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Signals from the Rocks

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Abstract**—** There is increasing evidence that earthquakes produce electromagnetic signals observable at the surface in the extremely low to very low freqency (ELF - VLF) range often in advance to the main event. These precursors are candidates for prediction purposes. Laboratory experiments confirm that material under load emits an electromagnetic signature, the detailed generation mechanisms however are not well understood yet.

Keywords**—**Earthquakes, ELF, EM signals from material under load, signal propagation in conductors.

I. INTRODUCTION

MEASUREMENTS over some decades point to a causal correlation between earthquakes (EQs) and recorded electromagnetic signals. Earthquakes have their mechanical origin in material rupture and stress relief. Electromagnetic (EM) radiation caused during and in advance to fracture of different materials is a phenomenon observed in laboratory for some decades [2]. But being a fact, that stressed or strained materials emit EM signals, explanations about the detailed generation mechanisms of the signals are not conclusive up to now, especially in complex geological situations [4]. Some possible mechanisms are discussed later. At first some remarks about EM signal propagation within the earth lithosphere as well as about sensoring and signal processing are appropriate.

II. SIGNAL PROPAGATION WITHIN THE EARTH

Electromagnetic wave propagation in conducting media is more or less attenuated with distance depending on the ratio $\frac{\sigma}{\omega\epsilon}$ with conductivity σ, dielectricity constant ϵ and $\omega = 2\pi f$.

Field amplitudes $\vec{E}$ and $\vec{H}$ are exponentially damped in space according to

$$\vec{E}(x) = \vec{E}_0 e^{-x/\delta_c} \quad (1)$$

$$\vec{H}(x) = \vec{H}_0 e^{-x/\delta_c} \quad (2)$$

For a good conductor this produces the well known skin effect. Electric conductivity in the earth varies over many powers of ten. A reasonable average conductivity value interval within the upper earth crust is $\sigma = 0.01 - 1\ S/m$ increasing within mantle and core. Assuming a mean relative dielectricity $\epsilon_r = 10$ the 'good conductor' condition [3] $\frac{\sigma}{\omega\epsilon} >> 1$ is fullfilled from lowest frequencies up to the MHz range. The typical penetration depth then is

$$\delta_c(\omega) = \sqrt{\frac{2}{\omega\mu\sigma}} \quad (3)$$

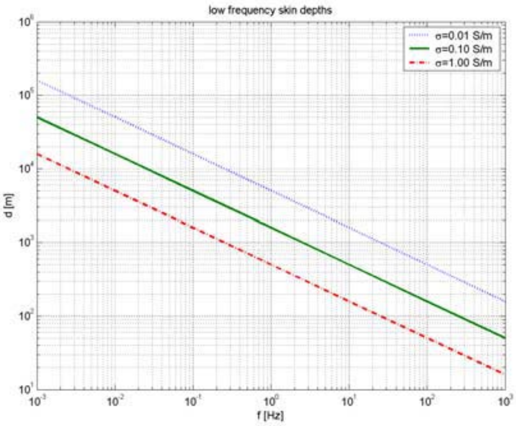

Fig. 1 Penetration depths $\delta_c(\omega = 2\pi f)$ for an interval of typical lithosphere conductivity values

Fig. 1 shows how penetration depth for the relevant conductivity range reduces for frequencies from 1 mHz to 1 kHz. So reasonable signal strengths from material rupture processes can penetrate to the surface only with extremely low frequencies (ELF = 3 - 30 Hz and below) at maximal distances of some tens of km. Once having reached the surface, these signals can propagate within the atmosphere ('bad' conductor) and can interact with the ionospheric plasma. But even within the earth-ionosphere cavity they are attenuated rather effectively - in contrast to VLF (very low frequency) signals above 1.5 kHz, as worldwide reception of sferics (signals from lightning) demonstrates impressively.

