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Seismic electric signals in seismic prone areas*

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Abstract The Varotsos-Alexopoulos-Nomicos (VAN) method of short-term earthquake prediction was introduced in the 1980s. The VAN method enables estimation of the epicenter, magnitude and occurrence time of an impending earthquake by observing transient changes of the electric field of the Earth termed seismic electric signals (SES). Here, we present a few examples of SES observed in various earthquake prone areas worldwide.

Keywords: seismic electric signals; VAN method; earthquake prediction; EMSEV-Bishkek RS-RAS cooperation

1 Introduction

Varotsos-Alexopoulos-Nomicos (VAN) method indicates major earthquakes (EQs) are preceded by transient changes of the Earth's electric field termed seismic electric signals (SES) (Varotsos and Alexopoulos, 1984a, b).

The motivation of the present paper is as follows: In general, a short term earthquake prediction method is of course more useful if it can be applied to seismic prone areas of different geological and tectonic environment. Thus, here we recapitulate various seismic areas at which SES experimentation has long been performed and include also those areas at which relevant experiments have recently started.

In Section 2, discrimination of SES from noise and the properties of SES useful for EQ prediction are summarized.

In Sections 3, 4, 5, and 6, we focus on SES that have been recorded in Greece, SES and SES-like signals observed in Japan, China and Mexico, respectively.

Finally in Section 7, we present possible SES recorded in Kyrgyzstan during the recent collaboration between the IAGA-IASPEI-IAVCEI Inter Association Working Group on Electromagnetic Studies of Earthquakes and Volcanoes (EMSEV http://www.emsev-iugg.org/emsev/) and the Bishkek Research Station of the Russian Academy of Sciences (RS-RAS http://www.gdirc.ru/en/) in Kyrgyzstan.

2 Background on seismic electric signals

2.1 Distinction of SES from noise

The simultaneous use of several long and short measuring dipoles with different directions and lengths was found necessary and effective for distinction of SES from noise. The fact that SES are emitted in the preparation volume of the future EQ usually at a distance of the order of 100 km away from the field station is exploited against to other sources such as magneto-telluric (MT), lightning or man-made artificial noises. Varotsos and Lazaridou (1991) showed that for SES the values of ratio $\Delta V/L$ for parallel measuring dipoles (ΔV is potential difference and L is length) are approximately the same. In

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the case of nearby man-made "artificial" noise and lightning, the $\Delta V/L$ values significantly differ even for parallel dipoles.

When installing a new station one has to identify the nearby areas prone to lightning or areas heavily industrialized and deploy long dipoles towards them.

MT variations are distinguished as they are simultaneously recorded at all stations (they are imposed by the ionospheric sources), while SES are usually recorded at a single station.

2.2 The physical properties of SES and their application to short-term earthquake prediction

2.2.1 SES properties useful to EQ prediction

1) Interrelation between SES amplitude and EQ magnitude.

Varotsos and Alexopoulos (1984a) found that, for SES recorded at a given station and originating from a given seismic area, the SES amplitude $\Delta V/L$ (for a dipole with a given orientation) scales with the EQ magnitude M according to the relation

$$\log \frac{\Delta V}{L} = (0.3 \text{ to } 0.4)\, M + b. \qquad (1)$$

The physical explanation of equation (1) is discussed in detail in Varotsos (2005) which reveals the fractal character of the SES emitting source (e.g., see Surkov et al., 2002). The intercept b varies when changing the seismic area-dipole pair.

2) The ratio of the SES components.

The ratio of the amplitudes in EW to NS directions, i.e. $(\Delta V/L)_{\mathrm{EW}}/(\Delta V/L)_{\mathrm{NS}}$, remains the same for EQs from the same seismic area with the same generation mechanism.

3) Sites appropriate for SES collection

SES cannot be observed at all points of the Earth's surface but only at certain sites called "*sensitive sites*". Theoretically sensitive sites can be either very close to the epicenter or near the outcrop of a conductive channel electrically coupled to the hypocenter (Varotsos et al., 1998; Sarlis et al., 1999). At such sites near the outcrop, numerical and analytical solutions of Maxwell equations show that the direction of the SES electric field is interrelated (Varotsos, 2005) with the position of the emitting electric dipole source (e.g., its distance from the outcrop), thus pointing to the importance of using the ratio of the two (horizontal) SES components in the determination of the future epicentral area, as it will be further discussed below.

