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Electrical precursors of earthquakes in Aegean Sea during the last decade (1997–2007)

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Abstract. The purpose of this study is to investigate some properties of the Seismic Electric Signals (SES) that preceded large earthquakes which occurred in the Aegean Sea (24–27)° E, (37–40)° N, during the last decade. Our main interest is focused on the important parameter of the lead time Δt, which is the time difference between the occurrence of the earthquake and the detection of the associated SES signal. Two groups of lead times, a short (i.e. $\Delta t\sim$ some weeks) and a long one ($\Delta t\sim$ some months) have been observed. We examine whether this difference could be related to the regional tectonics. Furthermore the property of SES selectivity is discussed.

1 Introduction

Since early eighties, variations in the electrotelluric field, the so called Seismic Electric Signals (SES), have been continuously monitoring by VAN stations at various sites in continental Greece and appeared to correlate with the occurrence of large earthquakes (Varotsos and Alexopoulos, 1984a, b, 1987).

The SES signals exhibit some interesting properties (i.e. selectivity) and features (e.g. lead time, duration) that will be discussed below. Thus, a VAN station can be sensitive to some specific seismic areas at long distances while it can sometimes remain inactive to some others at nearer distances. This property of the SES signal, called selectivity effect, plays a crucial role in the VAN predictions (Varotsos and Lazaridou, 1991; Varotsos et al., 1993).

Based on collected pairs of SES and corresponding earthquakes, as referred in their issued predictions (Varotsos et al., 1988), the VAN group constructed selectivity maps for those stations where significant number of data were available (Uyeda, 1996; Varotsos et al., 1993). These maps are empirical and they are subjected to continuous improvement through time.

An important feature of the SES is the lead time, Δt, which is the time difference between the earthquake occurrence and the SES detection. Cross correlation charts for a large number of SES and earthquakes of significant size showed that the lead time, Δt, can vary from several hours to some months.

The SES can appear as single signal with duration of some minutes or as electrical activity which is a sequence of electrical pulses within a short time (e.g. some hours). Very short lead time (e.g. $\Delta t\sim 7$ h) seems to be associated with signals of single type while SES electrical activities have lead times covering a large time span (e.g. weeks to months).

Geotectonically the greek region is divided to a western and an eastern part by Hellenides, the long mountain chain extending in a NNW-SSE direction. This tectonic ridge seems to also act as barrier for the detection of the SES. Up to now all VAN stations east of Hellenides, are sensitive only to earthquakes occurring in eastern Greece, mainly the Aegean sea, while all the stations situated west of this mountain chain selectively detect earthquakes from western Greece.

The Aegean Sea (Fig. 1) is one of the most seismically active and rapidly deforming regions in Europe. Its geodynamic evolution is controlled by three factors: the subduction of the African plate under Eurasian in the south, resulting to a northward dipping Benioff zone and a volcanic arc (McKenzie, 1972; Le Pichon and Angelier, 1981; Walcott and White, 1998), the collision between NW Greece-Albania coasts and Apulia-Adriatic microplate in the west and the westward motion of the Turkey relative to Europe which forms the right-lateral strike slip North Anatolian Fault, NAF, (McKenzie, 1972; Taymaz et al., 1991; Armijo et al., 1999; Koukouvelas and Aydin, 2002).

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Table 1. All PDE reported earthquakes with Mw (HRV)≥5 in the area (24–27)° E , (37–40)° N, their CMT solutions and characteristics of corresponding SES (time, station (STN) of detection and lead time, Δt), for the period 1 January 1997 to 1 December 2007.

n	EQ yy mm dd	H	MIN	S	LAT	LONG	depth	Mw (HRV)	CMT	COMMENT	SES yy mm dd	STN	Δt (days)
1	97 11 14	21	38	51.60	38.86	25.80	17	5.9	strike-slip	PSARA	97 10 18	MYT	27
2	01 06 10	13	11	04.23	38.58	25.61	33	5.6	strike-slip	PSARA	01 04 25	MYT	45
3	01 07 26	0	21	36.92	39.06	24.24	10	6.5	strike-slip	SKYROS	01 03 17	VOL	161
4	01 07 30	15	24	56.74	39.09	24.04	10	5.0	normal	aftershock			
5	03 04 10	0	40	15.11	38.22	26.96	10	5.7	strike-slip	TURKEY			
6	03 04 17	22	34	24.59	38.16	27.00	10	5.2	strike-slip	TURKEY			
7	05 10 17	5	45	16.00	38.13	26.50	8	5.5	strike-slip	SAMOS	05 03 21	MYT	210
8	05 10 17	9	46	53.90	38.20	26.50	10	5.8	strike-slip	SAMOS	05 03 21	MYT	210
9	05 10 17	9	55	30.00	38.14	26.61	20	5.2	strike-normal	aftershock			
10	05 10 20	21	40	04.09	38.15	26.75	10	5.9	strike-slip	SAMOS	05 03 23	MYT	212
11	07 11 09	1	43	03.96	38.82	25.74	2	5.1*	not available	PSARA	07 09 17	MYT	53