In a conducting medium (not ferromagnetic) the magnetic field lags in phase behind the electric field and bears most of the energy. For a good conductor the amplitude ratio is [3]

$$\frac{H}{E} = \sqrt{\frac{\sigma}{\omega\mu}} \quad (4)$$

or, with current density amplitude $j = \sigma E$ we have

$$H = \frac{1}{\sqrt{2}}\ \delta_c(\omega)\ j \quad (5)$$

Experiments [4], [5] show, that rocks under pressure emit radiation with frequencies up to the MHz range. High frequencies however are strongly attenuated within the lithosphere. If high frequency signals from earthquakes or precursors are observed [1] this only can mean, that rupture

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takes place very near or directly at the surface.

III. Sensors and Signal Processing

As pointed out in the preceding chapter magnetic field sensors near to the source (some tens of km) operating in the ELF and sub-ELF range are most appropriate to record signals from EQs and precursors. Only if ruptures directly penetrate to the surface, higher frequencies can be observed. Besides magnetometers (mostly flux gates) coils with a large number of turns (often up to a hundred thousand) on a high permability core with a large length to diameter ratio are used as broad band sensors for the magnetic field component of the ELF and sub-ELF radiation. An important point is a low ohmic to inductive impedance ratio $\frac{R}{\omega L}$ for good sensitivity at as low frequencies as possible. Output is fed to instrumentation amplifiers and after low pass filtering usually digitally processed.

Fig. 2 shows a waterfall display for the frequency range 0 - 10 Hz, i.e. a Fast Fourier power spectrum developing in time. The signal train at the bottom is the last one received and its FFT (diagram at the top) gives rise to the last active line in the waterfall.

To the right at the bottom a recurrence plot (RP) of the last recorded signal train is placed. In its most simple form (delay=0) for a signal $x(i)$ the picture matrix $RP(i, j)$ is colored according to the distance of $x(i)$ and $x(j)$ and so is sensitive to the degree of recurrence. In the example lighter colors point to large distances, dark colors to small distances (near recurrences). From this definition its obvious, that the matrix is symmetric $RP(i, j) = RP(j, i)$ and the diagonal $RP(i, i)$ is colored dark according to 0-distance. In Fig. 2 the main diagonal goes from the lower left to the upper right corner. Following the main diagonal is a way to go through the signal train in time. An RP is a valuable diagnostic tool for the qualitative assessment of dynamical time series and can give for example insight in deterministic vs. stochastic signal content [6], [7].

In parallel to the waterfall the time course of the logarithmic spectral average as well as standard deviation, skewness and kurtosis, i.e. the first, second and third moment of the signal value distribution are displayed. The log. standard deviation of the time signal value distribution is proportional to the log. average FFT power of the signal.

The narrow band traces with constant frequencies result from man made signals. The 3.33 Hz signal in this example is an alias from the 16.67 Hz German railway power lines signal folded around the 10 Hz limit (sample rate 20 SPS, low pass roll off starting above 16.67 Hz).

Candidates for earthquake precursors are burst plumes mostly below 1 Hz much like around 19:20 UT in the figure (not produced by an EQ). Systems like this are extremely sensitive to vibrations of the coil in the magnetic field of the earth as e.g. caused by traffic, but also by mechanical waves from earthquakes itself. They display as parallel streaks over part of or the whole frequency range. Of course electromagnetic pulses from switching etc. have similar appearances.

Fig. 3 shows an example for an ELF burst plume several hours in advance to the earthquake start (mechanical coil movement).
Around (7.8 +/- 0.5) Hz a faint broad signal band can be seen. This is the first Schumann resonance of the earth ionosphere cavity fed by worldwide lightning activity. Note, that an EM wave with $f = 7.5$ Hz has a wavelength exactly equal to the circumference of the earth, i.e. 40000 km.

Additional information about advanced signal processing methods used in this context can be found in [8], [9], [10].