A map showing all the seismic areas that emit SES detectable at a given station is called *selectivity map* of this station.

4) Magnetic field variations.

SES are accompanied (Varotsos et al., 2001a; Sarlis and Varotsos, 2002; Varotsos et al., 2003c) by detectable magnetic field variations when the magnitude of the impending earthquake is around 6.5 or larger. The shape of these magnetic field variations is similar to that of the electric field variations, but of course not exactly the same or simultaneous since diffusion equations govern the SES transmission (for more details see Varotsos, 2005; Varotsos et al., 2011b).

5) Determination of EQ epicenter and magnitude

SES is usually recorded at a single VAN station. We can rely on the selectivity map of that station and use also the ratio $(\Delta V/L)_{\mathrm{EW}}/(\Delta V/L)_{\mathrm{NS}}$ to find the EQ preparation zone that emitted the SES (Varotsos, 2005; Varotsos et al., 2011b), as mentioned in point (3) above. The expected magnitude is then estimated using equation (1).

6) The *lead time* of SES.

Single SES has a lead time that lies between 7 hours and 11 days (Varotsos and Lazaridou, 1991). On the other hand, the SES activities (when many SES appear in short time, they are called SES activity, Varotsos et al., 1993) have significantly larger lead times. Varotsos et al., (1996) suggested that the impending EQ occurs roughly during the fourth week after the SES recording or later. The time window of the impending EQ can be narrowed by employing natural time analysis (e.g. Varotsos et al 2011a, b, c; 2012; 2013, see also Sarlis et al., 2015 and references therein).

2.2.2 Time and frequency characteristics of SES

SES usually have a duration up to a few hours. During the last two decades, however, SES activities of appreciably longer duration, i.e., from several hours up to approximately one week or even more have been recorded in Greece (Figure 1) and Japan (e.g., see Uyeda et al., 2009). The duration of the SES pulses, in SES activities, varies in the range of a few to hundreds of seconds with an average duration around 15 s (e.g., see Varotsos et al., 2003a).

3 Examples of SES in Greece

The VAN stations currently operating in Greece are shown in Figure 1a. For Greece since 1995, after the recommendation of the Council of Europe, prediction is issued only when the expected magnitude is larger than (or equal to) 6. This information is also submitted to an international journal before the EQ occurrence.

