma$  depends only on depth  $z$ , so that the last term in (1) vanishes for the  $z$ -component. Since the influence of the magnetic field change on the motion of ground water is neglected and since  $|\vec{B} - \vec{B}_0| \ll |\vec{B}_0|$ ,  $\vec{F} = \nabla \times \vec{v} \times \vec{B}$  can be taken to be an externally specified excitation function. The

physical nature of the excitation function  $\mathcal{F}$  is discussed in section 4.

After Fourier transforming with respect to  $t, x$  the  $z$ -component of equation (1) can be written as;

$$\frac{d^2 B_z}{dz^2} - \kappa^2 B_z = \mu_0 \sigma F_z \quad (2)$$

where  $B_z(k_x, \omega, z)$  and  $F_z(k_x, \omega, z)$  are the transformed quantities of  $B_z$  and  $F_z$  respectively,  $\kappa = (k_x^2 + i\omega\mu_0\sigma)^{1/2}$ , and where there is no variation in any of the quantities in the  $y$ -direction. Although we simplify the problem by considering harmonic variations only in the  $x$ -direction, arbitrary forcing-function profiles as a function of  $x$  and  $y$  can be analyzed as a superposition of Fourier components in  $k_x$  and  $k_y$ . Equation (2) can be solved subject to boundary conditions formulated below.

For  $z < 0$   $B_{x,z} \sim B_{x,z}^a \exp(-ik_x z)$  and

$$B_x^a = -\frac{k_z}{k_x} B_z^a; \quad c^2(k_x^2 + k_z^2) = \omega^2 \quad (3)$$

where the superscript 'a' denotes fields in air. We note that the displacement current term in (3) cannot be neglected for  $z < 0$  since there is no conduction current in air. However,  $c^2 k_x^2 \gg \omega^2$  for the ULF range ( $\omega < 10^2$  s $^{-1}$ ) and for  $\lambda_x < 10^3$  km, so that  $k_z$  is imaginary and is given by  $k_z^2 = -k_x^2$ . The sign of  $k_z$  is chosen to provide vanishing field disturbances at large distances above the surface, so that  $k_z = ik_x$  for  $k_x > 0$ . Using this condition in (3) we have:

$$B_x^a = -i \frac{|k_x|}{k_x} B_z^a \quad (4)$$

Below the surface  $B_x$  and  $B_z$  are coupled through  $\nabla \cdot \vec{B} = 0$ :

$$-ik_x B_x + \frac{dB_z}{dz} = 0 \quad (5)$$

Assuming that there is no surface current, we have  $B_x^a = B_x(z = 0^+), B_z^a = B_z(z = 0^+)$ , so that (4) also holds for  $z = 0^+$ . Equations (4,5) lead to a boundary condition for  $B$  at  $z = 0$ :

$$|k_x| B_x - \frac{dB_z}{dz} = 0 \quad (6)$$

The second boundary condition for  $B_z$  can be obtained for  $z \rightarrow \infty$ . Since we assume that ground-water motion occurs only in a limited depth range ( $L_1 \leq z \leq L_2$ ) and that  $\sigma$  is constant for  $z > L_2$ , the solution of (2) is of the form  $B \sim \exp(\kappa z)$ . Choosing the sign of  $\kappa$  as  $Re(\kappa) < 0$  to provide vanishing magnetic-field disturbances for  $z \rightarrow \infty$  leads to the second boundary condition for  $B$  at  $z = L_2$ :

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$$\frac{dB_z}{dz} = \kappa B_z \quad (7)$$

In the next section, we present results of the numerical solution of equation (2) to obtain  $B_z(z)$  for given  $F(k_x, \omega, z)$  and for a model of the earth conductivity as a function of depth (i.e.,  $\sigma(z)$ ). The physical mechanisms of excitation are discussed in section 4.

### 3. Results

The conductivity model used is given in Figure 1a and assumes the existence of a highly conductive, water containing layer at a depth of 4-4.5 km in the form of a raised cosine variation with  $\sigma_{max} \simeq 0.1-4$  S/m at  $z=4.25$  km, and with  $\sigma = 10^{-2}$  S/m for  $0 < z < 4$  km. These values for  $\sigma$  are consistent with those estimated for ground water [Bailey, 1990] and with the geological data for the Loma Prieta region [Eberhart-Phillips et al., 1990]. The excitation function  $F$  is assumed to have a similar profile (as  $\sigma(z)$ ) in the water containing layer (Figure 1a).