* Mw adopted from EMSC since Mw Harvard was not available for this event

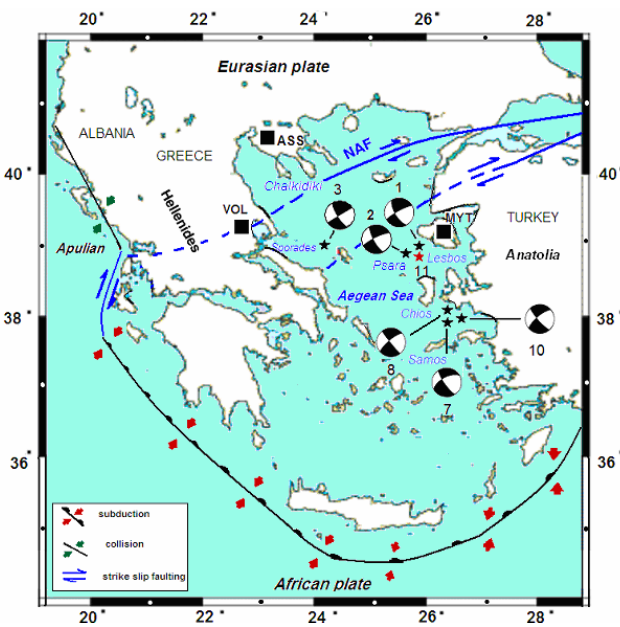

Fig. 1. Geotectonic map of Greece. All CMT fault plane solutions for the earthquakes under study of M_w≥5 listed in Table 1, from 1 January 1997 to 1 December 2007 in the area (24–27)° E , (37–40)° N. A lower hemisphere projection is used with black and white quadrants (beach balls) for compression and dilatation, respectively. Numbers attached refer to the events in Table 1. The black squares denote the positions of the VAN-SES stations sensitive to Aegean Sea, and the stars the epicenters of the earthquakes.

The northern and central Aegean is a broad zone of extension oriented approximately N-S and includes the western end of NAF which as it penetrates the region with a slip velocity of ∼25 mm/yr (Oral et al., 1995), splays out on several parallel faults. The expansion of the Aegean sea is reinforced by upwelling mantle material behind the arc, which is simply a consequence of conservation of volume when the mantle gives way before the intruding oceanic African plate. The region is characterized by high heat flow (Jongsma, 1974), which is related to thinned and deformed (stretched) continental crust. This thinning is continuing till now (McKenzie, 1972; Jackson et al., 1994). In the western part, the Sporades basin, contains a thick sequence of late Cenozoic sediments. Le Pichon et al. (1984) suggested that the Sporades basin coincides with a zone of extreme lithospheric stretching and that the crustal thickness is locally reduced to only 15 km.

The central Aegean has high heat flow, approximately three times higher than the surrounding eastern Mediterranean. It exhibits positive Bouguer and magnetic anomalies and is dominated by extensional tectonics with north-east and south-east trending faults (Jongsma, 1974; Le Pichon and Angelier, 1979; Makris, 1978; Makris and Vees, 1977; Makris and Todt, 1978; McKenzie, 1978).

Various studies reveal that two kind of mechanisms are mainly predominant in this region: the normal and the strike-slip types. In the western part (including a zone of mainland) the stress regime is extensional with normal faulting and T-axes trending NNW–SSE (Kiratzi and Louvari, 2003). In the central and eastern Aegean, right lateral strike-slip faults trending in NE-ENE (Kiratzi et al., 1991; Armijo et al., 1996; Koukouvelas and Aydin, 2002; Kiratzi and Louvari, 2003) as sub-branches of the western end of NAF, mostly prevail. The complexity of the plate interactions in Aegean Sea along with the crustal deformation are responsible for the large number of destructive earthquakes in the area.

In this paper we deal with the SES signals that preceded the large earthquakes in central and eastern Aegean Sea during the last decade, focusing on the investigation of possible correlation of their features with the regional tectonics.