What happened just after the recording and the

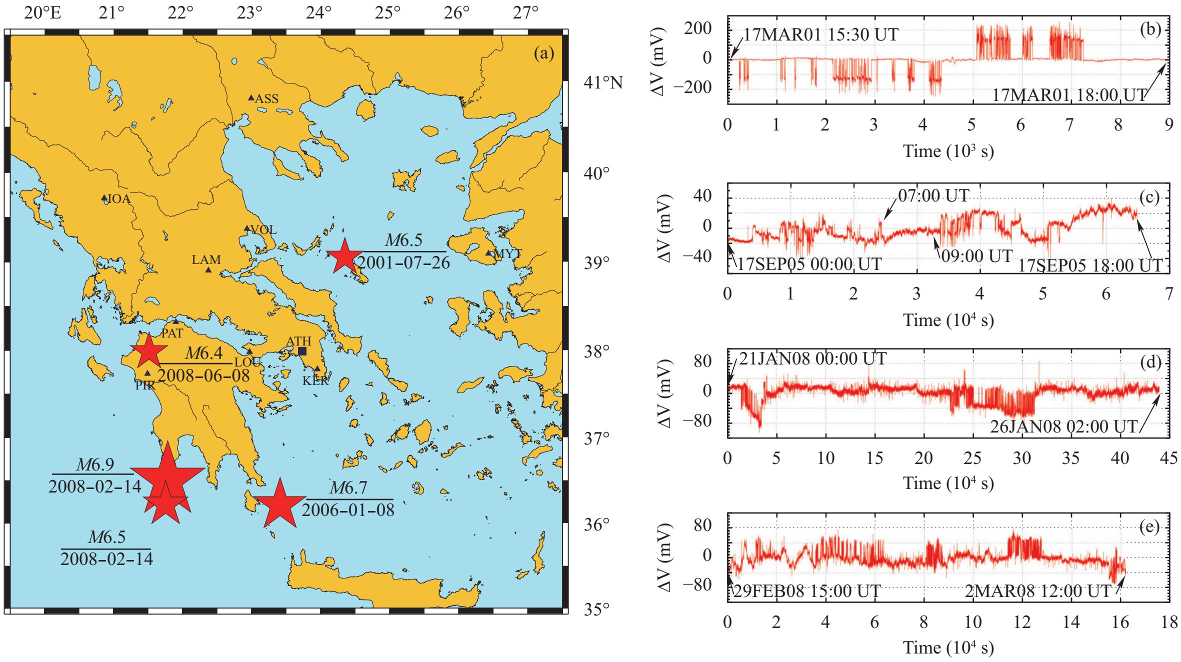

Figure 1 Map showing the VAN stations (triangles) operating in Greece together with epicenters of the EQs that followed the SES activities shown on the right. The short duration SES activity (b) was recorded at VOL in 2001, while the three long duration SES activities of (c), (d) and (e) at PIR in 2005 (c) and in 2008 (d, e)

subsequent analysis of the four SES activities depicted in Figures 1b, c, d, e is as follows. A report of SES activity in Figure 1b that preceded the M_W 6.5 (USGS) EQ on 26 July 2001 in the central Aegean Sea was submitted for publication on 25 March 2001 (see Varotsos et al., 2001b), i.e., almost one week after its recording at the Volos (VOL) station. Report of SES activity of Figure 1 c was submitted for publication on 22 October 2005 (Varotsos, 2006). It was followed by the M_W 6.7 (USGS) EQ on 8 January 2006 close to Kythira Island. Finally, the SES activities shown in Figures 1d, e, preceded the three strong M_W ≥6.4 (USGS) EQs (cf. two mainshocks) during 2008 in Peloponese and they were both publicized before the EQ occurrences (Sarlis et al., 2008; Uyeda and Kamogawa, 2008, 2010).

4 Examples of SES in Japan

During the period 1996–2000, an extensive network of VAN stations was operated in Japan, see Figure 2. This has led to various observations of geoelectric disturbances similar to SES (Uyeda et al., 2000; Orihara et al., 2012) and SES activities (Uyeda et al., 2002, 2009; Orihara et al., 2009). The observed characteristics of the preseismic electric signals were closely similar to SES and SES activities in Greece, but the denser network allowed (Uyeda et al., 2000) the simultaneous observation of SES in more than one station, see Figure 3. This observation is important because it excludes the possibility of local noise.

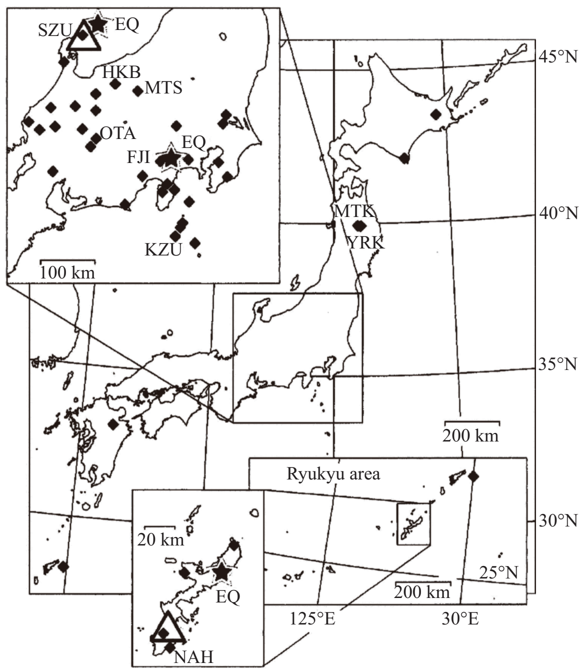

Figure 2 Distribution of stage 2 (1996–2000) geoelectric potential monitoring stations (filled diamonds). Stage 1 (1987–1995) stations (NAH and SZU) are also shown by open triangles. Some EQs (stars) and related stations are depicted in insets as needed. Taken from Uyeda et al. (2000)