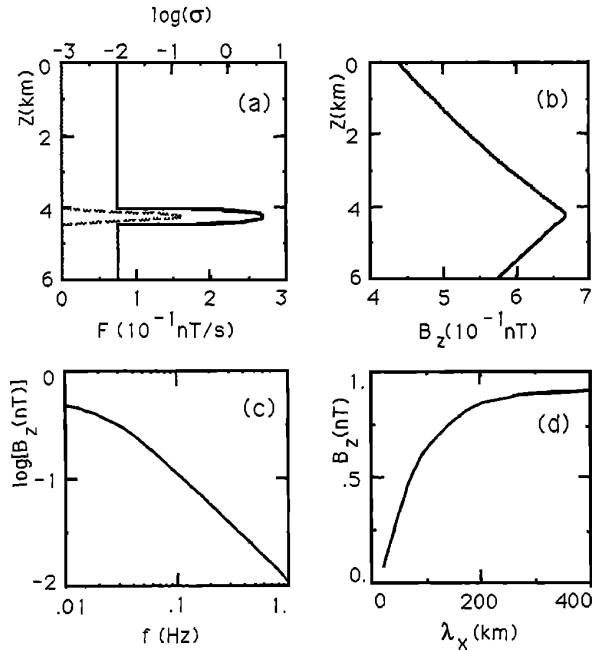


Fig. 1. Numerical results. (a) The solid line represents conductivity profile  $\sigma(z)$  as a function of depth  $z$ . The peak value at  $z=4.25$  km corresponds to  $\sigma=4$  S/m. The dashed line shows the assumed profile of the forcing function  $F_z$ . For constant  $k_x$ , the profile of the forcing function also corresponds to that of the velocity of ground water. (b) Magnitude of magnetic field fluctuations versus depth  $z$  for  $\omega = 0.1$  rad/s,  $k_x = 10^{-4}$  m $^{-1}$ , and  $F_z, \sigma$  as shown in (a). Note that only the perturbation components ( $\Delta B_z$ ) of the field are shown. The value of the forcing function  $F_z$  was chosen to correspond to magnitude of fluctuations at the surface ( $z=0$ ) of  $\frac{\Delta B_z}{B_z} \simeq 10^{-5}$ . (c) Magnitude of the surface magnetic field fluctuations versus frequency for  $k_x = 10^{-4}$  m $^{-1}$ ,  $F_z, \sigma$  as shown in (a). (d) Magnitude of the surface magnetic field fluctuations versus  $\lambda_x$  for  $\omega = 0.1$  rad/s, and  $F_z$  and  $\sigma$  as shown in (a).

With  $F(z)$  and  $\sigma(z)$  as given in Figure 1a, equation (2) is numerically solved using a two-point Runge-Kutta technique to determine  $B_z(z)$  subject to boundary conditions (6,7). The magnitude of  $B_z(z)$  is shown in Figure 1b for  $\omega=0.1$  rad/s,  $k_x = 10^{-4}$  m $^{-1}$  and for  $F_{max} = 1.6 \times 10^{-1}$  nT/s so that  $\frac{\Delta B_z}{B_z} \sim 10^{-5}$  at the surface. We note that the magnetic field disturbance peaks in the region of water motion, but that substantial field also penetrates to the surface.

The reported single point observations of ULF precursor signatures from the Loma Prieta earthquake [Fraser-Smith et al., 1990] do not permit the evaluation of the transverse dimensions of the region of perturbed magnetic field. However, a recent measurement of hydromagnetic waves over an earthquake center on a low-altitude satellite suggests that dimensions of such regions can be  $>100$  km [Chmyrev et al., 1989]. For our case,  $k_x \leq 10^{-4}$  m $^{-1}$  which corresponds to  $\lambda_x \geq 60$  km, and  $\omega=0.1$  rad/s ( $\sim 0.015$  Hz) is within the range of magnetic fluctuations observed in the Loma Prieta case [Fraser-Smith et al., 1990]. For  $z < L_1$  and  $z > L_2$  equation (2) has solutions of the type  $\sim \exp(\pm \kappa z)$ . In the case of a thin water containing layer where  $L_2 - L_1 \ll \frac{1}{|\kappa|}$  the forcing term in (2) provides the jump in the first derivative  $\frac{dB_z}{dz}$ , as seen in Figure 1b.