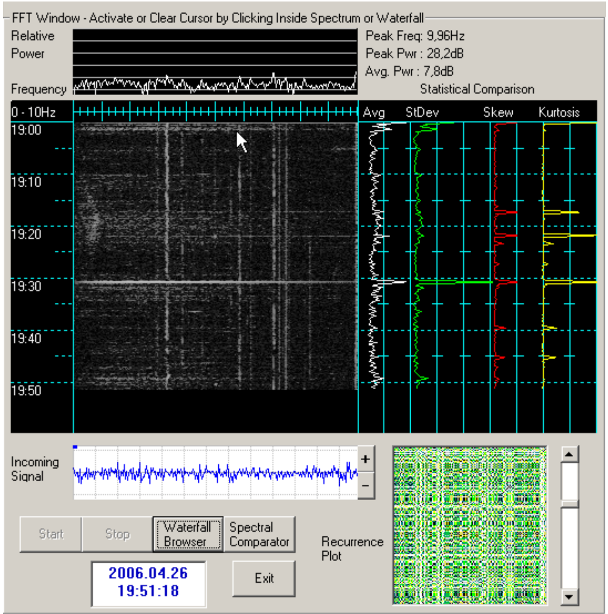

Fig. 2 Waterfall display for the 0 - 10 Hz range. Sample rate: 20 SPS; single signal train: 256 values, i.e $\Delta t = 256 * 20 = 12.8$ s

IV. Sources and Explanations

For using EM signals as earthquake predictors some understanding of the radiation generation processes is important. Quite different mechanisms have been proposed in the last years.
The first three mechanisms rely on EM generation by loading and cracking rocks. As mentioned earlier, on a laboratory scale it is an experimental fact, that materials (rocks, metals) under load emit EM signals. The last two proposed mechanisms use the fact that within a conductor moved in the earth magnetic field induction takes place (magnetohydrodynamic effect).
It may be assumed, that a combination of these mechanisms with situation dependent different weights gives a clue to the observed effects in the context of earthquakes.

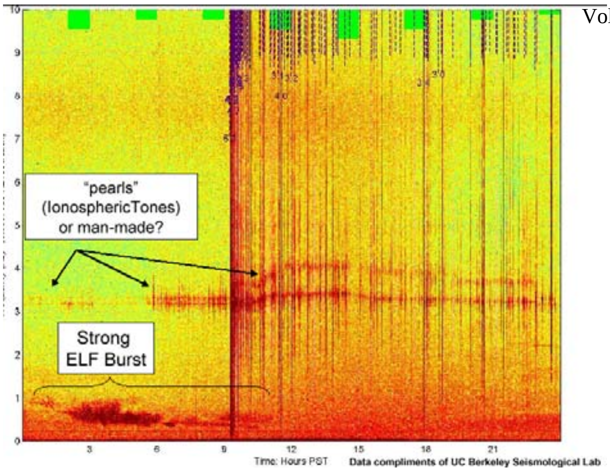

Fig. 3 0 - 10 Hz waterfall recorded near the Parkfield (California) EQ event Sept. 28, 2004, Mag. 6.0. (Image from: www.quakefinder.com, May 2006)

A. Lattice Rupture

Crushing crystalline rock (e.g. granite, gneiss) in fault zones is assumed to cause electrons to be ripped from the crystal lattice shells and falling back into stable states, they emit broadband electromagnetic radiation. A theoretical investigation of microfracturing electrification is given in [11].

B. Piezo Effects

Physically well known is the piezoelectric effect: Permanently-polarized material such as quartz (SiO2, constituent of many rocks) will produce an electric field when the material is deformed as a result of an imposed mechanical force. These materials are piezoelectric. In general certain types of rocks under deformation generate electric and magnetic fields and vice versa:

Straining a piezo-electric material $\leftrightarrow$ electric field

Straining a piezo-magnetic material $\leftrightarrow$ magnetic field

C. p-n Charge Carrier Currents

Experiments show that certain crystal oxydes become semiconductors under stress and/or elevated temperature. So prior to as well as during EQs rocks containing these materials set free moving electric charges (electrons, holes) producing electromagnetic fields. Additionally, if such charge carrier clouds reach the surface they cause electric fields that maybe responsible for discharges and earthquake lights [5].

D. Induction in Ionic Currents

Slowly moving ionic water is seeping to cracks opened up by the fracturing of rocks. This conducting fluid moving in the earth magnetic field generates an ULF EM field by induction.