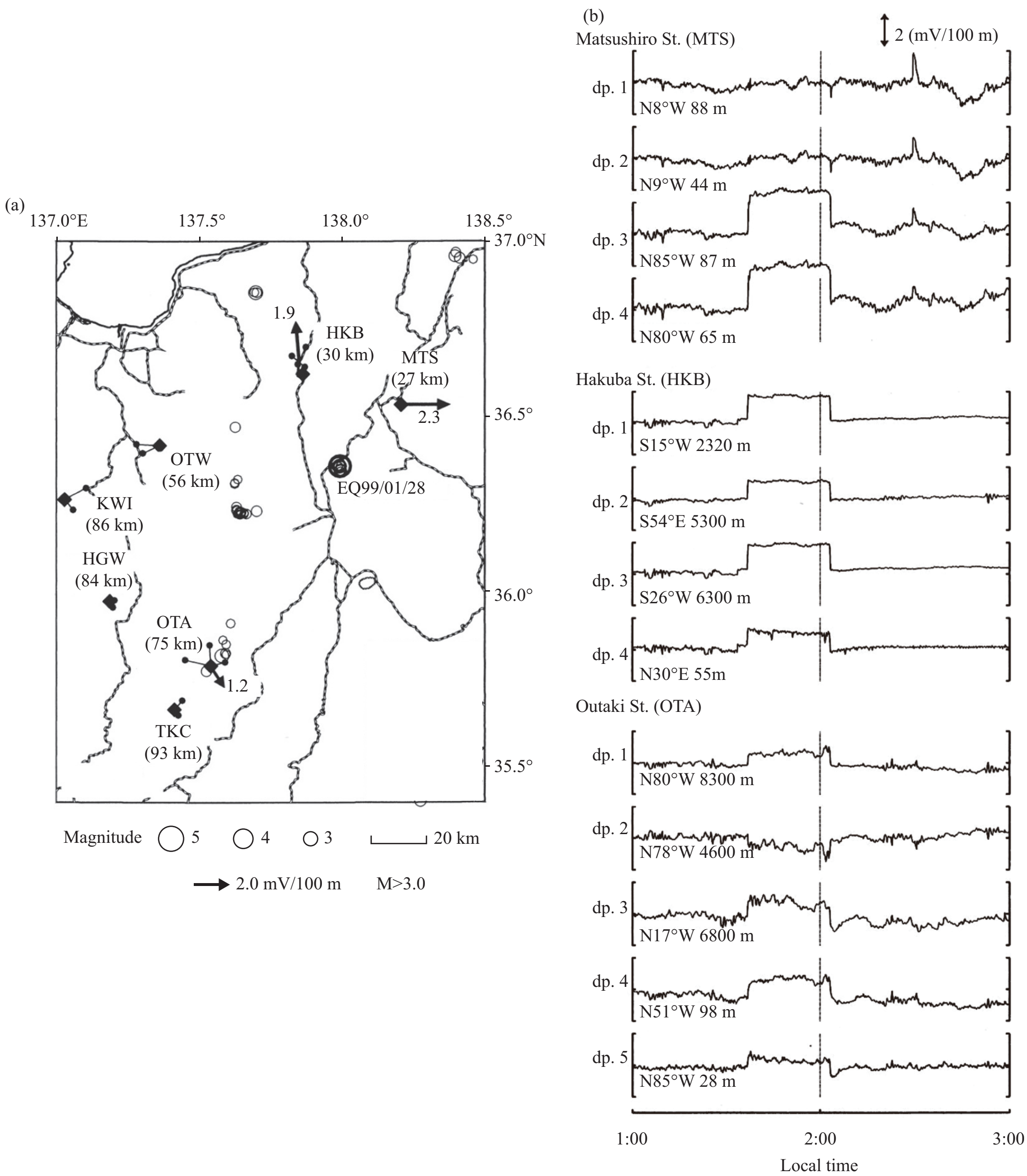

Figure 3 (a) Distribution of stations and seismicity (1 October 1998–31 May 1999) in central Japan. MTS, HKB, and OTA simultaneously recorded the change on 17 January 1999, whereas other stations did not. The arrow and the number attached to each station are the change vector and epicentral distance. (b) The change simultaneously observed at the three stations on 17 January 1999. The acronym dp stands for dipole. Taken from Uyeda et al (2000)

5 Examples of SES in China

Pre-seismic electric field variations were observed (Zlotnicki et al., 2001) in China before the 21 July 1995, *M* 5.7, Yongdeng EQ. More specifically, Zlotnicki et al. (2001) revealed a clear systematic variation of the frequency of the maximal spectral energy concentration on one of four measuring electric dipoles deployed at a site approximately 100 km North of the EQ epicenter that had started about one month before the EQ occurrence.

In what remains, we restrict ourselves to the most recent observations related to the devastating Sichuan $M_S 8$ EQ that occurred at 14:28 local time on 12 May 2008. This EQ is also known as the Wenchuan EQ (see Figure 4). It was the deadliest EQ since Tangshan EQ in 1976.

Huang (2011) reported that reliable geoelectrical precursory signals were observed before the Wenchuan EQ by stating: “The preliminary analysis of the extremely low frequency data during January-June, 2008 at the Hanwang station (which, at about 300 km distance, is the nearest station to the epicenter of the Wenchuan EQ) showed that the power spectra of electric and magnetic fields during

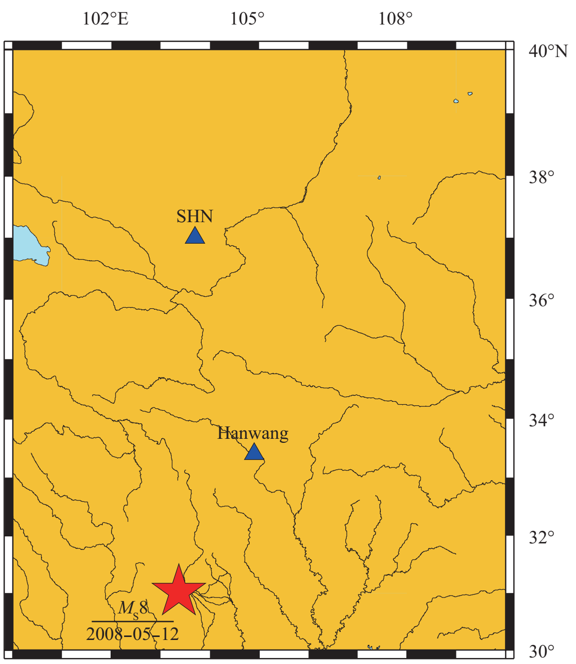