In the Loma Prieta case [Fraser-Smith et al., 1990] the anomalous ULF responses were primarily observed at frequencies of 0.01-0.5 Hz. The dependence of  $B_z^a = B_z(z=0^+)$  on frequency for  $F_{max} = 1.6 \times 10^{-1}$  nT/s and  $k_x = 10^{-4}$  m $^{-1}$  is given in Figure 1c and shows that  $B_z^a$  steadily decreases with increasing  $\omega$ , and is  $>10$  times smaller at 1 Hz than at 0.01 Hz. Detailed comparison of the spectrum in Figure 1c with the data is not appropriate since the observed spectrum is likely to be dominantly determined by the frequency spectrum of the source (velocity) fluctuations, which in turn would depend on the physical mechanisms that lead to the water flow.

The dependence of the surface magnetic field on the wavelength  $\lambda_x$  for  $F_{max} = 1.6 \times 10^{-1}$  nT/s and for  $\omega = 0.1$  rad/s is presented in Figure 1d. We note that the penetration of the magnetic field to the surface increases with increasing  $\lambda_x$ .

### 4. The Excitation Function $\vec{\mathcal{F}}$

In this section, we consider the different physical mechanisms that might lead to the values of excitation  $\vec{\mathcal{F}} = \nabla \times \vec{v} \times \vec{B}$  shown in Figure 1a.

The dependence of  $\vec{\mathcal{F}}$  on the spatial variations of  $\vec{v}$  and/or  $\vec{B}$  can be explicitly expressed as follows;

$$\vec{\mathcal{F}} = \nabla \times \vec{v} \times \vec{B} = (\vec{B} \nabla) \vec{v} - (\vec{v} \nabla) \vec{B} - \vec{B} (\nabla \cdot \vec{v}) \quad (8)$$

We assume  $\nabla \cdot \vec{v} = 0$ , so that a variety of spatial flow patterns for  $\vec{v}$  (with at least two non-zero components) will be consistent with our model. For  $\nabla \cdot \vec{v} = 0$  only first and second terms in the right-hand side of (8) may be non-zero, corresponding to two different mechanisms that might lead to magnetic field perturbations. The contribution to the excitation function of transverse variations in velocity ( $(\vec{B} \nabla) \vec{v}$ ) can be evaluated assuming  $\frac{dB_z}{dz} = 0$ . The particular nature of the velocity flow would depend on the physical causes of the flow that are not considered here. Evaluating, for example, the contribution to  $F_z$  from  $v_x$ , we have  $F_z = k_x v_x B_z$ , so that

the  $F_{max} = 1.6 \times 10^{-1}$  nT/s corresponds to  $v_x \sim 4$  cm/s for  $k_x \sim 10^{-4}$  m $^{-1}$  and for the earth's field of  $B_x \sim 4 \times 10^{-5}$  T. Calculations show that for 0.01 Hz to 1 Hz,  $k_x \leq 10^{-4}$  m $^{-1}$ , and  $\sigma$  for the water-containing layer of 0.1 to 4 S/m, velocities of  $v_x \sim 4$ –10 cm/s would be required for fluctuation intensity of  $\frac{\Delta B}{B} \sim 10^{-5}$  at the surface.

We note here that natural fluid motion in an inner layer of the earth crust should be such that the frequency  $\omega$  and wavenumber  $k_x$  are related through an appropriate dispersion relation based on the nature of motion. In Figures 2-4 we have given results for arbitrary selected values of  $k_x$  and  $\omega$ . However, depending on the nature of the water motion various combinations of  $k_x, \omega$  would be more likely than others. Comprehensive modelling of the ULF magnetic signatures of the earth motion in an inner layer should properly include the relations governing the motion.

