GROUND-ATMOSPHERE-IONOSPHERE INTERACTIONS RELATED TO EARTHQUAKES: HOW CAN EARTHSCOPE HELP?

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Recent EARTHSCOPE activities have been concerned with monitoring earthquake-related parameters from using surface stress (INSAR) to deep borehole stress measurements (SAFOD). In this paper we draw attention to other parameters possibly related to earthquakes (EQ) that can be monitored from the ground and from space. Specifically, we propose to initiate a similar activity under TERRASCOPE or under some other future mission concept.

Recent field studies and simultaneous satellite observations add confidence to reported observations of electromagnetic (EM) emissions before large earthquakes. There is likewise mounting evidence that, prior to seismic activity, electric fields are transmitted from the ground into the atmosphere, that thermal anomalies may become observable, that ions may be emitted from the ground, that the atmospheric conductivity is affected, that the ground potential may change locally or regionally, etc. Some authors have considered the possibility of an inverse connection - from the atmosphere to the ground, causing seismic activity. Increased lightning activity, due to growing seismic activity, and the large currents thus induced may have an effect on the fracturing or microfracturing of rocks, focusing the EQ energy release [Pulinets, 2000]. Several ongoing international satellite missions, COMPASS (Russia, Poland, 2001), DEMETER (France, Japan, Russia, 2002) and VARIANT (European Space Agency, Ukraine, 2001), are aimed at retrieving ionospheric plasma anomalies that may be related to EQ activity (M>5).

A recent experimental study [Freund, 2000] has indicated a direct connection between stress applied to rocks and the generation of charge carriers, causing electric currents and affecting surface potentials. These new results may intensify the interest in future similar studies.

1. Observable Changes on the Surface of the Solid Earth

1.1. Positive Holes

Electrical phenomena preceding large earthquakes have been mentioned or described in the literature for centuries. What has been lacking, however, was a fundamental understanding of the nature of the electric charges in rocks and how they may be generated in the crust.

The keyword is “water” – not liquid water that fills the pores in rocks but small amounts of H_2O that dissolve in minerals, even those that are nominally anhydrous, when they crystallize in H_2O-laden magmas or recrystallize in H_2O-laden metamorphic environments. It is widely (but wrongly) thought that the dissolution of H_2O ends with the formation of hydroxyl, OH^-. Instead, it has been noted early that hydroxyl pairs adjacent to cation vacancies undergo an electron transfer inside the mineral matrix by which two oxygens become oxidized from their usual 2– to the –1 oxidation state, while two protons, H^+, become reduced to molecular H_2 [*Martens et al*., 1976]. The O^- thus generated undergo spin pairing to form peroxy bonds or peroxy links, $O_3Si/^{OO}\backslash SiO_3$.

From the viewpoint of semiconductor physics, an O^- in an O^{2-} matrix is a defect electron or “positive hole”, i.e. a charge carrier that resides in and travels via the O 2p-dominated valence band. A peroxy represents a positive hole pair, PHP, electrically inactive and dormant. When the peroxy bond breaks, positive holes are released. These charge carriers are highly mobile and turn the mineral or rock momentarily into a p-type semiconductor [*King and Freund*, 1984].

After it was observed that stress, leading to dislocation movement, and even acoustic waves are capable of activating PHPs, the idea arose that, when rocks are subjected to ever-increasing stress in an EQ-prone region, they will undergo plastic deformation and massive microfracturing. Each dislocation that moves and each microcrack that opens and closes explosively, emitting an acoustic wavelet, would activate positive holes. The expected large number of charge carriers would lead to large currents – with predictable consequences amenable to remote sensing.

1.2 Changes in Ground Potential

Because the positive holes turn any rock momentarily into a pure p-type semiconductor [King and Freund, 1984], the charge carriers will propagate outward from their source volume. When they intersect the surface of the Earth, the ground potential is expected to become highly positive [*Freund and Liu*, 2000]. Two questions arise: (1). What would be the consequences of a regional ground potential that trends toward highly positive values? (2). How can the effects of an anomalously high positive ground potential be measured, either on the ground or from space?

1.3 Thermal Anomalies on the Ground

Using remote sensing and data from NOAA weather satellites 100-500 km patches of thermal anomalies have been identified in areas where strong earthquakes were to occur [Tronin, 1999]. It is possible that anomalies arise from the migration of positive holes to the Earth's surface. Using multi-spectral near-IR to mid-IR remote sensing techniques and data from Earth Observation System satellites (NASA/MODIS) we currently analyze the two large earthquakes that occurred in Jan. 2001 in El Salvador and NW India. Pending laboratory confirmation [Geeing et al. 1999], a correlation seems to exist between the EQ magnitude and the luminance temperature.

2.Atmopsheric Effects

2.1 Atmospheric Electricity

If ULF EM waves impinge on electrically charged clouds, their transverse components should be attenuated exponentially because of the so-called "anomalous skin effect". Electric currents induced by these waves could then be discharged by intercloud, cloud-to-cloud, cloud-to-ground lightning. When the attendant field leads to a diffuse discharge between the cloud layer and the upper atmosphere phenomena like "blue jets", "sprites", and upward "super bolts" may occur.