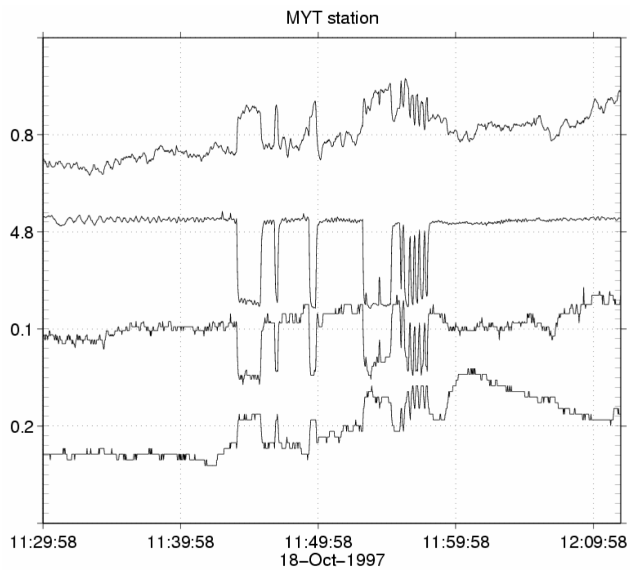

Fig. 2. Recordings at various channels at MYT VAN station of the SES signal detected on 18 October 1997 which preceded the earthquake (event 1) that occurred on 14 November 1997 in the eastern Aegean Sea close to Psara. Case of short lead time.

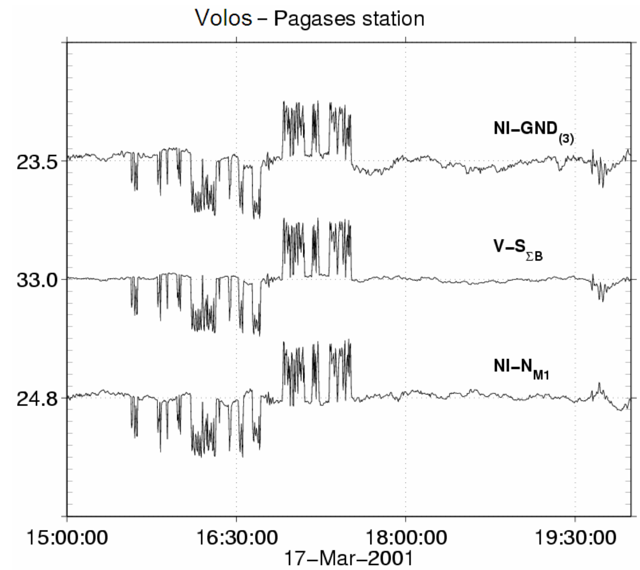

Fig. 3. Recordings at various channels at VOL VAN station of the SES signal detected on 17 March 2001 which preceded the earthquake (event 3) that occurred on 26 July 2001 in the eastern Aegean Sea close to Sporades. Case of long lead time.

2 Data and analysis

Three SES stations (Fig. 1) of the telemetric VAN network seem to be sensitive to the Aegean area; the ASS station, situated in the north, in Chalkidiki peninsula, the VOL station, in central Greece and the MYT station, on Lesvos island, close to the coast of Anatolia, Turkey, which started operating in 1997, several years later than the other two. As it will be explained below the up to now experience shows that the ASS is mostly sensitive to earthquakes occurring in northern Aegean Sea and in a northwestern narrow mainland zone, VOL is sensitive to the central Aegean and some parts of the central continental Greece while MYT mostly detects SES from earthquakes with epicentres located in the eastern Aegean sea along the western coast of Turkey.

During the period 1 January 1997 to 1 December 2007, eleven earthquakes with moment magnitude $M_W \geq 5$ occurred in the Aegean Sea (24–27)° E, (37–40)° N (Table 1). Among them 7 events were preceded by a SES signal (Varotsos, 2005; Varotsos et al., 2006b) either at MYT or VOL station while no event was detected by ASS station (Fig. 1). All these signals have been identified in advance as SES since they obey the so called ΔV/L criterion, (e.g. see Varotsos and Lazaridou, 1991; Sarlis et al., 1999). Of the remaining 4 earthquakes the two were aftershocks and the other two occurred in the mainland of Western Turkey. For all the events except for the last one, centroid moment solutions (CMT-Harvard) were available.