The contribution to  $\vec{F}$  due to ambient magnetic-field inhomogeneity ( $(\vec{v}\nabla)\vec{B}$ ) does not vanish if the earth crust is initially inhomogeneous and contains insertions with different magnetic features. Such inhomogeneities can result in magnetic-field fluctuations due to steady water flow even when  $\nabla\vec{v} = 0$ . This point is further discussed in the next section with reference to available data for the Loma Prieta region.

## 5. Summary and Discussion

The analysis presented above indicates that ULF magnetic field fluctuations such as those observed prior to the Loma Prieta earthquake may occur due to motion of water in an inner layer of the earth's crust while the surface layers do not move. Motion of highly conductive underground water at frequencies of  $< 1$  Hz can lead to magnetic field fluctuations at the surface in essentially two different ways; (i) velocity variations within the layer with wavelengths of a few tens of km, and/or (ii) displacement of the local spatial inhomogeneities in the surface magnetic field due to a homogeneous flow ( $\nabla\vec{v} = 0$ ). In both cases the source of temporal fluctuations in the surface magnetic field is ultimately the temporal fluctuations in velocity.

To investigate the first mechanism, we provided results for spatially harmonic motion for different values of  $\omega$  and  $k_x$ . For the parameters considered, we find that efficient coupling of magnetic field to the surface is obtained for low enough frequencies and large enough  $\lambda_x$  leading to  $\frac{\Delta B}{B} \sim 10^{-5}$  for velocity fluctuations of peak magnitude 4 cm s $^{-1}$  at  $\sim 4$  km depth at a frequency  $\omega = 0.1$  rad/s (0.015 Hz), and with  $k_x = 10^{-4}$  m $^{-1}$ . Although harmonic variation of velocity in the  $x$ -direction is adopted here for ease of analysis, realistic profiles of velocity can be analyzed in terms of a Fourier superposition of components in  $k$ -space. We also recognize that the nature of the water motion would dictate a relationship between  $\omega, k_x$  that can be derived from a fluid dynamics analysis. For divergence free water flow, at least two nonzero velocity components must be present.

Detailed investigation of the second mechanism requires knowledge of the existing inhomogeneities of the earth's surface magnetic field. This mechanism can lead to  $\frac{\Delta B}{B} \sim 10^{-5}$  for  $f \leq 0.1$  Hz and  $v \sim 10$  cm/s if the ambient magnetic field spatial derivative is at least of order of  $\frac{1}{B_0} \frac{dB_0}{dx} \sim 10^{-5}$  m $^{-1}$ . Aeromagnetic data indicate high gradients of magnetic field in the epicentral region of the Loma Prieta earthquake, known as the Corralitos magnetic field anomaly [Brabb and Hanna,

1981]. It is believed that this anomaly is caused by buried plutonic rock at a depth of 6 km and total rock magnetization of 1.5 A/m [Mueller and Johnston, 1990]. The magnetic field gradient on the surface is  $\sim 2$   $\mu$ T/km, corresponding to  $\frac{1}{B_0} \frac{dB_0}{dx} \sim 10^{-5}$  m $^{-1}$ . Our analysis indicates that such local magnetic-field inhomogeneities could have led to the observed  $\frac{\Delta B}{B} \sim 10^{-5}$  if homogeneous water flow of  $v \sim 10$  cm/s occurred prior to the earthquake. While this mechanism has yet to be investigated in further quantitative detail, it would appear that higher amplitude surface fluctuations would in general be expected in the vicinity of stronger magnetic field anomalies.