Figure 4 Distribution of the epicenter of the M_S8 Wenchuan EQ (red star) and the location of the measuring stations (blue triangles) mentioned in the text. The Chengdu station lies very close to the epicenter (35 km).

May 1–12, 2008 enhanced significantly with respect to the normal background level (Gao et al., 2010) ...”

In addition, Fan et al. (2010) reported that within half a year before the Wenchuan EQ some stations recorded significant geoelectric/geomagnetic field changes. For example, in the China-France cooperation Songshan station (SHN) lying 683 km from the epicenter (see Figure 4), Fan et al. (2010) reported that during about 50 days (i.e., from 21 March to 9 May 2008) before the Wenchuan EQ, large geoelectric field changes occurred similar to SES observed by VAN method. They also noticed that for low frequencies and in particular for $T < 3$ h the changes of the Power Spectrum Density (PSD) of geolectric field with time was increased by 1–3 orders of magnitude compared to that before 16 March. Notably from 10 May (two days before the Wenchuan EQ) PSD recovered the level before 16 March 2008. Furthermore, at Chengdu station which was the closest to the epicenter (≈ 35 km) and during the four-month period from 16 January to the Wenchuan EQ the PSD of all frequencies (1/2h down to 1/5d) displayed increasing and decreasing changes, but after the mainshock PSD became stable. These long-term signals appearing in a large frequency band was probably due to the proximity of the station to the EQ focus. Almost one month before the EQ, i.e., since almost 10 April 2008, especially the $T < 3$ h PSD increased significantly compared to that in the previous 40 days and the maximum increase was 3 orders of magnitude.