All 11 earthquakes numbered in chronological order along with their PDE seismic parameters (dates, epicentres), moment magnitudes M_w, source mechanism type (strike-slip, normal or thrust) based on Harvard CMT solutions and SES parameters (time of detection, station and lead time Δt), are listed in Table 1.

In the present paper we focus our interest only on the main shocks of Table 1 that occurred in the Aegean Sea. Thus, events 4 and 9 being aftershocks of the earthquakes 3 and 8, respectively, and events 5 and 6 with epicenters lying in continental Turkey, are excluded from our study.

An inspection at Fig. 1 and Table 1 shows the following remarks: all earthquakes under investigation (events 1, 2, 3, 7, 8, and 10 – we remind that for event 11 no CMT solution was available) have a focal mechanism of pure strike-slip type; their epicentres are mostly distributed in clusters in two confined areas, the Psara, southwest of Lesbos island (events 1,2 and 11) and the bay between Samos and Chios islands, in eastern Aegean (events 7, 8 and 10) while event 3 is isolated with epicentre lying north of Skyros island in the southern margins of Sporades basin, in central Aegean Sea. Although events 7, 8 and 10 are clustered not only in space but also in time, they can be considered as independent earthquakes since they have comparable magnitudes; all earthquakes were preceded by an SES recorded at MYT station except event 3 which precursory SES was detected at VOL; the lead time, Δt, values of the associated SES signals fall into two groups, one with short lead time (27–53 days) and another with much longer lead time (160–212 days).

Original SES records (Figs. 2 and 3) of the two representative cases of short and long lead time, respectively, are provided. Figure 2 depicts the recordings of various channels at

MYT station for the precursory SES signal of event 1 with short lead time (i.e. Δt=27 days). In Fig. 3 the records of different channels at VOL station of the SES signal that preceded the event 3 with long lead time (i.e. Δt=161 days) are shown. Note that the SES activities depicted in the above two figures correspond to the strongest earthquakes that occurred during the last decade in the under study area. These SES activities when analysed in the natural time domain (Varotsos et al., 2002, 2003a, b) with a procedure similar to that explained by Varotsos et al. (2006a), are found to exhibit all the properties that characterize a system that entered the critical stage but no significant difference among them was noticed.

3 Discussion

The selectivity properties of the VAN stations, sensitive to earthquakes in the Aegean Sea, seem to be constant through time. Thus, the MYT station (Fig. 1), situated in the East, detected only SES from earthquakes occurred in eastern Aegean and the VOL station responded only to the unique earthquake (event 3) with epicentre in central Aegean. On the contrary, no SES, associated to any of the under study earthquakes, was detected at ASS station since none of their epicentres was located either in the northern Aegean or in the eastern mainland zone of Greece, both consisting the ASS selectivity areas.

All earthquakes exhibit a strike-slip type of mechanism. This could be expected as their epicentres are located along sub-faults almost parallel to the major dextral strike-slip Anatolian Fault.

The two observed groups of different lead times, short and long, could may be attributed to significant local differences in the regional tectonics and geodynamics. It is worth to notice that the three events (1, 2 and 11) which belong to the cluster of Psara (Fig. 1) have all short lead times whereas events 7, 8, and 10, with epicentres falling in the cluster of Samos, exhibit much larger lead times. During the 25 year operation of the VAN network all over Greece such long lead times have been only observed in two cases; the cluster of earthquakes close to Samos island (events 7, 8, and 10) and the earthquake (event 3) southern of Sporades. In all other cases lead time values have been found to vary between few hours to some weeks.

In order to better understand these unusual long lead time values of events 3, 7, 8 and 10, we examined, with the aid of literature, the possible existence of local specific structural features underneath their epicentral areas. Indeed, we found reported for both areas, some common tectonic characteristics such as the small thickness of the crust and the high heat flow rate. In particular, the 3-D tomographic image of the shear wave velocity structure of the crust – uppermost mantle using the group velocities of Rayleigh waves showed that in a part of central Aegean sea a thin crust of approximately (20–22) km is observed, whereas the remaining Aegean sea area exhibits a crustal thickness of (28–30) km (Karagianni et al., 2005). In addition, Le Pichon et al. (1984) suggested that the Sporades basin coincides with a zone of extreme lithospheric stretching and that the crustal thickness is locally reduced to 15 km only. On the other hand heat flow measurements indicate a high heat flow in northern and central Aegean (Jongsma, 1974). Thus, the physical processes taking place inside the preseismic volume of the event 3 which is the only one located in the margins of Sporades basin in central Aegean, could be affected by these specific tectonic and geodynamic features. It will be of interest now to examine whether similar geotectonic features are observed in the second area , along the coast of western Anatolia, between Chios and Samos islands, where the other earthquakes with also long lead times (events 7, 8 and 10) are located. According to Akyol et al. (2006), the crustal structure along the western coast of Anatolia is characterized by velocities that are significantly lower than average continental values. The low velocities may be associated with high crustal temperatures, a high degree of fracture, or the presence of fluids at high pore pressure in the crust. Seismological research showed that the average depth to the brittle-ductile structural boundary is around 20 km in the studied area and a few foci are below this level (Ulugergerli et al., 2007). Additionally, high heat-flow rates and many geothermal spots have been observed in the region (Ilkisik, 1995; Aydin et al., 2005; Akin et al., 2006) indicating the existence of possible magma intrusions/chambers.