In terms of the coupling of the surface magnetic field disturbances to higher altitudes, we note that the boundary condition (6) was formulated to give  $B_z = 0$  at high altitudes ( $z \rightarrow -\infty$ ) so that the field intensity varies as  $\exp(-k_x h)$ , where  $h$  is the distance above the ground. At ionospheric heights ( $h \sim 100$  km), the magnetic field perturbations can be transformed to hydromagnetic waves, which can propagate to high altitudes without substantial reduction. We note that such coupling to the ionosphere would be more efficient for smaller  $k_x$  ( $|k_x| = |k_z|$ ). Satellite observations in the southern Pacific have shown that electromagnetic disturbances in the ionosphere prior to an earthquake may have had transverse dimensions of up to  $\sim 300$  km [Chmyrev et al., 1989]. Assuming that such disturbances are formed by spatial harmonics with wavelengths comparable to the transverse dimensions caused by magnetic-field perturbations at the ground level, the reduction in the magnetic field between the ground and the ionosphere would be  $\exp(-k_x h) \sim 10^{-1} \cdot 10^{-3}$  for  $\lambda = \frac{2\pi}{k_x} = \frac{2\pi}{k_z} = 200$ –60 km respectively. Thus, it appears that magnetic field disturbances observed in the ionosphere are likely to have larger transverse wavelengths than those on the surface of the Earth. Additional reduction in intensity may have occurred in the case reported by Chmyrev et al. [1989] due to the fact that the uppermost layer consisted of highly conductive ocean. Better coupling to the ionosphere may occur during daytime conditions when the  $D$ -region extends down to  $\sim 60$  km. The ULF fluctuations may cause current flows or couple with existing ionospheric currents and fields leading to some of the other reported cases of satellite and ground-based observations of ELF/VLF precursors before earthquakes [Gokhberg et al., 1982; Parrot and Mogilevsky, 1989], and volcanic eruptions [Yoshino and Tomizawa, 1989]. Quantitative assessment of this type of coupling must take proper account of the Hall and Pedersen conductivities of the lower ionosphere.

Recently, several mechanisms have been proposed for electromagnetic precursors to earthquakes. The electrokinetic effect [Mizutani et al., 1976, Fitterman, 1979] was discussed as a possible mechanism for electromagnetic field anomalies caused by mechanical stresses in porous rocks, leading to electric fields, which are accompanied by measurable magnetic-field changes. Electromagnetic precursors of earthquakes have been reported to occur also in the frequency range up to a few megahertz [Gokhberg et al., 1982]. In terms of further experimental work aimed at measurements of ULF precursors to earthquakes, vertical and horizontal antennas can be used to measure the phase shift between the two field components ( $B_x, B_z$ ), in order to determine if the magnetic field perturbations are of underground origin, since the phase shift should then be  $\frac{\pi}{2}$ , as given by condition (4). In terms of electric field measurements, we note that fluctuations of magnitude  $\frac{\Delta B}{B} \sim 10^{-5}$  in the  $B_z$  component should be accompanied

by variations of the horizontal component of electric field of amplitude  $\sim 3 \mu\text{V/m}$ .

While the analysis presented in this paper shows the theoretical possibility of ULF magnetic precursors of earthquakes being caused by fluid flow in deep layers, there remains serious issues that need to be addressed concerning the physical nature of such flow. Water flow may be caused by a pressure gradient, in which case the velocity of the flow is given by:

$$v = \frac{K}{\mu} \frac{dP}{dx} \quad (11)$$

where  $K$  is the permeability,  $\mu$  is water viscosity, and  $P$  is pressure [Turcotte and Schubert, 1982]. For permeability of  $K \sim 10^{-10} \text{ m}^2$  (typical for sand [Turcotte and Schubert, 1982]), and viscosity of water of  $\mu \sim 10^{-4} \text{ kg/m-s}$ , the velocity of  $v = 4 \text{ cm/s}$  can result from a reasonable pressure gradient of  $\frac{dP}{dx} \sim 4 \times 10^4 \text{ N/m}^3$ . If fluid reservoirs are located in the earth's crust [Bailey, 1990], then requirements for pressure gradients can even be much lower. Water flow can also occur due to the influence of gravitational forces. The pressure gradient would then be  $\sim 10^4 \text{ N/m}^3$ , and according to (11), would be appropriate for motion at several cm/s through sand. A complete assessment of the nature of water motion due to different geological causes is beyond the scope of this paper.

Finally, we note that the apparently efficient coupling between water motion in deep inner layers and the surface magnetic field suggests that ULF measurements can be used as a tool to study deep fluid motion within the earth crust. Such measurements would be most effective in the vicinity of surface magnetic field anomalies. In addition, magnetometer measurements at an array of stations can be used to detect and measure water flow, which would be registered as a corresponding shift of the local spatial inhomogeneity pattern.

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