6 Examples of SES in Mexico

SES-like geoelectric disturbances have been observed before the M7.4 Guerrero-Oaxaca earthquake (Ramírez-Rojas et al., 2008) on 14 September 1995, as well as prior to the M6.6 Pacific coast of Mexico EQ on 24 October 1993 (Ramírez-Rojas et al., 2011), see Fig. 5. They presented geoelectrical records preceding both earthquakes that exhibit the dichotomous behaviour observed for SES activities. Moreover, their analysis leads to the same criticality characteristics as those of the SES activities recorded in Greece (Varotsos et al., 2002a, b, 2003b, 2008, 2009).

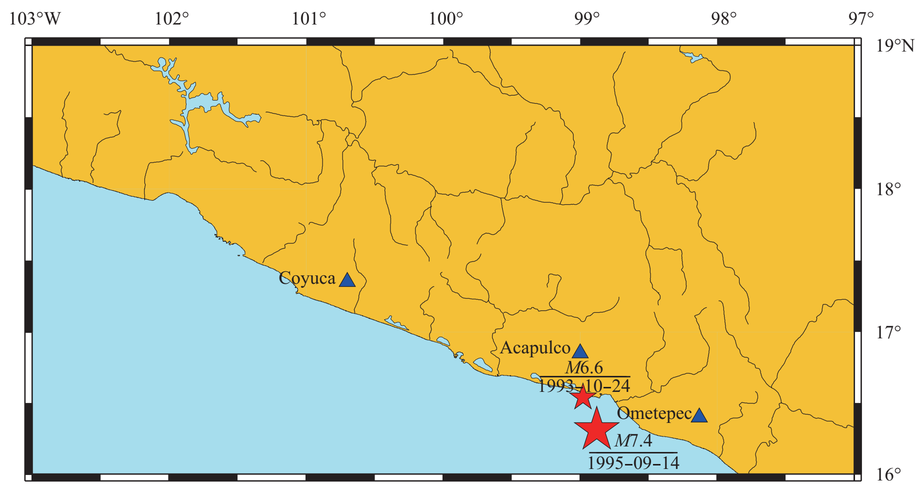

Figure 5 Distribution of the epicenters (red stars) of the EQs mentioned in Mexico in the text. The locations of the measuring stations that exhibited (Ramírez-Rojas et al., 2008) geoelectric precursors prior to the 1995 Guerrero-Oaxaca EQ are shown by blue triangles.

7 Possible SES in Kyrgyzstan

Since November 2011, EMSEV together with the Bishkek RS-RAS has operated two autonomous geoelectric stations in Kyrgyzstan. They are termed Shavai (SHA) and Issyk-Ata (ISA) and are located around 40 km and 24 km East and West of the Bishkek RS-RAS, see Figure 6. The preliminary analysis of the data collected so far has indicated the existence of a dichotomous geoelectric variation at SHA'an excerpt of which is shown in Figure 7, that started on 5 December 2011 and ended on 9 December 2011. Almost two months later, i.e., on 5 February 2012, a m_b5.2 EQ took place at around 130 km south-southeast from SHA. Another SES-like disturbance has been identified at ISA, see Figure 8, on 1 January 2015, i .e., 22 days before an *M*4.9 EQ that occurred 30 km south from ISA.