E. Inductive Seismo-Electromagnetic Effect

Mechanical seismic waves moving through a conductive medium are supposed to generate electromagnetic transients by magnetohydrodynamic conversion.
Following [12] we explain this in some detail. As high frequencies are quickly damped out with distance the slow field approximation to Maxwells equations can be used. It neglects the second time derivatives for fields or potentials. So, with electric potential ϕ and magnetic vector potential $\vec{A}$ and omitting $\frac{\partial^2 \Phi}{\partial t^2}/c^2$ as well as $\frac{\partial^2 \vec{A}}{\partial t^2}/c^2$ we are left with the diffusion equations in a homogeneous conducting medium

$$\frac{1}{D}\frac{\partial \Phi}{\partial t} - \Delta\Phi = -\frac{1}{\sigma}\nabla \cdot \vec{j}_s \tag{6}$$

$$\frac{1}{D}\frac{\partial \vec{A}}{\partial t} - \Delta\vec{A} = \vec{j}_s \tag{7}$$

From the potentials we get the fields:

$$\vec{E} = -(\nabla\phi + \frac{\partial \vec{A}}{\partial t}) \tag{8}$$

$$\vec{B} = \nabla \times \vec{A} \tag{9}$$

If the conducting lithosphere material is moved with velocity $\vec{v}$ by seismic waves in the earth magnetic field $\vec{B}_0$ an electric field $\vec{E}_{ind}$ is generated by induction. Lorentz force equilibrium of the charge carriers yields $\vec{E}_{ind} + \vec{v} \times \vec{B}_0 = 0$ assuming $B << B_0$. For the source current density $\vec{j}_s$ we get with $\vec{B}_0 = \mu\vec{H}_0$

$$\vec{j}_s = \sigma\vec{E}_{ind} = -\frac{1}{D}\frac{\partial \vec{u}}{\partial t} \times \vec{H}_0 \tag{10}$$

where $\vec{u}(\vec{x}, t)$ is the displacement at location $\vec{x}$ and time t caused by the seismic wave.

$$D := \frac{1}{\mu\sigma} \tag{11}$$

is the electromagnetic diffusion coefficient.

In this framework local movement of conducting material acts as sources for electromagnetic fields diffusing like a drop of ink in water.
In [12] a model for the seismic perturbation displacement $\vec{u}(\vec{x}, t)$ is discussed and a markedly diffusive time elongation of electromagnetic field transients compared to the originating seismic pulse duration is found.

Given the diffusion coefficient D the mean propagation depth for a field component within time t is

$$\delta_d(t) = \sqrt{2Dt} = \sqrt{\frac{2t}{\mu\sigma}} \tag{12}$$

Note, that, consistently with equation 3:

$$\delta_d(t = \frac{1}{\omega} = \frac{T}{2\pi}) = \delta_c(\omega) \tag{13}$$

So, fig. 1 can again be used, this time to read off propagation depths within a given time $t = \frac{1}{2\pi f}$. For example within a second ($t = 1$s, i.e. $f = \frac{1}{2\pi t} = 0.159$ Hz) an EM field pulse is propagated $1.3 - 13$ km within conducting material with $\sigma = 1 - 0.01$ S/m.

V. Conclusion

Laboratory experiments clearly show, that material like rock under load emits characteristic electromagnetic radiation transients originating in damage zones as e.g. microcrack domains. This can explain recordings of EM signals in advance to and during earthquakes, even if the detailed generation mechanisms are not yet completely understood. Induction in conducting material moved by seismic waves in the earth magnetic field is a further promising process for EM field generation. A superposition of several mechanisms might be necessary to explain the manifold of observed effects. As high frequency signal components are strongly attenuated within the lithosphere and the magnetic field prevails, magnetic sensors with broad band receiving capability in the extremely low frequency (ELF) range near to the source have the biggest chance to record earthquake precursor signals that may be used as predictors. In case of VLF or VHF signal recordings it is very probable that the damage zone reached the surface. Advanced signal processing methods are necessary to filter information about earthquakes out of manmade and natural noise.

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