The normal ground potential varies between 0.1- 100V/m, but, in the case of thunderstorms or in areas of an impending earthquake, it can rise to values up to 1000V/m. Such high ground fields influence the conductivity of the lower atmosphere. Gas emanation including radon release from the ground affect the aerosol content and causes the conductivity to increase up to fivefold above the background level [Alperovich and Fedorov, 1999]. As a result, prior to an EQ, the vertical profiles of humidity, pressure and temperature are changed; similar to the changes brought about by thunderstorms. Intense electrical field nears the ground that is normally seen as a result of meteorological events can generate clouds and ground-hugging fogs. Cloud-to-ground lightning strikes occur before the peak of the increased atmospheric conductivity in the air. Changes in the lower atmosphere-ground conductivity are related to the migration of EM carriers from lower atmosphere to the ionosphere (F–region).

2.2 Atmospheric Aerosol Content Variations

Aerosol content and atmospheric instability parameters also change under the influence of ground charges. It has been proposed that a thin aerosol layer appear due to light ions emitted from the ground. Fe ions and other aerosols possibly play a role in transmitting the field from the ground to the upper atmosphere and to ionosphere. Several studies propose different time scales for these processes, ranging from a weeks to a few days and hours before the main shock.

3. Ionospheric Changes Related to Strong Earthquakes

3.1 Lithosphere-Ionosphere Interactions

Anomalous VLF/ELF emissions from the ground and anomalous ionosphere reactions over seismic zones have demonstrated that, prior to strong EQ activity, the EM field and the plasma in the ionosphere and magnetosphere are affected. The ionospheric disturbances several days before the seismic event are reportedly identified in an anomalous absorption of long wavelength radio waves in the Earth-ionosphere wave guide, in variations of the electron density and the total electron content (TEC), both positive and negative, and in EM waves and electric fields measured at magnetospheric or ionospheric levels [Molchanov and Haykawa, 1995].

Different ELF/VLF EM emissions are divided into two groups: precursor emissions (a few hours before an EQ in the frequency range 0.01-1000Hz) and emissions after an EQ (or after a volcanic eruption), the latter being attributed to acoustic-gravity waves [Parrot, 1995]. Though the EM precursors cover a wide frequency range, they seem to have three common features: emissions appear 5-10 days before an EQ and few days afterwards; they are mostly related to the tectonic type of EQ; and they are only observable within a radius of 500 km of the focus.

4. Main Areas of Study in Ground-Atmosphere-Ionosphere Interactions Related to Strong Earthquakes and Possible Connection to Ongoing Programs

Ground perturbation – collecting all seismic and non-seismic data for ground-source models. Disturbances as evidenced by changes in strain, in deformation, in water levels, in the gas content, in the electromagnetic field, and their respective temporal and spatial distributions. Looking for correlation between EM and acoustic emission using very precise downhole observations. These emissions are considered to be the manifestation of micro-processes connected to micro fracturing. Mid-IR luminescence from the ground prior to strong earthquakes from data provided by GEOS and NASA EOS satellites. Most closely relevant activities are SAFOD, USArray, and GESS.

Upper atmosphere. Using VLF transmitter signals, fluctuations in the plasma density over the wave path may be correlated to EQ activity by measuring the shift in terminator time (tt). The tt is defined as the time when the diurnal phase variations exhibit a minimum around sunrise and sunset. Using this approach a correlation has been found between VLF emission and planetary waves. This has been used to postulate how near-to-ground electric perturbations might reach the upper atmosphere through slow atmospheric gravity waves, through changes in the ground potential or in lightning activity [Molchanov and Hayakawa, 1998;Clilverd et al., 1999]. Most relevant projects are GESS or future ground observation systems.

Plasma density fluctuations and wave emission. Sub-ionospheric signals are reflected at the lower D region of the ionosphere, and the question arises whether seismic or preseismic activity may affect the upper ionosphere? Latest satellite data from 500-700 km (low geomagnetic activity, the main ionospheric maximum and daytime observations), suggest a correlation between seismic activity and a variation in the electron density [Hayakawa, 2000]. There is no equivalent data as part of EARTHSCOPE.

GPS monitoring of the ionosphere. Using the 24 GPS satellites with local receiver networks it is possible to continuously monitor the ionosphere. The ionosphere acts as dispersive medium for the GPS signals, while the troposphere is non-dispersive. After removing from the received signal tropospheric effects on the carrier phase and correcting for the pseudo-range, the group delay of the propagating signal along the travel path becomes a measure of the Total electron Content (TEC). Recent studies have shown that anomalies of the TEC values correlate with strong EQs to 1-4 days before the main event [Liu at all, 2000]. Most relevant project is UNAVCO.

Conclusion

Several parameters, measurable from the ground or from space, reportedly correlate with strong EQ activity (M>5). We propose that these parameters be included into EARTHSCOPE. These parameters are apparently connected to and caused by the progressive build-up of high tectonic stress. They can be time-correlated by monitoring the ground, the atmosphere, and the ionosphere.

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