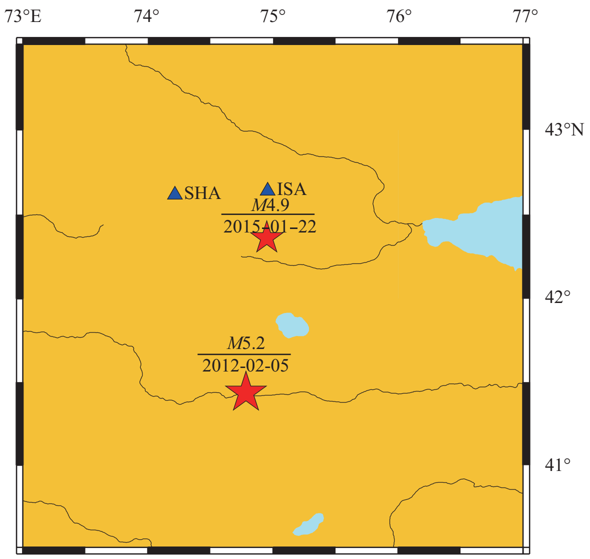

Figure 6 Map of Kyrgyzstan depicting the epicenters (red stars) of the EQs and the locations of the measuring stations (blue triangles) mentioned in the text.

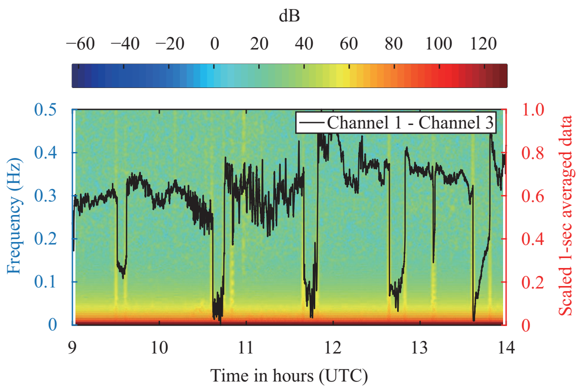

Figure 7 Geoelectric disturbance recorded at SHA on 5 December 2011 (as it results from the difference of the original records of channel 1 from channel 3 and after 1s averaging, right scale) superimposed over the corresponding spectrogram (frequency left scale, PSD color bar) estimated when using a Hanning window of 256 data points sliding by 1 data point each second.

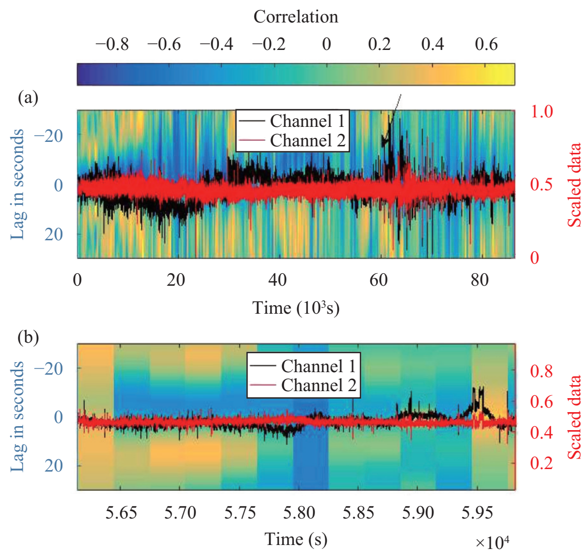

Figure 8 The geoelectric disturbance recorded at ISA on 1 January 2015 at channels 1 and 2 (original records, black and red, respectively, right scale) superimposed over the corresponding cross-correlation (time lag left scale, the color bar indicates the normalized cross-correlation value) estimated when using 300s non-overlapping windows. Panel (a) corresponds to the whole day, whereas panel (b) to an excerpt indicated by the arrow in (a). Note that this arrow points to the portion of the time-series where maximal cross-correlation is observed around 0-time lag, thus indicating a similar behaviour in both channels as expected for SES.

8 Conclusions

In summary, according to the VAN method-operating in Greece since 1980s-major EQs are preceded by a series of transient changes of the Earth's electric and magnetic fields that are termed Seismic Electric Signals (SES) activities. Criteria have been suggested that allow the distinction of SES from noise. Here, we focused on SES and SES activities that have been recorded in Greece, Japan, China and Mexico as well as possible SES registered in Kyrgyzstan.

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