We will now discuss whether an interconnection between Δt and geodynamics can be physically understood. We rely on the pressure stimulated currents (PSC) model, which may serve as a tentative idea for the explanation of the SES generation (Varotsos and Alexopoulos, 1986). This could be shortly summarized as follows: When aliovalent impurities are added to a crystal, point defects are formed for reasons of electrical neutrality (Varotsos and Mourikis, 1974; Varotsos and Milionis, 1974). Most of these defects are electrostatically attracted by the impurities, thus forming electric dipoles which can change their orientation in space. The relaxation time of these dipoles is given by the relation

$$\tau = (\lambda \nu)^{-1} \exp(g/\mathrm{k}T) \tag{1}$$

where T denotes the temperature, λ the number of jump paths accessible to jumping species with an attempt frequency ν and g the Gibbs energy for the (re)orientation process. Before an earthquake , the hydrostatic pressure (or the stress σ in general) gradually changes with a rate b (=dP/dt). This change of pressure affects the value of g (Varotsos, 1977; Varotsos and Alexopoulos, 1978) since

$$v = (dg/dP)_T \tag{2}$$

where v denotes the migration volume or the activation volume in general (e.g. Lazaridou et al., 1985; Varotsos et al., 1999). Thus, if $v<0$, an increase of pressure results in a decrease of the relaxation time τ. One can show that a transient current, arising from a cooperative (re)orientation of dipoles, is emitted when the pressure reaches a critical value $P{=}P_{cr}$ at which the following relation holds:

$$\frac{bv}{kT} = -\frac{1}{\tau(P_{cr})} \tag{3}$$

where τ (P_{cr}) the value of relaxation time when $P{=}P_{cr}$. The fracture of the solid occurs at a pressure P_{fr} , that is in general different from P_{cr} ,thus resulting in a lead time Δt between the emission of this current and the impending earthquake given by

$$\Delta t = (P_{fr} - P_{cr})/b \tag{4}$$

We clarify that the above relation, holds only if the value b is assumed to remain constant when the stress gradually increases during the last preparatory stage of a given earthquake. On the contrary, the condition for the appearance of the emission of the current, i.e. Eq. (1), is valid irrespective if b remains constant (Varotsos, 2005). It can be shown (Varotsos et al., 1993) that

$$db(P_{cr})/dP_{cr} = 1/\tau(P_{cr}) \tag{5}$$

which reveals that $(db/dP_{cr})_T$ is always positive. Thus, if b is smaller, the critical pressure P_{cr} becomes also smaller. This reflects that the numerator of the right hand side of Eq. (4) becomes larger. Hence, a decrease of b corresponds to an increase in the lead time. This might be the case of the event 3 where the crustal thickness is smaller, than that estimated for the surrounding areas, as mentioned above.

These complex features (i.e. small crustal thickness and high heat flow), which seem to be common for both areas with long lead times, may affect the quantities dP_{cr}, P_{fr} and b involved in the right hand side of Eq. (4) in a way that the ratio $(P_{fr}{-}P_{cr})/b$ becomes larger, thus resulting in a larger value of the lead time Δt.

4 Conclusions

First, the large earthquakes that occurred during the last decade (1997–2007) in the Aegean Sea (24–27)° E , (37–40)° N have been preceded by clear SES activities. In particular, the selectivity properties of the VAN stations, sensitive to earthquakes in the Aegean Sea, seem to be constant through time. Second, two groups of lead times, a short (i.e. $\Delta t\sim$ some weeks) and a long one ($\Delta t\sim$ some months) have been observed. Third, the difference between these two groups of lead times has been discussed in terms of tectonics and geodynamics.

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